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A dense grid of petroleum industry seismic reflection profiles, coupled with field mapping, exploratory trenching and geomorphic and structural analysis are used to characterize the Quaternary growth history of the Capriano del Colle Fault System, one of several inferred active buried thrusts that extend across the Po Plain in northern Italy. Shortening is characterized here by a deeply buried south-vergent forethrust and an associated north-vergent backthrust whose upward propagation is expressed by fault-propagation folding near the surface. Structural interpretation based on seismic data suggests that strain is accommodated at very shallow levels by secondary flexural-slip thrusts and reverse faults developed on synclinal flanks that emanate from active axial surfaces. Analysis of syntectonic growth strata document maximum rates of dip-slip of 3.45 ± 0.66 mm/yr (1.6 Myr–1.2 Myr) and 0.47 ± 0.22 mm/yr during a more recent time period (0.89 Myr–present). A quarry excavation at Capriano del Colle allows a preliminary paleoseismologic analysis of coseismic surface faulting and liquefaction exposed near the core of an active mid-Pleistocene to Holocene anticline. These features are interpreted to be generated during strong local earthquakes, consistent with the environmental effects and ground motions of an event similar to the December 25, 1222, Brescia earthquake (Io = IX MCS). This indicates, for the first time, that compressive folds and blind thrusts in the Po Plain are currently accommodating slow rates of modern contraction in an active zone of the Southern Alps that extends from Lake Garda to Varese. We thus argue that earthquakes similar to the December 25, 1222 Brescia event are likely to occur in this region and pose a direct threat to such a densely populated and developed area.

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1. Introduction

The Lombardian Po Plain (Northern Italy) is located at the southern fringe of the western Southern Alps, an orogenic retro-wedge where shortening is accommodated by a fold-and-thrust belt (Fig. 1a) mostly buried beneath a thick sequence of Plio-Pleistocene sediments. This region is characterized by low to moderate crustal strain rates and moderate to strong, infrequent seismic events, as documented by historical seismicity catalogues (Boschi et al., 2000; CPTI, 2004; Guidoboni and Comastri, 2005; Fig. 1b). Even though seismicity catalogues can be regarded as complete for the last ca. 1000 years, the seismic hazard of this region is still poorly constrained, particularly because geological evidence for past earthquakes is rare and has not been assessed in a systematic way. As a consequence, historic, destructive seismic events in this area are poorly correlated with well-defined, causative seismogenic structures. It is still unclear, for instance, which is the causative tectonic source for local damaging seismic events such as the well studied December 25, 1222, Io = IX MCS, Brescia earthquake, an earthquake which has had several possible epicenters proposed for its source (e.g.; Magri and Molin, 1986; Guidoboni, 1986; Serva, 1990; Boschi et al., 2000; CPTI, 2004; Guidoboni and Comastri, 2005).

Several studies have previously suggested the presence of active structures in the area we studied. Early work by Desio (1965) identified isolated hills, underlain by Quaternary marine and fluvi deposits (Castenedolo, Cilivergha and Capriano del Colle hills, see Fig. 7a for location), whose presence cannot be explained by glacial or fluvioglacial morphogenetic processes. These hills were in fact previously interpreted as the culmination of growing anticlines associated with underlying thrusts (Desio, 1965; Boni and Peloso, 1982; Baroni and
Cremaschi, 1986; Cremaschi, 1987; Castaldini and Panizza, 1991; Curzi et al., 1992) but a detailed structural analysis have never been performed until now.

“Blind” thrusts are known to be located near the epicentral area of the 1222 earthquake; we therefore investigated these structures in order to determine whether they were potential seismogenic sources. Many recent studies point to the importance of active folds as indicators of coseismic slip on underlying capable faults (Burbank et al., 1996; Shaw and Suppe, 1996; Mueller and Suppe, 1997; Benedetti et al., 2000; Champion et al., 2001; Shaw et al., 2002; Dolan et al., 2003; Ishiyama et al., 2004; Lin and Stein, 2006; Lai et al., 2006; Chen et al., 2007; Leon et al., 2007; Streig et al., 2007). Kinematic models of fault-related folds have also been developed for both kink band (Suppe, 1983; Medwedeff, 1992; Medwedeff and Suppe, 1997) and trishear (Erslev, 1991; Hardy and Ford, 1997; Allmendinger, 1998) deformation mechanisms. All these models allow restoration of deformed strata

![Figure 1](image-url)
based on quantitative geometrical relationships between faults and associated fold geometries and provide constraints on deep thrust geometry based on shallow folding.

The architecture of syntectonic strata deposited during growth of active folds (e.g. growth strata) also provides a powerful tool in documenting the growth history of compressive structures (e.g. Suppe et al., 1992; Shaw and Suppe, 1994; Allmendinger and Shaw, 2000). Based on these structural methods and fault-related fold theory, we combined an analysis of seismic reflection profiles with field studies and geomorphologic analysis to illustrate the geometry, kinematics, Plio-Pleistocene growth history and earthquake potential of active blind thrusts and secondary faults located at the northern fringe of the Po Plain. We then consider these results with respect to a preliminary paleoseismological analysis based on trench-scale features observed at the Monte Netto site, near Capriano del Colle (Brescia). Finally we compare the seismogenic potential of blind thrusts in this region to the felt effects, macroseismic intensity, and estimated magnitude of the AD 1222 earthquake to determine if they give us a consistent picture, that could fit into the local seismic landscape (sensu Michetti et al., 2005).

2. Regional setting of the Capriano del Colle Fault System: Geological and seismotectonic framework

The Capriano del Colle Fault System (CapFS; Fig. 2a) comprises the eastern end of an active fold-and-thrust belt located at the outermost buried structural front of the Southern Alps. The study area includes the piedmont zone of the chain and its foreland, in a sector located between Lake Garda and the Oglio River (Fig. 2).

The Southern Alps of Lombardy represent a typical example of an ancient passive continental margin, subsequently shortened into a compressive orogenic wedge (e.g., Bertotti et al., 1997). The region is characterized by an array of south-vergent thin-skinned thrust sheets, and is bounded to the East by a regional transfer zone, the Giudicarie deformation system (Fig. 1a; e.g. Castellarin and Cantelli, 2000). The outermost structural front of the Southern Alps is the Val Trompia–Giudicarie belt (Fig. 1a; e.g., Castellari and Vai, 1986; Castellari and Cantelli, 2000; Castellari et al., 2004; Castellari et al., 2006), which mainly developed during Oligocene to Late Miocene time.

The distribution and segmentation of blind thrusts that comprise the Capriano del Colle Fault System (Fig. 2a) was defined by regional mapping using an extensive database of ca. 18,000 km of seismic profiles provided by ENI E&P that were constrained with hundreds of deep boreholes.

Faults were defined by obvious truncation of strata on seismic profiles (e.g. footwall and hangingwall stratigraphic cutoffs) and by construction of structure contour maps of folded horizons of various ages in the Plio-Quaternary sequence that infills the Po Plain basin (Fig. 2b). We characterized segmentation of blind thrusts using several methods (e.g. de Polo et al., 1991; Mirzaei et al., 1999) that included mapping of single segment faults that terminate at a transverse structure (e.g. a transfer fault) or where folding decreases to zero at the end of structures as defined by the regional dip of mapped strata. Other folds were identified as en-echelon structures that may rupture in multi-segment events. Structure contour maps clearly show a belt of segmented, 10 to 20 km long, fault-propagation folds buried beneath the Po Plain (Fig. 2a and b; e.g. Vittori, 2004). The Capriano del Colle Fault System is composed by a south-vergent thrust (CCT) and an associated high angle backthrust (CCB) located within the Val Trompia–Giudicarie belt (Fig. 2a).

Shortening rates accommodated by this thrust belt slows during the Tortonian (“Confolite” Deformative Phase: Oligocene–Miocene, mainly Chattian and Burdigalian, and “Valsugana” Deformative Phase: Serravallian–Tortonian; e.g., Castellari et al., 2006). Subsequent strain is however, well expressed by folding of Plio-Pleistocene strata in this sector of the northern Adria (Sileo et al., 2007; Chunga et al., 2007). Evidence for ongoing, modern contraction is also defined by moderate historical and instrumental seismicity recorded in this region (i.e., the December 25, 1222, Io IX MCS, Brescia; March 12, 1661, Io VII-VIII MCS, Montecchio; May 29, 1799, Io VI-VII MCS, Castenedolo; the December 5, 1802, Io VIII MCS, Soncino; November 30, 1901, Io VIII MCS, Salò; November 13, 2002, MI 4.2, Iseo; November 24, 2004, MI 5.4 Salò earthquake; e.g., Magri and Molin, 1986; Guidoboni, 1986; Serva, 1990; Burrato et al., 2003; Guidoboni and Comastri, 2005). The distribution of epicenters, based on historical seismicity catalogues (Boschi et al., 2000; CPTI, 2004), highlights two main zones of seismicity along this sector of the northern Po Plain: a) a NW–ENE-trending zone of earthquakes, sub-parallel to the piedmont sector and to the buried thrusts and b) a NNE–SSW-trending zone, that is readily correlated with the Giudicarie fault System (Fig. 1b). Evidence for active shortening is provided by geodetic data; these indicate shortening rates in the range of 2.2 mm/yr in the Friuli area and ca. 1.1 mm/yr near Lake Iseo measured with GPS from a fixed point in the Western Alps along vectors oriented NNE–SSW (Serpelloni et al., 2005).

3. Stratigraphic setting of the Capriano del Colle region

This region of the Lombardian Southern Alps consists of a Mesozoic accretionary wedge including Late Triassic to Jurassic carbonatic deposits deposited in the Jura-Cretaceous Lombardian Basin, following the opening of the Tethys Ocean (Winterer and Bosellini, 1981; Gianotti and Perotti, 1987; Bertotti et al., 1997). The outset of the Alpine orogenesis shed sequences of flysch (Cretaceous to Eocene) and molasse (Confolite Lombarda Group, Oligo–Miocene in age) into the Po Plain Foredeep. The Molasse, outcropping in western Lombardy, constitutes a Tertiary clastic wedge in the subsurface of the northern Po Plain (e.g.; Gelati et al., 1988; Bernoulli et al., 1989; Gelati et al., 1981; Bernoulli and Gunzenhauser, 2001; Scinnach and Tremola, 2004; Fantoni et al., 2004).

The older stratigraphic sequence shown in the seismic profile in Fig. 3 has been constrained by deep boreholes drilled by ENI E&P (see locations in Fig. 2a). Stratigraphic age controls for Quaternary sediments are based on in-house stratigraphic, paleontological and magnetostratigraphic analysis by ENI E&P and Regione Lombardia (Carcano and Piccin, 2002; Scardia et al., 2006) and an extensive database of shallow well logs acquired in boreholes drilled for groundwater (Pecin, pers. comm.). The oldest strata visible in the profile belong to the Confolite Lombarda Group (GL), a foreland and foredeep sequence of terrigenous units that range from Oligocene to Miocene in age. The entire Quaternary sequence is deformed by fault-related folds that form ramps above underlying Mesozoic carbonates; these faults offset the overlying Tertiary clastic wedge and fold younger Plio-Pleistocene strata in the basin. Two decollement levels can be detected. The deeper one is located at the base of Carbonate Units while a shallower rheologically weak level can be identified at the Late Eocene Gallare Marls Fm., at the base of Confolite Lombarda Group (Fanton et al., 2004; Ravaglia et al., 2006).

The Confolite Lombarda Group has been divided into 3 mega-sequences (Fig. 3), based on internal tectono-sedimentary architecture and sequence stratigraphy. Details are discussed in Section 4.2. The Tertiary sequence is bounded at its top by a regional erosional surface, the Messinian Unconformity, related to an abrupt and long lasting sea level drop of the entire Mediterranean (e.g.; Cita and Wright, 1979; 1982; Cita et al., 1990). Deep incision and associated channel networks are clearly recognizable in the seismic profiles (Fig. 3). At the northern edge of the profile a well-imaged channel, ca. 5 km wide, is interpreted to record deep Messinian incision of the Paleo–Mella river, cut longitudinally by the seismic line. Plio-Pleistocene infilling of this sector of the Po Plain is recorded by a high frequency alternation of fine and coarse sediments, mainly influenced by eustatic sea level oscillations (e.g; Rossi and Rogledi, 1988; Carcano and Piccin, 2002).

The sequence defines a general aggradational trend, reaching a phase of progradation and offshore, by longitudinal sediment transport, between 1.2 and 0.9 Ma (Muttoni et al., 2003). This is recorded in
seismic profiles as a thick sequence of eastward prograding clinoforms, recognizable across the entire Po Basin, although this is not strongly developed in the study area. Three widespread reflectors in the seismic data correlate with sequence stratigraphic surfaces of known age (Carcano and Piccin, 2002), and are recognized in the profile. These include the Blue, Green and Red Surfaces, respectively dated ca. 1.6, 1.2 and 0.89 Myr (Fig. 3). These are penetrated by deep ENI E&P boreholes in the central Po Plain and are age dated with calcareous nannofossils (Carcano and Piccin, 2002). The Red surface, first recognized as outcropping in the Northern Apennines, was correlated with ENI E&P borehole data and dated by calcareous nannofossils and a magnetostratigraphic analysis based on data from a deep borehole drilled by Regione Lombardia (Muttoni et al., 2003; Scardia et al., 2006).

4. Structural model and quaternary fault activity

4.1. Subsurface structure of the Capriano del Colle Fault System

A seismic reflection profile through the Capriano del Colle Fault System was interpreted to constrain the geometry of the faults and the
Fig. 3. Raw depth-converted seismic profile and stratigraphic interpretation based on correlation with ENI E&P deep boreholes (for the boreholes and seismic line location see Fig. 2a). White arrows indicate structural crest and depocenter points where calculations on structure uplift rates were performed. Lombardian Gonfolite Group was subdivided into 3 tectono-sedimentary sequences (Pre-GS; GS1 and GS2) recording the growth history of CapFS structure.
Fig. 4. Depth-converted interpreted seismic profile, across the Capriano del Colle Fault System, constrained by constant-thickness fault-related fold theory. Location is shown on Fig. 2a. There is no vertical exaggeration. (a) Seismic line with structural features used to estimate fault trajectories of the Capriano del Colle Fault System. Numbers in yellow circles indicate principal constraints used for fault recognition: (1) faults cutoff, (2) termination of fold limb or kink band and (3) direct fault-plane reflection. Abbreviations are: CCT, Capriano del Colle thrust; CCB, Capriano del Colle backthrust; CCTFSF and CCBFSF are associated flexural-slip faults. Values above arrows indicate limb widths, measured on the section. Thick dashed lines, active axial surface; dash and dotted thin lines, inactive axial surface; blue dashed lines, erosional features. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Fig. 5. Assessment of uplift and in situ sedimentation rates relative to chronologic intervals: a) Sketch of the methodological approach (e.g., Masaferro et al., 2002) applied to calculate uplift rates; b) graphic summary of the results according to the considered time windows. Error bars and U/S ratio value are also indicated. (*) indicates minimum uplift rate value, according to a fill-to-the-top growth model.
ramps are usually visible while detachments often remain indistinguishable and cannot be resolved (Ishiyama et al., 2004). Thus only the largest faults, that have accommodated significant displacement, can be interpreted by analysis based on seismic profiles. We expect that many similar structures, at different scales, affect the sedimentary cover over fault-related folds and therefore are partially responsible in upward consumption of slip. The analysis of axial surfaces recognizable in the seismic line is consistent with this interpretation. Some of the axial surfaces relative to CCB are in fact crosscut by the CCBFS fault plane. This is generally diagnostic of break-back imbricate thrusting, where movement of the upper thrust is successive or at least coeval to the deeper one. Total slip calculated for CCBFS is ca. 1250±50 m, based on the width of the fault-bend fold backlimb. A shallow south-vergent secondary structure, visible in the first 500 m at the northern edge of the seismic line, cuts through Early Pleistocene strata, just below the Capriano del Colle hill (Fig. 4). A detailed analysis of this secondary fault and its relationship with present-day morphology is discussed in Section 5.

4.2. Tectono-sedimentary history of the Capriano del Colle Fault System

While sedimentation and erosion in the Po Basin is affected largely by orogenic loading of the foreland of the Alps and Apennines and regional climatic and base level change associated with eustacy, local stratigraphic architecture reflects growth of Late Quaternary folds. This allows us to measure rates of rock uplift on these structures, define the kinematic history and style of compressive strain and hence define seismic hazard. Syntectonic growth theory (Suppe et al., 1992) suggests that cumulative displacement will decrease upward within the stratigraphic interval deposited during deformation. In contractional fault-related folds, syntectonic strata typically thin across folds limbs towards structural highs. We focus on the GL unit, whose deposition is quite contemporaneous to the inception of the Val Trompia–Giudicarie structural front. This unit has been divided into three tectono-sedimentary sequences that record the timing, growth history, and strain rates for the Capriano del Colle Fault System (Fig. 3).

Pre-GS ( Chattian–Serravallian p.p.) strata comprise a clastic coarse sequence, up to ca. 2 km thick, that is faulted and folded by the CapFS. The pre-GS sequence predates tectonic deformation since no changes in sequence thickness and no major onlap-offlap geometries have been recorded. GS1 (Serravallian p.p.–Early Tortonian) strata record contemporary development of the CCT, marked by progressively onlapping reflectors. To the north, thickness remains constant across the CCB structure. This sequence has been therefore interpreted as CCT piggyback basin deposits whose deposition was contemporaneous with wedge growth. During this period the southward migration of the buried Alpine front created a belt of structures directly facing the most external (e.g. frontal) thrust sheets in the Apennines belt. GS2 (Tortonian) strata record fault/fold growth on structures in the frontal structures of both the Alps and Apennines, and thus constitute a wedge-top basin. The CCB began to develop, during this period, as an out-of-sequence north-verging backthrust. A kinematic solution for the Capriano del Colle Fault System and a detailed analysis of the Plio-Pleistocene syntectonic sedimentary record allows slip rates to be determined for the blind thrust beneath the folds. The geometry of growth structures is controlled primarily by the shape of the underlying fault and by the relative rates of sedimentation and uplift (Suppe et al., 1992). The ratio between sedimentation and uplift rate exerts a significant influence by either enhancing or masking thinning of strata across a particular structure. The crestal structural relief (McClay, 1992) at a specific time \( T \) has been obtained by subtracting the thickness of all the growth beds deposited on the anticline crest prior to time \( T \) from the thickness of the same growth beds in the basin adjacent to the anticline. Rock uplift rates (\( U \)) have then been calculated as the difference in structural relief, relative to the top and to the bottom of a specific growth bed (e.g., Suppe et al., 1992; Masoferro et al., 2002; Fig. 5a). Crest and basin depocenter points used for calculations are indicated on Fig. 3. In situ accumulation rates (\( S \)) were also calculated and compared to relative uplift rates (\( U/S \) ratio; Fig. 5b). A very high accumulation rate, with respect to uplift rate (very low ratio \( U/S \)), can in fact, obscure the tectonic signal and appear as an interval apparently not influenced by contemporary uplift. Uncertainties in uplift and sedimentation were evaluated in terms of the resolution and variability in seismic reflector character (ca. 25 m), and errors in age bracketing (ca. ±0.1–0.05 Myr, according to the considered surface). Errors were calculated following the error propagation rule for values with unequal standard deviations (Geyh and Schleicher, 1990). Results, relative to each structure, are summarized as follows (Fig. 5).

For the CCT, during the first chronostratigraphic interval (Pliocene–1.6 Myr) very low values of uplift and sedimentation rates have been recorded. Growth beds onlapping the fold limb and thinning as they approach the fold crest predominated during the first part of this period. Such a low value of average rock uplift rate may be related to averaging a relatively short episode of tectonic deformation over a very long time period (duration is ca. 3.6 Myr). The second time window

Fig. 6. Slip rates for the Capriano del Colle Fault System. Since there is no evidence for significant lateral displacement, only the net dip-slip throw has been considered. (*) indicates minimum slip rate value, according to a fill-to-the-top growth model.
(1.6–1.2 Myr) records higher values both in uplift and sedimentation rates. \( U = 0.51 \pm 0.19 \text{ mm/yr} \) and \( S = 2.45 \pm 0.19 \text{ mm/yr} \). \( U/S \) ratio is 0.21. The following period is characterized by a deactivation of this thrust, as testified by syntectonic growth strata that maintain the same thickness throughout the CCT crest. Since the \( S \) value (2.10 ± 0.33 mm/yr) is constant for this period, compared to the previous interval, it is apparent that the tectonic signal has not been concealed by a significant increase in sedimentation rates. The 0.89 Myr to present chronostratigraphic interval records a decrease both in uplift and sedimentation rates.

For the CCB, during a Pliocene to 1.6 Myr time window, our analysis suggests that this structure initially experienced similar low values of sedimentation and uplift rates. We maintain the same considerations discussed above for calculations on rock uplift CCT structures to be valid. During the 1.6–1.2 Myr time interval \( S = 1.63 \pm 0.19 \text{ mm/yr} \) and \( U = 1.35 \pm 0.19 \text{ mm/yr} \). In the following period (1.2–0.89 Myr) tectonic deformation is still active (\( U = 1.38 \pm 0.33 \text{ mm/yr} \)) contemporaneous to a significant decrease in sedimentation rates, as highlighted by the high value of \( U/S \) ratio. This drastic lowering in sedimentation rate is consequence of the progressive infilling of the Po Plain basin that, for this sector, was starting to shift to a continental, alluvial plain environment. The latest period (0.89 Myr–present) is characterized by a decrease in uplift rate (0.22 ± 0.06 mm/yr) and the onset of regional nondeposition and/or erosional conditions over the entire Po Basin area. The Red Surface is thus not visible throughout the entire CCB structural high. Thus, assuming a fill-to-the-top growth model, the calculated rate has to be considered as a minimum value. Calculated uplift rates were then used to obtain net dip-slip rates, assuming the underlying fault geometry (Fig. 6).

Seismic reflection profile interpretation and calculated uplift and slip rates have constrained the tectono-sedimentary history of CapFS from Pliocene to Middle Pleistocene time. The calculated slip rates (Fig. 6), relative to the youngest constrained chronostratigraphic interval (0.89 Myr–present), is 0.47 ± 0.21 mm/yr. More recent rock uplift above these faults could not be resolved by industrial geophysical data, since the available seismic profiles do not contain reflectors in the upper ca. 150 m and dated surfaces, younger than 0.89 Myr, are not mapped in this area.

5. Landscape response to fold growth: The Capriano del Colle hill

The Capriano del Colle hill is located at the northern fringe of the Lombardian Po Plain, just south of the city of Brescia (Fig. 7a). It is an isolated hill, almost rectangular in shape (ca. 5 km in length and 2 km in width), trending N 110 and sticking out ca. 30 m relative to the surrounding alluvial plain. The Garda piedmont glacier, coming from the north, has never reached this sector of the Po Plain, as testified by the most external terminal moraines of the Garda amphitheater (Fig. 7a). The hill exposes a gently tilted, fining-upward sequence of Pleistocene fluvioglacial and fluvial sediments (braided floodplain environment) that is unconformably overlain by loess sequences (Fig. 7b). The hill is deeply eroded on its sides. During Quaternary time, large glaciers extended along the valleys that now contain Lake Garda and Lake Iseo; these are located 15 and 10 km to the east and to the northwest of Capriano del Colle hill, respectively. The morphology of the piedmont belt in this area, except where it is covered by moraines, is essentially constituted by a huge outwash fan, developed during the last glacial maximum by a meltwater channel network (e.g., Baroni and Cremaschi, 1986; Marchetti, 1996) that has been subsequently incised by local drainages. The surface projection of the CCB fault is located just north of Capriano del Colle hill (Fig. 7b). The projected locations of hinge zone traces coincide with local structural and topographic relief. The Mella River cuts through the structures flowing from north to south and the trace of this river and its tributaries appear to be related to mapped structural features. Anticlinal hinge zone traces run in fact along alignments of river deviations and, as expected in areas of progressively decreasing gradient (e.g., Ouchi, 1985), an increase in river sinuosity is observed as each river crosses an anticlinal hinge zone (Fig. 7b). Minor drainage, deep entrenched gullies, affects mostly the southern side of the hill. These channels, ca. 3–6 m deep and 2–5 m wide, were excavated through the whole sequence of the hill during the fold growth.

The present channel of the Mella River flows around the western edge of the hill. Three paleo-channels, all attributed to older channels of the Mella River, were recognized both at the level of the modern floodplain and cutting through the hill surface. A 4-stage evolution model is thus proposed based on Mella River paleo-channel traces (numbered circles on Fig. 7b). Relative timing of these channels has been inferred from geomorphologic constraints and channel-bed relative height. This model implies a progressive increase in the area of rock uplift of the Capriano del Colle structure and a contemporary northward migration of the Mella River, which has been progressively deviated to the east (stages 1 to 3). During each stage, the Mella River was deviated to the east by the growing fold; each paleo-channel therefore records the former endpoint of the fold-related stratigraphic succession. Widening of the area undergoing rock uplift and related northward migration of the river channels are consistent with progressive forelimb widening above a kink-band migration model of fault-propagation fold rather than progressive tilting, as would be expected from fixed-axis models. Finally, in stage 4, the Mella River deviated to the west, to its present-day position.

A detailed structural analysis of the seismic line, performed on the original double-TWTT section, revealed the presence of a shallow south-verging structure, cutting through an Early Pleistocene sequence, recognizable in the northern sector of the seismic line, in the upper ca. 500 m (Cc0 on Fig. 8b). This structure consists of a multi-fan flexural-slip fault whose ramp sector is pinned, at its base, with the synclinal axial surface on the CCB (\( \alpha \) on Fig. 8b). Even though the front limb of CCB fold is not well imaged on the seismic line, both CCB and Ccox associated folds show narrower hinge zones and a growth strata architecture typical of constant-thickness model. As the CCB grows, slip is marked by northward migration of the \( \alpha \) axial surface. As a consequence, this secondary shallow flexural-slip fault passively accommodates strain southward. Growth triangles developed above the fault hangingwall indicate that fault movement probably started after 1.2 Myr (Green Surface) and has continued to the present (Fig. 8b and c). Topography of the central sector of Capriano del Colle hill, obtained through a total station survey (Fig. 9), corresponds exactly to the structural relief defined by two outcropping secondary antilines exposed on a quarry wall that fold and displacing Middle to Late Pleistocene deposits (Fig. 10). These antilines are located in the crestal sector of Cc0x associated fold (Fig. 9). Seismic reflection data are not resolved well enough to define the architecture of growth strata on this structure.

6. Surface faulting from folding: The Monte Netto site

In order to define the most recent evidence for compressive tectonics in the CapFS area, a detailed geological and geomorphological field survey was conducted. Investigation sites were selected based on Fig. 7. (a) 3D view of northern Po Plain and Capriano del Colle area. Vertical exaggeration: 5x; (b) geological map of Capriano del Colle area: fold hinges, paleo-channels and secondary folds are indicated. Numbered circles indicate progressive northward migration and deviations of Mella River around the hill. Note that present-day river deviations and pattern changes coincide with their passage across the folds. Mella River trace was derived from a 1968 topographic map.
Fig. 8. Multi-scale seismic reflection images and interpretations of the CCB fault and Capriano del Colle topographic profile. Topographic vertical scale is strongly exaggerated in order to highlight subtle geomorphic features. Light grey lines indicate line drawing; black continuous lines, modeled horizons; thick dashed lines, active axial surface; dash and dotted thin lines, inactive axial surface; α indicates CCB synclinal active axial surface and Ccα an associated passive flexural-slip fault, see text for details.
the most promising geomorphological evidence of recent tectonic activity and available outcrops of Quaternary deposits. A quarry excavation at the top of the Capriano del Colle hill, hereinafter referred to as the Monte Netto site, allowed us to conduct a preliminary paleoseismological analysis, supported by new trenching and soil stratigraphy data, on ca. 150 m long, 7 m high, north–south and east–west trending trench walls. The detailed paleoseismic analysis of the Monte Netto site is beyond the scope of this paper and will be the subject of a companion paper; here we provide the main preliminary results which are relevant for the understanding of surface slip propagation from the buried CCB fault, and related seismotectonic implications. Two secondary anticlines, tens of meters in size (ca. 4 to 9 m of exposed amplitude) and deforming a sequence of Quaternary continental strata (gravel, sand and clay), have been recognized (Fig. 10a and b). The core of the anticlines is composed of a sequence of fluvioglacial sediments. These units are overlaid by a loess–paleosols sequence, laterally thickening up to 6 m (Fig. 10b). The stratigraphy of this sequence has been described in detail by Cremaschi (1974, 1987) based on observations from an older quarry exposure located nearby. The paleosols sequence includes three different paleosol-parent materials, which are related to different episodes of pedogenesis. The oldest paleosol, red colored, was developed on the fluvioglacial sequence (Middle Pleistocene (?); Fg2), whereas the other two soils were developed on the loess sequence (Upper Pleistocene–Holocene (?); LL). Radiometric and OSL dating is in progress at this site, however some age constraints are provided from the development of paleosols and from paleo-ethnological studies. (e.g., Cremaschi, 1974). Recent flint artifacts findings give us an age range of 300 to 30 kyr B.P. for the whole loess sequence (Berlusconi et al., 2007).

The loess was deposited onto the topographic surface after folding of the fluvioglacial sequence and ongoing strain caused the development of brittle deformation. Deformation is characterized by extensional bending-moment faults, formed on the culmination of the northern anticline, that offset the entire exposed sequence (Fig. 10f). A reverse fault was exposed by trench excavation at the southern termination of the northern anticline (Fig. 10b and c). This fault offsets the sequence up to 3 m and reveals a southern vergence for the northern anticline.

Bending moment faults are interpreted to result from coseismic stretching of the top of the anticline where the uppermost soil is clearly displaced. The maximum throw on the exposed normal fault is ca. 2 m, measured at the top of the central graben (Fig. 10d). Offset across the faults decreases downward, confirming their origin as secondary structures that form in response to folding. This fault cuts at least the lower part of the Fg2 sequence, without evidence of colluvial re-deposition or strata thickening thus it clearly postdates the displaced sequence. Furthermore, the upper part of the paleosol sequence is characterized by the occurrence of sub-vertical parallel fissures, regarded as secondary brittle deformations successively affected by pedogenetic processes with illuvial clay infilling. The exposed section also contains a liquefaction feature (Fig. 10e) consisting of a sand and gravel dike cutting through ca. 60 cm of the sequence and whose presence is interpreted to be related to the strong ground motions produced by a local earthquake, possibly generated by the underlying CCB structure.

7. Discussion

Reconstruction of CapFS fault geometry and kinematics allow us to test the consistency between fault parameters and the seismotectonic framework depicted by historical seismicity. Available seismic data, although of good quality and resolution, do not allow us to derive a single deterministic model for maximum expected Magnitude for structures that are deforming at the low strain rate common in the Northern Alps. A better estimate can, however, be derived from an analysis of several scenarios for fault derived Mw, including uncertainties related to fault geometry. Table 1 summarizes the maximum and minimum values of for fault length, width, fault area, net dip-slip rates and range of derived Mw for each of the studied structures. Scalar relationships between fault area and maximum expected Magnitude (e.g. Wells and Coppersmith, 1994), indicate that both CCT and CCB, if considered active seismogenic sources, could be able to produce Mw = 5.9–6.5 earthquakes.

The maximum recorded historical earthquake in the region is the December 25, 1222 Brescia earthquake Io IX MCS), one of the largest events in the entire Po Plain, whose epicentral area has been located just south of Brescia city (Fig. 11). This event, which characterizes the seismotectonic framework of the Lombardian Southern Alps (e.g., Magri and Molin, 1986; Serva, 1990), produced significant damage across much of Northern Italy and generated ground effects in the
Fig. 10. (a) Western quarry wall on the top of Caprano del Colle hill. Location is shown on Fig. 7b; (b) detail on the sector between northern and southern anticline, location of the trench represented in (c) is also shown; (c) eastern trench wall excavated at the quarry floor: a high angle reverse fault, also indicated in (b), has been documented; (d) detail of the bending-moment normal faults affecting the upper part of the sequence: note the progressively downward decrease in offset of normal faults; (e) detail on the identified liquefaction feature: a sand and gravel dike, ca. 80 cm high, and an associated flame-like secondary deformation affecting the overlying light brown clays; (f) structural data of the northern anticline outcrop: fold limb, fractures and faults are indicated. Calculated paleo-stress (after Tucker, 1951) documents a $\sigma_1$ principal stress almost vertical and a $\sigma_3$ stress, directed N190. Abbreviation are: Fg2, Upper Fluvioglacial sequence (Middle Pleistocene?), LL, Loess deposits (Middle to Late Pleistocene?).
The tectonic source of this earthquake still remains questionable but some important observations can be summarized as follows:

- The CCB structure is located beneath the epicentral area of the earthquake (Fig. 10b) as well as the CastFS north-verging thrust (Fig. 2a); they both belong to the same structural front and show similar structural architecture.

- The Macroseismic field shows an almost ENE–WSW major axis, consistent with the average trend of the buried structures (Fig. 11).

- Intensity derived Magnitude for the Dec. 25, 1222 event is Me = 6.2 (Guidoboni and Comastri, 2005). This estimate is also in good agreement with the distribution of Magnitude values for each Intensity class, based on an extensive catalogue in the Mediterranean region (D’Amico et al., 1999). Mean value for Intensity (MCS) IX is Ms 6.2, in a range between 5.8 and 6.7. All these estimates are comparable with CCB seismogenic source characteristics (ca. Mw = 6.2–6.6, see Table 1).

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**Table 1**

Geometric and seismotectonic characteristics of the studied faults; minimum and maximum values are indicated.

<table>
<thead>
<tr>
<th>Fault name</th>
<th>W (Km)</th>
<th>L (Km)</th>
<th>Area (km²)</th>
<th>Slip (mm/yr)</th>
<th>Mwb</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCT</td>
<td>3.5–10.5</td>
<td>20–23</td>
<td>70–242</td>
<td>0.04</td>
<td>5.9–6.4</td>
</tr>
<tr>
<td>CCB</td>
<td>8–11.6</td>
<td>20–30</td>
<td>160–348</td>
<td>0.43</td>
<td>6.2–6.6</td>
</tr>
</tbody>
</table>

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*Average slip rate is considered over the most recent time interval (0.89 Myr–present, see Fig. 6). *

*Derived from empirical regression between Subsurface rupture area and Mw (Wells and Coppersmith, 1994).*
Surface environmental effects for such strong earthquakes usually include fracturing, surface displacement and liquefaction features (Serva, 1994; Guerrieri and Vittori, 2007). Features observed in Capriano del Colle site are consistent with such effects and with those quoted for the Christmas 1222 event (Guidoboni and Comastri, 2005). In particular surface deformation has been interpreted as due to secondary flexural-slip faulting, as observed for the CCB structure.

CapFS and adjacent structures (i.e. CastFS, to the east, see Fig. 2a) are characterized by similar fault geometry and Quaternary uplift rates (Livio et al., 2009). Deformation rates in the order of fractions of a mm per year are consistent with the earthquake size, slip per event and recurrence interval displayed by Christmas 1222-like earthquakes, regarded as the maximum historical earthquake experienced by the northern Po Plain (e.g., Serva, 1990; see the empirical relations presented in Slommons and DePolo, 1986).

Repeated 1222-like earthquakes occurred during the Late Quaternary in this area would have produced a cumulative observable effect of coseismic surface deformation and faulting, i.e., a specific seismic landscape (Michetti et al., 2005). The observations at Capriano del Colle site are consistent with this hypothesis.

8. Conclusions

This study defines the growth and seismic hazards posed by blind thrusts in the Po Plain using interpretation and structural analysis of seismic data, geomorphological analysis of rivers and trench-scale excavations of active folds and faults. A structural solution and geomorphic evidence are consistent with a deformation model that implies progressive kink-band widening above faults characterized by curved fold hinges. Bedding parallel faults, formed near the surface, play an important role in accommodating folding and induce surficial deformation, where no primary surface faulting has to be expected. This finding has primary importance for the identification of capable faults (sensu IAEA, 2002; Michetti et al., 2005) in active compressional tectonic environments and for surface faulting hazard evaluation in the Po Plain, particularly as related to siting and seismic design of critical facilities. The reconstruction of Quaternary tectono-sedimentary history of CapFS structures, based on geophysical data, demonstrates that both the CCB and CCT are active at least up to Middle Pleistocene time. Geomorphological data and our preliminary analysis on outcrops of folded strata probably record active strain during Late Pleistocene time. Work is in progress to obtain a complete dating of the Capriano del Colle quarry sequence through OSL and AMS analyses. Earthquake scenarios depicted for CapFS faults seismic potential have not been considered and their implications for earthquake seismicity haven’t been considered. This study greatly improved the manuscript. This research has benefited from funding provided by the Italian Presidenza del Consiglio dei Ministri – Dipartimento della Protezione Civile (DPC). Scientific papers funded by DPC do not represent its official opinion and policies.

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