Paleoproductivity drivers in the Banggai Waters, Sulawesi, Indonesia: insights from elemental analysis of marine surface sediment

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Abstract. Marine productivity, a pivotal factor in marine ecosystems and global carbon cycling, is influenced by various factors including upwelling and terrigenous nutrient influx. We investigated past marine productivity in Banggai Waters, Indonesia, using sediment samples (BUDEE22-29BC and BUDEE22-57BC) and Micro X-Ray Fluorescence (micro-XRF) analyses. Geochemical proxies (K/Ti, Ba/Al, and Zr/Al) help to assess terrigenous influx, upwelling events, and paleoproductivity. Our methodology categorizes productivity into upwelling-driven (UPW), terrigenous influx-driven (TER), and TUP (combined). The incorporation of geochemical proxy data has enabled a comprehensive understanding of historical marine productivity patterns. In BUDEE22-29BC, the K/Ti ratio initially rises and then falls below its threshold, whereas Ba/Al shows spikes and declines before rising again. Zr/Al ratios vary across depths, indicating different paleoproductivity drivers such as terrigenous influence and upwelling. BUDEE22-57BC displayed similar trends in K/Ti, Ba/Al, and Zr/Al ratios, with fluctuations indicating changes in paleoproductivity drivers, including mixing and upwelling effects. The unique positioning of Banggai Waters allows interactions between upwelling, terrigenous influx, and productivity. This study lays the groundwork for further research on past productivity changes and their drivers, thereby enhancing our understanding of marine dynamics.

1 Introduction

Marine productivity, the rate at which marine organisms produce organic matter through photosynthesis, plays a crucial role in shaping ocean ecosystems and in regulating global carbon cycling. Understanding past variations in marine productivity is vital for comprehending historical changes in marine environments and their implications on climate

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dynamics. One of the key factors influencing marine productivity is upwelling, a process that brings nutrient-rich waters from the deep ocean to the surface, fueling primary production by phytoplankton and other primary producers. The link between paleoproductivity and palaeoupwelling provides valuable insights into the functioning and responses of ancient marine ecosystems to environmental changes.

The Banggai Waters are uniquely situated, surrounded by land where nutrients can be supplied through terrigenous influx. Understanding the influence of marine paleoproductivity in Banggai Waters requires exploring the contributions of both terrigenous nutrient influx and upwelling processes. Nutrient influx from terrigenous sources such as rivers and coastal runoff is another critical driver of marine productivity. Terrigenous input brings essential nutrients, such as nitrogen and phosphorus, into marine ecosystems, supporting the growth of phytoplankton and other marine organisms. The interaction between paleoproductivity and nutrient influx from terrigenous sources offers a comprehensive understanding of how nutrient availability affects ancient marine ecosystems and how it might have influenced paleoupwelling patterns.

Geochemical analysis of marine sediments is a valuable tool for paleoceanographers and paleoclimatologists to understand the history of marine ecosystems and the global climate over geological timescales. The geochemical elements present in marine sediments can provide important clues and evidence regarding past environmental conditions, nutrient availability, and upwelling events. By analyzing sediment and fossil records, as well as proxies related to nutrient concentrations and upwelling events, we sought to unravel the complex interplay between these factors throughout geological history.

The Indonesian archipelago serves as a unique region that connects two major oceans: the Pacific and Indian [1]. This geographical position adds complexity to the variability of ocean dynamics in the area, along with its intricate topography, coastline geometry, and monsoonal winds. As a result, these factors have a significant impact on various oceanographic phenomena that occur in this region [2], [3]. Numerous studies have been conducted on the paleoceanography of various Indonesian regions to provide insights into historical environmental changes [4]–[7]. However, research on Banggai Waters has been limited. Despite its importance in the region and potential implications for understanding past climate dynamics and marine biodiversity, Banggai Waters remain relatively understudied in terms of paleoceanographic research.

To gain a comprehensive understanding of the historical oceanographic conditions in Banggai Waters, more focused research efforts are needed. Investigation of sediment cores and geochemical proxies could offer valuable information about past productivity events in this area. Furthermore, combining paleoceanographic data with modern observations could enhance our knowledge of long-term environmental trends and their connection to broader oceanic and climatic processes in the Indonesian archipelago. Expanding research in this region would contribute significantly to our understanding of upwelling dynamics and its historical context, ultimately supporting conservation efforts and the sustainable management of marine resources in Indonesian waters.

In this study, we aimed to explore the intricate relationship between paleoproductivity, paleoupwelling, and nutrient influx from terrigenous sources in Banggai Waters, Sulawesi, Indonesia. By utilizing sediment cores and geochemical proxies, we sought to assess the historical variations in marine productivity and their connection to upwelling events and nutrient availability from terrigenous sources. The integration of palaeoceanographic data with modern observations will provide valuable insights into the past and present dynamics of marine ecosystems in this unique region. The findings of this research hold significance for advancing our understanding of the complex drivers of marine productivity and their influence on marine biodiversity and global climate over geological timescales. Additionally, the outcomes will contribute to the broader field of paleoclimatology and paleoceanography, providing essential information for future conservation strategies and the sustainable management of marine resources in Indonesian waters.

2 Data and method

The data used in this research were collected from seafloor sediment samples taken from Banggai Waters (**Fig. 1**). The collection process involved a box corer measuring 50 cm × 50 cm × 50 cm. Subsequently, the sediment in the box corer was extracted using a 3-inch PVC pipe. Specifically, two sediment samples, BUDEE22-29BC with a length of 36.5 cm and BUDEE22-57BC with a length of 18.5 cm, were utilized for the study (**Fig. 2**).

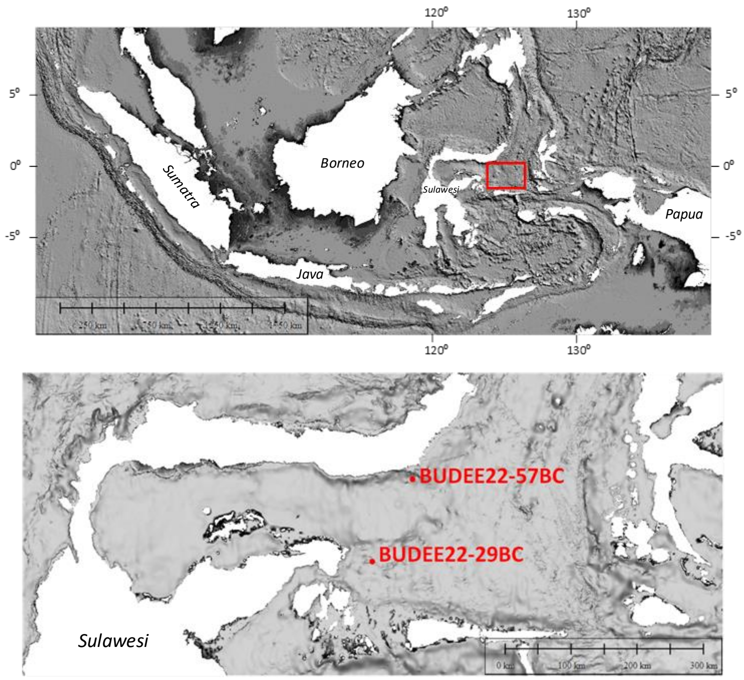

Fig. 1. The research site within the Banggai Waters (red square), with two core sampling locations for this study: BUDEE22-29BC (00°50'41.5709"S, 123°55'22.3885"E, -2324 m) and BUDEE22-57BC (00°15'55.8097"N, 124°25'28.7600"E, -2286 m).

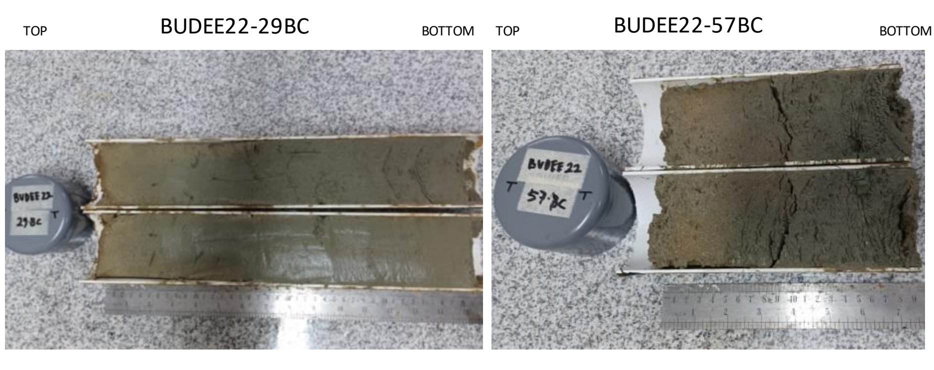

Fig. 2. Two clay sediment cores collected from the Banggai Waters.

To analyze the sediment samples, micro-X-ray fluorescence (micro-XRF) analysis was performed on both BUDEE22-29BC and BUDEE22-57BC samples. The analysis was conducted with a spatial resolution of 0.5 ~ cm using an ITRAX micro XRF sediment core scanner equipped with a Cr tube set to 30 kV and 50 mA. However, it is important to note that because of irregularities in the top and bottom sections of the sediment core, data collection intervals were adjusted accordingly. For core BUDE22-29BC, data were collected within depth intervals ranging from 1 cm to 35.5 cm, whereas for core BUDEE22-57BC, data were obtained from depths spanning from 1.5 cm to 17 cm. The ITRAX micro-XRF instrument generated elemental geochemistry data, which were reported in counts. In this study, our primary focus was on variations in the intensity of potassium (K), titanium (Ti), barium (Ba), zirconium (Zr), and aluminum (Al).

Elemental analysis was used in this study. We employed a vertical geochemical proxy analysis of the sediment samples. The vertical sequence of the sediment is correlated with a time series, assuming that the lower part of the sediment is older than the upper part. The geochemical proxies used were K/Ti, Ba/Al, and Zr/Al ratios. The K/Ti ratio serves as a reliable proxy for assessing the influx of terrigenous material into the marine environment because of its abundance in the continental crust, stability during transport and deposition, consistency in sedimentary records, ease of measurement, applicability across different environments, and relative insensitivity to diagenetic processes. The intensity of Ba/Al ratios serves as an indicator of marine productivity because barium (Ba) is enriched in marine environments because of its association with biogenic processes, particularly the formation of barite ($BaSO_4$) in the water column by phytoplankton, while aluminum (Al) is primarily derived from terrigenous sources and serves as a proxy for lithogenic input; thus, higher Ba/Al ratios imply elevated marine productivity. The Zr/Al ratio correlates with current intensity because zirconium (Zr) is predominantly sourced from terrigenous materials and has a relatively constant concentration in sediments, while aluminum (Al) is also primarily terrigenous but is influenced by changes in current intensity due to its transport and redistribution by fluvial and marine currents; thus, variations in Zr/Al ratios reflect changes in current intensity.

Both samples in this study were located in close proximity to the coastline, rendering the K/Ti ratio a reliable proxy for assessing the influx of terrigenous material into the marine environment [8]. Additionally, given that this area is traversed by Indonesian Throughflow (ITF), the K/Ti ratio serves as a suitable indicator of terrestrial runoff unaffected by the ITF [9]. This runoff can supply nutrients from land to the sea and increase marine productivity [10], [11]. An increase in marine productivity is indicated by an increase in the Ba/Al ratio. Therefore, it is logical that an increase in K/Ti can lead to an increase in the Ba/Al ratio.

Under upwelling conditions, marine productivity increases as currents transport nutrients from deeper ocean layers to the surface. We assume that the upwelling mechanism in coastal areas involves interactions between currents and suspended sediments. In this context, the Zr/Al ratio correlates with current intensity [12]. Consequently, an increase in the Zr/Al ratio may coincide with an increase in the Ba/Al ratio, indicating an enhanced upwelling and subsequent marine productivity.

The statistical method utilized in this research involved the use of a cut-off threshold to qualitatively determine the upwelling conditions. The second quartile (Q2) values from each ratio were employed because of their ability to provide insights into the central position of the data unaffected by extreme values or outliers. This stability is particularly valuable when assessing the central tendency or dispersion of data, without being influenced by extreme values [13].

For the statistical approach, productivity was categorized into three groups: productivity solely influenced by upwelling (UPW); productivity solely influenced by terrigenous influx (TER); and productivity influenced by both terrigenous influx and upwelling (TUP). UPW occurs when Ba/Al and Zr/Al surpass the Q2 value and K/Ti exceeds the Q2 value. TER occurs when Zr/Al is less than Q2, and Ba/Al and K/Ti are both greater than Q2. TUP occurs when Zr/Al, K/Ti, and Ba/Al are greater than the Q2 value.

3 Results

3.1 BUDEE22-29BC

In the core BUDEE22-29BC (**Fig. 3**), the K/Ti ratio displayed a distinct pattern. Initially, in the lower section, specifically in the interval from 27.5 to 35.5 cm below the seafloor (cmbsf), the values surpassed the Q2 threshold. However, as we progress towards the upper section, the K/Ti ratio gradually decreases and eventually falls below its Q2 threshold. The K/Ti ratio then stabilizes around the Q2 threshold (in the interval of 9.5-27.7 cmbsf) and consistently remains below the Q2 threshold throughout the upper part of the core.

The Ba/Al ratio exhibited a notable trend in the core. In the lower section (32-35.5 cmbsf), several data points indicate values exceeding the Q2 threshold. However, as we move upward, the Ba/Al ratio consistently remains below the Q2 threshold until a depth of 18 cmbsf. Beyond this depth, the Ba/Al ratio consistently exceeded the Q2 threshold towards the uppermost part of the core.

The Zr/Al ratios can be categorized into two distinct patterns. In the first pattern, observed between 18-35.5 cmbsf, the values were predominantly below the Q2 threshold. In contrast, in the second pattern, spanning the interval of 0.5-18 cmbsf, the Zr/Al ratio predominantly exceeded the Q2 threshold.

The paleoproductivity drivers at BUDEE22-29BC could be classified into four events. In the interval of 31.5-35.5 cmbsf, paleoproductivity is primarily influenced by terrigenous factors. Between 18-31.5 cmbsf, paleoproductivity was notably low. In the depth range of 10-18 cmbsf, a mixing driver was evident. The interval from to 1-10 cmbsf is predominantly characterized by the influence of upwelling on paleoproductivity.

3.2 BUDEE22-57BC

In the core BUDEE22-57BC (**Fig. 3**), distinct trends were observed in the K/Ti, Ba/Al, and Zr/Al ratios at various depths. The K/Ti ratio gradually decreased from 17 cmbsf to 12.5 cmbsf, eventually reaching the Q2 threshold. Between 10 cmbsf and 12.5 cmbsf, K/Ti values surpassed the Q2 threshold but then gradually declined from 10 cmbsf to 9 cmbsf, crossing the Q2 threshold once more. Subsequently, the K/Ti ratio exhibits a gradual increase, returning to the Q2 threshold at a depth of 7.5 cmbsf and consistently remains below the Q2 threshold down to 2 cmbsf.

The Ba/Al ratio shows a decrease from 17 to 14 cmbsf, crossing below the Q2 threshold at 14.5 cmbsf. It maintains a constant position, consistently below the Q2 threshold, until a depth of 12.5 cmbsf. The Ba/Al ratio values were predominantly on the right side of Q2, but they gradually declined as we reached a depth of 7 cmbsf, crossing below the Q2 threshold after 7.5 cmbsf. In the depth interval of 1.5-5.5 cmbsf, the Ba/Al ratio mostly aligns with the right side of Q2, but some depths veer towards the left and come close to Q2, with one depth significantly deviating to the left of Q2 at 3 cmbsf.

The Zr/Al ratio decreased from 17 to 15 cmbsf, rising slightly above the Q2 level at depths just above it. It steadily increases from 13.5 cmbsf to 9 cmbsf. Subsequently, it declined again, crossing below Q2 at 7.5 cmbsf. It experiences a slight rise within the 3-4 cmbsf interval but undergoes a significant drop at 3.5 cmbsf. Finally, it increases and once again crosses the Q2 threshold.

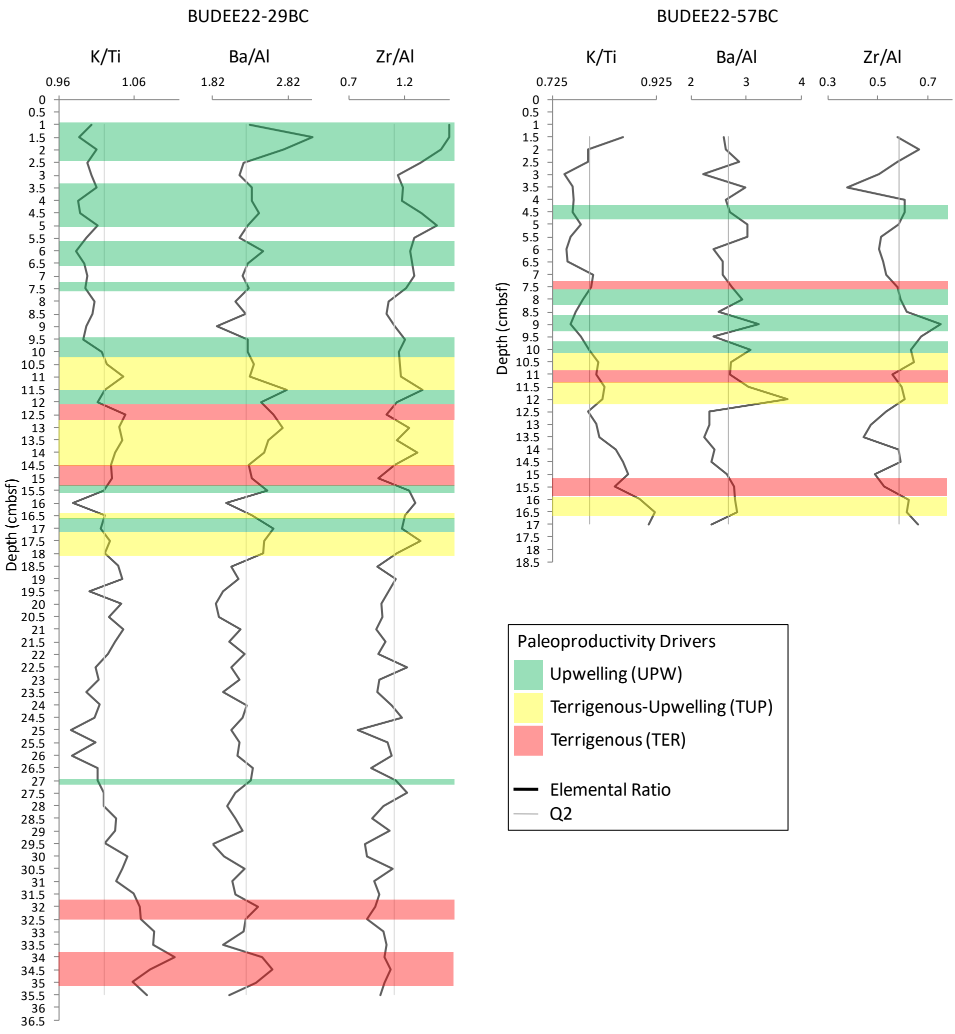

Fig. 3. Elemental ratios of BUDEE22-29BC and BUDEE22-57BC.

The paleoproductivity drivers in BUDEE22-57BC can be categorized into five distinct events. Initially, in the depth interval of 15-17 cmbsf, a mixing driver significantly influenced the paleoproductivity. Subsequently, between 12.5-15 cmbsf, the paleoproductivity notably decreases. In the depth range of 10-12.5 cmbsf, a mixing driver reappeared as an evident factor. Following this, the interval 7.5-10 cmbsf is primarily characterized by the influence of upwelling on paleoproductivity. Finally, between 1.5 and 7.5 cmbsf, there is a decrease in upwelling, leading to lower productivity.

4 Discussion

The observed variations in upwelling intensity patterns have significant implications for our understanding of marine productivity in Banggai Waters. The upwelling phenomenon, particularly in the lower sections of BUDEE22-29BC and BUDEE22-57BC, was closely associated with terrigenous influx. This suggests that land-based nutrient runoff can play a pivotal role in enhancing marine productivity, particularly when upwelling is concurrent with terrigenous influence. However, as we move towards the upper sections of the core, we see a decline in the influence of terrigenous influx, as indicated by decreasing K/Ti ratios and increasing Zr/Al ratios. This shift suggests a transition to an upwelling-dominated regime.

Based on the factors influencing paleoproductivity, the paleoproductivity dynamics in the research area can be delineated into four distinct phases: (i) driven by terrigenous influx (BUDEE22-29BC: 32-35.5 cmbsf), (ii) characterized by low productivity (BUDEE22-29BC: 18-32 cmbsf), (iii) representing a transitional phase (BUDEE22-29BC: 10-18 cmbsf and BUDEE22-57BC: 10-16.5 cmbsf), and (iv) influenced by upwelling (BUDEE22-29BC: 1-10 cmbsf and BUDEE22-57BC: 1.5-10 cmbsf). Notably, in the fourth category, BUDEE22-57BC experienced a reduction in upwelling, leading to decreased productivity.

The absence of a strong correlation between terrigenous influx and paleoproductivity (BUDEE22-29BC: 18-23 and 27.5-35.5 cmbsf, BUDEE22-57BC: 12.5-15 cmbsf) raises questions about the dynamics of nutrient delivery from land to the marine environment. It is evident that terrigenous influences alone do not always guarantee enhanced paleoproductivity. This may be attributed to various factors, including the composition of the terrigenous materials, nutrient content, and specific marine conditions at the time of deposition. The lack of nutrients in the terrigenous influx biases the transition interval (the second phase of paleoproductivity dynamics). Further investigations of the geochemical composition of terrigenous materials and their interactions with seawater are warranted.

The geological attributes of the Banggai-Sula Islands, classified as a microcontinent, are recognized for hosting inherently nutrient-poor soils. This geological aspect could potentially contribute to the limitations of nutrient availability within the marine environment. The geological challenges presented by these factors hinder an efficient supply of nutrients to the ocean. A comprehensive understanding of the interactions between geological, climatic, and oceanographic elements is essential to unravel the intricate dynamics of marine productivity in this particular region.

This study highlights the need for further research to comprehensively elucidate the drivers of marine productivity in Banggai. Future investigations should delve into the geochemical composition of terrigenous materials, the role of atmospheric and oceanographic conditions in nutrient transport, and long-term climatic trends affecting nutrient availability. Additionally, the incorporation of multi-proxy analyses, including stable isotopes and sedimentary microfossil assemblages, can provide a more holistic perspective on the paleoproductivity dynamics in this region.

5 Conclusion

Upwelling was a key driver of paleoproductivity in our research location. The changes in the Zr/Al and Ba/Al ratios clearly indicate a strong link to the upwelling intensity. As we moved up through the sediment core, we observed a gradual decrease in the K/Ti ratio, which stabilized below the Q2 threshold. This pattern indicates a shift towards an upwelling-dominated environment. In simpler terms, upwelling events significantly boosted paleoproductivity in the Banggai Waters, particularly in the middle to upper sections of both cores.

The relationship between terrigenous nutrient influx and paleoproductivity is complex. While terrigenous factors are conspicuous in the lower sections of both cores, coinciding with a rise in K/Ti, the impact of terrigenous influx wanes as we progress towards the upper sections of both cores. In particular, the intervals BUDEE22-29BC: 18-23 and 27.5-35.5 cmbsf and BUDEE22-57BC: 11.5-14 cmbsf, where terrigenous influx is pronounced, do not consistently correlate with heightened paleoproductivity. This suggests that terrigenous influence alone may not always ensure increased productivity.

The integration of these findings suggests that the interaction between upwelling and terrigenous nutrient influx is dynamic and varies along sediment core profiles. While upwelling was a consistent driver of paleoproductivity in both cores, the influence of terrigenous nutrient influx was more nuanced. The complex interplay of factors, such as terrigenous material composition, nutrient content, and local environmental conditions, determines the extent to which terrigenous influx influences paleoproductivity.

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