# Seismic images of an extensional basin, generated at the hangingwall of a low-angle normal fault: the case of the Sansepolcro basin (Central Italy)

*Massimiliano R.Barchi (1) & Maria Grazia Ciaccio* (2)*

*(1) University of Perugia, Italy, Dpt. Scienze della Terra, Perugia, Italy*

*Fax +39 075 5867167*

*e-mail mbarchi@unipg.it*

*(2) Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy*

*Fax +39 06 51860307*

*e-mail ciaccio@ingv.it*

## Abstract

The study of syntectonic basins, generated at the hanging-wall of regional low-angle detachments, can help to gain a better knowledge of these important and mechanically controversial extensional structures, constraining their kinematics and timing of activity.

Seismic reflection images constrain the geometry and internal structure of the Sansepolcro Basin (the northernmost portion of the High Tiber Valley). This basin was generated at the hangingwall of the Altotiberina Fault (AtF), an E-dipping low-angle normal fault, active at least since Late Pliocene, affecting the upper crust of this portion of the Northern Apennines.

The dataset analysed consists of 5 seismic reflection lines acquired in the 80s' by ENI-Agip for oil exploration and a portion of the NVR deep CROP03 profile. The interpretation of the seismic profiles provides a 3-D reconstruction of the basin's shape and of the sedimentary succession infilling the basin. This consisting of up to 1200 m of fluvial and lacustrine sediments: this succession is much thicker and possibly older than previously hypothesised. The seismic data also image the geometry at depth of the faults driving the basin onset and evolution. The western flank is bordered by a set of E-dipping normal faults, producing the uplifting and tilting of Early to Middle Pleistocene succession along the Anghiari ridge. Along the eastern flank, the sediments are markedly dragged along the SW-dipping Sansepolcro fault. Both NE- and SW-dipping faults splay out from the NE-dipping, low-angle Altotiberina fault. Both AtF and its high-angle splays are still active, as suggested by combined geological and geomorphological evidences: the historical seismicity of the area can be reasonably associated to these faults, however the available data do not constrain a unambiguous association between the single structural elements and the major earthquakes.

Keywords: Sansepolcro basin; seismic reflection profiles; extensional basin; Central Italy.

*Corresponding author: Ciaccio Maria Grazia, e-mail address: ciaccio@ingv.it

## 1. Introduction

The Altotiberina Fault (AtF) is a low-angle, NE-dipping normal fault (LANF), affecting the upper crust of Northern Umbria (Central Italy).  Since the 90s', when it was firstly evidenced during the CROP03 project, this fault has been intensively investigated by several research groups (Barchi et al., 1995, 1998; Brozzetti, 1995; Boncio et al., 1998; 2000). These researches integrate surface mapping, interpretation of seismic reflection profiles and studies of both instrumental and historical seismicity.  Seismic reflection data accurately define the subsurface geometry of a portion of AtF, located in Northern Umbria (between Sansepolcro and Perugia), where the fault strikes about N150° with a mean dip of 15°-20° and can be traced down to the depth of about 12 km (Barchi et al., 1999; Collettini et al., 2000). Abundant microseismicity, recorded by temporary local networks along the AtF surface, demonstrate that the LANF is presently active (Boncio et al., 1998;

Piccinini et al., 2003; Chiaraluce at al., 2007). Even if the geometry, kinematics and seismogenic potential of AtF has been intensively investigated, the Tectono-sedimentary evolution of the basin generated at the AtF hangingwall was poorly explored.

In this paper, we interpret previously unpublished seismic reflection profiles to investigate the depth, geometry and tectono-sedimentary evolution of the Sansepolcro basin (Northern Umbria), a Pliocene-Quaternary extensional basin, located at the AtF hangingwall. The Sansepolcro basin is a NW-SE elongated basin, about 10 km long and 6 km wide, presently occupied by the northernmost part of the High Tiber Valley (fig.1a). Observing the map on fig.1a, it can be noted that the alluvial plain of the High Tiber Valley from Sansepolcro to Perugia does not maintain a constant width: on the contrary, it consists of three different basins, separated by thresholds, where the width and depth of the continental basin is substantially reduced. The Sansepolcro basin represents the northernmost basin, located north of the Città di Castello threshold (fig.1b). It is infilled by Quaternary continental, fluvial and lacustrine sediments. Most Authors (e.g. Cattuto et al., 1995; Brozzetti, 1995; Barchi et al., 1998, but see also Bonini, 1998) recognised that the onset and evolution of the Tiber basin was driven by a complex system of NNW-SSE striking normal faults (fig.1).

We interpret a set of six seismic reflection profiles: four cross profiles, crossing the basin in WSW-ENE direction, perpendicularly to the main structural trends of the region; and two tie profiles, orthogonally connecting the former. The southernmost cross profile is a portion of the CROP03 NVR deep seismic profile (Barchi et al., 1998; Pauselli et al., 2006), whilst the other five seismic profiles were acquired in the 80's for oil exploration purposes.

By interpreting and correlating the seismic profiles, we reconstructed in detail the depth and geometry of the basin, as well as that of the faults bordering the basin. Considering these data, the tectonic evolution of the basin is temptatively reconstructed and considered in the regional framework. The inferences of these data on the seismotectonic setting of the basin and of the surrounding region are finally discussed. This area provides a good example of a basin, whose onset and evolution can be confidently associated to the movement along an active LANF, constraining both the kinematics and the timing of activity of the fault.

## 2. Stratigraphy and tectonics

From a morphological point of view, the Sansepolcro basin can be divided into three longitudinal (i.e. NW-SE trending) parallel bands. The central part of the basin corresponds to the present-day Tiber alluvial plain, at a mean elevation of 300 m a.s.l., infilled by recent (Late Pleistocene-Holocene) mainly gravely alluvium with minor fine-grained layers. The western side of the basin is bordered by a NW-SE alignment of smooth hills (Anghiari Ridge, fig.1 and fig.2), with a maximum elevation of 440 m a.s.l., where Early-Middle Pleistocene fluvial and lacustrine deposits are exposed: the lower part (up to 200 m thick) is mainly composed of grey clays with lignite levels, whilst the upper part (up to 400 m thick) mainly consists of gravels and sands (Brozzetti et al., 2001; ISPRA-CARG Project, F° 289). Along the eastern side of the basin, the contact between the Tiber recent alluvial and the bedrock is covered by several alluvial fans, generated by the tributaries of the Tiber river. Here only isolated outcrops of uplifted and eroded, fluviual and lacustrine sediments are present. The wells in the plain drilled the alluvial sediments with a maximum thickness of about 100 m, superposed to fine lacustrine sediments, which can be assimilated to the Pleistocene succession, exposed along the Anghiari Ridge.

The Quaternary deposits unconformably overly turbidites pertaining to the different tectonic units which the Northern Apennines thrust belt consists of, i.e. from the hinterland to the foreland: Ligurian Units (mainly cropping out at the northern edge of the basin), Tuscan Units (mainly in the western side), Umbria-Marche Units (mainly in the eastern side).

Both the SW and the NE sides of the basin are bordered by opposite dipping normal faults, dissecting the previous, N-S trending folds and thrusts (fig.1). Displacement along the NE-dipping Sovara fault is responsible for the westward tilting of the Pleistocene sediments, along the Anghiari Ridge (Cattuto et al., 1995; Brozzetti et al., 2001; Delle Donne et al., 2007; ISPRA-CARG Project, F° 289). Recently, the results of a high resolution seismic survey across the NE-dipping Anghiari fault and the SW-dipping Sansepolcro fault (fig.1) provided new evidences, supporting their present-day activity (Delle Donne et al., 2007).

## 3. Seismicity

The Apennines upper crust seismicity mainly occurs along a NNW-SSE trending belt, from Northern Tuscany to Northern Calabria (Chiarabba et al., 2005) and is characterised by extensional kinematics (Vannucci et al., 2004; Pondrelli et al., 2006). Most of the seismicity of the Italian peninsula is located within or very close to a set of intermountain basins, aligned close to the axial zone of the Apennines.

The Sansepolcro basin is part of this active extensional belt. The catalogue of historical earthquakes (CPTI Working Group, 2004) comprises five earthquakes, with estimated intensity larger than IX MCS (Mm=6.0), that occurred within or very close to the study area, i.e. the 1352 Monterchi earthquake, the 1389 Boccaserriola, the 1458 Città di Castello, the 1781 Cagliese and the 1917 Monterchi-Citerna earthquakes. Brozzetti et al. (2008) propose that some of these earthquakes would be generated by segments of the AtF, located at different depths, and by the NE-dipping faults splaying out from them.

The Sansepolcro basin is characterised by scarce instrumental seismicity (M > 2.5) if compared to the adjacent areas (Castello et al., 2005).

In particular, the area north of Sansepolcro has been struck in recent years by four minor sequences, occurred between 1987 and 2001 (fig.2). The 2001 mainshock (Mw=4.7; Ml=4.3), localised at a depth of 5.5 km (Ciaccio et al., 2006), displays a normal-fault mechanism with a NW-SE strike and a low-angle rupture plane. A SW-NE extension characterises also the mainshock of the 1997 (Mw=4.4; Ml=4.3) sequence. Finally, the focal sphere of the 1987 (Ml=3.7) mainshock shows a normal mechanism with an E-W strike. Summarising, these data are coherent with the SW-NE extensional stress field, active along the Apenninic belt. However, these data do not provide a clear image of the attitude and depth of the activated faults.

South of the study area, between Città di Castello and Gubbio, higher microseismic activity occurs. This seismicity was also surveyed by temporary networks, revealing a rather well defined E-dipping, low-angle fault, about 35 km wide, that cuts through the entire upper crust down to 12-15 km depth (Boncio et al., 1998; Piccinini et al., 2003), nicely fitting the Altotiberina fault (AtF) surface, as depicted by the seismic reflection data (Barchi et al., 1999). The relationships between structural setting and microseismicity along the AtF have been recently analysed in detail by Chiaraluce et al. (2007).

## 4. Seismic reflection profiles

The geometry of the Sansepolcro basin has been reconstructed by interpreting a set of 5 commercial seismic profiles and a portion of the CROP03 (fig.1B): 4 profiles (L1 to L4) are transversal to the basin (WSW-ENE), whilst the other 2 (T1 and T2) are longitudinal (NNW-SSE). Even if the seismic profiles were originally projected and acquired to unravel the deep structures, they show significant details of the shallow reflectors, useful in order to reconstruct the stratigraphic and tectonic setting of the basin.

First of all, we reconstructed the sedimentary succession infilling the basin, by interpreting and correlating the major reflections and the seismic facies observed along the profiles. The best image of the succession is provided by the cross profile L2, which crosses the central part of the Sansepolcro basin (fig.3A). The succession consists of four main seismic units. The lower unit (UA), up to near 400 ms thick, comprises irregular, lens-shaped and/or cross stratified reflections, characterised by high amplitude and low continuity, possibly corresponding to coarse, fluvial sediments. The intermediate units (UB and UC), whose maximum thickness is about 450 ms and 350 ms, are characterised by much more regular and laterally continuous reflectors: in particular, low-amplitude reflectors of UB depict a nearly transparent seismic facies, whilst UC is characterised by a lower frequency and a higher amplitude. These two units can be related to a lacustrine succession, mainly consisting of fine grained sediments, with lenses of coarser material, more frequent in the upper part (UC) and close to the basin's flanks. Above this sequence, a thin (less than 150 ms) nearly transparent uppermost unit (UD) occurs. Since no deep well is available in this area, the geological interpretation of the seismic stratigraphy is mainly based on the correlation with the surface geology: the ill-defined facies UD corresponds to the recent (late Pleistocene-Holocene) alluvial sediments of the Tiber Valley, whilst UC and UB are correlated with the Early to Middle Pleistocene fluvial and lacustrine succession, exposed along the Anghiari Ridge:  however it is possible that UB, which is thicker than the succession cropping out at the surface, comprises also older (Pliocene) lacustrine sediments, analogously to other southernmost sites of the Tiber basin (Todi, Spoleto), where Middle Pliocene lacustrine clayey sediments are exposed (Esu & Girotti, 1991; Argenti, 2004; Barisone et al., 2006).  The deeper unit UA is not exposed at the surface nor drilled by any well:  on the base of its position and seismic facies, we hypothesise that UA consists of Pliocene coarse sediments.

This succession unconformably overlies the pre-Pliocene bedrock (BS), mainly consisting of intensely deformed, deeply eroded turbidites, exposed at the surface along the basins flanks. The contact between the bedrock and the overlying succession is generally marked by a strong reflection, that can be easily explained considering the sharp increase of acoustic impedance at the sediments/bedrock interface:  the mean Vp values of the sediments is about 2000 m/s, whilst the turbidites are characterised by Vp values exceeding 3500 m/s (Bally et al., 1986;

Barchi et al., 1998).

Starting from this simple seismic stratigraphy, we used the tie profiles T1 and T2 to connect and calibrate the main reflectors (tops BS, UA, UB and UC) onto the entire network of the seismic profiles.

The profiles also show significant images of the structural setting: we focused on the normal faults, bordering the basin and affecting the recent sediments. In general, the profiles provide a reliable image at depth of the major faults recognised at the surface, showing that the western and the eastern flanks of the basin are bordered by two sets of normal faults, dipping towards ENE and WSW respectively, which can be regarded to as synthetic and antithetic splays of the AtF major E-dipping detachment.

Two main synthetic (ENE-dipping) splays are recognisable in the profiles: the westernmost fault (Sovara fault, SoF) is located along the Sovara River valley and separates the Tuscan turbidites from the Pleistocene sediments exposed along the Anghiari Ridge (fig.1). The eastern fault (Anghiari fault, AnF) is located at the base of the Anghiari Ridge. Both these faults have been mapped at the surface by previous geomorphological and geological surveys (Cattuto et al., 1995; ISPRA-CARG Project, F° 289). The upper portion of the Anghiari fault has been also clearly imaged by a recent high resolution seismic survey (Delle Donne et al., 2007), realising the connection between the deep faults, imaged by the commercial seismic profiles and their surface geomorphological and geological expression (fig.3B, section a-a). The high resolution seismic data show a detailed image of the shallower portion of the sedimentary succession: a thin (about 70 m) layer of recent alluvials (corresponding to UD), covering at least 200 m of lacustrine succession (UC). Using these data, Delle Donne et al. (2007) recognise that the Anghiari fault is active, with an average Holocene slip rate of at least 0.25 mm/yr. The Holocene activity of the NE-dipping fault system bordering the western side of the Sansepolcro basin is also constrained by the south-westward tilting of Late

Pleistocene alluvial terraces near Fighille (Brozzetti et al., 2008).

On the opposite flank, the major SW-dipping normal fault corresponds to the Sansepolcro fault, whose presence and Quaternary activity was recognised by Cattuto et al. (1995), mainly through a geomorphological analysis. A high resolution seismic profile, acquired along this margin of the basin, in correspondence of Sansepolcro town (fig.3B, section b-b, Delle Donne et al., 2007), shows that the recent alluvial fans, connected to the Tiber sediments (UD) with a thickness of about 30 m, are directly superposed to the pre-Pliocene bedrock, and affected by normal faulting.

It is also worth to note that in the transversal profiles the fluvial and lacustrine succession (UA to UC) appears gently folded with downward convexity, whilst the overlying Tiber alluvials are not involved in this folding. The significance of the internal deformation of the continental succession will be discussed in the final paragraph.

In the following we describe in detail three seismic profiles (L2, L4 and T1), which are representative of the stratigraphic and structural setting of the basin. In the description, the location of the reflectors at depth is always expressed in terms of seconds two way time.

### Profile L2 -

The L2 profile (fig.3A) crosses the central part of the Sansepolcro basin, where the plain of the Tiber valley reaches the maximum width (about 6500 m). The town of Sansepolcro is located very close to this profile, on the eastern side of the valley (fig.1B). The bedrock consists of Tuscan turbidites on the western flank and of Umbrian turbidites on the eastern one. The western part of the profile, crossing the Anghiari Ridge, is characterised by low amplitude and high frequency reflectors, imaging a set of faulted blocks, tilted towards SW, corresponding to the Pleistocene fluvial and lacustrine succession, exposed at the surface (UC and UB). East of the

Anghiari ridge, the sedimentary succession is thicker and covered by the recent alluvium of the Tiber plain. The whole succession appears gently folded, with upward concavity and is delimited by opposite dipping normal faults.

The two flanks of the basin are characterised by different structural styles. On the western side of the valley, a set of NE-dipping faults is present, splaying out from the AtF, whose trace is imaged in the deeper part of the profile. The emergence of the AtF is located some km to the west (fig.1A).

The two main synthetic splays correspond to the Sovara fault and Anghiari fault, respectively, delimiting the Anghiari Ridge, where the Early-Middle Pleistocene continental succession is exposed, tilted towards SW (e.g. Cattuto et al., 1995). On the opposite flank of the basin, the main Sansepolcro fault can be followed down to the depth of about 1.5 s TWT, where it stops on the AtF trace. On this flank, the reflectors are tilted towards the west, whose dip increases with depth.

### Profile L4 -

This profile corresponds to a portion of the CROP03 (between CDP 5300 and 5900, fig.1B), which crosses the southernmost part of the Sansepolcro basin (fig.4).

The stratigraphy and the internal structure of the basin is similar to that of L2, even if the maximum depth of the basin filling hardly exceeds 1 s below the present-day Tiber river. SW-tilted fault-bounded blocks characterise the western portion (below the Anghiari Ridge), whist a marked dragging of the reflectors along the SW-dipping Sansepolcro fault is observed in the eastern flank.

Below the basin, a strong E-dipping reflection is present within the bedrock, at depths ranging between 1 and 2s, representing the seismic expression of the main branch of AtF, from which both the Sovara Fault and the Anghiari fault splay out.

### Profile T1 -

The T1 profile (fig.5) longitudinally crosses the eastern part of the Sansepolcro basin close to the present-day Tiber river bed, where the maximum thickness of the continental sediments occurs (fig.1). The Ligurian units of the bedrock are exposed at the north-western end of the profile. The thickness of the continental sediments progressively increases towards the SE, covering the turbidites bedrock. The fluvial and lacustrine units UA, UB and UC are well recognisable in the central and southern part of the profile: however, UA cannot be traced with continuity below the central part of the profile. A portion of the AtF trace, with an apparent dip towards the North, is imaged at about 1.8 s in the southernmost part of the profile. A shallower fault, possibly corresponding to the Sansepolcro fault can be traced at depths of about 1.2 s.

## 5. Structural interpretation

The seismic reflection profiles were depth converted using a very simple 2-layers velocity model Vp values of 2000 m/s and 4000 m/s were assigned to the basin continental succession and to the turbiditic bed-rock, respectively. These are the average measured in the wells drilled throughout the Umbria-Marche region (e.g. Bally et al., 1986).

We constructed the geological section of fig.3Ac, crossing the central part of the Sansepolcro basin, by merging the depth converted L2 profile and the surface geology data derived by recent, detailed survey of the area (ISPRA-CARG Project).

In this section we recognise that the NE-dipping synthetic splays of AtF (i.e. the Sovara fault and the Anghiari fault) dip about 30°, whilst the Sansepolcro SW-dipping fault dips around 40° and joins the AtF trace at a depth of about 3 km. The section also shows the trace of a portion of the AtF, deepening toward ENE till a depth of about 4 km. The internal geometry of the Pliocene-Quaternary sedimentary sequence is markedly asymmetric: in fact the western flank is characterised by a set of westward-tilted fault blocks (Anghiari Ridge), in strong contrast with the upward concave geometry of the central and eastern part of the basin. The eastern flank is characterised by a pronounced dip of the sedimentary strata towards the basin, whose dip increases with depth, up to about 30°.

Considering this complex geometry in the regional framework, we propose that the present day-setting of the Sansepolcro basin is the result of a two-stage tectono-sedimentary evolution, where the basin initiated as a bowl-shaped depression, and was subsequently disrupted by the upward propagation of two sets of opposite-dipping normal faults. Pascucci et al. (1999), through the analysis of a wide set of seismic reflection profiles, showed that most "hinterland basins" of the western sector of the Northern Apennines show a similar, two-stage evolution.

In the case of the Sansepolcro basin, the initial bowl-shaped depression would have formed as an effect of displacement at the hanging-wall of a curviplanar low-angle normal fault, characterised by a staircase, flat-ramp-flat trajectory. A similar evolution was suggested by Brogi (2007) for the Radicofani basin, located about 50 km SW of the study area. In our case, previously published seismic profiles crossing the High Tiber Valley show that the AtF is actually characterised by a staircase geometry, possibly related to the heterogeneous mechanical stratigraphy of the upper crust (Barchi et al., 1999; Boncio et al., 2000; Collettini & Barchi, 2002). Subsequently, during the second deformation stage, the flanks of the basin would have been disrupted by the synthetic (NE-dipping) and antithetic (SW-dipping) splays of AtF. In this extensional framework, the SW-dipping growth strata observed in the eastern flank of the basin can be explained as the effect of the syn-sedimentary upward propagation of the SW-dipping Sansepolcro fault (e.g. Gawthorpe et al., 1997).

In order to obtain a map view of the basin geometry, we used the depth converted seismic profile to produce an isobath map of the basin bottom (fig.6), picking the depth value of the basin bottom along the available sections, and using current interpolation and common contouring techniques. In particular, we used the Kriging method (Cressie, 1990) to interpolate 256 data points: this is a geostatistical gridding method based on the theory of regionalized variables that allows visually appealing maps from irregularly spaced data to be produced. We obtained a regular grid line geometry spaced in X and Y direction of 0.0025 degree of latitude and longitude. The grid has been produced and elaborated by the program Surfer (Surface Mapping System, http://www.goldensoftware.com/).

The isobath map shows that the basin is strongly asymmetric, with the NE flank much steeper than the SW one. The maximum thickness of the sediments infilling the basin is ~ 1200 m and the isobaths are elongated in a NW-SE direction, slightly oblique with respect to the basin flanks. The deeper part of the basin is shifted towards the NE flank. At least in the central part of the basin, the present day position of the Tiber river grossly follows the lines of maximum depth, suggesting a fairly continuous history of subsidence.

In the Monterchi area, at the SW edge of the basin, the isobaths become very steep and are strongly bent, following the SW-NE edge of basin: here the thickness of the sediments abruptly increase from 0 to ~ 700 m. These features suggest that the southern termination of the Sansepolcro basin is controlled by a transversal (SW-NE trending) fault, down-throwing the basin with respect to the Città di Castello threshold. The presence of the fault crossing the entire basin was previously hypothesized by Cattuto et al. (1995) in their geomorphological study: however, we don’t have any seismic data supporting the continuation of the fault in the eastern flank. This fault can be interpreted as a transfer fault, segmenting the main NW-SE trending extensional system (fig.1). The occurrence of SW-NE trending transfer faults is very common in the hinterland extensional basins of the Northern Apennines; these faults are possibly inherited from pre-existing strike-slip faults, active during the Miocene compression (Pascucci et al., 2007).

Summarising, our data show that the Sansepolcro basin is bordered by two sets of opposite verging, NW-SE trending normal fault segments, about 15 km long, whose SE termination is defined by a transversal, SW-NE trending transfer fault. Both NE-dipping and SW-dipping normal fault segments splay out from the NE-dipping AtF. The basin shape, as depicted by the isobath map, can be easily related to the fault pattern, highlighted by the seismic profiles. In fact the gently sloping basin bottom of the SW flank is controlled by the gently dipping Sovara fault, merging at relatively shallow depth into the low-angle AtF. The other main NE-dipping splay of AtF, the Anghiari fault, separates the Anghiari Ridge from the presently active alluvial basin. The steep opposite flank is controlled by the steeper and deeper, SW-dipping Sansepolcro fault.

The structural setting of the basin is in good agreement with that previously proposed by Cattuto et al. (1995), mainly based on geomorphological observations, who proposed that also the northern termination of the basin is controlled by a further SW-NE trending fault. Our data cannot contribute to validate this reasonable hypothesis. The main difference is in the polarity of the master fault: in fact Cattuto et al. (1995) propose that the basin evolution is mainly controlled by the SW-dipping Sansepolcro fault, whilst in our reconstruction the extension is driven by the NE-dipping AtF and by its synthetic and antithetic splays: it is worth to note that the role of the AtF is mainly highlighted by the interpretation of the seismic profiles (e.g. Barchi et al., 1998), that were not available yet in 1995. Our reconstruction is also in agreement with the detailed structural map proposed by Brozzetti et al. (2008), even if these Authors do not recognise the role of the transversal fault, bordering the SE edge of the basin.

## 6. Discussion

In our view, the Sansepolcro basin is generated by extensional tectonics. This is in agreement with most of the previous literature, where the onset and evolution of the hinterland basins of the Northern Apennines is related to crustal extension, driven by the eastward roll-back of the Adriatic lithosphere, coherently with a wide range of both geological and geophysical evidences, as recently summarised by Pauselli et al. (2006). However, other Authors (e.g. Boccaletti et al., 1997) refer the generation of the hinterland basins, and of the Tiber basin in particular (Bonini, 1998), to late (till Middle Pleistocene) compressional events, interpreting them as thrust-top basins, generated by propagation of out-sequence thrusts. In this view, the initial bowl-shape basin is interpreted as a syncline, disrupted only in very recent time (Late Pleistocene to present) by later extensional faults. In the case of the Sansepolcro basin, the seismic data don't show any evidence of compressional structures, involving the Pliocene-Quaternary sequence. On the contrary, robust evidence of normal faults propagating through the basin sediments has been recognised.

The present-day activity of the normal fault system, driving the evolution of the Sansepolcro basin since Pliocene times, is supported by geomorphological, geological and geophysical (high resolution seismic) surveys (Cattuto et al., 1995; Delle Donne et al., 2007; Brozzetti et al., 2008; Basili et al., 2008). The geometry and kinematics of these normal faults, as reconstructed in this study, are consistent with the focal mechanisms of the instrumental earthquakes, indicating a SW-NE active extension, coherent with the regional seismotectonic framework, as defined by both geological and seismological data (e.g. Lavecchia et al., 1994).

These observations suggest that the NW-SE trending normal faults are the seismogenic sources of the historical seismicity of the area. However the actual relationships between the single faults and the single historical events are still not constrained. This is mainly due to the scarcity of the instrumental seismicity (M > 2.5) recorded below the Sansepolcro basin, that does not define the geometrical details of the seismogenic volume. Even for the relatively larger events, located north of the Sansepolcro area, the quality of the instrumental data is not good enough to effectively constrain the geometry of the seismogenic faults (such a connection was successfully achieved in the southernmost Colfiorito and Gualdo Tadino areas, see Chiaraluce et al., 2005; Ciaccio et al., 2005).

The NE-dipping splays of the AtF have been indicated as responsible for the 1352 and 1917 earthquakes (Delle Donne et al., 2007; Basili, 2008; Brozzetti et al., 2008). In fact the relatively small area where the Monterchi 1917 earthquake was adverted is compatible with a relatively shallow fault. Furthermore, the surface faulting observed during the earthquake occurred along the trace of the active Anghiari fault (Delle Donne et al., 2007). The SW-dipping Sansepolcro fault has the same geometry of, and is grossly aligned with, the set of SW-dipping normal faults which are thought to be responsible for the moderate seismicity of the Umbria region (Gubbio 1984, Colfiorito 1997, Norcia 1979, see Ciaccio et al., 2006 for a review). However, there is no evidence for associated instrumental seismicity.

Finally, the seismogenic role of the AtF has been widely debated (Basili et al., 2008): detailed survey, made by dense temporary networks, showed localisation of microseismicity ($M < 3$) along the AtF plane (Boncio et al., 1998; Piccinini et al., 2003; 2008). The possibility that larger (i.e. moderate) seismicity may be generated by a segment of AtF, i.e. of a regional LANF, is certainly a very stimulating and intriguing topic (Brozzetti et al., 2008) In particular, the possibility that moderate earthquakes can be generated by rupturing steeper segments (dip > 30°), along the staircase trajectory of AtF, is worth to be explored. Further studies, aimed to reduce the uncertainties on the localization at depth of the fault volume and of the seismic events, are needed to address this point.

## 7. Conclusions

In this paper, we interpreted a set of previously unreleased seismic reflection profiles, providing new insights on the stratigraphic and tectonic setting of the Sansepolcro basin, generated above the northern sector of the AtF, a regional NE-dipping LANF in the Northern Apennines.

The continental succession infilling the basin is up to 1200 m thick, much thicker than previously observed at the surface (e.g. Delle Donne et al., 2007; ISPRA-CARG Project, F° 289). The lower part of the succession is older (at least Middle Pliocene) than the succession exposed at the surface (Early Pleistocene). We identified 4 main stratigraphic units: the lower unit (UA) possibly corresponding to coarse, fluvial sediments, the intermediate units (UB and UC), that can be related to a lacustrine succession, and an uppermost unit (UD), corresponding to the recent alluvial sediments.

The basin is strongly asymmetric: the NE flank is much steeper than the SW one and the deeper part of the basin is clearly shifted towards the NE flank.

The basin evolution is driven by a complex extensional faults system, consisting of a low-angle, NE-dipping master fault (AtF) and by its synthetic and antithetic splays, bordering the opposite flanks of the basin. At the basin southern edge, a SW-NE trending transfer fault separates the basin by the Città di Castello threshold.

We reconstructed a two-stage tectono-sedimentary evolution, where the basin initiated as a bowl-shaped depression and was subsequently disrupted by the upward propagation of two sets of opposite-dipping normal faults. The initial bowl-shaped depression was generated at the hanging-wall of the Atf, which is characterized by a staircase, flat-ramp-flat trajectory.

The occurrence and distribution of historical and instrumental seismicity suggest that the normal faults of the study area are still active, even if a punctual correspondence between the single earthquakes and the single normal fault segments cannot be deduced with the currently available data.

## Acknowledgements.

We gratefully acknowledge: ENI- E&P, that provided most of the seismic data used for this study; Francesco Mirabella, Andrea Lupattelli and Simona Pierdominici for the useful discussions; two anonymous referees, whose suggestions helped to improve the paper.

## References

Argenti P. (2004) Plio-Quaternary mammal fossiliferous sites of Umbria (Central Italy). Geol. Rom., 37, 67-78.

Bally A. W., Burbi L., Cooper C., Ghelardoni L. (1986) Balanced sections and seismic reflection profiles across the Central Apennines. Mem. soc. geol. It., 35, 257-310.

Barchi M.R., Magnani M.B., Minelli G., Pialli G., Sotera B.M. (1995) Osservazioni geofisiche sul basamento della regione umbro-marchigiana; Atti GNGTS 14 th Conference, 2, 709-720.

Barchi M.R., De Feyter A., Magnani M.B., Minelli G., Pialli G., Sotera B.M. (1998) Extensioanl tectonics in the Northern Apennines (Italy): Evidence from the CROP03 deep seismic reflection line, Mem. Soc. Geol. It., 52, 527-538.

Barchi M.R., Paolacci S., Pauselli C., Pialli G., Merlini S. (1999) Geometria delle deformazioni estensionali recenti nel bacino dell'Alta Val Tiberina fra S. Giustino Umbro e Perugia: evidenze geofisiche e considerazioni geologiche. Boll.Soc.Geol.It., 118, 617-625.

Barchi M.R. (2002) Lithological and structural controls on the seismogenesis of the Umbria region: observation from seismic reflection profiles, Boll. Soc. Geol. It., vol. spec. 1, 855-864.

Barisone G., Argenti P., Kotsakisa T. (2006) Plio-Pleistocene evolution of the genus Castor (Rodentia, Mammalia) in Europe: C. fiber plicidens of Pietrafitta (Perugia, Central Italy), Geobios, 39, 757–770.

Basili R., G. Valensise, P. Vannoli, P. Burrato, U. Fracassi, S. Mariano, M.M. Tiberti, E. Boschi (2008) The Database of Individual Seismogenic Sources (DISS), version 3: summarizing 20 years of research on Italy’s earthquake geology, Tectonophysics, doi:10.1016/j.tecto.2007.04.014 (in press).

Boccaletti M., Gianelli G., Sani, F. (1997) Tectonic regime, granite emplacement and crustal structure in the inner zone of the Northern Apennines (Tuscany, Italy): a new hypothesis: Tectonophysics, 270, 127–143.

Boncio M., Ponziani F., Brozzetti F., Barchi M.R., Lavecchia G. and Pialli G. (1998) Seismicity and extensional tectonics in the Northern Umbria-Marche Apennines, Mem. Soc. Geol. It., 52, 539-555.

Boncio P., Lavecchia G. (2000) A structural model for active extension in Central Italy, J. of Geodynamics, 29, 233-244.

Boncio P., Brozzetti F., Lavecchia G. (2000) Architecture and seismotectonics of a regional low angle normal fault zone in central Italy, Tectonics, 19, 1038-1055.

Bonini M. (1998) Chronology of deformation and analogue modelling of the Plio-Pleistocene 'Tiber Basin': implications for the evolution of the Northern Apennines (Italy) Tectonophysics, 285, 1, 147-165.

Brogi A. (2007) The structure of the Monte Amiata volcano-geothermal area (Northern Apennines, Italy): Neogene-Quaternary compression versus extension. Int. J. Earth Sci.

Brozzetti F. (1995) Stile deformativo della tettonica distensiva nell'Umbria occidentale: l'esempio dei Massicci Mesozoici Perugini. Studi Geologici Camerti, 1, 105-119.

Brozzetti F., Boncio P., Lavecchia G. (2001) Una nuova interpretazione del profilo CROP03 nel tratto Castiglion Fiorentino – M. Castellaccio: vincoli da dati geologici di superficie di recente acquisizione. Studi per l'interpretazione del profilo CROP18, Siena, Dicembre 2001.

Brozzetti F., Boncio P., Lavecchia G., Pace B. (2008) Present activity and seismogenic potential of a low-angle normal fault system (Città di Castello, Italy): Constraints from surface geology, seismic reflection data and seismicity, Tectonophysics (in press), doi:10.1016/j.tecto.2008.09.023.

Castello B., Selvaggi G., Chiarabba C., Amato A. (2005) CSI Catalogo della sismicità italiana 1981-2002, versione 1.0. INGV-CNT, Roma http://www.ingv.it/CSI/

Cattuto C., Cencetti C., Fisauli M., Gregari L. (1995) I bacini pleistocenici di Anghiari e Sansepolcro nell'alta valle del F.Tevere. Il Quaternario, 8 (1),119-128.

Chiarabba C., Jovane L., Di Stefano R. (2005) A new view of Italian seismicity using 20 years of instrumental recordings, Tectonophysics, 395, 251-268. Chiaraluce L., Barchi M., Collettini L., Mirabella F., Pucci S. (2005) Connecting seismically active normal faults with Quaternary geological structures: the Colfiorito 1997 case history (Northern Apennines, Italy). Tectonics, Vol. 24, TC1002, doi: 10.1029/2004TC001627.

Chiaraluce L., Barchi M.R., Collettini C., Mirabella F., Pucci S. (2005) Connecting seismically active normal faults with Quaternary geological structures in a complex extensional environment: The Colfiorito 1997 case history (Northern Apennines, Italy) Tectonics, Vol. 24, TC1002, doi:10.1029/2004TC001627.

Chiaraluce L., Chiarabba C., Collettini C., Piccinini D., Cocco M. (2007) Architecture and mechanics of an active low-angle normal fault: Alto Tiberina Fault, Northern Apennines, Italy. Journal of Geophysical Research, 112, B10310, doi:10.1029/2007JB005015.

Ciaccio M.G., Pondrelli S., Frepoli A. (2006) Earthquake fault-plane solutions and patterns of seismicity within the Umbria Region, Italy ANNALS OF GEOPHYSICS, VOL. 49, N. 4/5, August/October 2006.

Ciaccio M.G., Mirabella F., Chiarabba C., Barchi M.R., Stucchi E. (2005) Seismological, geological and geophysical costraints for the Gualdo Tadino fault, Umbria-Marche Apennines (Central Italy), Tectonophysics, 406, 3-4, 233-247.

Collettini C., Barchi, M. R. (2002) A low angle normal fault in the Umbria region (Central Italy): a mechanical model for the related microseismicity. Tectonophysics, 359, 97-115.

Collettini C., Barchi M.R., pauselli C., Federico C., Pialli G. (2000) Seismic expression of active extensional faults in Northern Umbria (Central Italy), J. Geodyn., 29, 3-5, 309-321.

CPTI Working Group (2004) Catalogo Parametrico dei Terremoti Italiani versione 2004 (CPTI04). INGV, Bologna. http://emidius.mi.ingv.it/CPTI/

Cressie N., 1990. The origins of kriging. Mathematical Geology, 22, 239-252.

Delle Donne D., Piccardo L., Odum J.K., Stephenson W.J., Williams R.A. (2007) High-resolution shallow reflection seismic image and surface evidence of the Upper Tiber Basin active faults (Northern Apennines, Italy), Boll. Soc. Geol. It., 126, 2, 323-331.

Esu D., Girotti O. (1991) Late Pliocene and Pleistocene assemblages of continental molluscs in Central Italy. Il Quaternario, 4, 137-150.

Gawthorpe R.L., Sharp I., Underhill J.R., Gupta S. (1997) Linked sequence stratigraphic and structural evolution of propagating normal faults. Geology, 25, 795-798.

ISPRA – CARG Project - Carta Geologica d'Italia scala 1:50.000 - F° 289 - Città di Castello;
http://www.apat.gov.it/MEDIA/carg/Allestimento/289_CittaCastello/F°.html

Lavecchia G., Brozzetti F., Barchi M.R., Keller J.V.A., Menichetti M. (1994) Seismotectonic zoning in east-central Italy deduced from the analysis of the Neogene to present deformations and related stress fields. Geol. Soc. Am. Bull., 106, 1107-1120.

Pascucci V., Merlini S., Martini P. (1999) Seismic stratigraphy of the Miocene-Pleistocene sedimentary basin of the Northern Tyrrhenian Sea and western Tuscany (Italy). Basin Research 11, 337-356.

Pascucci V., Martini I.P., Sagri M., Sandrelli F. (2007) Effects of transverse structural lineaments on the Neogene–Quaternary basins of Tuscany (inner Northern Apennines, Italy) - In: Nichols G., Williams E. and Paola C. (Eds.) -

Sedimentary Processes, Environments and Basins: a Tribute to Peter Friend. I.A.S. Spec. Pubbl. n. 38, 155-181.

Surface Mapping System; http://www.goldensoftware.com/.

Pauselli C., Barchi M.R., Federico C., Magnani M.B., Minelli G. (2006) The crustal structure of the Northern Apennines (Central Italy): an insight by the Crop03 seismic line. American Journal of Science, 306, 428-450.

Piccinini D., Cattaneo M., Chiarabba C., Chiaraluce L., De Martin M., Di Bona M., Moretti M., Selvaggi G., Augliera P., Spallarossa D., Ferretti G., Michelini A., Govoni A., Di Bartolomeo P., Romanelli M. and Fabbri J. (2003) A microseismic study in a low seismicity area of Italy: the Città di Castello 2000-2001 experiment, Ann. Geophys., 46, 6, 1315-1324.

Pondrelli S., Salimbeni S., Ekström G., Morelli A., Gasperini P., Vannucci G. (2006) The Italian CMT dataset from 1977 to the present, *Phys. Earth Plan. Int.*, 159/3-4, 286-303.

Vannucci G., Pondrelli S., Argnani A., Morelli A., Gasperini P., Boschi E. (2004) An atlas of Mediterranean seismicity, Annals of Geophysics, Suppl. to vol. 47(1), 247-306.

## Figure Captions

Figure 1 Location of the region and structural sketch map showing the major extensional faults (A) (modified from Barchi, 2002); schematic structural map of the study area (B) in red traces of the seismic lines interpreted (modified from ISPRA-CARG, F° 289 Città di Castello, 1:50000). Trace of geological cross section (a-a; b-b) from high resolution seismic reflection profiles acquired in the area (Delle Donne et al., 2007), description in text.  SoF) Sovara normal fault; AnF) Anghiari normal fault; SsF) Sansepolcro normal fault. Umbria Fault System: a NNW–SSE-trending active fault system of the Northern Apennines, 150-km long alignment of SW-dipping normal faults, extending from Città di Castello as far south as Norcia.

Figure 2 Epicentral map of historical seismicity (crosses) with epicentral intensity ≥ IX (CPTI working group, 2004) and distribution of the epicentres of the main seismic sequences that have occurred in the area (circles); focal mechanisms of the mainshocks are also shown and hypocenter sections (modified from Ciaccio et al., 2006). Ss – Sansepolcro; CC – Città di Castello.

Figure 3 - 3Aa-b Line drawings (vertical scale in seconds TWT) of the seismic reflection profiles transversal to the study area, see location in fig.1. Key for the most evident reflectors: Note the sharp westward termination of the stratigraphic markers on the AtF splay fault plane (descriptions in text). Key for the most evident reflectors: SoF Sovara normal fault; AnF) Anghiari normal fault; SsF) Sansepolcro normal fault.

3Ac Vertical geological cross section of L2 profile (see location in fig.1) obtained integrating seismic reflection profile and surface geology from ISPRA-CARG, F° 289, Città di Castello, 1:50000.

3B Sections a – a and b – b : interpretation of high resolution seismic profiles integrated with morphometric data (Delle Donne et al., 2007), see positions in fig.1.

Figure 4 Line drawings (vertical scale in seconds TWT) of the portion analysed of the CROP 03 seismic reflection line, see location in fig.1: descriptions in text. Key for the most evident reflectors: SoF Sovara normal fault; AnF) Anghiari normal fault; SsF) Sansepolcro normal fault.

Figure 5 Line drawings (vertical scale in seconds TWT) of the seismic reflection profiles longitudinal to the study area, see location in fig.1: descriptions in text. Key for the most evident reflectors: AtF) Altotiberina normal fault; SsF) Sansepolcro normal fault.

Figure 6 Isobaths map (m) of the bottom of the basin, imaging the topography of the submerged bedrock. The location of the industrial seismic profiles is indicated in red, the green line indicates the location of the Crop 03 seismic reflection line. The isobaths were interpolated by Surface Mapping System (http://www.goldensoftware.com/).