Anomalous geomagnetic variations associated with the volcanic activity of the Mayon volcano, Philippines during 2009–2010

E.M. Takla [a],*, A. Yoshikawa [b,c], H. Kawano [b,c], T. Uozumi [c], S. Abe [c]

[a] *National Research Institute of Astronomy and Geophysics, Egypt*
[b] *Department of Earth and Planetary Sciences, Faculty of Sciences, Kyushu University, Japan*
[c] *International Center of Space Weather Science and Education, Kyushu University, Japan*

Abstract   Local anomalous geomagnetic variations preceding and accompanying the volcanic eruptions had been reported by several researchers. This paper uses continuous high-resolution geomagnetic data to examine the occurrence of any anomalous geomagnetic field variations that possibly linked with the volcanic eruption of the Mayon volcano, Philippines during 2009–2010. The nearest geomagnetic observing point from the Mayon volcano is the Legazpi (LGZ) station, Philippines; which is located about 13 km South of the Mayon volcano. The amplitude range of daily variations and the amplitude of Ultra Low Frequency emissions in the Pc3 range (Pc3; 10–45 s) were examined at the LGZ station and also were compared with those from the Davao (DAV) station, Philippines as a remote reference station. Both the LGZ and DAV stations belong to the MAGDAS Network. The result of data analysis reveals significant anomalous changes in the amplitude range of daily variations and the Pc3 amplitude at the LGZ station before and during the volcanic eruption of the Mayon volcano. From the obtained results, it appears that the observed anomalous variations are dependent on the change in the underground conductivity connected with variation in the physical properties of the Earth's crust due to the activity of the Mayon volcano. Therefore, these anomalous geomagnetic variations are considered to be of a local volcanic origin.
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1. Introduction

Observations and analysis of geomagnetic field measurements have been carried out in the vicinity of some active volcanoes in order to observe and detect any anomalous geomagnetic signals in association with the volcanic activities (Yukutake et al., 1990; Uyeda et al., 2002; Sasai et al., 2002; Okubo et al., 2006). Noteworthy observed geomagnetic field variations had been

considered as anomalous signals associated with some volcanic eruptions. These variations have small amplitudes, generally a few nTs; 5–15 nT (Rossignol, 1982). In addition, these previous studies are aimed to understand the generation mechanisms of the observed anomalous geomagnetic signals (Stacey et al., 1965; Johnston and Stacey, 1969; Tanaka, 1993; Uyeda et al., 2002). Generally, three mechanisms are widely accepted for explaining the occurrence of anomalous geomagnetic field variations associated with volcanic phenomena. The first mechanism is the Piezomagnetic effect that is related to changes in rock magnetization under varying crustal stress conditions accompanying the volcanic activities. The second one is the Electrokinetic effect due to the motion of electric charges associated with the underground fluid flow. The last one is the thermal effect related to thermal demagnetization/remagnetization of the volcanic rocks, which could be observed on the ground as anomalous geomagnetic signals (Yukutake et al., 1990; Tanaka, 1993; Okubo et al., 2006).

Continuous measurements of the geomagnetic field by ground magnetometer array are regarded as a powerful tool for monitoring volcanic activities. During the last few decades, a number of successful and promising results have been obtained from analyzing geomagnetic data recorded nearby some active volcanoes. Generally, short and long-term anomalous geomagnetic signals had been reported in association with geodynamic activities such as earthquakes and volcanoes. However, the number of observed anomalous signals related to volcanic activities is still small but some of these works are worth to be mentioned (Johnston and Stacey, 1969; Tanaka, 1993; Kotsarenko et al., 2005; Fujinawa et al., 2006).

The main aim of the present study is to analyze reliable geomagnetic data in the vicinity of the Mayon volcano at the Legazpi (LGZ) station, Philippines (Fig. 1), during the period

from August 2009 to December 2010 to look for geomagnetic anomalies that could be related to the activity of the Mayon volcano during that period. Conventionally, the comparison of geomagnetic field measurements near volcanoes and remote reference measurements can be used to observe and detect the anomalous signal associated with volcanic activities. Therefore, geomagnetic data from the Davao (DAV) station, Philippines were used as a remote reference station in the present study as shown in Fig. 1.

2. The geology and tectonics of the Mayon volcano

The Mayon volcano (13.26°N/123.69°E) forms the northern boundary of Legazpi City, the largest city in terms of population in the Bicol Region, Philippines, see Fig. 1. The Mayon volcano is the main landmark of Albay Province. In addition, the Mayon is the most active volcano in the Philippines having erupted over 48 times in the past 400 years (*The Philippine Institute of Volcanology and Seismology [PHIVOLCS]*; Catane et al., 2003).

The Mayon volcano is a symmetrical stratovolcano type capped by a small central summit crater. The cone is considered to be the world's most perfectly formed volcano for its symmetry, which was formed through layers of pyroclastic and lava flows from past eruptions and erosion. The upper slopes of the basaltic-andesitic volcano are steep averaging 35–40 degrees. It has frequent eruptions producing pyroclastic flows, mudflows and ash falls that repeatedly triggered large-scale evacuations. The Mayon's most violent eruption, in 1814, killed more than 1200 people and devastated several towns. Historical records of eruptions date back to 1616 and range from strombolian to basaltic plinian, with cyclical activity beginning with basaltic eruptions, followed by longer-term andesitic lava flows. Eruptions occur predominately from the central conduit and have also produced lava flows that travel far down the flanks. Pyroclastic flows and mudflows have commonly swept down many of the approximately 40 ravines that radiate from the summit and have often devastated populated lowland areas (*PHIVOLCS*).

Mayon volcano is part of the Pacific Ring of Fire. It is located on the eastern side of Luzon, near the Philippine Trench which is the convergent boundary where the Philippine Sea Plate is driven under the Philippine Mobile Belt. When a continental plate or belt of continental fragments meets an oceanic plate, the lighter continental material overrides the oceanic plate, forcing it down into the Earth's mantle. Magma may be forced through weaknesses in the continental crust caused by the collision of the tectonic plates. One such exit point is Mayon (*PHIVOLCS*).

3. The 2009–2010 eruption of the Mayon volcano

The PHIVOLCS raised the status from Alert Level 1 to Alert Level 2 on August 2009. On Wednesday, 28 October 2009 and 11 November 2009 minor ash explosions lasting for about one and three minutes respectively occurred in the summit crater.

Early in the morning of Tuesday 15 December 2009, a moderate ash explosion occurred at the summit crater. On 17 December 2009, there were five ash ejections with one reaching 500 ms above the summit, lava flows reached down to 1500 m below the summit, and incandescent fragments from the lava
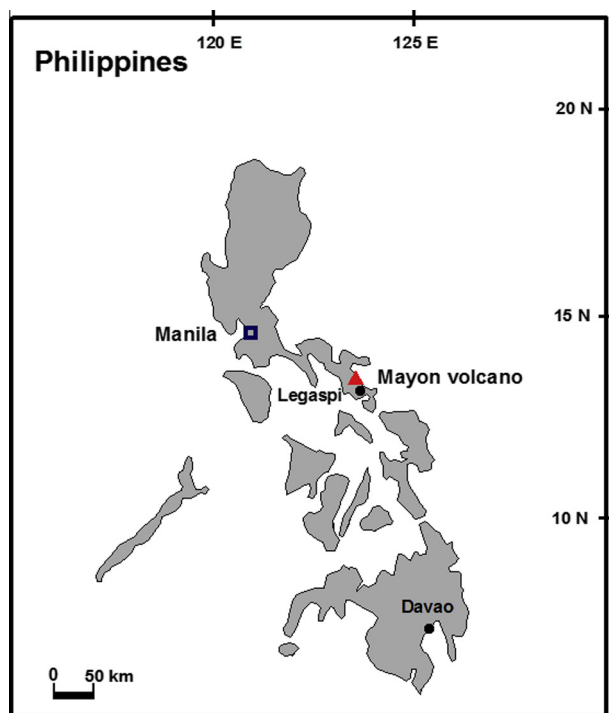

Figure 1 Location map shows locations of both the LGZ and DAV stations, and also the Mayon volcano, Philippines.

pile continuously rolling down Bonga Gully reached a distance of 3–4 km below the summit. PHIVOLCS raised Mayon's status level to alert level 4 because of an increasing lava flow in the southern portion of the volcano on 20 December 2009. Alert level 4 was maintained, as the volcano remained restive through the month of December, prompting affected residents to spend Christmas and the New Year in evacuation centers.

On 2 January 2010, PHIVOLCS lowered the alert level of the volcano from level 4 to level 3, citing decreasing activity observed in the past four days. The state agency noted the following observations as a trend of decreasing activity. On 13 January 2010, PHIVOLCS reduced the alert level from 3 to 2.

4. Instrumentation and data recording

The present study relies on geomagnetic data obtained from the LGZ (Geographic coordinates, 11.77°N and 77.16°E) and DAV (Geographic coordinates, 7.00°N and 125.40°E) stations. Both stations belong to the MAGDAS network in Philippines as shown in Fig. 1. The LGZ station is the nearest geomagnetic station from the Mayon volcano, while the DAV station is considered as a remote reference station.

The MAGDAS Project (*PI: Prof. A. Yoshikawa*) is Japan's most important contribution to the International Heliophysical Year and it belongs to the International Center of Space Weather Science and Education (ICSWSE), Kyushu University. The First MAGDAS magnetometer was installed in Hualien, Taiwan during May 2005 (Yumoto et al., 2006 and Yumoto et al., 2007). Since that time, more than 65 MAGDAS stations were installed all over the world. MAGDAS system is composed of two subsystems, which are MAGDAS-A and MAGDAS-B. MAGDAS-A consists of the magnetometer, data logger and data-transfer modules. MAGDAS-B is a subsystem of the MAGDAS to receive the data from MAGDAS-A, analyze the MAGDAS data and monitor the analyzed data and status of the oversea MAGDAS and CPMN stations (see Yumoto and 210° MM group, 1996; Yumoto, 2004).

The MAGDAS magnetometers are a 3-axis Fluxgate type. Three observation ranges of ±2000 nT, ±1000 nT, and ±300 nT can be selected for high, middle, and low-latitude stations, respectively. The resolutions of acquired data are 0.061 nT/LSB (Least Significant Bit), 0.031 nT/LSB, and 0.0091 nT/LSB for ±2000 nT, ±1,000 nT, and ±300 nT range, respectively (Yumoto et al., 2006). The noise level of the MAGDAS magnetometer is 0.02 nT. The sampling frequency is 16 Hz, but the instrument makes on-board calculations of the one second arithmetic averages of the 16-Hz data.

5. Data analysis and results

Geomagnetic data recorded at the LGZ station from August 2009 up to December 2010 were analyzed. We examined and measured the amplitude of geomagnetic daily variations (daily amplitude range) for the geomagnetic components during the whole studied period. Fig. 2 shows one day of geomagnetic data for the H, D and Z components recorded at the LGZ station on 21 September 2009. The daily amplitude range was calculated by subtracting the maximum and minimum values for each component, see Fig. 2. The variation in the daily amplitude range for the H and Z components recorded at the LGZ station as well as the EDst data during the studied period

are presented in Fig. 3. The EDst index is provided by the International Center for Space Weather Science and Education (ICSWSE), Kyushu University, Japan (Uozumi et al., 2008). Fig. 3 indicates significant anomalous changes in the daily amplitude of the geomagnetic components preceding and during the eruption period. The observed abnormal changes in the daily amplitude started a few months prior to the eruption with noteworthy changes during the eruption period (the period surrounded by a rectangle in Fig. 3). The anomalous changes occurred after the beginning of the activity of Mayon volcano that started around early August 2009. After the eruption, these anomalous variations were recovered and did not appear again during the studied period. To examine the source of these anomalous variations either an external or internal source, the EDst index during the same time interval was carefully checked as it shown in the upper panel of Fig. 3. From the EDst, there were no significant external geomagnetic variations during the volcanic eruption. To confirm that, we also examined the amplitude range of daily variations at the DAV station as a reference station during the same time interval. Fig. 4 shows the daily amplitude ratio (Z/H) for both the LGZ and DAV stations. As we can see in Fig. 4, the daily amplitude ratio (Z/H) at the LGZ station shows abnormal variation that occurred during the volcanic activity (the period surrounded by a rectangle in Fig. 4). On the other hand, we cannot observe such anomalous variation at the DAV station. The maximum abnormal variation occurred during the eruption time.

A number of previous studies had reported a remarkable anomalous variation in the geomagnetic pulsations nearby several volcanoes (Johnston and Stacey, 1969; Johnston, 1997; Kotsarenko et al., 2005, 2008). Therefore, in the present study, the amplitude of the geomagnetic pulsation (Pc3 range) is examined to detect any characteristic signals that may be generated in relationship with the activity of the Mayon volcano. The band-pass filter in the period range (10–45 s) was applied on the H and Z components recorded at the LGZ station during the period from August 2009 up to December 2010. After the band-pass filtering, the maximum and minimum peaks of the Pc3 amplitudes were determined for the wave train during the studied period in order to calculate the Pc3 amplitude by applying MATLAB scripts. The variations of Pc3 amplitude for the H and Z components recorded at the LGZ station are shown in Fig. 5 as well as the EDst index. The upper panel in Fig. 5 shows the EDst data during the studied period, while the last two panels show the daily averaged values of Pc3 amplitude for the H and Z components respectively. The red curves in Fig. 5 show the 10 day running average of daily average values, and the arrows indicate the timings of volcanic eruptions. The Pc3 amplitude of the H-component shows a decreasing trend during the volcanic activity. The maximum decrease occurred during the eruption time. Except the occurrence of two small peaks during the volcanic activity, there were no remarkable or clear anomalous changes in the Pc3 amplitude during the studied period for the Z component. To clarify the relationship between the variation in the Pc3 amplitude and the eruption of the Mayon volcano, we examined the Pc3 amplitude ratio (Z/H) as shown in the lower panel of Fig. 6. It is clear that there is a distinguished variation in that ratio as we can see in the period surrounded by a rectangle in Fig. 6. There is a gradual increase in the Pc3 amplitude ratio that started a few months before the volcanic eruption. The
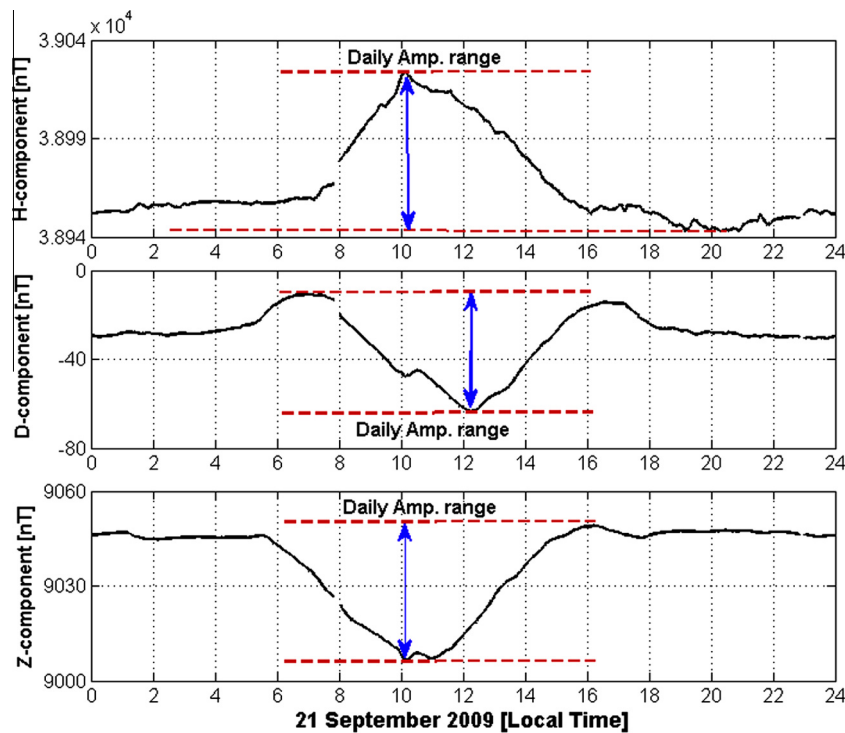
Figure 2 The three geomagnetic components (H, D and Z components) recorded at the LGZ station on 21 September 2009. The vertical blue arrows represent the daily amplitude range for each geomagnetic component.
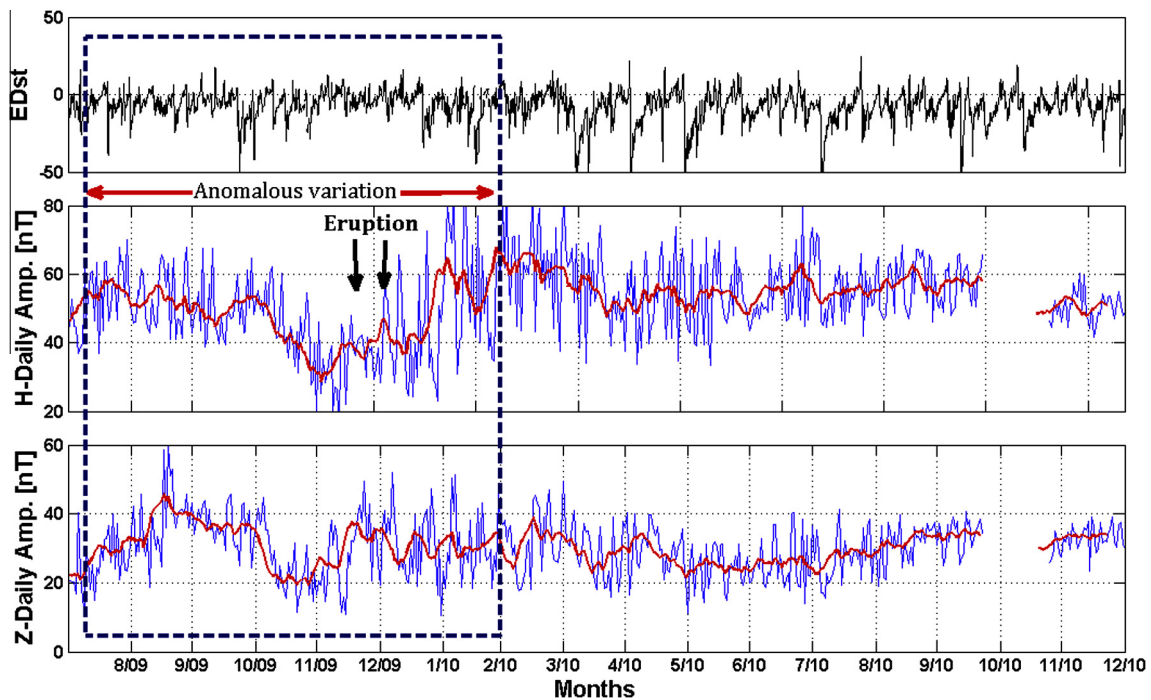

Figure 3 The upper panel shows hourly data of the EDst index from August 2009 until December 2010. The daily amplitude ranges for the H and Z components recorded at LGZ station during the same period are shown in the second and third panels respectively. The red curves show the 10 day running average.

maximum increase also occurred during the eruption periods. Here we can see evidence on a possible relationship between the variation of Pc3 amplitude and the volcanic eruption of the Mayon volcano. To confirm that observation, we examined the Pc3 amplitude ratio at the DAV station and compared it with that at LGZ station as we can see in the lower panel of
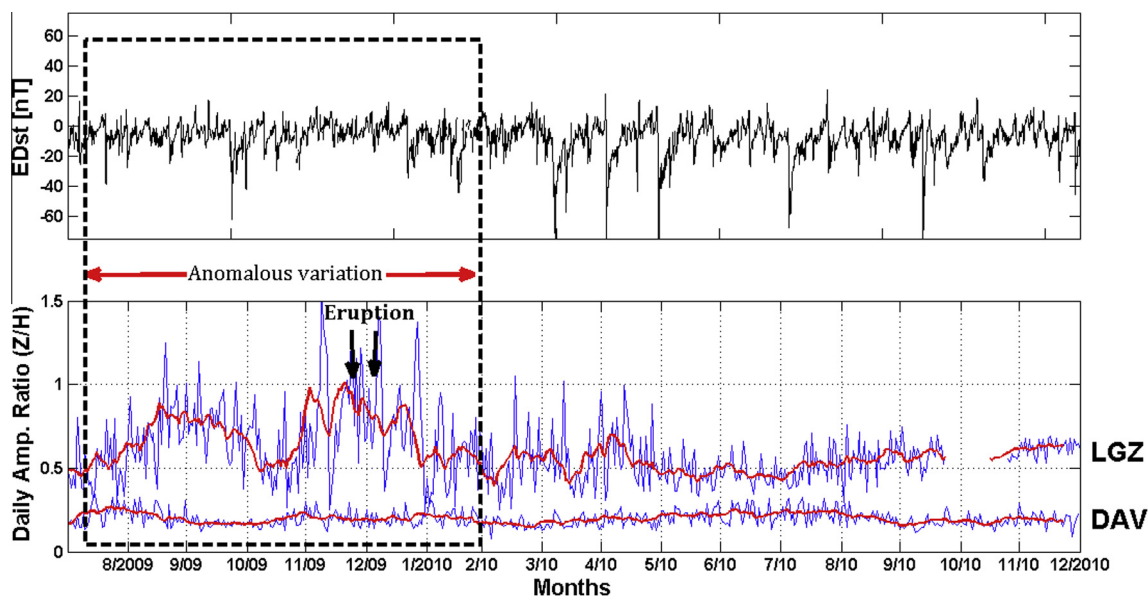
Figure 4 The comparison between the daily amplitude ratios (Z/H) at the LGZ and DAV stations. The red curves show the 10 day running average. The EDst data are represented in the upper panel to show that there were no remarkable external field variations during the eruption time.
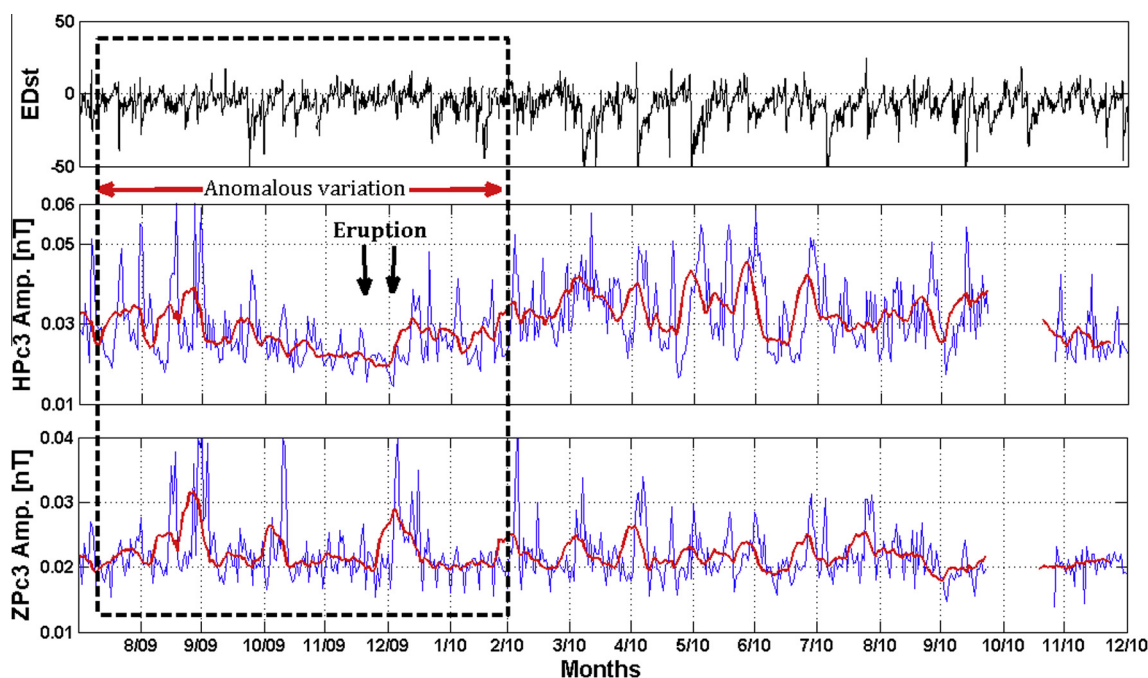

Figure 5 Hourly data of the EDst index from August 2009 until December 2010 are shown in the upper panel. The Pc3 amplitudes for the H and Z components recorded at LGZ station during the same period are shown in the second and third panels respectively. The red curves show the 10 day running average.

Fig. 6. The comparison between the two ratios indicates the occurrence of anomalous change in the Pc3 amplitude at the LGZ station with a maximum peak during the eruption stage. The anomalous variation recovered a few weeks after the eruption. The upper panel in Fig. 6 shows the EDst index between August 2009 and December 2010, which indicates that there are no remarkable external changes during the anomalous variations in the Pc3 amplitude ratio. It is noteworthy to state

that the Pc3 amplitude ratios from the two stations show no correlation during the activity period of the Mayon volcano (the period surrounded by a rectangle). On the other hand, there is a good correlation between the two stations after the eruption period as shown in the lower panel of Fig. 6.

After examining both the EDst index and the geomagnetic data recorded in the vicinity of the Mayon volcano (LGZ station) and those from a remote reference station (DAV station),
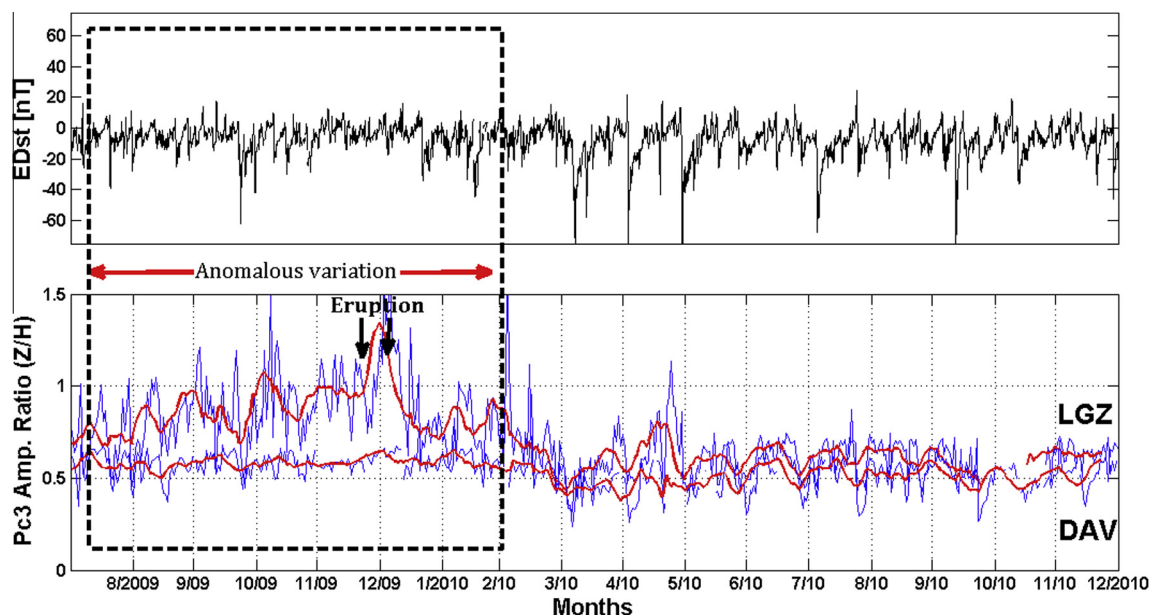
Figure 6 The comparison between the Pc3 amplitude ratios (Z/H) at the LGZ and DAV stations. The red curves show the 10 day running average. At previously mentioned, the EDst data indicate no remarkable external field variations during the eruption time as shown in the upper panel. The comparison indicates that the Pc3 amplitude ratios from the two stations show no correlation during the activity period of the Mayon volcano. On the other hand, there is a good correlation between the two stations after the eruption period as shown in the lower panel.

there is a high possibility that the observed anomalous variation (daily amplitude range and Pc3 amplitude) at the LGZ station has an internal origin linked with the activity of the Mayon volcano during 2009–2010.

6. Conclusion and discussion

Some studies examined the relationship between the geomagnetic field variations and the volcanic activities. Recently, the number of convincing cases of geomagnetic anomalies associated with volcanic activities is increasing significantly. This paper presents one case study showing anomalous geomagnetic variations that most probably linked with the eruption of the Mayon volcano during 2009–2010. Geomagnetic data from MAGDAS network at the LGZ and DAV stations were analyzed. The daily amplitude range and the Pc3 amplitude were examined at both stations along with the EDst index. The amplitude ratio (Z/H) for both daily amplitude range and Pc3 amplitude showed anomalous behavior at the LGZ station (nearby the Mayon volcano) in relationship to the activity of the Mayon volcano compared with those from a remote reference station (DAV) during the studied period.

Scientists are trying to find new tools to monitor the volcanic activity to not only help predict an eruption, but also to determine the intensity of eruptions. The amplitude ratio (Z/H) seems to be a promising tool to observe the anomalous geomagnetic field variations linked with volcanic activities. However, the amplitude ratio analysis is a simple method for extracting the anomalous geomagnetic variations associated with volcanic eruptions but at the same time it requires multiple-station analysis (reference stations). Only single station analysis is not adequate because the occurrence of anomalous

changes in the geomagnetic components depends on the relative location between the observing geomagnetic station and the eruption point.

In the present case study, the DAV station is selected as a remote reference station. The amplitude ratio analysis indicates a significant anomalous signal – at the LGZ station – preceding and during the 2009–2010 eruption of Mayon and it recovered after the eruption.

The origin of anomalous geomagnetic signal associated with the dynamic activities (earthquakes and volcanoes) has been theoretically investigated by several scientists (Rossignol, 1982; Del Negro and Ferrucci, 1994; Sasai et al., 2002, among many others). Generally, these anomalous geomagnetic signals are mainly related to the Piezomagnetic, Electrokinetic and Thermal effects. For the geomagnetic variations related to the volcanic activities, the problem is much more complex because the generation mechanism depends on the eruptive process involved and on the mechanical and physical properties of the volcanic edifices (Hattori, 2004). Most volcanic rocks have extremely low conductivity in the dry state; however, the conductivity can be enhanced by several orders of magnitude by the presence of water and/or high temperature (Quist and Marshal, 1968).

The observed anomalous changes in the geomagnetic field measurements can be an important tool for forecasting the volcanic eruptions, but the observed phenomena remain the object of future study to clarify the physical mechanism responsible for generating such observed anomalous variations.

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