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Some comments on the potential seismogenic origin of magnetic disturbances observed by Di Lorenzo et al. (2011) close to the time of the 6 April 2009 L'Aquila earthquake

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Abstract. In this paper we provide comments about the potential seismogenic origin of magnetic disturbances that Di Lorenzo et al. (2011) observed from few minutes before to about one hour after the 6 April 2009 L'Aquila earthquake. The coincidence with the earthquake induced the authors to think that the observed magnetic signals were linked to the main phase of the seismic event. Here, we will discuss the unusual polarization in the X–Z plane of the magnetic disturbances observed by Di Lorenzo et al. (2011), the model of source that the authors have proposed for the generation of these signals, and the time length of the magnetic data set shown in their paper. We will also discuss some possible generation mechanisms for electromagnetic seismogenic signals that could support the authors' findings. Finally, we will consider seismic and geodetic data from L'Aquila area just before and after the 6 April 2009 earthquake. We conclude that there is no evidence to support the hypothesis that magnetic disturbances documented by Di Lorenzo et al. (2011) had a seismogenic origin.

1 Introduction

In this paper we investigate in depth a particular claim of link between magnetic disturbances and a seismic event.

Many papers (e.g. Hayakawa et al., 1996, 1999; Hirano and Hattori, 2011; Prattes et al., 2008, 2011; Pulinets, 2007) have documented the observation of pre-earthquake disturbances that the authors have claimed to be induced by the seismic activity. The common characteristic of these reports is that the authors have linked the observed "anomalous" signals to subsequent earthquakes in a simplistic way, without considering the possibility that these events may be generated by other sources (see, e.g. Masci, 2012a, b, c, 2013a, b). The relevance of these papers is that they motivate the idea that one day short-term earthquake prediction based on these precursors may become a routine technique. Given a set of data it is always possible, by retrospective inspection, to find an unrealistic relationship between the occurrence of presumed anomalies and subsequent earthquakes. Just because an event occurs before another, it does not mean that they are related if there is no strong evidence, by means of independent data, of the suggested relation. Thus, there is a need for scientists to filter the many claims of earthquake-related signals that keep on appearing in the scientific literature. In recent years some researchers have reviewed many cases of observations of earthquake precursors (e.g. Campbell, 2009; Masci, 2010, 2011, 2012a; Moldovan et al., 2012; Thomas et al., 2009a, b, 2012a, b) showing that there is no strong relationship between the presumed precursors and the subsequent seismic events.

On 6 April 2009 at 01:32:39 UT (Universal Time), a $M_w = 6.3$ earthquake (Chiarabba et al., 2009) struck the town of L'Aquila. This event was preceded by a foreshock activity that lasted several months and culminated with the $M_w = 4.1$ event of 30 March 2009. Among thousands of aftershocks, two $M_w > 5.0$ events occurred on 7 April 2009 ($M_w = 5.5$) and on 9 April 2009 ($M_w = 5.4$), respectively (see Pondrelli et al., 2010). Figure 1 shows the locations of the epicentres of the seismic sequence up to the end of July 2009. Many papers (e.g. Akhoondzadeh et al., 2010; Boudjada et al., 2010; Cianchini et al., 2012; Eftaxias et al., 2009, 2010; Perrone

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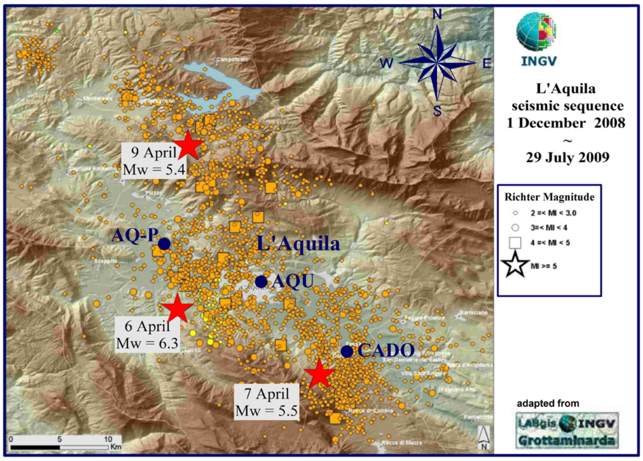

Fig. 1. L'Aquila seismic sequence from 1 December 2008 to 29 July 2009. Red stars refer to the main shock of 6 April 2009 and to the two $M_\mathrm{W} > 5.0$ aftershocks. AQ-P, AQU and CADO refer to the Geomagnetic Observatory of L'Aquila, to the seismic station located in the basement of the Spanish castle of L'Aquila, and to the GPS site of Fossa, respectively. The original view of the seismic sequence was realized by the staff of the LABgis of INGV (Istituto Nazionale di Geofisica e Vulcanologia, Italy) using seismic data from the Italian Seismological Instrumental and Parametric Database of INGV (http://iside.rm.ingv.it/iside/standard/index.jsp).

et al., 2010; Prattes et al., 2011; Rozhnoi et al., 2009; Tsolis and Xenos, 2010) have retrospectively documented the observation of pre-earthquake anomalies that the authors claim to be related to L'Aquila earthquakes. However, these studies do not show a strong correspondence between the presumed seismogenic signatures and the seismic activity, nor do they document expected co-seismic effects which should occur at time of the rupture when the primary energy is released. In some cases presumed precursory electromagnetic signals were observed several hundred kilometres from L'Aquila (see Eftaxias et al., 2009, 2010). Conversely, local observations from L'Aquila area do not show anomalous precursory and co-seismic signals which can be described as signatures of the 6 April 2009 earthquake (see Masci, 2012a; Masci and Di Persio, 2012; Villante et al., 2010). In the following paragraph we will investigate thoroughly the possible seismogenic origin of the electromagnetic disturbances documented by Di Lorenzo et al. (2011) at the time of the 6 April 2009 L'Aquila earthquake.

2 Discussion

Di Lorenzo et al. (2011) document the observation of magnetic disturbances close to the time of the 6 April 2009 L'Aquila earthquake. They estimated the residual magnetic field by means of inter-station impulse response functions between the Italian observatories of L'Aquila and Duronia. The observatory of L'Aquila is located only 6 km from the epicentre of the 6 April 2009 main shock, whereas the observatory of Duronia is about 130 km south of L'Aquila area. The sampling rate of magnetic data they used is 10 Hz. Figure 2 shows the main findings of Di Lorenzo et al. (2011). Very feeble signals in the residual magnetic field (maximum amplitude about 200 pT) are seen to occur in the frequency band 0.3–3 Hz during the minutes before and about one hour after the $M_\mathrm{w} = 6.3$ main shock. More precisely, leaving aside the evident co-seismic disturbance due to the shaking of the sensor in the earth's magnetic field caused by the arrival of the seismic waves, Fig. 2 shows that one magnetic burst is present during about 10 min before the main shock, whereas another two bursts occur during 01:38–01:50 UT and 02:03–02:22 UT, respectively. The authors claim that these anomalous signatures should be related to the main phase of the L'Aquila earthquake. They conclude the following: "these emissions do not give enough warning because they are too short in time. However these results do not preclude the possibility that the electromagnetic monitoring of seismogenic areas may help to understand the physical processes associated with earthquakes, especially those preceding the seismic activity in the preparatory phase". The study of the physical processes possibly associated with the preparatory phase of seismic events requires trustworthy seismogenic signals. Any potential anomaly, before it can be considered to be generated by the seismic activity, should be excluded as a random anomaly or as an anomaly induced by alternative sources, both natural and artificial. In the following sections we will discuss the characteristics of the magnetic disturbances reported by Di Lorenzo et al. (2011), the possible generation mechanisms for the observed magnetic signals, and finally we will investigate seismic and geodetic data close to the 6 April 2009 main shock.

2.1 Characteristics of the observed magnetic disturbances

In our opinion, the study by Di Lorenzo et al. (2011) shows three unclear points that do not support their claims. The three points are as follows: the polarization of the observed magnetic disturbances, the model of source proposed for these signals, and the time length of the magnetic data set.

Our first observation concerns the unusual polarization of the magnetic disturbances documented by the authors. Figure 2 shows that magnetic bursts occur synchronously in the geomagnetic field components X and Z. On the contrary, the Y component does not show corresponding disturbances. The X, Y, and Z components represent the N–S horizontal component, the E–W horizontal component, and the vertical component, respectively. As emphasized by Di Lorenzo et al. (2011), seismogenic magnetic fields could be generated on the earth's surface by electric currents flowing in earth's crust mainly in the horizontal plane. These almost horizontal electric currents should induce disturbance signals mainly in the vertical component of the geomagnetic field.

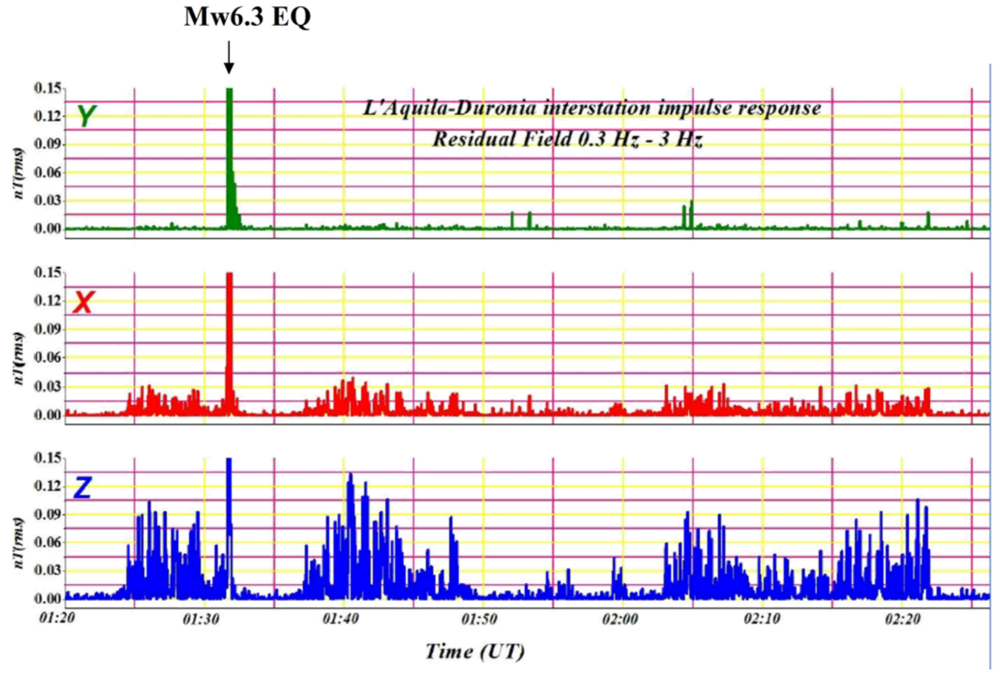

Fig. 2. A reproduction of Fig. 7 by Di Lorenzo et al. (2011). Root mean square (RMS) representation of the residual magnetic field at L'Aquila Geomagnetic Observatory close to the time of the 6 April 2009 earthquake. X, Y, and Z represent the N–S horizontal component, the E–W horizontal component, and the vertical component, respectively. See Di Lorenzo et al. (2011) for details.

The findings of Di Lorenzo et al. (2011) partially support this assumption. We can see (refer to Fig. 2) that the amplitude of the residual field of the Z component is larger (about three times larger) than the amplitude of the residual field of the X component. However, in our opinion, the lack of corresponding signals in the Y component, which indicates that the observed disturbances are polarized in the X–Z plane, does not support their seismogenic origin. If presumed magnetic seismogenic signals observed on the earth's surface are generated by underground electric currents having a significant horizontal component, we should expect that the magnetic disturbances prevail in the vertical direction, but they should not have a preferred plane of polarization. We believe that Di Lorenzo et al. (2011) would have to carry out a more careful investigation about the origin of the X–Z polarization of the magnetic signatures. The authors by means of simple considerations would have seriously doubted the seismogenic origins of their findings. Namely, in order to justify the polarization of the magnetic disturbances observed by Di Lorenzo et al. (2011), we can suppose two scenarios. The electromagnetic signals possibly generated in the focal zone of the 6 April 2009 earthquake are

1. polarized. In this case, these signals preserve the polarization after passing through the earth's crust.

2. not polarized. Consequently, the earth's crust polarizes these signals.

Both scenarios are unrealistic. Furthermore, assuming ad absurdum that the seismogenic signals reaching the earth's surface are polarized, what is the probability that these signals are observed perfectly polarized in the X–Z plane? In our opinion, this probability is almost zero.

Secondly, Di Lorenzo et al. (2011) propose a simple model of source as support of their findings. According to the authors the model is based on the measured magnetic field and it includes the 1-D profile of the resistivity of the local earth's crust which was calculated by a conventional magnetotelluric approach. However, their model does not consider any possible generation mechanism which could justify the X–Z polarization of the observed magnetic signals. The authors assume a magnetic dipole as equivalent source of these signals. The orientation of the dipole is obtained taking into account the amplitude of the residual field in each of the geomagnetic field components. That is, the magnetic moment of the dipole becomes to be approximately vertical, with a small component in the N–S direction, by imposing that the Y component of the residual field is null. In summary, the simple model proposed by Di Lorenzo et al. (2011) does not support their claims as it should be, but, on the contrary, their model is mainly adjusted to the author's findings.

Our third comment concerns the time length of the data set that the authors have reported. Di Lorenzo et al. (2011) show only about one hour of data closely to the time of the earthquake. They exclude the existence of magnetic signals during the foreshock and the aftershock activity, but they did not investigate the possible occurrence of similar magnetic disturbances in periods of time during which no earthquake occurs. We think that to exclude any possible occurrence of similar disturbances independently of the seismic activity, the authors would have to investigate the 10 Hz data sets of L'Aquila and Duronia observatories for a longer period of time (several months).

2.2 Possible generation mechanisms

Regardless of the comments reported in Sect. 2.1, now we would like to discuss some possible generation mechanisms of electromagnetic seismogenic signals that could support the findings of Di Lorenzo et al. (2011).

Several studies (see, e.g. Karakelian et al., 2002; Matsushima et al., 2002; Nagao et al., 2000) have documented the observation of magnetic and electric signals shortly after the occurrence of an earthquake. Such signals are observed in all the components of electric and magnetic fields for some tens of seconds. These signals are not generated in the focal region at the origin time of the earthquake, but they are related to the seismo-dynamo effect induced by the arrival of the seismic P waves at the point of observation. In the case of magnetic disturbances observed by Di Lorenzo et al. (2011), we can undoubtedly exclude the seismo-dynamo effect both for the duration of the observed signals and for the period of time in which they were observed.

At the time of fault rupture, direct electromagnetic signals may be generated in the earthquake focal region. These signals propagate in the earth's crust with electromagnetic wave speed. Therefore, they should be observed before the arrival of the seismic waves, few moments later the origin time of the earthquake. Mechanisms which may induce direct electromagnetic signals as piezoelectric and triboelectric phenomena have been excluded by Di Lorenzo et al. (2011). The piezomagnetic effect can be excluded as well. According to Cicerone et al. (2009), piezomagnetic phenomena can generate signals having a maximum magnitude of 10^{-2} nT. The amplitude of these signals is one order of magnitude less than the signals observed by Di Lorenzo et al. (2011). In our opinion, the electrokinetic effect, resulting from fluid diffusion through rocks, could be also excluded. Lucente et al. (2009) and Di Luccio et al. (2010) suggest a scenario in which deep fluids may have a fundamental role in the seismotectogenesis of L'Aquila area. The change in pore pressure along the fault planes could have controlled the space–time distribution of the events of the L'Aquila seismic sequence with reactivation of pre-existing structures. According to these researchers the rupture which generated the 6 April 2009 main shock was driven by fluid migration induced by the $M_{\rm w} = 4.1$ event of 30 March 2009. In addition to that, the NW–SE distribution of aftershocks should be compatible with a fluid migration in that direction (see Di Luccio et al., 2010). If the magnetic signals documented by Di Lorenzo et al. (2011) were generated by electrokinetic phenomena, the large amount of fluids that migrated in NW–SE direction should have generated similar magnetic disturbances for longer periods of time before and after the main shock. On the contrary, as Di Lorenzo et al. (2011) emphasize, no anomalous signal was observed the days before and after the earthquake main phase.

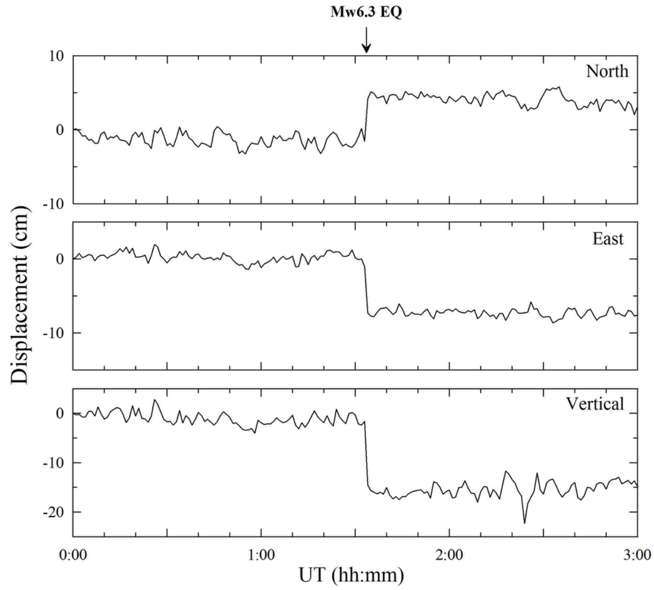

Fig. 3. Position time series at the three-component (north, east, and vertical) GPS site of CADO from 00:00 UT to 03:00 UT of 6 April 2009. Each panel shows GPS raw data (sampling 60 s). The station of CADO is located about 10 km from the epicentre of the 6 April 2009 earthquake (see Fig. 1).

Freund et al. (2006) have proposed a new physical mechanism for the generation of electric currents in the earth's crust – the so-called P hole mechanism. According to Freund and his colleagues, when dry rock is subjected to stress, electric charge carriers are activated (as in a semiconductor) and the rock behaves as if it were a battery from which current can flow out. When the stress is removed, the battery returns to the inactivate state. Recently, Johnston and Dahlgren (2012) have questioned the extrapolation of the Freund's model as generation mechanism of possible seismogenic electromagnetic signals. In any case, Freund's theory, which may explain possible pre-earthquake electromagnetic signals in case of crustal stress loading, does not support the observation of similar signals after the main phase of the earthquake when the stress is removed. However, at the hypocentral depth, the level of the local stress does not significantly change during the days to minutes before the earthquake (see Lay and Wallace, 1995). High-resolution borehole strain and pore pressure measurements in active fault areas do not indicate a significant precursory crustal stress increase in the hours to minutes before seismic events (see Johnston et al., 2006). Thus, if stress increase occurred during the months to weeks before 6 April 2009, the precursory magnetic signatures should

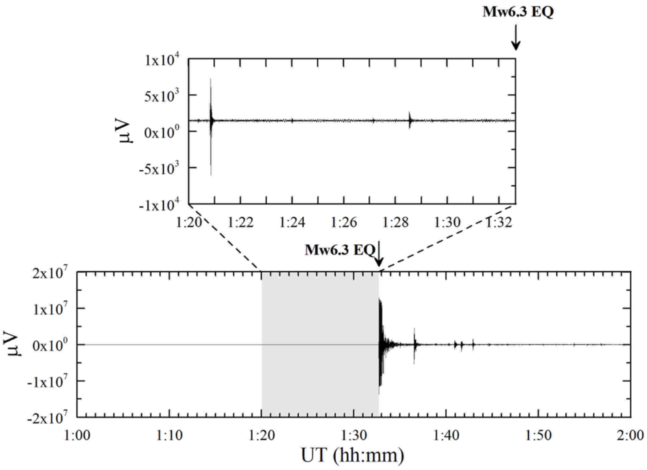

Fig. 4. Continuous seismic data recording (vertical component) at the AQU seismic station from 01:00 to 02:00 UT of 6 April 2009. The upper panel shows about 12 minutes of data before the main shock. The local magnitude (M_l) of the seismic event that occurred at 1:20:46 UT is 1.1. The AQU station is located in the basement of the Spanish castle, in the centre of L'Aquila.

have been observed for a long period of time, and not only for a few minutes before the main shock.

2.3 Seismic and geodetic data

Let us consider seismic and geodetic data just before and after the 6 April 2009 main shock. Figure 3 shows position time series at the three-component (north, east, and vertical) global position system (GPS) site of CADO. The GPS station of CADO is located about 10 km from the epicentre of the 6 April 2009 earthquake (see Avallone et al., 2011). Co-seismic displacements at 1:32:39 UT are clearly evident in all the components. The figure also shows that no evident surface displacements occurred just before and shortly after the main shock. Figure 4 shows the continuous recording of seismic data at the AQU station, which is located in the basement of the Spanish castle in the centre of L'Aquila. We can see that during the minutes before the 6 April 2009 main shock no significant seismic event occurred. In summary, seismic and geodetic data do not support the idea that, during the minutes before the 6 April 2009 main shock, the stress at the hypocentral depth is increased so as to generate magnetic disturbances documented by Di Lorenzo et al. (2011).

3 Conclusions

In this paper we have investigated the seismogenic origin of the magnetic disturbances documented by Di Lorenzo et al. (2011) close to the time of the 6 April 2009 L'Aquila earthquake. We have shown that the polarization in the X–Z plane of the observed magnetic disturbances is an unusual characteristic for a reliable seismogenic signal. Secondly, no possible generation mechanism of electromagnetic signals supports the hypothesis that the observed magnetic disturbances had a seismogenic origin. As a final analysis, the inspection of local geodetic and seismic data does not support the possibility that the magnetic disturbances documented by Di Lorenzo et al. (2011) may have been generated by crustal stress loading before the 6 April 2009 main shock. In our opinion the study of Di Lorenzo et al. (2011) does not show any strong evidence that the magnetic disturbances that they observed had a seismogenic origin. We think that the only argument which might support the claims of Di Lorenzo et al. (2011) is that the magnetic signals were observed very close to the time of the 6 April 2009 main shock. However, this does not mean that these signals undoubtedly came from seismogenic sources. In summary, we cannot exclude that these signals could have been just chance events or that they may have been generated by instrumental malfunction. In such cases, the additional analyses (e.g. calculation of the arrival direction of the signals) performed by the authors are only speculative.

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