

# Fossil landscapes and youthful seismogenic sources in the central Apennines: excerpts from the 24 August 2016, Amatrice earthquake and seismic hazard implications

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## Abstract

*We show and discuss the similarities among the 2016 Amatrice (M<sub>w</sub> 6.0), 1997 Colfiorito-Sellano (M<sub>w</sub> 6.0-5.6) and 2009 L'Aquila (M<sub>w</sub> 6.3) earthquakes. They all occurred along the crest of the central Apennines and were caused by shallow dipping faults between 3 and 10 km depth, as shown by their characteristic InSAR signature.*

*We contend that these earthquakes delineate a seismogenic style that is characteristic of this portion of the central Apennines, where the upward propagation of seismogenic faults is hindered by the presence of pre-existing regional thrusts. This leads to an effective decoupling between the deeper seismogenic portion of the upper crust and its uppermost 3 km.*

*The decoupling implies that active faults mapped at the surface do not connect with the seismogenic sources, and that their evolution may be controlled by passive readjustments to coseismic strains or even by purely gravitational motions. Seismic hazard analyses and estimates based on such faults should hence be considered with great caution as they may be all but representative of the true seismogenic potential.*

## I. INTRODUCTION

The 24 August 2016, Amatrice earthquake (M<sub>w</sub> 6.0), which devastated a portion of the Central Apennines causing nearly 300 victims and substantial property damage, occurred in an especially well monitored region. Hence it has taken merely two days to realize that the Amatrice earthquake, although sharing the general characteristics of other Apennines extensional events, exhibits peculiarities that took many earthquake geologists by surprise. Scientists

were once again confronted with a complex rupture, too deep and too shallow-dipping to connect with the active faults known in the region, and breaking across what many considered a major regional tectonic boundary (the Monti Sibillini Thrust).

The Amatrice earthquake is the last of three disastrous, similarly-sized earthquake sequences, all caused by normal faulting along planes dipping 40°-50° to the southwest. The 2016 sequence follows the 6 April 2009 L'Aquila earthquake (M<sub>w</sub> 6.3),

with its strong 9 April aftershock in the Campotosto-Monti della Laga area ( $M_w$  5.4), and the 26 September and 14 October, Colfiorito-Sellano earthquakes ( $M_w$  5.7, 6.0 and 5.6), respectively located to the southeast and to the northwest of Amatrice along the Apennines crest (Fig. 1). These earthquakes delineated a tectonic style that is largely at odds with the views on the active tectonics of the central Apennines that dominated the scientific debate over the past thirty years (see discussion in Vannoli et al. [2012]).

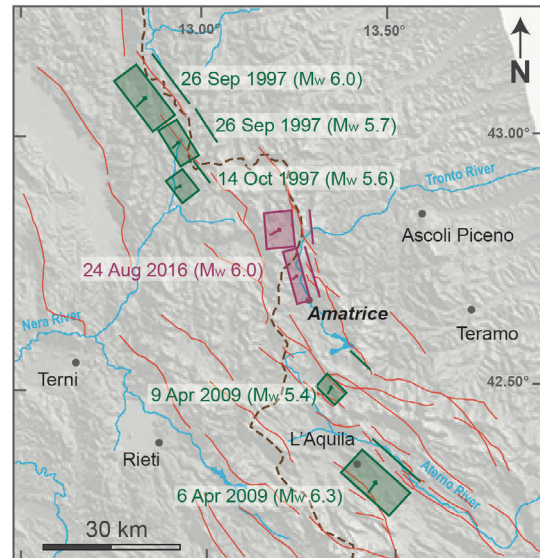
After summarizing the established facts concerning the epicentral region (§2) we discuss the constraints arising from the tectonic and landscape evolution of the central Apennines (§3) and from InSAR evidence for coseismic strains in recent extensional earthquakes (§4). Finally we focus on the implications of our findings for an improved assessment of the regional seismic hazard (§5).

The three sequences share the availability (a) of numerous and reliable earthquake data collected by the permanent INGV network and by temporary networks, and (b) of good quality InSAR data. The latter in particular proved fundamental for understanding the details of the source processes and unraveling the puzzle of their associated surface coseismic deformation, represented by limited or ambiguous surface breaks for all three earthquakes.

InSAR observations (Fig. 2) are by far the best tool available for modern Earthquake Geology, as they:

- carry a multi-wavelength signal that can be interpreted, with appropriate filtering, to investigate the properties of the main seismogenic source separately from the associated secondary and gravity-driven effects;
- provide a framework for interpreting the geology and landscape evolution resulting from repeated faulting;

- are sensitive to the fault patches that experienced the largest slip and insensitive to finer details of the coseismic ruptures.

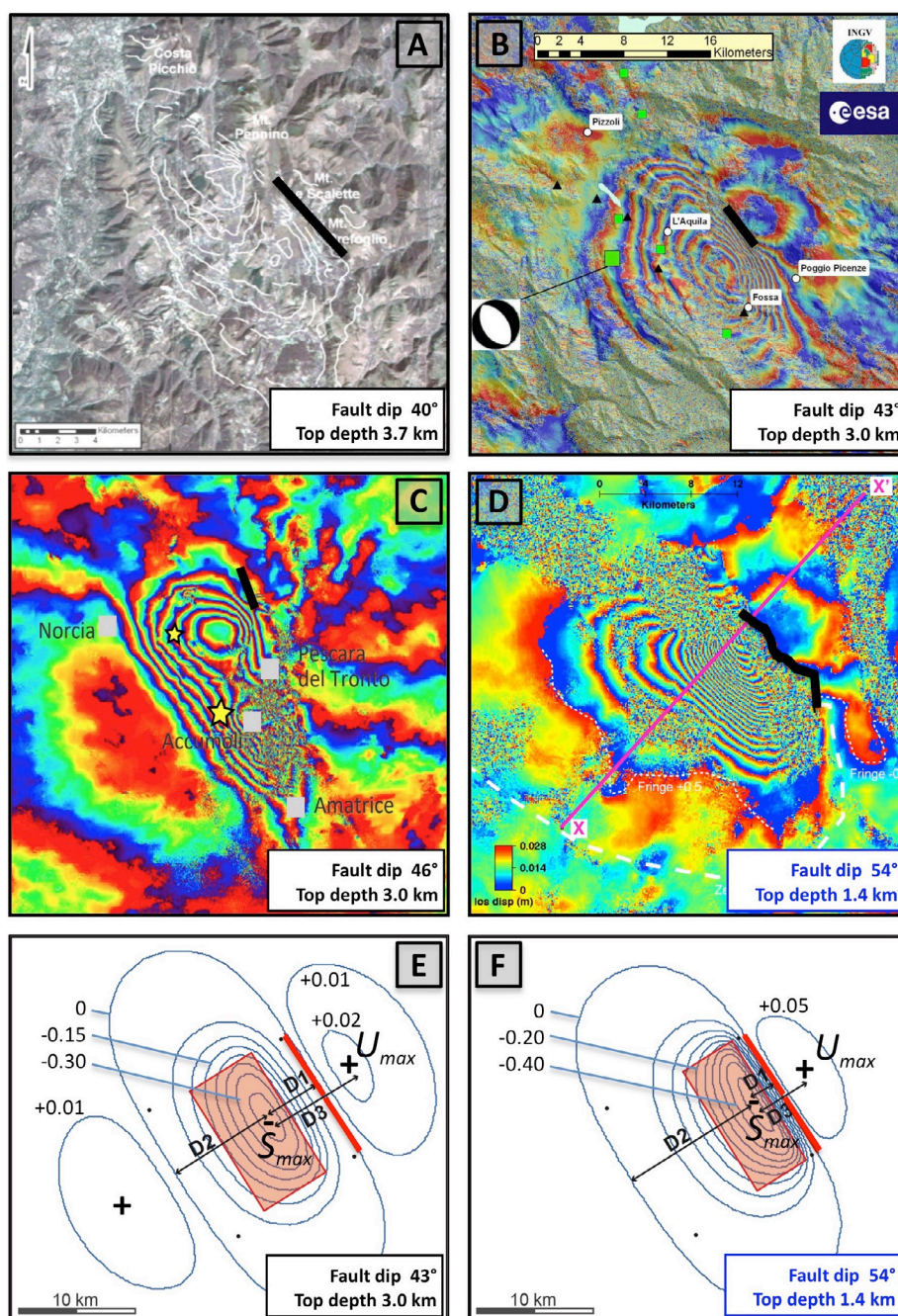


**Figure 1.** Geographic setting and seismogenic sources discussed in text. Active faults from various sources are shown in red. Sources in green are from the DISS database [DISS Working Group 2015]. The two sub-sources proposed for the Amatrice earthquake, in purple, are from Gruppo di Lavoro IREA & INGV [2016]. A dashed line shows the regional watershed.

## II. PREVIOUS AND ESTABLISHED KNOWLEDGE

Similarly to the L'Aquila and Colfiorito regions, the area that spawned the Amatrice earthquake has long been known as earthquake-prone. Yet, the understanding of the exact location and characteristics of its seismogenic sources has always been limited. Common characteristics of the 1997, 2009 and 2016 sequences are (see Fig. 2 and Table 1):

- faulting occurred between 3 and 10 km depth on southwest-dipping faults striking parallel to the local trend of the Apennines;
- little or no slip was observed above 3 km depth, either by seismological methods or by inversion of GPS and InSAR data;



**Figure 2.** Panels A-D: comparison of InSAR models. (A) 1997 Colfiorito earthquake [Moro et al. 2007]; (B) 2009 L'Aquila earthquake [ESA, 2009]; (C) 2016 Amatrice earthquake, solution obtained from Sentinel-1 data [Gruppo di Lavoro IREA & INGV 2016]; (D) 1995 Dinar, Turkey earthquake [Douglas and Funning 2016]. The observed or presumed – depending on cases - surface expression of the fault is shown by a thick black line. Panels E-F: comparison of the "coseismic signature" obtained for two distinct model faults, showing the extent of coseismic uplift and subsidence per unit slip: (E) is an average of the models obtained for the 1997, 2009 and 2016 earthquakes, (F) reproduces the 1995 Dinar earthquake. A thick red line shows the surface projection of the fault plane. See also Tables 1 and 2.

Name, date and origin time (UTC)	Ref	Strike (deg)	Dip (deg)	Rake (deg)	Fault Length (km)	Fault Width (km)	Fault top/bottom depth (km)	Avg slip (m)	M <sub>w</sub>	Surface breaks (ref)
Colfiorito I 1997, 26 Sep, 00:33	1	148	40	277	9.0	6.0	4.0/7.8	0.38	5.7	None (a)
Colfiorito II 1997, 26 Sep, 09:40	1	143	40	275	14.0	8.0	3.4/8.5	0.33	6.0	None (a)
Sellano 1997, 14 Oct, 15:23	1	144	40	260	6.0	6.0	2.5/6.5	0.28	5.6	Minor breaks (b)
L'Aquila 2009, 6 Apr, 02:32	2	133	43	275	14.0	9.5	3.0/9.5	0.60	6.3	A few cm along Paganica Fault (c)
Campotosto 2009, 9 Apr, 00:52	3	135	45	275	5.9	5.2	7.3/11.0	0.10	5.4	None
Amatrice 2016, 24 Aug, 01:35	4	165-175	39-51	295-290	8.0 12.0	8.0 5.0	3.0/8.0 2.5/6.4	0.70	6.0	Up to 20 cm along Vettore Fault (d)
Dinar (Turkey) 1995, 1 Oct, 17:57	5	148	54	277	11.4	8.6	1.4-8.0	1.44	6.1 (M <sub>s</sub> )	Up to 30 cm (e)

**Table 1.** Fault parameters for the 1997, 2009 and 2016 central Apennines earthquakes, and for the 1995 Dinar, southern Turkey earthquake: (1) DISS Working Group [2015]; (2) Vannoli et al. [2012]; (3) this work; (4) Gruppo di Lavoro IREA & INGV [2016]; (5) Wright et al. [1999]. Surface breaks reports: (a) Basili et al. [1998]; (b) Cinti et al. [2000]; (c) Vannoli et al. [2012]; (d) EMERGEO Working Group [2016]; (e) Wright et al. [1999]. Notice that the Amatrice fault was modeled using two distinct planes (parameters from Gruppo di Lavoro IREA & INGV [2016]).

- seismological, InSAR and GPS observations combined indicate that the dip of the seismogenic fault is in the range  $39^{\circ}$ - $51^{\circ}$ , much lower than the dip commonly reported for central Apennines active faults [e.g. Vannoli et al., 2012] but coherent with a recent elaboration on the fault dip distribution of global normal faulting earthquakes [Basili and Tiberti, 2016];

- as a result of the limited width of the rupture plane and of coseismic slip (<10 km and <1 m, respectively), the three earthquakes also exhibit a relatively small magnitude. Similarly to thrust faults, however, the shallow dip of the fault may allow for substantially larger ruptures;

- in all cases the rupture appeared to be vertically confined by the interference with thrust planes dating to the build-up of the Apennines fold-and-thrust belt (Fig. 3).

### III. RELATIONS WITH SURFACE STRUCTURES: LANDSCAPE FEATURES

Over the past two decades various investigators have pointed out that the extensional tectonic regime responsible for the normal faulting earthquakes that occur along the crest of the Apennines is relatively

young. For example, the age of inception of one of the main and oldest extensional structures in the central and northern Apennines, the Etrurian Fault System, dates back to the Late Pliocene-Early Pleistocene (see Pucci et al. [2014], and references therein). A straightforward implication of this finding is that, given the current rates of extension in the Apennines, the amount of topography that has been created at any point after the inception of this new stress field is only a fraction of the extreme topography seen along the chain axis; examples of that are the western side of the Mt. Vettore-Mt. Bove range, the northern side of the Gran Sasso range, and the Velino-Sirente, Majella and Matese massifs as a whole. In their turn most of the intervening basins do not show the architecture that would result from sustained extensional faulting. The Colfiorito Plain, the Castelluccio Plain, the Amatrice Basin, and the Mid-Aterno Valley, the main depressions that lie in front of the three normal faults being analyzed in this work (from north to south), are consistently too shallow, too narrow, and too short to be the long-term effect of the seismogenic faults that lie next to them; faults which should generate half-graben architectures that are not seen.



At first glance the three earthquakes do appear to have affected lowlands - where population and infrastructures naturally concentrate - lying next to fault-controlled ranges. Yet a closer inspection of the InSAR-detected elevation changes reveals that:

(a) most of the regions undergoing coseismic subsidence are areas of high topography, not basins or depressions; and

(b) the strain field associated with these typical Apennines earthquakes induces significant but relatively localized subsidence (15-30 cm for the earthquakes being considered here) and very mild uplift (2-4 cm) over a much broader region.

As for (a), it should be recalled that the observed topography reversal is the expected outcome - and in fact a proof - of the current extensional regime being rather youthful (see Valensise and Pantosti [2001] and references therein). As for (b) one should recall that Bagnaia et al. [1992] pointed out on a purely geological basis that the central Apennines are currently dominated by "gravity faults" that are disrupting and lowering the axial portions of the fold-and-thrust belt.

Finally, all three InSAR models show that the causative faults of the three investigated earthquakes tend to create a basin-and-range architecture whose wavelength perpendicular to the chain is at least twice the spacing between existing basin-bounding faults. Notice that any intervening afterslip or post-seismic relaxation would increase this wavelength, not reduce it. All these observations strongly suggest that the current landscape is largely a fossil terrain that is being slowly dismantled by the erosion caused by the well documented regional-scale uplift of the entire chain, and reshaped by the action of newly incepted normal faults such as those responsible for the three earthquake sequences investigated

here (e.g. Cavinato et al. [2002] and Santo et al. [2014]). Dealing with a fossil landscape implies also that several faults that punctuate it have ceased their activity and participate only passively to the ongoing deformation (see Bonini et al. [2014] for a thorough discussion on these circumstances). One of many such cases is that of the Pettino fault, near L'Aquila: seen by many as a major active fault, it turned out to be "floating" in the hanging wall of the fault that caused the 6 April 2009, L'Aquila earthquake [Bonini et al., 2014].

#### IV. RELATIONS WITH SURFACE STRUCTURES: FAULTS

InSAR data provide crucial evidence on the role played by any surface fault occurring in the region hit by a significant earthquake. Recall that InSAR observations record static slip - not just dynamic slip - over an interval of a few days before and after the event, and hence are suitable also to document postseismic readjustments, if any.

Figs. 2A, 2B, 2C show that for the 1997, 2009 and 2016 earthquakes most - if not all - interferometric fringes describing the subsidence associated with the mainshock are neatly closed in front of the presumed surface expression of the primary fault, implying that slip in the uppermost portion (up to 2-4 km depth) of the fault was much smaller than in its lower portions. In contrast, Fig. 2D shows the case of the 1995 Dinar (Turkey) earthquake (M. 6.1), where dynamic slip was modeled up to a depth of 1.4 km and where a 30 cm-high scarp was observed along the upward prolongation of the model fault: in this latter case the fringes are broken against the scarp, or not resolvable due to diffuse deformation, thus testifying that at least part of coseismic slip propagated all the way to the surface. This different behavior is illustrated in Figs. 2 E, 2F and in Table 2.



2) the elaboration of all of the three available InSAR datasets by different and independent groups (the Japanese ALOS-2, Sentinel-1 by the European Copernicus Program, and the Italian COSMO-SkyMed, developed by Agenzia Spaziale Italiana) and the slip model obtained by Tinti et al. [2016] from the inversion of strong motion records clearly shows that neither dynamic nor static slip occurred during the mainshock or in the following few days in the uppermost 3 km of the crust;

3) the Vettore Fault lies at the very northern end of the 2016 rupture: no sizable breaks have been observed along the central part of the rupture, for example along the well-known Gorzano Fault. The observed 5 km-long scarp is in an awkward position relative to the length of the earthquake source and is too short for a  $M_w$  6.0 quake.

4) the Vettore Fault lacks a basin/depocenter representative of its long-term activity, knowing that the Castelluccio Plain is a karst basin elongated almost perpendicular to the Mt. Vettore ridge and filled with a thin veneer of continental deposits;

5) the surface breaks seen along the Vettore fault have been shown to be largely the result of landsliding and sediment compaction [Gruppo di Lavoro IREA & INGV, 2016], as testified also by the recent geomorphological evolution of the portion of the Castelluccio Plain that lies at the base of the Vettore Mt. [Aringoli et al., 2014, and references therein].

For these reasons we maintain that the surface breaks seen along the western flank of the Vettore Mt. do not represent the primary expression of fault slip at depth, but rather some form of shaking-induced sliding along the Vettore Fault. This case is not isolated. In a large report written following the 13 January 1915, Avezzano-Fucino basin (central Apennines) earthquake ( $M_w$  7.0), Oddone [1915] described a large landslide affecting the talus deposits lying over the

large and well known Serrone Fault. He described the landslide as clearly separated from the shaking. All buildings of the village of Gioia dei Marsi, unwisely built on these deposits, were totally destroyed, and every single wall was reported overturned. This suggests that their foundations had become loose under the combined action of shaking and gravity sliding. Similarly to the Vettore Fault, the Serrone Fault lies at the very end of the 1915 rupture, to the southwest of the Fucino basin.

The literature of the central Apennines reports a number of faults that are considered both active and seismogenic. Vannoli et al. [2012], however, pointed out that these faults are too many, generally too small and too closely spaced to root in at seismogenic depth all at once. What is the evidence that they indeed play an active role in the current evolution of the region? Key observations include:

1) most, if not all, of the bedrock normal faults are closely associated with thrusts that were active between the Late Miocene and the Pliocene: if we admit that the onset of the current extensional regime is not older than the Early Pleistocene, these older normal faults may well be prone to be (passively?) reactivated, but they can hardly be seen as the primary expression of the current stress field;

2) the consistent lack of slip in the uppermost 3 km of the crust - either coseismic or slow/post-seismic - testified by InSAR data (Fig. 2) and consistent with the spatial distribution of aftershocks [Michele et al., 2016], indicates that the currently active seismogenic faults act independently from the structure and evolution of the shallowest portion of the crust;

3) basic knowledge on the structure of the Apennines fold-and-thrust belt aided by analogue models (see Bonini et al. [2015]) shows a sort of “vertical segmentation” of large active normal faults; these develop and

grow in-between major pre-existing sub-horizontal discontinuities – e.g. large thrust planes - that effectively isolate them from the surface;

4) InSAR evidence combined with the results of analogue modeling suggests that such discontinuities do not prevent the upward propagation of coseismic strain, but also that they do act as effective barriers for fault propagation, thus contributing to decouple the deeper from the shallower faults.

#### IV. CONCLUSIONS AND SHA IMPLICATIONS

We have provided and discussed evidence showing that, similarly to the 1997 Colfiorito, and 2009 L'Aquila earthquakes, the 24 August 2016 Amatrice earthquake has been generated by a shallow-dipping, blind fault. As such this fault bears no relationships with the presumed active faults mapped in the region over the past 40 years. While this paper was under revision two additional damaging earthquakes occurred on 26 October near Visso-Ussita ( $M_w$  5.9) and on 30 October near Norcia ( $M_w$  6.5). Preliminary analyses of these two events suggest that they were also generated by shallow-dipping faults, relatively deep faults, although the 30 October event appears to have caused a complex pattern of brittle surface deformation.

Once again the central Apennines seismogenic sources demonstrated to be youthful faults lying beneath a mattress formed by older thrusts and their accompanying extensional faults. The investigation of such deeper faults requires a new paradigm that finally acknowledges these circumstances and develops new and appropriate investigation strategies.

Our findings have four main categories of implications that need to be carefully considered to avoid gross misrepresentations of the local earthquake potential:

a) the complex structure of the central Apennines fold-and-thrust belt causes the effective decoupling between the normal faults that affect the uppermost 2-4 km of the crust and current extension accommodated by larger faults lying beneath them. As a result, surface faults are crucial for land planning but carry little information on seismogenic processes at depth (see #4 in previous section);

b) for the same reasons, the evolution of large-scale, long-term landscape features - e.g. the evolution of basin architectures and the distribution of fluvial or marine terraces - should be regarded as the main and most faithful indicators of ongoing long-term strain at depth;

c) as the current geodynamic and geomorphic evolution of the Apennines is controlled more by regional uplift than by localized faulting, and in consideration of the above #a), one has to be extra careful not to interpret the largely climate- and gravity-controlled evolution of steep Apennines mountain slopes as evidence for continuing activity of surface faults (an ample discussion on this topic is supplied in Kastelic et al. [2016]);

d) for exactly the same reasons, and based on the recent evidence from the Vettore Fault, from the Serrone Fault in the Fucino basin and from a number of large landslides controlled by older surface faults (see Moro et al. [2007] and Moro et al. [2011], respectively for the 1997 and 2009 earthquakes), extreme care should be taken when trenching scarps of unproven origin; since they may represent only the accumulation of deposits mobilized by shaking, they may carry information suitable for dating the shaking itself but not for deriving meaningful slip rates or  $M_w$  estimates.



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