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ORIGINAL ARTICLE

$\tau_p^{\max}$ magnitude estimation, the case of the April 6, 2009 L'Aquila earthquake

Marco Olivieri

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Abstract Rapid magnitude estimate procedures represent a crucial part of proposed earthquake early warning systems. Most of these estimates are focused on the first part of the P-wave train, the earlier and less destructive part of the ground motion that follows an earthquake. Allen and Kanamori (Science 300:786–789, 2003) proposed to use the predominant period of the P-wave to determine the magnitude of a large earthquake at local distance and Olivieri et al. (Bull Seismol Soc Am 185:74–81, 2008) calibrated a specific relation for the Italian region. The Mw 6.3 earthquake hit Central Italy on April 6, 2009 and the largest aftershocks provide a useful dataset to validate the proposed relation and discuss the risks connected to the extrapolation of magnitude relations with a poor dataset of large earthquake waveforms. A large discrepancy between local magnitude (ML) estimated by means of $\tau_p^{\max}$ evaluation and standard ML (6.8 ± 1.5 vs. 5.9 ± 0.4) suggests using caution when ML vs. $\tau_p^{\max}$ calibrations do not include a relevant dataset of large earthquakes. Effects from large residuals could be mitigated or removed introducing selection rules on τ_p function, by regionalizing the ML vs. $\tau_p^{\max}$ function in the presence of significant tectonic or geological heterogeneity, and using probabilistic and evolutionary methods.

Keywords Earthquake · Magnitude · Earthquake early warning systems

1 Introduction

Mitigation of earthquake damages remains an open task, despite the fact that many solutions have been proposed in the recent past. In this framework, the so-called earthquake early warning systems (EEWS) try to exploit the short time interval between the earthquake occurrence and the arrival of the destructive part of the wave train to warn population or to perform some automatic actions that can reduce damages induced by the ground shaking. Different kinds of EEWS are currently under development or under test in seismically active regions, like Japan (Odaka et al. 2003), California (Wurman et al. 2007), Mexico (Espinosa-Aranda et al. 1995), Taiwan (Wu and Kanamori 2005), and Southern Italy (Iannaccone et al. 2010). Early warning appears to be one of the few possible methods to initiate mitigation actions, despite the risks of false alarms. These risks are mainly connected with rapid estimate of the magnitude of the earthquake and of the corresponding predicted ground motion. Inaccuracy

M. Olivieri (✉)
Istituto Nazionale di Geofisica e Vulcanologia,
Sez. di Bologna, Via Donato Creti 12,
40128 Bologna, Italy
e-mail: marco.olivieri@bo.ingv.it

can stimulate unnecessary mitigation actions that in some case (e.g., evacuating an hospital or shutting down the reactors of a nuclear power plant) can involve risks larger than the earthquake itself.

The size of an earthquake at local or regional distance is commonly represented by means of local magnitude (ML), proportional to the maximum amplitude as recorded by a Wood–Anderson seismometer located 100 km from the epicenter (Richter 1935), and this is the case for ML values used in this work. Despite the fact that modern definitions of the magnitude provide a better or more consistent representation of the size of an earthquake, ML often remains the standard for monitoring activities and for communication with civil protection agencies and media. The estimation of ML requires the complete ground motion or at least the relevant part of the S-wave train to be recorded at a site, but this may take a long time, much too long in the time scale of EEWS. S-waves are slow and destructive, while P-waves are faster but weaker, and different authors have proposed P-wave-based magnitudes (e.g., Nakamura 1988; Tsuboi et al. 1995) to shorten the delay between earthquake occurrence and the time of magnitude estimation. Allen and Kanamori (2003) modified the original idea of Nakamura and introduced the use of the predominant period, whose logarithm scales approximately linearly with the local magnitude. The predominant period is usually measured along the vertical component of broadband seismograms, within the first few seconds after the P-wave arrival time. At short distances from the epicenter (i.e., less than 100 km), the predominant period shows the characteristics of being independent of distance consequently different linear relations for ML as function $\log(\tau_p^{\max})$ have been proposed for different parts of the world as well as for Italy (Olivieri et al. 2008). Some of the proposed relations suffer from the lack of large magnitude event data: broadband stations have a short history and large earthquakes rarely occur. Moreover, some of the regions where EEWS have been proposed are those where large earthquakes have been missing for long time so the lack of data usable for calibration and off-line tests is a serious problem. For the case of Italy, most of the regions where large earthquakes are likely to occur in the near future have been identified (Valensise and Pantosti 2001a, b) even though moderate but destructive earthquakes can occur in the entire country. This lack of data expands the uncertainty for large-magnitude events in terms of capability of the proposed EEWS to correctly determine magnitudes. This is also the main criticism with respect to EEWS implementation, because incorrect estimates of the ground shaking can trigger erroneous actions or, on the contrary, prevent actions in the first seconds following the earthquake and both these behaviors can have social, economic, and also legal drawbacks. For all these reasons, we tested the $\tau_p^{\max}$ magnitude relation from Olivieri et al. (2008) for the case of April 6, 2009 L'Aquila earthquake to validate, on a real case, the proposed relation:

$$\mathrm{ML} = 3.05 \times \log(\tau_p^{\max}) + 4.3 \tag{1}$$

where $\tau_p^{\max}$ is the maximum of the resulting dominant period computed on the time interval [+1,+4] seconds following the P onset of vertical seismogram. This relation was obtained by the regression of 225 observations in the range of magnitude from 2.5 to 6.0, but only three observations were available for magnitude ML>5.5. This could imply a weak constraint of the slope of the retrieved linear relation and, consequently, a low resolution for ML estimate of large earthquakes.

2 The earthquake

On April 6, 2009 at 01:32 GMT, a shallow Mw 6.3 earthquake hit Central Italy (Fig. 1). The epicenter was localized in the vicinity of L'Aquila, a city with almost 75,000 inhabitants that suffered much damage. Destruction involved several other villages in the surroundings. The collapse of buildings caused 308 casualties and more than 1,600 people were injured. The earthquake was widely felt (EMS intensity = 4 and 5) in Central Italy (Sbarra et al. 2010) including the city of Rome (three million people). This was the mainshock of a long sequence of earthquakes that started in late 2008 and it is still ongoing. In the first half of April 2009, about 2,200 earthquakes were instrumentally observed. The two largest aftershocks

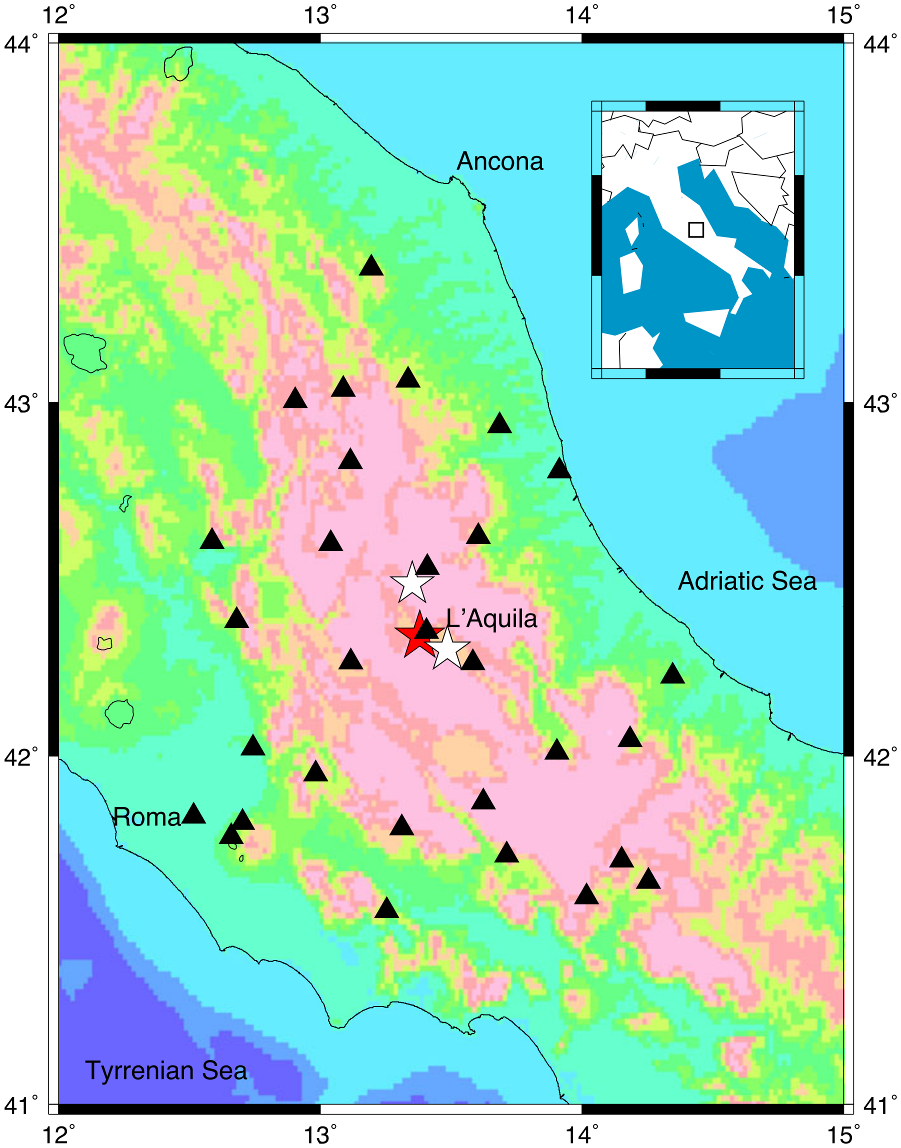


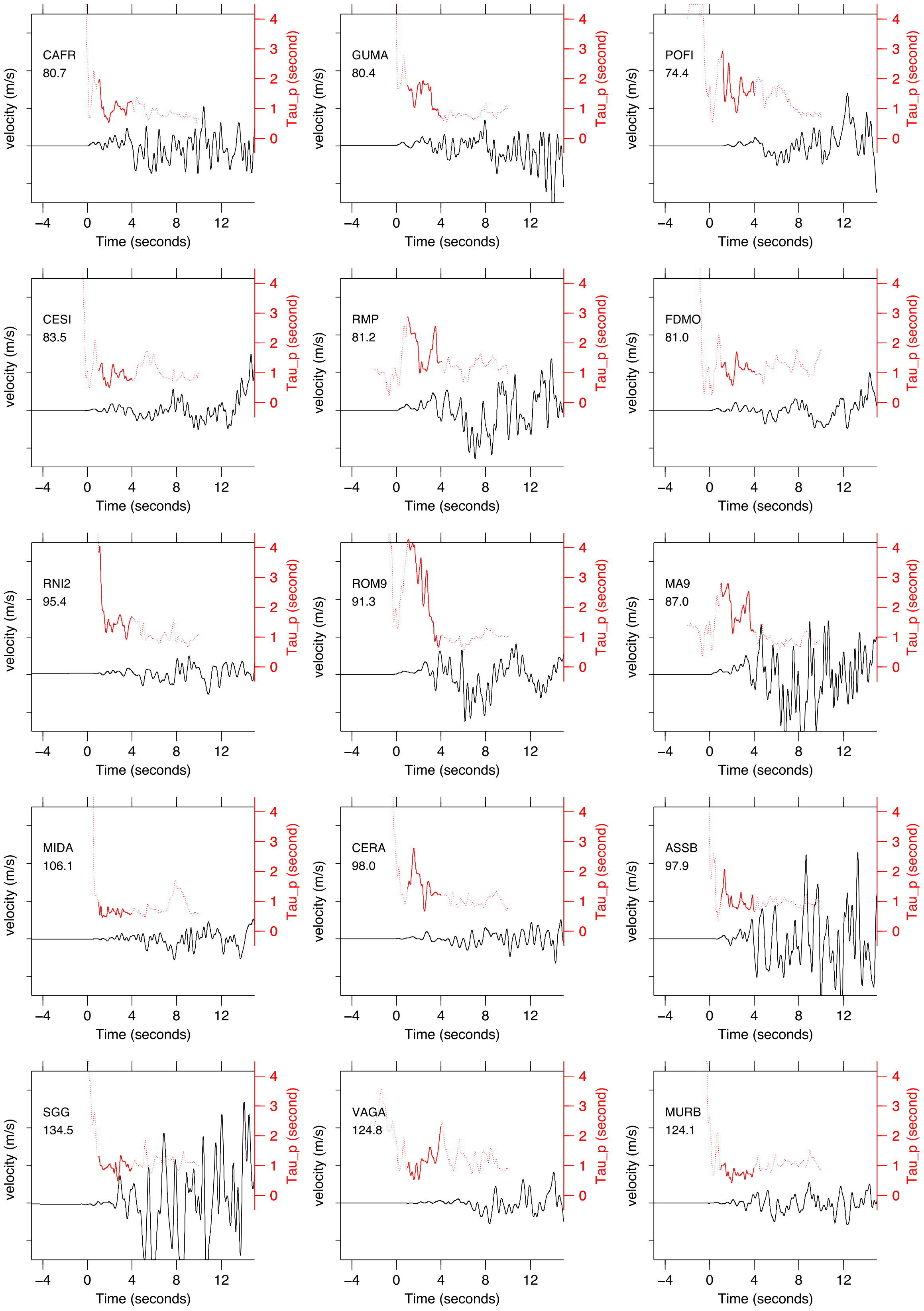
Fig. 1 Map of the region with the epicenter of the mainshock (*red star*) and of the two largest aftershocks (*white star*). Dimensions are not proportional to the magnitude size. *Triangles* represent broadband stations available on April 2009

occurred respectively on April 7 and April 9 (see Table 1 for a summary).

A network of 28 broadband stations (Amato and Mele 2008) within a radius of 100 km from the epicenter recorded the mainshock, but only six did not suffer clipping on the S-wave train while recording the mainshock (the closest unclipped station was 54 km from the epicenter). Saturation does not affect the $\tau_p^{\max}$ measure except for the case of station MN.AQU (Mazza et al. 2008) that was excluded because the S-waves arrived less than 1 s after the P onset and contaminated the P-wave train. For each station, $\tau_p^{\max}$ was measured and the corresponding ML value was retrieved by applying Eq. 1. Results are summarized in Fig. 3. Since a well-trained automatic picker was

Table 1 Source parameters of the earthquakes used in this study

Number	Event date	Lat	Long	ML	Mw
1	April 6, 2009 01:32	42.342	13.380	5.9 ± 0.4	6.3
2	April 7, 2009 17:47	42.303	13.486	5.4 ± 0.3	5.5
3	April 9, 2009 00:52	42.489	13.351	5.1 ± 0.1	5.4


CAFR
80.7
GUMA
80.4
POFI
74.4
CESI
83.5
RMP
81.2
FDMO
81.0
RNI2
95.4
ROM9
91.3
MA9
87.0
MIDA
106.1
CERA
98.0
ASSB
97.9
SGG
134.5
VAGA
124.8
MURB
124.1
velocity (m/s)
Tau_p (second)
Time (seconds)
−4
0
4
8
12
0
1
2
3
4

◀ **Fig. 2** Vertical component seismograms for the 15 closest stations used for analysis of the April 6, 01:32 earthquake (*black solid lines*). *Red lines* represent the τ_p value for the time interval [+1s, +4s] with respect to the P-wave onset. The complete τ_p function is represented by red dotted lines. On the right side, the amplitude bar is drawn. Scale is the same for all frames. Epicentral distance appears below each station name

not available, travel times used for determining the onset of the P-waves and the arrival time of S-wave were retrieved from the INGV bulletin. Testing a picker and the merge of picker and $\tau_p^{\max}$ determination was, indeed, out of the scope of this work.

Several authors (e.g., Allen and Kanamori 2003; Wurman et al. 2007) report that the reliability of magnitude estimates improves when these are averaged over a dataset of at least four stations. Assuming that close stations are processed earlier than faraway ones, stations are plotted as a function of distance and the corresponding average value refers to all the stations within the corresponding distance (incremental average). For comparison and check, the vertical seismogram of the 15 closest stations is drawn in Fig. 2 together with the corresponding τ_p function for the selected time interval [+1,+4] after the P-wave onset. Seismograms do not show peculiarities or artifacts except saturation for some of those (e.g., GUMA), but this occurs out of the time window selected for measuring $\tau_p^{\max}$. τ_p function, on the contrary, shows large fluctuations and some of those, as for the case of ROM9, display a different shape with a clear down-going trend that could imply that the transient, predicted by Allen and Kanamori (2003) and fixed at 1 s for this work, was not ended.

The first station provides low estimate equal to 3.5, while the average over the first three stations is 6.0, within the error bar of the final estimate released by the INGV Bulletin. Stations between 50 and 100 km show large scatters, and the final average results to be 6.8 ± 1.5, more than 1 order of magnitude larger than the standard ML for this earthquake that was reported to be 5.9 ± 0.4 (http://bollettinosismico.rm.ingv.it/), even though error bars overlap.

The large discrepancy between this estimate of the local magnitude (6.8) and the standard one (ML = 5.9) for the mainshock suggests that ML vs. $\tau_p^{\max}$ calibrations that do not include a relevant dataset of large earthquakes can lead to wrong magnitude estimates for the next relevant earthquake.

A similar analysis was conducted for the two most relevant aftershocks (ML 5.4 ± 0.3, April 7,

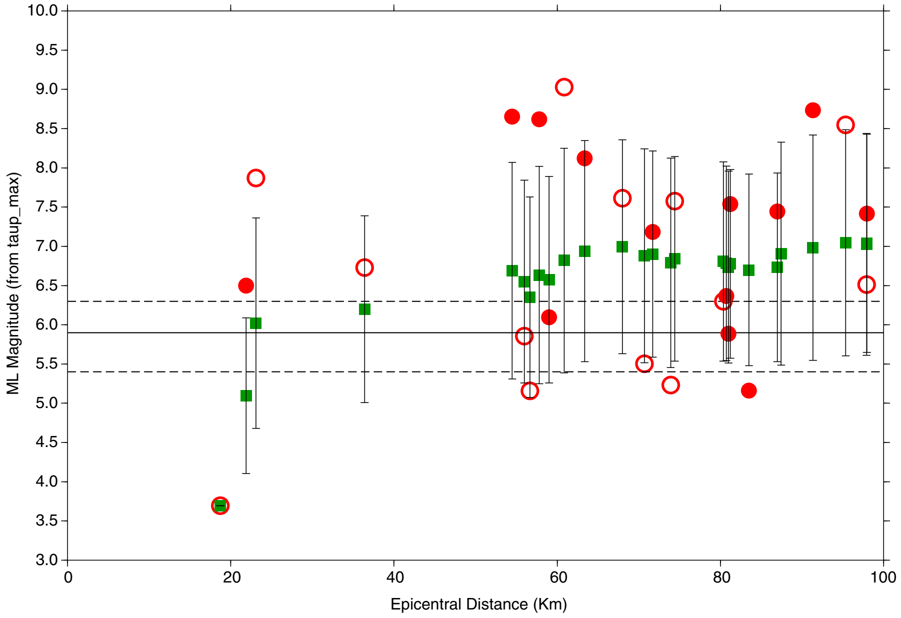


Fig. 3 ML magnitude as obtained from $\tau_p^{\max}$ measure with respect to epicentral distance (in *red*) for the ML 5.9 mainshock that occurred on April 6, 2009 at 01:32. *Open circles* distinguish clipped stations from unclipped (*solid circles*). In *green*, average incremental magnitude is plotted, with error bar. *Straight lines* represent the standard ML estimate, while *dashed lines* represent the corresponding error

2009 17:47, and ML 5.1 ± 0.2, April 9, 2009 00:52). A smaller number of stations suffered for clipping on the S-wave train, but for the two closest (MN.AQU and IV.FAGN), it happened in the 4-s time window and both were discarded.

Results are displayed in Fig. 4, following the same scheme of Fig. 3. Again, the first estimates are scattered but the average quickly stabilizes around the final standard magnitude. In detail, for the case of the ML 5.4, April 7, 2009 17:47 event, the average over the entire dataset results ML = 5.2 ± 1.5, while for the case of ML 5.1, April 9, 2009 00:52, the resulting average magnitude is 5.7 ± 1.3 (Fig. 4).

Some relevance, for the case of EEWS, is given to the time delay of the release of the magnitude estimates. Despite the fact that this strongly depends on the data transmission and processing

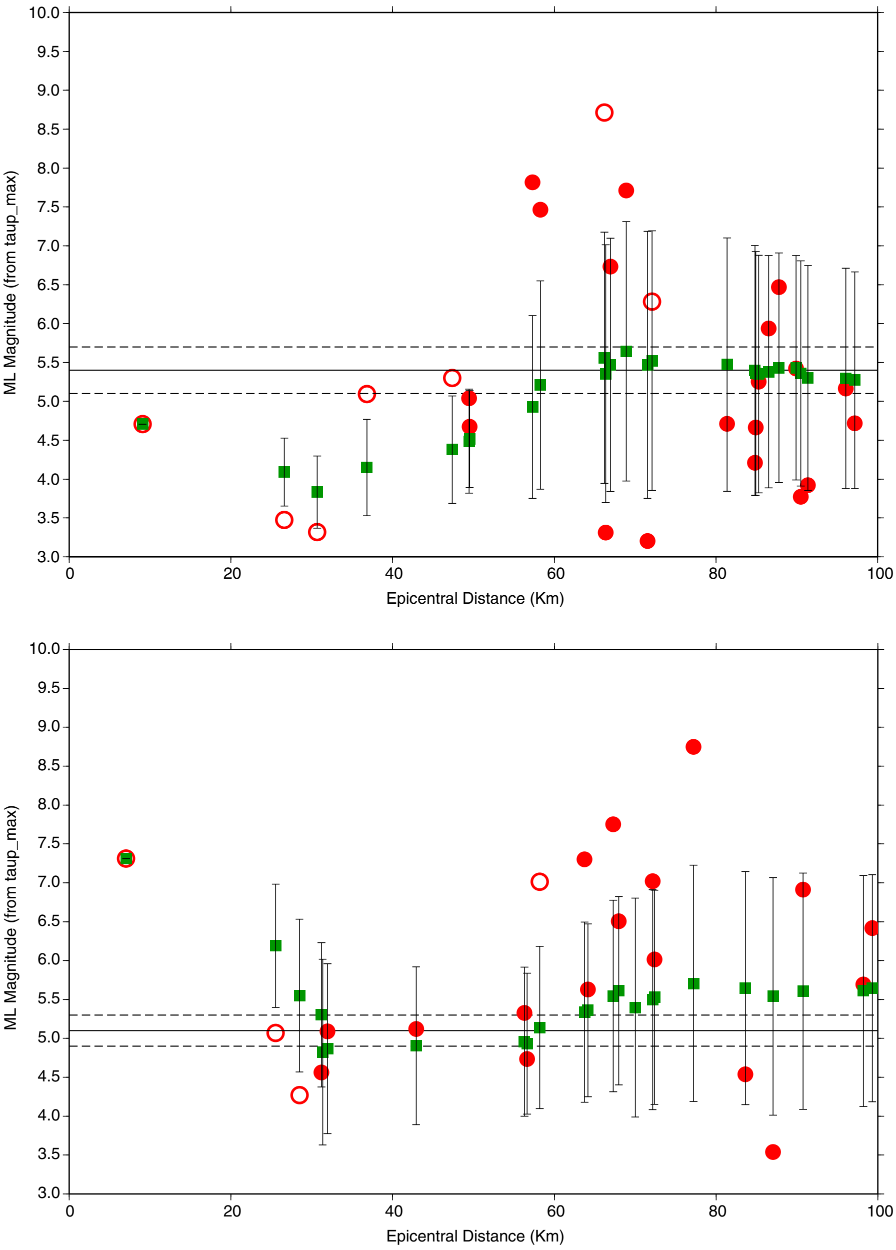


Fig. 4 Same as Fig. 3 for the two larger aftershocks: ML 5.4 April 07, 2009 17:47 (*top*), ML 5.1, April 9, 2009 00:52, (*bottom*)

performances, and not only on the travel time of the waveforms, one can roughly estimate that for the case of the mainshock, the first estimate could have been computed about 7 s after the origin time, while a stable average magnitude could have been available about 13 s after the origin time.

3 Discussion and conclusion

The regression relationship proposed by Olivieri et al. (2008) was evaluated for the three major events that occurred at L'Aquila (Central Italy) on April 2009. Waveform processing and magnitude calculation were performed without any data selection or visual inspection to emulate automatic real-time processing. This included low-pass filter at 3 Hz, standard τ_p computation, and a fixed time window to estimate the predominant period $\tau_p^{\max}$ (Allen and Kanamori 2003).

The results are encouraging, but this analysis identifies two issues that should be considered when implementing $\tau_p^{\max}$ magnitude computation in unmanned EEWS for Italy and suggests the need for further investigation that includes a larger set of waveforms for M 5+ earthquakes in the region.

S-wave contamination should be taken into account for those stations located at very short distance from the epicenter, where S–P travel time is shorter than 4 s.

Single station results for the case of these three events show wide scatters with respect to the average, and this confirms the remark by Allen and Kanamori (2003) about the risks of using single or few stations datasets. These results should be also taken into account for those regions where the expected earthquake magnitude exceeds, or is comparable with, the largest events used for $\tau_p^{\max}$ calibration.

In a recent paper, Zollo et al. (2010) estimated a predominant period (τ_c) for the 2009, L'Aquila earthquake. They found an average value of 1.5 s, which corresponds to a magnitude value of 6.5, based on the scaling relationship between average period and magnitude (Eq. 3 in Zollo et al. 2010). τ_c is defined by Wu and Kanamori (2005) as the average period of the P-wave and appears less influenced by instabilities that could be consequences of pre-event or background noise (Shieh et al. 2008). In a practical application of an EEWS, the combined use of two distinct rapid magnitude estimates, as for the case of $\tau_p^{\max}$ and τ_c, could improve the magnitude estimation and reduce uncertainties on the real-time magnitude estimation (Shieh et al. 2008). Equation 1 was calibrated by selecting seismograms with large signal-to-noise ratio, while for this case, we used waveforms that could be contaminated by larger noise also caused by the ongoing sequence. A similar approach was also proposed by Wurman et al. (2007) who suggested integrating $\tau_p^{\max}$ with magnitude from P-wave peak amplitude. In any case, a better constrained relation between local magnitude and dominant period of the P-wave, retrieved from a larger dataset, is mandatory.

ML should also be considered as potential source of error. At present, a calibrated attenuation relations for Italy remains still unpublished and INGV uses, for automatic and revised magnitude computation, the standard distance correction proposed by Hutton and Boore (1987) for California. A solution, to overcome part of the uncertainties possibly caused by weakly constrained ML estimates, could be to search for a relation, between Mw and the maximum of the dominant period $\tau_p^{\max}$. For the mainshock of the L'Aquila earthquake, most of the agencies reported Mw = 6.3 (Pondrelli et al. 2009, supplementary material). No evidences have been found that could motivate the discrepancy between ML and Mw for the mainshock, even though Mw seems to be closer to the result of this work as well as to the large damages and large PGV observed in the vicinity of the epicenter.

In conclusion, these results confirm the validity of the proposed methodology: error bars for standard ML and for ML predicted by Eq. 1 overlap. However, the large discrepancy between mean ML obtained in this work for the mainshock reveals that ML regression from $\tau_p^{\max}$ can be weakly constrained for those case in which the dataset of large earthquakes is poor. However, the large fluctuations in single-station magnitude estimates can suggest that τ_p is contaminated by some kind of noise or perturbed by site effects even though standard quality check by means of signal-to-noise ratio for the input seismograms is sufficiently high. Part of the discrepancy for the April 6 earthquake can be caused by the unexpected low value of standard ML with respect to MW = 6.3. Contamination by S-wave in the time window selected for measuring $\tau_p^{\max}$ should be prevented by means of implementing robust S-picker, when available, or by predicting the corresponding travel time from the resulting epicentral location. Large fluctuations of single-site ML also enlighten the importance of accurate and reliable error estimates which are, indeed, critical in the framework of EEWS. Modern probabilistic approaches can provide a more comprehensive approach and are strongly recommended. This is the case of PRobabilistic and Evolutionary early warning SysTem (Satriano et al. 2011). Selection rules to evaluate the goodness of τ_p functions could help to reduce the observed large fluctuations around the average. Finally, in the presence of geological and tectonic heterogeneity, some form of regionalization could be required to account for different fault mechanisms and wave propagation paths. This could remove one of the potential cause of uncertainties.

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