Nat. Hazards Earth Syst. Sci., 10, 19–24, 2010
www.nat-hazards-earth-syst-sci.net/10/19/2010/

Natural Hazards and Earth System Sciences

Strong foreshock signal preceding the L'Aquila (Italy) earthquake (M_w 6.3) of 6 April 2009

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Received: 31 October 2009 – Accepted: 9 December 2009 – Published: 11 January 2010

Abstract. We used the earthquake catalogue of INGV extending from 1 January 2006 to 30 June 2009 to detect significant changes before and after the 6 April 2009 L'Aquila mainshock (M_w=6.3) in the seismicity rate, r (events/day), and in b-value. The statistical z-test and Utsu-test were applied to identify significant changes. From the beginning of 2006 up to the end of October 2008 the activity was relatively stable and remained in the state of background seismicity (r=1.14, b=1.09). From 28 October 2008 up to 26 March 2009, r increased significantly to 2.52 indicating weak foreshock sequence; the b-value did not changed significantly. The weak foreshock sequence was spatially distributed within the entire seismogenic area. In the last 10 days before the mainshock, strong foreshock signal became evident in space (dense epicenter concentration in the hanging-wall of the Paganica fault), in time (drastic increase of r to 21.70 events/day) and in size (b-value dropped significantly to 0.68). The significantly high seismicity rate and the low b-value in the entire foreshock sequence make a substantial difference from the background seismicity. Also, the b-value of the strong foreshock stage (last 10 days before mainshock) was significantly lower than that in the aftershock sequence. Our results indicate the important value of the foreshock sequences for the prediction of the mainshock.

1 Introduction

The classification of earthquake space-time clusters has been examined around the world long ago. Omori (1894) introduced the concept of aftershock sequence that is a cluster of shocks following a larger mainshock with power-law time decay of the number of events known as Omori-law. Mogi (1963a) described three patterns of earthquake sequences: mainshock-aftershocks, foreshocks-mainshock-aftershocks, and earthquake swarm which is not dominated by a single principal shock (mainshock). This classification implies that foreshocks precede only some mainshocks and not others which is a common knowledge today. However, this may be only an apparent result given that in the routine daily seismic analysis low-magnitude shocks, including short-term foreshocks, usually escape recognition and are not listed in standard earthquake catalogues (e.g. Papadopoulos et al., 2006).

Foreshock sequences are characterized by some distinct features. Laboratory material fracture experiments (e.g. Mogi, 1963b; Scholz, 1968) along with numerical modeling in spring-block models (Hainzl et al., 1999) showed a clear acceleration of the fracturing process before the main fracture. Studies regarding seismicity in Japan, western United States, Greece, Italy and elsewhere verified this in nature showing that foreshock activity increases approximately as the inverse of time before mainshock (e.g. Papazachos, 1975; Kagan and Knopoff, 1978; Jones and Molnar, 1979). In the magnitude-frequency or Gutenberg-Richter (G-R) relation

$$\log N = a - bM \qquad (1)$$

the parameter b usually drops and becomes significantly lower in foreshocks than in aftershocks or in background seismicity (Mogi, 1963; Scholz, 1968; Papazachos, 1975; Jones and Molnar, 1979; Hainzl et al., 1999; Molchan et al., 1999); where N is the incremental or the cumulative number of events of magnitude $\geq M \pm \Delta M$ and a, b are parameters determined by the data (Gutenberg and Richter, 1944). Foreshocks occur from hours to a few months, and very rarely about 1.5 years before the mainshock (Jones, 1984; Jones and Molnar, 1979; Molchan et al., 1999; Papadopoulos et al., 2000; Sobolev, 2000). However, they precede only some mainshocks and not others. It seems that the incidence of foreshocks decreases with increasing depth of mainshock and possibly depends on the faulting type and orientation (Ohnaka, 1992; Abercrombie and Mori, 1996; Maeda, 1996; Reasenberg, 1999). Although these difficulties

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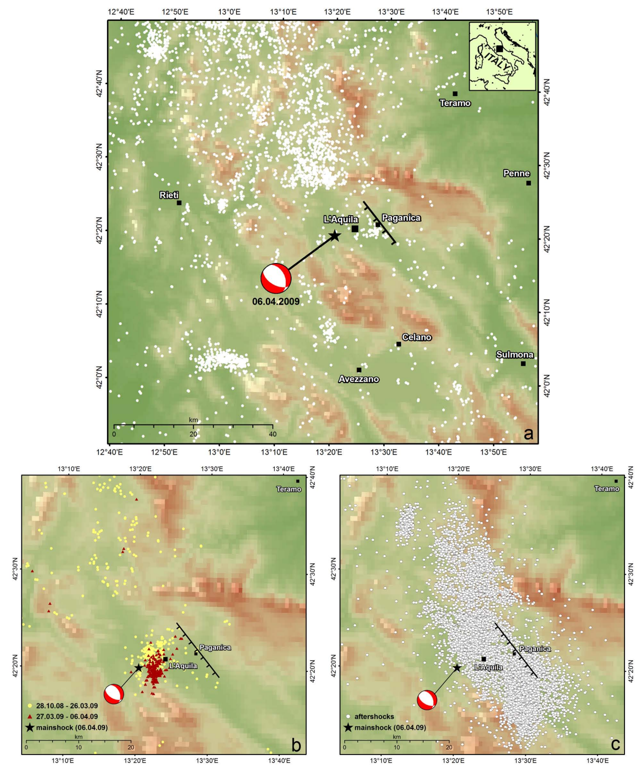

Fig. 1. Epicentral distribution of earthquakes in the time interval of background seismicity from 1 January 2006 to 27 October 2008 **(a)**, in the time interval of foreshock sequence from 28 October 2008 to 6 April 2009 before the mainshock occurrence **(b)**, in the time interval of aftershock sequence from 6 April 2009 to 30 June 2009 **(c)**. The cloud of aftershocks determines the seismogenic area activated. This is the area where epicenter plot has been made in panel (b). In panel (a) a more wide area was used for reasons explained in the text.

make earthquake prediction from foreshocks prone to several uncertainties, foreshocks are generally considered as one of the most promising tools for the prediction of earthquakes. Swarm-type activity is characterized by very high b-value but the time distribution of events does not follow a particular pattern.

In periods of earthquake space-time clusters, it is of particular interest to recognize in near real-time the foreshock, mainshock, aftershock or swarm nature of the seismic activity. A recent case was studied near Samos Island, East Aegean Sea, with two strong shocks occurring on 17 October 2005 (M_w 5.6 and M_w 5.8) and another one on 20 October 2005 (M_w 5.9). Seismologists were unable to evaluate in near real-time the foreshock, mainshock or aftershock nature of the strong events of 17 October 2005 and of 20 October 2005. A posteriori seismicity analysis showed that the event of 20 October 2005 was the mainshock and that it was preceded by foreshock activity for at least one week, the two strong events of 17 October 2005 being included in the foreshock sequence (Papadopoulos et al., 2006).

The strong ($M_\mathrm{w} = 6.3$) earthquake of 6 April 2009 in L'Aquila, Central Italy, occurred at 01:32:39 UTC and caused about 300 deaths and destruction in about 60 000 buildings of the area. The geometric and kinematic features and the source properties of the earthquake were studied by Atzori et al. (2009), Cirella et al. (2009) and Walters et al. (2009). It has been shown that the earthquake rupture very possibly was associated with the Paganica normal fault which strikes NW-SE and dips SW (Fig. 1). The seismogenic area activated with the earthquake sequence is determined by the geographic distribution of the aftershock epicenters, which is striking NW-SE at a length of about 45 km and maximum width not exceeding about 15 km (Fig. 1c). Marzocchi and Lombardi (2009) reported on the near real-time aftershock forecasting based on the ETAS model.

Apart from destruction the earthquake generated also great concern among the population as regards the possible precursory phenomena that supposedly were evident before the mainshock but were not taken into account for the prediction of the mainshock. Two are the main types of precursors involved: radon emission and foreshocks. However, the only scientifically documented precursor so far was described by Biagi et al. (2009) who reported on a radio emission in association to that earthquake. In this paper, we analyze a posteriori the seismicity before and after the L'Aquila earthquake, with the aim to detect foreshock signals bearing precursory value for the prediction of the mainshock.

2 Methodology and data

We performed three-dimentional analysis of seismicity, that is in the space, time and size domains, before and after the L'Aquila strong earthquake. The earthquake catalogue produced by the Istituto Nazionale di Geofisica e Vulcanologia (INGV: http://bollettinosismico.rm.ingv.it; last access 30 June 2009), for the time period from 1 January 2006 to 30 June 2009, was the data source for our analysis.

The date 1 June 2006 was selected as the beginning of the earthquake catalogue considered in our analysis because before that date the catalogue of INGV is inhomogeneous. The termination date of the catalogue was selected so that to include a long part of the aftershock sequence.

As a first step we examined the spatial distribution of seismicity in a broad area much larger than the seismogenic area and in several time intervals all of them starting on 1 June 2006. This examination showed that from the beginning of 2006 up to the end of October 2008 no particular earthquake activation was noted in the seismogenic area (Fig. 1a). On the contrary, from the end of October 2008 up to the occurrence of the mainshock of 6 April 2009 the seismogenic area was notably active (Fig. 1b). After these findings we focused our analysis in a target area centered at the mainshock epicenter with radius R=50 km which is slightly larger than the seismogenic area of the earthquake

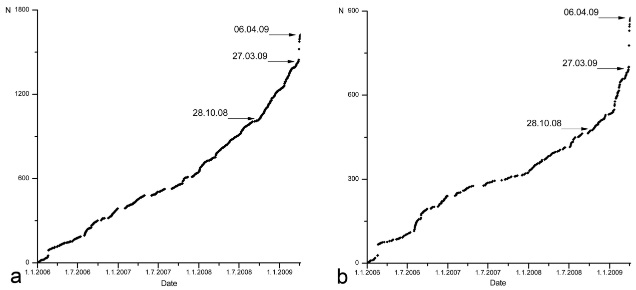

Fig. 2. Cumulative number of earthquakes of magnitude $\geq$1.3 as a function of time. Earthquakes occurring within the target area of radius 50 km and 30 km from the epicenter of the mainshock of 6 April 2009 were counted in **(a)** and **(b)**, respectively.

sequence, thus allowing for some error involved in the epicentral determinations. Plot of the cumulative number of earthquake events as a function of time in the target area (Fig. 2) clearly shows that from 28 October 2008 the earthquake activity increased but the increase became drastic in the last 10 days before the mainshock occurrence. Then we put forward three hypotheses: (A) From 1 January 2006 up to the end of October 2008 the seismicity remained in the state of background seismicity; (B) By the end of October 2008 the seismicity entered in the state of weak foreshock sequence which lasted up to the 26 March 2009; (C) In the last 10 days before the mainshock, that is from 27 March 2009 up to 6 April 2009, strong foreshock activity occurred.

To check the validity of our hypotheses we performed a series of statistical tests investigating significant changes in the state of seismicity in both the time and size domains. Significant changes in the time domain are determined when the seismicity rate, r (in events/day, 1 day = 24 h), changes at significance level of at least P=0.95 according to the statistical z-test. In the size domain, the parameter b was calculated by the maximum likelihood approach introduced by Aki (1965) and Utsu (1965). In this approach

$$b = \frac{N \log e}{\sum_{i=1}^{N} M_{\mathrm{i}} - N M_{\mathrm{c}}} \tag{2}$$

where N=number of events, $M_{\mathrm{i}} = i$th event and M_{c} = magnitude cut-off in the sample, that is the lower magnitude threshold for data completeness. Theoretically b=1 for background seismicity but in practice b often deviates from unit because of the local seismotectonics and the types of seismicity, e.g. background seismicity, swarms, aftershocks etc. Significance of difference between b-values at level of no more than p=0.05 was tested with the test introduced by Utsu (1992), which is based on AIC and allows to calculate the probability that two samples may come from the same population.

In practice, we produced several statistical samples of earthquakes by dividing the earthquake catalogue of the target area in several segments (Table 1). In each test we compared two earthquake samples as for the change of the parameters r and b from one segment of the catalogue to the other. With the aim to secure reliability of the statistics, each test for the change of r or b was performed in earthquake samples containing more than 100 events. In addition, only statistically complete earthquake samples were tested. Data completeness was examined on the basis of the magnitude-frequency or G-R diagram of the Eq. (1). Deviation of the G-R diagram from linearity in the left-hand side signifies data incompleteness. The minimum earthquake magnitude, M_{min}, as well as the magnitude cut-off, M_{c}, for data completeness were found to vary in the several segments of the earthquake catalogue (Table 1). In the time period before the mainshock occurrence, M_{min} varied from 0.2 to 0.7. However, in the first day of the aftershock sequence $M_{\mathrm{min}} = 1.3$, which is attributed to that because of the occurrence of a great number of events, seismograms of small events occurring very close in time are overlapping and, therefore, many small events are not detected. On the contrary, in the next stages of the aftershock sequence M_{min} gradually dropped to 0.0. Before the mainshock of 6 April 2009 maximum value of $M_{\mathrm{c}} = 1.3$ was found and, therefore, magnitude cut-off $M_{\mathrm{c}} = 1.3$ was considered for all the earthquake samples tested. In the aftershock period, maximum value of $M_{\mathrm{c}} = 2.4$ was found which is the magnitude cut-off inserted in the earthquake samples tested for that period.

The several segments of the earthquake catalogue tested are listed in Table 1 where the segments are ranked in three types and remarked according to the three hypothetical styles of seismicity: BG for background seismicity, FOR for foreshock sequence, AFT for aftershock sequence. All calculations were performed with the statistical software EQStat (Earthquake Statistics) developed by our team.

3 Seismicity analysis and results

In the entire period of background seismicity (BGALL), the activity was relatively stable in both the size and time domains and there is no evidence that foreshock activity occurred in BGALL. In fact, b-value was found equal to 1.09 which is in favour of hypothesis A that the period from 1 January 2006 up to 27 October 2008 represents background seismicity. Mean seismicity rate of r=1.14 events/day was calculated. To examine further the seismicity features of the period BG it was divided in six time segments remarked as shown in Table 1. In these segments the b-value varied around unity, that is from 0.93 to 1.22, which again favours hypothesis A that in that period the activity was in the state of background seismicity. The seismicity rate ranged from 0.85 to 1.54 events/day. Some clustering of swarm-type may have occurred in the segments BG3 and BG5 which are characterized by higher b-value with respect to the BG2 and BG4 segments, respectively.

Table 1. List of the catalogue segments tested in this study and results of tests. Each catalogue segment is tested for changes in r and b with respect to r and b in the catalogue segment preceding it in the list. For testing explanations see in the text. Key: BG = background seismicity, FOR = foreshock sequence, AFT = aftereshock sequence, M_c = magnitude cut-off, $M_{\min}$ = minimum earthquake magnitude in the catalogue segment, n = number of earthquakes, r = seismicity rate in events/day, b = parameter of the G-R relation, P = significance level for the change of r according to the z-test, p = significance level for the change of b according to the Utsu-test.

Catalogue Segment	From	To	M_{c}	$M_{\min}$	n	r	b	P	p
BG1	1 Jan 2006 00:00:00	30 Jun 2006 23:59:59	1.3	0.5	197	1.09	1.20	–	–
BG2	1 Jul 2006 00:00:00	31 Dec 2006 23:59:59	1.3	0.7	222	1.13	0.93	67.36	0.013
BG3	1 Jan 2007 00:00:00	30 Jun 2007 23:59:59	1.3	0.3	138	0.85	1.20	99.85	0.028
BG4	1 Jul 2007 00:00:00	31 Dec 2007 23:59:59	1.3	0.3	169	0.96	1.03	84.61	0.156
BG5	1 Jan 2008 00:00:00	30 Jun 2008 23:59:59	1.3	0.5	331	1.68	1.22	99.90	0.073
BG6	1 Jul 2008 00:00:00	27 Oct 2008 23:59:59	1.3	0.2	229	1.54	1.01	67.00	0.036
BG ALL	1 Jan 2006 00:00:00	27 Oct 2008 23:59:59	1.3	0.2	1286	1.14	1.09	–	–
FOR1	28 Oct 2008 00:00:00	25 Jan 2009 23:59:59	1.3	0.4	230	2.31	1.09	99.90	0.368
FOR2	26 Jan 2009 00:00:00	26 Mar 2009 23:59:59	1.3	0.5	154	2.46	0.97	51.99	0.193
FOR3	27 Mar 2009 00:00:00	6 Apr 2009 01:32:00	1.3	0.6	198	21.7	0.68	98.68	0.002
BG ALL	1 Jan 2006 00:00:00	27 Oct 2008 23:59:59	1.3	0.2	1286	1.14	1.09	–	–
FOR ALL	28 Oct 2008 00:00:00	6 Apr 2009 01:32:00	1.3	0.4	582	2.85	0.88	99.90	0.000
BG ALL	1 Jan 2006 00:00:00	27 Oct 2008 23:59:59	1.3	0.2	1286	1.14	1.09	–	–
AFT ALL	6 Apr 2009 01:33:00	30 Jun 2009 23:59:59	2.4	0.0	720	4.23	0.97	99.90	0.015
FOR3	27 Mar 2009 00:00:00	6 Apr 2009 01:32:00	1.3	0.6	198	21.70	0.68	–	–
AFT1	6 Apr 2009 01:33:00	8 Apr 2009 23:59:59	2.4	1.2	236	96.10	0.84	98.21	0.034
FOR3	27 Mar 2009 00:00:00	6 Apr 2009 01:32:00	1.3	0.6	198	21.70	0.68	–	–
AFT2	6 Apr 2009 01:33:00	9 Apr 2009 23:59:59	2.4	1.2	282	45.80	0.81	99.25	0.053
FOR3	27 Mar 2009 00:00:00	6 Apr 2009 01:32:00	1.3	0.6	198	21.70	0.68	–	–
AFT3	6 Apr 2009 01:33:00	10 Apr 2009 23:59:59	2.4	1.0	305	41.20	0.82	98.87	0.037

In the catalogue segment FOR1, that is from 28 October 2008 to 25 January 2009, r increased significantly to 2.31 events/day which doubled the mean rate of 1.14 events/day found in BGALL. However, b (=1.09) remained unchanged. In segment FOR2, from 25 January 2009 to 26 March 2009, r increased further to 2.46 events/day and b dropped to 0.97 but these slight changes with respect to FOR1 are not significant. By considering FOR1 and FOR2 together we found that r increased significantly at level P=0.999 with respect to r in BGALL, while b dropped slightly but insignificantly. The largest foreshock of M_{L}=4.1, which is the largest event that occurred in the target area from 1 January 2006 and before the mainshock of 6 April 2009, took place on 30 March 2009. These results are consistent with hypothesis B that in the period from 28 October 2008 to 26 March 2009 the seismicity was in the state of weak foreshock activity.

The state of seismicity changed drastically in the catalogue segment FOR3, that is in the last 10 days before the occurrence of the strong earthquake of 6 April 2009. In fact, r increased to 21.7 events/day at significance level P=0.987 and at the same time b dropped to 0.68 at significance level p=0.002. Thus, hypothesis C that the time period from 27 March 2009 to 6 April 2009 was a strong foreshock sequence was verified.

It is characteristic that the weak foreshock activity which developed from 28 October 2008 to 26 March 2009 spatially did not concentrated around the mainshock epicenter but it was widely distributed within the seismogenic area (Fig. 1b). On the contrary, the strong foreshock sequence from 27 March 2009 up to the occurrence of the mainshock on 6 April 2009 was concentrated in the hanging-wall domain of the normal Paganica fault, that is in area of no more than about 15 km from the mainshock epicenter (Fig. 2b). These results indicate that although with the weak foreshock activity the entire seismogenic area became unstable the strong foreshock activity of the last 10 days caused nucleation of the main rupture in the Paganica fault.

The distinguished features of the entire foreshock sequence FORALL, that is of FOR1, FOR2 and FOR3 considered together, with respect to the features of the background seismicity BGALL, become quite evident from that the mean seismicity rate increased from 1.14 events/day in BGALL to 2.85 events/day in FORALL and that the b-value dropped from 1.09 in BGALL to 0.88 in FORALL with the significance levels being very high: P=0.999 and $p \rightarrow 0$. At the same time, the b-value changed significantly from the foreshock sequence to the aftershock sequence. In fact, the b-value increased from 0.68 in FOR3 to 0.84, 0.81 and 0.82 ($p < 0.053$) in the first stages of the aftershock sequence, that is from 6 April 2009 to 10 April 2009 (AFT1, AFT2 and AFT3).

4 Conclusions

The cloud of aftershock epicenters indicates that the seismogenic area activated with the L'Aquila mainshock of 6 April 2009 was of about 45 km in length and 15 km in width. Analysis for the identification of significant changes in the state of seismicity in a target area of 50 km around the epicenter of the L'Aquila mainshock led us to the following conclusions.

From the beginning of 2006 up to the end of October 2008 the seismicity was relatively stable and remained in the state of background seismicity with mean seismicity rate r=1.14 events/day and parameter b=1.09. However, from 28 October 2008 up to the 26 March 2009 the rate r increased significantly to 2.46 events/day which implies that the seismicity was in the state of weak foreshock sequence. The b-value did not change significantly. The weak foreshock sequence was spatially distributed within the entire seismogenic area.

In the last 10 days before the occurrence of the mainshock the foreshock sequence concentrated in the hanging-wall domain of the normal Paganica fault, that is in an area of no more than about 15 km from the mainshock epicenter. The activity became very strong with significant drastic increase of the seismicity rate at r=21.70 events/day. At the same time the b-value dropped significantly to 0.68. The largest foreshock of M_L=4.1 took place on 30 March 2009. This is the largest event that occurred in the target area from 1 January 2006 but before the mainshock of 6 April 2009.

The significantly very high seismicity rate and the very low b-value in the entire foreshock sequence make a substantial difference from the background seismicity. In addition, the b-value of the strong stage of the foreshock sequence (last 10 days before mainshock) was significantly lower than that in the aftershock sequence.

5 Discussion

The results of this study were obtained by considering a target area of radius R=50 km around the epicenter of the mainshock of 6 April 2009. It has been explained that the target area is slightly larger than the seismogenic area activated with the earthquake sequence. To check the possible dependence of our results on the selection of the target area we repeated our calculations for target area of R=30 km. It was found that this change in the target area selection does not affect our results (Fig. 2b). The only influence is that in some of the earthquake samples tested the number of events is lower than that in the respective samples for target area of $R = 50$ km, which creates some instability in the results.

In the remaining part of this section, we investigate the lessons learned from the example of the L'Aquila earthquake case and their potential value for the short-term prediction of the mainshock. The present a posteriori analysis leaves no doubt that the state of seismicity before the L'Aquila mainshock gradually changed from background seismicity to weak foreshock activity and then to strong foreshock sequence. Those three states of seismicity lasted for nearly 3 years, 5 months and 10 days, respectively. One may argue that in a scheme of regular seismicity analysis and evaluation based on the daily updating of the earthquake catalogue from the national seismograph center, the ongoing state of weak foreshock activity would be detectable in about one or two months before the mainshock. Furthermore, the detection of the strong foreshock signal would require at least 4 or 5 days after its onset on 27 March 2009. Then, the strong foreshock signal, being evident in space (dense concentration of epicenters in a very narrow area), in time (drastic increase of the daily number of events) and in size (drastic drop of b-value) would be detectable a few days before the mainshock occurrence.

It is evident that a strong foreshock signal, such as the one described here before the L'Aquila earthquake, bears important predictive information for the forthcoming mainshock. The mainshock could be expected to occur at high probability level within few days from the detection of the strong foreshock signal. In fact, in the Corinth Gulf, Central Greece, which is one of the most active seismic zones in the European-Mediterranean region, it has been found that the strong foreshock activity occurs in about the last 10 days before the mainshock at probability level of 0.83 (Papadopoulos et al., 2000). In the classic example of Haicheng, China, high number of foreshocks occurring in a very narrow area were detected a few days before the mainshock (M=7.3) occurrence in the evening of 4 February 1975 (Wu et al., 1978). Prediction statement for a very strong earthquake to occur very soon was released by seismologists in the morning of 4 February 1975, while evacuation orders were also released (Wang et al., 2006).

In the space dimension, the concentration of the strong foreshock sequence in a very narrow zone of L'Aquila region would indicate well-enough the possible epicentral area of the forthcoming mainshock. However, the magnitude of the forthcoming strong earthquake would remain uncertain. In fact, no physical relation or empirical rule has been found so far between the magnitude of the mainshock and the foreshock properties. For example, the magnitude of the mainshock, M_0, does not depend on the magnitude of the maximum foreshock, M_{-1}, or on the time length of the foreshock sequence. Therefore, the only possible assessment could be that $M_0 > M_{-1}$.

To conclude, the most important lesson learned is that foreshock activity is quite promising for the prediction of the mainshock. For a systematic investigation of the predictive value of foreshock activity we need to organize real-time experiments, incorporating selection of target areas, regular updating of the earthquake catalogue in the target areas, seismicity analysis and evaluation in near real-time conditions, production of prediction statements, and finally evaluation of the success or failure of the prediction statements.

Acknowledgements. This paper is a contribution to the research project SAFER, European Commission, contract n. 036935, FP6-2005. We thank Dr Warner Marzocchi, INGV, for his help to compile the earthquake catalogue for the time period from 30.03.2009 to 30.06.2009.

Edited by: P. F. Biagi
Reviewed by: Y. T. Chen and A. Zavyalov

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