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Early orogenic normal faults and their reactivation during thrust belt evolution: the Gubbio Fault case study, Umbria-Marche Apennines (Italy)

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Abstract

Foreland (early-orogenic) and hinterland (late-orogenic) extensional domains have been widely documented in the Northern Apennines, where they are synchronous with contraction in the active part of the fold and thrust belt. The progressive eastward migration of the contractional front and the associated hinterland extensional field implies that early-orogenic extensional structures, developed in the foreland domains, may experience reactivation/inversion. We present new field data, integrated with seismic evidence, from the Gubbio normal fault, a 22 km long presently active fault, showing: a) evidence for early-orogenic extension since the Lower Miocene time; b) successive positive inversion during the Upper Miocene contraction; and c) renewed, late-orogenic, extension during the Quaternary age. Field data allowed two systems of mesoscale normal faults, respectively interpreted as early- and late-orogenic structures, to be recognised. Stress fields associated with contractional and early- late-orogenic extensional tectonic regimes, are characterised by an overall coaxiality, with directions of compression and tension consistently aligned NE-SW. The symmetry between the successive deformation stages is interpreted as a likely cause for the repeated reactivation of the Gubbio fault since the Miocene. Our analysis in the Gubbio area shows that normal faults play a key role during the evolution of a fold and thrust belt from the early-orogenic stages, when they influence the geometry and evolution of foredeep basins, to the late-orogenic stages when Quaternary activity, due to extension reactivation, controls the evolution of the intramountain basins.

Keywords: Gubbio fault; Northern Apennines; Reactivation; Normal faults; Inversion

1. Introduction

Since the 1970's, it has been recognised that the Miocene to present tectonic evolution of the Northern Apennines was characterised by contemporaneously active extension and contraction, spatially distributed within distinct domains from the hinterland to the chain region, respectively (e.g. Elter et al., 1975; Lavecchia et al., 1987, 1994; Lavecchia and Stoppa, 1990; Barchi et al., 1998a). More recently, earlier extensional systems have been recognised in the eastern foreland region, where they played a key role during the evolution of foredeep basins before the onset of the contractional phase s.s. (Mazzoli, 1994; Tavarnelli et al., 1998; Tavarnelli, 1999; Tavarnelli and Peacock, 1999; Scisciani et al., 2001, 2002). At any time during this tectonic history, contractional deformation along the outer Apenninic arc was spatially bracketed between two synchronous extensional domains developed in the hinterland and in the foreland region, respectively. The continuous eastward migration of both extension and contraction implies that early normal faults may either experience and record multiple reactivation events (Pizzi and Scisciani, 2000; Mirabella et al., 2004) or be cut by later reverse faults (Scisciani et al., 2001, 2002).

The structures developed within the described deformation domains have previously been defined as pre-, syn- and post-orogenic structures (Tavarnelli et al., 1998; Tavarnelli and

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Peacock, 1999; Scisciani et al., 2001, 2002). In this paper, we prefer the terms ''early-orogenic'' (instead of pre-orogenic) and ''late-orogenic'' (instead of post-orogenic) for two reasons. Firstly, both these extensional systems are strictly related to the orogenic process and occur while shortening is active in adjacent structural domains. Secondly, the Umbria-Marche fold and thrust belt involves previous passive margin environments, probably affected by older extensional events (e.g. Coward et al., 1999). Following this criterion, we use the term ''pre-orogenic'' to refer to structures that formed before the onset of contraction in the Northern Apennines and whose origin is not related to the orogenic processes (e.g. Jurassic extension, Bally et al., 1986; Cretaceous-Early Paleocene extension, Marchegiani et al., 1999; Tavarnelli, 1999).

We present new field data discussed in the context of already published seismic data (Mirabella et al., 2004), illustrating the tectonic evolution of the Gubbio fault, an early-orogenic normal fault that successively experienced tectonic inversion during the contractional phase, followed by late-orogenic reactivation. Field data provide information about the geometry and kinematics of the structures, allowing definition of the early- and late-orogenic fault kinematics and the associated stress fields. We finally discuss our results in the framework of the evolution of the Apennines fold- and thrust-belt.

2. Geological setting

The Umbria-Marche Apennines are a fold- and thrust-belt, developed in the outer part of the Northern Apennines in response to NE-SW contraction active since Middle Miocene, where both late- and early-orogenic extension have been recognised in the hinterland and in the foreland regions, respectively. The late-orogenic extension presently affecting the hinterland region of the Apennines is widely accepted even if its origin is still a debated issue (e.g. see different interpretations in Carmignani and Kligfield, 1990; Lavecchia and Stoppa, 1990; Doglioni, 1995; Jolivet et al., 1998; Doglioni et al., 1999). Independently from the particular geodynamical model to explain extension in the hinterland region, it is a line of evidence that extension regularly follows the eastward migration of the contractional front (contraction-extension pair in Elter et al., 1975; Barchi et al., 1998a).

In the Umbria-Marche Apennines late-orogenic extension is active since the Quaternary, producing a set of NW-SE trending continental basins bounded by SW-dipping active normal faults on the eastern margin (e.g. Boncio and Lavecchia, 2000b and references therein). Most of these faults are antithetic to a regional low angle ENE dipping normal fault, the Altotiberina Fault, which extends for at least 55 km from Città di Castello to Perugia (Boncio et al., 1998, 2000; Collettini and Barchi, 2002).

Early-orogenic extension, occurring in the foreland region, has been interpreted as the response to flexural bending of the lithosphere (peripheral bulge, e.g. Doglioni, 1995). This kind of tectonics, anticipating the onset of contractional deformation, have been evidenced by both field-examples and seismic data (Tavarnelli et al., 1998; Tavarnelli and Peacock, 1999; Scisciani et al., 2001, 2002; Mirabella et al., 2004). In some cases, early-orogenic normal faults apparently controlled the thickness, distribution and facies of the syntectonic, foredeep deposits (Scisciani et al., 2001, 2002; Mirabella et al., 2004).

The Gubbio area is characterised by the NW-SE striking, east verging, Gubbio anticline, where the Jurassic-Oligocene Umbria-Marche carbonatic multilayer is exposed. The Gubbio anticline contrasts with the smooth landscape of the surrounding areas, where the Miocene turbidites of the Marnoso Arenacea Formation extensively crop out (Fig. 1). Several deep gorges, incised across the anticline, provide outcrop where both stratigraphic and structural analysis can be performed. The Gubbio anticline originated during Middle-Upper Miocene, and its eastern, steeply dipping forelimb is affected by the splays of the main west-dipping Gubbio thrust as well as by subsidiary minor backthrusts (De Feyter and Menichetti, 1986; Menichetti and Pialli, 1986). The western backlimb is not exposed at the surface, since it is downthrown by the Quaternary Gubbio normal fault (Fig. 1c; Menichetti and Minelli, 1991; Collettini et al., 2003). The Gubbio normal fault is well exposed at the surface, with a 60°–70° SW-dipping main plane on the eastern margin of the 22 km long Quaternary Gubbio basin (Fig. 1a). The kinematics is extensional, on the basis of geological displacements and associated structural patterns of mesoscale faults, cataclasites and *sc* tectonites within the damage zone. The listric geometry at depth of the Gubbio normal fault, as reconstructed by Menichetti and Minelli (1991), has been confirmed and constrained by seismic data interpretations (Mirabella et al., 2004).

Tavarnelli and Peacock (1999) firstly presented and discussed field evidence of extensional structures pre-dating thrusting and folding in the Gubbio area. Early-orogenic extension in this area is also suggested by lateral facies and thickness variations within the Lower Miocene foredeep sediments (Ridolfi et al., 1995).

3. Seismic data

A series of seismic reflection profiles were acquired in the Gubbio area in the 1980's by Agip. The profiles cross the Gubbio anticline and the Gubbio fault from the SW to the NE. The interpretation of these data constrains the subsurface geology of the region and enables reconstruction of its tectonic history (Bally et al., 1986; Barchi et al., 1999; Pauselli et al., 2002; Mirabella et al., 2004). Mirabella et al. (2004) reconstructed the offset distribution of the Gubbio normal fault, locating the sub-surface tip-points and inferring a maximum offset of about 3 km, reached about 1 km NE of Gubbio.

We present three seismic lines (L1, L2 and L3, see location on Fig. 1a), imaging the geometrical and kinematical relationships between extensional and reverse faults (Fig. 2). The interpretation of the seismic profiles is based on the correlation of key-reflectors of some well identifiable horizons of the Umbria-Marche stratigraphy, which is composed of four main lithological units: Carboniferous basement rocks; Triassic evaporites (i.e. Anidriti di Burano formation – Martinis and Pieri, 1964); Lower Jurassic – Early Miocene carbonatic

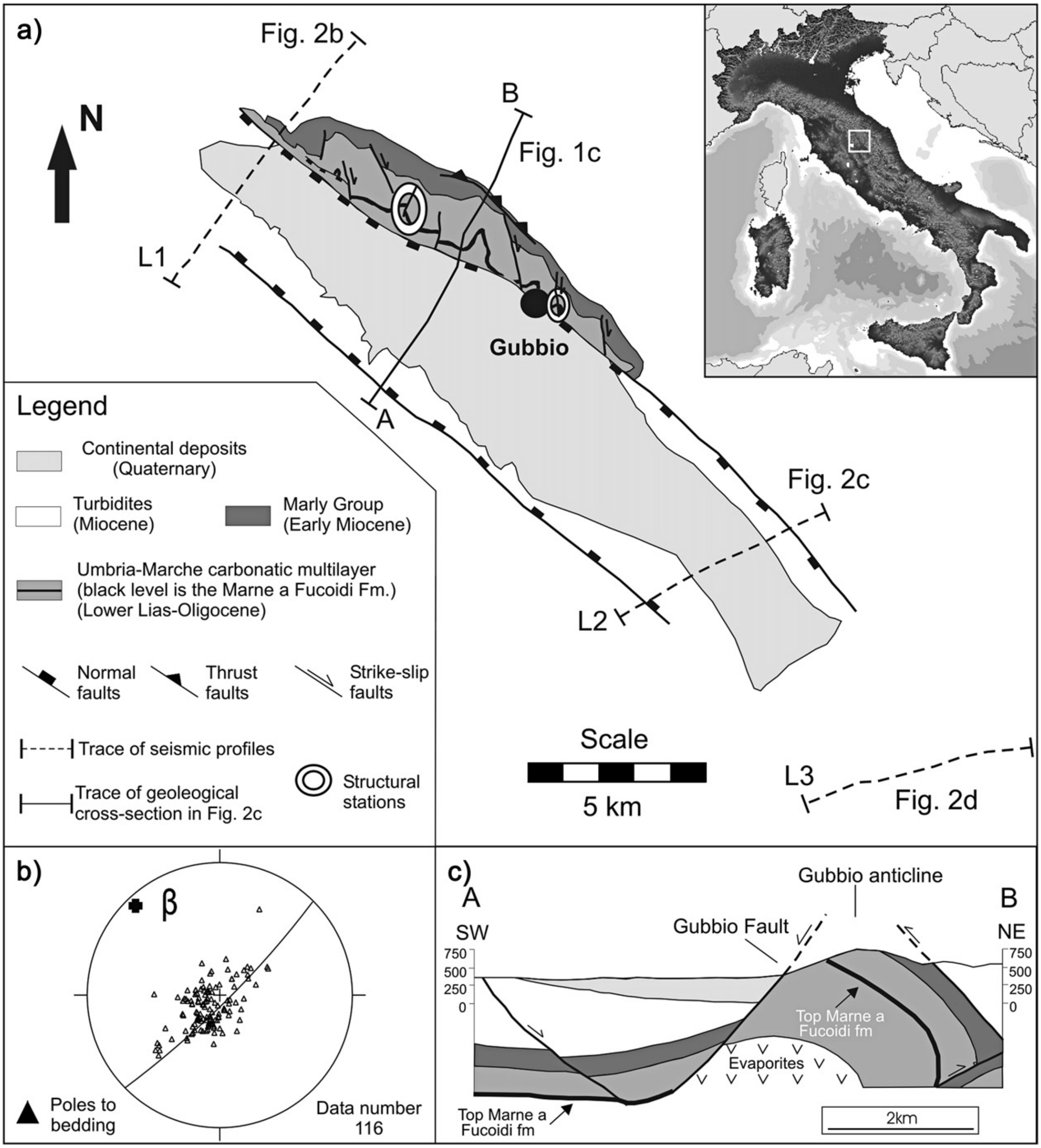

Fig. 1. (a) Geological-structural map of the Gubbio area showing the locations of the interpreted seismic reflection profiles, the main faults and the Quaternary Gubbio basin. Data source: Menichetti (1992), Boncio et al. (2000), and Collettini (2001). Inset shows the location of the study area. (b) Summary of the Gubbio anticline poles to bedding and their mean-great-circle (equal area lower hemisphere projection). The calculated β axis for the Gubbio anticline is ~N312°E. (c) Geological cross-section across the Gubbio anticline (trace in Fig. 1a) showing its NE vergence, the Gubbio normal fault downthrowing the backlimb of the anticline and the Quaternary Gubbio basin in the normal fault hanging-wall. The stratigraphic position of the Marne a Fucoidi Fm is added for further reference (modified after Menichetti, 1992).

multilayer; Miocene turbidites (Fig. 2a). The most important key-reflector, driving the seismic interpretation, corresponds to the Marne a Fucoidi formation (Aptian-Albian), located in the upper part of the carbonatic multilayer (Fig. 2a), whose strong reflection is due to the velocity contrast between its marly constitution ($V_p \sim 4.5$ km/s) and the surrounding limestones ($V_p \sim 5.0$–5.6 km/s). The seismic profile L1 (Figs. 2b,c, see location on Fig. 1a) crosses the Gubbio structure at the NW termination of the Gubbio anticline, whilst the profile L2 crosses the Gubbio basin, about 4 km SE of the southern termination, where the anticline is buried beneath the turbidites of the Marnoso Arenacea formation. Seismic profiles L1 and L2 both show the backlimb of the Gubbio anticline downthrown to the SW by the Gubbio fault. The

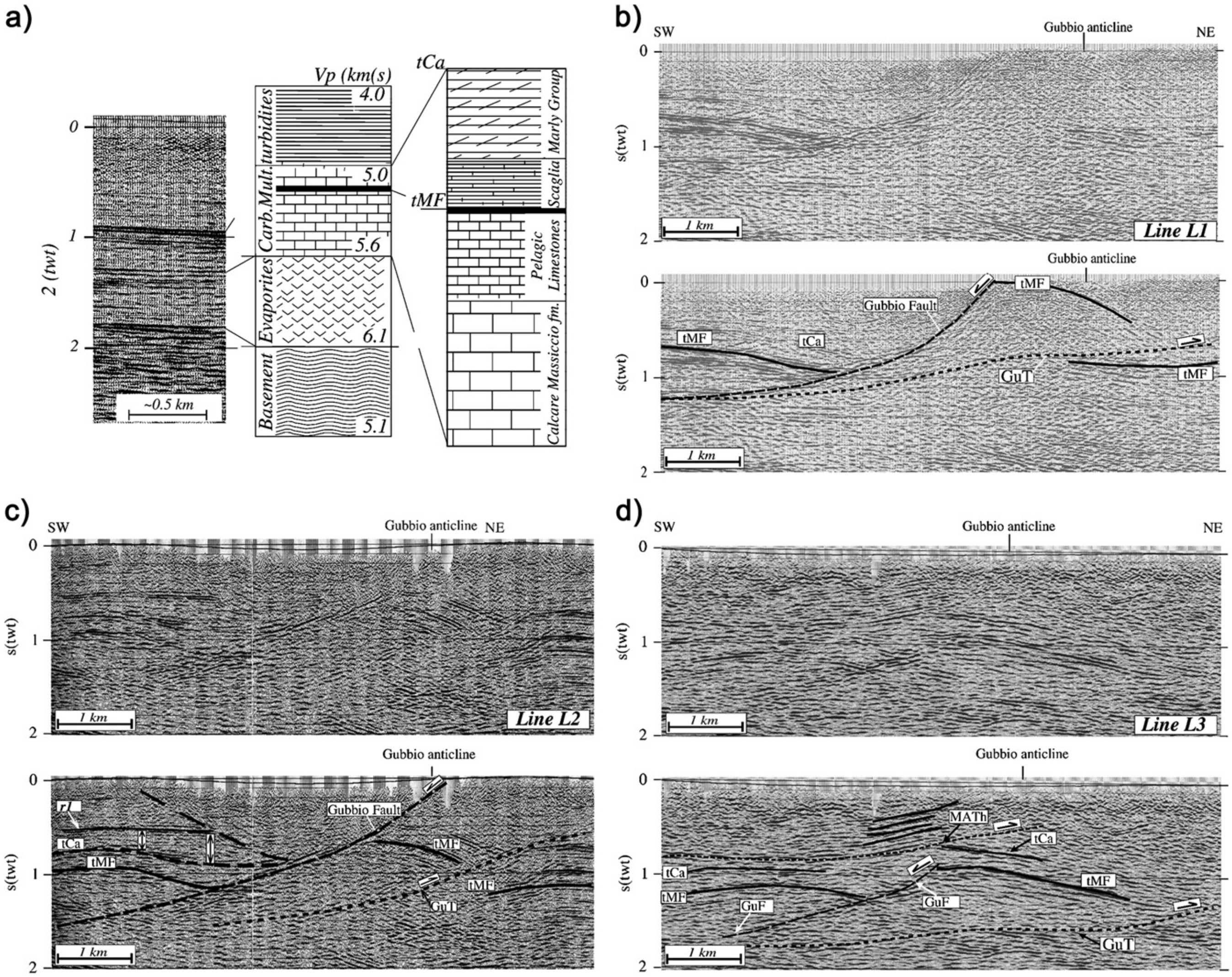

Fig. 2. Seismic data in the Gubbio area. (a) Seismic image of the Umbria-Marche stratigraphy (left), main litho-structural units with V_P interval velocities (middle) and detail of the Carbonatic multilayer (right). Interval velocity values are averaged from deep wells of the Umbria region (Bally et al., 1986; Barchi et al., 1998b). (b) Seismic profile *L1* (top) and geological interpretation (bottom) showing the geometry of the Gubbio anticline and the trace of the Gubbio fault merging with the Gubbio thrust at depth. (c) Seismic profile *L2* (top) and geological interpretation (bottom) showing the increase in thickness of the sediments comprised between *tCa* and *r1* reflectors. (d) Seismic profile *L3* (top) and geological interpretation (bottom) showing the trace of the Gubbio Fault being truncated by the shallow thrust (*MATh*) that was active during the Upper-Middle Miocene shortening. Keys to abbreviations, *tMF*: top Marne a Fucoidi Fm; *tCa*: top carbonatic multilayer; *r1*: key-reflector within the Marnoso Arenacea Fm; *GuT*: Gubbio Thrust; *MATh*: shallow thrust at the base of the Marnoso Arenacea Fm.

seismic expression of the Gubbio fault is marked by a SW dipping alignment of reflectors that truncate the group of reflections belonging to the carbonatic multillayer (from the top of the evaporites to the Marne a Fucoidi formation, Fig. 2b).

Evidence for early-orogenic extension has been observed on the seismic profile *L2* (Fig. 2c): at the hanging wall of the Gubbio fault, the lower part of the Marnoso Arenacea turbidic succession beneath the planar reflector *r1* (Fig. 2c) increases to a thickness of about 200 m moving towards the fault (i.e. from SW to NE). This thickening suggests growth during activity of the Gubbio fault during an early orogenic extensional phase, contemporaneous to the deposition of the lower part of the Marnoso Arenacea formation (up to Langhian time). Further evidence for early-orogenic extension is imaged on the seismic profile *L3*, about 4 km SE of the Gubbio basin southern termination (Fig. 2d), in an area where no geological or geomorphological evidence of Quaternary extensional faulting occurs at the surface. In this profile a normal fault with about 700 m of throw, aligned with the northwestern Gubbio fault, is imaged. The upper part of the fault is truncated by a shallow thrust (MaTh in Fig. 2d), which is detached at the top of the carbonates, involving upper Marnoso Arenacea turbidites (Middle Miocene in age). This thrust seals a segment of the pre-shortening extensional system, indicating early-orogenic extension. Though being about 4 km SE of the northwestern termination of the Gubbio fault, the structural position, geometry and alignment of this normal fault suggest that it represents a segment of a former, pre-shortening Gubbio fault system, active during the deposition of the lower part of the turbiditic succession and before the thrusts emplacement.

Seismic profiles also provide evidence for multiple reactivation of the Gubbio fault at depth. Fig. 2b shows that the trace of the Gubbio fault merges with that of the Gubbio Thrust (see Mirabella et al., 2004 for details). Hence, we propose that the deep part of the early-orogenic Gubbio normal fault was reverse-reactivated by the Gubbio thrust, possibly in the Late Serravallian-Tortonian time (age of the Marnoso Arenacea formation overlying the MaTh Thrust, Fig. 2d), and that the northern segment of the same fault system was successively reactivated in extension, generating the Quaternary Gubbio basin.

4. Structural data and kinematic analysis

Structural data have been collected along two sections across the Gubbio fault and Gubbio anticline (see location on Fig. 1a), in order to identify the reactivation history. The two sections extend through the Cretaceous upper part of the Umbria-Marche carbonatic multilayer (Marne a Fucoidi, Scaglia Bianca and Scaglia Rossa formations). Poles to bedding, measured at the two structural sites, belong to both limbs of the Gubbio anticline and yield a N312°E fold axis (Figs. 1b,c).

Crosscutting relationships between pre- and post-folding mesoscale fault patterns were examined (e.g. Tavarnelli and Peacock, 1999). The effects of folding have been removed on stereograms by rotating both mesoscale structures and bedding (restored to its original horizontal position) about a horizontal axis parallel to the Gubbio anticline trend. A horizontal rotational axis was chosen because both structural sections are far enough from the plunging structural terminations of the anticline (see Fig. 1a for location).

4.1. Pre-orogenic extensional mesocale fault patterns

The oldest structures recognised in the field (V_1 structures, Fig. 3), on the basis of crosscutting relationships, are two sets of vertical and orthogonal-to-bedding veins. They are filled with a reddish crystalline calcite and are cut by all the other mesoscale structures (Fig. 3a). The vein sets trend about ESE and about NS, respectively (Fig. 3b). Data distribution does not significantly improve after rotation. This is probably because of their origin as vertical structures oblique to the fold axis (Fig. 3c). No major faults associated with these veins have been observed.

These sets can be interpreted as related to extensional tectonics, affecting the Umbria-Marche Apennines during the Late Cretaceous − Early Tertiary (Montanari, 1988; Montanari et al., 1989; Marchegiani et al., 1999; Decandia et al., 2002; Tavarnelli and Alvarez, 2002).

4.2. Early-orogenic extensional mesoscale fault patterns

Sets of conjugate mesoscale faults (displacement <1 m) with almost dip-slip white calcite slickenfibres (F_2 structures) have been observed in the study area. Most of these faults display a normal offset, however, some of the conjugate pair (displaying a reverse offset) have a normal displacement only after bedding rotation (Fig. 4). The present-day attitude of the F_2 conjugate normal faults is variable and not consistent with a stress field characterised by a vertical σ_1 (Figs. 4a−d). The restoration of bedding to its original horizontal position shows that F_2 structures probably formed within an Andersonian stress field, with a vertical σ_1, when bedding was horizontal, i.e. before the shortening deformation took place (Fig. 4e). The rotated F_2 faults display a less scattered distribution and a symmetry about a vertical σ_1 compared to not-rotated data (Figs. 4d−f). Rotated conjugate normal faults have a mean NW-SE trend and an approximate 60° dip (Fig. 4f).

Stress inversion applied to rotated faults and slickenlines yields a tensional stress field, σ_1 is vertical, σ_2 and σ_3 are horizontal, trending N144°E and N054°E, respectively (Fig. 4g).

F_2 structures formed before the beginning of shortening and after V1 structures, therefore they can be related to an early Miocene event.

4.3. Mesoscale orogenic faults

Conjugate sets of ENE (left lateral) and approximately N-S (right lateral) trending faults (“F_3 structures”), with subhorizontal slickenfibres, have been observed (Figs. 5a,b). Rotation of bedding to the horizontal does not improve the distribution of F_3 structures. Sets of NE-SW trending veins, filled with white crystalline calcite, (V_3 structures), have been associated with the same deformation event that generated the F_3

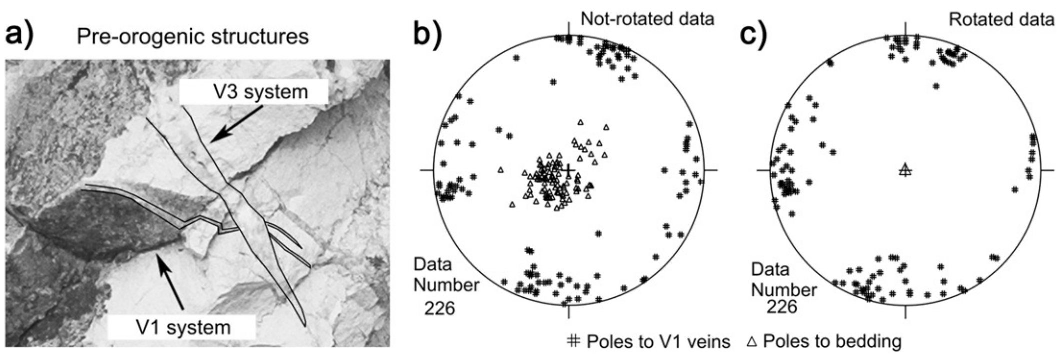

Fig. 3. (a) Cross-cutting relationships between V_1 and V_3 vein sets (see text for details). (b) Non-rotated and (c) rotated poles to V_1 veins (Equal area lower hemisphere projection).

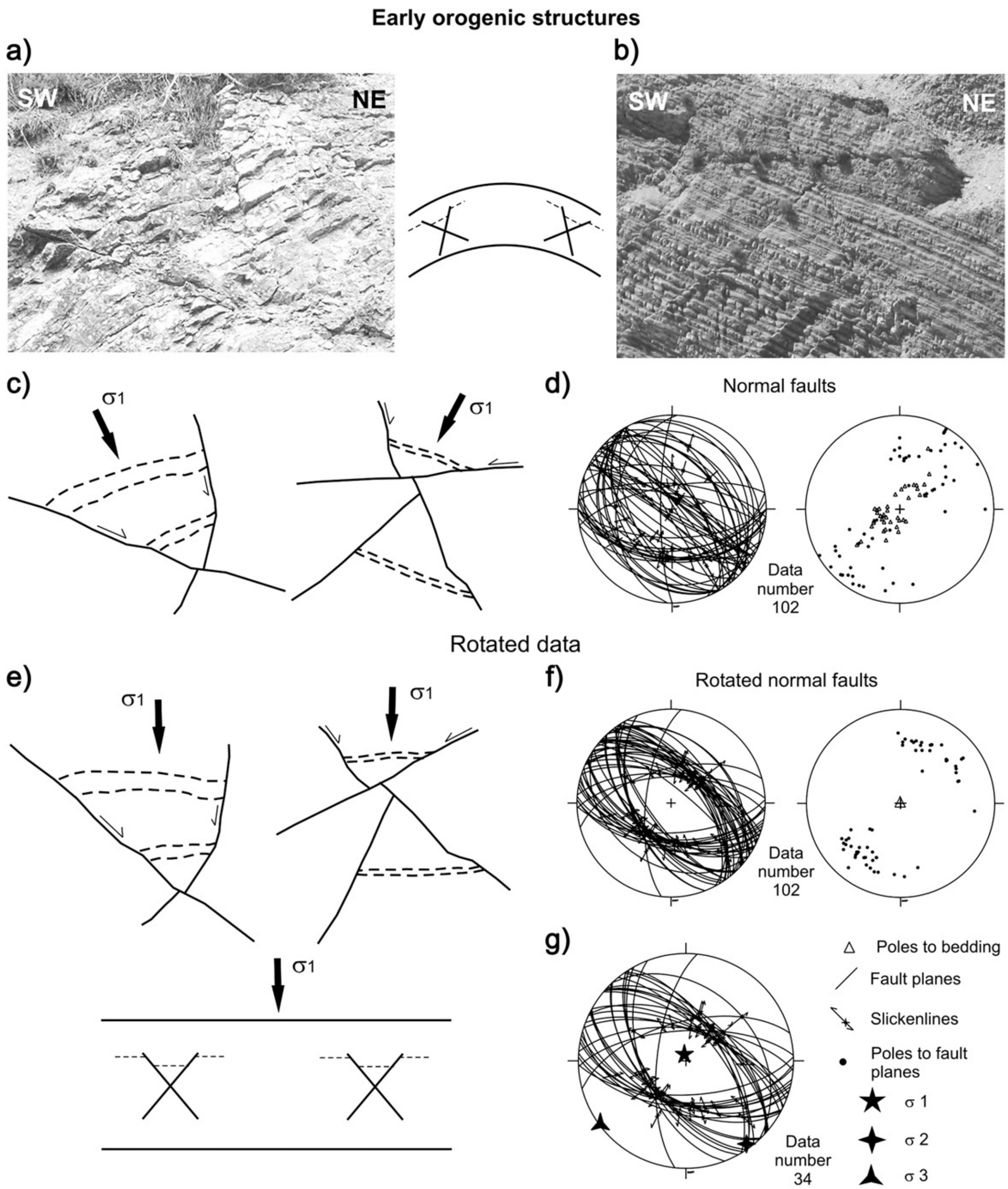

Fig. 4. (a, b) Andersonian normal faults displaying rotated geometry (F_2 structures in the text). (c) Drawings of Figs. 4a,b displaying conjugate normal faults symmetric about a non-vertical σ_1. (d) Stereoplots of bedding and mesoscale normal faults measured in the footwall of the Gubbio fault (all of the stereoplots in Fig. 4 are equal area lower hemisphere projections). (e) Same drawings as Fig. 4c but rotated to restore bedding to the horizontal. Note how conjugate normal faults now display an Andersonian geometry, symmetric about a vertical σ_1. (f) After rotation of bedding to the horizontal, stereoplots of the same dataset displayed in Fig. 4d show a less scattered distribution. (g) Stereoplot with stress axes calculated from stress inversion applied to rotated normal faults and slickenlines (Inversion routine supplied with Daisy 2, Salvini, 2001).

structures (Fig. 5c), on the basis of structural symmetry and crosscutting relationships with older and younger structures observed in the field (e.g. in Fig. 3a).

Stress inversion applied to faults and slickenlines dataset yields a transcurrent stress field with a horizontal N046°E σ_1, an about vertical σ_2 and a horizontal N137°E σ_3 (Fig. 5b).

F_3 and V_3 structures formed in response to a second order mesoscale stress field during the Late Miocene phase of NE-SW oriented contraction, which generated folding and thrusting in the Gubbio area (e.g. De Feyter and Menichetti, 1986; Menichetti and Pialli, 1986; Tavarnelli and Peacock, 1999).

4.4. Late-orogenic extensional mesoscale fault patterns

Conjugate sets of Andersonian normal faults, displaying slickenfibres with dip-slip kinematics, have been observed

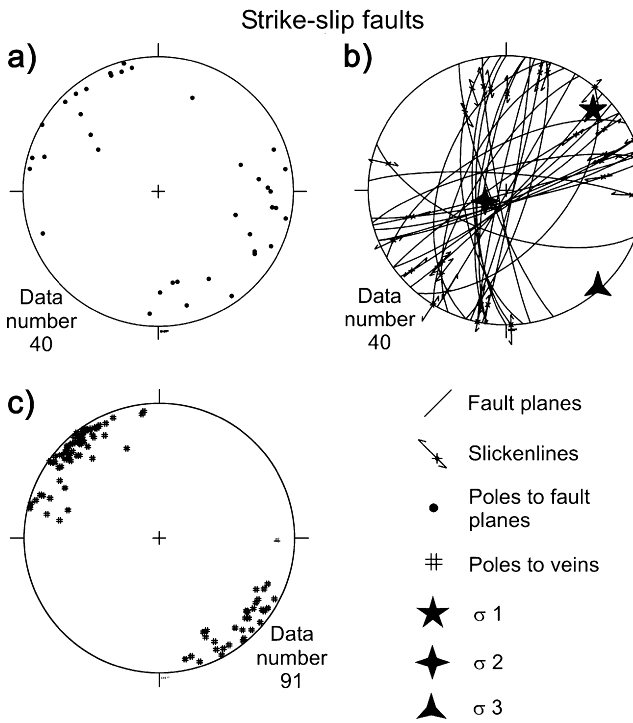

Fig. 5. (a, b) Stereoplots of strike-slip faults and slickenlines from the Gubbio fault-footwall (F_3 structures in the text), with calculated stress axes (b). (c) Stereoplot of sub-vertical veins associated with strike-slip faults (V_3 structures in the text). All stereoplots in Fig. 5 are equal area lower hemisphere projections. (see text for details).

(F_4 structures). Unlike the F_2 faults, these conjugate sets of normal faults are presently symmetric with respect to a vertical σ_1, i.e. they are interpreted to have formed after folding within an Andersonian stress field (Fig. 6). F_4 faults display a slightly dispersed distribution with a mean trend about a NW-SE direction, consistent with the regional trend displayed by the Gubbio fault (Figs. 1a and 6a; also see Boncio et al., 2000; Collettini et al., 2003). NW-SE trending vertical veins, (V_4 structures), filled with white crystalline calcite, are commonly associated with F_4 faults (Fig. 6b). V_4 structures post-date all the other structures.

Stress inversion applied to F4 faults and slickenlines dataset yields a stress field with a vertical σ_1, and a horizontal N045°E σ_3 and N135°E σ_2, respectively (Fig. 6c).

F_4 and V_4 structures developed in response to NE-SW oriented Quaternary extension (Menichetti and Minelli, 1991; Lavecchia et al., 1994; Boncio and Lavecchia, 2000a; Collettini et al., 2003).

5. Discussion

The Gubbio fault formed in a geodynamic context where both early- and late-orogenic extension are contemporaneous and geologically linked to the construction of the Umbria-Marche fold and thrust belt (Fig. 7a). The two extensional fields are localised in the foreland and hinterland regions, respectively, of the contractional front (Fig. 7a) and the entire system migrates toward the east through time. The spatial distribution of the three structural domains and their migration imply that the three deformation events are all synchronous across the chain (Fig. 7a), but, if observed at a fixed time, they are located in different positions, whilst if observed at a fixed site, they occur at different times (Fig. 7).

The tectonic history of the Gubbio fault and the inversion and reactivation events in particular, are coherently imaged by both seismic reflection and field data. Seismic data provide an image of the geometry of the Gubbio fault at depth, showing evidence of an early, extensional event (Fig. 7b), which occurred in Early Miocene time during the deposition of the turbidites, just before the onset of contraction. Early extension also generated conjugated normal faults, surveyed at mesoscopic scale in the Gubbio fault footwall (F_2 structures, Figs. 4 and 7c). The restoration of bedding to its original horizontal position allowed us to calculate the Lower Miocene paleostress field by the inversion of the striated rotated fault planes (maximum extension oriented about NE-SW, Fig. 7c). This event has been interpreted as related to the effects of lithospheric flexure induced by the load of the advancing stacking thrusts (peripheral bulge, Fig. 7a, e.g. Doglioni et al., 1999; Tavarnelli and Peacock, 1999; Scisciani et al., 2002). In this

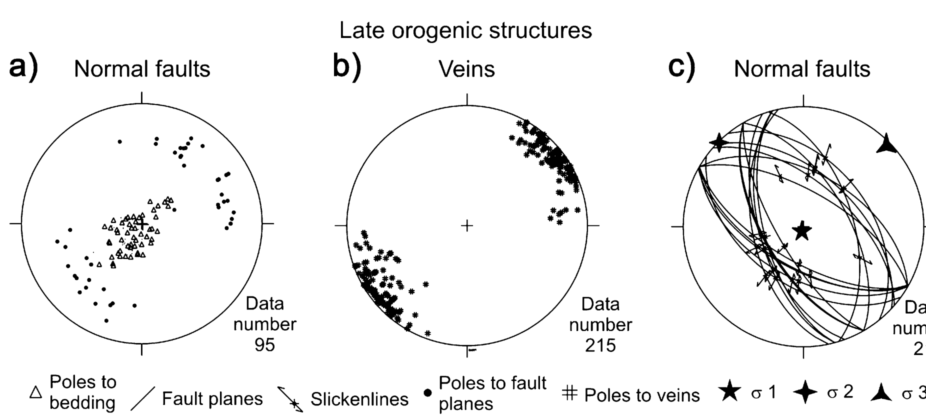

Fig. 6. (a, b) Stereoplots of poles to bedding, normal faults planes (a) and (b) associated veins (F_4 and V_4 structures in the text) that do not show evidence for rotation, i.e. they are post-folding structures. (c) Stereoplot of the same normal faults and slickenlines as in Fig. 6a represented as great circles. Calculated stress axes are also shown. All stereoplots in Fig. 6 are equal area lower hemisphere projections (see text for details).

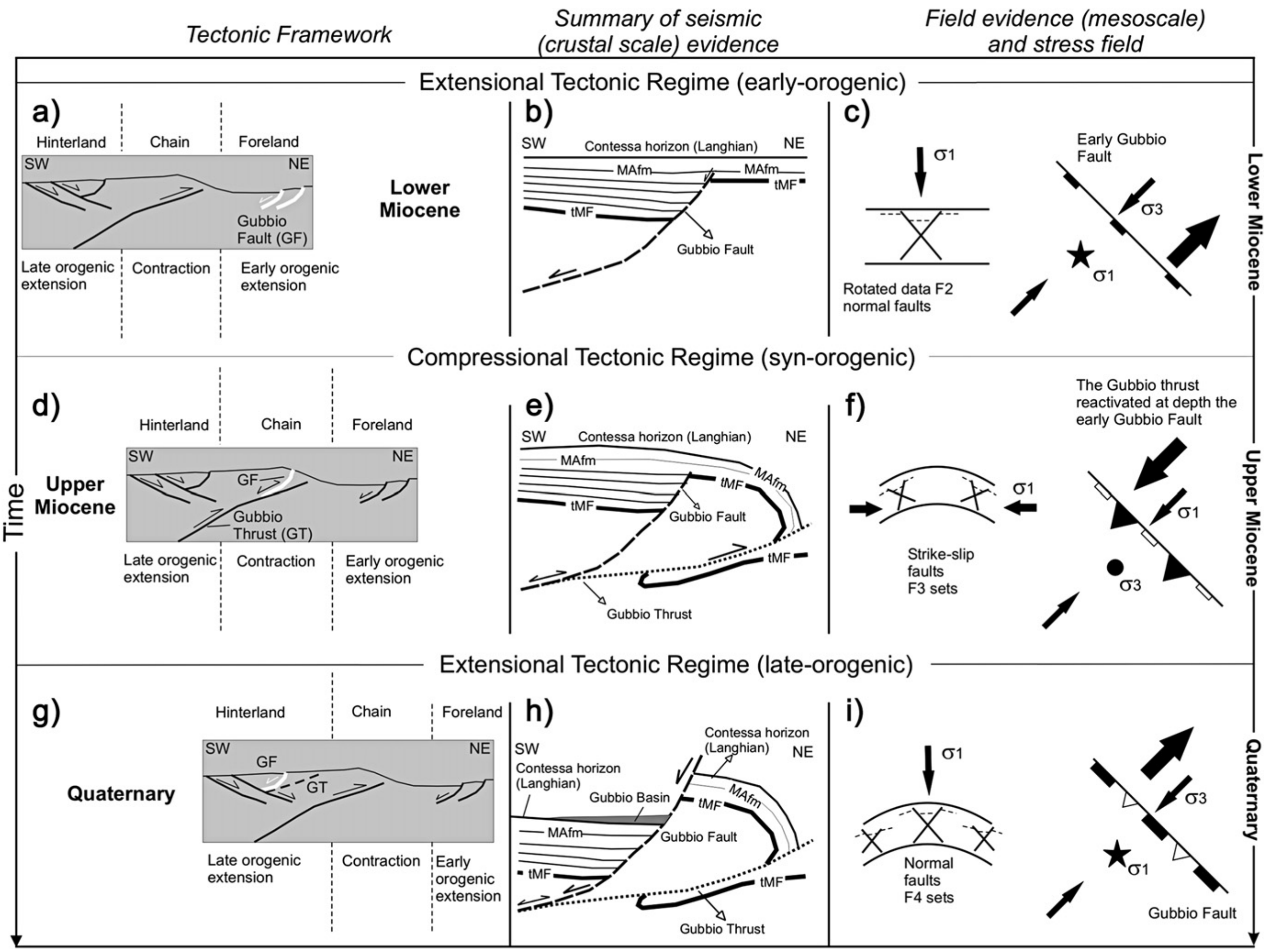

Fig. 7. Early-orogenic extension (Lower Miocene, a–c). (a) Geodynamic context with the Gubbio Fault (white thick line) active in the foreland of the chain. (b) Schematic drawing based on seismic data (Fig. 2) showing synsedimentary activity of the Gubbio Fault. (c) Mesoscale rotated normal faults formed when bedding was horizontal, i.e. before folding, and associated Lower Miocene stress field calculated from inversion of data shown in Fig. 4c. Contraction (Upper Miocene, d–f). (d) The deep shallowly dipping portion of the Gubbio Fault is inverted when contraction reaches the Gubbio area during eastward migration. (e) Schematic drawing based on seismic data (Fig. 2) showing the Gubbio fault inverted at depth. (f) Mesoscale strike-slip faults formed in response to second order stress fields associated with the Gubbio anticline and associated Upper Miocene regional stress field, consistent with the maximum shortening direction (NE-SW oriented, Fig. 5). Late-orogenic extension (Quaternary, g–i). (g) The Gubbio fault is active in the hinterland region of the chain. (h) Schematic drawing based on seismic data (Fig. 2) showing the reactivated Gubbio fault. (i) Andersonian conjugate normal faults formed after folding and associated Quaternary stress field calculated from inversion of data shown in Fig. 6.

case, extensional faults were possibly generated during the final emplacement of the Tuscan units over the easternmost Umbria-Marche units, in Late Burdigalian-Langhian times (Brozzetti et al., 2002).

Early extension was followed by contraction, active since the Late Serravallian in this portion of the chain and responsible for the growth of the Gubbio anticline and emplacement of the Gubbio thrust (Fig. 7d). Seismic data show that the Gubbio thrust reactivated the deep portion of the Gubbio fault (Figs. 2b and 7e). The mesoscale field expression of the contractional phase is given by the rotation of early normal faults (F_2 structures) during folding and by the formation of conjugate strike-slip faults and associated structures (F_3 structures, Fig. 7f) in response to a second order stress field with a NE-SW direction of σ_1, which is consistent with the regional direction of maximum shortening (Fig. 7f).

Contraction was followed by late orogenic extension, active in this area since the Early Pleistocene (Fig. 7g). During this phase, the northwestern segment of the Gubbio fault system, has been reactivated as a major normal fault (Fig. 7h), down-throwing the western limb of the Gubbio anticline and generating the Gubbio basin at its hanging-wall (Fig. 7h). The late orogenic reactivation of the northwestern segment of the Gubbio fault system produced most of the total extensional displacement, with a maximum throw of about 2500 m (Mirabella et al., 2004). At the mesoscopic scale, the Quaternary phase generated conjugate sets of Andersonian normal faults (F_4 structures, Figs. 6 and 7i) indicating a vertically oriented σ_1 (Fig. 7i) and an approximately NE-SW σ_3 direction (Fig. 7i), consistent with both local and regional active stress field (Montone et al., 1999; Boncio and Lavecchia, 2000a).

We illustrated that, despite quite different depths and scales of observation, both seismic reflection and field data define the tectonic history of the Gubbio fault since Early Miocene, discriminating the individual deformation events (Fig. 7). Seismic data image the geometry of the fault at depth, its early activity as a synsedimentary normal fault and its later reactivation and inversion. On the other hand, field data provide information about the fault kinematics and the stress fields orientation, helping in the formulation of a more complete tectonic-geodynamic scenario (Fig. 7). The late-orogenic extensional (Quaternary), the contractional (Late Miocene) and the early-orogenic extensional (Early Miocene) tectonic regimes are all coaxial, with σ_3 and σ_1 stress axes swapping position around an about NE-SW direction (Figs. 7c–f–i). Structures formed during the early extensional stage possess symmetry with respect to the associated stress field, which is maintained during the entire tectonic evolution of the area (Fig. 7). This implies that early structures are potentially well oriented for reactivation during the later deformation stages, even if the actual reactivation processes are additionally controlled by local factors, such as amount of block rotations and rheological and mechanical constraints. Our findings are different from what observed in the southeastern portion of the Central Apennines where little evidence for reactivation of pre-thrusting normal faults during the subsequent stages of deformation have been found (Scisciani et al., 2002), possibly because of the obliquity observed between the structures developed between the different tectonic events.

6. Conclusions

New field data, integrated with seismic data, from the Gubbio normal fault allowed us to recognise three different tectonic phases:

1) synsedimentary, early-orogenic extension, active since the Lower Miocene time;
2) successive positive inversion during the Upper Miocene contraction;
3) renewed, late-orogenic, extension (negative inversion) during the Quaternary age.

Stress fields, reconstructed from field data for each deformation event, show that in this sector of the Northern Apennines, eastward migration of the contractional front caused a repeated swap between σ_1 and σ_3 around an about NE-SW direction. This coaxiality between time migrating stress fields favoured the positive/negative reactivation of the early formed structures.

Our analysis in the Gubbio area shows that different type of normal faults can develop during the evolution of a fold and thrust belt. In particular, normal faults formed during the early-orogenic stages, in the foreland region, control the geometry and evolution of foredeep basins. These faults can be subsequently reactivated during the late-orogenic stages, when they exert a strong control on the evolution of the associated intramountain basins.

Documented reactivation phenomena can affect a correct evaluation of the slip rates of the presently active faults. In fact, in areas where active faults reactivate pre-existing coaxial early-orogenic faults, as the Gubbio area, a portion of the extensional displacement is not due to Quaternary activity. If this process is not correctly considered, it can lead to over-estimate the displacements and consequently, the slip rates of the active faults thus affecting the seismic hazard evaluation.

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