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Sedimentation and sediment geochemistry in a tropical mangrove channel meander, Sungai Kerteh, Peninsular Malaysia

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Abstract

Tropical mangrove swamps are commonly characterized by dense networks of tidal channels that may show pronounced meandering and dendritic patterns. Channel meanders are sometimes accompanied by cut offs, and, like classical fluvial meanders, record changes in hydrology and sedimentation over time. Channel meandering can, thus, be an important process that contributes to spatial and temporal variability in the preserved record of the sedimentology and geochemistry of mangrove sediments. The aim of this study is to highlight changes in channel meander sedimentation in response to a meander cut-off in a tropical mangrove swamp. Two short sediment cores were sampled, respectively from a point bar (core KR1, 122 cm) at the junction with the neck cut-off and inside the cut-off (core KR2, 98 cm) in the Sungai Kerteh mangroves of Peninsular Malaysia. The profile comparison was based on sediment characteristics, total organic carbon (TOC) and selected elements (Fe, Na, Mg, Mn, Ba and Sr). A smaller standard deviation of mean grain size (MGS) was found at the point bar (4.37±0.51 ϕ) than in the cut-off (4.43 ±1.76 ϕ), indicating a difference in flow velocity between the two settings. In turn, these changes in grain size influence channel meander evolution via associated changes in TOC and heavy metals. In order to clarify these relationships, we used principal components analysis and factor analysis. An increased accumulation of selected elements and TOC at the cut-off site from a depth of ~ 60 cm to the core-top segment was probably associated with a slowing down of sediment settling. A higher TOC recorded in the cut-off (2.74±1.42%) compared to the point bar (1.14±0.46%) suggests a propensity for prolonged in-situ accumulation of organic matter in the abandoned meander bend. This study provides grain-size and sediment geochemical information that is consistent with patterns of active and inactive sedimentation in the meander bends of mangrove channels.

Introduction

Tidal channels in mangroves are important pathways for the transport of sediments, dissolved oxygen, nutrients, seedlings and organic matter (Woodroffe, 1992; Anthony, 2009). Tidal network types and densities are highly variable, ranging from meandering to dendritic patterns, and, as noted by Allen (2000) for saltmarsh systems, they reflect several linked natural factors that are not well known, especially in comparison to the better known fluvial networks. One source of complexity is the bi-directional tidal flow, in comparison to the unidirectional flow in fluvial systems. As in the case of classical fluvial meanders (Leopold & Wolman, 1960; Ferguson, 1984; Howard, 2009), however, mangrove channel meanders are expected to record changes in channel hydrology and sedimentation over time. Meandering is formed by river flow momentum alternations from side to side within a channel, commonly across the floodplain, but the process is also inherent to shifting channels within a valley (Edwards & Smith, 2002). Meanders are dynamic systems that can be far from equilibrium, driven by complex linear and nonlinear processes (Argyris et al., 1994). Theoretically, the flow erodes sediment at the outside of a bend as it reaches a maximum velocity. The eroded materials are deposited as a point bar on the inside of the bend. These processes can lead to obstruction of flow at the neck, resulting eventually in the formation of a new shorter channel, a meander cut-off, and neck abandonment. Cut-offs have been considered as having an

important role in shaping river meander landscapes by leading to the isolation of meander bends and perturbing the local dynamics (Hooke, 1977; Camporeale et al., 2008; Schwenk & Foufoula-Georgiou, 2016). In mangroves and saltmarshes, entrenched tidal channel networks are deemed to evolve very slowly through processes that include meander-bend erosion and sedimentation, with subsequently, very slow change of these inherited forms over multi-decadal to centennial timescales (Anthony, 2009). Understanding these processes in mangrove forests can contribute to an understanding of changing present environments, under natural and human-induced processes that drive mangrove sedimentation, as well as of the paleo-environmental record (e.g., França et al., 2015; Cohen et al., 2016; Woodroffe et al., 2016). However, elucidation of these processes and the eventual messages that can be deduced regarding environmental changes can only be achieved through archives provided by sediment cores (e.g., Ellison & Stoddart, 1991; Ellison & Farnsworth, 1997). Such sedimentary archives provide a record of the type, rates, and patterns of sedimentation. Access to such information requires, however, both a classical sedimentological approach as well as geochemical characterization. Potential differences in sedimentation on meander convex banks and correlative erosion on meander concave banks have been evoked to explain differences in the vigour and health of mangroves that are generally clearly visible on aerial photographs and satellite images (Anthony, 2004). We know of no work, however, that has been undertaken to highlight the impact of channel meander evolution on mangrove sedimentation and on the sediment geochemistry. In this paper, we document changes in mangrove channel meander sedimentation associated with a meander cut-off in a Malaysian mangrove system (Fig. 1) using grain-size and geochemical characteristics of core sediments in the vicinity of an abandoned meander. We show that such sedimentological and geochemical characterization can be used in identifying change in mangrove environments.

Methods / Experimental

Study site

The mangroves of Sungai Kerteh are located in Kemaman District, Terengganu, Peninsular Malaysia (Fig. 1). The dominant mangroves are *Rhizophora apiculata* and *Avicennia sp*. A major morphological feature of the area is the Kerteh River, a coastal river approximately 23 km-long that originates in hilly terrain at ~ 350 m above sea level, before running through the mangroves and entering the sea just north of Kerteh Town. The Kerteh receives runoff from a number of smaller upstream tributaries. The lower reaches of the Kerteh are influenced by semi-diurnal tides. The tidal range in the area is mesotidal, ranging from 0.2 m at low tide to 3.3 m at high tide during spring tides (PHN, 2019). There are no data on water discharge of the Kerteh River, which is modulated seasonally by Monsoon rainfall (mean annual: ~2800 mm) and at shorter timescales by the spring-neap tidal range.

The tidal reaches of the Kerteh River display prominent meanders typical of mature mangrove swamps that are probably characterized by low substrate sedimentation rates, as suggested by the morphological stability of the channels. Locally, however, this stability has been affected or enhanced by embankments associated with villages and communities located on the channel banks. According to the classification

by Jackson (1978), the present Kerteh channel can be considered as muddy fine-grained, with a low width/depth ratio, steep point bar slopes and prominent levees. The study site is a mangrove swamp comprising a meander with a cut-off upstream of Kampung Gelugor (Fig. 1). The abandoned meander segment displays a straight, nearly 1 km-long cut-off channel. Sediments were sampled at two different locations in the mangroves (Fig. 1): the neck cut-off (core KR1) and the inside of the meander (core KR2). The KR1 site is located at the confluence of two tidal channels, one of which included the cut-off reach with sampling site KR2. The dominant species at KR1 is *Rhizophora apiculata* whereas KR2 consists of mixed *Avicennia* sp. and *Rhizophora apiculata*.

Sampling and sample pre-treatment

The two cores were collected at low tide by driving a 2.5 m polyvinyl chloride (PVC) tube with a diameter of 6.5 cm into the mangrove sediment. A tight cable and rope were attached to the middle part of the PVC tube in order to retrieve it from the mangrove. A cork and plastic were used to cover the top of the tube neatly to create a vacuum condition, enabling slow and cautious recovery of the cores. The pull-out process was conducted carefully to reduce loss of sample material and to maintain the lithological structure of the core sediment. The collected core samples were immediately processed in order to reduce the compaction effects. The lengths of core KR1 and core KR2 were 122 cm and 98 cm, respectively. Samples from both cores were cut and split into two segments. Each segment was sliced at 2 cm intervals, yielding a total of 61 samples for KR1 and 49 samples for KR2. In order to avoid contamination, the samples were stored in clean-labeled vinyl bags in the laboratory before analyses of grain size, metal content, and total organic carbon were carried out. The samples were oven-dried at 50 °C and powdered using an agate mortar with a pestle for further analysis except for sediment characteristics and grain size.

Sediment characteristics

Approximately 5 g of the sediment samples were transferred into a 100 ml beaker and diluted with distilled water as a medium for the digestion process. A few drops of hydrochloric acid (HCl) and 15% of hydrogen peroxide (H_2O_2) were added into the beaker to remove carbonate content and organic materials. Calgon solution (20% Sodium Thiosulphate) was added and acted as an agent to disperse the samples into single particles. The samples were left at room temperature for 24 hours to allow complete particle dispersion. Sediment samples were analyzed using a laser diffraction analyzer (MALVERN Mastersizer 2000). All data collected were subjected to statistical analysis using the moments statistical method (Friedman and Johnson, 1982). Grain-size characteristics (particle mean grain size and sorting) were calculated using the formula of Folk and Ward (1957). The relative proportions of sand, silt and clay were determined using the textural triangle proposed by USDA (1987).

Total organic carbon

The total organic carbon was determined based on the Walkley-Black chromic acid wet oxidation method (Walkley & Black, 1934; Allison & Moodie, 1965). Approximately 10 ml of potassium dichromate was added to 0.5 g of sample in a test tube. Then 20 ml of sulfuric acid was added and left in a beaker of boiling water (30 min). The test tube was rinsed with 200 ml of distilled water into a conical flask and 10 ml of phosphoric acid with a 1 ml Diphenylamine indicator added. The solution was mixed until it turned dark blue. Finally, Ferum (II) sulfate was titrated until the solution turned green and the total volume of Ferum (II) sulfate was recorded. The calculation of organic carbon content was as follows:

TOC (%) = (V1-V2) x 0.03 x 100 / sample weight (g)

where,

V1 = volume of potassium dichromate (ml)

V2 = volume of Ferum (II) sulfate (ml)

A set of blanks and standard research material (SRM) dextrose monohydrate was applied in every batch of sample analysis in order to determine the background content of organic carbon and as a control on the analysis. The standard percentage value of total organic carbon in dextrose monohydrate is 36 %, while, the average percentage of measured dextrose monohydrate of the analysis was 36±1.2 %. The crosscheck with three replicates at every 10-cm core depth for both core samples was also set up in the analysis to ensure the results are credible and acceptable.

Metal analysis

Sample digestion followed the published methods of Noriki et al. (1980) and Kamaruzzaman (1999) with the modification of mixed acid ratio and digesting temperature. Approximately 0.05 g of homogenized samples were digested in a concentrated mixed acid ratio of HF, HNO_3 and HCl (2: 3.5: 3.5) in a sealed Teflon vessel at 100°C for 7 hours. After cooling to room temperature, a clear digested solution was transferred into a 15 ml polypropylene test tube and diluted with deionized water. An inductively coupled plasma mass spectrometer (ICP-MS) was used for the precise determinations of selected heavy metals (Fe, Mg, Cu, Mn, Ba and Sr). The accuracy of the analytical procedure was assessed by analyzing standard research material in duplicate from the National Bureau of Standard (NBS) 1646a. The recovery test coincided with the certified values of NBS 1646a. The recovery percentage of measured metals was found to be acceptable, ranging between 86.99% and 109.50 % (Table 1).

Principal components analysis and factor analysis

Principal components analusis and factor analysis were used to highlight relationships among the variables. The main component was extracted using principal component analysis through the Eigen decomposition method. Factor analysis was used to explain the latent variables rendered in the data sets

using the Varimax method after Kaiser normalization. Factor loading scores were categorized as follows: VF > 0.75 (strong), 0.75 < VF > 0.5 (moderate) and < 0.50 (weak), corresponding to the absolute varifactor values (Liu et al. 2003). The statistical data processing and analysis were generated by using the software Minitab version 17 (Minitab Inc., State College, USA).

Results

Particle mean size and sorting, and sediment facies

Figure 2a shows the mean grain size (MGS) of sediment against depth for cores KR1 and KR2. Values ranged from 3.47 ϕ – 5.92 ϕ for KR1 and 1.52 ϕ – 6.47 ϕ for KR2. The highest and lowest MGS values in KR1 were recorded at depths of 32 cm and 52 cm, respectively. For KR2, the highest and lowest values occurred at depths of 56 cm and 82 cm. The profile of MGS in KR2 showed a significant change at 60 cm depth. Figure 2b shows the sorting values of sediment in both cores. KR1 ranged between 0.44 (moderately sorted) and 2.61 (moderately well sorted). The values of KR2 were between 1.60 and 2.30 (moderately sorted and moderately well sorted). The average value in KR2 was 1.60 ± 2.34 Ø with the highest value at 66 cm (2.61 Ø) and the lowest at 0.44 Ø. In KR1, the mean was 0.44 ± 2.61 Ø with the highest value at a depth of 32 cm (2.34 Ø) and lowest value at 102 cm (1.60 Ø). The best-sorted sediment was recorded at a depth of 80 cm in core KR1. As in the case of MGS, sorting also showed the same trend with depth. Figure 3 shows a textural classification plot of sediment in the two cores. The sediments in KR1 from the point bar exhibit a high percentage of sand (40% to 80%) in contrast to sediment from KR2 from the meander cut-off which is less sandy (10% to 4%).

Total organic carbon

The TOC was determined in KR1 and KR2 (Fig. 2c). The TOC content was significantly higher in core KR2 ranging from 0.6% – 5.5% as compared to core KR1 with values of 0.24% – 4.26%. The average TOC values in core KR2 and KR1 were 2.74% ± 1.42% and 1.14% ± 0.46 % (Fig. 2c). There were two obvious trends between TOC contents of cores KR1 and KR2. Like the metal and MGS trends, there were two apparent trends for TOC content in both core samples. The TOC content fluctuated from the bottom of the core towards the surface with no significant changes for core KR1. On the other hand, the content in core KR2 was only comparable to that of core KR1 at depths between 98 cm and 76 cm. The concentration of TOC drastically increased at a depth of 72 cm and remained high up to the surface of the core.

Metals

The element concentrations in core KR1 varied from 0.32 to 2.18 % (Fe), 0.51 to 2.38 % (Na), 0.49 to 0.95 % (Mg), 81.60 to 204.00 mg/kg (Mn), 22.40 to 47.60 mg/kg (Ba) and 1.37 to 7.98 mg/kg (Sr) (Fig. 4). The average concentrations of Fe, Na, Mg, Mn, Ba and Sr were 1.25 ± 0.30 %, 1.21 ± 0.77 %, 057.92 mg/kg,

63.01 ± 15.49 mg/kg, 17.48 ± 2.14 mg/kg and 9.1 ± 1.5 mg/kg. The element concentrations in core KR2 varied from 0.07 to 2.24 % for Fe, 0.30 to 2.14 % for Na, 0.01 to 0.71 % for Mg, 5.34 to 173.80 mg/kg for Mn, 3.20 to 34.20 mg/kg for Ba and 0.50 to 6.52 mg/kg for Sr. The average concentrations of elements in this study followed the order of Fe > Na > Mg > Mn > Ba >Sr. In general, the selected element content in KR1 did not show an abrupt change from the bottom towards surface. However, the element content in the core KR2 showed a significant increase at a depth of ~ 70 cm.

Discussion

The grain-size characteristics and selected aspects of the geochemistry of sediment cores in the vicinity of a mangrove tidal channel meander bend in Malaysia highlight an abrupt change in channel hydrodynamic and sedimentation regimes following a meander cut-off. The straight, nearly 1 km-long cut-off channel (Fig. 1) points out to a rather abrupt hydrological change, rather than being the product of the slow progressive rapprochement of two opposite channel segments that eventually coalesced to form a cut-off. A scrutiny of available aerial photographs and Google Earth images shows that the Kerteh cut-off has been extant over at least the last 13 years. The cut-off may well have occurred during the big flood event that hit Terengganu nearly a century ago from 21 to 29 December, 1926, accompanied by exceptional rainfall (1944 mm compared to the annual mean of ~2800 mm), and resulting in severe environmental damage and the destruction of thousand hectares of forests (Chan, 2012; Williamson, 2016).

Whatever the true age of the cut-off, the change engendered by this event is recorded in the grain-size and TOC trends. Sediment particle characteristics have been shown to provide information on the relationship between hydrodynamics and transport or deposition (e.g., Droppo, 2015). The dominantly fine-grained nature of the sediments found in KR1 and KR2, composed essentially of silts and, to a lesser degree, clays (Figs. 2, 3), reflects both the high degree of weathering of tropical soils and the effect of mangrove swamps on dampening water flows and favouring the accumulation of mud. Notwithstanding, differences in grain size have been found between the two cores in the Kerteh swamp. Core KR2 shows, in particular, a very sharp transition from coarse, through fine to medium sand, at a depth of about 80 cm, to relatively homogeneous silt and clay in the rest of the upper part of the core. We attribute this sharp change to the transition from an active channel meander to meander cut-off. Meander cut-offs in tidal environments have been shown to exhibit sharp upward changes in facies following abandonment (e.g., Anthony et al., 1996). The coarse basal deposits correspond to sand deposited in an active channel bed. Once the cut-off occurred, the diversion of flows through the straight new channel was accompanied by a shift to fine-grained deposits associated with settling in a low-energy, abandoned channel environment. The grain size in KR1 is relatively more homogeneous, though the upper part of the core (above 70 cm) shows a clearly overall fining trend. This characteristic may reflect a shift from relatively more coarser-grained sedimentation at the base to more continuously finer-grained point-bar sedimentation. The differences between the two cores are less manifest in sorting, with the exception of basal sediments in the point bar which show poor sorting, probably reflecting mixing of sediment in an energetic channel environment. It may be surmised that the abrupt change in sorting in this core may pinpoint the time of

the meander cut-off. Fleming (2017) identified a tendency for sorting to be homogeneous in sediment composed of a similar range of size, whereas poor sorting implies sediment mixing with different sizes of sediment.

The abrupt variation in grain-size and sedimentation rate in the meander cut-off is also consistent with an increase in OC, thus further reflecting the consequences of this event on local sedimentation. The grain size influence on channel meander evolution is embedded in these changes in OC but also in heavy metals. Both particle size distribution and OC concentrations changed significantly at ~70 cm, pointing to a change in the depositional environment. Meander cut-offs in tidal flats have been shown to be depocentres of organic matter following the instauration of quiescent hydrodynamic conditions, as flow becomes diverted through the cut-off, and the abandoned meander belt may also become progressively covered by vegetation (Anthony et al., 1996). This situation also concerns the Kerteh meander belt which appears to be progressively invaded by mangroves (Fig. 1). This increase in OC has also been shown to go with a decrease in grain size (Sutherland, 1999). Generally, OC binds more easily with fine sediment, clay or silt.

Previous studies have shown that the distribution of heavy metals in sediment is closely related to organic matter and mostly depends on the type of sediment (Karbassi et al., 2005; Abdul Razak et al., 2018). The metal concentration in the point bar is almost uniform from the bottom to the top of the core, whereas the concentration in the cut-off shows a clear transition phase at a depth of 70 cm, thus further providing evidence for a morpho-sedimentary change in the Kerteh channel associated with meander cut-off. The abandonment of the meander created conditions for the active accumulation of elements and OC in the cut-off, compared to the point bar. Louma (1990) has shown this relationship between the concentration of elements and sedimentation processes. The variability in metal concentration has also been shown to depend on the size and texture of sediments (Jicknell and Kump 1984; Ramos et al., 1994), with larger mean grain size being associated with a larger variation of metal concentration at the same area (Morse et al., 1993).

In order to further clarify the relationships in the grain size and geochemistry of these deposits, we used a correlation coefficient matrix for each core (KR1: Table 2; KR2: Table 3). The correlation of metals with mean grain size and TOC in cut-off was relatively stronger compared to the point bar. The highest correlation value of the latter is 0.76 (Fe-Mg), followed by Fe-Cu (r = 0.75), Cu-Sr (r = 0.74), Mg-Mn (r = 0.73), Mean Sediment-TOC (r = 0.71) and TOC-Fe (r = 0.71). The highest correlation value of the cut-off is r = 0.98 (Mg-Mn), whereas the lowest correlations occur between Ba-Fe (r = 0.59) and Ba-TOC (r = 0.53), although both are still considered as strongly correlated to each other. The strong positive correlation between all parameters in the cut-off suggests that grain size is an important criterion for the attachment of metals and TOC under the conditions of reduced flow energy that ensued following meander abandonment. Nguyen et al. (2005) have shown that highly correlated metals exhibited a similar behavior in the study area. Generally, the contents decreased as grain size increased.

Principal components analysis (PCA) highlighted two significant compounds (eigenvalue >1) that explained 71.2% (KR1) and 93.0% (KR2) of the total variance of the datasets (Table 4). For KR1, varifactor VF1 explained 28.3% of the total variance in the datasets with positive loadings on metal content such as Mg (0.89), Mn (0.79), Ba (0.75), and Sr (0.86). Varifactor VF2 accounted for 32.8% of the total variance with positive loadings on mean grain size (0.75) and total organic content (0.90). Meanwhile, for KR2, varifactor VF1 explained 54.7% of the total variance with strong loadings on MGS (0.83), total organic carbon (0.90) and metal, namely Fe (0.90) and Na (0.80), whereas varifactor VF2 accounted for 38.3% with negative loadings exhibited by the concentrations of Ba and Sr. The PCA shows that only Fe and Na are influenced by changes in MGS and organic content. In this study, communalities of the variance explained a higher value for KR2 (0.88 – 0.97) than KR1 (0.50 – 0.93), revealing that the extracted factor fitted well with factor solution.

It is noteworthy that a distribution pattern of metal content versus sample depth was clearly observed in KR2 (Fig. 5b) compared to KR1 (Fig. 5a). Two clusters were formed in KR2 in which metal accumulation in the upper depths had a higher concentration. The relationship between metal (Fe, Na) and MGS or organic content was much stronger for KR2 than KR1. This was highlighted by a straight line with a similar direction on the biplot graph (not shown). We deduce from this the relationship that the accumulation of finer-grained sediments following meander cut-off is favourable to binding between metals and organic matter.

The long-term (multi-decadal) mobility of mangrove tidal channels has been shown to depend essentially on sediment inputs into the system, which alter the morphodynamics of meanders, thus eventually generating, over even longer timescales (secular to millennial) the gradual reworking of mangrove tidal flats (Anthony, 2004). Active meander belt reworking in mangrove swamps occurs where high sediment loads in channels, notably bedload, induces instability in flow conditions. This has probably been the case in the Kerteh channel, given the ‘abrupt’ morphology of the meander cut-off (Fig. 1). The foregoing study of sediments associated with the tidal channel in the Kerteh Sungai mangrove swamp has shown that channel dynamics can be important in generating variability in the sedimentology and geochemistry of mangrove sediments. The reasons for the formation of a meander cut-off in this swamp are not clear. However, since its formation, the Kerteh channel and its meander cut-off have exhibited apparent stability at the timescale of available satellite images and aerial photographs covering the study area (13 years). This stability suggests that the swamp and its channel network may now be largely in equilibrium with flow conditions.

Conclusions

This study has shown that geomorphic changes in mangrove tidal channels can generate significant variations in sediment characteristics and geochemistry. The data from two cores in contrasting local geomorphic situations associated with channel meandering show clear trends in metal concentrations, MGS and sorting, and TOC. The most noteworthy aspect highlighted by the study is that abrupt changes in channel flow conditions generated by a meander cut-off can induce marked changes in the

sedimentology and geochemistry of sediments over time. Spatio-temporal changes in the dynamics of tidal channels in mangrove swamps are, thus, an important mechanism in generating variability in the long-term sedimentology and geochemistry of mangrove sediments.

Abbreviations

MGS: mean grain size; ICP-MS: inductively coupled plasma mass spectrometer; NBS: National Bureau of Standard; USDA: United States Department of Agriculture.

Declarations

Availability of data and material

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interest.

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Authors' contributions

Shaari H. conceived of the presented idea, developed the theory, performed the computations, verified the analytical methods and in charge of overall direction and planning. He also encouraged Nasir Q.M. and Naim E. to investigate the geochemical compounds and supervised them in order to accomplish the findings of this work.

Nasir Q.M. carried out the experiment, wrote the manuscript with supporting idea from Hasrizal Shaari.

Hui-Juan P helped in improving this manuscript by giving the critical thinking about the discussion and suitability of some old data in the original manuscript.

Mohamed C.A.R. carried out the experiment analysis in his laboratory at Universiti Kebangsaan Malaysia.

Yusoff A.H. helped interpretation and wrote the discussion of the modern condition in the study area.

Khalid W.M.A.W.M. provided the statistical analysis of data and carried out the calculations.

Naim E. carried out the experiment, wrote the manuscript with support from Hasrizal Shaari.

Setiawan R.Y. provided critical feedback and helped shape the research, analysis and manuscript.

Anthony E.J. contributed on conceptual ideas and proof outline. He verified the data and wrote the important part of the discussion with input from all authors.

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Tables

Table 1: The value of accuracy analysis for standard reference of trace elements

Trace Element	Certified Value	Analysis Value	Percentage (%)
Fe (%)	2.01 ± 0.04	2.20 ± 0.10	109.5
Mg (%)	0.40 ± 0.01	0.39 ± 0.27	97.5
Mn (mg/kg)	234.5 ± 2.80	204.0 ± 17.7	86.99
Sr (mg/kg)	68	65.2	95.88

Table 2: Correlation coefficient between MGS, TOC and selected metals in core KR1.

	MGS	*TOC*	*Fe*	*Na*	*Mg*	*Mn*	*Ba*	*Sr*
MGS	1							
TOC	0.71	1						
Fe	0.60	0.71	1					
Na	0.30	0.30	0.59	1				
Mg	0.46	0.50	**0.76**^{H}	0.58	1			
Mn	**0.18**^{L}	0.20	0.48	0.41	0.73	1		
Ba	0.27	0.36	0.53	0.40	0.78	0.56	1	
Sr	0.24	0.15	0.42	0.41	0.74	0.56	0.59	1

*note: H: Highest correlation; L: Lowest correlation

Table 3: Correlation coefficient between MGS, TOC and selected metals in core KR2.

	MGS	*TOC*	*Fe*	*Na*	*Mg*	*Mn*	*Ba*	*Sr*
MGS	1							
TOC	0.89	1						
Fe	0.92	0.94	1					
Na	0.88	0.88	0.89	1				
Mg	0.92	0.86	0.91	0.89	1			
Mn	0.89	0.83	0.89	0.84	**0.98^{H}**	1		
Ba	0.66	**0.53^{L}**	0.59	0.68	0.83	0.81	1	
Sr	0.74	0.63	0.66	0.72	0.86	0.85	0.90	1

*note: H: Highest correlation; L: Lowest correlation

Table 4: Varifactors of varimax rotated loading results

Variable	**KR1**			**KR2**		
	VF1	**VF2**	**Communality**	**VF1**	**VF2**	**Communality**
Depth	-0.07	-0.82	0.68	-0.91	0.23	0.88
MGS	0.18	0.75	0.60	0.83	-0.48	0.92
TOC	0.14	0.90	0.84	0.90	-0.32	0.92
Fe	0.54	0.71	0.81	0.90	-0.38	0.96
Na	0.58	0.34	0.50	0.80	-0.49	0.88
Mg	0.89	0.37	0.93	0.69	-0.69	0.97
Mn	0.79	0.09	0.64	0.65	-0.70	0.93
Ba	0.75	0.30	0.66	0.25	-0.93	0.94
Sr	0.86	-0.05	0.75	0.36	-0.89	0.93
% Variance	38.3	32.8		54.7	38.3	

Figures

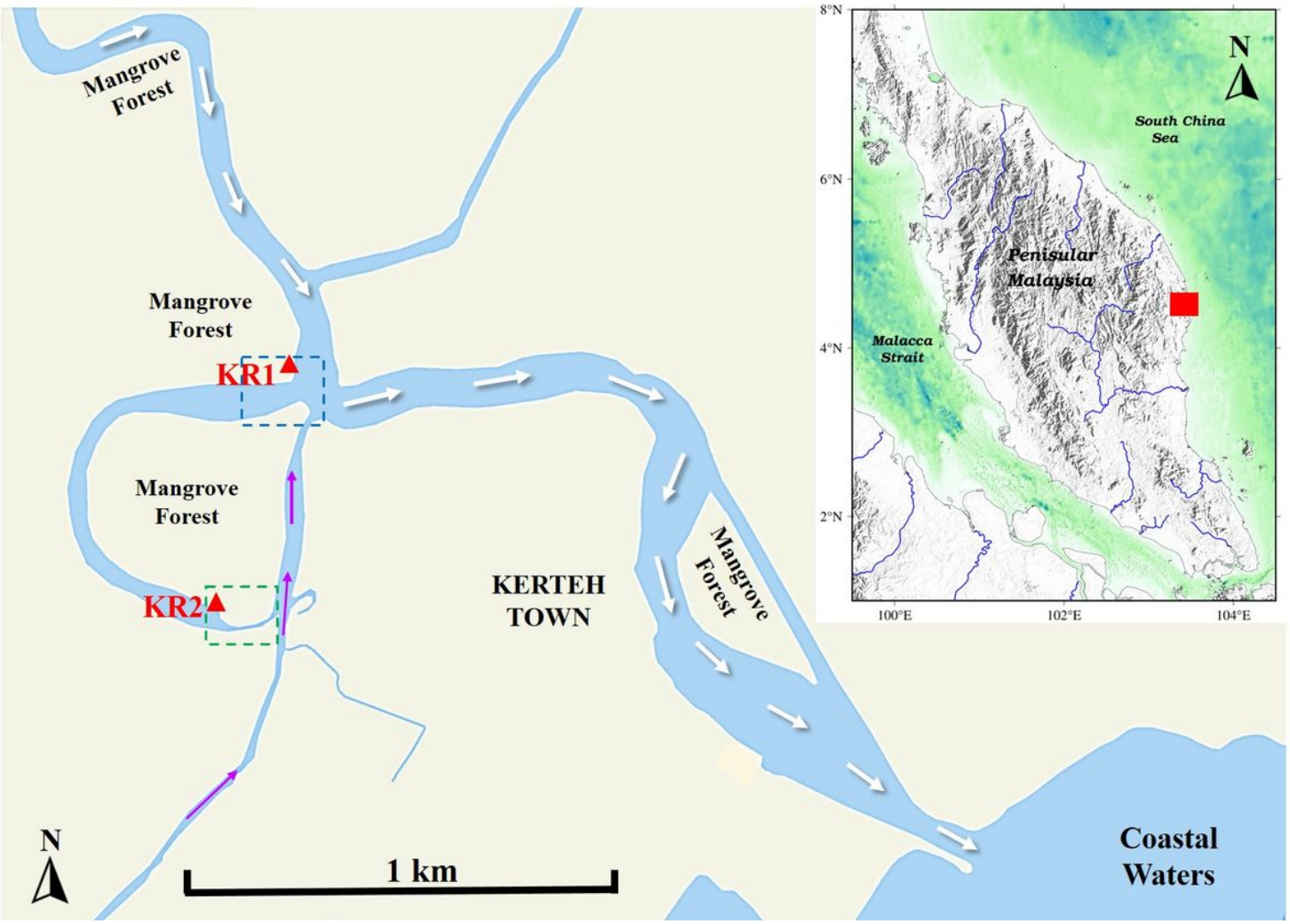

Figure 1

Map showing the Kerteh mangrove forest in Peninsular Malaysia and the locations of cores KR1 (4°31'27. 5"N, 103°26'25.91"E) and KR2 (4°31'10.98"N, 103°26'19.68"E). The white arrows indicate the river flow directions of main water body of Sungai Kerteh from upstream towards tidal channel and pink arrows indicate the river flow direction from small branch of Sungai Kerteh. The blue dash box indicates the cutoff location and the pale green dash box indicates new mangrove vegetation at the old river's pathway due to the active sedimentation process. (source: Google Earth).

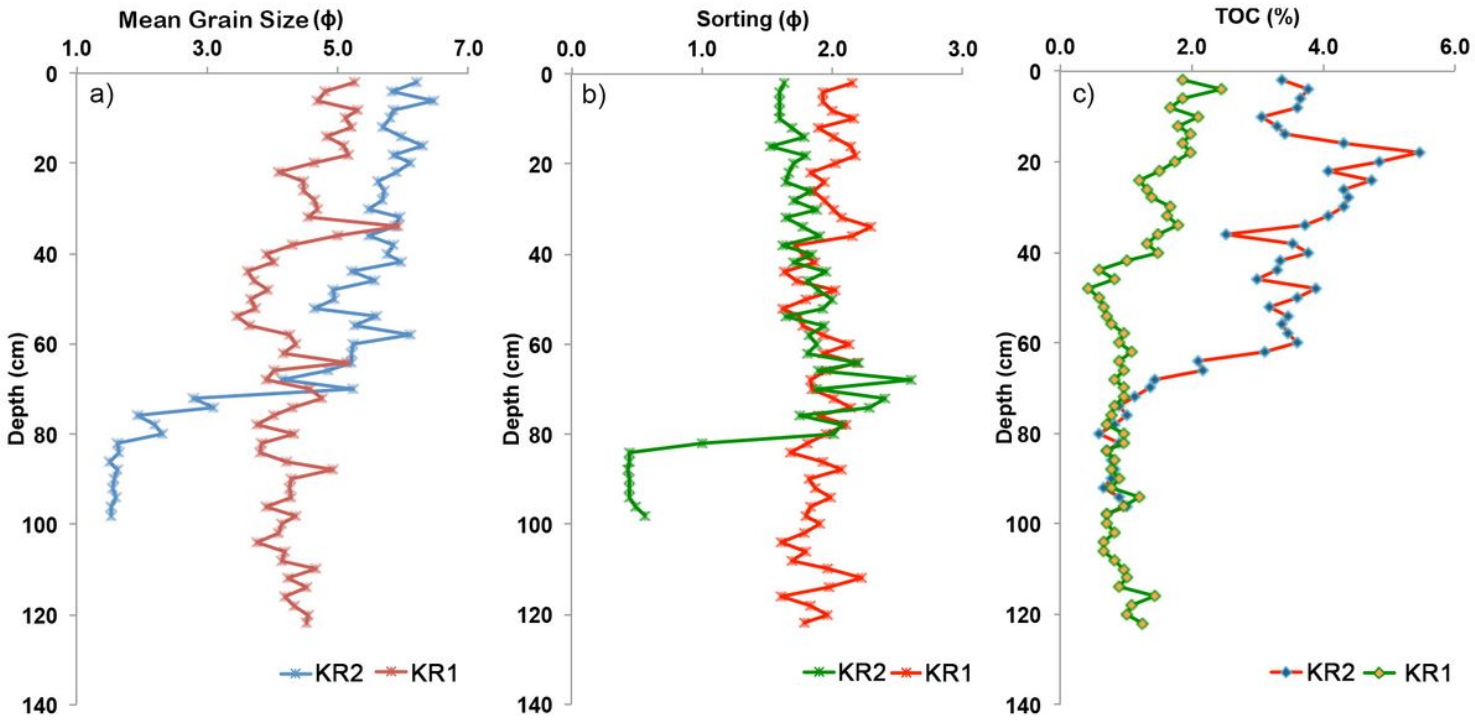

Figure 2

Vertical profile of: (a) mean grain size, (b) sorting, and (c) TOC.

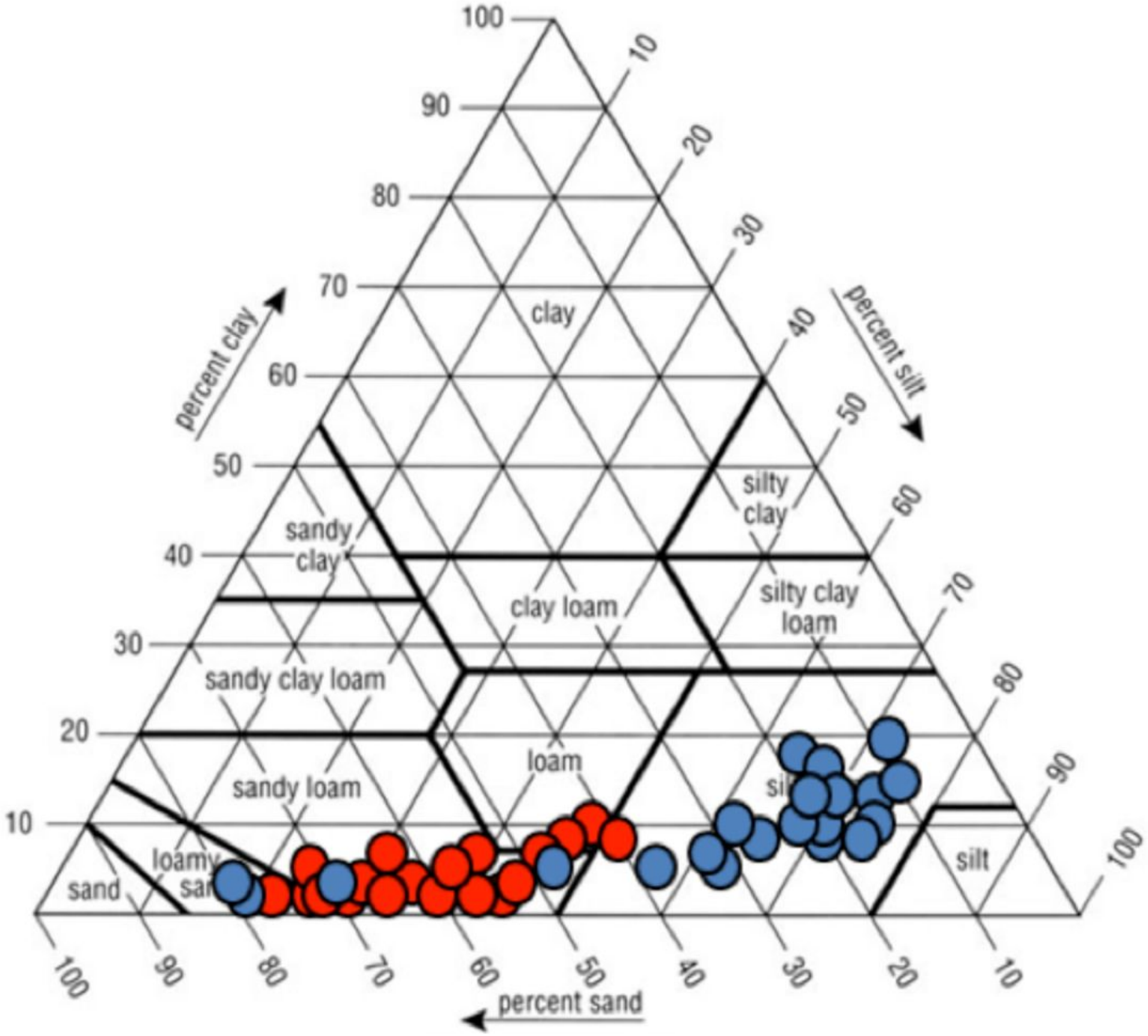

Figure 3

Textural classification of sediment from KR1 (red dots) and KR2 (blue dots)

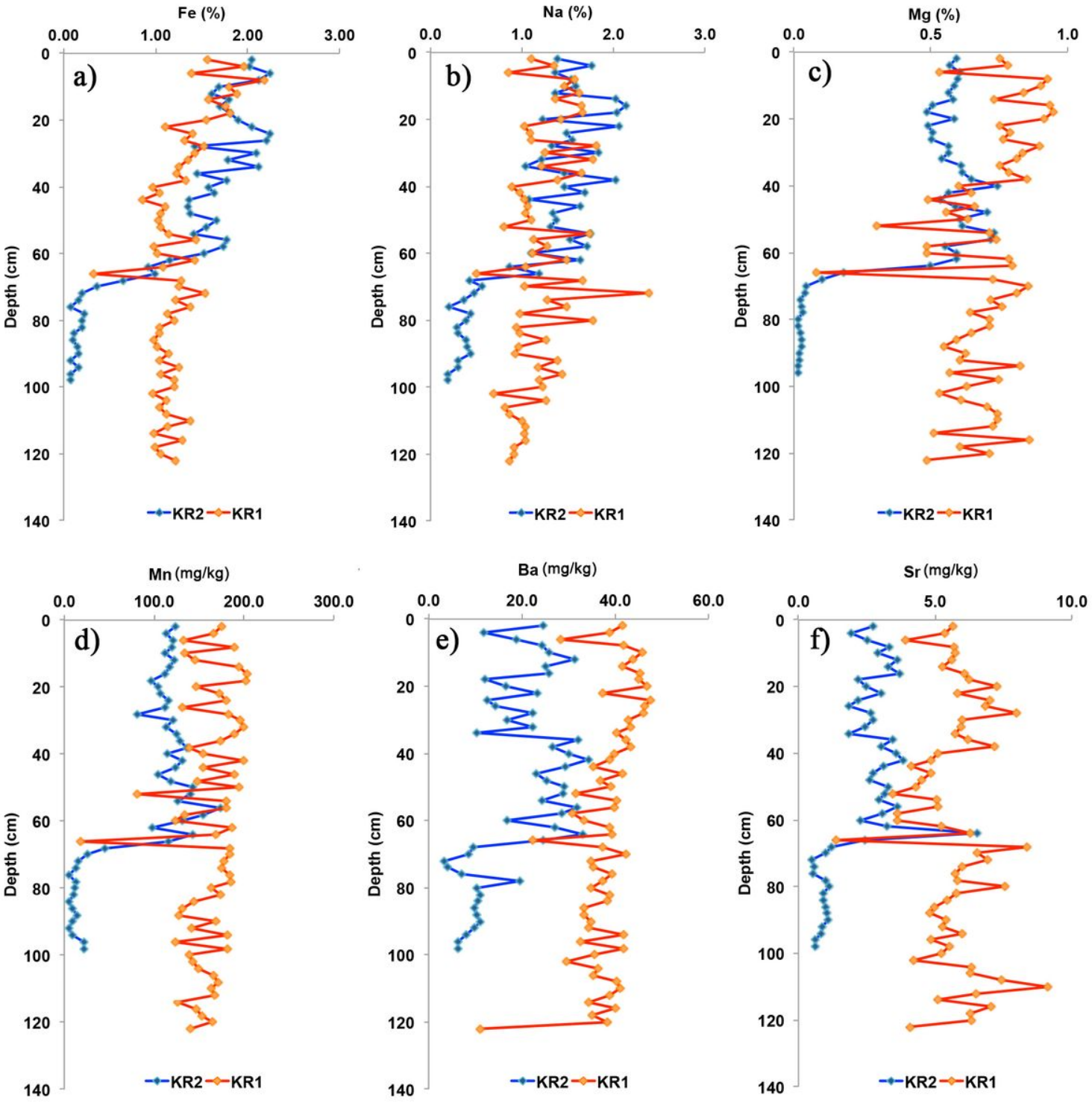

Figure 4

Selected metals concentrations in cores KR1 and KR2.

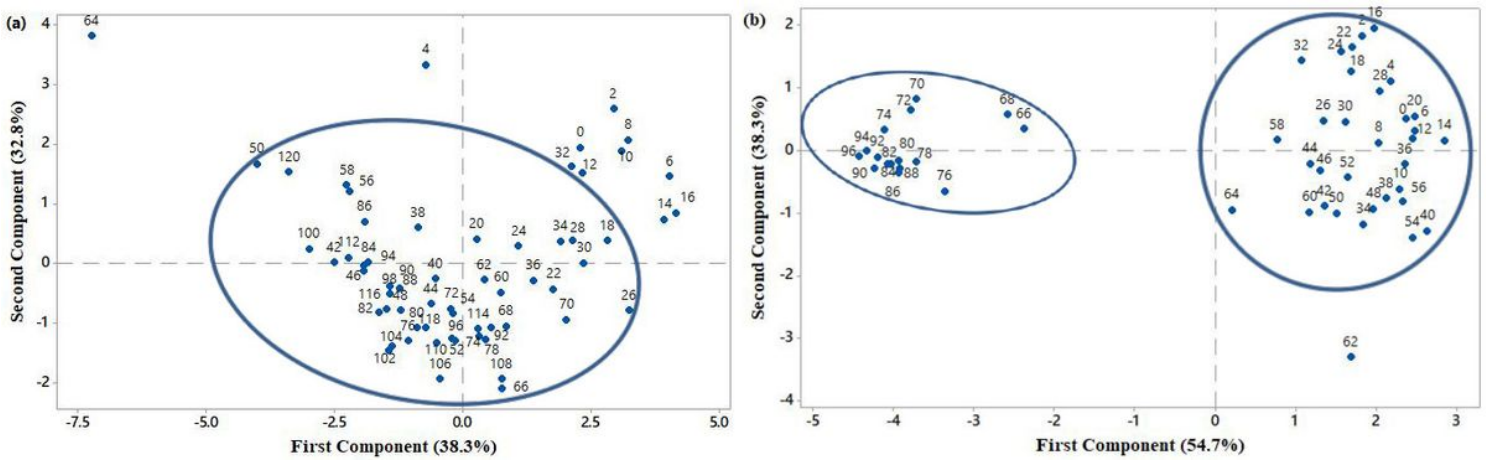

Figure 5

Loading plot of selected metals concentrations vs depth on KR1(a) and KR2 (b).

Supplementary Files

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- GraphicAbstractImage.jpg