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RESEARCH ARTICLE

THE IMPACT OF SEASONAL CHANGES ON HEAVY MINERALS CONCENTRATION FROM A PART OF EAST COAST OF INDIA

Ali Mohammad[a*], E.N. Dhanamjayarao[b]

[a] Research Scholar, Department of Geology, Andhra University, Visakhapatnam-530003.
[b] Professor, Department of Geology, Andhra University, Visakhapatnam-530003, India.
[*]Corresponding Author E-mail: ali.mooh89@Gmail.com; ali.mooh89@andhrauniversity.edu.in

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ABSTRACT

Pre and post monsoonal changes in the environment have led to a noticeable variation in sediment characteristics, heavy mineral concentrations and their distribution. The current study aimed to find out the effect of seasonal fluctuations on the concentration of heavy minerals along the coast and the variations in sediment textures and distribution. The study has revealed the effect of seasons on the sediments supply and its distribution along coast in the study area. The total heavy minerals concentrations are more in post monsoon than in pre monsoon and the concentration also increases from south to north in parts of the study area because of seasonal circulation of currents from south to north along the shore. The micro textural study of the heavy mineral grains from different locations in the study area revealed the mechanical and chemical erosions on the grain surfaces.

KEYWORDS

Seasonal Variations, Coastal Sediments, Texture characteristics, Heavy Minerals, Grain-Microtextures, Vishakhapatnam Coast.

1. INTRODUCTION

Climate fluctuations play a major role in the accumulation or removal of sediments in a specific area. Typically, the transport processes of big-sized and high-density sediments are active during seasons with heavy rains. Whereas, these sediments accumulate in the source area during the dry seasons. Grain size, density, and shape of the minerals also have an effect on the accumulation of heavies in different coastal environments (i.e. foreshore, backshore, and dunes). In the post-deposition stage, selective sorting and lateral transport work to concentrate the heavy minerals as placer deposits on the beach area (Bryan et al., 2007; Garzanti et al., 2009; Armstrong-Altrin et al., 2012). In general, most of the detrital minerals are formed in markedly different conditions (pressure and temperature) from the conditions on the Earth's surface (Nair et al., 2009; Andò et al., 2012). Weathering of igneous, metamorphic and sedimentary rocks by chemical, physical, and biological processes is the first step in the chain of processes that produce heavy mineral deposits (Boggs, 2006). The erosion of these rocks results in an increase in the concentrations of more resistant and higher specific gravity minerals (2.89). Physical agents (mainly rivers) transport the weathering products from their source area towards the depositional basins. Depending on the mode of origin and transportation, the placer deposits can be broadly classified into eluvial, deluvial, proluvial, alluvial, lateral (subdivided into lacustrine, beach, marine beach, and offshore placers), glacial and aeolian placers (Suresh and Raja, 2014). In general, the coastal placer deposits are the most widespread, due to the fact that most of the rivers terminate on the coastal zone, as this region is the last point of the sediments' journey.

The studies of the beach areas extremely vary around the world (Ergin et al., 2007; Örgün et al., 2007; Ibrahim et al., 2015; Ergin et al., 2018). The special characteristics of a particular beach change in time with the change of external processes, such as waves and currents. The temporal and spatial differences are not only correspondent with depositional conditions, but also with the hydrodynamic behaviour in the environment. Annual cycle of wind and seasonal changes in atmospheric circulation, which are known as *Monsoons*, are the main determiners of the beach characteristics along the east coast of India, as this coast is under two phases of stormy condition, which are South West and North East monsoons (SW and NE monsoons) (Aagaard et al., 2005; Magesh et al., 2014). SW monsoon is the major condition which produces most of beach processes. During this period, erosion becomes very active and the beach morphology changes significantly (Albino and Suguio, 2010; Gervais et al., 2012; Karunarathna et al., 2014; Jarmalavicius et al., 2016). Moreover, beach processes vary during monsoon periods and the sediment characteristics respond to these processes (Chauhan, 1995).

Thus, studying the variable parameters during successive periods can give clear perception of the beach processes, which can be used to understand the characteristics of old beaches. The modern sediments along the east coast of India contain considerable amounts of heavy minerals. The common heavy mineral placers include magnetite, ilmenite, garnet, rutile, monazite, zircon, etc. Several studies along the east coast of India have investigated the seasonal changes on the textural parameters and the concentration of heavy minerals (Chauhan, 1995; Quartel et al., 2008; Srinivasalu et al., 2010; Gandhi et al., 2011; Joevivek and Chandrasekar, 2014; Chauhan et al., 2014). By comparing these studies, it can be seen that

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the seasonal changes are not uniformed in nature. Besides being related to the monsoon, they are also related to several patterns that characterize each region such as wave height, current direction, coastal geomorphology, sediments supply, etc. Therefore, it is necessary to study each area separately and try to compare the results with neighbouring areas, thus it becomes possible to obtain a comprehensive picture of the spatial and temporal changes.

Visakhapatnam coast is located in the central part of the east coast of India. This area receives huge amounts of terrigenous materials transported from the Eastern Ghat Mobile Belt (EGMB) by major rivers, such as Sarada and Gosthani, in addition to several small streams. Moreover, this coast is considered one of the rich areas of heavy minerals (mainly, ilmenite and garnet) in the Indian peninsula (Cheepurupalli et al., 2012; Karuna, 2019). Earlier studies have investigated the concentration placer mineral deposits (i.e. garnet, ilmenite, zircon, monazite, etc.) along the coastal area between Yarada village and Bhimunipatnam (Mahadevan and Sriramadas, 1948; Sastry et al., 1987; Jagannadha Rao et al., 2005; Cheepurupalli et al., 2012; Murali et al., 2016; Rezaye et al., 2018; Karuna, 2019, Mohammad et al., 2020). These studies have found promising concentration of placer minerals in the modern sediments along Visakhapatnam coast. In spite of the multiplicity of studies in this region, the researchers only focused on studying the concentrations of heavy minerals in one season without examining the seasonal effects on the sediment characteristics and/or seasonal concentration of the heavy minerals along Visakhapatnam coast. Therefore, the present study is an attempt to examine the seasonal distribution of heavy mineral suites in sediments sourced from the beach sediments deposited in the area between the Sarada River mouth and the Gosthani River mouth. The study aims to estimate the influence of monsoon processes on the concentration of heavy minerals in the coastal sediments. This study is expected to provide economic information on the richest locations in heavy minerals that can be extracted in economic quantities. On the other hand, the micro textural study of the grain surfaces has proven its importance in determining the different environmental conditions to which these grains were subjected, such as physical and geochemical processes in the source and sedimentary regions (Madhavaraju et al., 2006; Hossain, et al., 2014; Costa et al., 2012; Hossain et al., 2020). This work also aims to determine the effect of seasonal variations on sediment characteristics, concentration and distribution of heavies in beaches along the study area.

2. The Study Area

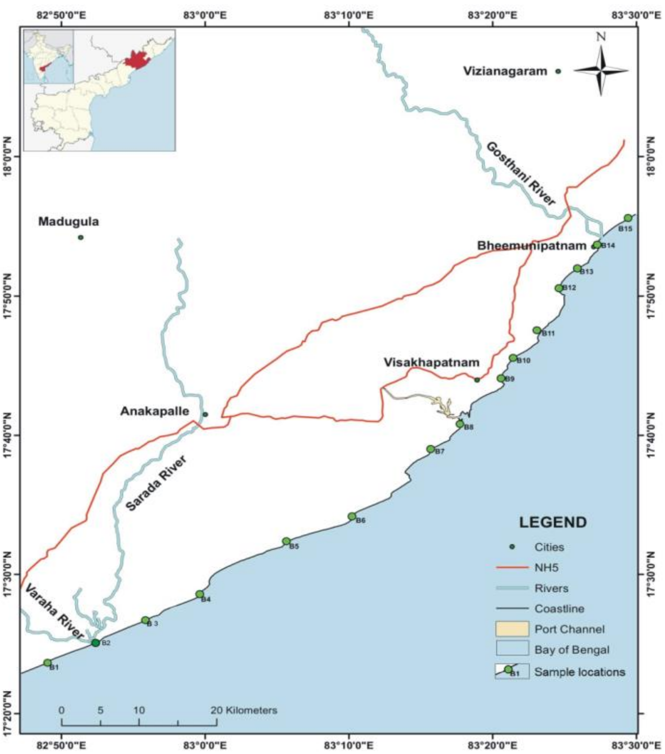

Figure 1: Location map of the study area.

The present study area is a part of Visakhapatnam coast of the Bay of Bengal (Figure 1). This coast runs roughly in the NE - SW direction with a width that varies from few meters to several tens of meters. The coastal area is characterized by numerous hills, bad land and sand dunes (Jagannadha et al., 2012). The study area is located between 17° 23' & 17° 55' N and 82° 23' & 83° 29' E with a beach stretch of approximately 100 km. Visakhapatnam is the headquarter of Visakhapatnam district and it is located in the central part of the study area, consequently, the present investigation has been divided into two parts, namely, southern and northern sectors, which are relative to the city position.

This area falls under tropical climate, i.e. humid mega thermal with seasonal rainfall controlled by the monsoon. The rainfall occurs mainly in the south-west monsoon period (July-September) and in the north-east monsoon (October). The average rainfall in the area varies from 900 to 1500 mm per year. The wave system along this area has two directions following the main direction of the wind (Suresh et al., 2012). Visakhapatnam district is located in the eastern part of the Eastern Ghat Mobile Belt (EGMB). The hills and rock bodies which are adjacent to beach area are composed of khondalites, hypersthene granites (charnockites), garnetiferous granites (leptynites), quartzites, and pegmatites. These rocks are exposed on the beach in some places, such as Revupolavaram, Pudimadaka, Yarada beach, and Bhimunipatnam.

Visakhapatnam coast exhibits many geomorphological features. These features have been classified according to the formation processes (waves, sea level oscillation, etc.). Sandy beaches, dunes and rocky beach are the main features that characterize the present study area (Jagannadha, 2012). Red sediments (or *Bad Lands*), which are located 2 km south of Bhimunipatnam (Gosthani River estuary), are the unique topography in our study area. These bad lands are recent deposits according to geological timescale with a distinctive red colour.

3. Materials and Methods

3.1 Sampling

The samples were collected during the pre-monsoon season (June, 2018) and post-monsoon season (January, 2019). A total of 82 representative surficial samples (41 each season) from three environments viz. foreshore, berm, and dune were selected to determine the heavy mineral concentrations. About 100 grams were taken from the bulk sample by coining and quartering. Every sub-sample was washed with distilled water to remove salts and suspended impurities. Free salt samples were soaked with HCl (1/10) for 12 hours to remove carbonate materials. Then the samples were soaked in H_2O_2 to remove organic matter. Later, each sample was soaked in $SnCl_2$ to remove iron coating. The dry samples were subjected to grain size analysis by standard Ro-Tap sieve shaker at ½ Ø intervals of ASTM meshes (Hegde et al., 2006).

3.2 Heavy Mineral Analysis

In order to separate heavy grains from other light grains, a heavy liquid named Bromoform ($CHBr_3$, sp.gr = 2.89) was used in this process. For this, different sizes of sieves were mixed to make the samples into two fractions (+60 coarse and +230 fine). Acetone was used to deodorize and remove the traces of the used Bromoform from the heavy mineral grains. Taking into account the fugitive character of acetone, hot air oven (60°C) was used to dry the separated heavy mineral grains. The weight percentage (wt.%) of the light and heavy minerals were calculated for each fraction. Franz isodynamic separator was used to separate the magnetic minerals, and the wt.% of these minerals has been calculated. About 200 to 300 heavy grains were mounted on a thin glass slide by using Canada balsam. Then, these slides were studied under the Petrological microscope with mechanical stage. Ribbon counting methods was used in heavy minerals counting (Galehouse, 1969). The weight percentage (wt.%) for each mineral was calculated by multiplying the occurrence number of respective minerals in the slide with its specific gravities.

3.3 Surface Microtextures Study

Scanning Electron Microscope (SEM) is one of the most reliable instruments used to study the micro-size textures on the sand surface. Four locations, namely, Revupolavaram beach, Sarada river estuary, Yarada beach and Gosthani river estuary have been chosen for this study. All the grains have been identified before fixing them on SEM stage. Gold coating is done for every grain to improve the imaging of the sample. The grain samples were analysed with JEOL, model JSM-66101LV SEM at the Advanced Analytical Laboratory, Andhra University. Microtextural features were observed with reference to the classifications (Krinsley et al., 1962a, b; 1973; Vos et al., 2014). Twenty-two features have been identified. Of these features, thirteen were a result of mechanical processes, four are of chemical origin, and five features have been formed as a result of interaction between chemical and mechanical processes.

4. RESULTS AND DISCUSSION

The sediment samples which are collected from the beach environments show variations from one environment to the other, which reflects the energy conditions of these environments. On the other hand, these changes were also found during both seasons (pre and post-monsoon) (Tables 1 and 2). In general, the mean grain size of the beach sediments is ranging from medium to fine sand with an exception at Yarada beach area, where the sediments of the three environments show abrupt change of grain size during both seasons. Sediments from foreshore environment of the study area show increase of grain size during post-monsoon season, which indicates the increase of transporting medium energy to carry coarse grains. However, berm samples consist of medium to fine sand, except for Yarada beach, where the sediments have more coarse grains.

Table 1: Textural parameters of pre- monsoon sediments from the beach area between Sarada and Gosthani rivers.

Location Name	Location No.	Pre-monsoon											
		Foreshore				Berm				Dune			
		Mean size	Sorting	Skewness	Kurtosis	Mean size	Sorting	Skewness	Kurtosis	Mean size	Sorting	Skewness	Kurtosis
Revupolavaram	L1	1.8 MS	0.604 MWS	-0.054 SY	0.892 PK	1.679 MS	0.449 WS	0.073 SY	1.004 MK	2.321 FS	0.412 WS	-0.057 SY	1.054 MK
Sarada estuary	L2	1.732 MS	0.485 WS	0.03 SY	0.958 MK	1.729 MS	0.47 WS	0.051 SY	0.953 MK	-	-	-	-
Rambilli	L3	2.762 FS	0.445 WS	0.045 SY	1.6 VLK	2.002 FS	0.518 MWS	-0.141 CSK	1.037 MK	2.524 FS	0.369 WS	-0.061 SY	1.128 LK
Pudimadaka	L4	2.498 FS	1.212 PS	-0.456 VCSK	0.911 MK	2.698 FS	0.45 WS	0.104 FSK	1.346 LK	2.784 FS	0.386 WS	0.148 FSK	1.457 LK
Muthyalammapalem	L5	2.003 FS	0.767 MS	-0.343 VCSK	0.79 PK	2.432 FS	0.467 WS	-0.165 CSK	1.197 LK	2.553 FS	0.428 WS	0.056 SY	1.212 LK
Appikonda	L6	2.406 FS	0.638 MWS	-0.319 VCSK	1.197 LK	2.631 FS	0.347 VWS	-0.015 SY	1.335 LK	2.728 FS	0.435 WS	0.046 SY	1.689 VLK
Yarada	L7	0.737 FS	0.434 WS	0.027 SY	0.909 MK	1.122 MS	0.692 MWS	0.067 SY	1.057 MK	1.333 MS	0.561 MWS	0.206 FSK	1.188 LK
Vizag Harbour	L8	1.607 FS	0.983 MS	-0.203 CSK	0.673 PK	2.323 FS	0.49 WS	-0.155 CSK	1.063 MK	-	-	-	-
Lawsons Bay	L9	2.599 FS	0.448 WS	-0.169 CSK	1.386 LK	2.465 FS	0.486 WS	-0.179 CSK	1.164 LK	-	-	-	-
Sagar Nagar	L10	0.528 CS	0.529 MWS	0.181 FSK	0.913 MK	2.048 FS	0.541 MWS	0.067 SY	0.893 PK	2.078 FS	0.53 MWS	0.108 FSK	0.932 MK
Rushikonda	L11	0.956 CS	0.654 MWS	0.098 SY	0.839 PK	1.778 MS	0.433 WS	-0.027 SY	1.067 MK	1.971 MS	0.489 WS	0.123 FSK	0.99 MK
Chepalappada	L12	1.899 MS	0.782 MS	-0.229 CSK	0.868 PK	2.172 FS	0.609 MWS	0.061 SY	0.936 MK	2.179 FS	0.609 MWS	-0.079 SY	0.937 MK
Red bed	L13	1.205 MS	0.74 MS	-0.171 CSK	1.04 MK	2.206 FS	0.577 MWS	-0.243 CSK	0.878 PK	2.309 FS	0.427 WS	-0.024 SY	0.905 MK
Gosthani estuary	L14	1.888 MS	0.595 MWS	0.016 SY	1.061 MK	2.665 FS	0.516 MWS	-0.054 SY	1.216 LK	-	-	-	-
Annavaram	L15	2.008 FS	0.677 MWS	0.024 SY	0.881 PK	2.54 FS	0.44 WS	-0.195 CSK	1.17 LK	2.139 FS	0.511 MWS	0.151 FSK	0.92 MK

* Note: Mws: Moderately well sorted, Ms: Moderately sorted, Ws: well sorted, Ps: poorly sorted, Sy: symmetrical, Fsk: fine skewed, Vfsk: Very fine skewed, Csk: Coarse skewed, Mk: Mesokurtic, Pk: Platykurtic, Lk: Leptokurtic, Vlk: Very leptokurtic.

Table 2: Textural parameters of post- monsoon sediments from the beach area between Sarada and Gosthani rivers.

Location Name	Location No.	Post-monsoon											
		Foreshore				Berm				Dune			
		Mean size	Sorting	Skewness	Kurtosis	Mean size	Sorting	Skewness	Kurtosis	Mean size	Sorting	Skewness	Kurtosis
Revupolavaram	L1	1.814 MS	0.638 MWS	0.045 SY	1.581 VLK	2.135 FS	0.459 WS	0.227 FSK	0.964 MK	2.235 FS	0.414 WS	0.14 FSK	0.88 PK
Sarada estuary	L2	2.134 FS	0.383 WS	0.23 FSK	0.925 MK	2.121 FS	0.42 WS	0.39 VFSK	0.966 MK	-	-	-	-
Rambilli	L3	1.89 MS	0.736 MS	0.009 SY	0.97 MK	2.096 FS	0.46 WS	0.239 FSK	0.976 MK	2.151 FS	0.621 MWS	0.219 FSK	1.182 LK
Pudimadaka	L4	1.696 MS	1.106 PS	-0.06 SY	0.924 MK	2.674 FS	0.588 MWS	0.001 SY	1.296 LK	2.627 FS	0.512 MWS	0.108 FSK	1.277 LK
Muthyalammapalem	L5	2.18 FS	0.853 MS	-0.263 CSK	1.308 LK	2.679 FS	0.641 MWS	0.013 SY	1.502 VLK	2.621 FS	0.452 WS	0.047 SY	1.429 LK
Appikonda	L6	2.628 FS	0.694 MWS	0.017 SY	1.201 LK	2.844 FS	0.456 WS	0.207 FSK	1.555 VLK	2.797 FS	0.491 WS	0.194 FSK	1.671 VLK
Yarada	L7	1.224 MS	0.721 MS	-0.207 CSK	1.103 MK	1.152 FS	0.73 MS	-0.02 SY	0.881 PK	2.221 FS	0.582 MWS	0.196 FSK	0.958 MK
Vizag Harbour	L8	2.18 FS	0.549 MWS	0.016 SY	0.874 PK	2.221 FS	0.588 MWS	0.251 FSK	1.206 LK	-	-	-	-
Lawsons Bay	L9	1.733 MS	0.729 MS	0.181 FSK	1.244 LK	1.964 MS	0.732 MS	0.031 SY	1.109 MK	-	-	-	-
Sagar Nagar	L10	1.234 MS	0.758 MS	-0.242 CSK	1.142 LK	2.236 FS	0.555 MWS	0.13 FSK	0.889 PK	2.213 FS	0.49 WS	0.293 FSK	0.949 MK
Rushikonda	L11	1.109 MS	0.803 MS	-0.271 CSK	0.762 PK	1.756 MS	0.411 WS	0.093 SY	1.389 LK	2.132 FS	0.388 WS	0.557 VFSK	0.966 MK
Chepalappada	L12	1.924 MS	0.576 MWS	0.268 FSK	0.898 PK	2.086 FS	0.449 WS	0.344 VFSK	0.957 MK	2.352 FS	0.592 MWS	0.046 SY	1.035 MK
Red bed	L13	1.702 MS	0.481 WS	0.104 FSK	1.35 LK	2.181 FS	0.682 MWS	0.132 FSK	0.937 MK	2.462 FS	0.521 MWS	-0.159 CSK	0.818 PK
Gosthani estuary	L14	2.209 FS	0.554 MWS	0.152 FSK	0.925 MK	2.829 FS	0.459 WS	0.069 SY	1.436 LK	-	-	-	-
Annavaram	L15	1.884 MS	0.562 MWS	0.212 FSK	1.183 LK	2.602 FS	0.471 WS	-0.117 CSK	1.208 LK	2.018 FS	0.456 WS	0.306 VFSK	1.07 MK

The berm and dune sediments exhibit a slight decrease in the mean size (fine sand); this is due to the addition of fresh sediment at the river mouth and later drifting of sediments by monsoonal generated long shore currents. This behaviour was reported by Sastry et al. (1987), where he gave an explanation of the mechanism for the movement of sediments in the beach area along the northern part of Visakhapatnam coast. In this area, foreshore micro-environment is considered as a high energy zone. The sediments that are transported along the straight coastline tend to have finer sand population, authenticate the trend of transport explained (Li and Komar, 1992). The sediments of this area are winnowed out the fine particles towards the berm by the actions of waves, which are very active in this zone, especially during the SW monsoon period.

On the other hand, wind plays an important role along the beach area, where the wind is generating normal waves, storm waves and long shore currents. During the action of the high waves (June to September), the fine particles are carried upslope as suspended materials leaving behind the very coarse particles, while the coarse and medium sand particles move on the slope in rolling motion (Friedman and Sanders, 1978). Storm and high waves during monsoon period cause a great erosion of beach; consequently, considerable quantities of beach sediments are transported as suspension by long shore currents. Thus, seasonal changes are quite common to observe in our study area as the changes on grain size are following the general direction of long shore currents from South to North. Moriarty et al. (2008) have studied the effect of seasonal variation on sediments which are transported by rivers and deposited at the collision margin area. This study revealed that the sediment budgets on beaches and continental slops are significantly associated with the seasonal input of sediments. This result can be used to describe the changes in grain size of input sediments along our study area, where the capacity of rivers varies and changes the size and sediments budget.

The seasonal sorting values from the coastal area under this study range from well to moderately sorted, where the values from foreshore range from 0.434Ø to 1.212Ø (av. 0.66Ø) during pre-monsoon (Table 1) and from 0.383Ø to 1.106Ø (av. 0.676Ø) during post-monsoon (Table 2). The sorting values from berm sediments range from 1.152Ø to 2.844Ø (av. 2.238Ø) during post-monsoon and from 0.347Ø to 0.692Ø (av. 0.49Ø) during pre-monsoon. Whereas the sorting values from dune environment vary from 0.38Ø to 0.59Ø (av. 0.48Ø) during post-monsoon and from 0.36Ø to 0.6Ø (av. 0.46Ø) during pre-monsoon. Well to moderate degree of sorting indicates that sediments contain one or two modes in equal amounts.

The variations of the seasonal sorting from beach area is mainly due to the variations on energy flow, where the area is under two types of wind systems SW (June-September) and NE (October-January). Up till now, no one have compared or even studied the beach area south of Yarada village with the northern beach. Yadhunath et al. (2014) have studied the monthly changes on the sediments' characteristics from Yarada beach. Their results came to explain the relation between the seasonal changes and sediment characteristics. Thus, most of the analysed sediments are moderately well sorted and of medium size, which corresponds with our study from same area. This moderately well sorted nature of the sediments is due to the contribution of coarser sediments from river or channel sources and mixing them with finer sands along the coast. The sand in Yarada beach is dumped on this area from two sources. The first source is from the south and north areas as this sand is transported to Yarada beach during SW and NE monsoons. The second source is the erosion of pre-existing rocks and the hills which surrounds this area by the continuous wave action.

4.1 Seasonal Distribution of Heavy Minerals from Beach Environments

The study of heavy mineral suites along the study area reveals that the predominant minerals are magnetite, ilmenite, garnet, sillimanite, rutile, zircon, and monazite. This study also shows that there is a correlation between the increase in the heavy mineral concentration and the decrease in the grain size of the sediments. The total heavy mineral (THM) weight percentage (wt.%) and the distribution of heavy minerals assemblage were studied during both seasons, i.e. pre and post-monsoon seasons from different environments.

4.2 Foreshore

The THM% during pre-monsoon ranges from 1.17 wt.% to 46.35 wt.% (av.11.48 wt.%). The weight percentage in the coarse fraction (+60) ranges from 0.15 wt.% to 35.86 wt.% with an average of 4.84 wt.% (Table 3), Ilmenite and monazite minerals show the highest concentration in the coarse fraction (32%, each), followed by rutile and magnetite. In fine fraction (+230), the weight percentage is ranging from 1.91% to 78.02%, while the average value is 18.14%, which contains 28% ilmenite, 19% magnetite, 18% sillimanite, and 16% garnet (see Supplementary 2).

Table 3: Pre-monsoon concentration of heavy mineral from the beach sediments between Sarada and Gosthani rivers.

location Name.	Sample No.	Pre-monsoon								
		Foreshore			**Berm**			**Dune**		
		Coarse Fraction	**Fine Fraction**	**THM%**	**Coarse Fraction**	**Fine Fraction**	**THM%**	**Coarse Fraction**	**Fine Fraction**	**THM%**
Revupolavaram	L1/A	0.25	2.102	1.176	0.642	3.38	2.011	0.228	9.122	4.675
Sarada estuary	L2/A	0.302	2.282	1.292	0.514	1.154	0.834	-	-	-
Rambilli	L3/A	0.34	10.782	5.561	0.502	17.438	8.97	0.42	16.498	8.459
Pudimadaka	L4/A	0.24	8.366	4.303	0.832	7.032	3.932	0.34	11.186	5.763
Muthyalammapalem	L5/A	0.32	6	3.16	1.562	13.98	7.771	0.22	4.754	2.487
Appikonda	L6/A	0.15	2.274	1.212	0.146	3.962	2.054	5.464	19.786	12.625
Yarada	L7/A	1.05	1.9098	1.48	9.434	85.032	47.233	4.724	57.51	31.117
Vizag Harbour	L8/A	1.682	4.754	3.128	35.292	59.442	47.37	-	-	-
Lawsons Bay	L9/A	1.984	7.892	4.93	35.292	59.95	47.62	-	-	-
Sagar Nagar	L10/A	0.286	7.082	3.68	15.254	56.472	35.86	20.852	55.518	38.18
Rushikonda	L11/A	3.43	24.716	14.07	5.998	12.652	9.32	11.256	42.83	27.04
Chepalappada	L12/A	15.866	14.45	25.16	44.392	77.128	60.76	22.25	51.272	36.76
Red bed	L13/A	3.062	63.618	33.34	17.234	90.54	53.89	4.934	44.2	24.57
Gosthani estuary	L14/A	9.002	37.884	23.44	14.862	77.474	46.17	-	-	-
Annavaram	L15/A	14.672	78.022	46.35	29.102	92.572	60.84	4.902	49.506	27.204
	Min	0.15	1.9098	1.176	0.146	1.154	0.834	0.22	4.754	2.487
	Max	35.866	78.022	46.35	44.392	92.572	60.84	22.25	57.51	38.18
	Av.	4.842	18.1423	11.485	14.071	43.881	28.976	6.872	32.926	19.898

The distribution of heavy minerals within foreshore sediments along the study area during post-monsoon shows increase from the southern sector towards the northern sector. The total heavy mineral percentage in the foreshore sediments ranges from 1.58 wt.% to 79.85 wt.% with an average 18.6 wt.% (Table 4). In the course (+60) fraction, the total heavy mineral weight percentage ranges from 0.016 wt.% to 62.23 wt.%. The average total heavy mineral weight percentage is 8.86 wt.%. Ilmenite is present with average value 29%, followed by magnetite (19%). Rutile and monazite are present in the coarse fraction with valuable ratios (18% and 16%, respectively), where the highest concentration was observed in the northern sector (location 15). Moreover, in the fine fraction (+230), this percentage is ranging from 3.12 wt.% to 97.46 wt.% with an average of 28.34 wt.%, which contains 34% sillimanite, 25% magnetite, and 12% ilmenite (see Supplementary 4).

Table 4: Post- monsoon concentration of heavy mineral from the beach sediments between Sarada and Gosthani rivers.

location Name.	Sample No.	Post-monsoon								
		Foreshore			Berm			Dune		
		Coarse Fraction	Fine Fraction	THM%	Coarse Fraction	Fine Fraction	THM%	Coarse Fraction	Fine Fraction	THM%
Revupolavaram	L1/A	0.526	4.268	2.397	0.254	9.662	4.958	0.27	9.13	4.7
Sarada estuary	L2/A	8.934	15.1	12.017	7.222	23.68	15.451	-	-	-
Rambilli	L3/A	0.214	6.614	3.414	0.0163	12.492	6.25	0.36	11.628	5.99
Pudimadaka	L4/A	0.18	3.156	1.67	0.428	4.322	2.37	0.514	7.534	4.02
Muthyalammapalem	L5/A	11.842	24.23	18.03	16.028	22.462	19.24	0.198	7.574	3.89
Appikonda	L6/A	0.588	4.656	2.62	1.406	8.394	4.9	1.41	9.722	5.57
Yarada	L7/A	0.038	3.124	1.58	5.778	84.752	45.26	2.986	17.11	10.05
Vizag Harbour	L8/A	4.132	4.898	4.51	37.132	42.386	39.76	-	-	-
Lawsons Bay	L9/A	0.818	6.118	3.47	9.398	73.354	41.38	-	-	-
Sagar Nagar	L10/A	0.45	10.572	5.51	37.39	85.862	61.62	28.836	59.958	44.4
Rushikonda	L11/A	1.992	5.68	3.84	2.954	16.34	9.64	3.224	34.356	18.79
Chepalappada	L12/A	0.294	5.742	3.02	1.706	11.94	6.82	15.87	34.036	24.95
Red bed	L13/A	1.366	29.08	15.22	12.464	88.856	50.66	5.606	77.584	41.59
Gosthani estuary	L14/A	5.246	17.79	11.51	53.162	91.506	72.33	-	-	-
Annavaram	L15/A	16.406	45.668	31.03	62.234	97.466	79.85	3.414	33.38	18.4
	Min	0.016	3.12	1.58	0.0163	4.322	2.37	0.198	7.534	3.89
	Max	62.23	97.46	79.85	62.234	97.466	79.85	28.836	77.584	44.4
	Av.	8.86	28.34	18.6	16.51	44.9	30.7	5.7	27.46	16.58

The spatial distribution of heavy minerals within coarse fraction shows abnormal value at Chepalappada (location 12), where the wt.% value during pre-monsoon is 15.866%. This might be due to the influence of geographical situation of this area; where the waves remove the fine fraction leaving behind coarse grains. Moreover, the high value of heavy mineral wt.% in the Sarada River estuary and Muthyalammapalem (locations 2 and 5 respectively) during post-monsoon is due to high supply of coarse heavies by this river and other streams. In addition, the concentration of heavy minerals within fine fraction reaches the highest values at Annavaram (location 15). Cheepurupalli et al. (2012) studied the distribution of heavy mineral suites at Bhimunipatnam coast. They found that the concentration of heavies increases from South to North, which is compatible with our result. In addition to the above-mentioned, they also concluded that the heavy minerals are associated with fine fraction and the most abundant minerals are opaque, sillimanite and garnet, whereas the rest minerals constitute only 15% of the total (Cheepurupalli et al., 2012). These results also support our finding.

4.3 Berm

During pre-monsoon period, the total heavy mineral weight percentage varies from 0.83 wt.% to 60.84 wt.% with an average of 28.97 wt.%. In the coarse fraction (+60), the heavy mineral weight percentage varies between 0.14 wt.% and 44.39 wt.%, while the average is 14.07 wt.%. In the fine fraction (+230), heavy minerals showed relatively very high concentrations, where these values ranged between 1.154 wt.% to 92.57 wt.%, with an average value of about 43.88 wt.%. Ilmenite mineral is the most abundant among the other heavy minerals (average 29%), where the highest concentration was found in Location 15 (Annavaram).

On the other hand, the total heavy minerals in the berm environment in the present study area during post-monsoon period have relatively high percentage compared to other environments. However, the average value of total heavy minerals during the post-monsoon season is 28.7 wt.%. The heavy minerals weight percentage within coarse (+60) and fine fractions (+230) is increasing from south to north along the study area, where the highest values are in location 15 (Annavaram).

In the coarse fraction (+60), the average total heavy mineral weight percentage is 16.51 wt.% (see Supplementary 3). Garnet shows high concentrations in the coarse fraction due to crystalline properties of this mineral. In the fine fraction (+230), the average total heavy mineral weight percentage is 44.9 wt.%. The concentration of magnetite during post-monsoon period show high values compared to that during pre-monsoon period, where the highest values are found in the northern sector on both sides of the Gosthani River mouth. This leads us to the conclusion that in the period after the monsoon, the sediment supply ratio increases, in addition to the influence of beach processes that ultimately lead to an increase in the concentration of some types of minerals in the estuaries.

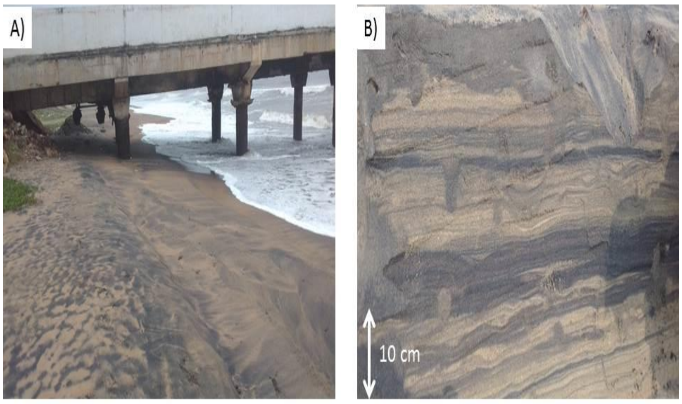

Figure 2: A. black sand from Annavaram beach, B. Alternate layers of heavy and light minerals

Alternate layers of light and dark sand (Figure 2) correspond to the seasonal changes, where the energy conditions osculate between low and high (Hegde et al., 2006). During high energy conditions, the high waves which reach the berm remove light minerals leaving the heavier ones. In this case, we can call the action winnowing waves action. Whereas during low energy condition, the waves roll back the earlier removed minerals (light minerals) and settle them down above the dark minerals. The repetition of these actions for a long period of time produces the alternate layers. On the other hand, the variations of wind energy during different seasons can also produce the same alternated layers in backshore and dunes.

4.4 Dune

The heavy mineral distribution values from dune environment along the coastal area show big variation between the coarse and fine fractions. In general, the concentration of heavy minerals increases from south towards north within dune sediments. This increase takes the same direction during both seasons. The weight percentages of heavies for the two size fractions from dune environment during both seasons are given in tables 3 and 4. The concentration of heavy minerals increases during the pre-monsoon season compared to that during the post-monsoon season, where the total heavy minerals wt.% ranges between 2.49 wt.% to 38.18 wt.% with an average of 19.9 wt.%. Magnetite and ilmenite show the highest concentrations among other heavy minerals (28% and 26%, respectively) during pre-monsoon period. On the other hand, the total heavy mineral in the dune sediments during the post-monsoon season ranges between 3.89 wt.% and 44.4 wt.% with an average of 16.58 wt.%.

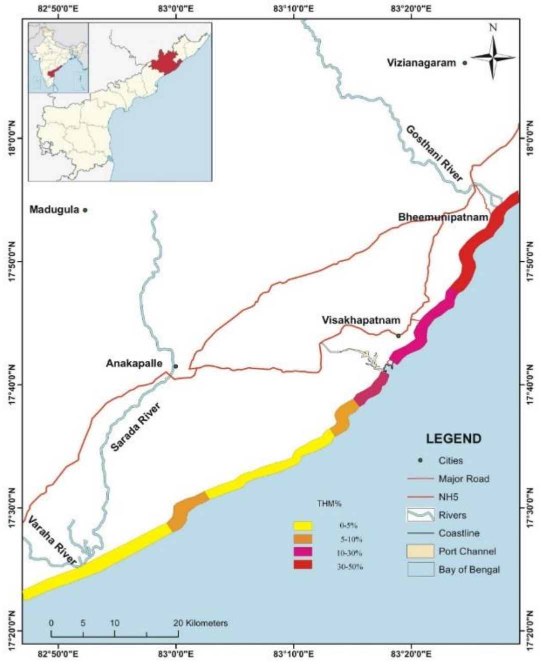

Figure 3: Pre-monsoon spitial distribution of heavy minerals concentration along the study area.

In general, dune environment receives its sediments from the winnowing action, which transports the sand grains from the beach and backshore environments when the wind direction is from sea side towards the land (Davidson-Arnott, 2019). On the other hand, when the wind is in the opposite direction (from land to sea), it works to move and transport the sand grains and other materials (silt and/or clay) from old dunes to new dunes (Friedman, 1961). However, the size and the type of minerals are associated with the energy of the wind (Appa and Karuna Karudu, 2018; Prodger et al., 2017). The spatial distribution charts of heavy minerals during both seasons show some differences between coarse and fine fractions. In general, the concentration of these heavies shows relatively low concentration in the southern sector, whereas this concentration increases towards North. However, in coarse fraction the concentration of heavies shows low values in Annavaram (location 15). In fine fraction, this concentration rises to reach relatively high values, which might be due to the decrease in the wind energy to move coarse fraction from backshore and beach towards dune environment.

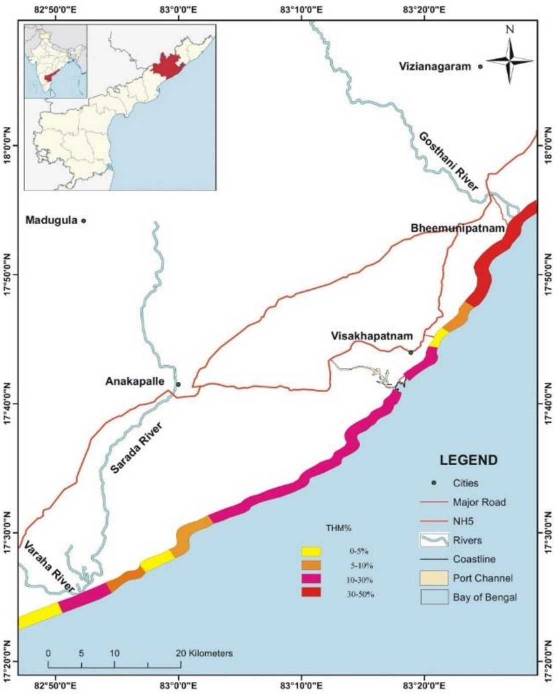

Figure 4: Post-monsoon spitial distribution of heavy minerals concentration along the study area.

Figures 3 and 4 show the spatial concentration of heavy minerals in coastal sediments during pre-monsoon and post-monsoon respectively. It is clear that the concentration of total heavy minerals is increasing from south to north along the coastal region under study. This is due to many factors, where the rate of sediments' supply and the direction of currents are the major factors that control the distribution and concentration of theses minerals. On the other hand, the seasonal changes seem to have their own impact on heavy minerals concentration. The concentration of heavy minerals is higher during the period after monsoon season. This is due to the increase in the supply rate and the increase in selective operations in the coastal region. On the other hand, the effect of seasonal changes appeared on the distribution of heavy mineral assemblages. In the coarse fraction, the concentrations of ilmenite, monazite, and rutile during pre-monsoon period (Figure 5) are higher than that during post-monsoon period (Figure 6), while the concentrations of garnet, sillimanite, and magnetite are higher during post-monsoon period. In the fine fraction, magnetite and sillimanite show wide distribution range during pre-monsoon season (Figure 7), whereas the concentration values of ilmenite, rutile, and zircon show higher values during post-monsoon season (Figure 8).

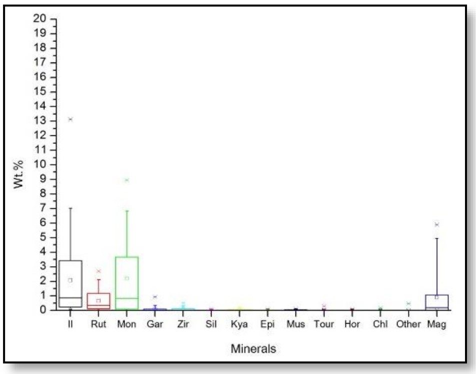

Figure 5: Pre-monsoon concentrations of heavy mineral assembleges in the coarse fraction (+60).

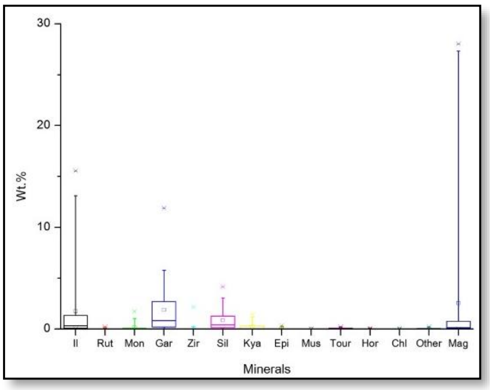

Figure 6: Post-monsoon concentrations of heavy mineral assembleges in the coarse fraction (+60).

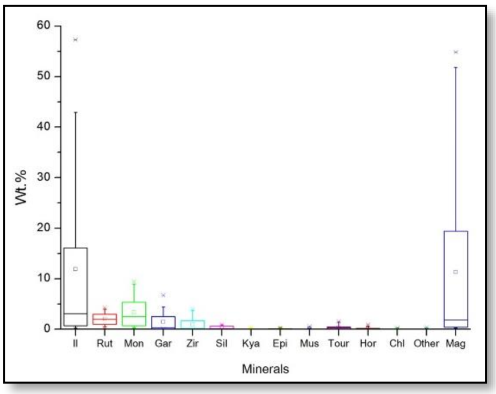

Figure 7: Pre-monsoon concentrations of heavy mineral assembleges in the fine fraction (+230).

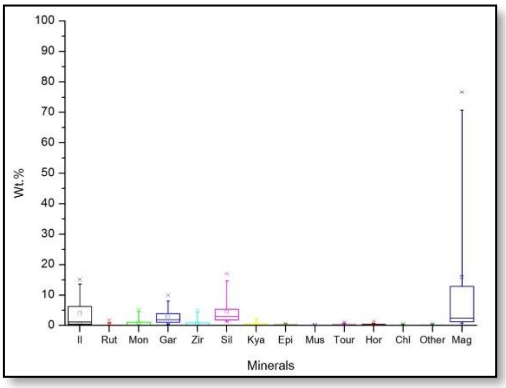

Figure 8: Post-monsoon concentrations of heavy mineral assembleges in the fine fraction (+230).

4.5 Surface Microtexture

The surface microtextures of sand grains have been used for decades to identify the diagnostic textures of particular environments (Itamiyaet al., 2019). In the later stage, after the rock fragments are released from the parent rocks, many chemical and physical changes take place on the grain surface to produce characteristic surface features. These features can be used as distinctive indicators to identify and attribute the various processes which occur during the sediments' journey from source to deposition area. Literature concerning the grain surface microtexture is replete with exhaustive laboratory investigations (Morton, 1991; Morton and Hallsworth, 1999; Dill, 2007; Costa et al., 2012; Bellanova et al., 2016; Costa et al., 2018).

Table 5: Identified microtextures and their abundance on heavy mineral grains from the study area

Location name	Heavy Minerals	Mechanical Origin	Mechanical / Chemical Origin	Chemical Origin
Revupolavaram	Sillimanite	**VA**	**A**	**AB**
	Garnet	**VA**	**P**	**C**
Sarada estuary	Monazite	**VA**	**C**	**C**
	Ilmenite	**C**	**R**	**A**
	Rutile	**VA**	**R**	**A**
	Kyanite	**VA**	**P**	**D**
Yarada	Garnet	**VA**	**R**	**A**
	Rutile	**C**	**R**	**VA**
	Zircon	**P**	**AB**	**A**
	Ilmenite	**VA**	**R**	**P**
Gosthani estuary	Ilmenite	**A**	**C**	**C**
	Garnet	**C**	**P**	**VA**
	Zircon	**C**	**C**	**A**
	Monazite	**A**	**P**	**C**

Note: VA: very abundant (>75%), A: Abundant (75-50%), C: Common (50-25%), P: Present (25-5%), R: Rare (<5%), AB: Absent

Depending on these investigations, the surface microtextures occur on detrital minerals (heavy and/or light) due to three factors. These factors are named depending on their formation origin, namely, mechanical, chemical and mechanical/ chemical origins (Table 5). In general, the mechanical and chemical marks on the grain surface are associated with the crystal structure of the mineral and also with its cleavages. Thus, the minerals with low abrasion resistance degree are more vulnerable to attrition and chipping (Krinsley and Doornkamp, 1973). The chemical features originate from the long/short interaction of grains with one or more of the chemical agents such as sea water, rain water or interstitial water. Moreover, the mechanical features are generally due to the collision between grains and with the riverbed rocks. These features occur during transportation and also after deposition.

We have studied the surface microtextures from four locations chosen from the beach of our study area. These locations are Revupolavaram beach, Sarada river estuary, Yarada beach and Gosthani river estuary. The surface microtextures show dominance of mechanical features. Most features are present as associations rather than in isolated forms. Garnet grins from Revupolavaram beach show extremely variable and rough surfaces. These features resulted from breaking the edges, impact-V pits and grooves (Figure 9, C and D). On the other hand, sillimanite grains show prismatic shape with smooth fracture surfaces with some solution bits as shown in Figure (9, A and B). From the above-mentioned results, we can conclude the importance of crystal structure of grains during transportation in determining the final shape of the grain.

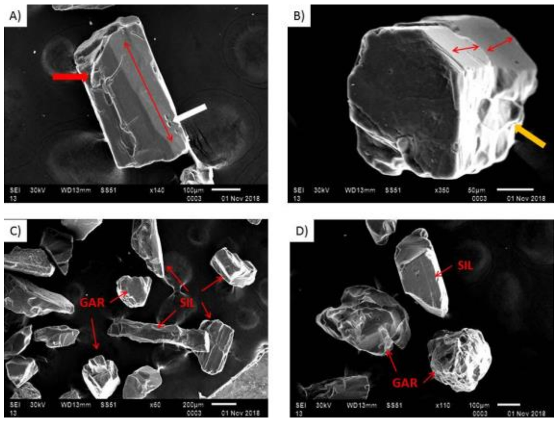

Figure 9: surface microtextures of heavy minerals from Revupolavaram beach .(A) and (B) Prismatic sillimanite grain shows conchoidal fractures, Arcuate steps (red arrow) and the main feature on the grain surface is fracture plates. (C) and (D) irregular grains of garnet and sillimanite with numerous mechanical features on their surfaces.

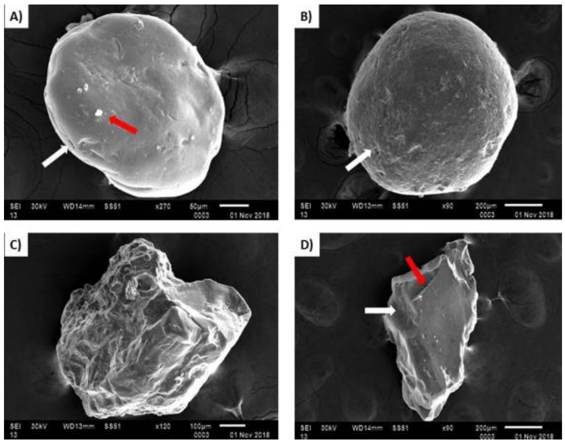

Figure 10: Surface microtextures of heavy minerals from Sarada river estuary. (A) Sub-rounded monazite grain shows small pits, Adhering particles (red arrow) and curved scratches (white arrow. (B) Rounded ilmenite grain with small pits and solution pits (arrow). (C) Rutile grain shows angular shape with some rounded edges and numerous conchoidal fractures, upturned plates and v-shape pits. (D) Kyanite grain shows elongated-angular shape with collision pits, arcuate steps (white arrow) and straight steps (red arrow).

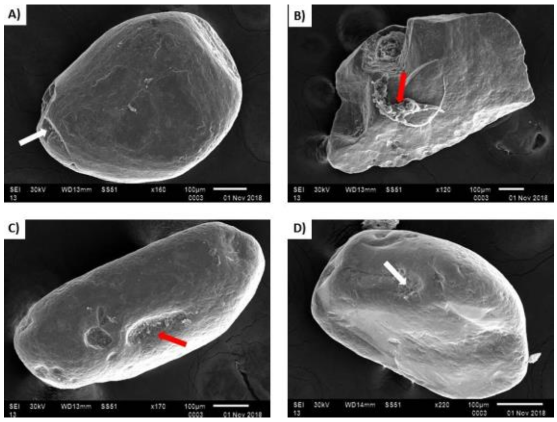

Figure 11: Surface microtextures of heavy minerals from Gosthani river estuary. (A) Ilmenite grain shows rounded shape with flakes features on the surface and straight steps (arrow). (B) Angular garnet grain shows crystalline overgrowth (red arrow), chemical solution and v-shape pits. (C) Sub-rounded zircon grain shows solution hole (red arrow) and big & small pits. (D) Sub-rounded monazite grain shows solution pits (arrow) and reworked conchoidal fractures.

Studied minerals from Sarada and Gosthani estuaries (Figure 10 and Figure 11) represent transported minerals through the river which are not subjected yet to beach processes (i.e. waves and dissolution in salty water). In this environment, the surface textures are depending mainly on the stability of the minerals. Grains from both estuaries show rounded (Anhedral) to sub-rounded grains. The rounded shape and edges are resulted specifically from the rolling motion of grains during transportation period. Many researchers have referred to the changes on the mineral surface as a result of the mechanical actions during transportation (Cardona et al., 2005; Andò et al., 2012; D'Haen et al., 2012; Costa et al.,2013; Gärtner et al., 2017). These changes are abrasion or attrition, where the size of the grains gradually decreases with the increase of the transportation distance. In additional to mechanical surface textures, theses grains also show numerous chemical morphologies, such as, solution pits, hollows and irregular solution surfaces. Monazite from both estuaries show rounded edges, solution pits and curved grooves on its surface. The garnet grains show euhedral morphology with conchoidal features. Crystalline overgrowth on garnet grains is a characteristic feature on the grain surface. In all locations, Ilmenite shows rounded morphology with solution pits.

In Yarada beach, which is considered an erosional area throughout various seasons (Ganesan and Raju, 2010), heavy mineral grains seem to be highly affected by chemical processes (Figure 12). Chemical textures are the dominant on the surface of these grains (solution pits and hollows). Garnet grains show sub-rounded outlines. These rounded edges appear contrary to what we noticed on Sarada and Gosthani estuaries. Thus, we can attribute these features to the high impact of the wave actions. On the other hand, mechanical processes have formed lots of features on these grain surfaces, such as, small pits, conchoidal fractures and scratches, which can be noticed on the garnet, rutile and zircon grains (Figure 12-A, B, C).

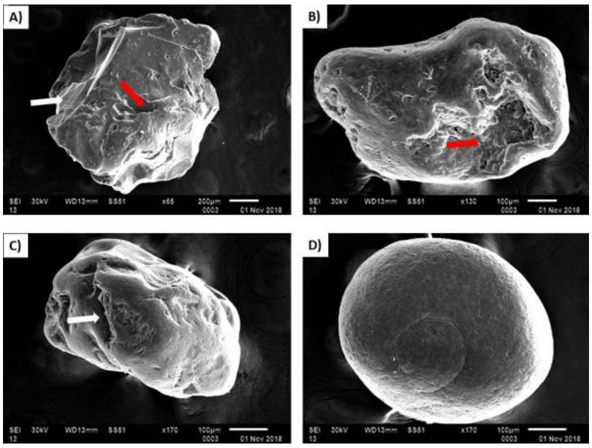

Figure 12: Surface microtextures of heavy minerals from Yarada beach. (A) Garnet grain shows sub-angular surface with rounded edges, this grain shows conchoidal fractures, straight scratches (white arrow) and big size curves (red arrow). (B) sub-rounded rutile grain shows big chemical hole and crystals growth (red arrow) and medium pits. (C) Sub-rounded zircon grain shows straight grooves (arrow) and reworked conchoidal fractures. (D) Rounded ilmenite with numerous small pits and chemical solution.

5. Conclusion

Seasonal studies of modern sediments from a part of Visakhapatnam coast, east coast of India revealed that the sediment characteristics and heavy mineral concentrations in the study area are associated with fluctuations in seasonal monsoons. The grain size parameters of these coastal sediments decrease from pre monsoon to post monsoon. As the concentration of heavy minerals are associated with size and sorting of the sediments, the grain size parameters also effect the distribution of heavy minerals. The total concentration of economic heavy minerals (such as magnetite, ilmenite, garnet and zircon) varies in these two seasons. Pre monsoon is characterized with relatively high concentration of heavy minerals when compared to post monsoon. The total concentrations also vary spatially, where the concentration of heavies increases from south to north along the study area.

In addition to the seasonal changes, there are other factors, i.e. sediment supply, selective sorting and circulation of currents along the shore that affect the distribution and concentration of these heavy minerals. Study of the grain morphology and surface micro textures of heavy minerals revealed the effect of the environment, i.e. energy and erosional processes on the surface of heavy mineral grains. The grain microtextures of the heavy minerals from the Sarada and Gosthani estuaries show the dominance of mechanical features, as these grains were subjected to long distance transport. The microtextures from the coastal area also shows the effect of mechanical and chemical erosion. Hence, the microtextural features on the surface of heavy mineral grains can be used to distinguish between the coastal and fluvial environments.

Article Highlights

- This paper deals with modern sediments along the coastal area of Visakhapatnam, East coast of India, and the seasonal changes in the sediment properties.
- Significant and potential concentrations of valuable heavy minerals have been found within the present study area.
- The main aim of this paper is to identify the effect of seasonal fluctuations on the concentration and distribution of heavy minerals in the beach region.

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Conflict of Interest

The corresponding author states that there is no conflict of interest.

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