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Structural evolution of a foreland fold-and-thrust belt: the Umbria–Marche Apennines, Italy

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Abstract—Outcrop-scale structures that record a progressive sequence of deformation can be used to clarify the kinematic evolution of an entire fold-and-thrust belt. The temporal progression of the compressional deformation as reconstructed by means of a mesoscopic structural analysis provides a key for unraveling the kinematic history of the Umbria–Marche Apennines (central Italy). Overprinting relationships at outcrop-scale allow for the recognition of three distinct structural stages which are, in sequence: A, layer-parallel shortening; B, folding; C, thrusting. Individual stages are explained in the framework of a progressive deformation model, where shortening of the sedimentary cover was continuous and occurred during a single contractional episode as a consequence of tip-line folding processes. A comparison of this history with those reported from other fold-and-thrust belts shows that layer-parallel shortening, folding and thrusting are sequentially dominant processes in areas which have experienced compressional deformation. © 1997 Elsevier Science Ltd. All rights reserved.

INTRODUCTION

Folding and thrusting are the principal macroscopic modes of deformation by which the upper part of the continental crust accommodates horizontal shortening during orogenesis. The structures originated by both processes are often geometrically and kinematically linked (Elliott, 1976; Suppe, 1985; Jamison, 1987; Mitra, 1990). Nevertheless, situations are also known where folds and thrusts, although occurring together, formed at different times (Crittenden, 1974; Geiser and Engelder, 1983; Van Der Pluijm, 1987; Hibbard and Hall, 1993), and therefore a kinematic link between folding and thrusting should not be assumed. An interesting question is how these tectonic processes relate to each other and evolve through time.

Observations of minor structures and their overprinting relationships provide a powerful tool to unravel the evolution of related map-scale structures, thus making it possible to test the hypothesis of linked versus unrelated fold-and-thrust interaction. This approach has proven successful in the study of fold-and-thrust belts which are exposed at shallow (Droxler and Schaer, 1979; Butler, 1992) to intermediate structural levels (Gray and Mitra, 1993; Fisher and Anastasio, 1994).

The Umbria–Marche Apennines of Italy, due to a combination of excellent outcrop and high relief, provide a suitable ground for the study of fold-and-thrust interaction. Regional cross-sections show thrust faults cutting steep fold limbs (De Feyter *et al.*, 1986; Bally *et al.*, 1986; Barchi *et al.*, 1988; Calamita *et al.*, 1994; Alberti *et al.*, 1996). This geometry has led to opposing interpretations on how folds and thrusts interact. One view is that folds and thrusts are independent, forming at different times (i.e. folds form first and are later truncated by thrusts produced during a distinct deformation episode separate from folding: Lavecchia *et al.*, 1983; Lavecchia, 1985; Barchi *et al.*, 1988). The other view is that folds and thrusts are related and develop together during a single deformation episode (Decandia and Giannini, 1977; Koopman, 1983; Calamita, 1990; Tavarnelli, 1993a). Either view implies an episodic (i.e. two-phase) or a continuous (i.e. progressive) deformation history, respectively.

The purpose of this paper is to provide further constraints to help unravel the structural evolution of the Umbria–Marche Apennine using overprinting mesoscopic fabrics and their relationships to larger structures. Evidence from integrated outcrop- and map-scale examples is consistent with a progressive deformation model, where folding and thrusting are interpreted as kinematically linked processes.

GEOLOGICAL SETTING

The Umbria–Marche Apennines are an arcuate fold-and-thrust belt which occupies the outer zones of the Northern Apennines of Italy (Fig. 1a). The belt developed during the Neogene, following the closure of the Ligurian Ocean and the consequent continental collision between the European Corsica–Sardinia Margin and the African Adria Promontory (Boccaletti *et al.*, 1971). Two main physiographic–structural provinces are distinguished: the Umbria–Marche Range and the Marchean Foothills Zone (Deiana and Pialli, 1996; Fig. 1a). Interpretations of the tectonic evolution of the belt based on palaeomagnetic data are not univocal (Channell *et al.*, 1978; Hirt and Lowrie, 1986), and the stratigraphic record of the foredeep deposits, extensively preserved in the Marchean Foothills Zone, is missing in the Umbria–

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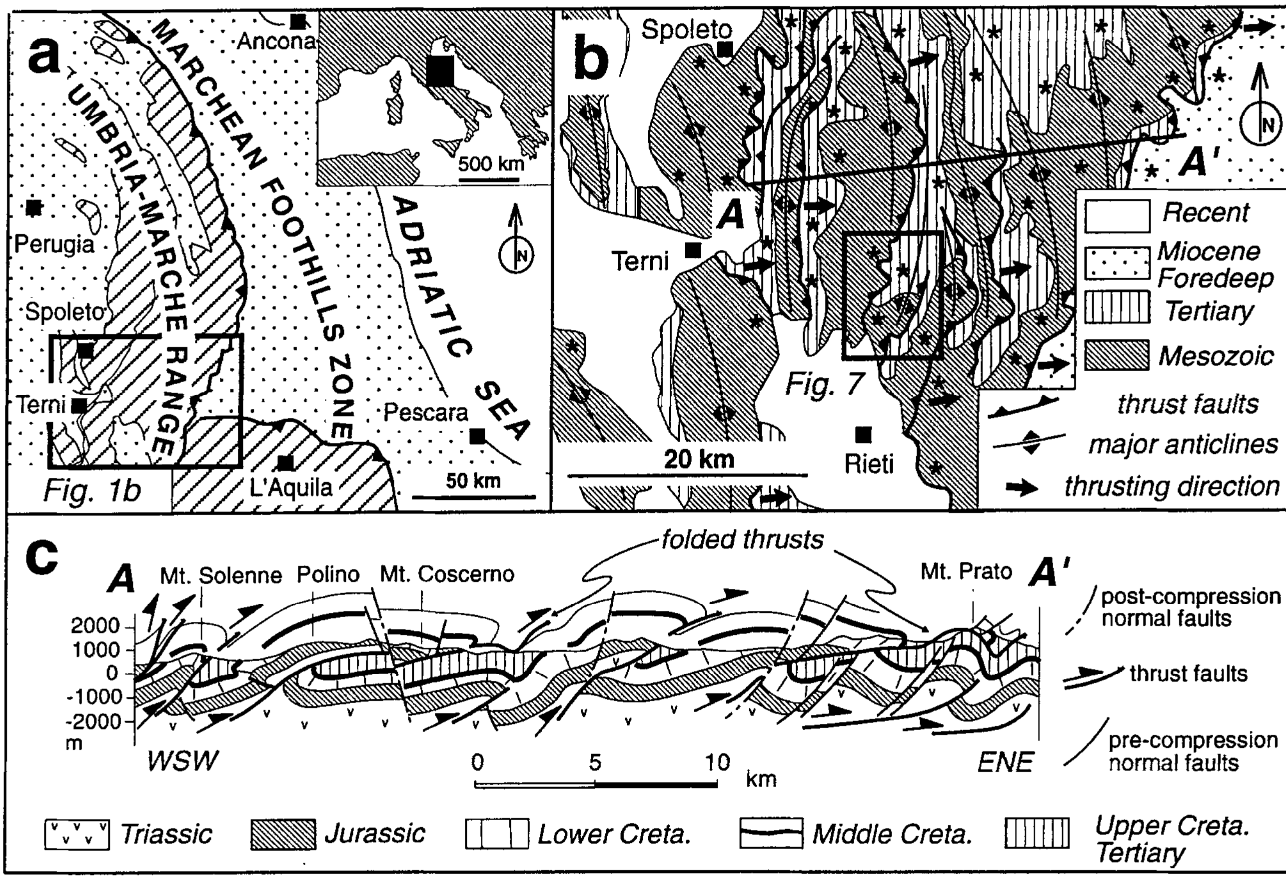


Fig. 1. (a) Tectonic sketch map of the outer zones of the Northern Apennines. (b) Simplified structural map of the study area (effects of post-orogenic extension are not shown); asterisks indicate the outcrop location of the structures described in this paper. (c) Balanced cross-section (A–A′ trace in b) through the southern part of the Umbria–Marche Range (modified after Alberti *et al.*, 1996).

Marche Range. Therefore, structural data are the only available evidence to constrain the deformation history of the latter province. The stratigraphic sequence cropping out in the Umbria–Marche Apennines is mainly composed of Meso-Cenozoic carbonates unconformably overlain by Miocene foredeep deposits. The Jurassic–Tertiary sections display abrupt lateral thickness variations controlled by synsedimentary normal faults (Bernoulli, 1967; Colacicchi *et al.*, 1970; Decandia, 1982). This mechanically heterogeneous rock pile forms the sedimentary cover, which was detached from the underlying basement during the Late Miocene–Early Pliocene interval (Patacca *et al.*, 1990) and experienced both folding and thrusting. Map-scale folds trend NNW–SSE, i.e. perpendicular to the mean ENE thrusting direction (Fig. 1b). A general hinterland-to-foreland thrust propagation is recorded by the synorogenic deposits of the Marchean Foothills Zone, which become progressively younger towards the east (Ricci Lucchi, 1986). Compressional deformation, which occurred under non-metamorphic conditions at burial depths not greater than 3.5 km (Corrado, 1995), was mainly accommodated by pressure-solution mechanisms (Alvarez *et al.*, 1976), whereas cataclasis was localized along the major thrust faults.

Since Pliocene time the region was affected by normal faulting (Elter *et al.*, 1975). Post-contractional extension, although locally very important, did not significantly modify the overall architecture of the belt (Fig. 1c). Therefore, its effects, along with synsedimentary pre-contractional extension, will not be considered in this study.

STRUCTURAL STAGES

During Neogene compression numerous minor structures formed with geometries and orientations consistent with the average NNW–SSE trend of the larger-scale fold-and-thrust structures (Koopman, 1983; Lavecchia, 1985; Tavarnelli, 1994). This section outlines the nature and relationship of minor structures generalized from many different outcrops in the southern sector of the Umbria–Marche Range (Fig. 1b). A detailed description of individual field locations is presented elsewhere (Tavarnelli, 1993b). Minor structures are placed into a sequence with three main stages (layer-parallel shortening, folding, and thrusting) which may be recognized in individual outcrops, although the full sequence is rarely developed. Mesoscopic fabrics are present throughout the stratigraphic sequence, and their overprinting relationships are observed in most exposed rocks.

Stage A: layer-parallel shortening

The earliest recognized stage of deformation is an episode of layer-parallel shortening (LPS). This is mainly expressed by development of bedding-normal pressure-solution cleavage, wedge faults and shear fractures. Cleavage shape and spacing vary with lithology. The morphology of the cleavage domains is wavy through sutured to planar, in coarse-, medium- and fine-grained rocks. The spacing of the cleavage domains ranges from millimetres, in the less competent units, to centimetres, in the most competent units (Fig. 2a). The mean bedding–LPS cleavage intersection lineation trends N 161° E (Fig. 3a). Shortening, which was taken up by dissolution in the carbonate layers, was accommodated by development of minor wedge faults in the interbedded chert nodules (Alvarez *et al.*, 1976) and in competent siliceous limestones (Fig. 2b). Layer-parallel shortening was accompanied by development of a set of conjugate shear fractures whose mean trend is N 164° E (Fig. 3b). The traces of the obtuse bisectors of these shear fractures on bedding are parallel to the LPS cleavage–bedding intersection lineations (Fig. 2c).

Stage B: folding

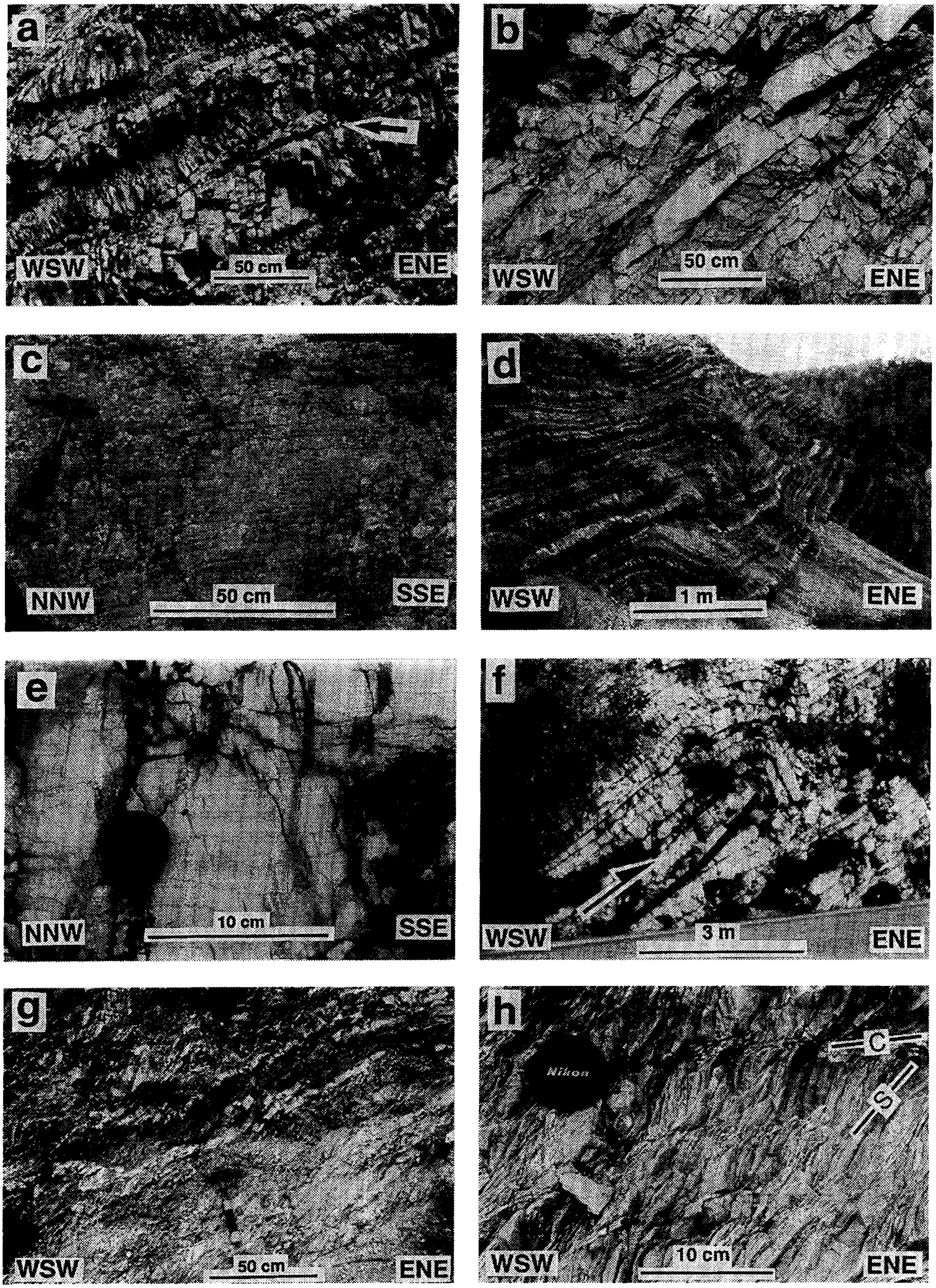
The second recognized structural stage is an episode of folding. Mesoscopic folds range in both wavelength and amplitude from centimetres to hundreds of metres. These structures, defined after Nickelsen (1963) as second- and third-order folds, are parasitic to the mapped anticlines and synclines, defined as first-order folds. Their geometry in profile is concentric and ranges from angular to curvilinear. The shape of second- and third-order folds changes with their position in the host first-order anticlines and synclines, from open and symmetrical in the hinge zone to tight and strongly asymmetrical in the limbs (Fig. 2d). The three-dimensional fold geometry is conical to periclinal, with marked along-strike plunge variations. The mean fold-axis trend is N 163° E (Fig. 3c). Although observed throughout the entire stratigraphic sequence, with the exception of the Lower Liassic Calcare Massiccio Fm., mesoscopic folds are particularly common in the Cretaceous–Tertiary formations. Folding was locally accompanied by development of related minor structures, such as cleavage, veins and small faults. The overprinting relationship among these structures provides some indication about the relative timing of folding as well as the strain distribution in minor folds. Two main sub-stages were recognized within folding (fold initiation; fold amplification and tightening).

Sub-stage B1: fold initiation. Pressure-solution cleavage produced during layer-parallel shortening is locally overprinted by cleavage domains which are bedding-normal in fold hinges and oblique to bedding in fold limbs (Fig. 4). This suggests that the latter fabrics are roughly coeval with the early stages of folding. Fold-related cleavage domains are convergent towards the fold inner arcs, whereas radial extension veins occupy the fold outer arcs (Fig. 4a), a geometry consistent with tangential–longitudinal strain (Ramsay, 1967). Bedding–cleavage angles in the fold limbs are 60°–70° in competent limestones and may decrease to 20° in less competent marls. This lithologically-controlled cleavage refraction pattern outlines a bedding-parallel shear towards the fold hinges (Fig. 4b). Fold-related cleavage is truncated by minor flexural-slip thrusts (Tanner, 1989) which cut through bedding with stepped, ramp-flat geometries (Fig. 4c). The observed fold geometry is therefore interpreted to result from a combination of tangential–longitudinal strain, layer-parallel shear and flexural-slip mechanisms.

Sub-stage B2: fold amplification and tightening. The three-dimensional geometry of minor folds is generally periclinal, more rarely cylindrical. Particularly abundant in fold culminations are fold axis-normal extension fabrics, such as mode I fractures and fibrous calcite veins (Fig. 2e). Both fabrics, whose average trend is WSW–ENE (Fig. 3d), overprint fold-related cleavage and flexural-slip thrusts, and are probably coeval. The coexistence of unfilled fractures and fibrous veins indicates that fold-axis normal extension was partly gradual. The observed along-hinge stretching could imply regional extension in a NNW–SSE direction after folding and prior to thrusting (Lavecchia *et al.*, 1983; Lavecchia, 1985). Alternatively, fold-axis parallel extension can be regarded as part of the folding process itself, due to periclinal fold amplification by anticlastic bending (Dietrich, 1989; Price and Cosgrove, 1990; Rowan, 1993). The parallelism between fold axes, poles to mode I fractures and calcite fibres (Fig. 3c & d) is consistent with the hypothesis of a common origin for all of these fabrics. Therefore, along-hinge extension is interpreted here as resulting from periclinal fold amplification. Fold amplification was accompanied by fold tightening. This is primarily expressed by bedding-parallel cleavage which offsets both bedding-normal cleavage and flexural-slip thrusts in the steep fold limbs. The stylolitic peaks are oblique to dissolution surfaces suggesting that dissolution took place along pre-existing bedding-parallel discontinuities, such as older stylolites related to diagenesis or synsedimentary extension (Winter and Tapponnier, 1991). Pressure-solution along these discontinuities was probably reactivated when sub-horizontal compression was at a high angle to bedding (i.e. in the steep limbs of tight folds).

Stage C: thrusting

The third recognized structural stage is an episode of thrusting during which minor reverse faults, thrusts and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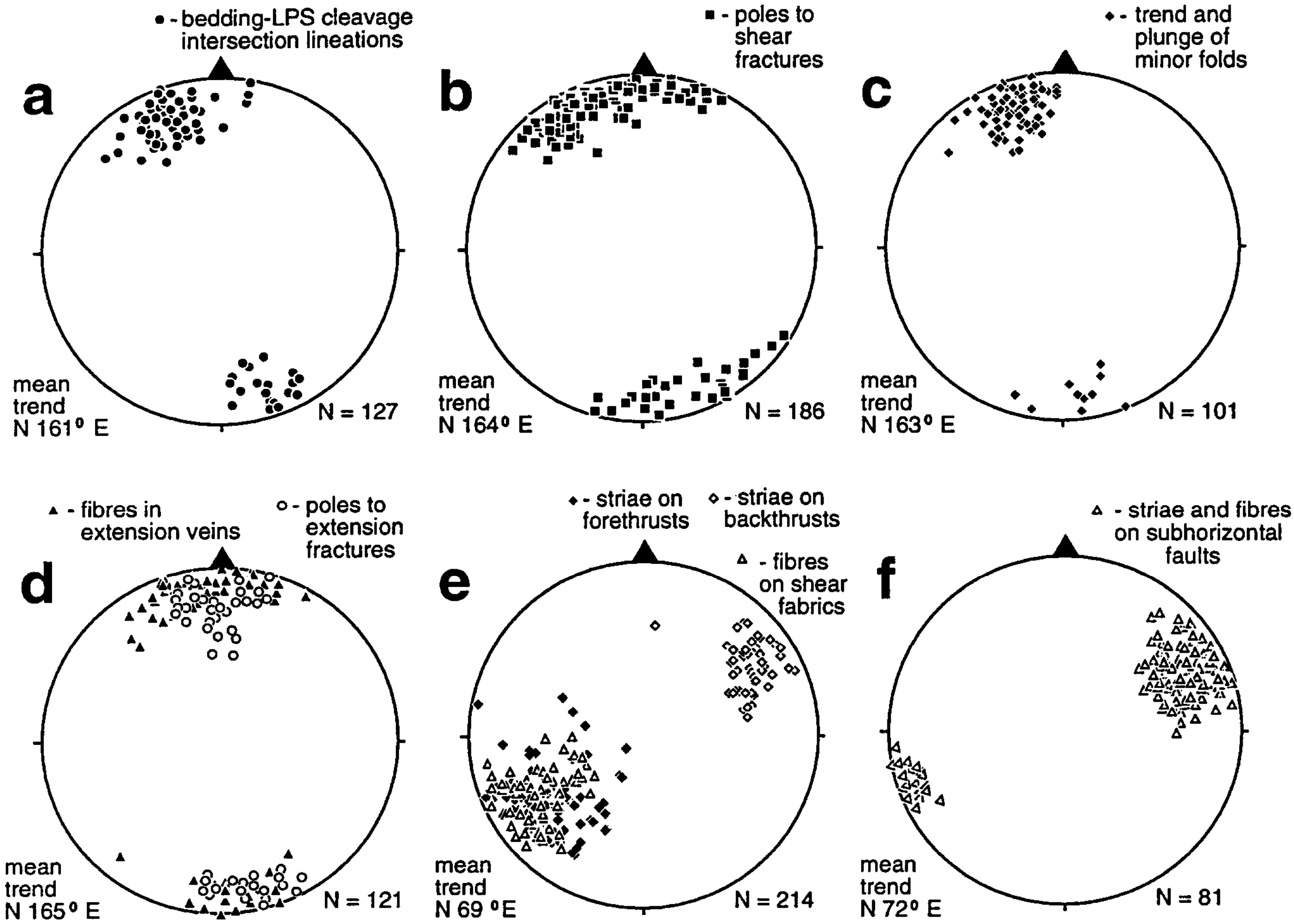

Fig. 3. Orientation of the minor contractional structures (equal area projections, lower hemisphere) produced during stage A (layer-parallel shortening: projections a, b), stage B (folding: projections c, d), and stage C (thrusting: projections e, f). These structures were used to infer a mean shortening direction for each structural stage (LPS pressure-solution cleavage was assumed to approximate the plane of finite shortening). The mean shortening direction for stage A (reconstructed with the data of projections a, b) is N 72° E; the mean shortening direction for stage B (reconstructed with the data of projection c) is N 73° E; the mean shortening direction for stage C (reconstructed with the data of projections e, f) is N 70° E. The mean extension direction inferred from poles to mode I fractures and fibres in extension veins (which were assumed to parallel instantaneous and incremental/finite extension, respectively), is N 165° E, consistent with the general WSW–ENE shortening direction. The parallelism in the obtained directions is consistent with the hypothesis of an unaltered stress field, from layer-parallel shortening, through folding to thrusting.

shearing fabrics were produced. Overprinting relationships among these minor thrust-related fabrics allows for recognition of two sub-stages (thrust and shear fabric development; thrust-related shear zone broadening).

Sub-stage C1: thrust and shear fabric development. Fold-related structures are overprinted by minor reverse faults. These structures, particularly abundant in the Jurassic–Cretaceous formations, produce displacements which range from a few centimetres to a few hundreds of metres. Their mean dip direction is towards WSW (Fig. 2f), with striations indicating hanging wall transport toward N 69° E (Fig. 3e). ENE-dipping back thrusts, although less abundant, are also present. Minor thrust faults cut through bedding at different angles, depending upon the dip of strata during thrusting. The cutoff angles

Fig. 2. Minor structures developed during the Neogene compressional deformation. (a) Spaced pressure-solution cleavage in cherty limestones (Lower Cretaceous Maiolica Fm.); the chert nodules are shortened by means of minor contractional wedge faults (arrow). (b) Wedge fault producing repetition of a competent siliceous limestone layer (Upper Cretaceous–Oligocene Scaglia Fm.). (c) Conjugate shear fractures as they appear looking down the bedding plane: the obtuse bisector coincides with the bedding–cleavage intersection lineation (Upper Cretaceous–Eocene Scaglia Fm.). (d) Asymmetrical parallel folds in the upright limb of the Mt Tilia anticline (Middle Cretaceous Marne a Fucoidi Fm., location in Fig. 7a). (e) Fold axis-normal extension veins in the culmination of a minor periclinal fold (Upper Cretaceous–Palaeogene Scaglia Fm.). (f) Minor reverse fault whose displacement decreases upwards into a pair of asymmetrical third-order folds (Lower Cretaceous Maiolica Fm.). (g) Array of imbricate minor thrusts where dip of individual faults decreases towards ENE (i.e. the foreland), suggesting a hinterland-to-foreland, piggy-back thrusting sequence (Upper Cretaceous–Oligocene Scaglia Fm. in the footwall of the Mt Solenne thrust, location in Fig. 1c). (h) Minor structures related to shearing fabric development (sub-stage C1) consisting of pressure-solution cleavage surfaces (*S*) and shear planes (*C*) (Upper Cretaceous–Oligocene Scaglia Fm. in the footwall of the Mt Coscerno thrust, location in Fig. 1c).

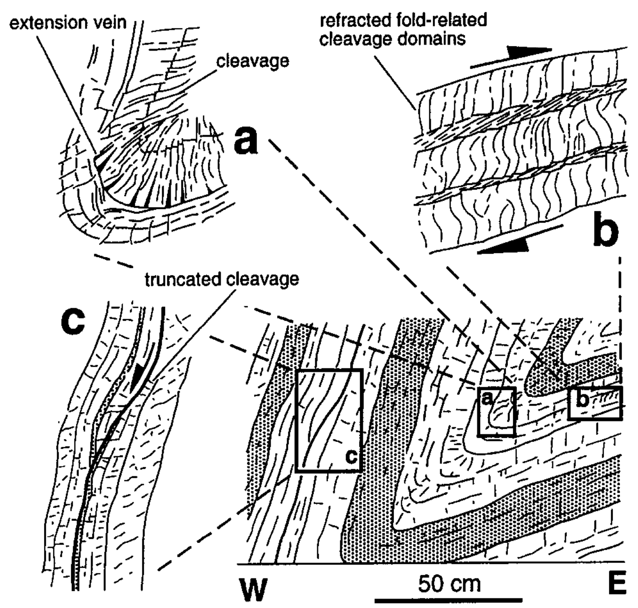

Fig. 4. Minor structures developed during fold initiation (sub-stage B1). (a) Convergent cleavage fans and outer arc radial extension veins in fold hinges. (b) Cleavage refraction phenomena in alternating limestones and marls. (c) Minor contraction fault off-setting cleavage as a consequence of flexural-slip (Upper Cretaceous–Oligocene Scaglia Fm. in the footwall of the Mt Coscerno thrust, location in Fig. 1c).

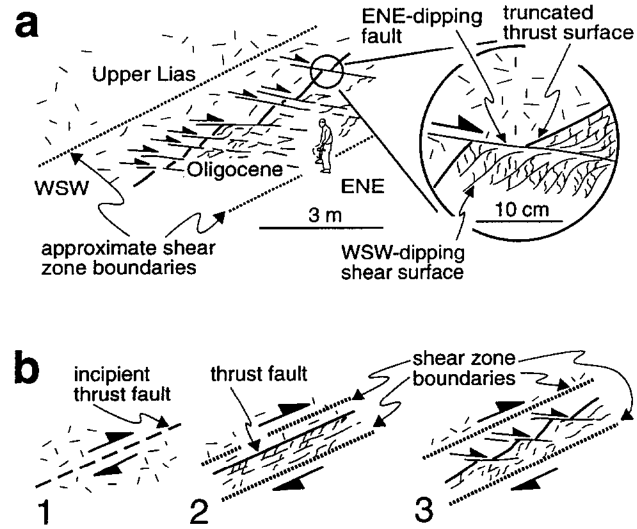

Fig. 5. Effects of thrust-related shear zone broadening (sub-stage C2). (a) Major WSW-dipping thrust fault offset by low-angle, gently ENE-dipping faults (Upper Cretaceous–Oligocene Scaglia Fm. in the footwall of the Mt Coscerno thrust, location in Fig. 1c). (b) Sequential model (1–3 in time) to account for the geometrical relationships illustrated in (a). The model assumes progressive broadening of the thrust-related shear zone during slip. A thrust fault forms during sub-stage C1 (1), accompanied by development of a pervasive thrust-parallel shear zone (2); continued slip during sub-stage C2 results in broadening of the shear zone and development of sub horizontal faults which truncate the thrust surface itself (3).

range from 20° to 70°, the latter values being characteristic of thrusts which cut through the steep limbs of asymmetrical folds. Outcrop-scale reverse faults often occur together defining linked thrust systems. These consist of ramps that sequentially decrease in inclination into their transport direction (Fig. 2g). The systematic decrease in inclination is interpreted to result from local piggy-back imbrication (terminology after Butler, 1987). Map-scale thrusts with displacement of several kilometres were probably also produced during this stage. Deformation in the vicinities of these major faults is expressed by 2–5 m thick zones of highly sheared rocks. The penetrative shearing fabric within the deformation zones consists of a steep WSW-dipping pressure-solution cleavage and shallow WSW-dipping shear surfaces that are roughly parallel to the deformation zone boundaries. The angle between the cleavage and the shear surfaces is generally 45°–55° (Fig. 2h). Steps in fibrous calcite veins along the shear surfaces indicate displacement of the hanging walls towards ENE.

Sub-stage C2 shear zone broadening. The major thrust faults and adjacent sedimentary rocks are overprinted by sub-horizontal to gently ENE-dipping faults and shear planes which produce displacements of a few centimetres towards the ENE (Fig. 5a). These faults and shear planes occur within deformation zones up to a few tens of metres thick along the major thrust fault traces. Mechanical striations and grooves were used to constrain the local fault kinematics. The mean slip direction inferred from these structures is N 72° E (Fig. 3f), consistent with the kinematics of reverse faults produced during the sub-stage C1. The overprinting relationships among shearing fabrics along map-scale thrusts are interpreted to represent the effects of a deformation zone broadening during emplacement of individual major thrust sheets (Fig. 5b). This interpretation agrees with that by Calamita (1991) for similar shearing fabrics in the northernmost Umbria–Marche Apennines.

The sequence of structural stages A, B and C (layer-parallel shortening, folding, thrusting), and sub-stages B1, B2, C1 and C2 (fold initiation, fold amplification and tightening, thrust and shear fabric development, shear zone broadening) recognized throughout the study area is illustrated in Fig. 6.

RELATIVE TIMING OF MAP-SCALE STRUCTURES

The overprinting relationships among mesoscopic fabrics and their distribution within the larger, map-scale structures provides a key for unraveling the relative sequence of structural stages of the latter. Pressure-solution cleavage fans around the first-order folds remaining at a high angle to bedding, indicating that macroscopic folding was preceded by layer-parallel shortening. The vergence of minor (i.e. second- and third-order) folds is generally consistent with that of larger (i.e. first-order) anticlines and synclines, suggesting that at a given location mesoscopic and regional folding were roughly coeval. No information is available to correlate the B1 (fold initiation) and B2 (fold amplifica-

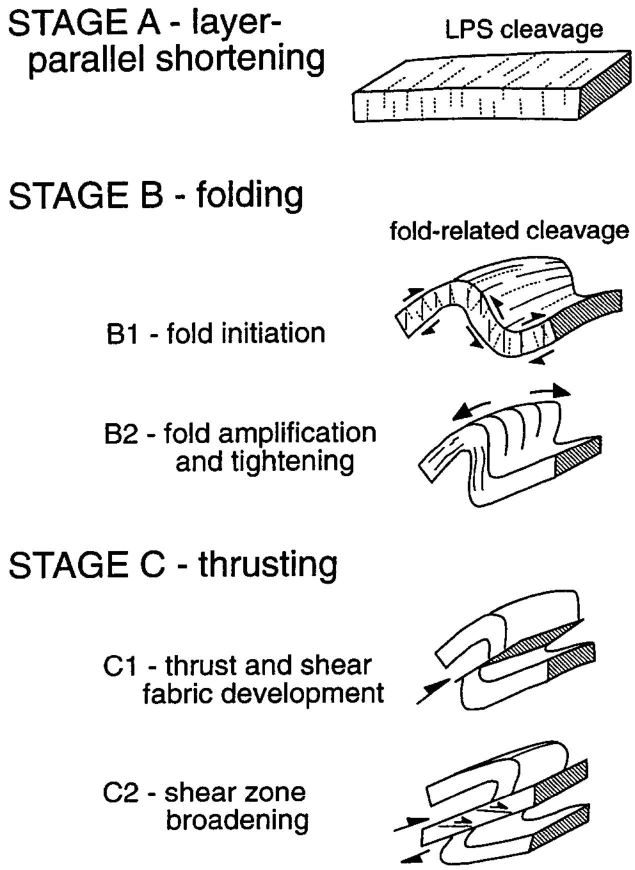

Fig. 6. Schematic sequence of the recognized structural stages (A–C in time) and sub-stages.

tion and tightening) sub-stages, recorded in minor fabrics, to the growth of first-order map-scale folds. Mesoscopic folds are truncated by both outcrop- and map-scale thrusts, which are in turn overprinted by sub horizontal to ENE-dipping shear planes. These relationships indicate that the whole sedimentary cover experienced a history of deformation similar to that inferred from minor fabrics. Therefore the sequence of recognized structural stages (layer-parallel shortening, folding, and thrusting) effectively constrains the relative timing of development of the larger folds and thrusts.

The overprinting relationships among the major, regional thrust faults allow for reconstruction of the local timing and relative age of emplacement of individual thrust sheets. In the Mt Prato area the Mt Sibillini thrust is folded by a more external thrust-cored anticline (Fig. 1c) which presumably grew in its footwall due to footwall-collapse mechanisms. These relationships, recognized elsewhere in the study area (e.g. the Mt Coscerno thrust, Fig. 1c; Tavarnelli, 1993b) suggest a forward, piggy-back thrust propagation, consistent with that inferred from mesoscopic imbricates (Fig. 2g). A general hinterland-to-foreland thrust propagation seems likely, in that it accounts for the eastward decreasing age of synorogenic deposits in the adjacent Marchean Foothills Zone (Ricci Lucchi, 1986).

RELATIONSHIPS BETWEEN FOLDS AND THRUSTS

The minor contractional structures are not uniformly distributed throughout the deformed sequence (reverse faults are more abundant at depth and folds prevail upwards). This vertical distribution could reflect structural controls by the heterogeneous sedimentary cover. However, it is also observed in individual outcrops where both folding and thrusting are produced at the expense of lithologically similar rocks. The displacement produced by minor thrust faults progressively decreases to tip points, where asymmetrical folds are developed (Fig. 2f).

The minor fold–thrust interaction pattern is similar to that reconstructed for some very well-exposed map-scale structures. The Mt Tilia–Mt Castiglioni structure (Fig. 7a) displays significant vertical and along-strike variations. In the south, it consists of an asymmetrical, east-verging anticline and syncline pair whose steep limb is cut by a gently west-dipping emergent thrust (Fig. 7b). In the north, thrust displacement decreases and terminates to a tip point, where an asymmetrical, blind-thrust cored fold pair is developed (Fig. 7b). The geometrical relationships observed at both outcrop- and map-scale suggest that folds and thrusts are kinematically linked structures.

The results from integrated meso- and macroscopic analysis can be used to test the applicability of current fold–thrust models to the structures of the Umbria–Marche Apennines. According to Morley (1994), the models which predict a linkage between folding and thrusting can be classified in two main groups: thrust-related folding, where folds form above or ahead of upward-propagating thrusts (e.g. fault-bend and tip-line folding, the latter including detachment and fault-propagation folding: Rich, 1934; Elliott, 1976; Suppe, 1985; Jamison, 1987; Mitra, 1990) and fold-generated imbrication, where buckle folds are breached in their steep limbs by upward- and downward-propagating faults (e.g. break-thrust folding: Willis, 1893; Dixon and Liu, 1992; Fischer *et al.*, 1992).

There are several ways to describe the observed structures in terms of fold–thrust models. A kinematic approach considers the *relative stretch* (e_r), a measurement of the ratio between fault-propagation rate (PR) to fault-slip rate (SR) during thrusting. The relative stretch is assumed to be highest ($e_r = 1$) in fault-bend folding, and to decrease in tip-line folding and break-thrust folding models (McNaught and Mitra, 1993). An estimate of the fault PR/SR ratio can be achieved through the use of displacement/distance graphs, where the distance from a point along the fault is plotted against the displacement of marker beds (Williams and Chapman, 1983). The construction of a displacement/distance graph for four thrust–fold structures ranging from centimetre to kilometre scale (Fig. 8) shows an overall linear trend, suggesting that thrust faults cut through the fold limbs with a fairly constant PR/SR ratio. The average relative stretch values (i.e. the slopes obtained by linking the

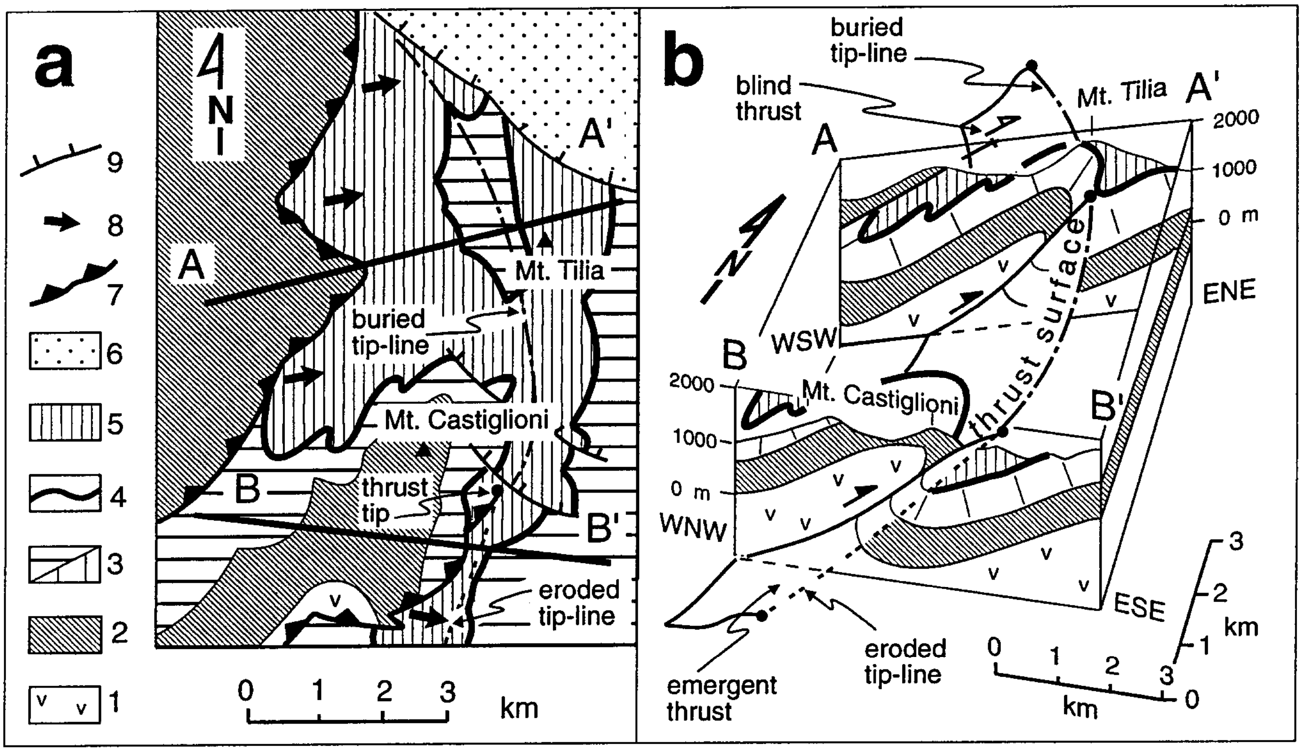

Fig. 7. The Mt Tilia–Mt Castiglioni structure. (a) Slightly simplified geological map (boxed area north of Rieti in Fig. 1b). (b) Serial cross-sections across the Mt Tilia anticline (A–A′) and the Mt Castiglioni thrust (B–B′). The style variations, both vertical and along-strike, are similar to those observed at the outcrop-scale (see Fig. 2f), and suggest that folds and thrusts are kinematically linked structures. Symbols: 1 — Upper Triassic; 2 — Lower Liassic; 3 — Middle Liassic—Lower Cretaceous; 4 — Middle Cretaceous; 5 — Upper Cretaceous–Oligocene; 6 — Recent deposits; 7 — thrust faults; 8 — thrusting direction; 9 — normal faults.

uppermost marker beds with a straight segment to the origin of the graph) range from 0.69 to 0.83. These values are consistent with those predicted by both tip-line folding and break-thrust folding models (Williams and Chapman, 1983; McNaught and Mitra, 1993).

Although geometrically similar, break-thrust and tip-line folds have different kinematic evolutions, in that they are assumed to nucleate and amplify with fixed and mobile hinges, respectively (Fischer *et al.*, 1992). Stewart and Alvarez (1991) demonstrated that some third- and second-order kink and detachment folds in the Umbria–Marche Apennines grew by the lateral migration of axial surfaces. The sense of shearing of mesoscopic refracted cleavage and imbricates around some first-order thrust-cored anticlines is not always consistent with that predicted by flexural-slip towards a pinned hinge. Moreover, unlike situations where extensive fracturing is observed in the hinge regions of major folds (Fischer *et al.*, 1992), mesoscopic fabrics in the Umbria–Marche belt are more abundant away from the hinges, their shear sense reversal very often occurring in the forelimbs of major anticlines. These two combined lines of evidence suggest that hinge migration could also have occurred during development of map-scale folds (Lavecchia *et al.*, 1983; Tavarnelli, 1993a, 1994). Because of evidence supporting hinge migration during meso- and macroscopic fold growth, the tip-line folding model (Elliott, 1976; Williams and Chapman, 1983) appears appropriate to describe the thrust–fold interaction in the Umbria–Marche Apennines. Tip-line folding also accounts for thrusts overprinting folds, consistent with the reconstructed sequence of structural stages. The available data do not allow for a choice between the fault-propagation or the detachment folding model. However, theoretical (McNaught and Mitra, 1993) and experimental work (Dixon and Liu, 1992) has shown that structures predicted by both models can co-exist and can represent different evolutionary stages in the framework of a common kinematic tip-line folding process.

TWO-PHASE OR PROGRESSIVE DEFORMATION?

The mesostructural data presented in this paper are in general agreement with those by Koopman (1983), Lavecchia *et al.* (1983) and Lavecchia (1985). The main difference with previous work is the interpretation of: (i) the significance of fold axis-parallel extension, and (ii) the relationships between folds and thrusts.

According to Lavecchia (1985), and references therein, fold-axis normal joints (mode I fractures) after folding and before thrusting represent the effects of a general switch in the stress field, from compression to extension.

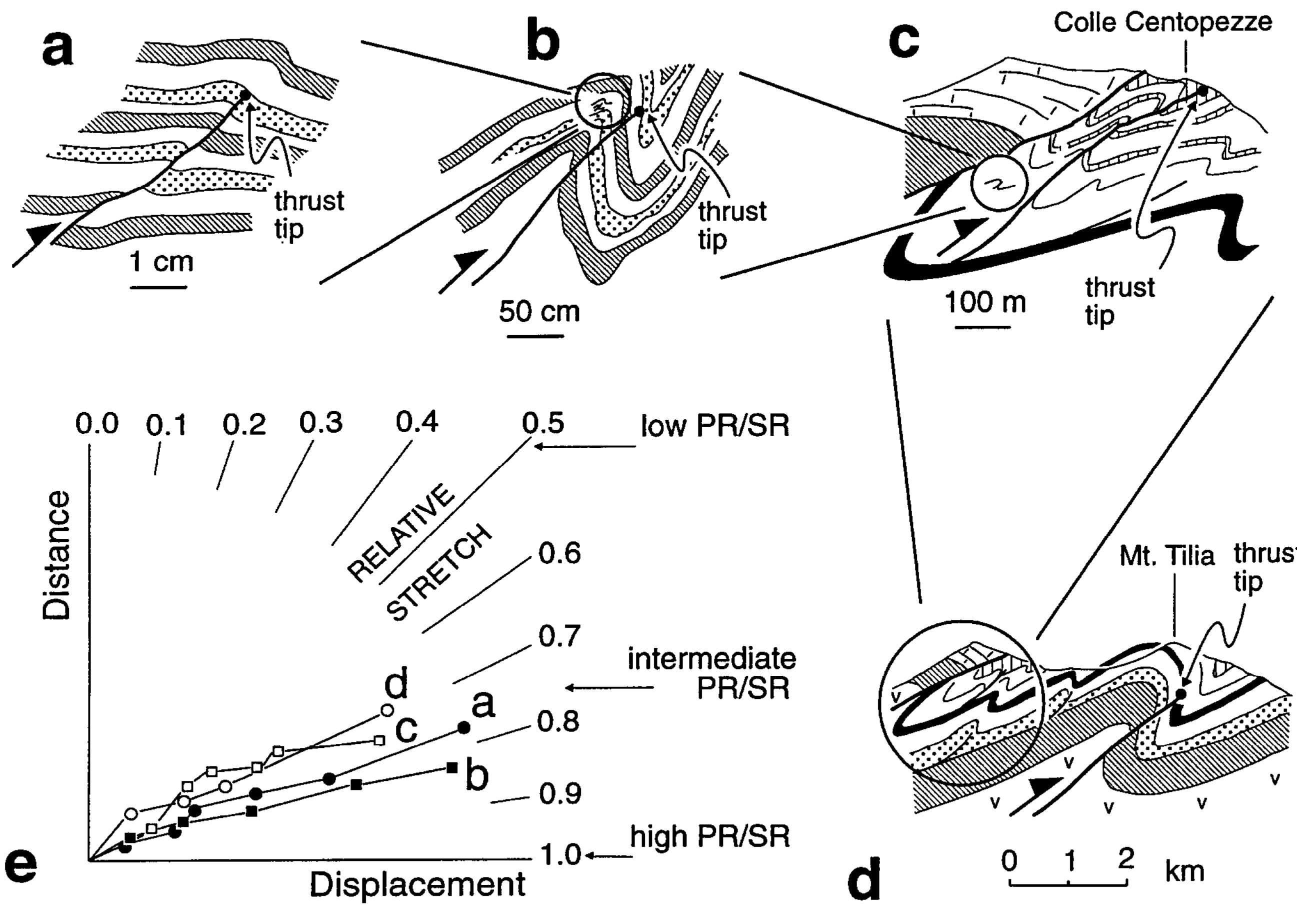

Fig. 8. (a–d) Well-exposed examples of structures where thrust faults lose displacement upwards and are replaced by asymmetrical fold pairs (structures c and d are slightly modified after Tavarnelli, 1993a, 1994). (e) Non-dimensional displacement–distance graph for structures a, b, c and d. The slightly more complex trend of large structures (c, d) with respect to that of small structures (a, b) is likely to reflect a higher lithological variability in the former. The mean *relative stretch* (e_r) is 0.69, 0.74, 0.77 and 0.83 for structures d, c, a and b, respectively. These values are consistent with those predicted by both tip-line folding and break-thrust folding models.

These fabrics were interpreted as evidence of a lack of kinematic linkage between early folds and late thrusts. An intermediate stage of axis-normal extension between folding and thrusting, and the consequent implications for the fold–thrust interaction, poses the question of whether deformation was progressive or two-phase in character.

The trends of minor structures were used to infer a regional shortening direction for each recognized structural stage (Fig. 3). The reconstructed mean shortening directions are N 72° E, N 73° E and N 70° E, for stages A, B and C, respectively. The N 165° E mean direction of axis-parallel extension (Fig. 3d) implies a sub-vertical or, alternatively, a sub-horizontal, N 75° E-trending, maximum shortening. A N 75° E direction of shortening, consistent with periclinal fold amplification, is remarkably parallel to the shortening directions inferred from structures developed during other stages and sub-stages. This parallelism suggests that the overall stress field did not significantly change in orientation through time, and therefore the hypothesis of a single progressive deformation episode appears reasonable. However, parallelism among sequentially younger structures does not prove that deformation was progressive. Structures which trend parallel could represent the effects of two or more distinct overprinting deformation episodes, provided that they were coaxial in character. According to Nickelsen (1979), Gray and Mitra (1993) and Connors and Lister (1995), deformation is proven to be progressive when structures produced during a stage (i.e. layer-parallel shortening) grow and amplify during the transition to the next stage (i.e. folding). Evidence for this in the Umbria–Marche Range is lacking and further investigation is required to determine whether this criterion is met.

The relationships between folds and thrusts are also questionable. The fold-thrust structures observed in this study display geometries consistent with those predicted by thrust-related folding models. The estimated values of fault *PR*/*SR*, and evidence for hinge migration during fold growth, agree with the hypothesis of a tip-line folding origin (including the solutions predicted by fault-propagation and detachment folding models). These elements, in combination, suggest that folds and thrusts are geometrically and kinematically linked structures. However, the reconstructed sequence of structural stages shows that folding occurred prior to thrusting, and therefore the interpretation of late thrusts truncating independent, pre-existing folds cannot be dismissed on this basis.

The structural evidence presented in this paper does not invalidate the two-phase model for fold–thrust development by Lavecchia (1985), and therefore the question of one- or two-phase deformation remains unanswered. Rather, the data presented in this paper show that a progressive deformation model, where both folds and thrusts are kinematically linked structures produced during a single continuous episode, represents a reasonable and viable alternative to the two-phase model by Lavecchia (1985).

A KINEMATIC DEFORMATION MODEL

A sequential kinematic deformation model for the Umbria–Marche sedimentary cover, based on integrated meso- and macroscopic evidence, is shown in Fig. 9. The implicit assumptions are that: (i) compressional deformation is gradual and progressively migrates from hinterland to foreland; and (ii) folds and thrusts are kinematically linked, the former growing ahead of the latters' terminations (tip-line folding). The model is similar to those by Koopman (1983) and De Feyter *et al.* (1986), yet differs from both in that it incorporates the sequence of structural stages as inferred from minor fabrics.

The history proposed for the Umbria–Marche Apennines shows marked similarities with those from other non-metamorphic (e.g. the French Subalpine Chains: Butler, 1992; the Swiss Jura Hills: Droxler and Schaer, 1979) and slightly metamorphic fold-and-thrust belts (e.g. the Appalachian Valley and Ridge Province, although here sequentially younger structures were not coaxial: Nickelsen, 1979; Gray and Mitra, 1993), which experienced progressive deformation. Moreover, analogies also exist with other complex arcuate belts, where early bedding-normal fabrics were overprinted by sequentially younger folds and thrusts prior to oroclinal bending (e.g. the Asturian–Cantabrian arc: Pares *et al.*, 1994). This similarity suggests that layer-parallel shortening, folding and thrusting are common deformation processes, whose role becomes sequentially dominant during the evolution of many fold-and-thrust belts.

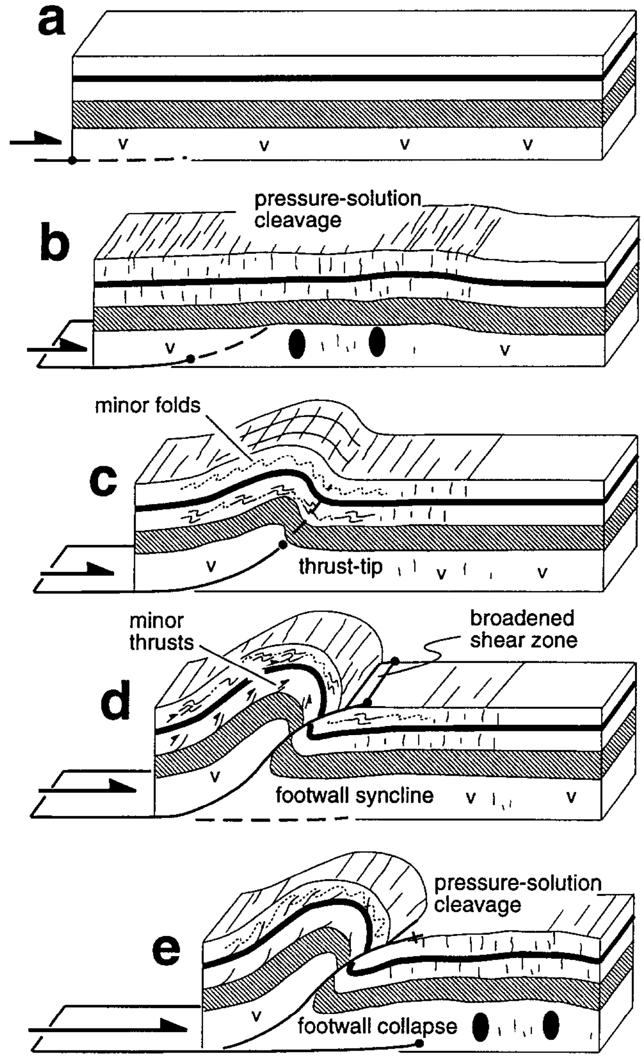

Fig. 9. Kinematic deformation model (a–e in time) for the Umbria–Marche sedimentary cover (grey and black layers are the Lower Liassic Calcare Massiccio Fm. and the Middle Cretaceous Marne a Fucoidi Fm., respectively). The model assumes a progressive character of the Neogene compressional deformation, a kinematic link between folding and thrusting (which are interpreted to result from tip-line folding processes), and a hinterland-to-foreland thrust propagation sequence.

CONCLUSIONS

Minor fabrics and their overprinting relationships indicate that the kinematic evolution of the Umbria–Marche Apennines was characterized by three sequentially younger structural stages: layer-parallel shortening, folding and thrusting. The geometry of interacting outcrop- and map-scale folds and thrusts, the pattern of thrust displacement variations and evidence for hinge migration during fold growth suggest that folding and thrusting are kinematically linked processes. These lines of evidence, consistent with the hypothesis of a continuous character of the Neogene contraction, are synthesized in a kinematic deformation model where the role of cleavage development, folding and thrusting becomes progressively dominant through time.

The comparison between the deformation history of the Umbria–Marche Apennines, inferred from mesoscopic fabrics, and those from other fold-and-thrust belts reveals a similar sequence of structural stages. The results from mesoscopic analysis can ultimately provide useful information for a better understanding of fold–thrust interaction in orogenic systems and similar geodynamic settings.

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