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Geometry, segmentation pattern and displacement variations along a major Apennine thrust zone, central Italy

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Abstract

Hundreds of kilometres-long, arc-shaped, continuous thrust faults commonly imply very large displacements by detachment-dominated thrusting. Therefore, their occurrence has a large impact on fold–thrust belt structure. One of the major thrust faults of the central-northern Apennines, the Umbria–Marche–Sabina Thrust Zone, is traditionally believed to represent one such feature, characterised by displacements of several tens of kilometres. However, detailed studies of this structure revealed that it is actually composed of a series of partially overlapping fault segments, rather than consisting of a single, continuous thrust. Cross-section balancing and restoration, carried out by the integration of surface geological data with available sub-surface information, points out relatively limited amounts of thrust displacement (<10 km). Displacement–distance profiles show moderate displacement gradients well compatible with those reported for coherent thrust sheets. They also suggest that individual thrust segments were originally isolated and then grew by lateral propagation, leading to overlap and variable fault interaction within relay zones. The relationship between maximum displacement and fault trace length tends to follow a power-law distribution, as it commonly occurs for fault populations. However, a better correlation could be obtained by further segmentation of the northernmost (blind) fault in an area of no seismic data, thus confirming that fault scaling relationships may be useful for pointing out possible problems with the structural interpretation of poorly constrained areas and for exploring viable alternative solutions.

Keywords: Fold–thrust belts; Balanced geological sections; Displacement–distance diagrams; Fault displacement–length relationships

1. Introduction

Continuous, arc-shaped thrust faults with strike lengths of hundreds of kilometres generally show large associated displacements (of several tens of kilometres at least), as predicted by the 'Bow and Arrow rule' (Elliott, 1976). One of the major thrust faults of the outer central-northern Apennines (Umbria–Marche–Sabina Thrust Zone; UMSTZ) is commonly believed to represent one such feature. Displacements of several tens of kilometres have been suggested for the UMSTZ by cross-section balancing and restoration (Bally et al., 1986; Hill and Hayward, 1988). The absence of crystalline basement within the outer part of the Apennines, together with the presence of evaporites at the base of the sedimentary cover, has led to a proliferation of thin-skinned, detachment-dominated models of the structural evolution of the Apennines (Calamita and Deiana, 1988; Ghisetti et al., 1993; Doglioni et al., 1998). The validity of these models has, however, been questioned, at least in the outer parts of the central-northern Apennines (Lavecchia et al., 1987; Calamita et al., 1994; Coward et al., 1999; Mazzoli et al., 2001; Butler et al., 2004; Tavarnelli et al., 2004). Alternative interpretations imply that, at least for the external structures located in the footwall to the UMSTZ (Fig. 1), thrusts pass to depth into basement without significant duplication of cover sedimentary

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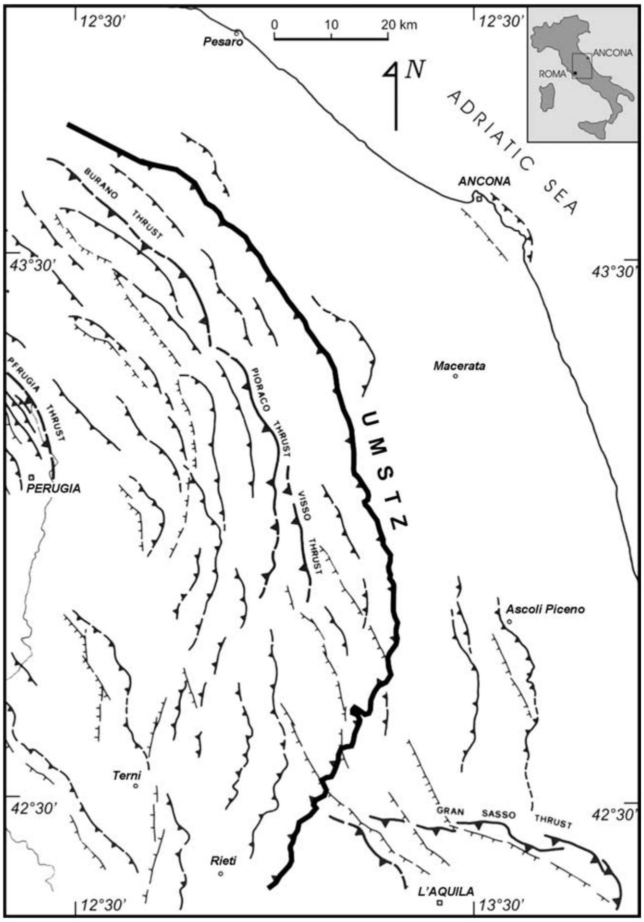

Fig. 1. Tectonic sketch map of part of the central-northern Apennines (after Bally et al., 1986), showing major, arc-shaped part of the thrust zone of this study (UMSTZ) mapped as a single, continuous fault. It is worth noting that, according to Bally et al. (1986), the UMSTZ extends farther north and south of the thrust terminations shown on the map (i.e. they are not lateral tip lines).

successions. These 'thick-skinned' interpretations (Coward, 1983, 1994) require far less orogenic shortening than equivalent 'thin-skinned' ones. Relatively limited amounts of shortening appear to be also associated with significant thrust segmentation in the central-northern Apennine foothills, east of the UMSTZ. Here a braided system of discontinuous thrust faults has been documented through detailed mapping of the surface geology and seismic interpretation (Coward et al., 1999).

Fault segmentation is known to occur at different scales and in all modes of faulting, including thrusting (Dahlstrom, 1969; Elliott, 1976; Aydin, 1988; Peacock and Sanderson, 1991, 1994; Walsh et al., 1999; Nicol et al., 2002). The aim of this paper is to discuss the geometry, segmentation pattern and displacement variations along the UMSTZ, based on the results of new, detailed geological mapping integrated with subsurface data and by the construction of a series of balanced and restored geological sections across this major structural feature of the central-northern Apennines.

2. Geological setting

The Apennines are an east to northeast vergent fold and thrust belt that developed as a result of convergence between the continental margins of Corsica–Sardinia (of European origin) to the west, and of the Adriatic block (of African affinity) to the east, within the general framework of late Cretaceous to Present Africa–Europe plate convergence (Dewey et al., 1989). Miocene to Early Pleistocene (Di Bucci and Mazzoli, 2002) thrust accretion across the Adriatic (or Apulian) continental margin was accompanied by Tyrrhenian back-arc extension (Mazzoli and Helman, 1994, and references therein). In the northern sector of the thrust belt, Liguride oceanic-derived units and Subliguride continental margin successions (Val Marecchia unit in Fig. 2) form part of a detached thrust sheet that tectonically overlies Miocene synorogenic strata of the Toscana–Umbria district and, to the east, the Umbria–Marche sedimentary succession (Fig. 2).

The study area (Fig. 2) is characterised by an arcuate shape and a main northeast vergence of asymmetric, mostly faulted anticlines involving Mesozoic–Tertiary sedimentary successions (Calamita and Deiana, 1988). Deeper parts of the Apennine geology are known from wells (Anelli et al., 1994) that penetrate Permo-Triassic continental siliciclastics (the Verrucano Group). These siliclastics in turn overlie crystalline basement units.

The Triassic strata include a thick wedge of evaporites (Burano Anhydrites Fm.) that mark the base of the carbonate-dominated continental margin succession. The evaporites form an important structural decoupling horizon so that the underlying strata remain buried. Until recently the pre-evaporitic rocks were commonly interpreted to lie beneath a basal detachment, with deformation restricted to regions much further to the west within the orogenic hinterland (Bally et al., 1986). Interpretation of the pre-Triassic strata as autochthonous was further supported by interpretations of the top to the magnetic basement as lying at depths in excess of 10 km, well below most of the thrust belt (Cassano et al., 1998). However, new data on the magnetic basement (Speranza and Chiappini, 2002) indicate that it is involved in thrusting, consistent with the results of the CROP 03 deep seismic reflection experiment (Barchi et al., 1998).

Much of the Apennine chain has been dissected by normal and strike-slip faults that locally post-date thrust structures. In the interior of the chain (e.g. Tuscany), these faults control Mio-Pliocene basins (Decandia et al., 1998) and therefore are coeval with thrust structures that were active further to the east (Elter et al., 1975). The thrust front migrated eastward over time, with extension following, so that folds and thrusts along the east margin of the Italian peninsula, which are the products of the final stages of contractional deformation in the Apennines, developed toward the end of the early Pleistocene. At 700–800 ka a major geodynamic change occurred and a new tectonic

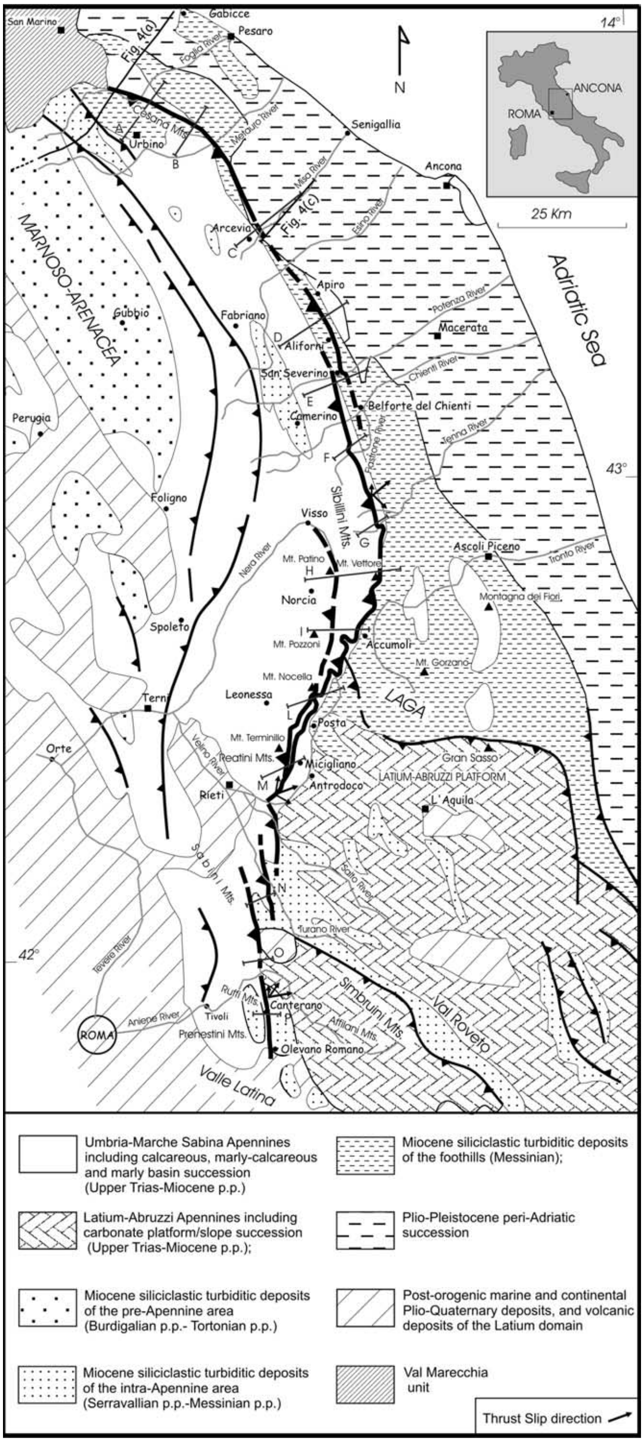

Fig. 2. Geological sketch map of the study area, showing the UMSTZ (bold thrust fault) with mean orientation of thrust slip direction (arrows; see text), together with traces of the seismic profiles shown in Fig. 4 and balanced cross-sections of Fig. 5 (capital letters).

regime established itself in the Apennine chain and adjacent foothill areas (Di Bucci and Mazzoli, 2002, and references therein). The structures related to this new regime are characterized by a NE–SW oriented maximum extension direction, consist of normal, oblique- and strike-slip faults that post-date and dissect the thrust belt, and remain seismically active (Di Bucci and Mazzoli, 2002, and references therein).

2.1. Stratigraphy

The stratigraphic units cropping out in the study area include three different sedimentary successions, reflecting the genesis and evolution of this portion of the Afro-Adriatic continental margin in Mesozoic–Tertiary times. These sedimentary successions include: (i) the Umbria–Marche basin succession, cropping out from the Urbino area, to the north, and to the Reatini Mts. to the south; (ii) the Latium–Abruzzi carbonate platform succession, exposed in the southern part of the study area; and transitional between these two successions, (iii) the Sabina succession, cropping out in the Sabini and Prenestini Mts. (refer to Fig. 2). These three successions are all capped by foredeep turbiditic deposits.

The lower part of the Umbria–Marche succession consists mainly of carbonates (Upper Triassic–Eocene), displays significant vertical and lateral variations of both facies and thickness of the formations (Fig. 3a) and records Jurassic rifting and subsequent development of a passive continental margin. Both rift-related 'complete' and 'condensed' successions (Centamore et al., 1971) are stratigraphically overlain by uppermost Jurassic to Oligocene limestones and marls of the Maiolica and Marne a Fucoidi Fms., and by the Scaglia Group. This latter group also shows significant facies and thickness variations, in part related to syn-sedimentary extensional tectonics (Decandia, 1982; Lavecchia, 1985; Tavarnelli, 1995). The stratigraphically overlying hemipelagic, turbiditic and also evaporitic units of Miocene–Pliocene age include the marker horizons of the Bisciaro (Lower Miocene) and Gessoso–Solfifera (Messinian) Fms. In the Marche foothills area (Fig. 1), the deformed Mesozoic–Paleogene sequence is mostly buried beneath these Miocene–Pliocene strata, the deposition of which was at least in part controlled by syn-sedimentary normal faults (Calamita and Deiana, 1980; Calamita et al., 1998; Tavarnelli et al., 1999; Deiana et al., 2002; Mazzoli et al., 2002).

The Latium–Abruzzi carbonate platform succession consists of Mesozoic dolomites, limestones and dolomitic limestones, unconformably overlain (following a Paleogene hiatus) by detrital limestones of the Calcari a briozoi e litotamni Fm. (Langhian–Tortonian) and hemipelagic and turbiditic deposits of Upper Miocene age (Parotto and Praturlon, 1975; Fig. 3b).

The transitional Sabina succession is made of carbonate slope deposits. It is similar to the Umbria–Marche basin succession, being, however, richer in detrital limestones (Corda and Mariotti, 1986). Here, the Scaglia Group—or, to the south (i.e. in the Prenestini Mts), shallow water carbonates—is overlain by the marly limestones of the Guadagnolo Fm. (Aquitanian–Langhian), which in turn

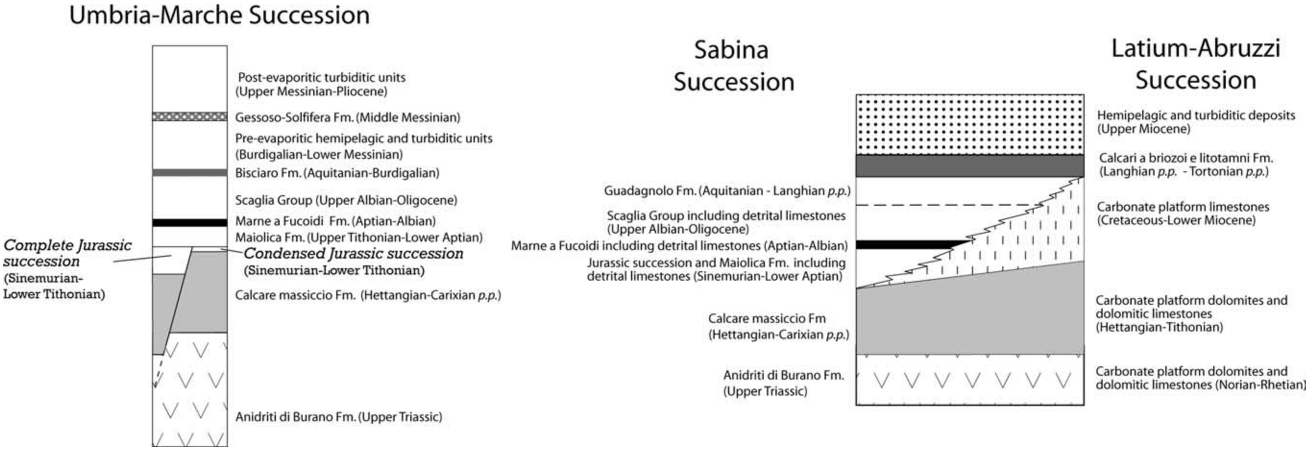

Fig. 3. Schematic stratigraphic column (left) for the Umbria–Marche basin succession, and (right) stratigraphic relationships between Latium–Abruzzi carbonate platform and Sabina transitional successions.

passes upwards into the Calcari a briozoi e litotamni Fm. and then into hemipelagic and turbiditic deposits of Upper Miocene age (Fig. 3b).

3. The Umbria–Marche–Sabina thrust zone (UMSTZ)

The most prominent mountain ridge (Umbria–Marche–Sabina ridge) of the Apennines in central Italy is bounded to the east by an important thrust zone (UMSTZ) extending for 250 km from Olevano Romano, in the south, to the Foglia River Valley to the north (Fig. 2). Recent detailed (1:25,000 to 1:10,000 scale) geological mapping along the UMSTZ (Deiana et al., 1996; Regione Marche, 2001; Borraccini, 2003; Borraccini et al., 2004; Pierantoni et al., in press) forms the basis for this new analysis. Our mapping shows that the UMSTZ includes several segments displaying a right-stepping en échelon geometry, rather than consisting of a single, continuous thrust fault. The two main portions of the UMSTZ form an overall arcuate feature corresponding to the thrust fault shown in Fig. 1. The northern portion (Belforte–Urbino Thrust, Fig. 2) extends from the Chienti River Valley, to the south, to the Cesana Mts. to the north. However, as the northern part of this fault segment consists of a blind thrust, further segmentation cannot be ruled out. The southern segment (Salto River–Sibillini Mts. Thrust) extends from the Potenza River Valley, to the north, to the Salto River, to the south. The southernmost part of the UMSTZ (corresponding in part to the ‘Olevano–Antrodoco line’; Salvini and Vittori, 1982) consists of two N–S-trending minor segments extending from the Salto River to Olevano Romano to the south. From north to south, these are the Ascrea and Canterano Thrusts, respectively. The southern termination of the latter thrust segment is buried below post-orogenic deposits.

The Belforte–Urbino Thrust shows a NW–SE trend, changing to WNW–ESE north of the Metauro River Valley (Fig. 1). Significant ($>45°$) paleomagnetic rotations about a vertical axis are recorded from this latter area (Mazzoli et al., 2001). North of the Esino River valley, where it is buried by Neogene foredeep deposits, the Belforte–Urbino Thrust is imaged by seismic reflection profiles in the areas of Arcevia and of Cesana Mts. (Calamita et al., 1994; Barchi et al., 1998; Coward et al., 1999; Mazzoli et al., 2001; Deiana et al., 2003; Figs. 2 and 4). It is between the latter two areas that the continuity of the blind thrust is, due to limited structural elevation and topographic relief and a lack of sub-surface data, poorly constrained.

The outcropping southern termination of the Belforte–Urbino Thrust is characterised by a 15-km-long overstep area (relay zone) with the Salto River–Sibillini Mts. Thrust. The latter, showing an arcuate shape throughout its entire length, is characterised by the occurrence of an important splay (Mt. Nocella Thrust) that originates from a branch point that outcrops in the Mt. Terminillo area (refer to Fig. 2).

3.1. Balanced and restored geological sections

The cross-sections presented in Fig. 5 were originally constructed at a 1:25,000 scale, mostly based on our new geological maps and structural data. Where sufficient outcrop and topographic relief allows, structure contours have been used to constrain the precise geometry of geological boundaries. The subsurface portions of the sections have been completed using, where available, seismic reflection profiles, including the CROP 03 deep seismic reflection profile (Barchi et al., 1998) and commercial seismic lines calibrated with deep well logs (Calamita et al., 1994; Coward et al., 1999; Borraccini, 2003).

Seismic interpretation was based on the recognition of a few key-reflectors (seismic markers) corresponding to (from top to bottom): (i) the Messinian evaporites, (ii) the Aptian–Albian Marne a Fucoidi Fm., (iii) the top of the lower Liassic massive carbonates of the Calcare massiccio Fm., and (iv) the inferred top to basement *s.l.* Apart from the latter, picking of these key-reflectors involved the

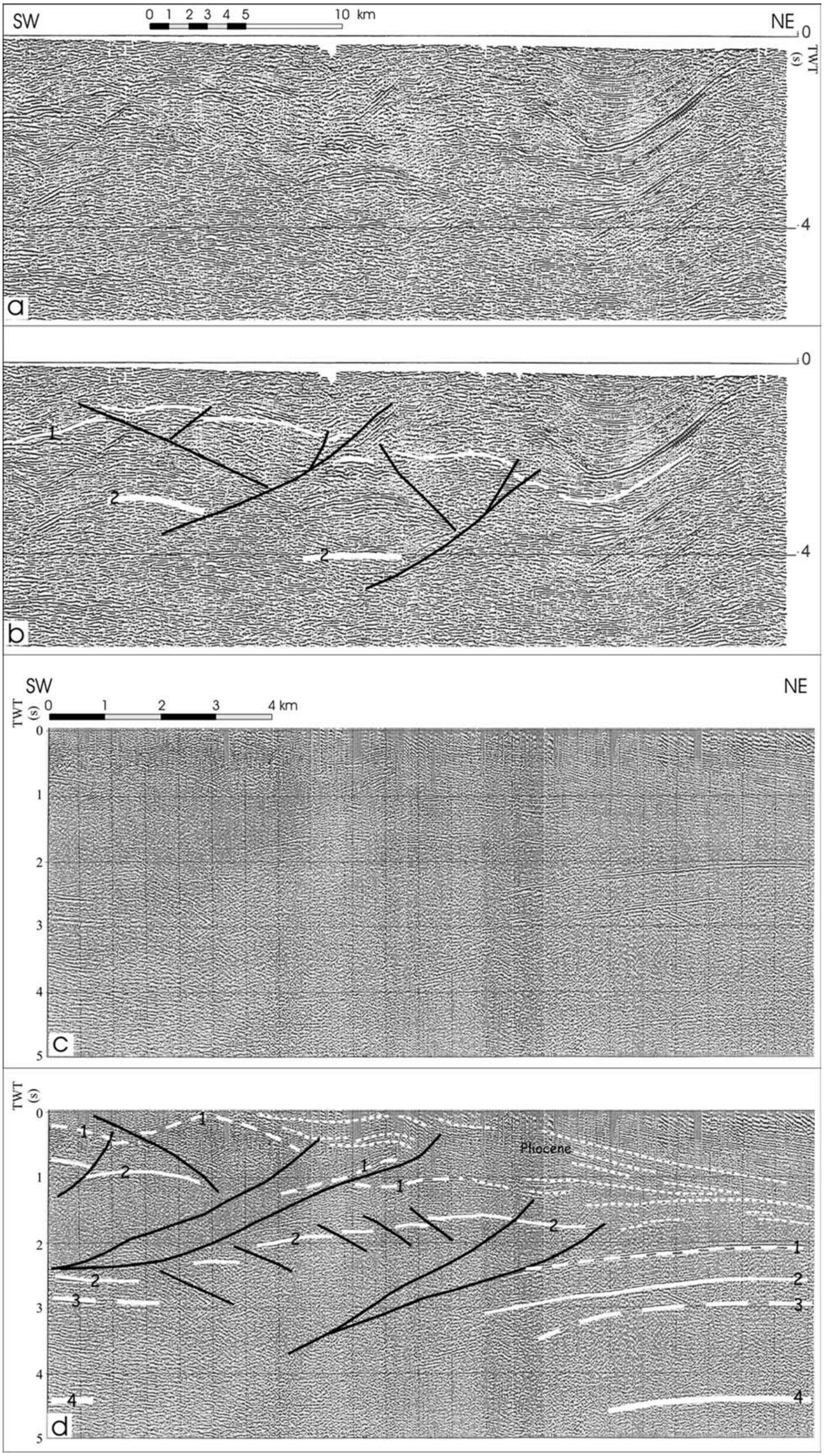

Fig. 4. Seismic reflection profiles (located in Fig. 2). (a) Outer (NE) part of the CROP 03 deep seismic reflection profile. (b) Interpretation of previous line: 1. Marne a Fucoidi Fm. (Aptian–Albian); 2. top basement *s.l.* (c) Commercial seismic profile. (d) Interpretation of previous line: 1. Messinian evaporites; 2. Marne a Fucoidi Fm.; 3. top Calcare massiccio Fm. (Lias); 4. top basement *s.l.*

calibration of seismic data with well logs drilled for hydrocarbon exploration.

The seismic reflection related to the Marne a Fucoidi Fm. is the best defined in the sub-surface data set. This is due both to the widespread regional occurrence of this thin (50–100 m), laterally continuous marly formation, and to its peculiar position within the stratigraphic succession; it is interposed between the Scaglia Group and the Maiolica Fm, these units being characterised by seismic interval velocities of 4000–4400 and 5700–6200 $\mathrm{m\,s^{-1}}$, respectively. The seismic marker corresponding to the Marne a Fucoidi Fm., is therefore characterised by a high reflection coefficient, and represents the main horizon guiding the interpretation within the Umbria–Marche and Sabina Mesozoic successions.

The top basement *s.l.* marker is interpreted below the Triassic Burano Anhydrites Fm. Seismic interpretation at these deep levels is guided by the consideration of: (i) the significant velocity inversion occurring between the Triassic evaporites (6.200–6.900 $\mathrm{m\,s^{-1}}$) and the underlying basement phyllites (4.800–5.800 $\mathrm{m\,s^{-1}}$)—recorded where these strata have been penetrated by deep wells (Anelli et al., 1994)—which is likely to produce a marked seismic reflection; and (ii) the thickness of the Triassic–lower Liassic succession (3000–3500 m) between the top Calcare massiccio Fm. and the inferred top to basement *s.l.* as determined from surface geological data (converted to depth using a mean velocity of 5.500 $\mathrm{ms^{-1}}$). In the profiles shown in Fig. 4, the top basement horizon has been related to the deep seismic reflections occurring at 4.0 s two way travel time (TWT) in the central part of line (a), and around 4.3 s TWT at both edges of line (c).

The geological sections have been restored using 2DMove software by both line-length balancing and the use of a restoration algorithm for individual folds. The dominant deformation mechanism within the thrust belt is flexural slip, as evidenced by ubiquitous shear fibres parallel to bedding and roughly perpendicular to fold-axes. These structures were therefore restored using the flexural-slip algorithm using pins located along zones of no interbed slip, i.e. parallel to axial surface traces in the plane of section (Dahlstrom, 1969). The cross-sections have been constructed assuming basement involvement in thrusting, according to the most recent data and interpretations on the deep geological structure of the thrust belt (e.g. Barchi et al., 1998; Speranza and Chiappini, 2002). In the cross-sections of Fig. 5, a reactivation of pre-existing (Triassic) normal faults is envisaged, as suggested by Coward et al. (1999), Butler et al. (2004) and Tavarnelli et al. (2004). As a result of the reactivation process, the top-basement horizon may have gone through the null point, developing reverse steps that are sometimes inferred in seismic profiles (Butler et al., 2004). In cross-sections H–M (Fig. 5), the occurrence of footwall shortcuts, with the development of neo-formed basement thrusts, is interpreted to be associated with the positive inversion. Our cross-sections are not extended down to a possible floor thrust located deep in the crust. It should also be noted that, according to Butler et al. (2004), it is not known whether Apennine thrusts actually ‘link downwards onto a discrete floor thrust in the middle or lower crust. It is plausible, particularly given the low net displacements in this system, that the thrusts pass downwards into a zone of more penetrative strain. These deep levels are not imaged on the available commercial seismic reflection profiles’.

Two-dimensional restorations commonly assume that there is no movement of material in or out of the section plane. In order to determine the correct orientation for such plane strain sections it is necessary to analyse the tectonic transport direction from minor structures in the field (S–C fabrics, slickensides and duplexes). The transport direction could not be directly determined for the northern (Urbino–Belforte) segment of the UMSTZ because most of this thrust segment is buried beneath Neogene deposits and there is, therefore, a lack of suitable outcrops. Throughout the rest of the UMSTZ, the transport direction has been obtained at a variety of locations based on published data sets (Coli, 1981; Salvini and Vittori, 1982; Koopman, 1983; Lavecchia, 1985; Calamita et al., 1987; Salvucci, 1994; Cacciamani, 1997) integrated with further original observations. The data show some variation in these directions between individual sites, and also at each site as a result of superposed kinematics (Fig. 2). As plane strain conditions appear not to fully apply in our study area, we considered the dominant slip direction obtained at each site closest to the traces of the cross-sections. The dominant kinematics varies from top-to-the-NE to top-to-the-ENE moving along strike from N to S.

3.1.1. Belforte–Urbino thrust

Balanced sections across the Belforte–Urbino Thrust show a buried tip line for the northern part of the structure (Fig. 5a–c), which is crossed by the CROP 03 deep seismic reflection line (Barchi et al., 1998). Reinterpretation of the latter seismic profile (Fig. 4a and b) suggests limited displacement and the involvement of basement in thrusting. To the south of the thrust, though emergent, it is not exposed along the forelimb of the major anticlinal structure constituting the mountain range. Rather, it crops out a few kilometres east of the mountain front, along the backlimb of the next (outer) anticline (Fig. 5d and e). In this area the thrust has a maximum displacement of about 3 km and offsets a set of pre-thrusting Miocene faults that are well exposed in the thrust hanging-wall (Deiana et al., 2002; Mazzoli et al., 2002).

3.1.2. Salto River–Sibillini Mts. thrust

Geological sections across the Salto River–Sibillini Mts. Thrust (Fig. 5f–m) display more asymmetric, east vergent, hanging wall fold structures than were observed within the Belforte–Urbino Thrust sheet. The hanging-wall anticline shows a gently dipping western limb and a vertical to overturned eastern limb. Minor thrust splays offsetting the

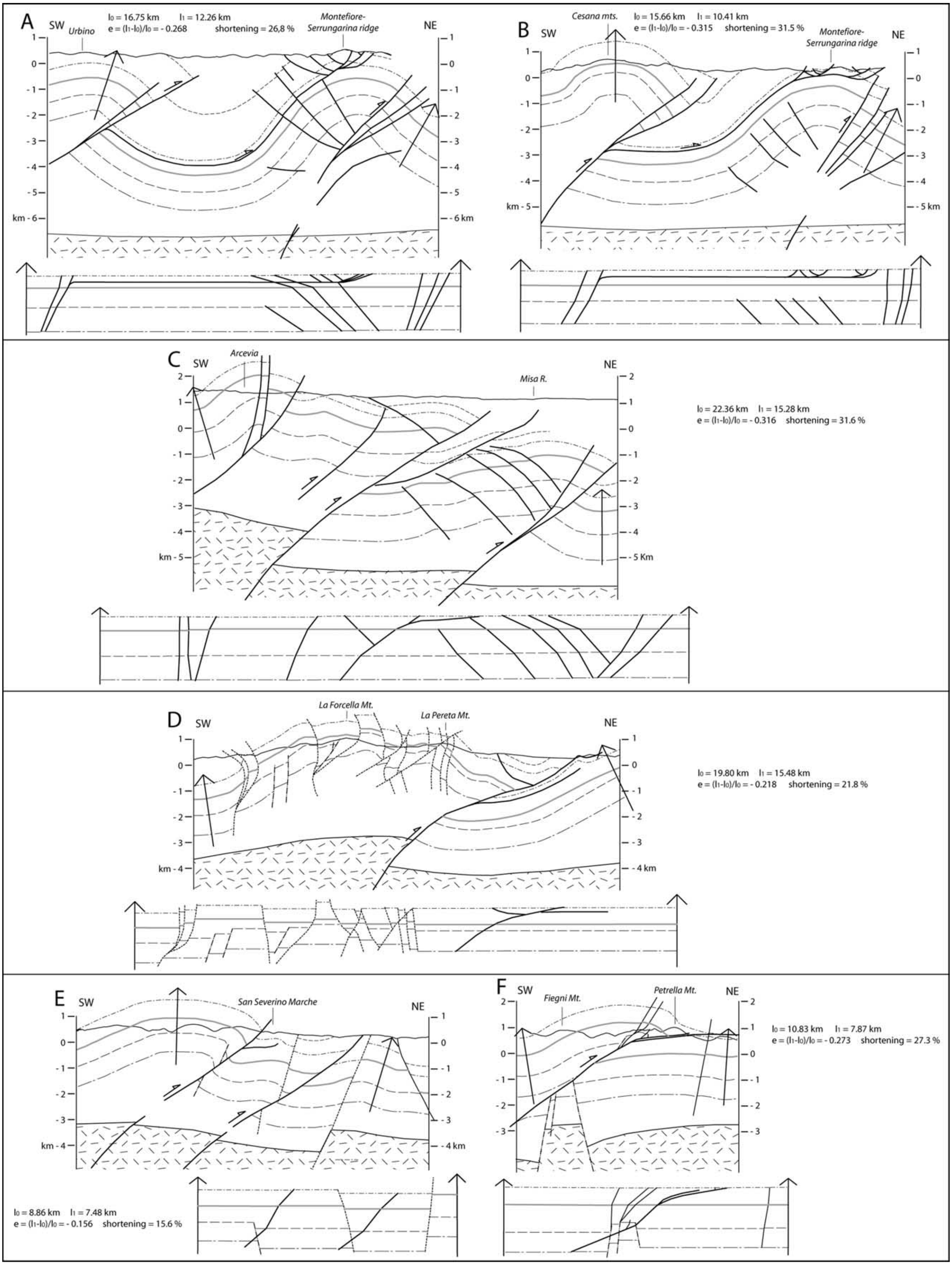

Fig. 5. Balanced geological sections (located in Fig. 2). Restoration is shown for pre-orogenic sedimentary cover succession only. Basement geometry in sections A and B is after Butler et al. (2004).

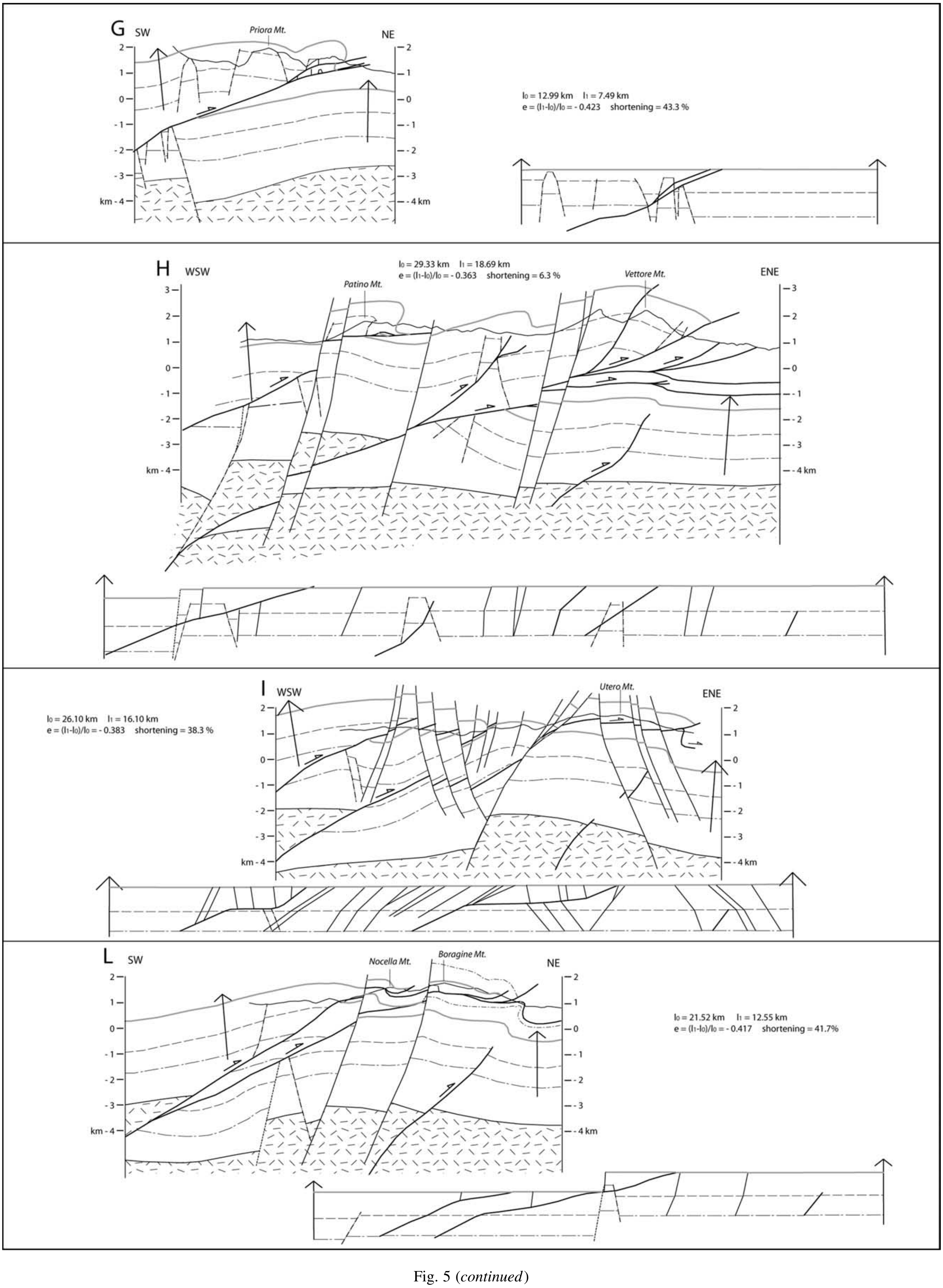

Fig. 5 (*continued*)

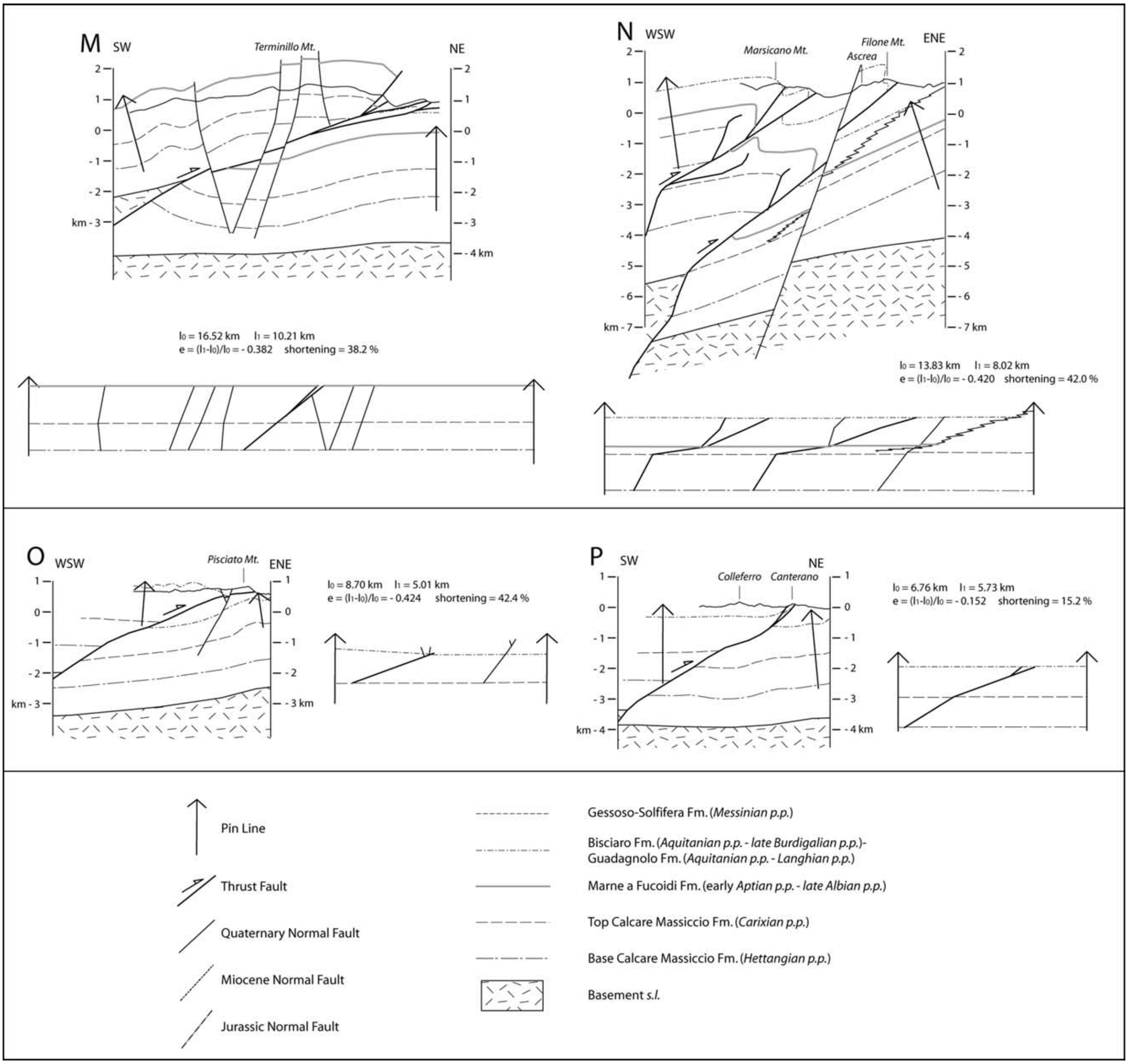

Fig. 5 (*continued*)

steep limb isolate several kilometres-long tectonic slices in which strata are overturned. A relatively simple structure characterises the northern portion of the Salto River–Sibillini Mts. Thrust (Fig. 5f and g), whereas the southern cross-sections (Fig. 5h–m) are rendered complex by the occurrence of a major splay, the Mt. Nocella thrust, that branches out from the main thrust fault (refer to Fig. 2). Significant topographic relief along the Salto River–Sibillini Mts. Thrust allows detailed observation not only of the main thrust zone fabric (Koopman, 1983; Lavecchia, 1985; Calamita et al., 1987) and hanging-wall cutoff relationships, but also of footwall cutoff geometry down to the stratigraphic level of the Maiolica Fm. Low- to moderate-angle thrust ramps characterise the Mesozoic–Paleogene strata, while thrust flats occur mainly in Miocene pre-turbidite, hemipelagic beds. The largest displacements (in excess of 8 km) are recorded along this segment of the UMSTZ. Between Mt. Vettore and Mt. Boragine areas the main fault is buried and forms a detachment, referred to as the Laga Detachment (Koopman, 1983), within intensely deformed Miocene hemipelagic strata underlying the Laga formation (Figs. 2 and 5i–l). The maximum thickness (>3 km) of the turbiditic upper Laga Fm. occurs in this region. This local thickening of turbiditic strata is thought to reflect a pre-thrusting basin architecture (Cantalamessa et al., 1984; Tavarnelli et al., 1999; Scisciani et al., 2002). The *Laga Detachment* is locally folded by later structures occurring at its footwall (Koopman, 1983; Calamita et al., 1987). Although the thrust faults did not propagate through a perfect layer-cake stratigraphy, pre-thrusting extensional

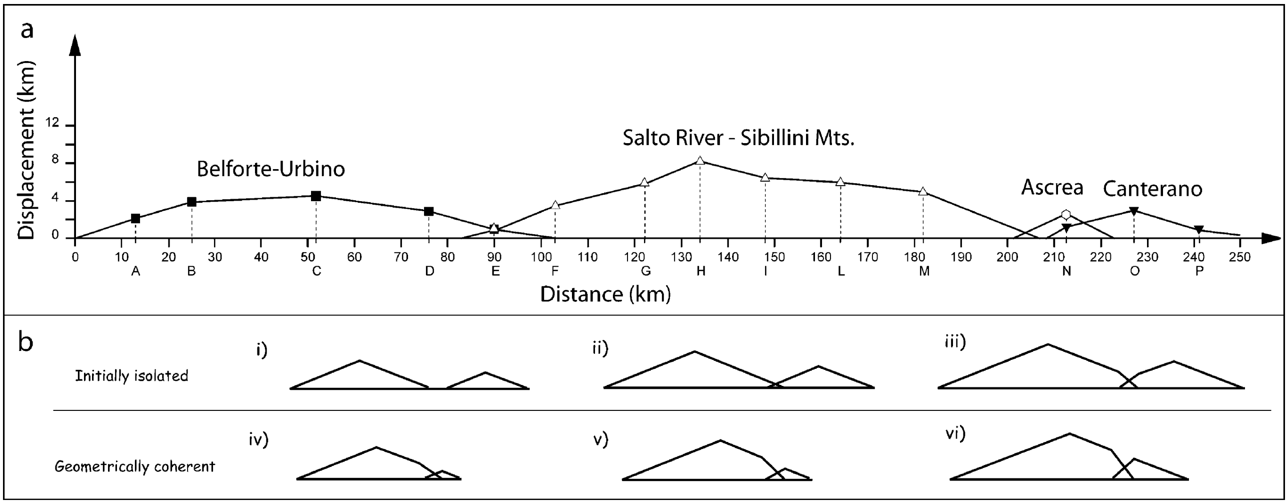

Fig. 6. Displacement profiles for UMSTZ fault segments (a), and (b) sketch of theoretical displacement profiles for initially isolated and geometrically coherent faults, showing increasing degree of interaction from left to right (after Nicol et al., 2002).

faults did not constitute efficient obstacles to thrust propagation along the base of the Laga Fm., as also shown by Tavarnelli et al. (1999).

3.1.3. Ascrea and Canterano thrusts

Balanced sections across the two right-stepping, en échelon Ascrea and Canterano Thrusts show a relatively simple structure characterised by limited displacements (reaching a maximum of 3 km). In this area, the UMSTZ and associated folds involve the Sabina transitional succession and the Latium–Abruzzi carbonate platform succession (Fig. 5n–p), together with unconformably overlying foredeep turbiditic deposits.

3.2. Displacement data analysis

For the analysis of thrust displacement it is necessary to take all measurements from a single horizon that is representative of the overall structure. The Marne a Fucoidi Fm. was selected for this because: (i) it represents the best defined horizon in the sub-surface data set, where it is commonly used to guide the interpretation within the Umbria–Marche and Sabina successions; (ii) it is the most laterally continuous horizon preserved in outcrop; and (iii) it retains the maximum pre-thrusting integrity, being not offset by Jurassic syn-sedimentary faults (as it forms part of the post-rift succession). The Marne a Fucoidi Fm. is only locally offset by pre-thrusting Miocene faults.

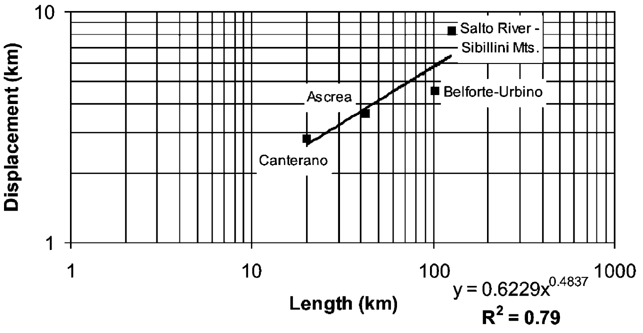

Fig. 7. Trace length vs. maximum displacement for individual UMSTZ fault segments.

These faults have not been reactivated during subsequent shortening, according to both our own and published evidence (Tavarnelli et al., 1999). Rather, they are offset and passively carried by the thrusts. Furthermore, there is no evidence here for the Cretaceous–Paleogene faults described to the west by Tavarnelli (1995). The two southernmost sections (Fig. 5o and p), involve the Latium–Abruzzi carbonate platform succession and do not include the Marne a Fucoidi Fm. For these sections, the Aquitanian–Langhian Guadagnolo Fm. was used as a marker horizon.

Thrust displacement across the UMSTZ has been measured as the distance, along the thrust surface, between hanging-wall and footwall cutoffs of the chosen marker horizon. Where the marker horizon is offset by different splays of the UMSTZ, the related cumulative displacement has been calculated. Displacement–distance diagrams are shown in Fig. 6a. The aggregate displacement profile shows that each fault segment is characterized by its own point of maximum displacement, hence suggesting that the fault segments were initially isolated from, and propagated toward one another (Fig. 6b; Nicol et al., 2002), resulting in variable amounts of fault overlap.

Thrust displacement gradients can be evaluated based on the parameter delta D (the ratio of fault displacement to strike-parallel distance; Johnson and Hennings, 1999). A steep displacement gradient (delta $D = 1{:}6$) characterizes the northern (Belforte–Urbino) thrust segment, near the northern fault tip line, a region in which there are significant changes in structural trends and large (>45°)

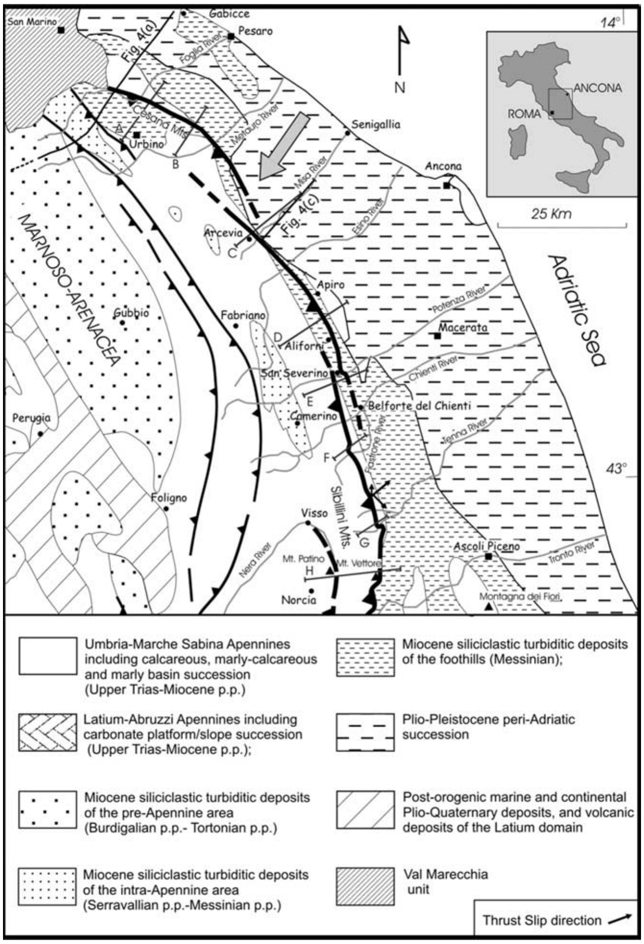

Fig. 8. Geological map of the northern part of the study area, modified by segmentation of the Belforte–Urbino Thrust (new hypothetical relay zone arrowed).

paleomagnetic rotations about a vertical axis (Mazzoli et al., 2001). On the other hand, the lack of a steep displacement gradient at the southern termination of the fault (delta $D=1{:}9$) suggests limited interaction with the next fault segment to the south (Salto River–Sibillini Mts. Thrust). Significant fault interaction appears to characterize the relay zones occurring farther south, at both terminations of the Ascrea Thrust. Although displacement gradients cannot be analysed for the Ascrea segment itself, as only one cross-section balancing and restoration data point has been obtained for this fault, steep displacement gradients characterize the southern termination of the Salto River–Sibillini Mts. Thrust (delta $D=1{:}5$) and the northern tip area of the Canterano Thrust (delta $D=1{:}2$; refer to Fig. 6a for thrust segment location).

Delta D values for the entire UMSTZ range between 1:6 and 1:20. These values are well compatible with existing data on differential transport in non-metamorphic thrust sheets maintaining lateral coherence (i.e. in the absence of intervening transverse structures such as tear faults or cross-strike discontinuities; Wilkerson, 1992; Johnson and Hennings, 1999). A graph (on logarithmic axes) of maximum displacement vs. trace length of individual fault segments shows a data point distribution that can be approximated by a straight line segment, spanning about one order of magnitude, with a slope of 0.48 and a correlation coefficient (R^2) of 0.79 (Fig. 7).

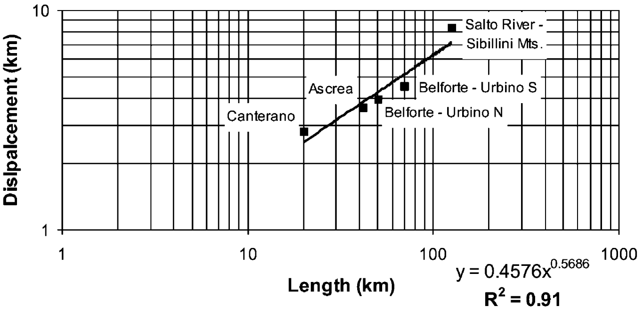

Fig. 9. Trace length vs. maximum displacement for individual UMSTZ fault segments, modified by segmentation of the Belforte–Urbino Thrust into two (N and S) segments.

4. Discussion

Power-law scaling relationships are well established for different parameters characterising fault populations, and tend to be self-similar over a range of scales (Walsh and Watterson, 1988; Wojtal, 1994). This is the case for the relationship between maximum displacements and maximum dimensions of faults, although significant scatter is common, especially for large normal fault populations (representing the vast majority of analysed structures; Yielding et al., 1996, and references therein).

Despite the fact that we are dealing with a rather small data set—as is often the case for thrust fault populations (Fermor, 1999; Hatcher, 2004)—the relationship between maximum displacement and trace length of thrust segments belonging to the UMSTZ is nevertheless likely to be significant, as it includes all fault segments belonging to the regional structure and it follows a power-law distribution, as expected for fault populations. The correlation coefficient of the straight line shown in Fig. 7 is acceptable taking into account published fault scaling relationships (which commonly include much larger data sets). However, a close inspection of Fig. 7 reveals that the data points relative to the two longer thrust segments (Belforte–Urbino and Salto River–Sibillini Mts.) show some deviation from the best-fit line. This deviation could well be a real feature indicating departure of these individual structures from the regionally established scaling relationship. Our analysis, in fact, may also be influenced by minor 'out of sequence' reactivation of parts of the UMSTZ (Calamita and Deiana, 1996) and/or by along-strike variations of the partitioning of the deformation between thrusting and folding (Pierantoni et al., in press).

We would like to suggest an alternative hypothesis to explain the anomalous scaling relationship of the long thrust

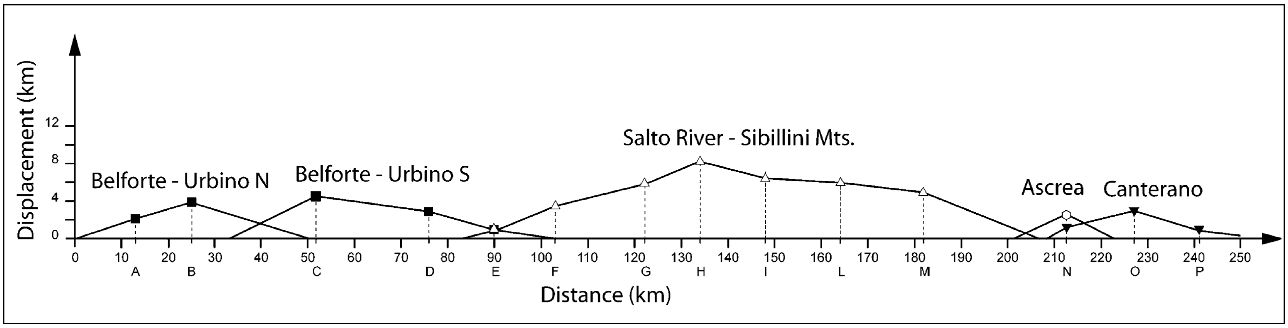

Fig. 10. Displacement profiles for UMSTZ fault segments, modified by segmentation of the Belforte–Urbino Thrust.

segments. The Belforte–Urbino Thrust is largely buried and it could be segmented in the area lacking seismic data (between Arcevia and Cesana Mts.; Figs. 2 and 4). Assuming the occurrence of a right-stepping, en échelon relay zone in this area (Fig. 8), a new graph of maximum displacement vs. trace length of individual thrust segments is obtained (Fig. 9), which considerably reduces the deviation of the scaling relationship data point of the longest thrust segment (Salto River–Sibillini Mts.) from the best-fit line. The resulting data point distribution yields a straight line segment with slope of 0.57 and a correlation coefficient (R^2) of 0.91. The accordingly modified displacement–distance profiles are shown in Fig. 10. The relatively steep displacement gradients occurring in the 'new', hypothetical relay zone (delta $D=1{:}4$ and 1:6 for the northern and southern fault segments, respectively) would suggest substantial fault interaction, similar to the more southerly overlap zones (i.e. at both terminations of the Ascrea Thrust).

5. Concluding remarks

A detailed analysis of a major thrust zone in the central-northern Apennines—the UMSTZ—shows that it is segmented into a series of right-stepping en échelon thrust faults, rather than consisting of a single, continuous feature for most of its length, as was previously reported. Interpretation of the UMSTZ as segmented is consistent with the relatively small displacement of the thrust zone (never exceeding 10 km), which is much less than would be expected for a continuous thrust hundreds of kilometres long.

Displacement gradients are generally moderate and compatible with published analyses of differential transport in coherent, non-metamorphic thrust sheets. Displacement–distance profiles suggest that individual thrust segments were initially isolated from, and subsequently propagated toward one another, resulting in variable degrees of overlap and fault interaction.

The relationship between maximum displacement and trace length of all thrust segments belonging to the UMSTZ appears to be self-similar for about one order of magnitude. However, a better correlation may be obtained by postulating further segmentation of the northernmost, blind thrust segment in an area of no seismic data cover and poor field constraints. We suggest that fault scaling relationships may be useful in identifying possible problems with structural interpretations in areas of poor field and/or sub-surface constraints. Viable alternative solutions, which yield better fits with the scaling relationships established in nearby, well-constrained areas, may then be identified and tested.

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