



**MINERAL ANALYSIS OF SEDIMENT SAMPLES COLLECTED ALONG THE
KRUSADAI – RAMESWARAM ISLAND, GULF OF MANNAR, TAMIL NADU,
INDIA**

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ABSTRACT

The mineralogical and granulometric characteristics of sediments collected from Krusadai and Rameswaram Islands in the ecologically sensitive Gulf of Mannar region were analyzed to understand their provenance and depositional environment. X-ray diffraction (XRD) studies were carried out for the of sediment samples and crustal silicate minerals such as quartz (SiO₂) and aluminium silicates (Al₂SiO₅) were predominantly identified in the Krusadai and Rameswaram Islands. Iron-bearing minerals, including hematite (Fe₂O₃), ilmenite (FeTiO₃), and fayalite (Fe₂SiO₄), are also present in significant amounts, particularly in the northern, eastern, and western parts of Rameswaram. Their distribution reflects contributions from lateritic soils and placer deposits, indicating mixed terrestrial and marine sources. Grain-size analysis indicated moderate to poor sorting, reflecting variable



hydrodynamic conditions influenced by littoral currents and coastal morphology. The mineralogical maturity of sediments highlights prolonged reworking and transport processes. These granulometric and mineralogical variations can influence key biological parameters in the coastal environment, particularly affecting crustacean distribution, habitat conditions and ecological interactions in the study region.

Keywords:

Granulometric analysis, X-Ray diffraction study, soil mineral analysis,

INTRODUCTION

Gulf of Mannar is a large shallow bay in the Indian Ocean. It lies between the south eastern tip of India and the western coast of Sri Lanka. It is one among the important marine biodiversity hotspots and harbours over 3,600 species of plants & animals, including many endemic species within its pristine coral environment and considered as one of the richest coastal biodiversity regions of Asia. The prominent biotic community of this marine biosphere reserve includes algal beds, seagrasses, coral reefs, rare fauna and numerous edible fish species. This region is commonly called as 'Biologist's paradise'. This region has been recognized and declared as the ecologically sensitive area under Coastal Regulation Zone Notification 1991 mainly because it serves as a breeding zone for a variety of marine species, many of which are either rare or of commercial importance. Considering this the Government of India and Government of Tamil Nadu jointly promulgated an ordinance declaring Gulf of Mannar as Marine National Park and Biosphere Reserve under the provisions of the Wildlife (Protection) Act 1972 [1]. This Biosphere Reserve encompasses a group of 21 islands (islets) with estuaries, mudflats, beaches, shore forests, salt marshes, mangroves & adjacent coral reefs and lies 1 to 10 km from the east coast of mainland, India.

The present study area comprises of Krusadai Island and Rameswaram Island, which are two adjacent islands separated by a narrow stretch of shallow innershelf region. This shallow innershelf region is noted for its plenitude of coral formation, coral reef algae and mangrove vegetation. These islands are a part of Mandapam region of Gulf of Mannar and are well known for their strategic geographical location at the random water current spot between the Palk bay and Gulf of Mannar. The study area also gains geopolitical significance and international



attention recently because of a proposed shipping canal project and its alleged impacts on the region's existing pristine coral environment that shelters a vast majority of endemic flora and fauna. In addition, this thriving natural habitat is now under the threat of getting curtailed because of the increase in the pollution caused due to industrial dumping and human activities. Recent industrial activities had several environmental effects in and around Rameswaram Island. Srikanth, Ahmad [2] have reported the increase in potentially toxic elements associated with rapid industrialization along the Gulf of Mannar region around Rameswaram Island and recommended continuous monitoring of these potentially toxic elements to protect the existing coral reefs in the region. Numerous reports on the water quality pattern are available on the study area. Subbiah, Chandrasekar [3] have studied the hydrogeochemistry of the groundwater. The physico chemical properties were studied and correlated with the marine ostracod population by Kuppusamy, Sridhar [4], Anandarao, S M [5] studied various ostracods and compared their presence in various core samples collected from neritic zone (shallow water depth cores at 58 m, 215 m) to bathyal zone (deep water cores at 510 m, 1235 m and 1887 m). Mageswari, Lekshmi [6] studied the mineralogical variations in the rock samples collected from the southern part of India. Several reports on the Gulf of Mannar region have studied the biology of the region and the environmental impacts of pollution [7-11]. Many islands are located along the Rameswaram Island, in which the most important one is the Krusadai Island. Krusadai island is also fondly termed as Biologist's Paradise [12] has many attractive features, even it once hosted a fully functioning Marine Biological Centre for the Mandapam region Island chains. Further, this study area had witnessed the tsunami attack on 26th December 2004 and several seasonal cyclones that might have added more sediments and altered the sedimentation pattern in this region. The present study gains prominence both as an investigation and as a comprehensive one involving two major islands that are slightly different from each other. Among, these two islands, Krusadai Island is uninhabited and highly protected as a coral reserve by the Forest department. While Rameswaram Island is inhabited and is thrown, open to the pilgrims and other public activities. In the light of these information an attempt has been performed to study the surface mineralogy of the samples collected from the Krusadai – Rameswaram Island region of the Gulf of Mannar, Tamil Nadu, India.

GEOLOGY AND SIGNIFICANCE OF THE STUDY AREA

The Rameswaram Island lies on the south-eastern side of the Indian sub-continent, lying between the Peninsular India and Sri Lanka, located geographically at 9°11' N and 9°19' N latitude and



79°12' E to 79°23' E longitudes. Rameswaram Island also called Pamban Island is the largest island in this region and the only inhabited island in the Gulf of Mannar Marine Biosphere Reserve. It stretches with a length of about 30 km and varies from 2 km to 7 km in width and occupies an area of 96 km². This Island is an important tourist attraction as a holy pilgrim destination and is well connected by road and rail and witnesses regular visit of tourists and heavy inflow of pilgrims during festivals making it vulnerable to serious pollution from human activities. Krusadai Island is an adjacent, isolated and uninhabited island, which lies to the south-western side of the Rameswaram Island located geographically at 9°14'00" N and 79°13'00" E and is also a part of Gulf of Mannar Marine National Park. The distance to the island from the nearby Rameswaram Island is nearly 5 kms. Krusadai Island has a length of 2050 meters and a width of 700 meters, making a total area of around 67 hectares. The island is under the total control of the Department of Forest, Government of Tamil Nadu. A marine biological station was set up by the fisheries department of the erstwhile Madras Presidency (British India) in this island and operated research activities. In addition, Krusadai Island is considered unique because of its rich biodiversity. The island ecosystem is entirely different from the mainland ecosystem mostly due to its long term isolation[13] and because of which many endemic species of crustacean and seed shrimps are noted here. The entire Krusadai Island is now covered with halophytic trees and bushes and also has dense mangroves all along its coast making it very difficult to go around or transverse the island and carry out the sampling. The lithological studies have revealed that the rock formation of the study area belongs to the Cambrian Era with unconsolidated sediments of quaternary age. The whole of Rameswaram – Mandapam circle has isolated patches of archaic crystalline and tertiary sandstones exposed in the study area. This archaic formation is mainly represented by charnockite group of rocks comprising of granitic gneiss and khondalite group of rocks made up of quartzite gneisses. Other commonly occurring rocks are the layer deposits of beach rocks which remain inclined towards the sea[14] and detached exposure of Laterite and Lateritic soil[15]. The minerals present in the area are mostly admixture of Quartz, Limonite, Garnet, Gypsum, Ilmenite, Graphite, Clay, Shell limestone and Coral limestone. Reports are not available on the presence of actinide bearing Monazite in this area[15].

The ground water pH analysis has been studied around Rameswaram Island and reported to be slightly acidic to basic nature. The values range between 6.7 and 7.3 with an average of 7.2 as pH [3]. The near shore sediment pH measurements were found to be uniform with an average pH of ≈ 8.0 in the study area. The absence of major variations in pH was due to the immense buffering



capacity of the sea water and low terrestrial runoff[16]. Reports on the Krusadai Island sediments reveal, that the average pH to be ≈ 8.08 with a reduced average salinity value of 31.95 ‰. The report also indicate that the calcium carbonate concentration is higher than the normal values, which might be due to the rich coral environment existing in the study area[17]. These reports convey that the pH values to be slightly acidic at the hinterland of the islands and basic along the coastal stretch of the islands.

The present study area Rameswaram & Krusadai Island are grouped under Mandapam circle and known to have random water current patterns. The corals stretch of Krusadai Island extends till south western coast of Rameswaram in the north and till Shingle Islands in the south making it one of the wide spread coral reefs of Gulf of Mannar. Moreover, the random water current patterns and existing sheltered environment conditions along the study area provides ample chances for the deposition of littoral sediments. The climatic conditions of the study area are tropical ($\leq 35^{\circ} \text{C}$) for which the south-west monsoon has little contribution, while the north-east monsoon during October to December contributes much to the annual rainfall making the mean annual rainfall to range from 762 to 1270 mm/year. The climate was reported to be calm during September and coldest climate was experienced in December with an average temperature of 25°C [1]. The ocean currents of Gulf of Mannar is swift with a tidal amplitude of half a meter.

Sample Collection and Sample Labelling

Soil / sediment samples from these two islands were collected during the post-monsoon period on the month of December - 2013, from the twenty-nine sampling sites as shown in Figure 1 (a) and (b), in which fifteen samples were collected in Rameswaram Island and fourteen samples were collected in Krusadai Island. The study area represents the Mandapam region of Gulf of Mannar. The sampling sites were earmarked using the geographical map and considering the accessibility to the site. The sites were visited once prior to the sampling and the sampling was done with the help of some local fishermen people and friends. A simple motor boat was used for collecting samples from the innershelf samples and to reach Krusadai Island from the Rameswaram Island. The motor boat facility was provided by the Department of Forest, Government of Tamil Nadu.

The surface samples were collected at one-foot depth from three places of approximately half-a-meter distance at each site and three samples collected from each site was mixed together



and considered as the sample representing that corresponding sampling site. The innershelf region samples were collected at the depth of approximately between 5 m to 7 m using Van-Veen Grab Sampler. The plant debris, corals and pebbles were segregated from the samples using a mesh with a pore diameter of 2 cm at the sampling site. The sampling sites were given sample code (labelled) based on its geographical region from which it is collected, the sampling site K-I-1 to K-I-5 denote the Krusadai Island - Innershelf region samples, K-C-6 to K-C-12 denote Krusadai Island - Coastal region samples, K-Is-13 and K-Is-14 denote the Krusadai Island - Hinterland samples. Similarly, labelling code R-H represents the samples collected along the hinterland region of Rameswaram Island and R-C represents the samples collected along the coastal region of the Rameswaram Island. Moreover, since the study area are island, the surface samples collected along the coastal stretch comprises of sediment fraction with minimal input from the soil fraction, while the soil component observed at the sampling site dominates constituents of the hinterland samples along with low proportion of sediments. Overall, the samples are an admixture of both soil and sediment fraction. The details on the sampling sites of the Krusadai – Rameswaram Islands were given in Table 1 and Figure 2.

EXPERIMENTAL ANALYSIS

Textural analysis

Textural analysis deals mainly with the proportion of sand, silt and clay present in the sample. This analysis is carried out for both soil and sediment samples. Ro-tap sieve shaker instrument is used for this analysis to segregate the samples based on the grain size.

Sample preparation procedure

Soil/Sediment samples (100 g) from each location were separated by involving miniature stockpile method from each sampling site for determining the grain size variation. The separated samples were oven dried at 110 °C for 12 h and separately packed in small zip-lock covers to prevent any interaction with atmospheric water vapour. Ro-tap sieve shaker with ASTM mesh no., 14, 18, 25, 35, 45, 60, 80, 120, 140, 230 and 270 were employed for categorizing the samples based on their particle size.

Sample analysis procedure

The grain size distribution of the soil/sediments plays a vital role in identifying the depositional environment and mechanisms which operated during the transportation of sediments (including soil samples). The hydrodynamic conditions prevailing during deposition of sediments control the size and composition of the sediments. Based on the transport condition, the grain size distributions are mixtures of two or more component distribution or populations.

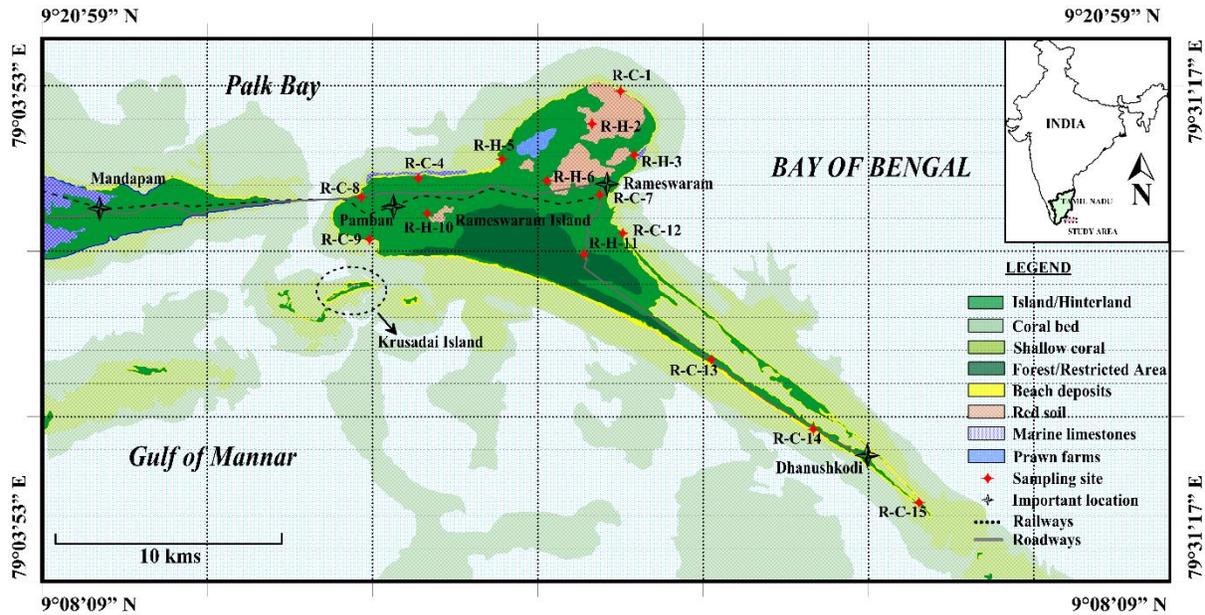


Figure 1 (a) Geographical location of the study area showing geological and geomorphological features [18]

Figure 1 (b) Enlarged geographical image of Krusadai Island showing sampling sites [19]

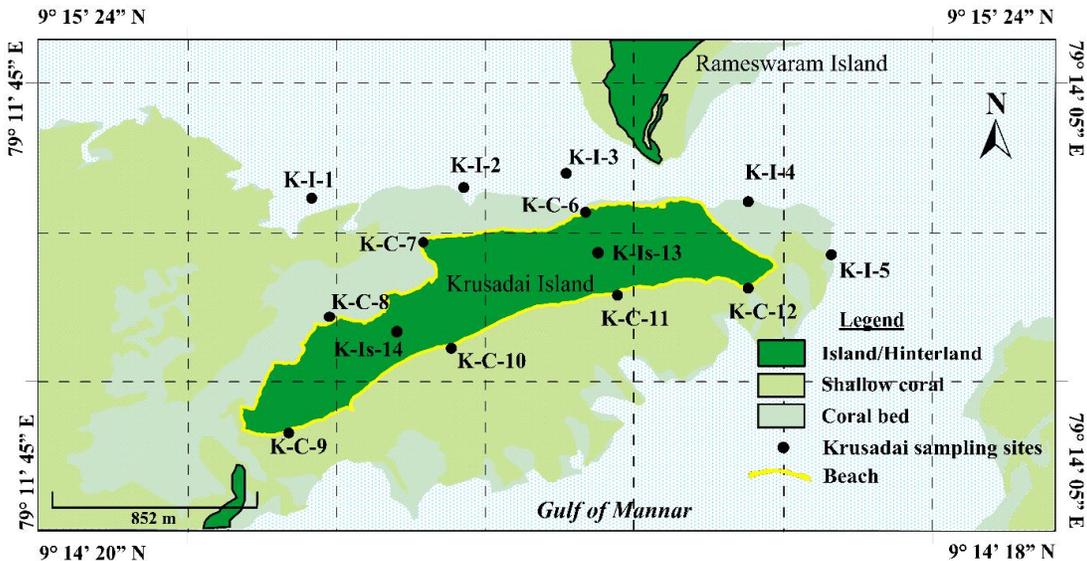


Table 1. The details of the geographical location and topography of the sampling sites of Krusadai – Rameswaram Island, Gulf of Mannar, India.

	S.Id.	Latitude	Longitude	Altitude (m)	Topographical region		S.Id.	Latitude	Longitude	Altitude (m)	Topographical region
Krusadai Island	K-I-1	9°15'8.31"N	79°12'15.49"E	7 < MSL	Inner shelf	Rameswaram Island	R-C-1	9°19'21.22"N	79°19'28.74"E	MSL	Coastal region
	K-I-2	9°15'6.90"N	79°12'36.56"E	4 < MSL	Inner shelf		R-H-2	9°18'39.61"N	79°18'17.40"E	3	Hinterland
	K-I-3	9°15'7.61"N	79°12'49.63"E	3.5 < MSL	Inner shelf		R-H-3	9°17'58.99"N	79°19'35.74"E	5	Hinterland
	K-I-4	9°15'3.99"N	9°15'3.99"N	3 < MSL	Inner shelf		R-C-4	9°17'27.02"N	79°14'22.98"E	3	Coastal region
	K-I-5	9°14'54.47"N	79°13'24.79"E	5 < MSL	Inner shelf		R-H-5	9°18'1.24"N	79°16'22.87"E	1	Hinterland
	K-C-6	9°15'0.21"N	79°12'52.74"E	1	Coastal region		R-H-6	9°17'21.85"N	79°17'57.30"E	7	Hinterland
	K-C-7	9°14'55.48"N	79°12'29.26"E	MSL	Coastal region		R-C-7	9°17'11.77"N	79°18'58.24"E	8	Coastal region
	K-C-8	9°14'45.01"N	79°12'16.44"E	1	Coastal region		R-C-8	9°17'0.11"N	79°12'49.83"E	5	Coastal region
	K-C-9	9°14'29.77"N	79°12'9.34"E	3	Coastal region		R-C-9	9°16'2.76"N	79°13'6.96"E	2	Coastal region
	K-C-10	9°14'42.42"N	79°12'33.63"E	3	Coastal region		R-H-10	9°16'35.57"N	79°14'39.31"E	7	Hinterland
	K-C-11	9°14'48.82"N	79°12'55.25"E	3	Coastal region		R-H-11	9°15'41.17"N	79°18'20.23"E	3	Hinterland
	K-C-12	9°14'49.95"N	79°13'14.57"E	2	Coastal region		R-C-12	9°16'1.09"N	79°19'13.65"E	1	Hinterland
	K-Is-13	9°14'55.34"N	79°12'53.49"E	4	Hinterland		R-C-13	9°12'59.91"N	79°21'4.64"E	MSL	Hinterland
	K-Is-14	9°14'43.67"N	79°12'26.10"E	2	Hinterland		R-C-14	9°11'19.39"N	79°23'49.13"E	MSL	Hinterland
MSL – Mean Sea Level ; < = values below sea level (depth)							R-C-15	9° 9'35.00"N	79°26'17.70"E	1	Hinterland



Figure 2. The sample collection done along the innershelf region of Krusadai Island using grab samples (a-d), the surface samples were collected using iron scoop (e-f) and the various sampling locations of Krusadai Island and Rameswaram Island (g-l)



Granulometry analysis

To illustrate the environment of deposition, granulometric calculations have been made accordingly for the analyzed samples. Each and every value of fractions weighed has been properly tabulated. The textural parameters were determined following the classification method proposed by Folk [20]. GRADISTAT grain size analysis program is used in the present study to classify samples based on their grain size value. This analysis includes plotting a S-curve is plotted on a semi-log sheet having particle size on logarithmic scale and cumulative percentage on a linear scale and five parameters (i) Mode (ii) Meansize (iii) Standard Deviation (Sorting) (iv) Skewness and (v) Kurtosis were calculated.

Mineralogical analysis

Mineralogical analysis gives the details of the presence of minerals in a particular area and the occurrence of minerals that vary based on the geology of the area. The mineralogical analysis mostly deals with the analysis of heavy minerals present. Heavy mineral analysis is one among the reliable methods to identify the geology of the study area. In the present study heavy mineral analysis and X-ray diffraction (XRD) analysis were carried out.

Heavy mineral analysis

The terrestrial geo-media is rich in silicate minerals, especially quartz. This common rock-forming mineral with density 2.65 g/cm^3 is abundant in the earth crust. Quartz along with other commonly occurring crustal minerals, such as feldspar and clay minerals (kaolinite), which have densities lower than 2.85 g/cm^3 are termed as light minerals based on their low density.

Sample preparation procedure

The grain size fraction with grain particle size between $250 \mu\text{m}$ and $125 \mu\text{m}$ (which is separated using Ro-tap sieve shaker) were selected and subjected to heavy mineral analysis. Heavy mineral analysis is carried out by implementing density separation method. Bromoform liquid (CHBr_3) with the density of 2.89 g/cc (2.89 g/ml) is used for separating the minerals based on their density. Accordingly, 250 ml of bromoform is taken in a 500 ml separator funnel (Fig. 2.7 (a)), in which the samples were suspended and then it is gently stirred to allow the soil/sediment particles to get dispersed in the heavy liquid and the mixture is kept undisturbed for 15 minutes.



Minerals with higher density get deposited at the lower end of the separator funnel, while the minerals with density lower than that of bromoform float or remain suspended and were collected

Table 2 Classification of heavy minerals[21]

Non-opaque minerals	
Ultra-stable	Rutile, tourmaline, zircon, anatase (uncommon)
Stable	Apatite, garnet (iron-poor), staurolite, monazite, biotite
Moderately stable	Epidote, kyanite, garnet (iron-rich), sillimanite, sphene, zoisite
Unstable	Hornblende, actinolite, augite, diopside, hypersthene, andalusite
Very unstable	Olivine
Relative stability not well established	Ankerite, barite, brookite, cassiterite, chloritoid, chondrite, clinozoisite, corundum, chromite, dumortierite, fluorite, glaucophane, lawsonite, magnesite, monazite, phlogopite, pitotite, pleonaste, pumpellyite, siderite, spinel, spodumene, topaz, vesuvianite, wolframite, xenotime, zoisite (many of the minerals in this group are uncommon as detrital grains in sandstones)
Opaque minerals	
Stable to moderately stable	Magnetite, ilmenite, hematite, limonite, pyrite, leucoxene

as light minerals. This density separation method is represented in Fig. 2.7 (a). Minerals having density higher than 2.89 g/ml were separated from the other light minerals. The heavy minerals in the separator funnel were collected in the funnel using a filter paper. The collected heavy minerals were weighed (Fig 2.7 (b)) and packed separately. Heavy mineral thin section slides were then prepared by sprinkling, approximately 5 mg of the heavy mineral collected at each site, over canada balsam coated thin micro section glass slides (Fig 2.7 (c)). The heavy mineral identification is carried out using “Leika DMLL Petrographic Microscope” at 10 X magnification.

Sample analysis procedure

Through optical observation, the heavy minerals are commonly divided into two groups based on optical properties as either opaque or non-opaque. Opaque heavy minerals include magnetite, ilmenite, hematite and limonite, pyrite, and leucoxene. The opaque minerals have iron as an essential component and are easy to identify with an ordinary petrographic microscope because of its opaque nature. In order to calculate the opaque mineral percentage, the number of



opaque minerals and non-opaque minerals are counted through the optical microscope from the thin-section of heavy minerals prepared for the respective sampling site. The following formula is used,

$$\text{Opaque mineral \%} = \frac{\text{Number of opaque minerals}}{\text{Number of total minerals}} * 100$$

The non-opaque heavy minerals include a large group of minerals, of which garnet, rutile, tourmaline, kyanite, sillimanite, sphene (titanite), amphiboles, epidote, staurolite, apatite, monazite, and zircon are particularly common.

Heavy mineral deposits are also termed as placer deposits and are formed by early settling of the heavy minerals from a transport medium when the flow energy decreases. Thus, certain minerals, which are stable to such chemical and mechanical weathering without any change in its chemical composition, are stable, while the minerals which deteriorate for weathering process are termed as unstable minerals. Based on this property the heavy minerals are classified as given in Table 2.

The minerals which do not get decomposed by chemical and mechanical processes are termed as ultra-stable minerals. There are three major ultra-stable minerals, namely, zircon, tourmaline, and rutile. These minerals are resistant to both chemical leaching and mechanical abrasions. Based on the morphology and quantity of zircon, tourmaline and rutile, the mineralogical maturity of the sediments can be determined using zircon–tourmaline–rutile (ZTR) index [22].

The ZTR index is calculated using the following equation,

$$\text{ZTR index} = \frac{\text{No. of zircon} + \text{No. of tourmaline} + \text{No. of Rutile}}{\text{No. of non-opaque minerals}} * 100$$

The number of zircon, tourmaline and rutile are identified and counted from the thin-section of the heavy mineral sample representing each sampling site, observed using the petrographic microscope. The presence of abundant rounded zircon, tourmaline and rutile in a sample that contains few of any other heavy minerals is suggested to have subjected to an episode of intensive chemical leaching or mechanical abrasion. The intense weathering would have caused the coarse angular nature of the mineral to get spherically round nature. This morphological nature of the stable minerals confirms the maturity of sediments. Thus, the minerals which are being



subjected to long distance transport consists of stable minerals with well-rounded morphology ((i.e.,) without angular projections along the surface of the mineral)[23].

The sediments are categorized as mineralogically mature, when the calculated ZTR index value is greater than 75 % ($ZTR > 75\%$). The While, the angular shaped morphology of the zircon, tourmaline and rutile grain, with significant concentration of other heavy minerals, with ZTR index values are lower than 75 % ($ZTR < 75\%$) indicate the sediments to be mineralogically immature to sub-mature in nature[22].

X-Ray diffraction spectroscopic analysis

The XRD is one of the powerful non-destructive techniques for qualitative identification of crystalline materials. The X-Ray diffraction technique is based on the Bragg's law, which describes the diffraction of X-rays from the atomic planes acting as a three-dimensional grating. The instrument used for the XRD characterization in this study is GE - XRD3003 TT (powder X-ray diffraction) operating in standard θ - θ geometry with $Cu K_{\alpha 1}$ radiation of wavelength 1.5406 Å. The Powder XRD technique is used widely for studying the nature of polycrystalline environmental samples.

Sample preparation procedure for XRD analysis

A small quantity of the selected samples collected for this study is pulverized using an agate mortar for 15 – 20 minutes. The powdered samples were passed through a mesh of pore size 53 μm (ASTM - 270) in order to get a homogeneity in the grain size of the particles. The pulverized samples were spread on an amorphous quartz sample holder and subjected to X-Ray diffraction study.

Sample analysis procedure for XRD analysis

The X-Ray diffraction pattern obtained is plotted and the 2θ value, full width half maxima and d -spacing values of a particular diffraction pattern were compared with the JCPDS-ICDD database of PCPDFWIN – Version 2.4 (2003).

RESULTS AND DISCUSSION

Granulometric analysis

The results of the grain size distribution and granulometric analysis are listed in Table 3. Various textural parameters such as graphical mean size, standard deviation (sorting), skewness



and kurtosis are determined based on the earlier reports on the depositional environment of the sediments in order to confirm the classification [20].

Frequency Curves

Determination of the modal nature of the samples is an important parameter in representing the nature of the occurrence of the sediment. The modal nature depends upon the various particle diameters of the sediments in the sample. It is determined based on the highest peak of the sample frequency curve. The presence of several modes indicates that the sediments have been derived from several sources. The modal nature of the samples are presented in Table 3.

Based on this analysis, the study area is characterized as *unimodal* to *trimodal* in nature. The samples collected along the innershelf region of the Krusadai Island exhibit a *unimodal* nature. The intense littoral water current pattern observed along the shallow innershelf region of Pamban pass might be the responsible for the *unimodal* nature of the samples. At the same time, most of the coastal sediment samples of Krusadai Island exhibit *bimodal* nature. The mixing of the sediments, while being transported by the littoral currents or the onshore and offshore drifting by the low tides could have caused the *bimodal* nature along the Coast of Krusadai Island. However, the samples collected along the coastal stretch of the northern part of Rameswaram Island have both *bimodal* (R-H-2 to R-H-5) and *trimodal* (R-C-1) nature. This might be attributed to the sheltered environment and low tidal activity. The barricade-like protection offered by the coastal configuration along the nearshore samples of R-C-7 and R-C-9 against the intense littoral currents might have caused the redistribution of lower grain size fraction with the beach sediment samples allowing it to exhibit *bimodal* and *trimodal* nature respectively. The samples collected in the hinterland region of Rameswaram Island also seem to be *bimodal* to *trimodal* in nature.

In addition to these, the intense water current along the Pamban pass is the reason for the sampling site R-C-8 to exhibit *unimodal* nature. Further, it is suspected that the random littoral current pattern around the Adam's bridge region resulting in the onshore and offshore drifting of sediments, might have influenced the samples of the southern part of Rameswaram island to exhibit *bimodal* (R-C-13 and R-C-15) and *trimodal* (R-C-14) nature.

Graphic mean size (Mz)

The graphic mean size is a function of the size range of the available materials (sediment/soil) and amount of energy impacted to the sediment/soil, depending on the current velocity or turbulence of the transporting medium. Graphical mean size of the sediments is also influenced by the source of supply, transporting medium and the energy conditions of the depositional environment. The



graphic mean size of the sediments usually represents the index of energy conditions and is usually represented as ϕ and is categorized based on the reports by Folk and Ward [24]. The graphic mean size of the sediment/soil samples of study area ranges from *coarse sand* to *fine sand* category. From the Table 3.4, it is observed that most of the samples collected along the coastal stretch are in *coarse sand* and *moderate sand* category. This might be due to the existence of high-energy environment in the coastal zone, probably by continuous tidal action, which reduces the sedimentation of clay particles in the coastal region. Nearly, 13 % of samples in this study are *coarse sand* in nature, while about 41 % of the samples fall under *moderate sand* category and 41 % of samples are in *fine sand* category. Most of the samples collected along the hinterland region in this study fall in *fine sand* category. The accumulation of lower grain size littoral sediments (fine grains) over the coral reef present in the shallow innershelf region might have caused the samples collected along the innershelf region (K-I-1 to K-I-5) to falls under *very fine sand* and *fine sand* category. Usually, the high-energy environment existing along the beach sector because of prolonged tidal activity makes the lower grain fraction of the sediment along the coast to get dispersed and the sediment would be of *coarse sand* category. In the present study, the samples collected along the coastal stretch are moderate sand in nature and this might be due to the sheltered environment conditions existing in the study area and confirms the low tidal activity along the coastal stretch. Certain sampling sites along the Pamban Pass (K-C-6, K-C-10, K-C-12 and R-C-8) and Vaerkkoddu (R-C-12) exhibit *coarse sand* nature, which confirms the prevailing high energy, water currents in that area. This result is in accordance with similar studies as given in earlier reports[25, 26]. **Standard deviation (σ)**

The measure of the standard deviation of the grain size in samples represents the spread of the grain size distribution with respect to the mean and is also known as sorting. It is an important parameter in sediment analysis because it reflects the energy conditions of depositional environment but it does not necessarily measure the degree to which the sediment has been mixed[27]. The standard deviation values obtained in this study ranges from 0.66 ϕ to 1.42 ϕ (Table 3.4) and indicate *moderately well sorted* to *poorly sorted* nature of the sediments. This may be attributed to the mixture of finer particles of the littoral deposits of the underwater sea current, along the coast and innershelf region, and the presence of clay along the hinterland region.

Skewness (Sk)

Skewness measures asymmetry of frequency distribution and marks the position of mean with respect to median. In a material with sufficient quantity of different sizes, a *coarsely skewed* sample implies that the velocity of the deposition agent had operated at a higher value than the average velocity for a greater length of time.



Sample Id.		Sand %	Silt %	Clay %	Mode	Mz (φ)	σ (φ)	Sk (φ)	K _G (φ)	Heavy Minerals %	Opaque Minerals %	ZTR index				
K-I-1	Krusadai Island	63.4	36.3	0.3	Unimodal	FS	0.94	MSo	-0.41	VCSk	0.90	M	7.60	32.43	65.78	
K-I-2		Inner-shelf region	51.6	48.0	0.4	Unimodal	VFS	0.88	MSo	-0.60	VCSk	0.98	M	6.80	49.58	49.24
K-I-3			48.7	51.1	0.2	Unimodal	VFS	0.66	MWSO	-0.53	VCSk	1.04	M	10.60	53.25	34.73
K-I-4			55.9	43.9	0.2	Unimodal	VFS	0.85	MSo	-0.49	VCSk	1.05	M	12.40	30.26	54.96
K-I-5			83.2	16.6	0.2	Unimodal	FS	0.97	MSo	-0.17	CSk	0.84	P	8.40	44.76	38.48
K-C-6			North coast	93.4	06.3	0.3	Bimodal	CS	1.03	PSO	0.48	VFSk	1.59	VL	10.30	44.55
K-C-7		88.5		11.4	0.1	Bimodal	MS	1.30	PSO	0.47	VFSk	1.07	M	4.50	30.21	39.75
K-C-8		91.2		08.6	0.2	Bimodal	MS	1.18	PSO	0.26	FSk	1.06	M	5.20	10.34	76.12
K-C-9		South coast	86.0	13.7	0.3	Bimodal	MS	1.41	PSO	0.42	VFSk	0.94	M	7.60	30.46	61.25
K-C-10			98.0	01.8	0.2	Unimodal	CS	0.82	MSo	0.19	FSk	1.15	L	3.20	19.81	73.41
K-C-11			95.4	04.4	0.2	Bimodal	MS	0.99	MSo	0.26	FSk	1.15	L	4.60	17.56	68.58
K-C-12			96.4	03.5	0.1	Unimodal	CS	1.05	PSO	0.39	VFSk	1.19	L	3.20	10.25	71.45
K-Is-13		Hinterland	98.20	1.40	0.4	Unimodal	MS	1.01	PSO	0.20	FSk	0.96	M	2.40	19.56	54.12
K-Is-14			97.00	2.20	0.8	Unimodal	MS	0.90	MSo	0.16	FSk	1.02	M	3.80	18.46	35.88
R-C-1	Rameswaram Island	90.3	6.8	2.9	Trimodal	MS	1.37	PSO	0.36	VFSk	1.30	L	30.4	48.61	67.57	
R-H-2		Sambai	60.3	25.2	14.5	Bimodal	FS	1.36	PSO	0.11	FSk	1.55	VL	11.2	31.80	62.67
R-H-3		Olakuda	48.8	38	13.2	Bimodal	VFS	1.21	PSO	-0.15	CSk	1.51	VL	10.6	37.00	61.90
R-C-4		Akkalmadam	87.8	10.3	1.9	Bimodal	MS	1.12	PSO	0.10	FSk	1.06	M	01.5	39.06	41.02
R-H-5		Ariyankundu	55.1	33.8	11.1	Bimodal	VFS	1.25	PSO	-0.02	Sy	1.66	VL	15.8	30.95	55.17
R-H-6		Athikadu	78.8	16.4	4.8	Trimodal	FS	1.06	PSO	-0.03	Sy	0.85	P	18.4	44.93	63.16
R-C-7		Rameswaram	31	55.2	13.8	Bimodal	VFS	1.18	PSO	-0.23	CSk	1.57	VL	07.8	33.33	58.33
R-C-8		Pamban	96.6	3.1	0.3	Unimodal	CS	0.76	MSo	0.21	FSk	2.93	VL	59.6	63.29	58.60
R-C-9		Kundukal	86.3	9.9	3.8	Bimodal	FS	1.16	PSO	0.22	FSk	0.99	M	13.1	33.80	48.90
R-H-10		Thankachimadam	90.7	7.6	1.7	Bimodal	MS	1.11	PSO	0.18	FSk	1.10	M	02.7	31.10	60.78
R-H-11		Padapai	73.5	19.5	7	Bimodal	FS	1.42	PSO	0.07	Sy	1.05	M	08.2	25.64	65.50
R-C-12		Vaerkkoddu	92.7	5.5	1.8	Trimodal	CS	1.30	PSO	0.45	VFSk	1.43	L	15.4	36.23	52.27
R-C-13		MKR Chathiram	91	6.7	2.3	Bimodal	MS	1.29	PSO	0.08	Sy	1.03	M	32.5	21.51	50.68
R-C-14		Dhanushkodi	92.7	6.7	0.6	Trimodal	MS	1.08	PSO	-0.02	Sy	1.59	VL	09.4	16.44	65.57
R-C-15		Dhanushkodi End	91.9	7.8	0.3	Bimodal	MS	1.05	PSO	0.10	FSk	1.09	M	03.5	18.06	74.58
		Note: CS = Course Sand; MS = Moderate Sand; FS = Fine Sand; VFS = Very Fine Sand; MWSO = Moderately well sorted; MSo = Moderately Sorted; PSO = Poorly sorted; VCSk = Very Coarse Skewed; CSk = Coarse Skewed; Sy = Symmetrical; FSk = Fine Skewed; P = Platykurtic; M = Mesokurtic; L = Leptokurtic; VL = Very Leptokurtic.														

Table 3. The grain-size variation and heavy mineral variation of the samples collected along the Krusadai and Rameswaram Islands, India



Skewness values ascertained in this study range from -0.60ϕ to 0.48ϕ (Table 3.4). Skewness values also indicate whether the samples vary from *very coarse skewed* to *very fine skewed*. This point out the random nature of the deposition environment existing in the study area. The samples collected along the innershelf region mostly exhibit *very coarse skewed* nature, which confirms the existence of intense littoral current pattern along the innershelf region especially near Pamban pass. While, the entrapment of lower grain size particles and coral debris over the coral reef ecosystem might be the reason for the accumulation of *very fine sand* along the shallow innershelf region. Most of the samples collected along the coastal stretch of the islands have *fine skewed* to *very fine skewed* nature, which denotes the low energy condition prevailing in the study area that results in the accumulation of finer sediments along with sand proportion found in the samples. At the same time, samples collected along the hinterland are *symmetrical* in nature, representing the uniform distribution of various grain size particles along the hinterland.

Kurtosis (K_G)

The kurtosis is the peakedness of the distribution and measures the ratio between the sorting in the tails and central portion of the curve. If the tails are better sorted than the central portions, then it is termed as *platykurtic*. Whereas, it is *leptokurtic* if the central portion is better sorted, if both are equally sorted then *mesokurtic* condition prevails. From the Table 3.4, it is observed that the kurtosis values of surface sediments of the present study ranges from 0.84ϕ to 2.93ϕ (Table 3.4). The kurtosis values confirm that almost 49 % of the samples of the region to be in the *mesokurtic* category with uniform distribution, which confirm the low energy environment prevailing in the study area.

The samples collected along the coastal region are *leptokurtic* to *very leptokurtic* in nature, which further confirms the sandy nature of the coastal samples and the dominance of two or three modes of deposition. The *platykurtic* nature is observed only in certain samples collected along the innershelf region and hinterland. This confirms the varied distribution of sediments and domination of silt and clay ratio along the Inner shelf region extending between Krusadai Island and Rameswaram Island. This can be related to the random water current patterns existing in the region inducing the clay particles to get dispersed. The silt particles present in the innershelf region are formed due to the weathering action of the water currents, with the existing coral and beach rock formation.



Mineralogical analysis

The analysis of the various minerals in the samples collected for the present study reveals their actual composition and provide information about their source of origin.

Heavy mineral analysis

Heavy minerals are dense components of sediments having higher density (higher specific gravity) and are of economic importance, as they are the main sources of zirconium, titanium, tungsten and other rare earth elements. In this regard, the heavy mineral analysis was performed and it is observed to have a low concentration of the heavy minerals in Rameswaram – Mandapam coastal region. This is mainly due to the water current pattern and coastal configurations, which influence the deposition the radionuclide bearing minerals from Kerala coast along the southern coast of Tamil Nadu and constantly get decreased towards the eastern coast of Tamil Nadu [28].

The heavy mineral analysis was carried out for samples collected in the Krusadai & Rameswaram Islands. The percentages of heavy minerals recorded for various sampling sites are presented in Table 3. In the present study, it is evident that samples collected along the northern and north-western coast of Rameswaram Island have higher percentage of heavy minerals in the sediment fraction of particle size between 250 μm to 150 μm (R-C-1 = 30.5 % and R-C-8 = 59.6 %) than those collected from the other sampling sites. The samples collected along the Krusadai Island and southern part of Rameswaram Island have very low concentration of Heavy minerals.

Heavy minerals are broadly classified into two types based on the optical property as opaque and non - opaque minerals. It is observed that the opaque minerals form a considerable part of the separated heavy mineral fraction (mainly ilmenite and magnetite). The non-opaque minerals or transparent minerals are mainly composed of rutile, zircon, tourmaline, monazite, garnet, sillimanite and biotite content in addition to minor content of chloritoid and kyanite [21]. The petro-microscopic observations of heavy minerals of the Krusadai & Rameswaram Islands confirm the presence of minerals such as Zircon, Tourmaline, Rutile, Garnet, Kyanite and Opaque minerals (Ilmenite and Magnetite) as major constituents of the heavy mineral fraction of the samples. The presence of these heavy minerals suggests the charnockite and granulite rocks as their probable source[29].

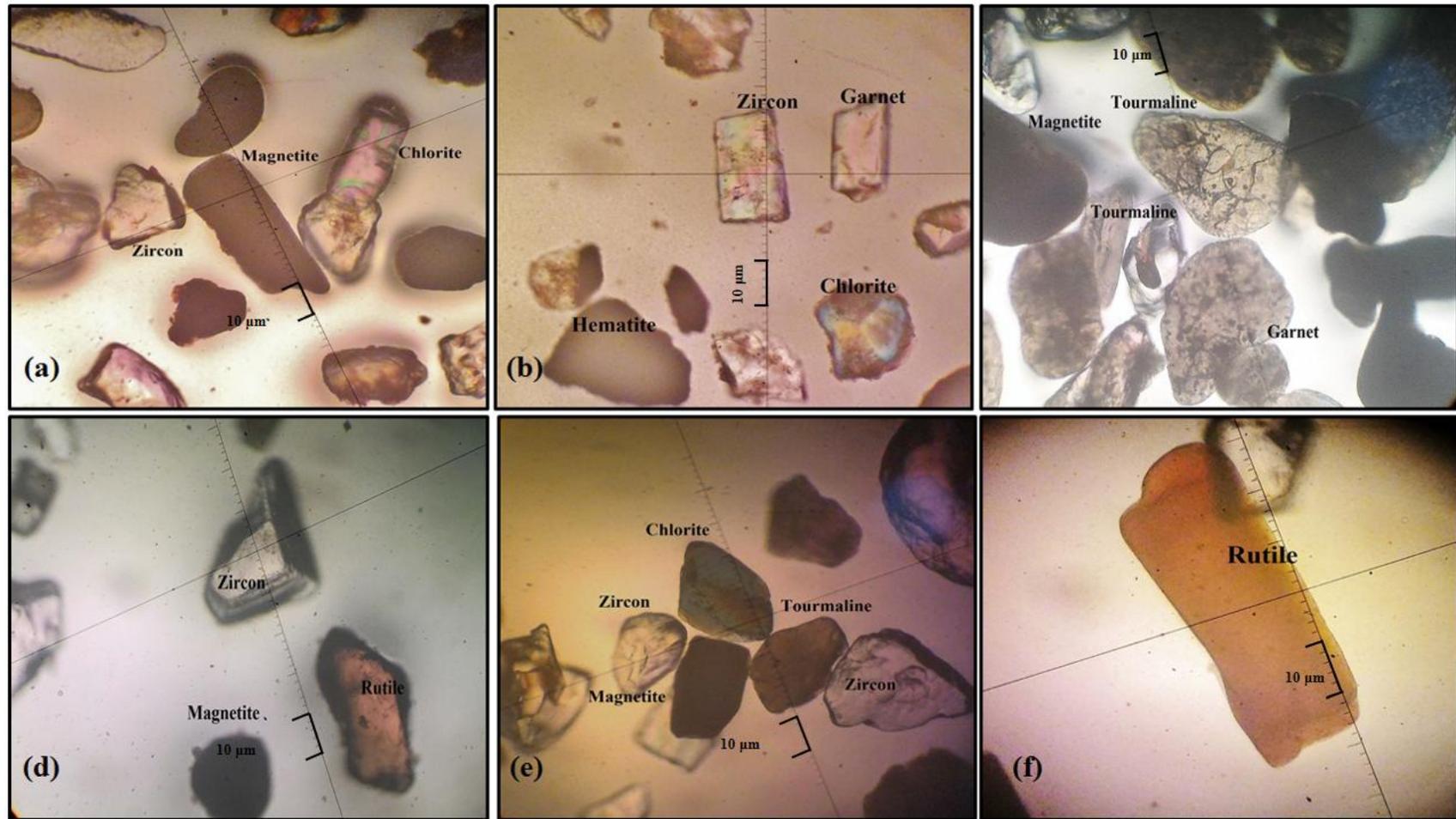


Figure 3. Photomicrographs of Heavy minerals at (a) Olakuda (R-H-3); (b) Pisasu Munai (R-C-1); (c) Pamban (R-C-8); (d) Krusadai Coast (K-C-6); (e) Vaerkkoddu (R-C-12) and (f) Dhanushkodi (R-C-14)



Based on their resistance to weathering processes such as chemical decomposition and mechanical abrasion, transparent minerals are classified into five categories as ultra-stable, stable, moderately-stable, unstable and very-unstable[21]. Accordingly, zircon, rutile and tourmaline are classified as ultra-stable minerals, as, they do not get deteriorated due to weathering processes. The presence of abundant ultra-stable minerals having a well-rounded grain morphology confirms that the sediments of the sampling site had undergone intensive chemical leaching and mechanical abrasion. Thus, the presence of zircon, tourmaline and rutile in high concentration confirms that the sediments were subjected to winnowing by strong water currents, wind pattern and other natural processes. Other stable and unstable minerals are easily affected by these processes and get dispersed. Based on this, Hubert [22] had proposed the ZTR index percentage, which states that if the ZTR index values are lower than 75 % ($ZTR \text{ index} < 75\%$), then the sediments are categorized as immature to sub-mature in nature; while, the greater values of ZTR index ($ZTR > 75\%$) indicates mineralogically matured nature of the sediments. Accordingly, when the ZTR index values are above 75 % then the heavy mineral assemblage of the sampling site is dominated by the Zircon, Rutile and Tourmaline minerals, while other minerals are more likely to be weathered and processed, confirming the maturity of the sediments.

The calculated ZTR index values for the present study is tabulated in Table 3. From the Table 3, it is inferred that the ZTR index in percentage varied between 34.73 % (K-I-3) and 76.12 % (K-C-8) for Krusadai Island. In the Rameswaram Island, it ranges between 41.02 % (R-C-4) and 74.58 % (R-C-15). For most of the samples, the ZTR index is below 75 %. Such a low ZTR index can be related to the minimal stable heavy mineral presence and confirms the sediments to be immature or sub-mature in nature[23, 30, 31]. It further confirms the minerals to have originated mostly from local bedrocks. The immature nature of the sediments in the present study area is also due to the sheltered nature of the depositional environment and the low tidal activity observed along the study area[1, 32]. The maximum ZTR index noted along the southern part of the Krusadai Island and near Dhanushkodi (R-C-15) can be related to the random littoral current pattern along the Adams Bridge near Dhanushkodi[33]. The microscopic observation of the heavy minerals as presented in Fig. 3, further reveal that the morphology of the heavy minerals encountered in the samples appear to be mostly non-spherical with angular projections (Fig. 3), which again confirms the textural immature nature of the sediments in this region and represent minimum sediment transportation by the littoral currents[34]. It further indicates that these minerals might originated from local bedrocks, re-affirming the absence of radionuclide-bearing



minerals transported from Kerala coast. Heavy minerals occurring along the coast are commonly termed as placer deposits, which mostly contain iron as one of the components in its matrix. Usually, minerals having iron (Fe) as one of its major element, such as ilmenite, magnetite and hematite, exhibit opaque property. The observed opaque mineral percentage in this study is presented in Table 3. The opaque minerals are mostly found in the northern and north-western part of the Rameswaram Island.

X-Ray Diffraction (XRD) analysis

The X-Ray diffractograms obtained for the selected samples are presented in Figure 4. The XRD patterns of the samples are compared with standard JCPDS card number. The XRD study confirms the presence of crystalline crustal silicate minerals (SiO_2 (JCPDS No. – 85-0797)) and aluminium silicates (Al_2SiO_5 (JCPDS No. – 88-0891)) as major constituent in all the samples. Calcium silicates (CaSi_2O_5 (JCPDS No. – 51-0092)) is also detected in the samples representing innershelf region of Krusadai island and Rameswaram island – east. This occurrence may be attributed to the interaction of coral environment present in the study area with the existing geomeidia. The X-ray diffraction patterns (Fig. 4 (a - e)) of the samples representing the Krusadai Island innershelf region (Fig. 4 (b)) and Rameswaram Island north, east and west (Fig. 4 (c), (e) & (f)) show prominent peaks corresponding to the quartz mineral. Aluminium silicate peaks are significantly present along with silicon dioxide peaks, which might have occurred due to the increase in aluminium silicate clay minerals. Most of the clay minerals are amorphous to semi-crystalline in nature, likely formed through the alteration of major silicate minerals such as quartz. The major iron-bearing minerals such as hematite (Fe_2O_3 (JCPDS No. – 89-8104)), ilmenite (FeTiO_3 (JCPDS No. – 89-2811)) and iron silicate mineral ($\text{Fe}_2(\text{SiO}_4)$ (JCPDS No. – 87-0320)) were identified to show significant presence in the samples of Rameswaram Island – north, Rameswaram Island – west and Rameswaram Island – east (Fig. 4 (c), (f) and (e) respectively). The presence of iron oxide minerals in the Rameswaram Island - north (Fig. 4 (c)) and Rameswaram Island - east (Fig. 3 (e)) may be attributed to unconsolidated patches of lateritic soil occurring in the northern and eastern part of Rameswaram Island. The iron oxide minerals present in the Rameswaram Island – West, is due to the deposition of placer deposits along the western coast of Rameswaram Island near Pamban coast (R-C-8).

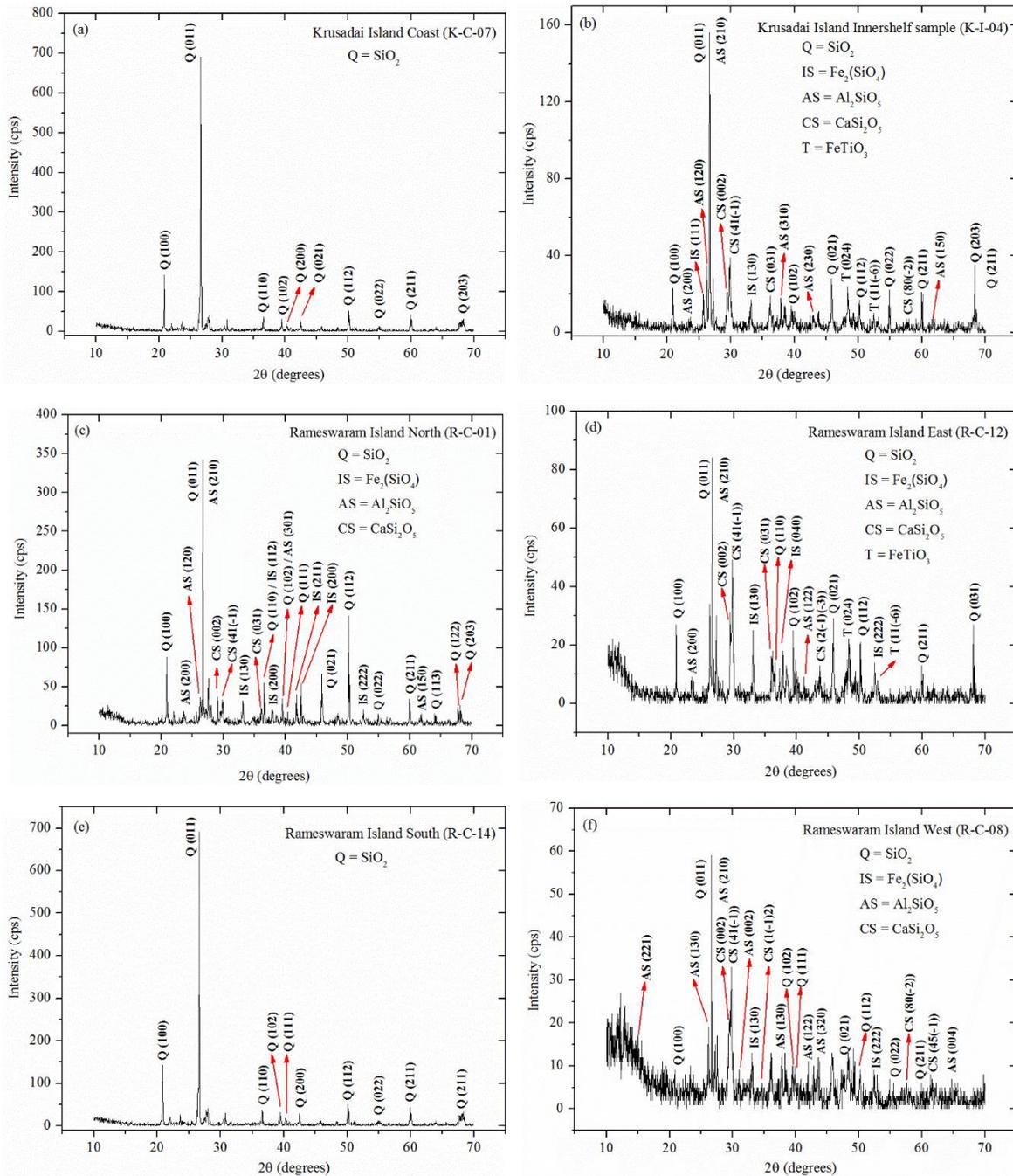


Figure 4. XRD spectrums obtained for the samples representing the various zones of the study area



CONCLUSION

The mineralogical and granulometric analyses of sediments from the Krusadai and Rameswaram Islands in the Gulf of Mannar reveal distinct variations influenced by geological setting, hydrodynamic conditions, and anthropogenic activities. The XRD results confirm that quartz (SiO_2) and aluminium silicates (Al_2SiO_5) dominate the mineral composition, accompanied by significant quantities of iron-bearing minerals such as hematite (Fe_2O_3), ilmenite (FeTiO_3), and fayalite (Fe_2SiO_4). The presence and distribution of these minerals indicate inputs from lateritic soils and placer deposits, suggesting active terrestrial and marine interactions in sediment supply.

The granulometric study shows that the sediments range from coarse to fine sand, with unimodal to trimodal frequency distributions, reflecting the influence of random littoral currents, sheltered coastal configurations, and varying energy environments. The coastal samples exhibit moderate sorting due to low tidal activity, while the inner shelf and hinterland samples show poorer sorting associated with mixed depositional processes.

Overall, the mineralogical maturity, reflected in the dominance of stable and ultra-stable minerals, indicates a high degree of sediment reworking and transport within the nearshore system. The findings highlight the dynamic sedimentary environment of the Krusadai–Rameswaram region, which plays a crucial role in shaping the local marine ecosystem. The identified mineral assemblages have direct ecological implications, influencing biological parameters such as crustacean distribution, coral health, and benthic community structure.

This study contributes to the baseline understanding of the mineralogical framework of the Gulf of Mannar, emphasizing the need for continued monitoring of sediment composition to assess future environmental changes and anthropogenic impacts on this ecologically sensitive marine biosphere.

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