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Styles of positive inversion tectonics in the Central Apennines and in the Adriatic foreland: Implications for the evolution of the Apennine chain (Italy)

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ABSTRACT

Integration of new field structural and geophysical data with existing information from the Apennines chain in Italy and its adjacent Adriatic foreland indicates that the styles of positive inversion tectonics and the modes of interaction between the extensional and the subsequent compressive structures vary. Starting from the Cretaceous, the contractional deformation induced by the mainly north-directed convergence of Africa/Adria with respect to the European plate promoted the closure of various arms of the Atlantic and the Neo-Tethys oceans, which opened in different times and with distinct orientations. The mosaic of continental blocks, carbonate platforms, rift basins and oceanic domains with several geometries and orientations with respect to the axis of the subsequent compression, and the resulting heterogeneities within the shallow sedimentary cover and the overall lithosphere, strongly influenced both the structural evolution of the Apennine orogenic belt and the intra-continental deformation within the Adriatic foreland.

Field observations reveal that the steeply E- and W-dipping Mesozoic–Cenozoic normal faults are systematically decapitated by sub-horizontal or gently west-dipping thrusts propagating with short-cut trajectories. Pre-thrusting normal faults were commonly deformed by later thrusts, but little evidence seems to support their entire reactivation as high-angle reverse faults. This suggests that these shallow- and steeply-dipping discontinuities were not suitable to be reutilized by the superficial thin-skinned thrust faults propagating within the sedimentary cover. In contrast, presumably late Paleozoic and Mesozoic W-dipping normal faults appear moderately reactivated in the Adriatic foreland, and strong positive inversion tectonics affect the deeper and buried structural levels of the Apennine chain. Within the latter, the syn-rift sediments in the hangingwall blocks of the fault-bounded basins were totally extruded and generated the strong uplift of the thinned Adria continental crust.

Finally, the contrasting styles of interactions of the pre-existing normal faults with later thrusts (i.e., passive truncation or positive reactivation) strictly result from the different evolution of the Apennine chain and the combined thin- and thick-skinned modes of deformation of the stretched lithosphere of the Adria plate.

1. Introduction

In the last decades, special attention has been given to reconstructing the role played by the inherited tectonic grain of foreland plates in the subsequent evolution of fold-and-thrust belts. Several foreland domains have been affected by rift-related extensional tectonics prior to being incorporated into the mountain belts and/or have suffered normal faulting induced by the flexure of the foreland plate (e.g., Dewey et al., 1989) contemporaneously to the advance of the fold-and-thrust belt (Hancock and Bevan, 1987; Harding and Tuminas, 1989; Bradley and Kidd, 1991). Moreover, in other cases, the stresses acting along the plate margins have been transmitted far into the foreland, promoting intra-continental deformation also resulting in the reactivation of pre-existing normal faults (Coward, 1994; Ziegler et al., 1995). The coupling or decoupling of the upper and lower plates has been envisaged as a main factor that controls, respectively, the compressional or extensional deformation affecting the foreland domain, and these dynamic processes can promote normal or reverse faulting at distinct times (Ziegler et al., 1998, 2002). Moreover, foreland

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domains previously affected by normal faulting adjacent to the advancing fold-and-thrust belts have been subsequently incorporated into the chain, and the resulting changes from early extension to later contraction have promoted positive tectonic inversion (Glennie and Boegner, 1981; Cooper and Williams, 1989; Letouzey, 1990; Coward et al., 1991; Mitra, 1993; Buchanan and Buchanan, 1995; Brun and Nalpas, 1996; Butler et al., 2006).

Although positive inversion tectonic processes are often assumed to occur by simple fault reactivation (Williams et al., 1989 – Fig. 1a), several studies have shown that inverted structures can display complex geometries with pre-existing fault surfaces that can be either truncated by, or reactivated as, younger faults (Butler, 1989; Hayward and Graham, 1989; Tavarnelli, 1996; Scisciani et al., 2002 – Fig. 2b and c).

The lateral stratigraphic variations created by the normal faults imply more complex structural–geological settings that must be considered when restoring thrusts that propagate through previously faulted continental margins (e.g., Tavarnelli et al., 2004); moreover the pre-existing faults constitute mechanically important perturbations that effectively control the nucleation and localisation of thrust ramps (Wiltschko and Eastman, 1983; Laubscher, 1977).

Positive inversion tectonics of the Mesozoic Tethyan continental margins have been widely recognised in a number of orogens surrounding the Mediterranean region (i.e., Alps, Pyrenees, Atlas – Davies, 1982; Hayward and Graham, 1989; De Graciansky et al., 1989; Butler, 1989; Coward et al., 1991; Casas Sainz and Simón Gómez, 1992; Coward, 1994, 1996; Beauchamp et al., 1996; Vergés et al., 2002; Butler et al., 2006), and the control exerted by the inherited normal faults on the geometry and evolution of the subsequent fold-and-thrust belt has been increasingly recognised in the Apennines of Italy (Tavarnelli, 1996; Coward et al., 1999; Scisciani et al., 2001, 2002; Calamita et al., 2002; Tozer et al., 2002, 2006; Tavarnelli et al., 2004; Butler et al., 2006).

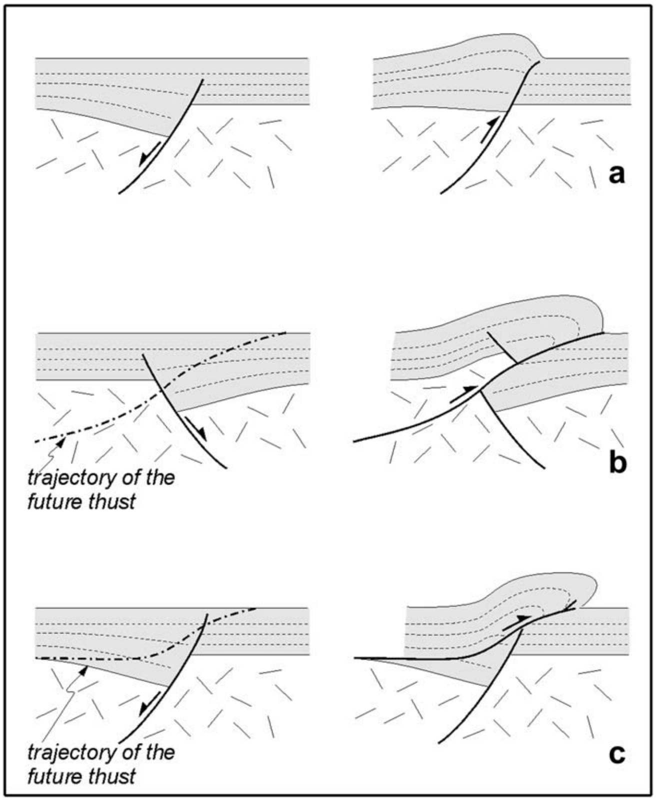

Fig. 1. Modes of interaction between pre-existing extensional and subsequent contractional structures (after Williams et al., 1989). (a) The early normal fault is reactivated as reverse. (b) The early normal fault is folded and passively truncated by a younger thrust. (c) The early normal fault provides stress concentration and promotes future thrust-ramp localisation.

This study focuses on the styles of positive inversion tectonics in the outer sector of the Central Apennines and in the Adriatic foreland. The good exposure and high vertical relief of this part of the Apennines provide an excellent laboratory to study the interaction of the pre-existing normal faults developed mainly during the Mesozoic and Neogene with the Pliocene–Quaternary thrusts through integrated analyses of new surface and subsurface data. In addition, the subsurface data (seismic reflection profiles and well-log stratigraphy) acquired in the Adriatic allow us to unravel in detail the deformation history recorded in the foreland adjoining the Apennine fold-and-thrust belt. We provide illustrated examples of pre-thrusting normal faults dipping towards both the foreland and the hinterland that are oriented at right angles or oblique to the subsequent compressive stress field. The resulting positive inversion tectonics with different magnitudes generate distinctive styles of reactivation, truncation and deformation of the pre-existing faults.

2. Regional geological framework

The Apennines of Italy are a foreland fold-and-thrust belt that developed from Oligocene time onward, following the closure of the Mesozoic Tethys Ocean and the collision of the African and European continental margins (e.g., Carmignani and Kligfield, 1990). This process was accompanied by the development of foredeeps and thrust-top basin migration towards the foreland from the more internal Tuscan Oligocene–lower Miocene basins to the present-day Pliocene–Quaternary Adriatic Basin (Fig. 2 – Ricci Lucchi, 1986; Patacca and Scandone, 1989; Boccaletti et al., 1990).

The general structural setting of the analysed sector of the Central Apennines is composed of several imbricated structural units originating in different palaeo-domains. In the inner part of the chain, Jurassic–Lower Miocene basinal units crop out (Ligurian and sub-Ligurian units). These units are commonly attributed by most authors to the Ligurian or Alpine Tethys oceanic domain (Figs. 2 and 3a, b), and they lie on top of the entire tectonic pile, juxtaposed towards the east with the Umbria-Marche Jurassic basinal units and the Apennine platform domains (e.g., Lazio-Abruzzi Platform).

In the axial part of the Apennine chain, and to the north of the platform-to-basin transition zone, an imbricate fold-and-thrust system, composed of several thrust-fault splays, affects mainly the Mesozoic–Tertiary carbonate basinal sequences. This thrust system is delimited to the east by a regional-scale thrust fault whose map trace is known in the literature as the Olevano–Antrodoco–Sibillini Mts. (Fig. 2). Moreover, towards the south a further regional thrust (the Gran Sasso thrust front) is responsible for the contact between the Lazio–Abruzzi carbonate platform and the basinal carbonate succession to the E and NE (Fig. 2). East of the Gran Sasso and Sibillini Mts. thrust fronts, Messinian–Lower Pliocene siliciclastic sediments widely crop out, and their conformably underlying carbonate substratum is exposed in three main anticlines (the Acquasanta, the Montagna dei Fiori, and the Maiella anticlines – Fig. 2).

In the Adriatic foreland, wedge-shaped Pliocene–Quaternary syn-orogenic sediments lie on top of Messinian evaporites and the carbonate substratum; the latter consists of shallow carbonates in the southern sector (i.e., in the Apulian Platform) and of Mesozoic basinal sequences in the surrounding area (i.e., in the Mesozoic Adriatic Basin).

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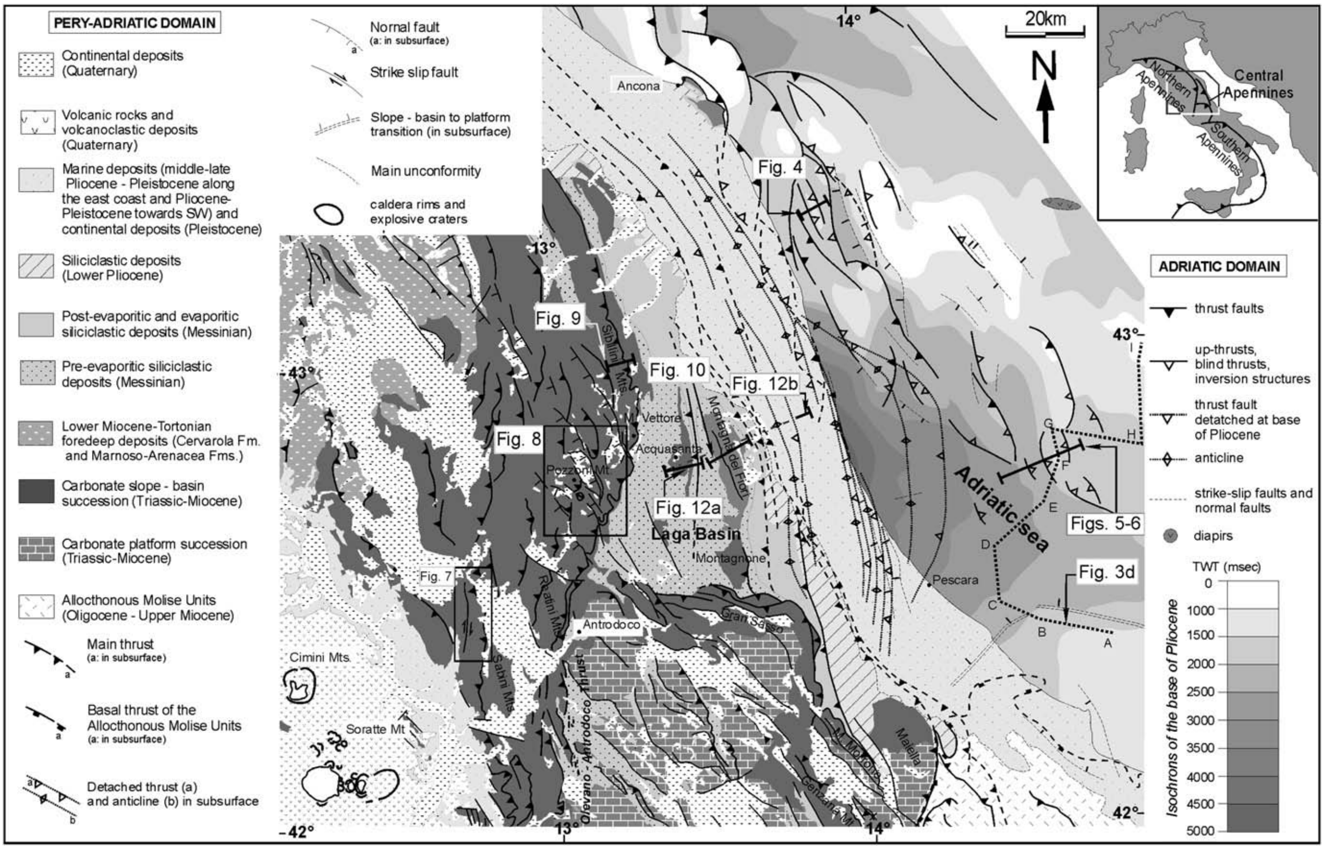

Fig. 2. Simplified structural and geological map of the study area (modified from Bigi et al., 1992). Inset shows the location of the Central Apennines with respect to the regional setting of the Apennine chain.

The Central Apennines have been classically interpreted as a thin-skinned fold-and-thrust belt, with imbrications of sedimentary units detached above a substantially undeformed crystalline basement (Bally et al., 1986; Hill and Hayward, 1988; Mostardini and Merlini, 1986; Calamita et al., 1991; Cavinato et al., 1994; Ghisetti and Vezzani, 1997). This model of orogenic deformation applied to the whole outer Apennine chain and combined with high-resolution stratigraphy of thrust-top and foredeep sediments (Patacca et al., 1991; Cipollari and Cosentino, 1995) led many authors to calculate large amounts of orogenic contraction of the continental lithosphere and anomalous shortening rates (15–50 mm/yr) compared to values inferred for other similar fold-and-thrust belts (Tozer et al., 2002 and references therein).

Alternatively, minor shortening has been assessed by authors who envisaged the Apennine chain in terms of thick-skinned tectonics, with the basement being partly involved within the structures in the sedimentary cover (Casero et al., 1988; Barchi, 1991; Lavecchia et al., 1987, 1994; Sage et al., 1991).

In the last few years, the acquisition of new deep seismic reflection profiles (e.g., the CROP 01-01A-03-04: Barchi et al., 1998; Menardi Noguera and Rea, 2000; Finetti et al., 2001) and aeromagnetic data (Chiappini and Speranza, 2002) has supported the hypothesis of basement involvement in the Apennine chain. Moreover, other studies based on field and subsurface data have revealed that many thrusts are localised on inherited pre-contractional structures, including pre-existing normal faults that formed either during foredeep development (peripheral bulge extension) or throughout the Mesozoic passive margin evolution (Tavarnelli, 1996; Coward et al., 1999; Mazzoli et al., 2000; Scisciani et al., 2000a,b, 2001; Tavarnelli et al., 2004).

3. Pre-Neogene stratigraphy and tectonics

Little is known about the basement beneath the Central Apennine chain. The only available data are derived from aeromagnetic studies (Arisi Rota and Fichera, 1987; Chiappini and Speranza, 2002), although other information can be extrapolated from the stratigraphies of deep exploration wells drilled in the Northern Adriatic foreland (Assunta 1 well – Fig. 3b) and from the outcropping basement in Tuscany (Gattiglio et al., 1989; Lazzarotto et al., 2003). The basement consists of Hercynian meta-sedimentary and igneous complexes that are unconformably overlain by Upper Paleozoic and Lower-early Late Triassic sediments (mainly phyllites or red sandstones and conglomerates generally referred to as the Verrucano Group (Aldinucci et al., 2007 and references therein – Fig. 3c)); the latter was penetrated by wells in both the inner part of the chain (Perugia 2 and S. Donato 1 wells – Martinis and Pieri, 1964; Anelli et al., 1994) and in the central Adriatic off-shore (Alessandra 1 well; Bally et al., 1986 – Fig. 3b). The remarkably low velocities (from 3900 to 5300 m/s) of the clastic intervals with respect to the underlying basement and the overlying Triassic evaporites/dolomites (6000–6400 m/s) generate strong reflectors that can be considered as near-top basement reference levels (Bally et al., 1986; Barchi et al., 1998; Del Ben, 2002).

During the Mesozoic, the Adria domain, including the present-day Central Apennines, was interposed between the Alpine Tethys to the N–NE and the Ionian Tethys (Palaeo-Tethys) towards the E–SE (Fig. 3a – Finetti, 1982, 1985; Catalano et al., 2001; Stampfli et al., 2001; Ciarapica and Passeri, 2002), and was affected by extensional tectonics induced by the opening of the two adjoining oceanic basins. Shallow marine sedimentation that prevailed during upper

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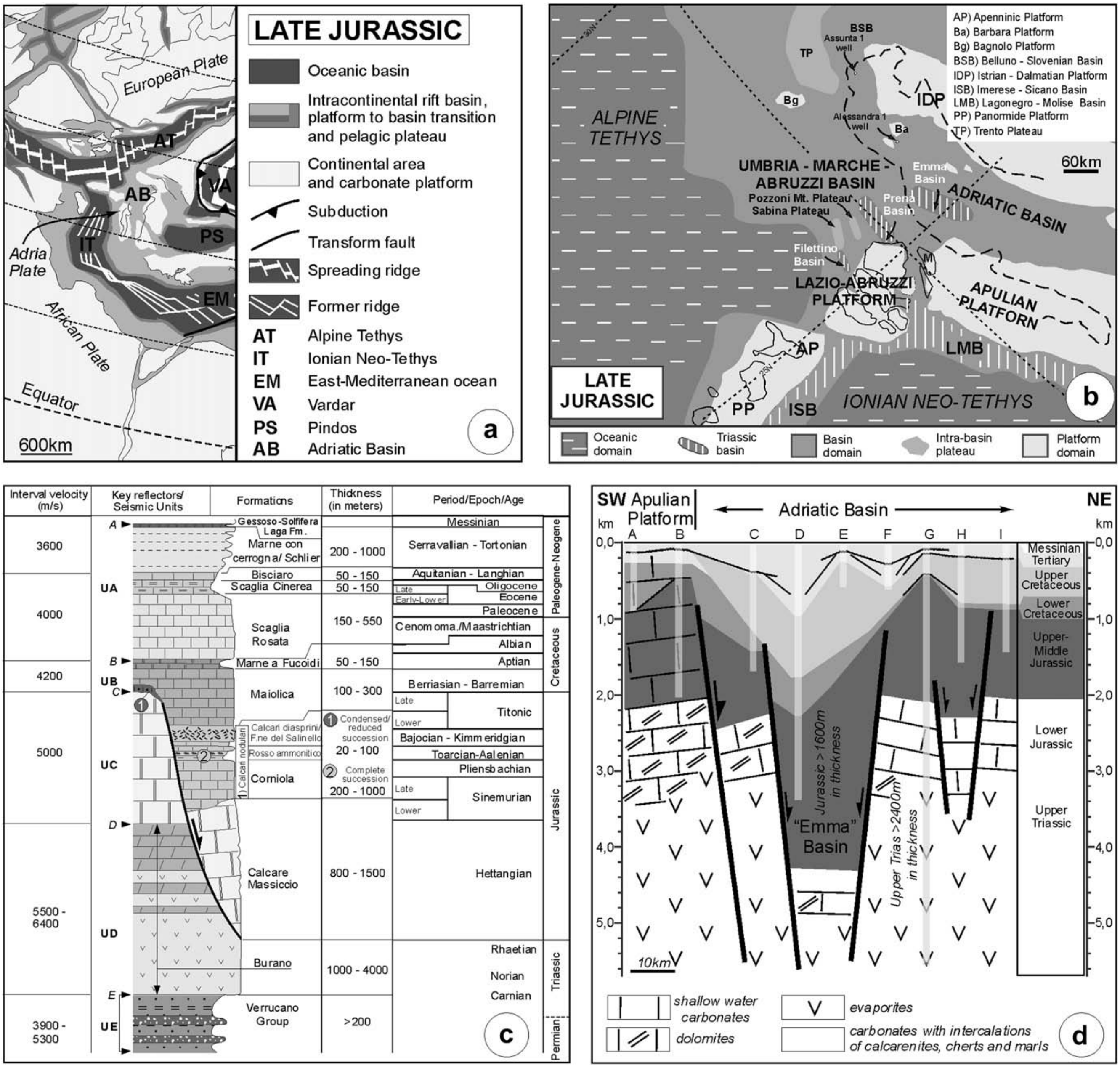

Fig. 3. (a) Late Jurassic reconstruction (modified from Stampfli et al., 2001 and Ciarapica and Passeri, 2002) of the Adria plate surrounded by the Alpine Tethys (AT) and the Ionian Tethys (IT)/East-Mediterranean ocean (EM). (b) Paleogeographic map of the Adria plate during the late Jurassic (modified from Ciarapica and Passeri, 2002 and Finetti et al., 2005). (c) Summary stratigraphic column based on exploration wells, seismic profiles and field data of the evaporitic-carbonate successions in the outer sector of the Apennine chain and the Adriatic foreland. (d) Transect based on well-log and seismic profile correlations across the Adriatic foreland showing the buried Apulian platform (SW) and the Mesozoic Adriatic pelagic basin (NE), including the Triassic and Jurassic "Emma Basin". The data are "flattened" to the top-Messinian level (i.e., the top of the pre-orogenic succession); see Fig. 2 for the location and horizontal scale.

Triassic-Liassic times persisted up to the Paleogene in only a few areas (e.g., in the Lazio-Abruzzi, Apennine, and Apulian platforms), whereas it was replaced by pelagic deposition in the fault-bounded basins (e.g., the Umbria-Marche-Abruzzi and the Adriatic Basins – Fig. 3b and d).

The outcropping stratigraphic section of the Central Apennines almost entirely consists of sedimentary rocks of a pre-orogenic Triassic–Miocene mainly carbonate sequence, overlain by Miocene–Pliocene syn-orogenic sediments (Cantalamessa et al., 1986a,b – Fig. 2). The older succession, which is exposed in only a few limited outcrops, is composed of upper Triassic shallow-water dolomites and anhydrites (Martinis and Pieri, 1964), replaced by euxinic sediments alternating with dolomites and carbonates in confined basins (e.g., the Prena Basin in the Gran Sasso range and the Filettino Basin in Fig. 3b – Adamoli et al., 1990; Cirilli, 1993; Bigozzi, 1994). These deposits are covered by Jurassic–Cretaceous limestones, sporadically interbedded with shales and local cherts in the deep-water pelagic sequences. These parts of the section exhibit substantial facies and thickness variations in the field related to the Mesozoic rifting and subsequent evolution of the passive margin (Fig. 3 – Bernoulli and Jenkyns, 1974; Ciarapica and Passeri, 2002). Within the Jurassic pelagic basins, some structural highs characterised by reduced thickness of the sediments (Condensed sequence – Fig. 3c and d) are separated by deep troughs where the sediments reach their maximum thickness (Complete sequence – Fig. 3c and d). These structural highs show

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a variable lateral extent ranging from a few hundred meters to few kilometres; some of the most remarkable structural highs exposed in the Central Apennines are the so-called Sabina and Pozzoni Mts. normal fault-bounded pelagic plateaus (Figs. 2 and 3b). The articulated Mesozoic paleogeography is also well-constrained in the Adriatic foreland, where extensive drilling by oil companies and geophysical surveys has revealed several Triassic and Jurassic basins interposed by fault-bounded structural highs II (e.g., the Emma Basin – Cati et al., 1987; Zappaterra, 1990; Grandic et al., 2002). This configuration can be clearly documented in the analysed area that traverses the Umbria–Marche–Abruzzi and the Adriatic Mesozoic basins (Figs. 2 and 3). In particular, a stratigraphic transect, based on well-log and seismic data, clearly shows a deep trough located to the north-east of the Apulian platform (Fig. 3b and d). The latter is characterised by persistently shallow-water carbonate sedimentation from the Jurassic to the Miocene that is replaced by a thick sequence of deep-water carbonates and marls in the adjacent basinal area (i.e., in the Mesozoic Adriatic basin). In the depocenter of the Mesozoic basin, the Jurassic sediments exceed 1600 m in thickness and overlie an Upper Triassic sequence (at least 2400 m thick) of dolomites and evaporites.

The articulated Mesozoic paleomorphology of the Umbria–Marche and Adriatic pelagic basins was levelled during Albian–Aptian time with the deposition of a continuous marly interval (Marne a Fucoidi Fm. – Fig. 3c). This stratigraphic marker can be unambiguously traced throughout the study area in both the outcropping Apennine sector and the Adriatic foreland, and it represents a useful reflector for seismic interpretation. In fact, the strong acoustic impedance contrasts between the marly rocks and the "fast" (about 5000 m/s) carbonates lying both above and below the Marne a Fucoidi Fm produces characteristic key reflectors.

The stratigraphic succession continues upward with basinal and hemipelagic cherty limestones with intercalations of argillaceous marls that became prevalent in the Oligocene and Miocene intervals (i.e., Scaglia Cinerea Fm. and Schlier/Marne con Cerrogna Fm. – Fig. 3c). Carbonate and shale deposition was replaced by siliciclastic foredeep-basin sedimentation during the Burdigalian–Tortonian in the inner sector (i.e., the Marnoso Arenacea Basin), Messinian in the central sector (i.e., the Laga Basin) and Pliocene in the Adriatic foreland basin (Fig. 2).

4. Positive inversion tectonics in the Adriatic foreland

The Central Adriatic Basin is the youngest foreland basin (Pliocene–Quaternary) of the Apennine chain; it clearly shows a wedge-shaped geometry in cross-section (Bally et al., 1986), and the siliciclastic sediments progressively on-lap towards the east along a gently-dipping foreland ramp.

The inner part of the Adriatic Basin is generally undeformed, whereas a NW–SE-trending uplifted ridge (Mid-Adriatic Ridge – Finetti, 1982; De Alteriis, 1995; Argnani and Frugoni, 1997; Argnani, 1998; Bertotti et al., 2001) that extends more than 100 km from the off-shore near Ancona towards the south and over the Italy–Croatia border zone affects the outer sector of the Adriatic foreland (Fig. 2). Different interpretations have been proposed to explain the geological setting and structural evolution of the Mid-Adriatic Ridge. It is considered as a zone of interaction between the frontal zones of the east-verging Apennine and the west-verging Dinaric fold-and-thrust belts (Bally et al., 1986; Casero et al., 1990) or a foreland deformation zone (Argnani and Frugoni, 1997; Argnani, 1998). Moreover, some authors envisage this area as the peripheral bulge of the two neighbouring opposite-verging chains (De Alteriis, 1995; Argnani and Frugoni, 1997), in which the structural setting is complicated by salt diapirism of the Triassic evaporites.

The Mid-Adriatic ridge is composed of several up-thrusts, inversion structures, high-angle transpressive faults and reverse blind-faults (Fig. 2). These structures are commonly arranged in en-echelon pattern, mainly oriented NW–SE and subordinately N–S, and their maximum longitudinal extents do not exceed 30 km. The faults only in few cases moderately off-set the Pliocene–Quaternary siliciclastic succession, but they show their maximum displacement at deeper stratigraphic levels. However, the blind-faults that affect the Mesozoic–Cenozoic carbonate succession produce folding and progressive unconformities in the overlying Pliocene–Quaternary siliciclastic strata.

The typical seismic expressions of inversion tectonics' structures that lie in the Adriatic foreland are illustrated in Figs. 4–6. In the northern sector of the Central Adriatic, Jurassic and Triassic basins developed in the hangingwall blocks of two opposite-dipping half-grabens were partially extruded, and syn-rift wedges fill the cores of high-angle reverse or transpressive fault-bounded anticlines (Fig. 4). The anticlines appear symmetric or asymmetric and show either Dinaric or Apenninic polarity (i.e., SW or NE vergence, respectively), depending on the attitude of the pre-existing extensional discontinuities at depth. The separation appears normal in the syn-rift Mesozoic sequence and decreases progressively upward to become reverse in the overlying post-rift interval (Fig. 4). The reverse displacement dies out in the syn-compressive succession (i.e., lower–upper Pliocene in age), and the contractional deformation is mainly accommodated by folding. Lateral thickness variations of the lower–upper Pliocene sediments towards the fold axes of the inverted anticlines clearly constrain the timing of the contractional event (Fig. 4). Moreover, closer inspection of the reflection geometries shows that this thinning is represented by on-laps and convergence onto the fold limbs.

This contractional deformation responsible for the reverse-reactivation of the Mesozoic normal faults in the Adriatic foreland is associated with the main phase of emplacement of the outer Apennine chain (Calamita et al., 1991); however, this sector was located more than 30 km ahead of the leading edge of the Apennine thrust front, suggesting that this type of deformation can be ascribed to foreland tectonics connected to the emplacement of the Apennine chain. Moreover, these structures frequently show early growth during the Upper Cretaceous–Miocene that mainly corresponds to the Alpine or Dinaric compressive phase, and the subsequent reverse-reactivation during the Apenninic stage, which is Pliocene–Quaternary in age (Figs. 5 and 6). In both cases, they represent examples of foreland tectonics with stresses that were transmitted several kilometres from the thrust fronts surrounding the Adriatic region.

The two phases of positive inversion tectonics recorded in the Adriatic foreland are clearly constrained by seismic examples collected along the southern sector of the Mid-Adriatic ridge.

A SW-verging fold formed by the positive reactivation of high-angle east-dipping Mesozoic normal faults exhibits a sub-horizontal crestal zone and a steeply-dipping fore-limb (Fig. 5). The Paleogene and especially Miocene sediments are extremely reduced in thickness in the axial zone of the fault-related anticline and abruptly increase in thickness in the fore-limb of the fold.

A major folded unconformity separates a lower seismic sequence that shows up-dip truncations of reflectors (Fig. 5b) from the overlying sequences, which exhibit tilted on-lap terminations onto the same sequence boundary. The age of the younger sediments (i.e., early Miocene) on-lapping onto this unconformity marks the main onset of folding. Moreover, the progressive up-section decreases in the dip of strata approaching the culmination of the anticline, and the parallelism between the late Miocene–middle Pliocene reflectors, unambiguously confine the cessation of the early phase of positive inversion.

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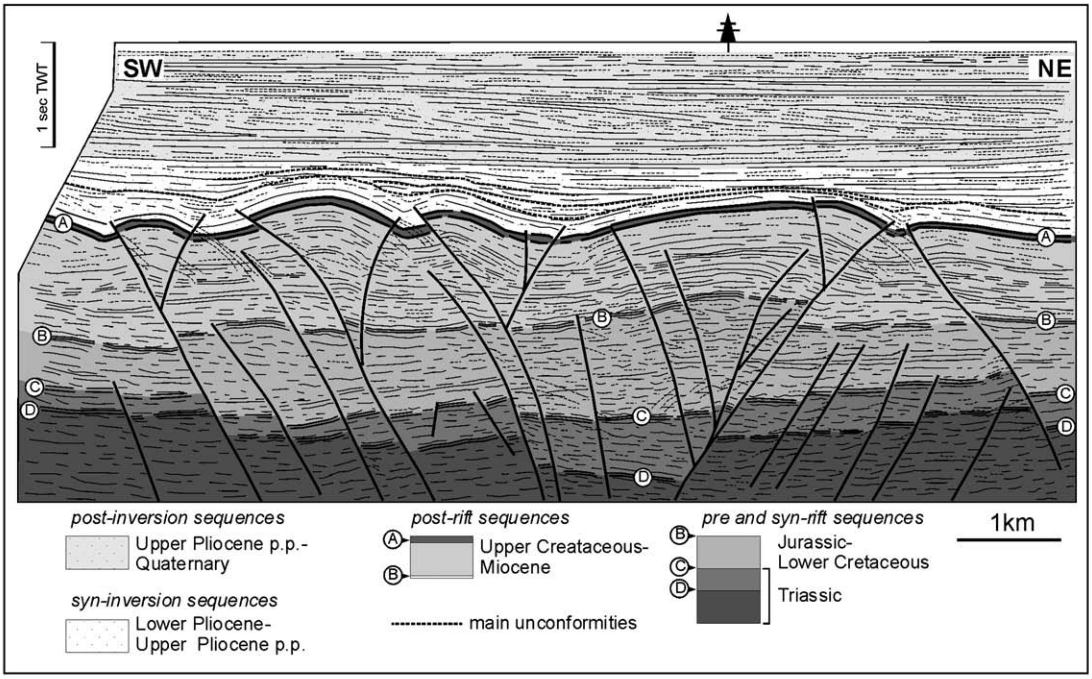

Fig. 4. Typical seismic expression of inverted structures within the Mid-Adriatic ridge (Adriatic foreland – see Fig. 2 for location). Mesozoic syn-rift wedged sediments in the hangingwall blocks of grabens and half-grabens were partially extruded and lie in the cores of the high-angle reverse/transpressive fault-bounded anticlines. The attitudes of the pre-existing extensional discontinuities strictly controlled the polarity of the anticlines originating by positive reactivation. Moreover, the growth of the anticlines during the Pliocene is indicated by the thinning of the siliciclastic sediments, the on-laps, and the convergence of reflection onto the fold limbs.

The reactivation of the positive structure generates a rejuvenation of thinning of the upper Pliocene–Quaternary strata in the vicinity of the fold crest (Fig. 5b) and a similar reflection configuration analogous to the above-described stratal pattern. This second phase of deformation is coeval to the growth of the outer thrust front of the Apennine chain (e.g., the Maiella anticline – Calamita et al., 2002),

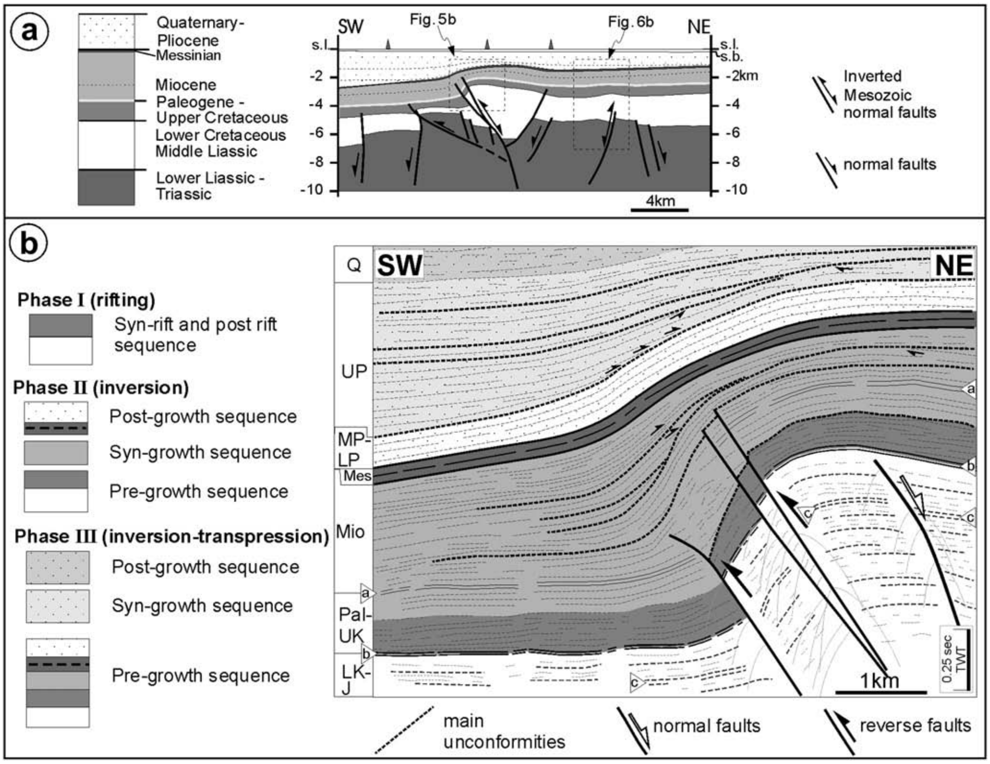

Fig. 5. (a) Geological cross-section based on seismic and well-log data across the southern part of the Mid-Adriatic ridge (see Fig. 2 for location). (b) Line drawing of a seismic reflection profile showing a close-up of the fold crest of the SW-verging anticline illustrated in (a); the fold is located in the hangingwall blocks of high-angle east-dipping Mesozoic normal faults reactivated during subsequent compressional events. The unconformities and reflection configuration along the axial zone of the anticline indicate two main phases of growth of the structure during the Upper Cretaceous–Miocene and late Pliocene–Quaternary time interval, respectively.

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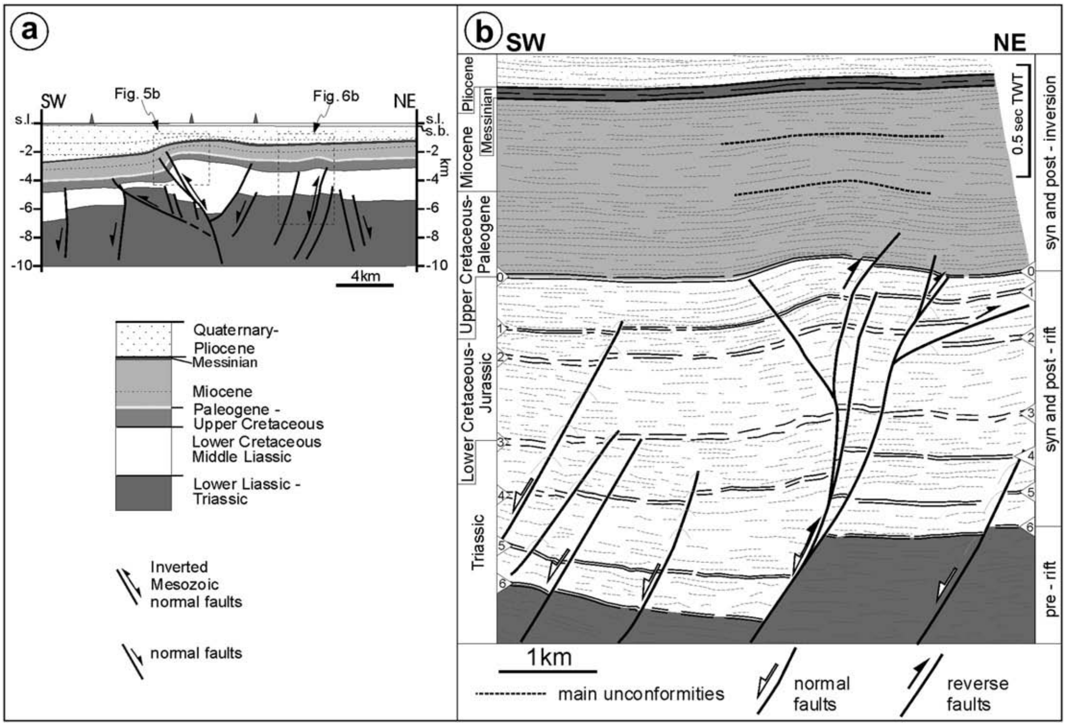

Fig. 6. Example of positive reactivation of Mesozoic normal faults in the Adriatic foreland during the Upper Cretaceous–Miocene time interval. (a) Geological cross-section based on seismic and well-log data – see Fig. 2 for location; (b) line drawing of a seismic reflection profile showing the reactivated W-dipping Mesozoic normal faults along the north-eastern part of the cross-section. The position of the null point within the top of the syn-rift sequence testifies to the low grade of inversion experienced by these structures. Moreover, the selective reutilization of the normal faults during compression is suggested by the coexistence of closely spaced "frozen" Mesozoic normal faults (SW) and reactivated discontinuities (NE).

which is located approximately 50 km to the west of this foreland area.

Positive reactivation of the Mesozoic normal faults identified in the Adriatic foreland is generally low, as suggested by the location of the null point commonly lying within the top of syn-rift sequences (Fig. 6b); moreover, a peculiar feature is observed in the Adriatic foreland: the coexistence over short distances of "frozen" (i.e., not reactivated) Mesozoic normal faults that are adjacent to inverted extensional discontinuities (Figs. 4–6). This fact suggests that the mechanism of reactivation did not indiscriminately affect all of the pre-existing discontinuities, but was strongly selective.

5. Interaction between extensional and contractional structures in the Apennines

The Triassic deposits in the Apennine chain are exposed in a few scattered outcrops, so the positive inversion of Triassic basins is extremely difficult to recognize. In contrast, Jurassic, Cretaceous and Miocene normal faults are frequent and their relationships with compressive structures can be clearly observed in the field.

The distribution of the Jurassic platform and basin domains was transverse, oblique or parallel with respect to the E–NE-trending axis of the subsequent compression (Figs. 2 and 3). The Mesozoic–Miocene normal faults, in the platform-basin transition zones and within the pelagic troughs, dip towards both the hinterland and the foreland. As a consequence, we can observe the occurrence of salient and recesses within the thrust belt, corresponding to the inherited Mesozoic paleogeography.

In the following sections, examples of positive inversion tectonics with interaction between the Neogene compressive structures and the pre-existing normal faults that either dip in the same or in the opposite direction to the maximum contractional stress field or that form a right angle with respect to the later axis of compression are illustrated.

5.1. *Inversion tectonics of Jurassic east-dipping normal faults*

One of the most spectacular examples of positive inversion of an east-dipping Jurassic normal fault is the so-called "Sabina fault" (Alfonsi et al., 1991; Pierantoni, 1997; Galluzzo and Santantonio, 2002), which is located within the Mesozoic Umbria–Marche pelagic basin (Figs. 2 and 3).

The Sabina fault is a N–S-trending high-angle transpressive to right-lateral strike-slip fault that extends for over 30 km and bounds the Sabina Plateau to the east (Fig. 7). The stratigraphy of the Sabina Plateau is described in detail by Galluzzo and Santantonio (2002); it consists of shallow-water carbonates (Lower Liassic in age) overlain by an extremely reduced Liassic to Lower Cretaceous pelagic succession. The condensed sequence ranges from 50 to 250 m in thickness and includes several hiatus and frequent neptunian dikes.

To the east of the Sabina fault, the outcropping Liassic–Lower Cretaceous basinal succession exceeds 1000 m (Fig. 7b and c). Here, the Lower Liassic deep-water limestones frequently contain huge olistoliths, which are made up of Liassic shallow-water carbonates, and the early Jurassic strata are interbedded by megabreccias, that are more abundant towards the west, along the contact between the reduced/complete sequence exposures. The nature and distribution of the resedimented materials suggest that they were collapsed from the uplifted footwall block of the east-dipping Jurassic normal fault. The coarser packages prevail in the lower portion of the pelagic succession; however, turbidites facies are found in the entire Middle–Lower Jurassic interval.

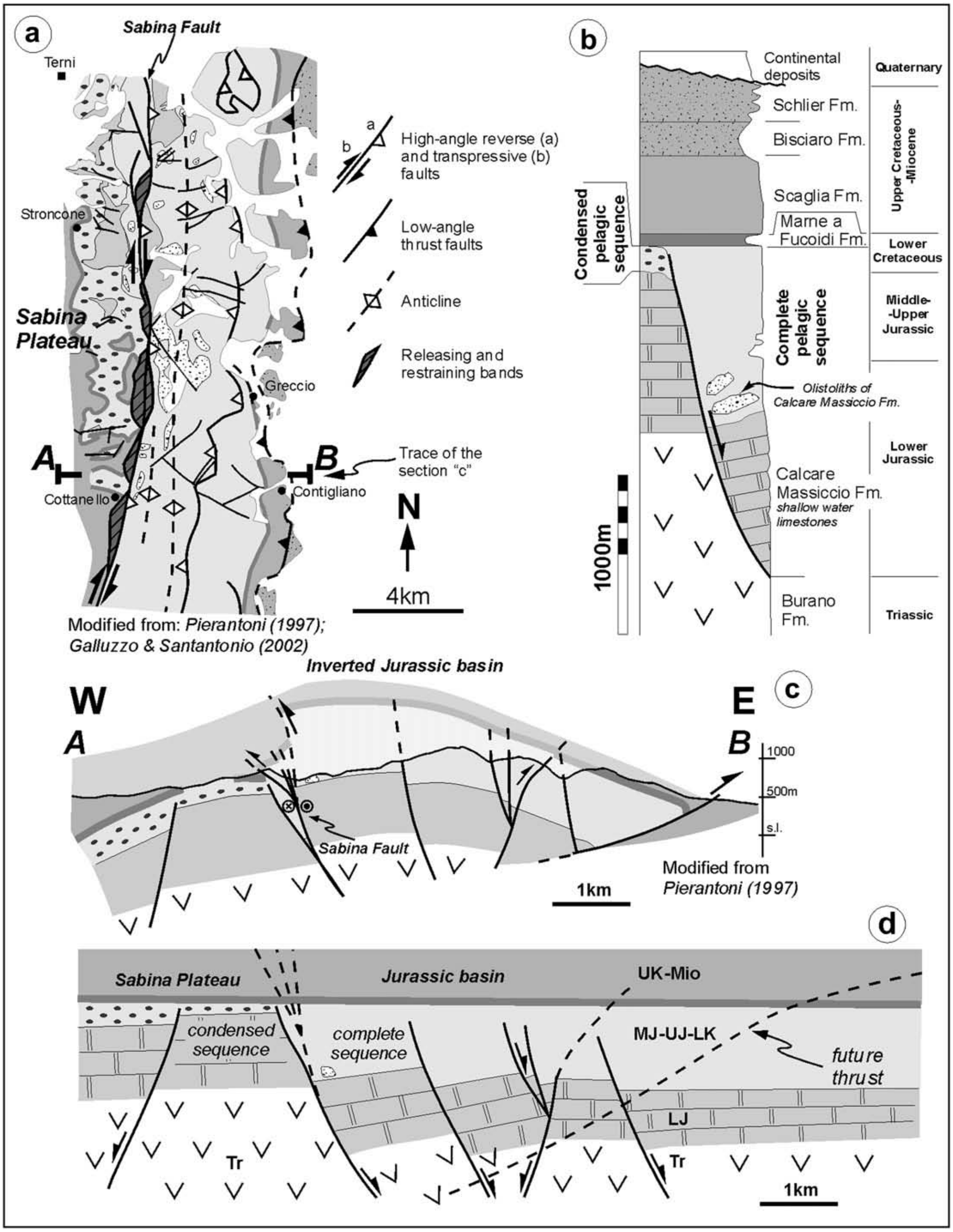

Fig. 7. Simplified structural and geological map (a) and stratigraphic column (b) of the Sabina area (see Fig. 2 for location). (c) Balanced cross-section across the Sabina fault. (d) Restored template (i.e., before the inversion of the Jurassic Sabina E-dipping normal fault) showing the Sabina Plateau capped by the condensed Jurassic sequence and the adjacent fault-bounded basin occupied by the complete Jurassic sequence with olistoliths of shallow-water Liassic limestones derived from the footwall block.

A gently east-verging and N–S trending box-shaped anticline is developed in the hangingwall block of the reverse-transpressive Sabina fault system (Fig. 7a). The Jurassic strata regularly dip to the east along the fault with an angle of about 30° in the eastern limb and then progressively flatten as they approach the high-angle discontinuities, where bedding dips moderately to the west (Fig. 7c). The asymmetric shape of the anticline appears to be due to the geometry of the pre-existing syn-rift wedge developed in the hangingwall block of the Jurassic normal fault, as illustrated in the restored cross-section (Fig. 7d). At present, the whole pelagic syn-sedimentary basin infill is completely extruded and forms the core of the fold; moreover, in the hangingwall block of the Sabina fault, the complete Jurassic succession is juxtaposed with a reverse downthrow of about 1000 m onto the Jurassic reduced sequence and the overlying Cretaceous sediments of the footwall block (Fig. 7c).

Some minor synthetic (i.e., east-dipping) normal faults are partially rotated and preserved in the hangingwall block of the Sabina fault; moreover, the east-dipping high-angle reverse fault affecting the Jurassic sediments along the eastern limb of the fold can be interpreted to be the result of the partial reactivation of a pre-existing normal fault, as suggested by the high cut-off angles between the fault plane and bedding (Fig. 7c).

About 6 km to the east of the outcropping Sabina fault, the back-limb of the anticline is truncated by a thrust fault that juxtaposes Upper Cretaceous–Paleogene sediments onto Miocene strata.

The detailed stratigraphic and structural data clearly allow us to constrain the evolution of this sector. The originally east-dipping Sabina normal fault strongly influenced the deposition of the pelagic strata during the Jurassic extensional event. Successively, during the early stage of compression (i.e., Neogene), the Sabina fault was positively reactivated and the syn-rift sediments in the hangingwall block of the normal fault were totally extruded towards the west. The fold was later truncated by a low-angle thrust fault and, during this final event, the pre-existing normal fault probably promoted stress partitioning of the SW–NE-directed compression. In fact, according to the previous interpretation (Pierantoni, 1997), the west-dipping thrust fault shows a main top-to-the-east sense of dip–slip reverse movement, while the inner-most Sabina fault exhibits a right-lateral sense of movement.

5.2. *Thrust decapitation, folding and reactivation of Jurassic east-dipping normal faults*

The Pozzoni Mt. thrust fault is located within the axial culmination of the carbonate Apennine chain, and it affects the Mesozoic Umbria–Marche pelagic succession (Figs. 2, 3b and 8). The Pozzoni Mt. thrust is exposed immediately to the south and south-west of Patino Mt. and exhibits a NW–SE-oriented frontal ramp with a near-parallel thrust-related anticline in the hangingwall block; towards the south (i.e., in the analysed area), it assumes a NNE–SSW trend (lateral ramp) that is oriented nearly parallel to the adjacent and outermost Sibillini Mts. thrust front (Figs. 2 and 8a).

The Pozzoni Mt. thrust separates a north-western domain (here called the "Pozzoni Mt. Plateau"), where condensed Jurassic pelagic sediments prevail in the field, from the adjacent footwall block, that exhibits a thick complete Jurassic sequence; the latter exceeds 1000 m in thickness and is composed of pelagic limestone and marl interbeds with local olistoliths and coarse-grained resedimented material mainly derived from erosion of the adjacent Pozzoni Mt. structural high (Fig. 8b). These abrupt facies and thickness variations are connected to a pre-existing Jurassic normal fault that was later truncated by a gently SE-dipping thrust fault. In fact, the ESE-dipping main fault that delimits the Pozzoni Mt. uplifted plateau is locally still preserved in the hangingwall block of the thrust fault. The original attitude of the Jurassic normal fault is distorted and partially rotated by the contractional deformation; at present it locally appears as a high-angle reverse lineament (Fig. 8c). This structural element separates a portion towards the SE where the Jurassic sediments are locally overturned and strongly deformed by folds and by several reverse shear zones. In contrast, the reduced Jurassic sequence that capped the original Pozzoni Mt. Plateau was passively translated on top of the stiff and thickly-bedded Liassic shallow-water limestones and crops out substantially undeformed in the hangingwall block of the thrust fault.

The present-day structural setting of the investigated area was furthermore complicated by widespread Quaternary normal faulting that fragmented both the hangingwall and the footwall blocks of the Pozzoni Mt. thrust (Fig. 8a and c). However, the reconstructed restored template obtained by removing both extensional (i.e., Quaternary) and contractional (i.e., Neogene) deformations clearly shows the original geometry of the Jurassic pelagic basin that bounded the Pozzoni Mt. Plateau to the east (Fig. 8d). The Jurassic normal fault was not reactivated but was simply decapitated by the Pozzoni Mt. thrust, which propagated with a short-cut trajectory.

5.3. *Thrust decapitation, folding and reactivation of Jurassic–Tertiary west-dipping normal faults*

The occurrence of normal faults in the back-limbs of thrust-related anticlines has long been recognised throughout the Apennine chain, and different interpretations have been proposed in order to explain the association of the two opposite dip–slip structures (see Scisciani et al., 2002 for a regional review).

In this paper, we illustrate three main examples of anticlines that exhibit pre-existing west-dipping normal faults in their back-limbs, and discuss the interaction between the extensional and the subsequent contractional structures.

One remarkable example of thrust faults that propagate through a previously faulted succession is clearly exposed along the Sibillini Mts. thrust front (Figs. 2 and 9). In the analysed area, the thrust fault affects a Jurassic succession articulated in pelagic horsts bounded by high-angle normal faults. The Mesozoic syn-sedimentary activity of the latter is suggested by significant thickness and facies variations of the Jurassic carbonate succession, which is extremely reduced (about 50 m) in the uplifted blocks and rapidly thickens towards the adjacent fault-bounded pelagic depressions (more than 700 m – Fig. 9).

Two main west-dipping Jurassic normal faults are exposed in the back-limb of the Sibillini Mts. east-verging thrust-related anticline. These are passively truncated and were carried to the east by a low-angle thrust plane (Fig. 9a). The reconstructed template suggests that the thrust fault propagated following a short-cut trajectory and the inherited Mesozoic horst is now preserved in the core of the thrust-related anticline (Fig. 9b). During the contractional event, the east-dipping Jurassic normal fault was rotated and partially reactivated as reverse, and it now appears as a blind up-thrust in the hinge of the Sibillini Mts. Anticline, where it separates the gently-dipping back-limb from the near-vertical to overturned strata of the fore-limb (Fig. 9a).

Analogue interactions between close coaxial extensional/contractional structures have been documented in the Montagna dei Fiori anticline, that is located in the outer sector of the Apennine chain (Fig. 2). This structure consists of an east-verging NNW–SSE-trending thrust-related fold that affects a Jurassic–Miocene pre-orogenic carbonate sequence overlain by the Tortonian–Messinian syn-orogenic succession. In outcrop, the main thrust surface is antiformally folded by a buried thrust-related anticline developed in its footwall (Fig. 10a – Calamita, 1990; Scisciani and Montefalcone, 2006).

Two steeply west-dipping normal faults affect the fore-limb of the Montagna dei Fiori anticline (Fig. 10). The westernmost produces an off-set of about 900 m and was active both during the Jurassic and Miocene, as suggested by the remarkable thickness and facies variations of the stratigraphic sections on both sides of the fault (Scisciani et al., 2002). The adjacent normal fault displays main Jurassic activity, as suggested by the reduced thickness of the Mesozoic pelagic sequence in its footwall compared to the complete succession exposed in the downthrown hangingwall block. Both normal faults were truncated during the subsequent thrust fault development and were passively transported towards the east in the hangingwall block of the thrust fault. The west-dipping normal faults substantially preserve their primary attitude, and the extensional character is confirmed by kinematic fabrics that indicate a dip–slip and top-to-the-west sense of movement along these faults. However, the dip–slip shear zones are over-printed by sub-horizontal striations and left-lateral strike-slip shear sense indicators (i.e., R-Riedel shear planes and minor scale

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WNW–ESE oriented normal faults). This strongly suggests that during the eastward-directed contractional event, the NNW–SSE-trending normal faults were reactivated with strike-slip left-lateral kinematics (Fig. 11a).

Similar overprinting relationships between dip–slip and strike-slip shear zones are also documented along the high-angle west-dipping pre-orogenic normal fault located in the back-limb of the Maiella anticline (Scisciani et al., 2002 – Figs. 2 and 11b).

In both cases, field relationships reveal that the steeply west-dipping normal faults were systematically truncated by sub-horizontal or gently west-dipping thrusts propagating with short-cut trajectories. Strike-slip reactivation was common, and the horizontal sense of movement along these faults (i.e., left-lateral in the Montagna dei Fiori fault and, respectively, left- and right-lateral for the N–S and NW–SE-oriented segments of the Maiella normal fault) strictly depends on the attitude of the pre-existing discontinuities with respect to the maximum stress orientation (Fig. 11). The contractional shortening was partitioned between the low-angle east-verging thrust faults and the high-angle west-dipping discontinuities located in the back-limb of the thrust-related

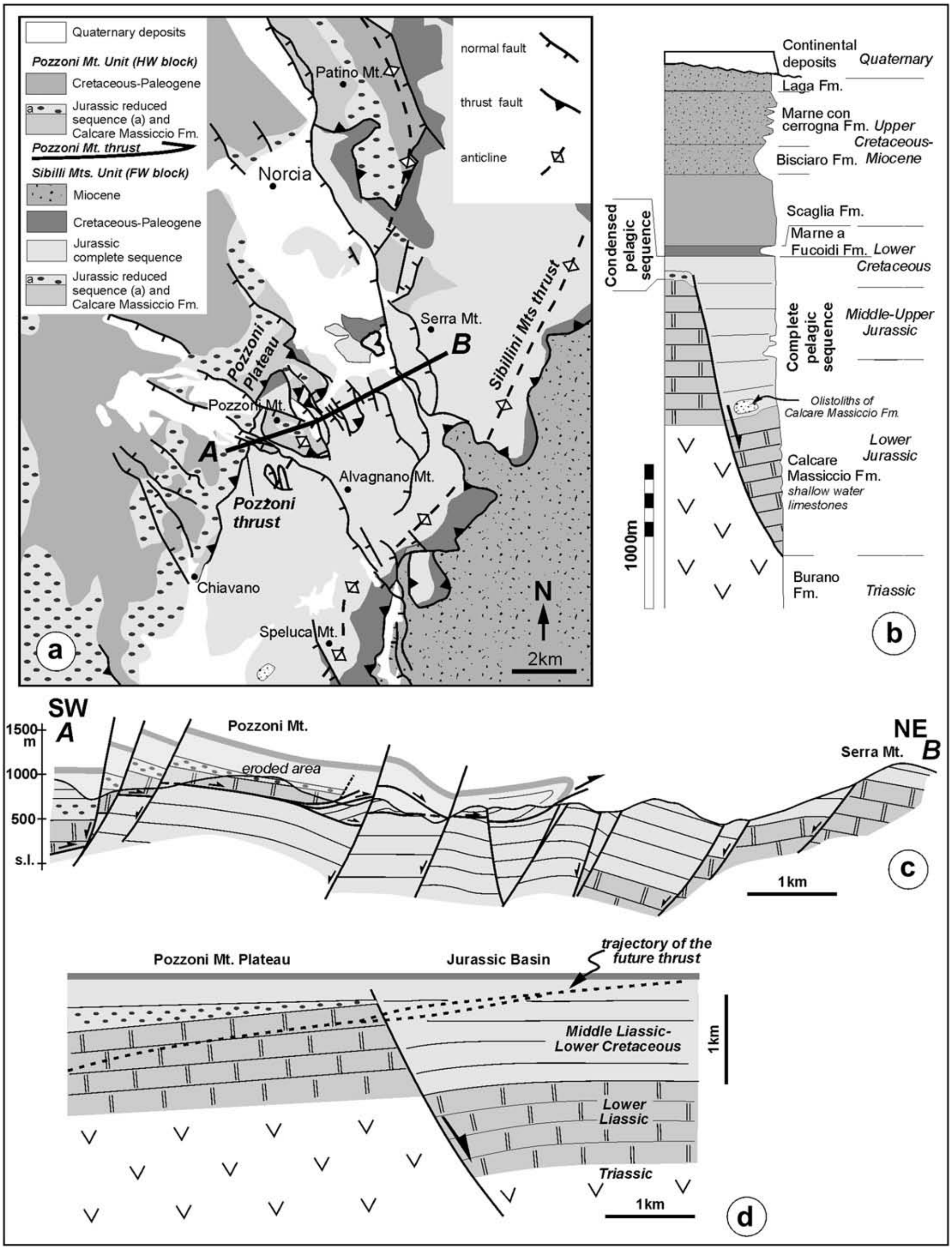

Fig. 8. Simplified structural and geological map (a – modified from Scisciani, 1994; Calamita et al., 1995) and stratigraphic column (b) of the Pozzoni Mt. area (see Fig. 2 for location). (c) Balanced cross-section across the Pozzoni Mt. thrust. (d) Restored template showing the Pozzoni Mt. Plateau with the condensed Jurassic sequence (western sector), separated by a SE-dipping normal faults from the adjacent Jurassic basinal complete sequence.

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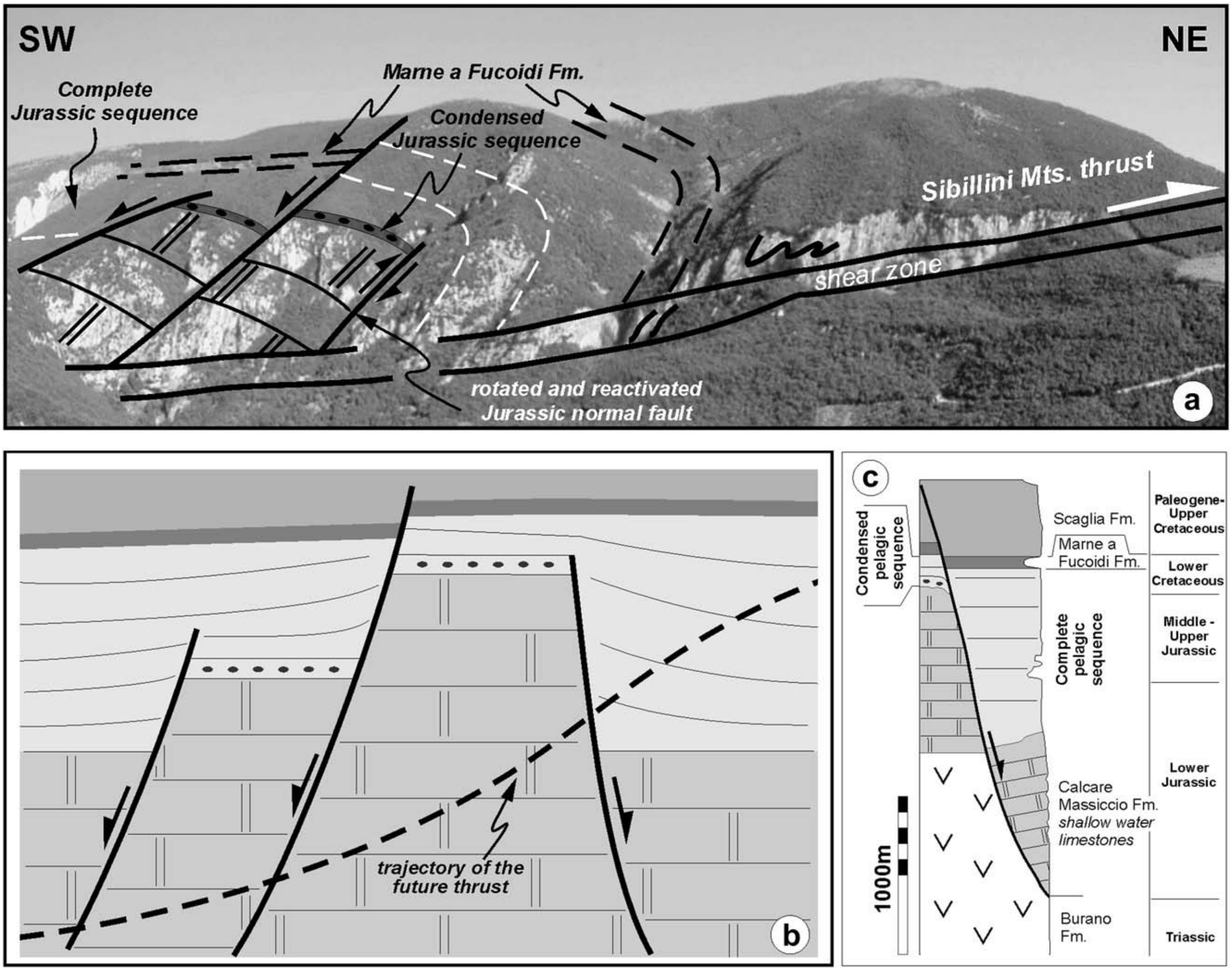

Fig. 9. (a) Panoramic view of the Sibillini Mts. thrust front (see location in Fig. 2). (b) Stratigraphic column of the Mesozoic–Tertiary succession cropping out along the Sibillini Mts. (c) Schematic restored template showing the Jurassic horst that was later truncated and passively transported in the hangingwall block of the Neogene Sibillini Mts. thrust.

anticlines; in all of the discussed examples the positive reactivation of the pre-existing normal faults can be neglected.

6. Positive inversion tectonics in the Apennine chain

In the inner sector of the Apennine fold-and-thrust belt the Permian–Triassic sediments are exposed in few scattered outcrops and are largely blanketed by younger sediments in the outer part of the chain. As a consequence, the real thickness of the complete late Paleozoic–Mesozoic cover overlying the Paleozoic crystalline basement remains mostly undefined beneath the Apennine chain, and little is known about the depth and buried physiography of the basement. The lack of these data and the poor resolution of the industrial seismics acquired during the preliminary campaigns in the 1970s and 1980s led several geologists to propose different and sometimes contrasting structural settings for the subsurface geology underneath the main thrust fronts (e.g., the Sibillini Mts., the Gran Sasso and the Montagna dei Fiori thrusts).

In the following sections, we present the deep structural setting of the Montagna dei Fiori area derived from integrated surface and subsurface (i.e., seismic reflection profiles) information. These study areas represent a prominent morphological and structural “step” of the top carbonate succession referred to as the pre-orogenic “regional” level. In the hangingwall block of the Sibillini Mts. thrust, the pre-orogenic succession crops out extensively, and the top of the carbonate sequence (Middle Miocene in age) is exposed at about 2000 m a.s.l.; moreover, in the axial culmination of the Sibillini Mts. thrust-related anticline, this Middle Miocene stratigraphic horizon is eroded, but it can be reconstructed as far as 4000 m of elevation. In the adjacent central sector (i.e., in the Laga basin – Fig. 2), the reference level is largely buried beneath Messinian syn-orogenic deposits of the Laga Fm. and is exposed in the crestal zone of two emerging folds called, respectively, the Acquasanta and Montagna dei Fiori anticlines. In the latter, the top carbonate succession shows an elevation of about 2000 m a.s.l. and it abruptly deepens to the east (i.e., in the Peri-Adriatic Basin), where it lies at more than 8000 m depth, beneath a thick Pliocene–Pleistocene syn-orogenic siliciclastic succession. Here, the top carbonate gently rises towards the east at an angle of about 5° along the Adriatic foreland ramp (Fig. 2).

The deep structural setting of the Montagna dei Fiori area has been broadly debated by many authors, and thin- and thick-skinned tectonic models have been applied (Paltrinieri et al., 1982; Bally et al., 1986; Calamita et al., 1991; Lavecchia et al., 1994; Artoni and Casero, 1997; Albouy et al., 2003; Tozer et al., 2002; Scisciani and Montefalcone, 2006).

Recently acquired seismic reflection profiles have allowed us to better understand the subsurface geology of the Montagna dei Fiori area and to constrain its deep structural setting (Fig. 12). Beneath the back-limb of the Montagna dei Fiori anticline, seismic data

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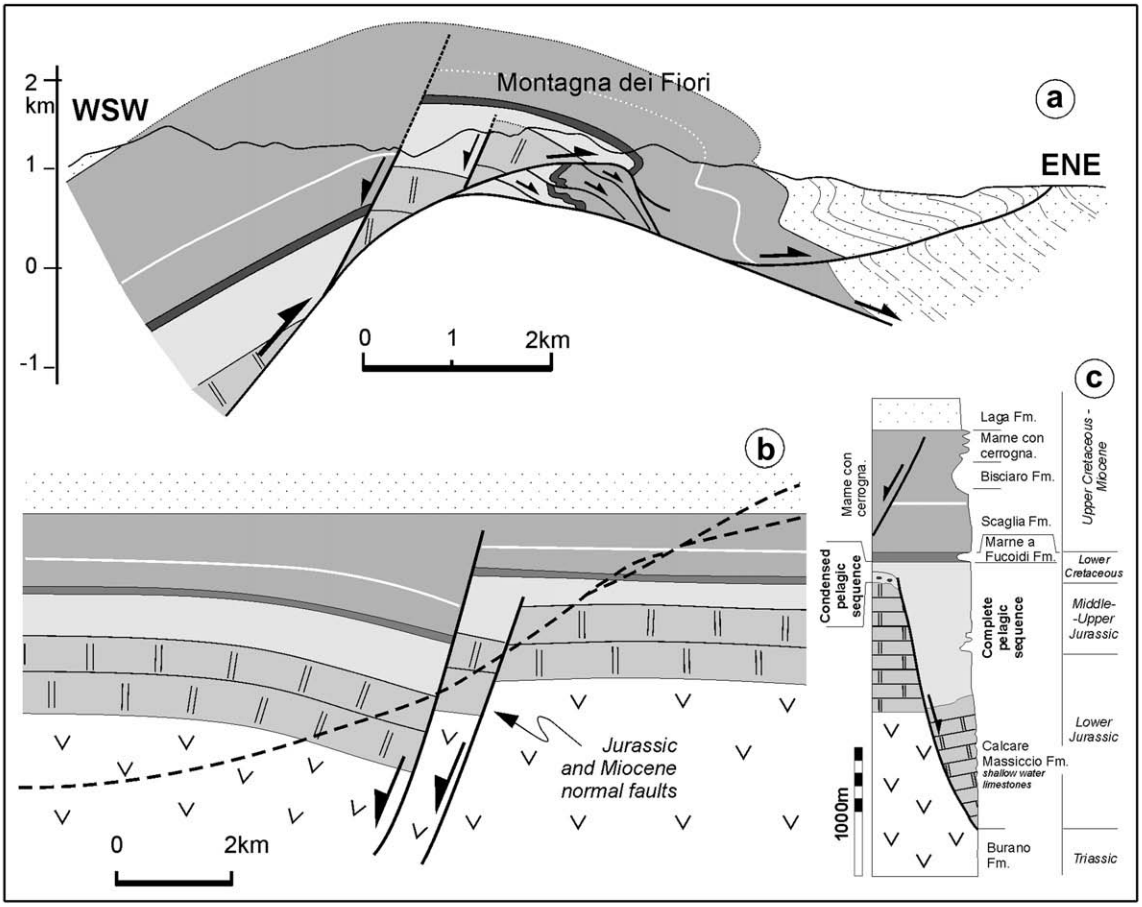

Fig. 10. (a) Balanced cross-section based on field geology and (b) restored template along the Montagna dei Fiori anticline (see Fig. 2 for location). The Miocene and Jurassic west-dipping normal faults are truncated by the later thrust propagating with a short-cut trajectory. (c) Stratigraphic column of the Mesozoic–Tertiary succession cropping out in the Montagna dei Fiori area.

show flat-lying or gently west-dipping high-amplitude, low-frequency and discontinuous reflectors (key reflector E in Fig. 3c) at time-depths of about 4 s TWT (Two-Way Traveltime – Fig. 12a). This package of strong reflectors shows a thickness of about 0.4 s TWT in the western sector, which decreases to 0.1 s TWT towards the east. This basal interval is overlain by a seismic unit mainly consisting of reflection-free to very weak and discontinuous reflections delimited at the top by a sharp signal corresponding to the base of the Calcare Massiccio Fm. (i.e., the base of the Jurassic – reflector D in Fig. 3C). The underlying weakly reflective interval shows typical seismic attributes and can be correlated to the Upper Triassic Anidriti di Burano Fm., represented mainly by dolomites with subordinate anhydrites in the closest exploration drills (i.e., Antrodoco 1, Villadegna 1 and Caramanico 1 wells). The basal package of reflectors, due to the lack of direct data, may correspond to early Triassic or late Paleozoic sediments, generally consisting of clastic rocks in the exposures and in the deep drilling (Patacca et al., 2008), close to the top of the metamorphic basement.

Reflector E (Fig. 12a) is interrupted by two major high-angle reverse faults, and the signal is downthrown towards the east where it occurs at a depth of about 6 s TWT. At depth, the thrusts ramp through sub-horizontal reflectors and create high cut-off angles; moreover, the latter progressively decrease up-section (i.e., in the Triassic seismic interval) and towards the east, where the thrust faults assume an approximately hangingwall flat geometry (Fig. 12a).

The anomalous thickness of the Permian(?)–Triassic seismic interval (>1.5 s TWT or >4000 m in thickness) in the undeformed part of the section and beneath the Montagna dei Fiori is a peculiar feature of this area compared to the 1500–2500 m of stratigraphic section penetrated in the deep exploration wells (Martinis and Pieri, 1964; Anelli et al., 1994) and estimated by seismic data in adjacent sectors (Bally et al., 1986; Barchi et al., 1998). Moreover, the convergence of reflectors and the westward thinning of the whole Permian(?)–Triassic interval is consistent with the total extrusion of the wedge-shaped syn-rift sediments in the hangingwall blocks of pre-existing W-dipping normal faults that were later reverse-reactivated beneath the Montagna dei Fiori area (Fig. 12). This interpretation is in agreement with the surface geology, which shows relatively limited shortening due to the nature of the "ramp on ramp" configuration in the outcropping Montagna dei Fiori thrust (Figs. 10 and 12). Moreover, the deep structural setting of the Montagna dei Fiori area resulting from the interpretation of the seismic data excludes the entire duplication of the sedimentary cover, including the siliciclastic sediments, by large flat on flat geometries as postulated by the thin-skinned tectonic models.

The structural elevation of the top carbonate succession in the Montagna dei Fiori anticline with respect to the adjacent down-thrown outer sector exceeds 9 km, and it appears to be completely achieved by the extrusion of the over-thickened late Paleozoic(?)–Mesozoic succession in the core of the structural high (Fig. 12). The contractional faults show ramp on ramp configurations at both deeper stratigraphic levels and up-section within the stiff carbonate succession, whereas they exhibit flat on flat geometries only in a few segments within the Triassic evaporites and within the marly-evaporitic levels at the base of the siliciclastic Messinian–Pliocene foredeep-basin infill (Fig. 12a and b).

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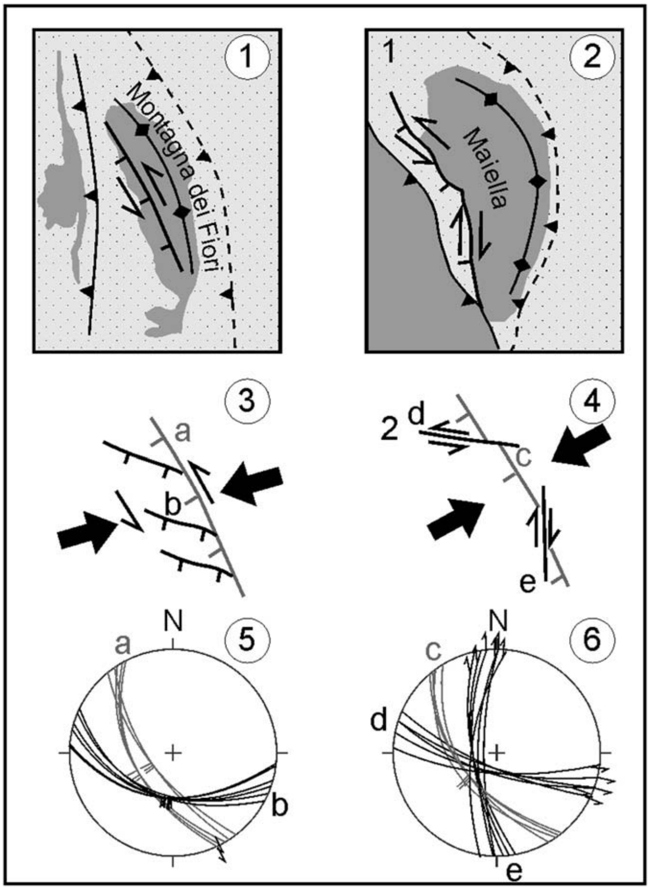

Fig. 11. Reactivation of the pre-thrusting W-dipping normal fault in the Montagna dei Fiori (1) and Maiella (2) areas (see Fig. 2 for location). The mesostructural analyses along the faults indicate: (3–5) the left-lateral reactivation of the pre-existing Montagna dei Fiori normal fault (a) and the generation of NNW–SSE-oriented normal faults (b) compatible with a simple-shear reactivation; (4–6) the development of WNW–ESE-trending left-lateral strike-slip faults (d) and N–S-oriented right-lateral strike-slip faults that suggest pure-shear deformation during compression along the Maiella normal fault (c).

Finally, several high-angle normal faults in both subsurface and outcrop (Figs. 10 and 12a) show a pre-thrusting origin (i.e., Miocene and Jurassic), and at shallow levels they are passively truncated by the reverse faults, propagating with a short-cut trajectory.

7. Discussion

The outer zone of the Central Apennines of Italy has been classically interpreted as a thin-skinned fold-and-thrust belt affecting the Mesozoic–Cenozoic sedimentary covers and detached above the underlying basement (Bally et al., 1986; Mostardini and Merlini, 1986; Hill and Hayward, 1988; Calamita et al., 1991; Cavinato et al., 1994; Ghisetti and Vezzani, 1997). The stratigraphic succession involved in the compressive deformation has typically been considered a “layer cake” multilayer with constant thickness and homogeneous lateral rheological properties. However, many papers have been devoted to describing facies and thickness variations within the late Paleozoic–Mesozoic stratigraphic section and to reconstructing the articulated architecture of the palaeomargin of the Adria plate (Bernoulli and Jenkyns, 1974; Cati et al., 1987; Alvarez, 1989; Zappaterra, 1990; Bernoulli, 2001; Ciarapica and Passeri, 2002; Pandeli, 2002; Aldinucci et al., 2007).

Stratigraphic and structural field studies clearly document Triassic rifting and Jurassic drifting between the European and Adria continental margins (Coward and Dietrich, 1989, and quoted references; Stampfli et al., 2001; Ciarapica and Passeri, 2002). These extensional events were responsible for the opening of the Alpine Tethys (an oceanic domain commonly envisaged as the eastern arm of the Atlantic Ocean) and also affected the analysed area, where they created an articulated paleogeography dominated by persistent carbonate platforms (e.g., the Apulian and Lazio-Abruzzi platforms), deep fault-bounded pelagic basins (e.g., the Umbria-Marche and Adriatic basins) and intra-basinal plateaus (e.g., the Sabina and Pozzoni Mts. Plateaus) resting on top of the Adria continental crust. Moreover, recent studies have indicated the existence of an ancient oceanic domain (i.e., the Ionian Neo-Tethys or East-Mediterranean Ocean – Stampfli et al., 1991), which is interpreted as the north-eastward propagation of the Neo-Tethys Ocean (the wide oceanic basin interposed between Laurasia and Gondwana), which opened during Permian–Triassic times. This oceanic domain, generated by the left-lateral transtensive tectonics induced by the counter-clockwise rotation of the Adria plate, is considered to be limited to the north by the present-day 41° parallel (Finetti et al., 2005). However, the presence of over-thickened early Mesozoic successions in the Adriatic region (Fig. 3d) and in the Umbria–Marche domain, including the Montagna dei Fiori and Gran Sasso range (Fig. 12), strongly suggests that this sector also suffered extensional tectonics induced by Permian–Triassic rifting. As a result, Permian–Triassic basins are expected beneath the outcropping part of the Central Apennines, where they have been largely blanketed by younger sediments. Combining the recent field studies carried out in Southern Tuscany (Pandeli, 2002; Lazzarotto et al., 2003; Aldinucci et al., 2007 and references therein), Northern Tuscany (Ciarapica and Passeri, 2002, and references therein), and the Molise region (Bertinelli et al., 2002) with our results, the Central Apennines appear to be a region of overlap between the Ionian Neo-Tethys and the Alpine Tethys, where Permian–Triassic extensional tectonics were overprinted by the later Late Triassic–Jurassic extensional event. The contrasting orientations of the two diachronous rifts (i.e., NW–SE or NNW–SSE for the Ionian Neo-Tethys and SW–NE for the Alpine Tethys before the CCW rotation of the Adria plate – Speranza and Kissel, 1993; Van der Voo, 1993) are consistent with the superposition of the two nearly-orthogonal normal faulting and the resulting cross-trend distribution of the Mesozoic fault-bounded structural highs and depressions (i.e., the “chocolate tablet” fault patterns of Ramsay and Huber, 1983, also proposed in the Central Apennines by Alvarez, 1989 and Ciarapica and Passeri, 2002).

In the Central Apennines, the significant lateral variations in both facies and thickness of the Mesozoic sedimentary cover and the pre-existing discontinuities affecting the basement influenced the subsequent (i.e., Oligocene–Quaternary) structural evolution of the Apennine chain significantly, analogous to several orogens that have been built from the thinned continental margins of the various arms of the Tethys and Neo-Tethys (D’Argenio and Alvarez, 1980).

The reverse-reactivation of Triassic and Jurassic normal faults clearly involved the Adriatic foreland at two different times. The Mesozoic normal faults were previously reverse-reactivated during the Upper Cretaceous–Miocene and were later locally reactivated during the Pliocene–Quaternary. The first contractional event is associated with the main phase of compression recorded along the chains surrounding the Adriatic domain (i.e., Alps, Apennines and Dinarides), and the second appears connected to the “coupling” of the two oppositely verging orogens (the NE-directed Apennines chain and the SW-directed Dinaric chain) with their common foreland plate. The original distance between the positively inverted NW–SE-trending Mid-Adriatic Ridge and the neighbouring fold-and-thrust belts indicates that in both phases of

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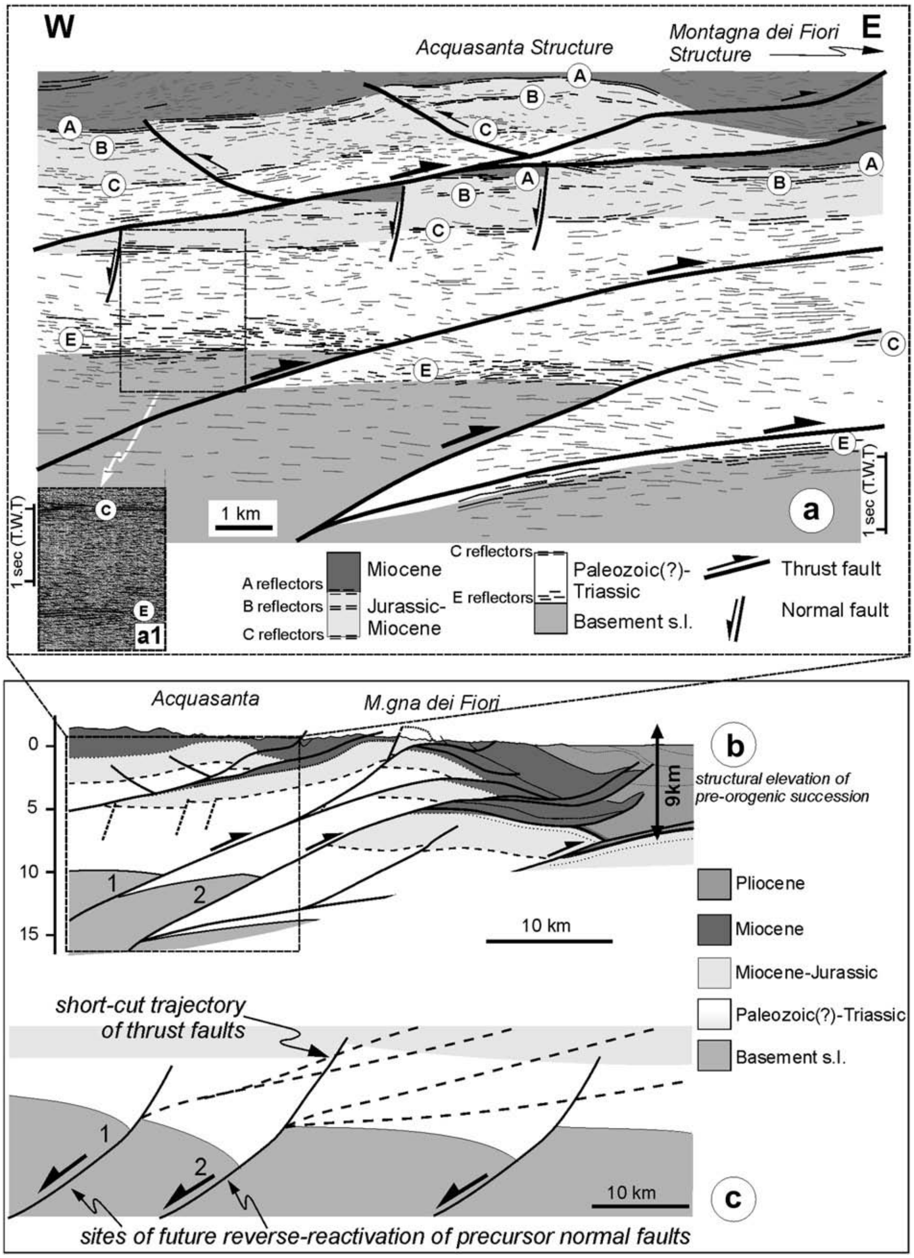

Fig. 12. (a) Interpretation of a seismic reflection profile across the back-limb of the Montagna dei Fiori anticline showing the combined effects of thin and thick-skinned tectonics in this part of the Apennine. The westward thinning and convergence of the Permian(?)–Triassic reflectors on top of sub-horizontal reflectors (E) suggest the reverse-reactivation of west-dipping normal faults and the total extrusion of the syn-rift sediments in their hangingwall blocks. (a1) Detail of the seismic profile showing a seismic unit mainly consisting of reflection-free to very weak and discontinuous reflections (about 1.0 s TWT in thickness) delimited at the top by a sharp signal corresponding to the base of the Calcare Massiccio Fm (reflector "C"). The transparent seismic interval, correlated to the Upper Triassic Anidriti di Burano Fm., overlays a package of strong reflectors (about 0.4 s TWT in thickness) on top of the basement. (b) Balanced cross-section based on the interpretation of composite seismic reflection profiles and schematic restored template (c) across the Montagna dei Fiori anticline (see Fig. 2 for location). The interval velocity adopted for time–depth conversion and the key reflectors used for interpretation are shown in Fig. 3c.

deformation, the compressive stresses were transmitted in the foreland several kilometres from the adjacent thrust fronts (foreland tectonics).

Several peculiar features observed in the Mid-Adriatic Ridge appear common to many other foreland areas affected by compressive deformation with reactivation of pre-existing discontinuities (e.g., North Sea; Aquitaine Basin; Atlas of Morocco – Cooper and Williams, 1989; Badley et al., 1989; Coward, 1994; Letouzey et al., 1995). The main characteristics are: (i) the opposite polarities of the asymmetric folds and the symmetric hangingwall folds appear to strictly depend on the original attitude of the pre-existing Mesozoic extensional faults (Figs. 4–6); (ii) the selective reutilization of normal faults as reverse faults occurred during positive inversion, suggested by the coexistence of "frozen" Mesozoic normal faults close to the reactivated extensional discontinuities (Figs. 4–6); (iii) the overall low grade of inversion, defined by the location of the null point within the top of the syn-rift sequence (Fig. 6); and (iv) the en-echelon arrangement of the inverted structures in map view and their reduced along-strike lengths (Fig. 2). According to De Alteriis (1995), the contribution of diapirism to the Mesozoic Adriatic basin inversion cannot be neglected; however, the mobilization of Triassic and probably Permian evaporites (Grandic et al., 2002; Finetti and Ben, 2005; Scrocca, 2006) is related to the main phases of compression

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affecting the Mid-Adriatic Ridge, and salt tectonics (*sensu* Coward, 1994) seem to be promoted by reactivation of the Triassic normal faults.

In the outcropping part of the Apennine belt, the Jurassic normal faults are very frequent; however, their positive reactivation is sporadic. The reconstructed distribution of Jurassic normal faults reveals that they were transverse, oblique or longitudinal with respect to the E–NE-trending axis of the subsequent compression (Fig. 2), and the Mesozoic discontinuities, in both the platform-basin transition zones and within the pelagic troughs, dip towards the hinterland or towards the foreland.

Field relationships reveal that the steeply W-dipping Jurassic normal faults are systematically truncated by gently W-dipping thrusts propagating with short-cut trajectories (Fig. 13). This is particularly clear in the hangingwall block of the Sibillini Mts. thrust (Fig. 9) and in the Montagna dei Fiori area (Fig. 10). Moreover, numerous similar examples of younger W-dipping extensional structures (e.g., Neogene and Cretaceous normal faults) interacting with subsequent thrust faults have been described in different parts of the whole Apennine chain (Alberti et al., 1996; Tavarnelli, 1996; Tavarnelli and Peacock, 1999; Scisciani et al., 2000a,b, 2001, 2002).

The occurrence of pre-thrusting normal faults in the back-limb of several thrust-related anticlines strongly suggests that the pre-existing discontinuities constituted an important mechanical anisotropy, effective in controlling the localisation of propagating thrust ramps and related fold development (Fig. 13a). The pre-thrusting normal faults were commonly cross-cut by thrust faults and passively transported in their hangingwall, although some evidence suggests reactivation of the pre-existing discontinuity with a strike-slip sense of movement during the compressional event (e.g., left-lateral strike-slip reactivation of the Montagna dei Fiori normal fault – Figs. 13a and 14). This situation occurs when the attitude of the normal faults is not quite perpendicular to the direction of compression; more specifically, the E–W oriented compression in the Montagna dei Fiori area (Averbuch et al., 1995; Calamita et al., 1998) was simultaneously partitioned into the left-lateral strike-slip reactivation achieved by the NW–SE-oriented W-dipping normal faults and the ENE-directed displacement along the Montagna dei Fiori thrust fault (Figs. 11 and 14).

Compressive strain partitioning along the Sabina N–S-trending Jurassic normal fault and the adjacent east-verging thrust fault was also considered a crucial mechanism of deformation by Pierantoni (1997), who compared the different families of shear sense indicators collected along the reactivated normal faults and the thrust fault. The right-lateral transpression that caused the inversion of the east-dipping Jurassic normal fault and the backward extrusion of the syn-rift sediments was coupled with the NE-directed right-lateral movement achieved by the W-dipping thrust fault (Figs. 7 and 14b). During the later stages of deformation, the NE-striking compression was probably decoupled and partitioned along the oblique pre-existing Jurassic discontinuity, resulting in the right-lateral strike-slip reactivation of the Sabina fault and the dip–slip reverse movement along the east-verging thrust (Fig. 14b).

The E/SE-dipping Jurassic, Cretaceous and Miocene normal faults that crop out across much of the Apennine chain are commonly truncated by the subsequent thrust faults (Figs. 8, 9, 13b and 14b). The pre-thrusting normal faults were steepened, rotated within the folds and partially reactivated as high-angle reverse faults in the back-limbs of the thrust-related anticlines (Figs. 8, 9, 13 and 14).

The truncation, folding and partial reverse-reactivation of the pre-existing E/SE-dipping discontinuities are extremely common

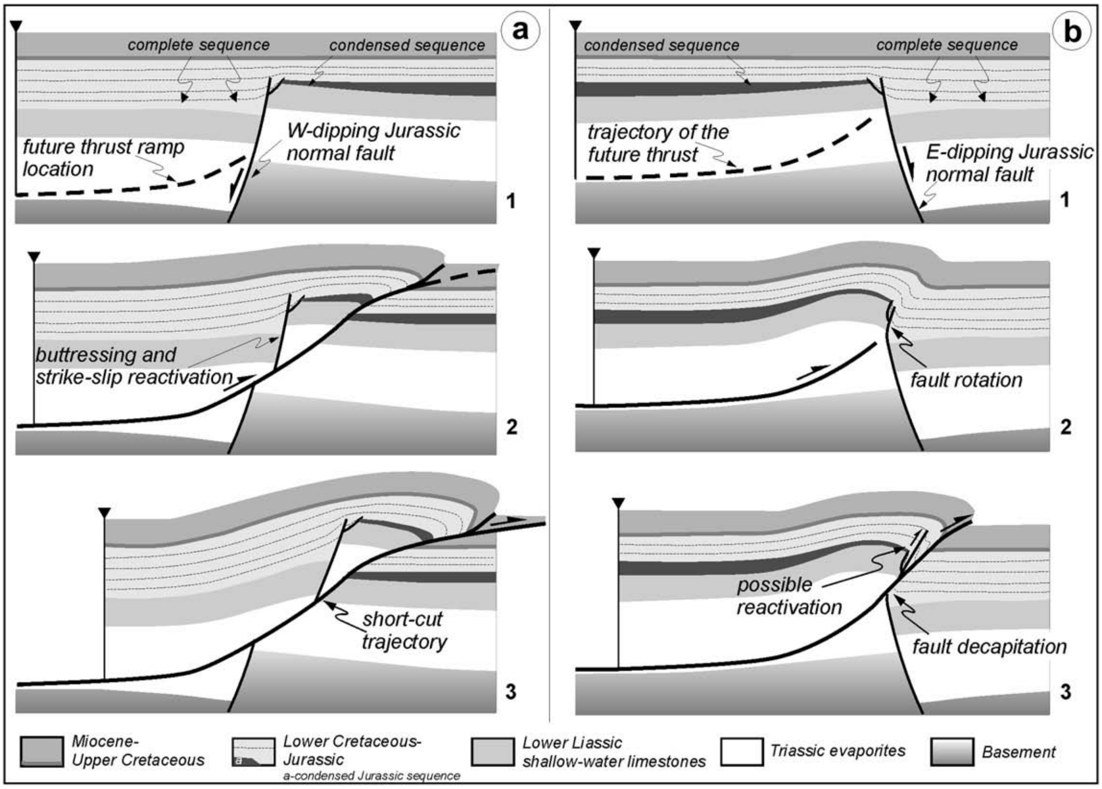

Fig. 13. Cartoon showing the modes of interaction between the W-dipping (a) and E-dipping (b) Jurassic extensional faults and the subsequent Neogene compressive structures in the Central Apennines of Italy. In both cases, the pre-existing discontinuities promote the thrust-ramp localisation and they are decapitated by the later thrust faults that propagate with short-cut trajectories (see text for explanation).

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throughout the Apennine fold-and-thrust belt (e.g., the Gran Sasso thrust front and the Maiella area – Scisciani et al., 2002), and condensed sequences in the hangingwalls of the thrust faults (e.g., the Pozzoni Mt. thrust) are frequently juxtaposed onto the complete and over-thickened sequences in their footwall blocks (Figs. 8 and 9). As a consequence, compressive structures emphasize the pre-existing variations in elevation, such that the platform or intra-basinal plateau areas remain high while half-grabens and basinal areas, in general, are still structural lows. Moreover, the arcuate-shaped or salient geometries of several thrust faults (e.g., the Pozzoni Mt. thrust and the Gran Sasso thrust front – Fig. 2) roughly reflect the trend of the pre-existing normal faults affected by the contractional deformation. Overall, this evidence strongly suggests control exerted by the inherited extensional fault geometry on the frontal (i.e., NW–SE or N–S oriented) and lateral (i.e., NE–SW or E–W oriented) thrust-ramp and related fold locations.

In contrast to some parts of ancient and deeply eroded orogens or in old intra-cratonic basins (e.g., Alps, Andean Cordillera, Central Europe – Gillcrist et al., 1987; Ziegler et al., 1995; Kley et al., 2005), where it is possible to demonstrate basement involvement and inversion tectonics from field investigations, the thick Mesozoic cover and overlying abundant Tertiary siliciclastic sequences largely blanket the deep structural setting of the young Apennine chain. However, several multi-disciplinary studies have recently tied disparate types of geological observations and newly acquired geophysical data (i.e., deep seismic reflection profiles, magnetic and gravimetric maps) into a structural investigation in order to unravel the relationships between deformation of basement and sedimentary cover in the buried part of the Apennine chain (Scarascia et al., 1998; Coward et al., 1999; Chiappini and Speranza, 2002; Finetti et al., 2005; Scisciani and Montefalcone, 2006). Basement involvement, as suggested by the CROP-03 deep seismic reflection profile (Barchi et al., 1998; Decandia et al., 1998; Finetti et al., 2001), can be consistent with models of structural evolution that include reverse-sense reactivation of Permian(?)–Triassic crustal extensional faults (Coward et al., 1999; Tozer et al., 2002, 2006; Butler et al., 2004, 2006; Tavarnelli et al., 2004; Scisciani and Montefalcone, 2006).

The data collected along a prominent “jump” in structural elevation of the pre-orogenic sedimentary cover within the Central Apennines, presented in the previous section, validate the hypothesis of Permian(?)–Triassic basin inversion beneath the Montagna dei Fiori anticline (Figs. 2 and 12). Moreover, this mechanism of deformation can also be applied to the Sibillini Mts. thrust, in agreement with the interpretations proposed by Tavarnelli et al. (2004).

The geometry of the buried and over-thickened Permian(?)–Triassic succession in the core of the Montagna dei Fiori structural high strongly suggests a severe extrusion of the syn-rift wedges in the hangingwall blocks of west-dipping pre-existing normal faults (Fig. 12). The strong structural elevation (about 9 km) of the Montagna dei Fiori anticline and of the analogous Sibillini Mts. anticline with respect to the relative adjacent downthrown eastern blocks does not appear to be produced by multiple duplications of the sedimentary cover including the siliciclastic sediments, as predicted by the thin-skinned tectonics models proposed by several authors (Bally et al., 1986; Hill and Hayward, 1988), but is instead accomplished by the reverse-reactivation of basement-rooted W-dipping normal faults and by the expulsion of the over-thickened Permian(?)–Triassic syn-rift succession (Figs. 12). This thick-skinned inversion tectonics model is robustly consistent with the strong structural elevation achieved by thrusts with respect to their reduced displacement, as supported by field observations and subsurface data in the Montagna dei Fiori area (Fig. 10) and by the stratigraphic separation diagram compiled for the Sibillini thrust front (Tavarnelli et al., 2004). In fact, surface geology shows relatively limited shortening by nature of the “ramp on ramp” configuration of the outcropping Montagna dei Fiori (Fig. 10) and Sibillini Mts. thrusts (Fig. 9), and seismic data interpretation rules out large “flat on flat” geometries, as postulated by the thin-skinned tectonic models.

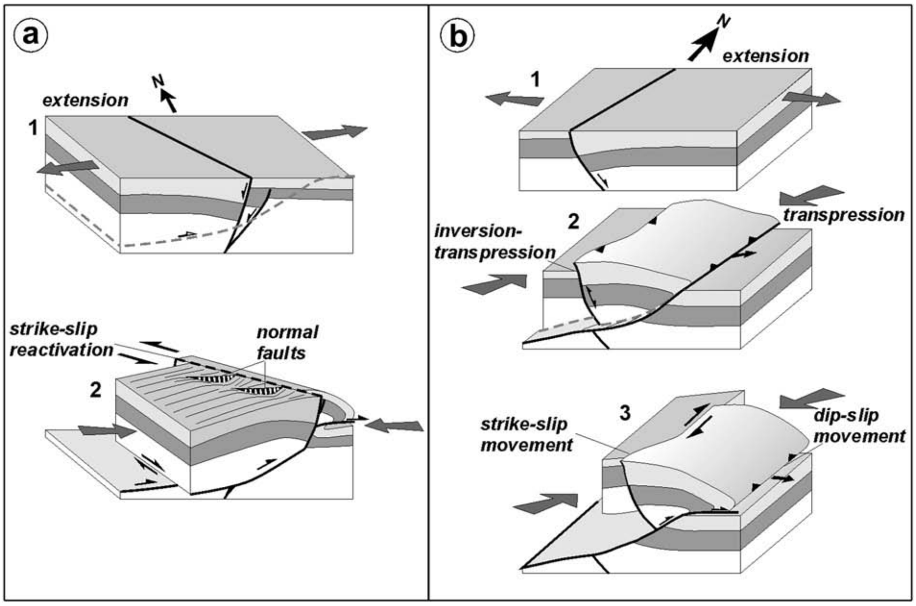

Fig. 14. Block diagrams showing the reactivation of the Montagna dei Fiori (a) and Sabina (b) pre-existing normal faults during compression. The left-lateral strike-slip reactivation of the NNW–SSE-trending Montagna dei Fiori normal fault (1a) produces the development of ENE–WSW-oriented normal faults in its hangingwall block (2a). The N–S-trending Jurassic Sabina Fault (b1) was positively reactivated with transpressive kinematics in the early stage of compressive deformation (b2); during the subsequent stage, the NE-oriented compression was decoupled and partitioned along the pre-existing discontinuity, resulting in the right-lateral reactivation of the Sabina fault and dip–slip reverse movement along the east-verging thrust fault (b3).

8. Conclusions

Surface and subsurface data from the Central Apennines and the Adriatic indicate distinct styles and amounts of positive inversion tectonics in the orogenic chain and its adjacent foreland. Moreover, the modes of interaction between the pre-existing discontinuities and the thrust faults in the Apennine belt differ strictly depending on the depth of rock volume affected by compressive deformation.

Field relationships from the exposed Central Apennines reveal that the steeply E and W-dipping normal faults, mainly Jurassic but also Cretaceous and Miocene, were systematically decapitated by sub-horizontal or gently west-dipping Neogene thrusts propagating with short-cut trajectories. Pre-thrusting normal faults were commonly deformed by later thrusts, and little evidence seems to support their entire reactivation as high-angle reverse faults. This peculiar mode of inversion, at odds with the conventional assumption of fault reactivation (e.g., Williams et al., 1989), but in agreement with field investigations across inverted structures (e.g., see Butler, 1989), suggests that these shallow discontinuities were not suitable to be reactivated by the thin-skinned thrust faults propagating within the sedimentary cover. This evidence could be explained by either the non-coaxial directions of early extension (approximately ENE–WSW at present) and late contraction (ranging from SW–NE to E–W), or by the steep dip of the pre-existing discontinuity (Sibson, 1995). However, the pre-existing normal faults constituted important mechanical anisotropies that were effective in controlling the localisation, spacing and kinematics of the propagating thrust ramps and related fold nucleation within the sedimentary cover.

Although in the Apennine chain the exposed Jurassic, Cretaceous and Miocene normal faults were passively truncated and translated by thrust faults, the strong positive reactivation of the buried Permian(?)–Triassic west-dipping discontinuities appears to be a recurrent mechanism of deformation inferred at deeper structural levels (e.g., in the Montagna dei Fiori and Sibillini Mts. area). These data suggest an attitude (both dip and orientation) of the pre-existing discontinuities consistent for reactivation as thrusts or other peculiar mechanical and rheological conditions that promote positive inversion tectonics. The implications regarding the shortening rates and structural styles of the Apennine chain are obvious but significant when assuming thick-skinned positive inversion tectonics with respect to the classical thin-skinned tectonic model with multiple duplications of the sedimentary cover.

In the Adriatic foreland, the Mesozoic normal faults experienced a selective and multiple reactivation and were moderately inverted under stress transmitted several kilometres from the adjacent chains (foreland tectonics).

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