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CENTRAL ITALY SEISMIC SEQUENCES-INDUCED LANDSLIDING: 1997-1998 UMBRIA-MARCHE AND 2008-2009 L'AQUILA CASES

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ABSTRACT: In Italy, the Central Apennines are characterized by significant seismic activity. In this region, individual earthquakes and prolonged seismic sequences produce considerable ground effects, including landslides. In this work, we attempt a comparison of the distribution, types and abundance of slope failures produced by two recent seismic sequences in central Italy: (i) the September 1997 – April 1998, Umbria-Marche sequence, and (ii) the December 2008 – July 2009 (ongoing), L'Aquila sequence. Preliminary results indicate that significant similarities exist between the mass movements produced by the two earthquake sequences. Both sequences produced chiefly rock falls, topples and minor rock slides. The distribution of the slope failures matches the macroseismic intensity fields. For the L'Aquila earthquake, slope failures are most numerous in the area where surface deformation was largest. For both earthquake sequences, the number of slope failures decreases with increasing distance from the earthquake epicenters. The decay in the number of failures with the distance from the epicenters is approximate by an exponential law.

INTRODUCTION

The Central Apennines of Italy are characterized by significant seismic activity (Amato et al., Ekström et al., 1998) In this region, individual earthquakes and prolonged seismic sequences produce multiple ground and environmental effects, including mass movements of different types (Bozzano et al., 1998; Esposito et al., 2000; Antonini et al., 2002; Guerrieri et al., 2008). In this work, we attempt a preliminary comparison of the distribution, types and abundance of slope failures produced by two recent seismic sequences in central Italy: (i) the September 1997 – April 1998, Umbria-Marche sequence (Esposito et al., 2000; Antonini et al., 2002), and (ii) the December 2008 – July 2009 (ongoing), L'Aquila sequence.

We base our analyses on two catalogues of earthquake induced landslides. For the Umbria-Marche seismic sequence, the catalogue represents a revised (and integrated) version of the individual catalogues originally prepared by Esposito et al. (2000) through field surveys, and by Antonini et al. (2002) through field surveys and the interpretation of stereoscopic aerial photographs taken shortly after the main earthquakes. For the L'Aquila seismic sequence, the catalogue is a compilation of information obtained through field surveys carried out immediately after the main shocks, aided by the interpretation of stereoscopic aerial photographs and monoscopic, very high resolution satellite images taken immediately after the earthquakes. Part of the field work was conducted during specific surveys performed in conjunctions with geologists of the National Department of Civil Protection, aimed at evaluating local conditions of landslide hazard and risk. Based on the available landslide information, we have prepared maps showing the geographical distribution of landslides triggered by the two earthquake sequences (Fig. 1 and Fig. 2). Further, we have investigated the decreasing abundance of the earthquake-induced landslides away from the earthquake epicentres, and from the fault segments where surface faulting was observed (Fig. 3 and Fig. 4). The preliminary results of our analyses indicate significant similarities in the type, abundance, and geographical patterns of the earthquake-induced landslides.

SETTING AND HISTORICAL SEISMICITY

The Central Apennines have a complex structural setting resulting from the superposition of two tectonic phases associated to the formation of the Apennines mountain chain. A compressive phase of Miocene to early Pliocene age produced large, east-verging thrusts with associated anticlines, synclines and transcurrent faults, and was followed by an extensional tectonic phase of Pliocene to Holocene age, which produced chiefly sets of normal faults. The region is seismically active, and has a long history of earthquakes (CPTI, 2004). In the area, seismicity consists of tens to thousands of earthquakes lasting from several weeks to a few years. Particularly destructive earthquakes struck the area in 1349, 1461, 1639, 1703, with an inferred macroseismic intensity (MCS) I = X, or larger (Table 1). Of all the sequences, probably the most devastating one occurred in 1703, when three major earthquakes occurred in a few days along a NNW-SSE alignment, devastating a large area between Norcia, to the N, and L'Aquila, to the S (Blumetti, 1995; Esposito et al., 2000; CPTI, 2004). Examining the temporal and the geographical distribution of the seismic activity in the Central Apennines, it is possible to infer a characteristic seismic style, consisting of multiple re-activation of relatively distant fault segments oriented roughly NNW-SSE. The individual fault segments are all parts of well-known active fault systems in the Umbria-Marche and Lazio-Abruzzi Apennines (ITHACA).

Table 1. Major earthquakes in Central Italy (CPTI, 2004)

Date	*Epicentre*	*I (MCS)*	*Date*	*Epicentre*	*I (MCS)*
1349/09/09	Aquilano	10	1762/10/06	Aquilano	9.5
1352/12/25	Monterchi	9	1781/06/03	Cagliese	10
1389/10/18	Bocca Serriola	9	1789/09/30	Val Tiberina	9
1458/04/26	Città di Castello	9	1799/07/28	Camerino	9.5
1461/11/26	Aquilano	10	1832/01/13	Foligno	8.5
1599/11/05	Cascia	8.5	1859/08/22	Norcia	8.5
1638/10/07	Amatrice	10	1904/02/24	Marsica	9
1703/01/14	Appennino Reatino	11	1915/01/13	Avezzano	11
1703/02/02	Aquilano	10	1917/04/26	Monterchi-Citerna	9.5
1730/05/12	Norcia	9	1979/09/19	Valnerina	8.5
1741/04/24	Fabrianese	9	1997/09/26	Colfiorito	9.5
1747/04/17	Fiuminata	9	2009/04/06	Aquilano	10
1751/07/27	Gualdo Tadino	10			

UMBRIA-MARCHE SEISMIC SEQUENCE OF SEPTEMBER 1997 – APRIL 1998

Earthquake tremors began in the Regions of Umbria and Marche, in the Central Apennines, Italy, on 3 September 1997, with an earthquake of M_W=4.5. On 26 September, at 2:33 a.m. (0.33 UTC) the area was shaken by a severe earthquake of magnitude M_W=5.7 (M_L=5.6). The epicentre was located to the south of the village of Colfiorito. A few hours later, at 11:40 a.m. (9:40 UTC), another earthquake of slightly larger magnitude (M_W=6.0, M_L= 5.8) shook the same area. Vertical accelerations of more than 0.4 g were recorded. The hypocentres of both earthquakes were located at a depth of about 12 kilometres. During the earthquake sequence that began in September 1997 and lasted for several months, hundreds of aftershocks were recorded in an area bounded to the north by the town of Gualdo Tadino and to the south by

Norcia. On 14 October, at 17:23 a.m. (15:23 GMT), the Umbria-Marche Apennines were shaken by an earthquake of similar magnitude (M_W=5.6, M_L= 5.5) with an epicentre located near the village of Forfi. Lastly, on 3 April 1998 an earthquake of magnitude M_W=5.3, M_L= 5.0 was recorded between Gualdo Tadino and Nocera Umbra (Amato et al., 1998; Ekström et al., 1998).

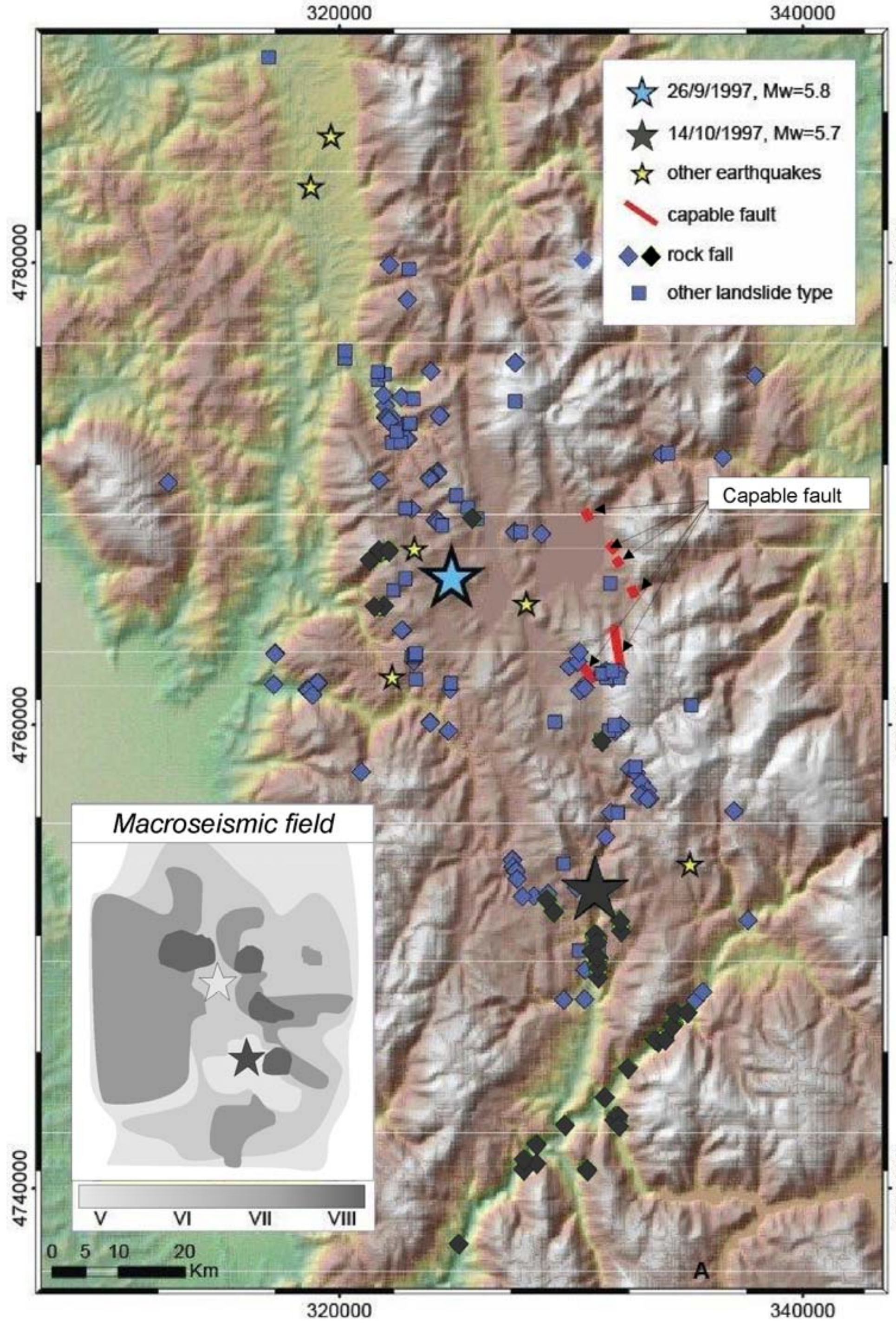

Fig. 1. Map showing the distribution of landslides triggered by the September 1997 – April 1998 earthquake sequence in the Umbria-Marche region, central Italy. Modified after Esposito et al. (2000) and Antonini et al. (2002). Stars indicate the location of the main earthquakes. Diamonds show the location of rock falls, topples, and minor rock slides. Squares indicate the location of other landslide types, including deep-seated slides. The symbol colour matches the colour of the star indicating the epicentre of the earthquake

that caused the mass movements. Red lines show (near-) surface faulting caused by the main earthquakes. Inset portrays a map showing macroseismic field, adopting the ESI intensity scale (Michetti et al, 2007). From Guerrieri et al. (2008).

In the Umbria-Marche region, the sequence of earthquakes killed ten people, left thousands homeless, and caused extensive damage to the towns and villages of the area. Damage to the cultural heritage was extremely large: tens of churches and historical buildings (including the upper basilica of San Francisco in Assisi) were severely damaged. The main shocks and the several hundreds of perceptible aftershocks caused numerous ground fractures and landslides, most of which were rock falls and topples (Fig. 1).

Landslides triggered by seismic shaking in the Umbria-Marche region were mostly rock falls, minor rock slides and rock topples. This is in agreement with what is expected from the energy released by earthquakes of M_L < 6.0 (Keefer, 1984; Rodríguez et al., 1999; Papadopulos et al., 2000). The distribution of rock falls fitted the observed macroseismic intensity pattern (shown in the inset of Fig. 1). Of about 250 mapped rock falls (of all sizes), 50% occurred within a radius of 13 km from the 26 September 1997 epicentres, and within a radius of 17 km of the 14 October 1997 epicentre. Ninety per cent of all rock falls occurred within 28 km of both epicentres, and the majority of the largest failures were located within 25 km.

The earthquakes of 26 September 1997 triggered rock falls, topples and small rockslides ranging in size from a few cubic decimetres to a few tens of cubic metres (for example, at Pale and Bagni di Stravignano). Some of the largest aftershocks also caused such mass movements (e.g., at Bagni di Stravignano). The earthquake of 14 October 1997 triggered tens of failures. Rockfalls and rockslides were particularly abundant near Triponzo, where they threatened a high voltage power line; along the Corno river, where artificial tunnels and defensive elastic fences were destroyed and state road no. 320 was damaged; between Piedipaterno and Triponzo, where elastic fences were destroyed and state road no. 209 was damaged; and along the Vigi Valley near Sellano, where the access road to a dam was blocked and a water channel was severely damaged. Rock falls were also triggered by relatively low-magnitude aftershocks (Antonini et al. 2002).

L'AQUILA SEISMIC SEQUENCE OF DECEMBER 2008 – JULY 2009

Earthquake tremors began in the L'Aquila area, Abruzzo Region, central Italy, on December 2008. On 6 April 2009, at 3:32 a.m. (1:32 UTC), the L'Aquila area was shaken by a severe earthquake of M_W = 6.3 (M_L = 5.8). The epicentre of the earthquake was located WSW of the city of L'Aquila, at a depth of about 8.8 km. On April 7 and April 9, two earthquakes of M_W > 5 occurred in the same general area: the first (M_L = 5.3) was located 11 km SSE of L'Aquila, and the second (M_L = 5.1) 15 km NNW of L'Aquila. In the period April – June 2009, at least 90 earthquakes with M_L > 3.5 and several thousands events of lower magnitude were recorded in the Aterno Valley by the Istituto Nazionale di Geofisica e Vulcanologia.

The sequence of earthquakes caused 299 fatalities, injured more than 1500 people, and left more than 17,000 homeless. Seismic shaking produced severe and widespread damage along the Aterno Valley. The Onna village suffered the highest damage, with a macoseismic intensity, I = X MCS. Damage to the cultural heritage was large, with tens of churches and historical buildings severely damaged. The main shocks and some of the most severe aftershocks triggered landslides, chiefly rock falls and minor rock slides. Some of these landslides caused severe damage to towns (e.g., Fossa, AQ), individual houses (e.g., San Demetrio ne' Vestini, AQ), and the transportation network (e.g., the San Venanzo gorges).

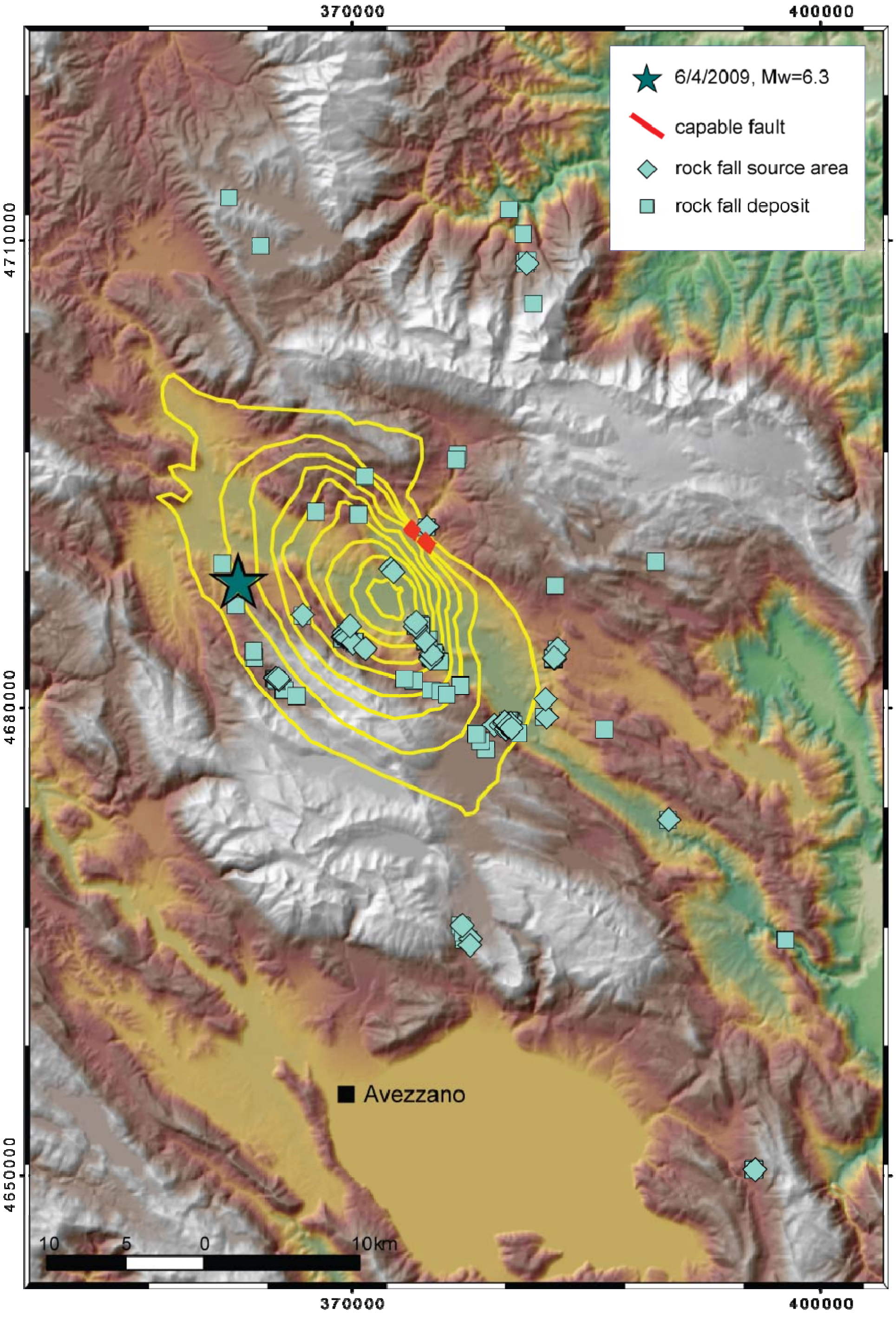

Fig. 2. Map showing the distribution of landslides triggered by the April 2008 earthquake sequence in the Abruzzo region, central Italy. Star indicates the location of the main earthquake, on 6 April 2009. Diamonds show the location of the source areas of individual rock falls, topples, and minor rock slides. Squares indicate the location of rock fall deposits, including single boulders. Red lines show (near-) surface faulting near Paganica. Yellow lines show approximate location of fringes obtained processing two SAR images taken by the ESA ENVISAT satellite on 11/3/2009 and 15/4/2009, i.e., before and after the 6 April 2009 earthquake. Each line corresponds to about 28 mm of displacement along the satellite line-of-sight (LOS). Given the satellite acquisition geometry, the prevailing deformation is vertical. Interferometric analysis performed by CNR IREA using the SBAS-DInSAR technique (http://www.irea.cnr.it)

DISCUSSION

Both seismic sequences, 1997-1998 Umbria-Marche and 2008-2009 L'Aquila, produced primary and secondary effects involving areas of at least 1000 kmq. Some significant analogies have been found as regard the typology, size and distribution of earthquakes-induced geological effect:

- primary effect, consisting in surface faulting phenomena occurred throughout the epicentral areas, along well-known segments of capable fault recognised on the regional structural setting;
- secondary effects, surface fractures were observed in wide areas, identified in the ground as well as artificial works. Widespread but generally minor compaction, liquefaction and hydrological variation phenomena have been recorded. Landslides phenomena were the most numerous among the induced effects and the number of them are quite similar for the two sequences (Bozzano et al.,1998; Esposito et al., 2000; Antonini et al., 2002).

During the 1997-1998 Umbria-Marche sequence, evidence of coseismic surface ruptures were recognized along three main segments of faults: Mt. Le Scalette-La Pintura fault (length of ca 550 m and 2-4 cm of displacement); Cesi-Costa fault (length of ca 1 km and 7-8 cm of displacent) and Dignano-Forcella fault (length of ca 1,8 km and 2-3 cm of displacement), (Guerrieri et al 2009 and references therein).

Slope movements specially rock falls (ca.60%) and rotational slides (35%) were the most frequently observed phenomena. The former interessed prevalently in the epicentral area due to the relatively high vulnerability of the densely fractured limestone and marly limestone. Most of the rock fall occurred along the artificial scarp which border main and secondary roads, consisting of some cubic meters (<10 mc) and only in rare cases involving larger volumes of materials as in the case of Sorifa (thousand of cubic meters) and Stravignano Bagni (hundreds of cubic meters); (Esposito et., 2000; Antonini et al., 2002). Rotational sliding phenomena were observed in recent debris deposits (Pliocene-Olocene) respectively at Afrile (Foligno), Acciano, and Bagnara-Colle Croce. Typical landslide crown, vertical displacement and soil deformation as well as source and deposition areas of debris flows were accurately mapped also on the base of degree of activity, depth of movement and velocity (Antonini et al. 2002). A deep-seted gravitational movements and surface features were observed at Franca and Pian dell'Aia associated to the October 14 shock.

The very dray condition of the late summer season prevented the occurrence of many rotational slides, being most of the area prone to this phenomenon in wet conditions (Guzzetti and Cardinali, 1989). The distribution of the 150 classified landslides, shows that most landslides occurred within a distance of 10 km from the rupture zones; the number of landslide decrease progressively and no landslides were observed beyond 25 km. Such distribution indicates that the area of highest concentration and dimensions of the sliding phenomena well fit the area of maximum macroseismic damage classified as VIII-IX MCS intensity (Gasperini et al., 1997; Esposito et al., 2000).

Surface effects produced by 2008-2009 L'Aquila seismic sequences also consist in coseismic reactivation of segments of capable fault recognised on the regional structural setting and secondary effects consisting in ground fractures, landslides and hydrological change. Of special interest was the reactivation of the Paganica fault resulting also from the field deformation computed by SAR images (CNR IREA, 2009). Along the reactivated capable fault segments, the maximum displacement was about 7-8 cm, with end-to-end lengths of 6 km. Other surface reactivation have been observed along the well studied segment of active fault such as Pettino fault, Bozzano fault and Roio-Canetre fault with displacement ranging from few cm to 20 cm (Blumetti et al., 2009; Boncio et al., 2009; Emergeo WG, 2009) that may reflect the coseismic reactivation of antithetical structures.

Based on field investigation secondary effects have been recognised in a ca.1000 kmq wide roughly elliptical area NW-SE oriented. Slope movement and ground fracture have been the most common type of secondary effects, largely widespread in the whole shaken area.

The most diffuse landslides were rock falls, specially multiple rock falls detached from the calcareous steep slope. Major rock fall took place above the villages of Fossa and Stiffe, wich were directly damaged by huge boulders (max volume in the order of some hundred of metric cubic), other relevant rock fall phenomena have been observed along the Gran Sasso and Mt Bazzano slope, and along the main roads (SS17, SS696, SS5), causing the temporal interruption of the viability. Few other types of slope movement affecting artificial deposits were localised along the SS 80 (Collebrincioni and Bazzano villages). Very impressive open fractures were observed along the shoreline of the Sinizzo Lake.

Central Italy is characterized by widespread seismicity generally felt in wide areas, including Rome and Po-Adriatic foreland. According to the historical research the maximum earthquake intensity reached XI MCS and maximum inferred Magnitude M=7.1 (CPTI 04), occurred in long seismic crises, sometimes preceded by foreshocks. The recurrence in space and time of such earthquakes in terms of earthquake size, location of seismogenic sources and effects on environment provide a valid tool to evaluate the natural hazard. In general way the historical seismic study shows the effect induced by the earthquake both on the manmade structure and effects on the natural environment. The latter include primary effects, tectonic features such as surface faulting, and secondary effects, mostly shaking-induced phenomena, such as ground crack, landslide, liquefaction and hydrological variation. Before the 1997-1998 Umbria-Marche three other similar seismic sequences (1279, 1791,1838) in terms of location and intensity took place, causing severe damage in many district and induced numerous natural phenomena consistent with regional structural setting and the general pattern of macroseismic field. As well as the 2008-2009 L'Aquila sequence, five significant earthquakes (1315, 1349, 1461,1703, 1915) struck the area, with similar geographic and parametric characteristics. Concerning the 1703 event is considered one the most devastating seismic sequence in Italy (I= 10 MCS; M=7.1) that struck a wide area including Umbria, Marche, Abruzzo and Lazio regions. Reactivation of tectonic structures as well as important secondary ground effects were recognised in the whole macroseismic field, illustrating their relevance for the seismic hazard assessment of the area (Blumetti 1995).

A preliminary comparison between the 1997-1998 Umbria-Marche sequence and the 2009 L'Aquila sequence was carried out. Significant analogies can be drawn: in both cases the rock falls were widely prevalent, while minor rockslides were subordinate and strongly dependent on the litology. The areas of sliding phenomena distribution can be also considered comparable being the Umbria-Marche at least 700 km^2, whereas L'Aquila affected area is at least 1000 km^2.

As regards the Umbria-Marche sequence, Fig. 3 shows the density histogram of slope failures (rock falls and other landslides types) from the epicentre of the 26 September 1997 and the 14 October 1997 earthquakes, and from the fault ruptures. The curves describe exponential model decay in the abundance of slope failures far from epicentres and fault segment. It is evident that most of the landslides occurred within a distance of c.a 10 km (60%) from the epicentre, whereas the number of events decreases with distance up to 25 km. The landslide distribution, compared with the cumulative macroseismic field, is in good agreement with the NW-SE elongation, which is a function of the structural elements of the southern Umbria-Marche and northern Lazio-Abruzzi Apennines.

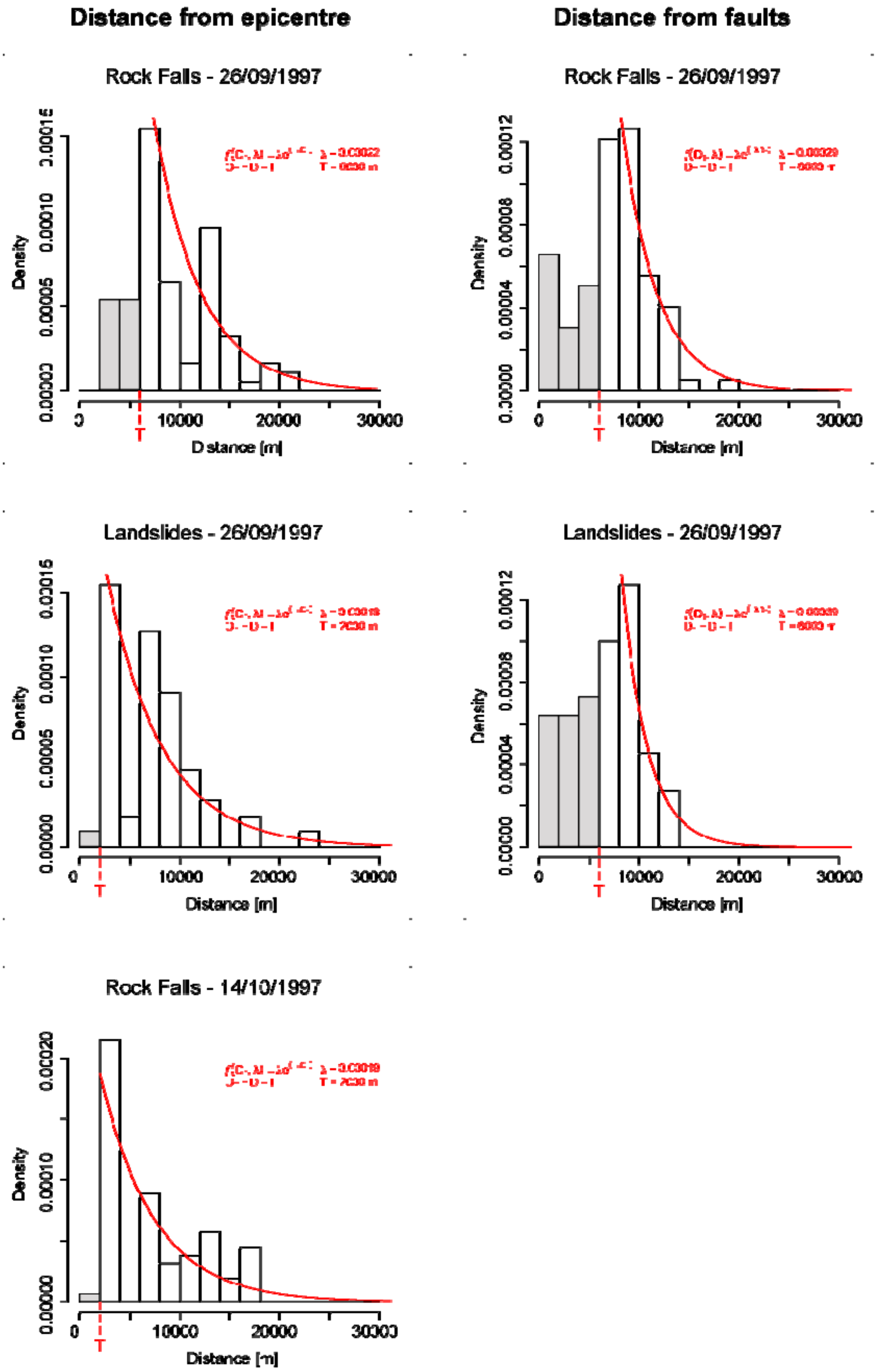

Fig. 3. Umbria-Marche area. Analysis of the distance of slope failures from the earthquake epicentres, and from the main fault line where (near-) ground rupture was observed. Histograms show the density of slope failures (rock falls and other landslide types) from the epicentres (left column) of the 26 September 1997 and the 14 October 1997 earthquakes, and from the fault ruptures (right column) caused by the 26 September 1997 earthquake. Red lines show exponential models to describe the decay in the abundance of slope failures away from the earthquake epicentres and the fault lines. Exponential models were obtained for the sections of the histograms shown by white bars.

The Abruzzo sequence in Figure 4 shows the density histograms of rock fall source areas from the epicentres, and from the fault ruptures observed after the 6 April 2009 earthquake. Curves show exponential models to describe the decay in the abundance of slope failures away from the earthquake epicentres and the fault lines. Also in this case a significant reduction of landslide density is observed for increasing distance both from epicentre and fault segment respectively at 25 and 20 km.

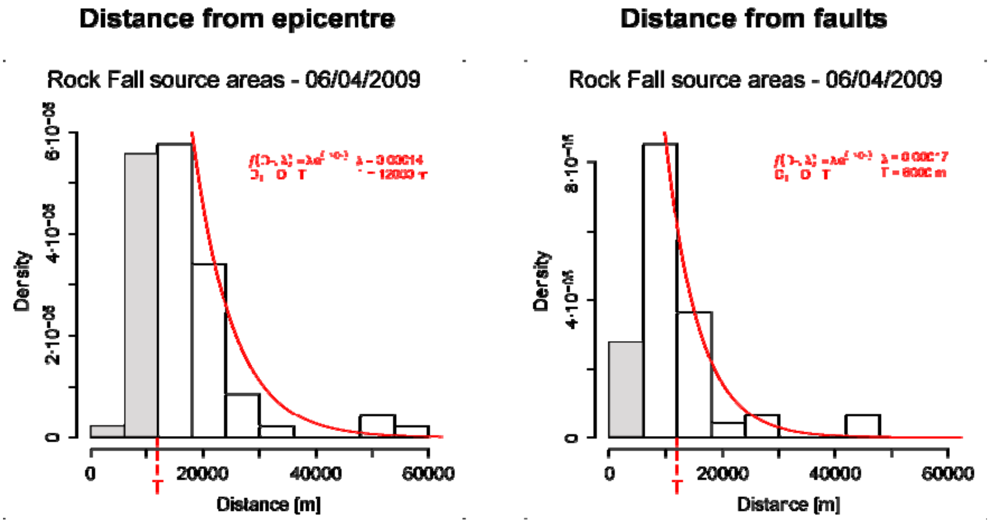

Fig. 4. Abruzzo Region. Analysis of the distance of rock falls from the epicentre of the 6 April 2009 earthquake (left), and from the main fault line where (near-) ground rupture was observed following the 6 April 2009 earthquake (right). Histograms show the density of rock fall source areas from the epicentres, and from the fault ruptures caused by the 6 April 2099 earthquake. Red lines show exponential models to describe the decay in the abundance of slope failures away from the earthquake epicentres and the fault lines. Exponential models were obtained for the sections of the histograms shown by white bars.

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