Active faults at the boundary between Central and Southern Apennines (Isernia, Italy)

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Abstract

This paper focuses on the boundary area between the Central and Southern Apennines thrust belt of the Italian peninsula, which separates two different patterns of distribution of active faults and strong earthquakes along the Apennines chain. In order to reduce the remarkable lack of data on this area, part of this boundary has been investigated. The study area corresponds to the surroundings of the town of Isernia, an important centre of the Molise region, and contains the Carpino and Le Piane (CLP) intermountain Basins of Quaternary age. The research was based on unpublished data, consisting of 65 well logs drilled in the CLP Basins, integrated with detailed field surveys (scale 1:10,000), mesoscale structural analysis and aerial photograph interpretation. This study allowed to define the geometry and kinematics of the CLP Basins. They result to be asymmetric half-grabens partially filled with fluvio-lacustrine deposits, where the sedimentation is controlled by the activity of a set of normal faults striking N30°W and NE dipping. This set of faults, which developed mainly during the Late Pleistocene–Holocene, is about 10 km long and is located close to the northwestern end of the Boiano Basin extensional Fault System. The average slip rate calculated for part of the Holocene for one of the recognised faults ranges from 0.75 to 1.00 mm/year. The identification of the active CLP Basins Fault System partially fills the gap of data at the boundary between the Central and Southern Apennines. From a more general point of view, we hypothesise that this boundary might be regarded as a "persistent segment boundary", forming a long-term barrier to the propagation of rupture of active fault systems. Under this perspective, a redefinition of the seismic zonation of Italy for the study area is suggested.

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1. Introduction

Active faults and strong earthquakes (magnitudes reaching values of about 7; Gruppo di Lavoro CPTI, 1999) along the Apennines chain (Italy) show different patterns of distribution, being organised in a few parallel zones all along the Northern and Central Apennines, and concentrated in one narrow belt along
The Southern Apennines (Gruppo di Lavoro CPTI, 1999; D’Addezio et al., 2001).

The degree of knowledge about these active faults is variable (e.g. Michetti et al., 2000b; Valensise and Pantosti, 2001a); as a result, the location of the seismogenic structures along the Apennines is still a matter of debate, and only a fraction of all the potential seismic source zones has already been fully investigated and characterised (Pantosti and Valensise, 1988, 1993; Boschi et al., 1993; Galadini and Galli, 1996, 2000; Pantosti et al., 1996; Cinti et al., 1997; Michetti et al., 1997; Peruzza, 1999; Barchi et al., 2000; Valensise and Pantosti, 2001a). In particular, a remarkable lack of data can be observed for the area between the two described patterns of distribution (Fig. 1A,B). Recent international literature suggests that this lack of data could be an evidence of a real change in the seismic sources’ distribution (Valensise and Pantosti, 2001b). Therefore, in this paper, we focus on this boundary area between the Central and Southern Apennines thrust belt, with the aim of reducing this lack of data regarding the presence of possible active faults. Moreover, our analysis also aims at better characterising the seismotectonic meaning of a major geological boundary such as that between the Central and Southern Apennines.

This part of the Apennines chain (Fig. 1A) was generated by progressive northeastward thrusting and stacking of passive-margin sediments, essentially during the Cenozoic. As all along the core of the Apennines, in our study area, a subsequent major phase of SW-NE extension (Lavecchia et al., 1994; Cavinato and De Celles, 1999; Cipollari et al., 1999) overprinted the compressional structures since Middle Pleistocene (Patacca et al., 1992; Corrado et al., 1997). This extension is still active today (Galadini and Galli, 2000; for breakout analysis see Montone et al., 1999); therefore, the youngest structural features of this part of the Apennines are due to extensional deformation. This young deformation is also responsible for the largest earthquakes of the region (Valensise and Pantosti, 2001b).

The study area extends along part of the described boundary between the Central and Southern Apennines (Fig. 1A,B). It corresponds to a zone close to the town of Isernia, hosting two Quaternary intermountain depressions, the Carpino and Le Piane Basins (which we refer to as CLP Basins). It is located between two regions well characterised from a seismotectonic point of view.

Some active fault systems were in fact recognised well several kilometres to the NW of the CLP Basins area (to the WNW of the boundary area of Fig. 1B). The northernmost, called Aremogna—Cinque Miglia—Mt. Rotella Fault System (Galadini and Galli, 2000; ACRFS in Fig. 1A), is composed of NW- to N-striking, W-dipping normal faults which displace Pleistocene and Holocene deposits and extend for a total length of 16 km. The seismic potential of this system was analysed by trench investigations, and at least three paleoevents were identified for the last 7000 years (D’Addezio et al., 2001). Further southwest, a second system parallel to the first one, the Upper Sangro Valley Fault System, consists of normal and left-lateral strike-slip NW–SE faults that were active in the Late Pleistocene (Galadini and Galli, 2000; USFS in Fig. 1A). Part of this system was interpreted as responsible for an earthquake that occurred along the Sangro River Valley in 1984 (Ms = 5.5; Gruppo di Lavoro CPTI, 1999). This interpretation is based on the integration of seismological data (aftershock distribution) with geological and structural field data (Boncio et al., 1998).

An active fault system was also identified immediately southeast of the CLP Basins area (to the ESE of the boundary area of Fig. 1B). Here, the Boiano Basin Fault System (Cucci et al., 1996; Naso et al., 1998; Gasperini et al., 1999; BBFS in Fig. 1A), which develops along strike for at least ca. 25 km, shows a complex extensional pattern. It consists of a system of NW–SE synthetic (NE dipping) and antithetic (SW dipping) Quaternary normal faults, linked by shallow pre-Quaternary E–W high-angle faults reactivated by the SW–NE-oriented active extensional stress field (Montone et al., 1999). The NE-dipping master fault develops down to a depth of at least 9 km and hosts the Boiano Basin in the hanging wall (Mazzoli et al., 2000). The activity of some faults of this system was recognised by Guerrieri et al. (1999) and by Blumetti et al. (2000). Moreover, this fault system, defined on the basis of surface and subsurface geological data, strictly coincides with the active fault system suggested by drainage network studies (Cucci et al., 1996) and with that derived from the damage field of the 1805 earthquake (1805 earthquake, $I_e=X$ MCS; Gruppo di Lavoro CPTI, 1999). Therefore, it
Fig. 1. (A) Geological map of the Central–Southern Apennines. USFS: Upper Sangro Valley Fault System (Boncio et al., 1998; Galadini and Galli, 1999); ACRFS: Aremogna–Cinque Miglia Plains–Mt. Rotella Fault System (Galadini and Galli, 1999; D’Addezio et al., 2001); BBFS: Boiano Basin Fault System (Cucci et al., 1996; Naso et al., 1998; Gasperini et al., 1999). (B) Largest earthquakes of the Central–Southern Apennines (data after Boschi et al., 1997). The size of the square symbols is proportional to an “equivalent magnitude” (Me) derived from the intensity data. The striped belt indicates the boundary area, cited in the text, between the Central and the Southern Apennines.
Fig. 2. Geological map of the Carpino–Le Piane (CLP) Basins, showing original data presented in this work and coming from geological survey performed at 1:10,000 scale, aerial photograph interpretation and well log analysis. (a) Bedding; (b) faults from: 1—well log analysis, 2—well log analysis and aerial photograph interpretation, 3—aerial photograph interpretation, 4—geological survey; (c) intrenched rivers; (d) wells location; (e) trenches location; (f) trace of the geological cross-sections; (g) Late Quaternary fluvial and lacustrine deposits (Giraudi et al., 1999); (h) Late Quaternary slope talus and associated alluvial fans (Giraudi et al., 1999); (i) Middle Pleistocene terraced slope talus and alluvial fans (Coltorti and Cremaschi, 1982); (j) paleo-landslide; (k) Middle Pleistocene conglomerates, gravels, sands and volcanoclastic deposits (“Riempimento principale”; Auct.; Delitala et al., 1983; Corrado et al., 2000); (l) Early–Middle Pleistocene travertine and concretional sands (AA.VV., 1983); (m) Early–Middle Pleistocene lacustrine clays (Esu, 1983); (n) Meso-Cenozoic marine successions—mainly carbonate and terrigenous deposits (Servizio Geologico Nazionale, 1971).
seems reasonable to associate a severe seismicity to the Boiano Basin Fault System.

Concerning the seismicity of the study area, another strong earthquake, which occurred in 1456 (Gruppo di Lavoro CPTI, 1999), needs some comments. This earthquake was in fact composed by three events, and the epicentre of one of these (Molise event; \( I_o = X \) MCS) was located in the Boiano Basin area. Nevertheless, its attribution to the Boiano Basin Fault System is problematic, due to the anomalously short recurrence interval with respect to the 1805 earthquake. Along the Apennines, these events generally show recurrence intervals of about 1–2 thousand years (Valensise and Pantosti, 2001b, and references therein), while in this case, we should deal with less than 400 years. This suggests that another seismic source, still unknown, could be hosted in the study area, where, in spite of this, neither active faults nor strong earthquakes are known.

Two factors make our study area favourable to the purpose of work:

(i) abundant continental Quaternary deposits allow a good reconstruction of the recent evolution of the area. In particular, the Isernia zone is filled by fluvial and lacustrine deposits. The top part of these has been referred to the Holocene (Coltorti and Cremaschi, 1982; Giraudi et al., 1999). Moreover, around the CLP Basins, Middle Pleistocene continental deposits have been recently dated by \(^{39}\)Ar/\(^{40}\)Ar methods (Corrado et al., 2000);

(ii) abundant subsurface data are available due to urban and industrial expansion in the CLP Basins.

The research was based on detailed field surveys (scale 1:10,000), mesoscale structural analysis and aerial photograph interpretation, integrated with unpublished subsurface data.

These last consist of the logs of 65 wells drilled in the CLP Basins during the last 10 years (courtesy of “Regione Molise” Administration; Fig. 2). These wells, which are some tens of metres deep, were drilled for civil engineering purposes; therefore, they are not accompanied by detailed micropaleontological or sedimentological analyses. Nevertheless, a detailed lithologic description accompanies all of the well logs, and the correlation of these lithologies was used to define the geometry of the basins and their recent evolution.

2. Geological setting

The Carpino and Le Piane basins are two few kilometres wide intermountain depressions, located at elevations of ca. 500 and 450 m a.s.l. (Fig. 2) in the core of the Molise Apennines. The area (Figs. 1 and 2) is bounded by the Matese Mountains to the South, the Montagnola di Frosolone Range to the ENE, the Alto Molise hills to the North and NW and the Isernia hills to the West. The first three relieves are formed by Meso-Cenozoic mainly carbonate successions referred to carbonate platform and slope facies, and by Cenozoic terrigenous successions referred to pelagic basin facies. On these relieves, Middle Pleistocene alluvial deposits, generally in perched terraces, and Middle–Late Pleistocene slope taluses can be found (Coltorti and Cremaschi, 1982).

The Isernia hills consist, instead, of an Early–Middle Pleistocene continental succession (Fig. 2) composed of, from the bottom to the top:

- lacustrine clays, referred to the Early–Middle Pleistocene boundary (Esu, 1983), the thickness of which tapers from some tens of metres to zero beneath the town of Isernia (Brancaccio et al., 2000);
- travertines with concretional sands at the top; the travertines mainly outcrop in the town of Isernia and show a maximum thickness of ca. 15 m; they are topped by a few metres of sands. Both are referred to the Early–Middle Pleistocene boundary (AA.VV., 1983). A paleolithic site of 0.73 Ma age was identified in correspondence with the upper boundary of the travertine (AA.VV., 1983; locality “Isernia La Pineta”, southernmost trench to the South of Isernia in Fig. 2);
- conglomerates, gravels, sands and volcanoclastic deposits; these facies are interfingered and have a total thickness that can exceed 100 m. This unit, the so-called “Riempimento principale” Auct., is Middle Pleistocene in age (Delitala et al., 1983); the youngest age obtained for these deposits by recent \(^{39}\)Ar/\(^{40}\)Ar dating (Corrado et al., 2000) is 232 ± 11 ka.

The flat-top Quaternary infill of the CLP Basins consists of fluvial-lacustrine sediments. For the shallowest part of these deposits in Le Piane basin, radiocarbon dating provided ages of 4020 ± 80 and 1560 ± 70 years BP (Giraudi et al., 1999). The contact of the CLP Basins with the surrounding relieves is commonly marked by alluvial fans parti-
ally interfingered with the fluvio-lacustrine infill (Giraudi et al., 1999).

Both the CLP Basins are located at the top of the same thrust sheet (the Matese–Montagnola di Froso-lone Unit). However, as is common throughout the Apennines, the most obvious structures in the study area are NW–SE-striking normal faults (Corrado et al., 1997), due to the extensional regime that has acted since the Middle Pleistocene. These faults are both NE- and SW-dipping, and are associated with pre-existing N–S-striking faults reactivated by the same tectonic regime (Corrado et al., 1997).

3. CLP Basins: new geologic data

A geological survey originally carried-out at 1:10,000 scale is summarised in Fig. 2. This figure also includes tectonic lineaments obtained by aerial photograph interpretation, as well as by the analysis of 65 well logs.

The flat-top of the CLP Basins (Fig. 3) is marked by the presence of fluvial-lacustrine sediments due to flooding of the Rava, Sordo and Carpino Rivers; where these deposits outcrop and are of Holocene age (Coltorti and Cremaschi, 1982; Giraudi et al., 1999; Fig. 2). Other Quaternary continental deposits, mainly slope talus (Servizio Geologico Nazionale, 1971), outcrop to the NE of the CLP Basins, especially along the Pesche relief slope (Fig. 2).

The steep slope of Pesche is defined by a set of N120°E oriented normal faults which dip ca. 65° toward SW; striations pitch ca. 90° on the fault planes. These faults develop along strike for at least 3 km.

To the south of Pesche, these faults displace a paleosurface developed at an elevation of ca. 600 m, which defines a perched terrace (Figs. 2 and 3). According to Coltorti and Cremaschi (1982), these

![Fig. 3. Digital Elevation Model of the study area.](Image)
terraces are referred to the Middle Pleistocene, and this age correlates with that of analogous terraces in the Botano Basin area (Corrado et al., 2000). Therefore, Pesche faults probably acted in the final part of the Middle Pleistocene, when the SW–NE-oriented extensional stress field was still active.

In the meantime, toward SW, a depressed area was hosting the sedimentation of the Isernia Middle Pleistocene continental succession. This thick succession is exclusively located at the surroundings of the town of Isernia; one can therefore hypothesise that, during the Middle Pleistocene (at least until ca. 200 ka BP), the area now hosting the CLP Basins was at an intermediate elevation between the Pesche slope and the Isernia basin. Moreover, its morphology was probably not favourable to the development of relevant continental sedimentation. This implies that a weak morphological inversion may have occurred in the last 200 ka.

A less evident yet recognisable set of tectonic lineaments was found to bound also the WSW side of both Carpino and Le Piane basins. On the aerial photographs, the morphological evidence for these lineaments is given by rectilinear streams, change in slope angles, rectilinear geological boundaries of subhorizontally layered deposits, valleys’ alignments. Some of these elements can be recognised in the Digital Elevation Model of Fig. 3. The whole set of lineaments is detectable for a length of at least 8 km. The interpretation of these lineaments as faults was independently supported by the well log analysis.

3.1. The Carpino basin

Concerning the Carpino basin, 25 well logs were available. The most representative one for the basin stratigraphy, identified with “Ar” (Fig. 2), comprises the whole continental succession and reaches the Meso-Cenozoic bedrock (Fig. 4). Below the active soil “A”, the upper part of the succession is characterised by a thin layer of silt “B”, followed by an easily recognisable layer of sand “C”. Below this, a thick succession of silty clay and clayey silt “D” rests on top of the Meso-Cenozoic bedrock “E”, here consisting of calcarenites.

The interpretation of the Carpino basin logs results in two geological cross-sections shown in Fig. 5. In both sections, the vertical scale is 10 times the...
horizontal one; the real dip of the faults is assumed to be about 60°.

The southernmost geological cross-section of the Carpino basin is the CA2 (Fig. 5). From top to bottom, below the active soil “A” (including talus deposits at the base of the slopes), all of the wells show a layer of silt and clayey silt “B”, characterised by the presence of phytoclasts and peat which is widespread to the SW. The thickness of unit “B” is ca. 3 m in the central part of the plain. Toward NE, this unit increases its thickness (maximum ca. 6.5 m), possibly because it is interfingered with an alluvial fan (Fig. 2, and “G” in Fig. 5). In addition, also toward the SW, this layer shows a thickness increase (maximum thickness of ca. 4.5 m) not accompanied, in this case, by an increase in grain size.

Below this unit, an easily recognisable thin layer of fine-grained grey sand “C” is present only in the southwestern part of the section; it shows a maximum thickness of ca. 2 m and tapers off to 0 m toward NE.

The lowest part of the Quaternary basin is filled by a thick layer of grey clayey silt and silty clay “D”. This unit shows its maximum thickness in the southwestern part of the basin, where it exceeds 20 m (none of the wells reached the bedrock), while to the NE, the Meso-Cenozoic bedrock “E” was found at a depth of about 10–13 m. To the NE, also the unit “D” is interfingered with the previously mentioned alluvial fan.

The northeastern slope of the Carpino valley is also characterised by some continental Quaternary deposits (“F” in Fig. 5). These are mainly composed of slope talus, as well as by subhorizontal thin layers of
imbricated, subrounded–subangular, centimetric to decimetric clasts in terrigenous silty matrix, probably related to fluvial transport; these deposits have been related to the Middle Pleistocene by Coltorti and Cremaschi (1982). In some cases, these deposits are exposed in the previously mentioned perched and faulted terraces at a mean elevation at ca. 600 m (Figs. 2, 3 and 5).

On the opposite side of the plain, the general thickening of the deposits toward the SW can be observed. Considering its affinity with the top of Le Piane infill (Giraudi et al., 1999), also the top of these deposits could be related to the Holocene. Moreover, these deposits are also interfingered with the alluvial fan “G”, which rests on the Middle Pleistocene slope deposits “F”. Therefore, they can be reasonably attributed to the Late Pleistocene–Holocene. Thus, the Carpino basin depression must have developed during this time span.

Further considerations come from the section CA1. The stratigraphy of the two wells, 4V and 5V (Fig. 5), is quite different from the others; here, the thickness of the basin infill does not exceed 10 m, as opposed to 24 m in the well “Ar” (Figs. 4 and 5). Moreover, in the wells 4V and 5V, the continental succession below the active soil is formed by silty-sandy clays, which cannot be divided into the units “B”, “C” and “D” recognised further to the East. The lineament located at the base of the Pettoranello slope on the basis of aerial photograph interpretation (Figs. 2 and 5) seems to continue just in correspondence with this strong variation in the basin infill succession. Therefore, we interpret this lineament as a fault acting during the infilling of the basin, and as the cause for the formation of a downthrown area (the hanging wall), where the fluvial-lacustrine sedimentation was fully developed. In contrast, the Quaternary stratigraphy on the footwall can be interpreted as a condensed succession. Another possible interpretation of the data along the section CA1 provides that the unit “C” may be a lens and its termination may be located between boreholes 4V and “Ar”. An erosion surface may divide unit “D” in the inner part of the basin from the deposits related to the area of the boreholes 5V and 4V. 4V and “Ar” may constrain the geometry of this erosion surface. In such case, the presence of a fault should not be necessary to explain the relationship between the SW stratigraphic setting and that related to the inner part of the basin.

However, this interpretation appears rather laboured and less applicable to the section CA2. Therefore, the first interpretation, which considers the sedimentation into the Carpino basin as controlled by a normal fault along its WSW side, seems to be preferable.

3.2. Le Piane basin

Forty-five well logs were available for Le Piane basin. The most representative one for the basin stratigraphy, identified with “3 C.SP.” (Figs. 2, 3 and 6), shows the maximum thickness known for...
the continental succession, even though it does not reach the Meso-Cenozoic bedrock. Note that, in this basin, the wells reach the Meso-Cenozoic bedrock in only a few cases where the plain infill is thin (i.e. near the surrounding slopes; Figs. 2 and 7a). Below the active soil “a” (Figs. 6 and 7a,b), the well drills through a few metres of silt “b” containing coal fragments and phytoclasts. Below this unit, an alternation of gravel and silty sand “c” has a total thickness that exceeds 10 m. The lowest part of the succession shows a decrease in grain size, being formed again by a few metres of silt “d” with fine coal layers and calcareous clasts.

Concerning the age of Le Piane basin infill, no data are available for the bottom of the succession. In any case, it is clearly different from the Isernia Early–Middle Pleistocene continental succession, and it does not contain volcanoclastic levels, which characterise the Middle Pleistocene continental successions of this region (Corrado et al., 2000). Therefore, the deepest
part of Le Piane infill could be reasonably attributed to the Late Pleistocene. The shallowest part of the infill is of Holocene age (Giraudi et al., 1999).

The interpretation of Le Piane basin logs results in five geological cross-sections SW–NE oriented (Fig. 2) shown in Fig. 7a,b. In all the sections, the vertical scale is 10 times the horizontal one; the real dip of the faults is assumed to be about \(60^\circ\).

The cross-section IS2 (Fig. 7a) represents the geological setting reconstructed for the central part of Le Piane basin. Towards the WSW, the section shows the lowest part of the typical Early–Middle Pleistocene continental succession of Isernia. It is formed by lacustrine clays “c1”, tapering from some tens of metres to zero just beneath the town of Isernia, and by the overlying travertine “t”. Towards the ENE, this one rests directly on the Meso-Cenozoic substratum “e”, here formed by limestones. At the top of the travertine, concretional sands “t*” outcrop in the study area (e.g. in the paleolithic site described before) and have been drilled by the wells no. 17, 18 and 19 (Fig. 7a). Further to the NNW (Fig. 7a, section IS1), the upper part of the Isernia succession (of Middle Pleistocene age) outcrops along the western side of Le Piane basin. It consists of conglomerates, gravels, sands and volcanoclastic deposits “v”, forming the “Riempimento principale” Auct. described in the Section 2. These deposits are confined along the basin slope, at the top of the concretional sands “t*”.

In the profile IS2, the basin appears characterised by a set of normal faults which cut the bedrock, travertine and concretional sands with displacement of at least 30 m, and form a depression that was progressively filled by the continental succession of Le Piane basin. Well no. 17 shows that this succession has a total thickness of ca. 13 m at the top of the concretional sands. On the
hanging wall of the easternmost fault, this succession is the only one drilled; it thickens for a total of at least 25 m and then gradually thins out towards the NNE. The attempt to correlate our data with the trench studied by Giraudi et al. (1999) ("trench" in Fig. 7a, section IS2) confirms this tendency. The vertical displacement of the boundary between the units "b" and "c" is of about 3 m, while the minimum vertical displacement of the boundary between "c" and "d" is of about 6 m. In the section IS3 (Fig. 7a), the vertical displacement of the boundary between "c" and "d" is of 4.5 m, and it is of 4.0 m in the section IS1. In summary, not only do the identified faults displace the Early–Middle Pleistocene Isernia succession, but they also cut the infill of Le Piane basin and have controlled sedimentation within the basin.

Toward NNW, this displacement is hypothesised to tend to zero (Fig. 7b, section IS4), although this part of Le Piane basin is badly constrained by well logs. Toward SSE (Fig. 7b, section IS5), wells 4 and 5 show a relevant thickness for the units "b", "c" and "d" with respect to the top of the buried travertine, here projected at the footwall of the fault from the wells 11, 17 and 20. Neither wells along the section IS5 allow defining the stratigraphy of the basin infill at the top of the buried travertine nor, consequently, any slip rate values for the boundary between "c" and "d". Nevertheless, the section IS5 confirms the development of the described faults toward SSE, i.e. toward the threshold of the Carpino basin (Fig. 2).

Summing up, the NNW–SSE fault system, which bounds the CLP Basins along their WSW sides, shows a significant homogeneity, both for geometry and age. Among these faults, a relevant role is played by the most internal one with respect to Le Piane basin. Not only did this fault show the main displacements, as outlined by the cross-sections of Fig. 7a,b, but it also seems to condition the drainage pattern of both Sordo and Carpino Rivers.

The natural tendency of the Carpino river (now intrenched for agricultural purposes) is to overflood the related plain. Once past the basin threshold, corresponding to this NNW–SSE fault, the Carpino River becomes intrenched in the carbonate bedrock, which has preserved some meanders (Figs. 2 and 3).

The Rava River flows from NNW to SSE in Le Piane basin. However, near the town of Isernia, this river abruptly deflects toward the SW, passes the described fault and immediately intrenches into the plateau of travertine and the underlying carbonate bedrock.

The coincidence of the described behaviour of these two rivers with respect to the same tectonic element led us to prefer the hypothesis of a recent tectonic activity of this one, rather than to attribute the location of both thresholds merely to regressive erosion from downstream.

Therefore, we conclude that the threshold of Le Piane basin is not controlled by the morphologic step represented by the travertines, but by the activity of the faults that border the western side of the basin. The behaviour of both rivers also suggests an antecedence of these with respect to the faults, as well as their capability to maintain sufficient erosive power to keep pace with footwall uplift. All the data presented above suggest an extremely recent activity for these faults.

4. Discussion

4.1. The active CLP Basins Fault System

Based on our investigations, it appears that the most recent tectonic activity in the CLP Basins is consistent with the extensional regime acting since Middle Pleistocene in this part of the Apennines chain (Patacca et al., 1992; Corrado et al., 1997; Di Bucci et al., 1999; Galadini and Galli, 2000; D’Addezio et al., 2001). These basins are mainly controlled by a set of normal faults N30°W oriented, ENE dipping, bordering the basins along their western slopes, which we refer to as CLP Basins Fault System. This set of faults is detectable almost continuously for at least 8 km along strike, both on surface and at depth, and perhaps for as much as 10 km considering the geometry and extension of the depression hosting the CLP Basins.

The age of this set of faults is worth some further considerations. We have discussed as the CLP Basins infill can be reasonably attributed to the Late Pleistocene–Holocene, and thus, this set of faults acted during this time span. The ages attributed to the upper part of Le Piane basin deposits by Giraudi et al. (1999) can also be usefully considered for our aims. These authors studied the trench of “Pratocicala” (Fig. 2), that we used to complete our cross-sections IS1 and IS2 of Fig. 7a. In particular, they dated with
radiocarbon methods deposits that we interpreted as part of the units “b” and “c”. A sample collected into the unit “b” gave an age of 1560 ± 70 years BP, while a sample collected near the top of the unit “c” gave an age of 4020 ± 80 years BP. As described in the previous section, the units “b” and “c” thicken toward the studied set of faults, indicating that these faults were active during sedimentation of these units. As a consequence, the faults along the western side of Le Piane basin must have been active during the upper part of the Holocene.

In the cross-sections IS1 and IS2 of Fig. 7a, the displacement of the boundary between the units “b” and “c” was measured along one of the faults; the results are 3 and 4 m, respectively, for the two sections. Therefore, a slip rate along this fault can be calculated for the last 4000 years; this is in the range of 0.75–1.00 mm/year, a value comparable with the slip rate calculated for many other active faults in the Apennines (Galadini, 1999; Galadini and Galli, 2000, and references therein).

Finally, we could speculate about the role of seismic source of the CLP Basins Fault System. Considering the contiguity of relevant seismogenic structures (see following paragraphs), we could expect this fault system to generate earthquakes. Besides, the Barrea seismic source, which is in the southernmost part of the USFS structure (Figs. 1 and 8), shows comparable direction, length and kinematics (Valensise and Pantosti, 2001a), and caused, in 1984, a 10-km-long structure with instrumental magnitude of 5.5 (Gruppo di Lavoro CPTI, 1999). According to Wells and Coppersmith (1994), a 10-km-long structure is able to cause earthquakes with moment magnitude exceeding 6. This value is comparable to the 6.6 macroseismic magnitude attributed to the Molise event of the 1456 earthquake (Gruppo di Lavoro CPTI, 1999), whose causative source is still unknown. The possible relationships between the CLP Basins Fault System and the 1456 earthquake could constitute an intriguing challenge for paleoseismological studies.

4.2. The CPL Basins Fault System relationships with the surrounding active systems

From a more regional point of view, the CLP Basins Fault System (CLPBFS; Fig. 8) is adjacent to the Boiano Basin Fault System (BBFS; Fig. 8). Surface data suggest that they are two distinct fault segments both in terms of geometry (they show a change in fault orientation: N330° for the CLPBFS and N310° for the BBFS) and geology (they are associated with distinct Quaternary basins and gravimetric lows—Blumetti et al., 2000—and show different topographic setting of the footwall—McCalpin, 1996, and references therein). On the other hand, the lack of seismological and paleoseismological data precludes definition of the CLP Basins Fault System as a seismogenic fault segment. Although a surface rupture of about 25 km (Cucci et al., 1996; Naso et al., 1998; Gasperini et al., 1999) seems more reasonable with respect to the energy release of the 1805 earthquake, our data cannot allow to exclude a simultaneous motion or triggering phenomena with respect to the Boiano Basin Fault System. This last hypothesis is suggested by Michetti et al. (2000a), which, based on historical data, propose a rupture length of about 45 km for the 1805 earth-

Fig. 8. Simplified map of the active fault systems discussed in the text. CLPBFS: CLP Basins Fault System (this work); USFS: Upper Sangro Valley Fault System (Boncio et al., 1998; Galadini and Galli, 2000); ACRFS: Aremogna–Cinque Miglia Plains–Mt. Rotella Fault System (Galadini and Galli, 2000; D’Addezio et al., 2001); BBFS: Boiano Basin Fault System (Cucci et al., 1996; Naso et al., 1998; Gasperini et al., 1999).
quake. If Michetti et al. (2000a) were correct, this would imply that not only the CLP Basins Fault System, but also other active faults that are still unknown should have slipped along with the Boiano Basin Fault System during the 1805 earthquake (e.g. towards the ESE of the Boiano Basin Fault System, as suggested by Esposito et al., 1987).

Towards the NW, we observe a lack of continuity (Fig. 8) between the CLP Basins Fault System and the previously mentioned active fault systems shown in Fig. 8 (ACRFS and USFS). This needs some specific discussion as it has more general implications in terms of seismogenic zonation and seismic hazard assessment.

4.3. Seismotectonic meaning of the boundary between Central and Southern Apennines

As shown in the previous paragraphs, the CLP Basins Fault System strictly locates along strike of the single narrow belt that hosts the main earthquakes and active fault systems at the core of the Southern Apennines (Valensise and Pantosti, 2001a,b; Fig. 1).

Under this perspective, our study enhances the discontinuity represented by the striped belt in Figs. 1 and 8. To the WNW of this belt, main earthquakes and known active faults (all roughly dipping toward SW; Galadini et al., 2000) are in fact spread over a wider area, on two wings at least (Galadini and Galli, 2000; Lavecchia et al., 2000; D’Addezio et al., 2001).

At depth, in the first kilometres of the chain, the analysed discontinuity corresponds to a main change in the geological setting of the Apennines thrust belt. WNW of it, the foreland unit (Apulia carbonate platform unit) appears to be strongly involved in thrusting (Mostardini and Merlini, 1986) and parts of these thrust sheets widely outcrop both in the Maiella Mountains and in minor structures along the axis of the chain (Mostardini and Merlini, 1986; D’Andrea et al., 1992; Corrado et al., 1998; Di Bucci et al., 1999; Fig. 1). ESE of the discontinuity, the Apulia foreland unit lays instead at depth, buried under 2–3 km thick, mainly terrigenous thrust sheets (Mostardini and Merlini, 1986; Corrado et al., 1997; Fig. 1). Moreover, shortening of this part of the foreland Apulia unit is extremely reduced (few units percent; Mazzoli et al., 2000).

This dramatic change takes place just in correspondence with the boundary marked by the striped belt in Figs. 1 and 8 and, with respect to the near active faults, it represents a geometric and structural discontinuity (sensus de Polo et al., 1991). Furthermore, it is characterised by a change in topography and in Bouguer anomalies (Carrozzo et al., 1992), and these variations define a change in the mechanical behaviour of this portion of the Apennines chain.

In this light, and also considering the regional scale (in general, only the larger features appear capable of arresting propagating earthquake ruptures; de Polo et al., 1991), we suggest that the boundary between the Central and Southern Apennines could be regarded as a main persistent segment boundary constituting a long-term barrier to the propagation of rupture of active fault systems (Das and Aki, 1977; Aki, 1979; McCalpin, 1996).

In the seismic zonation of Italy (Meletti et al., 2000), the boundary between Central and Southern Apennines corresponds to a long and narrow zone NNE–SSW oriented and characterised by prevailing NNE–SSW dextral strike–slip expected focal mechanisms. However, as also shown by Peruzza (1999), active extensional systems such as those of Fig. 8 partially occupy this zone. Therefore, considering the results of the present work in a general perspective, we conclude that a redefinition of the seismic zonation of Italy for this region would be necessary, improving the national seismic hazard assessment (Albarello et al., 2000) which is based on it.

5. Conclusions

This study allowed the geometry and kinematics of the CLP Basins to be defined. These basins are asymmetric half-grabens partially filled with fluviolacustrine deposits, the sedimentation of which was controlled by the activity of a set of normal faults N30°W striking and ENE dipping. This set of faults, which developed mainly during the Late Pleistocene–Holocene, is about 10 km long and is located close to the northwestern end of the Boiano Basin extensional Fault System. The slip rate calculated for part of the Holocene for one of the studied faults ranges from 0.75 to 1.00 mm/year.
The identification of the active CLP Basins Fault System partially fills the gap of data at the boundary between the Central and Southern Apennines, and has general implications for the seismotectonic setting of the Apennines, the Italian seismic zonation and the seismic hazard assessment. Moreover, it is also relevant in terms of seismic risk, as it occurs across the town of Isernia, an important centre of the Molise region. Such an active fault system could potentially generate earthquakes with magnitude values close to 6 (Wells and Coppersmith, 1994). Further studies, especially microtopographic and paleoseismological analyses, could be useful for a detailed definition of slip rates, recurrence intervals and elapsed times, and, as a consequence, for a more precise estimate of the seismic hazard in the studied area.

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