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Normal faults in thrust sheets: pre-orogenic extension, post-orogenic extension, or both?

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Abstract

In fold-and-thrust belts that experienced both pre-orogenic and post-orogenic extension, it may be difficult to establish whether observed normal faults pre-dated, post-dated, or were synchronous with thrusting. Geometrical structural patterns may be insufficient to constrain the relative chronology of extensional and contractional deformations. The systematic use of kinematic criteria makes it possible to unequivocally define the timing relationships of reverse and normal fault development, and hence to correctly unravel complex structural evolutions. Kinematic analysis in the southernmost Umbria–Marche Apennines of Italy, where both normal and thrust faults are present, revealed a history of repeated tectonic inversion, characterised by two distinct stages of extension separated by an episode of folding and thrusting. Structural overprinting relationships observed at thrust–normal fault intersections were useful for: (i) removing sequentially younger deformations; and hence (ii) separating and quantifying the effects of orogenic contraction from those of both pre-orogenic and post-orogenic extension.

1. Introduction

Inversion tectonics applies to regions that experienced a switch in deformation regime from extension to compression (positive inversion) or from compression to extension (negative inversion: Williams et al., 1989). A common characteristic of inverted regions is the modification of their previous architecture by newly formed structures (Butler, 1989; Hayward and Graham, 1989). The degree of modification may vary greatly depending upon scale, strain rate and intensity of deformation. Should deformation occur under brittle to semi-brittle conditions, pre-existing fault surfaces may either be truncated by, or reactivated as, younger faults (Welbon, 1988; Faccenna et al., 1995; McClay, 1995).

Because of their relatively long history, orogenic belts commonly bear the signature of at least one episode of positive inversion, from early passive-margin or continental rift extension to late collision (e.g. the French Western Alps: Gillcrist et al., 1987; the Spanish Pyrenees: Bond and McClay, 1995). Orogenic belts emplaced in passive-margins may also experience post-orogenic extension (e.g. the Northern Apennines: Carmignani et al., 1994; the North American Cordillera: Constenius, 1996), so that it is often difficult to establish whether observed normal faults either pre-dated or post-dated the thrusts (O'Dea and Lister, 1995). Yet, the effects of pre-thrust extension must be separated from those of post-orogenic extension, because a correct definition of the age of normal faults relative to thrusts can provide important constraints for quantitative estimates in cross-section restoration. Reliable criteria are needed to enable us to do so.

In multiply inverted settings, thrust sheets are often affected by hinterland-dipping normal faults, which terminate downwards against the thrust surfaces. In the absence of stratigraphic data, this geometrical pattern alone does not constrain the relative chronology of thrusting and normal faulting, as two distinct interpretations can be made: (i) thrust faults are older and are partly reactivated as low-angle normal faults (Fig. 1a); or (ii) thrust faults are younger, and propa-

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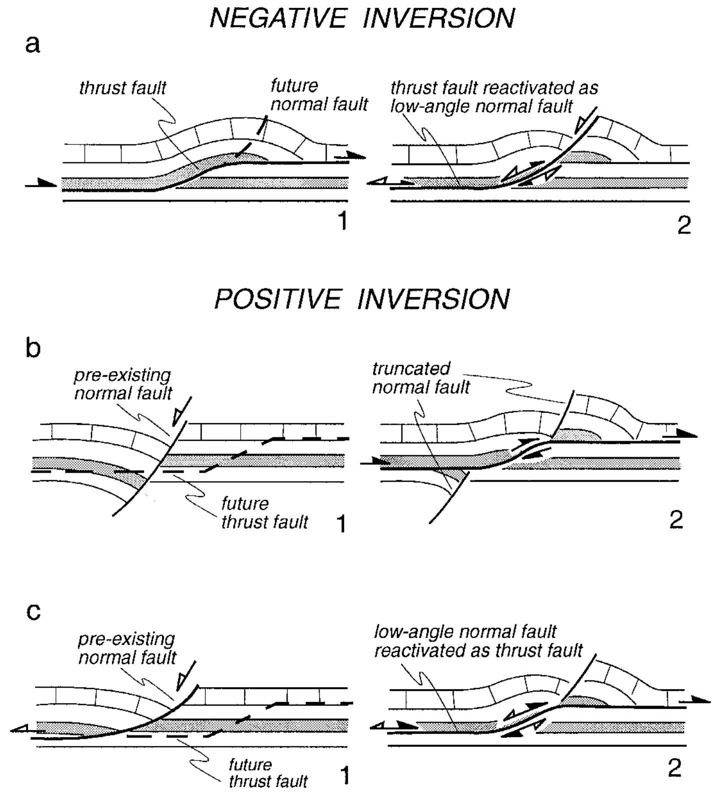

Fig. 1. Sequential diagrams to show structures with a similar final geometry that reflect different kinematic evolutions. (a) Pre-existing thrust partly reactivated as low-angle normal fault. (b) Pre-existing normal fault truncated by a younger thrust. (c) Partial reactivation of a pre-existing low-angle normal fault as a thrust.

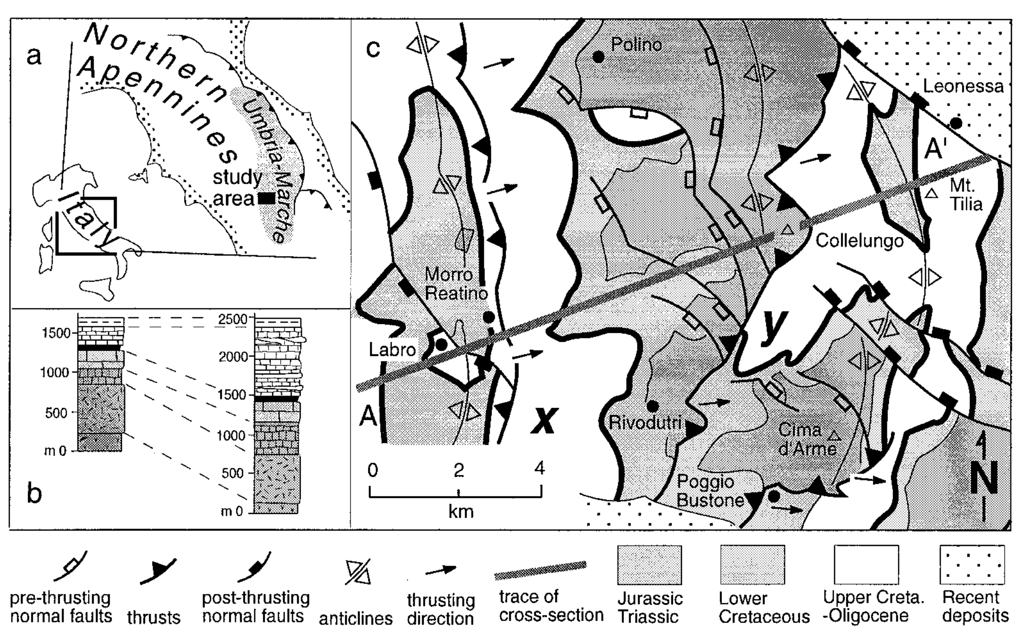

Fig. 2. (a) Location map of the Umbria–Marche Range. (b) Stratigraphic columns of measured sequences, showing lateral thickness variations in the Paleocene sections (shading matches stratigraphy from columns to maps). (c) Slightly simplified map of the Labro–Leonessa area. Localities x and y indicate the outcrop position of thrust–normal fault intersections (see Fig. 3 for more detail). The relative ages of normal faults to thrusts were inferred from kinematic data described in this paper.

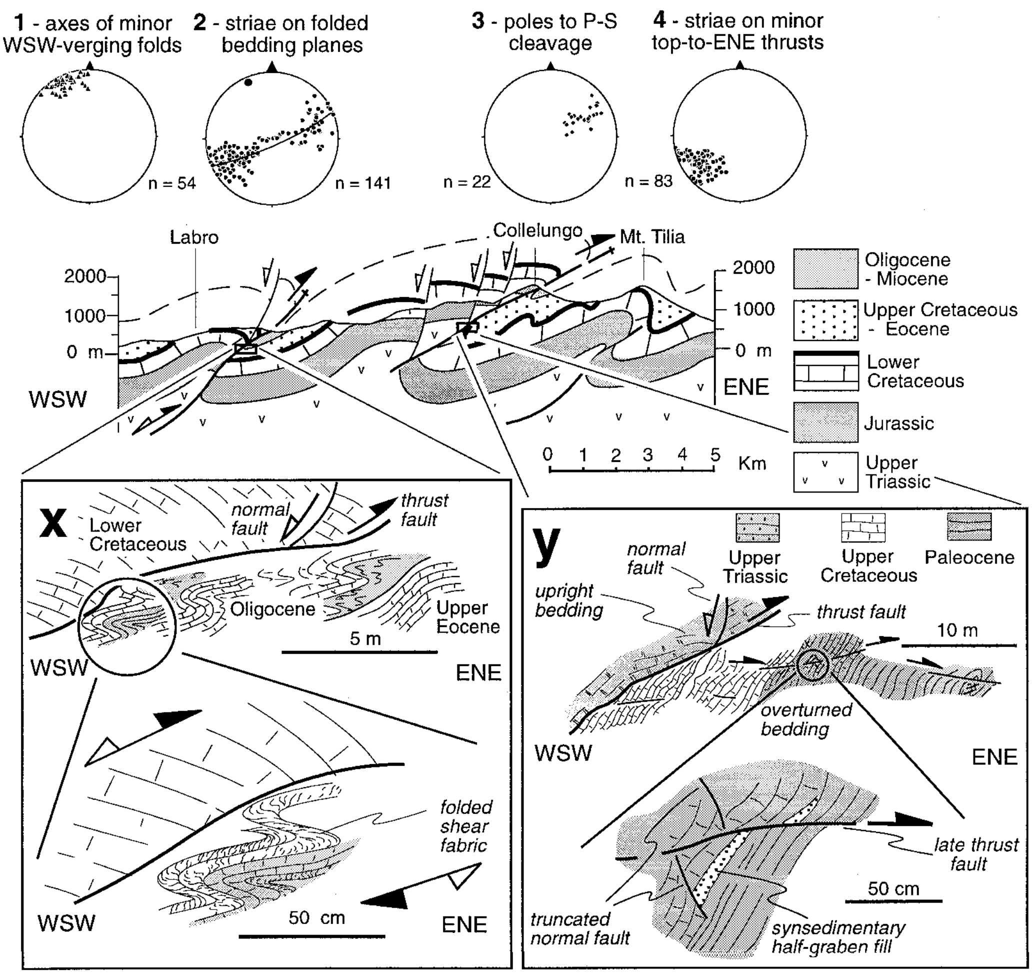

Fig. 3. The Labro–Mount Tilia cross-section (A–A′ of Fig. 2), showing hinterland-dipping normal faults terminating downward against thrusts. Mesoscopic orientation data (equal area projections, lower hemisphere) from the Labro (1,2) and Collelungo (3,4) structures are also shown. (x) Field sketch of the Labro thrust zone and close-up show that folds deform a top-to-ENE shear fabric. (y) Field sketch of the Collelungo thrust zone and close-up show a shallow WSW-dipping fault, probably a thrust, truncating a pre-existing growth normal fault and related sedimentary fill of Paleocene age.

gate across pre-existing normal faults (Fig. 1b and c). In contrast, the use of kinematic data such as sense of slip and structural overprinting relationships at thrust–normal fault intersections, may distinguish between these two mutually exclusive situations, allowing the chronology of deformation episodes to be correctly established. This paper documents a case from the Umbria–Marche Apennines of Italy where the relative timing of thrusts and normal faults was unravelled by kinematic rather than potentially misleading geometric data.

2. Geological history of the Umbria–Marche Apennines

The Umbria–Marche Range, in the Northern Apennines of Italy (Fig. 2a), is a Neogene fold-and-thrust belt that developed after the Europe–Africa collision during the Alpine orogeny (Boccaletti et al., 1980). The belt consists of Mesozoic and Cenozoic carbonates that recorded extension related to the opening and evolution of the Mesozoic Tethys Ocean (Bernoulli, 1967; Colacicchi et al., 1970). Since the Middle Miocene, as a consequence of positive inversion, the carbonate sequence was deformed by thrusts and related folds (Baldacci et al., 1967; Bally et al., 1986; Cipollari and Cosentino, 1995). Negative Plio-Pleistocene inversion (Carmignani et al., 1994; Keller et al., 1994; Lavecchia et al., 1994) produced new extensional structures that truncated and/or partly reactivated pre-existing thrusts as low-angle normal faults (Cooper and Burbi, 1986; Decandia and Tavarnelli, 1990; Barchi and Brozzetti, 1991), modifying the overall geometry of the stacked thrust pile.

The effects of contractional and extensional deformations are particularly visible in southeastern

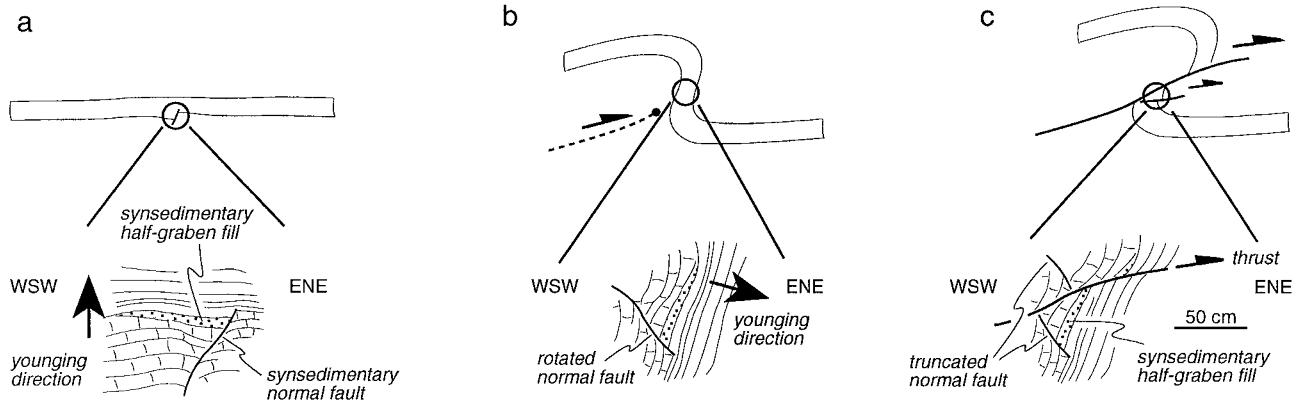

Fig. 4. Possible model to explain the structural overprinting relationships observed at Collelungo (detail in Fig. 3y). A WSW-dipping synsedimentary normal fault within a subhorizontal sequence (a) is rotated due to folding (b) and truncated by a thrust propagating across the steep fold limb (c).

Umbria, between Labro and Leonessa (Fig. 2a). The local stratigraphic sequence displays lateral thickness variations (Fig. 2b), which were controlled by WSW-dipping synsedimentary normal faults of Jurassic, Cretaceous and Paleogene age (Tavarnelli, 1996). Two main NNW–SSE-trending, WSW-dipping stepped thrusts of Late Messinian age, the Labro and Collelungo structures, separate three stacked thrust sheets and related folds (Fig. 2c). These structures are overprinted by Plio-Pleistocene NNW–SSE-trending normal faults that dip either toward the hinterland or toward the foreland. Hinterland-dipping faults are developed in the hanging walls of pre-existing thrusts and merge downward with the thrust surfaces producing geometries such as in Fig. 1. Foreland-dipping faults truncate all pre-existing structures, clearly post-dating thrusting: their geometry and kinematics will not be considered here.

Since many faults of different ages strike and dip consistently, they are suitable candidates for reactivation during repeated tectonic inversion. Of the criteria proposed by Holdsworth et al. (1997) to detect fault reactivation, only stratigraphic and structural criteria are easy to use directly in the field. However, since the stratigraphic record of pre-, syn- and post-orogenic deposition is almost completely lost due to recent uplift and erosion, the local deformation history could only be unravelled by means of structural overprinting relationships. Kinematic data collected at the thrust–normal fault intersections where overprinting occurred (locations x and y of Fig. 2c), are described below.

3. Kinematic analysis at Collelungo

Normal fault–thrust intersections are particularly well-exposed at Collelungo (y, Fig. 2c). The main structure consists of an asymmetrical ENE-verging anticline–syncline pair truncated in its common overturned limb by a gently WSW-dipping thrust (Fig. 3). Its hanging wall is affected by an array of hinterland-dipping normal faults that cut the Mesozoic–Cenozoic formations in the backlimb of the anticline and terminate downward against the thrust (Figs. 2c and 3), producing displacements of up to 900 m.

Analysis of mesoscopic fabrics along the thrust fault and in adjacent rocks revealed a relatively simple kinematic history, characterised by sequentially younger stages of folding and thrusting. The earliest recognised contractional fabric is a steeply WSW-dipping pressure-solution cleavage (3 in Fig. 3), which is axial planar to the footwall syncline and to its parasitic minor folds. Cleavage domains are bed-normal in fold hinges, where they produce slightly fanning patterns converging towards the fold inner arcs, and oblique to bedding in fold limbs, where they produce small (i.e. less than 1 cm) apparent offsets. The smallest bedding–cleavage angles (15–20°) occur at inflection points between adjacent fold pairs. The change in bedding–cleavage angles around fold hinges, and the slight convergence of cleavage domains toward the fold inner arcs, indicate that pressure-solution was triggered during fold nucleation and continued to operate during fold amplification (e.g. see Alvarez et al., 1976, and references therein). Consistently, the bedding–cleavage relationships observed at Collelungo are here interpreted to mean that cleavage development and folding were roughly coeval. Folding was followed by the upward propagation of the Collelungo thrust, which offset the overturned limb of the footwall syncline (Fig. 3y). The main thrust-related structures consist of subhorizontal minor faults locally coated by fibrous calcite veins, whose steps indicate displacement of the thrust hanging wall to ENE (4 in Fig. 3).

When seen in detail, however, structural overprinting relationships are more complex. At the thrust–normal fault intersection (detail in Fig. 3y), overturned Paleocene pelagic carbonates are affected by a steeply ENE-dipping fault, which loses displacement downward to a tip point and causes local stratigraphic variations in a 10 cm thick calcarenite bed. This structure is interpreted to be a synsedimentary normal fault of Paleocene age, which was rotated during folding. The rotated normal fault is truncated by a subhorizontal fault, which, although extensional with respect to bedding, also offsets axial planar pressure-solution cleavage, thus post-dating folding. Based on these relationships, the subhorizontal fault is interpreted as a mesoscopic thrust that propagated across the overturned fold limb. A possible sequence of deformation stages to explain the observed geometrical pattern is proposed in Fig. 4. No evidence was found for late top-to-WSW shear overprinting thrust-related fabrics, nor for early top-to-ENE shear pre-dating cleavage development.

4. Kinematic analysis at Labro

Normal fault–thrust relationships are also observed along the Labro thrust, which trends NNW–SSE and gently dips toward WSW (Fig. 2c). An important hinterland-dipping normal fault, with a maximum displacement of 750 m, deforms the hanging wall of the thrust and merges downward with the thrust surface (Fig. 3). In the area where the thrust and the normal fault meet (location *x* of Fig. 2c), the Oligocene marls of the footwall are deformed by mesoscopic NNW–SSE-trending (1 in Fig. 3), WSW-facing recumbent anticlines and synclines with gently ENE-dipping to subhorizontal axial surfaces (Fig. 3x). These folds overprint an earlier fabric, consisting of a gently WSW-dipping pressure-solution cleavage and bedding-parallel shear surfaces, which are interpreted to be produced during thrusting (detail in Fig. 3x). Mechanical striations and calcite fibres on bedding-parallel shear surfaces are scattered about a gently NNW-plunging axis, which is parallel to the axial plunge of the minor WSW-facing folds (2 in Fig. 3). When the effects of folding are eliminated and bedding is restored to horizontal, mechanical striations, calcite fibres and the dip of cleavage domains consistently indicate a top-to-ENE sense of shear.

5. Repeated inversion in the Labro–Leonessa area

The data described above suggest a different relative chronology of contractional and extensional deformations for the structures observed at Collelungo and Labro. At Collelungo, the normal faults in the hanging wall of the main thrust could have developed either before or during thrusting. Extension is theoretically predicted in some cases for layered sequences as they are transported over stepped thrust faults (Sanderson, 1982). Also, elastic stress relaxation can generate faults with a sense of slip opposite to that on the dominant structure (Du and Aydin, 1996). These possible explanations account for the presence of small normal faults in the hanging wall of major thrust faults in many orogenic belts (e.g. the Scottish Caledonides: Coward, 1982; the eastern Alps: Ratschbacher et al., 1989; the eastern Rockies: Yin and Kelty, 1991). However, the amount of extension produced in this way is very small when compared to the amount of displacement along the host thrust (Coward et al., 1992). The cumulative offset of the normal faults in the hanging wall of the Collelungo thrust approximately equals the displacement produced by the thrust (Fig. 3). Therefore, a syn-orogenic origin for these extensional structures seems unlikely.

The small synsedimentary normal fault in the footwall of the thrust at Collelungo (detail in Fig. 3y) dips toward the hinterland, when the effects of both folding and thrusting are eliminated and bedding is restored to horizontal (Fig. 4a). This geometry is consistent with the larger faults in the hanging wall of the thrust (Fig. 3). This similarity of geometry is interpreted to mean that both sets of extension faults are probably coeval and that they pre-dated ENE-directed thrust propagation. Also, the lack of kinematic evidence for shear-sense reversal along the thrust rules out fault reactivation by negative inversion (Fig. 1a), and hence, is consistent with the hypothesis of positive tectonic inversion. Thus, it is believed that early hinterland-dipping normal faults were truncated and passively incorporated in an ENE-directed thrust sheet during orogenic contraction (Fig. 1b). It is, however, possible that some or all of these faults were slightly reactivated with extensional slips as they were truncated and transported during thrusting.

At Labro, the structural signature is different. Pressure-solution cleavage and bedding-parallel shear surfaces, corrected for the effects of late folding, indicate a top-to-ENE sense of shear. These fabrics were probably produced during thrust sheet emplacement. The refolding of thrust-related fabrics by means of minor WSW-facing folds is interpreted to mean a reversal in the shearing sense, from top-to-ENE to top-to-WSW in the vicinity of the thrust.

Could this late folding represent the effects of reactivation of the thrust surface as a low-angle normal fault? Generally, folding of subhorizontal layering is regarded as a contractional mechanism responsible for crustal shortening. However, should layering be in non-horizontal attitude because of previous deformation, folding could develop during shear related to displacement on an adjacent extensional fault (Wheeler

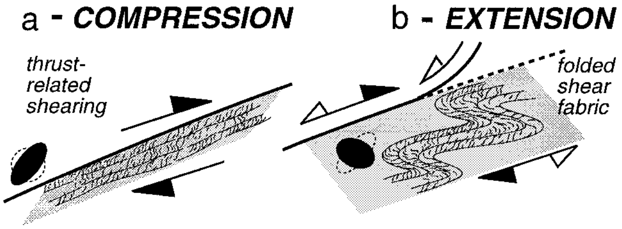

Fig. 5. Sequential diagrams to show recumbent folding produced by extensional shear resulting from shear-sense reversal along a pre-existing thrust. Reactivation is accompanied by broadening of the fault-related shear zone (shaded).

and Butler, 1994; Daniel et al., 1996). Bedding in the footwall of the Labro thrust dips 25–30° towards WSW, and this dip was probably acquired during thrusting (Fig. 5a). A shear-sense reversal along the thrust could have produced recumbent folding of gently WSW-dipping strata in its footwall (Fig. 5b). Structural overprinting relationships are therefore consistent with the hypothesis of negative tectonic inversion (Fig. 1a), where an early thrust surface was partly reactivated as low-angle normal fault during post-orogenic extension. The shear-sense reversal during reactivation was probably accompanied by broadening of the fault-related shear zone (Fig. 5), a behaviour commonly observed in faults which were reactivated under brittle to semi-brittle deformation conditions (e.g. see Holdsworth et al., 1997). Broadening of the fault zone would account for the occurrence of recumbent folds not just beneath the reactivated fault, but also immediately beneath a segment of the thrust that was not reactivated (Figs. 3x and 5b). In addition, broadening of the fault zone probably occurred at the expense of the thrust footwall sequence, which could explain why the footwall itself recorded folding while the reactivated fault surface did not (Figs. 3x and 5b).

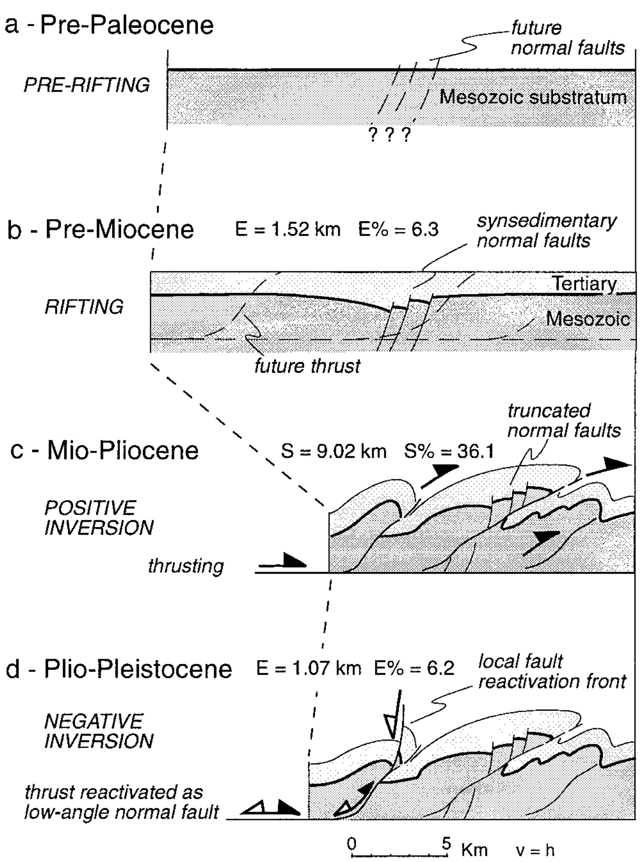

Fig. 6. Inferred history of repeated tectonic inversion across the Labro–Mount Tilia section.

In summary, although geometrically very similar, the Labro and Collelungo structures have recorded two different kinematic evolutions. The inferred history of repeated tectonic inversion from structural overprinting relationships is illustrated in Fig. 6. During the Paleocene, pre-orogenic, hinterland-dipping normal faults affected the Mesozoic substratum. They controlled the deposition of pelagic carbonates (Fig. 6a and b), producing thickness variations in the Cenozoic sequence. During the Mio-Pliocene interval, the Labro, Collelungo and Mount Tilia thrusts developed (Fig. 6c). Pre-existing normal faults were truncated and passively carried in the hanging wall of the Collelungo thrust. A late extension fault of probable Plio-Pleistocene age developed in the hanging wall of the more internal Labro thrust, branching downwards and partly reactivating the thrust surface as a low-angle extensional fault (Fig. 6d). The map trace of this normal fault, therefore, could help locate the position of the local fault reactivation front during post-orogenic extension. Shortening produced during syn-orogenic compression is 9 km, whereas the amounts of pre-orogenic and post-orogenic extension are 1.5 km and 1 km, respectively (Fig. 6). Although, these values just refer to the local Labro–Mount Tilia cross-section, they could have regional implications when considered in the context of multiple inversion recorded by the Apennine orogenic system. Published regional balanced cross-sections across the outer zones of the Central Apennines (Ghisetti et al., 1993) were restored with the assumption that all map-scale normal faults post-date thrusting. Thus, the effects of all normal faults were eliminated first, and the deformation of folds and thrusts, secondly. Since many regionally important normal faults pre-date thrusting (Tavarnelli, 1996; Calamita et al., 1997), their effects should be eliminated *after* those of contractional structures. Therefore, a systematic use of the criteria outlined in this paper could significantly improve our understanding of the kinematic evolution of this particular orogenic belt, and the relative magnitudes of separate tectonic events.

6. Concluding remarks

The structural evolution of orogenic belts is often unravelled by means of simple geometrical relationships. However, in those belts which owe their architecture to repeated episodes of positive and negative tectonic inversion, the geometrical interactions between thrusts and normal faults may not sufficiently constrain the relative age of extension and contraction. Kinematic analysis, instead, provides unequivocal criteria that make it possible: (i) to correctly unravel the timing of normal and thrust fault development; (ii) to separate and quantify the effects of orogenic contraction from those of pre- and post-orogenic extension; and (iii) to locate the fronts of fault reactivation during post-orogenic extension.

The results from structural analysis in southeastern Umbria provide useful information to correctly define a relative chronology of tectonic events in the Northern Apennines of Italy. The overprinting relationships of mesoscopic fabrics related to larger structures in the area between Labro and Leonessa outline a complex history of repeated inversion, with two distinct episodes of extension separated by a stage of folding and thrusting. Further study of minor structures occurring at thrust–normal fault intersections in adjacent areas could provide additional constraints to help unravel the evolution of the entire apenninic fold-and-thrust belt.

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