UPWELLING INFLUENCE ON ENVIRONMENTAL CHANGE AND SEDIMENTATION DYNAMICS FROM TRACE FOSSILS IN THE MOLUCCA SEA: IMPLICATIONS FOR SEDIMENT DATING

PENGARUH UPWELLING TERHADAP PERUBAHAN LINGKUNGAN DAN DINAMIKA SEDIMENTASI BERDASARKAN FOSIL JEJAK DI LAUT MALUKU: IMPLIKASI UNTUK PENENTUAN UMUR SEDIMEN

Taufan Wiguna[1*], Rina Zuraida[1], Agus S. Atmadipoera[2], Fareza S. Yuwono[1], Undang Hernawan[3], Vera Christanti[1], Nicolas Tournier[4], Adrianus Damanik[4], Hendrik Vogel[4], Sri Yudawati Cahyarini[1]

[1]Research Center for Climate and Atmosphere, National Research and Innovation Agency, Bandung 40135, Indonesia

[2]Department Marine Science, FPIK, IPB University, Bogor 16680, Indonesia

[3]Research Center for Oceanography, National Research and Innovation Agency, Ancol, Jakarta 14430, Indonesia

[4]Institute of Geological Sciences & Oeschger Centre for Climate Change Research, University of Bern, Bern 3012, Switzerland

*Corresponding author: taufan.wiguna@brin.go.id

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ABSTRACT: Bioturbation, the alteration of sediment layers by organism activities, plays a crucial role in shaping sedimentary environments. This process affects nutrient cycling, sediment stability, and habitat health, particularly in marine ecosystems like the Molucca Sea. Bioturbation can complicate age determination by disrupting the natural layering of sediments and potentially altering chronological records, which challenges the accuracy of dating methods. This study investigates bioturbation patterns and Zr/Rb ratios in sediment cores from the Molucca Sea to better understand past environmental conditions and assess the suitability of these sediments for age determination. Sediment samples were collected using a box corer from BUDEE22-29BC (within the upwelling region) and BUDEE22-57BC (outside the upwelling area). The cores were analyzed using CT scanning to identify bioturbation features, and the Bioturbation Index (BI) was applied to evaluate the intensity and impact of bioturbation on sediment dynamics. The Zr/Rb ratios were determined using an X-ray fluorescence (XRF) spectrometer, providing insights into grain size distribution. The results suggest the potential shifting of the upwelling center (BUDEE22-29BC) and variations in upwelling intensity (BUDEE22-57BC). Although Zr/Rb ratio shows that BUDEE22-29BC is a high-energy environment, as opposed to BUDEE22-57BC, both sites retain chronological integrity, making them suitable for paleoenvironmental and geochronological analysis.

Keywords: bioturbation, CT scan, paleoenvironment, Banggai, upwelling, BUDEE22

ABSTRAK*: Bioturbasi, perubahan lapisan sedimen akibat aktivitas organisme, memainkan peran krusial dalam membentuk lingkungan sedimen. Proses ini memengaruhi siklus nutrisi, stabilitas sedimen, dan kesehatan habitat, terutama di ekosistem laut seperti Laut Maluku. Bioturbasi dapat mengganggu pelapisan alami sedimen dan berpotensi mengubah catatan kronologis, yang menjadi tantangan dalam akurasi metode penentuan umur. Penelitian ini menyelidiki pola bioturbasi dan rasio Zr/Rb dalam inti sedimen dari Laut Maluku untuk memahami kondisi lingkungan masa lampau dan menilai kelayakan sedimen tersebut untuk penentuan umur sampel. Sampel sedimen diambil dari Laut Maluku menggunakan box corer, dengan sedimen inti diambil dari dua lokasi: BUDEE22-29BC (di pusat upwelling) dan*

BUDEE22-57BC (di luar area upwelling). Inti sedimen dianalisis menggunakan CT scan untuk mengidentifikasi fitur bioturbasi, dan indeks bioturbasi (BI) diterapkan untuk mengevaluasi intensitas dan dampak bioturbasi terhadap dinamika sedimen. Rasio Zr/Rb ditentukan menggunakan X-ray fluorescence (XRF) spectrometer, memberikan wawasan tentang distribusi ukuran butir. Hasil penelitian menunjukkan adanya potensi pergeseran pusat upwelling (BUDEE22-29BC) serta variasi intensitas upwelling (BUDEE22-57BC). Meskipun rasio Zr/Rb menunjukkan bahwa BUDEE22-29BC diendapkan di lingkungan berenergi tinggi, bertolak belakang dengan BUDEE22-57BC, kedua sampel menunjukkan bahwa perlapisan masih tidak terganggu sehingga dapat digunakan untuk analisis lingkungan masa lampau dan geokronologi.

Kata Kunci: *bioturbasi, CT scan, lingkungan purba, Banggai, upwelling, BUDEE22*

INTRODUCTION

Bioturbation refers to the alteration of sediment layers caused by the activities of organisms, including burrowing, tunneling, and movement. This process plays a critical role in marine ecosystems by influencing nutrient cycling, sediment stability, and habitat health (Bosworth & Thibodeaux, 1990). However, bioturbation also complicates sediment analysis by disrupting natural stratigraphy, potentially impacting interpretations of past environmental conditions and sedimentary dynamics.

The Molucca Sea, noted for its rich marine biodiversity and complex oceanographic conditions, presents an ideal environment for studying bioturbation. This region serves as a pathway for major ocean current (ITF: Indonesian Throughflow) which drive complex water mass dynamics. This current influence sediment deposition (Alongi et al., 2013; Iskandar et al., 2023), nutrient distribution (Taufiqurrahman et al., 2020; Xie et al., 2024), and benthic ecosystems (Alongi et al., 2013), creating a highly dynamic marine environment. Changes in water masses, driven by climatic and oceanographic shifts, have significantly shaped the depositional history of the Molucca Sea, making it an important site for investigating past environmental changes. Examining bioturbation in this region can provide valuable insights into marine ecosystem dynamics and the reconstruction of sedimentary histories. Understanding bioturbation is crucial for accurate paleoenvironmental interpretations and for inferring past environmental conditions.

In sediment cores, bioturbation manifests through various features such as cylindrical or conical burrows, mucus-lined tubes from worms and mollusks, feeding traces like fecal pellets or bite marks, and biogenic structures such as mounds and pits. These features are critical for interpreting sediment cores, as they can alter sedimentary records and influence the reconstruction of past environmental conditions (Qunhui et al., 2008). The study of bioturbation is called ichnology, a branch of paleontology. Bioturbation features, also known as traces, and their fossilized versions, trace fossils (may be identified as ichnogenus and ichnospecies) are grouped into assemblages called ichnofacies. Marine ichnofacies have been used to interpret past environmental conditions across various geological ages (Crimes & Droser, 1992; Frey & Pemberton, 1985; Löwemark, 2007; Luo et al., 2020).

Bioturbation complicates sediment analysis by disrupting the natural layering of sediments. Burrowing organisms can create complex structures and mix sediment layers, challenging the principle of superposition, where older layers should lie beneath younger ones (Hülse et al., 2022; Pisias, 1983). This issue is particularly pronounced in high-biodiversity and dynamic environments such as the Molucca Sea. Understanding these complexities is essential for achieving accurate paleoenvironmental reconstructions and for interpreting the sedimentary history of marine ecosystems. Moreover, bioturbation can substantially impact age determination methods, both radiometric and non-radiometric, by disrupting the chronological integrity of sediment layers. Therefore, it is imperative to consider and account for the effects of bioturbation when conducting age determinations to ensure the accuracy and reliability of the results.

The Molucca Sea is renowned for its rich marine biodiversity and complex oceanographic conditions. Key factors such as water temperature, salinity, currents, and nutrient availability significantly influence the marine ecosystems in this region. One of the most prominent oceanographic features is the Banggai Upwelling, located in the southwest of the Molucca Sea, which plays a critical role in nutrient dynamics and marine productivity (Atmadipoera et al., 2018; Wiguna et al., 2024) emphasize that upwelling and past upwelling events bring nutrient-rich waters, profoundly impacting productivity in

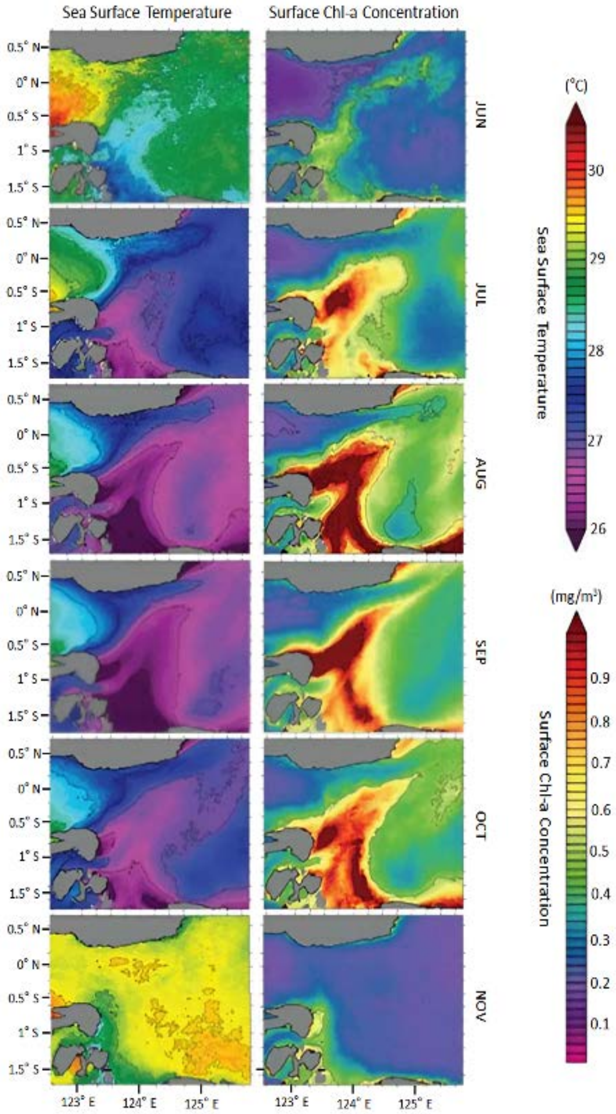

Figure 1. Upwelling events in the Molucca Sea, referred to as the Banggai Upwelling. The sea surface temperature (SST) (left) shows a low range of values (<27°C) during July–October 2015, which correlates with an increase in surface chlorophyll-a concentration (right) (modified from Atmadipoera et al., 2018).

this area (Figure 1). Bakun et al. (2015) suggested that an increase in global temperature will increase the intensity of the Eastern Boundary Upwelling System (EBUS) which lead to rising ocean acidity which will affect carbonate skeletal organisms. Further study by Petrick et al. (2015) inferred an expansion of Benguela Upwelling during warm events. To date, no published study on past upwelling has been carried out in the Indonesian Seas. To fill the gap, multi-discipline research was conducted in the Maluku Sea, Banggai Upwelling Dynamics Experiments and Ecosystem (BUDEE) cruise, onboard RV Baruna Jaya VIII in 2022 by the Research Center for Climate and Atmosphere – BRIN in collaboration with IPB University. The cruise successfully acquired five box core samples and four gravity cores that will help reveal past upwelling conditions to predict future changes. Studying sedimentary dynamics through trace fossils in the Maluku Sea is crucial because these biogenic structures provide direct evidence of benthic activity and environmental conditions during sediment deposition. High levels of bioturbation, characterized by diverse and complex trace fossils, often indicate favorable environmental conditions such as adequate oxygenation, stable sedimentation rates, and nutrient availability. Conversely, reduced or simplified bioturbation structures and the presence of lamination may reflect stressful conditions, such as low oxygen levels (hypoxia), high sedimentation rates, or environmental disturbances. Hypoxia in marine sediments has been observed to be related to upwelling (Moffitt et al., 2015). Trace fossils serve as valuable proxies for reconstructing past depositional environments, revealing variations in hydrodynamic energy, sediment supply, and ecological stressors over geological time. These features can be analyzed to better understand the interactions between biological activity and sedimentary processes, providing key insights into how marine ecosystems respond to environmental changes and climatic variability.

This study aims to identify biogenic activities in seabed sediments to understand environmental changes in the study area. It will focus on assessing the density of bioturbation features to determine their impact on sediment dynamics. Additionally, this study will evaluate the viability of determining the age of these sediments by examining how bioturbation affects sediment structure. Furthermore, this study aims to investigate the influence of upwelling on trace fossil density and its relationship with environmental changes and sedimentary dynamics in the Molucca Sea.

MATERIALS AND METHODS

The data utilized in this study were derived from sediment samples collected from the seabed of the Molucca Sea (Figure 2) using a box corer with dimensions of 50 cm × 50 cm × 50 cm during BUDEE cruise in 2022 The sediment was extracted using a 3-inch PVC pipe and then split into two parts. One segment underwent CT scanning and XRF scanning for further analysis. Two sediment cores were utilized in this study (Figure 3a): BUDEE22-29BC (36.5 cm) collected from the upwelling region at coordinates 00°50'41.5709"S, 123°55'22.3885"E, with a depth of 2423 m, and BUDEE22-57BC (18.5 cm) collected from outside the upwelling area at coordinates (00°15'55.8097"N, 124°25'28.7600"E, with a depth of 2286 m.

Bioturbation data were obtained through CT scan imaging using a Siemens Somatom X.cite device (Figure 3b), which allows for the acquisition of 128 slices with a 0.5 mm thickness and a spatial resolution of 0.30 mm. The images were analyzed to identify bioturbation features using Synedra software. For data analysis, the bioturbation index (BI) as described by Gani (2020) was applied to evaluate and interpret the extent and impact of bioturbation in the sediment samples. The identification of trace fossil types and ichnogenera was conducted based on morphological characteristics observed in CT scan imagery. The interpretation refers to standard ichnological literature, including Fernández & Pazos (2012), Frey & Pemberton (1985), and Martin (2004), which provide diagnostic criteria for ichnogenera such as *Thalassinoides*, *Chondrites*, and *Planolites* in marine sedimentary environments.

The Zr/Rb ratio was used as an approach to grain size analysis because Zr and Rb are distributed differently across various sediment grain size fractions. Zr typically accumulates in heavy minerals found in coarser fractions, while Rb tends to concentrate in clay minerals found in finer fractions. Thus, the Zr/Rb ratio in sediments can provide information about changes in sediment grain size. A high Zr/Rb ratio indicates a dominance of coarse grains, whereas a low ratio suggests a predominance of fine grains (Dypvik & Harris, 2001). These elements were analyzed using an ITRAX micro XRF sediment core scanner with a Cr-tube set to 30 kV and 50 mA at the University of Bern in Switzerland. Due to irregularities, data collection intervals were adjusted, with BUDEE22-29BC ranging from 1 cm to 35.5 cm and BUDEE22-57BC from 0.5 cm to 16 cm. The vertical spatial resolution was set to 0.5 cm.

RESULTS

The sample BUDEE22-29BC exhibits significant bioturbation (Figure 4), indicative of active biological disturbance. Interestingly, the bioturbation in this core shows vertical segregation where the top part of the core (0-8 cm) is dominated by small-scale unlined bioturbation (0-8 cm) while the lower part of the core (8-36.5 cm), large-scale unlined bioturbation is predominant. The small-scale bioturbation (~0.2 cm) is characterized by lighter-color sediment-filled tunnel networks with small numbers of vertical systems. These structures are often associated with the ichnogenus *Chondrites*, known for their distinctive burrowing patterns. This ichnogenus is classified as feeding trace or fodichnia (Fernández & Pazos, 2012) and it is viewed as an adaptation to reduced oxygen condition (Martin, 2004). We use the presence of this ichnogenus as an indicator of hypoxia, which in turn signifies higher productivity due to upwelling.

The large bioturbation (0.5-1 cm) formed lateral tunnels of various sizes. The tunnels are darker in color than surrounding sediments, unlined and unornamented. Based on the characteristics that can be determined from the CT scan image, these

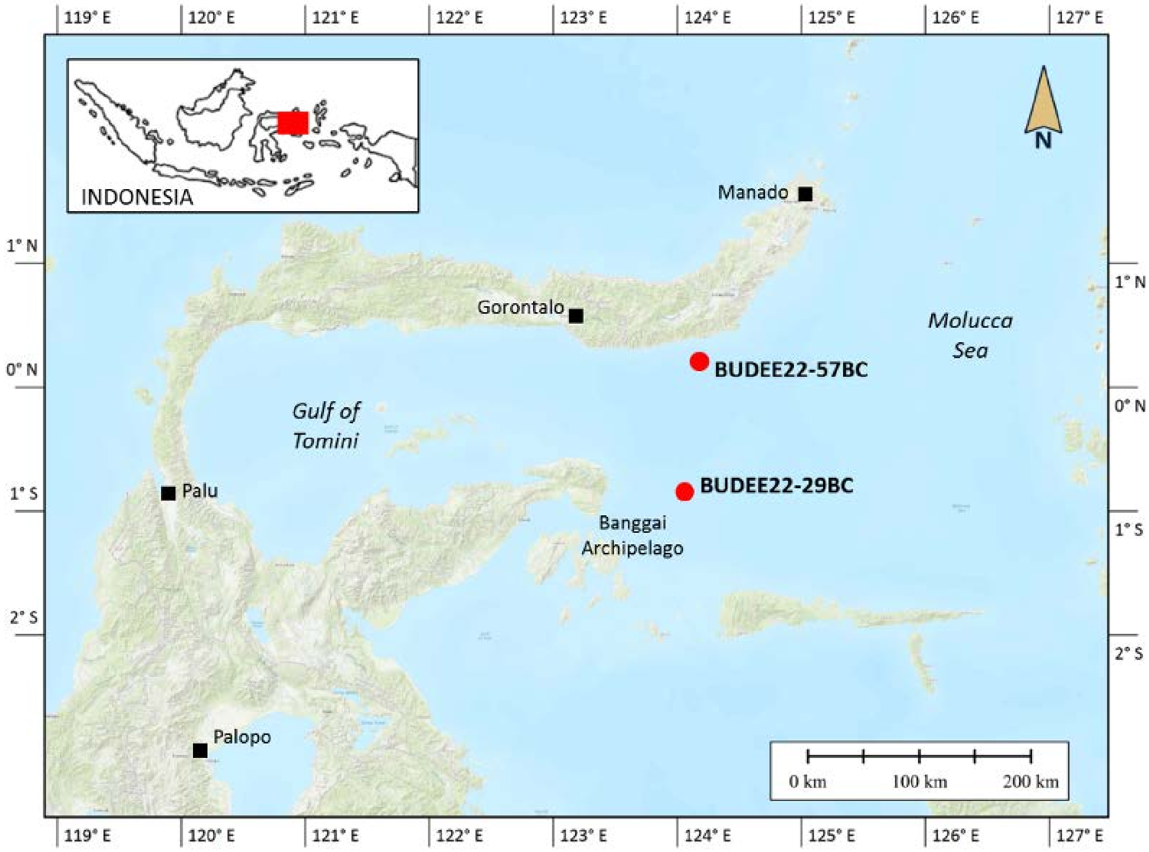

Figure 2. The research area situated in the Molucca Sea (inset map: highlighted in red square) includes two primary sites for core sampling in the study; BUDEE22-29BC and BUDEE22-57BC.

Figure 3. (a) Two samples were utilized in this evaluation; (b) CT scan applied in this study.

structures are identified as belonging to ichnogenus *Thalassinoides*, which is known for its extensive and complex burrowing activities.

Chondrites show increasing abundance to the upper layer, while *Thalassinoides* exhibit opposite trend. Based on the abundance of bioturbation, sample BUDEE22-29BC can be differentiated into two layers:

- Upper layer (0-8 cm) composed of clay that is moderately disturbed (50%) by bioturbation which is predominantly *Chondrites*, the traces are discrete with no overlap observed. From those characters, the bioturbation in this layer is classified as Bioturbation Index (BI) 3.
- Lower layer (8-36.5 cm) that consists of clay that is highly disturbed (70%) by some overlapping of tunnels and burrows that are dominated by *Thalassionoides*. Based on those features, the lower layer is classified into BI 4.

Sample BUDEE22-57BC also demonstrates bioturbation activities, though with distinct characteristics compared to BUDEE22-29BC. This core can be divided into 3 layers based on their bioturbation index (Figure 5):

- The upper part of the core (0-4.5 cm) shows intense bioturbation (diameter < 0.5 cm) and about 95% of the layer is disturbed. Two types of bioturbations were observed in this layer: cylindrical horizontal traces that are darker colored than surrounding sediments, and lighter colored burrows, that disturb sediment layers. Possible identification of the traces is hindered by the position of the traces that overlap each other. Because of these characteristics, this layer can be classified into BI 5.
- The middle part of the core (6.5-8.5 cm) is characterized by low to moderate bioturbation (BI 3-2, diameter ~0.5 cm). The traces that were observed in this layer are small unlined burrows that might be related to the ichnogenus
- *Planolites*, which are often found in marine sediments and are known for their simple, unlined burrowing patterns.
- The lower part of the core (8.5-18.5 cm) exhibits high bioturbation (75%) that destroys sedimentary structure. These characteristics put this layer into BI 4. The dominant bioturbation in this layer is large-scale bioturbation (diameter ~1cm), darker color than surrounding sediments, forming angled or J-shaped burrows, and associated with the ichnogenus *Thalassinoides*. These larger burrows suggest the presence of more robust organisms capable of creating extensive tunnel networks. The combination of small and large-scale bioturbation highlights a dynamic and diverse benthic ecosystem in the depositional environment of this sample.

The environmental profile of sample BUDEE22-29BC suggests fluctuating depositional conditions over time. The lower part of the sample exhibits less bioturbation, implying more stable and favorable conditions for benthic organisms, including increased bottom oxygenation. Conversely, the upper part of the sample shows more intense bioturbation, indicating a stressful environment for organisms, possibly due to upwelling-related low oxygenation, higher energy conditions, or variations in sediment supply. The environmental profile of sample BUDEE22-57BC reveals a more complex history of environmental changes. The middle part of the sample shows relatively undisturbed mud, indicating stable conditions that allowed for the preservation of fine sediment layers, or low oxygenation that various reasons, including upwelling, can cause. However, the upper and lower parts of the sample exhibit more intense bioturbation, suggesting periods of more extreme environmental fluctuations, such as changes in sedimentation rates or energy conditions that increase bottom oxygenation.

The Zr/Rb ratio in core BUDEE22-29BC fluctuates between 0.821 and 1.419, indicating substantial variability in sediment grain size across the depth profile. Higher ratios are observed at specific depths, such as at 16 cm (1.419) and 7 cm (1.358), suggesting the presence of coarser sediment layers. Conversely, lower ratios are recorded at 15 cm (0.845) and 32 cm (0.821), indicating layers with finer sediment. In contrast, the Zr/Rb ratios in core BUDEE22-57BC exhibit a more consistent pattern, with values ranging from 0.282 to 0.654. These relatively low Zr/Rb ratios indicate a general predominance of fine-grained sediments throughout the core. The lowest ratio is observed at 2.5 cm (0.282), while higher ratios, such as at 13.5 cm (0.654), reflect slightly coarser sediment layers. Despite these variations, fine-grained sediments

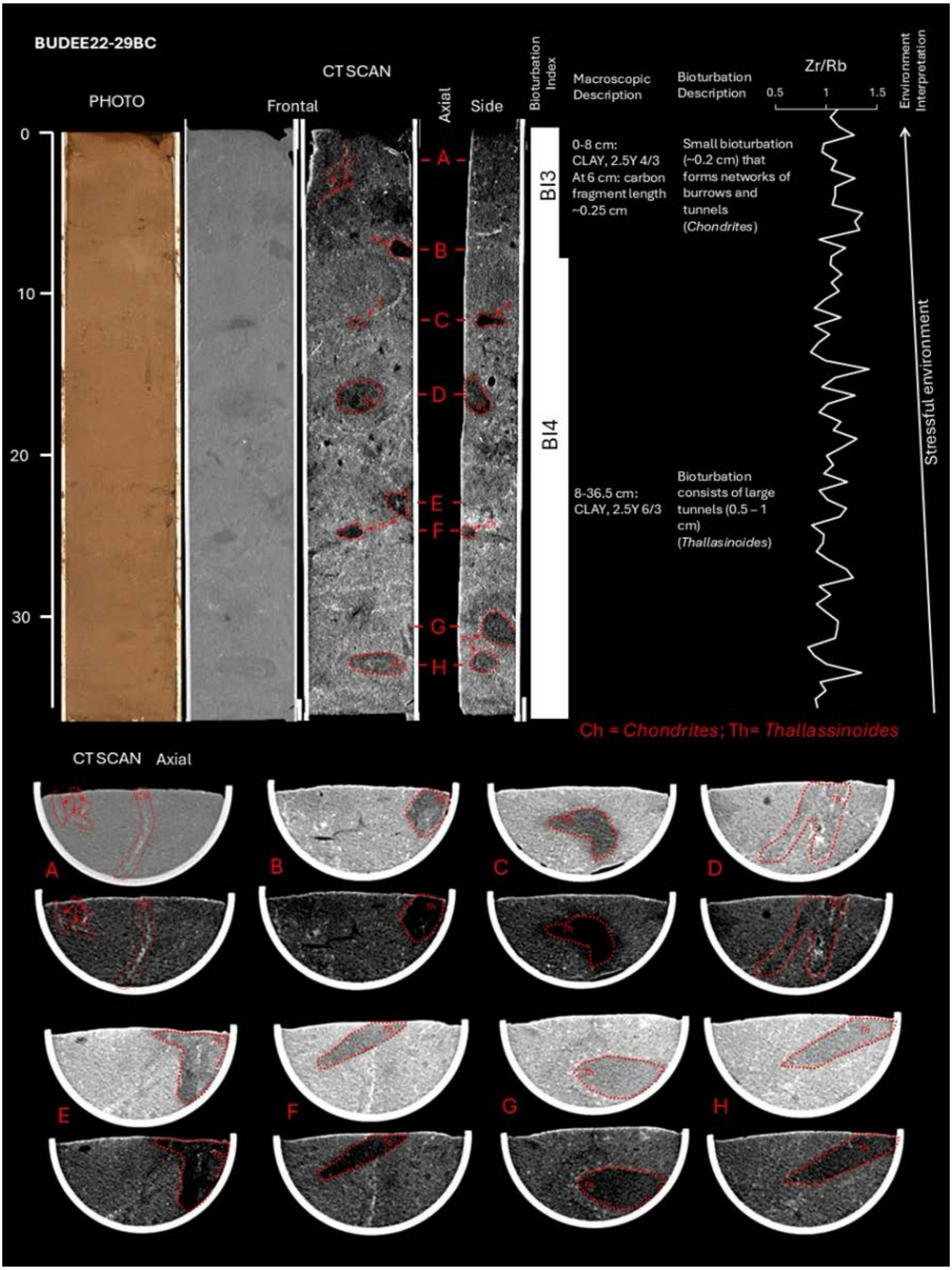

Figure 4. Core photo, CT scan, characteristics of sediments, ichnogenus, bioturbation density, and environment interpretation of BUDEE22-29BC. A-H indicates an axial CT scan showing each slice's lateral section.

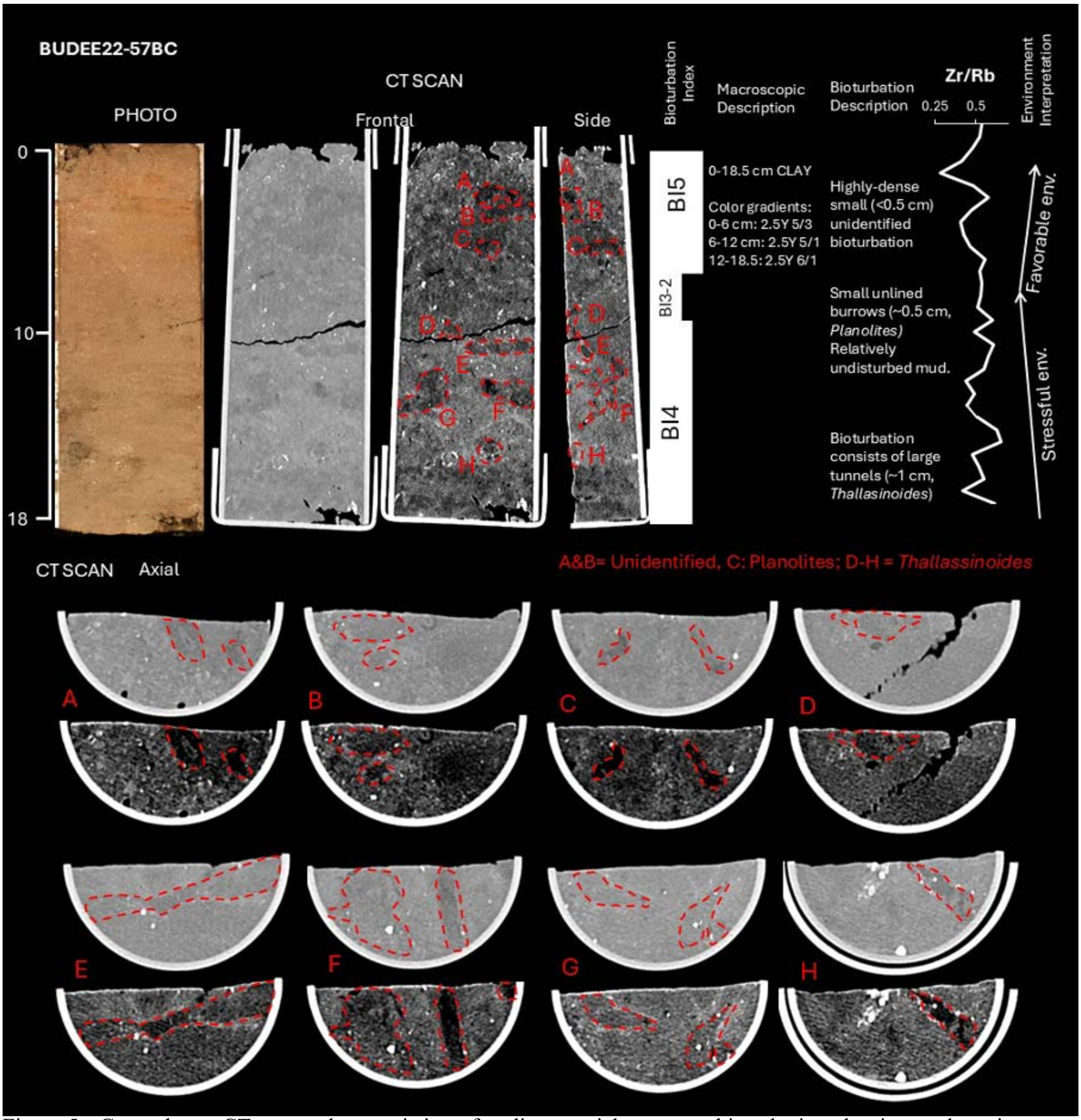

Figure 5. Core photo, CT scan, characteristics of sediments, ichnogenus, bioturbation density, and environment interpretation of BUDEE22-57BC. A-H indicates an axial CT scan showing each slice's lateral section.

dominate the overall profile in BUDEE22-57BC.

The upward increase in Zr/Rb ratio in BUDEE-29BC (Figure 4), indicating a transition toward coarser sediments, suggests higher-energy depositional conditions in the upper layers. This trend aligns with the reduced bioturbation intensity (BI 3) observed in the same layers, reflecting a more stressful environment over time, that might be formed as low oxygenation. In contrast, the lower layers, characterized by lower Zr/Rb ratios and high bioturbation intensity (BI 4), represent stable, low-energy depositional conditions with finer sediment with higher bottom oxygenation. The consistently low Zr/Rb ratios in BUDEE22-57BC (Figure 5) indicate a predominance of fine-grained sediments, corresponding with the intense bioturbation in the upper layers (BI 5). This combination suggests low-energy depositional conditions in the upper layers, while the middle layers, with reduced bioturbation intensity and simpler burrow structures, indicate periods of environmental stress, such as low oxygenation, or rapid sedimentation.

DISCUSSIONS

The two sediment samples, BUDEE22-29BC and BUDEE22-57BC, offer valuable insights into past depositional environments, particularly bottom oxygenation, and the influence of bioturbation on sediment dynamics. By reconstructing bottom oxygenation, we can infer changes in past upwelling, and by understanding the sediment dynamics, we can evaluate the viability of these sediments for age determination.

Depositional Environments in the Center of Upwelling (BUDEE22-29BC)

In sample BUDEE22-29BC, the bioturbation index (BI) decreases upward, with smaller bioturbation features becoming more prevalent. This trend suggests increasingly stressful environmental conditions over time, potentially due to lower bottom oxygenation, and/or increase of sedimentation rates and water energy conditions. This interpretation is supported by the Zr/Rb ratio that increases upward, indicating a shift towards coarser-grained sediments in the upper layers (Figure 4). An increase in Zr relative to Rb suggests higher-energy depositional conditions, consistent with the reduced bioturbation intensity observed in the upper layers (lower BI). This could reflect more stressful environmental conditions, such as higher sedimentation rates or less stable water conditions, which would limit bioturbation activity.

The high bioturbation intensity observed in core BUDEE22-29BC, particularly in its lower layers, suggests a stable depositional environment with moderate sedimentation rates. This is evidenced by the dominance of large-scale burrows attributed to the ichnogenus *Thalassinoides*. These features reflect conditions that likely supported robust benthic organisms, indicative of an oxygenated and nutrient-rich environment. The upper layers, characterized by smaller-scale bioturbation from *Chondrites*, point to a shift towards more stressful conditions, potentially caused by increased sedimentation rates or reduced oxygen availability, or increased energy that is indicated by increased grain size. This gradual transition highlights the dynamic nature of sediment deposition over time.

The absence of lamination, even though there is a slight increase in grain size, suggests mild hypoxia that in turn indicates upwelling (Moffitt et al., 2015). Two interpretations can be drawn based on BI and bioturbation sizes from this site: 1) there was a shift in the position of the upwelling center to site BUDEE22-29BC at present; 2) there was a change in upwelling intensity that increased to the present.

Depositional Environments in the Edge of Upwelling (BUDEE22-57BC)

Sample BUDEE22-57BC exhibits a more complex bioturbation pattern. The succession of bioturbation features suggests an increasingly stressful environment from the lower part of the core to the middle, potentially linked to higher energy conditions, sediment supply fluctuations, or other stressors. In contrast, the upper part of the core seems to transition to a more hospitable environment, possibly characterized by reduced turbidity, improved oxygen levels, and stable salinity and temperature, along with the presence of organic matter. The increased density of bioturbation features in the upper layers indicates these improved conditions, reflecting enhanced water column stability and sediment conditions. The presence of both small-scale and large-scale bioturbation features, associated with genera such as *Planolites* and *Thalassinoides*, highlights a diverse benthic community and shifting environmental conditions over time.

BUDEE22-57BC exhibits consistently lower Zr/Rb ratios, indicative of predominantly fine-grained sediments throughout the core with a slight upward decrease, aligning with the increasing bioturbation intensity (BI) in the upper layers (Figure 5). The decreased Zr/Rb indicates a shift toward finer-grained sediments, which is characteristic of lower-energy depositional environments. The corresponding increase in BI reflects a transition to more stable and hospitable conditions, likely driven by improved oxygen levels, reduced sedimentation rates, or changes in water dynamics.

Based on the BI and bioturbation sizes and ichnogenera, site BUDEE22-57BC shows changes in past upwelling intensity. The lower part indicates intermediate upwelling intensity that increased to stronger intensity in the middle layer before it became weaker. Although this site is at the edge of present-day upwelling center, the area could be affected by local coastal upwelling from July to October (Atmadipoera et al., 2018). Thus, changes in upwelling intensity in this site might be related to coastal upwelling instead of Banggai Upwelling system.

Viability of Sediments for Age Determination

The predominant bioturbation structures observed in sample BUDEE22-29BC are characterized by horizontally oriented tunnels, indicative of lateral sediment displacement. This distinctive pattern of bioturbation offers potential for chronological analysis, as it may preserve undisturbed sediment layers within the tunnel infill, thereby providing suitable targets for age determination.

In contrast, BUDEE22-57BC shows more drastic environmental fluctuations, with a period of persistent stress followed by improved conditions in the upper layers. The lower and middle layers of BUDEE22-57BC remain viable for age determination. The bioturbation in these layers, primarily consisting of tunnels and burrows, does not significantly disrupt the vertical stratigraphy. The preservation of vertical layering in these sections supports their viability for chronological studies.

CONCLUSSIONS

The study on bioturbation densities and sizes, as indicators of sediment viability for age determination has been carried out on two box cores from Banggai Waters, Molucca Sea. The results suggest the potential shifting of the upwelling center (BUDEE22-29BC) and variations in upwelling intensity (BUDEE22-57BC), which have significantly influenced biogenic structures and sediment characteristics.

Trace fossil assemblages and bioturbation patterns reveal distinct environmental changes in the Molucca Sea. The transition from large-scale *Thalassinoides* in deeper layers to finer-scale *Chondrites* in upper layers of BUDEE22-29BC indicates increasing environmental stress, possibly driven by hypoxia related to upwelling. In contrast, BUDEE22-57BC reflects more complex environmental fluctuations with an initial period of stress followed by improved benthic conditions. These patterns provide strong evidence of past upwelling influence on bottom water oxygenation and ecosystem dynamics.

Sedimentary dynamics inferred from Zr/Rb geochemical proxies and bioturbation intensity indicate variations in depositional energy and sediment grain size. Upward increases in Zr/Rb ratios and reduced BI in BUDEE22-29BC reflect coarser-grained, higher-energy conditions, whereas BUDEE22-57BC shows fine-grained deposition under lower-energy conditions. These findings demonstrate the interplay between biological activity, physical sedimentation processes, and upwelling-driven environmental forces.

The preservation of stratigraphy and trace fossil characteristics in the lower parts of both cores confirms the viability of sediments from BUDEE22-57BC and BUDEE22-29BC for age determination. Despite potential bioturbation disturbances, the sedimentary sequences retain chronological integrity, making them suitable for paleoenvironmental and geochronological analysis.

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