Volcanomagnetic Evidence of the Magmatic Intrusion on 13th May 2008 Etna Eruption

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Abstract

During the onset of 2008 volcanic crisis at Mt Etna, the near-real time magnetic data provided a continuous updating of the volcano activity state on the northern flank. On the morning of 13th May 2008, significant local magnetic field changes marked the resumption of the eruptive activity characterized by the opening of a fracture field on the northern flank, and an eruptive fissure in the Valle del Bove. In agreement with the northward propagation of seismic events, magnetic signals at 5 stations in the summit area revealed a nearly NNW-SSE oriented magmatic intrusion, which started at about 9:00 GMT, propagated northward for about 2 km, and stopped at 14:00 GMT before reaching the North-East Rift. Magnetic variations, with amplitude ranging between 1.8 nT and -6.5 nT, are consistent with those calculated from piezomagnetic models, where stress-induced changes in rock magnetization are produced by the magmatic intrusion.

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Introduction

The volcanic activity of Mt Etna, during the last five years has been characterized by several eruptive events occurred at the base of the South East summit crater [Neri et al., 2008a]. These events, generally, started as passive flank effusions which lasted some hours, except the 2006 eruption, and were accompanied only by a constant increasing in the volcanic tremor amplitude, while no evident geophysical parameter changes, such as seismicity and ground deformation related to dike intrusion and fissure opening, were observed [Bonforte et al., 2008].

In the morning of 13th May 2008, an intense and superficial seismic swarm indicated resumption of Mt Etna eruptive activity. From 08:40 to 15:00 GMT more than 200 earthquakes, the largest being Ml 3.9, occurred in a NNW-SSE elongated area at the eastern base of Mt Etna summit craters, with hypocentral depth ranging between 1500 m b.s.l. and 1500 m a.s.l. Epicenters time pattern evidenced an almost stationary distribution in the upper flanks of the Valle del Bove until 9:30 GMT, then a clear migration of the seismic events occurred toward the top of the North-East Rift, suggesting a northward propagation of a magmatic intrusion. Earthquakes were accompanied by a gradual and intense increase in the intensity of volcanic tremor. The main release of seismic energy occurred up to 10:00 GMT when the tremor amplitude drastically decreased but returned to normal background levels only on 14th May [Patanè, 2008].

The volcanic activity was characterized by the opening of a fracture field on the northern flank of the volcano, and an eruptive fissure in the upper sides of the Valle del Bove. The fracture field, which remained dry (non-eruptive), is wide about 800 m and extended from the base of the North-East crater for 2000 m along the NNW-SSE direction. The eruptive fissure, 1400 m long and with a direction ranging between N140°E and N120°E, opened immediately to the East of summit craters and extending into the upper flanks of Valle del Bove, between 3055 m and 2620 m a.s.l. This fissure fed a flank eruption involving sustained strombolian activity, and lava emission [Neri, 2008b; 2008c]. At the time of writing the lava flow is still active.

Remarkable changes in the local magnetic field were observed on 13th May, in coincidence with the seismic swarm onset. In agreement with other available geophysical data, magnetic observations constrain the emplacement of a dike and its northward propagation, suggesting a possible evolution of the ongoing activity, which would have involved the reactivation of the North-East Rift. Below, we examine the magnetic data which gave hints about the spatio-temporal evolution of the magmatic intrusion on the northern flank. On the basis of the past activity, this scenario alerted the scientific community for the volcanic and seismic hazard related to the northern flank of the volcano [Andronico and Lodato, 2005].

Magnetic observations during May 2008

The permanent magnetic network of Etna set up in 1998 [Del Negro et al. 2002] was improved during recent years. At present, the network consists of 5 scalar magnetometers (BVD, BCN, PTL, PDN, DGL) and 2 magnetic gradiometers (CST, PDG), which simultaneously sample the Earth's magnetic field at 5 s. The magnetic gradiometer stations consist of two sensors (namely CSTsouth, CSTnorth, PDGsouth and PDGnorth) horizontally spaced by about 50 m. The magnetic reference station (CSR) is installed further west (about 27 km) on the Nebrodi Mountains (Fig. 1).

Magnetic field measurements are usually differentiated with respect to the reference station to isolate local magnetic field changes and cancel out common noise from ionospheric and magnetospheric sources. A daily mobile averaging with an overlapping window of 2 h is performed on magnetic data recorded in May to remove diurnal components (Fig. 2). No significant variations are observed before May 13th, while step-like variations at almost all stations are observed in time correspondence with the northward seismic swarm propagation. The total magnetic field undergoes an irreversible change. In Figure 2 the 10-minute means of total intensity variations on May 13th after removal of diurnal components using notch filter centered at 8, 12, and 24 h are shown. Until 09:00 GMT no significant changes were observed at all magnetic stations. Soon after, large negative changes in local magnetic field occurred at the stations placed on the northern flank of the volcano within a few hours coinciding with the quick epicentral migration of the seismic events from Valle del Bove toward the North-East Rift. The total intensity decreased by about 2.0 nT at PDN and 1.8 nT at PTL. Both sensors of PDG show the largest change among all the other sites. The total intensity of the magnetic field decreases more than 6.5 nT during the 5-hours period. The amount of the decrease falls off northward and no significant variations are observed at DGL. During the same period, the magnetic stations placed on the southern flank of the volcano show minor variations. Particularly, a negative change is detected at BVD (-1.8 nT), whereas the magnetic field at CST is almost unchanged. A slight positive variation of 1.8 nT was observed at BCN. The magnetic data clearly show a fast change from 09:00 to 10:00 GMT. In this time interval most of the earthquakes (about 150 of 230) were recorded [Patanè, 2008]. Then, a decrease in the rate of magnetic variations was observed from 10:00 to 14:00 GMT during which a fall in the earthquake rate was observed. We can rule out that the displacement of the sensors is the cause of these observed magnetic changes, since the monitoring sites have low magnetic gradient (2-3 nT/m at the sensor height of 4 m) and the recorded ground uplift does not exceed 0.1 m. After the seismic swarm ended, no further magnetic variations were detected at all stations.

Magnetic interpretation

A preliminary interpretation of magnetic data can be performed taking into account also evidences from other available geophysical data. The spatio-temporal evolution of seismic events seems to indicate the occurrence of a dike intrusion to a shallow depth ranging between 1500 m b.s.l. and 1500 m a.s.l. in the eastern slope of the NE crater. Changes in the local magnetic field are also in correspondence of tilt variations at PDN, where a change of about 100 μrad is observed since 09:00 GMT [Puglisi et al., 2008]. The magnetic changes could have resulted from stress redistribution due to magmatic intrusion. In these cases, the piezomagnetic effect is the primary mechanism that could justify the amplitude, the extent and the time-scale of the magnetic changes. The magnetic field changes might also be expected as a result of electrokinetic effects generated by fluid flow. However, to explain the observed rapid changes in terms of electrokinetics would require rapid and intense fluid flow. Thus, even if the electrokinetic mechanism cannot be ignored, we favor a more straightforward explanation in terms of the piezomagnetic effect. Therefore, we apply the formulation of Utsugi et al. [2000] for estimating the expected piezomagnetic field at the ground surface (Fig. 3). Model parameters were also constrained by the hypocentral location of the recorded seismic events.

The values of the parameters of the magneto-elastic medium used in these calculations are shown in Table I. The rock magnetization was calculated from surface samples near the various magnetometer sites [Del Negro and Napoli, 2002]. The Lame's constant were set up to $\lambda = \mu = 30$ GPa giving a Poisson's ratio of 0.25, a reasonable approximation to the values estimated in the upper crust on Mt Etna. Fig. 3 shows the calculated anomaly from the piezomagnetic model. Predicted values at the magnetometer sites provide a reasonable fit to the observed data.

This piezomagnetic model displays a response to a tensile mechanism coherent with an intrusion crossing the volcano edifice along a ca. NNW–SSE direction in the northern flank. The estimated intrusive dike, which explains the observed magnetic data, engenders a deformation pattern [Okada, 1992] that well fits the ground deformation (Fig. 3) recorded by the continuous GPS network operating on Mt Etna [Puglisi et al., 2008].

We disregard the eruptive fracture opened at the base of the SE crater. It would give only a minimal contribution to the piezomagnetic changes (few sub-nanoteslas) at the stations on the northern flank of the volcano, since it was quite shallow and located rather far away from the stations (Fig. 1). Piezomagnetic variations are not expected at the stations located on the southern flank, even if the fracture is nearer. Indeed, fracture openings occurred at the base of the SE crater during the 2004-2007 period did not ever engender significant magnetic variations. Since 2004, this zone has been affected by flank effusions and eruptive paroxysms consisting of the passive draining of magma which had resided in the shallow central conduit system [Burton et al., 2005]. Similarly to recent past activity, the opening of the eruptive fissure in the Valle del Bove was not accompanied by seismic events. Moreover, GPS data showed only a significant deformation pattern related to the northern intrusion [Puglisi et al., 2008]. Therefore, it is reasonable to hypothesize that the eruptive activity from this fracture did not engender high stress field, probably thanks to the increasingly fractured nature of this area [Bonaccorso et al., 2006], and hence no related piezomagnetic changes are expected. As a result, we associated the significant magnetic changes only to the northward propagation of the magmatic intrusion. Further evidence supporting this hypothesis is the presence of rapid coseismic magnetic changes clearly identified on the northern flank in correspondence of 4 most energetic seismic events (Fig. 4). Step-like magnetic variations with amplitudes from 0.5 nT to 1 nT have been detected in the 1-minute mean differences of the magnetic signals. Significant rapid changes are clearly seen at PDG station, where the gradiometer configuration allows to discriminate sub-nanotesla variations thanks to the 50 m horizontal distance between the two sensors. The gradient at PDG shows magnetic offsets of about 0.3 nT in coincidence of the seismic events.

Discussions and conclusion

The spatio-temporal evolution of magnetic variations has enabled to understand the mechanism of the volcanic activity resumed on 13th May 2008. After differential magnetic fields were filtered from the external noise [Del Negro et al., 2004], we detected conspicuous short-time changes accompanying the magmatic intrusion that occurred on the northern flank. The variations are clearly observed at all the summit sites, and the simultaneity and proximity in space indicate a common geophysical mechanism as source of the anomaly. In particular, a piezomagnetic origin related to the response of the Earth's crust under stress due to changes in gas pressure or magma injection or a combination of both was proposed. The position and the geometry of source, which could explain the total intensity changes, were estimated. We suppose that the volcanic crisis was triggered by magmatic overpressure of a magma batch, injected within the summit conduits, and when reached enough pressure to overcome the strength of the surrounding rocks a lateral propagation of a dike occurred along the eastern side of the summit craters. Lateral dike propagation produced an 800 m wide fracture field, which developed in a few hours in the northern flank of the volcano. The lack of significant seismicity during preceding days of the eruption onset, except the tremor increase associated with the 10th May lava fountain, indicated the fast propagation of magma. Magnetic variations, according with ground deformations, clearly indicate that a magmatic intrusion traveled between 09:00 and 14:00 GMT from the base of the NE crater toward the North-East Rift in the same area as the 2002 intrusion [Del Negro et al., 2004]. Then, in coincidence with the fall in seismic energy release, a decrease in the rate of magnetic variations was observed up to 14:00 GMT (Fig. 2). High stress field changes are expected at the dike-tip during its propagation. Numerical models indicate that a dike propagating through the crust under significant magmatic overpressure can exert very high stress fields rising between 10-100 MPa [Currenti et al., 2008]. The significant piezomagnetic changes at PDG confirm a very high stress gradient field at depth around the dike-tip as magma pressure builds in the fracture zone until rupture occurs and the fracture propagates [Currenti et al., 2007]. After 14:00 GMT no further magnetic variations were observed, and geomagnetic total intensity at all stations turned almost flat at a new level, suggesting that intrusion stopped and the stress field released. It is worth noting that, on 13th May no significant changes were observed at DGL station, which is located at the altitude of 2600 m, at about 2 km from PDG station, therefore dike did not propagate farther the PDG station and stopped before reaching the North-East Rift. Discrete gravity measurements carried out on 14th May along the North-East Rift did not show significant variations supporting that no new mass was here injected [Budetta et al., 2008].

Summing up, magnetic data allow to describe the most likely scenario occurred during the eruption. At around 9:00 GMT on 13th May magma was rapidly injected from the central conduit and laterally propagated along the northern flank for about 2 km producing a NNW-SSE fracture field, 800 m wide. Intrusion stopped at 14:00 GMT before reaching the North-East Rift structures and no lava emission occurred. The effusive activity from fissures in the Valle del Bove could have drained magma reducing the magma pressure of the northern intrusion.

Successively, no significant variations in all the monitored geophysical parameters were detected [Patanè, 2008; Puglisi et al., 2008] and the hazard alert level in the northern flank, related to the opening and propagation of eruptive fissure, was lowered. During the last 200 years the northern flank of the volcano has been affected by several eruptive events triggered by magmatic intrusion fed by the central conduit, which produced the opening of long eruptive fissures [Branca and Del Carlo 2005]. Lava flows emitted in this area are generally characterized by a high effusion rate and have seriously threatened, and some times destroyed the near inhabited areas as happened during the 2002 eruption [Andronico and Lodato, 2005]. All these aspects highlight that flank eruptions still represent a high hazard to populated areas and infrastructure located on this side of the volcano. To provide an effective early warning it is essential to image the spatial-temporal evolution of propagating dikes even in situations of very fast emplacement. Similarly to the 2001 and 2002-2003 eruptions [Del Negro and Currenti 2003; Del Negro et al 2004], remarkable changes of the local magnetic field observed at Mt Etna during the early stages of 2008 volcanic activity marked the opening of a magma-filled fracture (dike), which intersected the volcano flank within hours to form an eruptive fissure. Finally, magnetic data tracked dike propagation proving to be a key tool for monitoring Etna volcano and in particular for detecting and modeling the stress field evolution within the volcano edifice.

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Table

X center (km)	Y center (km)	Depth (m)	Length (km)	Width (km)	Strike	Dip	Opening (m)
4179	500.6	250	2.5	2	-20°	80°	2

Table 1 - Dike parameters of the piezomagnetic model. Magneto-elastic properties of the medium: magnetization 2 A/m, inclination 53.0°, declination 2°, stress sensitivity 0.0001 bar^{-1}, and rigidity 30 GPa.

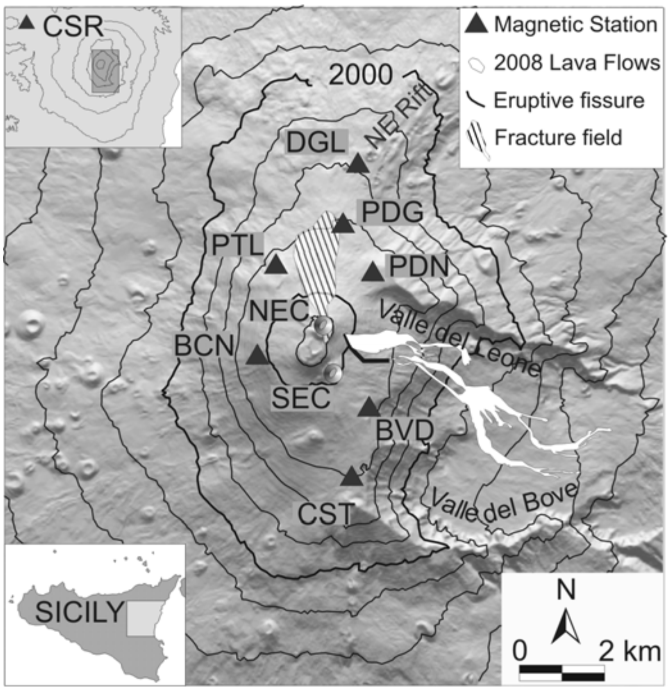

Figure 1 – Schematic map of the Etna summit area covered by the lava flows of the 2008 eruption. Locations of magnetic stations are also shown. Inset shows the position of the CSR reference station.

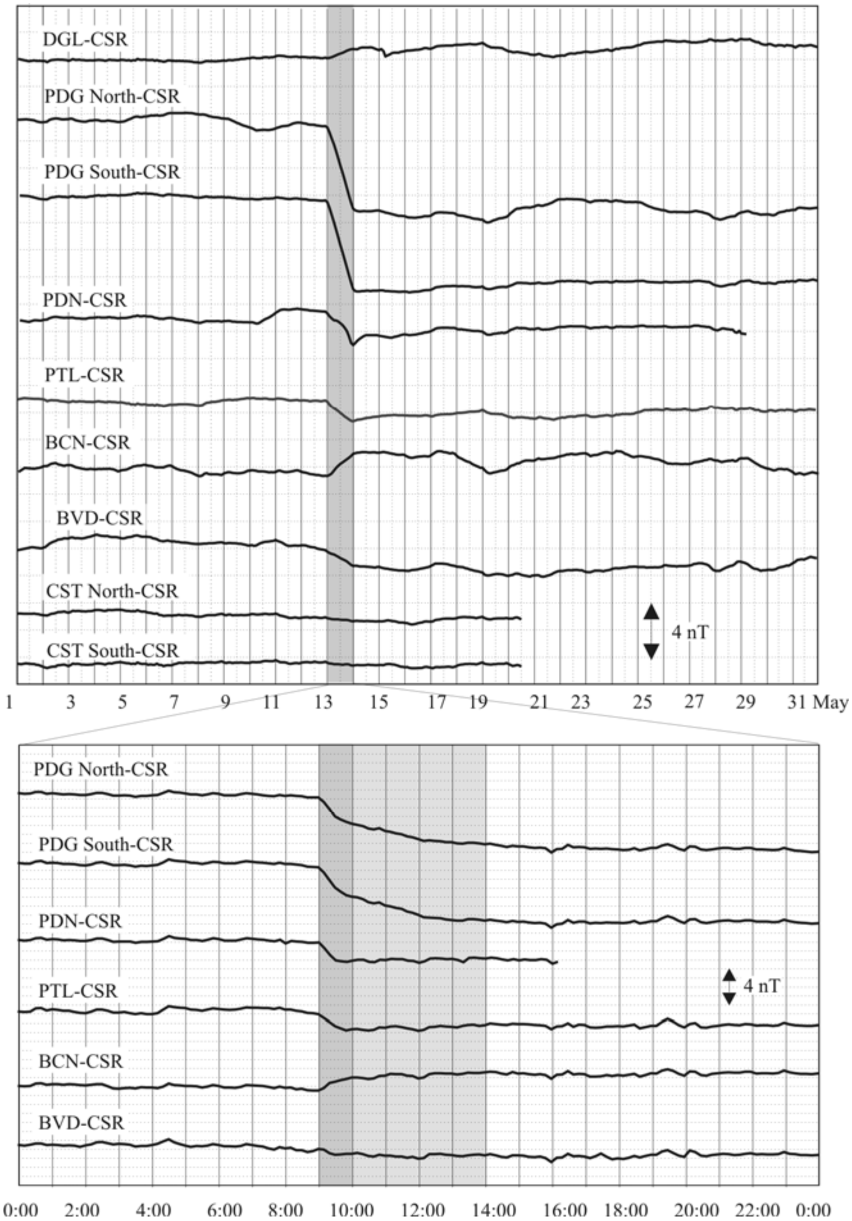

Figure 2 – Daily mean differences of total magnetic intensity with respect to CSR station in May 2008 (top). 10-minute means of total intensity variations on 13th May 2008 after removing diurnal components (bottom).

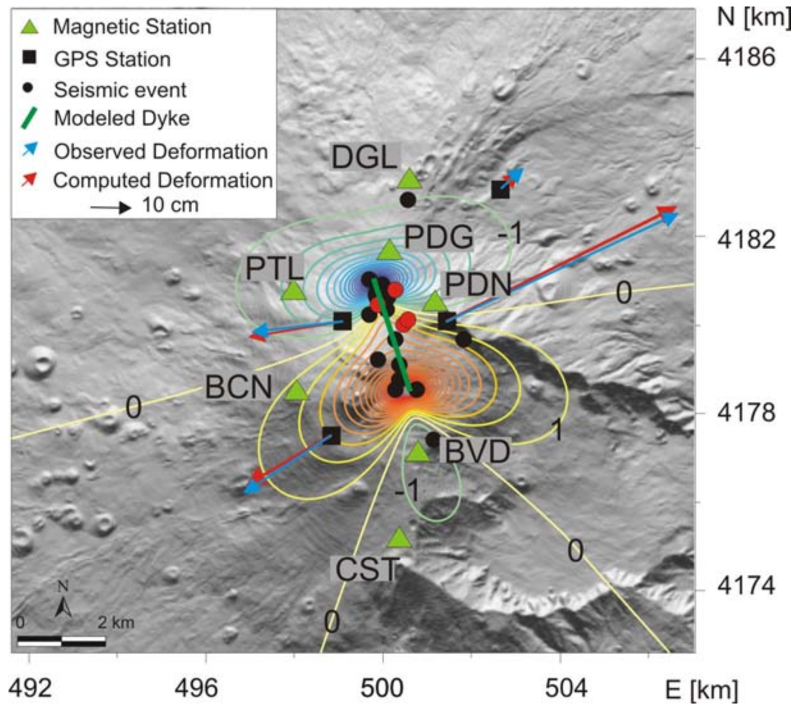

Figure 3 – Piezomagnetic anomaly (contour lines at 1 nT) generated by the intrusive dike. Observed [after Puglisi et al., 2008] and computed deformation at the summit permanent GPS stations are also reported. The epicenters of the most energetic seismic events are shown with circles [after Patanè, 2008]. The red circles are the seismic events in correspondence of the step-like magnetic changes. The coordinates are in UTM projection, zone 33 N.

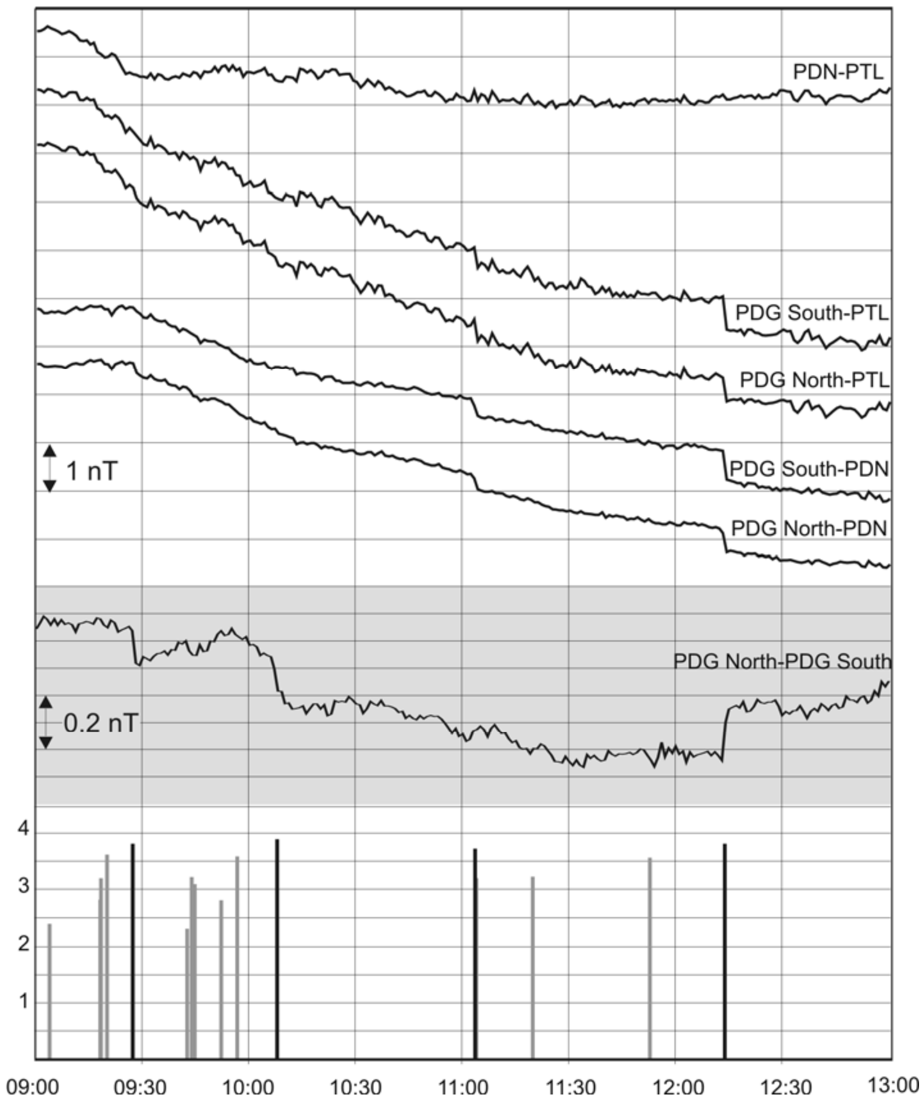

Figure 4 – Minute means of differenced magnetic field variations are showed at the stations on the northern flank (top). The minute means of the gradient signal at PDG is also reported (center). The seismic events [after Patanè, 2008] recorded at the time of step-like magnetic changes are highlighted in black (bottom).