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Review Article

Geochemistry of Foraminifera in the Marginal Seas of the Sunda Shelf: A Review

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ABSTRACT

Foraminiferal geochemistry applies geochemical elements embedded in foraminiferal calcites through bioaccumulation to interpret and reconstruct past oceanic climate histories. Due to its extensive variability and abundance, foraminifera is the easiest to retrieve and the best indicator of marine productivity and ocean temporal changes. In this review, we discuss the development of foraminiferal geochemistry studies in Southeast Asia, analyzing its current status and potential areas to be developed, namely, the Sunda Shelf. The Sunda Shelf is one of the world's largest low-latitude shelves, bordered by marginal seas and sensitive to sea-level changes. The shelf response towards changes in ocean salinity affected the isotopic signals in foraminiferal calcites, which can indicate sea-level changes ideally. The Sunda Shelf has the potential to be developed as a study area for eustatic sea-level changes as it is located far from major glaciation centers; hence through this review, we aim to highlight the potential of exploring the application of geochemical elements in foraminifera as an indicator for sea-level changes. To date, literature on foraminiferal geochemistry in this region is very limited, thus inhibiting progress in such studies. A comprehensive summary of past studies in this region is provided to give a general overview of the direction of foraminiferal geochemistry studies and serve as guidelines for future research.

Keywords: *F*oraminifera, geochemical element, sea-level changes, Southeast Asia, Sunda Shelf

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INTRODUCTION

Foraminifera is a member of a large phylum of amoeboid protists that can be found abundantly in marine sediments and usually produce tests or shells made up of calcium carbonate-shaped chambers. In micropalaeontology studies, foraminifera is often used to reconstruct past climate histories. Due to their extensive variability, abundance, and ability to evolve rapidly, foraminifera can also be considered the best indicator for biostratigraphy (Boltovskoy & Wright, 2013). According to the crystal latticework of foraminiferal calcites, almost 99% are composed of pure calcite, while minor and trace elements are accumulated as a substitute for calcium (Ca) or carbonate ions (CO_3^{2-}) to make up for the remaining 1% of the foraminiferal calcites (Lea, 1999). By accumulating trace elements onto the foraminifera calcites, scientists have been able to extract information on past climate histories based on geochemical proxy applications on foraminifera.

The earliest studies on geochemical proxy applications in foraminifera (e.g., Emiliani, 1955; Epstein et al., 1951, 1953; Shackleton, 1967; Urey, 1947) were mostly conducted on the stable carbon and oxygen isotope signatures of foraminifera, commonly expressed as $\delta^{18}O$ and $\delta^{13}C$. The findings from these studies established the utilization of carbon and oxygen isotopic records retrieved from measurements of fossil foraminifera calcites in response to inquiries regarding the evolution and history of ocean climates (Ravelo & Hillaire-Marcel, 2007). The stable isotopic values in foraminiferal calcites are usually influenced primarily by ocean processes such as water mass transport and mixing and secondarily by environmental effects such as microhabitats and carbonate ions (Rohling & Cooke, 1999). More geochemical proxies were developed to complement the stable isotopic analysis data, such as alkenone UK'_{37}, TEX 86, and trace element/calcium ratios of foraminiferal calcites to increase the accuracy of the data obtained from the stable isotopic analyses, more (Schmiedl, 2019). Recent studies have found that paired stable isotopic analyses and trace element/calcium ratio analyses could aid in monitoring sea-level changes, but this only applies to deep-sea dwelling foraminifera (Gupta, 2003). Paired Mg/Ca – $\delta^{18}O$ palaeothermometry of foraminifera, particularly on benthic species, enables the $\delta^{18}O$ paleotemperature equation to be solved for seawater $\delta^{18}O$ ($\delta^{18}O_{sw}$) as it may be related to global ice volume that can be associated with sea-level changes and Mg/Ca ratios acts as independent temperature proxy to estimate $\delta^{18}O_{sw}$ changes caused by ice-volume variations (Evans et al., 2016; Miller et al., 2020). Emiliani (1955) elucidated that the $\delta^{18}O_{sw}$ is greatly influenced by the global ice volume in which glacial ice has a large amount of ^{16}O stored in it while simultaneously the content of ^{18}O in oceanic water will be high. The waxing and waning of the ice will influence the oxygen isotopes, and the isotopic ratio changes indicating the foraminifera will record the sea level. Mg/Ca ratios will then discriminate the local freshwater effect from the global ice volume signal (Felder et al., 2022).

During the Paleogene period, short-term but dramatic environmental changes were detected through the utilization of high-resolution foraminifera isotopic analysis, $\delta^{13}C$, and $\delta^{18}O$, in which the former was used to detect variations in carbon contents and distributions while the latter is used to constrain the timing and scale of temperature and ice volume changes. The study evaluated the abrupt climatic transitions and found evidence from geochemical and sedimentological analyses suggesting two cases of climate extremes during the Paleogene and early Oligocene, accompanied by reorganizations in ocean circulation and major perturbations in marine productivity and the global carbon cycle (Zachos et al., 1993). This study provides an example of utilizing foraminiferal geochemistry to investigate past ocean climate histories.

In comparison, foraminiferal geochemistry in Southeast Asia has yet to be developed into an impactful research area. Regionally, publications in foraminiferal geochemistry were driven by their proximity to the Indo-Pacific Warm Pool (IPWP) and Intertropical Convergence Zone (ITCZ) and how these phenomena influenced foraminiferal geochemistry have only been based in Indonesia and the Philippines. The impact of these phenomena on the global climate could be reflected through data from the Mg/Ca ratio analyses that reported sea surface temperature (SST) variability during the early Holocene period (Haberle et al., 2004; Lo Giudice Cappelli et al., 2016). Other countries such as Thailand, Singapore, and Malaysia have limited contributions to foraminiferal geochemistry research, as most publications on foraminifera focus on foraminiferal ecology and distribution.

In this review, we discuss the development of foraminiferal geochemistry studies in Southeast Asia to provide a general outlook on this area of research. Furthermore, this review highlights the potential of exploring the application of foraminiferal geochemistry as an indicator for sea-level changes, particularly on the Sunda Shelf, due to its high sensitivity to variations in sea-level changes. Based on this gap in the scientific understanding of this area of study, this review is expected to create new ideas and opportunities for the future progress of foraminiferal geochemistry studies in this region.

STATUS OF FORAMINIFERAL STUDIES IN THE SOUTHEAST ASIA REGION

Western Southeast Asia (SEA) is situated on a pre-Mesozoic continental crust called the Sunda Shelf, consisting of a geologically stable continental crust. While, eastern SEA is situated on an oceanic crust. The Sunda Shelf consists of an area between the southern part of the Indo-China Peninsula, the Malay Peninsula, and the large islands of Sumatra, Borneo, and Java forming the south-western part of the semi-enclosed marginal South China Sea (SCS) basin and serving as a connection between the SCS and the Indian Ocean through the Malacca Straits (Szarek, 2001). Sea-level changes in the region have occurred on different magnitudes over thousand to a hundred million-year timescales and have been categorized according to orders; the first-order represents the highest magnitude of sea-level changes at one hundred million-year timescales, and the fifth-order defines the lowest magnitude changes on ten thousand-year timescales. Tectonic activity in SEA occurs during temporal intervals that are too short and, therefore, cannot be considered as global third-order sequences, which usually correspond to rifting, thermal subsidence, and global eustatic sea-level changes (Gold, 2021). However, if simultaneous sea-level occurrences or trends are found in multiple basins, they will likely hold regional or global significance.

Additionally, the carbonate system in SEA is generally influenced by terrestrial runoff, monsoonal effects, and the Indonesian Throughflow Current (ITFC) in western SEA seas, while eastern SEA seas are commonly impacted by major nutrient upwelling and the El Niño-Southern Oscillation (ENSO) (Wilson, 2011). The changes in the carbonate chemistry of seawater could affect its carbon and oxygen isotopic values, as well as the trace element/calcium ratios, which can signal past changes in oceanic climate (Gray et al., 2018; Spero, 1998).

As mentioned earlier, the numbers of publications considering foraminiferal studies in Malaysia are scarce. Over the past 20 years, most publications have focused on foraminiferal distribution and ecology (Minhat et al., 2018; Parham et al., 2014). The reasons behind the low numbers of foraminiferal studies in Malaysia include the microscopic size of foraminifera, which makes their study difficult, a lack of knowledge of regional taxonomies, and financial constraints to sampling beyond the intertidal zone (Parham et al., 2014). Currently, references on regional taxonomies are incomplete and do not include several genera endemic to the region (Minhat et al., 2018). One of the earliest research attempts in Malaysia that applied foraminiferal geochemistry proxies successfully established a new SST record for the last 7200 years using sediment cores recovered off Sarawak waters (Woodson et al., 2017). The study by Woodson et al. (2017) can serve as evidence that foraminiferal studies can divert their focus from species distribution and ecology to foraminiferal geochemistry and initiate the generation of a new dataset of Malaysia's climate history. In our opinion, past studies have covered almost every aspect of the marine environment of the coastal waters of Malaysia, for instance, intertidal zones (Culver et al., 2015; Minhat et al., 2019; Satyanarayana et al., 2014; Suriadi et al., 2013) and coastal waters (Yahya et al., 2014). Therefore, a new shift in foraminifera studies could open up/initiate new research interests. Table 1 summarizes the foraminiferal studies conducted in Malaysia, which consists of 1 geochemistry study, 2 sea-level reconstruction studies, and 8 distribution studies detailing the locations, geographic or hydrographic characteristics, and methodologies used.

Similar to Malaysia, other countries like Thailand and Singapore have also had a common approach to foraminiferal research and have limited publications on the topic. It can be explained by Singapore's location, namely the Strait of Singapore, the second most dense navigational traffic globally, where most foraminifera species do not prefer coastal water turbidity. It was reported that in the Strait of Singapore, the complicated geometry and varying bathymetry depth could cause higher tidal amplitude and currents, and turbidity at the straits would increase as an effect of the tidal current (Rusli, 2012). A recent publication by Martin et al. (2022) observed that the monsoon-driven currents impacted the pH in the strait caused by the remineralization of terrestrial dissolved organic carbon (DOC), which would have affected calcifying organisms, especially foraminifera. The study areas are classified into two colors according to their field of study to illustrate the discrepancy between foraminiferal ecology and geochemistry studies in the SEA region (Figure 1). It can be concluded that foraminiferal geochemistry is understudied in the region. Based on Figure 1, 31 study areas were recorded for foraminiferal ecology studies, while 17 were recorded for foraminiferal geochemistry. Most of the studies were conducted in areas that have prominent hydrographic characteristics. In contrast, foraminiferal ecological studies were more widespread comparatively, covering many ecosystems such as mangroves and open oceans.

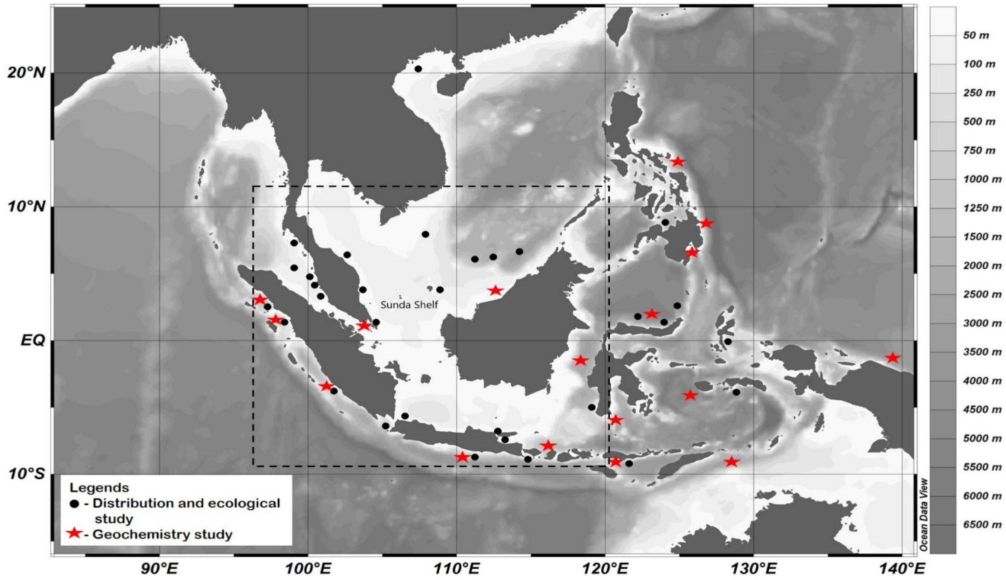

Figure 1. Visual representation of discrepancy between foraminiferal ecology and geochemistry studies in Southeast Asia. Sunda Shelf is located within the illustrated dashed-line box. Black circles represent distribution and ecological studies, while red stars represent geochemistry studies.

Contrary to its neighboring countries, studies in Indonesia and the Philippines have been conducted since the late 1990s. The findings could serve as guidelines for developing foraminiferal geochemistry studies in SEA. Indonesia has published the most articles regionally on foraminiferal research, comprising work on species' distribution or ecology and the application of geochemical proxies. The Philippines have also contributed several publications on geochemical proxy research. Indonesia and the Philippines are geographically strategic for foraminiferal research due to their proximity to the IPWP and ITCZ. As the regional and monsoonal circulations (e.g., Indonesian Throughflow and Mindanao Current) surrounding the Indonesia and Philippines waters could affect the biogeochemical cycle of the study area, the foraminifera sensitivity to hydrological parameter changes is utilized by analyzing the stable calcite isotopes and trace elemental ratios.

Table 1
Summary of the foraminiferal studies conducted in Malaysia

Aspect of foraminiferal studies	Author(s)	Location	Geographic/ hydrographic characteristics	Methodology used
Geochemistry	Woodson et al. (2017)	Off Bintulu, Sarawak	East Asian Monsoonal influences Shallow continental shelf settings (Sunda Shelf)	Mg/Ca ratios on *Globigerinoides ruber* and *Globigerinoides sacculifer*
Sea-level constructions based on a foraminiferal assemblages transfer function	Minhat et al. (2016)	East coast Johor	Centre of the Sunda Shelf Monsoonal influences (Northeast and Southwest Monsoon)	Transfer function based on foraminiferal assemblages' data
Sea-level constructions based on a foraminiferal assemblages transfer function	Culver et al. (2015)	Setiu Wetland, Terengganu	El Nino-related changes affected coastal evolution Located on the inner part of Sundaland, a tectonically stable region	Transfer function based on foraminiferal assemblages' data
Distribution	Razak et al. (2022)	Sungai Kilim, Langkawi	Combination of several ecosystems such as mangrove swamps, limestone caves, lagoons, and estuaries	Species distribution using foraminiferal diversity indices (e.g., Shannon-Wiener and Fisher's alpha) Statistical correlation between a distribution and environmental parameters

Table 1 *(Continue)*

Aspect of foraminiferal studies	Author(s)	Location	Geographic/ hydrographic characteristics	Methodology used
Distribution	Minhat et al. (2021)	Northern Malacca Strait	Multiple ecosystems Monsoonal influences	Species distribution using foraminiferal diversity indices (e.g., Shannon-Wiener and Fisher's alpha) Cluster analysis on biozonation of foraminiferal assemblages Statistical correlation between a distribution and environmental parameters
Distribution and ecological indicator	Minhat et al. (2020)	Northern Malacca Strait	Study areas are subjected to river discharges	Species distribution using foraminiferal diversity indices (e.g., Shannon-Wiener and Fisher's alpha) Statistical correlation between a distribution and environmental parameters Foraminifera Stress Index
Distribution and composition	Minhat et al. (2019)	Northern Malacca Strait	3.9 m sediment core providing species composition and distribution data during Early Holocene	Raw foraminiferal count data Sediment grain analysis.

Table 1 *(Continue)*

Aspect of foraminiferal studies	Author(s)	Location	Geographic/ hydrographic characteristics	Methodology used
Distribution and abundance	Minhat et al. (2014)	Penang National Park, Penang	Monsoonal influences Sampling sites were based on anthropogenic activities in the area	Species distribution using foraminiferal diversity indices (e.g., Shannon-Wiener and Fisher's alpha) Cluster analysis Nutrient and grain-size analysis
Distribution	Yahya et al. (2014)	Penang National Park, Pemamg	Monsoonal influences Sampling sites were based on anthropogenic activities in the area	Species distribution using foraminiferal diversity indices (e.g., Shannon-Wiener and Fisher's alpha)
Distribution	Satyanarayana et al. (2014)	Kapar and Matang Mangrove Area	Mangrove areas that are strongly influenced by their location in the tropics	Faunal abundance using Bray-Curtis similarity Statistical correlation between a distribution and environmental parameters
Distribution and abundance	Suriadi et al. (2009)	Kelantan Delta	Exposed to strong northeasterly waves from the South China Sea during Northeast Monsoon.	Species distribution using foraminiferal diversity indices (e.g., Shannon-Wiener and Fisher's alpha) Faunal abundance using cluster analysis and non-metric Multi-Dimensional Scaling (nMDS)

Earlier studies by Ahmad et al. (1995) and Spooner et al. (2005) had noted monsoonal influence on foraminiferal $\delta^{18}O$ and implicated that the Banda Sea had undergone numerous changes in water stratigraphy and hydrographical parameters such as salinity through the past ~ 80 000 years. Other than that, the foraminiferal stable isotopic interpretations of the Southwest and West Indonesia had revealed that $\delta^{18}O$ corresponds well to SST during Southeast and Northwest Monsoon (SEM and NWM) and interspecies $\delta^{13}C$ values differences could potentially be used as a productivity proxy as $\delta^{13}C$ and productivity are inversely related (Mohtadi et al., 2007). The water mass mixing from upwelling and freshwater advection as reflected from trace elemental ratios Ba/Ca (Setiawan et al., 2017) are seen to affect the depth of deep chlorophyll maximum, which in turn influenced foraminiferal calcification depth and Mg/Ca-based temperature (Hollstein et al., 2018). In most literature reporting findings from study areas in Indonesia and the Philippines, regional and monsoonal circulations are often considered in analyzing the factors influencing foraminiferal geochemistry; hence the foraminiferal studies are often narrowed to only exploring these aspects, although foraminiferal geochemistry has the potential to elucidate regional sea-level changes.

The status of foraminiferal studies in SEA can be described as underdeveloped since not much information can be gathered from current publications on foraminiferal geochemistry. The factors mentioned above that have contributed to the scarcity of foraminiferal research in Malaysia could also affect other countries in the SEA region, resulting in the stagnant state of foraminiferal geochemistry studies.

FORAMINIFERA AS GEOCHEMICAL TOOLS

The increasing use of isotope and trace element geochemical proxies has contributed to enhancing the use of foraminifera in understanding oceanic climate histories. Over the past decades, there has been great progress in using geochemical proxies in foraminifera especially trace elemental and isotopic proxies. Among them is the application of coupled Mg/Ca palaeothermometry with $\delta^{18}O$ that can yield high-accuracy SST readings compared to other SST reading proxies (Katz et al., 2010; Lea, 2013) and to date, the development of geochemical proxies applied in foraminiferal carbonate tests have enabled us to reconstruct various parameters of past ocean climates (Table 2). Early publications in the SEA region focused on traditional proxies such as stable oxygen and carbon isotope analyses. However, for the past ten years, there has been a slow emergence of publications that have utilized trace elemental proxies (Figure 2).

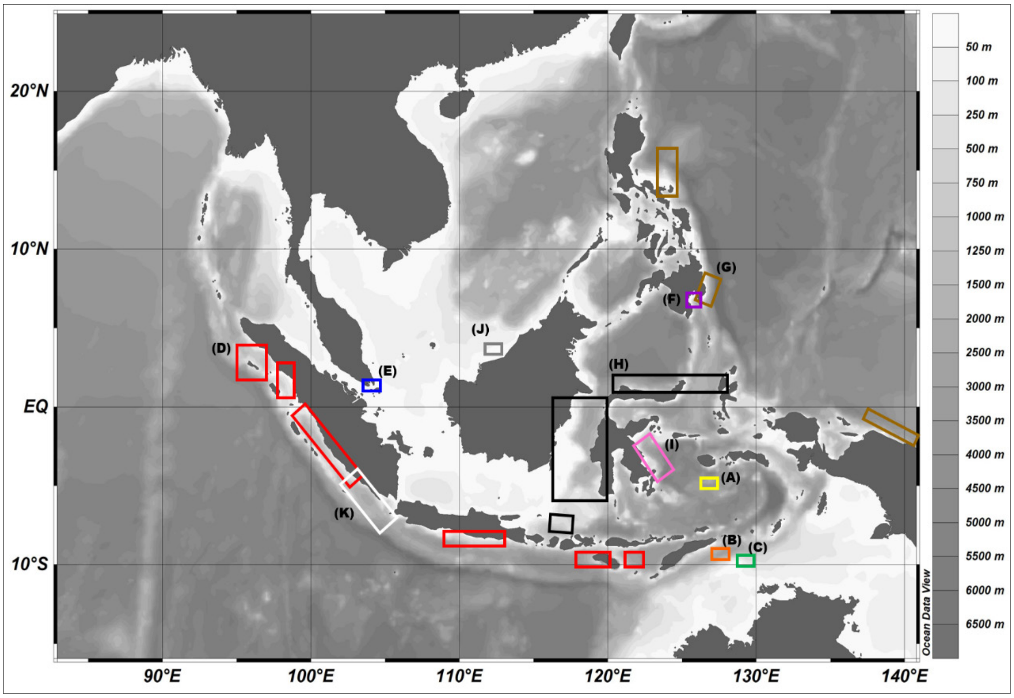

Figure 2. Map of Southeast Asia with bathymetry. The map is produced using Ocean Data View software (ODV). Bathymetry data was obtained from World Ocean Atlas 2018 from NOAA. Previously studied areas are denoted using alphabets with colored boxes for easier identification; note that multiple same-colored boxes represent studies that covered many areas. (A, yellow) Ahmad et al. (1995), (B, orange) Spooner et al. (2005), (C, green) Lo Giudice Cappelli et al. (2016), (D, red) Mohtadi et al. (2007), (E, blue) Michael I Bird et al. (2010), (F, purple) Fraser et al. (2015); (G, brown) Hollstein et al. (2017), (H, black) Zhang et al. (2016, 2019), (I, pink) Rosenthal et al. (2006), (J, grey) Woodson et al. (2017) and (K, white) Setiawan et al. (2017).

Before geochemical proxies were widely used for ocean climate reconstructions, transfer functions based on foraminiferal assemblages were commonly applied since the method does not require complicated procedures and can produce quantitative estimations that can be applied to reconstruct paleoenvironments (Jorissen et al., 2007). An attempt to estimate SST using FP-12E and SIMMAX was unsuccessful as the methods could not reflect true SST variations for the glacial southern SCS due to the amplification of glacial SST from the abnormally high abundance of *Pulleniatina Obliquiloculata* (Li et al., 2010). Infaunal foraminifera and water depth-related faunal shifts in foraminiferal assemblages could also affect paleoenvironmental interpretations (Minhat et al., 2016; Suriadi et al., 2009). Due to a large degree of uncertainty in the assemblage-based proxy, as previously reported, the methods have become less popular. Due to their accuracy, geochemical proxies such as stable isotopic and trace element/calcium ratio analyses have become a better option for past ocean climate reconstructions.

Table 2

Geochemical proxies used frequently in foraminiferal carbonate tests

Geochemical proxies	Measured parameters or uses	Reference
Stable isotopes		
$\delta^{18}O$	Ice volume Temperature reconstructions	Rohling et al. (2017) Salgueiro et al. (2020)
$\delta^{13}C$	Water mass circulation Marine productivity Chemostratigraphy	Mohtadi et al. (2007) Peeters et al. (2002)
Physical proxy		
Mg/Ca	Temperature reconstructions	Rosenthal and Linsley (2013)
Nutrient proxy		
Ba/Ca	Water mass circulation Distribution reflects biogeochemical cycling	Setiawan et al. (2017)
Cd/Ca	Water mass circulation Behavior mimics phosphate distribution	Ripperger et al. (2008)
Zn/Ca	Water mass circulation Carbonate saturation Behavior mimics silica distribution	Marr et al. (2013)

Isotopic Proxies

The use of stable isotopic proxies such as oxygen and carbon isotopes began in the mid-20th century and has played an important role in the development of paleoceanography. The geochemical composition of foraminiferal test calcite reflects numerous environmental variables that occur during calcification (Schmiedl, 2019), where simultaneous kinetic oxygen isotope fractionation is also occurring. While certain foraminifera species are in oxygen isotopic equilibrium with seawater when producing shells, some other species are in disequilibrium due to biological 'vital' effects. These effects do not imply the kinetic fractionation of carbon isotopes because the "equilibrating" pools of oxygen from seawater are far bigger than those of carbon (Ravelo & Hillaire-Marcel, 2007). Common strategies used while analyzing isotopic proxies are limited to only one species used to generate records to minimize the variability caused by specific biological effects. The studied species are selected from established ecological preferences and are generally predictable across locations with varying oceanographic conditions (Table 3). The strategy to pre-select the studied species based on ecological preferences is a good approach since the tested geochemical proxies established in other regions may not apply to a specific region, for example, the Sunda Shelf (Zhang et al., 2019).

Table 3

Foraminifera species used for stable isotopic proxies across Southeast Asia

Author(s)	Location	Isotopes	Foraminifera Species
Ahmad et al. (1995)	Banda Sea, Indonesia (Figure 2A)	$\delta^{18}O$	Planktonic*: Globigerinoides Ruber* Benthic*:* Uvigerina spp. & Cibicides spp.
Spooner et al. (2005)	Banda Sea, Indonesia (Figure 2B)	$\delta^{18}O$, $\delta^{13}C$	Planktonic: Globigerinoides Ruber
Mohtadi et al. (2007)	West and Southwest Indonesia (Figure 2C)	$\delta^{18}O$, $\delta^{13}C$	Planktonic: *Globigerinoides Ruber, Neogloboquadrina Dutertrei*
Bird et al. (2010)	Singapore (Figure 2D)	$\delta^{18}O$, $\delta^{13}C$	Benthic: Ammonia spp. & Elphidium spp.
Fraser et al. (2015)	Davao Gulf, Philippines (Figure 2E)	$\delta^{18}O$ coupled with $U_{37}^{K'}$ -temperature	Planktonic: Globigerinoides Ruber
Lo Giudice Cappelli et al. (2016)	Southern Timor Strait (Figure 2F)	$\delta^{18}O$ coupled with Mg/Ca ratio	Planktonic: *Globigerinoides Ruber* Benthic: Hoeglundina Elegans
Zhang et al. (2016)	Indonesia Throughflow (ITF) Region: Sulawesi Sea, Maluku Sea, Bali Sea, Flores Sea, and Timor Sea (Figure 2G)	$\delta^{18}O$, $\delta^{13}C$	Planktonic: *Globigerinoides ruber,* *Globigerinoides sacculifer,* *Pulleniatina obliquilocata,* *Neogloboquadrina dutertrei*
Hollstein et al. (2017)	Offshore Philippines and Papua New Guinea (Figure 2I)	$\delta^{18}O$ coupled with Mg/Ca ratio	Planktonic: *Globigerinoides ruber,* *Globigerinoides sacculifer,* *Globigerinoides elongatus,* *Pulleniatina Obliquilocata,* *Neogloboquadrina dutertrei,* *Globorotalia tumida*
Zhang et al. (2019)	Indonesia Throughflow (ITF) Region: Sulawesi Sea, Maluku Sea, Bali Sea, Flores Sea, and Timor Sea (Fig 2G)	$\delta^{18}O$ coupled with Mg/Ca ratio	Planktonic: *Globigerinoides ruber,* *Globigerinoides sacculifer,* *Pulleniatina obliquilocata,* *Neogloboquadrina dutertei*

Referring to the strategies and the table above, we can conclude that *Globigerinoides ruber* is the most preferred species for stable isotopic studies, given that it is a stress-tolerant species and has a cosmopolitan distribution across warm water regions, usually dwelling in the top ~30 m of the water column (Mulitza et al., 1997). The oxygen isotopic composition indicates that the species' life cycle is completed within the top surface layer of the water column (Anand et al., 2003; Richey et al., 2019; Venancio et al., 2017). Other species, such as *Globigerinoides sacculifer, Pulleniatina obliquilocata*, and *Neogloboquadrina dutertrei,* are often selected as studied species as most can be found in warm water regions. *G. sacculifer* is the most abundant species in tropical waters. However, it is sometimes replaced by *G. ruber,* which is more abundant in the sub-tropics and does not prefer higher salinity water than *G. sacculifer* (Haynes, 1981). Based on the calcification depth, *G. ruber* is classified as a mixed layer dweller, while both *P. obliquilocata* and *N. dutertrei* are thermocline dwellers; for *G. sacculifer,* it was recently reported that the species could usually be found dwelling at a depth ranging from the mixed layer to the upper thermocline (Zhang et al., 2019).

Considering past works in the literature on stable isotopic proxies in SEA, it can be concluded that other areas apart from Indonesia and the Philippines have been significantly understudied. The hydrological system in a marginal sea, for example, the SCS, is highly sensitive to changes on both continents and in oceans because it is at the intersection of river runoff and oceanic currents (Wang et al., 2014). Any slight changes in the water carbonate system would affect the isotopic composition of the foraminiferal calcites and would thus also affect the reliability of regional calibrations established from isotopic calibration studies (Hollstein et al., 2017; Dang et al., 2018).

Trace Elemental Proxies

The study of trace elemental proxies started late compared to isotopic proxies, with the earliest research dated around the 1960s. During shell precipitation, trace elements are integrated into the calcites with an abundance of 0.25% or less to make up the remaining 1% of the foraminiferal calcite composition (Lea, 1999). The application of trace elemental proxies can be classified into four main groups, namely, nutrient proxies (e.g., Cd and Ba), physical proxies (e.g., Mg, Sr, and F), chemical proxies (e.g., Sr and Nd isotopes), and diagenetic proxies (e.g., Mn). The seawater composition and environmental conditions control the trace elements in the foraminifera shells during calcification. The trace element compositions are then interpreted to determine the relationship between the concentration and physical conditions at the time of calcification.

Elemental ratios are reported relative to calcium to reduce any uncertainties associated with using multiple proxies since they are usually measured on the same phase with $\delta^{18}O$ and $\delta^{13}C$. We may thus use the strategy mentioned in the earlier sections to select a foraminifera species as the study subject (Katz et al., 2010). Many earlier studies have applied the paired Mg/Ca, and $\delta^{18}O$ methods to reconstruct water temperatures and estimate relative changes in seawater. There is a good agreement between the three calibration methods, suggesting a similar temperature sensitivity for all planktic species. For benthic foraminifera, on the other hand, the paired Mg/Ca and $\delta^{18}O$ method can be utilized to study changes in bottom water temperature and $\delta^{18}O$ compositions in the seawater of the global ocean. The use of trace elements (e.g., Cd, Zn, and Ba) as nutrient proxies is most suitable because they have a much shorter residence time in seawater than physical proxies. Also, the oceanic behavior of the trace elements closely imitates that of the nutrients in the seawater, which can then be used to study nutrient paleaochemistry (Lea, 1999).

In the SEA region, the application of trace elements in foraminifera is currently understudied and, to date, only. The earliest work from this region (Figure 2I) was published around 15 years ago, studying the potential application of Mg/Ca and Sr/Ca ratios in benthic foraminifera *Hoeglundina elegans* to reconstruct bottom water temperatures (BWT), which discovered that aragonite saturation could influence the applicability of trace elemental ratios to reconstruct BWT or changes in carbonate ions (Rosenthal et al., 2006). Other than benthic and planktonic foraminifera, researchers have also tested the applicability of trace elemental proxies on reef foraminifera. Reef foraminifera *Operculina ammonoid*s could provide a more accurate foraminifera-based Mg/Ca_{sw} reconstruction and seawater Sr/Ca estimation (Evans et al., 2013). In recent years, more studies on trace elemental proxies in planktonic foraminifera have been conducted in Malaysia (Woodson et al., 2017) and Indonesia (Setiawan et al., 2017), and findings from these studies show promising outcomes for the use of trace elemental proxies in foraminifera (Figures 2K and 2J).

Overall, more study is needed to comprehensively assess this region's foraminiferal geochemistry and how it may be utilized to comprehend how the ocean evolves through time. It is critical to enhancing the understanding of oceanic temporal variations to grasp better the biogeochemical cycles influencing foraminiferal geochemistry. It will thus give us updated data on marine geochemical parameters at the microscale. The knowledge expansion on foraminiferal geochemistry would increase the comprehension of biogeochemical cycles and could potentially indicate sea-level changes that occurred on the studied timescale.

FORAMINIFERA AS AN INDICATOR OF SEA-LEVEL CHANGES

The Sunda Shelf is one of the world's largest low-latitude shelves. As marginal seas surround it, it is highly sensitive to sea-level changes (Wang et al., 2014). The shelf is also located in a far-field site, distant from major ice sheets and, theoretically, less affected by isostatic deformation (Clark & Mix, 2002). The total ice-sheet to-sea-level interaction can thus be represented and provides a potential record of eustatic function (Lambeck et al., 2014; Stanford et al., 2011). Indeed, this region can be considered an ideal location for eustatic sea-level change studies. In a marginal basin such as the Sunda Shelf, responses to sea-level changes from the reduced exchange with the open ocean through narrow gateways lead to amplified changes in surface water salinity. It affects foraminiferal $\delta^{18}O$ values as these are dominated by sea-level changes, especially in a semi-isolated basin such as the southwestern SCS (Lea, 2013; Rohling et al., 2004; Schmiedl, 2019; Siddall et al., 2003).

Eustatic sea-level changes can be defined as a uniform shift in the height of the ocean surface that happens because of the input of meltwater into the ocean without gravitational and rotational effects, ocean dynamics, and solid Earth deformation (Farrell & Clark, 1976). Different opinions on the Holocene sea-level high stand in areas surrounding the southern SCS, particularly in the Sunda Shelf, have created debates mainly due to its complicated topography and lack of high-quality dating results (Wang et al., 2014). Investigating eustatic sea-level changes can be deemed important as it provides an independent method for calibrating the marine oxygen isotope record obtained from foraminifera calcites and the total volume of continental ice during the Last Glacial Maximum (LGM) (Whitehouse & Bradley, 2013). The current proposed sea-level high stand of +2.0 to +3.0 m from 6 to 4 kyr BP on the Sunda Shelf is questionable since the effects of differential crustal movements evident from Malaysian sea-level records (Hassan, 2002; Parham, 2016) suggest that the generalized sea-level curve (Figure 3) could be affected by palaeofluvial systems (Sathiamurthy & Rahman, 2017). It could influence the composition of stable isotopes in foraminiferal calcites.

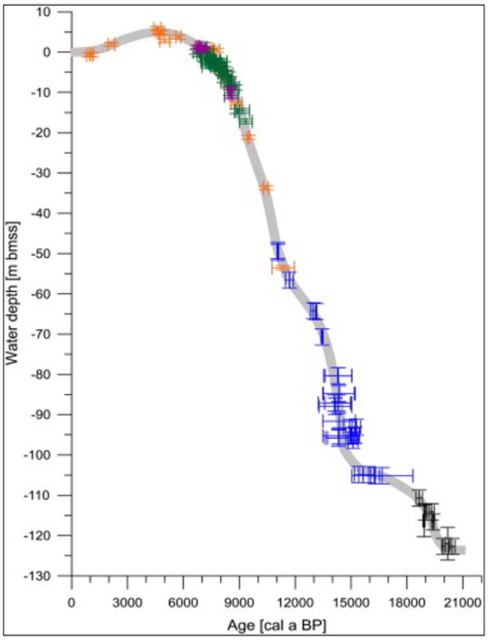

Figure 3. Temporal sea-level changes on the Sunda Shelf constructed from previously studied Sunda core regions (orange: Strait of Malacca; purple: Sungei Nipah and Pulau Semakau, Singapore; blue: Sunda Shelf; green: Singapore; black: Sunda Shelf). Graph illustrated based on a compilation of data from multiple sources (Geyh et al., 1979; Hanebuth et al., 2000; Hanebuth et al., 2009; Hawkes et al., 2007; Hesp et al., 1998). The figure is from Hanebuth et al. (2011).

While using corals as a proxy to reconstruct the sea-level changes is common in far-field study sites, it becomes problematic when interpreting glacio- and hydro-isostatic effects expressed by locally differential vertical movements of the Earth's crust (Lambeck et al., 2002) and dating precisions (Hanebuth et al., 2009). In addition, caution needs to be exercised when using corals as a proxy due to the difficulty of verifying whether coral growth depth remains constant during all rates of sea-level rise. It can only provide discrete data rather than continuous estimations of sea-level changes (Rohling et al., 2017; Whitehouse & Bradley, 2013).

Previous studies have dismissed the potential of stable oxygen isotopes as a proxy to reconstruct sea-level curves due to their lower resolution over the past 30 cal kyr BP (Hanebuth et al., 2009). However, as the study of foraminiferal geochemistry advanced, Schmiedl (2019) reported that at present, quantitative reconstructions of past global sea-level changes had been refined by utilizing not only stable oxygen isotopic records of deep-sea benthic foraminifera from the open ocean (Waelbroeck et al., 2002) but also stable oxygen isotopic records of planktonic foraminifera from marginal basins (Grant et al., 2014; Rohling et al., 2014; Siddall et al., 2003). Additionally, it has been suggested that eustatic sea-level curves that reflect oxygen isotope trends are more reliable than relying solely on coastal onlaps. Continuing research into the oxygen isotopes of foraminifera deposited over geological time can provide high-resolution data on variations in past climate and global sea-level changes (Gold, 2021). These recent findings emphasize the potential suitability of foraminiferal geochemistry in sea-level studies, as it can provide more extensive data due to its variability.

Locally, Minhat et al. (2016) attempted to evaluate the potential of subtidal foraminifera on the east coast of peninsular Malaysia to reconstruct Holocene sea-level changes using a weighted-average (WA) transfer function. They determined that the WA transfer function resulted in a less robust prediction ($r^2_{jack} = 0.40$) with lower precision ($RMSEP_{jack} = \pm 5$ m), possibly affected by salinity and wave transport factors which were not included in the investigation. However, the findings suggest that subtidal foraminifera can be used to detect sea-level changes. The WA transfer function approach to reconstructing sea-level changes was also utilized by Culver et al. (2015) in their study in the Setiu Wetlands, Terengganu. In addition, another study employed a multi-proxy approach in the same study area to refine and extend the sea-level curves constructed by Bird et al. (2007). The study successfully linked sea-level records with benthic foraminifera's isotopic values, which suggested a period of no or minimal eustatic sea-level rise between 7800 to 7400 cal yr BP, separated by intervals of more rapid rise before and after. It thus provides crucial information that explains the hiatus in the rate of sea-level rise during 7.7 ka BP (Bird et al., 2010). The discovery was made possible as a result of the multi-proxy approach, including benthic foraminiferal isotopic analysis, demonstrating the need to develop similar studies for meaningful comparisons with existing data. It will subsequently facilitate a deeper understanding of eustatic sea-level changes in this region.

Due to the limited availability of publications on how foraminiferal geochemistry enables the reconstruction of eustatic sea-level changes in the SEA region, we are unable to provide more sample studies as a reference. However, other far-field sites, such as the Japan Sea, have records of 20 planktonic foraminifera-derived $\delta^{18}O$ curves, of which almost all demonstrated extremely light $\delta^{18}O_{\text{Planktonic Foraminifera}}$ peaks during the LGM. In their study, Oba and Irino (2012) compared data from all 20 oxygen isotopic curves (e.g., Oba et al., 1980, 1991; Kido et al., 2007) and picked three to represent the Japan Sea $\delta^{18}O_{PF}$ curves. The representative curves were later compared to a standard oxygen isotopic curve obtained from a stacked $\delta^{18}O_{BF}$ curve of benthic foraminifera in 57 sediment cores collected from globally distributed sites (Lisiecki & Raymo, 2005). As a result, the eustatic sea level calculated for the LGM is 120 ±7 m below the present level based on a proportionate connection between the standard $\delta^{18}O$ curve in deep-sea cores and globally averaged sea-level changes. It suggests that the Japan Sea, although located far from the continental ice sheets, could provide essential insights into estimating eustatic sea levels. A comparison between the circumstances in the Japan Sea and the Sunda Shelf will therefore allow deductions on the use of isotopic proxies for sea-level determination to be made, with the availability of appropriate data. Further investigations are needed to provide new perspectives on the comprehension of eustatic sea-level change mechanisms in this region, as currently available data is still inadequate to understand the mechanisms at work fully.

CONCLUSION

As geologically advantaged countries, Indonesia and the Philippines lead the research on foraminiferal geochemistry in SEA. A few selected publications are highlighted in this paper. However, there is still a lack of information on the response of foraminifera toward the geochemical cycles in this region and how they can help reconstruct paleoenvironmental parameters. Most studies on foraminifera have focused on ecology and used foraminifera assemblage-based transfer functions to reconstruct sea-level changes and other oceanic parameters. Although this method is widely used, it can be affected by a large degree of uncertainty, hence defining the use of foraminiferal geochemical proxies as a better method for dealing with paleoenvironmental parameter reconstructions.

The Sunda Shelf provides an ideal site for reconstructing sea-level history. It is in a far-field site and has preserved a near-complete early history of sea-level changes during the last glaciation. Despite this, the oceanic climate histories of the Sunda Shelf are still relatively poorly understood. Hence, the research on foraminiferal geochemistry would contribute not only to the understanding of its climate history but also to the biogeochemical cycles that have occurred within it. Attempts to utilize geochemical proxies in foraminifera should be encouraged since the data obtained will help to combat coastal environmental issues in Southeast Asian countries and coastal cities that are surrounded by marginal seas and plagued with the risk of sea-level rise. Also, foraminifera-based climate research could complement the gaps in inter-disciplinary research, such as combining proxy studies with numerical model simulations to create temperature projections based on the response of foraminifera toward rising SST. The strategic geographical location should be taken advantage of to explore more climate histories through accumulated records of foraminiferal calcites.

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