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The Gubbio normal fault (Central Italy): geometry, displacement distribution and tectonic evolution

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Abstract

Normal faults within orogenic belts can be pre-, syn- or post-orogenic features. We studied the Gubbio normal fault (central Italy), which is an example of a pre-orogenic fault reactivated in a post-orogenic stage. The Gubbio Fault is a 22-km-long fault bordering a Quaternary basin and part of an active faults system in the Umbria–Marche region (Central Italy). The interpretation of a set of seismic profiles enables us to reconstruct the fault geometry in detail and to measure displacement and throw distributions along the fault strike. Seismic data indicate that the Gubbio Fault represents an example of multiple reactivation: at least a portion of the fault was active in the Miocene and only a part of the total displacement was achieved in the Quaternary. The reconstruction of the fault geometry at depth shows that the fault is characterised by listric geometry. The fault is also characterised by a bend along strike and structure contours show that this geometry is maintained at depth. As the fault is commonly addressed as presently active, the maximum fault dimensions are correlated to the maximum expected earthquake, and the presence of the fault bend is discussed as a possible barrier to seismic ruptures propagation.

Keywords: Listric normal faults; Fault reactivation; Seismic profiles; Displacement distribution; Earthquakes

1. Introduction

Normal faults commonly occur within orogenic belts and they can be related to pre-, syn- or post-orogenic stages (e.g. Holdsworth et al., 1997; Tavarnelli et al., 1998; Tavarnelli, 1999; Tavarnelli and Peacock, 1999; Scisciani et al., 2001, 2002). In some cases, they show more than one activation episode, e.g. a pre-orogenic normal fault can be reactivated during post-orogenic stages. Pre-orogenic normal faults can be reactivated during thrust tectonics, whilst thrusts can be extensionally reactivated during post-orogenic collapse.

Commonly, the analysis of the time and space relationships between extensional and compressional features, observed in the field, are used to address reactivation phenomena. However, when reactivation occurs at depth, surface observation cannot completely address this problem. In these cases, seismic reflection data can help to unravel the tectonic history (e.g. Bally et al., 1986).

In this paper we reconstruct the tectonic history of the Gubbio normal fault (central Italy) by the interpretation of a partly unpublished seismic data-set acquired by Agip (presently Eni S.P.A.) during the 1980s for oil exploration purposes.

The Gubbio Fault is a 22-km-long normal fault, which borders a Quaternary basin and pertains to the active fault alignment of the Umbria Fault System (Barchi, 2002) in Central Italy (Fig. 1). We interpreted 20 seismic profiles which cover an area of about 1200 km^2, located between Cittá di Castello to the north and Perugia to the south and bordered by the Tiber Valley to the west and by the Umbria–Marche Inner Ridge (‘Ruga Interna’ of Scarsella 1951) to the east (Fig. 2). The data-set interpretation enabled us to define the displacement and throw distribution of the fault and to reconstruct its tectonic history.

The typical distribution of displacement along fault strike has been described as a Gaussian-shaped curve which

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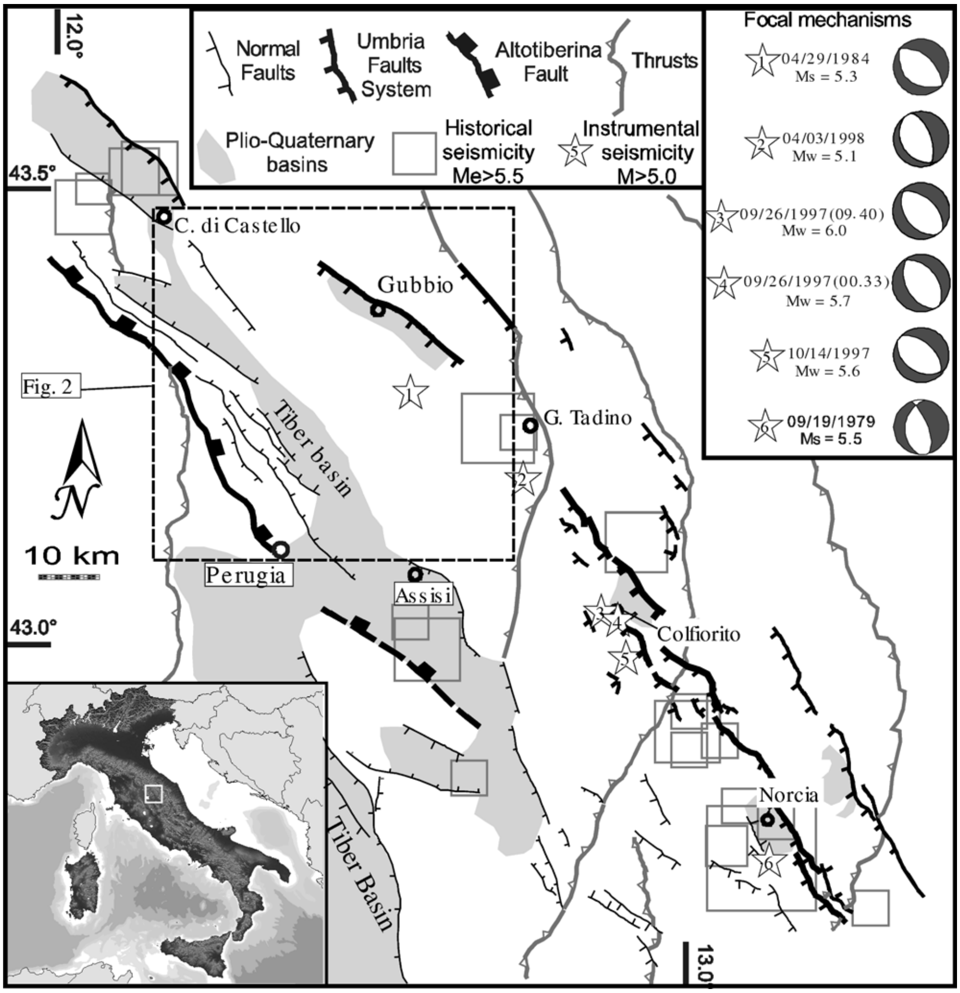

Fig. 1. Schematic structural map of the Umbria–Marche region showing the alignment of the intramountain basins along the Umbria Fault System. Historical seismicity is reported for the 461 BC–1979 AD period (Boschi et al., 1997). Focal mechanisms and magnitudes are for the 1997–98 Colfiorito sequence (Ekstroem et al., 1998), for the 1979 Norcia earthquake (Deschamps et al., 1984) and for the Gubbio earthquake (Dziewonski et al., 1985).

ideally reaches its maximum in correspondence of the central part of the fault and gradually decreases to zero towards the fault tips (Walsh and Watterson, 1988; Peacock and Sanderson, 1991; Cowie and Scholz, 1992; Gupta and Scholz, 2000). Length–displacement data range in scale from a few metres up to tens of kilometres as measured by restored cross-sections (Elliott, 1976) surface geology (e.g. Muraoka and Kamata, 1983; Krantz, 1988; Marrett and Allmendinger, 1991; Peacock and Sanderson, 1991; Dawers et al., 1993; Gawthorpe et al., 2003), coal mines (Walsh and Watterson, 1987) and seismic reflection profiles (e.g. Contreras et al., 2000). In tectonically active regions the geomorphic expression of faults reflects fault activity. Moreover, in areas undergoing nearly pure dip-slip extension, a direct correlation between geologic throw and morphologic throw is expected (e.g. Scholz, 1998; Burbank and Anderson, 2001).

We constructed displacement and throw distribution along the Gubbio normal fault on the basis of the presence of a good stratigraphic marker (i.e. Marne a Fucoidi Fm, a lower Cretaceuos marly interval within a carbonatic succession). Since the rocks in the hanging wall of the Gubbio Fault are covered with Quaternary sediments, it is not possible to evaluate the real displacement of the fault by means of surface mapping. This opportunity is given by seismic data that allow us to reconstruct the tectonic history of the fault and to measure the actual dimensions of the fault (i.e. length, displacement, area) from the surface to depth. Since the fault is commonly interpreted as currently active (Haessler et al., 1988; Boncio and Lavecchia, 2000b), the effect on topography (morpholgic throw) of the Gubbio Fault is compared with the measured geologic throw in order to discuss the neo-tectonic role of this structure. Finally, a seismotectonic analysis of the Gubbio Fault is proposed on the basis of the inferred fault dimensions (maximum length, area) and of the relationships with present-day seismicity.

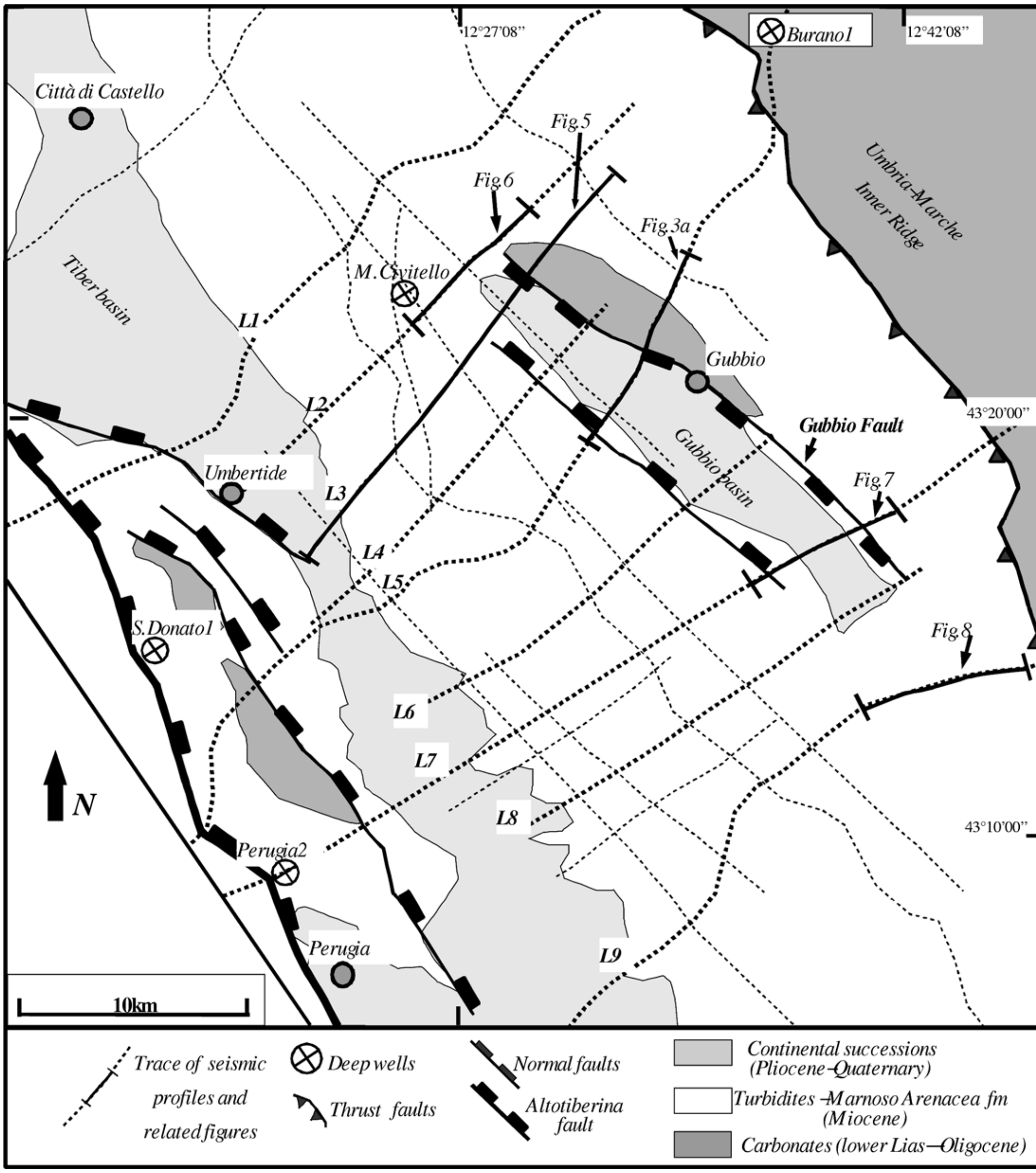

Fig. 2. Study area with traces of the interpreted seismic profiles, locations of the deep wells, main faults and related Pliocene–Quaternary basins.

2. Geologic setting

The Umbria–Marche Apennines are a fold and thrust belt generated by a northeast-directed compressional tectonic phase which started during the middle Miocene and which is still active near the Adriatic coast (e.g. Barchi et al., 1998b). The contractional tectonic features were subsequently dissected by extension which started to affect the Umbria–Marche Apennines in the upper Pliocene.

Extension is characterised by a minimum principal stress σ_3 oriented about NE–SW (Menichetti and Minelli, 1991; Lavecchia et al., 1994; Boncio and Lavecchia, 2000a). Extension within the Umbria–Marche Apennines generated by a NW–SE-trending set of continental basins. The most important basins (Gubbio, Colfiorito, Norcia, Cascia and Castelluccio basins) are bordered by the alignment of SW dipping normal faults of the region (Fig. 1). The extensional nature of recent (i.e. upper Pliocene to present) deformations in the Umbria–Marche region, and its superposition to the previous, coaxial contractional deformations has been recognised and documented by a wide literature (Elter et al., 1975; Lavecchia et al., 1987; Keller et al., 1994; Lavecchia et al., 1994) and confirmed by the results of the CROP03 project (Pialli et al., 1998). This view has recently been questioned by Cello et al. (1997), who consider the recent structures of the Apennines as reflecting a bulk, regional strike-slip deformation field, with associated NNW–SSE directed shortening, acting parallel to the orogenic belt. This interpretation contrasts with a large amount of available data, all indicating that the Quaternary tectonic evolution of the region is driven by extensional tectonics. In fact, recent extension is confirmed on the basis of geomorphologic (e.g. Ficcarelli and Mazza, 1990; Coltorti et al., 1998; Messina et al., 1999), geologic (e.g. Lavecchia et al., 1994; Calamita et al., 1999; Barchi et al., 2000; Boncio and Lavecchia, 2000b; Mirabella and Pucci, 2002) and seismological evidences (Deschamps et al., 1984; Haessler et al., 1988; Amato et al., 1998; Ekstroem et al., 1998; Mariucci et al., 1999; Stramondo et al., 1999; Barba and Basili, 2000). Historical seismicity (maximum intensity = 10 of the modified Mercalli scale (Mercalli–Cancani–Sieberg intensity scale, MCS; CPTI, 1999) and recent earthquakes (Norcia, 1979: Ms = 5.9; Gubbio, 1984: Ms = 5.2; Colfiorito, 1997–98: Mw = 6.0; Deschamps et al., 1984, 2000; Haessler et al., 1988) indicate that the currently active stress field is consistent with the geological long-term stress field, active since the Quaternary (Mariucci et al., 1999).

Seismic profiles have shown that at least the northern part of the Umbria Fault System is antithetic to a low angle, east dipping normal fault (Altotiberina Fault: Keller et al., 1994; Brozzetti, 1995; Barchi et al., 1998a; Boncio and Lavecchia, 2000a; Boncio et al., 2000). The Altotiberina Fault borders the Tiber Valley (Fig. 1) and has been recognised to be a regional feature extending for a length of at least 55 km from Cittá di Castello to Perugia (Barchi et al., 1999; Boncio et al., 2000; Pauselli et al., 2002). The area is characterised by the surface occurrence of Miocene Turbidites (Marnoso Arenacea Fm; e.g. Ricci Lucchi and Pialli, 1973), which overlay the well known lower Liassic–Oligocene carbonates of the Umbria–Marche succession (Cresta et al., 1989). The carbonate multilayer crops out only in correspondence with the Perugia Mts., north of Perugia, and of the culmination of the NE verging Gubbio anticline (Barnaba, 1958; DeFeyter and Menichetti, 1986). The Gubbio anticline formed during the upper Serravallian–lower Tortonian interval and is characterised by a remarkable plunge of its hinge-line towards NW and SE of the fold terminations. The forelimb of the anticline is characterised by the presence of splays of the main, east verging, Gubbio thrust and by backthrusts (e.g. DeFeyter and Menichetti, 1986; Menichetti and Pialli, 1986). The backlimb of the Gubbio anticline does not crop out, as it is downthrown by the later, SW dipping, Gubbio normal fault (Menichetti and Minelli, 1991).

At the surface (Fig. 3a), the Gubbio Fault hanging wall hosts the Gubbio basin, also named ‘Assino graben’ (by the name of the ‘Assino river’) in an early attempt to relate this basin to the Gubbio Fault activity (Barnaba, 1958). The Gubbio basin is about 22 km long in the NW–SE direction, has a maximum width of about 4 km (Menichetti, 1992; Pucci et al., 2003) near the town of Gubbio and is infilled with early Pleistocene (late Villafranchian) fluvio-lacustrine deposits (Esu and Girotti, 1991). A 3D reconstruction of the base of the basin obtained by using borehole and geoelectric data (Menichetti, 1992) shows that the basin thickness changes along strike (i.e. NW–SE) and across strike (i.e. SW–NE). The thickness of the deposits increases (up to 400 m) towards the fault and decreases in the SE sector (Fig. 3b).

The Gubbio Fault borders the eastern side of the basin for its entire length (about 22 km) but has different topographic expressions, probably due to the differences in erodibility of the formations in its footwall. In fact the Gubbio Fault is splendidly exposed in the northern portion of the basin, where the carbonates of the Gubbio anticline crop out at its footwall for a length of about 12 km. In this portion the Gubbio Fault expresses as a 60°–70° SW-dipping plane, trending about N135°, with associated cataclasites and *sc* tectonites (Menichetti and Minelli, 1991; Collettini, 2001). On the other hand, the continuation of the Gubbio Fault southeast of the Gubbio anticline (Fig. 2) does not have such a well-developed topographic expression. This is probably due to the fact that in this area the fault footwall mainly consists of the Marnoso Arenacea Fm turbidites, which are more erodible than the underlying carbonates. The kinematics of the Gubbio Fault (Fig. 3c) has been unequivocally interpreted as related to normal fault displacement (e.g. Boncio et al., 1996; Boncio and Lavecchia, 2000a; Collettini et al., 2003). The diagrams of the structural data in Fig. 3c show the attitude of the striated surfaces collected along the Gubbio Fault strike (Collettini et al., 2003) and evidence a SW-dipping fault with normal to slightly transtensional kinematics.

3. Seismic stratigraphy

The seismic reflection profiles clearly show four main lithological units of the Umbria–Marche stratigraphy (Fig. 4). From bottom to top these are: Palaeozoic–Triassic Basement rocks, Triassic evaporites (Anidriti di Burano Fm; Martinis and Pieri, 1964), a carbonatic multilayer (Lower Jurassic–Early Oligocene) and a Miocene turbiditic sequence (Marnoso Arenacea Fm).

The major reflectors of this stratigraphy correspond to the Basement–evaporites boundary, to the Aptian–Albian Marne a Fucoidi Fm, a marly interval within the carbonate multilayer and to the top of the carbonatic succession (top Scaglia Fm) at the base of the marls (marly group), which precedes the turbidites of the Marnoso Arenacea Fm (Miocene). These reflectors show good continuity in the seismic profiles and have been calibrated with the available boreholes in the region, especially M.Civitello1 (location in Fig. 2).

The Marne a Fucoidi Fm owes its clear reflection in the seismic profiles to the strong velocity contrast between its marly constitution ($Vp = 4.5$ km/s) and the surrounding limestones (i.e. ‘pelagic limestones’ and ‘Scaglia’ in Fig. 4, $Vp = 5.6$ and 5.0 km/s, respectively). The Basement–evaporites boundary is also very clearly imaged because of the velocity contrast between the upper part of the Basement phyllites ($Vp = 5.1$ km/s) and the evaporites ($Vp = 6.1$ km/s). Moreover, the evaporites show good

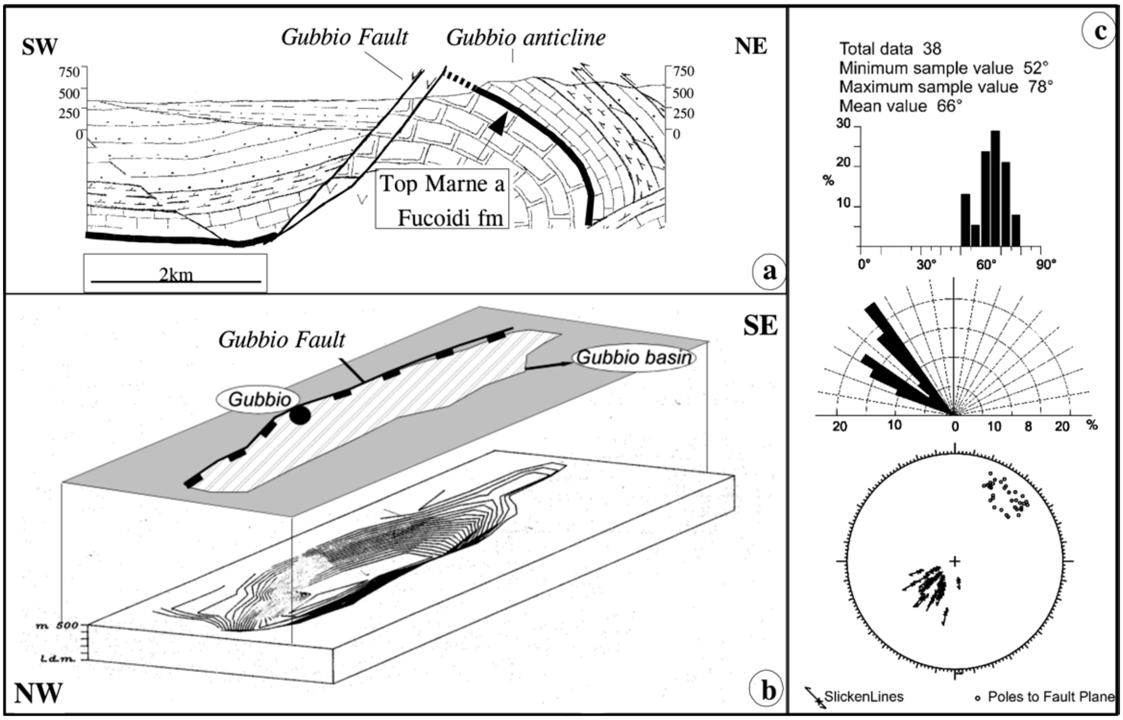

Fig. 3. (a) Geological cross-section across the Gubbio anticline (the section is drawn along the trace of seismic profile *L5* in Fig. 2); (b) 3D reconstruction of the Gubbio basin (modified after Menichetti, 1992); (c) Structural data collected for the Gubbio Fault concerning dip, strike and stereoplot (Schmidt equal area projection, lower hemisphere) (modified after Collettini et al., 2003).

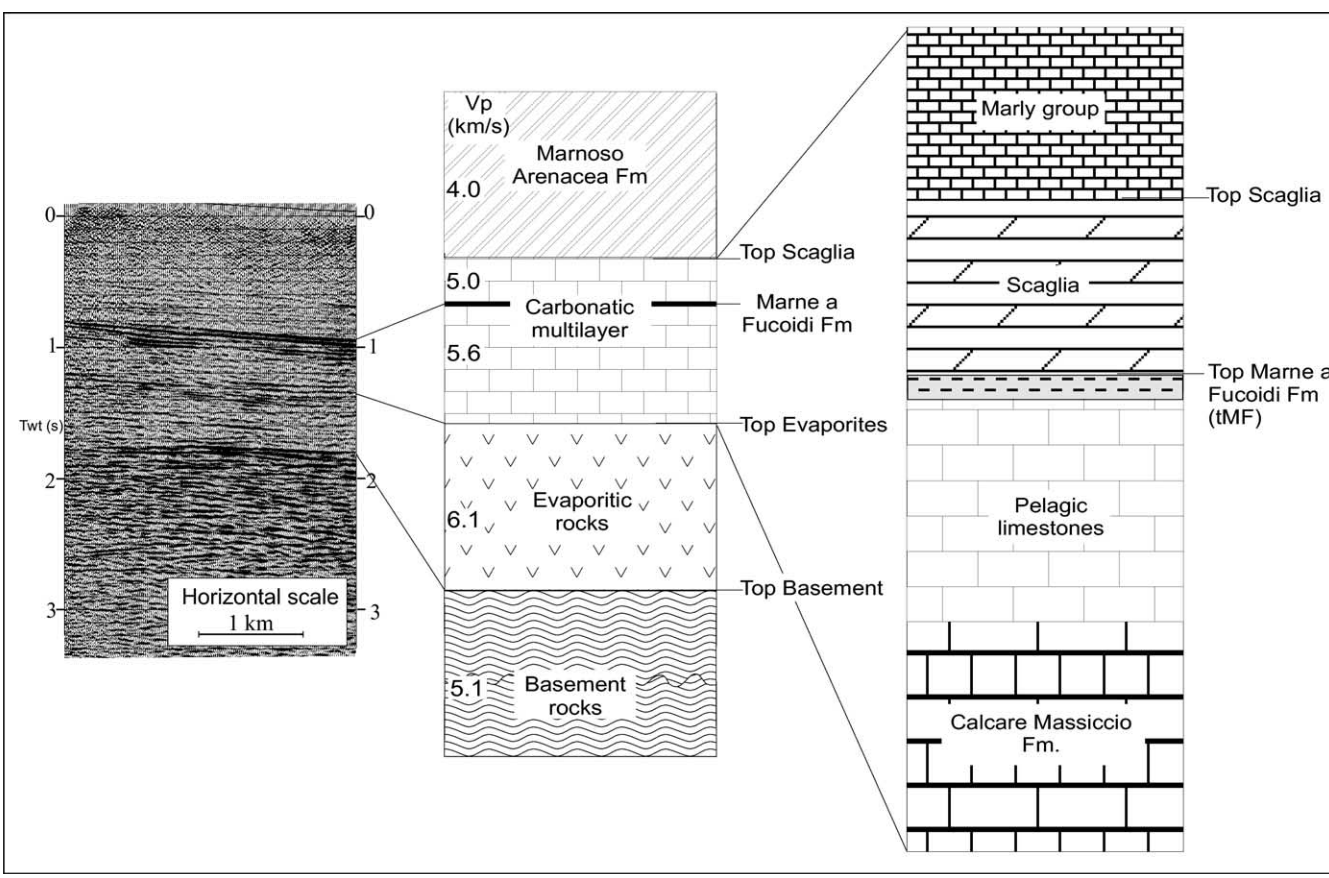

Fig. 4. Seismic image of the Umbria–Marche stratigraphy (left); main lithological units and *Vp* interval velocities (middle) and detail of the carbonatic multilayer (right).

transparency and are characterised by a light seismic facies, in strong contrast with the good reflectivity of the Basement rocks.

The interpreted, migrated profiles were converted to depth using seismic interval velocities (Fig. 4), which were averaged from deep well data derived from literature (Bally et al., 1986; Barchi et al., 1998b), in particular M.Civitellol and S.Donatol (see location in Fig. 2). The depth conversion was performed using the commercial software Geosec 4.1 (Cogniseis Dev.).

4. Seismic images of the Gubbio Fault

The interpreted seismic profiles were acquired by Agip in the 1980s for oil-exploration in the study area (Fig. 2). These lines were mostly acquired by explosives and provide very good images of the subsurface down to pseudo-depths of about 3.5–4.0 s (two-way-time, hereinafter twt). In Fig. 2 the seismic lines across the Gubbio Fault are numbered from *L1* to *L9*. The seismic profile *L3* (Fig. 5) offers a representative image of the structures in the area. The profile shows the Gubbio Fault trace extending from the surface to a depth of about 1.7 s. The seismic expression of the Gubbio Fault at depth consists of an alignment of reflections where the signals of the sedimentary cover (top evaporites and top Marne a Fucoidi Fm) in the backlimb of the Gubbio anticline are truncated. The Gubbio Fault trace continues at depth within the evaporites and inverts the Gubbio thrust without offsetting the top of the Basement. To the west, both the Gubbio Fault trace and the sedimentary cover abut against the Altotiberina Fault, a low-angle ESE dipping normal fault interpreted as the major regional extensional detachment (Barchi et al., 1998a; Boncio et al., 2000; Collettini and Barchi, 2002).

In the Gubbio Fault hanging wall, the top of the Marne a Fucoidi Fm is located at time depths ranging from 1.2 to 0.9 s twt, corresponding to about 2500 and 1200 m, respectively. In the Gubbio Fault footwall, the depth of the top of the Marne a Fucoidi Fm is at a minimum in correspondence with the culmination of the Gubbio anticline (approximately 100 m below the topographic surface) and is at its maximum, 0.8 s twt (about 1750 m) in the Gubbio thrust footwall. The structural setting of the area does not significantly change along strike and analogous features are observed in other seismic profiles of the data-set, in particular seismic profiles *L2* (Fig. 6) and *L7* (Fig. 7).

It can be observed that the top of the Marne a Fucoidi Fm of the Gubbio anticline is located at different depths: about 0.7 s twt in seismic profile *L2* and about 1.3 s twt in line *L7*. This is probably due to the anticline geometry, characterised by its axis plunging towards NW and SE at its lateral terminations.

Seismic profiles between *L2* and *L7* also show that the Gubbio basin is bordered to the west by a N135° striking normal fault which dips towards the NE and is antithetic to the Gubbio Fault. This fault dips approximately 40° and intercepts the Gubbio Fault at depths not greater than 0.9 s twt (about 1800 m; see Fig. 5). These antithetic faults have also been recognised at the surface (Pucci et al., 2003). An interesting feature can be seen in seismic profile *L7* (Fig. 7). This line displays a variation in thickness of the strata overlaying the top of the carbonates, from about 400 m at the western border of the profile to about 600 m towards the fault plane. The thickened sequence stops in correspondence of a clear reflector (*r1*) within the Marnoso Arenacea Fm, suggesting extensional fault activity during the deposition of the lower part of the Marnoso Arenacea Fm (early–middle Miocene). In general the Gubbio Fault geometry reconstructed by seismic profiles shows a good correspondence with the fault length mapped at the surface (22 km).

Seismic profiles provide new information about the Gubbio Fault length at depth. The Gubbio Fault can be recognised in all the studied reflection profiles from *L2* to *L8*, excluding the northernmost profile (*L1*) located 5 km north of seismic profile *L2*. In seismic profile *L1* the Gubbio Fault is no longer observed, most reflectors are continuous and there is no evidence of faulting. This suggests that the northwestern tip of the Gubbio Fault is located between seismic profiles *L1* and *L2*, corresponding at the surface with the termination of the Gubbio basin.

Towards the SE the Gubbio Fault termination is more complex: the seismic profile *L9* (Fig. 8; for location see Fig. 2) shows the presence of a normal fault with dip and geometry (SW dipping normal fault at the backlimb of an anticline) very similar to that of the Gubbio Fault observed in lines from *L2* to *L8*. This fault is aligned with the Gubbio Fault and its throw is still substantial (about 715 m) although no recent continental basin is associated with this feature. Furthermore, the upper part of this fault appears interrupted by a shallow thrust, detached above the top carbonates and involving the Miocene turbidites. This suggests that the normal fault activity predates thrusting and possibly occurred soon before or during turbiditic (Marnoso Arenacea Fm) sedimentation. Although located about 4 km south of the Gubbio basin, seismic profile *L9* exhibits features that are very similar to those observed in the more northern profiles. However, in seismic profile *L8*, which is located at the southern edge of the Gubbio basin, the Gubbio Fault still displays a throw of about 670 m, suggesting a SE prosecution of the Gubbio Fault at least until the *L9* seismic profile. Alternatively, the normal fault observed in *L9* could be a distinct segment, sub-parallel to the main Gubbio Fault. The role of this SE prosecution of the Gubbio Fault is discussed later in the text.

5. Displacement distribution along the Gubbio Fault

We measured the geologic displacement and its vertical component (geologic throw) in the interpreted seismic

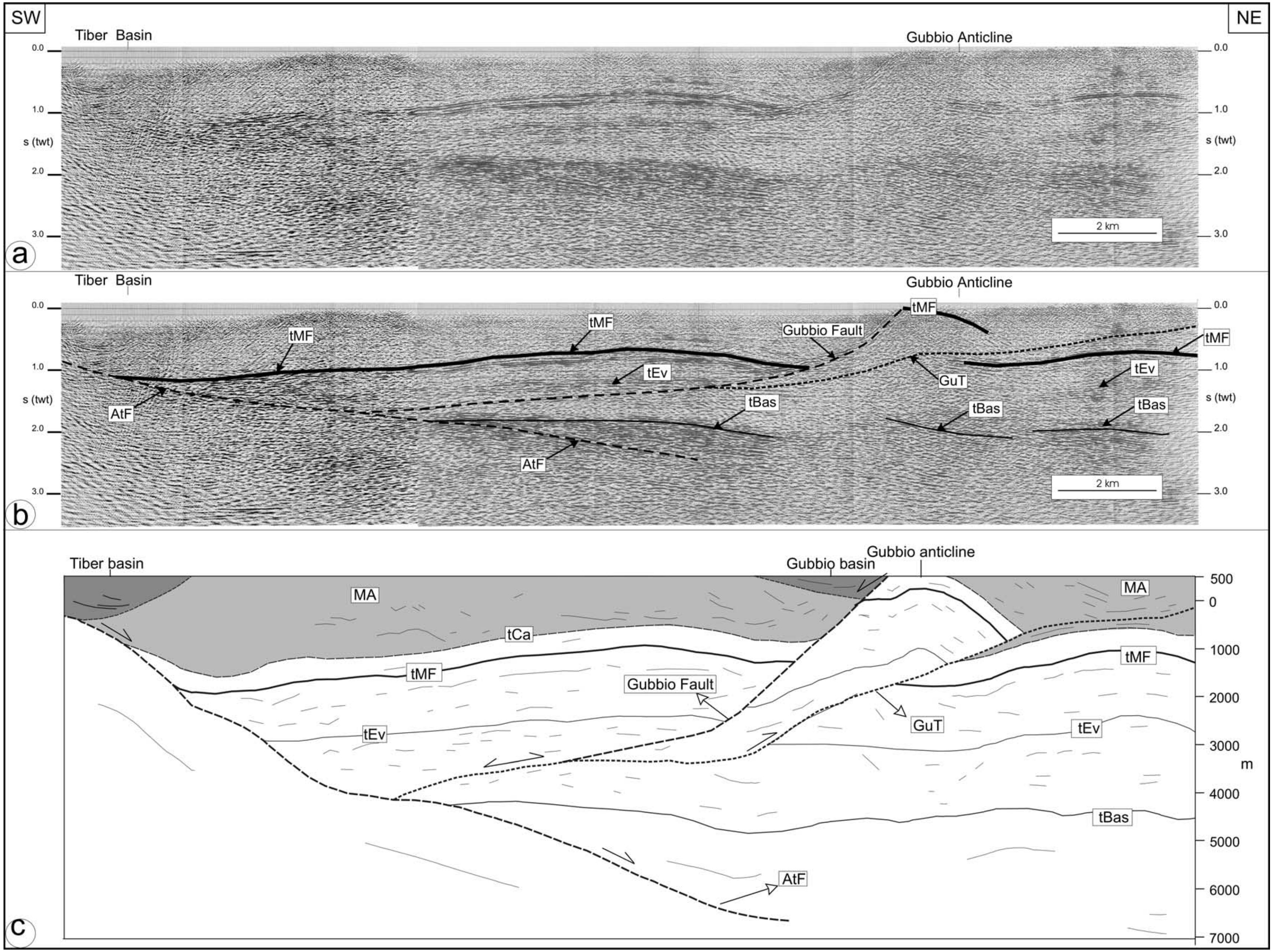

Fig. 5. (a) The *L3* seismic profile (location in Fig. 2); (b) geological interpretation of main reflectors and faults; and (c) depth conversion. tBas: top basement; tEv: top evaporites; tMF: top Marne a Fucoidi Fm; tCa: top carbonates; MA: Marnoso Arenacea Fm; GuT: Gubbio thrust; GuF: Gubbio normal fault. Velocities for depth conversion are in Fig. 4.

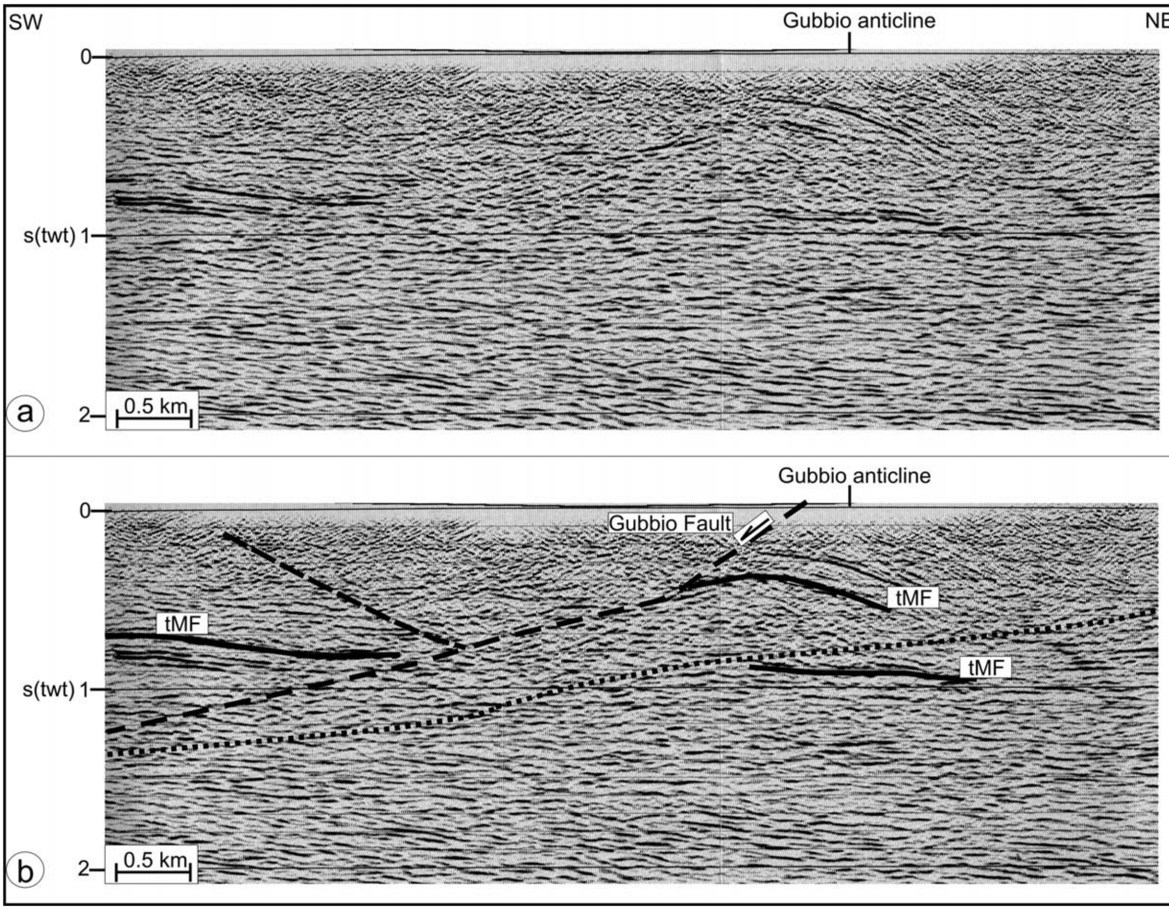

Fig. 6. (a) Part of the *L2* seismic profile (location in Fig. 2) and (b) geological interpretation of main reflectors and faults. GuF: Gubbio normal fault; tMF: top Marne a Fucoidi Fm (aptian–albian).

profiles and drew the distribution of the values along the Gubbio Fault strike (Fig. 9). The values of the geologic throw were compared with the differences in topography between fault hanging wall and fault footwall (footwall relief) and plotted on the same graph (Fig. 9). The geologic throw was measured using the top of the Marne a Fucoidi Fm for its easy detection in the seismic profiles. At the Gubbio Fault footwall, the Marne a Fucoidi Fm crops out only in the central part of the Gubbio anticline: hence, the cut-offs of the top Marne a Fucoidi Fm were picked both from surface data (Fig. 10a) and from seismic sections (where the Marne a Fucoidi Fm does not crop out) (Fig. 10b). At the Gubbio Fault hanging wall all the cut-offs were picked in the seismic sections, since Marne a Fucoidi Fm never crops out. On the base of the obtained depths, throw and displacement values were calculated and plotted along the fault strike (Fig. 9).

In the north, the point of the zero displacement of the graph of Fig. 9 is located between seismic profiles *L1* (where the Gubbio Fault is not present) and *L2*. The southern termination is less constrained, since there are no seismic profiles to the SE of *L9*.

Hence, since line *L9* still displays a slightly greater throw than *L2*, we located the SE zero about 4 km SE of the *L9* seismic profile.

The depth of the cut-offs, measured by the seismic profiles, is subjected to two types of errors: (i) a systematic error, which is due to the uncertainty in the velocities adopted for depth conversion and (ii) a non-homogeneous error, which depends on the different quality of the interpreted seismic profiles and affects the precision in determining the cut-off position.

The error due to the adopted interval velocities (*Vp*) can be easily estimated. For the depth conversion of the seismic profiles we used the available data measured in the deep bore-holes of the region: a review of the velocities of the Umbria–Marche Apennines stratigraphy is reported in Barchi et al. (1998b). Considering the velocity values reported in different data-sets, a maximum error of 5% can be estimated. The error due to seismic lines quality is variable from line to line and depends on the quality of the profiles, affecting the precision in measuring the cut-off depth: in poor quality profiles, it is commonly observed that the termination of the stratigraphic reflectors against the fault is less sharp, and can be set within a range, rather than at a precise position. This type of error does not exceed

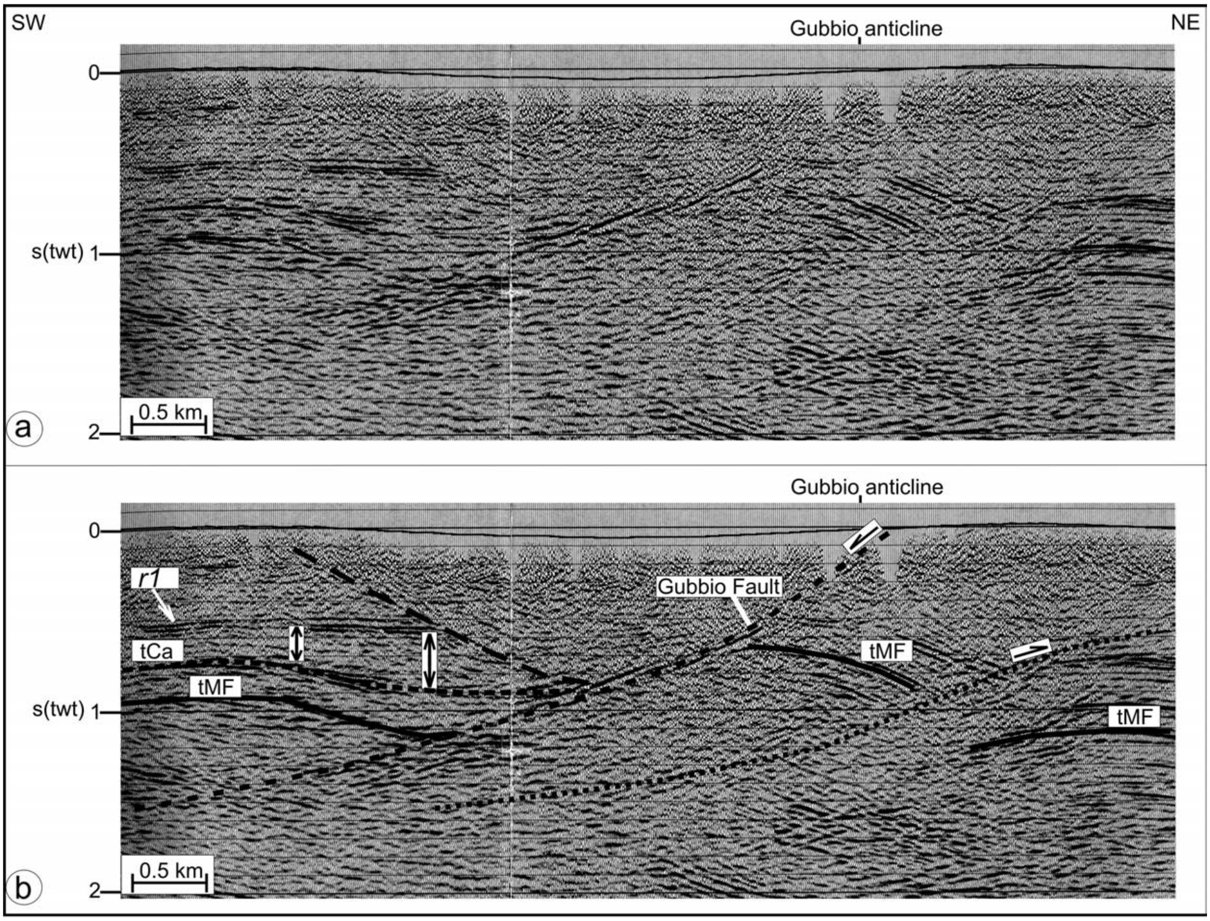

Fig. 7. (a) Part of the *L7* seismic profile (location in Fig. 2) and (b) geological interpretation of main reflectors and faults, showing evidence for thickness increment in the strata overlaying the top of the Carbonates–lower part of the Marnoso Arenacea Fm. GuF: Gubbio normal fault; r1: key-reflector within the Marnoso Arenacea Fm, see text for explanation; tMF: top of Marne a Fucoidi Fm; tCa: top carbonates.

250 m (corresponding to about 200 m of throw) in the lowest quality profiles (Fig. 9).

The values of fault length, maximum and minimum throw, and maximum and minimum displacement are reported in Table 1. The average values between minimum and maximum throw and displacement were plotted on the graph of Fig. 9, together with the corresponding error bar for each measurement.

The graph of Fig. 9 approximates an asymmetric or skewed, bell-shaped curve with a steeper northwestern flank than the southeastern one. The maximum values of displacement (about 3000 m) and throw (about 2000 m) are achieved in correspondence of the *L4* and *L5* lines. A decrease of about 2000 m on the displacement value is distributed in about 8 km along the fault strike along the northwestern part of the fault and in more than 19 km in the southeastern part. Two steps are observed SE of the *L5* and *L7* lines, respectively.

In adjacent regions, it has been suggested that the morphologic throw, defined as the sum of basin thickness

Table 1
Minimum, maximum throw and displacement values measured along seismic profiles *L1–L9*; located in Fig. 2. All data of distance along fault strike, displacement and throw are in metres

Profile	Distance	Min. throw	Max. throw	Ave. throw	Min. displ.	Max. displ.	Ave. displ.
L1	0	0	0	0	0	0	0
L2	5000	575	575	575	887	1153	1019
L3	7500	1115	1415	1265	2096	2679	2387
L4	10750	1800	2100	1950	2728	3189	2958
L5	14500	2175	2175	2175	2954	3023	2984
L6	19500	1075	1275	1175	1969	2499	2234
L7	23500	975	1175	1075	1938	2255	2096
L8	27750	675	675	675	1290	1311	1301
L9	32000	715	715	715	1054	1354	1204

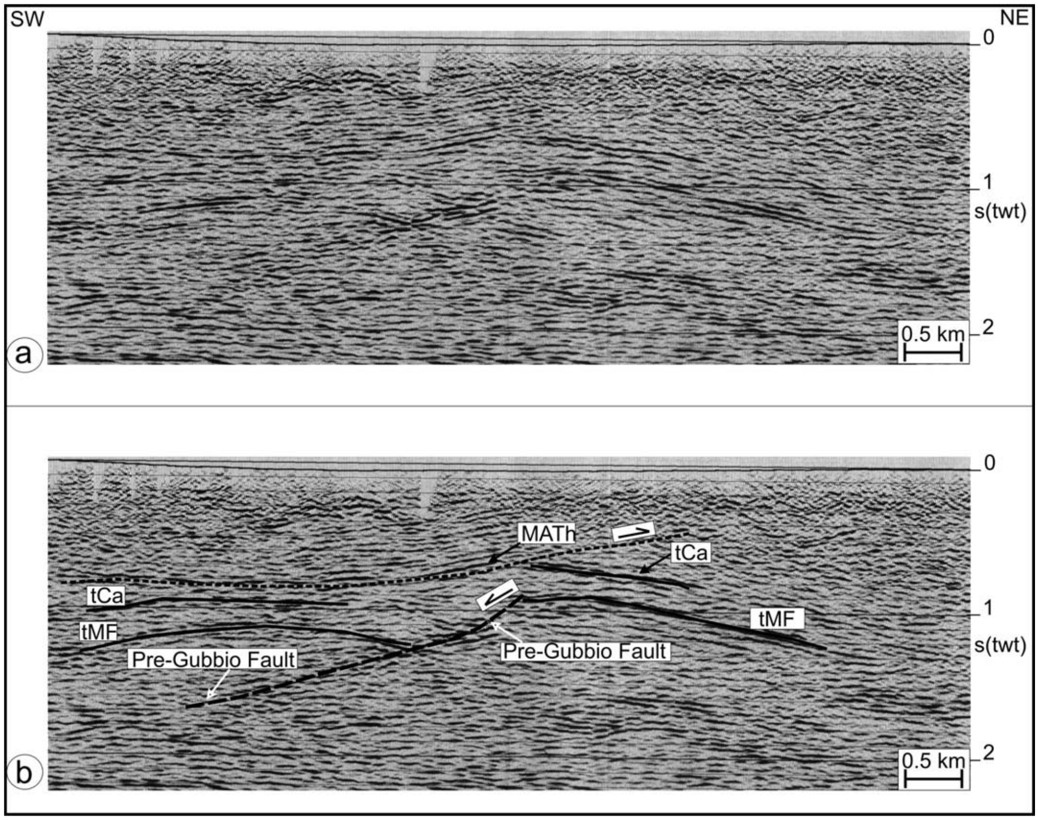

Fig. 8. Part of seismic profile *L9* (location in Fig. 2) and geological interpretation of main reflectors and faults. PGuF: Pre-Gubbio Fault; tMF: top Marne a Fucoidi Fm; tCa: top Carbonates; MATh: trace of a thrust emplaced at the base of the Marnoso Arenacea Fm.

and footwall relief, reflects the long-term Quaternary geologic throw achieved by a normal fault with nearly dip-slip kinematics (e.g. Coltorti and Pieruccini, 2000; Burbank and Anderson, 2001; Pizzi et al., 2002). Hence, the activity of a Quaternary normal fault such as the Gubbio Fault is registered by variations in topographic elevations and geologic and morphologic throw are expected to display similar values. On the graph of Fig. 9 we also drew the footwall relief (550 m) produced by the Gubbio Fault activity, which is represented by the difference between the maximum elevation of the crests at the Gubbio Fault footwall and the elevation of the basin at the Gubbio Fault hanging wall (Fig. 10a). The difference between the footwall relief (550 m) and geologic throw (2200 m) is approximately 1650 m (Fig. 9).

If we consider also the maximum thickness of the sediments infilling the Gubbio basin (about 400 m), obtained by integrated borehole and geo-electric surveys (Menichetti, 1992), the morphologic throw (footwall relief and basin thickness) reaches a value of (550 + 400) = 950 m.

The obtained 950 m value is still small if compared with geologic throw (2200 m) (Fig. 9). The discrepancy between the geologic (2200 m) and morphologic throw (950 m) is 1250 m and could be explained either with a longer (pre-Quaternary) activity of the Gubbio Fault (i.e. the observed geologic throw would have been achieved over a longer time, > 2 Myr) or by considering the Quaternary erosion of the material on the top of the Gubbio anticline at the Gubbio Fault footwall. In the latter case approximately 1250 m of material consisting of the upper part of the marly limestones (Scaglia Variegata and Scaglia Cinerea Fms) and Marnoso Arenacea Fm would have been eroded. In this case, the resulting topography would not be indicative of fault activity and the observed geologic throw would have all been achieved in the last ∼2 Myr due to extension accumulated from upper Pliocene to Quaternary.

If we consider that the geologic throw (2200 m) is the sum of footwall relief (550 m), basin thickness (400 m) and Quaternary erosion (unknown), we can estimate a value of Quaternary erosion of about 1250 m (2200 − 550 − 400 = 1250 m).

In fact the geologic throw is drawn from seismic data (Fig. 10), the topographic data is measured and the basin thickness is provided from the literature (Menichetti, 1992).

The value of 1250 m of erosion should correspond to the missing material above the top of the Gubbio anticline (i.e. Marnoso Arenacea Fm + Marly Group), the maximum thickness of which is about 400 m. If this estimate is correct, the difference between the Quaternary erosion (1250 m) and the Marnoso Arenacea Fm + Marly Group thickness (400 m) can be assigned to a pre-Quaternary throw of the Gubbio Fault, hence being 850 m (1250 − 400 = 850 m).

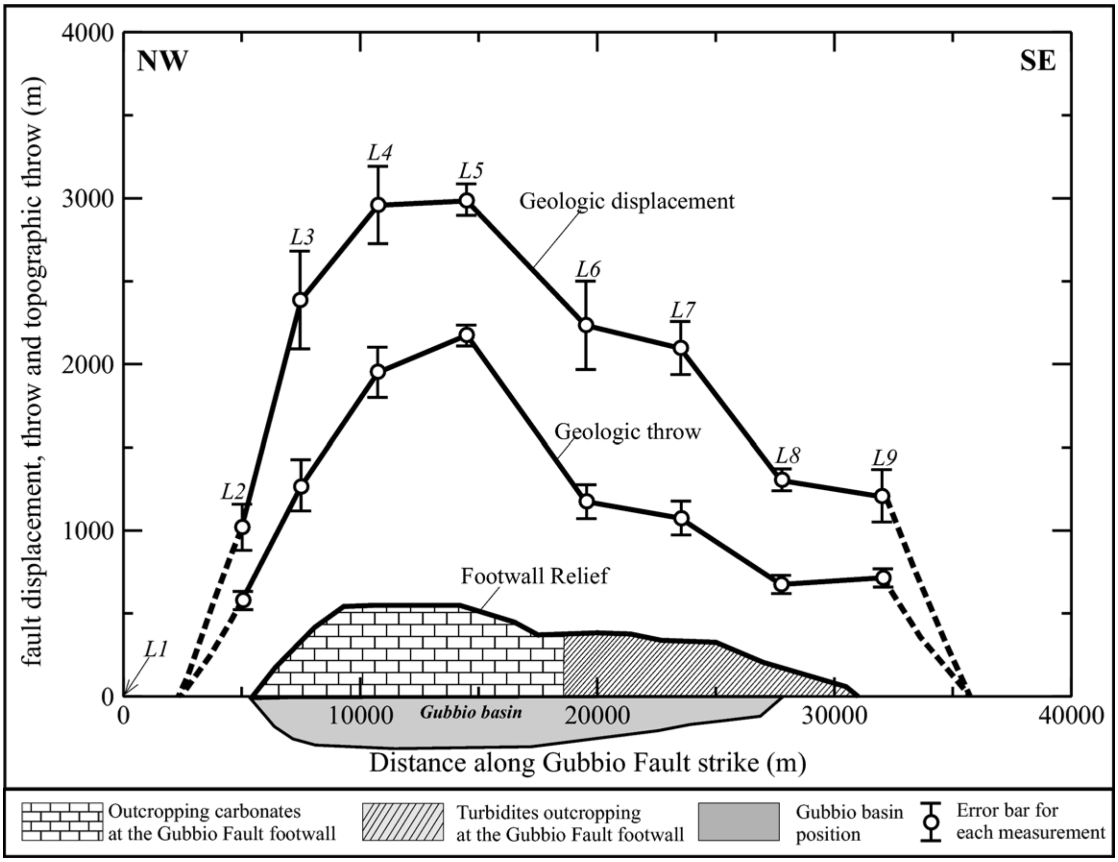

Fig. 9. Geologic displacement, geologic throw and footwall relief, along the Gubbio Fault strike; measures of geologic displacement and geologic throw were measured in seismic profiles *L1–L9*.

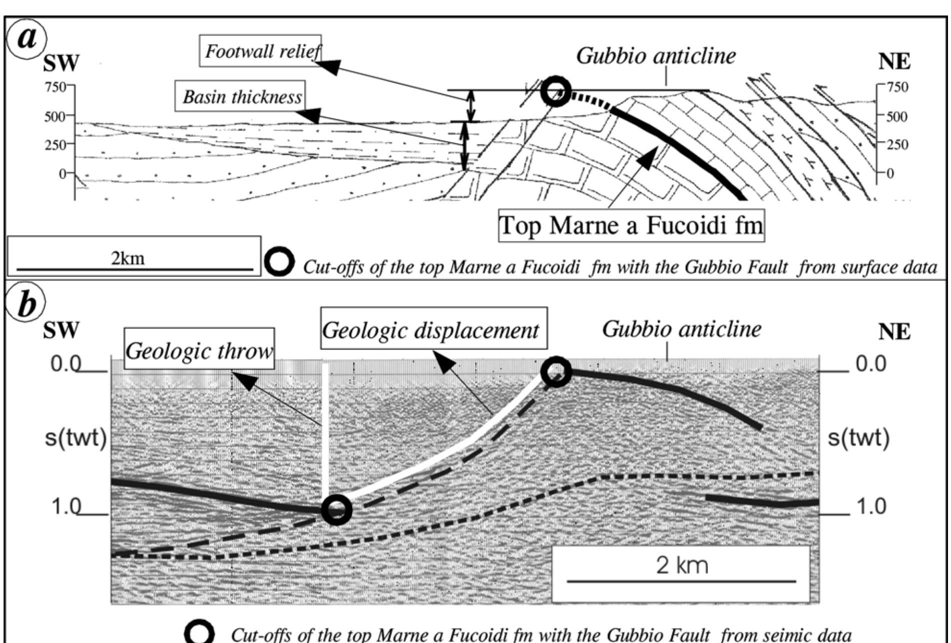

Fig. 10. (a) Cross-section and (b) interpretation of seismic profile across the Gubbio Fault, showing the method of measurement of geologic throw, geologic displacement and footwall relief. The footwall relief can easily be measured at surface as the difference between the maximum and minimum heights at the fault footwall and hanging wall (top). Geologic throw and geologic displacement can only be measured on seismic reflection profiles, as the fault hanging wall is buried under the basin sediments (bottom); time values of the measured data are converted to depth using seismic velocities of Fig. 4.

6. A pre-Quaternary activity?

Evidence for pre-Quaternary extensional faulting for the Gubbio Fault is observed in the *L9* seismic profile (Fig. 8). This seismic line shows the presence of a normal fault dipping SW, which downthrows the backlimb of NE-verging anticline with geometry and structural position strictly corresponding to the Guf. The fault is truncated by a thrust emplaced above the top of the carbonatic sequence suggesting that it was active before thrusting, possibly during the deposition of the Marnoso Arenace Fm (Miocene). These observations and the fact that the projection of this fault at the surface is aligned with the Gubbio Fault, suggest that this fault is very likely to be a pre-Quaternary segment of the Gubbio Fault (pre-Gubbio Fault).

The geologic throw of the pre-Gubbio Fault is over 700 m. This value is very similar to the pre-Quaternary throw of 850 m, inferred in the previous paragraph. The non-recent activity of the pre-Gubbio Fault is confirmed by the absence of a recent continental basin at the surface, south of Gubbio. Further evidence for pre-Quaternary activity can be found in the *L7* seismic profile (Fig.7), which displays the fault growth associated with the pre-Gubbio Fault. In fact, the profile shows that the thickness of the lower part of the turbidites (Burdigalian–Langhian) increases towards the fault plane, indicating that the fault was active during this period of time.

Further evidence of lower Miocene, synsedimentary tectonics is provided by stratigraphic data, reported in the literature by Ridolfi et al. (1995). These authors measured the thickness variations of the Marnoso Arenacea Fm, below a clearly recognisable Langhian (Luchetti, 1997) stratigraphic marker (‘Contessa horizon’: Ricci Lucchi and Pialli, 1973). According to Ridolfi et al. (1995), the Gubbio anticline divides two different sectors of the original Marnoso Arenacea basin, which consistently shows greater thickness (in the order of hundreds of metres) in the western sector than in the eastern one (in the order of tens of metres). These variations can be interpreted as evidence for synsedimentary activity of a normal fault in the early Miocene. Extensional tectonics in Miocene successions have been hypothesised by different authors in other parts of the Apennines (Alberti et al., 1996; Calamita et al., 1998). This extension would be located in the external part of the foredeep (foreland ramp and peripheral bulge) and would be related to the flexural bending of the lithosphere. Calamita et al. (1998) also suggest Quaternary extensional reactivation of these features (e.g. Montagna dei Fiori fault).

Extensional pre-thrusting faults at the outcrop scale have also been more recently recognised by Tavarnelli and Peacock (2002) in this area, affecting the Marnoso Arenacea Fm within the Gubbio Fault footwall, consistently with a wide literature (Alberti et al., 1996; Tavarnelli et al., 1998; Scisciani et al., 2001, 2002).

In a proposed reconstruction (Fig. 11) the Gubbio Fault experienced three tectonic events: (i) a lower Miocene event, during which the Gubbio Fault, or a part of it (addressed as Pre-Gubbio Fault), was active in extension, producing thickening of the lower part of the turbiditic succession; (ii) an upper Miocene event, during which the deep part of Pre-Gubbio Fault was reactivated as a thrust fault (reverse reactivation): the corresponding thrust generated the Gubbio anticline, passively transporting at its hanging wall the shallow part of the Pre-Gubbio Fault; (iii) a Quaternary event, during which the Pre-Gubbio Fault was completely reactivated in extension (normal reactivation): the resulting normal fault (Gubbio Fault) produced most of the present-day extensional displacement and generated the Gubbio basin.

7. Seismotectonic implications

The Umbria–Marche Apennines are characterised by shallow extensional seismicity, confined at depths varying from about 4 km to about 12 km, with minimum principal stress (σ_3) oriented NE–SW (e.g. Haessler et al., 1988; Boncio et al., 2000; Chiaraluce et al., 2003).

Historical earthquakes that occurred in the Gubbio area present moderate intensity ranging between I = V–VI (MCS) and I = VII (CPTI; Boschi et al., 1997). In 1471 an event of I = VI occurred very close to the epicentre of the 1984 Perugia earthquake (I = VII), the strongest instrumental earthquake which occurred in the study area on April the 29th (Ms = 5.2; Haessler et al., 1988).

The Gubbio Fault is commonly considered to be an active fault. The available earthquake locations suggest that the Gubbio Fault is active, even if we cannot unambiguously associate any instrumental or historical event to it and do not have any information as to whether there were any surface breaks during the 1984 Perugia earthquake. Moreover, the Gubbio Fault is part of a system of clearly documented active faults (Umbria Fault System, see Fig. 1) of the Umbria–Marche region from Cittá di Castello to Norcia, which consists of a set of SW dipping normal faults (e.g. Barchi et al., 2000), showing a very similar geologic and geomorphologic Quaternary evolution.

As it is very likely that the Gubbio Fault is active, it would be useful to speculate about the maximum intensity of an expected earthquake. As presented above, our data allowed us to present a very detailed reconstruction of the fault geometry and dimensions: structure contours of the fault plane at depth have also been derived by interpolating the depth converted profiles (Fig. 12).

Previous work by Wells and Coppersmith (1994) has shown that rupture length and rupture area of an active fault can be related to earthquake magnitude. Therefore, the reconstructed fault geometry of the Gubbio Fault can be used to estimate the maximum expected earthquake magnitude. The maximum length (L) of the Gubbio Fault is approximately 22 km with a maximum depth of about

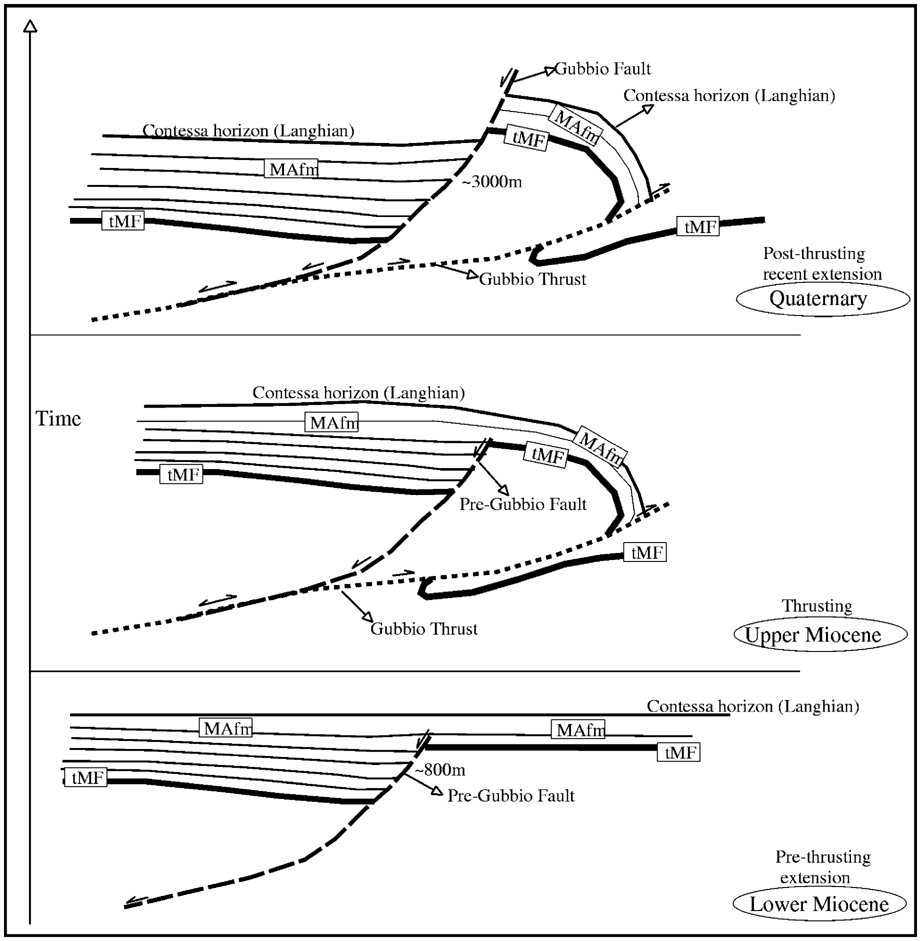

Fig. 11. Sketch showing the geological evolution of the Gubbio Fault since lower Miocene to Quaternary; see text for explanations.

6 km. Seismic profiles show that the Gubbio Fault has an essentially listric shape well imaged by the structure contours (Fig. 12), characterised by dips of 60° at surface, 40° until a depth of 3–4 km and 10°–15° until 6 km where it inverts the Gubbio thrust (Fig. 5). According to the relationship of Wells and Coppersmith (1994) $M=4.86+1.32\mathrm{Log}(L)$, (where L is the fault rupture length), it may cause an earthquake of magnitude M = 6.5 if an event broke the entire fault plane. A similar value of maximum magnitude is obtained if we consider the maximum fault plane area (220 km^2). However, the fault plane exhibits a bend, both at the surface (Fig. 12; e.g. Menichetti, 1992; Collettini et al., 2003) and at depth (Pauselli et al., 2002). The fault bend is oriented NS as indicated by the fault structure contours (Fig.12). This bend divides the fault plane into two segments, a northwestern and a southeastern one with lengths of 5 and 17 km, respectively, at the surface. Since the fault bend strikes approximately NS and the Gubbio Fault strikes N135°, the two areas are roughly the same (i.e. 110 km^2), which would result in an earthquake of about M = 6.0.

Fault bends have been recognised to play a role in the initiation and termination of ruptures. King and Nabelek (1985) suggested that rupture in individual earthquakes is often limited to regions between fault bends. On the basis of a compilation of geological observations from earthquakes in Turkey, Barka and Kadinsky-Cade (1988) proposed 30° as a maximum bend angle for earthquake propagation in strike-slip environments. Concerning normal fault systems, geometric patterns of surface ruptures in the Dixie Valley in Nevada (USA) indicate a bend of nearly 90° along the ruptures associated with the 1954 earthquake (Zhang et al., 1991). This bend seems to have nearly arrested the propagation of the main earthquake rupture and have significantly attenuated the seismic energy.

In the case of the Gubbio Fault, it is not clear to what extent the fault bend may affect the propagation of ruptures during an earthquake. Data by Haessler et al. (1988) and a recent detailed relocation of the aftershock sequence (Collettini et al., 2003) identify the presence of two clusters of seismic events separated along the fault bend. Therefore, it could be argued that the Gubbio Fault is divided into two segments and that the 1984 earthquake occurred at the SE edge of the northwestern segment. It then propagated toward the NW, as inferred by the position of the mainshock (Fig. 12). These data may suggest that only the NW segment of the fault was activated in 1984 and the fault bend acted as a barrier to rupture propagation. On the other hand, the bend

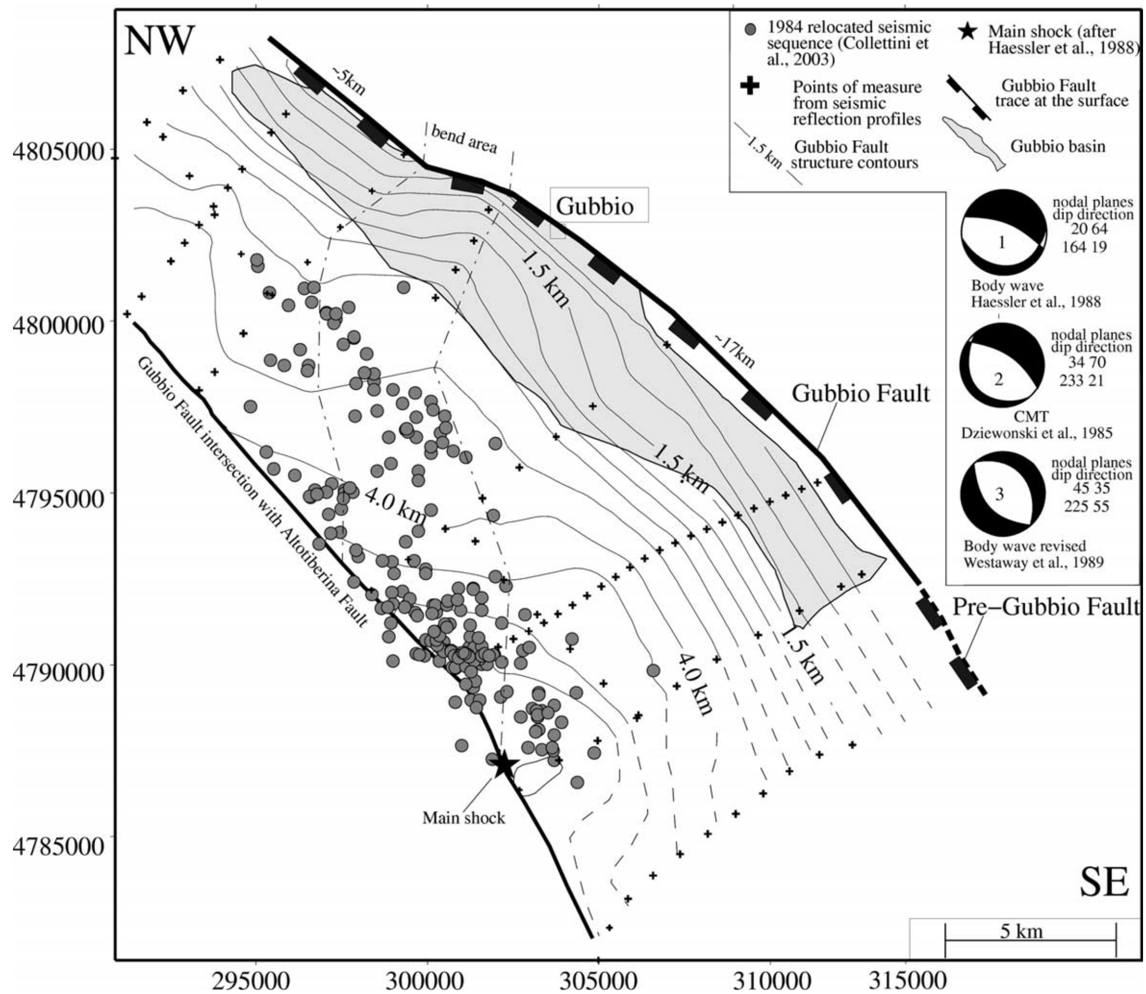

Fig. 12. Structure contour map of the Gubbio Fault, derived from seismic reflection profiles interpretation. On the map, the Gubbio Fault trace at surface and its intersection with the Altotiberina Fault at depth are also drawn. The seismic sequence is taken from Collettini et al. (2003) and the mainshock position is after Haessler et al. (1988). Structure contours are closely spaced in the shallower, steeper part of the fault where it dips 40°, and more spaced in the deeper part where the fault gently dips at about 10°–15°. The fault is characterised by a bend that affects the fault plane at surface and which is preserved at depth as indicated by the structure contours.

in the Gubbio Fault has an angle of about 20° with respect to the fault trace at surface, a small value compared with those found to influence rupture propagations.

A different interpretation regarding the seismotectonic role of the Gubbio Fault could also be made by hypothesizing a depth connection with the other SW-dipping active normal faults of the Umbria Fault System (see Fig. 1). In this case the Gubbio Fault would represent a segment of a larger SW-dipping fault. Similar hypotheses were made for the Pleasant Valley fault segments which produced an Ms = 7.6 earthquake with simultaneous rupture of several en-échelon segments (Ferrill et al., 1999). This could be a possible scenario for the future long-term evolution of the Umbria Fault System. However, it has to be taken into account that: (i) both recent and historical seismicity do not record M > 6.0 earthquakes suggesting that the seismic energy is released by moderate seismicity; (ii) it has been proposed (Barchi, 2002) that the maximum size of the segments of the active Umbria Fault System may be influenced by heterogeneities represented by the pre-existing arcuate-shaped thrust fronts developed during the middle-Miocene which are cross-cut by the active normal faults only locally in the Colfiorito and Norcia area (see Fig. 1); (iii) a recent detailed microseismic study performed in the area (Piccinini et al., 2003) has revealed the presence of a consistent background seismicity consisting of low magnitude earthquakes (Ml < 3.2), suggesting that a part of the fault activity may be released nearly aseismically.

Summarising, the seismotectonic role of the Gubbio Fault is not a trivial matter. Although the position of the 1984 mainshock and the aftershock sequence may suggest that the seismic rupture occurred at the edge of the northwestern portion of the fault plane, the quality of the available seismological data is quite poor and do not allow us to exclude the possibility of a seismic rupture which could potentially break the whole fault surface (about 220 km^2). On the other hand, the available data do not let us suppose a depth connection of the Gubbio Fault with the other active faults of the Umbria Fault System.

8. Summary and conclusions

In this work we have analysed the Gubbio normal fault as an example of a normal fault occurring in the Umbria–Marche Apennines orogenic belt (Central Italy). The fault has been studied by interpreting a set of good quality seismic profiles running across the fault which allowed us to reconstruct the three dimensional geometry of this feature. In particular we focussed on: (1) fault geometry; (2) the fault tectonic history; (3) its seismotectonic role.

1 The Gubbio Fault is a 22-km-long structure striking about N135° and dipping about 60° towards SW. Earlier works by Menichetti and Minelli (1991) and Keller et al. (1994) reconstructed the depth of detachment of the Gubbio Fault by using the 'modified chevron reconstruction', to be at 8 km, with a listric profile. Our data show that the depth of the detachment is shallower, being located at about 6 km (see Fig. 5). The area of the fault surface is about 220 km^2 and is characterised by a bend which divides the fault into two segments of roughly the same area (i.e. 110 km^2). The fault has a listric geometry, dipping 60° at the surface and flattening to a dip of 40° to a depth of 3–4 km, then to 10°–15° where it inverts a pre-existing thrust fault.
2 The combined seismic interpretation and analysis of the morphologic and geologic throw led us to propose a tectonic evolutionary model according to which the Gubbio Fault is an example of multiple reactivation in an orogenic belt. In the proposed model the fault experienced three phases of deformation: lower Miocene extension, upper Miocene compression and Quaternary extension.
3 As this fault pertains to an active fault alignment and is commonly considered to be presently active, we merge the detailed fault geometry with the available earthquakes locations. On the basis of the presented data, a bend in the fault plane, though not being a striking structure, may represent a barrier to seismic rupture propagations. If the barrier is effective and the activation of a single fault segment is considered, the maximum expected earthquake is about M = 6.0. However, the quality of available seismological data and the low angle of the bend do not let us exclude the possibility of a major earthquake activating the whole fault surface, generating a greater than M = 6.5 earthquake.

In this work we propose that a detailed study of the tectonic history of a presently active fault is important when addressing the seismotectonics of a given region. In this context, the definition of the detailed geometry of an active fault, combined with good quality seismological data can help to better understand the propagation of seismic ruptures for normal faults. In tectonically active regions, well-constrained displacement distribution data can provide reliable information about fault growth and the rate of present-date deformation.

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