Growth, interaction and seismogenic potential of coupled active normal faults (Isernia Basin, central-southern Italy)

Daniela Di Bucci,1 Giuseppe Naso,1 Sveva Corrado2 and Igor M. Villa3

1Dipartimento della protezione civile, Servizio Sismico Nazionale, Via Vitorchiano n. 4, 00189 Rome; 2Dipartimento di Scienze Geologiche, Università degli Studi ‘Roma tre’, L.go S. L. Murialdo n. 1, 00146 Rome; 3Institut für Geologie, Universität Bern, 3012 Bern, Switzerland; Dipartimento di Scienze Geologiche e Geotecnologie, Università di Milano Bicocca, 20126 Milan, Italy

ABSTRACT

The inception and growth of the active Carpino-Le Piane Basin Fault System (CLPBFS; central-southern Apennines, Italy) was analysed with respect to the neighbouring Isernia and Surrounding (ISFS) and Boiano Basin (BBFS) extensional Fault Systems. 39Ar–40Ar dating showed that the BBFS was already active 649 ± 21 ka BP and that the ISFS was active at least 476 ± 10 ka BP, whereas the activity of the CLPBFS started certainly later than 253 ± 22 ka BP, and very probably as recently as <28 ka BP. These ages, combined with structural data (geometry and kinematics of the fault systems), indicate that the inception and development of the CLPBFS could be strictly related to the stress changes caused by earthquakes occurring on the BBFS.

Introduction

The boundary area between the central and southern Apennines thrust belt of the Italian peninsula includes the surroundings of Isernia, an important town of the Molise region (Fig. 1). Here, a recent study identified two local intramontane basins as half-grabens formed by a 10-km long, N30°E striking and NE dipping set of normal faults (Di Bucci et al., 2002; Figs 2 and 3). The late Holocene activity of these faults (called Carpino-Le Piane Basins Fault System (CLPBFS); Fig. 4) was constrained for the last 4000 years by analysing 65 wells drilled on modern fluviolacustrine deposits that fill the intramontane basins.

Field data suggest that the CLPBFS formed during the Upper Pleistocene–Holocene and is one of the most recent parts of a regional tectonic depression N30°E oriented, which developed since Middle Pleistocene from the Isernia surroundings to the Sepino Plain, for a length of about 40 km (Corrado et al., 1997; Figs 2 and 3). We refer to the northernmost part of this depression as the Isernia and Surroundings Fault System (ISFS), and to the adjacent central part as the Boiano Basin Fault System (BBFS; Fig. 2). These are distinct fault segments both in terms of geometry and geology (McCalpin, 1996, and references therein); moreover, according to some authors (e.g. Porfido et al., 2002), they host the seismogenic faults responsible for the 1805 Boiano earthquake mainshock (Io = X MCS; Gruppo di Lavoro CPTI, 1999) and for one of the related strong aftershocks.

This work aims at showing how the growth and interaction of two important adjacent extensional systems in the Apennines, the ISFS and the BBFS, led to the formation of new late Upper Pleistocene to Holocene faults and associated sub-basins within one of the said structures (the CLPBFS within the ISFS). This is not well understood and can have significant impact on the knowledge of ongoing extensional processes and fault linkage, as well as on the associated landscape evolution and seismicity in the Apennines. This topic was addressed by applying structural analysis and 39Ar–40Ar technique, which provided new data and allowed a totally novel interpretation based on the integration of geological data and physical models of interaction between seismogenic sources.

Structural data

The Quaternary development of the ISFS, BBFS and CLPBFS is an expression of the SW–NE extension that has been acting in the study area since Middle Pleistocene (Patacca et al., 1992; Corrado et al., 1997; Ferranti, 1997; Porfido et al., 2002). All along the axis of the chain, this extension is still active today and responsible for strong earthquakes (Gruppo di Lavoro CPTI, 1999; Montone et al., 1999; Galadini and Galli, 2000, D’Addezio et al., 2001; Roberts et al., 2004; Roberts and Michetti, 2004; Fig. 1).

It is widely accepted that extension on the BBFS is acting since Middle Pleistocene (for instance, see Corrado et al., 1997; Galli and Galadini, 2003, and references therein). This age is compatible with the tectonic evolution of the Matese Massif (Calabrò et al., 2003) and derives from Middle–Upper Pleistocene tephra deposits filling the Boiano Basin, faulting of Middle Pleistocene tephra deposits and Pleistocene slope-scree, and offset of Pleistocene remnant surfaces. However, no 39Ar–40Ar isotopic ages were available before the present work to quantitatively constrain the age of this extension.

The BBFS is a well-known active extensional structure (Cucci et al., 1996; Naso et al., 1998; Basili et al., 1999; Guerrieri et al., 1999; Blumetti et al., 2000; Valensise and Pantosti, 2001; Porfido et al., 2002; Galli and Galadini, 2003; Figs 1 and 2), which develops with N30°E strike for about 25–28 km, with a complex extensional pattern. This consists of a NE-dipping master fault, which develops down to a depth of at least 9 km (Mazzoli
et al., 2000; Butler et al., 2004), and of synthetic and antithetic Quaternary normal faults linked by shallow, pre-Quaternary, mainly E–W-oriented high-angle faults, reactivated by the present-day extensional stress field (Fig. 3, plots G–M).

An example comes from S. Giorgio area (Fig. 5), where normal faults affect a succession of Pleistocene lacustrine and pyroclastic sediments (samples San2 and San3) forming a terrace along the main slope of the BBFS (Brancaccio et al., 1979). This site gave us the possibility to quantitatively constrain the Middle Pleistocene tectonic activity of the BBFS.

This fault system strictly coincides with that revealed by drainage network studies (Cucli et al., 1996) and with the seismogenic fault inferred

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**Fig. 1** (A) Geological map of the central-southern Apennines (after Di Bucci et al., 2002, modified). (B) Largest earthquakes of the central-southern Apennines (data after Boschi et al., 1997, and Valensise and Pantosti, 2001). The size of the square symbols is proportional to an ‘equivalent magnitude’ (Me) derived from intensity data.
from the damage field of the 1805 earthquake ($I_o = X$ MCS; Gasperini et al., 1999; Gruppo di Lavoro CPTI, 1999). Thus, it is widely accepted that the BBFS is a source of severe seismicity.

Moving towards the town of Isernia, mesostructural analysis provided two different pieces of evidence which allowed to better discriminate the CLPBFS from the ISFS.

The first mesoscale evidence refers to the ISFS, that is characterized at the landscape scale by the Pesche fault (Figs 2 and 3). Mesostructural data come from some outcrops of the Middle Pleistocene ‘Riempimento principale’ Fm., which constitutes the upper part of a Lower–Middle Pleistocene continental succession (Corrado et al., 1997 and references therein; Brancaccio et al., 2000). Integrated data (geomorphology, field survey, stratigraphic correlations) indicate that this continental succession did not overcome the Middle–Upper Pleistocene boundary (Coltorti, 1983). At the outcrop scale, a fault network can be observed (Fig. 3, plots A–E), which is composed of newly formed WNW–ESE to NW–SE-oriented normal faults (among these the syn-sedimentary faults of Fig. 6; sample San9b was collected in this site) and by E–W oriented faults. The latter pre-existed in the Meso-Cenozoic buried units and propagated in the overlying Quaternary succession with an oblique component of motion, because of the reactivation under the extensional regime (Fig. 7). Therefore, fault orientation and kinematics of this Middle Pleistocene pattern are comparable with those of the BBFS (Fig. 3, plots H–M). As shown in Fig. 3, this fault network is pervasive and widespread all over the study area.

Fig. 2 Schematic map of the Isernia and Boiano areas. Box 1, surface projection of the fault model proposed by Cucci et al. (1996) based on dislocation modelling of selected landscape features. The fault dips to the NE and projects to the surface along the NE edge of the Matese Mts. Box 2, surface projection of the source of the 1805 earthquake, as proposed by Gasperini et al. (1999) based on modelling of intensity data. Sampling sites are indicated. ISFS, Isernia and surroundings fault system; BBFS, Boiano Basin Fault System; CLPBFS, Carpino-Le Piane Basin Fault System.
The second piece of evidence is given by the CLPBFS that, instead, is concentrated along a N330° trending narrow zone (Di Bucci et al., 2002; Fig. 4). This trend is significantly different (30°) with respect to the general direction of the BBFS and ISFS tectonic depression (N300°; Fig. 3). Its activity post-dates the ‘Riempimento principale’ Fm., whose deposits constitute the bedrock for the fluvial lacustrine sediments directly related to the CLPBFS (Di Bucci et al., 2002).

**Geochronological data**

Five samples of pyroclastic rocks were analysed. Three (San9b, San30 and San31) came from the surroundings of Isernia (concerning both ISFS and CLPBFS), and two (San2 and San3) came from the BBFS area (Fig. 2).

The former three samples were collected in the ‘Riempimento principale’ Fm. Conglomerates, gravels, sands and pyroclastic deposits form this part of the succession; these facies are interfingered and have a total thickness that can exceed 100 m.

The remaining two samples came from the succession of lacustrine and pyroclastic sediments that form a terrace along the main slope of the BBFS (Brancaccio et al., 1979; Fig. 5). These deposits are deformed by syn-sedimentary faults belonging to the BBFS. The thickening of tens of metres of these lacustrine sediments towards faults belonging to the BBFS is derived from field survey and suggests synsedimentary tectonic activity (Corrado et al., 2000). Moreover, these sediments are presently faulted, suggesting a more recent activity of the same faults.

The sedimentary environments described imply that all the samples are affected by some reworking. However, the large size and angular shape of the pumices rule out significant transport after their deposition. Sandines were separated for 39Ar–40Ar dating. Analytical protocols follow Villa et al. (2000). Results are shown in Fig. 8 and Table 1.

All samples show some degree of chemical heterogeneity, highlighted by variations in the Cl/K and Ca/K ratios (for a discussion about these chemical indicators, see Villa, 2001, and references therein). Basing on Ar isotope systematics, the analysed samples can be divided into two groups.

The first group, formed by samples San2, San3 and San9b, shows modest chemical variations, probably indicating an almost monogenetic origin. For the second group (samples San30 and San31), a heterogeneous provenance, i.e. a higher degree of reworking, is suggested by the concomitant presence of large variations in the chemical indicator ratios and of a younger component mixed to one or more older components. A reliable age can be calculated by only considering ‘isochemical’ steps, i.e. those steps whose uniform chemical indicators imply the smallest chemical (and genetic) heterogeneity (Table 1).
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In summary, inception of BBFS predates 649 ± 21 ka, as the deposits containing samples San2 and San3 show syn-sedimentary deformation related to this fault system.

Some faults of the pervasive and widespread Middle Pleistocene ISFS acted during the deposition of the sediments containing sample San9b. Therefore, the ISFS was active at least 476 ± 10 ka (Fig. 6); it can be compared with the BBFS inasmuch it has coincident orientation, kinematics and age.

On the contrary, as the CLPBFS activity post-dates the deposition of the ‘Riempimento principale’ Fm., it is younger than sample San30 from the upper part of this formation, which is 253 ± 22 ka. Thus the CLPBFS inception occurred well later with respect to the ISFS activity. As a matter of fact, the fluvo-lacustrine sediments filling Carpino and Le Piane basins are generally attributed to the Upper Pleistocene–Holocene (Di Bucci et al., 2002 and references therein). In detail, they can be more precisely attributed to the final part of the Upper Pleistocene and Holocene, based on the lines of evidence described in Table 2. These arguments concordantly assign <28 ka to the inception of the filling of the Carpino and Le Piane basins, and therefore to the inception of the CLPBFS activity.

A significant lapse of time (more than 90 kyr) separates the inception of Carpino and Le Piane basins filling from the end of ‘Riempimento principale’ Fm. deposition (0.125 Ma).

Discussion and conclusions

The BBFS and the ISFS are oriented according to the extensional stress field which is acting along the core of the Apennines (Montone et al., 1999), while the CLPBFS is not aligned. Thus, a local variation of the stress field orientation could be invoked for the evolution and present-day activity of this fault system.

It is well known that the occurrence of earthquakes perturbs the stress state in the surroundings of the source fault (Stein et al., 1992; King and Cocco, 2001, and references therein). Not only can this promote and/or delay subsequent ruptures, but it can also influence the attitude of adjacent seismogenic sources, which could be rotated with respect to the considered source fault (depending on the amplitude of coseismic stress changes with respect to the regional stress; King et al., 1994). In particular, the effects of a normal faulting earthquake have been analysed by Nostro et al. (2001). For a seismogenic normal fault comparable with the BBFS (Fig. 9), they obtain a stress increase in well-defined lobes at the tips of the source fault; one of these coincides with the location of the CLPBFS. Moreover, they calculate the expected focal mechanism for an earthquake generated in such zone, obtaining nodal planes comparable with the attitude of the CLPBFS.

This suggests a possible evolution for the analysed active fault systems. The study area underwent an extensional tectonic regime since Middle Pleistocene. This stress field caused the progressive development of a N300° oriented tectonic depression, given by a pattern of new NW–SE-oriented faults and of reactivated pre-existing E-W-oriented faults, which encompasses the ISFS and BBFS. The BBFS was growing for at least 620 ka; by c. 28 ka BP, it should have been sufficiently developed to cause earth-
quakes which are able to induce significant stress changes at its tips. This in turn caused the inception and the development of the CLPBFS, which is in fact younger, less developed (10 km), differently oriented (N330°/C176°) and located in the right position (at the western tip of the BBFS).

Contrasting interpretations are less likely. A first alternative hypothesis on the geometrical relationship between BBFS and CLPBFS active fault systems is that there is in fact no relationship at all: this part of the Apennine fold-and-thrust belt has a complex structural setting (Patacca et al., 1992; Speranza et al., 1998) and the orientation of the CLPBFS could be controlled by local pre-existing lineaments. In this way, the CLPBFS would evolve independently from the BBFS. However, pre-existing lineaments have been recognized (they have been described within the ISFS) and are not oriented like the CLPBFS. Furthermore, all over the Apennines the extensional tectonics overprints previous compressional structures, which do not condition the direction of the active normal faults. In addition, this hypothesis does not explain why inception of the CLPBFS inception is younger than that of the other systems.

A second hypothesis considers the CLPBFS as a transfer fault (Gawthorpe and Hurst, 1993) of the BBFS towards the NW. In this way, the development of the CLPBFS would be strictly connected to the evolution of the BBFS, also explaining why the former is younger. However, the transfer system appears dead-ended, as no seismic activity (neither active fault systems comparable with the BBFS, nor destructive historical or instrumental earthquakes) is presently known at the north-western tip of the CLPBFS.

A third hypothesis considers the CLPBFS simply as a set of late, small faults in the subsiding hangingwall of the Pesche fault, i.e. as part of the ISFS. This hypothesis is compatible with the role of seismogenic fault system attributed by some authors to the ISFS (Porfido et al., 2002) and with the relatively younger age of the CLPBFS. However, we consider the inception and growth of the CLPBFS as mainly induced by the BBFS development for the following reasons.

1. The orientation of the CLPBFS is a relevant datum. The CLPBFS is
not inherited, and the different fault trend is not comparable with the variable fault orientation characterizing the ISFS and BBFS (Fig. 3), caused by inherited (mainly E–W oriented) faults reactivated by the present-day stress field.

2 The CLPBFS strike (as well as its location at the tip of the BBFS) is not random, but it coincides with the location and orientation expec-
Fig. 8 Age spectra of sanidines from Boiano (San2 and San3) and Isernia (San9b, San30 and San31).
As the CLPBFS is responsible for
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3 As the CLPBFS is responsible for the development of the most relevant late Upper Pleistocene–Holocene features of the area (i.e. the asymmetric filling of the Carpino and Le Piane basins), this fault system cannot be interpreted as a set of minor antithetic faults with respect to the Pesche fault. If so, the filling of the basins should be thicker towards the latter, and this is not the case.

The Pesche fault is a well-developed normal fault. It shows a displacement of hundred of metres measured on the Jurassic–Cretaceous boundary (SGN, 1971), and activity in the final part of the Middle Pleistocene (Di Bucci et al., 2002, and references therein). Its present-day activity is hypothesized by some authors (Michetti et al., 2000; Porfido et al., 2002; Galli and Galadini, 2003) based on the interpretation of historical records related.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Constrained fault system</th>
<th>Considered steps (refer Fig. 8)</th>
<th>Average age</th>
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<tbody>
<tr>
<td>San2</td>
<td>BBFS</td>
<td>Four adjacent steps having Cl/K &lt;0.00012 and containing 52% of the sample Ar</td>
<td>621 ± 6 ka</td>
</tr>
<tr>
<td>San3</td>
<td>BBFS</td>
<td>Four adjacent steps having Ca/K &lt;0.021 and containing 70% of the sample Ar. Note that the ages of San2 and San3 are statistically indistinguishable, and indistinguishable from the age of the sanidine-bearing basal eruption of the nearby Roccamonfina volcanic complex, 630 ± 2 ka (Ballini et al., 1991).</td>
<td>649 ± 21 ka</td>
</tr>
<tr>
<td>San9b</td>
<td>ISFS</td>
<td>Five adjacent steps having Ca/K &lt;0.030 and containing 63% of the sample Ar</td>
<td>476 ± 10 ka</td>
</tr>
<tr>
<td>San30</td>
<td>CLPBFS</td>
<td>An anticorrelation trend (Fig. 8) is defined by the fifth step (age 647 ± 24 ka, Ca/K = 0.0261 ± 0.0009) and by three steps (3, 4, 8) having the highest Ca/K ratios (uniform at 0.0299 ± 0.0004) and the lowest ages. The age of the older component is identical to that of samples San2 and San3; this could represent erosion of a primary 0.63 Ma tuff exposed on the hillslope above the basin</td>
<td>253 ± 22 ka (weighted average age of the younger component)</td>
</tr>
<tr>
<td>San31</td>
<td>ISFS/CLPBFS</td>
<td>At least three components can be recognized</td>
<td>504 ± 12 ka (mean age of the three steps with the lowest CaK ratio: 5, 6, 9)</td>
</tr>
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</table>

<table>
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<tr>
<th>Reference</th>
<th>Constraint</th>
<th>Additional constraint</th>
<th>Age of sedimentation</th>
</tr>
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<tbody>
<tr>
<td>Giraudi et al. (1999)</td>
<td>The development and areal distribution of the sediments filling Le Piane basin requires a climatic phase characterized by relevant stream load</td>
<td>In Central Italy this occurred at 18 000 years BP (Frezzotti and Giraudi, 1989).</td>
<td>&lt;18 000 years BP</td>
</tr>
<tr>
<td>D’Addezio et al. (2001)</td>
<td>In the region, small intramontane basins similar to the Carpino and Le Piane basins (e.g. Aremogna, Cinque Miglia) are filled by sediments deposited during the deglaciation following the last glacial peak (21–18 ka) and by modern alluvial fans</td>
<td></td>
<td>&lt;21–18 ka</td>
</tr>
<tr>
<td>Di Bucci et al. (2002)</td>
<td>The stratigraphy of the infill of the Carpino and Le Piane basins is totally different from the ‘Riempimento principale’ succession. In particular, the thick strata of pyroclastic deposits characterized by centimetric pumices, occurring in the ‘Riempimento principale’ Fm., are totally lacking in the basins’ filling</td>
<td>De Rita and Giordano (1996) proposed to derive these pyroclastic sediments from the activity of the nearby Roccamonfina volcanic complex, which ended its explosive phase 295 ± 2 ka (Ballini et al., 1991). Therefore, the basins’ filling post-dates this age</td>
<td>&lt;295 ± 2 ka</td>
</tr>
<tr>
<td>Giraudi et al. (1999), Di Bucci et al. (2002)</td>
<td>The sedimentation rate for the youngest part of sediments filling Le Piane basin is of 0.75 mm a⁻¹ (value derived from the trench analysed by Giraudi et al., 1999). This corresponds to a deposition rate of 1.8 mm a⁻¹ in the basin depocentre. The homogeneity of sediments shown by the wells analysed by Di Bucci et al. (2002) for both Carpino and Le Piane basins suggests that this sedimentation rate also prevailed in the older part. For the Carpino basin, the filling thickness at the depocentre is about 35 m; therefore we obtained a maximum age of 20 ka for the sedimentation inception. For Le Piane basin, the minimum depth explored by the wells is of 25 m (Di Bucci et al., 2002); this depth corresponds to 14 ka</td>
<td>An indirect attempt to identify the substratum depth by applying the Nakamura technique (D’Amico et al., 2004) returned a maximum depth of about 50 m. In this case, the age for the inception of sedimentation in Le Piane basin would be 28 ka</td>
<td>&lt;20 ka, &gt;14 ka, &lt;28 ka</td>
</tr>
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</table>
to the 1805 Boiano earthquake. However, no detailed and specific geological studies on the recent activity of the Pesche fault are available in the literature. Summing up, data available at the moment for the study area suggest that Holocene activity mainly occurred on the CLPBFS; therefore, at depth this should prevail on the Pesche fault. However, Pesche fault activity cannot be ruled out, and further geological studies are needed for a complete definition of this structure.

The relationship of the CLPBFS with the seismic activity of the BBFS is in agreement with the hypothesis of a seismogenic fault in the Isernia area. Simple empirical relationships (Wells and Coppersmith, 1994) suggest that the BBFS has a potential for an $M_w$ 6.6–6.8 earthquake. Based on the same relationships, in case of CLPBFS rupture for the entire length mapped, this would yield $c$ $M_w$ 6.0 estimation. A rather different scenario would be one where the entire 40-km long extensional belt ruptures in a single $M_w$ 7.0–7.2 earthquake. The discussion before suggests that at present this scenario is perhaps unlikely and that this extensional belt tends to rupture in limited size episodes rather than all at once. However, the long-term implication of the interpretation here presented is that CLPBFS and BBFS are going to link more and more efficiently, and that in the geological future 40 km coseismic ruptures will be increasingly frequent.

This conclusion leaves the fate of the CLPBFS fully open and in need for further investigations. Up to now only a moderate instrumental seismicity is known for the Isernia area (Valensise and Pantosti, 2001, and catalogues therein); neither palaeoseismological data nor detailed seismological information is available for this structure. Moreover, the causative sources for historical earthquakes that struck this area in the past (e.g. in AD 1456; Gruppo di Lavoro CPTI, 1999) are still unknown. Further studies, such as a long-term analysis of instrumental data or a deeper revision of the historical information, are needed to substantiate the CLPBFS as a seismogenic fault system.

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