EGU Stephan Mueller Special Publication Series, 1, 195–209, 2002

Miocene fault-controlled sedimentation and thrust propagation in the previously faulted external zones of the Umbria-Marche Apennines, Italy

S. Mazzoli[1], **G. Deiana**[2], **S. Galdenzi**[3], **and G. Cello**[2]

[1]Facoltà di Scienze Ambientali, Università di Urbino, Campus Scientifico Sogesta, 61029 Urbino (PU), Italy
[2]Dipartimento di Scienze della Terra, Università di Camerino, Via Gentile III da Varano, 62032 Camerino (MC), Italy
[3]Viale Verdi 10, Jesi (AN), Italy

Received: 22 January 2001 – Revised: 9 May 2001 – Accepted: 16 May 2001

Abstract. Thrust propagation through previously faulted continental margins may result in fold and thrust belts whose structure is strongly controlled by the inherited basin architecture. A detailed geological study has been carried out in the external zone of the Umbria-Marche Apennines, from Monte San Vicino to the north, to Montagna dei Fiori to the south. Stratigraphic and structural data, together with the construction of a series of balanced and restored geological sections, point out the fundamental role played by the pre-orogenic basin architecture in controlling the geometry and evolution of the fold and thrust belt. Pre-thrusting structures include not only those inherited from the Mesozoic rifted continental margin, but also synsedimentary faults associated with Miocene extension which occurred ahead of the advancing thrust front. The latter structures produced important facies and thickness variations in the units deposited during the late Burdigalian-early Messinian, pre-evaporitic stages of foredeep development. In the southern sector (Montagna dei Fiori), high values of Messinian regional subsidence, bathymetry and sedimentation rate overcome the effects of synsedimentary extensional tectonics, which is best recorded in pre-Messinian sequences. On the other hand, Messinian regional subsidence was significantly less in the northern sector (Monte San Vicino). Here, several minor sub-basins developed within the foredeep, generally reaching evaporitic conditions during the middle Messinian (marked by the deposition of the Gessoso-solfifera Fm). In this area, a major control by pre-thrusting normal faults on sedimentation is recorded in the foredeep siliciclastic sequences. Late Burdigalian-early Messinian extension, possibly associated with flexure of the foreland lithosphere, peripheral bulge uplift and/or foreland tectonic activity, was followed by a late Messinian (post-evaporitic) contractional episode of regional extent. During shortening, inversion of preexisting Miocene extensional structures was quite limited. Hanging wall basin fills were retained and pre-thrusting faults show very limited or no reversal of slip. However, these faults and their hanging wall basin fills are generally deformed by buttressing phenomena, and fault planes are often tilted and/or locally reactivated in strike-slip. The present-day structure is dominated by newly-formed thrusts that cut across the pre-existing extensional architecture, which is in general quite well preserved within different thrust sheets.

Correspondence to: S. Mazzoli (s.mazzoli@geo.uniurb.it)

1 Introduction

In the last few years, geologists have increasingly appreciated the role of the pre-thrusting basin architecture in controlling the structure of foreland fold and thrust belts. Simple thrust tectonics models based on the assumption of original layer-cake (or wedge-shaped) stratigraphic templates have become progressively more complex (and more realistic) as thrust propagation through previously faulted continental margins has been taken into account (e.g. Butler, 1989; Welbon and Butler, 1992, and references therein). In the Umbria-Marche Apennines, as in most fold and thrust belt around the world, the fundamental role played by pre-orogenic structures related to rifting and subsequent passive margin development is now well established (e.g. Tavarnelli, 1996a; Coward et al., 1999; Marchegiani et al., 1999). On the other hand, the occurrence of synsedimentary normal faults which developed during continental collision ahead of the advancing thrust front has also been demonstrated by several workers (e.g. Calamita and Deiana, 1980; Cantalamessa et al., 1981; Mazzoli, 1994; Calamita et al., 1998; Tavarnelli et al., 1999). These studies however mainly deal with detailed structural features associated with Miocene pre-thrusting extension in a foreland basin setting. The aim of this work is to discuss the effects of these processes on a larger scale, taking into account the control exerted by Miocene pre-thrusting normal faults on both foreland basin sedimentation and on the architecture of the fold and thrust belt as a whole. To this purpose, a series of regional balanced and restored sections have been constructed by integrating structural and stratigraphic data with available subsurface information. This will hopefully allow us to obtain a new, comprehensive picture of the structural evolution of the external zones of the northern Apennines fold and thrust belt. That of the present study is in fact a key area for the understanding of the tectonic evolution of the frontal part of the Apennine orogen, as: (i) the widespread occurrence of Mio-Pliocene deposits provides an almost complete record of the Neogene deformation history, and (ii) the Late Miocene Apennine thrust front and its relationships with the adjacent foredeep can be analysed.

2 Regional Setting

The northern Apennines are a northeast verging fold and thrust belt which 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. Miocene to Early Pleistocene thrust accretion across the Adriatic (or Apulian) continental margin and Tyrrhenian back-arc extension (Kastens et al., 1988) were driven by gravity-induced sinking of the Adriatic and Ionian Sea lithosphere and related subduction roll-back (e.g. Malinverno and Ryan, 1986; Patacca and Scandone, 1989; Mazzoli and Helman, 1994, and references therein). In the northern and central sectors of the thrust belt, Liguride oceanic-derived units and Subliguride continental margin sequences form part of a detachment sheet tectonically overlying Oligo-Miocene synorogenic strata of the Toscana-Umbria district (including the Falterona-Trasimeno Unit in Fig. 1) and also (in Montefeltro) the Umbria-Marche sedimentary succession (Fig. 1).

The Umbria-Marche sector of the thrust belt (Fig. 1) is characterized by an arcuate shape and a main northeast vergence of asymmetric, mostly faulted anticlines involving a Mesozoic-Tertiary sedimentary succession (e.g. Calamita and Deiana, 1987). Deeper parts of the Apennine geology are known from deep wells (Anelli et al., 1994) which penetrate Permo-Triassic continental siliciclastics (the Verrucano Group). These, in turn, overlie crystalline basement units.

Understanding the depth to orogenic basement beneath the cover sequences of the Apennines has been a major problem. The Triassic strata include a thick wedge of evaporites (the Anidriti di Burano Formation) 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. Indeed for many workers the pre-evaporitic rocks are not involved in Apennine thrust tectonics until much further back towards the orogenic hinterland (e.g. Bally et al., 1986). The top to the magnetic basement lies at depths in excess of 10 km below most of the thrust belt (Cassano et al., 1998). However, the Verrucano lies between the evaporites and the crystalline, magnetic basement. Deep seismic data of the CROP 03 transect show that this succession is up to 6 km thick (e.g. Decandia et al., 1998).

While the Triassic evaporites are widely considered to have acted as a regional detachment, other levels within the Mesozoic and Cenozoic successions are also thought to have acted as thrust flats locally, particularly shales and marls within the otherwise carbonate-dominated units (e.g. Barchi et al., 1998). However, the notion that some fold-thrust structures in the Apennines might not conform to the simple fault-bend relationships developed by compression acting on a layer cake stratigraphy has been questioned recently. In the Umbrian Apennines, Tavarnelli (1996b) shows that folds initiated as buckles, apparently nucleated at pre-existing (Jurassic-age) normal faults. The thrusts which cut these folds have relatively little displacement, with the geometry essentially defined by “ramp-on-ramp” structures. However, this author maintains that basement units were not involved in the thrust systems and that there was regional detachment along the base of the sedimentary cover. Elsewhere however, basement involvement has been postulated by several authors (e.g. Lavecchia et al., 1987; Menichetti et al., 1991; Sage et al., 1991; Coward et al., 1999) and appears to be confirmed by the interpretation of the CROP 03 deep seismic reflection profile (Barchi et al., 1998).

Above the Mesozoic-Eocene (mainly carbonate) multilayer of the Umbria-Marche domain, hemipelagic, turbiditic and also evaporitic sediments were deposited from the Oligo-Miocene to the Pleistocene. In the Marche foothill area (Fig. 1), the deformed Umbria-Marche multilayer is mostly buried beneath such recent strata, whose deposition was at least in part controlled by synsedimentary normal faults (e.g. Calamita and Deiana, 1980; Cantalamessa et al., 1980, 1981; Mazzoli, 1994; Calamita et al., 1998; Scisciani, 1998, Tavarnelli et al., 1999; Deiana et al., 2002).

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 (e.g. Decandia et al., 1998) and therefore are coeval with thrust structures active further to the east. Indeed the entire chain has been convincingly described as a paired tectonic belt with extension in the orogenic hinterland balancing orogenic contraction on the forelandward side of the orogen (e.g. Lavecchia, 1988; Decandia et al., 1998). At about 700–800 ka, a major geodynamic change occurred and a new tectonic regime was established in the Apennine chain and adjacent foothill areas (e.g. Bertotti et al., 1997, and references therein). The structures related to this new regime, 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, being often also seismically active (e.g. Bertotti et al., 1997; Cello et al., 1997, and references therein).

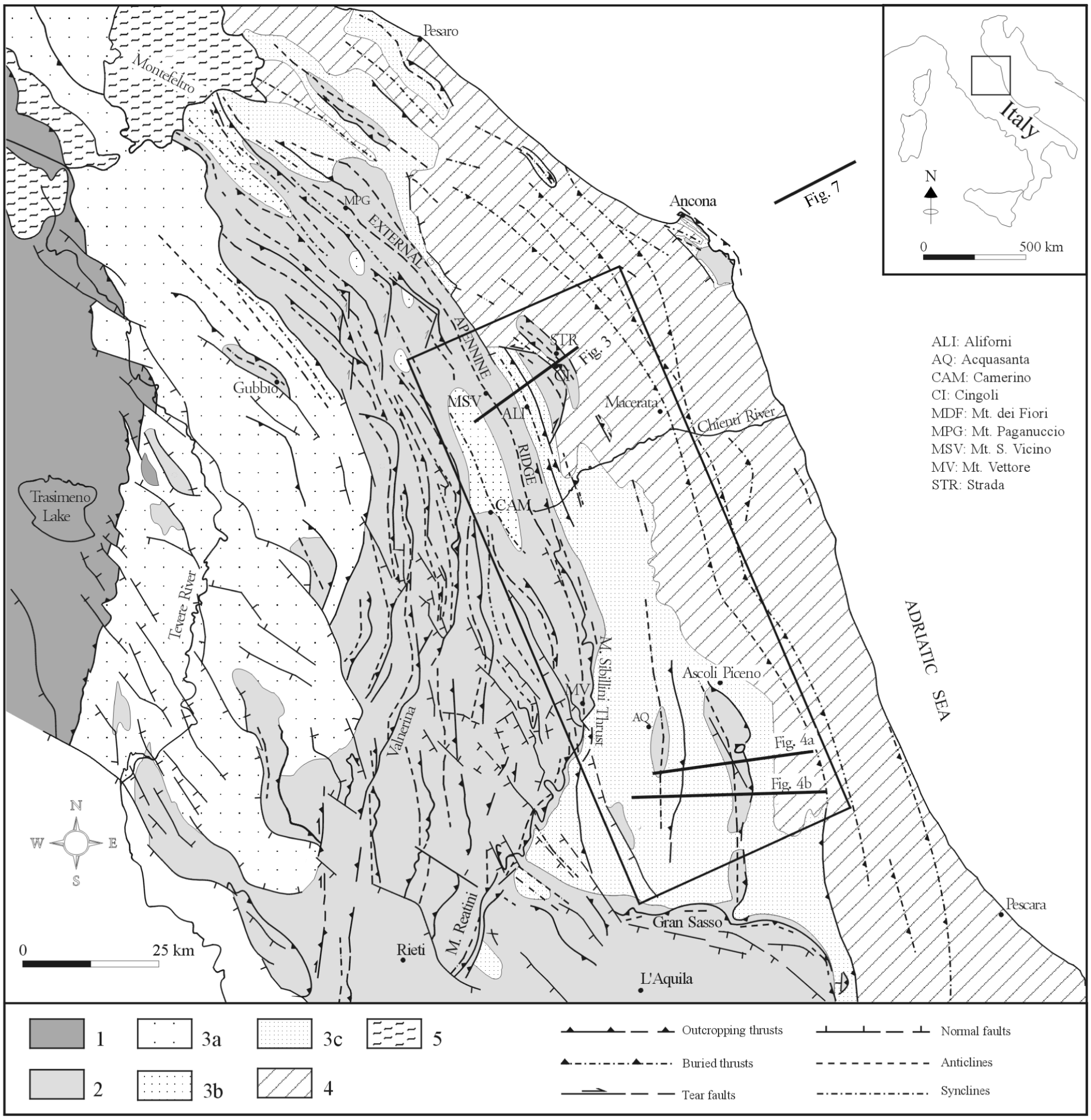

Fig. 1. Tectonic sketch map of the Umbria-Marche Apennines (modified after Deiana and Pialli (1994)), showing location of field study area. (1) Monte Falterona-Trasimeno Unit. (2) Calcareous, marly-calcareous and marly Umbria-Marche succession (Lias-Miocene). (3) Umbria-Marche siliciclastic turbiditic deposits: **(a)** Internal (Preapennine) area (Burdigalian-Tortonian); **(b)** Intra-Apennine basins (Tortonian-Messinian); **(c)** Foothill area (Messinian). (4) Plio-Pleistocene peri-Adriatic succession; (5) Liguride and Subliguride Units.

3 Geological data

The study area, located in the central-southern part of the Marche region, includes (from west to east; Fig. 1):

(i) the Camerino basin;

(ii) the external Apennine ridge (Deiana and Pialli, 1994); and

(iii) part of the foothills, including the ridges of Cingoli and Strada (to the north), and of Acquasanta and Montagna dei Fiori (to the south).

The Camerino depression consists of a syncline cored by the Messinian Gessoso-solfifera Fm. The external Apennine ridge consists of a regional anticlinal structure extending from Monte Vettore, to the south, to Monte Paganuccio to the north (Fig. 1). It is made of Mesozoic-Palaeogene, calcareous and marly-calcareous sedimentary cover units overthrusting the Tertiary units of the foothill zone to the ENE. The major tectonic contact (Monti Sibillini Thrust; (Scarsella, 1941)) is well exposed south of the Chienti River valley (Fig. 1), where it crops out along the base of the Apennine mountain front and links to the south to the so-called "Olevano-Antrodoco-Posta Line" (Salvini and Vittori, 1982). Several hypothesis have been put forward concerning the northern prosecution of this structure. According to Dallan Nardi et al. (1971), the thrust fault (corresponding to part of the so-called "Ancona-Anzio Line") should correspond to the boundary between the Apennines s.s. and the "Marche-Romagna Mio-Pliocene basin", being in part masked by a cover of Upper Miocene deposits. On the other hand, Calamita (1986) and Calamita and Deiana (1988) suggested that the Sibillini Thrust would be buried by a frontal backthrust. The integration of geological data with the analysis of commercial seismic reflection profiles allowed Calamita et al. (1990) to interpret the occurrence of the Sibillini Thrust at depth below the Monte San Vicino area (Fig. 1). According to the latter authors, the Sibillini Thrust in this area would form an intercutaneous wedge bounded above by a passive backthrust. In the last few years, however, a surface emergence of the Sibillini Thrust along the base of the mountain front in the Monte San Vicino area has been suggested by Barchi et al. (1996) and is confirmed – although in a different position with respect to that suggested by the latter authors – by detailed geological mapping (Deiana et al., 2002) (Fig. 1).

The foothill zone in the study area (Fig. 1) includes the NNW-SSE trending Cingoli anticline, which is cored by Mesozoic-Palaeogene units and is bounded on its northern and southern terminations by transpressive high-angle faults. Lower Pliocene deposits onlap the eastern limb of the anticline, whereas west of it the NNW-SSE trending Aliforni syncline occurs, which is cored by Messinian siliciclatic turbidites stratigraphically overlying Tortonian to Oligocene hemipelagic deposits. East of the Cingoli anticline, the Strada anticline occurs. This displays a NNW-SSE to N-S trend and is cored by Tortonian hemipelagic marls.

In the southern part of the study area, the major structural features of the foothill zone consist of the Acqusanta and Montagna dei Fiori anticlines. This area is characterized by extensive outcrop of a turbiditic siliciclastic succession pertaining to a Messinian foredeep (Laga basin) bounded to the south by the Gran Sasso ridge. The latter includes carbonate rocks from a Triassic-Tertiary succession ascribed to a transitional domain located between the Lazio-Abruzzi platform (to the south) and the Umbria-Marche basin (to the north). The tectonic contact between the Gran Sasso unit and the underlying Laga deposits consists of a roughly E-W trending thrust at whose footwall the major (Acquasanta and Montagna dei Fiori) structures of the foothills are observed to plunge southwards beneath the Gran Sasso thrust sheet (e.g. Ghisetti and Vezzani, 1991).

3.1 Stratigraphy

The outcropping stratigraphic units are those of the Umbria-Marche sedimentary succession, which reflects the genesis and evolution of this sector of the Afro-Adriatic continental margin since Triassic times (Fig. 2). The lower part of this succession, essentially of carbonate composition (Upper Triassic-Eocene), displays significant vertical and lateral variations of both facies and thickness of the formations. These resulted from rifting and subsequent development of a passive continental margin, from a continental environment (Middle Triassic Verrucano Fm), to a platform one (Burano Anhydrites and Calcare massiccio/Castelmanfrino Fms), to pelagic conditions during the deposition of the Jurassic successions. The latter include both so-called "complete" and "condensed" successions (e.g. Colacicchi et al., 1970; Centamore et al., 1971). The former, typical of the depressed areas of the Jurassic basin, includes (from bottom to top): the Corniola, the Rosso ammonitico, the laterally equivalent Calcari a Posidonia (northern area) and Salinello (southern area) Fms, and the Calcari diasprigni Fm. The "condensed" succession, characterizing the elevated (i.e. footwall) fault-bounded blocks, consists essentially of nodular limestones (Bugarone Formation). Both "complete" and "condensed" successions are stratigraphically overlain by uppermost Jurassic to Eocene (p.p.) limestones and marls of the Maiolica, Marne a Fucoidi, Scaglia bianca, Scaglia rossa, and Scaglia variegata Fms.

The stratigraphically overlying hemipelagic succession is made of the Scaglia cinerea, the Bisciaro, and the laterally equivalent Schlier Fm (northern area) and Marne con cerrogna-Marne a Pteropodi Fms (southern area) of Eocene to lower Messinian age. It displays a progressively younger stratigraphic top towards the external zones of the chain and a southward increasing carbonate detrital component (due to sediment shedding from the Lazio-Abruzzi carbonate platform). This succession can be interpreted as a foreland ramp sequence marking the onset of flexure of the foreland lithosphere. Thickness variations within the uppermost Burdigalian to lowermost Messinian Schlier and Marne con cerrogna-Marne a Pteropodi Fms suggest the existence of significant submarine topography prior to the deposition of the siliclastic turbidites (e.g. Cantalamessa et al., 1980).

The foredeep sequences capping the whole sedimentary succession show variable stratigraphic characteristics, mainly lateral variations in both facies and thickness of the formations, as well as a progressive younging to the east. In the southern sector of the study area, Upper Miocene foredeep deposits consist entirely of the Laga Fm of Messinian age (e.g. Crescenti, 1966; Girotti and Parotto, 1969; Ricci Lucchi, 1975; Mutti et al., 1978; Cantalamessa et al., 1986; Ridolfi, 1993; Bigi et al., 1999) exposed in the footwall to the Sibillini Thrust (Fig. 1). It consists of a clastic wedge whose thickness (3 000 metres according to Ricci Lucchi (1975); more than 4 000 metres according to Parotto and Praturlon (1975)) is indicative of very high sedimentation rates (in excess of 200 cm/ky). The lithologic characters of the Laga Formation are quite variable, giving rise to a complex vertical and horizontal organization of facies associations showing the main features of a first-order transgressive sedimentary cycle. According to Cantalamessa et al. (1986), three members can be distinguished:

(i) a pre-evaporitic member, in which arenaceous and arenaceous-pelitic associations are dominant, representing the lowest term of the formation, unconformably overlying the pre-siliciclastic substratum;

(ii) an evaporitic member, characterized by the occurrence of gypsum-arenitic turbidites alternating with siliciclas-

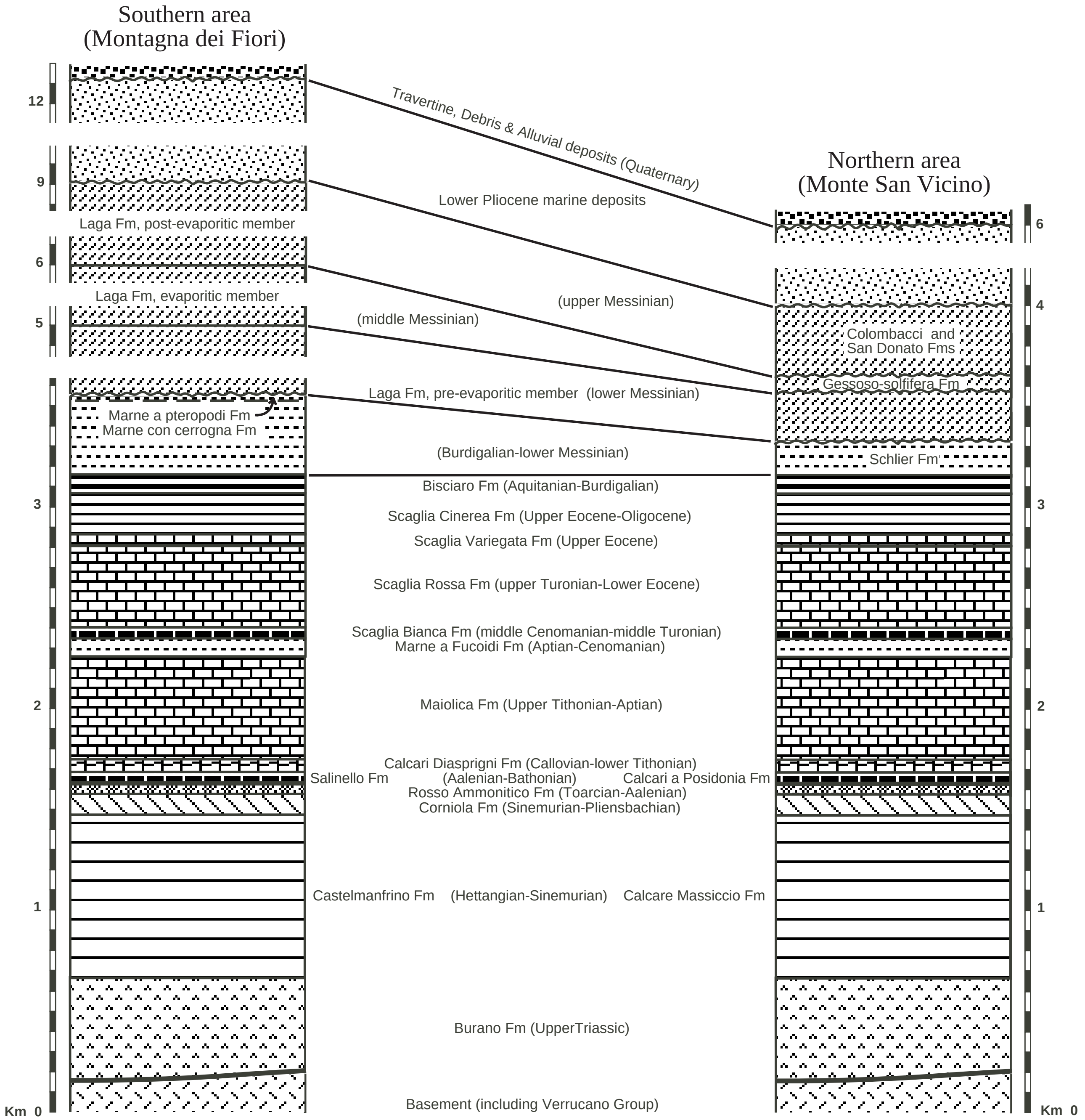

Fig. 2. Schematic stratigraphic columns for the study area (note diferrent thickness of Upper Miocene deposits in the northern and southern sectors).

tic turbidites, constituting the intermediate part of the succession; and

(iii) a post-evaporitic member, which includes both arenaceous-pelitic and pelitic associations, representing the highest part of the formation.

In the lower part of the latter member, a 1–2 metres thick volcanoclastic layer also occurs (Girotti and Parotto, 1969; Cantalamessa et al., 1986). In the upper part, a few thin beds of creamy limestones are also observed. These creamy limestones are quite similar to those belonging to the Colombacci Formation cropping out in the northern part of the study area (see below). Paleocurrent measurements from the whole Laga Fm suggest that most of the siliciclastic sediments flowed into the Laga Basin in a roughly N-S direction, except for those of the post-evaporitic member which are characterized by paleocurrent directions with an opposite polarity (Cantalamessa et al., 1986). Furthermore, petrographic analyses also point out a different composition of the post-volcanoclastic sandstones, which appear to be particularly enriched in carbonate clasts (Centamore et al., 1991). This would suggest that their deposition may mark a new sedimentary cycle within the Miocene foredeep, as proposed by Patacca et al. (1991).

Based on the stratigraphic outlines above it is clear that, in the southern part of the study area, bathymetry and sedimentation rate in the foredeep in front of the Sibillini Thrust were so high during the Messinian that even the effects of the well known Mediterranean salinity crisis (Hsu et al., 1978) were almost completely overprinted. In fact, only the gypsumarenitic turbidites occurring within the evaporitic member of the Laga Fm record evaporitic conditions in the source area. The situation is quite different in the northern part of the study area, where several minor sub-basins developed in the Messinian foredeep (e.g. Calamita et al., 1979). These generally reached evaporitic conditions during the middle Messinian (marked by the deposition of the Gessoso-solfifera Fm), while sedimentation in the upper Messinian is characterized by both siliciclastic (San Donato Fm) and alternating siliciclastic and evaporitic units (Colombacci Fm) that are in part laterally equivalent to the post-evaporitic member of the Laga Fm.

In the northern sector of the study area, Upper Miocene foredeep and thrust top basin deposits occur both in the hanging wall and footwall to the Sibillini Thrust (Fig. 1). They are also progressively younger to the east: the Camerino basin, located west of the Monte San Vicino ridge, hosts the Camerino Fm of upper Tortonian to lower Messinian age; the Aliforni basin, located between the Monte San Vicino and Cingoli ridges, contains the pre-evaporitic member of the Laga Fm, followed by the Gessoso-solfifera, San Donato and Colombacci Fms, all of Messinian age; the Marche foothill zone, east of the Cingoli ridge, hosts the post-evaporitic member of the Laga Fm and the Colombacci Fm, of Messinian age, stratigraphically overlain by Lower-Middle Pliocene deposits. These sequences are bounded by unconformities located:

(i) at the base of the pre-evaporitic siliclastic turbidites,

(ii) at the base of the Gessoso-solfifera Fm,

(iii) between the latter and the San Donato Fm,

(iv) at the base of the Colombacci Fm,

(v) at the base of the Pliocene strata, and

(vi) within the Pliocene succession.

These unconformities mark the main deformation events within the syntectonic basins and provide a record of the structural evolution of this sector of the Apennine chain. The Late Miocene turbiditic sedimentation is characterized by quite sharp lateral facies variations. The coarser (arenaceous) deposits occur in the most depressed areas of the basins. They often contain intercalations of paraconglomerates and chaotic materials whose elements derive from the erosion of the Miocene or even pre-Miocene substratum. The Camerino basin, for instance, is strongly asymmetric, with the most depressed area located towards the Monte San Vicino ridge. In this area, the arenaceous turbidites display intercalations of very coarse, chaotic deposits containing elements of even Eocene and Cretaceous age (Calamita and Deiana, 1980). The Aliforni basin, showing significant thickness variations in a longitudinal sense, is characterized by unconformable contacts of the pre-evaporitic clastic bodies and also of the Messinian evaporites onto the pelagic substratum of the fold limbs. The Pliocene succession is also characterized by significant lateral facies and thickness variations, with the greater thicknesses occurring in the external (more distal) zones of the Pliocene basin, where fine grained deposits are dominant, whereas thinner bodies of coarser material occur along the basin margin (Deiana et al., 2002).

3.2 Structure

The structure of the study area is shown in the balanced and restored geological sections of Fig. 3 (northern area) and Fig. 4 (southern area). In the northern sector, seismic data are available (Calamita et al., 1990) which permit to identify the major thrust faults underlying the Monte San Vicino and Cingoli culminations. However, the geometry of the basement is not imaged in sufficient detail for it to be included in the cross-section of Fig. 3, which therefore shows exclusively the structure of the sedimentary cover. For all the cross-sections, we have used the top of the Lower Liassic as a key horizon (in the sense of Geiser (1988)) to obtain a value of shortening in the cover. All of the geological profiles show the occurrence of pre-thrusting faults which will be discussed in the following sections.

3.2.1 Fold-thrust structures

The structure of the northern part of the study area is shown in the cross-section of Fig. 3. To the east of the cross-section, the Strada anticline lies in the hanging wall to three thrust splays, the eastermost of them being sealed by Lower Pliocene deposits ascribed to the Globorotalia puncticulata biozone (Calamita et al., 1990; Deiana et al., 2002). West of this structure, the Cingoli anticline lies in the footwall to the Sibillini Thrust. The prosecution of the latter north of the Chienti River (Fig. 1) is an important, new structural element recognized in the northern sector of the study area. It crops out within the Miocene units exposed in the western limb of the Cingoli anticline, about 4–5 km away from the mountain front. The thrust carries the Aliforni syncline in the hanging wall and shows a NNW-SSE to N-S strike. In outcrop, it carries the Schlier Fm and the stratigraphically overlying Messinian succession on top of the Gessoso-solfifera Fm, which represents the youngest unit in the footwall, or locally on top of the sandstones of the pre-evaporitic member of the Laga Fm. Minor thrust splays occur in the footwall to the major thrust fault, producing a trailing imbricate fan thrust geometry (Boyer and Elliot, 1982). The frontal part of the outcropping thrust surface is also folded into antiforms

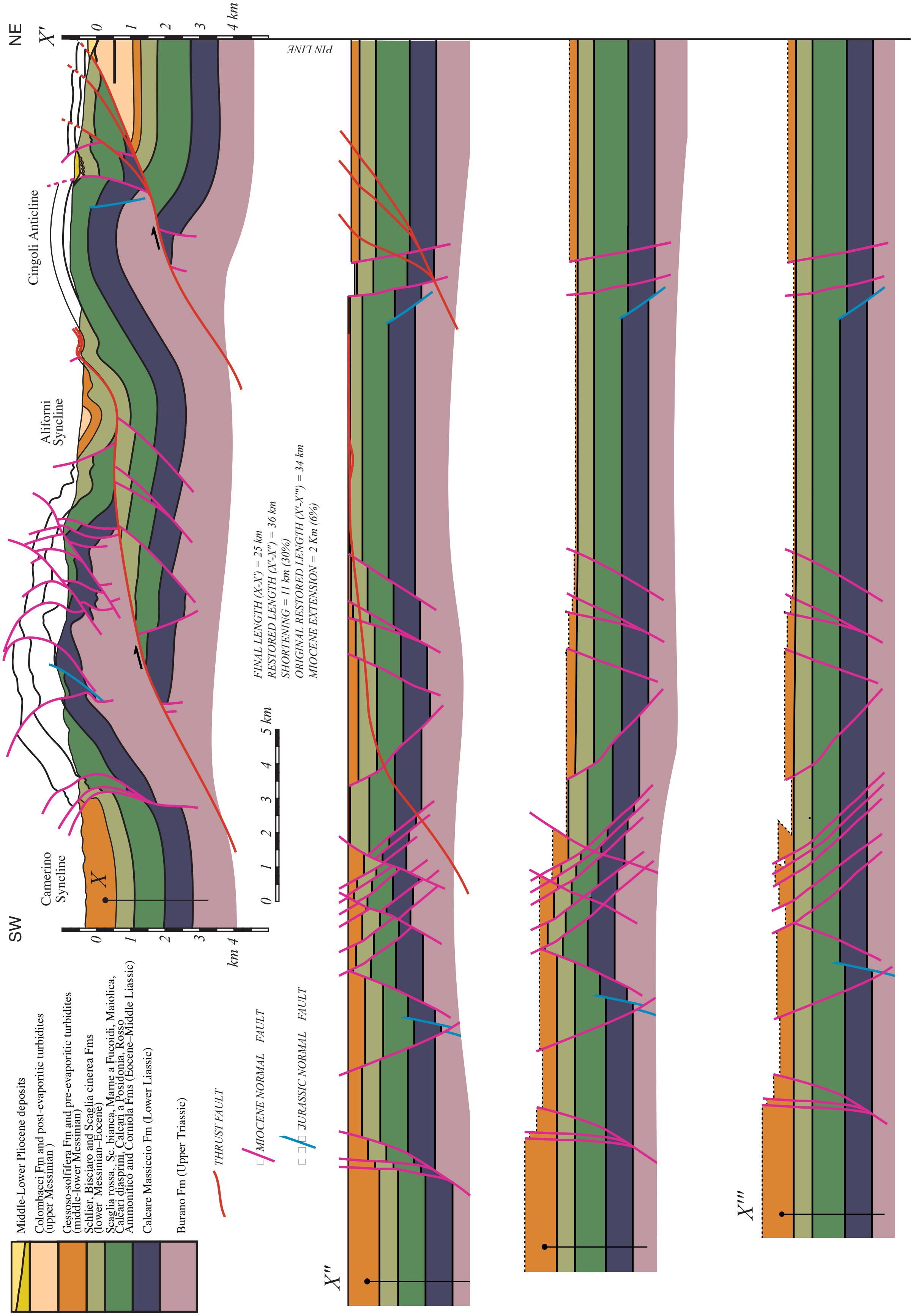

Fig. 3. Geological section (located in Fig. 1) across the northern part of the study area, constructed by the integration of subsurface information (Calamita et al., 1990) and field data. Sequential restoration has been carried out for the Liassic-Tortonian part of the succession by eliminating folds and thrusts first (restoring to pre-shortening length X''-X'), and then different generations of Miocene normal faults (restoring to pre-extension length X'''–X'). Area occupied by lower Messinian fault-controlled deposits is also shown in the restorations.

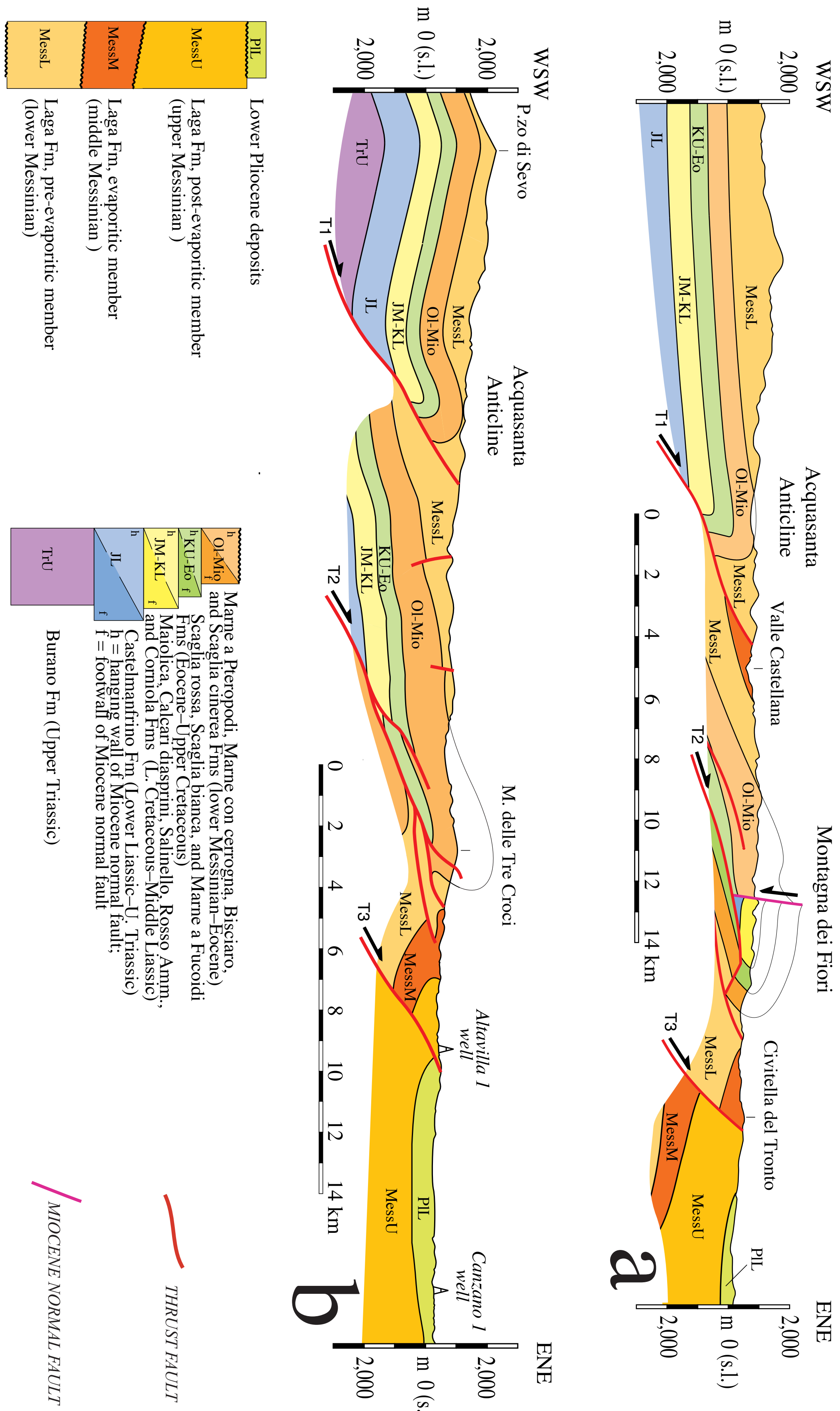

Fig. 4. Geological sections across the southern part of the study area (located in Fig. 1)

and synforms of a few hundreds metres wavelength. Erosion of these structures has produced local synformal klippen ahead of the major fault trace. In the hanging wall to the Sibillini Thrust, the Monte San Vicino ridge shown in the cross-section of Fig. 3 represents a complexly faulted, local culmination of the Monte Vettore-Monte Paganuccio regional anticlinal structure (external Apennine ridge). In this culmination, all the terms of the Jurassic-Palaeogene succession, down to the Lower Liassic shallow-water carbonates, are exposed.

In the southern part of the study area, the structure in the footwall to the Sibillini Thrust is dominated by the Acqusanta and Montagna dei Fiori major anticlines (Fig. 4). These structures display general sub-cylindrical geometries (Ramsay, 1967) and NNW-SSE trends (Fig. 5a, b). The Acquasanta structure is made up of a north-plunging asymmetric anticline showing a shallow dipping (10–15°) western limb, and a sub-vertical to inverted eastern fold limb. The oldest rocks exposed in the anticline are represented by strata of the Scaglia rossa Fm cropping out in its core. The Acquasanta anticline rests in the hanging wall to a high-angle thrust (T1 in Fig. 4a, b) which produces in outcrop the superposition of the pre-evaporitic onto the evaporitic member of the Laga Fm. The latter is involved in a roughly north-south trending footwall syncline, which shows a steeply-dipping western limb well exposed in the southern termination of the structure.

The Montagna dei Fiori structure is the largest, easternmost positive structure cropping out in this sector of the foothill area of the Apennines. It is characterized by an eastern fold limb (including rocks of post-Liassic age) which is inverted and thrusted, together with the underlying Calcare Massiccio Fm, over a footwall succession consisting of inverted strata of the Scaglia rossa Fm (Fig. 4a). The southern termination of the Montagna dei Fiori structure is characterized by a gently dipping (less than 20°) western flank and a steeply dipping to inverted eastern limb cut by several thrust faults (Fig. 4b). In the area of the Altavilla 1 Well, one of these thrust splays produces the tectonic superposition of the Laga Fm onto Lower Pliocene marls to the east.

The beds of the Scaglia rossa Fm cropping out in the northern sector of the Montagna dei Fiori antiform show steep northern dips, as well as minor, roughly E-W trending, gentle to close folds, with a few metres wavelength and steeply inclined to vertical axial surfaces. The latter structures are superposed on NNE-SSW trending mesoscopic folds which are parasitic to the major structure.

Parasitic folds to the Acquasanta and Montagna dei Fiori major anticlines, showing wavelengths of a few metres and close to tight shapes with dominantly kink or chevron geometries, are mostly developed in the Marne a Fucoidi, Scaglia rossa and Scaglia cinerea Formations. Fold shape alternates between class 1 and class 3 of Ramsay (1967): competent limestone layers have more rounded hinges and show class 1B or class 1C geometries, whereas less competent pelitic layers have angular to rounded hinges and typically exhibit class 3 geometries. Mesoscopic folds are of symmetric (*m*) type on the hinge zone of the main structures, whereas they display typical *s* and *z* asymmetries on the limbs. Fold axial surfaces range mostly from moderately dipping to steeply dipping. Fold hinges are sub-horizontal to moderately plunging and display a pattern of preferential orientation around a roughly NNW-SSE direction (Fig. 5c, d).

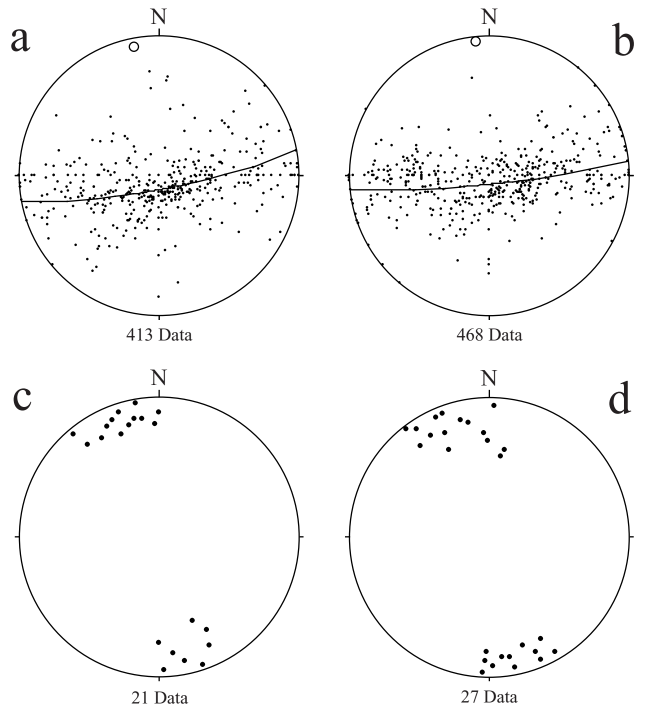

Fig. 5. Orientation data from the southern part of the study area (lower hemisphere, equal area projections). **(a)** Poles to bedding (dots) and pole to the best-fit great circle to the poles to bedding (π fold axis, circle: 349/08) for the Acquasanta major anticline. **(b)** Poles to bedding (dots) and pole to the best-fit great circle to the poles to bedding (π fold axis, circle: 354/05) for the Montagna dei Fiori major anticline. **(c)** Minor fold hinges (parasitic folds) associated with the Acqusanta major anticline. **(d)** Minor fold hinges associated with the the Montagna dei Fiori major anticline.

Major folds and associated parasitic structures clearly deform preexisting fabrics (cleavage, S-C tectonites, reverse shear planes) developed in the Oligo-Miocene (presiliciclastic) terms of the succession. These consistently show an original top-to-the-east sense of shear, most probably associated with an early detachment of the Laga clastic wedge from the underlying Mesozoic-Palaeogene substratum. Early detachment and eastward transport "en masse" of the thick Laga sedimentary wedge were most probably the result of an eastward propagation of the Sibillini Thrust which occurred, in the southern part of our study area, into a higher flat located along the Oligo-Miocene (presiliciclastic) terms of the succession (e.g. Koopman, 1983; Ridolfi, 1993).

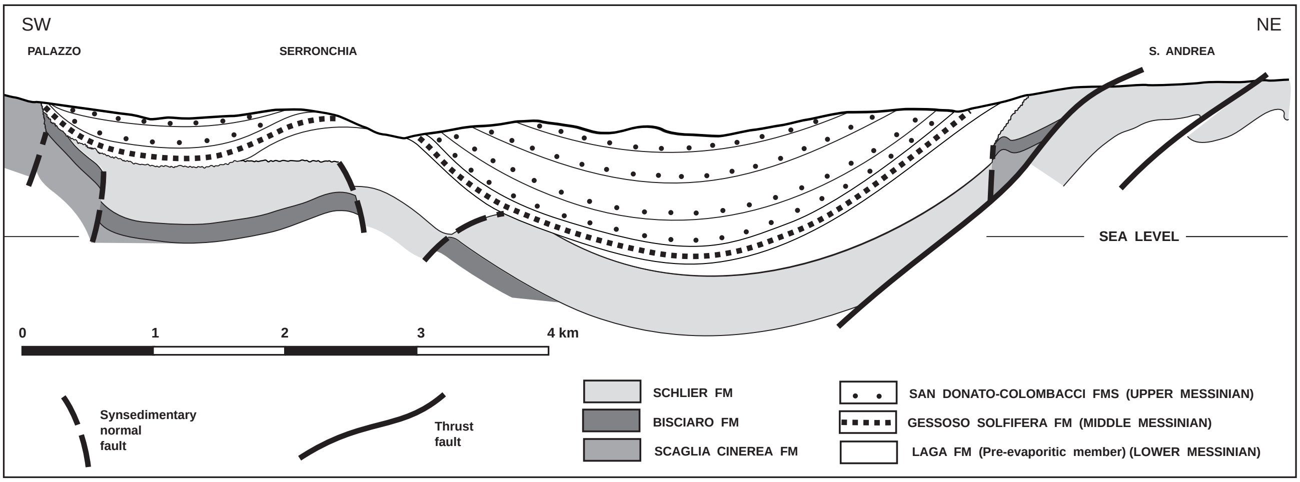

Fig. 6. Schematic geological section across the northern part of the Aliforni syncline, showing: (i) synsedimentary Miocene faults (pre-Gessoso-solfifera), (ii) unconformities among the Miocene pre-evaporitic units on the fold limbs, and (iii) growth strata of the San Donato Fm. Note fault controlled deposition of lower Messinian turbidites (below the evaporites) and onset of contraction and folding marked by upper Messinian growth strata.

3.2.2 Faults

Different types of faults, showing variable timing of activity and geometric relationships with respect to the fold and thrust structures described above, are exposed within the study area (Figs. 3 and 4).

Jurassic faults (and/or palaeofault scarps), either exposed or outlined by the distribution of the lithological associations, occur in several localities along the external Apennine ridge and are also exposed in the core of the Montagna dei Fiori anticline. The cross-section of Fig. 3 encounters two of such faults, but the extension produced by them is minimal, as these structures represent two roughly N-S oriented transfer faults among different WNW-ESE striking normal fault segments (Deiana et al., 2002). These faults will be not discussed into further detail here, as they are not the subject of the present study.

Synsedimentary faults of main interest here are those controlling deposition in the Miocene foreland basin. Typical elements of the Miocene synsedimentary tectonic activity are of both mesoscopic and regional type. Mesoscopic synsedimentary faults at a high angle with respect to bedding are observed throughout the study area in the pre-evaporitic member and (in the southern part of the study area) in the evaporitic member of the Laga Fm. These faults, generally planar or nearly so, show extensional offsets with respect to bedding and have displacements ranging from a few centimetres to several metres. In several instances, upward deacreasing fault offsets can be observed, the faults being sealed by unfaulted strata. In many cases, the faults appear to be broadly conjugate with respect to bedding, as the intersection line of fault plane pairs lies approximately within a plane parallel to bedding and the acute bisector is roughly perpendicular to bedding. This geometric relationship is maintained irrespectively of the variable attitude of the beds, which resulted from folding of the strata, providing a strong argument for faulting prior to tilting of the strata. Furthermore, sand and pelite lenses (often arranged in discontinuos bands along the fault surfaces) also suggest that these faults were active before sediment lithification was complete. Minor (i.e. showing centimetric displacements) shear fractures oblique to bedding most commonly offset competent (sandstone) layers, dying out into adjacent incompetent shaly or marly horizons. Many of the minor shear fractures showing normal-fault offsets display a dilational component, where adjacent incompetent material flowed into the voids (suggesting that most of these structures actually formed as hybrid shear/dilation fractures). These features suggest that the observed shear fractures can be classified as semi-ductile (Price and Cosgrove, 1990), recording early deformation in semi-lithified sediments. Fracturing occurred in at least partially indurated (due to early cementation) sandstones, while in the adjacent, and still mobile muds or clays deformation was accommodated by ductile flow.

Regional features associated with Miocene synsedimentary extension include:

(i) unconformable contacts of the turbidite strata and overlying evaporites on top of the hemipelagic substratum;

(ii) paraconglomerates and chaotic deposits (made of substratum material) occurring at the base or within the turbidite units; and

(iii) slump structures.

Unconformable contacts among Miocene units occur, for instance, along the margins of the Aliforni turbiditic basin in the northern part of the study area. Here, the pre-evaporitic member of the Laga Fm pinches out laterally and the overlying evaporites locally lie directly on top of the hemipelagic substratum. In the northern part of this basin (Palazzo area;

Fig. 6), the Gessoso-solfifera Fm rests directly above the Scaglia cinerea along an irregular surface steeply dipping to the ENE. This surface, formerly interpreted as a late (i.e. post-thrusting) fault (Calamita et al., 1990), is actually very likely to represent a palaeofault scarp associated with a synsedimentary fault. The latter would have been tilted and steepened during the later contractional deformation (Scisciani, 1998). Moving from Palazzo to the east, the evaporites unconformably overly the Bisciaro and Schlier Fms and then the pre-evaporitic sandstones (Fig. 6). The latter crop out in the core of an open anticline which can be best interpreted as the result of inversion of a synsedimentary graben. Also along the eastern margin of the Aliforni basin, the Gessoso-solfifera Fm overlies the Schlier Fm or the lower Messinian turbidites. In synthesis, the evaporites appear to fill out a residual topography produced by extensional faults, representing therefore a post-rift unit with respect to the Miocene faults. Among the latter, also important is the discontinuity separating the Eocene-Oligocene succession of the eastern limb of the Cingoli anticline and the adjacent Messinian-Pliocene deposits (Calamita et al., 1990). This discontinuity most probably represents a palaeoscarp associated with a synsedimentary fault (Scisciani, 1998) which evolved similarly to that exposed near Palazzo.

Several faults, mainly trending N-S to NNW-SSE, cut through the Mesozoic-Palaeogene succession of the Monte San Vicino ridge (Fig. 3). Apart from the Mesozoic faults mentioned above, most of these faults cannot be directly constrained in age because of the lack of related syntectonic deposits (which have been eroded). However, the following characteristics can be taken into account:

(i) fault-related morphology is planated by a Pliocene “palaeosurface” (Calamita et al., 1980);

(ii) the faults consistently show extensional offsets with respect to bedding, even where they are steepened and overturned to show apparent reverse geometries; and

(iii) fault surfaces are locally observed to be strongly deformed and have been often reactivated in strike-slip.

In the southern sector of the study area, a major Miocene pre-thrusting fault has been described by Calamita et al. (1998). The syn-rift sequence to this fault consists of upper Burdigalian-Tortonian calcarenites, whereas the overlying Messinian Laga Fm appears to constitute mostly a post-rift sequence with respect to it, filling the residual topography.

4 Discussion

The data exposed above point out the important role played by the pre-orogenic basin architecture in controlling the structure of the Apennines fold and thrust belt in the study area. Major inherited structures include both those of the rifted continental margin, of Mesozoic age, and those related to Miocene foreland deformation, which are the subject of the present study.

The occurrence of Miocene pre-thrusting normal faults has long been recognized in the Umbria-Marche Apennines. Calamita and Deiana (1980) discussed a Late Miocene extensional phase in the turbiditic Camerino basin (refer to Fig. 1). According to these authors, NW-SE trending normal faults (also accompanied by sedimentary dikes) separated the basin from the Monte San Vicino ridge to the east and controlled the deposition of the turbidites. On the other hand, the synsedimentary tectonic contacts separating the structural highs from the adjacent depressions in the Messinian Laga basin are also of extensional type as suggested by Cantalamessa et al. (1980, 1981). Miocene extensional faults recorded within Messinian foredeep turbidites have more recently been described by Mazzoli (1994), Alberti et al. (1996), Calamita et al. (1998), Scisciani (1998), and Tavarnelli et al. (1999). Some of these authors have interpreted these structures as related to the Neogene flexure of the foreland (Apulian) lithosphere.

Important extensional activity during the Miocene is recorded in the study area mainly by the facies and thickness variations of the units characterizing the late Burdigalian-early Messinian (pre-evaporitic) stages of foreland basin evolution. In the southern part of the study area, Middle Miocene-Tortonian extensional faulting is recorded most dramatically by the hanging wall basin fill associated with the Montagna dei Fiori west dipping normal fault (Calamita et al., 1998) (see Fig. 4). Facies and thickness variations in the Laga Fm (Cantalamessa et al., 1980, 1981) suggest that extensional activity continued also during the early Messinian, although high values of regional subsidence, bathymetry and sedimentation rate made its effects much less impressive. The situation is quite different to the north, where Messinian regional subsidence was significantly reduced and a more extreme control exerted by synsedimentary Miocene faults on the deposition of foredeep clastics is evident. In fact, although extension is not very large in terms of the strain involved (i.e. 6%), steep faults produced almost all the accommodation space for the clastics (Fig. 3). In the structurally elevated footwall areas, the Messinian evaporites often directly overly the substratum, and little or no foredeep sediments occur.

Subsequent positive inversion of the Miocene extensional structures was quite limited. Apart from local minor uplift and antiformal folding of hanging wall basin fills (e.g. in the Serronchia area; Fig. 6), generally hanging wall basin sequences were retained and were not uplifted above regional. Newly-formed thrusts have cut across the preexisting extensional structure (Figs. 3 and 4). Furthermore, most pre-thrusting Miocene faults within the study area show very limited or no reversal of slip during contractional deformation. Fault planes and related hanging wall basin fills mostly appear to have been deformed by buttressing processes (see also Calamita et al. (1998)).

As already mentioned above, most of the N-S to NNW-SSE trending faults involving the Mesozoic-Palaeogene suc-

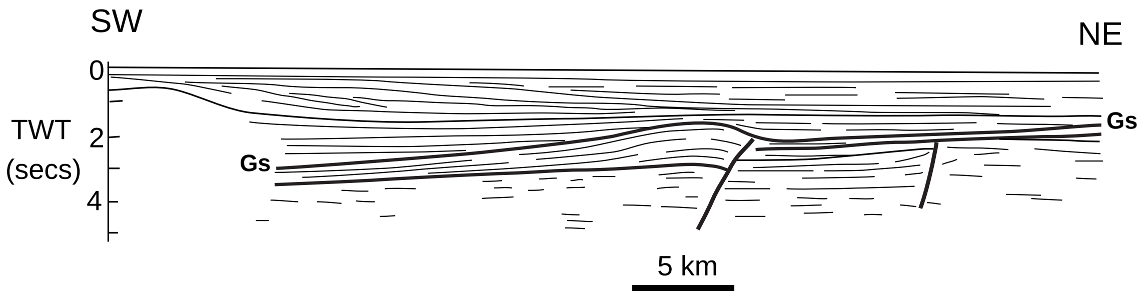

Fig. 7. Line drawing of a marine seismic reflection profile from the Adriatic (located in Fig. 1), modified after Argnani and Gamberi (1995). Prominent reflector (Gs) corresponds to the Messinian evaporites.

cession of the Monte San Vicino ridge cannot be directly dated because of the lack of related syntectonic deposits. As these structures do not control facies nor thickness variations in Mesozoic and Palaeogene units, a post-Palaeogene age can be inferred for their activity. On the other hand, the fact that they are planated by the Pliocene "palaeosurface" (Calamita et al., 1982) indicates that a Miocene age of activity is very likely. If this is the case, then these faults are exposed within a Mesozoic-Palaeogene sequence which is of pre-rift type with respect to their activity. In the high-topography area of the Monte San Vicino ridge, in fact, the Miocene syn-rift sequences most probably associated with these faults have been eroded away. The consistent extensional cut-off relationships with respect to bedding (Fig. 3) suggest that these structures can be either interpreted as: (i) crestal collapse faults, associated with outer-arc extension due to the curvature of the anticline, or (ii) pre-thrusting normal faults which were later tilted during folding. The observation that these faults have been deformed and variably reactivated (mainly in strike-slip), together with the important occurrence of Miocene pre-thrusting extensional faulting within the study area, all suggest that the second hypothesis might be more likely.

The end of extensional tectonics is marked in the northern part of the study area by the deposition of the Gessoso-solfifera Fm, which represents a post-rift sequence with respect to the Miocene faults. On the other hand, significant thickness variations within the Schlier Fm and its lateral transition to the Marne con Cerrogna (rich in calcareous detrital material) suggest a pre-Messinian onset of this tectonic activity. This is clearly documented by the major west dipping normal fault of Montagna dei Fiori, which controlled the sedimentation of the upper Burdigalian-Tortonian Marne con Cerrogna Fm in the southern sector of the study area (Fig. 4). It is worth of note that, in Middle Miocene times, the main foredeep depocentre of the Apennine system was located in a far more internal (i.e. southwestern) area, where the turbiditic Marnoso-Arenacea Fm was being deposited (Deiana and Pialli, 1994, and references therein). Therefore, the extensional tectonic activity documented in this study mostly took place in the foreland area, ahead of the coeval main foredeep depocentre.

The onset of contractional deformation within the study area coincides with the end of the deposition of the evaporitic member of the Laga Fm and of the laterally equivalent Gessoso-solfifera Fm. It is marked by the resedimented gypsum bodies which characterize the upper part of this unit, and especially by the growth strata of the post-evaporitic turbidites exposed in the Aliforni synform (Fig. 6). The latter lies in the hanging wall to the Sibillini Thrust, and may therefore be considered as a thrust-top basin during the late Messinian. The Messinian evaporites and gypsum-arenitic turbidites mark the change from extension to shortening within the study area. This occurs also in a more external area of the thrust belt, in the coastal structures of the Pesaro area (Fig. 1), where the Messinian evaporites mark again the onset of contraction and there is evidence for synchronous growth of different anticlinal structures during the late Messinian (De Donatis et al., 1998; Coward et al., 1999). Marine seismic data from the northern Adriatic (Argnani and Gamberi, 1995) suggest that similar features occurred in even more external areas of the thrust belt. Offshore Ancona (refer to Fig. 1), upper Messinian-Pliocene strata are disconformable upon Messinian units that form particular strong, characteristic reflectors (which can be ascribed to the Gessoso-solfifera Fm (e.g. Calamita et al., 1990; Coward et al., 1999)). As shown in Fig. 7, the post-evaporitic sediments in the area onlap a folded Messinian surface. In the same figure, there is clear evidence of late Messinian-early Pliocene folding. This fold structure has a complex history, as, at depth, other reflectors show net extensional throws across a fault. There is an increased stratigraphic thickness in the hanging-wall to the fault. This structure has the geometry of an inverted normal fault, and again the change from extension to contraction is marked by the Messinian evaporites. In fact, the latter mark the onset of inversion and folding in a large area of the central Adriatic Sea (Cirilli et al., 2000).

Based on the foregoing discussion, it appears that Middle Miocene-early Messinian extensional tectonics, possibly associated with flexure of the foreland lithosphere (e.g. Bradley and Kidd, 1991) and/or foreland tectonic activity, was followed by a late Messinian (post-evaporitic) contractional episode of regional extent. The former exerted a strong control in foreland basin deposition, whereas the latter produced mild inversion (Corfield et al., 1996), folding and synchronous thrusting (e.g. Boyer, 1992) in a large area of the external northern Apennines and adjacent offshore. It can be inferred that this regional contractional deformation was the result of far-field propagation of the compressional stresses in a wide area of the foreland plate. This is also confirmed by the fact that the Plio-Pleistocene sequences of the external Umbria-Marche Apennines record a general foreland migration of the thrust front (Ori et al., 1991; Deiana et al., 2002) across those areas that had already been affected by late Messinian mild shortening.

5 Conclusions

In the Umbria-Marche Apennines, as in many other collisional orogens around the world, the pre-orogenic basin architecture played a fundamental role in controlling the structure of the fold and thrust belt. However, pre-thrusting features include not only those, somehow obvious, inherited from the Mesozoic rifted continental margin, but also structures related to Miocene extension ahead of the active thrust front. These produced important facies and thickness variations in the upper Burdigalian-lower Messinian (pre-evaporitic) sedimentary units of the study area. In the southern sector (Acquasanta-Montagna dei Fiori), high values of Messinian regional subsidence, bathymetry and sedimentation rate overcome the effects of synsedimentary extensional tectonics, which is best recorded in pre-Messinian sequences. In the northern sector (Monte San Vicino-Cingoli), on the contrary, Messinian regional subsidence was significantly less and several minor sub-basins developed in the foredeep which reached evaporitic conditions during the middle Messinian (marked by the deposition of the Gessoso-solfifera Fm). Here, a strong control by pre-thrusting normal faults on sedimentation is recorded in the foredeep siliciclastic sequences. In fact, although extension is not very large, steep faults produced almost all the accommodation space for the clastic deposits in the related hanging wall basins.

During subsequent shortening, inversion of the Miocene extensional structure characterizing the study area was quite limited. Generally hanging wall basin fills have not been uplifted above regional. Pre-thrusting Miocene faults show very limited or no reversal of slip during contractional deformation. However, buttressing phenomena are common and faults are generally tilted and/or deformed, and locally show minor reactivation in strike-slip. The present-day structure is dominated by newly-formed thrusts that cut across the preexisting extensional structure. The latter is almost “frozen in” and quite well preserved within each single thrust sheet, allowing a comprehensive picture of the tectono-sedimentary evolution of the area to be obtained.

Middle Miocene-early Messinian extensional tectonics, possibly associated with flexure of the foreland lithosphere and related uplift of the peripheral bulge, and/or foreland tectonic activity, was followed by a late Messinian (post-evaporitic) contractional episode of regional extent. The latter, most probably related to the propagation of the compressional stresses in a wide area of the foreland plate, produced mild inversion (Corfield et al., 1996), folding and synchronous thrusting (e.g. Boyer, 1992) in the external northern Apennines and the Adriatic offshore. Afterwards, during the Pliocene, contractional deformation propagated “in sequence” towards the external zones of the thrust belt (Deiana et al., 2002).

Miocene extensional faults formed ahead of the thrust front clearly played a primary role in controlling both foredeep sedimentation and the whole architecture of the fold and thrust belt in the study area. Thrust propagation across preexisting structures imply that balanced geological sections cannot be constructed assuming a simple layer-cake or wedge-shaped stratigraphy. This is particularly true in the study area, where the pre-orogenic stratigraphic template is complicated by the superposition of Miocene faults on top of Mesozoic (rift-related) structures. Balanced and restored cross-sections constructed taking into account these complexities can largely improve our understanding of the structure of the Apennine chain. This has fundamental implications for any attempt to reconstruct the tectonic evolution of the fold and thrust belt, as well as to estimate the related bulk shortening and to infer time-averaged shortening rates.

Acknowledgements. We wish to thank all those involved in the geological survey of the study areas, in particular Eugenio Pistolesi, Antonio Romano, Dino Gazzani, Gianni Boldrini and Paolo Andreani. Constructive reviews by D. A. Nieuwland and an anonymous referee are gratefully acknowledged.

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