Assessment of metal pollution in sediment components of a monsoon-dominated coastal water at Malacca Strait

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Abstract
Fluctuation levels of geochemical elements, sediment texture and nutrients were analysed from five surface sediments taken from the northern Malacca Straits. These samples were obtained during the RV Discovery Scientific cruises in September 2017 and April 2018 to assess pollution sources during monsoon events. The results show a higher output of clay and silt revealing that the monsoonal season and cross-shelf inputs affect textural sediment.

On the other hand, fluctuations in geochemical concentrations are due to industrialization and urbanization along the Malacca Straits contributed by the local drainage basin. The presence of the monsoon also affects the diffusivity and absorption at the water-sediment interface leading to constant fluctuation along the straits. Principal component analysis of the association between geochemical elements sediment texture and nutrients revealed hydrological factors, mobility and accumulation at the sediment interface.

Keywords: Weathering, pollution, monsoon, sediment, Malacca Strait

Introduction

The Malacca Strait is located between the west coast of Peninsular Malaysia and the east coast of Sumatra Island and is connected with the Strait of Singapore at the south-east end. There are also smaller straits such as the Johor Strait, Bengkali Strait and Rupat Strait. Together, these straits play an important role in international shipping routes linking the Indian Ocean to the Pacific Ocean[29]. The tropical climate in the Malacca Strait results in an annual precipitation of 3000 mm yr^{-1} leading to severe weathering on the adjacent peninsula.

Tides and currents present in the Malacca Straits are mainly semi-diurnal following the monsoonal current as the main force around the surrounding coast[7]. Low to medium high turbidity was recorded with transparency ranging from 10 to 30 m. Primary productivity is influenced geographically but constant throughout the whole year. Shallower water along the coastlines leads to vertical mixing and nutrient inputs from drainage basins adjacent to the Malacca Straits[28]. A high volume of annual precipitation also leads to severe terrestrial weathering towards the straits, resulting in elevated sediment discharge. On the west coast of Peninsular Malaysia, a number of discharged sediment sources are the result of physical and chemical weathering with most of the weathered material originating from igneous rock. Granitic rock present in Peninsular Malaysia originates from the Central and Western Belts for which the primary source is the Titiwangsa Ranges[24,33].

According to Shoieb et al[26], the Sibumasu Terrane which consists of the Peninsular Malaysia Western Belt was derived from the NW Australian Gondwana margin within the late Cambrian- Early Permian period. Thus, the discharged weathered sedimentary rock material is Palaeozoic shale.

An earlier study by Zakariah et al[34] on the sustainability of the Kuala Muda basin located in the Kedah River revealed a large quantity of granitic-bearing rocks, where most of it originated from the Bintang Range granites. In Penang and Langkawi Island, the formation of bedrock surrounding both islands originated from the quaternary deposits, where most of the discharge was feldspar and plagioclase[1,12]. This has thus resulted in a constant supply of igneous rocks to the Malacca Straits. In term of temporal influences, the Malacca Strait is affected by monsoonal seasons where the northeast monsoon prevails from November to March and the southwest monsoon runs from May to September.

In essence, the energy generated by the monsoonal season leads to corresponding changes in sea currents through eddies and cyclonic and anti-cyclonic events, thus altering the sinking processes in the Malacca Strait[2]. These monsoonal seasons also affect hydrological processes in the straits, thus leading to the distribution of weathered material around the coast.

The Malacca strait is replete with natural resources and many socio-economic activities related to metal processes and consumption such as husbandry, industry and residential activities are concentrated in this area, resulting in an increased load of contaminants due to rapid urbanization and increased population density[20]. Urban development and industrialisation over the previous decade have raised major environmental issues. Pollutants in rivers are severe problems in many rapidly growing cities because water quality and sanitary infrastructure do not keep up with population and urban expansion, particularly in developing countries.

Human activities such as sand mining, land reclamation, deforestation, landfill leachate and urban water runoff are common anthropogenic problems of environmental concern[21]. Contaminants are deposited in aquatic environments as a result of physical erosion, chemical weathering and soil leaching[18].

Furthermore, monsoon-induced events (i.e. storms, flash flood and landslides) can be devastating in mountainous tropical environments, causing severe soil erosion with both on-site and downstream repercussions and when combined with anthropogenic inputs, result in severe damage to the local population. These hazards also elevate geochemical concentration and sedimentation.

Sediment is a major source of concern when it comes to environmental quality because of its importance in monitoring both human and ecosystem health. The importance of sediment is seen in its constant deposition for many sources of contamination leading to bioaccumulation and bioassimilation in aquatic life through source and sink processes. In theory, the high level of pollution surrounding the Malacca Straits is the result of natural and anthropogenic inputs, backed with monsoonal seasons enhancing concentration under physical and hydrological processes.

The objective of this study is to identify the source of geochemical elements within the Malacca Straits while assessing several factors influencing these geochemical elements. This study thus examines pollution concentrations in the Malacca Strait and the prominent factors affecting geochemical elements along the straits.

Material and Methods

During a UKM-FIO Scientific cruise in August 2017 and May 2018, five surface sediment samples were collected using Veen Van Grab at a location on the western coast of Peninsular Malaysia (Figure 1). The water depth in the study area ranged from 15.5 m to 67.8 m. The sediment samples in this study were taken using a plastic scoop rather than a metal one to prevent cross contamination. Samples were stored in zipped polyethylene bags and frozen below 15 °C onboard before being shipped back to UKM.

Sediment textural analysis was performed according to the method of Miller and Miller[13,14]. Calgon solution was used as proposed by Kaur and Fanourakis[11]. The 4 g bulk sample was mixed in a 50 ml centrifuge tube with 4.2% Calgon solution for better separation into clay, sand and silt layers. The sample was then mixed and dispersed by sonication for 15 – 30 minutes. The sample was centrifuged at 770 rpm for 3.3 minutes to allow the clay to settle. The clay was then removed at 2.5 cm below the centrifuge tube meniscus level. Silt was obtained via wet sieving through a 45μm sieve and total sand was calculated via subtraction of total clay and silt[6]. For organic matter, the following procedure was followed: the dried and homogenized sample was weighed and treated by heating to 550 °C and 950 °C to acquire organic matter and calcium carbonate[4].

Geochemical element analysis was conducted following the methods of Rahim et al[18]. In summary, the dry and homogenized sediment was used and mixed with a mixture of 10 mL nitric acid (HNO_3), 5 mL perchloric acid ($HClO_4$) and 1 mL hydrofluoric acid (HF) for 2 h in a Teflon beaker at 120°C. With the acquisition of three replicates for each sample, the concentrations of Al, Fe, Ti, Mn, Mg and Cr were determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Standard reference material (NIST 1633b) was used with five replicates of reference material to assess the yield and effectiveness of the established method. The yield obtained was between 88% and 92% with an average result of 13.54 ± 0.1% for Al, 7.00 ± 0.03% for Fe, 0.71 ± 0.02% for Ti, 0.43 ± 0.04% for Mg, 118.55 ± 1.1 µg/g for Mn and 174.41 ± 1.3 µg/g for Cr.

For organic matter and $CaCO_3$, the loss of ignition (LOI) method was used as suggested by Santisteban et al[23]. The dried, finely ground and homogenized sediment was weighed accordingly and treated with high combustion heat for 4 hours at 550 °C in a furnace. After heating, the sample was cooled down in a desiccator and weighted again. The same sample was then treated for 2 hours at 950 °C for $CaCO_3$ determination.

Results and Discussion

The data in table 2 show that the average percentage was 10.93% for clay, 37.99% for silt and 51.08% for sand while organic matter and $CaCO_3$ averaged at 5.87% and 9.51% respectively along the Malacca Strait. There was an average difference of organic matter (5.41%) and $CaCO_3$ (9.51%) between stations N95 and N108 where station N95 dominated with a higher value for organic matter and $CaCO_3$. In the meantime, the difference between N95 and N108 was apparent in textural sediment where a higher value was present in silt for N95, while N108 secured a higher value for clay and sand content in sediment.

Table 1
Sampling stations along the Malacca Straits

Station	Longitude	Latitude	Sampling Date	Depth (m)
N95	99.9606	6.0069	1/5/2018	39.5
N99	99.9811	5.4428	2/5/2018	40.8
N103	100.44	4.9433	2/5/2018	15.5
N106	100.4561	4.3733	2/5/2018	22.0
N108	100.4828	3.8247	2/5/2018	67.8

This suggests that constant remobilization acts on surface sediment and that this occurred at station N108, as the constant discharge of particulates due to anthropogenic inputs and frequent precipitation from the nearby drainage basin led to the dominance of clay and sand at station N108[16].

According to Ramaswamy et al[19], sediment discharge from the Irrawaddy River due to continuous weathering onto igneous rock leads to accumulation within the Irrawaddy Delta.

In addition, the severity of the monsoonal seasons affects Andaman Sea extending to the Gulf of Martaban. Hence, the tides, waves and Ekman transport generate a net motion via the monsoonal season causing mass migration of suspended particulate towards station N95 before they sink to the bottom. In nutrient distribution along the Malacca Strait, the average organic matter and $CaCO_3$ acquired were 5.87 ± 0.12% and 9.51 ± 0.28% respectively.

There is a difference in organic matter (5.41%) and $CaCO_3$ (8.24%) content between stations N95 and N108 due to the exposure of the neighbouring shelf, where hydrological changes affect the total distribution along the Malacca Strait. Higher organic matter and $CaCO_3$ contents at N95 compared to N108 are due to hydrological factors taking place within the Malacca Straits.

The presence of the monsoonal season affects seabed sediment as the major sink where the rate of removal is higher in accordance with diffusion rates in the seabed sediment[15]. Similar to compositional differences in textural sediment, the monsoonal season affects the coastal region where the reworking process on seabed sediment is present leading to the constant production of nutrients along the station.

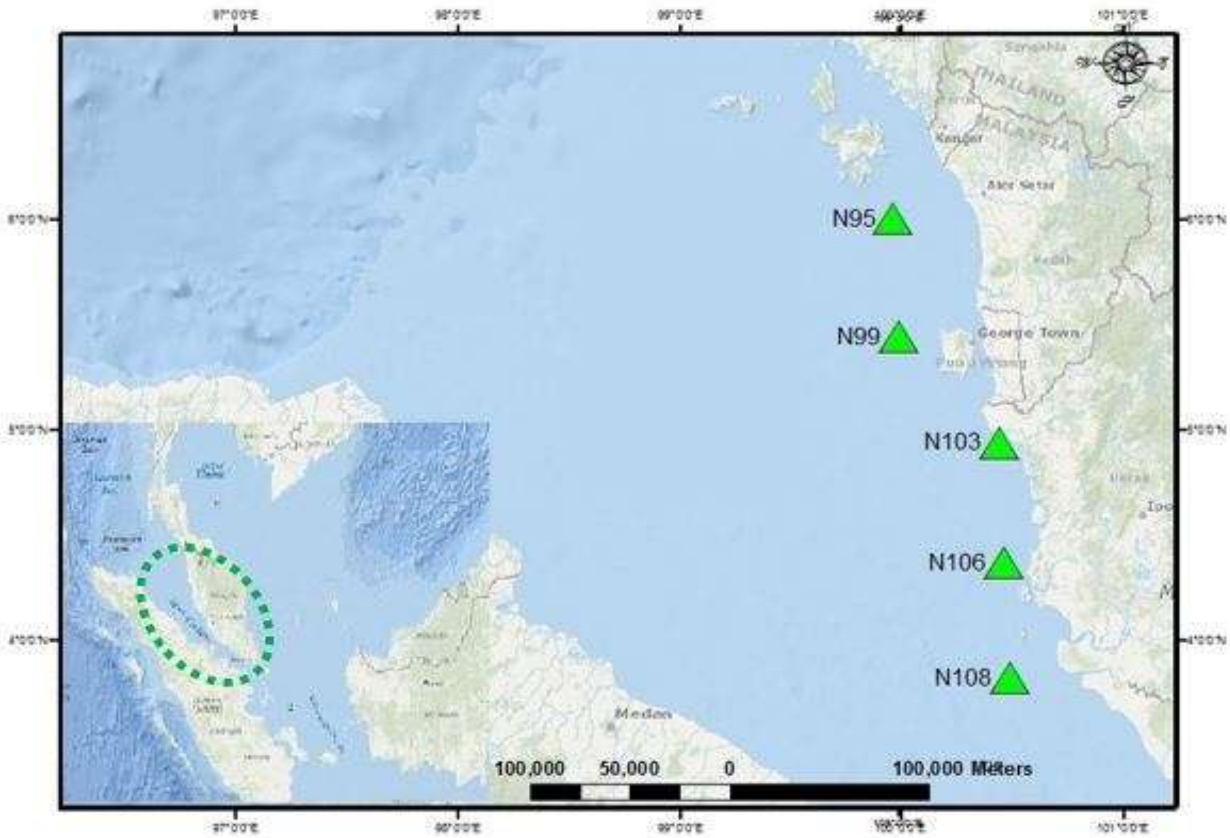

Figure 1: Sampling station in Malacca Straits

Table 2
Physico-chemical characteristic of sediment in Malacca Straits

Station	Clay (%)	Silt (%)	Sand (%)	OM (%)	$CaCO_3$ (%)
N95	7.23	21.98	70.79	8.53 ± 0.11	14.42 ± 0.34
N99	11.30	15.09	73.61	6.73 ± 0.02	10.02 ± 0.19
N103	13.24	65.70	21.06	4.24 ± 0.2	3.9 ± 0.47
N106	11.44	83.43	5.12	7.63 ± 0.2	6.68 ± 0.13
N108	11.41	3.77	84.81	3.12 ± 0.19	6.18 ± 0.45

Table 3
Concentrations of geochemical elements in the Malacca Straits

Station	Al (%)	Fe (%)	Ti (%)	Zn (µg/g)	Cr (µg/g)	Mn (µg/g)	Mg (%)
N95	6.09 ± 0.29	3.01 ± 0.31	0.19 ± 0.02	55.09 ± 1.09	121.46 ± 6.25	371.62 ± 20.18	3.01 ± 0.12
N99	5.51 ± 0.24	2.68 ± 0.19	0.23 ± 0.02	46.05 ± 0.6	85.08 ± 5.07	319.86 ± 26.62	2.1 ± 0.1
N103	6.4 ± 0.96	3 ± 0.58	0.28 ± 0.05	59.78 ± 1.05	91.78 ± 9.77	564.96 ± 89.81	1.81 ± 0.32
N106	8.11 ± 1.56	3.75 ± 0.95	0.27 ± 0.06	73.09 ± 1.11	128.35 ± 5.97	598.15 ± 91.47	2.44 ± 0.46
N108	3.31 ± 0.09	1.48 ± 0.03	0.13 ± 0.01	52.57 ± 1.26	39.42 ± 2.07	505.4 ± 2.52	1.59 ± 0.06

The geochemical elements shown in table 3 reveal that the average concentration of each element is 5.00 ± 0.5% (Al), 2.88 ± 0.34% (Fe), 0.23 ± 0.03% (Ti), 51.41 ± 0.9 µg/g (Zn), 94.56 ± 6.4 µg/g (Cr), 526.08 ± 41.95 µg/g (Mn) and 1.92 ± 0.18% (Mg).

According to the obtained concentrations above, the concentrations of several elements were different from those reported by Shaari et al[25] who found higher levels of Fe and Zn with 44% and 10% differences respectively, on the east coast compared with the west coast of Peninsular Malaysia. This suggests continuous inputs from several sources i.e. the Gulf of Thailand, Western Pacific and the Natuna Straits. The weathering rate is more apparent as the monsoonal season elevates the precipitation rate leading to a higher discharge rate.

Furthermore, the industrialization occurring along both river channels also contributes to the increase in geochemical elements. Cross-shelf inputs towards the semi-marginal basin also affect the total geochemical elements being supplied to the east coast of Peninsular Malaysia. The cross-shelf input via the Western Pacific which mobilizes via longshore currents of the Vietnamese coastal through the Luzon Strait and the southern South China Sea (sSCS) coupled with periodic monsoonal seasons led to fluctuations of geochemical elements on the east coast of Peninsular Malaysia.

On the west coast, the prominent contributor is the Andaman Sea with origins in the Bay of Bengal and Martaban Bay. Martaban Bay is the drainage basin for the Irrawaddy River for Martaban Bay and the Bay of Bengal for the Ganges River, contributing most of the geochemical elements in the sea. Depth differences along the west coast may affect the bottom current trajectory leading to a difference in upwelling and downwelling dynamics. This results in less transport in deeper water leading to a lower rate of remobilization of seabed sediment.

According to Väli et al[30], the difference in dynamic uplift due to water depth suggests a larger difference in nutrient transport leading to a lower nutrient content in shallower coastal waters due to constant remobilization. Furthermore, the difference in topography may lead to a lower current output due to convergence at the northern Malacca Strait. Haditiar et al[8] stated that the Malacca Strait facilitates a small water mass exchange between the Andaman Sea and the Malacca Strait compared to the east coast of Peninsular Malaysia under the influence of the monsoon resulting in a lower transport dynamic between the two coast.

To assess geochemical pollution at the sampling stations, principal component analysis (PCA) was used to assess the significance of sediment contamination levels to aquatic ecosystem and environmental management. It also provides better quantification of the dataset regarding geochemical elements in sediments and their controlling factors. The results of the PCA are presented in table 4 for two principal components. The analysis shows that about 54% of the total variation is explained by the first principal component followed by 38% for the second principal component.

The first PCA is defined by the hydrological action that results in the accumulation preserved in silts. The input from the local drainage basin leads to elevated geochemical elements, as incorporation within silt was via absorption and diffusion, hence leading to a high concentration in the analysed silts. Higher removal rates through sand suggest that hydrological influences may affect the rate of removal[5]. Constant remobilization on surface sediment in the Malacca Strait may occur due to a difference between depths in the straits leading to severe fluctuations in coastal transport dynamics[30].

The presence of high Al in seabed sediment suggests normal occurrences in the sediment, as feldspar and plagioclase are the main constituents in the sediment surrounding Peninsular Malaysia through weathering. Dilution effects onto the sand suggest high concentrations in the sediments as aluminium is susceptible to physical impact[31]. Furthermore, the absorbent nature of Fe-Mn oxyhydroxides also leads to sorption of most of the geochemical elements into silt leading to higher affinity as well as through oxidation and reduction. Fe-Mn acts as a scavenger in coastal environments where the coprecipitating process occurs leading to strong enrichment of geochemical elements[27]. The higher affinity of zinc in silt also suggests natural and anthropogenic inputs influencing sediment content in sampling stations.

Zinc is one of the geochemical elements that can be found in agricultural waste, herbicides and antifouling coatings. Weathering effects in the natural environment lead to the conversion of common zinc species into the soluble form which is then discharged into the aquatic environment[32].

Table 4
Principal component loadings

	Component	
	1	2
Clay	0.265	**-0.893**
Silt	**0.985**	-0.166
Sand	**-0.976**	0.218
Al	**0.941**	0.316
Fe	**0.897**	0.412
Ti	**0.868**	-0.063
Mg	0.285	**0.943**
Cr	**0.759**	**0.649**
Mn	**0.619**	**-0.635**
Zn	**0.873**	-0.101
Organic Matter (OM)	0.374	**0.91**
$CaCO_3$	-0.307	**0.952**
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.		

Study by Zakariah et al[34] and Salam et al[22] stated that pollution in the Kedah and Perak rivers was the result of anthropogenic inputs, hence higher levels of heavy metals (e.g. Pb, Zn and Cu) are present and are channelled out through both states' respective rivers. This would then lead to the differences in geochemical element distribution in the Malacca Straits.

The second PCA is defined by mobility where clay acts as a carrier for geochemical elements and organic matter. A high negative value of clay represents removal by the clay as the main carrier for nutrients and geochemical elements. This can be seen in table 4 where a lower clay gradient is apparent with respect to nutrients (i.e. OM and $CaCO_3$). According to Pitt et al[17], a lower clay content represents the elevated infiltration of nutrients in the sediment and thus increasing the availability of nutrients within the sediment.

Furthermore, Bobrowsky and Marker[3] suggested that the association of Mg, Cr and Zn with clay (Table 4) is a dispersive clay rather than ordinary clay. A characteristic of dispersive clay is imbalanced forces between ions leading to repulsive charges which are easily eroded by water with low ion concentrations such as rainwater. This characteristic explains why there is elevation in Mg and Cr but less in Mn, as the dispersivity process prohibits clay from forming small clumps.

Furthermore, Mg and Cr are known pollutants within the marine ecosystem where higher levels of water hardness are contributed by Mg while toxicity and persistent Cr which accumulate in muscles and gills could lead to severe mortality of aquatic life.

According to Ismail et al[10], a medium to high level of chromium was detected due to various industrialization and shipping activities adjacent to the coastal area. Similar connections were present where Idriss[9] stated that the Juru River contributed to elevated Cr levels due to frequent land reclamation surrounding its deltaic region and deforestation within Penang Island leading to mobilization along the Juru River.

Conclusion

Sediment in the Malacca Strait face elevated geochemical elements from natural and anthropogenic inputs. Cross-shelf inputs contributed to the distribution and differences in concentration along the Malacca Strait. Furthermore, the Malacca Strait is subject to physical and hydrological factors leading to fluctuations in geochemical element distribution.

In addition, local drainage basins channel out pollutants from natural sources via weathering and through anthropogenic sources via deforestation and land reclamation.

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