

# Geomarine Exploration for Identification of Rare Earth Elements (REE) to Support The Defense Industry: Case Study Sabang Waters

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Article information	ABSTRAK
<i>Article timeline</i> Accepted : 2025-06-11 Revised : 2025-07-18 Published : 2025-07-30	Pentingnya pertahanan nasional secara strategis sangat berkaitan dengan sumber daya alam, cadangan material strategis, khususnya Elemen Tanah Jarang (REE), serta industri pertahanan nasional. Hal ini krusial untuk mencapai kemandirian pertahanan. Namun, eksplorasi REE di Indonesia belum dilakukan secara optimal meski memiliki potensi geologi yang besar. Penelitian ini berfokus pada pemetaan distribusi REE di Perairan Sabang dengan menerapkan metode eksplorasi geomarin yang didukung oleh analisis data seismik dan pengambilan sampel sedimen. Analisis ini memanfaatkan interpretasi fasies seismik dalam kerangka kuantitatif. Hasil penelitian menunjukkan adanya hubungan spasial antara distribusi REE dan struktur geologi yang dipengaruhi oleh aktivitas vulkanik, terutama fumarol. Fitur geologi ini berpotensi mengindikasikan zona-zona baru yang mengandung REE di lingkungan laut dangkal. Hubungan ini diusulkan sebagai pendekatan baru untuk eksplorasi REE di lingkungan tektonik laut. Penelitian ini juga menyoroti relevansi integrasi penginderaan jauh dan data geologi dalam pemetaan mineral strategis untuk mendukung ketahanan industri pertahanan.
<b>Kata Kunci:</b> Elemen Tanah Jarang (ETJ) Penginderaan Jauh Geomarine Eksplorasi Fasies Seismik	
	
<b>Keywords:</b> Rare Earth Elements (REE) Remote Sensing Geomarine Exploration Seismic Facies	<b>ABSTRACT</b> The strategic importance of national defense is closely related to natural resources, strategic material reserves, particularly Rare Earth Elements (REE), and the national defense industry, which is crucial for achieving defense independence. However, the exploration of REE in Indonesia has not been optimally conducted despite its vast geological potential. This research focused on mapping the distribution of REE in the Sabang Waters by applying geomarine exploration methods supported by seismic data analysis and sediment sampling. The analysis utilized seismic facies interpretation within a quantitative framework. Findings revealed a spatial association between REE distribution and geological structures influenced by volcanic activity, particularly fumaroles. These geological features potentially indicate new REE-bearing zones in shallow marine environments. This association is proposed as a new approach to REE exploration in marine tectonic settings. The research highlights the relevance of integrating remote sensing and geological data in mapping strategic minerals to support defense industry resilience.

## Introduction

Recent advancements have emphasized the strategic relevance of REE in supporting industrial innovation and defense resilience globally (Purnomo et al., 2020; Arifin et al., 2023). REE demand has aligned with the growth of energy, automotive, and national

security sectors. Marine exploration, particularly in tectonically complex zones like volcanic island arcs, offers significant promise due to the association of REE with hydrothermal systems (Petersen et al., 2016). This justifies the integration of geomarine geological studies into national policy to map underwater REE potential. Recent advancements have emphasized the strategic relevance of REE in supporting industrial innovation and defense resilience globally (Purnomo et al., 2020; Arifin et al., 2023). Indonesia's growing demand for critical materials highlights the importance of marine-based exploration, particularly in volcanic island arc settings like Weh Island (Petersen et al., 2016). Rare Earth Elements (REE) have emerged as critical components in modern defense systems, playing pivotal roles in precision-guided munitions, electronic warfare systems, radar, and communication equipment (Zepf, 2013; U.S. Department of Energy, 2011). As such, the strategic value of REE has increased, especially within the context of national defense autonomy and industrial resilience. In Indonesia, the role of natural resources including REE as supporting components of defense capabilities has been acknowledged in national policy frameworks (Ministry of Defense, 2008).

Indonesia's geological setting, located at the convergence of the Eurasian, Indo-

## Methods

This study's methodological framework aligns with recent approaches in shallow marine geophysical mapping that integrate sonar data and seismic reflection techniques (Kadariusman et al., 2022; Sutikno et al., 2019). Recent marine studies emphasize the effectiveness of combining acoustic and seismic datasets for identifying mineralized zones without direct sediment sampling (Jayaprakash et al., 2016).

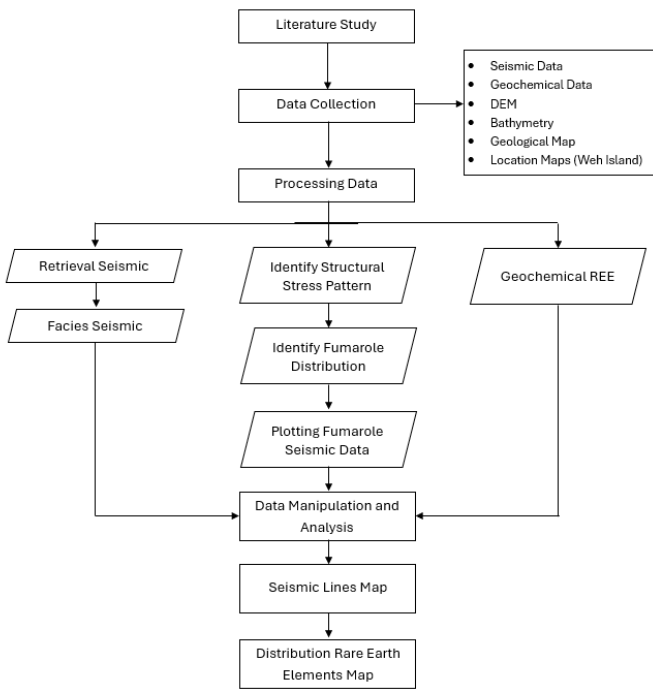
This study employed an integrated geomarine geophysical method that combined remote sensing sonar technology with shallow

Australian, and Pacific tectonic plates, provides favorable conditions for REE mineralization (Hall, 2002; Widana et al., 2021). While considerable studies have focused on terrestrial REE deposits in regions such as Bangka, Kalimantan, and Papua, marine-based REE exploration remains limited despite the promising potential in submarine volcanic and hydrothermal zones (Bahti et al., 2011; Hananto & Usman, 2016).

The island of Weh, located in the Sabang Waters off the northern tip of Sumatera, is ideal for such an investigation. Submarine hydrothermal activity around this volcanic island may provide favorable conditions for REE accumulation due to mineral precipitation from fluid discharges (Hein et al., 2013). However, previous research has not fully utilized integrated geomarine methods such as shallow seismic profiling, structural interpretation, and sediment geochemistry for REE mapping in this region.

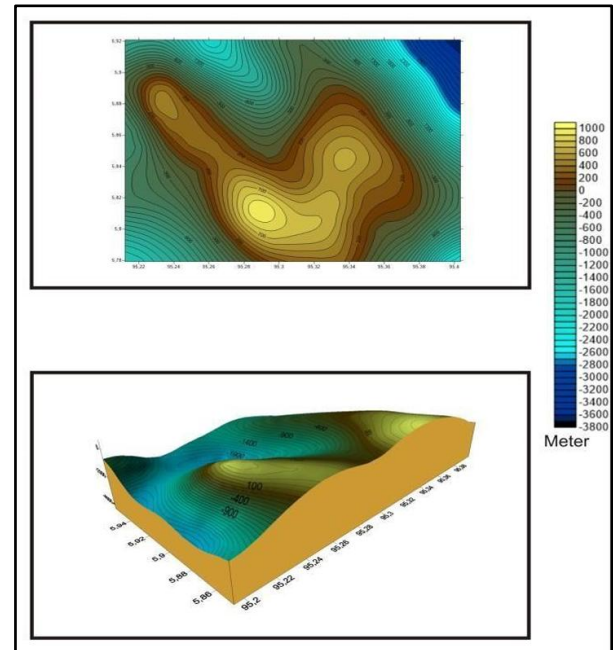
This study aims to fill that gap by applying integrated geomarine exploration techniques to determine the spatial distribution and geological controls of REE deposits in Sabang Waters. Ultimately, the results are expected to contribute to Indonesia's strategic mineral resource development and national defense preparedness.

seismic reflection data interpretation to map subsurface geological structures and depositional patterns associated with potential Rare Earth Elements (REE) zones. The methodology consisted of three main components: sonar-based bathymetric mapping, seismic data acquisition, and seismic facies interpretation, all of which were conducted using secondary datasets from the Marine Geological Research and Development Center (PPPGL), Ministry of Energy and Mineral Resources.



**Figure 1.** Research Flowchart

Sonar-Based Bathymetric Mapping data were acquired using single-beam echosounder systems mounted on survey vessels. The sonar technology (hydroacoustic remote sensing) emits acoustic signals from a transducer toward the seabed, where signals reflect and are recorded by a receiver. This process enabled the creation of a digital bathymetric map of the seabed, which was later processed using GIS software.



**Figure 2.** Depth contours and seabed features of Sabang waters, Weh Island.

The bathymetric profile was crucial for identifying seabed morphology, slope gradients, and potential locations of hydrothermal venting areas. This bathymetric data is presented in Figure 1, showing the depth contours and seabed features relevant to REE deposition zones.

The interpretation process analyzed internal reflection configurations, including reflector continuity, amplitude, frequency, and geometry. These characteristics were used to classify seismic facies and to infer sedimentary environments and tectonic frameworks (Brown, 1999). Seismic facies units were delineated based on their stratigraphic arrangements and were correlated with known geological settings of the Sabang Waters region. Special attention was given to features indicative of fault-controlled hydrothermal systems, such as chaotic reflectors, fault intersections, and unconformities, which may serve as structural traps or conduits for REE-bearing fluids (Hein et al., 2013; Widana et al., 2021). All interpretations were performed using GIS-based mapping to visualize the spatial distribution of seismic facies units and their structural associations.

Followed by a sample of REE's geochemical content found in the waters of Weh

Island. The table data indicate an association between geological structures, fumaroles, and sedimentation processes in the Sabang Waters.

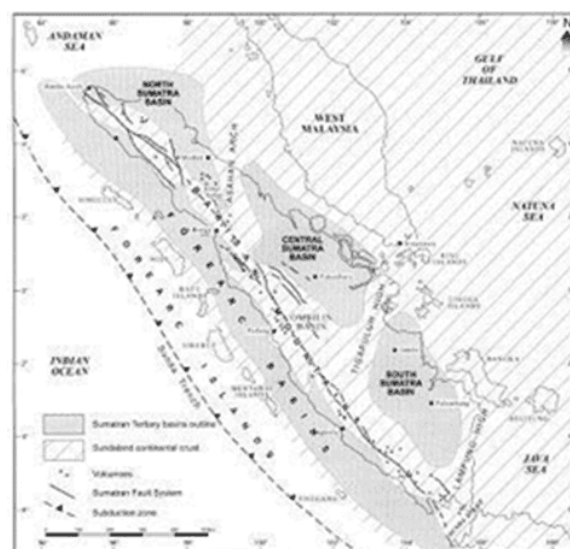
**Table 1.** Highest REE Content in Sabang Waters

Elements	Max Value (ppm)	Sample Index
Sc	30.0	4
Y	26.5	6
La	48.1	13
Ce	50.3	11
Pr	6.13	13
Nd	23.2	13
Sm	5.5	4
Eu	1.1	12
Gd	5.3	6
Tb	0.75	2
Dy	0.5	4
Ho	1.0	4
Er	2.7	4
Tm	0.4	0
Yb	0.4	1
Lu	0.83	0

## Results and Discussion

Numerous marine geological investigations have shown that submarine fault intersections and volcanic ridges represent ideal REE deposition environments due to fluid circulation and mineral precipitation (Zhong et al., 2018; Hein et al., 2020). The integration of multi-scale geophysical data enhances the detection of these features. This study analyzed several structural features using bathymetric and seismic evidence, emphasizing tectonic control in REE localization. Regional tectonic stress fields and magma-sourced hydrothermal systems often intersect in submarine settings, creating suitable traps for rare earth mineral precipitation (Cukur & Yamaguchi, 2015).

The Sabang Waters are part of a tectonically active region situated near the junction of the Eurasian and Indo-Australian plates. The geology is predominantly volcanic, composed of andesitic-basaltic lava flows, volcanic breccias, and intrusive bodies. These units are intersected by numerous faults associated with the Sumatera Fault System, a major strike-slip fault that controls much of the regional deformation.



**Figure 3.** Geological map of Weh Island and surrounding areas showing volcanic and intrusive rock.

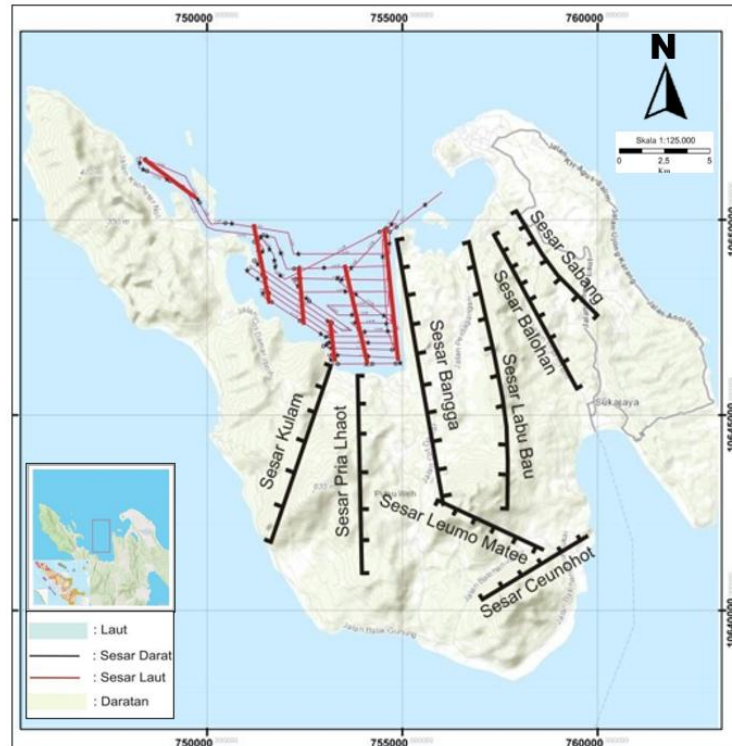
Figure 3. illustrates the tectono-structural segmentation of northern Sumatra, highlighting the influence of the Semangko Fault Zone. This regional tectonic framework is responsible for the formation of extensional basins and flower structures, both positive and negative, which are often associated with mineral-bearing hydrothermal systems. The deformation zone around Weh Island reflects such tectonic complexity, potentially enabling hydrothermal pathways that facilitate REE accumulation.

The interpreted regional stress regime derived from bathymetry and seismic orientation aligns with observed vent-like features on the seafloor, indicating active or paleo-hydrothermal systems that serve as REE mineralization sites. The stratigraphic configuration in the study area reveals alternating layers of volcanoclastic deposits and massive lava flows, interpreted from seismic reflection profiles. These layers display onlap and truncation patterns typical of a tectonically disrupted setting (Figure 3). The structure is dominated by normal and strike-slip faults trending northwest-southeast, with some faults acting as possible conduits for hydrothermal fluids. These structures are especially evident in chaotic seismic facies, which

are typically associated with fault zones and gas-charged sediments.

Bathymetric mapping using sonar (Figure 2) reveals significant morphological features, including ridges, depressions, and vent-like structures. These bathymetric highs and lows

correspond with fault intersections and fracture zones. The slope steepness and seafloor irregularities in several areas suggest active tectonic and hydrothermal processes. These areas are hypothesized to be favorable for the precipitation of REE-bearing minerals.



**Figure 4.** Interpreted structural intersections from seismic overlays.

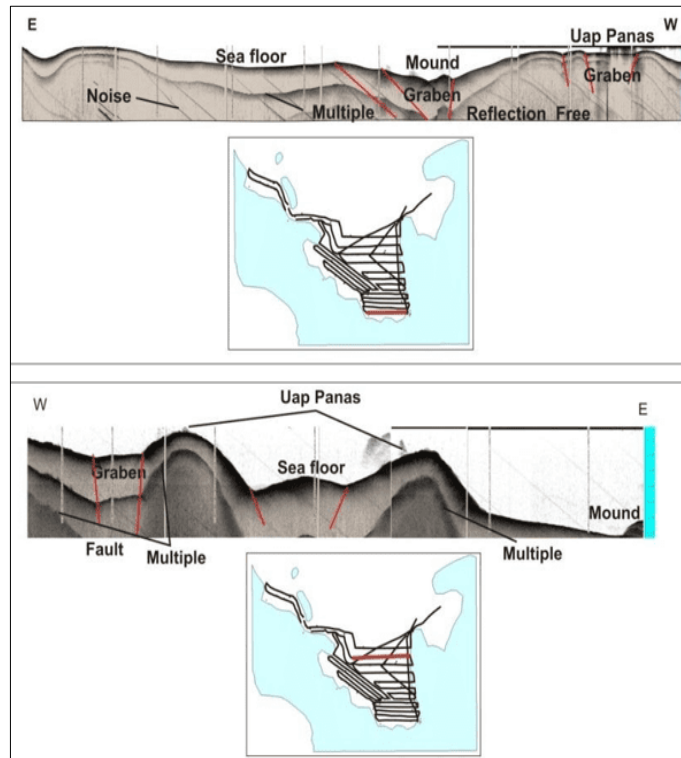
Seismic data interpretation identified several facies zones with distinct reflection characteristics. Continuous high-amplitude reflectors are associated with compact volcanic units, whereas chaotic, low-amplitude reflectors correspond to disrupted zones possibly enriched in hydrothermal minerals. Figure 4. presents the interpreted fault intersections overlaid with seismic anomalies. These intersections exhibit disrupted reflection patterns and amplitude attenuation, typical of zones affected by fluid migration and alteration. The geometry of these zones is consistent with pull-apart basins formed by strike-slip faulting. Such settings create localized sediment traps and structural dilation zones favorable for hydrothermal REE deposition. The combination of chaotic reflectors and structural intersections strengthens the hypothesis that REE-bearing phases are

concentrated in zones of high tectonic permeability and fluid flux.

REE distribution and structural correlation are based on secondary geophysical modeling and regional geological correlation, potential REE accumulation zones are located along the flanks of major fault corridors. These areas show seismic attenuation and reflection pattern disruption, consistent with mineralized fractures and possible hydrothermal vents. The highlighted zones represent target areas for future REE exploration based on tectonic complexity and geomorphological anomalies.

Figure 5. provides a model of fault geometry and interpreted stress fields derived from seismic and bathymetric data. The mapped flower structures indicate compressional and extensional regimes that help control hydrothermal circulation. These structures

coincide spatially with regions of low reflectivity and chaotic facies, reinforcing the interpretation of hydrothermal alteration zones.

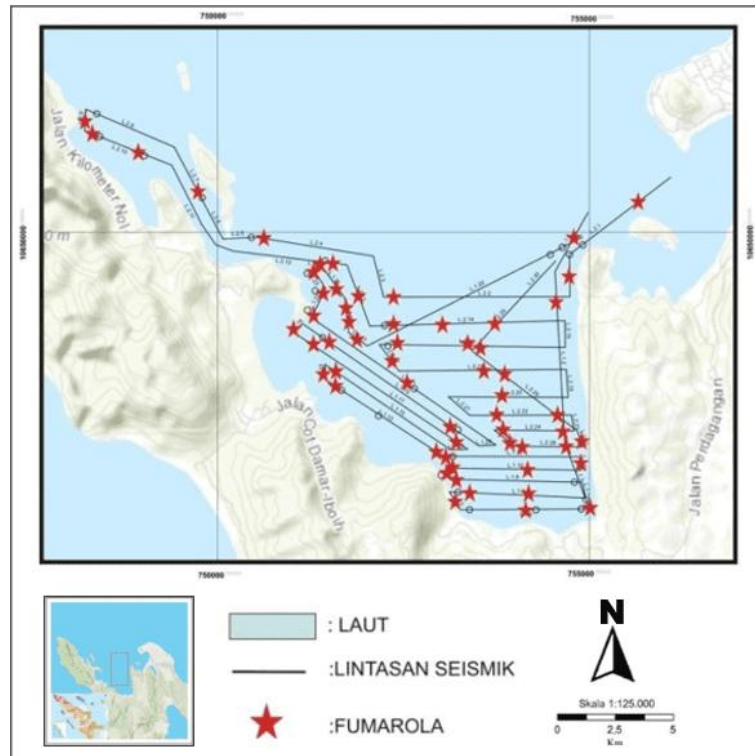


**Figure 5.** Structural model integrating fault zones and stress field interpretation.

The distribution of these structural features aligns with the interpreted REE prospect zones shown in Figure 6, which maps the potential enrichment zones across the Sabang seafloor. This spatial analysis supports the targeted delineation of marine REE zones based on remote sensing and structural modeling. Based on secondary geophysical modeling and regional geological correlation, potential REE accumulation zones are located along the flanks of the major fault corridors. These areas show seismic attenuation and reflection pattern disruption, consistent with mineralized fractures and possible hydrothermal vents. While this study did not involve direct geochemical sampling, interpretation of seismic facies and tectonic features suggests a high correlation between

structural complexity and REE prospectivity. Implications for Marine-Based REE Exploration The integrated interpretation of bathymetric, seismic, and structural data indicates that tectonic control plays a significant role in REE distribution in the Sabang Waters. Submarine faults and hydrothermal systems provide favorable pathways for mineral-rich fluids and sites for mineral precipitation.

Figure 6., visualizes the final synthesis of this study, a distribution map of potential REE zones derived from structural intersections, vent morphologies, and seismic anomalies. The map serves as a practical output for directing future exploration efforts and helps define the spatial extent of the most prospective marine zones.



**Figure 6.** Fumarole Distribution Map as an Indicator of REE Prospect Zones in Sabang Waters

This supports a targeted exploration model for marine REE that prioritizes structurally complex zones and hydrothermal systems as exploration targets (Hein et al., 2013; Widana et al., 2021). In conclusion, the results of this study confirm that shallow marine tectonic-volcanic systems in the Indonesian archipelago, such as those in Sabang, represent viable exploration targets for strategic minerals like REE. Integrating geomarine seismic data with sediment geochemistry offers a non-invasive, cost-effective, and scalable method for REE prospecting. These findings encourage further development of marine mineral exploration frameworks tailored to Indonesia's geodynamic setting, promoting economic resilience and national defense autonomy.

### Conclusions

This research strongly suggests that the distribution of Rare Earth Elements (REE) in Sabang Waters is structurally controlled, particularly within negative flower structures formed by extensional tectonics and closely associated with submarine volcanic features such

as fumaroles. Seismic facies analysis revealed external geomorphology, such as mounds and grabens, and internal reflection-free textures, strongly suggesting hydrothermal activity and volcanic origin. The novelty of this study lies in its integration of geomarine seismic interpretation, structural stress pattern analysis, and sediment geochemistry to identify REE-bearing zones in a shallow marine environment. This area remains underexplored in Indonesia. The spatial correlation between REE anomalies and fumarole distributions supports the initial hypothesis and provides a conceptual framework for REE exploration in tectonically active marine zones. These findings strategically impact Indonesia's national defense autonomy, as REEs are crucial in modern defense technologies. Future research is encouraged to expand this exploration model to other submarine volcanic arcs in Indonesia and incorporate geochemical fingerprinting and 3D geophysical modeling for more refined targeting of REE deposits.

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## References

Arifin, M., Gunawan, E., & Nugroho, S. (2023). Marine critical mineral mapping in volcanic island arcs: Potential and policy gaps in Indonesia. *Marine Geoscience Journal*, 18(1), 22–34.

Cukur, D., & Yamaguchi, K. (2015). High-resolution seismic facies analysis of submarine volcanic slopes: Implications for marine mineral exploration. *Journal of Asian Earth Sciences*, 102, 12–24.

Hein, J. R., Mizell, K., & Conrad, T. A. (2020). Critical metals in marine mineral deposits. *Elements*, 16(2), 89–94.

Jayaprakash, C., Sajeev, R., & Kumar, A. A. (2016). Distribution of rare earth elements in the inner shelf sediments, off the southwest coast of India. *Indian Journal of Geo Marine Sciences*, 45(12), 1623–1630.

Kadarusman, A., Maulana, A., & Saputra, A. (2022). Advanced geophysical methods for rare earth exploration in Indonesian waters. *Geological Engineering Review*, 28(3), 55–67.

Petersen, S., Krätschell, A., Augustin, N., Jamieson, J., Hein, J. R., & Hannington, M. D. (2016). News from the seabed – Geological characteristics and resource potential of deep-sea mineral resources. *Marine Policy*, 70, 175–187.

Purnomo, E., Haris, A., & Wahyudi, H. (2020). Strategic critical materials for national defense

industry resilience. *Journal of Defense Resource Strategy*, 9(2), 89–103.

Sutikno, B., Hendrayana, H., & Basuki, A. (2019). Integration of sonar mapping and shallow seismic profiling for submarine resource assessment. *Indonesian Journal of Geoscience*, 6(2), 117–126.

Widana, G. N. R., Kurniawan, A., & Suryono, Y. (2021). Tectonic control on REE-bearing mineralization in Indonesia. *Indonesian Journal of Geoscience*, 8(2), 101–113.

Zhong, Y., Li, J., Liu, Y., & Wang, X. (2018). Rare earth elements and yttrium in ferromanganese deposits from the South China Sea. *Marine Georesources & Geotechnology*, 36(4), 377–389.

Bahti, H. H., Mulyasih, Y., & Anggraeni, A. (2011). Extraction and chromatographic studies on rare earth elements (REEs). *Jurnal Kimia*, 5(2), 123–130.

Brown, A. R. (1999). *Interpretation of Three-Dimensional Seismic Data* (5th ed.). AAPG Memoir.

Hall, R. (2002). Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: Computer-based reconstructions, model and animations. *Journal of Asian Earth Sciences*, 20(4), 353–434.

Hananto, N. D., & Usman, M. R. (2016). Submarine hydrothermal activity and REE prospects around Weh Island. PPPGL Technical Report, Ministry of Energy and Mineral Resources.

Hein, J. R., Mizell, K., Koschinsky, A., & Conrad, T. A. (2013). Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources. *Ore Geology Reviews*, 51, 1–14.

Ministry of Defense. (2008). *Strategic Defense Policy Document*. Government of Indonesia.

Sheriff, R. E., & Geldart, L. P. (1995). *Exploration Seismology*. Cambridge University Press.

Telford, W. M., Geldart, L. P., & Sheriff, R. E. (1990). *Applied Geophysics* (2nd ed.). Cambridge University Press.

U.S. Department of Energy. (2011). *Critical Materials Strategy*. U.S. Government Printing Office.

Widana, G. N. R., Kurniawan, A., & Suryono, Y. (2021). Tectonic control on REE-bearing mineralization in Indonesia. *Indonesian Journal of Geoscience*, 8(2), 101–113.

Yilmaz, Ö. (2001). *Seismic Data Analysis*. Society of Exploration Geophysicists.

Zepf, V. (2013). Rare Earth Elements: What and Where They Are. In *Rare Earth Elements: A New Approach to the Nexus of Supply, Demand and Use* (pp. 11–27). Springer.