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PALEO-COASTAL EVOLUTION OF SOUTHWEST SRI LANKA DURING THE HOLOCENE FROM LAGOONAL SEDIMENTARY RECORDS

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ABSTRACT

Understanding the history of coastal systems is important for interpreting the paleo-environments of early human occupation sites, forecasting future environmental conditions and comprehending the impact of abrupt events such as the 2004 Indian Ocean tsunami. Hence, this study aims to reconstruct the Holocene paleo-environmental evolution of southwestern coast in Sri Lanka in order to understand the past environmental conditions and sea level variations. Four sediment cores were retrieved from two lagoons at Ratgama and Koggala in southwest of Sri Lanka for this research study. To infer the depositional environments and provenance of the sediments, textural properties of sediments including grain size distribution and particle shape, chemical composition, gamma ray intensity, loss on ignition and micro and macro fossil content were determined. Grain size, chemical composition and gamma ray intensity were analyzed at 1 cm interval while organic matter content was analyzed at 2 cm interval by loss on ignition. Based on proxy evidences, three stratigraphic units (I, II and III) can be recognized in both lagoons. Units III and I represent a closed lake system with less marine influence while Unit II represents a lagoon/bay with direct marine influence. This shows that southwestern low-lying coastal areas were submerged during Mid Holocene transgression followed by transformation of these flooded area in to lakes and lagoons due to barrier formation at sea level stabilization or at the end of the transgression phase. Approximate age of the transgression phase, calculated with a regional age-model, correlates with other local and regional records.

Keywords: Holocene, Paleo-environment, Stratigraphic unit, Southwestern coast, Sri Lanka

INTRODUCTION AND BACKGROUND

Studying paleo-coastal environmental changes is important to understand the susceptibility of coastal systems to regional and global climatic and sea level changes as well as to realize the impact of rapid abrupt events such as the 2004 Indian Ocean tsunami (Ranasinghe et al., 2013). Coastal environments are usually characterized by geomorphologic features such as deltas, estuaries, lagoons, reefs etc. Climate and sea-level changes play important role in coastal evolution, and therefore, sedimentary records that have been preserved in the coastal back-barrier environments will provide useful insights into past coastal environmental conditions, coastal evolution, and a more detailed imprint of paleo coastal events (Cabral, 2006; Caballero, 2005; Ranasinghe et al., 2013). Hence, this study aims to reconstruct paleo-coastal evolution of southwestern coast in Sri Lanka in order to understand the past environmental conditions and sea level variations by studying sedimentary records in coastal lagoons. Furthermore, to build a better understanding of the local effects of past sea-level changes and climatic changes along the coast, more data are required especially covering the areas where limited studies have been done. Therefore, this study on the paleo-coastal evolution of Ratgama and Koggala lagoons in the southwestern coast of Sri Lanka is a fulfillment for the current necessity of such investigations in the coastline of Sri Lanka.

SEA LEVEL AND CLIMATIC CHANGES IN SRI LANKA – PREVIOUS STUDIES

Weerakkody (1992) reconstructed the coastal development of the southern coasts of Sri Lanka since the mid-Holocene and analyzed the chronology of the landforms with the help of published radiocarbon dates. It was interpreted that maximum sea level along eastern and southeastern Sri Lanka was 5 m higher than the present msl at 5200±60 yrs BP. Katupotha (1995) analyzed the Holocene shell beds on the southern coastal zone of Sri Lanka and recognized mid Holocene sea level was at least 1.5 m above the present level during three episodes of (a) 6240-5130 yrs BP (first episode of high sea-level) (b) 4390-3930 yrs BP (second episode of high sea-level), and (c) 3280-2270 yrs BP (third episode of high sea-level). The three episodes were derived based on height of the beach ridges and ^{14}C radiometric dating of inland buried coral deposits, emergent coral reef patches along the western and southwestern coasts, and several shell beds on the southern coast in Sri Lanka. Ranasinghe et al., (2013) studied the mid-late Holocene coastal environmental changes in southeastern Sri Lanka and recognized how the coastal environment in tectonically stable eastern and southeastern coasts of Sri Lanka had changed during that period. The evidence of sea level variability derived from the study showed that the submergence of coastal environments by mid-Holocene transgression began around 7300 yrs BP and existed until 3000 yrs BP (Ranasinghe et al., 2013).

METHODOLOGY

STUDY AREA

Ratgama and Koggala lagoons are situated in southwestern coast of Sri Lanka (Figure 1a and 1b). Various land use practices exist around these wetlands, which mainly resulted due to small-scale fishing industry within lagoon and paddy cultivation close to the landward end of the lagoon. Ratgama lagoon is situated in Dodanduwa, which is close proximity to Hikkaduwa and Galle area. It is located two kilometers away from the southwestern coastline and it is not connected to major fresh water resources. Koggala lagoon is a nationally important wetland site according to the currently adopted environmental valuation criteria (CEA 1995 and 1999). It covers a relatively large

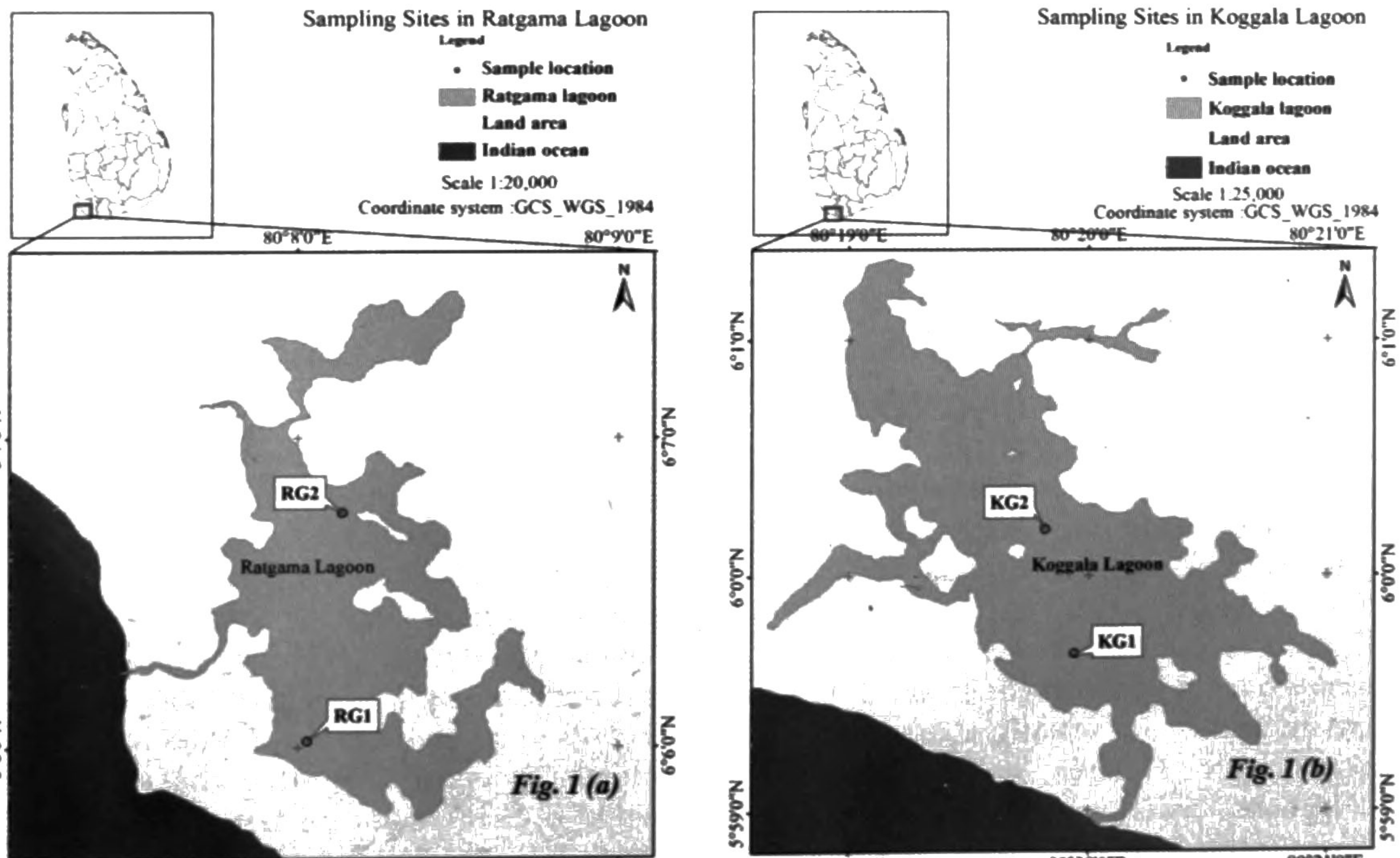


Fig. 1 (a) Coring sites at Ratgama lagoon in Southwestern Sri Lanka. RG 1 is the seaward core while RG 2 is landward. (b) Coring sites at Koggala lagoon in Southwestern Sri Lanka. KG 1 is the seaward core while KG 2 is landward.

surface area (approx. 727 ha) measuring 4.8 km in length and 2 km across, and is relatively deeper (1.0- 4.0 m) compared to other coastal water bodies along the southwestern coast (Silva, 1996). Its innermost region receives a large influx of freshwater from few streams, and the seaward end has a narrow outlet named 'Pol Oya' (CEA 1995).

The main rock types in this coastal zone are undifferentiated, tectonically intercalated meta-sediment and metaigneous rocks, charnockite and charnockite gneiss (Silva et al., 2013). Weathering of these meta-sedimentary rocks formed the ridge and valley topography in the area demarcating the initial shape of the lagoons, and they supply fine sands and clay minerals to the lagoons. Besides the above, coral has thrived in these paleo lagoons, which were formed in headland-bay beaches during the high sea level rise in the mid-Holocene period (Katupotha, 1988a and b; Weerakkody, 1988 and 1992) now designated as buried coral deposits.

FIELD SAMPLING

Ratgama and Koggala lagoons situated in the southwestern coast of Sri Lanka (Figure 1a and 1b) were selected for sediment sampling. Two sediment cores (RG1 and RG2) were retrieved from Ratgama lagoon in proximal and distal locations relative to the present coastline at about 500 m (6° 6.849'N, 80° 8.003'E) and 1500 m (6° 6.676'N, 80° 8.104'E), respectively (Figure 1a). The core RG1 is 258 cm in depth whereas the depth of RG2 is 128 cm. Similarly, two sediment cores (KG1 and KG2) with the depth of 225 cm and 186 cm were retrieved about 500 m (5° 59.6'N, 80° 20.016'E) and 1500 m (6° 17'N, 80° 19'E) distance relative to the present coastline in Koggala lagoon (Figure 1b). These sediment cores were collected in aluminum tubes with a diameter of 2.5 inches without disturbing to the sediments (Figure 2a and 2b).

CORE LOGGING AND LABORATORY ANALYSES

The sediment cores RG1, RG2, KG1 and KG2 were logged and photographed. Then they were analyzed for textural properties of sediments including grain size distribution and particle shape, elemental composition, loss on ignition, gamma ray intensity, and micro and macro fossil content were also studied and used to study the depositional environments and provenance of sediment sources. Organic matter (OM) was analyzed by loss on ignition (LOI) method (British Standard, 1990) in sub samples taken at 2 cm interval through the cores retrieved from both lagoons. In this method, sediment samples were kept in a furnace at 500 °C for 2 hours after removing moisture at 105 °C about 8 hours until a constant weight is received. Total of 192 sub samples were analyzed for OM in both RG1 and RG2 cores. Similarly, 205 samples were analyzed for LOI in KG1 and KG2 cores.

Grain size distribution in sediments was analyzed covering 785 sub samples in four cores at 1 cm interval. Those sub sediment samples,

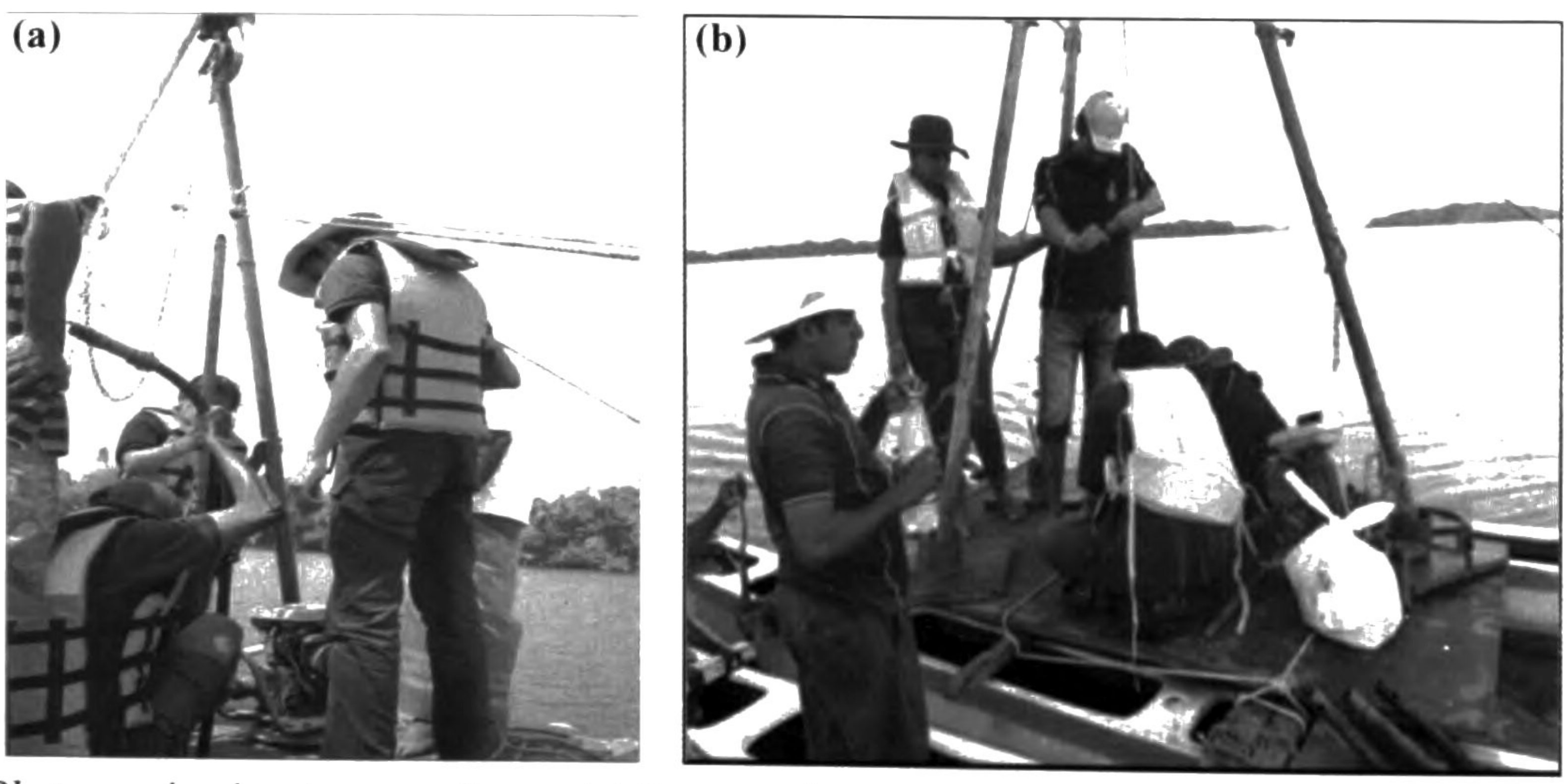


Fig. 2 Photographs showing sampling at (a) Ratgama lagoon and (b) Koggala lagoon.

each having about 8 g, were oven dried at 105 °C to remove moisture, and then dry weight was obtained. Subsequently, they were wet sieved using 63 µm sieve. Then, coarse fraction was oven dried at 105 °C to remove moisture and dry weight was obtained.

Geochemical variations of sediment in the cores were determined by using handheld X-ray fluorescence analyzer (Bruker S1) facility available at the Geological Survey and Mines Bureau (GSMB). Both major (Fe, Ti, K, Ca, Mn, Cl and S) and trace elements (Sr, Zr and Zn) in 785 sub sediment samples were determined in the four cores of RG1, RG2, KG1 and KG2 (Table 1).

Gamma ray intensity is commonly used as a proxy to detect mineralogy with radioactive elements in soil and sand samples (Almayahi et al., 2012). Gamma ray intensity was measured at 1 cm interval for RG cores and at 2 cm interval for KG cores using gamma ray spectrometer.

In reconstructing coastal history related to sea levels, different proxies have been employed to identify different environments.

1) Cl and S are considered paleo-salinity indicators (Chagué-Goff, 2010, Chen & Chen, 1997).
2) Terrestrial sedimentation with prevailing anoxia is indicated by dark gray color, silt-clay sediments, richness in the detrital elements Fe, Zn, and Ba and low levels of biogenic materials. In contrast, terrestrial sedimentation under oxidizing conditions is indicated by brownish silt-clay that is rich in detrital elements (Ranasinghe et al., 2013).
3) Sand that is rich in marine proxy elements such as Ca, Sr, Cl, S, rich in biogenic materials such as shells and microfossils is taken to indicate shallow marine to open-

Table 1 Geochemical variation in Ratgama cores (RG1 and RG2) and Koggala cores (KG1 and KG2)

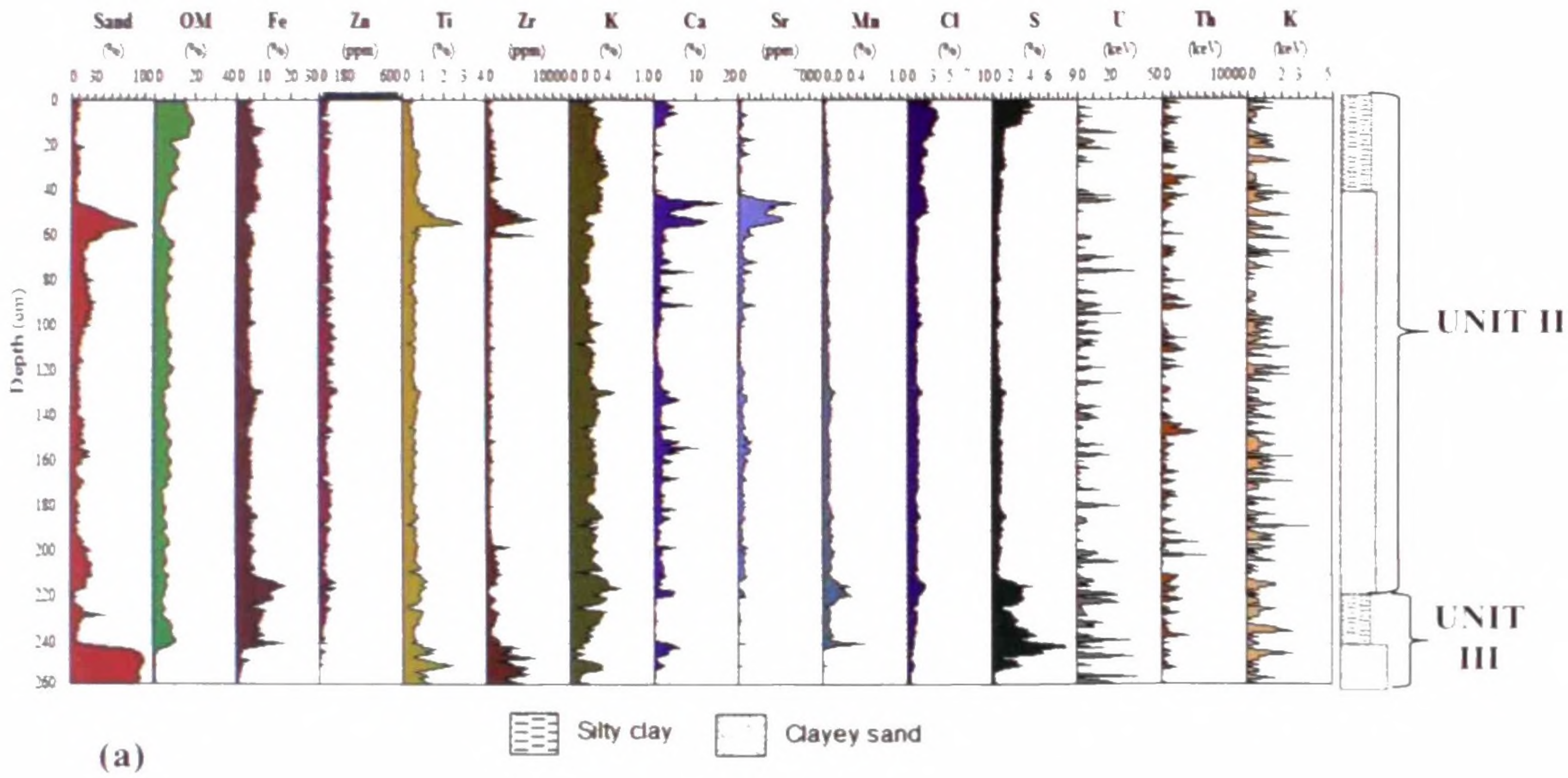
Lagoon	Core	Unit	Fe_2O_3 (%)	TiO_2 (%)	K_2O (%)	CaO (%)	MnO (%)	Cl (%)	S (%)	Zn (ppm)	Sr (ppm)	Zr (ppm)
Ratgama	RG1	II	3.24-18.70	0.28-2.95	0.08-0.62	0.25-16.60	0.02-0.36	0.65-3.78	0.35-4.62	0.00-0.01	0.00-0.50	0.00-0.62
		III	1.03-18.00	0.25-2.42	0.13-0.33	0.10-6.36	0.00-0.51	0.37-1.38	0.18-8.07	0.00-0.01	0.00-0.01	0.05-0.59
	RG2	I	0.46-11.50	0.00-0.99	0.01-0.66	0.06-3.32	0.00-0.10	0.91-8.88	0.00-1.82	0.00-0.10	0.00-0.04	0.00-0.27
		II	4.09-9.86	0.49-0.99	0.17-0.62	0.15-4.23	0.04-0.09	1.97-6.85	0.59-1.91	0.00-0.01	0.01-0.39	0.05-0.26
Koggala	KG1	I	3.30-9.70	0.27-1.40	0.20-0.59	0.81-10.00	0.02-0.14	2.09-5.28	0.40-1.40	0.00-0.02	0.02-0.34	0.07-0.47
		II	4.26-9.61	0.37-1.14	0.31-0.68	5.34-31.70	0.04-0.12	1.69-6.86	0.69-1.85	0.00-0.01	0.11-0.74	0.12-0.23
		III	2.72-8.64	0.45-1.38	0.18-0.65	2.81-18.60	0.02-0.11	1.57-3.61	0.60-1.81	0.00-0.01	0.09-0.42	0.00-0.49
	KG2	I	3.37-12.3	0.29-2.00	0.04-0.62	0.49-13.70	0.04-0.18	1.62-4.94	0.38-1.72	0.00-0.02	0.00-0.52	0.00-0.70
		II	1.43-12.40	0.11-1.01	0.05-0.63	0.42-42.30	0.01-0.24	0.74-4.56	0.36-3.15	0.00-0.03	0.00-0.56	0.00-0.14

bay but brackish conditions (Ranasinghe et al., 2013).

4) High concentrations of Ti and Zr indicate sediment layers composed of beach sand or dune sand, which consist of medium to coarse and rounded to subangular sand rich in ilmenite, garnet, and rutile. On the other hand, river sands are rich in angular to subangular grains of quartz, feldspar, and mica, and minor quantities of hornblende and ilmenite. High organic matter content also helps to distinguish river sand from other sources (Ranasinghe et al., 2013).

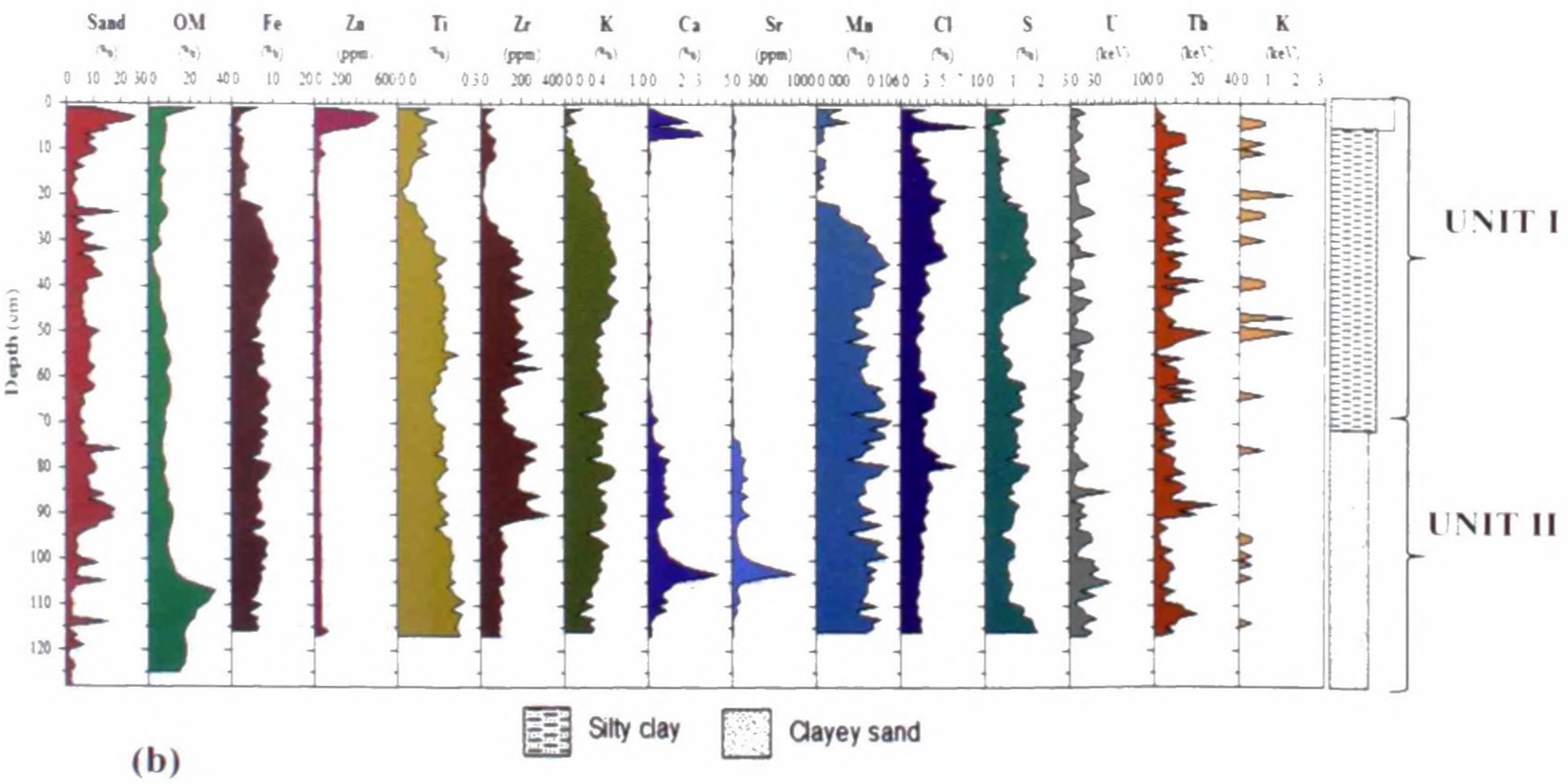
5) Certain minerals are indicative of reducing conditions. Such conditions cannot be achieved in highly turbulent, aerated waters. Minerals formed in stagnant anaerobic waters include sedimentary pyrite and siderite. In certain lagoons and estuaries, however, where wave and current action is negligible, these materials are formed in the muds in comparatively shallow water (Pettijohn, 1984).

RG 1



(a)

RG 2



(b)

Fig. 3 (a) Down core variation of physical and chemical parameters for core RG1
(b) Down core variation of physical and chemical parameters for core RG2

After the identification of different depositional environments and important events using the amounts of sand percentage and other chemical properties, sub samples were taken from those areas and identified them through binocular polarized microscope. The shapes (whether rounded, angular, sub angular) of quartz, micro and macro fossil content, heavy minerals and sulphide spherules were checked for its availability.

RESULTS AND DISCUSSION

STRATIGRAPHY AND SEDIMENTOLOGY

In sediment core RG1 (Figure 3a), the depth from 220 - 258 cm consists of dark grey, sandy silty clay layer with a yellowish clayey sand layer at the top. The layer of 1 - 220 cm in RG1 is greyish silty sand with a 20 cm length yellowish grey silty sandy clay layer. Greyish silty sand is also abundant in 72–128 cm in RG2 (Figure 3b). At the top 1 – 71 cm sediment layer in RG2 contains silty clay and clayey sand. The bottom sediments in core KG1 from 186–225 cm consist of clayey sand. Sediments in KG1 (Figure 4a) from 53–185 cm comprise with silty clay with shale, sand and sandy clay with shale from bottom to top. The top 52 cm of sediments from KG1 contain silty clay with shale and sand.

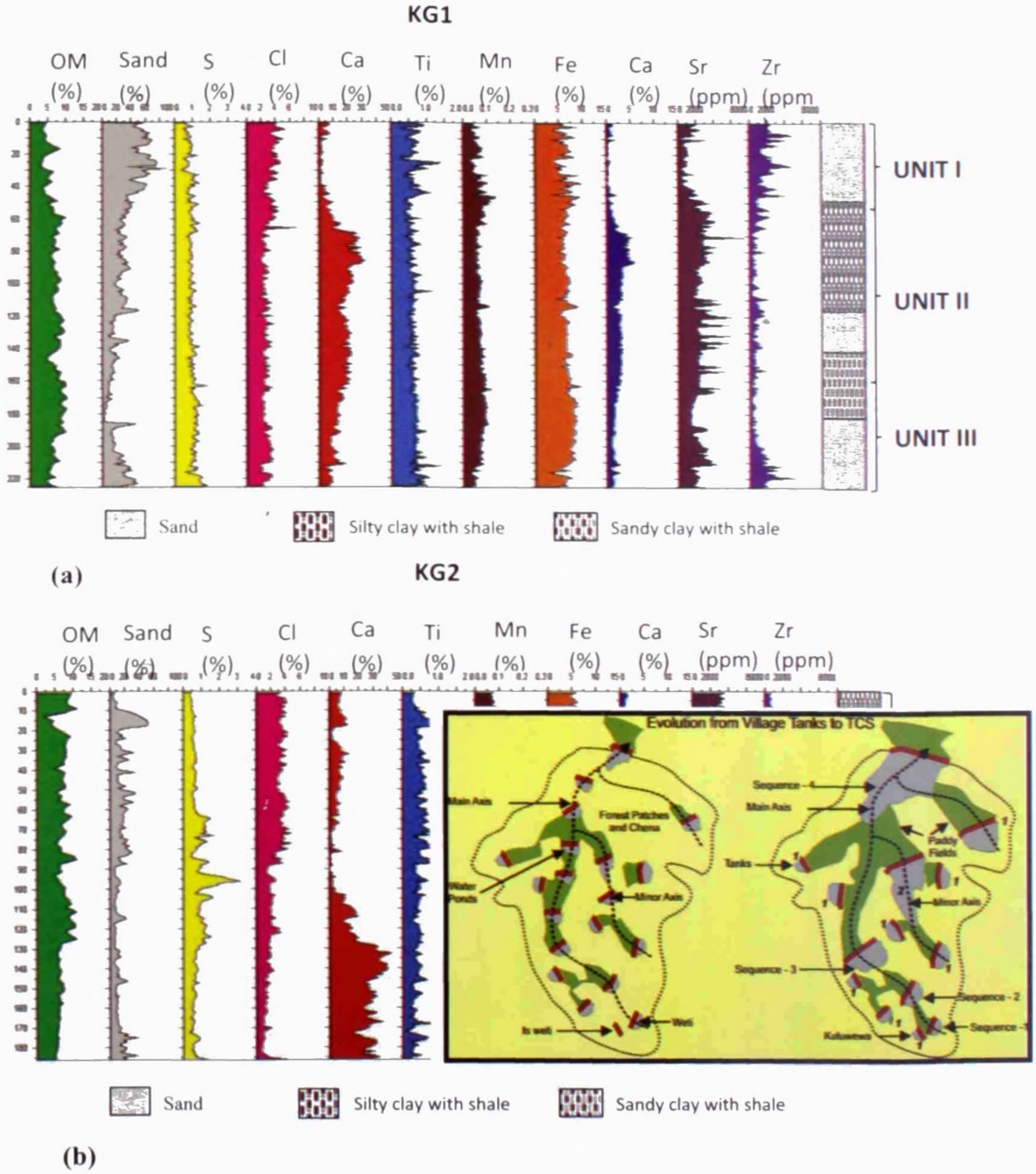


Fig. 4 (a) Down core variation of physical and chemical parameters for core KG1
(b) Down core variation of physical and chemical parameters for core KG2

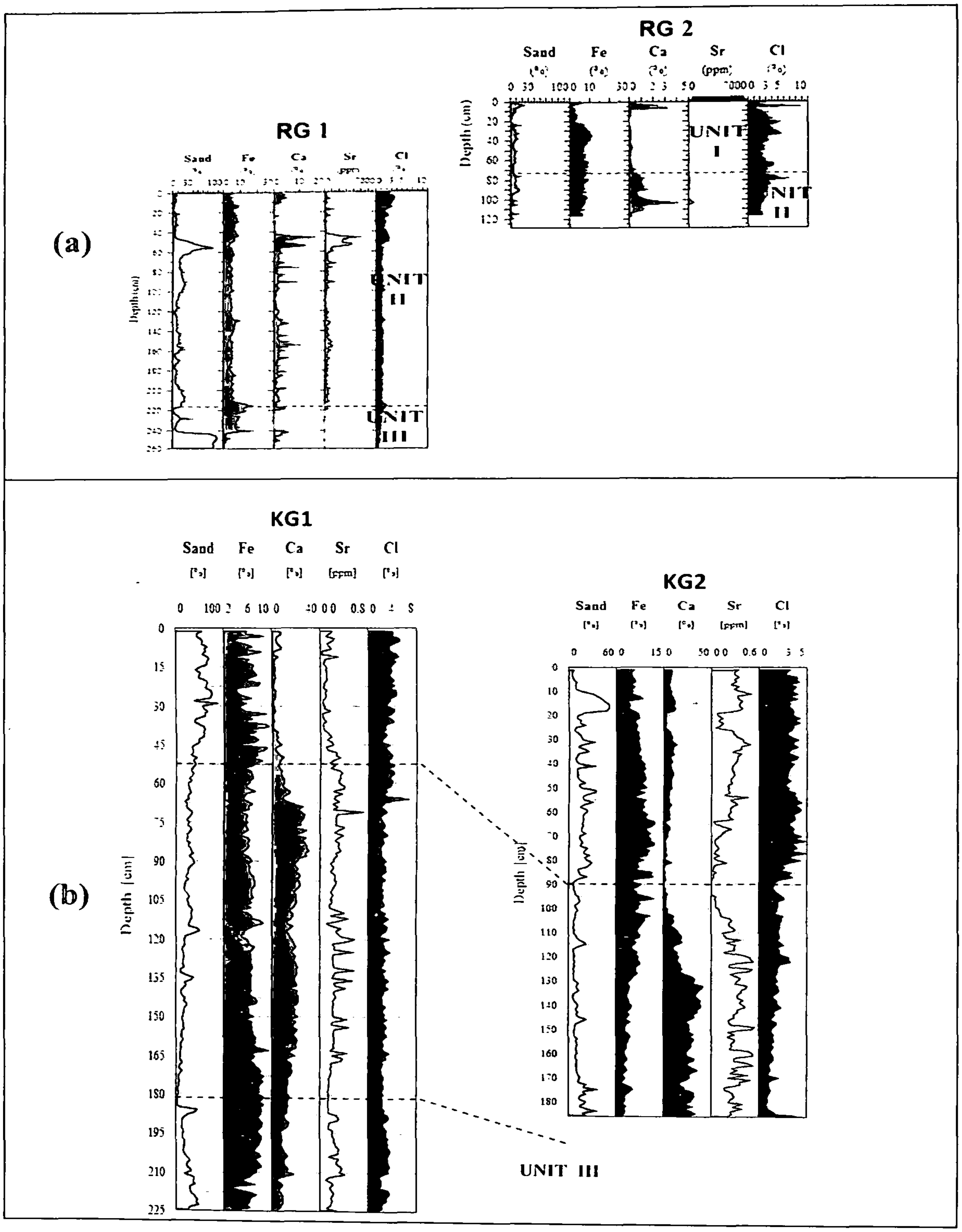


Fig. 5 (a) Stratigraphic correlation between Koggala cores. (b) Stratigraphic unit boundaries Koggala cores. Stratigraphic unit boundaries marked in dash lines were identified using proxy data. Corrections have been made to the elevation difference.

Sand, silty clay with shale and sand layer could be recognized in the 90 – 186 cm layer of core KG2 (Figure 4b). The top 90 cm sediments from the same core consist of both silty clay and sandy clay with shale and sand layer.

PALEO-ENVIRONMENTAL EVOLUTION OF SOUTHWESTERN COAST OF SRI LANKA

Evolution of Ratgama lagoon can be understood by correlating the three stratigraphic units (Figure 5a). Similarly, evolution of Koggala lagoon (Figure 5b) can also be understood by three stratigraphic units with similar characteristics as recognized in Ratgama lagoon. Based on the analyses of geochemical, biological, textural properties including grain size and shape of sediments, the southwestern coastal evolution of Sri Lanka could be reconstructed using stratigraphic units recognized in Ratgama and Koggala lagoons (Figure 6). Unit III and Unit I represent a closed lake system with less marine influence while Unit II represents a lagoon/bay with direct marine influence. Unit III, in Ratgama core RG1 and Koggala core KG1 (Figure 5a and 5b), provides clues for a closed lake system with less marine influence and low energy environment (Appendix Table 1). This was a dark grey, sandy, silty, clay layer with yellowish grey, clayey, sand layers. Low levels of sand with angular and sub angular shapes represent a low energy lagoon with terrestrial influence. Detrital elements such as Fe and Zn showed relative increase during this unit (Figure 3a and 3b). In addition, deposition of terrestrial clay can be identified by the relative increase of K which originates from the terrestrial clay. Furthermore abundant wood fragments, limonitic fragments and sulphide spherules were also helpful for the identification of terrestrial conditions because, when wave and current action is negligible, these materials are formed in the muds in comparatively shallow water such as terrestrial environments. Therefore it can be identified that these lagoons have been existed as water logged, reducing environment due to the abundance of organic matter and high levels of sulphide spherules. In such conditions the rate of organic matter decomposition was at a low level. Greyish clayey silt also indicates the presence of Fe mainly as Fe^{+2} within such water logged conditions. Taking all these information, presence of a barrier lagoon with low sediment supply from marine sources can be identified in Ratgama and Koggala lagoons during of Unit I and Unit III depositional periods.

Table 2 Variation of sand (%) and organic matter (%) in stratigraphic units of Ratgama and Koggala lagoons.

Lagoon	Core	Stratigraphic Unit	Sand (%)	Organic Matter (%)
Ratgama	RG1	II	2.5-80.1	2.2-5.4
		III	2.6-90.0	1.2-7.4
	RG2	I	2.1-25.6	2.3-23.1
		II	1.1-19.9	7.2-32.6
Koggala	KG1	I	32.5-89.6	3.0-8.7
		II	2.3-51.3	4.9-10.4
		III	12.0-48.7	4.5-9.9
	KG2	I	4.1-52.5	2.2-11.1
		II	4.1-52.5	5.0-11.0

Unit II in both Ratgama (RG 1 and RG 2) and Koggala (KG1 and KG2) cores (Figure 5a and 5b) represents a lagoon/bay with direct marine influence and a higher-energy environment due to the contact with the ocean. Unit II could be identified according to the following information. This unit is greyish silty sand layer with yellowish grey sandy silty clay layers. The sand layer is composed of angular, sub angular and rounded grains which indicate shallower and/or higher-energy environments. High levels of fine to medium sand mostly in rounded to sub angular shapes indicate higher-energy events or environments in this unit. Broken shell fragments of pelecypods and gastropods as well as planktonic foraminifera were abundant in this layer (Figure 7). During the period of Unit II, ilmenite and rutile rich beach sand brought from

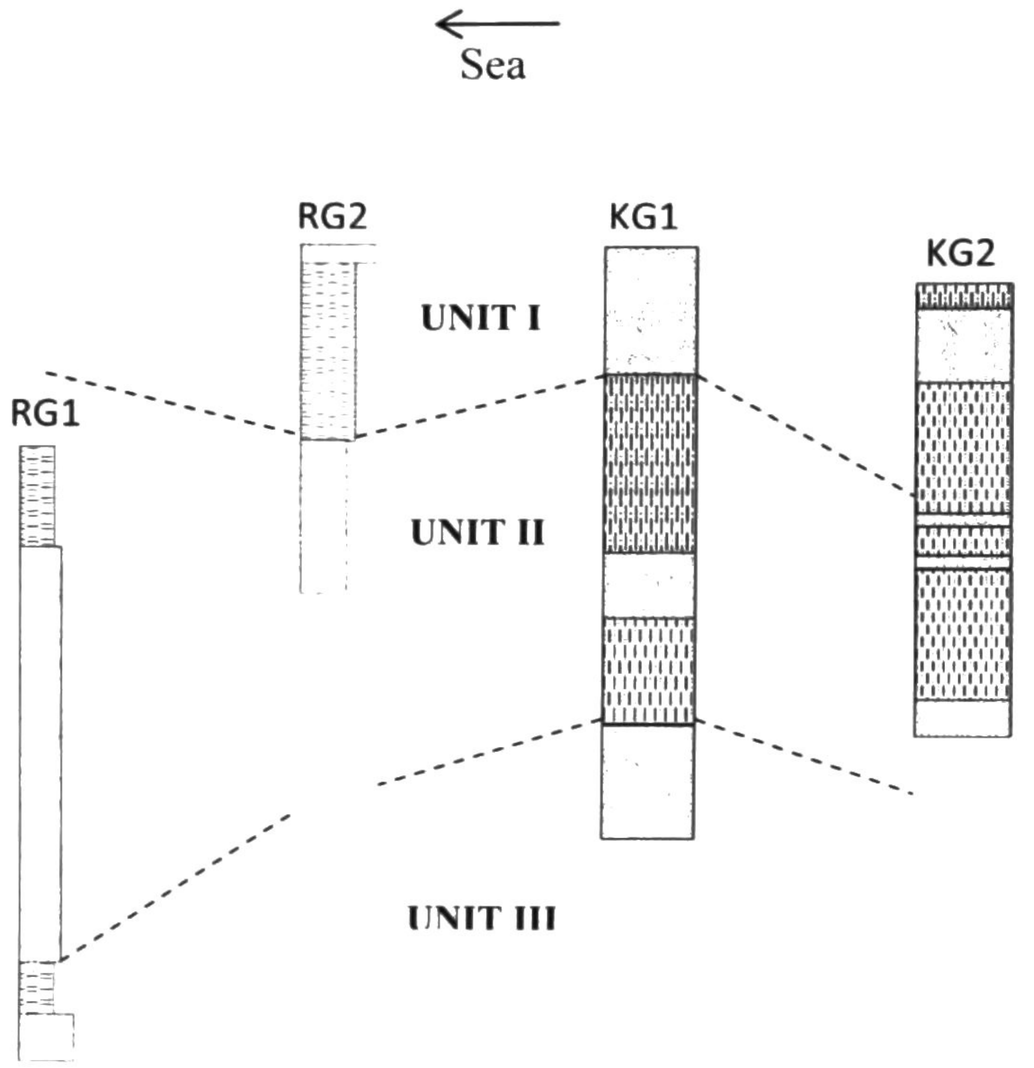


Fig. 6 Correlation of stratigraphic units among two locations of Ratgama lagoon and Koggala lagoon.

the seaward were deposited in RG 1 and RG 2 sites. The source of increased Ti, Zr, Ca, Sr and Mn in these regions (Figure 3 and Figure 4) might be supported deposition of heavy minerals such as ilmenite, rutile and carbonate materials in the beach sand respectively. The increase of Cl and S indicate high salinity levels of marine influence (Chagué-Goff, 1999, Chen & Chen, 1997) as shown in this unit. Detrital elements such as Fe and Zn as well as K, derived from terrestrial clay deposits show relative decrease at the positions of high sand levels. Gamma ray intensity, which infers to the radioactive mineralogical composition, shows a relative increase within this unit presuming the levels of radioactive beach sands deposited. The organic matter content (Table 2) does not show a significant change and the small fluctuations are related with rainfall patterns during Unit II. Indeed, the organic matter content shows an inverse relationship with Fe. It could be used to interpret the source of organic matter as the marine biological materials but not the terrestrial. All these evidences could be gathered to synthezise a lagoon/bay model with direct marine influence with shallower depths and/or higher energy environment during the Unit II depositional period. After passing a period of sea level ransgression, the environment has again become calm due to the regression or sea level stabilization. This change of the environment has been preserved in Unit I in cores RG2, KG1 and KG2 (Figure 3b, 4a and 4b).

Assuming similar sedimentation rates, approximate ages for onset and termination of the trangression phase were calculated using regional AMS ^{14}C age-depth model developed by Ranasinghe et al., (2013). According to the model the onset of the transgression occurred around 6200 -5500 yrs BP and conversion of the open lagoon/bay in to a barred lagoon/lake was occurred between 3000-2000 yrs BP. It confirms that the transgression phase represents the mid-Holocene transgression which was previously reported from Sri Lanka.

Similar submergence phase was reported in Sri Lanka (Katupotha, 1995; Weerakkody, 1992; Ranasinghe et al., 2013) as well as in neighboring Indian Ocean countries (Banerjee, 2000, Kench et al., 2009). However, this high resolution sediment record does not recognize

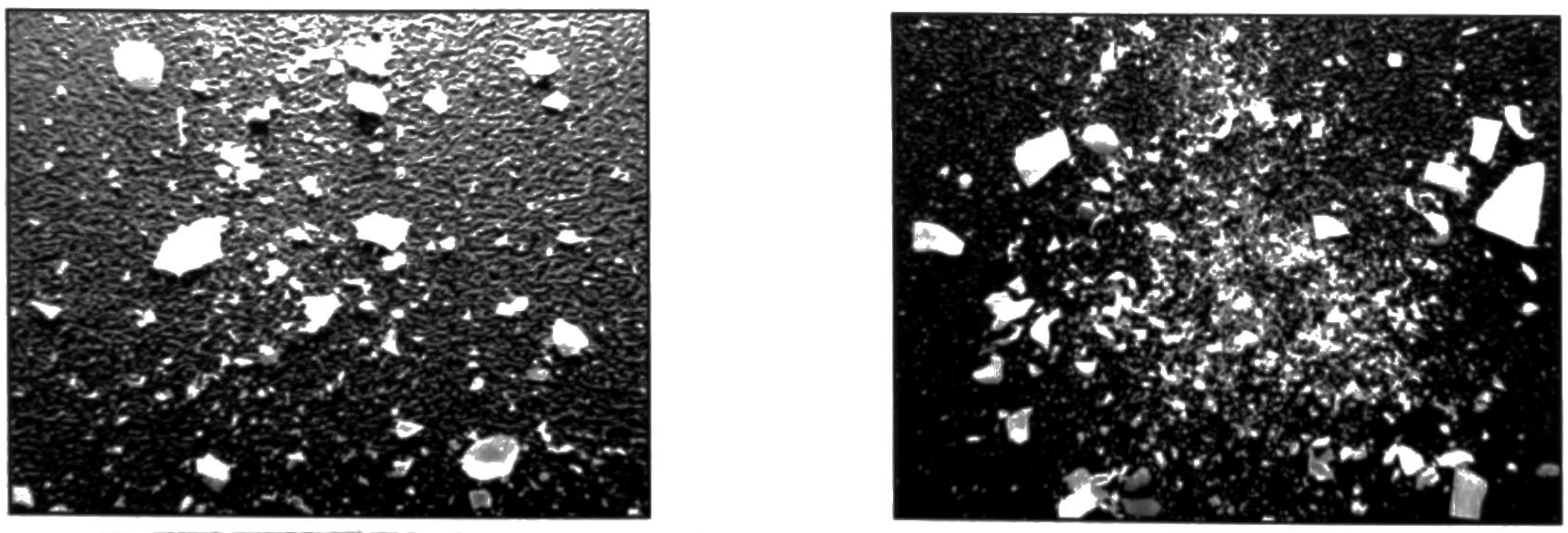


Fig. 7 Broken shell fragments of pelecypods and gastropods in Unit II

multiple sea level highstands and lowstands reported by Katupotha, (1995) from Sri Lanka and Banerjee, (2000) and more similar to single highstand reported in Sri Lanka by Ranasinghe et al., (2013), in Maldives by Kench et al., (2009), in Madagascar by Camoin et al., (2004) and in Seychelles by Pirazzoli et al., (1990).

In summary, these results show that the low-lying areas in the southwestern coast of Sri Lanka have been submerged during Mid-Holocene sea level transgression and at end of the transgression or after the sea level stabilization, these flooded areas have become lakes or lagoons due to barrier formation.

CONCLUSIONS

Ratgama and Koggala lagoon sediments in southwestern Sri Lanka indicate coastal changes in response to relative sea level fluctuations during the Holocene. Stratigraphy, biological assemblages, physical and textural properties and chemical composition of sediments provide evidences for the reconstruction of the southwestern coastal environment and sea level variations.

Based on proxy evidences, three stratigraphic units could be recognized in both lagoons. Unit I and unit III represent deposits in a closed lake system with less marine influence while unit II represents a lagoon / bay with direct marine influence due to sea level transgression. Therefore, the southwestern coast of Sri Lanka has evolved to the present barred lagoonal environment after a submergence phase occurred during a transgression. Age estimates suggests that this transgression phase represents the Mid Holocene transgression reported from Sri Lanka as well as other neighboring countries. However, in contrast to the multiple sea level highstands reported from Sri Lanka and India during mid-later Holocene by some previous workers, this study identified a single highstand, similar to sea level records from Maldives and other western Indian Ocean records. Coastal low-lying areas of the southwestern Sri Lanka were flooded during this transgression period and after sea level stabilization or at the end of the transgression, flooded areas were transformed in to lakes, or lagoons due to barrier formation.

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APPENDIX

Appendix Table 1 Properties used to distinguish stratigraphic units of Ratgama and Koggala lagoons

Unit	Distinguishing properties	Sediment type / Depositional environment
Unit I	Greyish silty clay. Enriched in Fe, K, Ti, Zr, Mn, Cl ad S. Depleted in Ca and Sr. Low levels of OM content and gamma ray intensity. Broken shell fragments of pelecypods and gastropods, angular, subangular and rounded quartz	Sea level stabilization or regression promoted emplacement of a barrier bar, ending the marine influence in to the lake.
Unit II	Greyish silty sand. A yellowish grey silty sandy clay layer (about 20 cm) at the bottom. The top of this Unit was enriched in Ca, Sr and Cl while Fe, Zn and K were relatively depleted. Medium in Ti, Zr, Mn and S. OM was relatively high. Gamma ray intensity was in medium. Broken shell fragments of pelecypods and gastropods as well as planktonic foraminifers were abundant in this layer	A lagoon/bay with direct marine influence
Unit III	Dark grey sandy silty clay layer. A yellowish grey clayey sand layer was at the top. Enriched in Fe, K, Ti, Zr and S. Depleted in Ca and Sr. Relative increase in OM content and medium levels of gamma ray intensity. Low levels of shell fragments and foraminifers. Abundant limonitic fragments and sulphide spherules. Angular to subangular quartz	A closed lake system with less marine influence and low energy