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Analysis of ULF Geomagnetic Anomalies as Earthquake Precursor Indicators in Bengkulu

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ABSTRACT

Earthquake prediction remains an unresolved scientific challenge, motivating extensive efforts to identify physical phenomena that can serve as reliable precursors to seismic events. This study investigates Ultra Low Frequency (ULF) geomagnetic signal anomalies using the ratio of the vertical to horizontal geomagnetic field components (Z/H) as potential earthquake precursor indicators. In addition, the relationship between anomaly amplitude and earthquake characteristics is evaluated. The analysis utilizes geomagnetic H and Z component data recorded at the Kepahiang Geomagnetic Station (KPY), earthquake events with magnitudes greater than 4.5 that occurred in Bengkulu Province between May and December 2022, and the Disturbance Storm Time (Dst) index to distinguish seismogenic anomalies from geomagnetic storm effects. ULF anomalies were identified using the moving average and standard deviation of the Z/H ratio, followed by lead-time analysis, Dst-based validation, and linear regression to examine the relationship between anomaly amplitude and earthquake magnitude. The results show that most earthquake events were preceded by detectable ULF anomalies occurring 3–25 days before the mainshock. Furthermore, a positive linear relationship was observed between the Z/H anomaly amplitude and earthquake magnitude, although the correlation strength was relatively weak. These findings suggest that ULF geomagnetic anomalies derived from the Z/H ratio have potential as earthquake precursor indicators in Bengkulu Province, while further studies using longer observation periods and larger datasets are required to improve their reliability and predictive capability.

Keywords: Ultra Low Frequency (ULF); earthquake precursor; geomagnetic; *Z/H* ratio; Bengkulu

ABSTRAK

Prediksi gempa bumi masih menjadi tantangan ilmiah yang belum terselesaikan, sehingga mendorong berbagai upaya untuk mengidentifikasi fenomena fisik yang dapat berfungsi sebagai prekursor yang andal sebelum terjadinya peristiwa seismik. Penelitian ini bertujuan untuk menganalisis anomali sinyal geomagnetik Ultra Low Frequency (ULF) menggunakan rasio komponen medan geomagnet vertikal terhadap horizontal (Z/H) sebagai indikator prekursor gempa bumi. Selain itu, penelitian ini juga mengevaluasi hubungan antara amplitudo anomali dan karakteristik gempa bumi. Analisis dilakukan menggunakan data komponen geomagnet H dan Z yang direkam di Stasiun Geomagnet Kepahiang (KPY), data gempa bumi dengan magnitudo lebih dari 4,5 yang terjadi di Provinsi Bengkulu selama periode Mei hingga Desember 2022, serta indeks Disturbance Storm Time (Dst) untuk membedakan anomali yang bersifat seismogenik dari pengaruh badai geomagnet. Anomali ULF diidentifikasi menggunakan metode rata-rata bergerak (*moving average*) dan simpangan baku (*standard deviation*) dari rasio Z/H, yang kemudian dilanjutkan dengan analisis *lead time*, validasi berdasarkan indeks Dst, serta analisis regresi linear untuk mengkaji hubungan antara amplitudo anomali dan magnitudo gempa bumi. Hasil penelitian menunjukkan bahwa sebagian besar kejadian gempa bumi didahului oleh anomali ULF yang terdeteksi 3–25 hari sebelum terjadinya gempa utama. Selain itu, ditemukan hubungan linear positif antara amplitudo anomali rasio Z/H dan magnitudo gempa bumi, meskipun kekuatan korelasinya relatif lemah. Temuan ini menunjukkan bahwa anomali geomagnetik ULF yang diturunkan dari rasio Z/H memiliki potensi sebagai indikator prekursor gempa bumi di Provinsi Bengkulu. Namun demikian, penelitian lebih lanjut dengan periode pengamatan yang lebih panjang dan jumlah data yang lebih besar masih diperlukan untuk meningkatkan keandalan dan kemampuan prediksinya.

Kata kunci: Ultra Low Frequency (ULF); Prekursor gempa bumi; geomagnetik; rasio *Z/H*; Bengkulu

1. Introduction

A total of 42 earthquake events with magnitude M > 4.5 were recorded in the Bengkulu region over an eight-month period (May–December 2022), reflecting the high seismic activity influenced by the Sumatra subduction zone and active fault systems on land [1], [2]. This high level of seismic activity has driven the development of various studies related to earthquake hazard potential and the characteristics of phenomena associated with earthquake preparation processes, such as anomalous seismicity patterns, ground deformation, radon gas concentration changes, thermal infrared anomalies, and electromagnetic or geomagnetic emissions. One phenomenon that has been extensively studied is ULF geomagnetic anomaly-based earthquake precursors, which have the potential to serve as early indicators of seismic activity and are associated with physical changes in the lithosphere before earthquakes occur [3].

The presence of the MAGDAS (Magnetic Data Acquisition System) geomagnetic station in Kepahiang provides an opportunity to more deeply investigate the relationship between seismic parameters particularly magnitude and hypocenter depth and the characteristics of ULF signals recorded before earthquake events.

Several previous studies have reported the emergence of ULF geomagnetic anomalies as earthquake precursors with varying characteristics. ULF anomalies have been reported to appear within the first two weeks, up to 13 days, before earthquake events [4]; however, in some cases these anomalies have been observed to extend up to 26 days beforehand [5]. These variations indicate that the characteristics of ULF anomalies are influenced by tectonic conditions, earthquake source mechanisms, and the local characteristics of the observation area [6]. In addition to lead time variations, ULF anomaly amplitudes can differ depending on earthquake magnitude, depth, and epicentral distance, making the analysis of the relationship between anomaly amplitude and earthquake parameters important to investigate further [7].

Z/H ratio-based analysis is one of the most widely used approaches in ULF geomagnetic anomaly studies, focusing on the Pc 3–Pc 4 range (0.007–0.1 Hz), which is more sensitive to variations in geophysical activity in the lithosphere as an earthquake precursor indicator [8], [9]. The use of the Disturbance Storm Time (DST) index is important as a validation parameter for distinguishing anomalies originating from lithospheric activity and global geomagnetic disturbances [10]. Linear regression is subsequently used to evaluate the quantitative relationship between anomaly amplitude and earthquake parameters [11].

A number of studies indicate that the relationship between geomagnetic anomalies and earthquake parameters still shows varied results. Takla & Yoshikawa [12] reported that anomaly amplitude tended to increase with earthquake magnitude, whereas Rachman, Widodo, & GNR [13] found only a weak correlation between the two parameters. These differing results indicate that the relationship between geomagnetic anomalies and earthquake parameters still requires further investigation, particularly in regions with different tectonic characteristics.

Although previous studies have reported the occurrence of ULF geomagnetic anomalies prior to earthquake events in various regions, quantitative studies that specifically evaluate the relationship between anomaly amplitude and earthquake parameters in the Bengkulu region using validated geomagnetic observation data remain limited. This gap is particularly relevant considering that Bengkulu is one of the most seismically active regions along the Sumatra subduction zone, yet a systematic quantitative link between ULF anomaly characteristics and local earthquake parameters, supported by DST-based validation, has not been extensively investigated in this region.

USGS states that valid earthquake prediction must simultaneously satisfy three elements: time of occurrence, location, and magnitude [14]. To date, no method has been able to accurately fulfill all three elements. This study attempts to assess the potential of ULF geomagnetic anomalies in meeting these three elements step by step through source location estimation via anomaly azimuth analysis, event time estimation via anomaly lead time analysis, and magnitude estimation via linear regression between *Z/H* ratio anomaly amplitude and earthquake magnitude. Accordingly, this study specifically addresses three research questions: (1) whether ULF geomagnetic anomalies based on the Z/H ratio emerge prior to earthquake events in Bengkulu Province; (2) whether the amplitude of these anomalies is correlated with earthquake magnitude and hypocenter depth; and (3) whether these anomalies can potentially serve as earthquake precursor indicators in the region. To answer these questions, this study aims to identify and characterize ULF signal anomalies based on the Z/H ratio as earthquake precursor indicators in Bengkulu Province, and to quantitatively determine the relationship between geomagnetic anomaly amplitude and earthquake parameters (magnitude and hypocenter depth) using linear regression analysis.

2. Methods

2.1. Study Design

This study is a quantitative investigation using a geomagnetic data analysis approach to identify ULF signal anomalies based on the *Z/H* ratio as earthquake precursor indicators in Bengkulu Province. All collected data were then systematically processed using MATLAB and Microsoft Excel through five main stages: (1) calculation of the *Z/H* polarization ratio, (2) anomaly identification using a moving average and standard deviation approach, (3) lead time determination, (4) validation using the Disturbance Storm Time (DST) index, and (5) analysis of the relationship between *Z/H* ratio anomaly amplitude and earthquake parameters (magnitude and hypocenter depth) using linear regression.

2.2. Data Collection

The data used include geomagnetic horizontal (*H*) and vertical (*Z*) component data from the Kepahiang Geomagnetic Station (KPY), earthquake data with magnitude > 4.5 during May–December 2022 comprising 42 earthquake events, and the Disturbance Storm Time (DST) index for validation of global geomagnetic activity. The magnitude threshold of M > 4.5 was set because it falls exactly in the middle of a range that is high enough to ensure that precursor signals can be detected, and it is commonly used in preliminary ULF studies conducted in the Sumatra region [6], [7], which reported reliable anomaly identification and validated lead-time estimates for earthquakes within this magnitude range. The observation period (May–December 2022) was selected because it covers the interval with the most complete and continuous MAGDAS data availability at the KPY station during the study year, providing a sufficient and consistent dataset comprising 42 qualifying earthquake events for anomaly identification and statistical analysis. The locations of earthquake events are shown on the seismicity map presented in Figure 1.

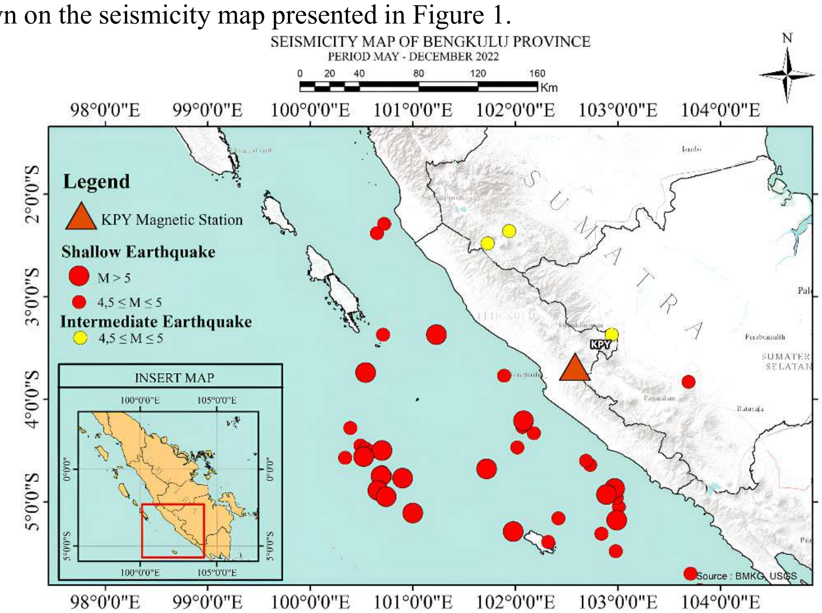

Figure 1. Location of earthquake events used (modified ArcGIS 10.4 basemap)

2.3. Data Analysis

2.3.1. Z/H Ratio Analysis

The *Z/H* polarization ratio was calculated following the method of Hayakawa, Kawate, Molchanov, & Yumoto [15] as expressed in Equation 1, where Z is the vertical component of the magnetic field and H is the horizontal component of the magnetic field (Equation 1).

$$P_{Day} = \frac{Z_{Day}}{H_{Day}} \quad (1)$$

2.3.2. Anomalies Identification

Anomalies were then identified using the moving average and standard deviation approach following Yusdesra, Namigo, & Mega [7]. The moving average was calculated using Equation 2, where $\overline{X}_t$ is the moving average of the *Z/H* ratio data at time t_i and X_i is the value of the *Z/H* ratio data, and n is the number of data points within one observation window (Equation 2).

$$\overline{X}_t = \frac{1}{n}\sum_{i=1}^{n} X_i \quad (2)$$

The standard deviation was calculated using Equation 3 [7], where S_t is the standard deviation of the *Z/H* data at time t (Equation 3).

$$S_t = \frac{\sqrt{\sum_{i=1}^{n}(X_i - \overline{X}_t)^2}}{n-1} \quad (3)$$

Based on the moving average and standard deviation, the upper and lower anomaly thresholds were determined according to Hamidi, Ahadi, Friska, & Marzuki in [5] using Equations 4 and 5. *Z/H* ratio values that exceed U_t or fall below L_t are identified as anomalies (Equations 4 and 5).

$$U_t = \overline{X}_t + S_t \quad (4)$$

$$L_t = \overline{X}_t - S_t \quad (5)$$

In this study, the moving average was calculated using a window size of n = 72 data points, equivalent to a 3-day period given the hourly sampling rate of the geomagnetic data (24 data points per day). This window length was selected to smooth short-term, sub-daily fluctuations in the Z/H ratio while remaining short enough to preserve sensitivity to anomaly signals at the relevant precursor timescale of several days to weeks.

Lead time was determined as the time interval between anomaly onset and earthquake occurrence using Equation 6 [4], where L_t is the lead time (days), t_e is the time of the earthquake event, and t_a is the time of anomaly onset (Equation 6).

$$LT = t_e - t_a \quad (6)$$

2.3.3. DST Validation

Validation was performed using the Disturbance Storm Time (DST) index to ensure that the observed anomalies were not influenced by global geomagnetic activity. Dewi et al. in [6] state that geomagnetic conditions are considered relatively quiet when the Dst value ≥ −30 nT, so anomalies appearing under such conditions can be categorized as candidate precursor signals. Conversely, anomalies coinciding with DST < −30 nT are not categorized as earthquake precursors because they may be influenced by magnetic storms.

2.3.4. *Analysis of Anomaly with Earthquake Magnitudes*

The final stage of analysis was determining the relationship between *Z/H* ratio anomaly amplitude and earthquake magnitude using linear regression [13] as expressed in Equation 7, where y is earthquake magnitude, x is the *Z/H* ratio anomaly amplitude, a is the regression coefficient, and b is the constant (Equation 7).

$$y = ax + b \quad (7)$$

These stages were used to evaluate the potential of ULF anomalies as earthquake precursor indicators in Bengkulu Province.

3. Results and Discussions

Theoretically, the emergence of ULF anomalies is linked to the accumulation of rock stress during the earthquake preparation phase, which triggers the formation of electromagnetic emissions due to microfracturing processes or changes in the physical properties of rocks in the lithosphere [16]. This phenomenon propagates through the atmosphere and influences the ionosphere, forming a Lithosphere–Atmosphere–Ionosphere (LAI) Coupling mechanism as shown in Figure 2, thereby potentially being recorded as anomalies before earthquake occurrences [16].

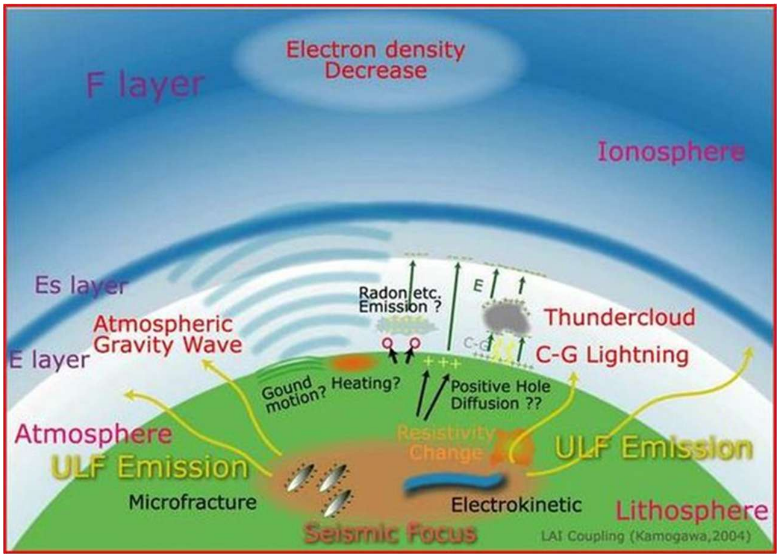

Figure 2. LAI Coupling Theory adapted from Liu et al. in [17]

3.1. Identification of Z/H Ratio Anomaliest

Based on the data processing results, of the 42 earthquake events analyzed, 37 events (88.1%) were identified as being preceded by ULF anomalies that satisfied all validation criteria: the *Z/H* ratio value exceeded the anomaly threshold, geomagnetic conditions were quiet (Dst ≥ −30 nT), and the anomaly azimuth direction corresponded to the earthquake epicenter direction. The remaining 5 earthquake events (11.9%) did not meet these criteria. Of these five events, some detected anomalies coincided with DST index values ≤ −30 nT, indicating the presence of global geomagnetic disturbances, so the anomalies could not be categorized as precursor signals. Additionally, in some other events, no anomaly was detected within the 27-day observation window prior to the earthquake. The validated ULF anomalies exhibited lead times ranging from 3 to 25 days before earthquake occurrence, with an average lead time of 12.2 days. These results indicate that the occurrence time of validated ULF anomalies varied among the analyzed earthquake events, with precursor signals appearing several days to several weeks before earthquake occurrence.

The absence of validated anomalies in five earthquake events may be explained by several factors. For two events, the detected anomalies coincided with geomagnetic disturbances (Dst ≤ −30 nT), indicating that the observed signals were likely influenced by external geomagnetic activity rather than lithospheric processes. For the remaining events, no anomaly was detected within the 27-day observation window. This may reflect weak precursor signals, signal attenuation during propagation, or local observational conditions that prevented anomaly detection. However, these possible factors were not evaluated quantitatively in the present study and therefore require further investigation.

The results of ULF anomaly identification, lead times, and DST index values for each earthquake event are presented in Table 1.

Table 1. Summary of ULF Anomaly Identification Results

Earthquake Date	Anomaly Date	Hypocenter (Km)	*Z/H*	Magnitude	*Lead time* (Days)	DST Index (nT)	Validation
21 May 22	02 May 22	38.7	5.887	4.6	19	-13.19	Yes
23 May 22	12 May 22	59.6	-5.896	4.9	11	-19.42	Yes
24 May 22	07 May 22	62.6	-4.257	4.9	17	-28.6	Yes
18 Jun 22	09 Jun 22	61.3	10.244	5.3	9	-16.97	Yes
06 Jul 22	23 Jun 22	24.9	8.561	4.7	13	-7.06	Yes
06 Jul 22	11 Jun 22	22.2	10.024	5.3	25	11.4	Yes
18 Jul 22	14 Jul 22	26.4	13.535	4.5	4	6.19	Yes
19 Jul 22	30 Jun 22	62	10.17	5.8	19	-15.12	Yes
20 Jul 22	11 Jul 22	18.7	2.899	4.7	9	-15.72	Yes
24 Jul 22	18 Jul 22	133.9	10.17	4.5	6	-15.12	Yes
07 Aug 22	19 Jul 22	54.1	11.527	5	19	4.52	Yes

Earthquake Date	Anomaly Date	Hypocenter (Km)	*Z/H*	Magnitude	*Lead time* (Days)	DST Index (nT)	Validation
15 Aug 22	07 Aug 22	43.3	8.216	5	8	-7.6	Yes
17 Aug 22	06 Aug 22	34.2	-4.239	4.7	11	3.71	Yes
23 Aug 22	-	63	-	6.6	-	-	No
25 Aug 22	-	43.4	-	5.2	-	-	No
04 Sep 22	25 Aug 22	56.9	12.711	5.1	10	-8.26	Yes
05 Sep 22	17 Aug 22	23.3	6.519	4.7	19	11.63	Yes
07 Sep 22	24 Aug 22	67	6.44	5.4	14	-8.96	Yes
08 Sep 22	16 Aug 22	66.1	5.285	4.7	23	-10.43	Yes
10 Sep 22	-	23.6	-	4.6	-	-	No
19 Sep 22	16 Sep 22	10	4.153	4.6	3	17.05	Yes
29 Sep 22	17 Sep 22	10	5.689	4.5	12	29.45	Yes
01 Oct 22	20 Sep 22	13.5	6.533	4.6	11	-5.422	Yes
14 Oct 22	4 Okt 22	10	10.822	4.9	10	-25.52	Yes
20 Oct 22	1 Okt 22	14.8	8.771	4.8	19	-12.49	Yes
11 Nov 22	21 Okt 22	10	11.434	5.1	21	10.22	Yes
16 Nov 22	07 Nov 22	21.3	14.364	5.7	9	-7.44	Yes
16 Nov 22	13 Nov 22	10	4.402	4.7	3	9.15	Yes
16 Nov 22	-	3.7	-	4.7	-	-	No
16 Nov 22	27 Okt 22	31.3	5.032	4.6	20	47.57	Yes
18 Nov 22	-	21.6	-	6.7	-	-	No
18 Nov 22	02 Nov 22	10	14.507	5.3	16	-3.95	Yes
18 Nov 22	02 Nov 22	29.3	14.507	5.8	16	-3.95	Yes
18 Nov 22	13 Nov 22	28.7	4.402	4.9	5	9.15	Yes
18 Nov 22	13 Nov 22	10	4.402	4.7	5	9.15	Yes
18 Nov 22	13 Nov 22	29.4	4.402	4.8	5	9.15	Yes
18 Nov 22	13 Nov 22	31.2	4.402	4.7	5	9.15	Yes
21 Nov 22	17 Nov 22	25.2	18.265	5.2	4	15.59	Yes
24 Nov 22	17 Nov 22	38.9	16.227	5	7	18.32	Yes
26 Nov 22	19 Nov 22	179.5	7.236	4.6	7	-11.15	Yes
01 Dec 22	17 Nov 22	13.8	18.265	5.1	14	15.59	Yes
16 Dec 22	23 Nov 22	184	-5.759	4.6	23	13.41	Yes

To illustrate the identified ULF anomalies, two representative earthquake events are presented in Figure 3. These examples demonstrate the application of Z/H ratio analysis, azimuth verification, and DST validation in identifying potential earthquake precursor signals. One earthquake event on July 19, 2022, with magnitude 5.8, had a depth of 62 km and an epicentral distance of 81.162 km from the Kepahiang geomagnetic station (KPY), and showed several ULF anomalies before the earthquake as presented in Figure 3(a). Azimuth analysis in Figure 3(b) shows that the anomaly on June 30, 2022 had an azimuth direction of 210.930°, pointing toward the earthquake source area with an azimuth of 226.693°, with an amplitude of 13.535 and a lead time of 19 days. The DST index remained above −30 nT during the anomaly period, indicating the absence of significant global geomagnetic disturbances, strengthens the conclusion that the observed anomaly most likely originated from internal lithospheric processes.

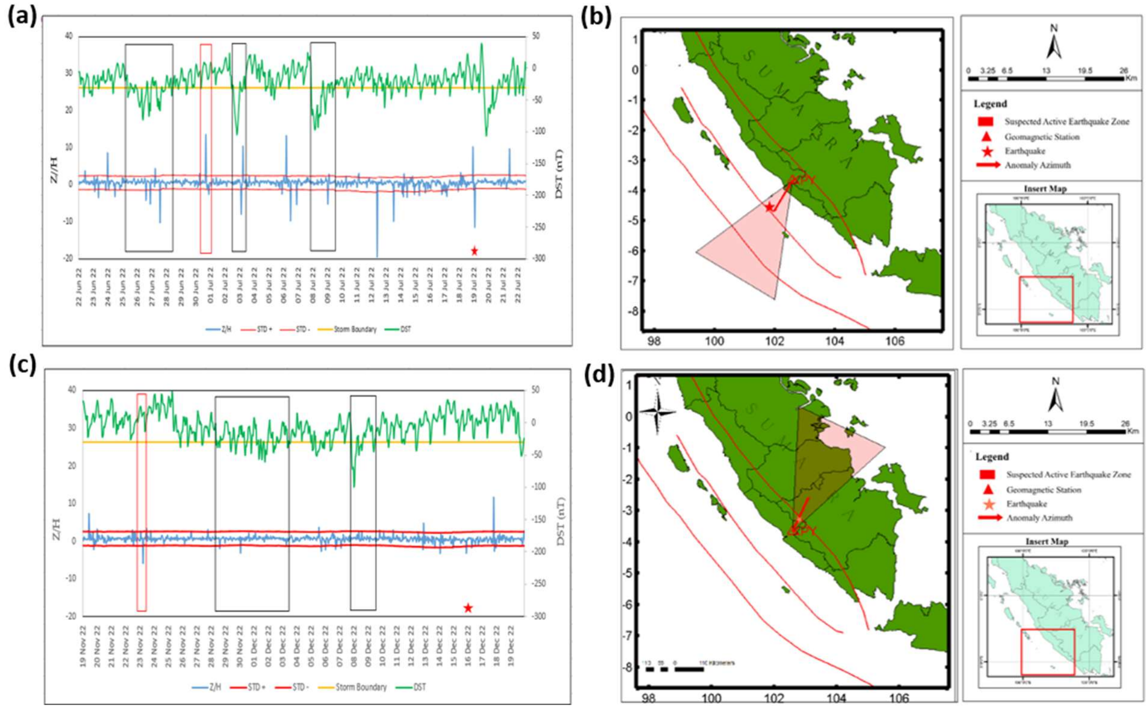

Figure 3. Representative examples of validated ULF geomagnetic anomalies prior to the July 19, 2022 and December 16, 2022 earthquakes: (a) Z/H power ratio polarization graph at KPY station, onset time (red box), magnetic storm (black box), for earthquake (M 5.8) July 19, 2022 (red star); (b) ULF emission anomaly azimuth for earthquake July 19, 2022 (M 5.8); (c) Z/H power ratio polarization graph at KPY station, onset time (red box), magnetic storm (black box), for earthquake (M 4.6) December 15, 2022 (red star); (d) ULF emission anomaly azimuth for earthquake December 16, 2022 (M 4.6).

Another representative event occurred on December 16, 2022 earthquake (M 4.6), an anomaly was also detected on November 23, 2022 as presented in Figure 3(c), with an azimuth direction consistent with the earthquake epicenter as shown in Figure 3(d), and no increase in DST value during that period. Anomalies in small-magnitude earthquakes indicate that geomagnetic precursor activity is not only influenced by earthquake magnitude, but also by other factors such as local geological conditions, epicentral distance from the observation station, and instrument sensitivity. Therefore, even when an anomaly is detected, its interpretation as an earthquake precursor must be done carefully and supported by additional parameters such as the anomaly source azimuth direction and DST index validation. Overall, these representative events demonstrate that anomaly validation using the Dst index effectively distinguishes anomalies occurring under quiet geomagnetic conditions from those associated with external geomagnetic disturbances. In addition, agreement between the anomaly azimuth and the earthquake epicenter direction provides further support for interpreting the detected anomalies as potential lithospheric precursor signals.

These findings are consistent with Marzuki et al. in [4], who identified ULF anomalies at KPY station before the 2020 Pagai earthquake swarm with lead times ranging from 3–13 days and showed azimuth direction agreement with the earthquake epicenter, supporting the use of azimuth analysis as a spatial parameter in precursor identification. Additionally, Hamidi et al. in [5] reported that 86% of 29 earthquake events in Sumatra during 2019–2020 were preceded by ULF emissions with lead times of 1–26 days, with validated anomalies having azimuth directions pointing toward epicentres.

The narrower lead-time range reported by Marzuki et al. [4] (3-13 days) likely reflects the fact that their study analyzed a single earthquake swarm (the 2020 Pagai sequence) originating from a spatially confined source, which tends to produce more temporally clustered anomalies. In contrast, the wider range reported by Hamidi et al. [5] (1-26 days) and the range obtained in the present study (3-25 days) instead aggregate independent earthquakes distributed across a broader area and time span, which naturally produces greater variability in anomaly onset timing. This comparison indicates that the lead-time consistency reported in some previous studies partly reflects the spatial-temporal clustering of the analyzed events, rather than solely the intrinsic behavior of ULF precursor signals, and should therefore be interpreted with this distinction in mind when comparing lead-time ranges across studies.

3.2. Relationship Between Anomaly Amplitude and Earthquake Magnitude

Linear regression analysis between *Z/H* ratio anomaly amplitude and earthquake magnitude produced the Equation 8.

$$Mag = 0.0449(\frac{Z}{H}) + 4.5269 \quad (8)$$

The regression analysis yielded a coefficient of determination (R^2) of 0.2859, indicating a weak positive relationship between Z/H ratio anomaly amplitude and earthquake magnitude. This result suggests that earthquake magnitude alone explains only a limited proportion of the observed variation in anomaly amplitude. Nevertheless, the positive regression slope indicates that larger earthquakes tend to be associated with higher anomaly amplitudes.

The relatively low coefficient of determination suggests that the recorded ULF anomaly amplitude is influenced by multiple factors in addition to earthquake magnitude. Possible contributing factors include the complexity of lithospheric processes, geological heterogeneity, and the relatively wide range of epicentral distances (81–259 km), which may affect the propagation and attenuation of ULF electromagnetic signals before they are recorded at the observation station [18]. A stronger relationship between ULF anomaly amplitude and earthquake magnitude ($R^2 = 0.805$) has previously been reported [Rachman, Widodo, & GNR , 15]. Compared with that result, the weaker correlation obtained in the present study may be related to differences in earthquake characteristics, observation periods, observation geometry, and local geological conditions between the two study areas.

The stronger correlation reported by Rachman, Widodo, & GNR [13] ($R^2 = 0.805$) was likely obtained from a more geologically homogeneous study area and a narrower range of epicentral distances, which reduces signal attenuation variability across events. In contrast, the present study covers 42 earthquakes with epicentral distances spanning 81-259 km across a tectonically heterogeneous segment of the Sumatra subduction zone, introducing greater variability in signal propagation paths and thus lowering the observed R^2. From a physical standpoint, this also suggests that ULF emission amplitude is governed not only by the scale of the seismic source, but also by localized micro-fracturing dynamics and stress-induced piezomagnetic effects that vary independently of magnitude [16]. Because the LAI coupling process requires the electromagnetic signal to propagate through a heterogeneous crust before reaching the surface, variations in local rock conductivity and fracture density can amplify or suppress the recorded Z/H signal independently of the earthquake's energy release [17]. Taken together, these considerations indicate that the strength of the Z/H-magnitude relationship is not purely a property of the precursor phenomenon itself, but is also strongly conditioned by the spatial homogeneity of the observation network relative to the seismic source region.

3.3. Relationship Between Anomaly Amplitude and Earthquake Depth (Hypocenter)

In addition to the relationship between anomaly amplitude and earthquake magnitude, an analysis was also conducted on the relationship between the *Z/H* ratio and earthquake hypocenter depth using simple linear regression. Linear regression analysis between the *Z/H* ratio and hypocenter depth produced Equation 9:

$$\frac{Z}{H} = -0.0184(Hypo) + 9.517 \quad (9)$$

with a coefficient of determination (R^2) of 0.0331, indicating a very weak relationship between ULF anomaly amplitude and earthquake hypocenter depth, consistent with previous studies, which reported a very weak relationship between earthquake depth and ULF anomaly amplitude [Yusof, 18]. One possible explanation is that ULF electromagnetic signals may experience attenuation and dispersion during their propagation through heterogeneous geological media, reducing the influence of source depth on the anomaly amplitude recorded at the surface [Yusof, 18]. However, this propagation process was not evaluated directly in the present study.

Graphs of the relationship between *Z/H* ratio anomaly amplitude and earthquake magnitude and hypocenter depth are presented in Figures 4 and 5, respectively.

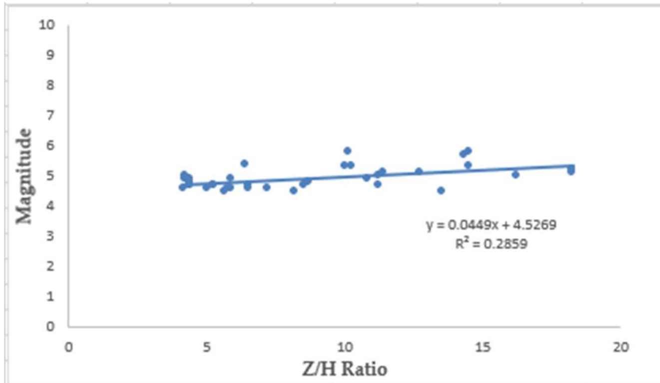

Figure 4. Correlation graph of *Z/H* polarization amplitude vs. Earthquake Magnitude.

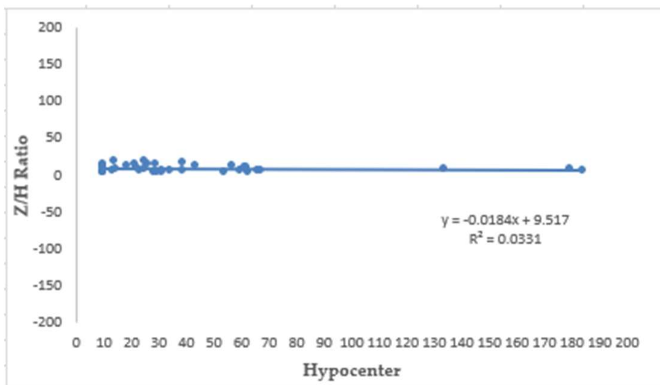

Figure 5. Correlation graph of *Z/H* polarization amplitude vs. Earthquake Hypocenter Depth.

Based on both results, it can be seen that the *Z/H* ratio amplitude has a relatively larger correlation with earthquake magnitude compared to hypocenter depth, although both remain in the category of weak relationships. Thus, *Z/H* ratio amplitude cannot be used as a single indicator for determining earthquake characteristics, but must be interpreted together with other validation parameters, including agreement between the anomaly source azimuth and the earthquake epicenter direction, anomaly lead time, and geomagnetic conditions represented by the Dst index.

These findings, taken together with the amplitude-depth analysis, indicate that a multi-parameter framework combining Z/H amplitude, azimuth, lead time, and DST validation remains necessary for reliable precursor interpretation. Several methodological limitations of the present study, and the corresponding directions for future work, are discussed in the following subsections.

3.4. Limitations

This study has several limitations that should be considered when interpreting the results. First, the analysis relies on geomagnetic data from a single station (KPY), which limits the ability to triangulate anomaly source locations and may introduce station-specific noise that cannot be distinguished from genuine precursor signals. Second, the observation period is restricted to eight months (May-December 2022), which, while covering the most complete MAGDAS data availability at KPY, may not capture longer-term seasonal or solar-cycle-related variations in background ULF activity. Third, the statistical analysis in this study is limited to simple linear regression; more rigorous statistical validation, such as significance testing (p-value) or non-linear regression models, could not be performed at this stage because verification against the original raw dataset was not feasible, so the reported R^2 values should be interpreted as indicative rather than conclusive measures of relationship strength. These limitations do not undermine the qualitative findings regarding ULF anomaly occurrence, azimuth agreement, and lead time, but they should be addressed in future multi-station, longer-duration studies.

3.5. Recommendations for Future Work

Future work should include observations from multiple geomagnetic stations to obtain more representative results and reduce the influence of local conditions at the observation station. Analysis can also be developed by incorporating additional parameters such as ULF signal spectral analysis, as well as integration with other geophysical data such as GPS or seismic data, and further data processing methods such as machine learning to improve the ability to identify anomaly patterns as earthquake precursors. In addition, the precision of azimuth direction determination needs to be continuously developed to improve the accuracy of associating anomalies with earthquake epicenters.

4. Conclusion

This study demonstrates that ULF geomagnetic observations using the Z/H ratio combined with Dst index validation can identify potential earthquake-related geomagnetic anomalies in Bengkulu Province. Most analyzed earthquakes were preceded by validated anomalies, indicating that the proposed multi-parameter approach is effective for distinguishing potential lithospheric signals from external geomagnetic disturbances. However, the weak correlation between anomaly amplitude and earthquake magnitude, and the very weak correlation between anomaly amplitude and hypocenter depth, indicate that the Z/H ratio and DST index alone are not yet sufficiently valid or convincing as a standalone early-warning predictor of seismic events. Their reliability as an earthquake precursor indicator depends on integration with anomaly source azimuth and lead time analysis within a multi-parameter framework, rather than use as an independent predictive tool.

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