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Potential for Marine Ion-Adsorption Rare Earth Deposits: Sedimentary Facies Controls in Southwestern Vietnam

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ABSTRACT

The southwestern Vietnam continental shelf in the Gulf of Thailand represents a shallow marine depositional system influenced by terrigenous input and variable hydrodynamic conditions. This study evaluates the potential for marine ion-adsorption rare earth element (REE) deposits, focusing on the role of sedimentary facies in controlling REE enrichment. Surface sediments are dominated by fine-grained siliciclastic materials and are classified into three main facies: gravelly sandy mud ((g)sM), sandy mud (sM), and sandy clay (sC). Total rare earth oxide (TR₂O₃) contents range from 0.019% to 0.027%, with higher values (>0.02%) consistently associated with fine-grained muddy facies, particularly sandy mud and sandy clay, whereas lower concentrations occur in coarser sediments. The results indicate that sedimentary facies exert a primary control on REE enrichment through their influence on grain size and the abundance of fine particles that provide effective adsorption sites. Hydrodynamic conditions further regulate REE distribution, with low-energy environments favoring the accumulation of REE-enriched fine sediments. These findings highlight mud- and clay-dominated facies as favorable settings for marine ion-adsorption REEs, suggesting a promising and underexplored resource potential on the southwestern Vietnam continental shelf.

Keywords: Ion-adsorption rare earth elements; surface sediments; sedimentary facies; hydrodynamic conditions; southwestern Vietnam shelf

1. Literature Background and Research Methods

1.1 Literature Background

Rare earth elements (REEs) are widely recognized as sensitive geochemical tracers in marine sediments, reflecting the integrated effects of sediment provenance, depositional processes, and environmental conditions. In marine systems, REEs are typically enriched in sediments relative to seawater due to efficient adsorption and scavenging during sedimentation and early diagenesis, making marine sediments a major sink in the global REE cycle (Ruban et al., 2024; Liu et al., 2025). This enrichment is primarily controlled by adsorption onto reactive mineral phases, particularly clay minerals, which provide large surface areas and high cation-exchange capacities (Wu et al., 2023; Abbott et al., 2019), as well as Fe–Mn oxyhydroxides and organic matter, which enhance REE retention through surface complexation (Ohta and Kawabe, 2001; Liu et al., 2017). Ion-adsorption REEs, defined as REEs weakly bound to mineral surfaces via ion-exchange processes, are commonly associated with these fine-grained components, and their distribution is strongly influenced by physicochemical conditions such as pH, redox state, and ionic strength (Wu et al., 2023; Liu et al., 2019; Hong et al., 2024). Among the controlling factors, grain size plays a fundamental role, with fine-grained, clay-rich sediments exhibiting higher REE concentrations due to their greater adsorption capacity

(Pattan, 2024). On continental shelves, the spatial distribution of REEs is therefore closely linked to sedimentary environments and hydrodynamic regimes, where low-energy, mud-dominated depositional facies act as effective traps for fine particles and associated trace elements, leading to enhanced REE enrichment compared to coarser, high-energy settings (Ge et al., 2020; Pattan, 2024).

1.2 Geological setting of the southwestern Vietnam shelf

The southwestern Vietnam continental shelf is located in the eastern part of the Gulf of Thailand and represents a shallow marine environment characterized by low relief and gentle bathymetric gradients. Water depths generally range from less than 10 m near the coast to approximately 50–60 m offshore. This region forms part of the Sunda Shelf and is influenced by monsoonal circulation, tidal currents, and seasonal variations in sediment supply, all of which play key roles in controlling sediment transport, deposition, and seabed hydrodynamics (Liu et al., 2016; Ta et al., 2002).

Surface sediments across the shelf are predominantly siliciclastic in origin. Mud-dominated sediments are typically distributed in low-energy environments on the inner and middle shelf, whereas sandy sediments are more common in areas affected by stronger hydrodynamic conditions. Extensive muddy depositional zones have been identified offshore of the Mekong Delta and along parts of the southwestern shelf, reflecting the accumulation of fine-grained materials transported from riverine and coastal sources (Ta et al., 2002; Liu et al., 2016).

The Mekong River is the primary source of terrigenous sediment to the region, delivering large volumes of suspended material annually to the Gulf of Thailand. These sediments are subsequently redistributed by coastal currents and monsoon-driven circulation. In addition to fluvial input, coastal erosion and reworking of older shelf deposits also contribute to the regional sediment budget.

Despite these well-documented sedimentary processes, the relationships between sedimentary facies, hydrodynamic conditions, and the enrichment of ion-adsorption rare earth elements (REEs) in surface sediments of the southwestern Vietnam shelf remain poorly constrained.

1.3 Research Methods

1.2.1 Study area and sampling

Sediment samples were collected from the southwestern Vietnam continental shelf in the Gulf of Thailand, approximately 60 km offshore from the An Giang coastal area (Figure 1). The study area is located in a shallow marine environment with water depths ranging from about 20 to 30 m, representing a typical depositional setting influenced by riverine input, coastal processes, and bottom hydrodynamic conditions.



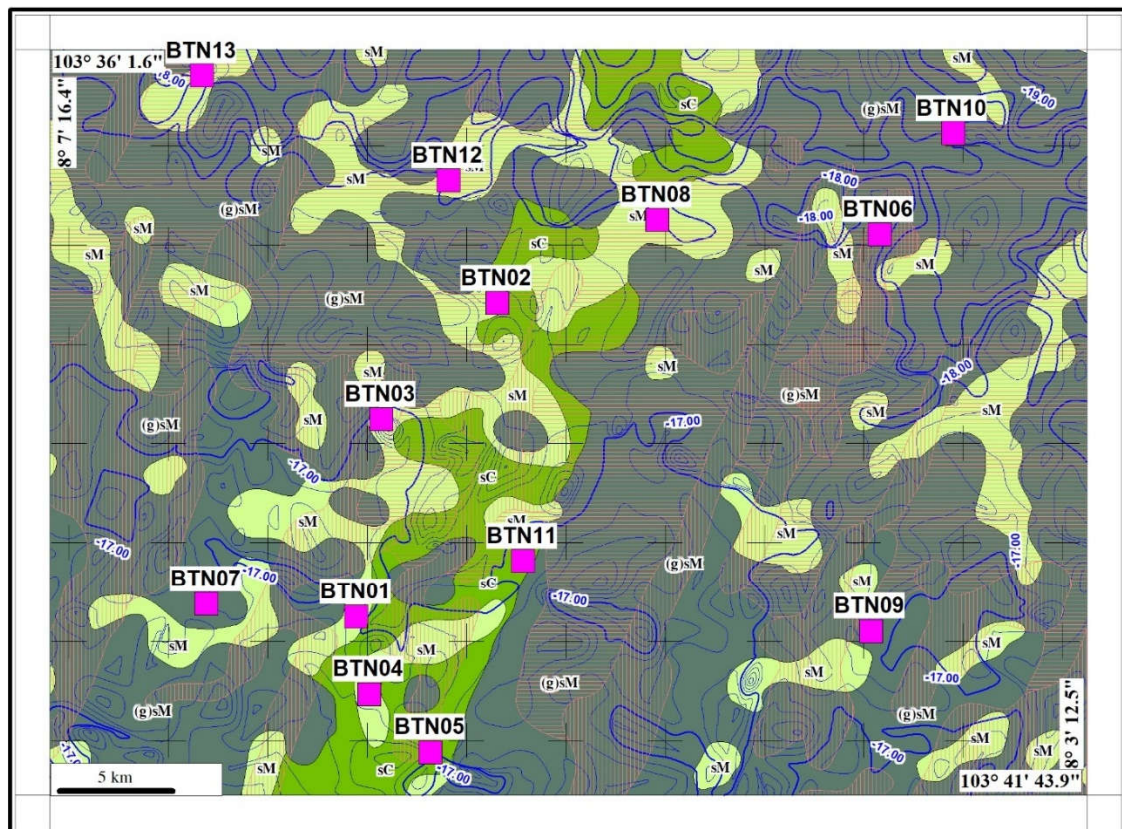
Figure 1. Map showing the location of the study area.

A total of 12 representative samples were selected for rare earth element (REE) geochemical analysis. Surface sediments were obtained using a grab sampler to recover the uppermost layer, reflecting modern depositional conditions. Grain-size analysis was conducted using a laser particle size analyzer following appropriate pre-treatment and dispersion procedures, and sediments were classified according to standard sedimentologic schemes. REE concentrations were determined using inductively coupled plasma mass spectrometry (ICP-MS) after the sample were dried, homogenized, and subjected to complete acid digestion. The concentrations of individual REEs were converted to total rare earth oxide content (TR_2O_3) to evaluate enrichment levels. Statistical analyses were applied to examine the relationships between REEs and sediment characteristics, and spatial mapping techniques were used to illustrate the distribution patterns of sediment facies and REE concentrations across the study area

2. Research Content and Results

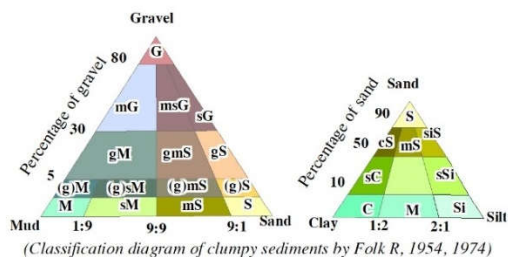
2.1 Sedimentary characteristics of surface sediments

Grain-size characteristics of surface sediments were analyzed following the Wentworth (1992) classification, and sedimentary facies were defined by using the Folk (1974) scheme based on gravel, sand, silt, and clay proportions. The surface sediments of the southwestern Vietnam shelf are predominantly fine-grained siliciclastic materials, forming three main facies: gravelly sandy mud ((g)sM), sandy mud (sM), and sandy clay (sC), which reflect spatial variations in hydrodynamic conditions and depositional processes.

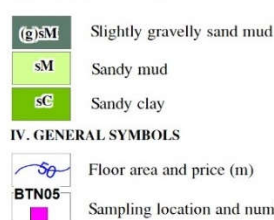


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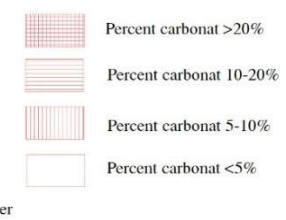
I. SEDIMENT CLASSIFICATION SYSTEM



II. SEDIMENTARY FIELDS



III. CARBONATE FIELDS



IV. GENERAL SYMBOLS

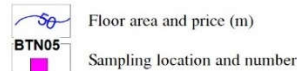


Figure 2. Surface sediment map of the study area

The (g)sM facies is the most widespread, mainly distributed at water depths of 16–20 m, and is characterized by a dominant fine-grained matrix (silt + clay >60%) with minor gravel content (1.0–4.97%). Median grain size ($M_d = 0.032\text{--}0.067\text{ mm}$) and poor sorting ($S_o = 2.23\text{--}4.33$) indicate deposition under generally low-energy conditions with occasional higher-energy inputs. The sM facies occurs discontinuously and shows similar grain-size characteristics but lacks gravel and exhibits slightly better sorting ($S_o = 2.00\text{--}2.33$), suggesting more stable, low-energy depositional conditions with continuous suspension settling. In contrast, the sC facies is more restricted and concentrated in topographic lows, displaying the finest grain sizes ($M_d = 0.02\text{--}0.047\text{ mm}$) and higher clay content, indicating deposition under persistently weak hydrodynamic conditions and acting as a sink for fine sediments Figure2).

Overall, these facies reflect a transition from (g)sM to sM and sC corresponding to decreasing hydrodynamic energy and increasing sediment stability. The dominance of fine-grained sediments and suspension settling processes indicates that the study area is characterized by low-energy shelf environments. Such conditions favor the accumulation of clay-rich sediments with high specific surface areas, providing suitable sites for the adsorption and preservation of trace elements, particularly rare earth elements (REEs), with muddy facies

(especially sM and sC) representing the most favorable environments for geochemical enrichment.

2.2 Distribution of rare earth elements

The concentrations of rare earth elements (REEs) in surface sediments show clear spatial variability across the study area, with total rare earth oxide (TR₂O₃) contents ranging from 0.019% to 0.027% (Table 1), indicating moderate enrichment under shallow marine conditions. Higher TR₂O₃ values (>0.024%) are predominantly associated with fine-grained sedimentary facies, particularly sandy mud (sM) and sandy clay (sC), whereas lower values (~0.019–0.020%) occur mainly in gravelly sandy mud ((g)sM) facies.

This pattern reflects the strong control of grain size and sedimentary facies on REE enrichment. Fine-grained sediments, characterized by higher proportions of silt and clay, provide abundant adsorption sites due to their large specific surface area and elevated cation-exchange capacity, promoting the accumulation of ion-adsorbed REEs. In contrast, coarser sediments with lower fine-particle content exhibit reduced adsorption capacity and consequently lower REE concentrations.

Table 1. Results of analysis of rare earth element content

No.	Sample	ppm			sedimentary facies
		La–Sm	Gd–Lu	TR ₂ O ₃	
1	BTN13	40.12	4.99	240.06	sM
2	BTN07	33.07	4.15	196.36	(g)SM
3	BTN12	36.36	4.63	214.82	sM
4	BTN03	45.79	5.77	269.68	sM
5	BTN01	41.26	5.52	248.04	sM
6	BTN02	37.58	5.17	230.76	sM
7	BTN04	37.4	4.68	216.45	sM
8	BTN08	42.5	5.21	252.08	sM
9	BTN11	41.33	5.11	248.6	sC
10	BTN05	41.58	5.47	248.73	sC
11	BTN06	32.77	4.07	193.15	(g)SM
12	BTN10	32.27	4.06	190.98	(g)SM
13	BTN09	34.22	4.32	202.11	(g)SM

The distribution of individual REEs shows a consistent enrichment of light rare earth elements (LREEs: La–Sm) relative to heavy rare earth elements (HREEs: Gd–Lu), indicating a dominant terrigenous source, likely associated with sediment supply from the Mekong River system. During transport and deposition, REEs are progressively scavenged and incorporated into fine-grained mineral phases.

A comparison among sedimentary facies further highlights this relationship, with the highest average TR₂O₃ values observed in sandy clay (sC), followed by sandy mud (sM), and lower values in gravelly sandy mud ((g)sM). This trend reflects the increase of clay content and reactive surface area from coarse- to fine-grained sediments.

Overall, the spatial distribution of REEs is primarily controlled by sedimentary facies and grain-size characteristics, with fine-grained, mud-dominated environments representing the most favorable settings for REE enrichment on the southwestern Vietnam shelf.

2.3 Relationship between REEs and sediment properties

The relationship between REE concentrations and sediment properties indicates a strong control of grain size and sedimentary facies on REE enrichment. A clear positive correlation is observed between total rare earth oxide (TR_2O_3) contents and the proportion of fine-grained fractions (silt and clay). Sediments dominated by sandy mud (sM) and sandy clay (sC) facies consistently exhibit higher REE concentrations compared to coarser gravelly sandy mud ((g)sM) facies. This pattern reflects the fundamental role of fine particles in REE adsorption, as clay minerals and associated phases provide abundant reactive surfaces for ion exchange and surface complexation.

From a sedimentological perspective, fine-grained sediments are preferentially deposited under low-energy conditions, where suspended particles settle and are efficiently preserved. These environments enhance REE accumulation by promoting adsorption and limiting resuspension. In contrast, higher-energy settings associated with coarser sediments reduce the residence time of fine particles and constrain REE enrichment.

Integrated analysis suggests that REE distribution is governed by a coupled sedimentary–hydrodynamic system, in which grain size controls adsorption capacity, while hydrodynamic conditions regulate sediment transport, deposition, and preservation. Consequently, low-energy, mud-dominated depositional environments represent the most favorable settings for the accumulation of ion-adsorption REEs in the southwestern Vietnam shelf.

3. Discussion

3.1 Sedimentary controls on REE enrichment

The results demonstrate that sedimentary facies exert a primary control on REE distribution. Fine-grained sediments, particularly sandy mud (sM) and sandy clay (sC), consistently show higher TR_2O_3 contents than coarser facies such as gravelly sandy mud ((g)sM). This reflects the fundamental role of grain size in controlling adsorption capacity. Clay minerals and associated fine particles provide abundant reactive surfaces for ion exchange and surface complexation, making them the dominant hosts for ion-adsorbed REEs.

REE enrichment in muddy facies is therefore interpreted as a result of grain-size-dependent partitioning, where REEs are preferentially concentrated in fine fractions during transport and deposition. The relatively consistent enrichment across sM and sC facies suggests that once a threshold of fine-grained content is reached, adsorption processes become the dominant control on REE accumulation.

3.2 Hydrodynamic control on sedimentation and REE accumulation

Hydrodynamic conditions play a key role in regulating sediment distribution and REE enrichment. The dominance of poorly sorted, fine-skewed sediments indicates deposition mainly through suspension settling under low-energy conditions. Such environments promote the accumulation and preservation of fine particles, enhancing REE retention.

In contrast, higher-energy settings associated with (g)sM facies tend to show lower REE concentrations due to the removal of fine particles and reduced adsorption capacity. The transition from (g)sM to sM and sC reflects decreasing hydrodynamic energy and increasing sediment stability, corresponding to progressively higher REE enrichment. Local seabed morphology, such as depressions, further enhances the trapping of fine sediments and contributes to localized enrichment.

3.3 Integrated sedimentary–geochemical model

An integrated model can be proposed to explain REE accumulation in the study area. Terrigenous input, primarily from the Mekong River system, supplies fine-grained sediments containing REEs. These particles are transported in suspension and deposited in low-energy environments, where they accumulate and are preserved. The abundance of clay minerals and fine particles provide favorable conditions for ion adsorption, leading to REE enrichment. This process can be summarized as a coupled system: (i) sediment supply and transport, (ii) hydrodynamic sorting and facies distribution, and (iii) geochemical enrichment in fine-grained sediments.

3.4 Implications for REE resource potential

The observed enrichment of REEs (TR_2O_3 commonly $>0.02\%$) in fine-grained sediments suggests that the southwestern Vietnam shelf represents a promising target for marine ion-adsorption REE resources. Mud-dominated facies (sM and sC) in low-energy environments are identified as the most favorable settings.

These findings highlight the importance of integrating sedimentological and geochemical approaches in resource assessment and suggest that shallow continental shelves influenced by major river systems may represent underexplored reservoirs of ion-adsorption REEs.

4. Conclusions

This study demonstrates that the distribution and enrichment of ion-adsorption rare earth elements (REEs) in surface sediments of the southwestern Vietnam shelf are primarily controlled by sedimentary facies and associated depositional processes. REE concentrations show clear spatial variability, with higher values consistently associated with fine-grained facies, particularly sandy mud (sM) and sandy clay (sC), which provide abundant reactive surfaces for REE adsorption.

Total rare earth oxide (TR_2O_3) contents commonly exceed 0.02% in these sediments, confirming that mud-dominated depositional environments act as effective geochemical sinks for REEs in shallow marine systems. Hydrodynamic conditions play a key regulatory role, as low-energy environments promote the deposition and preservation of fine particles, thereby enhancing REE accumulation, whereas higher-energy conditions limit enrichment through sediment reworking.

Overall, REE enrichment is governed by the coupled influence of grain size, sedimentary facies, and hydrodynamic conditions. Fine-grained, low-energy depositional environments represent the most favorable settings for the accumulation of ion-adsorption REEs, highlighting their potential significance as emerging targets for marine critical mineral resources on the southwestern Vietnam shelf.

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