Shallow subsurface structure of the 2009 April 6 $M_w$ 6.3 L’Aquila earthquake surface rupture at Paganica, investigated with ground-penetrating radar


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SUMMARY
The shallow subsurface structure of the 2009 April 6 $M_w$ 6.3 L’Aquila earthquake surface rupture at Paganica has been investigated with ground penetrating radar to study how the surface rupture relates spatially to previous surface displacements during the Holocene and Pleistocene. The discontinuous surface rupture stepped between en-echelon/parallel faults within the overall fault zone that show clear Holocene/Pleistocene offsets in the top 10 m of the subsurface. Some portions of the fault zone that show clear Holocene offsets were not ruptured in 2009, having been bypassed as the rupture stepped across a relay zone onto a fault across strike. The slip vectors, defined by opening directions across surface cracks, indicate dip-slip normal movement, whose azimuth remained constant between 210° and 228° across the zone where the rupture stepped between faults. We interpret maximum vertical offsets of the base of the Holocene summed across strike to be 4.5 m, which if averaged over 15 kyr, gives a maximum throw-rate of 0.23–0.30 mm yr$^{-1}$, consistent with throw-rates implied by vertical offsets of a layer whose age we assume to be $\sim 33$ ka. This compares with published values of 0.4 mm yr$^{-1}$ for a minimum slip rate implied by offsets of Middle Pleistocene tephras, and 0.24 mm yr$^{-1}$ since 24.8 kyr from palaeoseismology. The Paganica Fault, although clearly an important active structure, is not slipping fast enough to accommodate all of the 3–5 mm yr$^{-1}$ of extension across this sector of the Apennines; other neighbouring range-bounding active normal faults also have a role to play in the seismic hazard.

Key words:

1 INTRODUCTION
The 2009 April 6 $M_w$ 6.3 L’Aquila earthquake ruptured a fault zone running through the town of Paganica, evidenced by field observations of surface ruptures (Emergeo Working Group 2009; Falcucci et al. 2009; Galli et al. 2009; ISPRA Report 2009; Messina et al. 2009; Boncio et al. 2010; Wilkinson et al. 2010), and fringe geometries defined by InSAR (Atzori et al. 2009; Walters et al. 2009; Papanikolaou et al. 2010) (Fig. 1). The surface ruptures exhibited maximum surface throws of 7–12 cm, which are consistent with global values expected for earthquakes of this magnitude (Fig. 2; Wells & Coppersmith 1994). The fault had been
Figure 1. (a) and (b) Map of active faults with Holocene offsets in central Italy, with interpreted positions of historical surface ruptures. Holocene offsets are commonly indicated by the presence of bedrock fault scarps that occur along most of the faults shown (see Table 1). Rupture traces are adapted from our own interpretation of shaking intensities documented in http://storing.ingv.it/cfti4med/; with guidance from Pantosti et al. (1996); Pace et al. (2002); Basili et al. (2008); Galli et al. (2008) and a large number of papers cited therein. Note that the positions of many of the historical surface ruptures are equivocal and are discussed in this paper. (c) InSAR fringes (28 mm) and modelled fault trace to the 2009 April 6 $M_w$ 6.3 L’Aquila earthquake from Walters et al. (2009) and (d) Geological map around the town of Paganica, located in (b), modified from Vezzani & Ghisetti (1987); APAT 2005. Surface ruptures are schematic, but are shown in more detail in Emergeo 2009, Falucci et al. 2009, ISPRA Report 2009 and Boncio et al. 2010. (e) Detail of a 20 m DEM, showing the dramatic geomorphic expressions of range-bounding normal faults, and the subdued geomorphic expression of the Paganica Fault. Rf = Rieti Fault; LeF = Leonessa Fault; MRF = Montereale Fault; LF = Laga Fault; MMF = Mt Marine Fault; AsF = Assergi Fault; CIF = Campo Imperatore Fault; AF = L’Aquila Fault; SeCoF = Sella di Corno Fault; FiF = Fiamignano Fault; CamF = Campo Felice Fault; CaF = Carsoli Fault; PP = Piano di Pezza fault; VF = Velino Fault; ScF = Scurcola Fault; FuF = Fucino Fault; TF = Trassaco Fault; LF = Liri Fault; SuF = Sulmona Fault; MF = Maiella Fault; CMF = Cinque Miglia Fault; SF = Scanno Fault; PF = Pescasseroli Fault; CaSF = Cassino South Fault; Parasano Fault; Roccapreturo Fault.
recognized prior to the earthquake, but its slip rate was poorly de-
fined (see Carta Geologica d’Italia Teramo 1962; Bagnaia et al. 
1992; Vezzani & Ghisetti 1998; Boncio et al. 2004; APAT 2005; 
Pace et al. 2006). The slip-rate was poorly defined because (1) the 
ruptured fault displays a subdued geomorphic expression, lacking 
an exposed fault plane along an extensive bedrock scarp, at least 
near the centre of the ruptures at Paganica, that typifies other active 
faults in the area (Galadini & Galli 2000; Roberts & Michetti 2004; 
Papanikolaou et al. 2005) (see Table 1) and (2) to our knowledge, 
no detailed palaeoseismic studies of this fault zone had been pub-
lished prior to the earthquake. Thus, it was unclear how the Pa-
ganica fault zone related, in terms of its slip-rate, to neighbouring 
range-bounding faults that have more obvious geomorphic signs 
of Holocene activity such as bedrock scarps, and have published 
values for their slip-rate defined by palaeoseismic studies (Fig. 1; 
Table 1).

The observations in this paper address the uncertainty regard-
ning Holocene slip-rates, the rate of deformation and implied earth-
quake recurrence intervals associated with the Paganica fault zone. 
We show that the portion of the fault zone within which the 2009 
ruptures occurred contains faults whose individual Holocene vertical 
offsets are small (<4.5 m) implying throw-rates averaged since 
15 kys of 0.23–0.30 mm yr$^{-1}$. These individual faults are arranged 
in en-echelon/parallel geometries, so throw-rates should be summed 
across strike. However, we find no evidence for summed throw-rates 
high enough to accommodate measured rates of regional extension 
(3–5 mm yr$^{-1}$; D’Agostino et al. 2008), implying that at least some 
of the faults mapped by others (see Fig. 1a and Table 1; Bosi 1975; 
Vittori 1994; Giraudi & Frezzotti 1995; Galadini & Galli 2000; 
Michetti et al. 2000; Galli et al. 2002; Pizzi et al. 2002; Roberts & 
Michetti 2004; Papanikolaou et al. 2005; Pace et al. 2006; Roberts 
2008) along range-bounding escarpments are active and contribute 
to the extension, consistent with published palaeoseismic studies 
(Galli et al. 2008).

2 BACKGROUND TO ACTIVE FAULTS, 
EARTHQUAKE SURFACE RUPTURES, 
SLIP-RATES AND FAULT SCARP 
MORPHOLOGIES NEAR L’AQUILA

The area around L’Aquila is part of the zone containing active 
normal faults that stretches from the northern Apennines to Cal-
abria (Anderson & Jackson 1987; Michetti et al. 2000; Valentis & 
Pantosti 2001a; Pace et al. 2006; Basili et al. 2008; Roberts 2008) 
(Fig. 1). Historical earthquakes, and those recorded by palaeosie-
mology, have produced coseismic surface ruptures with vertical 
offsets that are at least as large as 0.1–2.0 m (Uria de Llanos 1703; 
Oddone 1915; Westaway & Jackson 1987; Pantosti et al. 1993; 
Blumetti 1995; Pantosti et al. 1996; Galli et al. 2008; see Palumbo 
& 2004 for possible evidence of even larger amounts of co-
seismic surface slip). Such coseismic surface offsets, if repeated in 
large magnitude earthquakes, would produce a clear expression in 
the geomorphology in the form of prominent scarps along the active 
faults (Blumetti et al. 1993). However, here we point out that the 
form of the scarp varies, depending on the local lithologies, sedi-
mentation and erosion rates and the rates and cumulative amounts 
of vertical offset (including the durations of interseismic periods) 
across the active fault at each site in question. This suggests three 
main scarp forms, which are described below, although note these
forms are a continuum of scar morphologies (values given for rates are indicative rather than exact values; refer to Table 1 for examples near L’Aquila).

(1) Type 1 Scars—with high throw-rates (>0.2–0.4 mm yr\(^{-1}\)), low erosion and sedimentation rates (<0.2–0.4 mm yr\(^{-1}\)) and cumulative offsets of several hundred metres or more of pre-rift strata (Mesozoic/Tertiary), bedrock scarps form along the active normal faults (if the bedrock is carbonate that is resistant to erosion) (see Piccardi et al. 1999; Galadini & Galli 2000; Roberts & Michetti 2004; Papanikolaou et al. 2005 or examples, such as those along the Velino, Assergi, Mt Marine, Campo Imperatore, L’Aquila and Sulmona faults shown in Fig. 1b). Such bedrock scarps offset slopes formed during the high erosion and sedimentation rates that existed during the last glacial maximum (ca. 18 ka) (see Roberts & Michetti 2004 for details), and hence post-date this age. Such ages have been proved through in situ \(^{14}C\) cosmogenic exposure dating, with fault planes on the bedrock scarps dated to ~12 ka in the Apennines (e.g. Palumbo et al. 2004; Schlagenhaufer 2010). Such sites will form where there is a relatively small sediment flux from the footwall of the normal fault, and as such, will be characterized by the lack of local footwall drainage courses, yet throw-rates are still >0.2–0.4 mm yr\(^{-1}\), the scarp may be subtle, or obscured. In such cases activity on the fault can be proven if a palaeoseismic trench is excavated with a view to examining offsets of Holocene sediments (see Michetti et al. 1999; Pantosti et al. 1996; Galli et al. 2002; Galli et al. 2008 for examples along the Fucino/Piano di Pezza, Campo Imperatore and Cinque Miglia Faults). At such sites, Holocene organic-rich sediment, with human artefacts in places, such as ceramics, overlies organic-poor Pleistocene conglomerates/breccias that formed during and prior to the last glacial maximum. Alternatively, geophysical techniques such as ground-penetrating radar can be used to image offsets of the Holocene (e.g. Salvi et al. 2003; Jewell & Bristow 2004).

(3) Type 3 Scarps—if throw-rates on the fault are low (<0.2–0.4 mm yr\(^{-1}\)), subtle scarps in Quaternary/Holocene sediment can be preserved if the sedimentation/erosion rates are also <0.2–0.4 mm yr\(^{-1}\). Such low throw-rates typically result in relatively small cumulative vertical offsets (<1 km) in the Apennines because faults have only been active since ~2–3 Ma or less, and relatively small vertical offsets of the Holocene (< ~4–6 m if organic-rich sediments started to form during the demise of the last glacial maximum at 15–18 ka). Such sites will form where there is a very low sediment flux from the footwall of the normal fault (<0.2–0.4 mm yr\(^{-1}\) sedimentation}

<table>
<thead>
<tr>
<th>Fault name</th>
<th>Observation</th>
<th>Throw-rate (mm yr(^{-1}))</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paginaca</td>
<td>GPR and trench data</td>
<td>&lt;0.23–0.3</td>
<td>This paper</td>
</tr>
<tr>
<td>Paginaca</td>
<td>Offset Quaternary terraces with Tephas</td>
<td>&gt;0.4</td>
<td>Messina et al. (2009)</td>
</tr>
<tr>
<td>Assergi</td>
<td>Quaternary? Holocene offset</td>
<td>0.7–1.0</td>
<td>Barchi et al. (2000); Pizzi et al. (2002)</td>
</tr>
<tr>
<td>Mte. Marine</td>
<td>Post-glacial scarp 15 ± 3 ka</td>
<td>0.3–0.5</td>
<td>D’Addezio et al. (2001)</td>
</tr>
<tr>
<td>Mte. Marine</td>
<td>Offset of late Pleistocene slopes and trenches</td>
<td>0.25–0.43</td>
<td>Galadini &amp; Galli (2000)</td>
</tr>
<tr>
<td>Campo Felice</td>
<td>Post-glacial scarp 15 ± 3 ka</td>
<td>0.6 ± 0.2</td>
<td>Faure Walker (2010)</td>
</tr>
<tr>
<td>Campo Felice</td>
<td>Offset moraines</td>
<td>0.8–1.3</td>
<td>Galadini &amp; Galli (2000)</td>
</tr>
<tr>
<td>Campo Imperatore</td>
<td>Post-glacial scarp 15 ± 3 ka</td>
<td>1.7 ± 0.7</td>
<td>Faure Walker (2010)</td>
</tr>
<tr>
<td>Campo Imperatore</td>
<td>Post-glacial scarp 18 ka</td>
<td>0.8–1.0</td>
<td>Giaudi &amp; Friezott (1995)</td>
</tr>
<tr>
<td>Campo Imperatore</td>
<td>Trench into Holocene</td>
<td>&gt;0.68</td>
<td>Galli et al. (2002)</td>
</tr>
<tr>
<td>Assergi</td>
<td>Post-glacial scarp 15 ± 3 ka</td>
<td>0.9 ± 0.3</td>
<td>Papanikolaou et al. (2005)</td>
</tr>
<tr>
<td>Fiamignano</td>
<td>Post-glacial scarp 15 ± 3 ka</td>
<td>1.0</td>
<td>Papanikolaou et al. (2005)</td>
</tr>
<tr>
<td>Fucino</td>
<td>Offsets of late-Pleistocene and Holocene deposits</td>
<td>0.37–0.43</td>
<td>Galadini &amp; Galli (2000)</td>
</tr>
<tr>
<td>Fucino (Ovindoli-Pezza)</td>
<td>Offsets of 0.5 Ma tephra</td>
<td>0.5–1.0</td>
<td>Valensise &amp; Pantosti (2001)</td>
</tr>
<tr>
<td>Fucino</td>
<td>Trench into Holocene</td>
<td>0.7–1.2</td>
<td>Pantosti et al. (1996); D’Addezio et al. (1996)</td>
</tr>
<tr>
<td>Laga</td>
<td>Offsets of late-Pleistocene and Holocene deposits</td>
<td>0.7–0.9</td>
<td>Galadini &amp; Galli (2000)</td>
</tr>
<tr>
<td>Mte. Ocre</td>
<td>GPR, trench and scarp data</td>
<td>0.2 ± 0.1</td>
<td>Salvi et al. (2003)</td>
</tr>
<tr>
<td>Parasano</td>
<td>Post-glacial scarp 15 ± 3 ka</td>
<td>0.6 ± 0.2; 0.7 ± 0.03; 0.4 ± 0.2</td>
<td>Faure Walker et al. (2009)</td>
</tr>
<tr>
<td>Pescasseroli</td>
<td>Post-glacial scarp 15 ± 3 ka</td>
<td>0.6 ± 0.2</td>
<td>Roberts &amp; Michetti (2004)</td>
</tr>
<tr>
<td>Pettine</td>
<td>Offset of alluvial terrace</td>
<td>0.47–0.86</td>
<td>Galadini &amp; Galli (2000)</td>
</tr>
<tr>
<td>Roccapreturo</td>
<td>Post-glacial scarp 15 ± 3 ka</td>
<td>0.3 ± 0.7</td>
<td>Faure Walker (2010)</td>
</tr>
<tr>
<td>Roccapreturo</td>
<td>Offset of 0.15–1.5 Ma landforms</td>
<td>0.33–0.43</td>
<td>Bertini &amp; Bosi (1993), Galadini &amp; Galli (2000)</td>
</tr>
<tr>
<td>Trassaco Fault</td>
<td>Post-glacial scarp 15 ± 3 ka</td>
<td>0.5 ± 0.2</td>
<td>Faure Walker (2010)</td>
</tr>
<tr>
<td>Tre Monti</td>
<td>Post-glacial scarp 15 ± 3 ka</td>
<td>0.2–0.5</td>
<td>Faure Walker (2010)</td>
</tr>
<tr>
<td>Velino-Magnola</td>
<td>Post-glacial scarp 15 ± 3 ka</td>
<td>0.7</td>
<td>Piccardi et al. (1999)</td>
</tr>
<tr>
<td>Velino-Magnola</td>
<td>Post-glacial scarp 15 ± 3 ka</td>
<td>0.6 ± 0.2</td>
<td>Faure Walker (2010)</td>
</tr>
</tbody>
</table>

Notes: Where a fault has several values, the values do not conflict because values are reported for different positions along the strike of the fault in question, reflecting throw-rate gradients along strike. A more complete review of throw-rates in Lazio Abruzzo is given in Faure Walker (2010). Alternative reviews are given by Galadini & Galli (2000) and Pace et al. (2006).
rate), and as such, will be characterized by the lack of obvious footwall drainage courses. Such sites are relatively uncommon in the literature (although see Salvi et al. 2003 for a possible example). Offsets of the Holocene are needed to prove activity, and this can be achieved by palaeoseismic trenching or using shallow geophysical techniques. Such subtle scarps can be disturbed and hence obscured by human activity.

Prior to the 2009 L’Aquila earthquake, the ruptured fault near Paganica, downthrowing Holocene and Pleistocene continental deposits against post-Mesozoic sediments, where exposed NW of the large, incised footwall drainage course of the Raiale gorge (Fig. 1d), was considered by some of the present authors to be a possible example of a Type 3 morphology. This is because no clear bedrock scarp was obvious near Paganica (the nearest being on en echelon structures to the NW—see Boncio et al. 2010), yet the lack of obvious drainage courses immediately in the footwall of the scarp has allowed preservation of a subtle and perhaps equivocal 4–5-m high scarp in colluvium on a ca. 150-m wide, 20–30-m high escarpment (Figs 3c and d). If this equivocal scarp was indeed an indicator of fault activity, and not modified by human activity, the above implies that the throw-rate would be relatively low compared to other faults around L’Aquila (Table 1), perhaps with a throw-rate value of <0.2–0.4 mm yr–1, although we emphasize that we are aware of no palaeoseismic study confirming such values published prior to the earthquake. Such low rates of activity on the Paganica fault zone may be supported by the observation that the total vertical offset of Mesozoic-Cenozoic strata across the fault is 200–300 m, a value that is small compared to neighbouring faults that have throws of 600–1200 m (e.g. Mt Marine & Assergi Faults; see Pizzi et al. 2002; Roberts & Michetti 2004). If it is assumed that all the faults started to slip at the same time (2–3 Ma or less; see Roberts & Michetti 2004 for a discussion), the observation of relatively small post-Mesozoic throw is consistent with low throw-rates and a Type 3 Scarp at Paganica. Despite the low throw-rates envisaged for the Paganica fault zone, evidence for active faulting was present and recognized, in the form of incised footwall drainage. The Raiale gorge (Figs 1d and e), incises down into the footwall of the Paganica fault zone, with incision ending at the fault trace, indicating differential vertical motions across the fault in the Quaternary. We are aware of no studies published prior to the earthquake that used observations of incision to derive a throw-rate for the Paganica fault zone. Since the earthquake, Messina et al. (2009) have examined tephras around the Paganica fault zone to study rates of vertical offset. Through microprobe and lithological comparison of fresh glass shards with dated tephras from elsewhere in Italy, they identify tephras that may correlate with eruptions of the Colli Albani and Sabatini volcanoes in western Italy at ~560, ~456, ~450 and ~360 ka. Messina et al. (2009) use these ages alongside the elevations of the tephras to suggest a few hundred metres of offset across the Paganica fault zone since the Middle Pleistocene, stating a ‘minimum slip-rate of ~0.4 mm yr–1’. Also, a palaeoseismic study of faults in a trench across the ruptures published since the earthquake (Boncio et al. 2010), suggests a throw-rate of 0.24 mm yr–1 for post-24.8 kyr activity based on radiocarbon dates.

Other studies discuss the possibility of higher rates of activity on the Paganica fault zone. Pace et al. (2006) suggested a possible slip-rate of 0.6 mm yr–1 for what they term the ‘Paganica Fault’. However, Pace et al. (2006) did not provide new data on the rates of deformation, instead citing reviews of regional active fault locations as the source of the value (Barchi et al. 2000; Valensise & Pantosti 2001b). Chiarabba et al. (2009) suggest that, ‘The present obser-

3 GEOLOGICAL SETTING OF SURFACE RUPTURES ALONG THE PAGANICA FAULT ZONE

The Paganica fault zone is not composed of a single fault trace; here we describe the architecture of the fault zone in detail. A ca. 20 km-long Paganica fault zone is clearly shown on published geological maps of the area (Fig. 1d; Vezzani & Ghisetti 1998; APAT 2005). Where exposed in the Raiale gorge near Paganica, the fault separates a hangingwall succession of Upper Eocene-Miocene marly limestones and calc-arenites overlain by Holocene-Pleistocene fluvioglacial, alluvial, colluvial and lacustrine sediments, from footwall Miocene carbonates and calc-arenites overlaying Mesozoic bioclastic carbonates (Fig. 1d). The hangingwall Holocene-Pleistocene sediments are suggested to be a few hundred metres thick (Messina et al. 2009), implying that the total throw of the Mesozoic across the Paganica Fault is 200–300 m; however, note that the value may be less as drill holes for water research penetrated limestones (Miocene?) at 30–70 m depth. Importantly, the surface ruptures occurred about 300 m into the hangingwall of the fault offsetting the Mesozoic marked on the map of Vezzani & Ghisetti (1998)
Figure 3. (a) Map of surface ruptures/cracks and subsurface faults inferred from ground-penetrating radar data, overlain on an Ikonos image (located in Fig. 1d). Surface ruptures are schematic as individual cracks spaced a few metres apart across strike cannot be shown at this scale. (b) Inset map showing the location of the water pipe and roads. H = Houses that may be responsible or refraction hyperbolae on Fig. 6. (c) View of the gorge excavated by water escape from the ruptured water pipe. (d) Topographic profile from LiDAR data showing the subtle morphology of the scarp (located in (a)). Fault 1 and Fault 2 correlate with the same in (a). F2, F3, F4 and F5 in red correlate with fault numbers in Boncio et al. (in press). (e) Along-strike-profiles of the rate of vertical Holocene offset (throw-rate) measured with ground-penetrating radar data (summarizing Figs 5, 6, 7 and 8). Uncertainty in throw-rate interpretation is indicated. Note that if the rates from Sites 2 and 3 are summed across strike, a value of 0.2–0.3 mm yr$^{-1}$ is gained; thus the throw-rate profile remains at a constant rate across the relay zone, showing that the faults are sharing the deformation over a Holocene timescale. A tentative correlation between the faults visible in the water-pipe gorge and those interpreted from GPR is shown (compare d and e).
Surface ruptures produced by the 2009 earthquake in the vicinity of the town of Paganica are best displayed NW and SE of the Raiale gorge on an abandoned Pleistocene alluvial fan surface that has been incised by the modern river. The ruptures are a set of discontinuous ground cracks and surface faults that, individually, can be traced for distances of 15–20 m. Together, these discontinuous features form a NW–SE trending zone of surface rupture that, as a semi-continuous structure, can be traced for ∼2.5 km along strike, and are considered to be the un-ambiguous primary surface expression of the earthquake rupture due to its consistency and continuity (Emergeo Working Group 2009; Falcucci et al. 2009; ISPRA Report 2009). However, note that other, less continuous ground cracks and ruptures have been reported along a zone that may be as long as 13–19 km in length (see Galli et al. 2009; Boncio et al. 2010).

Vertical offsets of up to 12 cm were measured, as were horizontal opening across cracks of a similar amount (Bonacci et al. 2010).

We have chosen to study sites around a water pipe that was ruptured in the earthquake (Fig. 3). The ∼70 cm diameter pipe was at ∼40 bars water pressure, carrying water to the city of L’Aquila from the nearby mountains. The water pipe ruptured in the main shock, as reported by local people, who heard water escaping from the pipe during the early morning of April 6. The ensuing water jet excavated a gorge through Holocene and Pleistocene gravels, allowing examination of the subsurface stratigraphy (Fig. 3c). In the vicinity of the water pipe, the ruptures occurred along a subtle fault escarpment, with the ground rising by 20–30 m over distances of about 150 m (Figs 3c and d). The ruptures occurred about 15 m into the hangingwall of a poorly defined 4–5-m scarps that exists about halfway up the 20–30-m high escarpment (Fig. 3d). In the vicinity of the area we study near the ruptured water pipe, there are no significant footwall drainage courses, and the fan surface has abandoned due to incision of the modern river, so we expected the site to have a very low Holocene sedimentation rate (see below).

It is important to note that the scarps and escarpment are not easy to recognize in the field, as the area contains many concrete constructed houses, tarmac/concrete roads and small quarries (Fig. 3a), and has therefore been modified by human activity; the topographic profile we scanned with LiDAR (Fig. 3d), is probably the only relatively un-disturbed portion of the scarp for hundreds of metres along strike, and itself does not cover the entire across-strike width of the escarpment due to building and road construction.

5 RESULTS

First, we augment the observations of Emergeo Working Group (2009); Falcucci et al. (2009); Galli et al. (2009); ISPRA Report (2009) and Boncio et al. (2010) with slip-vector azimuths measured with a compass and clinometer (Fig. 4). Slip-vector azimuths were in the range of 210–232° over a distance of ca. 2.5 km along the strike of the fault, with a mean vector azimuth of 218°. The slip-vector azimuth is almost perpendicular to the strike of the ruptures (∼127°), indicating a pre-dominant dip-slip normal motion. This slip-vector azimuth was maintained despite the fact that the rupture was discontinuous and appeared at different heights on the subtle escarpment along the Paganica fault zone. For example, in the area 100 m to the east of the ruptured water pipe, the rupture deviated from its general NW–SE orientation, to run as discontinuous cracks in an E–W direction, climbing in elevation by ca. 20–30 m between the water pipe and a hairpin bend on a tarmac road (Figs 3a and b). This elevation was maintained as the discontinuous cracks continued to the SE near and/or through some houses and into a small quarry, before they turned into a NNW–SSE orientation, descending by ca. 30 m as the cracks crossed a concrete road (Fig. 3a, Site 4), and then the main tarmac road in the Raiale gorge (Fig. 1d). This change in elevation and strike of the zone containing the discontinuous surface ruptures suggested that the subtle escarpment along the ruptured portion of the fault zone was formed as a result.
of activity on an anastomizing set of small faults that make up the overall fault zone. This is consistent with observations of the fault zone in the trench excavated by water escape from the ruptured water pipe, where at least four faults can be seen at outcrop within the conglomerates, sandstones and soils (Boncio et al. 2010; Fig. 3d). It is also consistent with relay zone, en-echelon geometries for the mapped surface ruptures reported along strike, south east of the Raiale gorge (Emergeo Working Group 2009; ISPRA Report 2009, see their Annex 3, (Boncio et al. 2010). This prompted the second part of our study to investigate the shallow subsurface structure using ground-penetrating radar to ascertain how the 2009 ruptures relate spatially to previous Holocene and Pleistocene slip within the Paganica fault zone, and possible relay zone structures in the subsurface that do not have a prominent geomorphic expression. Ground-penetrating radar revealed a clear fault zones at four sites (Fig. 3).

5.1 Site 1–20–30 m NW of the ruptured water pipe across a field

In this location, ruptures from the April 6 earthquake were found as three parallel discontinuous fractures spaced 2–3 m apart, associated with bending of the ground surface (Boncio et al. 2010). Three palaeoseismological studies of the trench exposed through rupture of the water pipe published since the earthquake have provided radiometric ages for sediments deformed by faults exposed in the trench (Falcucci et al. 2009; Galli et al. 2009; Boncio et al. 2010). Fig. 3d summarizes their findings, showing that a number of faults contribute to the deformation. Boncio et al. (2010) suggest a throw-rate of 0.24 mm yr\(^{-1}\) for post-24.8 kyr activity measured in the water pipe trench, that is shared between the faults that they name F5, F4 and F3 (see Fig. 3d). The three parallel fractures exposed on the ground surface 20–30 m to the NW

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**Figure 4.** (a) Map of sites from which the kinematics of the 2009 surface ruptures were measured (UTM coordinates). (b) Variation in the slip-vector azimuth along strike measured across ground cracks. Error is similar in size to the symbols. (c) Lower hemisphere stereographic projection of opening vectors across ground cracks from the 2009 ruptures. (d) Typical field measurements supporting (a), (b) and (c) (from the concrete road at Site 4).
appear to correlate with F5 and faults in its footwall (Boncio et al. 2010). Below, we attempt to correlate faults and rates of deformation between the water pipe trench and our GPR line 20–30 m to the NW.

A 46-m long GPR survey running NE–SW across the ruptures achieved depth penetration of about 10 m on a topographic slope that decreased in elevation by 20 m over a horizontal distance of 46 m (Fig. 5).

Figure 5. Site 1 (a) Un-interpreted, and (b) interpreted depth converted ground-penetrating radar profiles. Vertical scales are time in nanoseconds and depth in metres. The GPR data were collected on a soil covered slope.

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A stratigraphy of cemented, white conglomerates lying beneath ceramic-bearing Holocene colluvium that is exposed in the trench excavated by water escape from the ruptured water pipe (Fig. 3c), has also been imaged in the subsurface using GPR. The cemented, white conglomerates (probably Unit U9 of Boncio et al. 2010), are characterized by thin, continuous and parallel radar returns in both the footwall and hangingwall of the rupture. At depth, these returns are offset by a steeply dipping fault(s) on the GPR profile; the vertical offset of this unit is 8 m. As the 2009 earthquake produced only ~10 cm of vertical motion at this site, the rest of the 8 m offset must be attributed to previous surface faulting along this active fault. Overlying the cemented, white conglomerates both at outcrop and imaged by the GPR, are organic-rich colluvial conglomerates and soil that in places contain ceramic fragments (Boncio et al. 2010). These organic-rich colluvial deposits have been dated to 5718 B.C./5467 B.C. to 5403 B.C./5387 B.C. via radiocarbon dating (Falucci et al. 2009), ~5 kys by Boncio et al. (2010) and 2.5 ka–900 A.D. with AMS (Galli et al. 2009). These Holocene ages are consistent with the organic-rich nature of the sediments and the fact that they contain fragments of ceramics, which must be associated with the youngest reported ages. The base of this Holocene unit is clear in the footwall of the rupture on the GPR profile. The basal contact dips towards the rupture, and incises down into the underlying cemented, white conglomerate in the 4 m closest to the interpreted fault. The base of the Holocene is less easy to interpret in the hangingwall of the fault on the GPR profile. The base Holocene is either (1) a subhorizontal radar return defining the top of the aforementioned white, cemented conglomerate (Interpretation B in Fig. 5b), or (2) is a SW-dipping radar return that is above, and separated from the white, cemented conglomerate by a wedge-shaped unit, truncating the white-cemented conglomerate between 40–46 m along the profile at an angular unconformity (Interpretation A in Fig. 5b). If the former is correct, the vertical offset of the base Holocene across the fault is 8 m implying a throw-rate of 0.53 mm yr⁻¹, assuming an age for this contact of 15 ka (the oldest probable age of organic-rich sediments that would have formed after the demise of the last glacial maximum) (Interpretation B on Fig. 5b).

If the latter is correct, the vertical offset of the base Holocene across the fault is a maximum of 3.5 m implying a maximum throw-rate of 0.23 mm yr⁻¹, again assuming an age for this contact of 15 ka (Interpretation A on Fig. 5b). We are unsure which of these two interpretations is correct as we have no age control along the line of the GPR profile. However, combined ^14C dating of organic material (34 970 ± 470 BP) and U/Th dating of a tufa fragment (33 000 ± 4100 yr BP) by Falucci et al. (2009) in the neighbouring trench suggests that the wedge-shaped unit may date from ~33 ka (this probably correlates with units U7 and U8 of Boncio et al. 2010, that they dated to 24 890 ± 140 yr BP), supporting our Interpretation A. Thus, we prefer Interpretation A on Fig. 5b, where the rate of Holocene vertical offset is 0.19–0.23 mm yr⁻¹, depending on the age assigned to the base of the ceramic-bearing, organic-rich sediments (15–18 ka). Importantly, this rate is similar to that implied from the offset of the top of the cemented white conglomerate (8 m offset; 33 ka; 0.24 mm yr⁻¹), assuming its age is 33 ka. Also, note that the fault that is clear at depth, truncating the radar returns that we interpret as the white, cemented conglomerate, is not very clear in the Holocene deposits in the GPR data, although field observations confirm that three parallel fractures and a warp of the ground surface formed at precisely this location in the 2009 earthquake. The white, cemented conglomerate underlies the Holocene, and the wedge-shaped unit that probably dates from ~25–33 ka, and is thus in interpreted to be >25–33 ka, perhaps dating from the Middle or Upper Pleistocene. The white, cemented conglomerate, and an underlying unit that is not exposed at outcrop with less clear radar returns, show possible, but equivocal ‘lap’ relationships with underlying angular unconformities near the base of imaged section. We tentatively interpret these as offlap of alluvial fan sediments above basal erosional truncation surfaces. However, the base of this unit is poorly imaged and we indicate this with a dashed line and question marks on Fig. 5.

Overall, the fault imaged with GPR has not been directly traced into the water pipe trench due to lack of outcrop, but we suggest an interpretation where it correlates with the surface rupture location shown in Figs 3c and d. Our preferred throw-rate of 0.19–0.23 mm yr⁻¹ compares with the rate of 0.24 mm yr⁻¹ for post-24.8 kyr activity measured in the water pipe trench, that Boncio et al. (2010) suggest is shared between the faults that they name F5, F4 and F3 (see Fig. 3d). We suggest the Holocene throw associated with the fault interpreted on our GPR line may be shared along-strike between faults F5, F4 and F3 of Boncio et al. (2010). This may explain why displacements are less on the ruptured fault F5 in the water pipe trench (1.0 m, Boncio et al. 2010) compared to the ruptured fault imaged with GPR (3.5 m). Note that in this interpretation, the location of the ruptured fault does not coincide exactly with the poorly defined scarp measured with LiDAR (Fig. 3d). Instead, the rupture is ~20 m into the hangingwall, with Holocene slip shared possibly between faults F5, F4 and F3. The degraded nature of the scarp suggests that it may be an erosional feature on the unconsolidated slope, where a fault scarp associated with three closely spaced sub-surface faults (F5, F4 and F3) has formed, eroded and thus retreated upslope, and not a simple fault scarp. Thus, although more strain may be accommodated across strike of the ruptured fault, we have found no evidence for rates of Holocene throw accumulation higher than ~0.23–0.30 mm yr⁻¹.

5.2 Sites 2 and 3–70 m SE of the ruptured water pipe across tarmac roads

Site 2 is a 38-m long survey running NE–SW along a tarmac road that achieved depth penetration of about 10 m on a topographic slope that decreased in elevation by 10 m over a horizontal distance of 38 m (Fig. 6). This survey did not cross the rupture (Fig. 3), but was along strike from Site 1, and across strike from Site 3. Site 3 is a 16-m long survey running NE–SW across a hairpin bend in a tarmac road (Fig. 7). It achieved depth penetration of about 10 m on a topographic slope that decreased in elevation by 2 m over a horizontal distance of 16 m. This survey did cross the rupture, which offset the surface of the tarmac road. Although Sites 2 and 3 appear quasi-continuous on the map in Fig. 3, they are separated by a vertical drop of several metres across a concrete road parapet (Fig. 3b), explaining why we did not combine these sites into a single survey. Site 3 is also ca. 8 m along strike from Site 2. However, as they neighbour each other, we interpret them together.

Sites 2 and 3 appear to show very similar stratigraphic patterns to that at Site 1. We use the stratigraphy in the trench at the ruptured water pipe (70 m away to the NW), and comparison of radar-return patterns from Site 1 to aid our interpretation. Our interpretation of Site 2 is complicated by the existence of possible hyperbolic reflections produced by air returns from a nearby concrete house. The radar signal is non-directional, and hence can sample objects above the ground surface, erroneously placing them at depth; such air-return signals can be recognized because they have relatively long wavelength, hyperbolic shapes. Site 2 runs close to
Figure 6. Site 2 (a) Un-interpreted, and (b) interpreted depth converted ground-penetrating radar profiles. Vertical scales are time in nanoseconds and depth in metres. The profile was collected on a tarmac road. Convex upwards hyperbolae in the upper part of the section are interpreted to be from point sources (subsurface boulders?). Long wavelength hyperbolae in the lower right of the view may be air returns from nearby houses (see Fig. 3), producing uncertainty in the interpretation of the hanging wall geometry indicated with ‘question marks’.
a concrete house, and we note the existence of possible examples of hyperbolic reflections from this house in the data from Site 2 (Fig. 6a).

Despite the occurrence of possible hyperbolic reflections produced by air returns from a nearby house, we suggest that Site 2 shows truncation of radar returns at depth that resemble a fault. In detail, we interpret thin, continuous and parallel radar returns in the hangingwall as the lateral continuation of the white, cemented (>25–33 ka) conglomerates that crop out in the water pipe trench. The white, cemented conglomerate is therefore downfaulted at this site. These thin, continuous and parallel radar returns are separated from overlying sediment by a possible angular unconformity, similar to that noted at Site 1. This angular unconformity also exists in the footwall, allowing us to reconstruct the vertical offset. We interpret the material above the angular unconformity to be the ceramic-bearing, organic-rich colluvial conglomerates, sandstones and soil that have been dated to 5718 BC/5467 BC to 5403 BC/5387 BC and younger via radiocarbon and AMS dating in the nearby trench (Falucci et al. 2009; Galli et al. 2009; Boncio et al. 2010). Here, several convex-upwards radar returns may be evidence of channels-like features, but we are wary of this interpretation as flow in the channels would be oblique to the slope. Like Site 1, there is some uncertainty as to the exact position of the base Holocene in the hangingwall of the fault, but the vertical offset of the base Holocene is in the range of 2.0–3.5 m, with uncertainty produced by the possible air-return hyperbolae. This suggests a post-base-Holocene throw-rate of 0.23–0.13 mm yr\(^{-1}\) assuming an age for this contact of 15 ka. This rate should be compared to that implied from the offset of the top of the cemented white conglomerate (3.5 m offset; 33 ka; 0.11 mm yr\(^{-1}\)), assuming its age is 33 ka. Again, the white, cemented conglomerate, and an underlying unit that is not exposed at outcrop with less clear radar returns, may show ‘lap’ relationships with underlying angular unconformities near the base of imaged section. Again, we tentatively interpret these as offlap of alluvial fan sediments above basal erosional truncation surfaces. The base of the section is not well imaged so again, we are uncertain of the offset of these older units at depth. We note that there is one clear example where the radar had poor contact with the ground, producing a delay, and hence vertical feature that continues to the surface. However, we have interpreted two other vertical features as faults rather than artefacts of poor radar contact, because these vertical discontinuities do not continue to the surface, with continuous layers across them at the shallowest levels. Note that Site 2, with clear Holocene offset, was not ruptured in 2009, as the rupture occurs at a higher elevation on the fault escarpment, at Site 3. Thus, despite the problem with possible air returns, our working hypothesis is that this site has a throw-rate of 0.23–0.13 mm yr\(^{-1}\) assuming an age for this contact of 15 ka; confirmation of this working hypothesis requires additional data from shallow geophysics, or a trench excavation.

Site 3 shows a similar radar return stratigraphy to Site 2. Thin, continuous and parallel radar returns are truncated at depth by a fault, so again we interpret this as downfaulting of the white, cemented (>25–33 ka) conglomerates that crop out in the nearby trench. Again, an angular unconformity separates this unit from
overlying deposits that we interpret to be the ceramic-bearing, organic-rich colluvial conglomerates, sandstones and soil that have been dated to 5718 BC/5467 BC to 5403 BC/5387 BC or younger. The up-dip continuation of the fault through the Holocene deposits is unclear on the GPR data, but field observations show that this site was ruptured in 2009, because a set of cracks with 5–7 cm vertical downthrow to the SW was observed on a hairpin bend in a tarmac road. The vertical offset of the base of the Holocene appears to be no greater than 1.5 m, implying a throw-rate of 0.1 mm yr⁻¹ assuming an age for this contact of 15 ka. This rate is similar to that implied from the offset of the top of the cemented white conglomerate (3 m offset; 33 ka; 0.09 mm yr⁻¹), assuming its age is 33 ka. Again, the base of the section is not well imaged so we are unsure of the offsets and hence implied throw-rates for these older units.

5.3 Site 4—concrete road 420 m SE of the water pipe

Site 4 is a 70-m long survey running NE–SW across the rupture that achieved depth penetration of about 7–10 m on a topographic slope that decreased in elevation by 36 m over a horizontal distance of 70 m (Fig. 8). The rupture exhibited about 7 cm of vertical offset at this site. A study of post-seismic deformation using LiDAR demonstrates afterslip at this site and growth in amplitude and wavelength of a post-seismic hangingwall syncline (Wilkinson et al. 2010). Although conglomerates are exposed 60 m to the NNW in a small quarry, there are no outcrops nearby that are along strike from the GPR survey. Thus, any interpretations of the subsurface stratigraphy are more subjective than those for Sites 1, 2 and 3; the radar returns are also less clear, with less spatially complete depth penetration than for Sites 1, 2 and 3. Also, as for Site 2, we have some concerns about possible air returns, in this case from a concrete post carrying electricity power cables (Fig. 8). However, despite a possible example of a long wavelength hyperbola, consistent with an air return from the post and power cables, we think sufficient subsurface geology has been imaged by the GPR to make an interpretation of the Holocene throw-rate. However, we feel the interpretation of this site may be less robust than that for Sites 1, 2 and 3.

The GPR data show layered stratigraphy, and appear to reveal a faulted offset of the base of this layered sequence at a depth of 4–5 m below the 7 cm offset surface rupture on the concrete road. A second fault offsets the base of the layered unit, about 10 m into the footwall of the rupture, again coincident with a surface crack (1 cm opening with 4 mm throw) observed on the concrete road. The surface that we interpret to be offset is an angular unconformity at the base of the layered stratigraphy (Fig. 8b). We tentatively interpret vertical offsets of 70 cm across each of the two aforementioned faults, although we note this is close to the resolution of the data. Beneath this angular unconformity, we interpret a syncline defined by relatively weak radar returns that cross the long wavelength hyperbola that may be due to the electricity pole. Thus, these relatively weak radar returns are likely to be real geological layers rather than air returns. This syncline is in the same location as the post-seismic hangingwall syncline that has been shown to have grown using repeated LiDAR surveys (Wilkinson et al. 2010). The LiDAR data are thus consistent with our interpretation of a hangingwall syncline imaged with GPR. Two localized, vertically stacked sets of radar returns within the syncline may mark discontinuities associated with fractures. The interpreted syncline, and the layered stratigraphy have not been dated. However, if we assume that the hangingwall-layered radar stratigraphy correlates with the ceramic-bearing, organic-rich colluvial conglomerates, sandstones and soil that have been dated to 5718 BC/5467 BC to 5403 BC/5387 BC or younger (Falcucci et al. 2009; see also Galli et al. 2009; Boncio et al. 2010), the implied throw rate is 0.08–0.09 mm yr⁻¹, assuming an age for the base of the layered stratigraphy of 18–15 ka. However, if the stratigraphy within the syncline is also Holocene, the implied throw rate is 0.25–0.3 mm yr⁻¹, again assuming an age for the base of the syncline sequence of 18–15 ka; we prefer this latter interpretation (A plus C in Fig. 8b), but only because it reveals a similar throw-rate to that from Site 1; clearly this needs more work, perhaps in the form of a palaeoseismic trench study.

5.4 Summary

The ground-penetrating radar data from the four sites and rupture observations define two major subparallel, but en-echelon faults within the Paganica fault zone (Fig. 3). All four sites display Holocene throws, and three show late Pleistocene throws. Throws vary along strike defining throw-gradients (Fig. 9). The throw and throw-rate gradients, and the map geometry of the faults define a relay zone (Figs 3a and e, Fig. 9). Existence of the relay zone may explain possible examples of channels in the Holocene deposits whose flow was oblique to the overall slope, perhaps influenced by oblique ground warping of the relay ramp. The 2009 rupture stepped across this relay zone, but the slip-vector azimuth was constant across this structure (Fig. 4). Rates of throw accumulation implied by vertical offset of Holocene and older layers are consistent through time. When summed across strike, the combined throw-rate across these two faults, averaged since 15 ka, is a maximum of 0.23–0.30 mm yr⁻¹ (Fig. 3e), although higher values may exist if (a) throw-gradients continue away from the area studied, or (b) other faults active in the Holocene, but unknown to us, lie across strike. Another relay zone, not imaged by GPR, but clear on the published rupture maps exist ∼200 m NNW of the ruptured water pipe. Other examples of relay zones are clear in the rupture map provided by ISPRA Report (2009); Boncio et al. (in press) and Emergeo Working Group (2009) located ∼1 km to the ESE of the ruptured water pipe.

6 DISCUSSION

The surface ruptures to the 2009 earthquake occurred within the Paganica fault zone. However in detail they occurred along a subtle escarpment in the hangingwall of the main fault shown on the geological map of Vezzani & Ghisetti (1998) (Fig. 1d). This hangingwall fault is itself subdivided into at least two active fault strands that both show Holocene displacements revealed by ground-penetrating radar (Fig. 3), and several others revealed by observations of at least four faults in Pleistocene gravels exposed in the trench excavated by water escape along the ruptured water pipe. The rate of throw accumulation (0.23–0.30 mm yr⁻¹; Fig. 3e) is relatively low compared to other faults around L’Aquila (see Table 1, and Vezzani & Ghisetti 1998; Galadini & Galli 2000; Galli et al. 2002; Pizzi et al. 2002; Roberts & Michetti 2004; Papanikolaou et al. 2005; Galli et al. 2008), suggesting this is an example of a Type 3 scarp, as defined earlier. The throw-rate of 0.23–0.30 mm yr⁻¹ suggests that the Paganica fault zone cannot accommodate all of the 3–5 mm yr⁻¹ extension known for this sector of the Apennines (D’Agostino et al. 2008; see also Roberts & Michetti 2004); other faults have a role to play. Although our observations do not rule out the possibility that the 1461 AD and 1762 AD earthquakes
Figure 8. Site 4 (a) Un-interpreted, and (b) interpreted depth converted ground-penetrating radar profiles. Vertical scales are time in nanoseconds and depth in metres. The profile was collected on a concrete road. Convex upwards hyperbolae in the upper part of the section are interpreted to be from point sources (subsurface boulders?). The long wavelength hyperbolae centred on the 7 cm surface rupture may be an air return from a pole supporting an electricity power cable.
occurred within the Paganica fault zone, the relatively low throw-rate we have measured suggests this may be unlikely, because as pointed at by Tertulliani et al. (2009), the implied recurrence interval seems very short. In Fig. 1 we suggest alternative locations for the surface ruptures to the 1461 AD and 1762 AD earthquakes based on the locations of towns damaged at Mercalli intensity >IX documented in the website http://storing.ingv.it/cfti4med/. Although we have not proved these rupture locations are correct in this paper, or better than those suggested by Tertulliani et al. (2009), they provide an alternative to recurrence of >M6 earthquake on the Paganica fault with ‘∼three centuries recurrence intervals’. The locations we suggest occur along well-known faults with relatively high slip-rates (Table 1, e.g. Vezzani & Ghisetti 1998; Galadini & Galli 2000; Galli et al. 2002; Roberts & Michetti 2004; Papanikolaou et al. 2005; Galli et al. 2008). Given the uncertainty in historical shaking intensity reports described by Tertulliani et al. (2009), we doubt the surface rupture locations we suggest can be differentiated from repeated rupture of the Paganica fault based on these data alone, because shaking intensity is probably more sensitive to site conditions and building vulnerability than differences in epicentral distance of a few kilometres. Clearly, palaeoseismological studies are needed to differentiate between possible sites for the ruptures to the 1461 and 1762 AD earthquakes.

With hindsight, it is now clear that the incised drainage in the footwall of the Paganica fault was perhaps the only obvious indicator of fault activity prior to the earthquake, due to the relatively low throw-rate on this fault in the Holocene (Type 3 scarp). It is clear that such incised drainage patterns should be utilized in the ongoing search for active normal faults in the Italian Apennines and elsewhere (e.g. Roberts 2008). However, it must be borne in
mind that other indicators of fault activity, such as bedrock scars (Type 1) and faulted alluvial fans seen in palaeoseismic trenches (Type 2) should not be forgotten. Although tragic, we must not focus our attention with regard to seismic hazard in central Italy solely on the Paganica Fault; neighbouring range-bounding normal faults, marked by bedrock scars and faulted alluvial fans and moraines, have higher throw-rates (Table 1), and are known to slip in metre-sized events in destructive earthquakes evidenced by dating of colluvial wedges in trenches (Galli et al. 2008), cosmogenic exposure dating (Palumbo et al. 2004) and historical observations (Oddone 1915); the probability of rupture of one of these faults in a given time period, assuming similar-sized slip events, will be higher than that for the Paganica fault if they have higher throw-rates.

7 CONCLUSIONS

Observations with ground-penetrating radar reveal how the surface rupture to the April 6 L’Aquila earthquake relates spatially to previous surface displacements during the Holocene and Pleistocene. In Paganica, the discontinuous surface rupture stepped across a relay zone between en-echelon/parallel faults. Some portions of the fault zone that show clear Holocene offsets were not ruptured in 2009, having been bypassed as the rupture stepped across a relay zone onto a fault across strike. The slip-vector azimuth, defined by opening directions across surface cracks, shows dip-slip motion, and remained constant between 210–228° across the zone where the rupture stepped between faults. Maximum vertical offsets of the base of the Holocene summed across strike are 4.5 m, which if averaged over 15 kyrs, gives a throw-rate of 0.23–0.30 mm yr⁻¹. The values are consistent with throw-rate values implied by offsets of an older layer whose age we assume is ~33 ka. The post-base-Holocene and post~33 ka throw-rate values compare with published values of 0.4 mm yr⁻¹ for a minimum throw-rate implied by the vertical offset of Middle Pleistocene tephas (Messina et al. 2009), and a throw-rate 0.24 mm yr⁻¹ since 24.8 kyr from a palaeoseismic trench study (Boncio et al. 2010). The Paganica fault, although clearly an important active structure, is not slipping fast enough to accommodate all of the 3–5 mm yr⁻¹ of extension across this sector of the Apennines. Other neighbouring range-bounding active normal faults also have an important role to play in the seismic hazard. These faults have slip-rates that are generally higher than that displayed by the Paganica fault, suggesting that, on average, they will have shorter earthquake recurrence intervals for a given earthquake magnitude.

ACKNOWLEDGMENTS

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<td>Author: The publication year of Tertulliani et al. (2009) has been inserted to match the publication year given in the text. Please confirm that this is correct. Also, Please supply the doi code or page range (or both) for the same, or indicate if it is a one-page reference.</td>
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</table>
Key words

Authors are requested to choose key words from the list below to describe their work. The key words will be printed underneath the summary and are useful for readers and researchers. Key words should be separated by a semi-colon and listed in the order that they appear in this list. An article should contain no more than six key words.

GEOPHYSICAL METHODS
Time series analysis
Image processing
Neural networks, fuzzy logic
Numerical solutions
Fourier analysis
Wavelet transform
Instability analysis
Inverse theory
Numerical approximations and analysis
Persistence, memory, correlations, clustering
Probabilistic forecasting
Spatial analysis
Downhole methods
Tomography
Interferometry
Thermobarometry
Fractals and multifractals
Non-linear differential equations
Probability distributions
Self-organization

GEODESY and GRAVITY
Satellite geodesy
Reference systems
Sea level change
Space geodetic surveys
Seismic cycle
Transient deformation
Gravity anomalies and Earth structure
Geopotential theory
Time variable gravity
Earth rotation variations
Global change from geodesy
Lunar and planetary geodesy and gravity
Radar interferometry
Plate motions
Tides and planetary waves
Acoustic-gravity waves

GEOMAGNETISM and ELECTROMAGNETISM
Electric properties
Electromagnetic theory
Magnetotelluric
Non-linear electromagnetics
Archaemagnetism
Biogenic magnetic minerals
Dynamo: theories and simulations
Environmental magnetism
Geomagnetic excursions
Geomagnetic induction
Ground penetrating radar
Magnetic anomalies: modelling and interpretation
Magnetic and electrical properties
Magnetic fabrics and anisotropy
Magnetic mineralogy and petrology
Magnetostatigraphy
Palaeointensity
Palaeomagnetic secular variation
Palaeomagnetism applied to tectonics
Palaeomagnetism applied to geologic processes
Rapid time variations
Remagnetization
Reversals: process, time scale, magnetostatigraphy
Rock and mineral magnetism
Satellite magnetics
Marine magnetics and palaeomagnetics
Marine electromagnetics

GENERAL SUBJECTS
Geomorphology
Geomechanics
Glaciology
Hydrogeophysics
Ionsphere/atmosphere interactions
Ionsphere/magnetosphere interactions
Gas and hydrate systems
Ocean drilling
Hydrology
Ultra-high pressure metamorphism
Ultra-high temperature metamorphism
Tsunamis
Thermochronology
Heat flow
Hydrothermal systems
Mantle processes
Core, outer core and inner core

COMPOSITION and PHYSICAL PROPERTIES
Microstructures
Permeability and porosity
Plasticity, diffusion, and creep
Composition of the core
Composition of the continental crust
Composition of the oceanic crust
Composition of the mantle
Composition of the planets
Creep and deformation
Defects
Elasticity and anelasticity
Equations of state
High-pressure behaviour
Fracture and flow
Friction
Fault zone rheology
Phase transitions

SEISMOLOGY
Controlled source seismology
Earthquake dynamics
Earthquake ground motions
Earthquake source observations
Seismic monitoring and test-ban treaty verification
Palaeoseismology
Earthquake interaction, forecasting, and prediction
Seismicity and tectonics
Body waves
Surface waves and free oscillations
Interface waves
Guided waves
Coda waves
Seismic anisotropy
Seismic attenuation
Site effects
Seismic tomography
Volcano seismology
Computational seismology
Theoretical seismology
Statistical seismology
Wave scattering and diffraction
Wave propagation
Acoustic properties
Early warning
Rheology and friction of fault zones

TECTONOPHYSICS
Planetary tectonics
Mid-ocean ridge processes
Transform faults
Subduction zone processes
Intra-plate processes
Volcanic arc processes
Back-arc basin processes
Cratons
Continental margins: convergent
Continental margins: divergent
Continental margins: transform
Continental neotectonics
Continental tectonics: compressional
Continental tectonics: extensional
Continental tectonics: strike-slip and transform
Sedimentary basin processes
Oceanic hotspots and intraplate volcanism
Oceanic plateaus and microcontinents
Oceanic transform and fracture zone processes
Submarine landslides
Submarine tectonics and volcanism
Tectonics and landscape evolution
Tectonics and climatic interactions
Dynamics and mechanics of faulting
Dynamics of lithosphere and mantle
Dynamics: convection currents, and mantle plumes
Dynamics: gravity and tectonics
Dynamics: seismotectonics
Heat generation and transport
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# MARKED PROOF

Please correct and return this set

Please use the proof correction marks shown below for all alterations and corrections. If you wish to return your proof by fax you should ensure that all amendments are written clearly in dark ink and are made well within the page margins.

<table>
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<th>Instruction to printer</th>
<th>Textual mark</th>
<th>Marginal mark</th>
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<td>Leave unchanged</td>
<td>· · · under matter to remain</td>
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<td>Insert in text the matter indicated in the margin</td>
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<td>New matter followed by <img src="image" alt="Mark" /> or <img src="image" alt="Mark" /></td>
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<td><img src="image" alt="Mark" /> through single character, rule or underline or <img src="image" alt="Mark" /> through all characters to be deleted</td>
<td><img src="image" alt="Mark" /> or <img src="image" alt="Mark" /></td>
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