Geological analysis and seismic hazard in the Central Apennines (Italy)

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Abstract

This study puts forward a segmentation model applied to active faults with the aim of assessing seismic hazard in the Central Apennines. The model, whose reliability had been ascertained during the 1997 Umbria–Marche earthquake sequence, also implies a review of the key terms used in the analysis of active faults and points out the need for a specific procedure in geological analysis for seismic hazard evaluation. Earthquake events which occurred in the Central Apennines in the past decades show that several surface faults can be activated throughout a single seismic event. As a result, the segmentation model proposed herein is based on the fact that surface faults are, on the whole, the superficial manifestation of a single deep seismogenic structure. Therefore, this model is based on the possibility to recognize similar geological, structural, historical, geometrical and rheological features at the surface, in order to infer the main properties of the fault zone at depth. Eventually, on the grounds of the specific features of the fault array, one may assess the geometry, kinematics, slip-rate and size of the deep seismogenic structure, i.e., all the required parameters to evaluate the seismic potential of the area. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

The earthquake events which occurred in the central Apennines in the past decades (Norcia, 1979; Colfiorito, 1997) as well as the examination of well-documented historical earthquakes (Norcia-L’Aquila, 1703; Fucino, 1915) have shown that several surface faults are activated...
Fig. 1. Location area (a); Tectonic map of the Central Apennines and epicentre location of historical earthquakes (b).
during a single seismic event (Fig. 1). Multiple ruptures occurred during the 1997 Umbria–Marche earthquake sequence (Cello et al., 1998b), where reactivations of already mapped capable faults were observed along three different active segments (Cello et al., 1997; Tondi et al., 1997). Historical documents and paleoseismic data (Blumetti, 1995; Cello et al., 1998a) also show that, during the earthquake of 14 January, 1703 (Imax = XI° MCS), ruptures and ground cracks occurred within at least four active faults zones. Detailed paleoseismic analyses show that, as a consequence of the Fucino earthquake in 1915 (Imax = XI° MCS), at least four faults were reactivated (Michetti et al., 1996; Galadini et al., 1997). The activation of several faults during a seismic event may have strong implications for the assessment of seismic hazard.

During earthquake faulting, surface deformation and geodetic analysis, as well as radar interferometry, indicate that the earth surface in the mesoseismal area deforms permanently and that deformation is strongly dependent on the geometry, kinematics and dimension of the seismic source (Chinnery, 1961). These results are generally represented by a continuous curved surface in spite of the fact that what is really observed is a broken line, where deformation is localized in correspondence of the main fault zones.

The segmentation model proposed herein is based on the fact that surface faults activating during a single seismic event are, on the whole, the superficial manifestation of a single deep seismogenic structure. Therefore, the model is based on the possibility to recognize similar structural, historical, geometrical and rheological features at the surface, since they record the long-term behavior due to several earthquake events arising from the same seismogenic structure. Segmentation is thus applied to an area instead of a single fault segment. Eventually, on the grounds of the specific features of a given area, we may assess all the required parameters to evaluate the seismic potential.

In this paper, available geo-structural data from the Central Apennines are used with a view to assessing seismic hazard by means of an areal segmentation model applied to the Colfiorito, Norcia and Fucino basins, epicentral areas of major destructive events occurred in this sector of the Apennines. In particular, the Colfiorito basin is a key area for comparing the results of already available seismic hazard estimates (Cello et al., 1997; Tondi et al., 1997) with those derived from field investigations carried out soon after the 1997 Umbria–Marche seismic crisis (Cello et al., 1998b).

2. Areal segmentation

The ability of subdividing a major fault array into sectors showing different historical, geometrical, structural and rheological behavior is the basis on which fault segmentation lies (Schwartz and Sibson, 1989).

The segmentation technique using a single-segment rupture model (Schwartz, 1989; Scholz, 1989) is based on the principle that the portions of the fault zone ruptured during a single earthquake are defined as earthquake segments (Machette et al., 1991; de Polo et al., 1991; Crone and Haller, 1991). According to the authors, the area of the ruptured fault surface,
Fig. 2. The Colfiorito fault map, epicentral area of the 1997 Umbria–Marche earthquake.
defined by the length of a surface rupture and the down-dip width of the fault, is directly proportional to the magnitude of the causing earthquake (Wyss, 1979; Hanks and Kanamori, 1979; Bonilla et al., 1984; Abercrombie and Leary, 1993). The recognition of the size of rupture-prone segments allows predicting maximum earthquake magnitudes in a region, and thus, its seismic hazard potential.

In the following sections, the validity of the above model will be discussed with reference to three seismogenic zones in the Central Apennines, and some modifications will be introduced in order to account for multiple ruptures occurring within the study areas.

2.1. The Colfiorito basin seismic zone

The Colfiorito basin lies in the Umbria–Marche Apennines, a segment of the neogenic fold and thrust belt of Central Italy (Fig. 1). Quaternary faults, generally high-angle normal, transtensive and transcurrent faults are superimposed over the neogenic compressional features of the belt. In the axial zones, they are mostly NW–SE to N–S oriented, and border a few tectonic depressions (as that of Colfiorito) filled with Pleistocene and Holocene deposits.

The geostructural setting of the Colfiorito basin area is controlled by N–S to NNW–SSE oriented macroanticlines (the M. d’Acciano–M. d’Annifo, M. Pennino–M. Orve, M. Tolagna–M. le Scalette anticlines), which are associated with three main eastern-verging thrusts (Fig. 2). The whole area is characterized by ridges and tectonic depressions originated in response to the activation of a set of Quaternary faults (Centamore et al., 1978; Calamita and Pizzi, 1992; Cello et al., 1997) that controlled their geometry and evolution, as well as the deposition of fluvio-lacustrine continental sediments dating back to the late lower Pleistocene (Ficcarelli and Silvestrini, 1991).

The geometry and kinematics of the fault segments belonging to the Colfiorito fault array may be summarized as follows (Fig. 2):

- the WSW-dipping faults, having a N 140–160° average direction, are characterized by a normal to left-lateral transtensive motion
- the N–S trending faults mostly show left-lateral transcurrent motion
- subvertical faults, having a N 70–90° average direction, are subordinate as to frequency and dislocation and are mainly characterized by a normal and/or right-lateral transtensive motion.

Within this Quaternary fault array, the main capable faults which may cause coseismic surface faulting were also mapped (Fig. 2). These are located at the northern termination of the CAFS (Central Apennines Fault System, Cello et al., 1997, 1998a).

After having mapped the capable faults and qualified their structural and geometric characteristics, a segmentation model was applied to the area in order to relate active faulting to the deep-seated seismogenic structure (Fig. 3). On the grounds of the specific features characterizing the Colfiorito basin area, it was also possible to evaluate the main parameters (geometry, kinematics and size) of the deep seismogenic structure. Determining the relationship
between surface faults and seismogenic structure allows us to calculate the maximum expected magnitude in the area (Tondi et al., 1997).

According to the existing ratio between fault surface and released energy in a single seismic event, by determining the maximum length of the seismogenic fault it was possible to calculate seismic moment, hence, the highest corresponding magnitude, on the grounds of the ratio between seismic energy and fault area:

\[
Mo = \mu ADu
\]

where:

\[
A = \text{fault surface}; \quad \mu = \text{rigidity} = 3 \times 10^{11} \text{ dyn/cm}^2; \quad Du = \text{last slip increment on the fault.}
\]

From this, it also follows that \(M_w = (\log Mo/1.5) - 10.73\) (Kanamori, 1977). In the study area, if one assumes a maximum length of about 15 km, a seismogenic layer depth of ca. 12–15 km and a coseismic dislocation of 0.3–0.5 m, we get a maximum seismic moment \(Mo = 1.8 \times 10^{25} \text{ dyne/cm}^2\) corresponding to a maximum magnitude \(M_w = 6.0\) (Tondi et al., 1997).

On September 26, 1997, at 00:33 and 09.40 (GMT), two moderate earthquakes (\(M_w = 5.7\) and \(M_w = 6.0\)) struck the Umbria–Marche region of Central Italy. The epicenter of the first

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**Fig. 3.** Areal segmentation of the Colfiorito seismic zone.
shock was located within the Colfiorito basin, midway between Cesi and Costa, whereas, the second shock occurred south of Annifo (Fig. 2; Amato et al., 1998). Observed surface ruptures due to the 1997 seismic sequence were mapped along three main capable faults: the Colfiorito border fault; the M. Tolagna and the Cesi–Costa faults (Fig. 2), whereas, interferometric analysis and GPS measurements carried out soon after the mainshocks, confirm ground dislocation within the basin area (Strasmondo et al., submitted).

The kinematic behavior of the seismogenic structure (obtained from the preliminary CMT solutions of the 1997 mainshocks; Fig. 2) suggests nearly pure normal faulting on northwest–southeast trending planes dipping 40–50° to the southwest.

In the Colfiorito area, slip-rates on the capable faults have been calculated and the stratigraphic throw added to obtain the total throw of the deep seismogenic structure (Fig. 4). Assuming, for example, a 1000 ky startpoint for fault activity (Ficcarelli and Silvestrini, 1991), we obtain a 0.3 mm/year ‘geological’ slip-rate. According to the Italian seismic catalogues, the strongest earthquake with an epicentral area close to that of the 1997, occurred in 1279 (I = X MCS). If this event is similar to that of the 1997 seismic sequence, we can infer a 50 cm coseismic slip at the hypocentre. Hence, we obtain a ‘historical’ slip-rate of approx. 0.8 mm/year, which suggests a 1–3 ratio between the geological and historical slip rates. As far as the 1997 seismic sequence is concerned, we get a 15 cm total surface coseismic throw from fault reactivation (Cello et al., 1998b; Fig. 4), which is approx. 1/3 of that calculated at the hypocentre.

These results suggest therefore, that geological information in the area records only about 1/3
Fig. 5. Norcia–Cittareale fault map, epicentral area of the 14 January 1703 and 19 September 1979 earthquake.
of the fault slip at depth, and that the long-term consistency of this result as the sum of numerous seismic events, may possibly be controlled by both the dislocation depth and the outward slip decrease from a rupture volume.

2.2. The Norcia seismic zone

The activity of the Norcia seismic zone (Fig. 5) is characterized by moderate events and by strong earthquakes with maximum intensities of X–XI degrees MCS and equivalent magnitudes around 6.5–7.0 (Postpischl, 1985; Gasparini et al., 1985; Westaway, 1992).

The 1703 earthquake sequence is known for its destructive effects recorded over a large area in response to southward propagating multiple shocks occurring from January 14 to February 2, whereas, the September 19 1979 earthquake, with a magnitude $M_s = 5.9$ and focal depth of 6 km, struck a much smaller area, south of Norcia. Available seismological data show that the geometry of the current stress field acting in the area is constrained by a focal mechanism solution with an NNW–SSE trending P-axis and an ENE–WSW oriented T-axis, whereas, the aftershock sequence points out the existence of a roughly 10 km wide, sub-vertical seismogenic zone extending from a depth of 2–3 km to about 14–16 km (Cello et al., 1997; see also Brozzetti and Lavecchia, 1994).

The highest damage area for the 14 January 1703 earthquake runs roughly in a north–south direction from Norcia to Cittareale. According to Stucchi (1985), this earthquake affected a 10 km wide, and about 40 km long area causing approx. 6000 casualties. The epicentral area of the event shows clear overlapping relationships with the central fault set (the Norcia–Cittareale set) of the CAFS, thus suggesting a direct link between the tectonic structure at depth and the surface fault pattern of the area. In Fig. 5, the structural details of earthquake faulting and related phenomena are also shown.

From a structural point of view, the area around Norcia is affected by two major NNW–SSE trending faults turning north–south at both ends (Fig. 5). The main active faults in the area are those bordering the Norcia basin, a tectonic depression filled with Pleistocene–Holocene fluvio-lacustrine sediments. Evidence of recent activity along these faults is due to the existence of fault scarps in slope deposits and deep slope gravity deformation, which are supposed to have reactivated during the 1703 earthquake sequence (Blumetti, 1995). Within this sector of the epicentral area of the 1703 seismic sequence, at least three surface ruptures have been related to this earthquake (i.e., the Castel Santa Maria and the Monte Pizzuto faults, as well as the fault bordering the west of the Norcia basin; Cello et al., 1997). The latter tectonic structure is clearly visible from satellite images as a sharp and continuous lineament generating a fresh morphotectonic scarp in Holocene deposits, east of Misciano. Due to the overall geomorphic characters of the scarp, this surface rupture was considered to be a very young fault, therefore relating to the 1703 earthquake sequence. The geological vertical throw across this NNW–SSE trending lineament is several 100 m in the Norcia area and decreases to the south, where the fault becomes north–south oriented and displays a large (about 1 km) horizontal (across the Velino valley) offset.

The Cittareale fault set includes a north–south trending fault showing, at its southern
termination, a major left-lateral offset (about 1 km) of the Velino river valley. At its northern termination, the Cittareale fault set is characterized by a more complex discontinuous pattern including several lower-rank faults showing strike-slip and transtensional left-lateral motion and defining small tectonic depressions such as that of Castel Santa Maria (Fig. 5). Here, the occurrence of a 10–20 cm high scarplet at the base of a 8 m high scarp in bedrock was interpreted by Calamita and Pizzi (1992), as the result of coseismic slip associated with the September 9, 1979 Norcia earthquake, whereas, the fault scarp bordering the Castel Santa Maria basin (Fig. 5) was related by Cello et al. (1998a) to the 14 January 1703 event. The north–south trending segment of the Castel Santa Maria fault shows a net horizontal offset of about 25 m as inferred from the displacement of a minor channel of the Holocene drainage pattern (Blumetti, 1995).

A paleoseismological study of the western basin-bounding fault of the Norcia tectonic depression was carried out at Misciano, where a fresh fault scarp in Holocene colluvial deposits is found. Preliminary results from trench investigations (Cello et al., 1998a) show that here surface faulting and earthquake related liquefaction phenomena represent geological markers of the recent seismic activity. Cumulative vertical displacements of about 1.5 m, recorded in two parallel trenches from partial offsets of a paleosol containing Roman artifacts show that surface ruptures occurred at least twice in this area since Roman times. The above data also show that a 1703-like earthquake is capable of generating coseismic displacements.

After determining the capable faults and recognizing similar geo-structural and geometrical characteristics in the area being concerned, a segmentation model is proposed, which is based on the fact that the surface capable faults activating during a single seismic event are, on the whole, the superficial expression of a single deep seismogenic structure. On the grounds of the specific features of the investigated area, we may assess the geometry, kinematics, slip-rate and size of the deep seismogenic structure (see Fig. 6).

As far as the Norcia seismic area is concerned, assuming a 35–40 km maximum length, a 12–15 km seismogenic layer depth (Cello et al., 1997) and a 1.0–1.5 m coseismic dislocation (Wells and Coppersmith, 1994), we obtain a $Mo = 2.5 \times 10^{26}$ dyn/cm$^2$ maximum seismic moment, corresponding to a maximum magnitude ranging between $M_w = 6.5$ and $M_w = 7.0$ (Fig. 6).

Based on the geo-structural features as well as on the historical and instrumental seismicity of the area, we may divide the Norcia seismic area into three sub-areas: the Preci sub-area in the north; the S. Scolastica and the Castel S. Maria seismic sub-areas in the south (Fig. 6). The sub-areas represent the surface evidence of traits belonging to the Norcia seismogenic structure, which have repeatedly caused earthquakes in the past, thus determining similar geological, structural and morphostructural features within the wider Norcia area, without causing the whole structure to rupture. The size of these sub-areas, and thus the size of the relevant seismogenic segments, allows one to calculate a similar maximum magnitude for the three sub-areas, i.e., $M_w = 6.0$. The Norcia seismogenic structure is therefore capable of causing both strong earthquakes, whose magnitude are within the 6.5–7.0 range (similar to the 14 January 1703 earthquake) and $M_w = 6.0$ earthquakes (similar to the 19 September 1979 shock) which only cause the rupture of portions of the seismogenic structure.
2.3. The Fucino seismic zone

The Fucino basin is characterized by a plain at approx. 650 m above sea level, extending over a 160 km² area and surrounded by mountain peaks over 2000 m (Fig. 7). This morphological depression is the result of a geological evolution dating back to the Pliocene; sedimentation of a significant continental sequence within the basin was dependent upon the
interaction of climate changes and tectonic pulses affecting the erosional sedimentary system in the area.

The 13 January 1915 earthquake, one of the strongest seismic events in Italy ($M_w = 6.6$; Ward and Valensise, 1989), caused 30,000 victims within a large area surrounding the Fucino basin. This event generated both deformations on a regional scale and directly perceived surface strains within the basin, as shown in the isoseismal map of Oddone (1915), Fig. 7.
Recent paleoseismologic studies (Michetti et al., 1996; Galadini et al., 1997) discovered several faults responsible for past earthquake events in the Fucino area. Namely, during the 13 January 1915 earthquake, four re-activated faults were found: the Marsicana fault; the S. Benedetto–Gioia dei Marsi fault; the Trasacco fault and the Luco dei Marsi fault (Fig. 7; Galadini et al., 1997).

The segmentation model proposed for the area includes two deep seismogenic structures...
(Fig. 8) joining, at depth, in a single fault zone (Fig. 7). The model predicts that both structures simultaneously contribute to seismic radiation and, on long time scales, to the evolution of the Fucino basin area. Assuming the easternmost structure as having a length of about 20–25 km and the westernmost one as having a 10 km length (Fig. 8), the cumulated maximum magnitude happens to be similar to that of the 13 January 1915 earthquake, i.e., within a 6.5–7.0 magnitude range (Ward and Valensise, 1989).

3. Discussion and conclusions

In this paper it is suggested that the sum of geological effects caused by several earthquakes arising from the same seismogenic structure produces well developed fault patterns which can be recognized and limited areally by means of geological analysis. Based on areal segmentation models, one can determine the length ($L$) and width ($W$) of the area interested by seismic activity. Length is computed along the preferred orientation of the existing surface structures, and width perpendicular to it (Fig. 9). For assessing the maximum expected magnitude one may use $L$, which is in direct ratio with the seismogenic structure length and $W$ which is directly dependent upon the dip of the structure.

This method allows one to determine whether, within a given seismic area, one or several seismogenic structures, can be activated during an earthquake. Consequently, fault terminology as well as the distinction between deep and surface structures also need to be better defined.

Fig. 9. Definitions and geometry of the seismic area.
A fault is considered to be active if it originated and/or activated within the stress field currently affecting a given area. As far as central and southern Apennines are concerned, we may define as active those faults that originated and/or re-activated in the past 700 ky or so (Cello et al., 1997). Among these we must distinguish between surface and deep structures (Fig. 9). Active surface structures (which can be directly observed in the field) are named capable faults (IAEA, 1991; see also below), whereas, deep structures and related features (including fault core, damage zones, and protolith; Caine et al., 1996) represent the seismic source.

On the grounds of the recurrence times of the most significant earthquakes, we may also distinguish capable faults from potentially capable faults. In the Apennines, faults are defined capable if they generated surface faulting during a seismic event in the past 20 ky (post-wurmian). This timescale is, in fact, appropriate for analyzing the behavior of seismogenic faults which have recurrence times, for large earthquakes, in the order of the millenium (Pantosti et al., 1996). Those faults that had generated surface faulting before the last 20 ky, are, however, still responsive to the current stress field, hence they also have the potential of being re-activated.

When applying the areal segmentation method, special attention must be paid to paleoseismologic studies which are commonly used to identify the typical fault in an earthquake event, evaluate maximum throw and slip-rates, and determine the time sequence of seismic events, since one also needs to take into account the possibility that the investigated fault is not necessarily the only one activating during the seismic event being concerned. Moreover, one should not suppose that all seismic events in the given area have always activated the capable fault being investigated. As a consequence, only when the full array of capable faults is available, the use of trenches is helpful in identifying paleo-earthquakes.

In conclusion, as Cello et al. (1997) puts it, the study of earthquake events which occurred in the central Apennines in the past few decades, as well as the study of historical earthquakes, suggest that single-segment rupture models must be used with caution in seismic hazard analysis, and the criteria adopted to characterize the fault segments should be carefully checked and specified, for each area, with regards to the different settings that might occur within a regional seismogenic zone. It is clear, in fact, that segmentation may only rarely apply to individual faults; more often it should refer to large parts of the whole system of active structures characterizing a given setting, hence, it should apply to areas and not to linear features such as individual faults.

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