1.2 Historical earthquakes and seismic hazard of the L'Aquila area

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1.2.1 Introduction

Several strong or devastating earthquakes occurred in the past in the L'Aquila area (see paragraph 1.2.2). The city of L'Aquila shows a remarkable seismic history (Fig. 1), which tells about familiarity with earthquake damage; the most severe occurred on February 2, 1703, three weeks after the event of January 14, which caused destruction in the Norcia zone and damage in the L'Aquila area too. Figure 1 shows also the seismic history of Onna, Castelnuovo and Sulmona.

The municipality of L'Aquila was assessed as "seismic" since the Fucino earthquake of 1915. In 1927 the seismic zones were introduced and the L'Aquila area, likewise most municipalities of the region, was assigned to the 2nd one. Ten more municipalities of the Province were added after 1962, 4 of them after the 1958 earthquake. In 2003 the Prime Minister "Ordinanza" (OPCM) 3274/2003 updated the Italian seismic zoning for the building code: 6 municipalities (Barete, Cagnano Amiterno, Capitignano, Montereale, Pizzoli, Tornimparte) were assigned to the zone 1, while the remaining ones of the whole Province of L'Aquila were confirmed in zone 2.

In April 2004 the Istituto Nazionale di Geofisica e Vulcanologia (INGV) released a PSHA of Italy (MPS04; http://zonesismiche.mi.ingv.it), elaborated following the criteria proposed by the "Ordinanza" OPCM 3274/2003. According to that study, the whole area struck by the April 6 earthquake, including the L'Aquila municipality, belongs to the seismogenic zone 923 and lays inside one of the highest-hazard bands in Italy, characterized by expected Peak Ground Acceleration (PGA) values with 10% probability of exceedance in 50 years slightly higher than 0.25g (Fig. 2).

Further seismic hazard parameters were released by the INGV-DPC 2004-2006 project "S1 - Continuation of assistance to DPC for improving and using the seismic hazard map compiled according to the "Ordinanza" OPCM 3274/2003 and planning future initiatives" (http://esse1.mi.ingv.it).

In the following the historical seismicity of the area is shortly described. Then, the input elements used to perform the MPS04 seismic hazard assessment are recalled and analyzed, with reference to the L'Aquila area. In particular, we

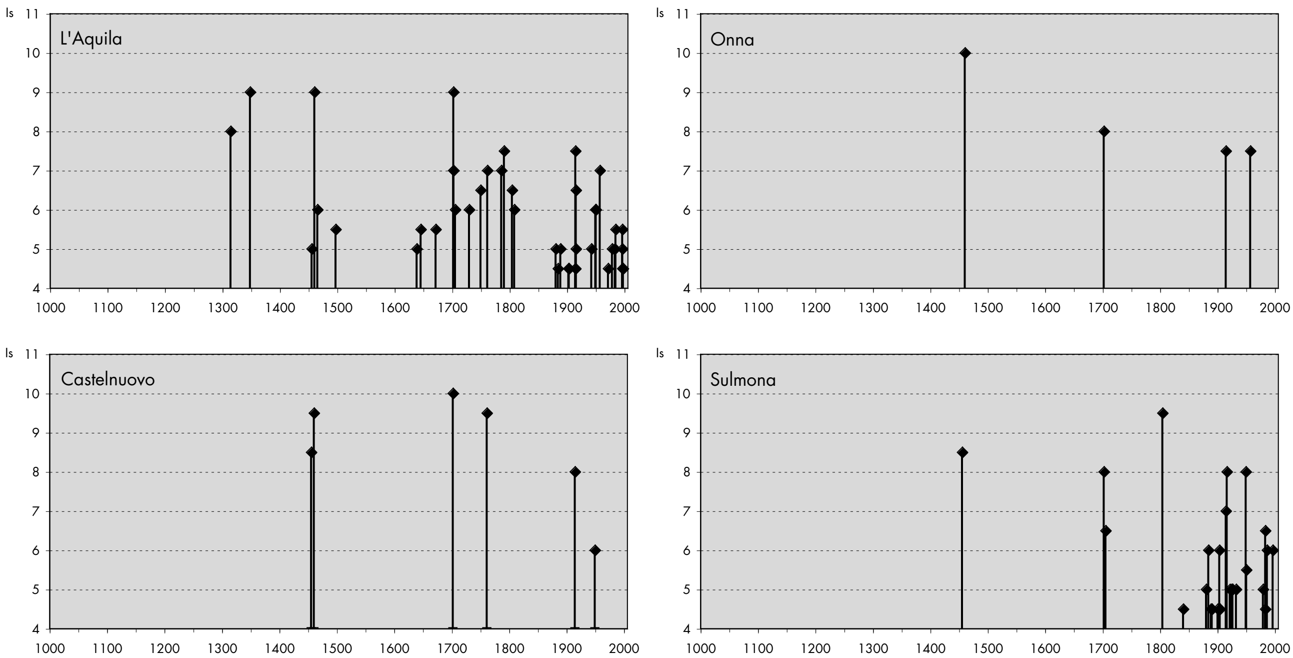

Fig. 1
Seismic history of L'Aquila, Onna, Castelnuovo and Sulmona
(from Stucchi et al., 2007).

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show that the April 6, 2009 earthquake falls within the seismogenic framework adopted for that hazard study. Finally, the chronology of the seismic zoning in Italy is analyzed; it is also shown that the design spectra provided by the present building code (NTC 2008), based on the results of the INGV-DPC 2004-2006 project S1, are similar to those expected by the OPCM 3274/2003 (in force up to June 2009) for seismic zone 2.

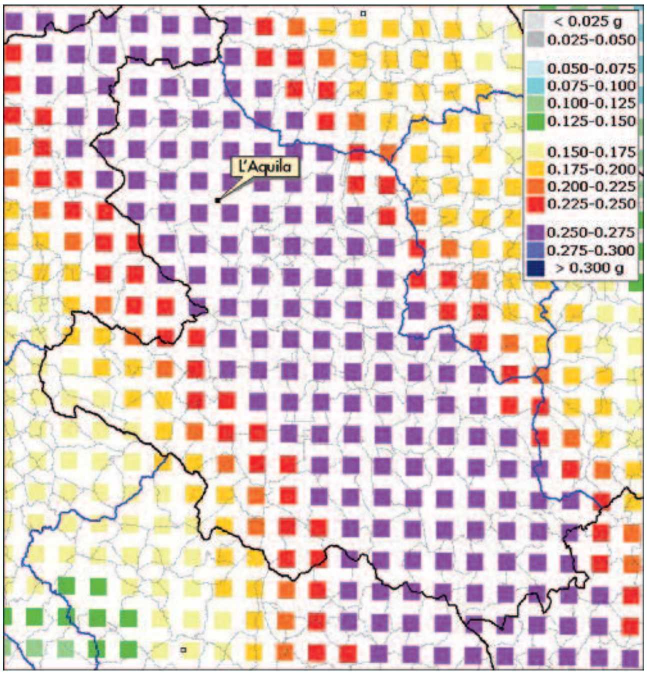

Fig. 2
PGA values with 10% probability of exceedance in 50 years in the L'Aquila Province (MPS Working Group, 2004).

1.2.2 Historical earthquakes and macroseismic parameters of the 2009 event

As stated above, several earthquakes occurred in the L'Aquila area; the seismic history of the city (Fig. 1) is one of the most remarkable ones in Italy since 1300. L'Aquila was heavily damaged (MCS intensity 8 or 9) due to the events of 1315, 1349, 1461 and 1703. Afterwards it suffered lower damage, although quite frequently.

Little is known about the 1315 earthquake, though historical sources report damage to castles in the L'Aquila area. The 1349 earthquake is quite complex; sometimes it is interpreted as a multiple event, produced by simultaneous activation of several seismogenic sources. The 1461 earthquake can be considered a potential "twin" of the April 6 one: in fact, similarly to that event, destructions are reported from Onna, Poggio Picenze, Castelnuovo and L'Aquila. It has to be noted that few years before, the great 1456 earthquake, sometimes interpreted as the result of several simultaneous events too, caused damage up to Navelli and Castelnuovo. If this information is correct, one should consider that the 1461 event struck a zone where buildings had already been weakened; thus, the actual earthquake size might be partly overestimated.

The best documented earthquake occurred in 1703. After being hit, although not heavily (I = 7 MCS), by the strong event of January 14 which destroyed the Norcia area and was felt (with some damage) in Rome, the city of L'Aquila suffered severe destruction from another strong event on February 2. In this case too, the effects of the second earthquake overlapped those of the first event; therefore, documentary sources do not allow to reasonably discriminate between the effects of the two events. However, notwithstanding a possible overestimation of the effects caused by the earthquake of February 2, this was certainly a very strong event felt at large distance (close to the damage threshold in Rome).

These two earthquakes were then followed by another in 1706, which struck the Sulmona/Maiella area, already partly damaged in 1703, and increased the damage (not yet completely repaired) in the L'Aquila area. In 1762 a poorly documented earthquake occurred; it could be located in the same zone of the 2009 event, as it produced severe damage at Castelnuovo and Poggio Picenze and light damage at L'Aquila.

Strong earthquakes did not occurred in the XIX century. In the last century the study area was

significantly struck by the 1915 Fucino earthquake; later, by the sequence of events in 1950 and 1951, located in the Gran Sasso area, and in 1958, located in the area of Onna and Bazzano but characterized by moderate magnitude (5.2) and maximum intensities 7-8 MCS.
The tectonic setting responsible for the seismogenic potential of the area is analyzed in this volume by Galadini et al. In figure 3 the epicentres of the earthquakes described above are shown along with main active faults.
In figure 4 the intensity datapoints with I ≥ 8 MCS of the largest earthquakes are displayed, to outline the areas of heaviest damage. This representation, together with figure 3, may suggest that some segments of the active faults are not associated with any historical earthquake.

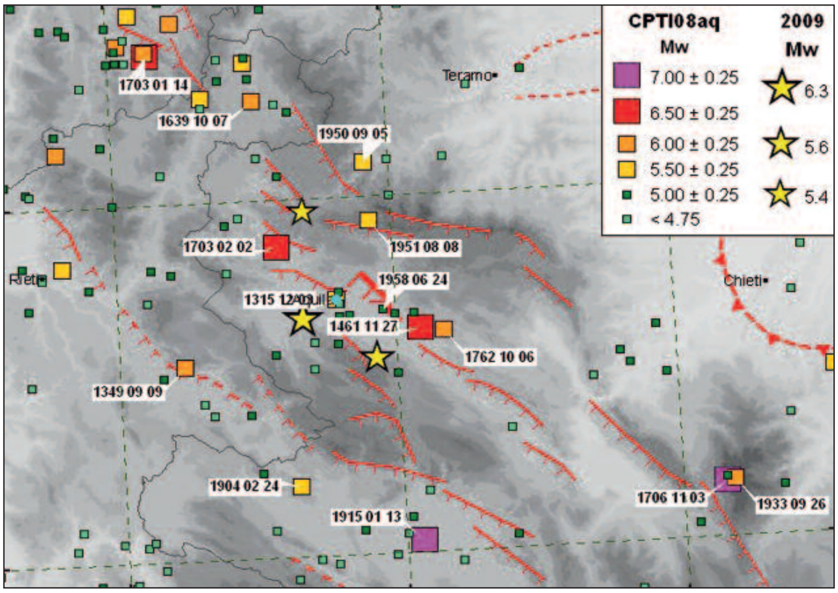

Fig. 3
Seismicity of the L'Aquila area from CPTI08aq (Rovida et al., 2009) and main active faults (from Galadini and Galli, 2000; Boncio et al., 2004; Galadini and Messina, 2004).

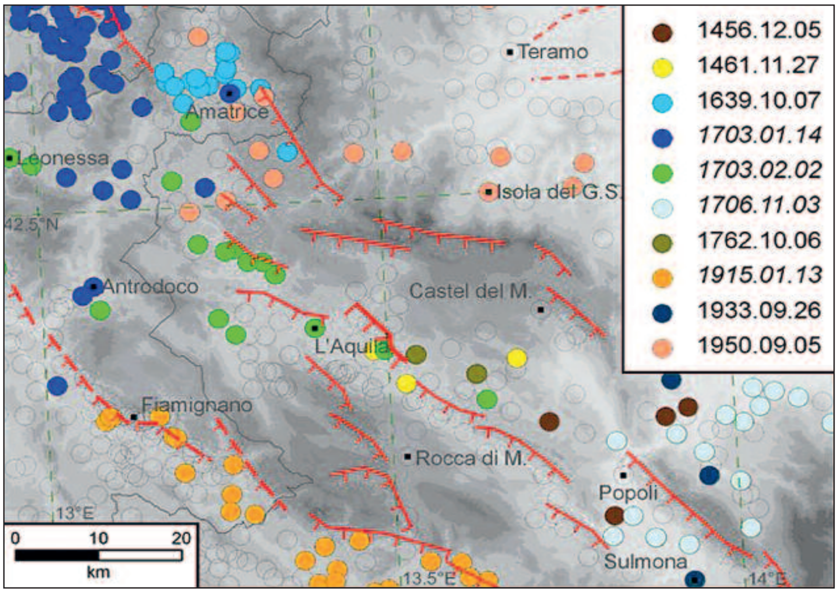

Fig. 4
Intensities ≥ 8 MCS (≥ 9 for earthquakes in 1703, 1706 and 1915) felt in the L'Aquila area since 1400 and location of main active faults (from Galadini and Galli, 2000; Boncio et al., 2004; Galadini and Messina, 2004).

As regards to the 2009 event (Fig. 5), the Mw value computed from the "final" distribution of 316 macroseismic datapoints (Galli and Camassi, 2009) through the Boxer method (Gasperini et al., 1999) is 5.96 ± 0.10. Previously, a similar value of Mw was obtained using a preliminary damage survey in the first week after the event; this shows that, unlike other events, the subsequent aftershocks did not significantly contributed to the overall damage.
The value of Mw = 6.0 is lower than the instrumental estimate (6.3); it corresponds to a seismogenic box length of 12.6 ± 1.6 km, in good agreement with the geological estimate (see

Galadini et al., this volume). The azimuth of the seismogenic box (N124° ± 17°) is also consistent with the strike of the source determined from instrumental, geological and geodetic data.
The location of the macroseismic epicentre has been also assessed by the Boxer method, which uses the six datapoints of higher intensity (I = 9-10 MCS, Onna and Castelnuovo; I = 9 MCS, San Gregorio, Sant'Eusanio Forconese, Tempera and Villa Sant'Angelo). As shown in figure 5, the macroseismic epicentre, which lies in the central part of the area of maximum damage, is significantly far away (about 11 km) from the instrumental one of the April 6 event. The reasons for such a discrepancy do not seem ascribed to local conditions of the most damaged localities. Indeed, the only intensity value which looks anomalous with respect to the context is the one of Castelnuovo, which has often suffered damage higher than surrounding localities in the past (see Fig. 1). If the intensity datapoint at Castelnuovo is removed, the epicentre represented with a black triangle in figure 5 is obtained. Altogether the epicentre computed by Boxer appears robust; the main reason for the discrepancy between the macroseismic and the instrumental epicentre should be found in the directivity of the rupture process, also suggested by Messina et al. (2009).
This well-documented case helps to further assess the value of the parameters of historical earthquakes and the caution to be used when dealing

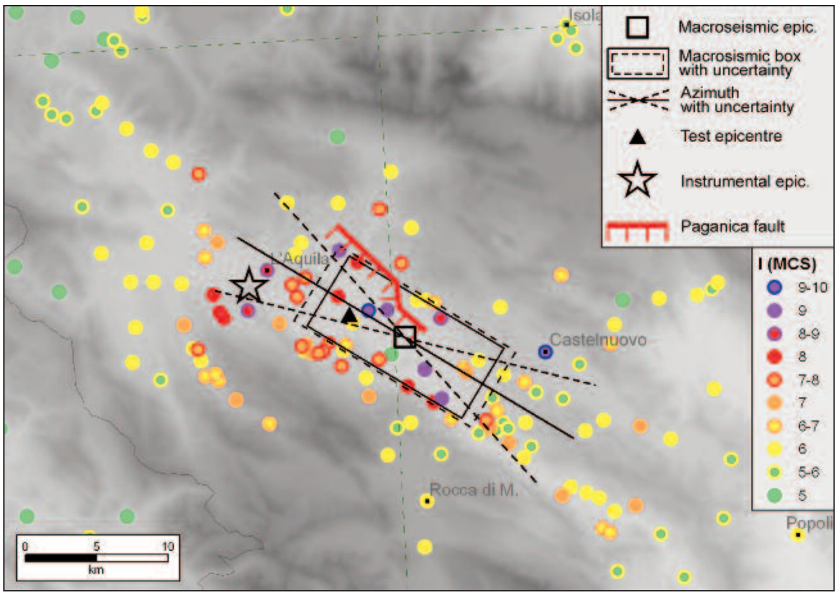

Fig. 5
Intensity distribution and macroseismic parameters of the April 6, 2009 earthquake. The box and relevant azimuth are displayed along with associated uncertainty. Black triangle corresponds to the epicentre determined discarding the intensity datum at Castelnuovo.

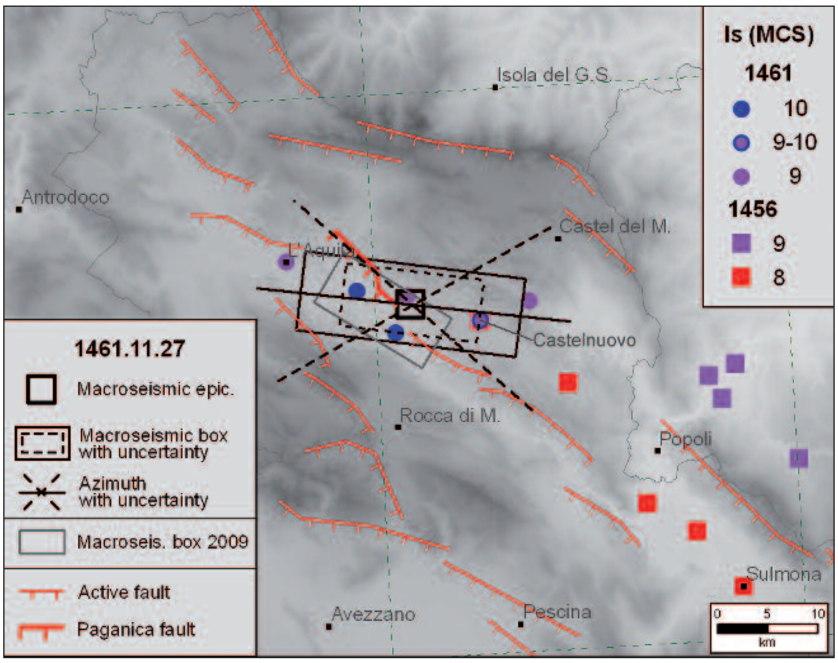

Fig. 6
Intensity distribution of November 27, 1461 (circles) and December 5, 1456 (squares) earthquakes. Macroseismic parameters and relevant uncertainties of the 1461 event are also shown, together with the macroseismic box computed for the April 6, 2009 earthquake and active faults of the area.

with them. As an example the macroseismic estimate of the 1461 event, possible "twin" of the April 6 one, is Mw 6.41 ± 0.34 (Rovida et al., 2009), corresponding to a seismogenic box length of about 22 km. However, in the hypothesis that the Mw value is overestimated (see discussion above), this length could be reduced to 14 km (Fig. 6). Moreover, the relevant azimuth is N100° ± 35.1 and the epicentre is quite similar to that of the 2009 event. The damage distribution could be associated in principle either to an epicentre and rupture process like those of the 2009 event or to the rupture of a fault segment located south of the one responsible of it. In the absence of instrumental data, it is not possible to decide between the two options.

1.2.3 The seismic hazard according to MPS04

The April 6, 2009 earthquake occurred inside the source zone ZS 923 of the ZS9 seismogenic model (Meletti et al. 2008) adopted for the MPS04 seismic hazard assessment of Italy (MPS Working Group, 2004).

The whole belt from Lunigiana to the Abruzzo-Molise boundary (Fig. 7) corresponds to the most internal sector of the Apenninic chain, characterized by important active faults and associated seismogenic sources. In the area from central Umbria to Abruzzo, these faults dip towards SW (Galadini et al., 2001; Valensise and Pantosti, 2001). ZS9 partitioned this long band in three source zones (915, 919 and 923) including the sources of the largest earthquakes occurred in northern and central Apennines. These have generally surficial expression that allows the characterization and assessment of the relevant kinematic parameters through conventional geomorphological and paleoseismological approaches. The subdivision of this belt in three zones was mainly suggested by seismological data. The southernmost source zone (923, to the south of the 1997 Colfiorito earthquake area) is characterized by the longest faults and the largest earthquakes. The 1654 Sora event, whose seismogenic source has not yet been identified by geological investigations, falls inside this source zone, too.

According to Meletti et al. (2008), the main characteristics of the 923 source zone are:

a) average depth: in the range of 8-12 km, derived from instrumental data and consistent with geological information;
b) prevailing faulting mechanism of the main earthquakes: normal type, consistent with the reference seismotectonic model (Meletti et al., 2008);
c) expected Mmax: 7.00, according to seismological estimates from CPTI04, with return period of about 700 years; 6.7 according to tectonic considerations from DISS 2.0 (Valensise and Pantosti, 2001);
d) b-value of the G-R relation equal to 1.05.

The data of the April 6, 2009 earthquake (http://portale.ingv.it/primo-piano/archivio-primo-piano/notizie-2009/terremoto-6-aprile/localizzazzione-del-terremoto-del-6-aprile-aggiornata) are in good agreement with the

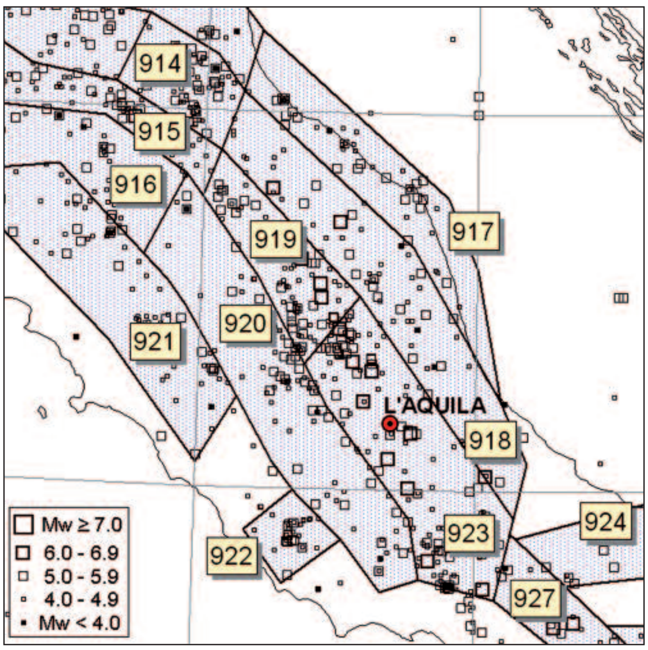

Fig. 7
Seismic source zones of Central Apennines (Meletti et al., 2008).

above characteristics. In particular, with reference to points a) and b), the estimated hypocentral depth is 9.5 km and the faulting mechanism is normal (http://portale.ingv.it/primo-piano/archivio-primo-piano/notizie-2009/terremoto-6-aprile/meccanismi-focali).

As for the earthquake occurrence frequency, MPS04 considers that completeness of the CPTI04 catalogue for ZS 923 above Mw 6.3 starts from 1300. The seismic history of ZS 923 is shown in figure 8. The seismicity rates used by MPS04 are shown in figure 9.

From 1300 to 2002 (end of the CPTI04 catalogue) 11 earthquakes with magnitude higher or equal to 6 occurred: the largest one is the event of January 13, 1915 (Mw 6.99); three of these earthquakes occurred in a short time/space interval (the two events in 1703 and the one in 1706). The seismicity rate for earthquakes with M ≥ 6 results 1.49 in 100 years, which corresponds to an average inter-event time of about 67 years. Thus, the April 6 earthquake seems perfectly consistent with the seismicity features of this area.

A "sanity check" has been performed to evaluate the influence of seismicity rates on the seismic hazard of the area, adding the April 6 event to the rates of the source zone 923. The results of this test show that the peak acceleration expected in L'Aquila with 10% probability of exceedance in 50 years increases of little more than 1%, much below the uncertainty of the MPS04 estimate, defined as the difference between median value and 16th or 84th percentile, which is about 9%.

Moreover, due to the April 6 earthquake, the CPTI working group sped up the publication of a new release of the catalogue (called CPTI08aq) limited to Central Italy and extended up to 2006 (Rovida et al., 2009).

Figure 10 shows the seismicity rates derived from this new catalogue, which contains 12 events of Mw ≥ 6.0 in the zone 923 starting from 1300 (Fig. 11). Considering the completeness time-intervals of the catalogue, one obtains a rate of 1.12 Mw ≥ 6 events in 100 years, corresponding to a return period of 89 years. Therefore, the rates of M ≥ 6.0 earthquakes do not substantially change with respect to the previous assessment.

No important change affects the seismic hazard estimates as well: actually, if the rates shown in figure 10 are used, the peak acceleration expected in L'Aquila decreases with respect to MPS04 of 2.5% and less than 1%, for the expected acceleration with a probability of exceedance respectively equal to 10% and 2% in 50 years.

As described in MPS Working Group (2004), the MPS04 hazard estimates were computed following a logic-tree approach, to take into account alternative options of the input elements. Many combinations of several options are explored by the logic tree: two options were considered for the definition of the completeness intervals of the earthquake catalogue, two options for the assessment of seismicity rates, four options for ground-motion attenuation models. One hazard estimate is computed for each branch; the final value of hazard is given by the weighted median value (50th percentile), while the 16th and 84th percentile values provide an

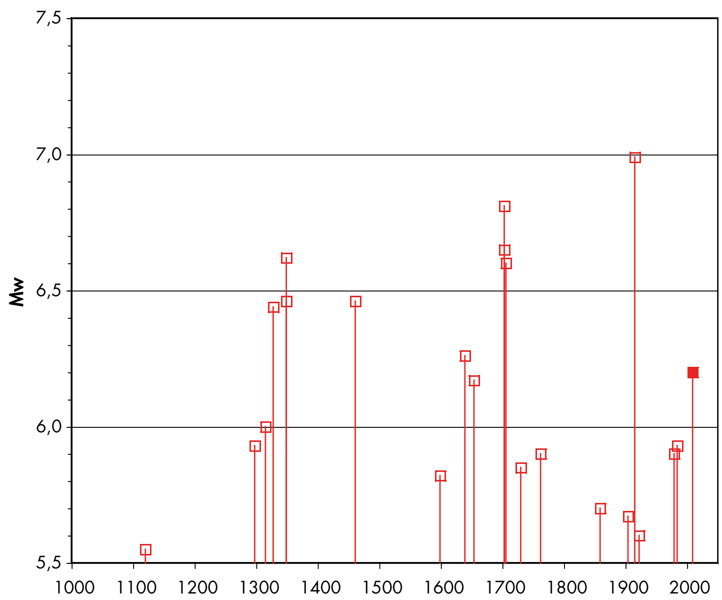

Fig. 8
Earthquakes distribution inside the source zone ZS923 according to the CPTI04 catalogue (CPTI Working Group, 2004). The last event is the one of April 6, 2009.

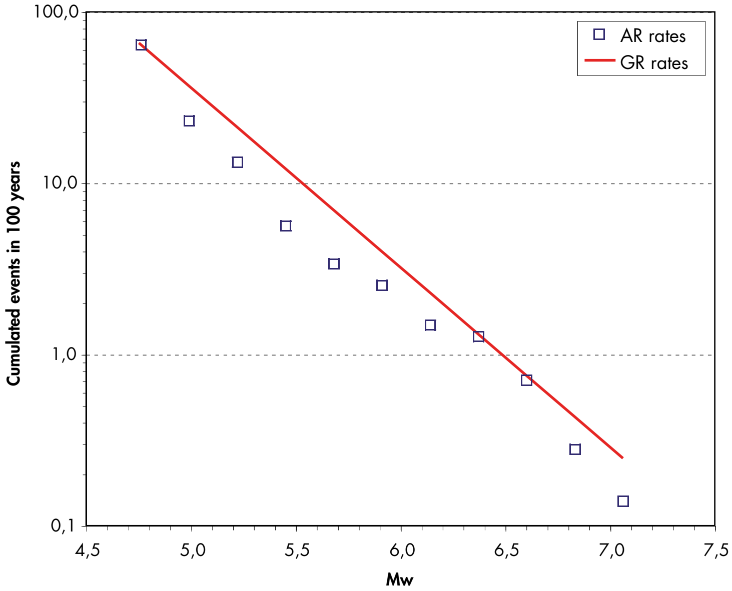

Fig. 9
Seismicity rates used in MPS04 for ZS923 (MPS Working Group, 2004). AR values (Activity Rates) are computed for each magnitude class separately; GR values are computed according to the Gutenberg and Richter (1944) distribution.

estimate of the uncertainty.

After the April 6 event, much the attention of the international scientific community focused on ground-motion attenuation models, which appears to be critical. In fact, whereas the earthquake characteristics do not seem to impact on the MPS04 hazard estimates, this event supplied strong-motion recordings in the very near field, i.e. at distances where few data are available and attenuation relationships are usually extrapolated; this could play a crucial role for future hazard evaluations (about this aspect, see Crowley et al. and Pacor et al., this volume).

The next figures present additional seismic hazard parameters for this area, particularly for the city of L'Aquila, computed in the framework of the INGV-DPC project S1 (http://esse1.mi.ingv.it).

Figure 12 shows the disaggregation of the PGA value expected in L'Aquila with 10% probability of exceedance in 50 years (475-year return period). The graph displays the contribution of all possible seismogenic sources to the seismic hazard of a given site: the sources are discretised for bins of epicentral distance and magnitude. It results that the highest contribution in percentage to the hazard is given by sources within 10 km of L'Aquila with Mw in the range 4.5 - 6.5; actually, about 75% of the hazard derives from seismogenic sources close to the city, like the causative one of the April 6 earthquake.

Figure 13 shows the uniform hazard spectra computed at L'Aquila for several probabilities of exceedance in 50 years.

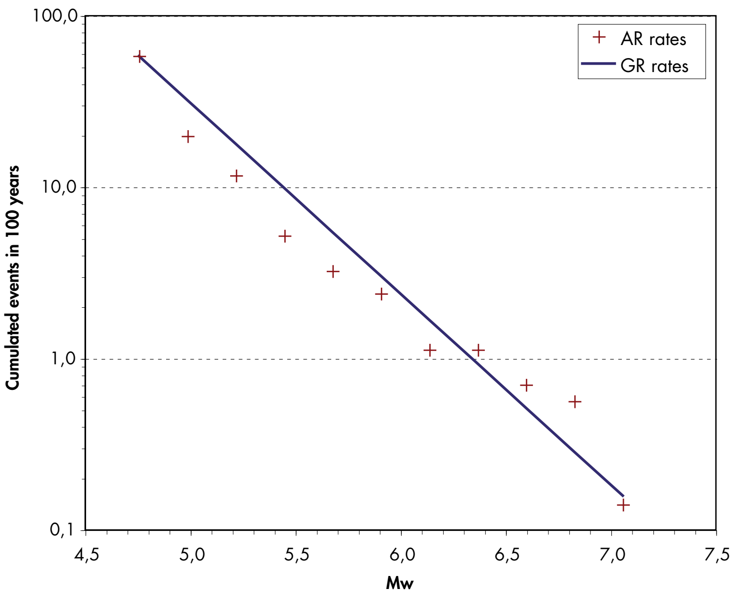

Fig. 10
Seismicity rates for ZS923 computed using the CPTI08aq catalogue (Rovida et al., 2009). AR values (Activity Rates) are computed for each magnitude class separately; GR values are computed according to the Gutenberg and Richter (1944) distribution.

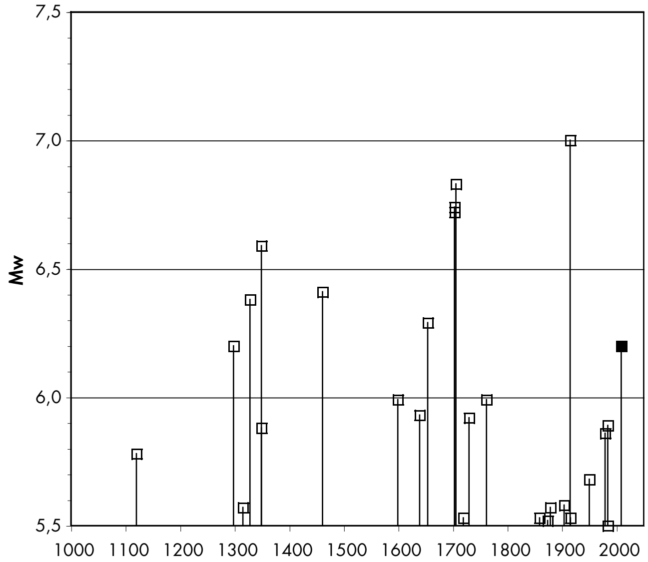

Fig. 11
Earthquakes distribution in the source zone ZS923 according to the CPTI08aq catalogue (Rovida et al., 2009).

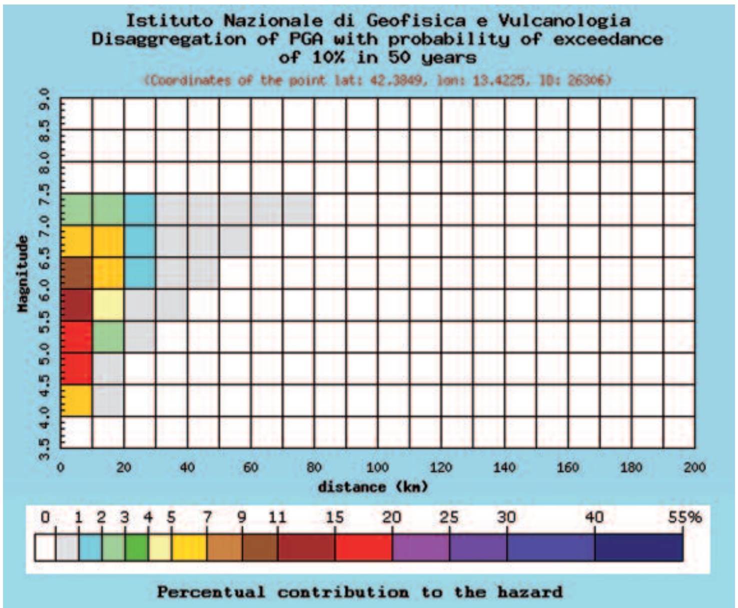

Fig. 12
Disaggregation of the hazard estimate with 10% exceedance probability in 50 years (http://esse1.mi.ingv.it). In percentage, contribution of the seismogenic sources around L'Aquila to the expected PGA value.

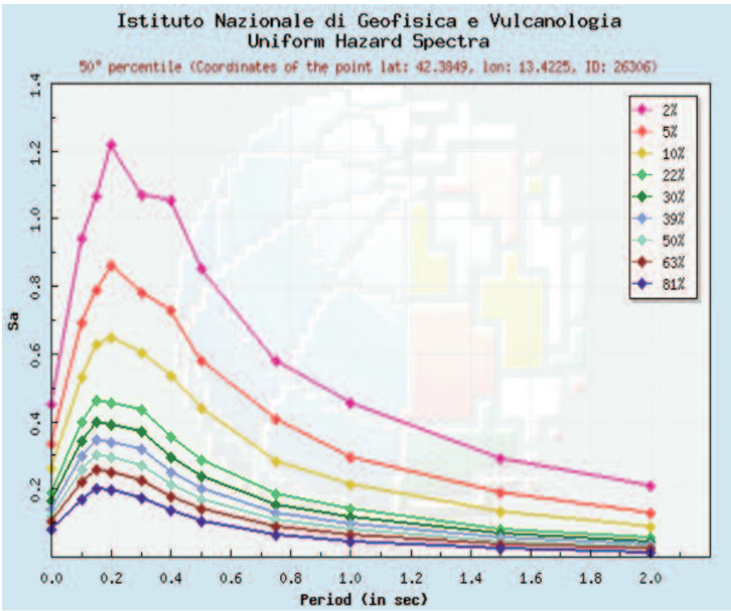

Fig. 13
Uniform hazard spectra of the city of L'Aquila for several probabilities of exceedance in 50 years (http://esse1.mi.ingv.it). These data were used to define the reference design spectra of the new building code (NTC, 2008) come into force on July 1, 2009 (see next paragraph).

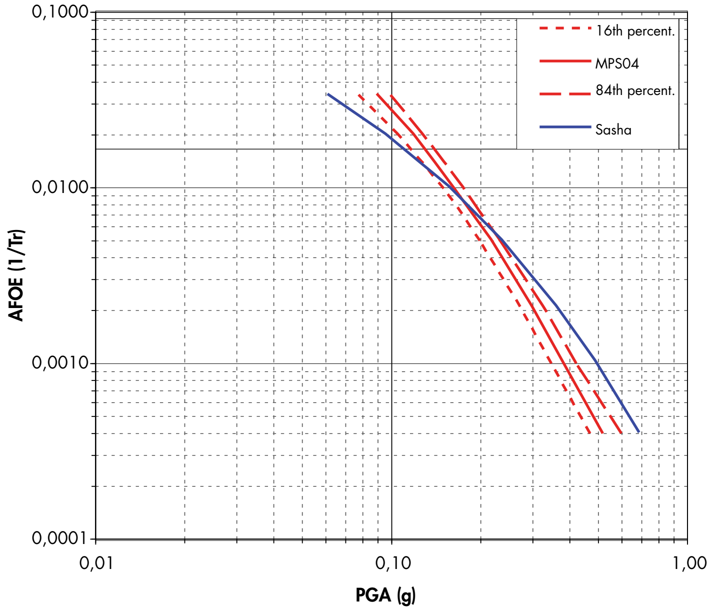

Fig. 14
Hazard curves for a site close to L'Aquila city re-determined for soil type B compared with the curve derived with the SASHA approach (D'Amico and Albarello, 2008).

Figure 14 presents the hazard curve, that is the expected PGA values computed for different return periods (displayed through the inverse, i.e. the annual frequency of exceedance – AFOE), for the node of the computation grid closest to L'Aquila. For long return periods (low probability of occurrence) the expected PGA reaches 0.5 g. The 16th and 84th percentile curves represent the uncertainty of the estimate. The hazard curves of the INGV-DPC project S1 (http://esse1.mi.ingv.it) refer to soil type A, as defined in NTC (2008); thus we applied to these curves the coefficient provided by NTC (2008) for soil-type B sites, as L'Aquila seems to be on the basis of the investigation at the accelerometric station closest to the city centre.
As a "sanity check", these estimates have been compared with those derived from intensity data through an alternative methodology ("site" approach) developed by Albarello and Mucciarelli (2002), recently implemented by D'Amico and Albarello (2008) in the SASHA computer program. This approach computes the hazard of a site trough the analysis of its seismic history, without considering any source zones model. For each site, the seismic history is built using intensity datapoints or, in their absence, the effects predicted at the site from epicentral parameters through an attenuation relationship. Results are given in terms of exceedance probabilities for each intensity value; these estimates can be then converted in terms of peak acceleration through empirical relations intensity/PGA. Figure 14 also displays the hazard curve derived through the site approach (D'Amico and Albarello, 2008) using intensity data from DBMI04 (Stucchi et al., 2007), and converting from intensity to PGA through the empirical relation by Faccioli and Cauzzi (2006). The two approaches are conceptually different and make use of attenuation relations for different shaking parameters (PGA or intensity). Nevertheless, the estimates provided by the site approach do not substantially diverge from those of MPS04, also considering the large uncertainties involved in the conversion from intensity to PGA. Actually, the differences between the two hazard curves reach a maximum of 15% (11% for 475 year), with the only exception of the estimate for the 30-year return period (difference of 21%); this provides a further, although indirect, "sanity check" for the PGA hazard assessment.

1.2.4 Seismic zones, building code and conclusions

As mentioned in the introduction, the municipality of L'Aquila was assessed as seismic by the building code after the 1915 Fucino earthquake. In 1927 the seismic zones were introduced and the L'Aquila region was assigned to zone 2, like most municipalities of the area. Ten more municipalities of the Province were added after 1962, 4 of these following the 1958 earthquake (Fig. 15).
In 1984 the Italian zoning was re-designed following the proposal by the "Progetto Finalizzato Geodinamica" (CNR-PFG, 1980), compiled following homogeneous criteria after the 1980 Irpinia-Basilicata earthquake. For the L'Aquila region, the foregoing zoning was confirmed: the areas struck by the events in 1915 and 1933

remained in zone 1, the other ones in zone 2 (Fig. 16).

In 2003, the Prime Minister "Ordinanza" (OPCM) 3274/2003 updated the seismic zoning, combining the one of 1984 with the one of the so called "Proposal 1998" (Gruppo di Lavoro, 1999; Fig. 17). It confirmed the previous zoning for the entire Province of L'Aquila, except for 6 municipalities (Barete, Cagnano Amiterno, Capitignano, Montereale, Pizzoli, Tornimparte) which moved to zone 1. The Abruzzo Region (DGR n.438 of 03/29/2003) adopted the decisions of the "Ordinanza" without any change (Fig. 18). According to MPS04, the whole area hit by the April 6 earthquake (municipality of L'Aquila included) lies at the boundary between zone 2 and zone 1, characterized by the highest seismic hazard (Fig. 2); therefore the whole area could in principle be assigned to zone 1.

Recently the new building code (Decree of 01/14/2008 of the Infrastructure Ministry; Official Gazette n.29 of 02/04/2008), effective since July 1, 2009, has introduced a different approach. In fact, the design spectra of the new buildings are determined at each site on the basis of the seismic hazard estimates released by the S1 project (http://esse1.mi.ingv.it). In particular, for any site the elastic response spectrum is built using a set of coefficients derived by interpolation of the hazard values computed at the 4 neighbouring nodes of the computation grid, corrective coefficients are then applied to take into account soil type and topographic conditions.

In figure 19 we compare the design spectra provided for L'Aquila by the previous code for zones 1 and 2 (in force up to June 30, 2009), with the design spectrum according to the new building code (NTC, 2008). As shown, the present spectrum is closer to the spectrum for zone 2 of the "Ordinanza" OPCM 3274/2003, rather than to the one of zone 1.

Summarising, the analyses presented in this paper confirm that the area struck by the April 6, 2009 earthquake was, and still is, a highly

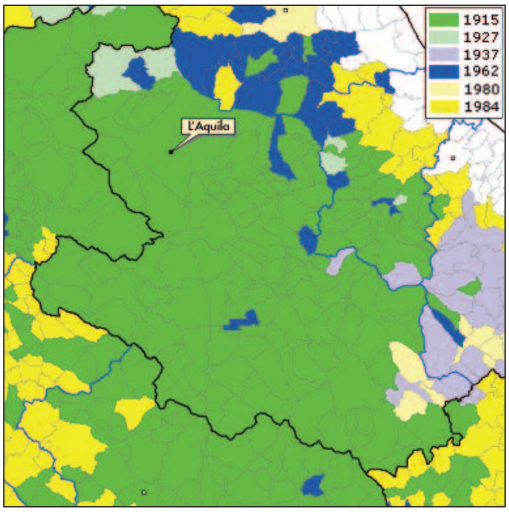

Fig. 15
Year of first assignment to the seismic zoning of the municipalities in the L'Aquila area.

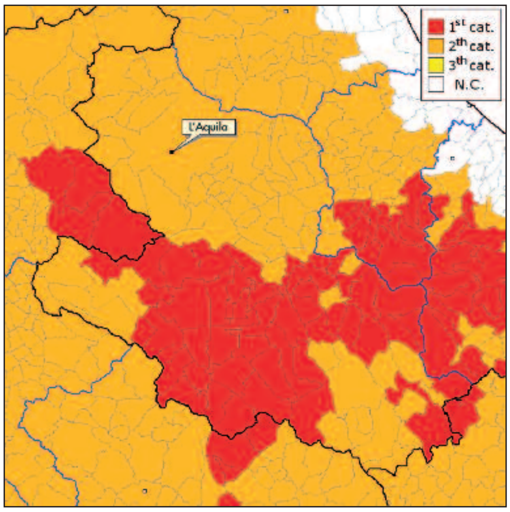

Fig. 16
Seismic zoning in force since 1984.

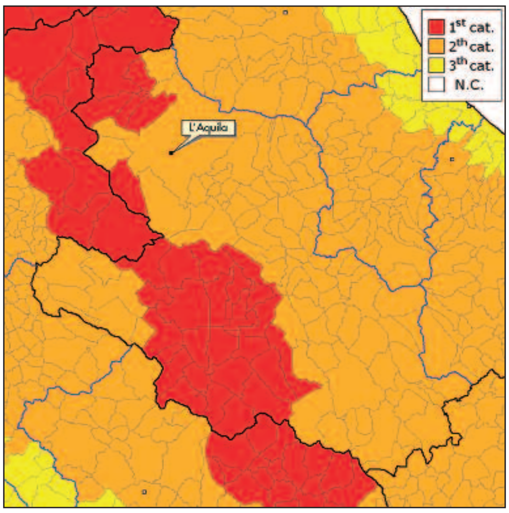

Fig. 17
Proposal of zoning by Gruppo di Lavoro (1999).

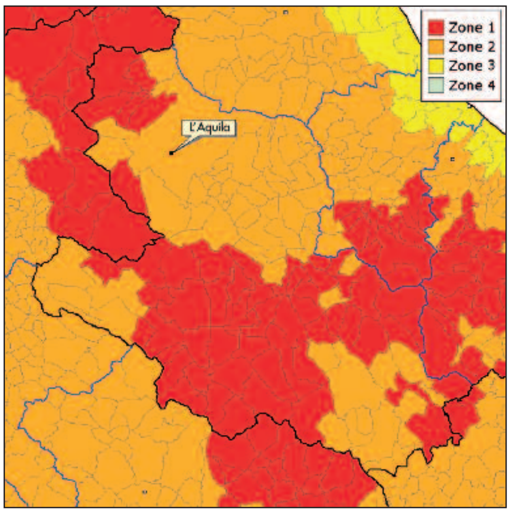

Fig. 18
Seismic zoning updated by the OPCM 3274/2003 and adopted by the Regions.

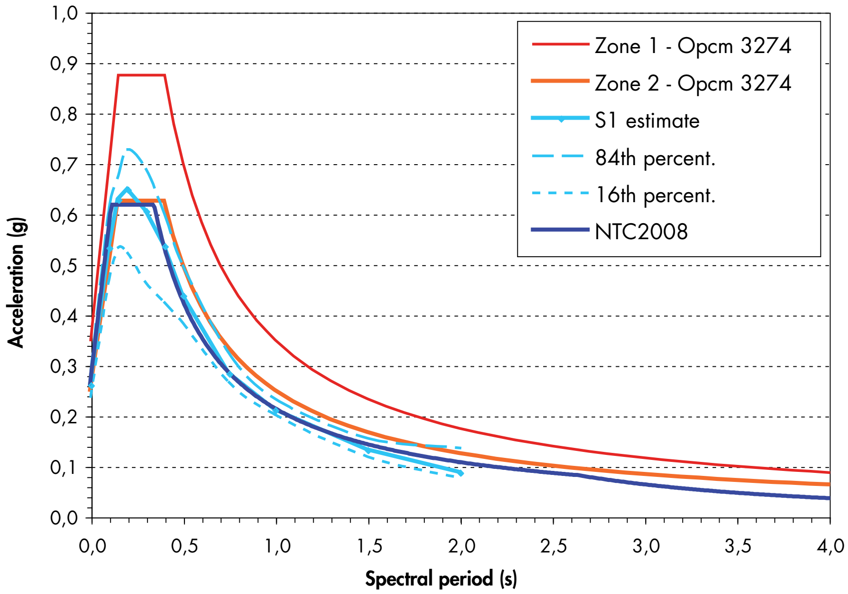

Fig. 19
Comparison among the design spectra provided by the previous building code (OPCM 3274) for zones 1 and 2 and the one expected for L'Aquila according to the new NTC 2008 derived from the hazard estimates of project S1. All spectra refer to soil type A.

seismic area characterized by the highest seismic hazard of the Italian territory. The features of the April 6 event are consistent with the seismogenic characteristics expected by the seismic hazard studies (MPS04 and results of the INGV-DPC project S1) used to update the seismic zoning and to define the design spectra of the new building code (NTC, 2008). The widely raised issue about the non-assignation of the L'Aquila municipality to be assigned to seismic zone 1 appears to be not relevant: in fact, the design spectrum of the present building code (NTC, 2008) does not substantially differ from the one provided by the "Ordinanza" PCM 3274/2003, in force up to June 2009, for zone 2.

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