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Research Article

Anomalous Geomagnetic Variations Possibly Linked with the Taiwan Earthquake (Mw = 6.4) on 19 December 2009

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On 19 December 2009, the eastern part of Taiwan at approximate depth of 45 km was struck by a strong earthquake (Mw = 6.4). The epicenter was located about 20 km away from the Hualien (HLN) station in Taiwan. By analyzing data from the HLN station and Amami Oshima (AMA) in Japan as a remote reference, the geomagnetic east-west (D) and vertical (Z) components recorded at the HLN station are showing no correlation with those at the AMA station in December 2009. Anomalous variations of ∼10–15 nT started about one week before the occurrence of the earthquake and lasted for about two weeks. Also, an enhanced ULF signal in the range of Pc 3 (10–40 s) was observed a few days before the onset of the earthquake. Moreover, the polarization ratio (Z/H (north-south component)) of the Pc 3 amplitude at the HLN station decreased a few days preceding the earthquake. The mechanism behind these anomalous variations is not fully understood. However, we expect that crustal stress perturbations and underground conductivity changes associated with the earthquake played an important role for generating such observed geomagnetic variations.

1. Introduction

The geomagnetic field measurable on the ground surface is not constant, and several sources can cause variations in the intensity of that field. The sources of such variations can be classified as either external or internal sources with respect to the earth's surface. The external variations are generally related to the solar wind and the magnetosphere, while the internal variations are mainly due to the induced and remanent magnetization within the lithospheric crust [1, 2]. Crustal geomagnetic anomalies are generally caused by the magnetic minerals that respond to the change in the planetary field or react to the crustal stress variations. During the tectonic processes, the changes in the mechanical properties of the earth's lithosphere can generate crustal geomagnetic variations [3]. Several theoretical and experimental studies examined the tectonomagnetic effect by studying the effect of stress variation on the rock magnetic properties [4–6].

The anomalous geomagnetic variations observed by ground-based measurements in association with earthquakes are generally accepted, and many studies have reported precursory phenomena (a few nT's) associated with some earthquakes (see [7–12], among many others). In general, the amplitude of the precursory anomalies can be correlated with the magnitude of the earthquakes (i.e., large precursory anomalies can be observed in association with large earthquakes) [13]. Furthermore, the precursory anomalies tend to occur closer to both the occurrence time and the epicenter of the earthquakes [14].

When and where upcoming earthquakes will occur is an important question that needs to be answered. Until now, no reliable answer has been given for such a question. As a result of the devastating effects of earthquakes, there is a great interest in the scientific community to predict both location and occurrence time of earthquakes. Recently, the geomagnetic anomalies associated with the tectonic stress variation are considered as one tool for the earthquake prediction research in Taiwan; mainly after the Chi-Chi earthquake that hit the center of the Taiwan Island on 21 September 1999. Clear

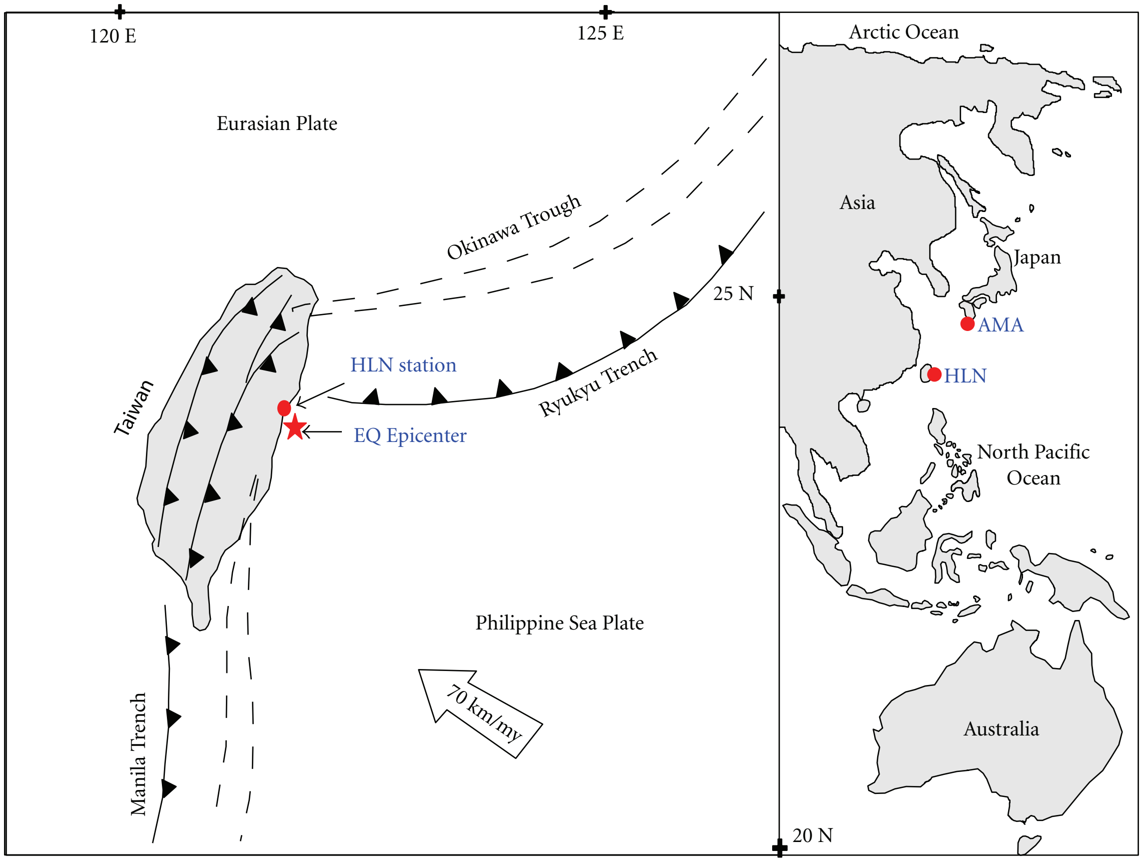

Figure 1: The plate boundaries and the tectonic elements near the Taiwan Island (after [16]) and also the locations of the HLN and AMA stations as well as the epicenter of the 19 December 2009 earthquake.

geomagnetic fluctuations were observed more than a month prior to the Chi-Chi earthquake [7].

The purpose of the present study is to examine the relationship between geomagnetic anomalies and seismic activity. Thus, we analyzed the geomagnetic data recorded at the HLN station in order to discover anomalous geomagnetic variations associated with the 19 December 2009 earthquake. Observations of the local variations in the geomagnetic field at the HLN station during 2009 have afforded us some evidence that the observed geomagnetic anomalies are linked with the above-mentioned seismic event.

2. The Tectonic Setting and the Taiwan Earthquake on 19 December 2009

The island of Taiwan is located in a seismically active zone at the boundary between the Eurasian plate to the west and the Philippine Sea Plate to the east as shown in Figure 1. The Philippine Sea Plate is being forced under the Eurasia plate in northeastern Taiwan, while the Eurasia plate is going beneath the Philippine Sea Plate in south Taiwan. At the subduction zone, the folding and thrust belts resulting from the compression lift the surface of Taiwan Island [15, 16]. Generally, from the geological point of view, Taiwan is a very young land mass and, still, developing island. The unique location of Taiwan at the conjunction point between the Eurasian and Philippine Sea plates leads to some geological structures at Taiwan such as folds, faults, and uplifting movements. Thus, Taiwan experiences frequent earthquakes. Most of the earthquakes detected in Taiwan are due to the convergence between the Philippine Sea plate and the Eurasian Plate especially in the east of the island [17, 18].

A strong earthquake (Mw = 6.4, 23.763°N, 121.689°E) hit Taiwan on Saturday, 19 December 2009 at 13:02 UTC. The epicenter was located in the eastern part of Taiwan Island (near Hualien) at an approximate depth of 45 km; see Figure 1. This earthquake occurred as a result of the collision between the Philippine Sea Plate and the Eurasian Plate (US Geological Survey).

3. Instrumentation and Data Acquisition

The MAGnetic Data Acquisition System, MAGDAS Project (PI: Professor K. Yumoto), is recently considered the world's largest array of magnetometers. The project effectively started in May of 2005, with the first installation of the MAGDAS magnetometer at Hualien, Taiwan [19, 20]. Installation at Taiwan was just the starting point and after that, over 50 MAGDAS realtime magnetometers have been installed all over the world.

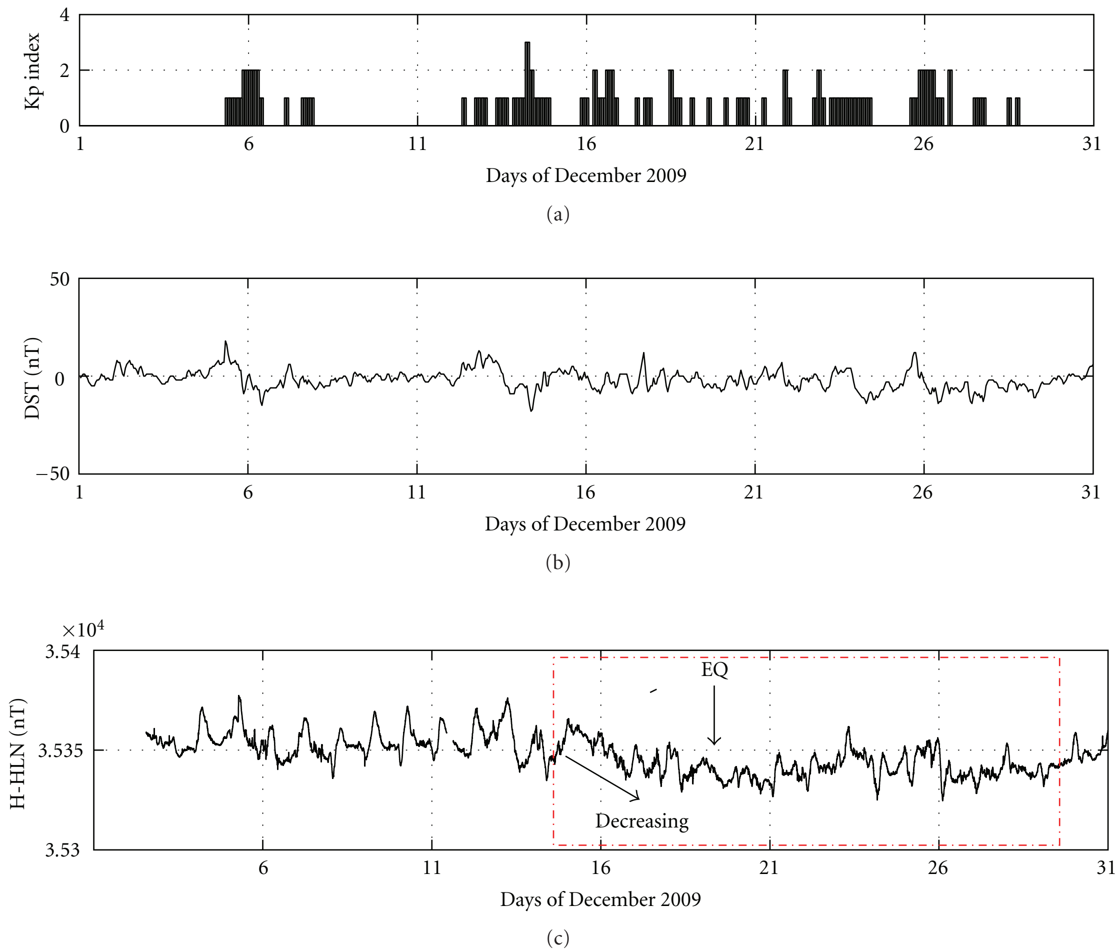

Figure 2: The comparison of the H-component recorded at the HLN station with the Dst and Kp index data from World Data Center (WDC) for Geomagnetism, Kyoto. The rectangle indicates to the abnormal variation of crustal origin in the H-component. It has been revealed from the DST and Kp index that there is no significant external field variation during the occurrence time of the earthquake.

The magnetometer installed at the HLN station is called MAGDAS magnetometer. The MAGDAS magnetometer is a ring core-type fluxgate magnetometer that can measure even small-amplitude geomagnetic fluctuations. It has three sensors along three orthogonal directions and measures the three components of the geomagnetic field (north-south component (H), the east-west component (D), and the vertical component (Z)). Three observation ranges of ±2,000 nT, ±1,000 nT, and ±300 nT can be selected for high, middle, and low-latitude stations, respectively. The resolutions of MAGDAS data are 0.061 nT/LSB (least significant Bit), 0.031 nT/LSB, and 0.0091 nT/LSB for ±2,000 nT, ±1,000 nT, and ±300 nT range, respectively [19]. 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 1-second arithmetic averages of the 16 Hz data. The acquired geomagnetic data are transferred from the overseas stations to Space Environment Research Center (SERC), Japan in near realtime. Also, the same data are stored in a compact flash memory card in situ.

4. Data Analysis, Results, and Discussion

4.1. Short-Term Anomalous Fluctuations in the Geomagnetic Components. One-minute averaged data of the H-component from the HLN station in Taiwan (geographic coordinates, 23.9°N and 121.55°E) were compared with the Dst and Kp index data from the World Data Center (WDC) for Geomagnetism, Kyoto, in December 2009 as shown in Figure 2. The H-component at HLN station showed abnormal decreasing pattern which started about one week before the occurrence of the earthquake. The comparison indicates that the observed geomagnetic fluctuation in the H-component at the HLN station (bounded by a rectangular in Figure 2) was not related to an external source, since the Dst and Kp index did not indicate any abnormal external variations or activity.

To identify any anomalous geomagnetic field variations associated with earthquakes, the variations originating from the external sources such as the solar wind and the magnetosphere should be removed. A simple technique

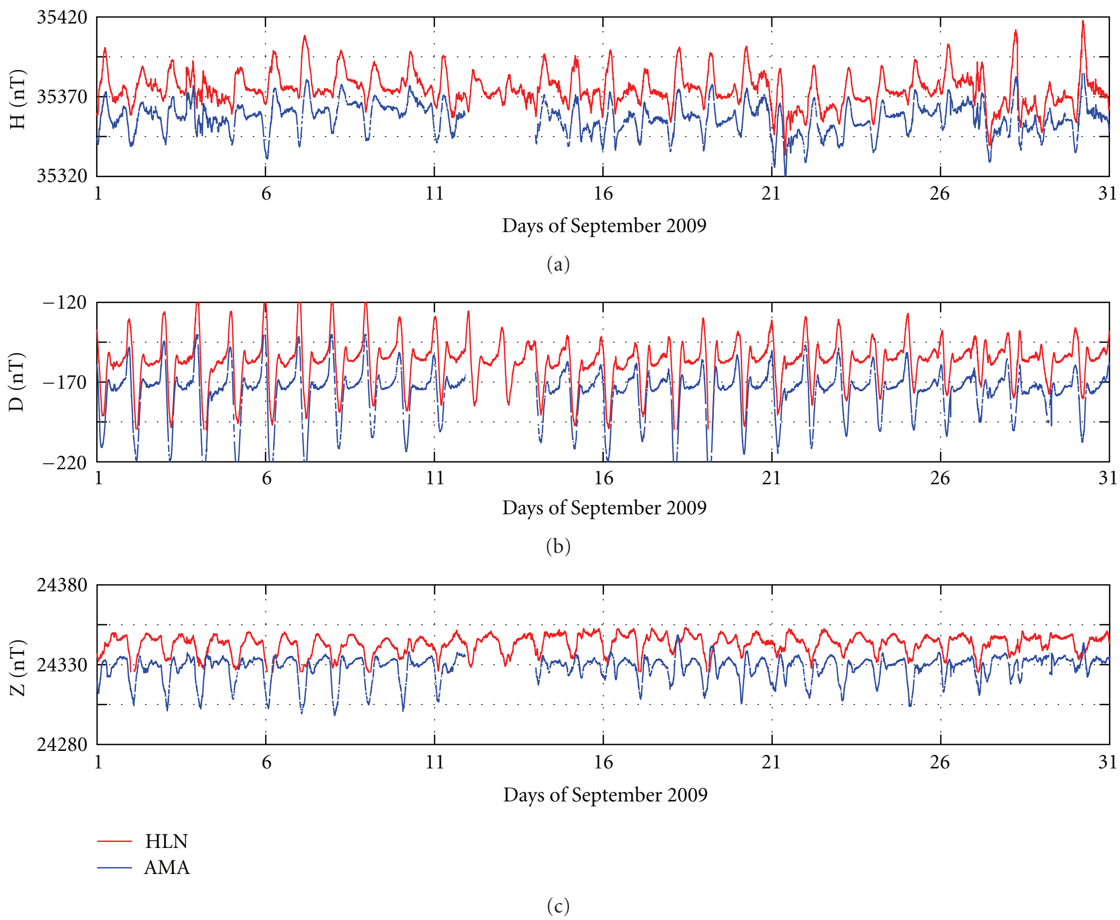

Figure 3: One-minute average values of the H (a), D (b), and Z (c) components recorded at the HLN (red curves) and AMA (blue curves) stations in September 2009.

to obtain this aim is to calculate the differences of the geomagnetic data recorded at a station near the epicenter and other remote reference stations that are located outside the epicentral region [21, 22]. The HLN station is located about 20 kilometers from the epicenter of the 19 December 2009 earthquake. So, we compared the geomagnetic data obtained from the HLN station with those at the Amami Oshima (AMA) station (geographic coordinates, 28.17°N and 129.33°E) in Japan as a remote reference station (about 900 kilometers away from the epicenter); see Figure 1. Since the intensities of the geomagnetic field at the HLN and AMA stations are not the same, we added (plus or negative) certain values to the geomagnetic components (H, D, and Z) recorded at the AMA station in order to plot the two sets of geomagnetic data together in one plot (i.e., we just shifted the baseline of the AMA data). Figures 3 and 4 show the comparisons between the geomagnetic data recorded at the HLN (the upper red curves) and AMA (the lower blue curves) stations in September and December 2009, respectively. Figure 3 shows normal geomagnetic field variations at the HLN and AMA stations; no abnormal fluctuations were observed except the observation of some baseline variations appeared in the H-component. These anomalous variations in the H-component were apparent due to an external source as it revealed from the Dst index data. On the other hand, clear anomalous fluctuations were observed in the H-, D-, and Z-components recorded at the HLN station in December 2009 as shown in Figure 4. These anomalous geomagnetic fluctuations started about one week before the occurrence of the earthquake and lasted for about two weeks.

Furthermore, the differences between the geomagnetic components recorded at the HLN and AMA stations (HLN-AMA) from August to December 2009 were calculated as shown in Figure 5. The nighttime data (1100–2100 UT (local time at HLN $\approx$ UT + 8)) were used to avoid the magnetic diurnal variations and other daytime geomagnetic variations. Figure 5 reveals that the differences fluctuated significantly about one week before the earthquake and lasted for about two weeks. The amplitudes of these geomagnetic fluctuations were about 10–15 nT. Thus, we expect that the observed anomalous fluctuations at the HLN station in December 2009 had an internal (crustal) source related to the seismic event on 19 December 2009. In addition, the same anomalous variations in the H-, D-, and Z-components that occurred in December 2009 were also observed in the beginning of August 2009 but with smaller magnitude. We found that two earthquakes occurred on 2 and 11

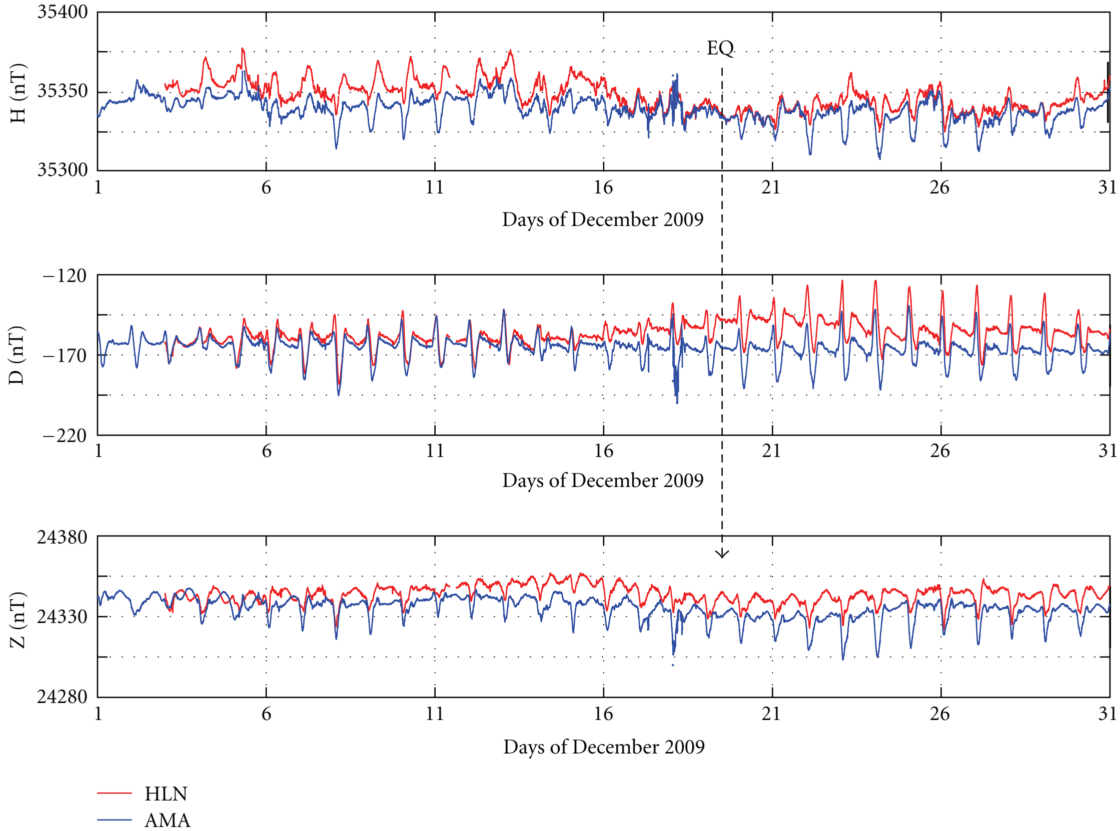

Figure 4: One-minute average values of the H- (top), D- (middle), and Z- (bottom) components recorded at the HLN (red curves) and AMA (blue curves) stations in December 2009.

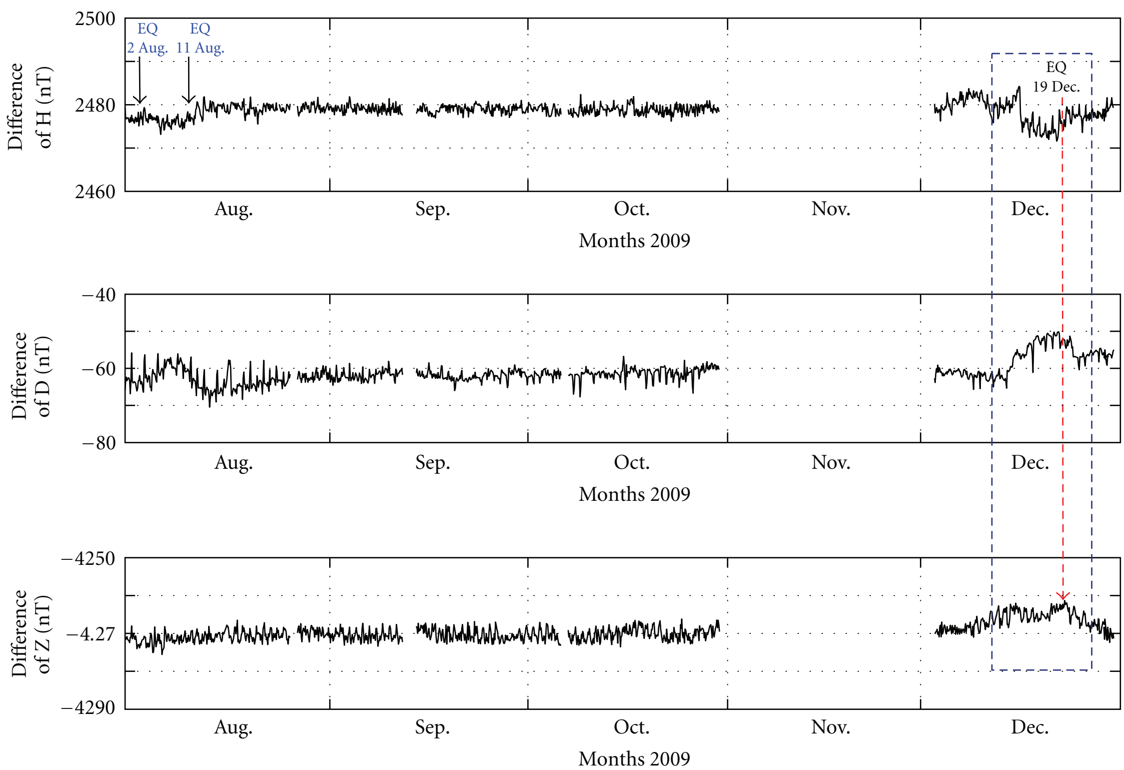

Figure 5: The differences between the hourly averaged values of the H-, D-, and Z-components recorded at the HLN and AMA stations between August and December 2009 during nighttime (1100–2100 UT).

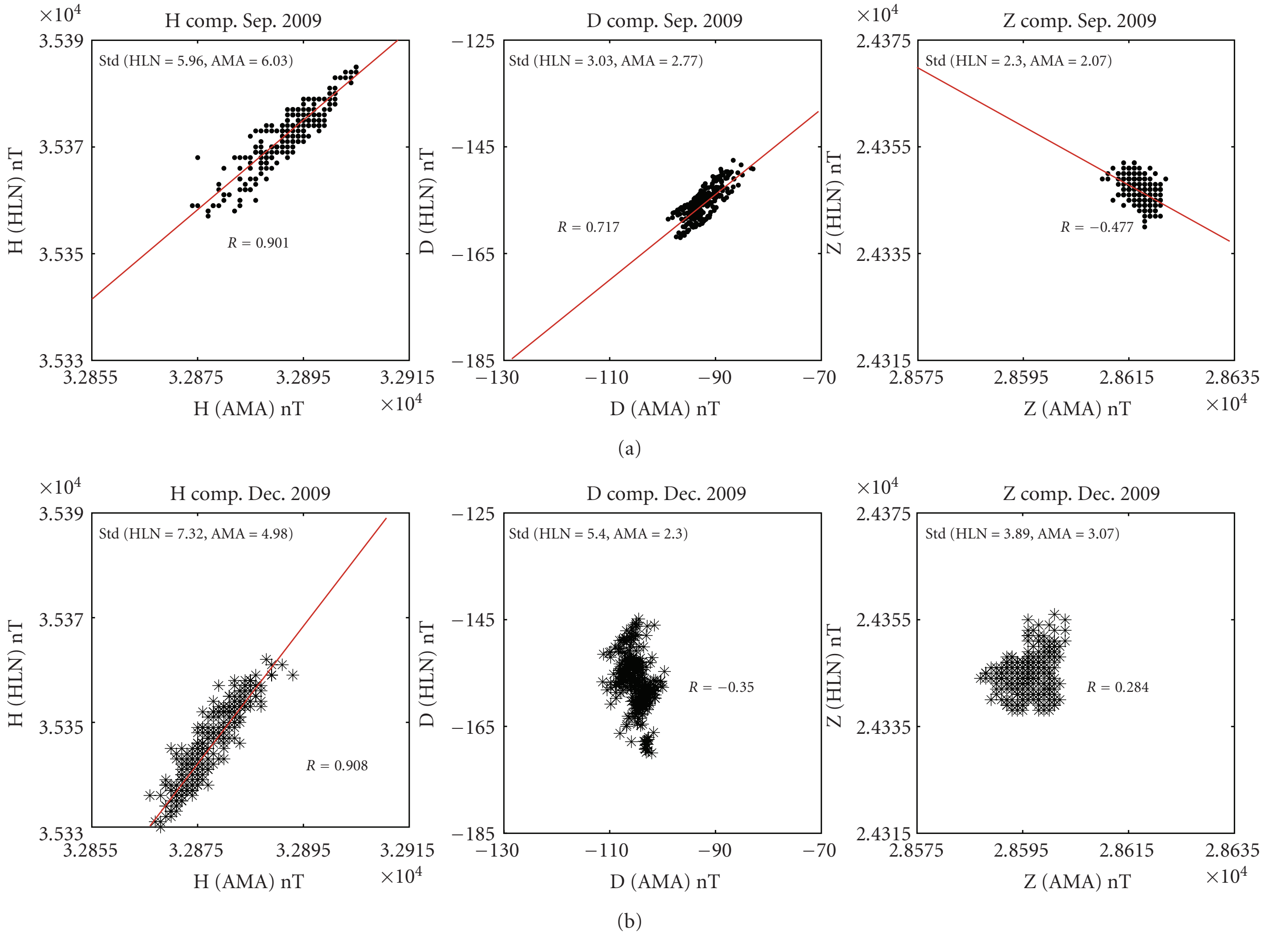

Figure 6: The correlation plots of the geomagnetic data acquired at the HLN and AMA stations in September (a) and December 2009 (b) with the standard deviation value for each component during the two months (nighttime data 1100–2100 UT).

August 2009 with magnitudes 4.5 and 4.3, respectively, as shown in Figure 5. The epicenters of these earthquakes were located about 40 km away from the HLN station. Since these earthquakes had relatively small magnitudes, so the observed geomagnetic anomalies related to these earthquakes were smaller than those occurred in association with 19 December 2009 earthquake.

The correlations between each geomagnetic component at the HLN and AMA stations were plotted for the hourly averaged values of the nighttime data in September and December 2009 as shown in Figure 6. The correlation coefficient (R) values became smaller in December 2009 compared with those in September 2009; see Figure 6. In September 2009, positive correlations between the HLN and AMA stations are found at the H- and D-components while the Z-component showed a negative correlation. In December 2009, the H-component correlation plot between the HLN and AMA stations was still showing a positive linear correlation, but the D-, and Z-components correlation plots between the HLN and AMA stations showed no correlation. We found that the geomagnetic data recorded at the HLN station in December 2009 show anomalous behavior compared to that recorded in September 2009. The hourly values of the D- and Z-components recorded at the HLN station during the nighttime of December 2009 were much more scattered than those recorded in September 2009. Moreover, the dynamic range of variations for the H-, D- and Z-components at the HLN station in December 2009 became large compared with that of September 2009 and also compared with the variations ranges of the geomagnetic components at AMA station. The standard deviation (Std) values for H-, D-, and Z-components recorded at the HLN and AMA stations were almost the same in September 2009. In contrast, the Std values at the HLN station became larger in December 2009.

4.2. Short-Term Anomalous ULF Signal. Ultra low frequency (ULF) emission is recently considered as one of the precursors of earthquakes. The early ULF observations were carried out in California to study the anomalous electromagnetic signals associated with the Loma Prieta earthquake on 18 October 1989. The observed anomalous ULF activities were considered as precursor signals before the Loma Prieta earthquake [23, 24].

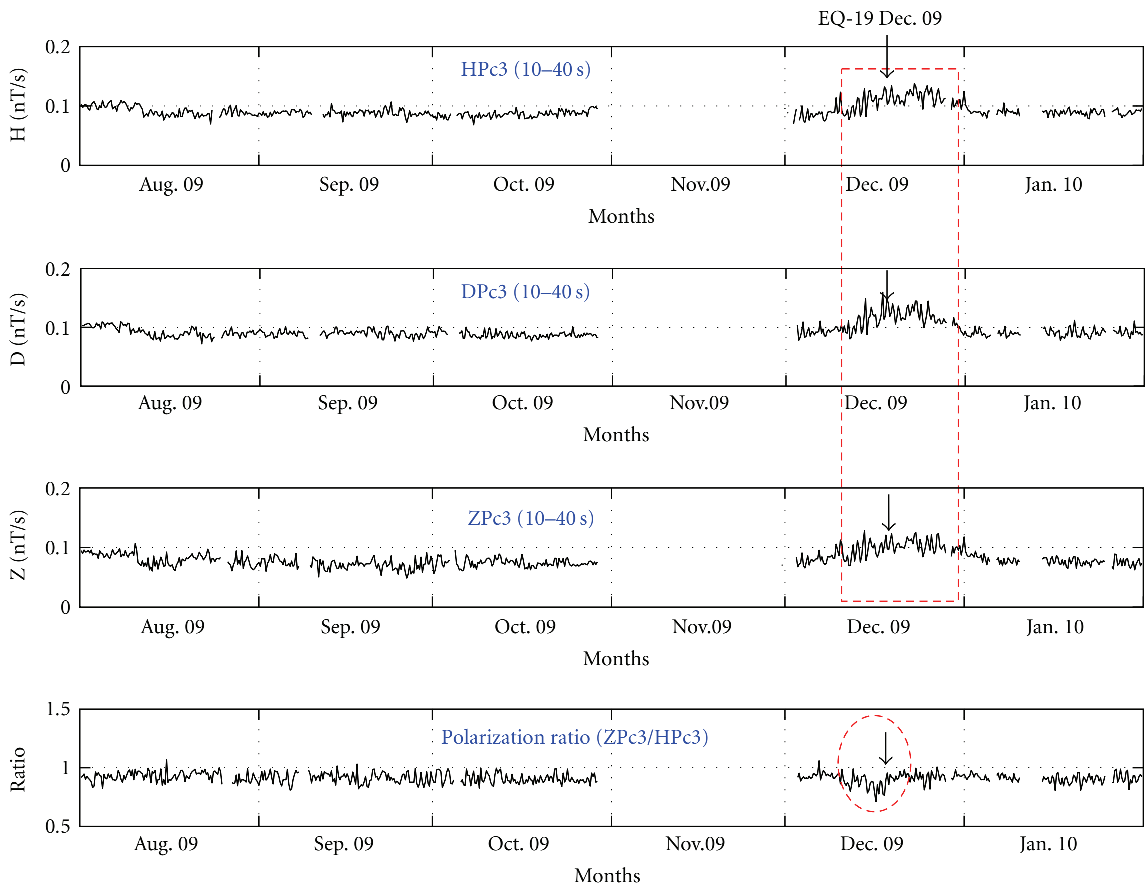

FIGURE 7: Six-hours average values of the Pc 3 amplitude of the geomagnetic components (H, D, and Z) at the HLN station between August 2009 and January 2010 (band-pass filter (10–40 s)) and the Polarization ratio Z/H of Pc 3 (10–40 s) amplitude observed at the HLN station during the same period (the lower panel).

Recently, many studies have reported the occurrence of anomalous electromagnetic signals in different frequency ranges associated with the seismic activities ([12, 22, 25–28], among many others). Furthermore, the ULF signal observed in Taiwan (at about 130 km away from the epicenter of the Chi-Chi earthquake) was considered as a precursory signature for the Chi-Chi earthquake [29].

In this study, we present some observations and preliminary results of the geomagnetic pulsations (10–40 s) that maybe associated with the seismic activity that occurred on 19 December 2009 in Taiwan. To discover some ULF signature of the 19 December 2009 earthquake, the electromagnetic activity at the HLN station was examined. The natural emissions (ULF signals) are radiated from the hypocenter of earthquakes due to some tectonic processes during their preparation phase. Moreover, an enhancement of the ULF amplitude can occur as a result of some changes in the conductivity of the lithosphere (for more details, see [22]). In order to examine the possible occurrence of any anomalous ULF signal in the time interval preceding the seismic activity near the HLN station, we applied the band-pass filter in the period range (10–40 s) for the geomagnetic data recorded at the HLN station. Figure 7 shows the six-hour averaged values of the Pc 3 amplitudes (10–40 s) for the H-, D-, and Z-components at the HLN station between August 2009 and January 2010. The relation between the variation in the Pc 3 amplitude and the onset of the earthquake was clear. There was an enhancement in the Pc 3 amplitude a few days before the onset of the earthquake.

For further understanding of the relationship between the ULF emissions and the occurrence of the seismic event, we calculated and plotted the polarization ratio (Z/H) for the Pc 3 pulsations [22, 30]. We found that the onset of the seismic event in the region was correlated with the change in the polarization ratio. There was a good correlation between the occurrence time of the earthquake in December 2009 and the polarization ratio Z/H, where there was a decrease in the polarization ratio (Z/H) at the HLN station that started a few days before the onset of the 19 December earthquake (the lower panel in Figure 7).

5. Discussion

Most of the observed geomagnetic variations related to the tectonic activities were in the range of a few to 10 nT's, although large geomagnetic variations have been observed before. In China, Zhu [31] indicated about 20 nT variation in the total intensity of the geomagnetic field that was observed about 15 months prior to the 1975 Haicheng earthquake (M7.3). Yen et al. [7] indicated a variation of about 200 nT prior to the Chi-Chi earthquake in Taiwan. Recently, Moldovan et al. [32] reported about 40 nT variation observed at about 70 km far away from the epicenter of an earthquake with moderate magnitude ($M = 5$). The analysis and comparisons of the geomagnetic data at the HLN and AMA stations indicate the presence of anomalous geomagnetic variations (10–15 nT) at the HLN station in December 2009. These variations maybe linked with the earthquake on 19 December 2009 as shown in Figures 4 and 5.

Previously, different mechanisms were purposed to explain the observations of anomalous geomagnetic variations related to the earthquakes. Generally, changes in the magnetic susceptibility, conductivity, remanent and induced magnetization of the rocks as a piezomagnetic effect [4, 6, 33] or changes of the underground conductivities and the earthquake-related currents along the fault planes [34, 35] can cause such geomagnetic changes in association with the seismic activities.

The generation mechanism of the observed anomalous fluctuations in December 2009 is not fully understood. Freund [36] interpreted the variation in geomagnetic field that occurred prior to the Chi-Chi earthquake in Taiwan as a result of the earthquake-related underground electric currents along the fault plane. On the other hand, Yen et al. [7] interpreted such anomalous variations as a result of the accumulation and release of stress related to Chi-Chi earthquake. We expect that during the preparation period of the earthquake (on 19 December 2009), the stress accumulation led to an enhancement of the conductivity structure of the lithosphere as well as a rotation in the geomagnetic vectors near the HLN station. Thus, our observed geomagnetic fluctuations (10–15 nT) can be interpreted as seismomagnetic variations due to the crustal stress perturbation (the process of stress accumulation and release) related to the 19 December 2009 earthquake.

Concerning the ULF signal, a number of mechanisms have been proposed to explain the generation of ULF precursory signals. The first possible mechanism is the so-called piezomagnetic effect, where a secondary magnetic field is induced due to a change in rock magnetization in response to stress variations [33]. The second possibility is the microfracturing processes due to the relaxation of the charges at the walls of crack openings [37]. The third mechanism is the electrokinetic effect due to water diffusion through the stressed rock or the flow of ground water in the fracture zone [38]. Finally, Merzer and Klemperer [35] proposed that the generation of the ULF signal associated with the Loma Prieta earthquake can be related to the formation of a high conductive layer along the fault zone. Moreover, Chi et al. [39] proposed that the amplitude of the ULF activity can be approximated by using the following equation:

$$A = B[f(t)]\sigma, \tag{1}$$

where A is the approximate wave amplitude observed on the ground, B is the magnitude of the wave event, $f(t)$ is the local time dependence, and σ is amplification factor which depends on the underground conductivity structure. In our case, the stress accumulation preceding the 19 December 2009 earthquake can drive the underground fluids and led to an enhancement of the underground conductivity. In this case, σ (near the HLN station) will have a high value, thus the amplitudes of the ULF signal will also have high values. Therefore, the enhancement in the Pc 3 (10–40 s) amplitude in December 2009 (see Figure 7), can be linked with the 19 December 2009 earthquake.

6. Summary and Conclusion

In the present study, we deal with geomagnetic anomalies related to the seismic event that occurred on 19 December 2009 in Taiwan. We analyzed geomagnetic data acquired at the HLN station for about 6 months between August 2009 and January 2010. Data from the AMA station, Japan, was used as a remote reference. The geomagnetic data at the HLN station (in the vicinity of the epicenter) were compared with those at the AMA station (about 900 km away from the earthquake epicenter). We tried to find out if there is any signature of the geomagnetic field in December 2009 seismic event or not.

The comparison between the geomagnetic data at the HLN station and those at the AMA station revealed the presence of short-term baseline fluctuations in the geomagnetic components (HDZ) at the HLN station that started about one week prior to the occurrence of the earthquake and lasted for about two weeks. The correlations of H-, D-, and Z-components (hourly values during nighttime) at the HLN and AMA stations showed positive, positive, and negative linear relations, respectively, in September, 2009. On the other hand, the D-, and Z-component between the HLN and AMA stations showed scattered non-correlations in December, 2009. In addition, the values of the correlation coefficient became smaller in December, 2009, compared with those in September, 2009. These anomalous geomagnetic fluctuations had amplitude of $\sim$10–15 nT. Concerning the anomalous ULF signal, there was an enhancement in the Pc 3 amplitude (10–40 s) a few days before the onset of the earthquake. Also there was a good correlation between the onset of the seismic event and the polarization ratio (Z/H) of the Pc 3 (10–40 s).

The short-term (order of days) magnetic baseline fluctuations and the anomalous ULF signal at a station near the epicenter can be useful in the future for earthquake warnings.

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