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Recent and active tectonics of the external zone of the Northern Apennines (Italy)

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Abstract We present a comprehensive study of the recent and active tectonics of the external part of the Northern Apennines (Italy) by using morphotectonic, geological–structural, and stratigraphic analysis, compared with the current seismicity of the region. This analysis suggests that the external part of the Northern Apennines is characterised by presence of three major systems of Quaternary compressive structures corresponding to (1) the Apenninic watershed, (2) the Apennines–Po Plain margin (pede-Apenninic thrust front), and (3) the Emilia, Ferrara, and Adriatic Fold systems buried below the Po Plain. Geological data and interpreted seismic sections indicate a roughly N–S Quaternary deformation direction, with rates <2.5 mm/year. The shortening decreased since the Pliocene, when our data indicate compression in a NNW–SSE direction and rates up to 7 mm/year. The trend and kinematics of the structures affecting the Apennines–Po Plain margin and the Po Plain subsoil fit well the pattern of the current seismicity of the area, as well as recent GPS and geodetic levelling data, pointing to a current activity of these thrust systems controlled by an overall compressive stress field. Close to the Apenninic watershed, earthquake focal mechanisms indicate that shallow extension is associated to deep compression. The extensional events may be related to a secondary extensional stress field developing on the hangingwall of the thrust system affecting the Apenninic watershed; alternatively, this thrust system may have been recently deactivated and overprinted by active normal faulting. Deeper compressive events are related to the activity of both a major basement thrust that connects at surface with the pede-Apenninic thrust front and a major Moho structure.

Keywords Active tectonics · Northern Apennines (Italy) · Compressive structures

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Introduction

The convergence between the European and African plates, currently occurring at rates of ∼6–8 mm/year in a ∼NW direction (e.g., DeMets et al. 1994), is accommodated within a complex, broad plate boundary zone in which minor plates and smaller crustal blocks (i.e., Adria) play an important role in controlling the distribution and kinematics of deformation (e.g., D'Agostino et al. 2008; Devoti et al. 2008). In the Northern Apennines (Fig. 1), plate interaction results in a diffuse seismicity (e.g., Chiarabba et al. 2005; Fig. 1b) and a complex deformation pattern resulting from an active stress field characterised by predominant extension in the Tyrrhenian (internal) side and compression in the Adriatic (external) sector of the chain (e.g., Mariucci et al. 1999). Consequently, normal faulting is the dominant active deformation style in the Tyrrhenian area, whereas the active tectonics of the Adriatic sector is

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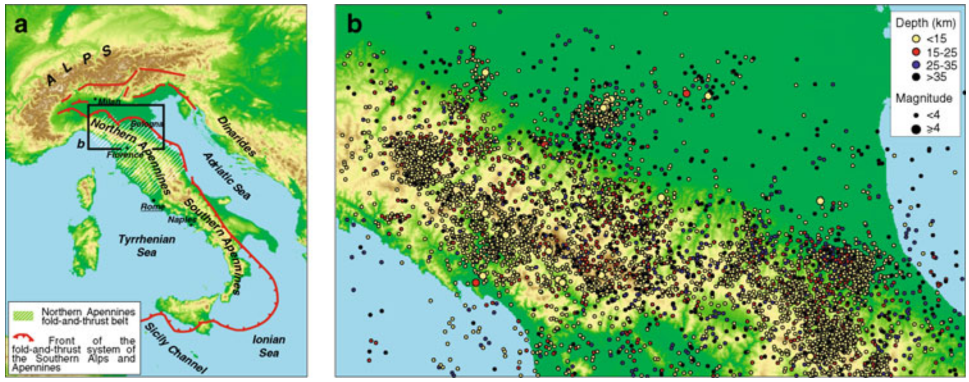


Fig. 1 **a** Schematic tectonic framework of Italy. **b** Seismicity of the Northern Apennines (after Boccaletti et al. 2004)

accommodated by folding and thrusting (Benedetti et al. 2000, 2003; Burrato et al. 2003; Vannoli et al. 2004; Boccaletti et al. 2004; Basili and Barba 2007; DISS Working Group 2007; Picotti and Pazzaglia 2008; Wilson et al. 2009). Active shortening is well constrained by the analysis of earthquake fault plane solutions (e.g., Gasparini et al. 1985; Boccaletti et al. 1985; Anderson and Jackson 1987; Frepoli and Amato 1997; Selvaggi et al. 2001; Pondrelli et al. 2002, 2004; Lavecchia et al. 2004; Chiarabba et al. 2005; Piccinini et al. 2006; Boncio and Bracone 2009), stress analysis (e.g., Mariucci et al. 1999; Mariucci and Muller 2003; Montone et al. 2004), and geodetic measurements (e.g., Battaglia et al. 2004; Serpelloni et al. 2005; D'Anastasio et al. 2006). However, the knowledge of the main recent and active structures remains limited to scattered areas (e.g., Benedetti et al. 2003; Burrato et al. 2003; Vannoli et al. 2004; Piccinini et al. 2006; Picotti and Pazzaglia 2008; Picotti et al. 2009; Wilson et al. 2009). In this paper, we aim to fill this gap by presenting a comprehensive study of the active tectonics of the external part of the Northern Apennines. In particular, in "Recent and active structures of the external Northern Apennines" section, we illustrate and characterise the main recent and active structures, mapped in the frame of a Regione Emilia-Romagna (RER)–Consiglio Nazionale delle Ricerche (CNR) project (Boccaletti et al. 2004); then, in "Uplift and slip rates" section, we try to quantify the uplift and slip rates along the main deformation systems. Finally, in "Summary of the main recent and active structures of the external Northern Apennines and comparison with seismicity, geodetical data and stress field analysis" section, we summarize the main recent and active structures and compare them with the seismicity, active stress field, paleostress analysis, and geodetic data (GPS and geodetic levelling) available for the investigated area.

Geological setting of the Northern Apennines

The Northern Apennines are a fold-and-thrust belt composed of a pile of NE-verging tectonic units that developed as a consequence of Cenozoic collision between the European plate (Corso–Sardinian block) and the Adria plate (e.g., Boccaletti and Guazzone 1974; Principi and Treves 1984). The tectonic units belong to two different domains (Figs. 2, 5): the Ligurian (and Subligurian) units and the Tuscan and Umbria-Romagna units. The Ligurian units represent the uppermost tectonic units in the Apennine nappe pile and correspond to allochthonous terrains originally deposited in an oceanic realm (i.e., the Ligurian–Piedmontese sector of the Alpine Tethyan ocean) composed of ophiolites and their Jurassic to Eocene sedimentary cover. These units tectonically overlie the Tuscan and Umbria-Romagna units, originally deposited on the passive margin of the Adria Plate since the middle Triassic, and consisting of an upper thick succession of siliciclastic foredeep sediments of Oligocene–Miocene age and a lower succession of carbonate rocks of Mesozoic–Cenozoic age. Both successions rest on a thick Triassic evaporites.

The structuring of the Ligurian and Subligurian tectonic units was related to the transpressive subduction of the oceanic crust of the Ligurian–Piedmontese under the western Adria continental margin (Boccaletti and Guazzone 1970; Boccaletti et al. 1971). Remnants of these oceanic units are scattered in Corsica and in the Apennines. After oceanic closure, a continental stage started when the western Adria margin collided with the Corso–Sardinian block, giving rise to the development of the Apennines s.s. (Late Oligocene-Present). These main orogenic phases were marked by the development of foredeep basins progressively migrating eastward (i.e., towards the foreland), following the propagation of deformation in the same direction (e.g., Boccaletti et al. 1990). The deformation affected the external part of chain since the Pliocene (e.g., Castellarin et al. 1985).

Contemporaneous crustal shortening (in the external part) and extension (in the internal part) have been long recognized in the Northern Apennines (Boccaletti et al. 1971) and used to argue for models of rollback of the subducting slab (e.g., Malinverno and Ryan 1986). However, important thrust reactivations in the more internal sector of the

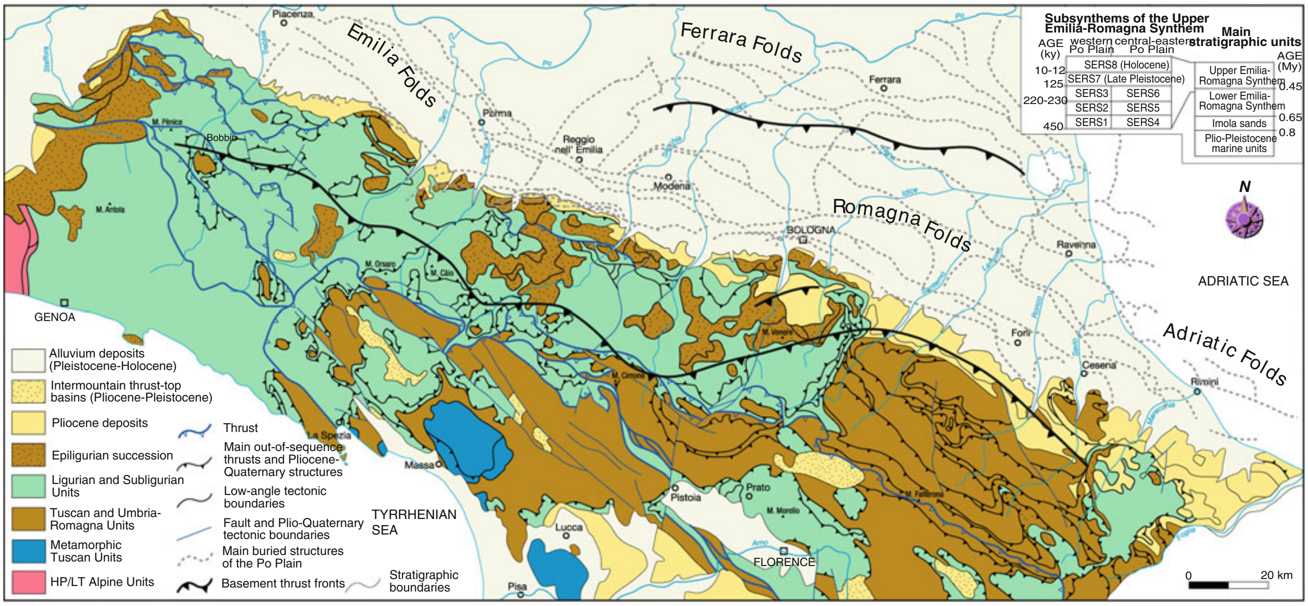


Fig. 2 Tectonic scheme of the Northern Apennines (after Pieri and Groppi 1981; Cerrina Feroni et al. 2002). *Inset on right upper corner* shows a stratigraphic scheme of the Neogene-Quaternary units of the Po Plain and the Apennnines–Po Plain margin

Northern Apennines (e.g., Boccaletti and Sani 1998) suggest a more complex structural setting, which is also characterised by strike-slip deformation parallel to the axis of the chain. At the end of the Early Pleistocene, the Northern Apennines are shaped and the geography of the chain is similar to the present. Since the Middle Pleistocene, the sedimentation in the external sector is due to the Apenninic rivers and to the Po river, with alluvial deposits ascribed to the Emilia-Romagna Supersynthem (RER-EniAgip 1998; Boccaletti et al. 2004). The Quaternary stratigraphic succession of the external sector of the Northern Apennines and the Po Plain is summarized in the inset of Fig. 2.

Recent and active structures of the external Northern Apennines

The main recent and active structures of the external Northern Apennines, mapped in the frame of a RER–CNR project (Boccaletti et al. 2004), are subdivided in three distinct sectors of the fold-and-thrust belt: the Apennine chain, the Apennines–Po Plain margin, and the Po Plain (Figs. 3, 4, 5, 6). In the following, these different sectors are described starting from the more internal (Apenninic chain) to the more external (Po Plain).

The Apenninic chain

The Apenninic chain is characterised by the presence of a major system of thrust faults, developing in correspondence and parallel to the main Apenninic divide (Figs. 3, 4, 5). Recent (post-Pliocene) movement on this fault system determined the development of main "tectonic windows" and out-of-sequence structures that locally invert the superposition relations of the Ligurian units onto the Tuscan units (Fig. 5a, cross sections B–B′ and D–D′). One of these out-of-sequence thrusts emerges in the area of Castiglione dei Pepoli giving rise to uplift of a major anticline, whose recent deformation is suggested by the strong morphotectonic signature with presence of prominent faceted spurs, wind gaps, hanging valleys, river captures testifying an important control on the local drainage pattern (Fig. 4e; Finetti et al. 2005). This thrust system extends to the north-west parallel to the water divide up to the Mt. Orsaro area, where the surface expression of the active deformation is a fault scarp with normal displacement affecting Late Quaternary glacial deposits, which has been interpreted as a superficial collapse related to the uplift induced by the movement of the thrust system (Boccaletti et al. 2004).

In other areas of the Apenninic chain, recent activity of compressive structures is evidenced by deformation or differential uplift of Quaternary deposits or river terraces. For instance, in the Santa Sofia area (Bidente Valley, Romagna Apennines), movement of a back thrust system is responsible for displacement of late Pleistocene–Holocene deposits (Marabini et al. 1986), with associated anomalous uplift of river terraces (Figs. 6a, 9, Bidente Valley). This back thrust system has been suggested to extend for about 30 km in a northwestward direction (Bonini 2007). NE-trending transversal structures in the Santa Sofia are also currently active (Fig. 3); these faults, characterised by

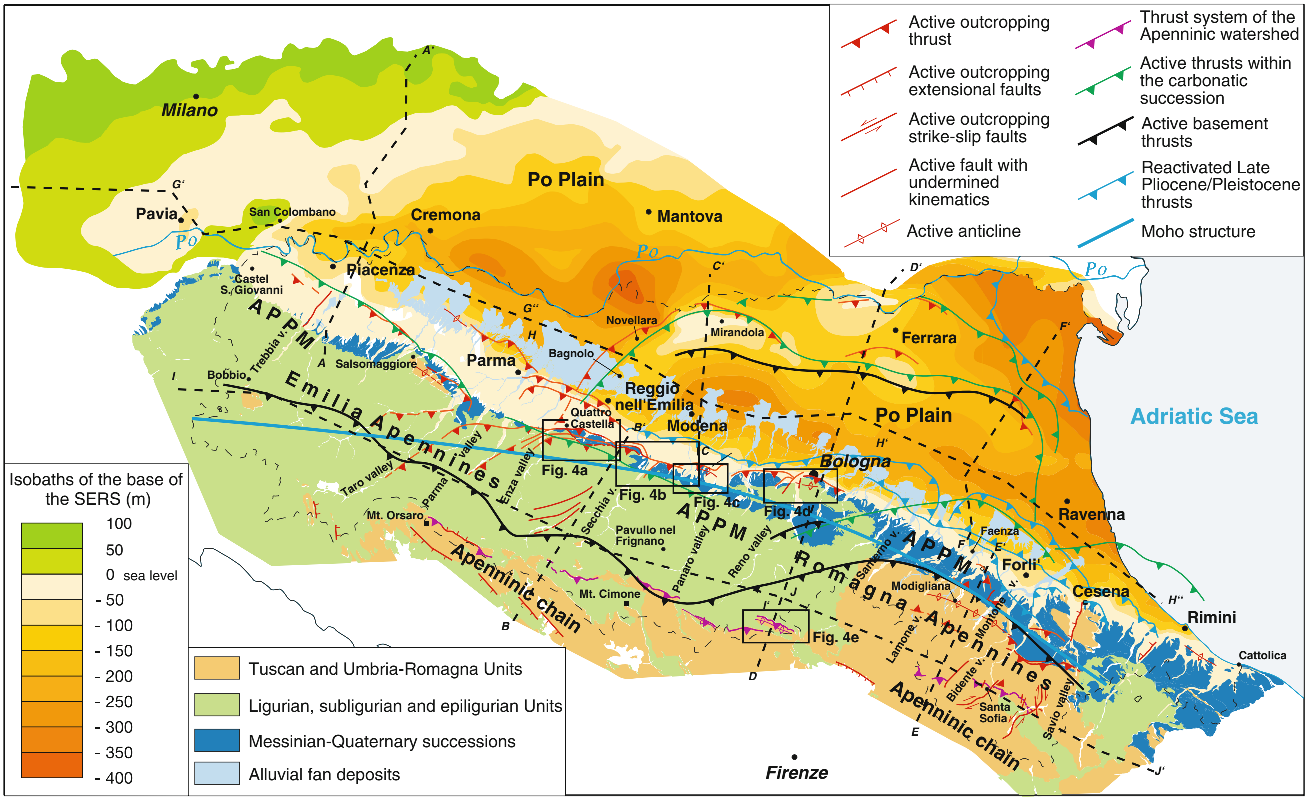


Fig. 3 Recent and active structures of the Emilia-Romagna. Subsurface geology in the Po Plain is illustrated as isobaths of the base of the Upper Emilia-Romagna Synthem (450,000 year). *APPM*: Apennines–Po Plain margin. *Solid lines with letters* indicate the trace of cross sections reported in Fig. 5

dominant transcurrent kinematics, affect Late Pleistocene (<20,000 years) terraces (Marabini et al. 1986; Achilli et al. 1990; Farabegoli et al. 1994; Martelli 1994, 2002).

Similarly, to the NW, the recent deformation pattern is characterised by the presence of a major blind back thrust, with associated anticline (Modigliana anticline), affecting the local drainage pattern and determining an anomalous, rapid uplift of a portion of the Lamone Valley (Simoni et al. 2003).

The major effects of the recent tectonics in the chain are localised at the top of a major basement thrust that connects at surface with the pede-Apenninic thrust front (Figs. 3, 5a). Folding and the doubling of both the basement and the carbonatic succession clearly explain the thickness variations of the Ligurian allochthonous nappe, the formation of the out-of-sequence structures and the tectonic windows (Figs. 3, 5a, c).

In the Adriatic side of the Apenninic chain, no major normal faults are present; the extensional structures affecting this portion of the chain have local extent and limited vertical displacement (as for instance documented in the Romagna Apennines; see Martelli 2002). The origin of these structures has not been related to a regional stress field, rather they have been interpreted to represent a response to a stress release (Gargini et al. 2006, 2008) induced by erosion of the overlying units with consequent unloading (Zattin et al. 2000) and to the gentle folding of the Romagna Apennines (Fig. 5c; Anelli et al. 1994; Cerrina Feroni et al. 2001) with development of a local outer arc extension.

A quantitative analysis of the recent deformation affecting the Upper Emilia-Romagna Synthem (SERS) in the chain and along the Apennines–Po Plain margin is described in the following "Uplift and slip rates" section.

The Apennines–Po Plain margin

The analysis of the Apennines–Po Plain margin evidences the presence of two distinct sectors with different morphostructural characters, extending north-west and south-east of Bologna (Fig. 3). The north-western sector (Emilia Apennines) is marked by presence of the major pede-Apenninic thrust front (PTF; Boccaletti et al. 1985), characterised by a prominent morphotectonic signature (Figs. 4, 5a, cross sections B–B′ and D–D′); the south-eastern sector (Romagna Apennines) is characterised by a monoclinal setting with north-east immersion, which determines the development of tilted surfaces connecting the plain with the Apenninic relieves. The tilting affects Quaternary deposits and is connected with movement along blind back thrusts (Fig. 5a, cross section E–E′).

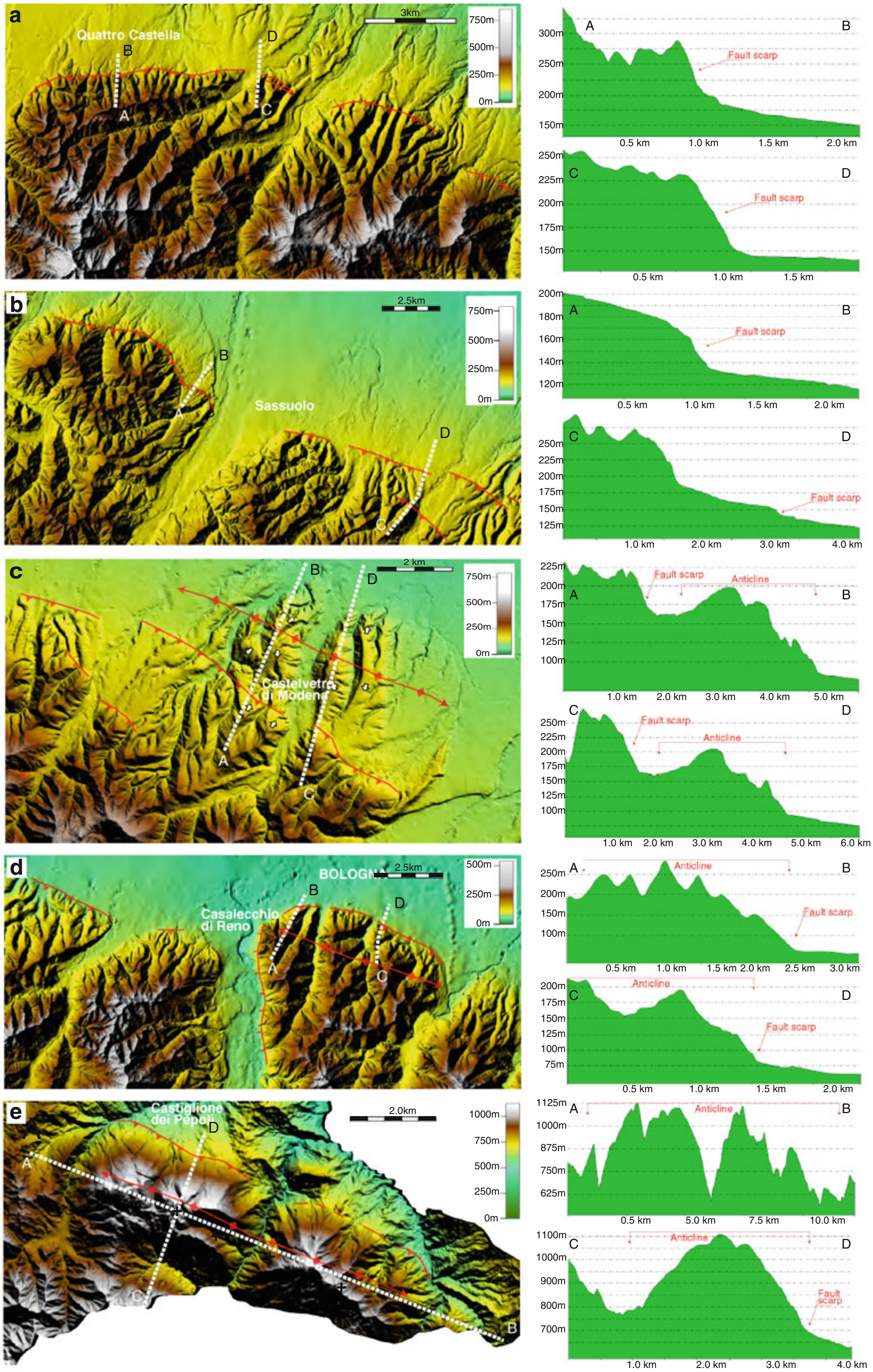
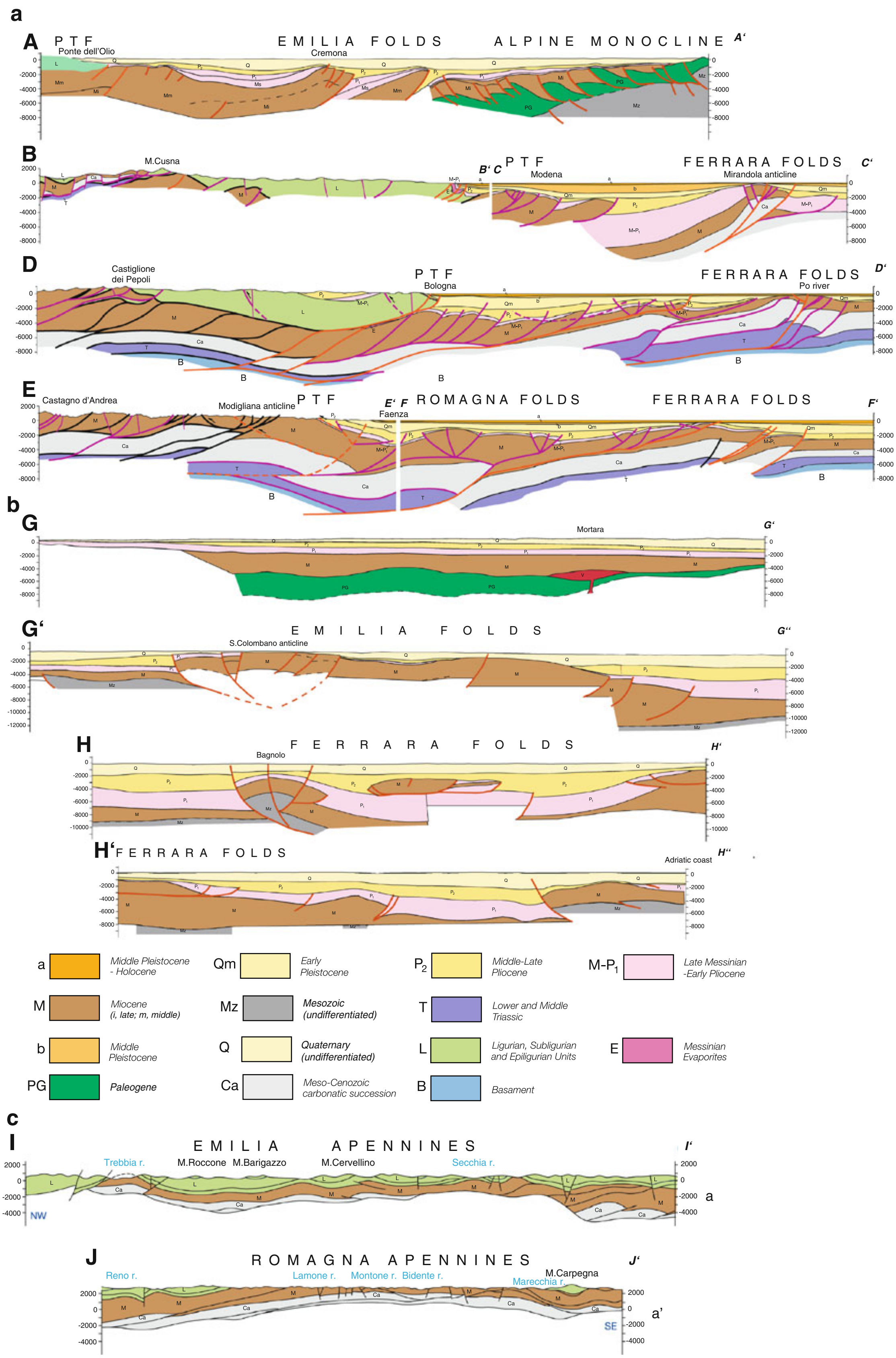


Fig. 4 Details of recent and active structures in the external part of the Northern Apennines illustrated as digital elevation models (DEMs) with 10-m resolution (*left panels*) and topographic profiles of the main structures (*right panels*). *Insets on left panels* represent a structural sketch of the main structures. **a** Pede-Apenninic Thrust Front near Quattro Castella. Note the prominent fault scarp associated with typical morphostructural features (such as triangular facets). **b** Pede-Apenninic Thrust Front near Sassuolo. **c** Pede-Apenninic Thrust Front and associated growing anticline in the Castelvetro di Modena area. *Arrows* indicate the tilting direction of paleo-surfaces. **d** Pede-Apenninic Thrust Front and associated growing anticline in the Bologna area. **e** Castiglione dei Pepoli thrust front and growing anticline. Location of different panels is reported in Fig. 3



a
A
P T F
Ponte dell'Olio
E M I L I A F O L D S
Cremona
A L P I N E M O N O C L I N E
A'
B
M.Cusna
B' C
P T F
Modena
F E R R A R A F O L D S
Mirandola anticline
C'
D
Castiglione dei Pepoli
P T F
Bologna
F E R R A R A F O L D S
Po river
D'
E
Castagno d'Andrea
Modigliana anticline
P T F
E' F
Faenza
R O M A G N A F O L D S
F E R R A R A F O L D S
F'
b
G
Mortara
G'
G'
E M I L I A F O L D S
S.Colombano anticline
G''
H
F E R R A R A F O L D S
Bagnolo
H'
H' F E R R A R A F O L D S
Adriatic coast
H''
a
Middle Pleistocene - Holocene
Qm
Early Pleistocene
P2
Middle-Late Pliocene
M-P1
Late Messinian -Early Pliocene
M
Miocene (i, late; m, middle)
Mz
Mesozoic (undifferentiated)
T
Lower and Middle Triassic
b
Middle Pleistocene
Q
Quaternary (undifferentiated)
L
Ligurian, Subligurian and Epiligurian Units
E
Messinian Evaporites
PG
Paleogene
Ca
Meso-Cenozoic carbonatic succession
B
Basament
c
I
E M I L I A A P E N N I N E S
Trebbia r.
M.Roccone
M.Barigazzo
M.Cervellino
Secchia r.
I'
NW
a
J
R O M A G N A A P E N N I N E S
Reno r.
Lamone r.
Montone r.
Bidente r.
Marecchia r.
M.Carpegna
J'
SE
a'

◀ **Fig. 5** Transversal (**a**) and longitudinal (**b–c**) geological cross sections of the external Northern Apennines. Location in Fig. 3. Modified from Pieri and Groppi (1981), Cassano et al. (1986), and Boccaletti et al. (2004). In the cross sections, unit a (Middle Pleistocene–Holocene) coincides with the Upper Emilia-Romagna Synthem and unit b (Middle Pleistocene) coincides with the Imola Sands + Lower Emilia-Romagna Synthem (see inset of Fig. 2). Note the occurrence of major thrust systems affecting the basement (*B*) close to Castiglione dei Pepoli (section *D–D′*) and Modigliana (section *E–E′*)

Along the Emilia Apennines–Po Plain margin, the structures showing geological indications of recent activity, north-west of Parma, coincide with the buried Emilia Folds (Figs. 2, 3), the SE continuation of the Broni-Stradella thrust of Benedetti et al. (2003). West and south-west of Parma, the Apenninic margin coincides with the PTF that is responsible for the formation of the anticline and the tectonic window of Salsomaggiore (Fig. 3).

Between Parma and Bologna, a continuous active front can be traced, coinciding with the Apenninic margin and the PTF (Fig. 3). The relieves just south of the margin also present much evidence of active structures, both morphological and geological: Middle Pleistocene deposits are faulted and the terraces of the upper Po Plain, with Late Pleistocene deposits, are tilted (Fig. 6b–d). Throughout the area, seismic profiles of the subsoil confirm that Middle Pleistocene sediments are folded and faulted (Fig. 7). Reconstruction of the base of holocenic sediments shows that the greatest depth of this surface is in front of the Apenninic margin, between Reggio Emilia and Bologna (Fig. 8) suggesting an holocenic activity of the PTF (see also "Po Plain" section). South of Parma-Reggio Emilia sector, the pede-Apenninic structure is characterised by SW splays, as in the Parma and Taro valleys; these splays define a horsetail-like geometry typical of dextral strike-slip structures (Woodcock and Fischer 1986).

In the Quattro Castella area (Fig. 4a), the PTF separates Upper Miocene-Lower Pliocene marine deposits to the south from the Holocene alluvial deposits of the Po Plain to the north; prominent faceted spurs (with a mean height of ~50 m), a laterally continuous basal scarp, and strong fluvial erosion in the hangingwall (Fig. 4a, b) testify the current activity of the structure, which is additionally supported by calculation of geomorphic indices of landforms (Boccaletti et al. 2004) and analysis of seismic profiles. West of Quattro Castella, the PTF bifurcates giving rise to blind thrusts whose recent activity, although not associated to a morphostructural signature at surface, is evidenced by analysis of seismic lines (Barbacini et al. 2002).

South-east of Quattro Castella, active deformation is taken up by development of some active anticlines associated with movement of the PTF, which is buried below recent alluvial deposits of the Po Plain (Fig. 5a, cross section B–B′). Particularly evident is the Castelvetro di Modena anticline (Fig. 4c) that determines the uplift and deformation of marine and continental deposits with ages varying from Pliocene (Argille Azzurre Fm.) to the Middle Pleistocene–Holocene (Upper Emilia-Romagna Synthem, SERS). The uplift of the anticline gave rise to tilting (both towards the plain and the Apenninic chain) of Holocene paleo-surfaces and to modification of the local drainage pattern, with deflection of minor streams and inversion of the local drainage direction (Fig. 4c). More to the south-east, an active anticline deforms the Ligurian rocks and marine-continental deposits of the hills south of Bologna,

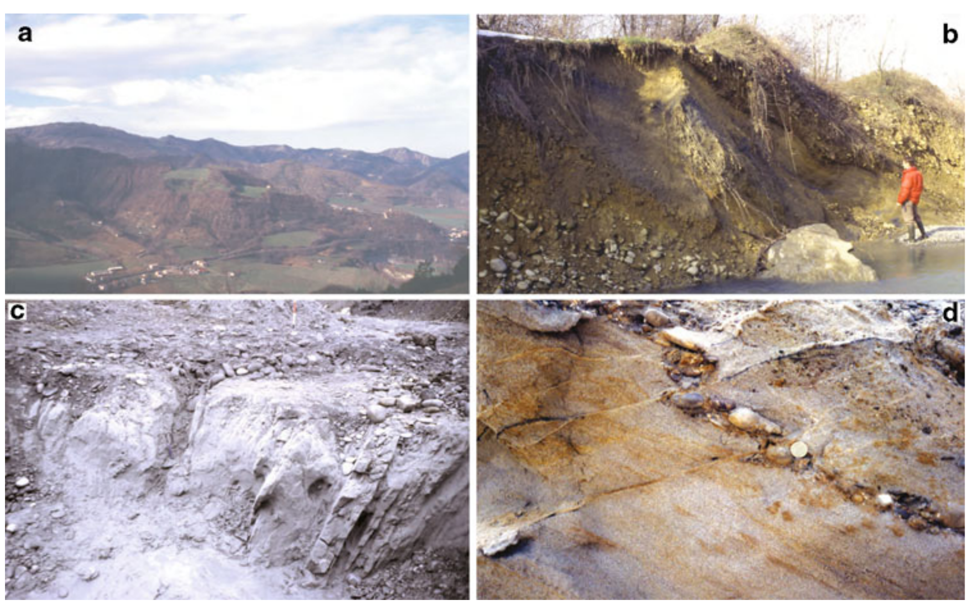


Fig. 6 **a** Alluvial terraces (<220,000 year) in the S. Sofia area (Bidente valley); **b** tilted alluvial deposits (Lower Emilia-Romagna Synthem, 0.65–0.45 M year) (Tiepido valley, Modena Apennines–Po Plain margin); **c** overturned Imola Sands (0.8–0.65 M year) (Reno valley, Bologna Apennines–Po Plain margin); **d** Thrust faults affecting the Imola Sands (0.8–0.65 M year) (Panaro valley, Modena Apennines–Po Plain margin)

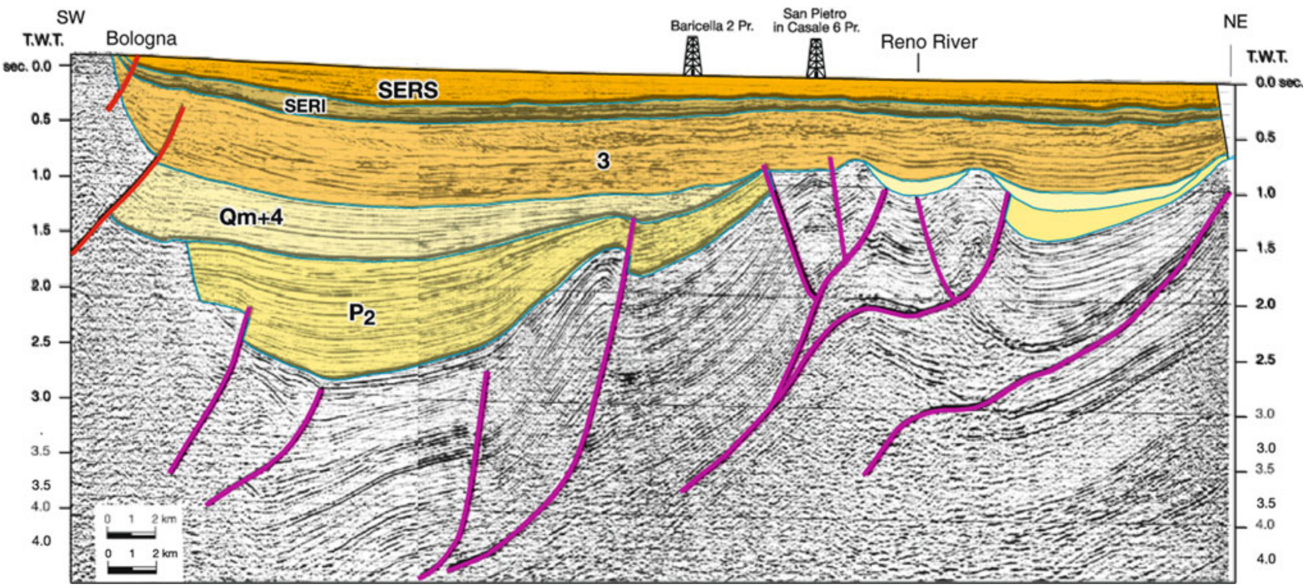


Fig. 7 Example of interpreted seismic line (modified from RER and ENI-Agip 1998). Note that Middle Pleistocene and Late Pleistocene units (*3*: Imola Sands; *SERI*: Lower Emilia-Romagna Synthem; *SERS*: Upper Emilia-Romagna Synthem) are folded and faulted. *P2*: Late Pliocene; *Qm*: Lower Pleistocene marine sediments; *4*: Yellow Sands (1–0.8 M year)

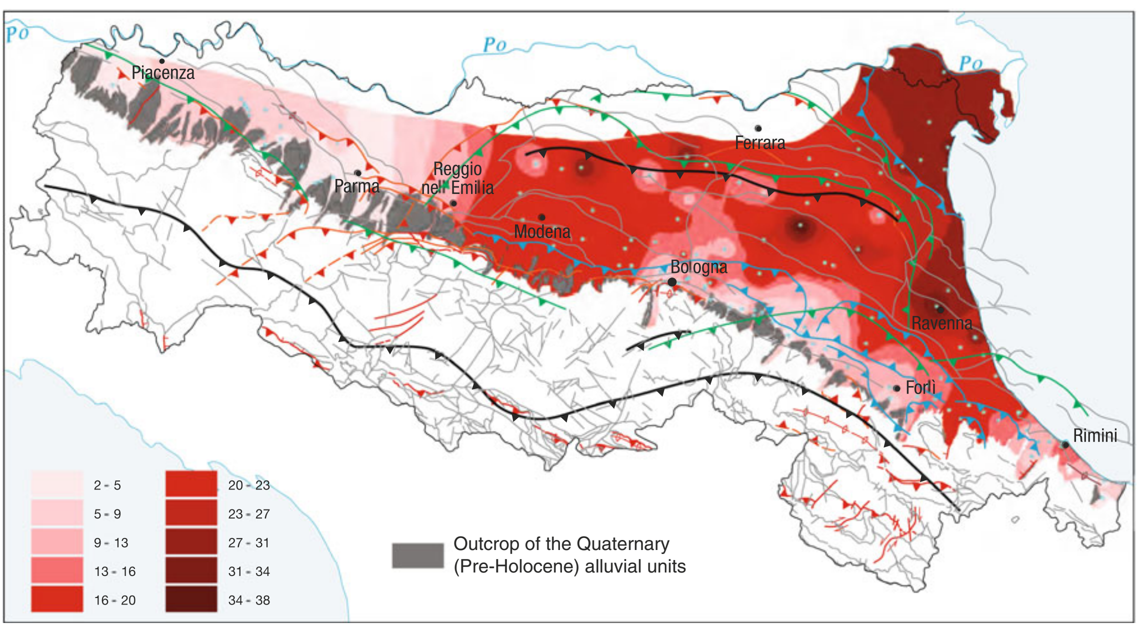


Fig. 8 Depth of the base of the Holocene (map legend indicates depths in metres from the surface)

with ages ranging from the Messinian (Formazione Gessoso-Solfifera) to the Middle Pleistocene (Imola Sands; Fig. 4d). Active shortening in the area has been interpreted to be associated with a trishear deformation kinematics at the mountain front (Picotti and Pazzaglia 2008). Along the margin immediately south-east of Bologna, the Middle Pleistocene deposits (Imola Sands and the alluvial sediments of the Lower Emilia-Romagna Synthem, SERI) are strongly deformed, being characterised by vertical or overturned attitude, cut by reverse fault or thrusted by Serravallian marls of the Epiligurian formations (Ghiselli and Martelli 1997; Boccaletti et al. 2004). Current activity of the PTF and associated active anticline is documented by the presence of fault scarps locally affecting Holocene alluvial fans (Boccaletti et al. 2004), uplift of different orders of tectonic terraces, calculation of geomorphic indices of landforms (Gualtierotti 1998), and analysis of the evolution of the erosion-depositional system of the chain-Po Plain (Amorosi et al. 1996). Analysis of the uplift of the tectonic terraces allows an estimation of the mean incision rates that varies between ~6 mm/year for the 18,000–13,000 year interval and ~3.5 mm/year for the last 13,000 year (Gualtierotti 1998). Although influenced by the fluvial dynamics related to climatic changes and by the diapiric tectonics of the clayey formations of the Ligurian units (Borgia et al. 2005), these values give important information concerning the rates of activity of the pede-Apenninic thrust in the area. Notably, the uplift of the Bologna anticline is associated by development of minor Holocene normal faults trending perpendicular to the fold axis (Fig. 4d).

Along the Romagna Apennines–Po Plain margin, between Bologna and Forlì, the main signs of activity consist mainly of the blind back thrust localised at the base of the Pliocene sequence and in the Marnoso-Arenacea south of Faenza and Forlì (Fig. 5a, cross section E–E′), and the Cesena "high" (Fig. 3). The structural architecture of the Cesena hills is more complex, with thrusts and folds cut by an extensional anti-Apenninic structure in the Savio valley. South-east of Rimini, an anticline deforms Middle Pleistocene deposits; probably, this structure is the NW-trending continuation of the active anticline described in Vannoli et al. (2004), at the top of the buried Rimini–Ancona thrust (Adriatic Folds).

Previous mesostructural analyses (Ghiselli and Martelli 1997) evidenced the presence of active structures affecting Middle-Late Pleistocene deposits between the Enza Valley and Bologna as well as in eastern Romagna; the recent activity of the PTF in the south-eastern sector is also supported by a morphostructural study by Vannoli et al. (2004).

Po Plain

The study of the active tectonics of the Po Plain has been achieved through the analysis of published seismic sections (Pieri and Groppi 1981; Cassano et al. 1986; Boccaletti et al. 2004) (see, for example, Fig. 7). This analysis highlights deformation of the sedimentary infill of the Po Plain, with thrusts and folds affecting the Plio-Quaternary formations (Fig. 5). These structures have a typical arcuate shape in plan view, giving rise to the so-called Emilia and Ferrara folds (Pieri and Groppi 1981) (Figs. 2, 5); many of these structures affecting the Plio-Quaternary sedimentary cover correspond at depth to major basement thrusts and folds (Figs. 3, 5).

The large number of subsurface data collected through exploration projects for hydrocarbons and water research (boreholes and seismic profiles) allowed to map the principal quaternary unconformities. Among these, the most recent surface, mappable at regional scale, is the base of the Upper Emilia-Romagna Synthem (SERS; Fig. 3), estimated approximately 450,000 years old (RER and ENI-Agip 1998; RL and ENI-Agip 2002). It is evident that this surface is folded: it is very shallow, i.e., near to the surface, at the top of the Emilia and Ferrara Folds while it is very deeper in the footwall of the buried thrust fronts of the PTF-Romagna Folds system and of the Emilia and Ferrara Folds.

C_{14} analysis carried out on samples collected during numerous drillings (420 Regione Emilia-Romagna analysis, available in the accompanying notes of the geological maps of the Po plain http://www.regione.emilia-romagna.it/wcm/geologia/canali/cartografia/sito_cartografia/sito_cartografia.htm) allowed to reconstruct the Holocene base surface of a significant part of the Po Plain subsurface of Emilia-Romagna (Fig. 8). The Holocene base is located at a depth of <9 m west of Reggio Emilia and in western Romagna, whereas it is located deeper (>20 m) along the Adriatic coast, between Ravenna and the Po river delta, and in some sectors of the Modena and Bologna plain; additionally, it plunges rapidly, almost to define a scarp, immediately north of the Apennines–Po Plain margin between Reggio Emilia and Bologna and in eastern Romagna. Although these values cannot be directly attributed to natural subsidence (being the soil subsidence also determined by compaction of sediment and, in areas characterized by high anthropic concentration such as the Po Plain, by exploitation of groundwater resources; e.g., Carminati and Martinelli 2002; Bitelli et al. 2005; ARPA Emilia-Romagna 2007; Stramondo et al. 2007), two factors suggest a tectonic control on the geometry of Holocene deposit: (1) the good correspondence between the geometry of the Holocene base and the distribution of late Quaternary structures and (2) the poor correspondence between highs and lows of the Holocene base with maximum or minimum water exploitation (Boccaletti et al. 2004).

The recent activity of the Ferrara Folds can also explain some peculiarities of the hydrographic pattern such as the direction changes of the Po river near the Bagnolo-Novellara high (Reggio Emilia plain), the direction changes of the Secchia and Panaro rivers near the Mirandola high (Modena plain) (Figs. 2, 3), and the swamping of some rivers between the Romagna Folds and the Ferrara Folds (see also Burrato et al. 2003; Boccaletti et al. 2004).

The analysis of the seismic profiles also highlights that the active and recent structures affecting the external Northern Apennines are connected at depth with compressive structures affecting the carbonate sequence and the basement (Fig. 5a). The carbonate sequence is thrust-faulted; these thrusts link up with the active structures of the upper Apennines, with the pede-Apenninic front, and with the Ferrara ridge. The structures affecting the basement also connect up with surface active thrust fronts, in particular with the pede-Apenninic thrust and with the Ferrara ridge.

Uplift and slip rates

The Apennines–Po Plain margin and the Apenninic chain

The Plio-Quaternary stratigraphic units are almost non-existent in the Apenninic chain, due to erosion or non-deposition, with the exception of the area along the margin. The best preserved quaternary deposits in the Apenninic sector are very recent sediments, ascribable to the youngest sub-units of the Upper Emilia-Romagna Synthem (SERS), i.e., the subsynthems SERS7 and SERS8 (see inset in the Fig. 2), which date from the Late Pleistocene (0.125–0.010 M year) and the Holocene (0.010 M year—Present), respectively (Sarti et al. 1997). These deposits are well preserved along the margin and in the intramontane valley terraces of the Apennines. The elements that have enabled us to establish the chronology of the terraces and the correlation with the deposits of the Po Plain-Adriatic subsoil are both geometric (height of terrace outcrops, presence of particularly significant erosive scarps and unconformities, dip angle of various terraces) and stratigraphic (archaeological finds, radiometric dating, the nature of pedogenesis) (Sarti et al. 1997). Data obtained from monitoring has been summarized in profiles localized along the valleys of the main Apenninic rivers (Fig. 9). These profiles were constructed by projecting the base unconformities of terraces along the entire valley. The difference in elevation between the terraces along these profiles and the modern valley profile corresponds to the river incision and is therefore also indicative of chain uplift. Indeed, in the external Northern Apennines, incision has been shown to balance rock uplift (Cyr and Granger 2008), particularly when integrated across at least one glacial cycle and when rivers are located at or near sea level (see Wilson et al. 2009), which is the case for the streams traversing the Apennines–Po Plain margin. This supports the use of vertical channel incision as a proxy for rock uplift, at least for the Late Pleistocene. In the Holocene, the influence of other parameters such as distal base-level changes, climatically modulated variations in watershed hydrology, and/or anthropic-induced changes in river beds may increase the discrepancy between downcutting and uplift.

Base of the SERS (Upper Emilia-Romagna Synthem)

Data on the basal limit of SERS (450,000 years) in the chain are available only for the Panaro basin. Lacustrine deposits at Pavullo nel Frignano (north of Mt. Cimone, see Fig. 2) have been correlated with the basal portion of SERS. Currently, these deposits lie at an elevation of between 670 and 690 m above sea level, i.e., around 400 m above the present-day Panaro river bed. The average incision rate over the last 450,000 years in this sector is therefore ~0.9 mm/year.

Subsynthem SERS6

For the Bidente and Reno valleys, data on deposits of the last middle Pleistocene climatic cycle are also available (0.22–0.125 M year). In the Bidente and Reno valleys (Figs. 6a, 9), terraces attributable to the subsynthem SERS6 (base unconformity 220,000–230,000 years in age; Sarti et al. 1997) have also been identified at an elevation of over 150 m above SERS7 terraces. From these data, it emerges that during the last climatic cycle of the Middle Pleistocene, the average incision rate, and therefore the average uplift rate, in these valleys was of 1.5–1.7 mm/year. Moreover, in the Reno valley, the SERS6 base lies at an elevation of 150 m above the current river bed all the way to the margin and is not in continuity with the corresponding surface in the Po Plain subsoil, lending weight to the presence of a fault in proximity to the Apennines–Po Plain boundary, as supposed from the analysis of the SERS7 profile.

Subsynthem SERS7

The analysis of the profile of SERS7 (unconformity base ~125,000 year) highlights deformation of these deposits along the Apennines–Po Plain margin between the Reno and Taro valleys (Fig. 9), with the exception of the Panaro valley where very little data are available.

An anticline-type deformation is observed between the Taro and Secchia valleys, with the major evidence in the Enza valley (Fig. 9).

In the Reno valley, the profile of the SERS7 always stands at least 50 m above the current river bed and cannot be directly correlated with the corresponding buried Po Plain deposit, suggesting the presence of a fault system along the Po Plain-Apenninic margin.

On the contrary, the SERS7 shows no evidence of deformation in Romagna (Santerno, Lamone, Montone, Bidente, and Savio valleys) and in the Piacenza Apennines (Trebbia valley), where this horizon dips regularly towards the plain and can be clearly correlated with the corresponding deposit of the Po Plain subsoil, testifying to more gradual uplift/subsidence of the chain-plain system.

Towards the interior of the chain, SERS7 profiles can only be traced in the Trebbia and Reno valleys in the Emilia Apennines and along the Santerno and Bidente valleys in the Romagna Apennines. SERS7 stands 150 m

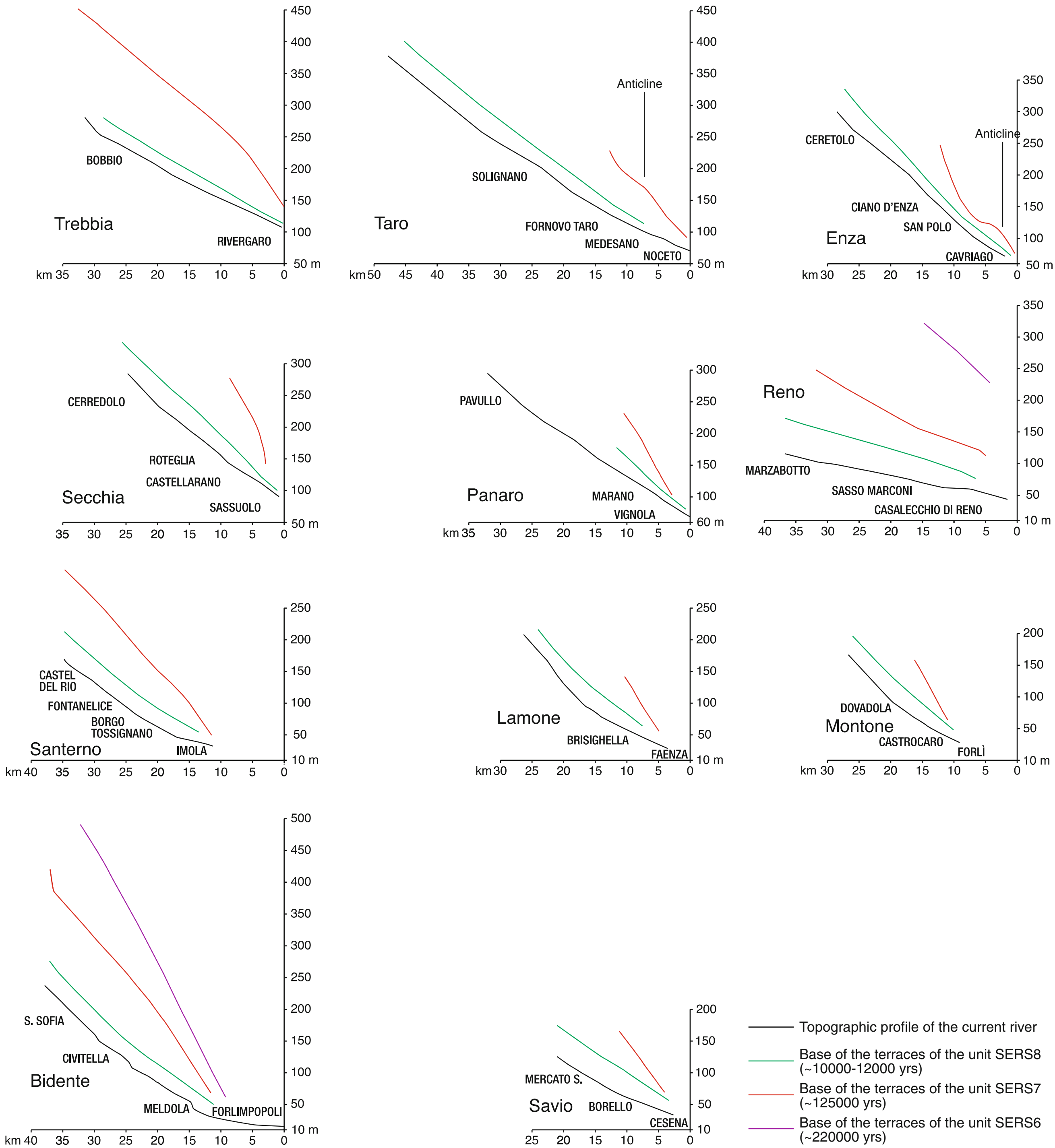


Fig. 9 Topographic profiles, along the main Apenninic valleys, showing the elevations of the Late Pleistocene and Holocene terraces and the current river bed. Note that the survey of alluvial terraces was carried out at a 1:10.000 scale in the frame of the project "Geological and soil mapping of the Emilia-Romagna Region" (http://www.regione.emilia-romagna.it/wcm/geologia/canali/cartografia/sito_cartografia/sito_cartografia.htm), so that it is impossible to represent all the measurement points in each profile

above the present-day river bed in the Reno and Bidente valleys, 15–20 km from the margin, while it does not exceed 130 m elevation in the Trebbia and Santerno valleys. Notably, the difference in height between SERS7 and the present-day river bed tends to increase upstream, indicating that the incision, and hence the uplift of the chain, gradually increases from the margin to the Apenninic watershed.

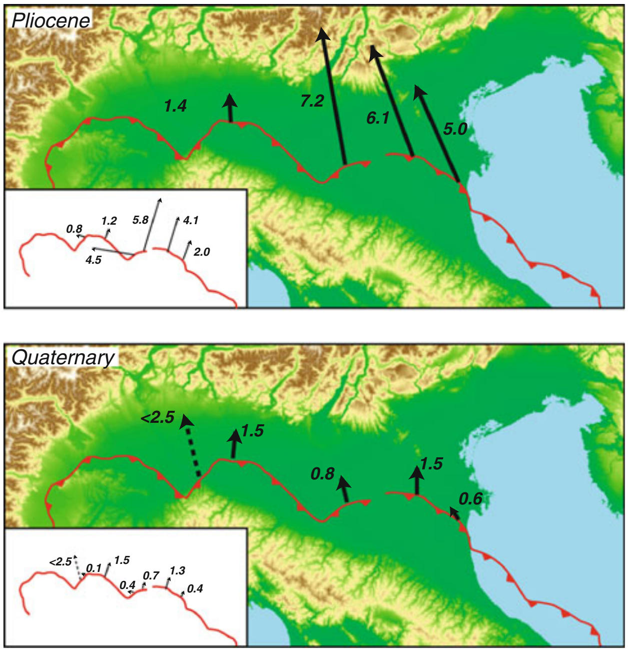


Fig. 10 Pliocene and Quaternary slip rates calculated from the main structures from analysis of available seismic sections. *Inset* shows rates along WNW–ESE and NNE–SSW seismic lines used to calculate the real shortening directions (see "Appendix" for details of calculations)

Subsynthem SERS8

The analysis of the uplift of the SERS8 (unconformity base ~10,000/12,000 year) (Fig. 9) shows that the difference in height between the base of these deposits and the river bed tends to becoming constant at 10–15 km from the margin. This may indicate greater activity by faults along the margin over the past 10,000 years.

In addition, this difference in height increases from west to east in the Emilia Apennines (30 m in the Trebbia valley and 50–55 m in the Reno valley) while it decreases sharply in western Romagna (around 30 m in the Santerno and Lamone valleys) and only to increase again towards the east, peaking in eastern Romagna (70 m in the Savio valley). Notably, the valley incision rate is higher in the Holocene (30–70 m/10,000 years) compared to that of the Late Pleistocene (130–150 m/125,000 years). This may indicate that incision is influenced by various factors besides chain uplift, such as postglacial fluvial dynamics and the significant anthropic excavation of river beds for extraction of gravel. Nonetheless, in both cases, the highest incision rates are found in eastern Romagna and in the Reno valley, while the lowest are found in western Romagna and the Trebbia valley. Average values are recorded in the valleys between the Panaro and the Taro and in central Romagna (Montone and Bidente valleys).

Po Plain and Adriatic Coast

Pliocene and Quaternary slip rates and directions of shortening along the main structures have been reconstructed from the analysis of published seismic sections, with the procedure reported in "Appendix". Results, illustrated in Fig. 10 and Tables 1, 2, show that during the Pliocene, the direction of maximum shortening of the Emilia Folds trends approximately N–S, with an average slip rate of ~1.4 mm/year, while maximum shortening in the Ferrara-Romagna folds system trends NNW–SSE with much higher average slip rates (from ~5 to ~7 mm/year, increasing from east to west). In the Quaternary, we can observe a general clockwise rotation of slip vectors. The maximum slip direction of the Emilia Folds is between N–S and NNE–SSW, with an average slip rate of ~1.5 mm/year, still comparable with that of the Pliocene. For the Ferrara-Romagna folds system, the maximum fault slip direction varies around N–S, with a clear decrease in average slip rates, which reveal values between ~0.6 and ~1.5 mm/year. The shortening direction and average slip rates calculated for the Emilia Folds during the Quaternary are entirely in line with those estimated by Benedetti et al. (2003), which attributes to this structure a maximum slip rate direction between NNW–SSE and N–S with a slip rate <2.5 mm/year.

The SERS base reaches a depth of between 350 and 400 m in the footwall of the thrust front of the Ferrara Folds, giving a maximum subsidence rate ~0.8–0.9 mm/year; considering a ~50–60% correction for sediment compaction (Scrocca et al. 2007) gives tectonic subsidence rates of ~0.3–0.5 mm/year. Conversely, above the San Colombano anticline (Emilia Folds) and above the Mirandola anticline (Ferrara Folds), the SERS base is at a depth of only a few tens of metres (<50 m); in these areas, the subsidence rate is therefore of ~0.1 mm/year and we can estimate an average uplift of the Emilia and Ferrara folds (corrected for compaction) of ~0.2–0.4 mm/year. These values are in the range of estimates based on backstripping high-resolution stratigraphic data (Scrocca et al. 2007), indicating uplift rates of 0.53 mm/year on the Mirandola anticline, with a decrease during the last 125 ka to values of 0.16 mm/year. However, analysis of the subsoil data (seismic profiles and well logs stratigraphy) does not allow evaluating more recent movement, although field data indicate deformation of Holocene deposits along the Apennines–Po Plain margin (see "The Apennines–Po Plain margin and the Apenninic chain").

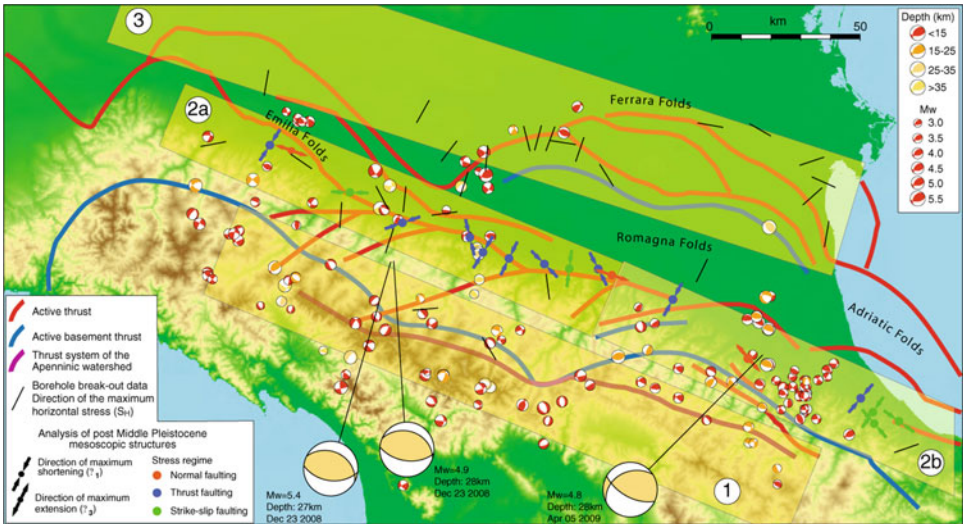


Fig. 11 Summary of the recent and active structures of the external Northern Apennines with superimposed focal mechanism solutions (Boccaletti et al. 2004), stress fields from mesoscopic analysis (Ghiselli and Martelli 1997) and borehole breakout data (Mariucci and Muller 2003). Enlarged are three focal mechanisms of main events of the seismic sequences that effected the external Apennines on December 23, 2008, and April 5, 2009 (from INGV data, http://www.ingv.it). *Numbers in circles* indicate the main fault systems: (*1*) Apenninic chain; (*2a*) Apennines–Po Plain margin (North-Western sector); (*2b*) Apennines–Po Plain margin (South-Eastern sector); (*3*) buried Emilia and Ferrara Folds

Summary of the main recent and active structures of the external Northern Apennines and comparison with seismicity, geodetical data, and stress field analysis

As highlighted above, the main Quaternary structures affecting the external part of the Northern Apennines cluster in three distinct sectors, namely: the Apenninic chain, the Apennines–Po Plain margin, and the Po Plain. This pattern well reconciles the scattered data available in the literature (e.g., Benedetti et al. 2003; Burrato et al. 2003; Vannoli et al. 2004; Piccinini et al. 2006; Basili and Barba 2007) and shows an overall good agreement with the analysis of focal mechanisms (Pondrelli et al. 2002, 2004, 2006; Chiarabba et al. 2005; Boncio and Bracone 2009), GPS data (Serpelloni et al. 2005), and the vertical velocity field revealed by geodetic levelling data (D'Anastasio et al. 2006), as discussed in the following.

In particular, the main recent and active structures of the external Northern Apennines are summarized in Fig. 11. From the distribution and frequency of recognisable surface structures, it emerges that these are not uniformly distributed throughout the region, but are clearly localised in three different areas.

1. An almost continuous fault system can be identified along the Apenninic watershed, coinciding approximately with the Tuscan units thrust front, although minor strike-slip and minor extensional faults are also recognisable. This fault system is characterised by prominent morpho-tectonic signature indicative of Pleistocene activity, as summarised in the above "The Apenninic chain" section. The Apenninic chain is marked by localised Pleistocene and current uplift (e.g., Balestrieri et al. 2003; D'Anastasio et al. 2006; Thomson 2009) and moderate seismicity. Analysis of focal mechanism solutions within the chain indicates superposition of two different deformation fields with depth (e.g., Lavecchia et al. 2003). The shallow (<15 km) seismicity is characterised by low-moderate magnitude events with dominant extensional focal mechanisms, with subordinate strike-slip (and compressional) events (Fig. 11; see also Pondrelli et al. 2006); major extensional events are confined to the Tyrrhenian side of the chain with earthquakes up to $M = 6$ in the Garfagnana-Lunigiana and Mugello basins (e.g., Sani et al. 2009). These shallow extensional events within the Apenninic chain may be related to a secondary extensional stress field developing on the hangingwall of the thrust system (e.g., Bonini 2007 and references therein) affecting the Apenninic watershed; alternatively, this thrust system may have been recently deactivated and overprinted by active normal faulting in the shallow crust (<15 km; e.g., Bonini and Tanini 2009).

Seismic events within the intermediate crust (15–25 km) are dominantly compressive as testified by the 2003 Monghidoro seismic sequence related to thrust faulting associated with a NNW-striking compression (Piccinini et al. 2006). These events may be related, at least in part, to the activity of the major crustal thrust doubling the basement and the carbonatic succession below the chain

Table 1 Pliocene and Quaternary shortening along the main structures reconstructed from the analysis of published seismic sections

Shortening direction	Studied sections	Pliocene shortening (km)	Quaternary shortening (km)
NNE–SSW	Piacenza Apennines—Emilia Folds	4.25	2.75
	Modena Apennines—Ferrara Folds	17–24.5	1–1.25
	Bologna Apennines—Ferrara Folds	11.5–18	1.5–3
	Faenza Apennines—Ferrara Folds	4.75–9.75	0.75
WNW–ESE	Emilia Folds	3	0.25
	W Ferrara Folds—N Adriatic Folds	16.25	0.75

Table 2 Pliocene and Quaternary slip-rates along the main structures estimated from the analysis of published seismic sections

Shortening direction	Studied sections	Pliocene slip rate (mm/year)	Quaternary slip rate
NNE–SSW	Piacenza Apennines—Emilia Folds	1.2	1.5
	Modena Apennines—Ferrara Folds	4.7–6.8	0.6–0.7
	Bologna Apennines—Ferrara Folds	3.2–5	0.9–1.8
	Faenza Apennines—Ferrara Folds	1.3–2.7	0.4
WNW–ESE	Emilia Folds	0.8	0.15
	W Ferrara Folds—N Adriatic Folds	4.5	0.4

and connecting at surface with the pede-Apenninic thrust front (Fig. 5a). Deeper seismic events (down to depths of >35 km) are most probably associated with a major Moho structure causing this boundary to be on average 5 km deeper in the plain and below the Apenninic margin than in the Apennines (Bigi et al. 1990). Although few focal mechanisms are available for these depths, they show a consistent compressive kinematics. These findings are in agreement with those of Boccaletti et al. (2004) that highlighted a cluster of earthquake hypocentres along a strongly S-dipping band that could correspond to an active structure affecting the Moho. Alternatively, these deep events have been associated to the flexure of the subducting Adria continental lithosphere (e.g., Chiarabba et al. 2005).

2. Another active fault system coincides with the Apennines–Po Plain margin. Based on frequency and evidence of the structures, two distinct sectors can be identified along the margin: (a) the area NW of Bologna; (b) the area SE of Bologna.

2a. The north-western sector of the Po Plain margin is marked by presence of the major pede-Apenninic thrust (PTF, Boccaletti et al. 1985); its activity is testified by both a prominent morphotectonic signature and analysis of seismic lines. The main thrust faults display a typical en-echelon arrangement, with a striking correspondence between the trace of the buried thrust systems and the direction of the maximum horizontal stress S_H (Fig. 11). This is also consistent with the post-Middle Pleistocene and the current stress field derived from analysis of mesoscopic structures (Fig. 11; Ghiselli and Martelli 1997; Boccaletti et al. 2004), as well as structural analysis of mud volcanoes fields (Bonini 2008). Notably, active deformation along these structures results in maximum values of relative elevation changes located in correspondence to the Apennines–Po Plain margin, as suggested by geodetic levelling data (D'Anastasio et al. 2006). Remote sensing (DInSAR) data (Stramondo et al. 2007) confirm the existence of active displacement of the pede-Apenninic thrust.

2b. The south-eastern sector is characterised by a north-east dipping monocline, which determines the development of tilted surfaces connecting the plain with the Apenninic relieves. Tilting of these surfaces, developed in Quaternary deposits, is connected with movement along blind thrusts; in this area, no clear evidences of emerging faults are present. However, the area is characterised by clusters of earthquakes down to depth of 15–25 km which are consistent with the occurrence of N–S-trending splays of the thrust front below Forlì and Cesena (Figs. 3, 11). The dominant strike-slip or oblique-reverse kinematics deduced from analysis of focal mechanisms is consistent with the reported fault geometry under roughly N–S convergence. Structures transversal to the chain, which are characterised by surface expression close to the Apenninic divide (see Fig. 3), display an important transcurrent component of motion consistent with the analysis of focal mechanisms showing dominant strike-slip solutions (Fig. 11).

3. Lastly, an important active fault system coincides with the buried Ferrara Folds and the Emilia Folds. These structures, affecting the 7- to 8-km-thick Plio-Quaternary infill of the Po Plain (Pieri and Groppi 1981), are possibly connected to surface faulting events (Pellegrini and Vezzani 1978). Analysis of high-resolution seismic data sup-

port Late Quaternary activity of these active blind thrusts (Scrocca et al. 2007). It is worth noting the prominent arcuature of structures characterising both the sedimentary infill of the Po Plain (Emilia, Romagna, Ferrara and Adriatic Folds) and the Apennines–Po Plain margin (Fig. 3). There is a good correspondence between the seismic events below the Po Plain and the arcuate thrusts of the Emilia and Romagna folds. Focal mechanisms of earthquakes show compressive solutions along these structures up to depth of >35 km; their geometry and kinematics (dominant strike-slip mechanisms or oblique shortening) is consistent with movement along strongly arcuate structures under a constant stress field (Fig. 11). Additionally, borehole breakout data are strongly consistent with active shortening along these structures, as testified by the good agreement between the direction of the maximum horizontal stress S_H and the arcuate traces of the buried thrusts (Fig. 11; Mariucci and Muller 2003).

Although each of these systems have distinct structural and morphotectonic features (summarised in the sections above) and may be locally associated with minor strike-slip and extensional faults, the dominant structural framework suggests that the recent evolution of the external part of the Northern Apennines has been dominated by a compressional stress field. Estimates based on geological data and seismic sections indicate a Quaternary deformation vector oriented roughly N–S, with rates 0.6–1.5 mm/year (Fig. 10). The shortening direction and average slip rates calculated for the Emilia Folds during the Quaternary are entirely in line with those estimated by Benedetti et al. (2003), which attributes to this structure a maximum slip rate direction between NNW–SSE and N–S with a slip rate <2.5 mm/year. These findings are also in agreement with recent GPS data (Serpelloni et al. 2005). Shortening has decreased since the Pliocene, when our data indicate compression in a NNW–SSE direction at rates up to 7 mm/year. A decrease in deformation rates from the Pliocene to the Quaternary is supported by the analysis of high-resolution seismic data (Scrocca et al. 2007).

Concluding remarks

Morphotectonic, geological–structural, and stratigraphic data suggest that the Quaternary evolution of the external part of the Northern Apennines has been dominated by shortening accommodated by three major systems of compressive structures corresponding to (1) the Apenninic watershed, (2) the Apennines–Po Plain margin (pede-Apenninic thrust front), and (3) the Emilia, Ferrara, and Adriatic Fold systems buried below the Po Plain. Our analysis indicates a roughly N–S Quaternary deformation direction, with rates <2.5 mm/year; shortening rates decreased since the Pliocene, when our data indicate compression in a NNW–SSE direction and rates up to 7 mm/year. Analysis of the current seismicity of the area, as well as recent GPS and geodetic levelling data, indicates a good fit with the pattern of the structures affecting the Apennines–Po Plain margin and the Po Plain subsoil, pointing to a current activity of these thrust systems controlled by an overall compressive stress field. Conversely, earthquake mechanism solutions close to the Apenninic watershed indicate superposition of a shallow extensional stress field with a deeper compression. The shallow extensional events may be related to a secondary extensional stress field developing on the hangingwall of the thrust system affecting the watershed, or, alternatively, this thrust system may have been recently deactivated and overprinted by active normal faulting. Deeper (>15 km) compressive events are related to the activity of a major basement thrust connecting at surface with the pede-Apenninic thrust front and a major Moho structure.

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Appendix

Cumulative displacement and average slip rates along main structures have been reconstructed from the analysis of published seismic cross sections (Pieri and Groppi 1981; Cassano et al. 1986; Boccaletti et al. 2004). These cross sections allow calculation of the movement of the Po Plain thrust fronts in relation to several chronological intervals; in particular, in the current study, we have analysed the displacement along the main structures of the base of Pliocene deposits (5.4 M year) and that of Pleistocene deposits (1.8 M year). Given the geometry and trend of the main structures in the external Northern Apennines, most of the published cross sections in the above mentioned studies have WNW–ESE and NNE–SSW trends, allowing estimates of cumulative deformation and slip rates in these directions (Fig. 10; Tables 1, 2).

The transects that have been chosen for the calculation of Pliocene and Quaternary shortening in the NNE–SSW direction are:

- Cross sections 6 of Pieri and Groppi (1981) and Cassano et al. (1986), between Ponte dell'Olio and Soresina, which allows us to estimate the shortening of the Emilia Folds from the Piacenza Apenninic margin to the Po river (Fig. 5a, cross section A–A′);

- Cross sections A–A′ and B–B′ of Boccaletti et al. (2004), cross section 9 of Pieri and Groppi (1981) and Cassano et al. (1986) which allow us to calculate the shortening of the Folds of Emilia, Romagna, and Ferrara from the Modena Apenninic margin to the Po river (Fig. 5a, cross sections B–B′ and C–C′);
- Cross sections C–C′ of Boccaletti et al. (2004) and cross section 10 of Pieri and Groppi (1981) and Cassano et al. (1986) which allow us to estimate the shortening of the Emilia Folds and the Ferrara Folds from the Bologna Apenninic margin to the Po river (Fig. 5a, cross section D–D′);
- Cross sections D–D′ and E–E′ of Boccaletti et al. (2004), cross section 11 of Pieri and Groppi (1981) and Cassano et al. (1986) which allow us to estimate the shortening of the Romagna, Adriatic, and Ferrara Folds from the Faenza Apenninic margin to the Po river (Fig. 5a, cross sections E–E′ and F–F′).

For the WNW–ESE direction, cross section 13 of Pieri and Groppi (1981) and Cassano et al. (1986) have been used to estimate the Pliocene and Quaternary shortening of the Emilia folds (Battuda-Taro area), and that of the Ferrara, Romagna, and Adriatic Folds (Castelnuovo-Ravenna area) (Fig. 5b).

Estimated Pliocene and Quaternary cumulative shortening is summarised in Table 1; since the age of the deformed surfaces is known, one can estimate the slip rates. Slip rate estimates for the Pliocene (5.4–1.8 M year) and Quaternary (1.8 M year—Present), in a NNE–SSW and WNW–ESE directions, are illustrated in Table 2 and Fig. 10. Notably, since the studied sections are the result of interpretation of indirect observations, such as seismic profiles, estimated shortening depends heavily on the interpretation of the geometry of structures. A margin of uncertainty must therefore be allowed for the values obtained, which range from possible minimum and maximum shortenings. Hence, Tables 1 and 2 present estimates of possible minimum and maximum values.

Considering the distribution of shortening values along the thrust fronts, we have hypothesized that the values contained in Table 2 are components of displacement vectors which express the "true" shortening directions and maximum slip rates. Thus, from the sum of the NNE–SSW and WNW–ESE displacement vectors, we have obtained the estimates of the "real" shortening directions and slip rates, as summarized in Fig. 10. Comparison of these directions of shortening with the geological, geodetical, and seismological constraints on the Late Quaternary-current deformation vectors (see Fig. 11) supports this approach.

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