IDENTIFICATION OF ELECTROMAGNETIC ULTRA LOW FREQUENCY (ULF) SIGNAL ANOMALIES AS PRECURSORS OF A MAGNITUDE 5 EARTHQUAKE IN THE SULAWESI REGION

Delfira Anggraini[1], Ratni Sirait[2] , Lailatul Husna Lubis*[3], Christofel Haposan Great Sibuea[4]

[1,2,3]Department of Physics, Science and Technology of Faculty, Universitas Islam negeri Sumatera Utara
Jl. Lap. Golf Kec.Pancur Batu, Kab.Deli Serdang, Sumatera Utara, Indonesia
[4]Geophysical Agency, Deli Serdang Sumatera Utara
Jl. Geofisika No.1, Tuntungan I, Kec. Pancur Batu, Kabupaten Deli Serdang, Sumatera Utara, Indonesia

Received: 27th February 2024; Revised: 2nd May 2024; Accepted: 4th May 2024

ABSTRACT

Sulawesi is situated at the intersection of three tectonic plates the Indo-Australian, Eurasian, and Philippine plates. The Palu Koro fault is one of the primary causes of seismic activity in the Sulawesi region, making it vulnerable to earthquakes on this Island. As an initial step in disaster mitigation, the information provided is useful in determining the initial signs before the occurrence of an earthquake, it is necessary to identify Ultra Low Frequency (ULF) Signal Anomalies as earthquake precursors. The methods employed are those of power spectrum density (PSD) and single-station transfer function (SSTF). The analysis of anomalies suspected of being precursors to 5 earthquake events revealed that in the February 27, 2023 earthquake, the anomaly appeared twice with a lead time of 17 days. In the February 28, 2023 earthquake, the anomaly appeared twice. In the March 7, 2023 earthquake, the anomaly appeared 3 times with a lead time of 20 days. The March 28, 2023 earthquake had 6 anomalies with a lead time of 24 days. The April 6, 2023 earthquake had 5 anomalies with a lead time of 29 days. anomalies were detected with lead times ranging from 17 to 30 days. The anomaly source azimuth direction was also determined.

Keywords: Anomaly; Precursors; Earthquake; Lead Time; Azimuth.

Introduction

Sulawesi is situated at the intersection of three converging tectonic plates: the Indo-Australian, Eurasian, and Philippine plates. As a result, it is highly susceptible to seismic activity.[1] Sulawesi is also one of the most earthquake-prone areas in Indonesia because of the large faults on the island, one of the known faults in Sulawesi is the Palu Koro Fault.[2] BMKG stated that throughout 2022, the palu-koro fault and the Matano fault are the most active faults in triggering earthquakes. As an effort to see the early signs before an earthquake occurs or what are called precursors, currently, many methods have been developed to observe these precursors.[3] Earthquake precursors are physical changes in nature that can serve as early indicators before an earthquake occurs. These changes are observed through various parameters, including geo-atmospheric, geochemical, geodetic, and geophysical factors.[4]

One of the extensively researched areas is the correlation between earthquakes and electromagnetic (EM) fields in the Ultra Low Frequency (ULF) range. The process of rock formation breaking in the plate collision area that causes earthquakes, known as the seismogenic process, produces electromagnetic wave emissions. The electromagnetic wave spectrum ranges from

*Corresponding author.
E-Mail: lailatulhusnalubis@uinsu.ac.id

extremely low frequencies, such as Ultra Low Frequency (ULF), to high frequencies, such as Ultra High Frequency (UHF).[5] Ultra Low Frequency (ULF) signals originate from both internal and external sources.[6] Ultra Low Frequency signals (<1 Hz) are believed to be capable of monitoring crustal activity as earthquake precursors due to their longer wavelength, which allows for easier detection at greater depths.[3] In contrast, UHF signals are absorbed by the medium, making them difficult to detect.[7]

Therefore, research on earthquake precursors is important in reducing the impact of earthquakes and mitigating disasters. This research analyzes the Ultra Low Frequency (ULF) Signal Anomaly as a precursor to a magnitude 5 earthquake in the Sulawesi region. The aim is to determine whether there is an Ultra Low Frequency (ULF) Signal Anomaly as a precursor to an earthquake and to determine the lead time using magnetic data at the Gorontalo station. This information is expected to support one of the early signs of an earthquake and serve as an early step in disaster mitigation.

Previous studies have identified ULF signal anomalies as precursors to earthquakes with small magnitudes in the Nias Islands region, using geomagnetic data 30 days before the earthquake. It was found that there were 3 earthquakes with ULF signal anomalies, and the ULF anomaly lead time for the three earthquakes had a shorter duration than previous studies in the Sumatra region with large earthquakes[8] Observations analyzing signal anomalies were carried out using the Detrended Fluctuation Analysis method for a large earthquake of magnitude 6.1 in the Lebak region of Banten. This is a follow-up study to previous observations that found ULF signal anomalies 7 and 11 days before the earthquake occurred.[9] Research has also been conducted on the analysis of ULF signal anomalies as earthquake precursors in the Lampung region. The results show that for 10 earthquakes with a magnitude greater than 5, precursors were detected between 11 to 30 days before the earthquake event. It is known that the time of the increase in the ULF pre-earthquake signal is at a frequency of 0.012-0.022 Hz.[10]

Methods

This study utilizes data on earthquakes with a magnitude of 5 that occurred on Sulawesi Island between January and May 2023. A total of five earthquake events with a magnitude of 5 can be accessed through the IRIS catalog source. The earthquake magnitude data was obtained from the MAGDAS program of the BMKG Gorontalo Station (GTO) in the Sulawesi region, using the MAGDAS-9 sensor type owned by BMKG. This research employs ArcGIS, Microsoft Excel 2019, and BMKG's MAGDAS application to analyze ULF signal anomalies associated with earthquake precursors.ULF emission anomalies can be identified using the SZ/SH ratio polarization method. The onset time can be determined when the SZ/SH ratio exceeds the standard deviation limit. At this point, the ULF emission anomaly can be expressed as the onset time, which marks the beginning of the emission anomaly.[11]

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

The Disturbance Storm Time (DST) index is a parameter used to measure geomagnetic activity as an indicator of geomagnetic disturbances, specifically geomagnetic storms. These storms are characterized by a decrease in DST index movement intensity.[12]

To identify the location of the earthquake epicenter, determine the azimuth direction of the ULF signal anomaly source.[13]

$$\theta(\omega) = arctan\left(\frac{B(\omega)}{A(\omega)}\right) \quad (2)$$

The SSTF method is utilized to display the anomaly and onset time of the earthquake precursor, as well as estimate the epicenter location of the impending earthquake. The earthquake source location is determined based on the direction of the ULF anomaly, with an azimuth tolerance of 22.5 degrees up and down from the actual azimuth. The

analysis of ULF emission anomalies suggests that the results of this earthquake azimuth estimation may serve as earthquake precursors.[14]

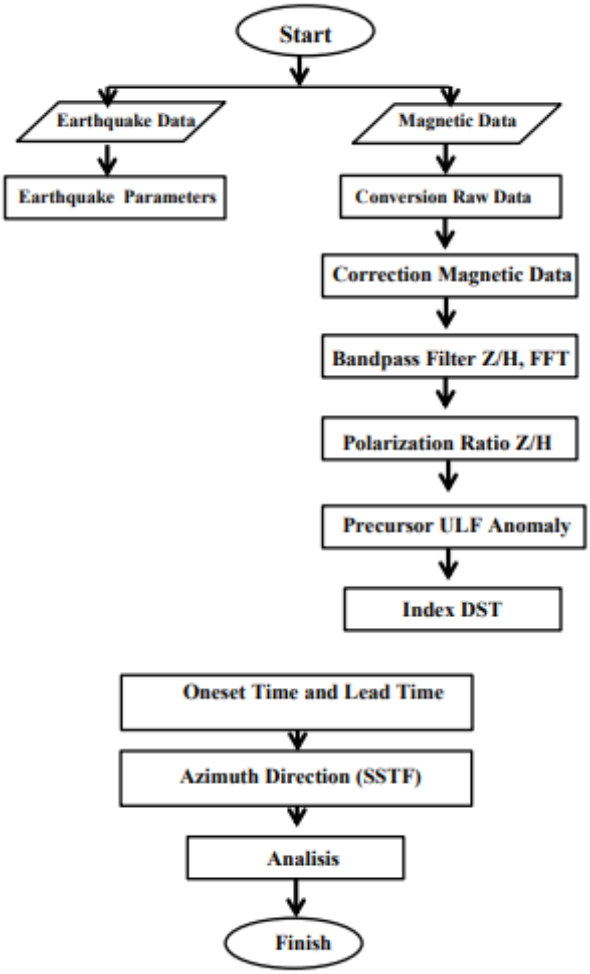

Figure 1. Research Flow Chart

Result and Discussion

Between January and May 2023, five earthquakes with a magnitude of 5 occurred in the Sulawesi region, as shown in Table 1. This table will serve as a reference for processing magnetic data as earthquake precursors obtained from the Gorontalo magnetic station (GTO) in the BMKG Sulawesi region. The research utilizes Ultra Low Frequency (ULF) earth magnetic field data processing, which employs frequencies ranging from 0.012 to 0.22 Hz. Lower frequencies are capable of detecting early signs of earthquakes.

During five earthquake events in the Sulawesi region, fluctuations in the polarization value of the Z/H ratio were observed outside the standard deviation limit. This is considered an anomaly in the Earth's magnetic field and is believed to be a precursor to earthquakes. It is important to analyze ULF data as a precursor.

The procedures for collecting data and processing ULF anomaly data related to earthquake precursors are:

1. Earthquake data can be obtained by IRIS catalog sources.
2. The MAGDAS-9 sensor station code (GTO) produces raw data that is converted into binary data (.mgd) and then into ASCII format (.gea). The resulting ASCII data contains the magnetic field of the X, Y, and Z components per second in nanoTesla (nT) units. Daily trend correction is applied to each component.
3. The magnetic data was corrected to remove noise using the diff method. If the diff value exceeds 1 nT, the data cannot be used to determine ULF anomalies.
4. Bandpass filter process is applied to the H and Z components in the frequency range of 0.012-0.022.
5. Anomalies that exceed the standard deviation are then validated using the DST index sourced from the World Data Center for Geomagnetism- Kyoto University. The Z/H polarization is derived from lithospheric activity. Magnetic storms occur when the DST index value reaches -30 nT.
6. An analysis was conducted to determine the onset time and lead time of earthquake precursors.
7. The azimuth direction of the ULF emission anomaly source was determined using the Single Station Transfer Fourier (SSTF) method in the ArcGIS application. The anomaly is believed to originate from the earthquake preparation zone.

Table 1. 5th magnitude earthquake data for the period January-May 2023

Date	Time (UTC)	Latitude (°)	Longitude (°)	Depth (km)	Magnitude
2023-02-27	1:26:05	-1,6029	120,254	34,8	5,5
2023-02-28	14:42:50	1,3696	125,7758	64,5	5,1
2023-03-07	20:31:28	1,3696	124,5479	40.2	5,3
2023-03-28	4:19:09	-0,3747	123,5348	75,1	5,2
2023-04-06	0:32:02	-0,536	122,1838	10	5

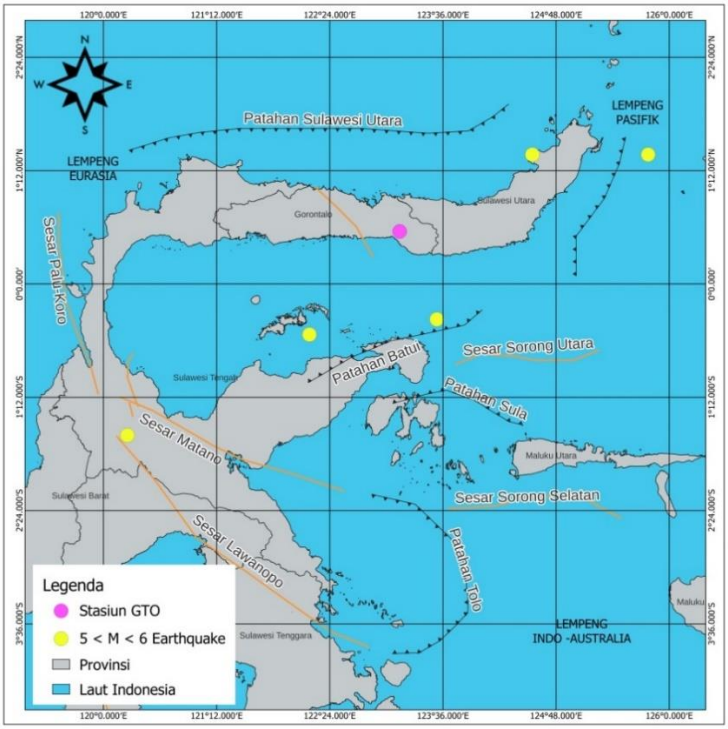

Figure 2. Map of the distribution of magnitude 5 earthquakes in the Sulawesi region

1. Earthquake 27 February 2023

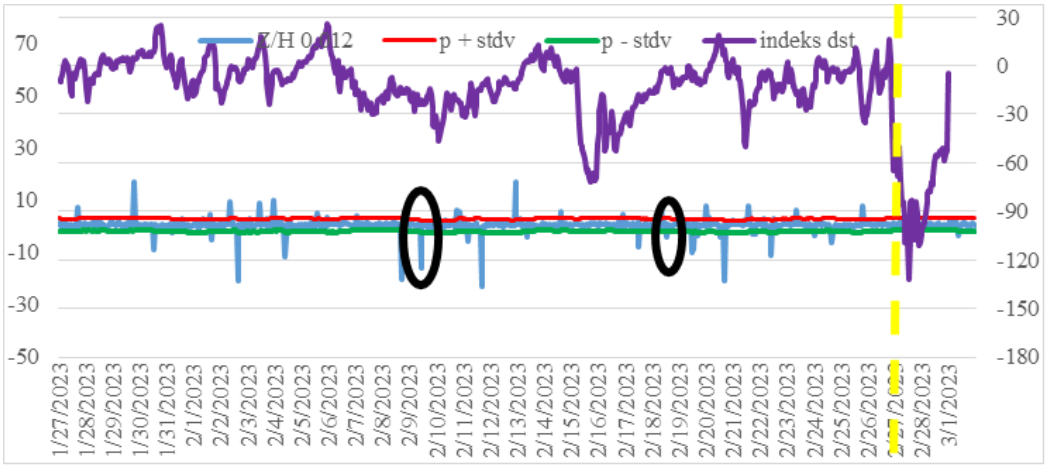

Figure 3. Graph showing ULF signal anomalies during the February 27, 2023 earthquake

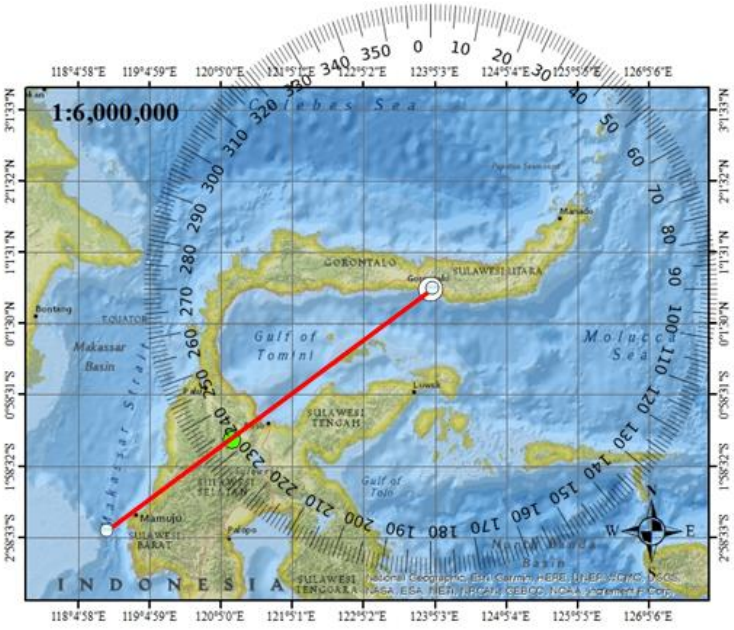

Figure 4. Mapping the azimuth direction of the earthquake at the GTO station on February 27, 2023.

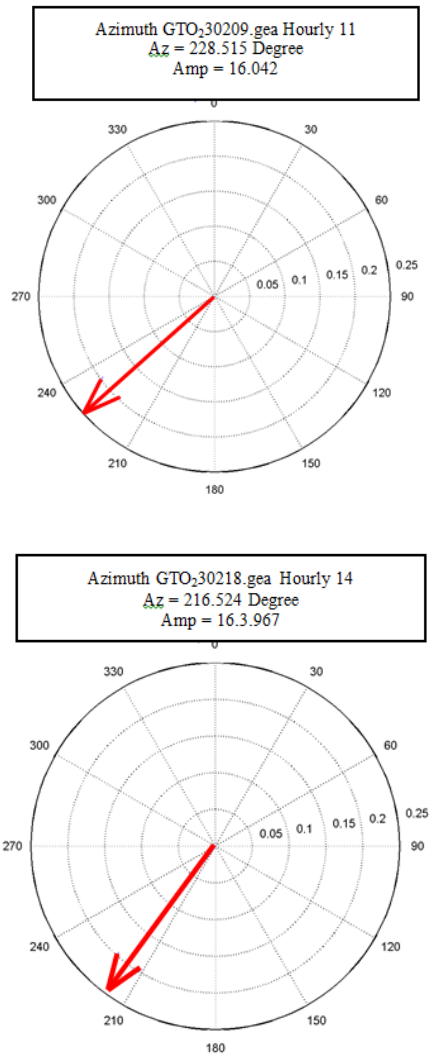

Figure 5. Azimuth direction of earthquake anomaly source February 27, 2023.

An earthquake measuring 5.5 on the Richter scale occurred in the Poso area of Central Sulawesi. The earthquake had a depth of 34.8 km and was located at latitude -1.6029 and longitude 120.254. The epicenter of the earthquake was 818 km away from the station

The Sz/Sh ratio was polarized 30 days prior to the earthquake on February 27, 2023. The anomaly appeared 34 times, with 3 anomalies detected due to magnetic storms. Specifically, on February 16, an anomaly with an intensity of -30nT was detected, and on February 25, an anomaly with an intensity of -35nT was detected. Figure 3 shows a suspected earthquake precursor anomaly in the black circle, which appeared twice: on February 9 with an amplitude of 16.042 and on February 18 with an amplitude of -3.967. The onset time of the anomaly was February 9, with a lead time duration of 17 days.

Figure 4 clarifies the determination of the anomaly that is considered the initial sign of the earthquake under study through the analysis of the direction of the ULF anomaly emission source. The earthquake azimuth direction obtained using the Single Station Transfer Function (SSTF) method is 234^o. The anomaly azimuth direction leading to the Earthquake preparation zone is also determined using a standard deviation of ±22.5^o for the azimuth direction range, which is approximately 211.5^o-256.5^o. Figure 4 shows that the azimuth direction of the earthquake agrees with the azimuth direction of the earthquake anomaly source, as shown in Figure 5.

2. Earthquake 28 February 2023

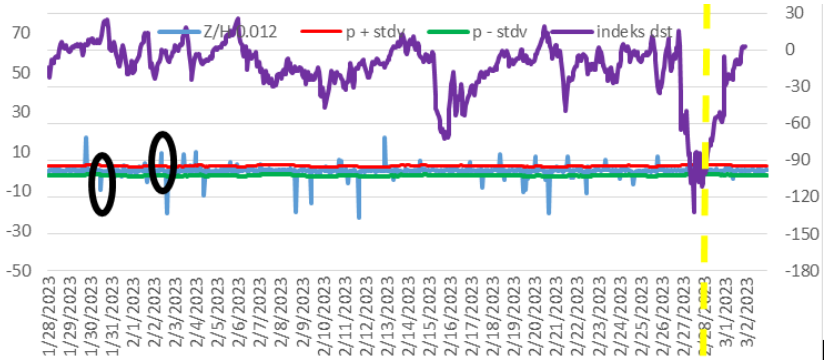

Figure 6. Graph showing ULF signal anomalies during the February 28, 2023 earthquake.

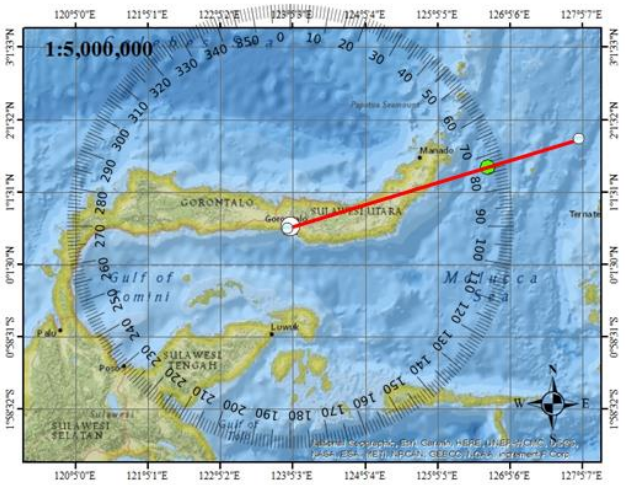

Figure 7. Mapping the azimuth direction of the earthquake at the GTO station on February 28, 2023.

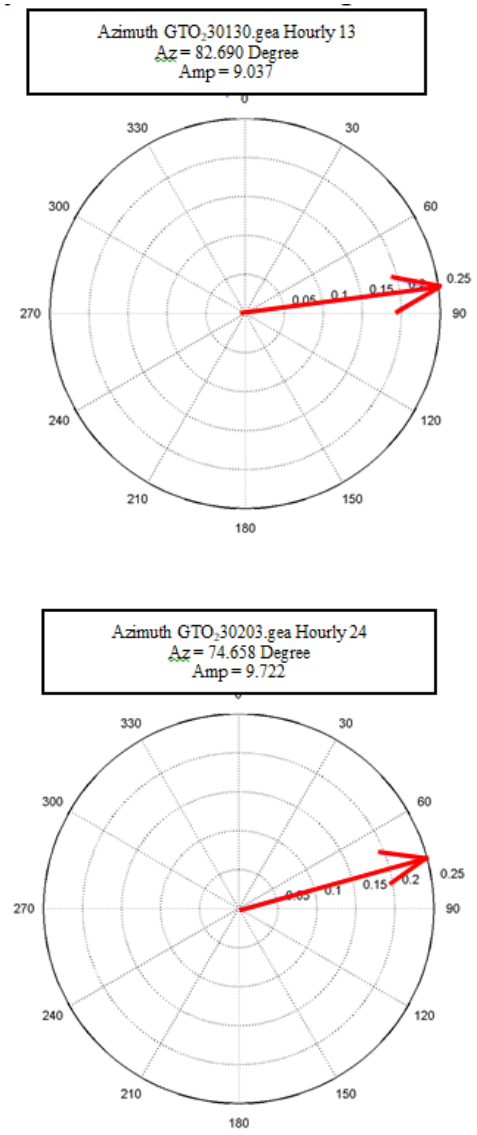

Figure 8. Azimuth direction of earthquake anomaly source February 28, 2023.

3. Earthquake 7 March 2023

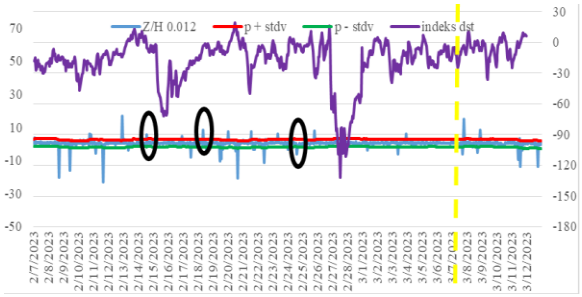

Figure 9. Graph showing ULF signal anomalies during the March 7, 2023 earthquake.

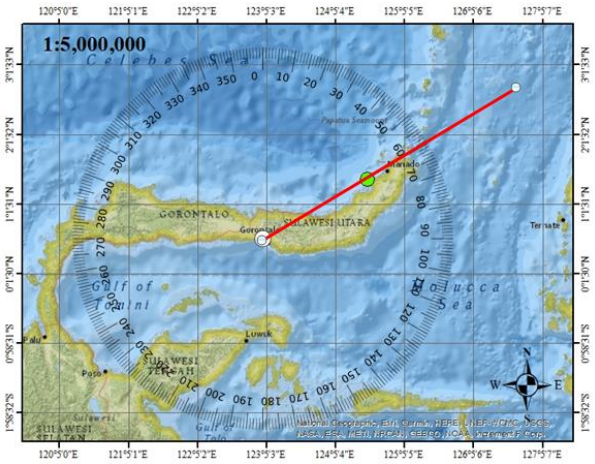

Figure 10. Mapping the azimuth direction of the earthquake at the GTO station on March 7, 2023.

An earthquake of magnitude 5.1 was recorded in the Laikit area (North Sulawesi) at a depth of 64.5 km, precisely at latitude -1.3696 and longitude 125.7758. The distance from the epicenter to the station is 604 km.

The Gorontalo Station (GTO) recorded anomalies that could be validated as earthquake precursors. The Sz/Sh ratio polarization 30 days before the earthquake on February 28, 2023, showed the anomaly appearing 20 times. Two anomalies were detected due to magnetic storms on February 21 and February 25, each with an intensity of -30nT. Figure 6 shows an anomaly in the black circle suspected to be an earthquake precursor. The anomaly appears twice, on January 30 with an amplitude of -9.037 and on February 3 with an amplitude of 9.722. The onset time of the earthquake precursor anomaly was on January 30 with a lead time of 28 days.

In Figure 7, the results of the analysis show that the azimuth direction of the earthquake is 73^o and the azimuth direction of the anomaly leads to the earthquake preparation zone with a standard deviation of ±22.5^o for the azimuth direction, which is about 50.5^o-95.5^o. The azimuth direction of the earthquake in Figure 7 is consistent with the azimuth direction of the earthquake anomaly source as shown in Figure 8.

An earthquake measuring 5.3 on the Richter scale occurred in the Tomohon area of North Sulawesi. The earthquake had a depth of 40.2 km and was located at latitude 1.3696 and longitude 124.5479.

The Gorontalo Station (GTO) recorded anomalies that could be validated as earthquake precursors. Specifically, the polarization of the Sz/Sh ratio 30 days before the earthquake on March 7, 2023, showed that the anomaly appeared 27 times. Three anomalies were also detected due to magnetic storms, on February 15 with an intensity of -35nT, and on February 21 and 25 with an intensity of -30nT each. Figure 9 displays the black circle of anomalies suspected to be earthquake precursors. The anomaly appeared three times: on February 14 with an amplitude of 5.602, on February 18 with an amplitude of 8.569, and on February 24 with an amplitude of -6.252. The graph indicates that the onset time of the earthquake precursor anomaly was on February 14 with a lead time of 20 days.

Figure 10 displays the earthquake's azimuth direction as 69°, while the anomaly leading to the earthquake preparation zone has an azimuth direction of approximately 46.5° to 91.5° with a standard deviation of ±22.5°. The earthquake's azimuth direction in Figure 10 agrees with the azimuth direction of the earthquake anomaly source in Figure 11.

The earthquake had a depth of 75.1 km and its epicenter was located at latitude -0.3747 and longitude 123.5348. An earthquake measuring 5 on the Richter scale occurred in the Luwuk area of Central Sulawesi. The distance between the epicenter and the station was 209 km.

Based on the analysis of the Gorontalo Station (GTO) recording, anomalies that can be validated as earthquake precursors were found. The polarization of the Sz/Sh ratio 30 days before the earthquake on March 28, 2023, showed that the anomaly appeared 32 times. One anomaly was detected due to a magnetic storm on March 25, 2023, with an intensity of -33 nT. Figure 12 displays anomalies suspected to be earthquake precursors in the form of a black circle. The anomaly appeared six times: on March 3 with an amplitude of -6.011, on March 7 with an amplitude of -6.033, on March 16 with an amplitude of -4.119, and on March 22 at 12 o'clock with an amplitude of 7.609 and at 24 o'clock with an amplitude of -5.431. Additionally, on March 27, the anomaly appeared with an amplitude of 7.353. According to the graph, the earthquake precursor anomaly began on March 3, with a lead time of 24 days.

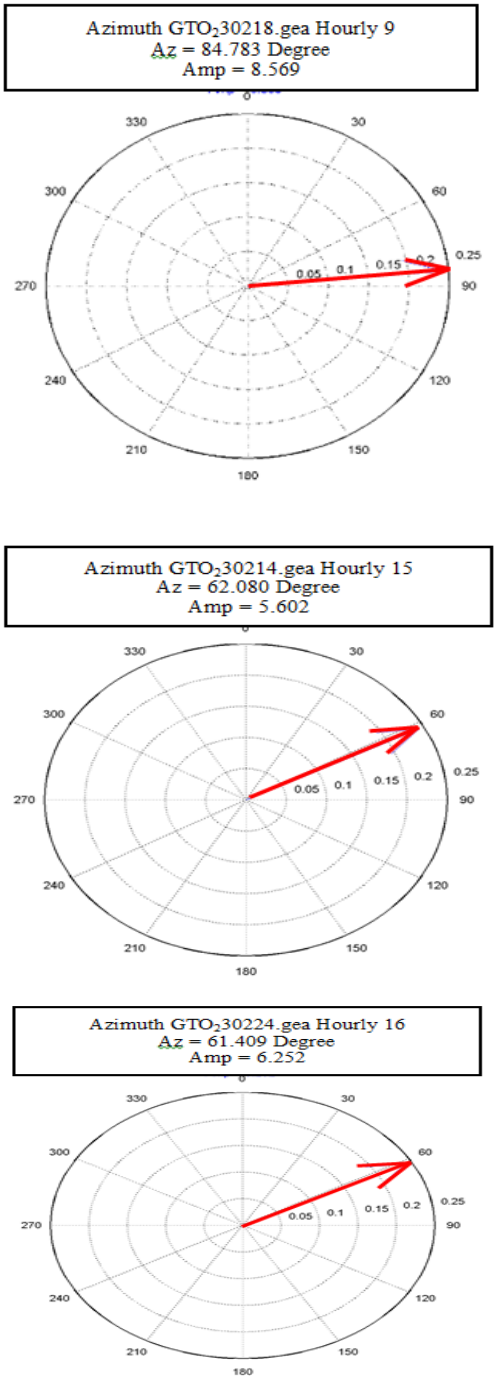

Figure 11. Azimuth direction of earthquake anomaly source March 7, 2023.

4. Earthquake 28 March 2023

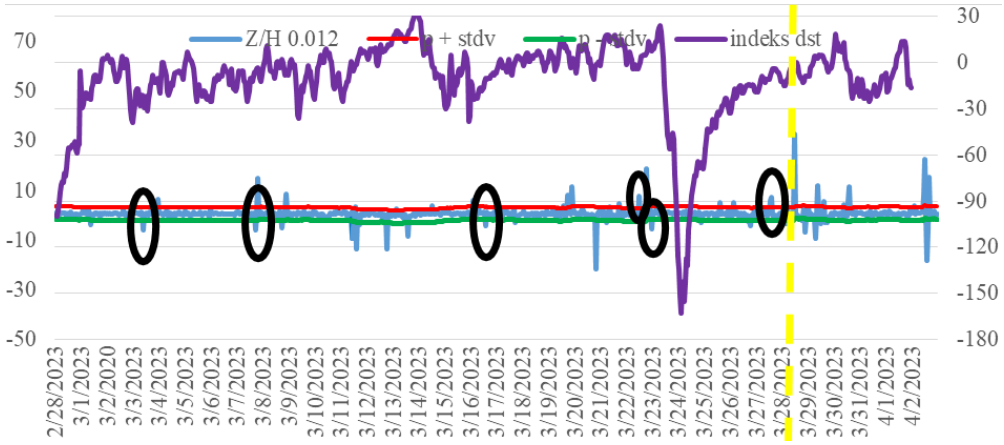

Figure 12. Graph showing ULF signal anomalies during the March 28, 2023 earthquake

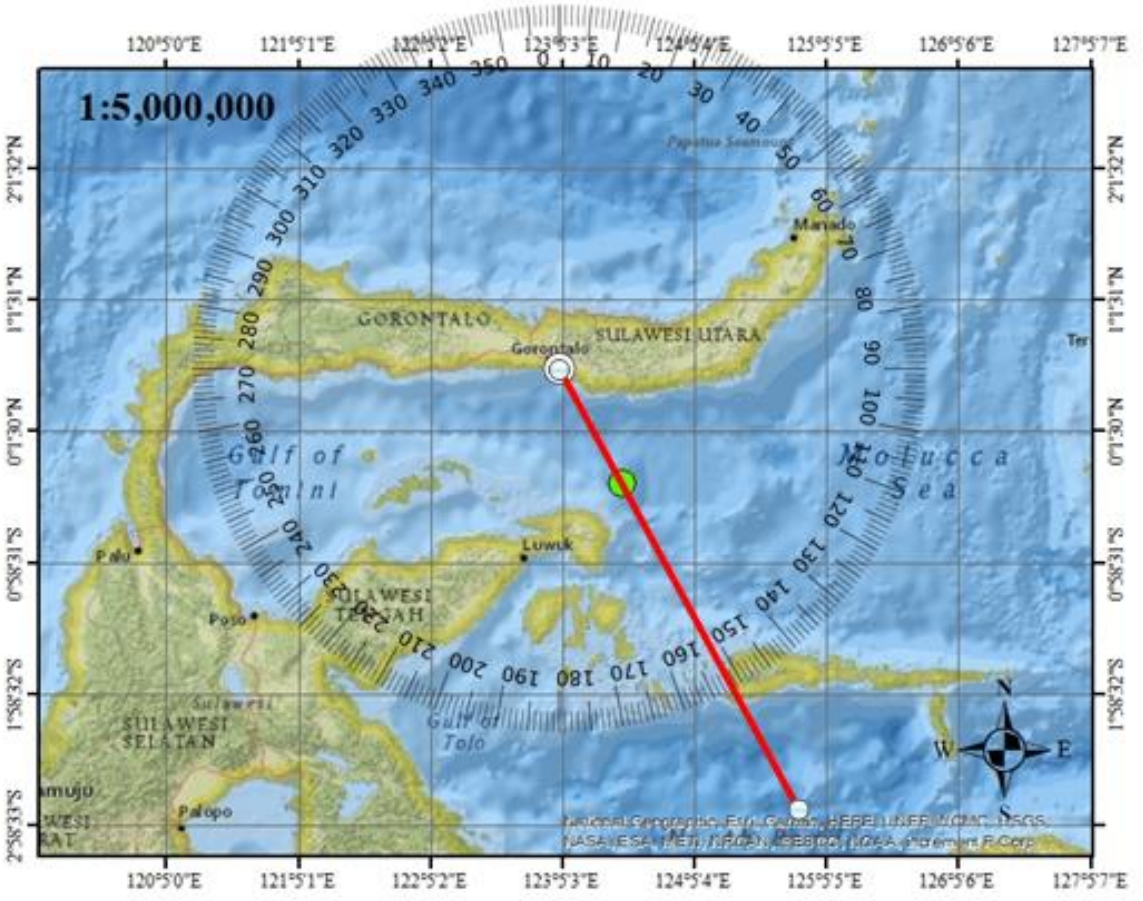

Figure 13. Mapping the azimuth direction of the earthquake at the GTO station on March 28, 2023

In Figure 13, the analysis results indicate that the earthquake azimuth direction is 152°, and the anomalous azimuth direction leading to the earthquake preparation zone is within a standard deviation of ±22.5°, which is approximately 129.5°-174.5°. The earthquake's azimuth direction in Figure 13 is consistent with the azimuth direction of the earthquake anomaly source shown in Figure 14.

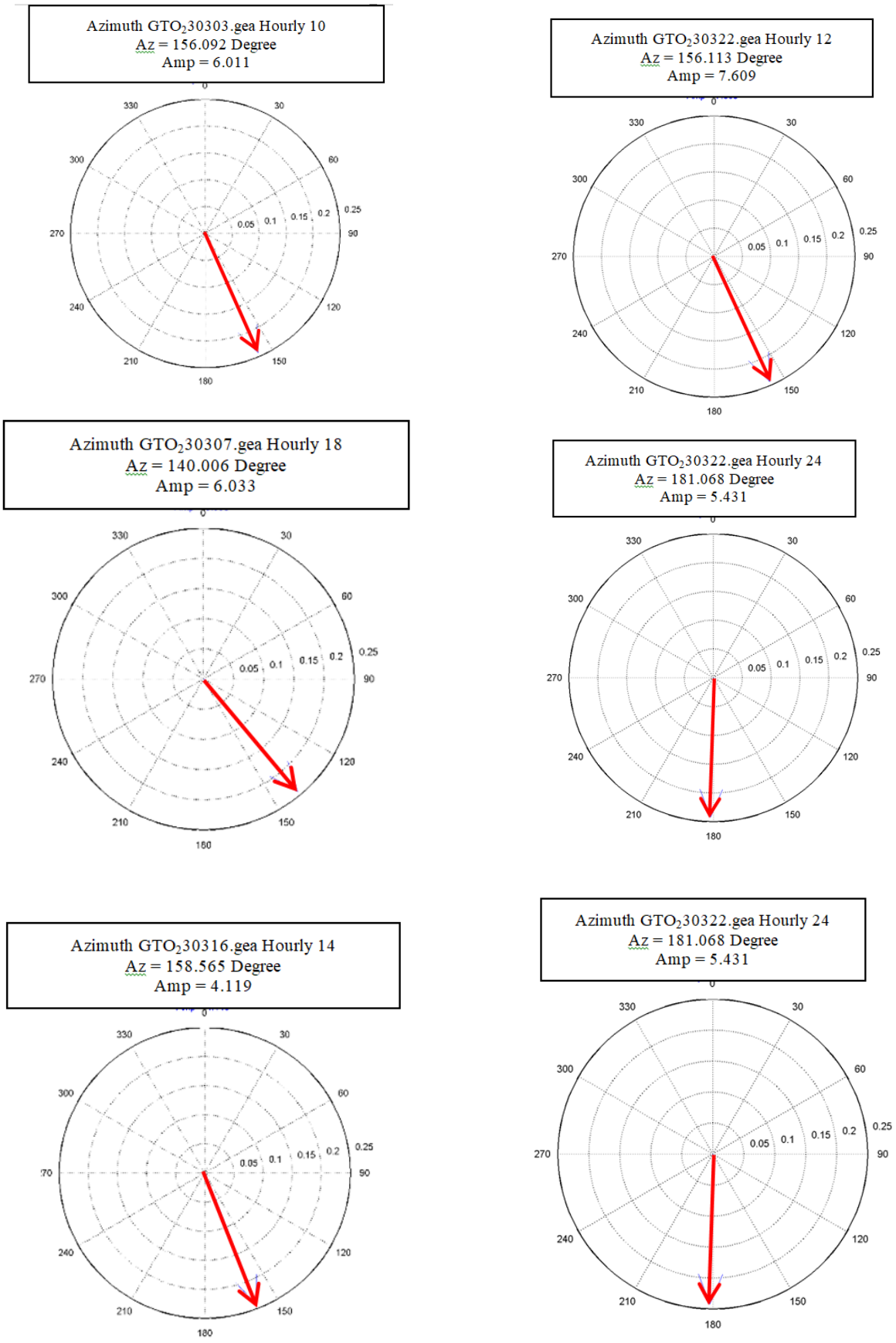

Figure 14. Azimuth direction of earthquake anomaly source March 28, 2023.

5. Earthquake 6 April 2023

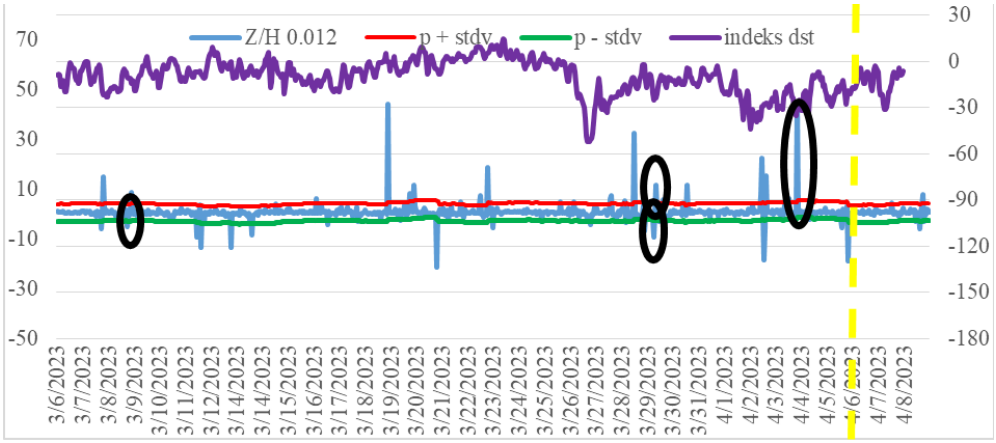

Figure 15 Graph showing ULF signal anomalies during the April 6, 2023 earthquake

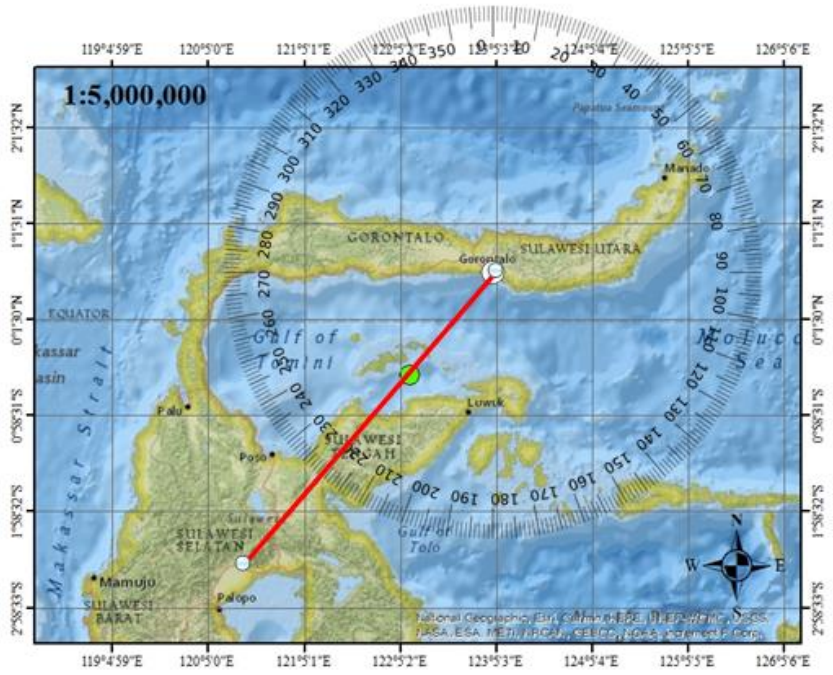

Figure 16. Mapping the azimuth direction of the earthquake at the GTO station on April 26, 2023.

An earthquake measuring 5.2 on the Richter scale struck the Luwuk area of Central Sulawesi at a depth of 10 km. An earthquake measuring 5.2 on the Richter scale struck the Luwuk area of Central Sulawesi at a depth of 10 km. The epicenter was located at latitude -0.536 and longitude 122.1838, approximately 328 km from the nearest station.

The Gorontalo Station (GTO) recorded anomalies that can be validated as earthquake precursors of Sz/Sh ratio polarization 30 days before the occurrence of the earthquake on April 6, 2023. The anomalies appeared 29 times. No anomalies indicated by magnetic storms or DST indices were observed during this earthquake, suggesting that all anomalies originated from lithospheric activity. Figure 15 displays the black circle of anomalies suspected to be earthquake precursors. The anomalies appeared five times: on March 8 with an amplitude of -4.888, on March 29 at 7 and 9 o'clock with respective amplitudes of -9.051 and 11.823, on April 2 with an amplitude of -18.27, and on April 3 with an

amplitude of 44.547. The graph indicates that the onset time of the earthquake precursor anomaly was on March 8 with a lead time of 29 days.

In Figure 16, the analysis results indicate that the earthquake azimuth direction is 220^o and the anomaly azimuth direction leading to the earthquake preparation zone is calculated to be within a standard deviation of ±22.5^o, which is approximately 197.5^o - 242.5^o. The earthquake's azimuth direction in Figure 16 agrees with the azimuth direction of the earthquake anomaly source shown in Figure 17.

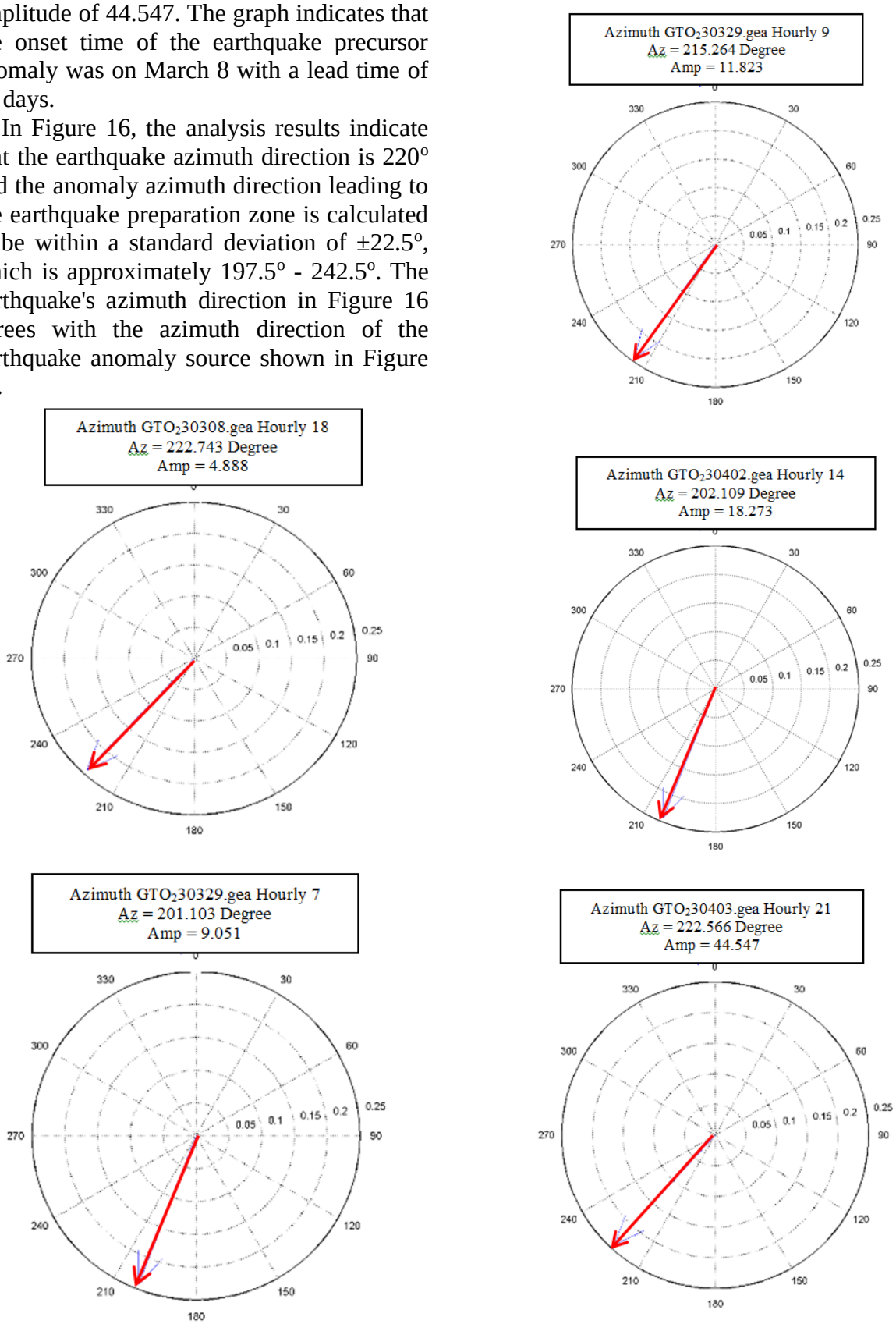

Figure 17. Azimuth direction of earthquake anomaly source April 26, 2023.

Earthquake events can be influenced by magnetic field phenomena that produce anomalies in ULF signals. The appearance of the anomaly is indicated by the Z/H ratio value that exceeds the standard deviation in the results of the ULF signal anomaly analysis of the earthquake event in the Sulawesi region of magnitude 5 at a frequency of 0.012-0.022 Hz.

Research conducted by Wahyuningsih (2016) found that Ultra Low Frequency (ULF) signal anomalies always appear after 5 magnitude 5 earthquake events in the Sulawesi region. These anomalies can be used as an initial sign (precursor) of an earthquake. The lead times for ULF anomalies as earthquake precursors in the Sulawesi region vary between 17-30 days. The direction of the earthquake's azimuth is consistent with the anomaly source's azimuth direction, as determined by research conducted by Masruri (2017). The anomaly source is considered to be a representation of the earthquake epicenter.

Conclusion

An Ultra Low Frequency (ULF) Signal Anomaly was observed as a precursor to the Magnitude 5 Earthquake in the Sulawesi Region during the period of January-May 2023. Specifically, in the February 27 earthquake, the anomaly appeared twice, on February 9 and February 18, with a lead time of 17 days. In the February 28, 2023 earthquake, the anomaly appeared twice, on January 30 and February 3, with a lead time of 28 days. The earthquake anomalies for March 7, 2023, appeared three times on February 14, February 18, and February 24, with a lead time of 20 days. The March 28, 2023, earthquake had six anomalies on March 3, March 7, March 16, March 22, and March 27, with a lead time of 24 days. On March 22, there were two anomalous occurrences at 12:00 and 24:00. The earthquake that occurred on April 6, 2023, had five anomalies. Additionally, there were two anomalies on March 8 and March 29, respectively, at 7 and 9 o'clock. Two more anomalies were observed on April 2 and April 3, with a lead time of 29 days. The lead times for ULF anomalies as earthquake precursors in the Sulawesi region vary between 17-30 days. The direction of the earthquake's azimuth is consistent with the anomaly source's azimuth direction In the context of disaster mitigation efforts to minimize the impact of loss and damage, the research encompasses the identification of potential early signs of earthquakes and the characterization of earthquake sources on the island of Sulawesi. This information is essential for the development of accurate predictions of risk hazards and the assessment of potential risks in the Sulawesi region.

Acknowledgment

The author would like to express gratitude to Mrs. Ratni Sirait, M.Pd, and Mrs. Lailatul Husna Br. Lubis, M.Sc for their guidance, input, and advice during the research process. Additionally, thanks to the BMKG Geophysical Station for their assistance in processing the research data.

References

1. Bock, Y., L. Prawirodirdjo., J.F. genrich.,C.W. Stevens., R.McCaffrey., C.Subarya. SSOP dan EC. Crustal motion in Indonesia from Global Positioning System measurements. Journal of Geophysical Research. 2003;108(B8). doi:10.1029/2001JB000324
2. Sompotan AF. Geological Structure of Sulawesi. 2012. Book.
3. Masruri, M Fakhrul Islam., Bayu Merdeka Tri Fristiyan Nanda. dan MS. Preseismic Event Analysis Using Geomagnetic Data Case Study: Sunda Strait Earthquake 28 June 2016 M 5.0. Jurnal Fisika.
   doi: https://doi.org/10.15294/jf.v7i2.13370
4. Pakpahan, Suliyanti., Drajat Ngadmanto. & M. Seismicity Analysis in Palu Koro Fault Zone, Central Sulawesi. Jurnal Lingkungan dan Bencana Geologi. 2015;6(3):253–64.
   doi: http://dx.doi.org/10.34126/jlbg.v6i3.88

5. Yumoto K. MAGDAS project and its application for space weather. 2006. ILWS Workshop.
6. Hobara Y, Koons HC, Roeder JL, Yumoto K, Hayakawa M. Characteristics of ULF magnetic anomaly before earthquakes. Physics Chemistry of The Earth. 2004;29(4–9):437–44. https://doi.org/10.1016/j.pce.2003.12.005
7. Yumoto K, Ikemoto S, Cardinal MG, Hayakawa M, Hattori K, Liu JY, et al. A new ULF wave analysis for Seismo-Electromagnetics using CPMN/MAGDAS data. Phys Chem Earth. 2009:34(6–7):360–6. doi:10.1016/j.pce.2008.04.005
8. Hamidi, M. EL namigo dan M. Identification of Ultra Low Frequency Geomagnetic Signal Anomalies as Precursors to Small Magnitude Earthquakes in the Nias Islands Region. Jurnal Ilmu Fisika Andalas University. 2018: 10(1):53–62. doi: 10.25077/jif.10.1.53-62.2018 53
9. Fazriyanti L, Tahjono A, Febriani F. Geomagnetic Signal Anomaly Analysis Using the Detrended Fluctuation Analysis Method in a 6.1 Magnitude Earthquake in Lebak, Banten. Al-Fiziya: Journal of Materials Science, Geophysics, Instrumentation and Theoretical Physics. 2020;3(1):53–60. doi: https://doi.org/10.15408/fiziya.v3i1.15091
10. Wahyuningsih, Ulfa . Syamsurijal rasimeng., karyanto. rudianto. Analysis Of Ultra Low Frequency Signal Anomalies Based On Geomagnetic Measurement Data As An Earthquake Precursor Indicator In The Lampung Region Year 2016. Jurnal Geofisika Eksplorasi. 2020:4(2):187–200. doi: https://doi.org/10.23960/jge.v4i2.16.
11. Suaidi, Ahadi ., Puspito N.T ., Saroso S., Ibrahim G., Siswoyo. S. Precursor to the 2009 Padang Earthquake Based on the results of Polarization Analysis Power Ratio and Single Station Transfer Function. Jurnal Ilmu Geomatika. 2013;Vol : 19(1):49–56. doi:https://doi.org/10.24895/JIG.2013.19-1.%25x
12. Sari RA. Determination of Empirical Equations to Predict Earthquake Magnitude Using Earthquake Precursor Parameters from Magnetic Anomalies in Lombok, West Nusa Tenggara. Skripsi. 2019.
13. Hattori, Katsumi. ULF geomagnetic changes associated with large earthquakes. Terrestrial Atmospheric and Oceanic Science. 2004:15(3):329–60. doi:10.3319/TAO.2004.15.3.329
14. Hamidi M, Ahadi S, Friska V, Marzuki M. Investigating ultra-low frequency emissions and total electron content anomalies as earthquake precursors in Sumatra (2019–2020). Kuwait Journal of Science. 2024;51(2):100196. doi:https://doi.org/10.1016/j.kjs.2024.100196
15. Subakti H, Damayanti Purnama Ratri A, Muslim B. Analysis Of Ionospheric Anomalies Before The Massive Earthquake In Java Using Gps Tec Data. Jurnal Meteorologi Klimatologi dan Geofisika. 2017. Vol:4. 51(2):100196 doi:10.1016/j.kjs.2024.100196