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Coexistence of thin- and thick-skinned tectonics: An example from the Central Apennines, Italy

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ABSTRACT

In this study, the outer sector of the Central Apennines of Italy and the Adriatic foreland have been analyzed in order to reconstruct the geological-structural setting and the Neogene-Quaternary evolution of the fold-and-thrust belt.

Based on fieldwork data, existing geological maps, new seismic data, and well information, a regional balanced cross section has been realized. The transect, ~140 km in length from the inner mountain belt to the Adriatic foreland, illustrates the structural style of the Apennines thrust system, the geometry of the different thrust fronts, the physiography of the foreland ramp, and the setting of the syn-tectonic basins infill. Moreover, by sequential balancing and subsequent forward modeling of the restored cross section, the migration of the contractional deformation and the tectonic evolution of the chain-foredeep-foreland system has been unraveled, and shortening rates have been calculated.

The complex structural setting of the Central Apennines fold-and-thrust belt derived from this study mainly results from the interaction between an extremely thin-skinned thrust system and a thick-skinned tectonics. The former mainly affects the syn-orogenic siliciclastic foredeep deposits and generally predates the emplacement of the second one (i.e., the deeper thrust system) that crosscuts the whole sedimentary cover (i.e., Triassic-Miocene carbonates and the overlying Messinian-Pliocene siliciclastic sediments) and locally involves the basement. The uncoupling in space and time between thin- and thick-skinned tectonics strictly controls the evolution and the migration of syn-tectonic basins and influences the sequence of thrust-system propagation; the latter, with respect to the deeper stratigraphic levels, is mainly toward the foreland even if breaching thrusts are present. Moreover, spacing and location of thrust ramps are strictly controlled by preexisting discontinuities that affect the foreland ramp.

Keywords: fold-and-thrust belt, thin-skinned tectonics, thick-skinned tectonics, sequential balancing, forward modelling, Central Apennines, Italy.

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INTRODUCTION

The aim of this study is to investigate the structural style, the timing of deformation, the amount of shortening, and the tectono-sedimentary evolution of the outer sector of the Central Apennines of Italy and of the adjacent Adriatic foreland.

The Central Apennines are an ENE-verging fold-and-thrust belt located in the eastern frontal sector of the Appennine-Maghrebian orogen (Figs. 1 and 2). The whole orogenic system is the result of the collision of the Corsica-Sardinia block (of European affinity) with the adjacent continental blocks of African origin (i.e., the Adriatic-Apulian foreland domain to the east and the Pelagian domain to the south). This process took place during the late Oligocene and Neogene (Boccaletti et al., 1971; Reutter et al., 1980; Malinverno and Ryan, 1986; Carmignani and Kligfield, 1990; Séranne, 1999, and references therein) and followed the consumption and the partial obduction of the Mesozoic Alpine (or Ligure) and Ionian Tethyan oceanic domains that were interposed between the two continental blocks (Finetti, 1985; Stampfli et al., 2001; Catalano et al., 2001; Ciarapica and Passeri, 2002; Fig. 3). The progressive southeastward migration of the contractional deformation was accompanied at rear by extension and the opening of the Ligure-Provençal and Tyrrhenian back-arc basins (Rehault et al., 1987; Guéguen et al., 1998 and references therein; Fig. 1).

At present, the roll-back toward the southeast of a northwestward subducting slab of the remnant Ionian oceanic lithosphere is clearly documented beneath the Calabrian arc (Doglioni et al., 1999; Faccenna et al., 2001) where the thrust front is active, whereas in the adjacent sectors, starting from late Pliocene, the contractional deformation strongly decreased and stopped in the Central Apennines belt (Patacca et al., 1991; Kruse and Royden, 1994).

The Central Apennines of Italy developed in a transition zone between the northern and the southern arcs (i.e., the Northern and Southern Apennines, respectively) that compose the whole Apennines fold-and-thrust belt. It consists of oceanic-derived terrenes (Ligurian and Ionian Allochthonous units) that are found on top of siliciclastic foredeep sequences both in the inner (Tuscany-Umbrian domain and Southern Apennines) and the western outer

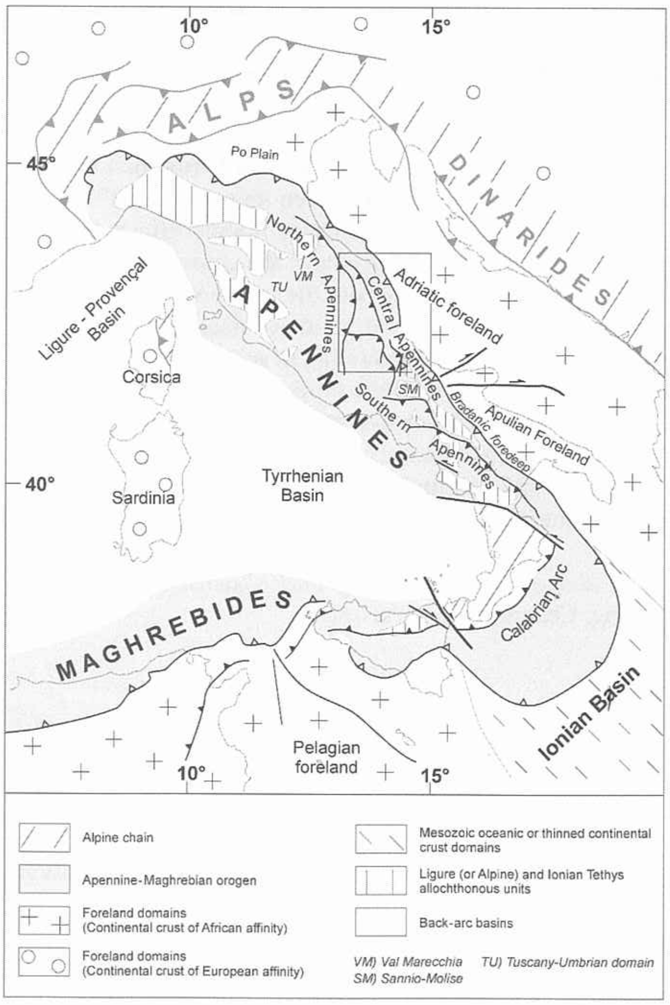

Figure 1. Tectonic sketch map of the Apennine-Maghrebide orogen and of the adjacent foreland domains. The box indicates location of the study area presented in Figure 2 and discussed in the text.

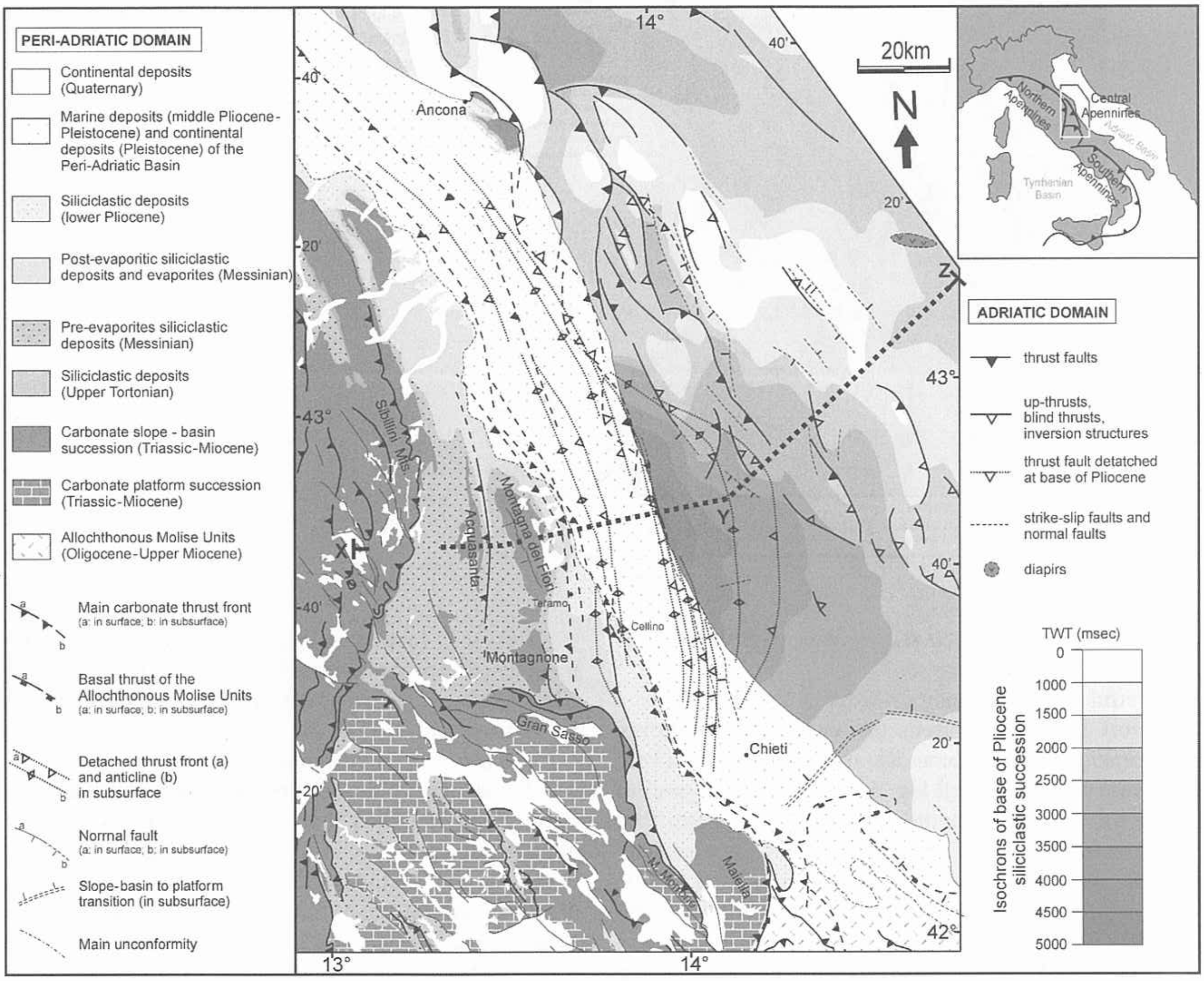

Figure 2. Structural and geological sketch map of the outer sector of the Central Apennines of Italy and of the adjacent Adriatic Foreland. XYZ refers to the location of the transect illustrated in Figure 5; the dotted line indicates the trace of the composite seismic reflection profile of Figure 7A and of the geological cross section of Figure 8E, both discussed in the text.

sector (Val Marecchia, Sannio-Molise, Bradanic foredeep) of the Apennine chain (Fig. 1). In the central mountain belt, which corresponds to the high-topography zone in the Central Apennines, a mainly carbonate Triassic-Miocene syn-rift and passive-margin succession of the Tethys Ocean is uplifted by folds and thrusts. Eastward, running from the inner Po Plain through the Romagna-Marche-Abruzzi foothills and to the inner Bradanic Trough, the deformed carbonate successions are buried beneath upper Miocene-Pliocene syn-orogenic siliciclastic deposits, whereas farther east they are found beneath a thick Pliocene-Quaternary foredeep sequence that exceeds 8,000 m in the Po Plain and in the Adriatic Basin (Bigi et al., 1992; Ori et al., 1991).

The progressive migration of the foredeep depocenters developed in front of the advancing Apennines fold-and-thrust belt is well established by the eastward younging (i.e., toward the foreland) of the basal syn-orogenic basin-infill (Ricci Lucchi, 1986; Boccaletti et al., 1990; Patacca and Scandone, 1989; Ori et al., 1991). Diachronous foredeep siliciclastic deposits were subsequently incorporated in the Apennine thrust system and were uplifted and eroded in the inner part of the chain. The older siliciclastic sediments crop out in the western mountain belt where they are intensively deformed, and they are found in few scattered outcrops, strongly dissected by arrays of postorogenic, mainly Quaternary, normal faults; in contrast, the widespread occurrence of such syn-orogenic and postorogenic sediments in the frontal zone of the thrust system provides an exceptional record of the timing of the array of fold-and-thrust structures (Fig. 2). However, to the east of the present-day topographic ridge of the Apennines, the thick upper Miocene-Quaternary siliciclastic covers mask the structural setting of the underlying buried fold-and-thrust belt. Here, however, the thrust systems are preserved in subsurface, and the good quality of seismic reflection allows the

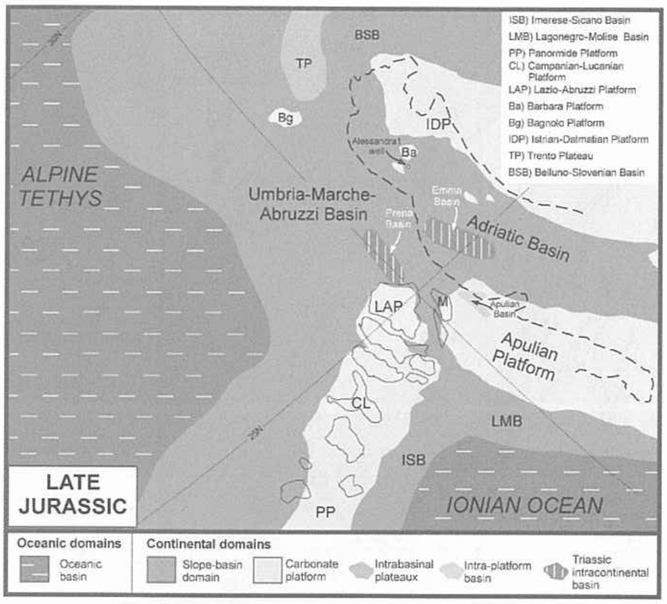

Figure 3. Late Jurassic paleogeographic reconstruction showing the distribution of oceanic and thinned continental domains in the Central Mediterranean region (modified from Ciarapica and Passeri, 2002).

compressive structures and their relationships with syn-tectonic sedimentation to be clearly imaged.

A powerful method to study the external zones of foreland fold-and-thrust belt derives from the integration of surface geological-stratigraphic-structural data with the analysis of subsurface information (i.e., well-log data and seismic profiles interpretation). Such an integrated approach was performed along the Montagna dei Fiori transect by several authors (Paltrinieri et al., 1982; Bally et al., 1986; Calamita et al., 1991; Lavecchia et al., 1994; Artoni and Casero, 1997; Albouy et al., 2002; Tozer et al., 2002a,b; Albouy et al., 2003a,b) as well as in the present work, and it allowed constraining a regional balanced and restored cross section that depicts the structural setting of the outer Central Apennines and of the adjacent Adriatic foreland (Fig. 2). Moreover, sequential balancing and forward modeling methodologies were applied in order to validate the cross section and to illustrate better the tectono-stratigraphic evolution of the fold-and-thrust belt. We paid particular attention to identifying the structural style (i.e., thin- and/or thick-skinned) of the main thrust fronts and to defining the sequence of thrust system propagation.

REGIONAL GEOLOGICAL AND STRUCTURAL SETTING

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 (Carmignani and Kligfield, 1990). This process was accompanied by foredeeps and thrust-top basins that migrated toward the foreland from the more internal Tuscan Oligocene-lower Miocene basins to the present-day Pliocene-Quaternary Adriatic Basin (Ricci Lucchi, 1986; Boccaletti et al., 1990; Patacca and Scandone, 1989).

This study focuses on the outer sector of the Central Apennines, which are characterized by the occurrence of several E-NE verging asymmetric faulted anticlines and a thrust front located in the Adriatic foreland (Fig. 2).

This sector of the Apennines classically has been interpreted as a thin-skinned fold-and-thrust belt, with imbrication 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 in 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 and anomalous shortening rates (15–50 mm per year) if compared with values inferred from other similar fold-and-thrust belts (Cipollari and Cosentino, 1996; Artoni and Casero, 1997; Tozer et al., 2002a).

Alternatively, a minor shortening has been assessed by authors that envisaged the Apennine chain in terms of thick-skinned tectonics, with basement being partly involved within the structures of the sedimentary cover (Lavecchia et al., 1987; Casero et al., 1988; Sage et al., 1991; Lavecchia et al., 1994; Albouy et al., 2002; Tozer et al., 2002a,b; Albouy et al., 2003a,b; Casero, 2004).

In the last few years, the acquisition of new deep seismic profiles (e.g., the CROP 01–01A-03: Barchi et al., 1998, Coward et al., 1999; Menardi Noguera and Rea, 2000; Finetti et al., 2001; Argnani et al., 2003) and aeromagnetic data (Chiappini and Speranza, 2002) supported the hypothesis of the basement involvement in the Neogene deformation of the Apennine chain. Moreover, plenty of recent studies based on field and subsurface data revealed that many thrusts have localized on inherited precontractional structures, including preexisting normal faults that formed either during foredeep development (peripheral bulge extension) or throughout Mesozoic passive margin evolution (Hyppolite et al., 1995; Tavarnelli, 1996; Coward et al., 1999; Mazzoli et al., 2000; Scisciani et al., 2000a,b, 2001; Tavarnelli et al., 2004).

Little is known about basement beneath the Central Apennines chain. The only available data come from aeromagnetic studies (Arisi Rota and Fichera, 1987; Chiappini and Speranza, 2002), and other information can be extrapolated from stratigraphy of deep exploration wells drilled in the Northern Adriatic foreland (Assunta 1 well) and from the outcropping basement in the Tuscany (Gattiglio et al., 1989; Lazzarotto et al., 2003). It consists of Hercynian metasedimentary and igneous complexes that are discordantly overlaid by Upper Paleozoic and lower-middle Triassic sediments (mainly phyllites or red sandstones and conglomerates: Verrucano and Tocchi Formations; Fig. 4); the latter were penetrated in the inner sector of the chain (Perugia 2 well) and in the central Adriatic offshore (Alessandra 1 well). The, remarkably low velocities (ranging from 3,900 to 5,300 m/s) of the clastic intervals with respect to the underlying basement and the overlying

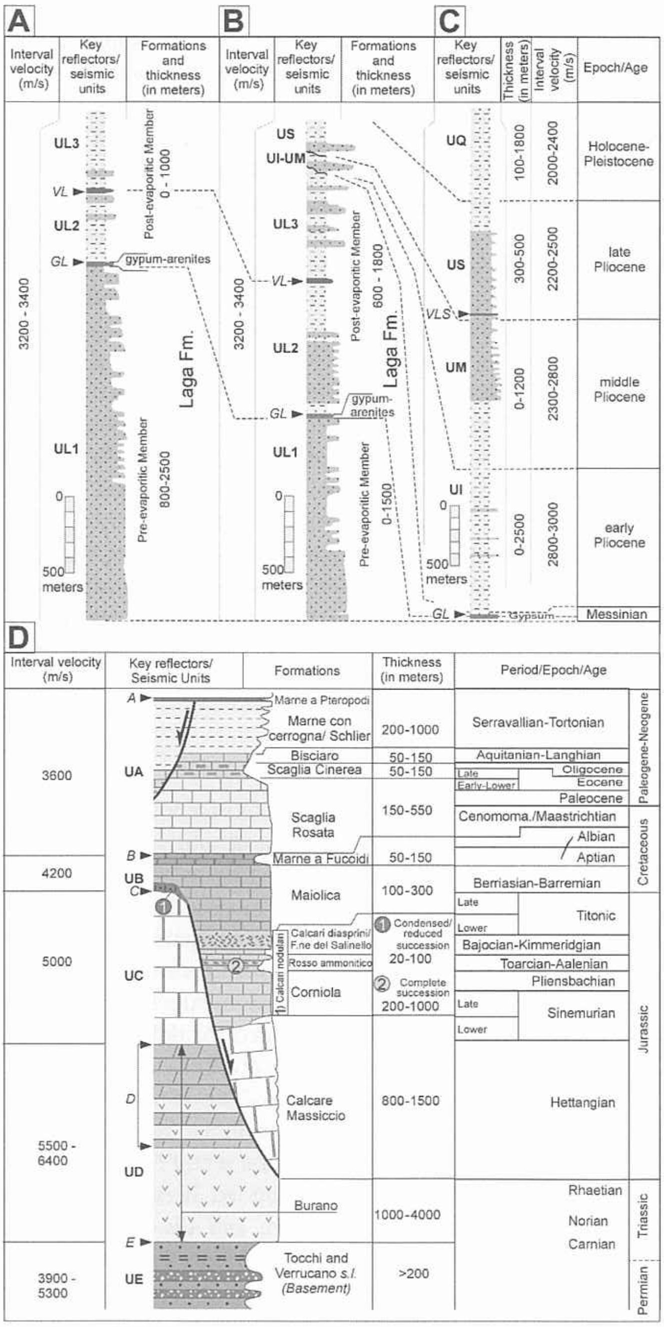

Figure 4. Summary stratigraphic column of the siliciclastic (A, B, and C) and carbonate successions (D) in the study area; data are based on exploration-well penetrations, seismic stratigraphy, and outcrops. Seismic units, key reflectors, and interval velocity are indicated, and this terminology is adopted both for all the figures and in the text. (A) Neogene siliciclastic succession in the inner sector (west of Montagna dei Fiori area); (B) Neogene siliciclastic succession in the central sector (east of Montagna dei Fiori area); (C) Neogene siliciclastic succession in the outer sector (Adriatic foreland); VL: volcanoclastic level.

upper Triassic evaporites/dolomites (6,000–6,400 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).

The outcropping stratigraphic section of the Apennines almost entirely consists of sedimentary rocks of a preorogenic Triassic-Miocene mainly carbonate sequence, overlain by Miocene-Pliocene syn-orogenic sediments (Cantalamessa et al., 1986a,b; Centamore et al., 1986; Figs. 2 and 4). The older succession is composed of upper Triassic anhydrites and dolomites that are exposed in the inner sector of the chain and that were penetrated in several exploration wells in the Adriatic foreland. The Triassic sediments are covered by Jurassic-Cretaceous limestones, sporadically interbedded with shales and local cherts in pelagic basin sequences. These parts of the section exhibit substantial facies and thickness variations related to the Mesozoic rifting and the subsequent evolution of the passive margin (Bernoulli and Jenkyns, 1974; Stampfli and Mosar, 1997; Ciarapica and Passeri, 2002). During this stage, the Adria domain was fragmented by extensional tectonics, and the shallow marine sedimentation that prevailed during upper Triassic-Liassic times persisted up to the Paleogene only in a few areas (e.g., the Lazio-Abruzzi, Campania-Lucanian, and Apulian platforms), whereas it was replaced by pelagic deposition in the fault-bounded basins (i.e., Umbria-Marche-Abruzzi Basin, Adriatic Basin; Fig. 3). Moreover, within the pelagic basins, some structural highs capped by reduced thickness of sediments (Condensed sequence; Fig. 4D) were separated by deep troughs where Jurassic sediments show the maximum thickness (Complete sequence; Fig. 4D). This configuration can be clearly documented in the analyzed area that traverses the Umbria-Marche-Abruzzi and the Adriatic Mesozoic basins (Fig. 2).

The articulated Jurassic paleomorphology of the pelagic basins was leveled during the Albian-Aptian times with the deposition of a continuous marly interval (Marne a Fucoidi Fm.). This stratigraphic marker can be undoubtedly traced throughout the study area, and it represents a useful reflector for seismic interpretation (Fig. 4D).

The stratigraphic succession continues upward with basinal and hemipelagic cherty limestones with intercalations of argillaceous marls that became prevalent in the Oligocene and in the Miocene intervals (i.e., Scaglia Cinerea Fm. and Schlier/Marne con Cerrogna Fm.). Carbonate and shale deposition is replaced by siliciclastic foredeep basin sedimentation during the Messinian in the inner sector (i.e., Laga Basin) and Pliocene in the Adriatic foreland basin (Fig. 4). In this latter, the wedge-shaped Pliocene-Quaternary syn-orogenic sediments overlay Messinian evaporites (Fig. 4C). The impedance contrast between siliciclastic foredeep deposits and gypsum is responsible for a high-amplitude reflector that can be followed over large areas in the Adriatic domain. Moreover, an analogous acoustic signal can be traced in the inner sector where Messinian evaporites are replaced by gypsum-arenites in the Laga foredeep Basin (Fig. 4B).

In the Periadriatic and Adriatic basins, extensive drilling by oil companies and geophysical surveys allows a high-resolution stratigraphy and a detailed geometrical analysis of the basin infill to be made (Crescenti et al., 1980; Ori et al., 1991; Artoni and Casero, 1997; Dattilo et al., 1999). The Neogene-Quaternary foredeep and thrust-top basin successions show a marked sedimentary facies variability and diachroneity from the internal sector toward the foreland, coupled with progressive foreland migration of the foredeep and facies differentiation within the basin (Casnedi and Serafini, 1994).

The whole sedimentary cover shows a different mechanical behavior in response to the compressive regime. This is suggested by the existence of discrete detachment levels that separate lithotectonic units, which accommodated shortening in different ways. The main basal decollement horizon occurs in Upper Triassic evaporites (Bally et al., 1986; Calamita and Deiana, 1986; De Feyter et al., 1986; Calamita et al., 1991; Coward et al., 1999) and separates high competent Lower Liassic massive platform carbonates from the underlying basement.

The second relevant detachment is located at the base of the syn-orogenic wedge. It was widely documented in the outcropping sector of the Apennines (Laga Basin), where it is found within the Paleogene-Miocene marly sequence (Laga detachment: Koopman, 1983; Cooper and Burby, 1986; Mattei, 1987; Calamita et al., 1991; Invernizzi and Ridolfi, 1992; Marsili and Tozzi, 1995; Ghisetti and Vezzani, 2000; De Feyter and Delle Rose, 2002; Mazzoli et al., 2002) and in subsurface in the Periadriatic and Adriatic basins. Here, seismic shows arrays of thrusts that branch off from a common flat-lying detachment level located along Messinian evaporites (i.e., the top of carbonate succession) or near the base of the siliciclastic foredeep basin-infill (Bally et al., 1986; Ori et al., 1991; Casnedi and Serafini, 1994; Artoni and Casero, 1997; Dattilo et al., 1999; Calamita et al., 2002; Bolis et al., 2003).

SURFACE DATA

The geological and morphological setting of the study area strictly results from the structural setting of the outer sector of the Central Apennines. It consists of three main domains characterized by two prominent morphological and structural steps that coincide with the main thrust fronts both in surface and in subsurface. In the inner sector, which corresponds to the mountain front, the pre-orogenic succession extensively crops out, and the top of the carbonate sequence (Middle Miocene in age, hereafter called the reference level) is exposed at ~2,000 m a.s.l., and it can be reconstructed as far as 4,000 m of elevation in the hangingwall block of the Sibillini Mts. thrust front (Figs. 2 and 5).

In the adjacent central sector (i.e., the Laga basin) the reference level is largely buried beneath Messinian syn-orogenic deposits of the Laga Fm., and it 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 ~2,000 m a.s.l., and it abruptly

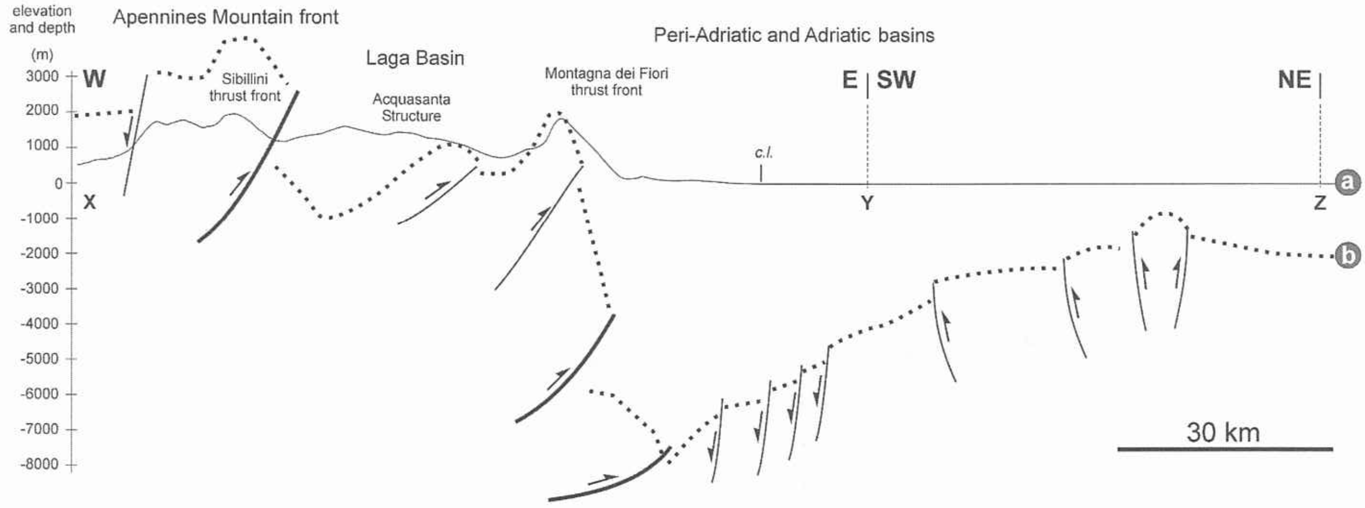

Figure 5. Comparison between the average topography (a—continuous line) and the reconstructed elevation/depth (b—dotted line) of the top of pre-orogenic carbonate succession (Middle Miocene stratigraphic level) along the outer sector of the Apennines and the Adriatic foreland. The two main steps correspond to the Sibillini Mts. and Montagna dei Fiori thrust fronts. The trace of the transects (XYZ) is reported in Figure 2.

deepens immediately to the east (i.e., in the Periadriatic Basin), where it is found at a depth of more than 8,000 m beneath a thick Pliocene-Pleistocene syn-orogenic siliciclastic succession. Here, the top-carbonate gently rises toward the east at an angle of ~5° along the Adriatic foreland ramp (Fig. 5).

In the next sections, we present the results of geological and structural field studies carried out along the main contractional structures exposed in the outer sector of the Central Apennines (Fig. 6). We focus on the most commonly observed geometries, the deformation styles, and the relative chronology of thrusts and folds that affect the Neogene syn-orogenic deposits and their pre-orogenic substrata.

The Acquasanta Anticline

The Acquasanta structure is an east-verging, N-S trending, thrust-related anticline that extends for over 50 km in the foothills of the Central Apennines (i.e., in the Laga Basin; Figs. 2 and 6). This sector is largely occupied by the Laga Formation of Messinian age (Figs. 6A and 6B), and its general stratigraphy consists of two siliciclastic sequences (preevaporitic Member and postevaporitic Member) separated by a gypsum-arenitic level (Cantalamessa et al., 1986b; Centamore et al., 1992; Figs. 4A, 4B, 5A, and 5B).

The Acquasanta anticline uplifts and affects the preorogenic Paleogene-Miocene marly and carbonate sequence and the overlaying Messinian sediments. The fold shows an asymmetric profile with a gently west-dipping back-limb. In the forelimb, the steeply dipping and overturned Miocene succession is truncated by a west-dipping thrust fault (Figs. 6A and 6C). Immediately to the south of Castellana Valley, the reverse structure juxtaposes the preevaporitic onto the postevaporitic Member of the Laga Fm., and the evaporitic level is offset ~2 km. The shortening produced by the thrust fault progressively decreases toward both the north and the south where the strata of the forelimb of the Acquasanta anticline merges with the overturned flank of the adjacent syncline.

In the core of the anticline, the preorogenic succession is intensively deformed by hectometric folds, small scale thrust faults, arrays of shear zones with S-C fabrics, and synthetic R-Riedel shear-planes. This intense zone of deformation was called Laga detachment by Koopman (1983) and was described in detail by many authors (Mattei, 1987; Calamita et al., 1991; Invernizzi and Ridolfi, 1992; Marsili and Tozzi, 1995; Ghisetti and Vezzani, 2000; De Feyter and Delle Rose, 2002; Mazzoli et al., 2002). One of the most prominent pieces of evidence is that the siliciclastic Messinian deposits are not affected by this kind of deformation and that along the Acquasanta anticline, the original on-lap pattern of the preevaporitic turbidites onto the foreland ramp is preserved (Fig. 6C). In fact, the contractional structures die out at the top of preorogenic succession along a detachment located within shale-rich levels.

In the back-limb of the Acquasanta anticline, the shear planes moderately dip toward the west and are near-parallel to the bedding (Fig. 6C). Slickensides and mechanical striations collected along the C-planes constantly indicate top-to-east displacements. Along the forelimb, where bedding steeply dips toward the east, the shear-planes constantly show the same attitude with respect to the strata, and shear-sense indicators show a normal sense of movement for these planes (Fig. 6C). Moreover, these bedding-parallel shear zones are truncated by high-angle reverse planes that offset the whole Paleogene-Miocene preorogenic succession and, in turn, generate folds in the overlaying Messinian siliciclastic sediments (Fig. 6C).

The overall geometry of the shear zones observed along the Acquasanta anticline suggests that they were emplaced after the deposition of the preevaporitic Member of Laga Formation (early Messinian) and were subsequently antiformally folded by

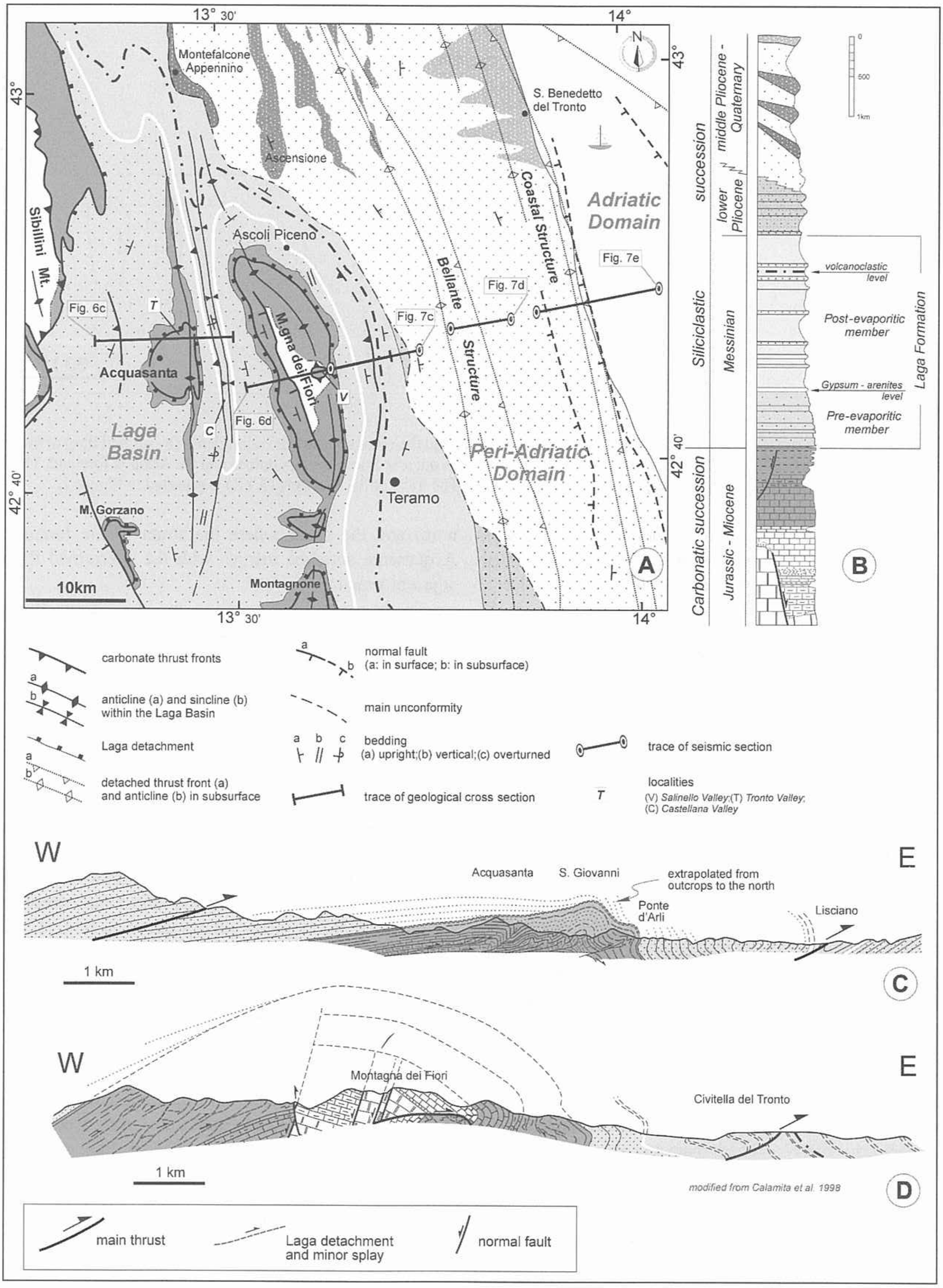

Figure 6. Structural and geological map (A) and stratigraphic column (B) of the Laga Basin and the Periadriatic domain (outer sector of Central Apennines of Italy). Geological cross sections based on field data across the Acquasanta (C) and Montagna dei Fiori (D) anticlines.

the growth of the younger and deeper Acquasanta thrust-related anticline in their footwall, in agreement with the interpretations proposed by different authors (Koopman, 1983; Marsili and Tozzi, 1995).

The Montagna dei Fiori Anticline

The Montagna dei Fiori anticline is a thrust-related structure developed to the east of the Acquasanta overthrust (Figs. 2 and 6A). The fold extends over 50 km with a general N150E trend and affects a Jurassic-Miocene preorogenic carbonate sequence, overlain by syn-orogenic Messinian deposits of the Laga Fm. (Figs. 6A and 6D; Koopman, 1983; Mattei, 1987; Calamita, 1990; Invernizzi and Ridolfi, 1992).

The geological cross section based on field data transects the axial culmination of the anticline along the Salinello valley and illustrates the deep structural setting of the core of the fold (Fig. 6D).

The Montagna dei Fiori anticline appears asymmetric, and it is east-verging. In the core of the fold, the main out-cropping thrust surface is antiformally folded by the growth of a younger and deeper thrust-related anticline in its footwall (Fig. 6D; Calamita, 1990). Toward the east, a west-dipping thrust crosscuts the Messinian siliciclastic deposits of the Laga Fm., which moderately dip toward the east.

In the back-limb of the anticline a high-angle normal fault realizes the contact between the Miocene hemipelagic sequence and the Jurassic-Cretaceous carbonates in the footwall block (Mattei, 1987; Ghisetti and Vezzani, 2000). A prethrusting Miocene activity of this normal fault is suggested by overprinting relationships between extensional and contractional structures and by stratigraphic variations across the fault (Calamita et al., 1998; Scisciani et al., 2002); moreover, a postorogenic activity of the normal fault has been suggested by Ghisetti and Vezzani (2000).

An intense deformation is observed along the back-limb of the Montagna dei Fiori anticline as expressed by S-C tectonites, cleavage, reverse shear planes, and detachment folds that are particularly persistent in the hangingwall block of the normal fault (Figs. 6A and 6D). Locally the S-C fabrics are reoriented and deformed by extensional synthetic features (R-Riedle shears, shear bands, or extensional crenulation cleavage). The shear zones are near parallel to the gently west-dipping strata and are confined in the upper section of the Miocene marly sequence, whereas the overlying Messinian turbidites appear substantially undeformed.

An analogous deformation affects the same stratigraphic interval along the eastern flank of the anticline. Here, the shear zones are near vertical or steeply dip toward the east, and shear sense indicators persistently show top-to-east displacements (Figs. 6A and 6D). Moreover, parasitic folds associated with the Montagna dei Fiori anticline clearly deform the preexisting originally bedding-parallel shear zones (Koopman, 1983; Invernizzi and Ridolfi, 1992; Mazzoli et al., 2002).

The similarity between the geometries and the kinematics of the shear-zones observed along the flanks of the Montagna dei Fiori and Acquasanta anticlines indicates that the Paleogene-Miocene preorogenic succession acted as a decollement level along which the whole thick Laga sedimentary wedge was translated toward the east with respect to the underlying Mesozoic substratum. This latter was only later affected by the contractional deformation that was responsible for the folding of the previously developed upper detachment.

SUBSURFACE DATA

In this study, more than 1,000 km of seismic reflection profiles have been analyzed. They mainly consist of time migrated dip-lines loop-tied with strike-lines that record up to 5.0–8.0 sec in TWT (two-way time). Correlation between seismic, surface data, and exploration well-logs drilled in the Adriatic off-shore and in the Apennines foothills allowed calibration of the main key reflectors adopted for seismic interpretation. Fault planes were imaged both by seismic reflections and by reflector terminations; moreover, wells information was tied to seismic data by adopting velocity profiles at wells and interval velocity based on published data (Bally et al., 1986; Barchi et al., 1998). The main seismic sequences, their interval velocity, and the key horizons that have been identified and correlated throughout the study area are summarized in Figures 4 and 7. Seismic data show a good quality in the Adriatic off-shore and in the adjacent on-shore sector of the Apennines, where the siliciclastic sedimentary cover is in crop-out; however, the signal/noise ratio decreases when seismic data were acquired in the fractured carbonates, which are commonly characterized by steep dips and strong lateral variations in velocity due to variable surface geology, or where the negative effects of extreme topographic variations were partially removed by severe static corrections.

A composite transect that contains a main dogleg was drawn in order to match the best surface and subsurface data while remaining roughly perpendicular to the structural trends (Fig. 2); the line drawing of the seismic reflection profile is presented in Figure 7.

The seismic section significantly illustrates the structural setting of the Apennine thrust front and of the adjacent Adriatic foreland. In the inner sector, two prominent structures can been recognized beneath, respectively, the Acquasanta and Montagna dei Fiori thrust-related anticlines. Both the structures affect the whole preorogenic carbonate sequence and the overlying syn-orogenic Messinian and lower Pliocene siliciclastic sediments. Moreover, underneath the Montagna dei Fiori structural high, a complex array of thrust faults are imaged. Both the structures affect the basement and the whole overlying cover and define a thick-skinned thrust front (Figs. 7A and 7B).

Eastward, four main buried thrust-related anticlines can be observed in subsurface. Proceeding toward the east, they correspond to the Bellante, Coastal, Emilio, and Camilla structures, respectively. These structures only affect the Neogene-Quaternary

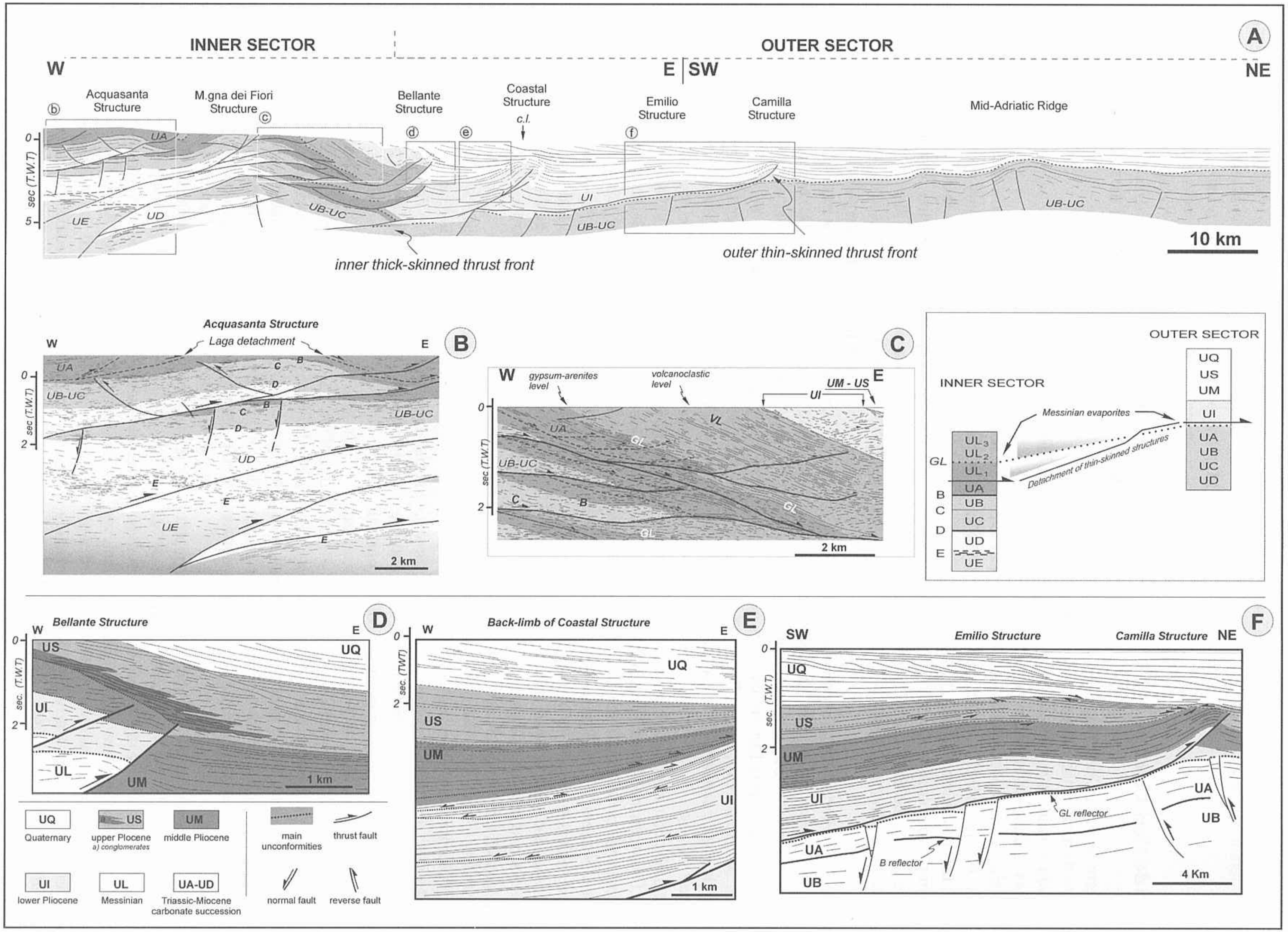

Figure 7. (A) Seismic interpretation of a composite reflection profile through the outer Central Apennines and the Adriatic foreland (see Figure 2 for location). The insets show close-ups of: the Acquasanta structure (B); the forelimb of Montagna dei Fiori anticline (C); the forelimb of Bellante structure (D); the back-limb of Coastal structure (E); and the Emilio-Camilla structures (F). See the box of Figure 7A and Figures 2 and 6 for location. The seismic units and key-reflectors abbreviations are summarized in Figure 4.

syn-orogenic siliciclastic sediments, and the thrust ramps appear to sole out into two main detachment levels. The decollement horizon is located in the Oligocene-Miocene preevaporitic succession in the inner sector (i.e., in the Bellante structure), while it corresponds to the near-top carbonate sequence or to the Messinian evaporites for the external structures.

The Adriatic foreland ramp dips gently toward the east with an angle of ~5°. The Pliocene sedimentary infill is wedge-shaped in cross section, and even if it was partially translated toward the east, the on-lapping pattern of the base of the foredeep sequence onto the Messinian evaporites is clearly preserved.

The foreland ramp is moderately deformed by high-angle reverse to transpressive faults in the outermost sector of the Adriatic. Convergence of reflectors toward the crest of the fault-related anticlines suggests two main phases of growth for these structures during Upper Cretaceous-Miocene and Quaternary, respectively (Bally et al., 1986; Argnani and Frugoni, 1997; Montefalcone, 2004). These indicators are also supported by numerous unconformities and erosive truncations in the several wells drilled in the crestal zones of these anticlines.

Lower Pliocene normal faults that disrupt the continuity of the Messinian reflector occur approximately beneath the present-day coastline (Artoni and Casero, 1997; Bolis et al., 2003; Calamita et al., 2002). Their down-throw does not exceed 0.7 sec in TWT (i.e., ~1,000 m), and they are interpreted as the response to the foreland flexure (Calamita et al., 2002, Bolis et al., 2003).

The Acquasanta Structure

The seismic interpretation clearly shows the duplication onto the flat-lying Jurassic-Miocene carbonate succession (see reflectors B, C, and D in Fig. 7B) beneath the Acquasanta anticline. The Triassic unit in the hangingwall block (hangingwall-flat) is juxtaposed onto the flat-lying Jurassic-Miocene interval (footwall-ramp) along a main thrust fault that gently dips toward the west with an angle of ~10°. Minor back-thrusts affect the back-limb of the Acquasanta anticline, whereas the forelimb is truncated by a minor splay of the main east-verging thrust fault that corresponds to the outcropping thrust (Figs. 6A and 6C). Eastward, the deep Acquasanta thrust assumes a flat geometry in the Oligocene-Miocene interval, and its continuation can be traced in the detachment zone that crops out in the back-limb of the Montagna dei Fiori anticline (Figs. 6A and 6C).

The footwall block of the Acquasanta thrust is truncated by high-angle, west-dipping faults; the relationships between these faults and the reverse fault suggest that high-angle structures were preexisting normal faults. Moreover, the numerous diffractions and the over-thickening of the Oligocene-Miocene succession in the hangingwall block of the Acquasanta thrust reveal also in subsurface the occurrence of the Laga detachment. The underlying Marne a Fucoidi reflector (B in Fig. 7B) can be undoubtedly traced continuously along the entire anticline; this evidence suggests the uncoupling between the shallower deformation (i.e., related to the upper detachment) with respect to the folding induced by the deep thrust.

The cut-off points of the D reflector are constrained by the seismic data (Fig. 7B); they are displaced by ~12 km along the deep portion of the Acquasanta thrust, whereas the shortening along the exposed thrust splay is much less. The data imply that a large amount of the orogenic contraction must be recorded in shallower stratigraphic levels toward the east.

Beneath the outcropping Acquasanta anticline, seismic shows flat-lying or gently west-dipping high-amplitude and discontinuous reflectors (key reflector E near the top basement in Fig. 4D) at ~4.0 sec TWT (Fig. 7B). These signals are interrupted by two main high-angle reverse faults, and toward the east they occur at 6.0 sec TWT. The high cut-off angle between the deeper reflectors and the reverse faults decreases up-section and toward the east in the Triassic interval (UD), where the thrust faults assume a flat geometry.

The Montagna dei Fiori Structure

The subsurface structural setting of the Montagna dei Fiori structure appears more complex if compared with the adjacent Acquasanta area (Fig. 7A). In contrast, to the east of the outcropping Montagna dei Fiori carbonate mountain front, seismic data clearly image the monocline setting of the Messinian Laga Fm. (Fig. 7C). In fact, this monocline shows a general eastward dipping with an angle of ~40°, clearly constrained by two prominent reflectors (i.e., Messinian gypsum-arenites and volcanoclastic level; Figs. 4B and 7C) that can be undoubtedly traced from the surface up to 2.5–3.0 sec TWT (~5,000 m b.s.l.). The Messinian evaporites reflector is moderately offset by minor thrust faults that lose displacement up-section and show tip points within the near top-Laga succession. In the underlying Oligocene-Miocene sequence, the numerous interruptions of reflectors accompanied by diffractions suggest strong deformation that can be correlated to the east-dipping detachment level inferred from surface data collected along the forelimb of the Montagna dei Fiori anticline (Fig. 6D). Moreover, the numerous thrust faults that separate tectonic slices cored by carbonate units merge upward into the aforementioned detachment.

Consequently, the whole geometry of the thrusts array describes a sort of duplex structure beneath the Montagna dei Fiori area with a roof-thrust located within the Oligocene-Miocene preevaporitic succession (i.e., the Laga detachment) and a sole-thrust presumably buried at more than 15 km of depth (i.e., beneath the depth resolved by seismic). Three main horses compose the antiformal stack underneath the upper tectonic unit that crops out in the Montagna dei Fiori anticline. The structural elevation of top-carbonate succession produced by the duplex emplacement exceeds 10 km. The timing of the compressive deformation is constrained by two prominent unconformities that separate the upper Messinian, the lower Pliocene, and the middle-upper Pliocene siliciclastic deposits, respectively (Figs. 7A and 7C).

The displacement achieved by the Montagna dei Fiori thrust front is transferred farther east along another detachment level located near the base of the Pliocene-Quaternary syn-orogenic wedge and on top of carbonate succession (i.e., along Messinian evaporites).

The Bellante Structure

An approximately N-S trending buried anticline located 15 km to the east of the Montagna dei Fiori was penetrated by several exploration wells (Figs. 2 and 6A; Crescenti et al., 1980; Casnedi et al., 1979; Ori et al., 1991). The thrust-related anticline affects the Messinian-Pliocene siliciclastic sediments (Fig. 7D), and it is composed of three main thrust ramps that branch off toward the west from the Montagna dei Fiori east-dipping detachment (Fig. 7A). Seismic profiles tied with well-log data (Bellante 2) show lower Pliocene sediments underlain by a main unconformity (at 1.2 sec TWT) that truncates upward the Messinian Laga postevaporitic deposits. Immediately to the west, borehole data and seismic interpretation indicate that the Messinian Laga Fm. siliciclastic deposits terminate and are replaced by a thin interval of Messinian shales with evaporites interbedded (total thickness of ~100 m); moreover, this stratigraphic level is imaged on seismic up to 5.0 sec TWT b.s.l. This evidences suggest that the strong structural elevation produced by the Bellante structure mainly was achieved during lower Pliocene times. The final onset of the deformation is clearly constrained by the upper Pliocene sheet-like conglomerates that seal the thrust-related anticline in its forelimb (Fig. 7D), in agreement with the interpretations proposed by different authors (Ori et al., 1991; Dattilo et al., 1999).

The Thin-Skinned Thrust Front in the Adriatic Basin

The thrust front of the Apennine fold-and-thrust belt is located in the Adriatic Basin, and it is composed of three main thrust-related anticlines corresponding to the Coastal (Ori et al., 1991; Artoni and Casero, 1997; Dattilo et al., 1999), the Emilio, and the Camilla structures. These east-verging anticlines affect the Pliocene-Quaternary syn-orogenic siliciclastic sediments, and the thrust ramps branch off from a common decollement level located close to the top carbonate sequence (Messinian evaporites). The leading edge of this thin-skinned thrust system, which corresponds to the Camilla structure, is situated ~40 km from the inner carbonate thrust front (i.e., the Montagna dei Fiori thick-skinned thrust front), and the single anticlines are spaced ~15 km.

The Emilio structure is a minor detachment fold (*sensu* Jamison, 1987) located in the hangingwall block of the Camilla structure; the latter and the Coastal structure correspond to fault-propagation folds.

The detailed stratigraphy of the Pliocene-Pleistocene Adriatic foredeep-basin infill is constrained by cross-log correlation of several exploration wells that allow the timing of contractional deformation to be defined in detail. The Coastal structure affects the Pliocene sediments and is sealed by Quaternary deposits that offlap the crest of the anticline (Fig. 7A). In its back-limb, the lower Pliocene sediments thicken toward the east and apparently downlap (tilted on-lap pattern) toward the west against two prominent unconformities (Fig. 7E). In contrast, the overlying middle-upper Pliocene sequences abruptly thin toward the east and terminate with on-lap and tilted on-lapping patterns onto the uplifted fold crest. Moreover, the same convergence and thinning of middle-upper Pliocene reflectors are clearly imaged on seismic also in the forelimb of the anticline (Fig. 7A). The above-mentioned reflectors' configuration and their terminations with respect to the sequence boundaries allowed inference in the timing of growth of the Coastal structure. The early onset of contractional deformation occurred during lower Pliocene, and the fold was strongly uplifted during middle-upper Pliocene.

The thinning of the upper Pliocene sequences toward the crest of the Emilio fold is clearly imaged on seismic (Figs. 7A and 7F). Convergence, top-lap truncations, and gentle on-lap both onto the eastern and western limbs of the anticline (Fig. 7F) provide a sure indication of the timing of fold growth.

In the crestal region of the adjacent thrust-related Camilla anticline, the prominent unconformity at the base of Quaternary sediments appears moderately deformed and gently dips toward the east (Figs. 7A and 7F); this feature confines the estimation of the time at which the compressional deformation effectively ceased.

The Camilla thrust front forms the eastern margin of a wide middle-upper Pliocene open piggy-back basin (*sensu* Ori et al., 1991), which is confined between the leading-edge of the Apennine thin-skinned thrust system and the inner carbonate thick-skinned thrust front (Fig. 7A). In this tectono-stratigraphic setting, the inner and older thin-skinned thrust-related anticlines are progressively frozen and passively carried forward by the basal detachment. Moreover, thrust ramp location is strictly controlled by preexisting discontinuities (i.e., normal faults in the inner sector and reverse faults toward the east) that interrupt the continuity of the detachment level.

Toward the east, the distal sediments of the late Pleistocene prograding complex show a plane-parallel pattern that is reduced in thickness and locally deformed by high-angle reverse fault-related anticlines along the so-called Mid-Adriatic Ridge (Fig. 7A; Finetti, 1982; De Alteriis, 1995; Argnani and Frugoni, 1997).

SEQUENTIAL BALANCING AND FORWARD MODELING OF THE GEOLOGICAL CROSS SECTION

A regional balanced geological cross section based on the previously described field and subsurface dataset has been reconstructed. It illustrates the structural and stratigraphic setting of the inner Apennine thrust fronts, of the outer thin-skinned thrust system, of the siliciclastic foredeep basins, and of the Adriatic foreland. The cross section constitutes an example of the entire chain-foredeep-foreland system in the outer sector of the Central Apennines of Italy.

The transect was obtained by merging the surface geological cross sections with depth-converted seismic lines; interval velocity adopted for seismic time-depth conversion derives from velocity profile at wells drilled along the section and from published data (Fig. 4; Bally et al., 1986; Barchi et al., 1998). The bend in the line of section (Fig. 2) was drawn in order to remain roughly perpendicular to the structural trends, and plane strain deformation was assumed.

The geological cross section has been restored using the sequential-balancing process, according to principles and methods of sequential restoration proposed by different authors (Cooper and Trainer, 1986; De Celles et al., 1991; Burbank and Vergés, 1994; Artoni and Casero, 1997); in such an approach, the geometries of the distinct compressional structures and their relationships with the configuration of the basin infill have been taken into account. Restoration and balancing of the cross section allows the minimum shortening and the deformation history across the fold-and-thrust belt to be quantified.

Finally, a forward modeling technique has been applied in order to simulate the main geological-structural and stratigraphic evolutionary stages that accompanied the Messinian-Quaternary evolution of the Apennine fold-and-thrust belt. This method has been useful to validate the balanced cross section and to analyze both the sequence of propagation of the deformation and the relationship between contractional tectonics and the contemporaneous sedimentation.

The complex tectono-stratigraphic setting of the analyzed area appears strictly dependent on the interaction of thin- and thick-skinned tectonics, from the Messinian postevaporitic event until lower Pleistocene.

The restored template (step A in Fig. 8) shows the physiography of the foredeep-foreland domain during the Messinian preevaporitic event. The siliciclastic basin infill (Laga Fm.) exceeded 2,000 m in thickness in the depocenter of the foreland basin, and it was replaced by hemipelagic sedimentation at ~70 km from the western edge. The clastic wedge progressively thinned toward the east along a gently west-dipping foreland ramp, with an angle of ~3°.

The Tortonian-Messinian succession was affected by west-dipping normal faults; the outermost of these structures strongly influenced the Miocene presiliciclastic sedimentation, and at present it can be found in the back-limb of the Montagna dei Fiori anticline.

In the foreland, thickness variation and deformation of the Upper Cretaceous-Miocene carbonate succession suggest an early stage of contractional deformation. The shortening produced during this phase was obtained by flattening of the Marne a Fucoidi horizon (Lower Cretaceous) and its amount is ~1.5km (Fig. 8A).

In the inner sector, the wedge-shaped siliciclastic basin infill was translated toward the east on top of a decollement (i.e., the Laga detachment) along which the displacement of the inner carbonate thrust fronts (e.g., the Sibillini Mts. thrust; Fig. 2) was transferred. The Laga detachment was subsequently antiformally folded during the Messinian postevaporitic stage when the contractional deformation also affected the carbonate succession and promoted the development of the Acquasanta thrust-related anticline (Fig. 8B). The thrust ramp location of the Acquasanta structure was controlled by the preexisting west-dipping normal faults that were found in the footwall-block of the main thrust fault. The latter juxtaposed the Triassic-Miocene succession onto the Miocene carbonate sequence and propagated toward the foreland along a wide detachment zone confined in the Oligocene-Miocene marly preorogenic succession; the minimum shortening calculated for this structure is ~13 km. During this stage, the leading edge of the thrust system corresponded to the Bellante thin-skinned thrust front, which was located ~40 km from the inner carbonate cored anticline. A minor high-angle splay thrust breached the Laga detachment above; this breaching thrust is exposed in the eastern limb of the Acquasanta anticline (Figs. 6A, 6B, 8B, and 8E).

The growth of the Acquasanta anticline induced the antiformally folding of the preexisting detachment and related shear zones, which was most probably the frontal flat of an earlier inner carbonate thrust front (i.e., the Sibillini Mts. thrust front; Figs. 2 and 6).

The depocenter of the Messinian postevaporitic foredeep basin was interposed between the inner Acquasanta anticline and the outer Bellante structure; this area was subsequently uplifted by the growth of the Montagna dei Fiori structure.

During the lower Pliocene (*Gb. margaritae* Biozone) the physiography of the foredeep depocenter was strongly conditioned by syn-sedimentary west-dipping normal faults located in its outer edge, whereas toward the west the sedimentation was reduced in the axial region of the Bellante structural high (Fig. 8C).

In the uppermost lower Pliocene (*Gb. puncticulata* Biozone; Fig. 8D), the growth of the thick-skinned Montagna dei Fiori structure triggered the folding both of the overlaying siliciclastic foredeep-wedge and of the preexisting detachment (i.e., the frontal flat of the Acquasanta structure). The displacement realized by the carbonate horses that compose the whole Montagna dei Fiori duplex was partially transferred toward the foreland, where the basal detachment was reactivated. This thin-skinned deformation was achieved by the amplification of the Bellante structure and by the early stage of development of the outer Coastal Structure. In contrast, in the inner sector, the deeper thrusts climbed upward and locally cut across the overlying detachment (in the style of the breaching thrusts in Butler, 1987), generating at shallow levels the superposition of Messinian onto lower Pliocene siliciclastic sediments.

The final step of Figure 8E depicts the present-day structural setting of the Central Apennines thrust front and the pattern of the syn-tectonic sedimentation in the adjacent foredeep basin. During middle-upper Pliocene, the uplift induced by the thick-skinned shortening caused the strong exhumation of the entire Messinian-lower Pliocene siliciclastic-wedge. In fact, in the inner sector the extrusion of basement blocks generated a wide-scale uplift of the whole sedimentary cover and of the earlier thrust-related anticlines (e.g., Acquasanta anticline). Moreover, the structural elevation of the top of carbonate succession in the Montagna dei Fiori

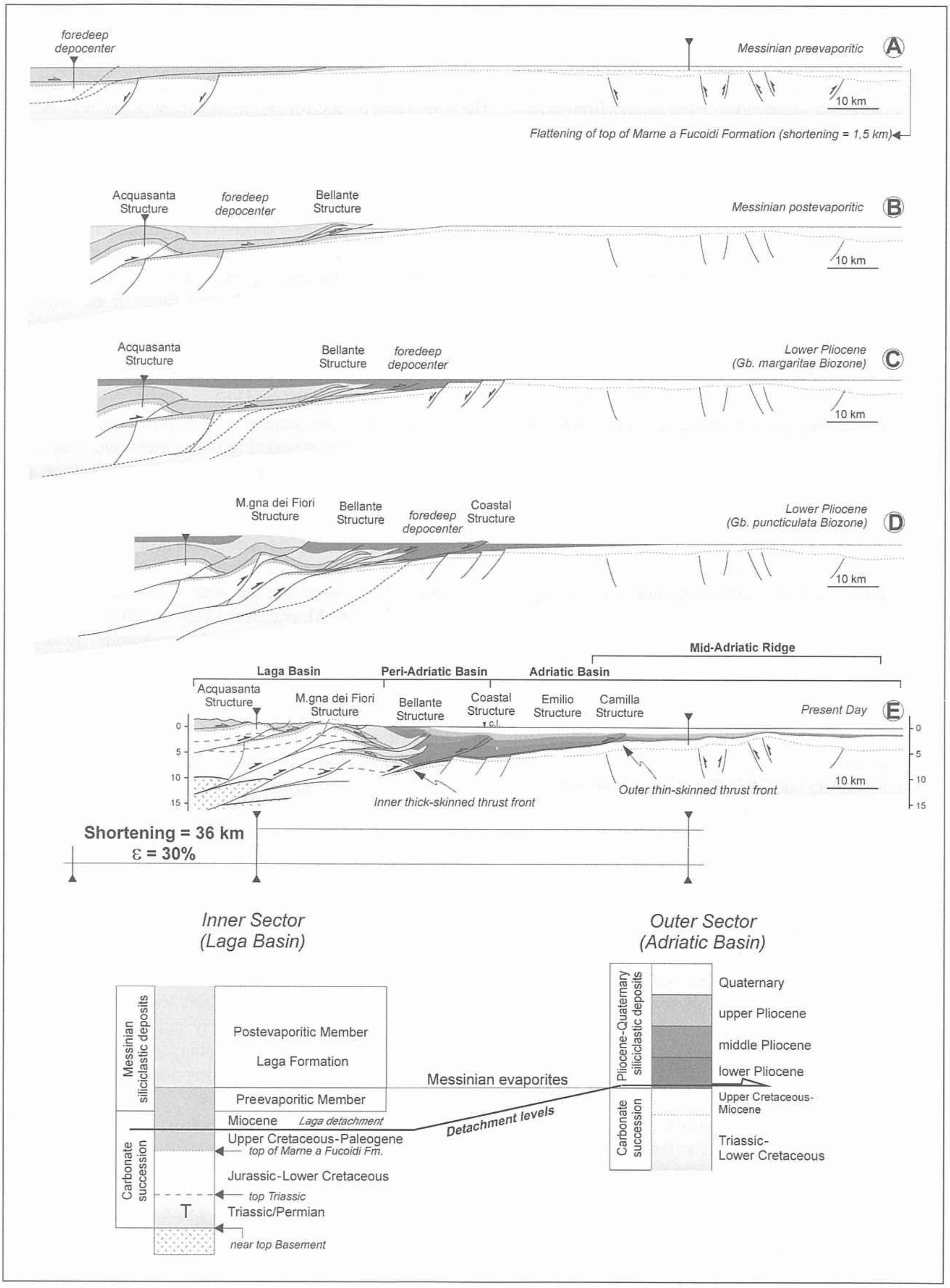

Figure 8. Forward modeling that illustrates the Neogene-Quaternary evolution of the outer Central Apennines fold-and-thrust belt and the Adriatic foreland. Step E is the present-day configuration that was obtained by depth-conversion of the composite reflection profile of Figure 7A. The adopted interval velocities are reported in Figure 4. See Figure 2 for the seismic profile location.

anticline mainly occurred in this interval. This final contractional event produced a shortening of ~14 km, and a minor portion of the total displacement was realized along the thin-skinned thrust front, which was composed by the Coastal, the Emilio, and the Camilla structures. In the late Pliocene-early Pleistocene, the compressional deformation strongly decreased, and the outer thin-skinned thrust front was located 40 km from the inner Montagna dei Fiori thick-skinned thrust front.

During the middle-upper Pliocene, shallow-water, coarse-grained deltas supplied by the erosion of the inner sector of the growing fold-and-thrust belt replaced the deep-water turbidite system in the Periadriatic Basin. The progressive infill of the foredeep basin promoted the eastward migration of a deltaic system that covered the whole outer Apennines thrust-system. Only the distal sediments of this Quaternary sequence appear affected by compressional deformation in the outermost sector of the Central Adriatic (Mid-Adriatic Ridge). The reduced thickness of the late Quaternary sediments in this sector suggests a recent activity of the structures that affect the Adriatic foreland.

The total shortening calculated in the Messinian postevaporitic/base of Quaternary interval (i.e., from 5.50 to 1.43 Ma; first occurrence of *Hyalinea Baltica*) is ~36 km (30%) and the average shortening rate is ~0.8 cm a^{-1} (Fig. 8). Instead, the shortening rate reduces to 0.6 cm a^{-1} in the *Gb. puncticulata–Gb. Inflata* Biozones interval (i.e., from 4.52 to 2.09 Ma,–calibrated to the Berggren et al., 1995 timescale).

DISCUSSION AND CONCLUSIONS

The complex tectono-stratigraphic evolution of the Neogene-Quaternary Central Apennines fold-and-thrust belt results from the coexistence and the interaction of thin- and thick-skinned contractional deformation. In fact, the structural style of the analyzed area is characterized by inner thick-skinned thrust fronts that affect basement and the whole sedimentary cover (i.e., Triassic-Miocene carbonates and the overlying Messinian-Pliocene siliciclastic sediments) and by outer thin-skinned thrust fronts that deform only the Neogene-Quaternary siliciclastic foredeep sequences. The inner thick-skinned thrust ramps are connected to the outer thin-skinned thrust fronts by wide thrust-flats, ranging from 30 to 50 km in length. These detachments are generally located at the base of siliciclastic foredeep wedges that correspond in the inner sector to the Oligocene-Miocene marly and carbonate preorogenic succession (i.e., "Laga detachment" in Koopman, 1983) and to the Messinian evaporites in the external domain, respectively (Fig. 9). The thick sedimentary wedges are passively transported toward the east on top of these flats, and the high efficiency of the decollements, composed by low permeability clayey horizons interbedded with more competent calcareous or evaporitic units, is probably facilitated by the poorly lithified sequences that are affected by compressional deformation (Ghisetti and Vezzani, 2000). Moreover, the overpressure pore fluids induce the development of broad and complex shear zones (cleavage, calcite-filled shear veins, S-C tectonites, Riedle shear-planes) that precedes the growth and the amplification of folds. The wide distribution of these peculiar structures, which are found throughout different sectors of the Apennines (Koopman, 1983; Cooper and Burby, 1986; De Feyter and Menichetti, 1988; Calamita et al., 1991; Invernizzi and Ridolfi, 1992; Marsili and Tozzi, 1995; Barchi et al., 1998; Ghisetti and Vezzani, 2000; De Feyter and Delle Rose, 2002; Mazzoli et al., 2002) and are often traced more than 20 km along strike and 30 km along dip (e.g., see Fig. 6A), indicates that this detachment tectonics can be regarded as a process of regional, rather than local, significance.

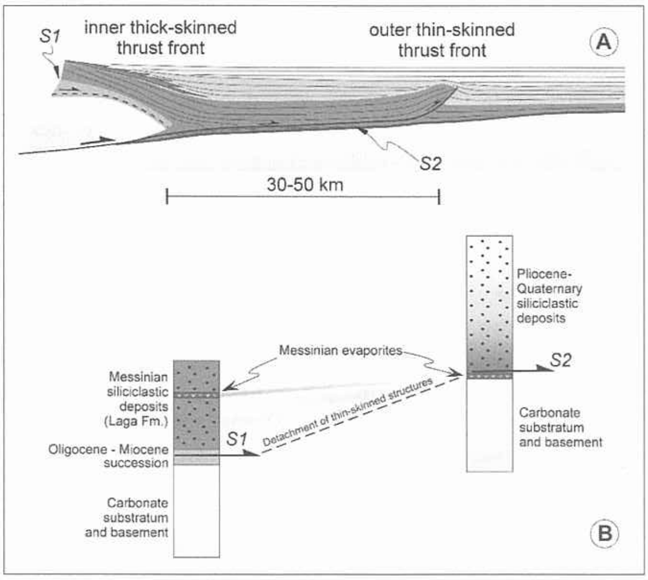

Figure 9. Reconstructed structural style of the outer Central Apennines fold-and-thrust belt (A). The outer thin-skinned thrust front (i.e., that affects only syn-orogenic siliciclastic sequences) is connected to the inner thick-skinned thrust front by a wide flat, ranging from 30 to 50 km in length. (B) In the Periadriatic and Adriatic domains (outer sector), such detachment is located at the base of the Pliocene siliciclastic succession or within Messinian evaporites (S2). In the inner sector it occurs in the Oligocene-Miocene preorogenic calcareous-marly succession (S1), at the base of the Messinian foredeep-basin infill (Laga Fm.).

The inner thick-skinned carbonate-cored thrust related anticlines are generally delimited at depth by low-angle thrust ramps (i.e., 10–30°) that cut off the Jurassic-Cretaceous carbonate succession and flatten into the deeper evaporitic Triassic stratigraphic levels (Fig. 9). Moreover, beneath the Acquasanta-Montagna dei Fiori area, the thrust system also affects the basement (Figs. 8E, 7A, and 7B). Seismic interpretation shows that the carbonate-evaporitic sedimentary cover affected by the compressional deformation is not constant in thickness as hypothesized by several authors (Bally et al., 1986; Hill and Hayward, 1988; Calamita et al., 1991). In fact, it locally exceeds 6,000 m, and the main thickness variations are documented in the Triassic sequence, which provides evidence for an early Mesozoic extensional event.

Generally, the Central and the Northern Apennines are envisaged as an imbricate thrust system (Bally et al., 1986; Mostardini and Merlini, 1986; Hill and Hayward, 1988; Calamita et al., 1991; Patacca et al., 1991; Cavinato et al., 1994; Ghisetti and Vezzani, 1997). However, the results of this work confirm the hypotheses formulated by Bally et al. (1986) that supposed a possible duplex structure beneath the Montagna dei Fiori anticline. In detail, seismic interpretation and geological field data suggest that the several juxtaposed horses of the duplex are essentially composed by carbonate and evaporites rocks because the roof thrust is located near the base of the siliciclastic sedimentary cover (i.e., Laga detachment; Koopman, 1983; Invernizzi and Ridolfi, 1992). A large amount of the total displacement achieved by the slices that compose the duplex is transferred toward the east along the thin-skinned thrust front located in the Adriatic Basin (Figs. 7A and 8E).

The uplift generated by the emplacement of the thick-skinned thrust front causes the folding of the preexisting detachment and the relative thin-skinned thrust front (i.e., the Bellante structure). The latter represents the leading edge of the Messinian-early lower Pliocene thin-skinned thrust system that achieved the shortening of the more internal carbonate thrust fronts (i.e., Acquasanta and Sibillini Mts. structures). Large volumes of the hangingwall block on top of the aforementioned detachment were carried out by erosion during both the growth of the thin-skinned thrust front (Figs. 8A-8D) and of the deeper thick-skinned units (Figs. 8D and 8E); however, a portion of the thrust sheet is preserved in the monocline located to the east of the Montagna dei Fiori anticline (Figs. 6D, 7A, and 7C). Moreover, the basal shear zones related to the Messinian-lower Pliocene detachment are now well-exposed in the Acquasanta and Montagna dei Fiori tectonic windows, whereas they are largely buried beneath the Messinian Laga deposits in the Apennines foothills (Fig. 6).

In the Messinian postevaporitic/early lower Pliocene, the reconstructed distance between the leading edge of the Apennine fold-and-thrust belt (i.e., the Bellante thin-skinned thrust front) and the relative inner carbonate trailing edge (i.e., the Acquasanta structure) was ~40 km (Fig. 8C); this spacing is equal to the present-day configuration (Fig. 8E). These evidences suggest the self-similar evolution of the Apennine fold-and-thrust belt during Neogene.

The history inferred from structural field data and by sequential balancing restoration makes it possible to unravel the sequence of propagation of contractional deformation in the outer sector of the Central Apennines. Thin and thick-skinned thrusts acted contemporaneously, and the compressive deformation migrated ENE. The orogenic contraction was transferred from the inner and deeper levels toward shallower detachment levels in the foreland; along the latter, the shortening was partitioned in a multiple array of thrust ramps (Fig. 10A). Thick-skinned thrusts generally anastomosed at shallow levels (i.e., beneath the Neogene foredeep deposits), and locally they reactivated the upper detachments generating a duplex geometry (Figs. 7 and 8). Consequently, the earlier thin-skinned thrusts were folded to assume a steeper dip. These evidences suggest that the deformation propagated in a piggy-back sequence (Fig. 10B). However, in some cases, the deep thrust ramps breached the roof thrust and offset the overlying syntectonic sediments. These thrusts appear as out-of-sequence at

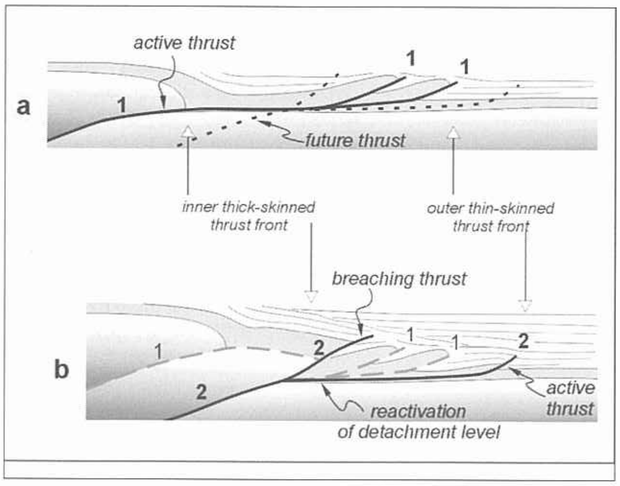

Figure 10. Sequence of thrust-system propagation in the outer sector of the Central Apennines. The inner thick-skinned and the outer thin-skinned thrust-systems acted contemporaneously (A). At deeper structural levels, thrust-system deformation propagates toward the foreland ("piggy-back sequence"), whereas in the shallow sedimentary cover, the eastward migration of contractional deformation is accompanied by the activity of the inner thrust front that locally breaches the former detachment level (B).

shallow level (Casnedi and Serafini, 1994; Ghisetti et al., 1994; Ghisetti and Vezzani, 1997) because they show high cutoff angles between the thrust faults and the previously deformed bedding and because they have an internal position with respect to the outer thrust front (Figs. 8 and 10B).

Cross-section restoration and seismic profiles in the Adriatic foreland clearly show that the present location of the thin-skinned thrust-related anticlines is strongly influenced by the distribution of discontinuities that disrupt the main detachment levels (i.e., high-angle normal or reverse faults; Figs. 7 and 8). This coincidence suggests that the prethrusting faults generate a significant mechanical and/or rheological anisotropy that was effective in controlling the localization and spacing of propagating thrust ramps (Schedl and Wiltschko, 1987; Brown, 1988). Moreover, the control exerted by preexisting discontinuities can be recognized also at deeper levels. The changes in stratigraphic thickness of Triassic interval and the convergence of relative reflectors toward the west and toward the underlying basement blocks suggest a possible positive inversion of Mesozoic west-dipping normal faults beneath the Montagna dei Fiori area, in agreement with other reconstructions (Tozer et al., 2006).

Previous studies documented the involvement of basement both in the inner (Barchi et al., 1998; Mazzoli et al., 2000; Menardi Noguera and Rea, 2000) and outer sector (Coward et al., 1999) of the Northern and Southern Apennine chain. The results of this work allow extension of the thick-skinned structural style into the outer sector of the Central Apennines. Consequently, thick-skinned tectonics can be regarded as a process of deformation that would be applied in the whole Apennine fold-and-thrust belt. The strong structural elevation of the preorogenic succession compared to the low values of shortening are the main features that indicate the basement involvement in the Apennine chain. These elements are particularly useful for defining thick-skinned tectonics in young chains that are generally largely buried beneath thick sedimentary covers.

Moreover, thin-skinned models imply that structural elevation of a regional level and shortening amounts are proportional and that the elevation is confined in the region where thrust-sheets are juxtaposed (Butler, 1982; Boyer and Elliot, 1982; Butler, 1987; Coward, 1996). The Apennines fold-and-thrust belt shows an eastward decrease of structural elevation of the regional level along two main steps (Figs. 2 and 5). In terms of thin-skinned tectonics, this structural setting implies that different tectonic units are piled beneath the most elevated sector of the thrust belt. This geometric solution was adopted by Bally et al. (1986), who considered almost three thrust sheets (composed by the carbonate sedimentary cover and the overlying siliciclastic sediments) in order to fill the room interposed between regional level in outcrop and in the Adriatic monocline. In contrast, our data suggest that structural elevation is not strictly dependent on values of shortening or even perhaps that there is no straightforward relationship. Comparison of shortening values/structural elevation in the Acquasanta and Montagna dei Fiori thrust-related anticlines indicates that the structural elevation of the entire inner sector of the Apennine chain is mainly due to the basement involvement (Figs. 7 and 8).

The combined thin- and thick-skinned structural style recognized in this sector of the Apennines obviously implies low values of orogenic contraction with respect to models that predict simple thin-skinned tectonics (e.g., see discussion in Coward, 1996). This reduced mean rate of shortening ($\sim$0.8 cm a^{-1}) appears to be clearly evidenced by the moderately deformed Pliocene-Pleistocene sediments that are well-preserved in the Adriatic basin (Figs. 7 and 8). Moreover, the calculated shortening rates are more in accord with values inferred from other analogous fold-and-thrust belts (Cipollari and Cosentino, 1996; Artoni and Casero, 1997; Tozer et al., 2002a and references therein).

Geodynamic Implications

The modes and styles of contractional deformation inferred from this study combined with the structural setting of the entire Apennine chain provide new constraints for the geodynamic evolution of the Apennine orogen.

Thin-skinned tectonics models that predict large amounts of orogenic contraction ($\sim$50%: Bally et al., 1986; Hill and Hayward, 1988) at high shortening rates (15–50 mm a^{-1}: Patacca et al., 1991; Cipollari et al., 1995) imply that large volumes of the westward-subducted continental Adriatic lithosphere must be found beneath the Apennines of Italy (Patacca and Scandone, 1989; Doglioni, 1991). Beneath the Apennine chain, a partial overlap of the shallow Tuscan Moho (hinterland) and the deeper west-verging Adriatic Moho was reported by different geophysical studies (Gualtieri and Cassinis, 1998; Barchi et al., 1998; Scarascia et al., 1998; Mele and Sandvol, 2003). The westward deepening of the Adriatic Moho in the Northern-Central Apennines is also consistent with the subcrustal seismicity down to $\sim$90 km in depth (Selvaggi and Amato, 1992; Olivieri and Ekstrom, 1999). Moreover, recent tomographic images show an almost continuous cold body that dips WSW at $\sim$70–80° reaching depths ranging from 250 to 600 km (Spakman, 1991; Lucente et al., 1999; Faccenna et al., 2001). The presence of this slab was also predicted by Royden and Karner (1984) in order to explain the high subsidence rates recorded within the Apennine foredeep basins.

The thick-skinned structural style of the Central and Northern Apennines inferred from different studies (Coward et al., 1999; Albouy et al., 2002; Tozer et al., 2002a; Butler et al., 2004; Tavarnelli et al., 2004; Boccaletti et al., 2005; Scisciani and Montefalcone, 2005; Tozer et al., 2006) implies that the shortening experienced by the Adriatic continental margin was limited. Instead, large volumes of strongly duplicated oceanic-derived units (i.e., Allochthonous Units: Ligurides and Sicilides) were overthrust onto the Adriatic foreland (Figs. 1 and 2). These Allochthonous Units are exposed both in the inner and outer sectors of the Apennines, and they are also hypothesized to have been present on top of the Central Apennines chain. In fact, vetrinite reflectance and apatite fission tracks analysis indicate that the

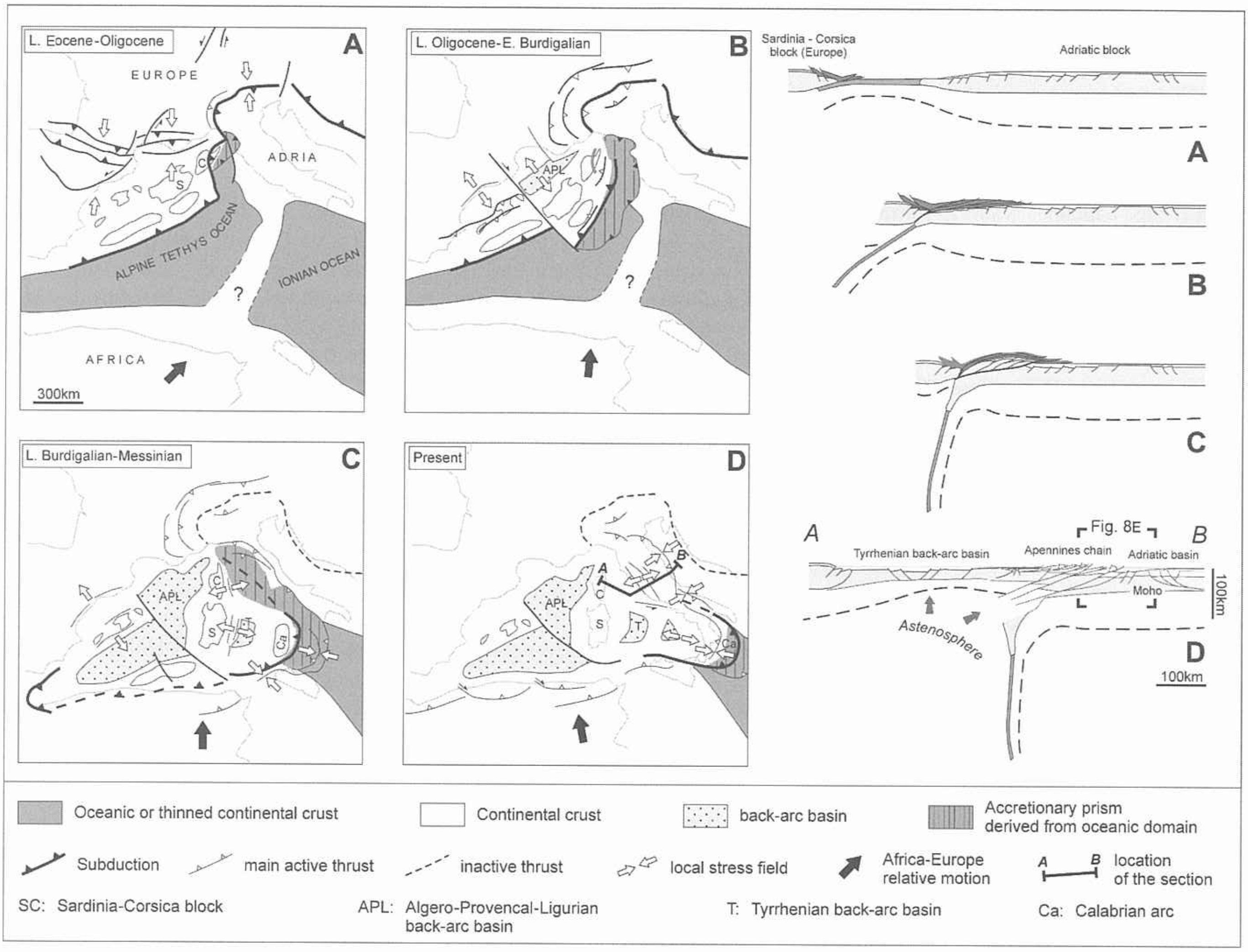

Figure 11. Suggested geodynamic evolution of the Apennine orogen from Eocene to Present (A-D), compiled from different sources including: Rehault et al., 1987; Carmignani et al., 1995; Séranne, 1999; Malinverno and Ryan, 1986; Guéguen et al., 1998; Argnani, 2002. The accretionary prism off-scraped from the down-going oceanic lithosphere (Alpine Tethys) was juxtaposed onto the western Adriatic thinned continental margin (A-B). Starting from middle Oligocene, contractional deformation affected the Adriatic domain after collision with the Sardinia-Corsica block. The contractional deformation was accommodated by thin-skinned tectonics along multiple detachments within the sedimentary cover, whereas the contemporaneous thick-skinned tectonics produced the exhumation of the overlying previously deformed units (C-D).

Adriatic-derived units were generally deeply buried and subsequently exhumed during the Apennine chain development (Bartolini et al., 1996; Zattin, 1999; Calamita et al., 2004 and references therein), although limited sectors of the chain do not record the early overburden (Corrado, 1995). These evidences suggest that a large portion of the subducted slab imaged beneath the Central Apennines is derived from the early downgoing of the Alpine Tethys oceanic lithosphere. In contrast, only a few hundred kilometers of Adriatic continental crust have been delaminated beneath the Apennine orogen (Fig. 11).

In conclusion, we propose that the Apennine fold-and-thrust belt results from the interaction between thin- and thick-skinned tectonics that affected the Mesozoic stretched margin of the continental Adria microplate. The thin-skinned deformation prevailed during the subduction of the oceanic Tethyan crust (Fig. 11A) when the Ligurian accretionary prism was juxtaposed E onto the Adria domain (Fig. 11B). However, such thin-skinned tectonics also continued during the postcollisional stage (Fig. 11C) when the eastward translation of the sedimentary cover along multiple detachments was coupled with the thick-skinned tectonics (Fig. 11D).

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