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Key Points:

- We investigate effects in magnetic field data in correspondence of the 2009 L'Aquila earthquake
- We show that these effects are caused by the movement and permanent displacement of the sensors caused by the passing seismic wave
- We rule out that these effects are induced by an electric current as a result of the earthquake

Supporting Information:

- Supporting Information S1

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Evidence of underground electric current generation during the 2009 L'Aquila earthquake: Real or instrumental?

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Abstract We investigate magnetic effects in correspondence of the M_w6.1 L'Aquila earthquake. Magnetic and seismic records are analyzed. Rapid and distinct changes and an offset can be seen in magnetic field components after the main shock. We show that these effects result from electromagnetic induction due to the movement of the sensors through the Earth's magnetic field and from a permanent displacement of the sensors from their original position caused by the passing seismic waves. A transient signal in total field data from an overhauser magnetometer apparently occurs in correspondence with the earthquake. Our analysis shows that the transient was not observed by other sensors that were operating in close proximity to the overhauser. Thus, the transient signal in the total magnetic field data, and the offset in the magnetic field components, cannot be associated with a hypothetical underground electric current generated by the earthquake, as suggested by Nenovski (2015).

1. Introduction

Changes in electric and magnetic fields have been reported to occur prior to, during, and shortly after the earthquake rupture [see, e.g., *Fraser-Smith et al.,* 1990; *Huang,* 2011; *Johnston et al.,* 2006]. Whether or not these changes are anomalous and seismogenic is an important question for understanding the physical processes associated with earthquakes. The debate on the possible occurrence of magnetic precursory signals of earthquakes is still active. However, despite the many papers showing changes in magnetic field data that precede earthquakes [see, e.g., *Fraser-Smith et al.,* 1990; *Hayakawa et al.,* 1999], causal relationship between these changes and the seismic activity has never been actually demonstrated. Furthermore, many reported pre-earthquake changes have been refuted as precursors by subsequent evidence [see, e.g., *Campbell*, 2009; *Masci*, 2010, 2011; *Masci and Thomas*, 2015; *Thomas et al.,* 2009].

Magnetic effects observed in correspondence or shortly after the shock are more convincing earthquake-related effects. Step-like offsets of few nT in records from total field magnetometers have been observed in correspondence with earthquakes [see, e.g., *Johnston et al.,* 1994, 2006]. The step-like offset is regarded as resulting from the piezomagnetic effect [*Stacey and Johnston*, 1972] related to the change in the crustal magnetization generated by the stress release [*Johnston et al.,* 2006]. Disturbances in magnetic field data may be observed shortly after large earthquakes as a result of ionospheric electric currents induced by atmospheric waves generated by the strong motion of the ground or the sea level [see, e.g., *Utada et al.,* 2011]. Other reports show electric and magnetic signals in high-frequency data in correspondence with the arrival of seismic waves in the observation site [see, e.g., *Honkura et al.,* 2004; *Nagao et al.,* 2000; *Huang*, 2011]. These signals are waveform-like disturbances similar to seismograms, and are considered local effects caused by the passing seismic waves, and not generated in the focal region during the earthquake. Electric and magnetic signals possibly generated during the earthquake rupture should be observed long before the arrival time of seismic waves because they propagate at the electromagnetic wave speed. Some authors [see, e.g., *Matsushima et al.,* 2002; *Ujihara et al.,* 2004] consider that a seismoelectric component in electric and magnetic waveform-like disturbances observed in correspondence with the arrival of the seismic waves may be due to electromagnetic induction caused by the shaking of the electrically conducting crust through the Earth's magnetic field, the so-called seismic dynamo effect. Other theoretical studies suggest that the piezoelectric effect [*Huang*, 2002] and the electrokinetic effect [*Huang et al.,* 2015; *Ren et al.,* 2012, 2015] are potential mechanisms of coupling between the seismic waves and electromagnetic disturbances.

However, the strong similarity (in shape and duration) with seismograms and ground acceleration waveforms from adjacent stations may indicate that waveform-like electric and magnetic disturbances observed at the arrival of seismic waves are generated in large part by the electromagnetic induction caused by the movement of the electrodes and magnetic coils of the sensors through the Earth's magnetic field as a result of the earthquake shaking [*Johnston et al.,* 2006].

As should be done in reports of alleged precursors of earthquakes, also, papers showing coseismic electric and magnetic changes should provide an adequate control of the origin of the reported effects. The correspondence between the identified electric and magnetic effects and the shock may be just a coincidence, may result from careless data analysis, or may be an instrumental effect [see, e.g., *Masci and De Luca*, 2013]. Independent measurements may provide convincing evidence that an observed coseismic disturbance is or is not related to an actual seismoelectric effect.

2. The 6 April 2009 L'Aquila Earthquake

On 6 April 2009 at 01:32:40.400 UT a M_w6.1 earthquake struck L'Aquila area devastating the town and surroundings. The two largest aftershocks occurred on 7 April (M_w5.4) and 9 April (M_w5.2) (see Figure S1a and Table S1 in the supporting information). There are reports showing magnetic changes preceding this earthquake that sometimes were observed many hundreds of kilometers from the epicenter [see, e.g., *Eftaxias et al.,* 2009]. Studies using data from L'Aquila area, instead, did not identify magnetic changes that can be actually put in relation with the 6 April earthquake [see, e.g., *Masci and Di Persio*, 2012; *Villante et al.,* 2010]. No actual coseismic electric and magnetic effects in correspondence to the 6 April main shock have been yet identified, and reported magnetic changes claimed to be related to this earthquake have been shown not to be seismogenic [*Masci*, 2012; *Masci and De Luca*, 2013].

In a recent report, *Nenovski* [2015] shows magnetic records at the time of the 6 April 2009 L'Aquila earthquake from a triaxial fluxgate and an overhauser magnetometer in the INTERMAGNET (International Real-time Magnetic Observatory Network) station at the Geomagnetic Observatory of L'Aquila managed by the Italian Istituto Nazionale di Geofisica e Vulcanologia (INGV). The observatory is about 7 km away from the epicenter of the 6 April main shock (see Figure S1a and Table S2 in the supporting information). The overhauser measures the total magnetic field, whereas the fluxgate measures the variation of the magnetic field components in the HDZ orientation, and not, as incorrectly reported by *Nenovski* [2015] in the geographic reference frame XYZ (see Text S1 in the supporting information). *Nenovski* [2015] shows two effects in correspondence with the 6 April 2009 main shock, a coseismic offset in the fluxgate magnetic field components and a transient signal in the total magnetic field from the overhauser. We can see these effects in Figure 1. According to *Nenovski* [2015] the transient appears in correspondence with the main shock lasting for approximately 300 s. Still, the transient is a local effect because total magnetic field data from the observatory of Castello Tesino (46.05°N, 11.65°E, more than 400 km away from L'Aquila) do not show such an effect. *Nenovski* [2015] hypothesizes that the magnetic effects were induced by an electric current generated in the earthquake nucleation zone by electrification processes that, however, are not well identified. He concludes that offsets and the transient are actually seismoelectric disturbances because they appear simultaneously in magnetic records from two different instruments. However, we can see that *Nenovski* [2015] is unclear in describing the onset time of the reported magnetic effects. Sometimes, he describes that these effects occur simultaneously with the earthquake rupture; other times, he argues that they occur at the arrival of the seismic waves in the geomagnetic observatory (see Text S2 in the supporting information). In the next sections, we report our findings on the effects occurring in magnetic data in correspondence with the 6 April 2009 L'Aquila earthquake.

3. Data

A careful analysis should demonstrate convincing causality between earthquake and reported coseismic, as well as precursory, electric and magnetic effects. The consistency of the observed effects with other independent data may help us to demonstrate this causality. Thus, in order to contribute to the understanding of the physical processes associated with the L'Aquila earthquake, we investigate magnetic field measurements from multiple magnetometers at the Geomagnetic Observatory of L'Aquila. Seismic and strong motion records are reported as well.

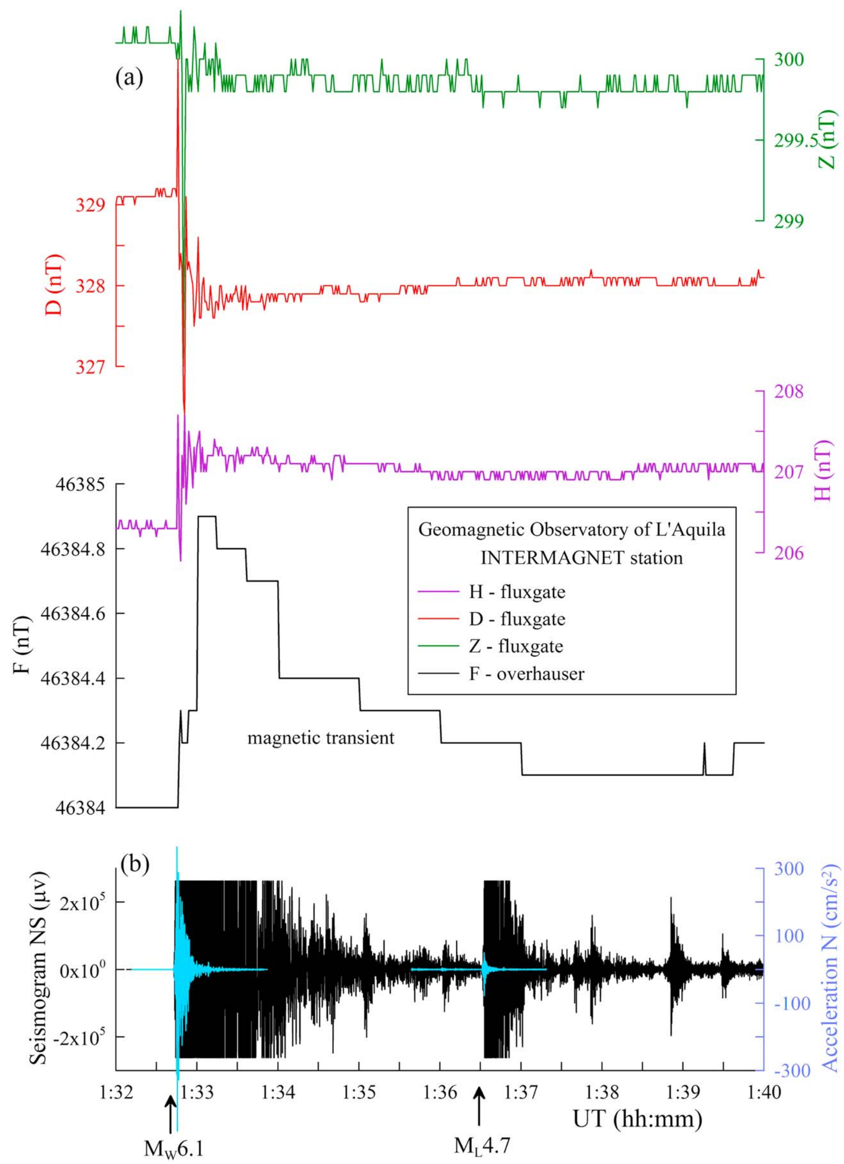

Figure 1. (a) Magnetic field *H*, *D*, and *Z* components and the total magnetic field *F* from the fluxgate and overhauser magnetometers of the INTERMAGNET station at the Geomagnetic Observatory of L'Aquila at the time of the 6 April 2009 M_w6.1 earthquake. (b) The NS seismogram from the RSA seismometer at the observatory and the *N* component of the ground acceleration from the station of Colle dei Grilli. Several aftershocks, whose waveforms sometimes overlap, can be seen in the seismogram. The first large aftershock (M_L4.7) occurs at 01:36:29.190. The ground acceleration is shown only for the main shock and the M_L4.7 aftershock. Seismic waves reach the observatory a few tenths of a second later than the station of Colle dei Grilli because the strong motion station is closest to the earthquake epicenter (see Figure S1a in the supporting information).

3.1. Seismic Data

The seismic sequence that occurred during 2009 in L'Aquila area has been recorded by the three-component seismometers of the Italian seismic networks RSN (*Rete Sismica Nazionale*) and RSA (*Rete Sismica regionale-Abruzzo*) [*De Luca*, 2011] managed by the INGV and by the three-component stations of the Italian strong motion network RAN (*Rete Accelerometrica Nazionale*) managed by the Italian Civil Protection. Here we show seismic data from the RSA seismometer at the Geomagnetic Observatory of L'Aquila and strong motion data from the RAN station of *Colle dei Grilli*, 2 km away from the observatory (see Figures S1a, S1b, and Table S2 in the supporting information for details). The *P* wave and the *S* wave reached the observatory approximately 2.4 s and 4 s after the origin time of the M_w6.1 main shock, respectively (G. De Luca, personal communication, 2016).

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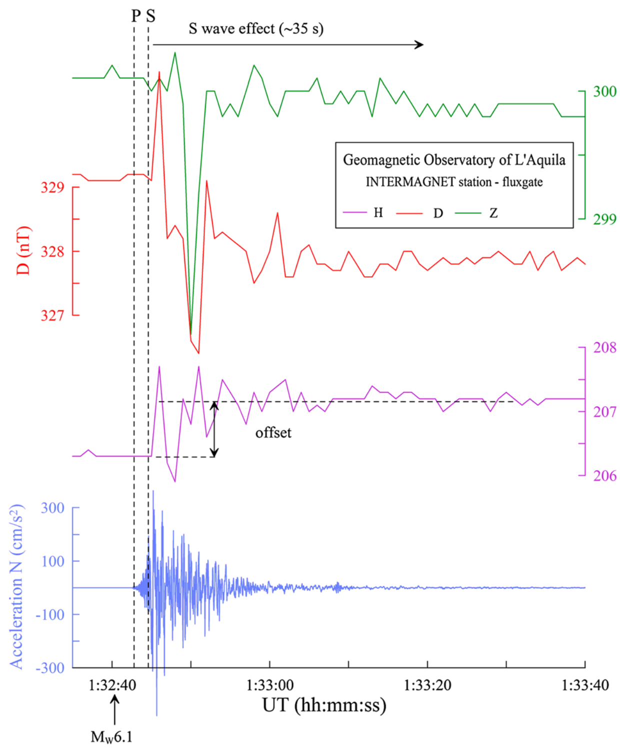

Figure 2. Magnetic field *H*, *D*, and *Z* components from the fluxgate of the INTERMAGNET station at the Geomagnetic Observatory of L'Aquila. The *N* component of the ground acceleration from the station of Colle dei Grilli is shown as well. *P* and *S* are the arrival times in the observatory of the *P* wave and *S* wave of the M_w6.1 main shock, respectively.

3.2. Magnetic Data

We analyze magnetic data (sampling interval 1 s) from the triaxial fluxgate and overhauser magnetometers in the INTERMAGNET station at the Geomagnetic Observatory of L'Aquila, the same magnetic data shown by *Nenovski* [2015]. The two magnetometers are in the same building at a distance of approximately 2 m. Total magnetic field data from a second overhauser (sampling interval 60 s) usually used in the Helmholtz coil system are also investigated. The second overhauser is 60 m away from the INTERMAGNET station. We also analyze magnetic field *H*, *D*, and *Z* components from the triaxial fluxgate and induction magnetometers (sampling interval 1 s) of L'Aquila University station (UNIVAQ), 200 m away from the INTERMAGNET station. See Figure S1b and Table S3 in the supporting information for the location and brief description of the magnetic sensors.

4. Discussion

Four types of changes can be seen in magnetic data after the origin time of the 6 April main shock. Magnetic field components from fluxgate and induction sensors show rapid changes and offsets. After the offset, a slow recovery to the pre-earthquake level having a time decay of approximately 30 min can be seen in the induction sensors as well. An anomalous transient signal is present in data from the INTERMAGNET overhauser.

4.1. The Rapid Changes and Offset in Magnetic Field Components

In Figure 1 we report magnetic records from the INTERMAGNET station, the NS seismogram, and the *N* component of the ground acceleration from the station of Colle dei Grilli at the time of the 6 April main shock. Figure 2 shows that anomalous rapid and distinct changes occur in the fluxgate components approximately 4 s after the origin time of the earthquake in correspondence with the *S* wave that reaches the observatory. The rapid changes disappear after about 35 s in correspondence with very low values of the ground acceleration. This shows that the rapid changes measured by the fluxgate are induced by the passing *S* wave. Still, the delay of 4 s between the onset of changes in fluxgate data and the origin time of the main shock makes us to rule out that these changes are magnetic disturbances induced by an electric current generated during the earthquake rupture. This is because, taking into account the great difference in magnitude order between the seismic wave speed (km/s) and the speed of electromagnetic waves (10^5 km/s), electromagnetic waves would arrive at the observatory a few microseconds after the main shock and would thus be observed long before the arrival time of the seismic waves.

Figures 2 and 3 show that a small offset having amplitude of about 0.9, −1.2, and −0.2 nT is also evident in the fluxgate *H*, *D*, and *Z* components, respectively. Figure 3 shows that rapid changes and offset in correspondence with the passing seismic waves generated by the main shock can also be seen in magnetic records from the fluxgate and induction sensors of the UNIVAQ station. Note that the induction magnetometer shows the onset of rapid changes in data before the two fluxgates and more precisely in correspondence with the arrival in the observatory of the *P* wave (see also Figure S2 in the supporting information). This is

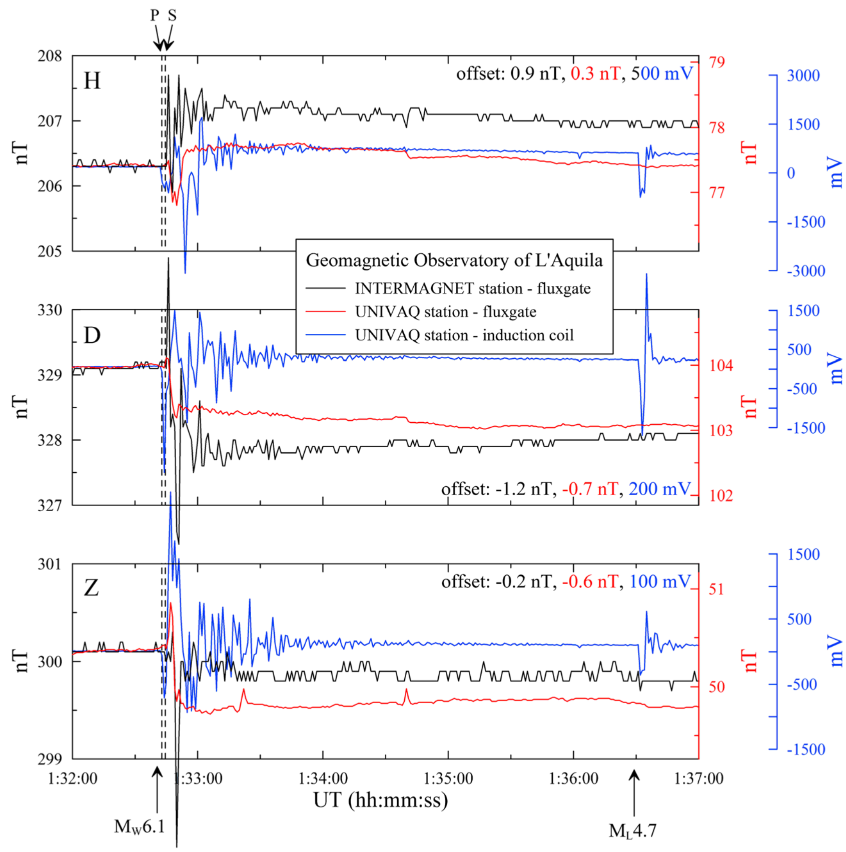

Figure 3. Magnetic field *H*, *D*, and *Z* components from the fluxgate of the INTERMAGNET station and from the fluxgate and induction magnetometers of the UNIVAQ station at the Geomagnetic Observatory of L'Aquila. *P* and *S* are the arrival times in the observatory of the *P* wave and *S* wave of the M_W6.1 main shock, respectively.

due to the greater sensitivity to the movement of the induction sensors with respect to the fluxgate sensors. The different onset time of rapid changes in fluxgate and induction magnetometers data at the arrival of seismic waves shows that these changes are caused by the movement of the magnetic sensors through the Earth's magnetic field in response to the earthquake shaking. Possible disturbances as a consequence of a local seismoelectric effect induced by the passing seismic waves should be detected simultaneously in fluxgate and induction sensors.

In Figure 4 we can see the strong acceleration induced by 6 April main shock that at the station of Colle dei Grilli reaches approximately 0.5 *g* (where *g* is the gravity acceleration), whereas the maximum acceleration is 0.13 *g* and 0.07 *g* in correspondence with the largest aftershocks of 7 and 9 April, respectively, and 0.07 *g* for the M_L4.7 aftershock of 6 April. Note that fluxgate data do not show an offset nor clear magnetic changes caused by the passing seismic waves in correspondence with the first large M_L4.7 aftershock (see Figure 3), as well as in correspondence with the two largest aftershocks that occurred on 7 and 9 April (see Figures S3a and S3b in the supporting information). Instead, due to the high sensitivity to movement of the induction sensors, magnetic components from the induction magnetometer show the effect of the earthquake shaking, but not a clear offset, in correspondence of low values of the ground acceleration at the observatory induced by the M_L4.7 aftershock, as well as by many other aftershocks, e.g., the two largest aftershocks that occurred on 7 and 9 April (see Figure S3c in the supporting information). In Figure 2 we can see, e.g., in the *H* component that the offset occurs shortly after the arrival of *S* wave generated by the main shock in correspondence with the maximum values of the ground acceleration. Afterward, due to the earthquake shaking, each magnetic component shows rapid changes around the new level for about 30 s. Therefore, the offset in magnetic field components from the fluxgate and induction magnetometers may be caused by the permanent displacement from their original position and tilting of the sensors due to the strong acceleration induced by the arrival of the *S* wave, as well as by the permanent displacement and subsidence of the ground

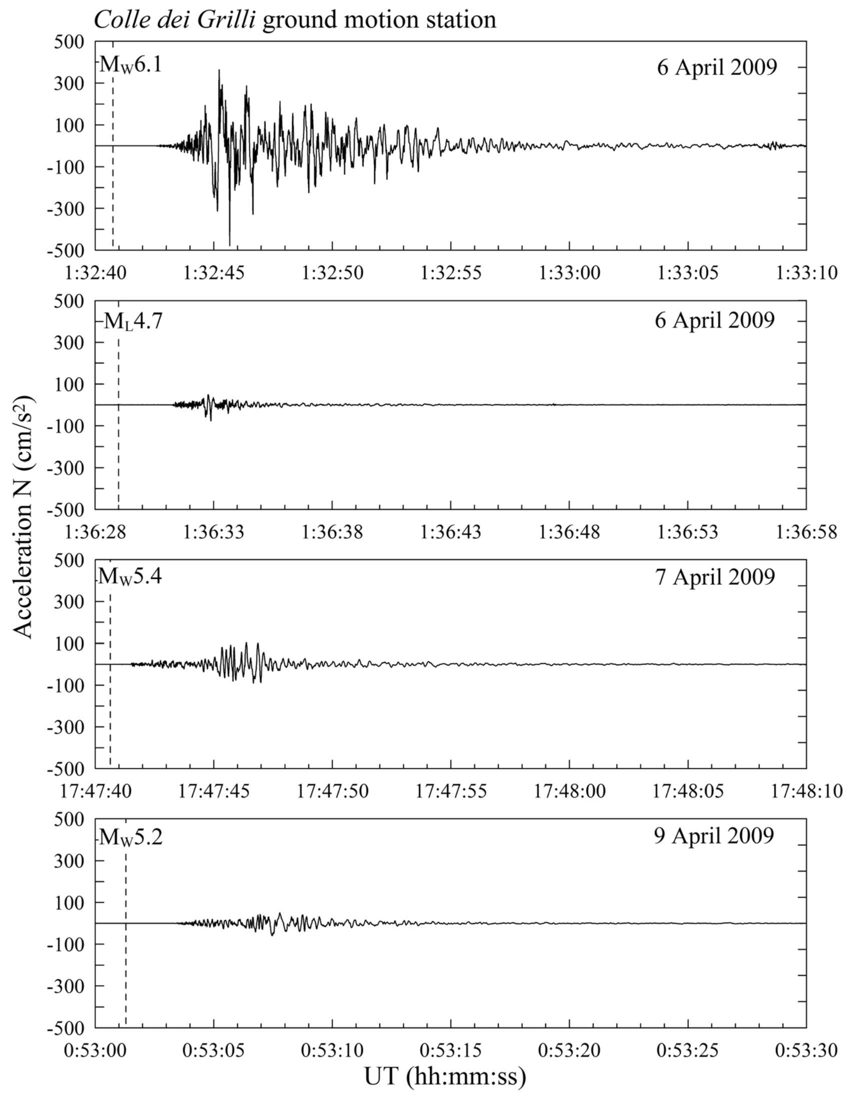

Figure 4. The *N* component of the ground acceleration from the strong motion station of Colle dei Grilli in correspondence with the 6 April M_w6.1 main shock and M_L4.7 aftershock, and the two largest aftershocks of 7 and 9 April.

in the area of the observatory as a result of the earthquake [*Anzidei et al.,* 2009]. The offset in magnetic field components from fluxgate and induction sensors rules out again that the disturbances occurring in these data shortly after the 6 April main shock may be related to seismoelectric effects. This is because possible disturbances as a result of seismic dynamo or electrokinetic effects should disappear in magnetic data soon after the passage of the seismic waves [see, e.g., *Ren et al.,* 2012, 2015; *Ujihara et al.,* 2004].

In the INTERMAGNET station, the fluxgate and the overhauser are placed onto two concrete pillars, whereas in the UNIVAQ station the magnetometers are placed onto the floor of the building where they are housed. Thus, the different amplitudes of the offset in the components from the two fluxgates that we can see in Figure 3 may be related to different permanent displacements of magnetic sensors in response to the strong acceleration induced by the seismic waves. Instead, the different shapes of the shaking effect in the components from the three magnetometers may be related to the different mechanical responses of the sensors to rapid movements, as well as to a different response in frequency of their electronic equipment.

After the offset, a slow decay can be also seen in induction magnetometer data. As can be seen in Figure S4 in the supporting information, each induction sensor reaches the pre-earthquake level approximately after 30 min, long after the passage of the seismic waves. The long recovery time of the induction sensors is

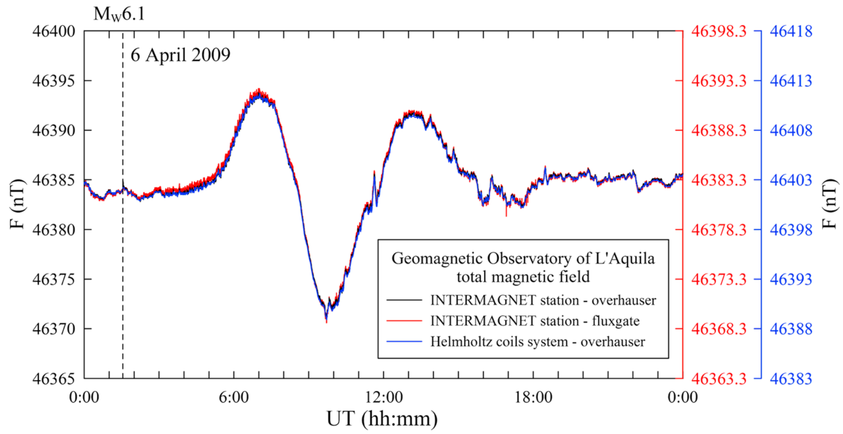

Figure 5. Total magnetic field at the Geomagnetic Observatory of L'Aquila during 6 April 2009 from the two overhausers and that calculated from the fluxgate components. The fixed offset between the total field records ($\Delta F_{\mathrm{INTERMAGNET}} = 1.7$ nT, $\Delta F_{\mathrm{overhauser}} = -18$ nT) is related to the distance between the sensors.

due to the response of the sensors to the impulsive disturbances induced by the arrival of seismic waves that cause their saturation.

4.2. The Transient Signal in the Total Magnetic Field

In Figure 1 we have shown the magnetic transient in total field data from the INTERMAGNET overhauser that according to *Nenovski* [2015] appears in correspondence of the main shock lasting for approximately 300 s. Here we compare total magnetic field data from three magnetometers at the Geomagnetic Observatory of L'Aquila: the overhauser and the fluxgate of the INTERMAGNET station and the overhauser of the Helmholtz coil system. Total field data have been obtained from the fluxgate components by means of the closest measurement (4 April 2009) of the magnetic declination and inclination using a DIM (Declination Inclination magnetometer) fluxgate theodolite (courtesy of M. Di Persio). In Figure 5 we report the total magnetic field at the Geomagnetic Observatory of L'Aquila during the 6 April 2009 from the three magnetometers. The figure shows that the three total field records are very close and show a regular daily variation. Therefore, after the passage of the seismic waves, total magnetic field data from the INTERMAGNET fluxgate components appear to be reliable and comparable with magnetic records from the two other magnetometers in the observatory. This is because the permanent displacement of the magnetic sensors caused by the passing seismic waves is small.

Figure 6 is an enlarged view of Figure 5 in correspondence with the 6 April main shock. Total field data calculated from fluxgate measurements during the earthquake shaking (from 01:32:44 to 01:33:19 UT) are not reported in the figure but are shown in Figure S5 in the supporting information. Note that the transient signal in the total magnetic field record from the INTERMAGNET overhauser is not present in total field data calculated from the INTERMAGNET fluxgate components, as well as in total field data from the overhauser of the Helmholtz coil system. Thus, our analysis does not support the hypothesis that the transient might have been induced by an underground electric current. If an electric current was generated deep in the Earth's crust under L'Aquila area as a result of the 6 April main shock, it is unlikely that magnetic disturbances induced by this current were detected in the INTERMAGNET station only by the overhauser and not by the fluxgate 2 m away, as well as not detected by the second overhauser 60 m away from the INTERMAGNET station.

5. Conclusions

The relationship between the 6 April 2009 L'Aquila earthquake and changes in magnetic records is investigated. We have analyzed magnetic and seismic data from the Geomagnetic Observatory of L'Aquila and strong motion waveforms from a station 2 km away from the observatory. No anomalous change in magnetic field data prior to the arrival of seismic waves at the observatory is observed. Therefore, we rule out the generation of detectable magnetic disturbances resulting from an electric current induced during the earthquake rupture, because these disturbances should have been detected long before seismic waves. We rule

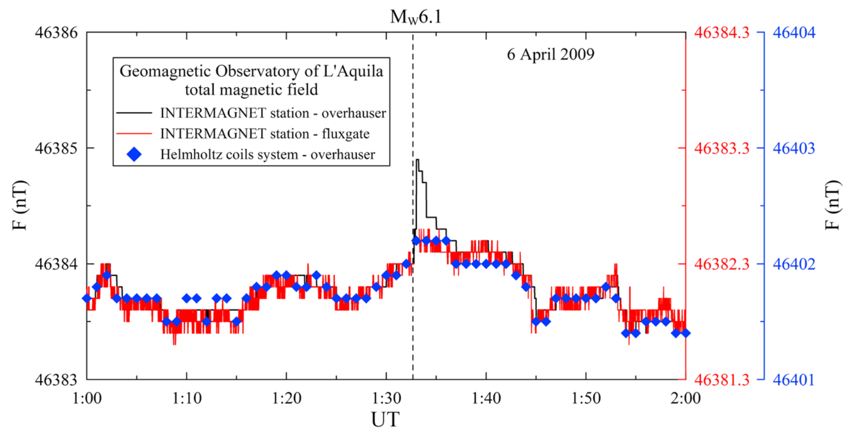

Figure 6. Enlarged view of Figure 5 from 01:00 to 02:00 UT. Total field data from fluxgate measurements during the shaking effect (from 01:32:44 to 01:33:19 UT) are not shown. The transient effect in the total magnetic field data from the INTERMAGNET overhauser is not present in the total field calculated from the INTERMAGNET fluxgate components, as well as in the total field from the second overhauser. See text for details.

out any possible local seismoelectric effect as well. Changes and offset in magnetic field components from fluxgate and induction magnetometers are caused by the passing seismic waves in the observatory, which induce the movement of the magnetic sensors through the Earth's magnetic field and a permanent displacement of the magnetometers from their original position. We have shown total magnetic field data from three magnetometers at the Geomagnetic Observatory of L'Aquila. We have found that the transient signal that can be seen in total magnetic field data from the INTERMAGNET overhauser magnetometer is not present in the measurements from the other two instruments. Thus, contrary to what is suggested by *Nenovski* [2015], our analysis rules out the hypothesis that this transient and the offset in fluxgate and induction magnetometers are effects that may have been generated by an electrification process as a result of the earthquake. Even if the origin of the transient is not clear yet, based on independent measurements we hypothesize that the magnetic transient in the INTERMAGNET overhauser record may be an instrumental effect.

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