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TEXTURAL AND CONCENTRATION PATTERN OF HEAVY MINERALS IN BEACH AND DUNE SANDS OF CYCLONE PRONE AREA ALONG NORTHERN PARTS OF ANDHRA PRADESH COAST, INDIA

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Abstract

In this paper, an attempt is made to study the textural and grain size distribution, heavy mineral distribution pattern and chemical characteristics of representative samples collected from different village areas such as Kalingapatnam, Bandaruvani peta, Komaravani peta, Mogadal padu, Vatsavalasa, Chinna vastavalasa and Yerraguddi in a coastal stretch of 20 kms from NE side of Kalingapatnam town to SE side of Srikurmam in Srikakulam District, Andhra Pradesh, India. The results of these studies indicate that the percentage of magnetic heavy minerals is significantly more compare to non-magnetic heavy minerals in all beach sand samples collected from Kalingapatnam to Yerraguddi. It is also observed that distribution pattern (concentration) of ilmenite in beach sand decreases from Kalingapatnam (4.9%) to Yerraguddi (1.8%), whereas percentage of garnet increases from Kalingapatnam (10.6%) to Yerraguddi (15.6%). Zircon concentration is almost constant in beach and dune sand samples from Kalingapatnam coast to Yerraguddi. Thus these deposits contain economic minerals such as garnet, ilmenite, sillimanite, rutile and zircon in order of abundance. The results of rougher spirals using sea water for recovery of the total heavy minerals (THM) indicate that a concentrate contains 98% THM by weight with 22.7% yield and 89% recovery from a composite sample containing 25% THM.

Key words: *Beach sand, Dune sand, Heavy minerals, Ilmenite, Garnet and Zircon.*

1. Introduction

Kalingapatnam town, which is a cyclone prone area (18° 20' 0" North, 84° 7' 0" East) and Srikurmam, a tourist place (18° 16' 0" North, 84° 1' 0" East) are situated along the south east coast in Srikakulam District, Andhra Pradesh, India [1] (Fig. 1).

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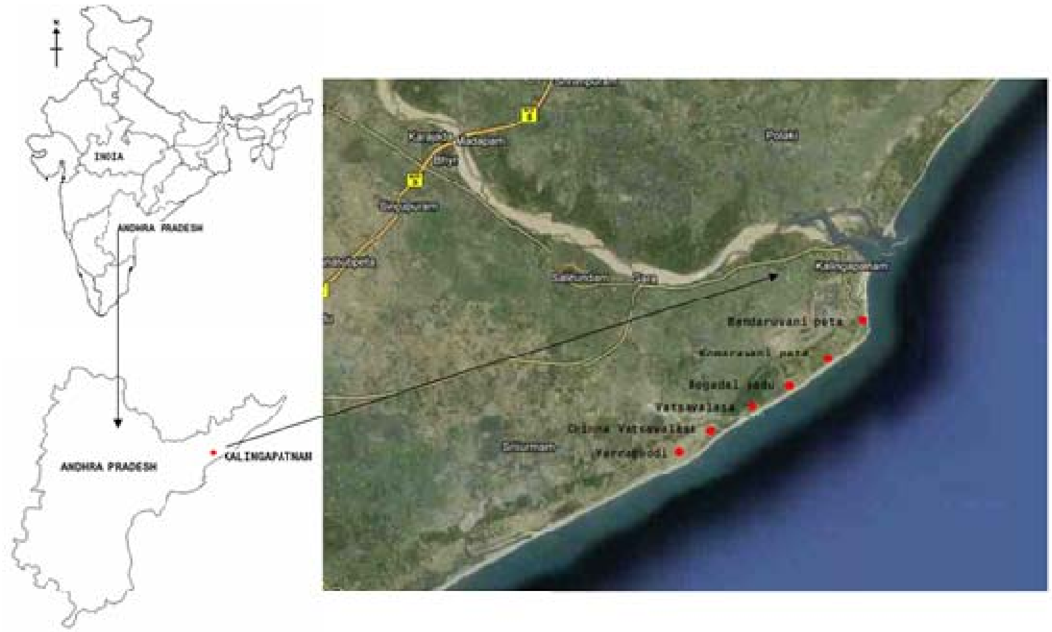


Figure 1. *Sample location map of Kaligaptaman-Yerraguddi coastal area in Srikakulam District, Andhra Pradesh, India*

There are two beneficiation plants are being operated by private owners one lies at Chinna Vastavalasa by M/s Trimax Industries Private limited to recover ilmenite, garnet, sillimanite, rutile and zircon minerals [2]. The other one lies at Srikurmam by Trans World Garnet (India) Private Limited, to recover garnet minerals only [3]. Both these plants are lying in between Kalingapatnam - Srikurmam coast of the present study area. The area can be morphologically sub divided in to dunes, beach (back shore and fore shore), near shore and off shores. Typical beach and dune morphological photos are shown in Fig. 2. This coast is essentially consists of placer alluvial and unsorted fine to medium grained, rounded to sub-rounded sand mixed in varying degrees with heavy minerals (ilmenite garnet, sillimanite, rutile, zircon) and light minerals (quartz and feldspar). The sandy coastal beach plain extends from the Ocean edge to the river Vamsadhara. River Vamsadhara (also called Bansadhara in Orissa) is an important east flowing river between Mahanadi and Godavari, in Southern Orissa and North Eastern Andhra Pradesh states in India. The river originates near Lanjigarh village in Kalahandi district of Orissa and runs for a distance of about 254 kilometers and joins the Bay of Bengal at Kalingapatnam, Andhra Pradesh. Name of this river originates from words bansa (bamboo) and dhara (water flow). This river originates from forests with bamboo trees. So, it was named as Bansadhara in Oriya and transliterated as Vamsadhara in Telugu. The area between Kalingaptnam and Srikurmam is characterised by a number of well-developed sand dunes.

2a) Kalingapatnam coast (ilmenite mineral rich)

2b) Density stratification at grab sampling, Kalingapatnam coast

2c) Komaravani peta coast

2d) Komaravani peta coast (fine garnet minerals)

2e) Yerraguddi coast (garnet mineral rich)

2f) Yerraguddi dune (garnet mineral rich)

Figure 2. *Typical beach and dune morphological area*

These sand dunes occupy considerable area along the coastal plain and are more or less parallel to the sea coast. These beach and dune sands have variable range of heavy minerals like garnet, ilmenite, sillimanite, rutile and zircon in order of abundance.

Many authors have studied the heavy minerals of this coast as well as on beneficiation studies to recover individual heavy minerals [4-9] Most of the work related to exploration on heavy minerals but not published the correlation between the particle size distribution of total heavy minerals, magnetic and non magnetic heavy minerals, very heavy and light heavy minerals and the geo chemical behavior with TiO_2, ZrO_2, SiO_2, Fe_2O_3 etc.

Since this area is situated between two perennial rivers such as Nagavali and Bamsadhara and agriculturally, it is a fertile land and hence the area is always known for rice producing land in the district. This area has good habitation with well connected roads and infrastructure facilities like schooling and medical aid. Both technical and non technical people are available for employment in the activities of sand mining in and around the adjoining areas. Hence any attempt to study the heavy mineral concentration pattern and its potentiality for industrialization is an important task. In this paper an attempt has been made to study on the textural and concentration pattern of heavy minerals in beach and dune sands of cyclone prone area along northern parts of Andhra Pradesh coast, India and its possibility to preconcentrate the heavy minerals using sea water spirals.

2. Materials and methods

The representative thirty bore hole samples (fifteen beach and fifteen dune samples), containing heavy minerals, were collected by the grab sampling method up to the water table from different village areas such as Kalingapatnam, Bandaru-vani peta, Komaravani peta, Mogadal padu, Vatsavalasa, Chinna vastavalasa and Yerraguddi in a coastal stretch of 20 Kms from NE side of Kalingapatnam town to SE side of Srikurmam in Srikakulam District, Andhra Pradesh, India. About 25 kilograms of the sand samples were collected from each location. All the samples were washed with fresh water before characterization studies as the sample contains around 0.1% of salt. Physical properties such as bulk density, true density and angle of repose along with size analyses of all the samples were carried out using standard sieves. The d_{80} percent passing size of each grab sample has been calculated from the size analysis data. Each close size range of the grab samples were subjected to sink-float studies. Heavy liquid separation studies were carried out using bromoform (specific gravity 2.89) for determining the total heavy minerals present in the feed samples. Magnetic separation studies were carried out using dry high intensity magnetic separator using Permroll magnetic separator, developed by ELB-YANTV and supplied by Ore Sorters (Australia) Pty., Ltd. Mineralogical studies were carried out by X-ray Diffraction (PANalytical, X-Pert X-ray powder diffractometer with Mo-Kα radiation). Elemental analyses of the samples were carried out by XRF (PANalytical; PW2440 (MagiX PRO).

In order to study the response to recovery of total heavy minerals by using sea water spirals, an attempt was made to prepare bulk (composite) feed sample from all the samples collected at different locations. Initially an attempt was made to reject lean tailings by using cleaner spirals. Subsequently, the tailings were subjected to scavenging spirals and recovered the final total heavy minerals.

3. Results and discussion

a) Textural and grain size distribution

The heavy mineral concentrates are found as discrete dark patches (Fig. 2a) within beach sands consisting dominantly of quartz and ilmenite. In the cross section of the grab sampling points the discrete dark heavy mineral layers occur with alternate dark black and brownish white bands (Fig. 2b) whose thickness varies from 1 to 5 cm. Typical grain size distribution for beach sand and dune sand samples and heavy minerals present in beach and dune sand samples are presented in Fig. 3 for Kalingapatnam, Komaravani peta and Yerraguddi coastal areas.

It is seen from Kalingapatnam beach sand sample (Fig. 3a) that the size frequency mode gradually increases from 300 µm to 150 µm (maximum) and gradually decreases to 75 µm size range. The heavy mineral size frequency mode in beach sand (Fig. 3a) apparently starts from 150 µm and maximum at 75 µm size range and then sharply falls down to 45 µm. The observation for dune sand is not much similar to beach sand. The maximum size frequency mode observed is at 210 µm for dune sand (Fig. 3b). The heavy mineral size frequency starts from 210 µm (150 µm for beach sand). However, the maximum size frequency mode in dune sand is at 75 µm, as observed earlier for beach sand.

The observation for beach sand sample collected from Komaravani peta (Fig. 3c) indicate that the highest size frequency mode is at 300 µm and for heavy minerals 100 µm is the highest frequency mode. The dune sand sample (Fig. 3d) shows the highest frequency mode is at 210 µm and for heavy minerals the highest frequency mode observed is 75 µm size range.

The beach sand sample collected from Yerraguddi at distance of 20 Km from first sample location (Kalingapatnam) point, indicates bimodal frequency modes at 300 µm and 100 µm (Fig. 3e). The heavy mineral size distribution mode indicates that the frequency mode is at 300 µm (where coarse garnets are concentrated) followed by 100 µm and 75 µm. The highest size frequency mode (150 µm) is observed for both dune sand sample and for heavy minerals present in dune sand (Fig. 3f).

Size frequency modes of all samples collected from beach and dune sand samples and the heavy minerals present in these samples are shown in Figs. 4 and 5. It observed from the Figs. 3 to 5 that the size frequency modes are distinctly differ for beach and dune sand samples as well as heavy minerals present in these samples. Thus it is concluded that the heavy minerals and light mineral (quartz) are distinctly varying in size range from Kalingapatnam to Yerraguddi sampling area.

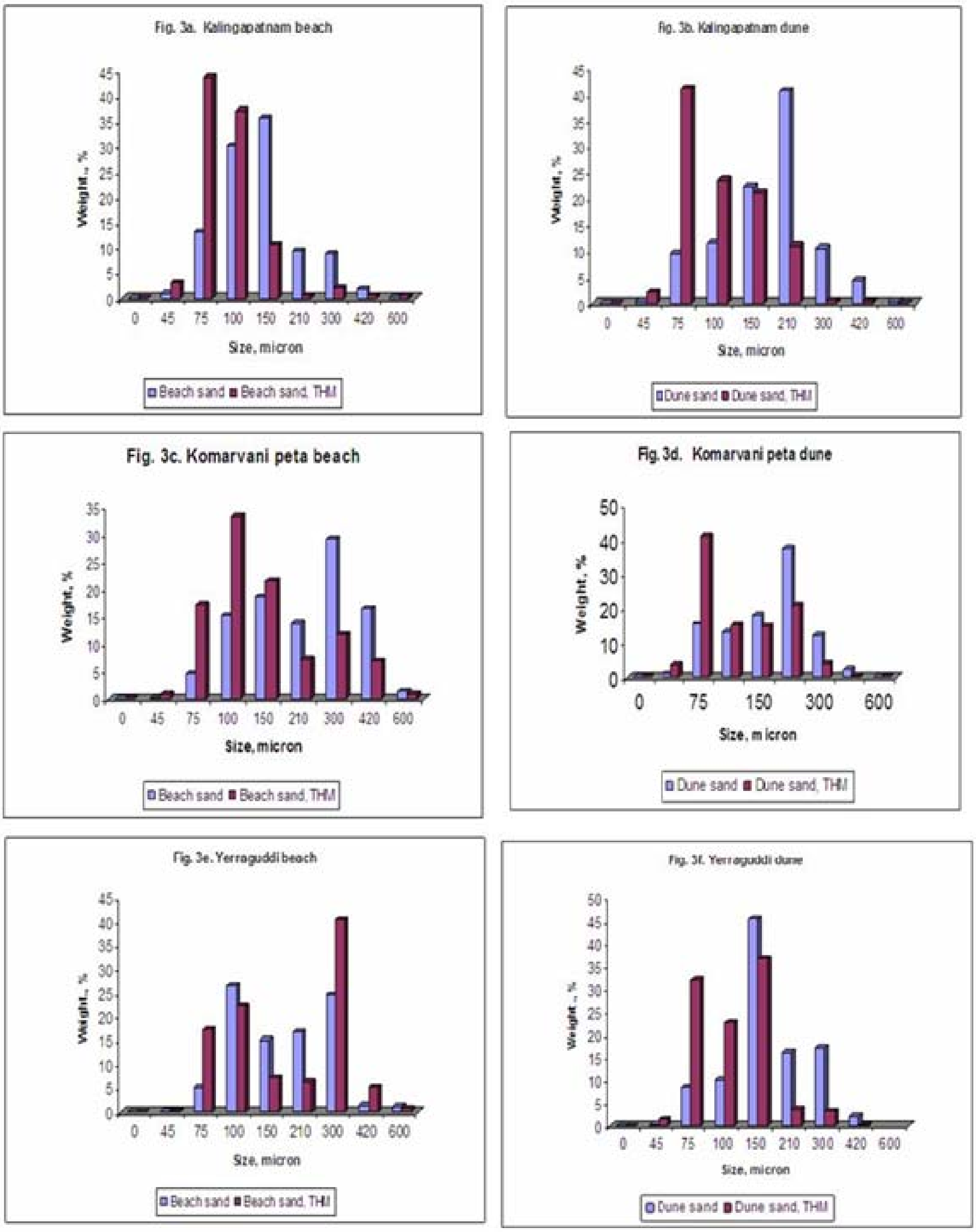
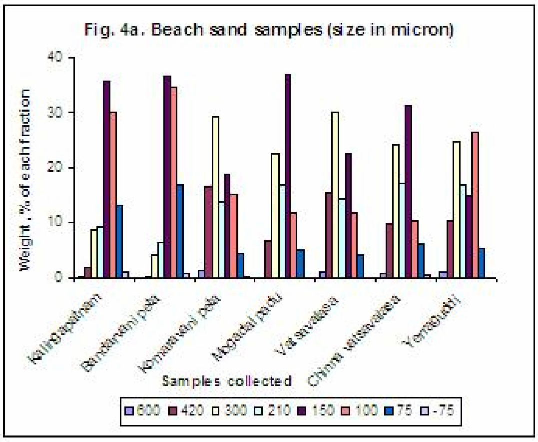


Figure 3. *Grain size distribution and heavy minerals present in beach and dune sand samples*



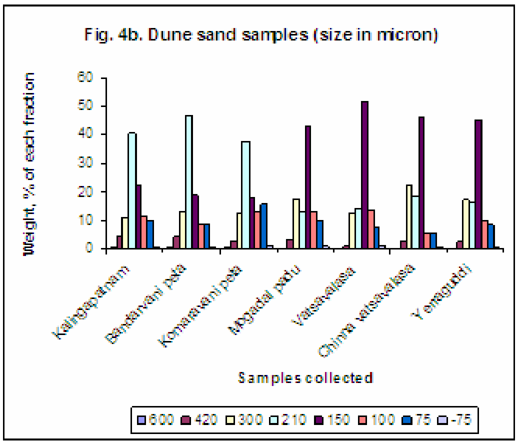
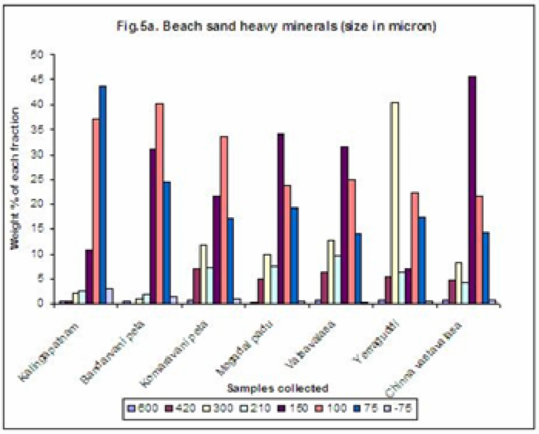


Figure 4. *Grain size distribution of the beach and dune sand samples*



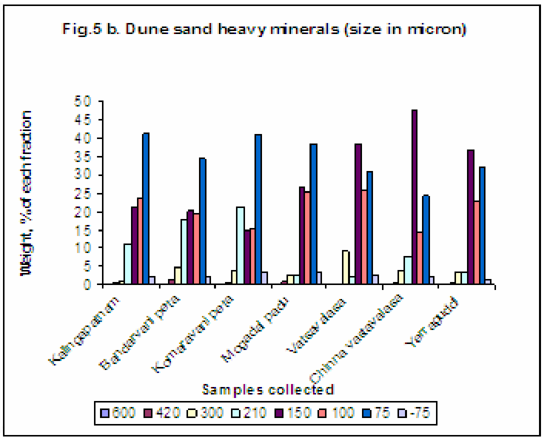
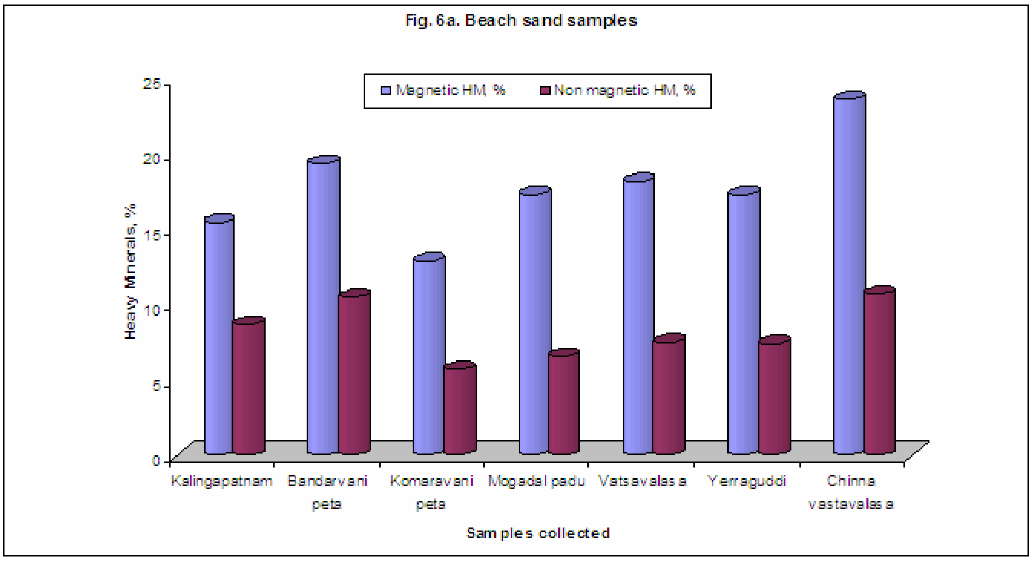


Figure 5. *Distribution of heavy minerals in the different size fraction of the beach and dune samples*

All the grab samples collected from beach and dunes of different villages from Kalingapatnam to Yerraguddi subjected to a gravity separator for recovery of total heavy minerals, which has been further subjected to dry high intensity magnetic separator to collect magnetic heavy and non magnetic heavy minerals separately and the data are presented in Figs 6a and 6b. It can be seen from Fig. 6a where magnetic and non-magnetic heavies of beach sand data presented, indicate that the percentage of magnetic heavy minerals are significantly more compare to non-magnetic heavy minerals. The trend is similar for magnetic heavy minerals in dune sand (Fig. 6b). It is interestingly observed that the percentage of non-magnetic heavies are almost same with magnetic heavy minerals for Kalingapatnam, Komaravani peta, Vatsa-valsa and Chinna Vatsavalasa. The sillimanite is the maximum mineral concentration in the non-magnetic heavy minerals.



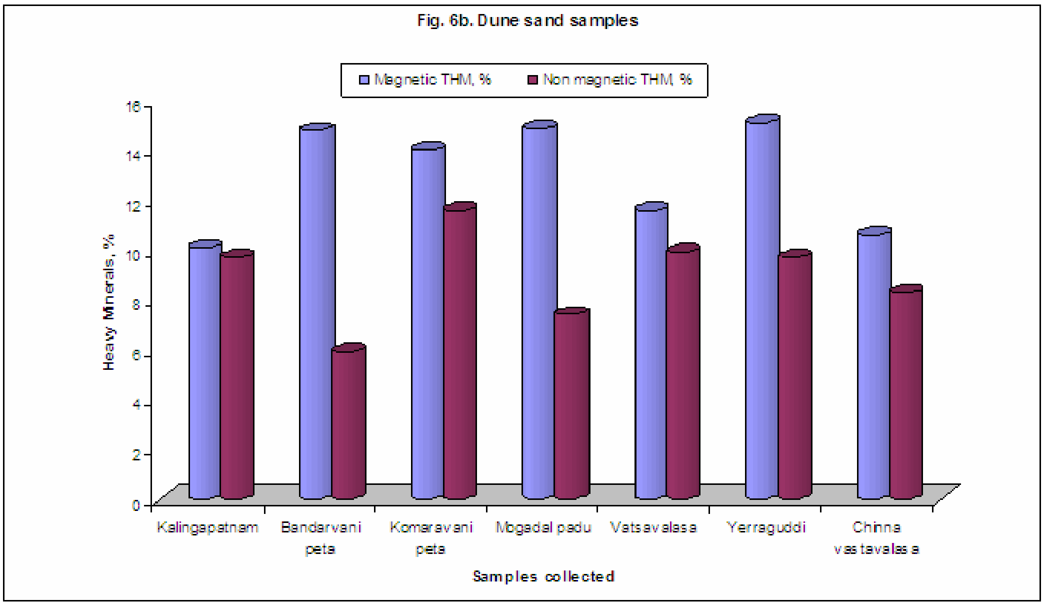


Figure 6. *Content of heavy minerals in magnetic and nonmagnetic fraction of beach and dune sand samples*

The physical properties such as true density, bulk density, porosity and angle of repose for all the grab samples of beach and dune are given in Tables 1 and 2 respectively. The d_{80} passing size of each grab sample is correlated with physical properties of the sample especially with true density of the sample.

The distribution pattern for true density of minerals present in the beach and dune sand samples are shown in Figs. 7 and 8.

***Table 1.** Physical properties of the beach sand samples of Andhra Pradesh*

Sample	d_{80} (μm)	Bulk density (gm/cc)	True density (gm/cc)	Porosity (%)	Angle of repose(degree)
Kalingapatnam	220	1.6	2.8	42.9	16.7
Bandaruvani peta	190	1.63	2.85	42.8	18.7
Komaravani peta	410	1.63	2.76	40.9	15.1
Mogadal padu	342	1.65	2.85	42.1	17.2
Vatsavalasa	400	1.67	2.76	39.5	15.6
Chinna vastavalasa	360	1.64	2.72	39.7	13.5
Yerraguddi	380	1.66	2.71	38.7	16.7

***Table 2.** Physical properties of the dune sand samples of Andhra Pradesh*

Sample	d_{80} (μm]	Bulk density (gm/cc)	True density (gm/cc)	Porosity (%)	Angle of repose (degree)
Kalingapatnam	290	1.66	2.71	38.7	14.6
Bandaruvani peta	280	1.65	2.63	37.3	15.1
Komaravani peta	280	1.64	2.89	43.3	15.1
Mogadal padu	310	1.63	2.9	43.8	15.6
Vatsavalasa	235	1.66	2.85	41.8	15.1
Chinna vastavalasa	320	1.65	2.75	40.0	14.6
Yerraguddi	300	1.6	2.6	38.5	14.6

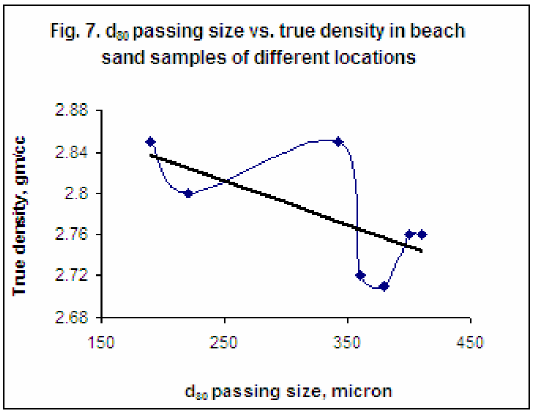


***Figure 7.** d_{80} passing size vs. true density in beach sand samples of different locations*

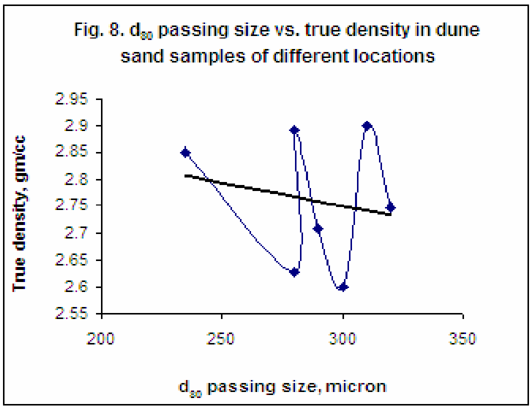


***Figure 8.** d_{80} passing size vs. true density in dune sand samples of different locations*

It can clearly be seen from these Figs. 7 and 8, that with increase of particle size (d 80 passing size 200 μm to 400 μm) the true density of minerals is falling down.

This observation can be expected as with increasing particle size, the total heavy mineral concentration decreases and the gangue minerals (Quartz, Feldspar etc.) whose specific gravity (2.6gm/cc) increases. Hence, the decrease in true density of the samples is justified. As expected, the percentage of THM present in beach or dune sand samples show a decreasing trend (Figs. 9 and 10) from a d_{80} passing size 200 µm to 400 µm.

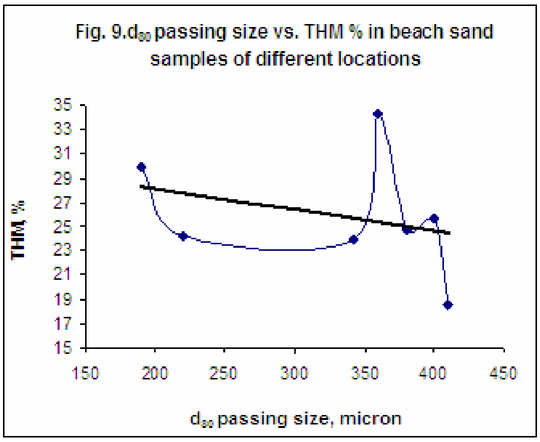


Figure 9. *d_{80} passing size vs. THM % in beach sand samples of different locations*

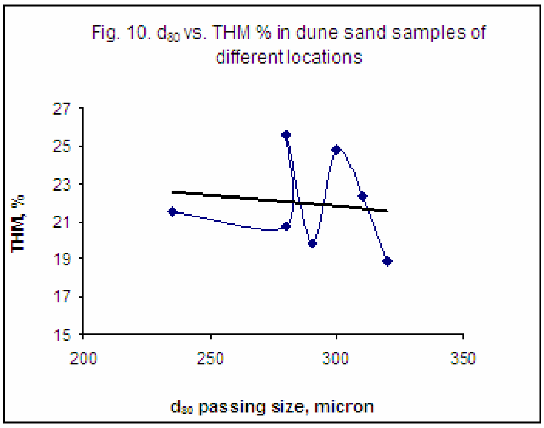


Figure 10. *d_{80} passing size vs. THM % in dune sand samples of different locations*

This observation is supported from sink float data that the THM are concentrated more in finer fractions.

The distribution pattern for magnetic heavy minerals present in the beach and dune sand samples, shown in Figs. 11 and 12 indicate that the grain size of the magnetic minerals closely follows with the d_{80} passing sizes of the samples from 200 µm to 400 µm.

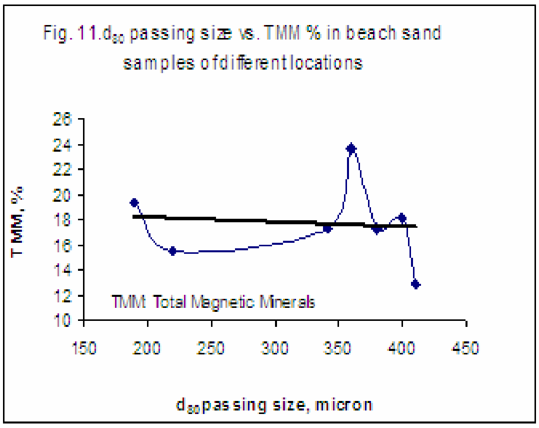


Figure 11. *d_{80} passing size vs. TMM % in beach sand samples of different locations*

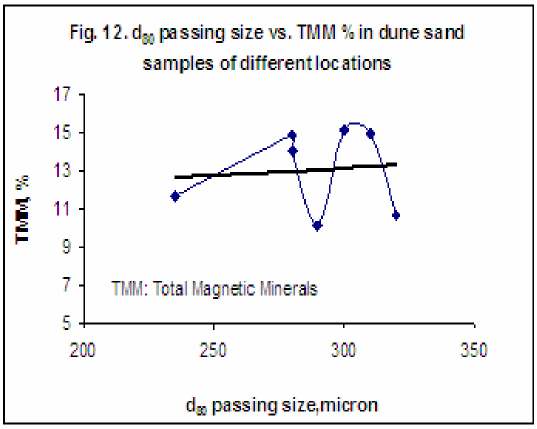


Figure 12. *d_{80} passing size vs. TMM % in dune sand samples of different locations*

This observation is distinctly differing for non magnetic heavy minerals present in beach and dune sand samples. Figs.13 and 14 represent the data for non magnetic heavy minerals of beach and dune sand minerals with d_{80} passing sizes from 200 µm to 400 µm.

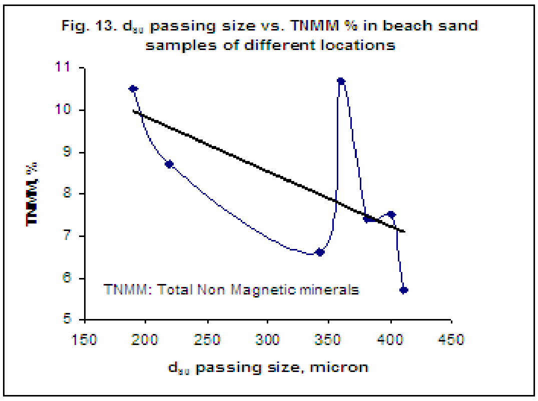


Figure 13. *d_{80} passing size vs. THMM % in beach sand samples of different locations*

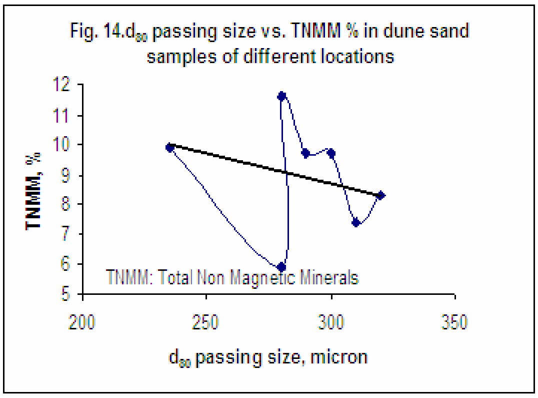


Figure 14. *d_{80} passing size vs. THMM % in dune sand samples of different locations*

It can clearly be seen from these Figs. 13 and 14 that with increase of particle size (d_{80} 200 µm to 400 µm) the percentage of non magnetic heavy minerals are falling down. This observation indicates that the magnetic heavy minerals are relatively coarser than the non magnetic heavy minerals.

b) Heavy minerals distribution pattern

Mineralogical studies carried out using XRD pattern on these heavy minerals obtained from beach as well as dune; indicate the presence of almandine garnet, ilmenite, sillimanite, rutile and zircon (Fig. 15).

Each grab sample collected from different locations of beach and dune has been subjected to sequential sink-float separation at 2.89 and 3.3 specific gravities and the results are given in Tables 3.

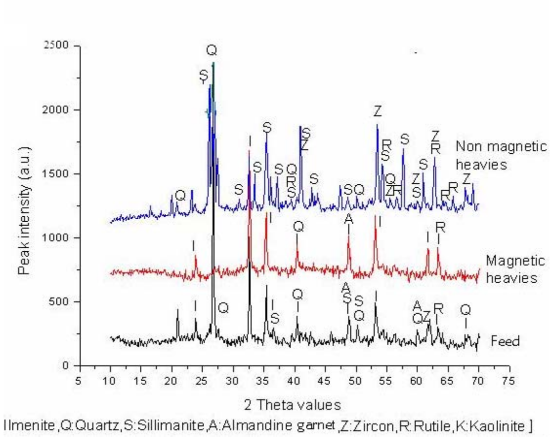


Figure 15. *X-ray diffraction data on feed heavies, magnetic heavies and non-magnetic*

The distribution of mineralogical modal analysis of all grabs samples collected from different villages from Kalingapatnam to Srikurmam is determined by microscope. The distribution pattern of beach placer minerals and dune placer minerals in different locations of the study are given in Tables 4 and 5.

Similarly, the distribution of heavy minerals present in beach placer minerals as well as dune sand placer minerals are also given in Tables 6 and 7. The data are analyzed in terms of distribution pattern trend for individual heavy minerals in beach and dune sand samples of different locations.

Table 3. *Results of sequential sink-float studies assessment of heavy mineral concentration in beach and dune sand samples*

Sample	*Light heavy minerals [%]		**Very heavy minerals [%]	
	Beach	Dune	Beach	Dune
Kalingapatnam	9.4	10.9	8.9	14.8
Bandaruvani peta	14.0	8.9	11.8	15.9
Komaravani peta	2.5	14.1	11.5	16.1
Mogadal padu	1.3	12.7	9.6	22.6
Vatsavalasa	2.8	11.8	9.7	22.9
Chinna vastavalasa	7.2	10.3	8.6	27.1
Yerraguddi	6.8	14.5	10.3	17.9

*Light heavy minerals: >2.9 and < 3.3 specific gravity minerals
** Very heavy minerals: >3.3 specific gravity minerals

Table 4. *Distribution of beach placer minerals in different locations of the study area (average)*

Minerals	Kalingapa-tnam (%)	Bandaru-vani peta (%)	Komara-vani peta (%)	Mogadal padu (%)	Vatsava-lasa (%)	Chinna vastavalasa (%)	Yerra-guddi (%)
Ilmenite	4.9	6.8	3.0	3.0	1.7	1.0	1.8
Garnet	10.6	12.6	9.9	14.3	16.5	22.6	15.5
Sillimanite	7.9	8.8	4.7	5.7	6.4	9.3	6.4
Rutile	0.3	0.7	0.4	0.3	0.3	0.3	0.2
Zircon	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Others	0.4	0.8	0.5	0.5	0.7	1.0	0.7
Quartz	75.8	70.1	81.4	76.1	74.3	65.7	75.3
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 5. *Distribution of dune placer minerals in different locations of the study area (average)*

Minerals	Kalingapa-tnam (%)	Bandaru-vani peta (%)	Komara-vani peta (%)	Moga-dal padu (%)	Vatsava-lasa (%)	Chinna vastavalasa (%)	Yerra-guddi (%)
Ilmenite	2.9	6.0	3.3	5.5	3.1	2.1	4.2
Garnet	7.2	8.8	10.7	9.4	8.5	8.5	10.9
Sillimanite	9.1	5.4	10.8	6.9	9.5	7.9	9.1
Rutile	0.2	0.2	0.3	0.1	0.2	0.1	0.2
Zircon	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Others	0.3	0.2	0.4	0.3	0.1	0.2	0.3
Quartz	80.2	79.3	74.4	77.7	78.5	81.1	75.2
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 6. *Distribution of beach placer heavy minerals in different locations of the study area (average)*

Minerals	Kalingapa-tnam (%)	Bandaru-vani peta (%)	Komara-vani peta (%)	Moga-dal padu (%)	Vatsava-lasa (%)	Chinna vastavalasa (%)	Yerra-guddi (%)
Ilmenite	20.2	22.8	16.1	12.6	6.6	2.9	7.3
Garnet	43.8	42.1	53.2	59.8	64.2	65.9	62.8
Sillimanite	32.6	29.4	25.3	23.9	24.9	27.1	25.9
Rutile	1.2	2.3	2.2	1.3	1.2	0.9	0.8
Zircon	0.4	0.7	0.5	0.4	0.4	0.3	0.4
Others	1.7	2.7	2.7	2.1	2.7	2.9	2.8
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 7. *Distribution of dune placer heavy minerals in different locations of the study area (average)*

Minerals	Kalinga-patnam (%)	Bandaru-vani peta (%)	Komara-vani peta (%)	Moga-dal padu (%)	Vatsava-lasa (%)	Chinna vastavalasa (%)	Yerra-guddi (%)
Ilmenite	14.7	29.0	12.9	24.7	14.4	11.1	16.9
Garnet	36.4	42.5	41.8	42.2	39.5	45.0	44.0
Sillimanite	46.0	26.0	42.1	30.9	44.2	41.8	36.7
Rutile	1.0	1.0	1.2	0.4	0.9	0.5	0.8
Zircon	0.5	0.5	0.4	0.4	0.5	0.5	0.4
Others	1.5	1.0	1.6	1.3	0.5	1.1	1.2
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Distribution pattern trend of ilmenite in beach and dune sand samples is shown in Fig. 16. It is seen that the ilmenite concentration is decreasing from NE Kalingapatnam to Yerraguddi (SE Srikurmam, 20 Km distance from Kalingapatnam). The decrease in ilmenite mineral concentration trend is more significant in beach sand than dune deposits.

The distribution pattern trend of garnet present in both beach and dune sand, shown in Fig. 17, indicate that the garnet concentration is increasing from Kalinga-patnam coast to Yerraguddi. The garnet mineral concentration trend is more significant for beach sand compare to dune sand.

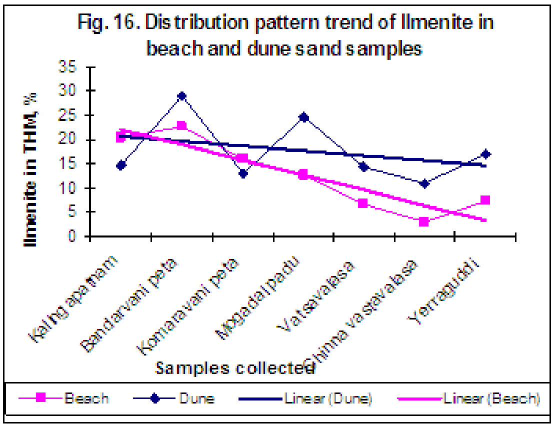


Figure 16. *Distribution pattern trend of ilmenite in beach and dune sand*

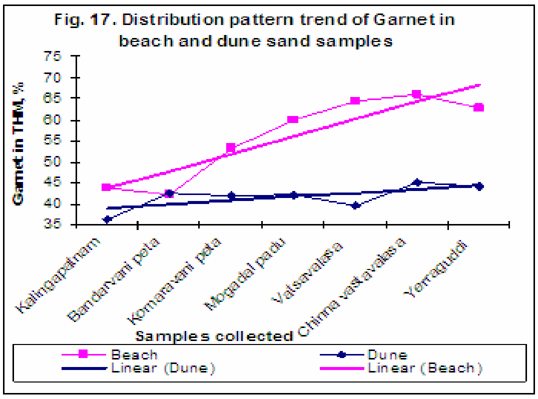


Figure 17. *Distribution pattern trend of garnet in beach and dune sand*

The concentration of sillimanite in beach sand and dune sand from Kalingapatnam to Yerraguddi has shown diverse nature. It is observed that in beach sand, the sillimanite mineral concentration is decreasing, where as the sillimanite concentration is increasing in dune sand. This can clearly be seen from Fig. 18, where the distribution pattern trend for sillimanite mineral is shown from samples collected from beach and dune sand.

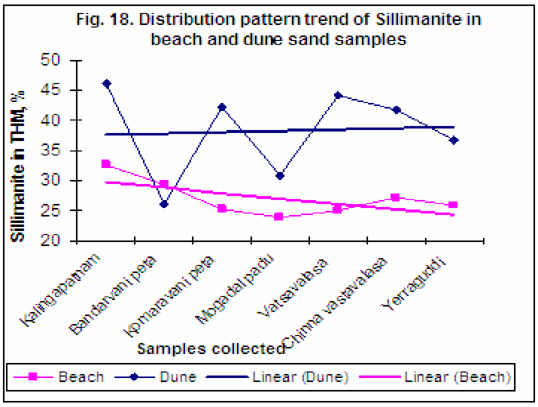


Figure 18. *Distribution pattern trend of sillimanite in beach and dune sand*

The distribution pattern trend for rutile mineral concentration in beach and dune sand samples shown Fig. 19 indicate that rutile mineral concentration decreases from Kalingapatnam coast to Yerraguddi for samples collected from beach and dune.

The zircon mineral concentration (percentage in the total heavy minerals) in the beach and dune sand samples collected from Kalingapatnam coast to Yerraguddi is shown in Fig. 20. The data indicate that the zircon concentration is almost constant in beach and dune sand samples collected from different locations at stretch of 20Kms.

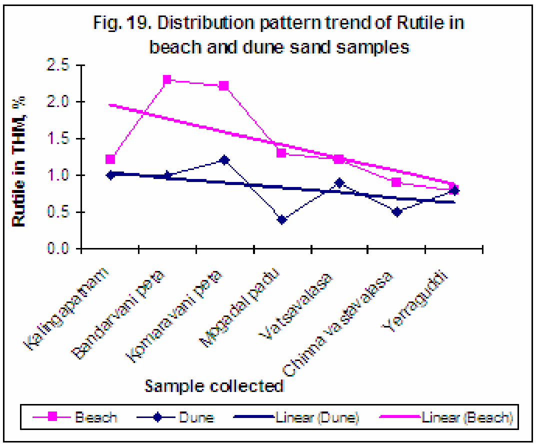


Figure 19. *Distribution pattern trend for rutile in beach and dune sand samples*

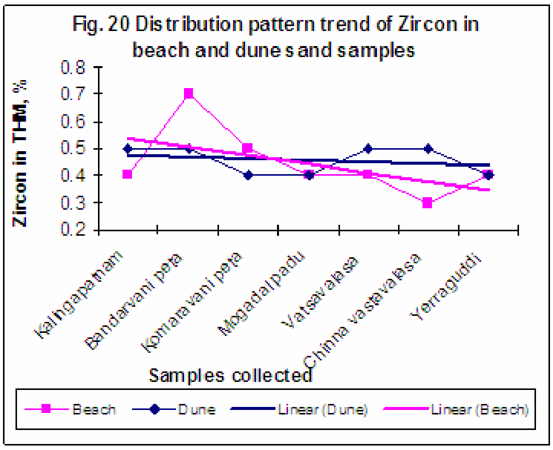


Figure 20. *Distribution pattern trend for zircon in beach and dune sand samples*

It can be concluded from Figs. 16 to 20 that garnet mineral is significantly concentrating in beach towards SE direction of Kalingapatnam; where Trans World Garnet Company is operating to recover garnet from the beach sand. Concentration of garnet mineral in the beach can clearly be seen in Fig. 2c.

c) Chemical characteristics

Chemical analysis of the magnetic very heavy minerals, non magnetic very heavy minerals and non magnetic light heavy minerals of beach and dune sand samples of Kalingapatnam to Yerraguddi coastal stretch are given Tables 8 and 9.

The results of chemical analysis are correlated with reference to particle size distribution (d_{80} passing size, µm) and possible mineral concentration. The data are presented in Figs. 21 to 25.

The distribution pattern of TiO_2 and ZrO_2 content with reference to d_{80} passing sizes of the beach and dune sand samples are seen.

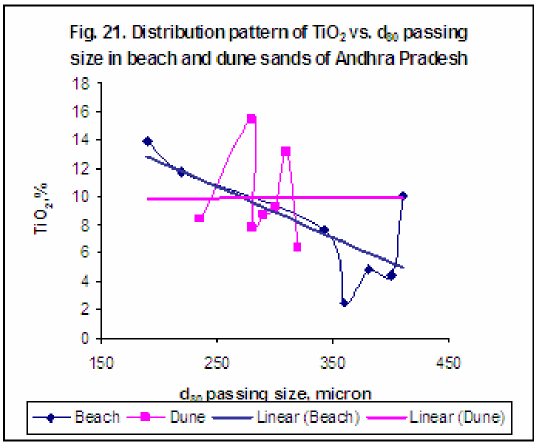


Figure 21. *Distribution pattern of TiO_2 vs d_{80} passing in beach and dune sands of Andrhra Pradesh*

It is interesting to note from Fig. 21 that the percentage of TiO_2 content decreases with increasing d_{80} passing size for beach sand and for dune sand the TiO_2 content closely follows the particle size.

Similarly, ZrO_2 content decreases with increasing d_{80} passing size for beach sand and for dune sand the ZrO_2 content closely follows the particle size (Fig. 22).

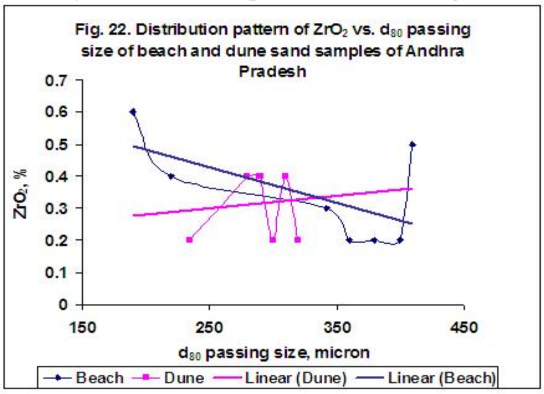


Figure 22. *Distribution pattern of ZrO_2 vs d_{80} passing in beach and dune sands of Andrhra Pradesh*

The correlation between TiO_2 and Fe_2O_3 in the magnetic heavy minerals (mostly garnet and ilmenite) is plotted in Fig. 23.

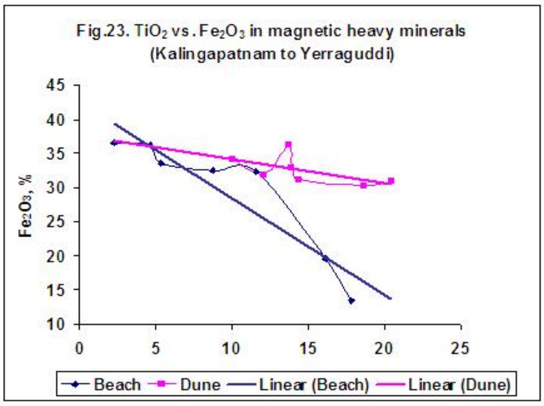


Figure 23. *TiO_2 vs. Fe_2O_3 in magnetic heavy minerals*

Table 8. *Typical chemical analysis of sequential sink-float products of beach sand samples*

Sample area	Products	Wt, %	Al_2O_3 %	Fe_2O_3 %	MgO %	SiO_2 %	TiO_2 %	ZrO_2 %	HfO_2 %
Kalingapatnam	Non-magnetic very heavy minerals	0.8	16.1	9.5	1.1	27.9	38.9	6.27	0.139
	Non-magnetic light heavy minerals	7.9	57.8	0.6	0.4	40.6	0.5	0.04	0.081
	Magnetic heavy minerals	15.5	20.1	19.5	4.0	40.1	16.1	0.18	0.004
	Total	24.2	32.3	13.0	2.7	39.9	11.8	0.30	0.030
Bandaruvani peta	Non-magnetic very heavy minerals	1.7	17.3	10.4	1.2	27.6	36.6	6.99	0.135
	Non-magnetic light heavy minerals	8.8	52.2	1.0	0.4	45.2	0.8	0.38	0.087
	Magnetic heavy minerals	19.4	24.9	13.5	3.4	40.2	17.8	0.20	0.004
	Total	29.9	32.5	9.6	2.4	40.9	13.9	0.60	0.040
Sample area	Products	Wt, %	Al_2O_3 %	Fe_2O_3 %	MgO %	SiO_2 %	TiO_2 %	ZrO_2 %	HfO_2 %
Komaravani peta	Non-magnetic very heavy minerals	1.0	17.0	12.8	1.3	27.1	34.2	7.50	0.149
	Non-magnetic light heavy minerals	4.7	55.1	1.3	0.4	42.1	0.7	0.25	0.083
	Magnetic heavy minerals	12.9	13.5	32.3	4.2	38.3	11.6	0.11	0.003
	Total	18.6	24.2	23.4	3.1	38.7	10.0	0.50	0.030
Mogadal padu	Non-magnetic very heavy minerals	0.9	18.4	15.0	1.7	31.0	30.1	3.63	0.115
	Non-magnetic light heavy minerals	5.7	52.0	1.0	0.4	45.9	0.5	0.10	0.085
	Magnetic heavy minerals	17.3	14.0	32.4	4.4	40.2	8.8	0.12	0.004
	Total	23.9	23.3	24.3	3.4	41.2	7.6	0.30	0.030
Vatsavalasa	Non-magnetic very heavy minerals	1.1	18.9	19.9	2.1	33.0	23.1	2.98	0.110
	Non-magnetic light heavy minerals	6.4	55.7	1.2	0.4	42.1	0.5	0.03	0.082
	Magnetic heavy minerals	18.2	11.8	36.3	5.1	42.0	4.7	0.06	0.003
	Total	25.7	23.1	26.8	3.8	41.6	4.4	0.20	0.030
Chinna vastavalasa	Non-magnetic very heavy minerals	1.4	18.8	23.6	2.2	33.2	18.9	3.13	0.112
	Non-magnetic light heavy minerals	9.3	54.2	2.0	0.5	42.1	0.8	0.25	0.082
	Magnetic heavy minerals	23.6	11.6	36.5	5.4	44.2	2.3	0.05	0.004
	Total	34.3	23.4	26.6	3.9	43.2	2.5	0.20	0.030
Yerraguddi	Non-magnetic very heavy minerals	1.0	19.5	19.2	2.0	32.9	22.9	3.37	0.113
	Non-magnetic light heavy minerals	6.4	50.6	1.3	0.5	47.1	0.5	0.05	0.086
	Magnetic heavy minerals	17.3	13.1	33.6	4.9	43.1	5.3	0.09	0.004
	Total	24.7	23.0	24.6	3.6	43.7	4.8	0.20	0.030

Table 9. *Typical chemical analysis of sequential sink-float products of dune sand samples*

Sample area	Products	Wt. %	Al_2O_3 %	Fe_2O_3 %	MgO %	SiO_2 %	TiO_2 %	ZrO_2 %	HfO_2 %
Kalingapatnam	Non-magnetic very heavy minerals	0.6	14.7	8.5	0.8	28.2	37.8	9.92	0.176
	Non-magnetic light heavy minerals	9.1	58.9	0.6	0.3	39.7	0.5	0.0	0.080
	Magnetic heavy minerals	10.1	14.4	31.1	3.9	36.1	14.4	0.15	0.006
	Total	19.8	34.8	16.4	2.2	37.5	8.7	0.40	0.050
Bandaruvani peta	Non-magnetic very heavy minerals	0.5	17.5	7.7	1.0	31.6	30.0	11.92	0.200
	Non-magnetic light heavy minerals	5.4	50.1	0.7	0.3	48.5	0.3	0.0	0.086
	Magnetic heavy minerals	14.8	14.1	30.9	3.2	31.1	20.4	0.15	0.004
	Total	20.7	23.6	22.5	2.4	35.6	15.4	0.40	0.030
Komaravani peta	Non-magnetic very heavy minerals	0.8	26.5	7.9	1.0	30.0	32.1	10.25	0.201
	Non-magnetic light heavy minerals	10.8	54.8	1.0	0.4	43.1	0.5	0.07	0.082
	Magnetic heavy minerals	14.0	13.6	31.8	4.1	38.2	12.1	0.15	0.006
	Total	25.6	31.4	18.1	2.5	40.0	7.8	0.40	0.040
Mogadal padu	Non-magnetic very heavy minerals	0.5	29.3	4.8	0.6	31.2	24.8	9.03	0.166
	Non-magnetic light heavy minerals	6.9	55.3	0.6	0.3	43.2	0.4	0.07	0.082
	Magnetic heavy minerals	14.9	14.5	30.2	3.5	33.0	18.6	0.20	0.006
	Total	22.3	27.5	20.5	2.5	36.1	13.1	0.40	0.030
Vatsavalasa	Non-magnetic very heavy minerals	0.4	17.0	3.1	0.4	24.8	46.2	8.27	0.161
	Non-magnetic light heavy minerals	9.5	54.3	0.4	0.3	44.4	0.4	0.09	0.083
	Magnetic heavy minerals	11.6	10.8	36.2	4.0	35.2	13.7	0.09	0.003
	Total	21.5	30.1	19.8	2.3	39.1	8.4	0.20	0.040
Chinna vastavalasa	Non-magnetic very heavy minerals	0.4	19.6	9.6	1.3	32.2	31.4	5.78	0.143
	Non-magnetic light heavy minerals	7.9	53.5	0.6	0.3	45.1	0.4	0.02	0.083
	Magnetic heavy minerals	10.6	11.9	34.1	4.3	39.5	10.0	0.09	0.004
	Total	18.9	29.5	19.6	2.6	41.7	6.4	0.20	0.040
Sample area	Products	Wt. %	Al_2O_3 %	Fe_2O_3 %	MgO %	SiO_2 %	TiO_2 %	ZrO_2 %	HfO_2 %
Yerraguddi	Non-magnetic very heavy minerals	0.6	19.4	7.6	1.3	34.9	29.3	7.29	0.155
	Non-magnetic light heavy minerals	9.1	53.8	0.5	0.3	45.1	0.3	0.0	0.082
	Magnetic heavy minerals	15.1	13.0	33.0	3.9	36.0	14.0	0.13	0.004
	Total	24.8	28.2	20.5	2.5	39.3	9.3	0.20	0.040

It is observed from TiO_2 vs. Fe_2O_3 (Fig. 23), with increase of Fe_2O_3 the TiO_2 content is decreasing in the magnetic heavy minerals (mostly garnet and ilmenite) of beach and dune sand samples. This observation can be explained in two ways: i) as expected with decrease of Fe_2O_3 content the TiO_2 content increases as the process of alteration of mineral ilmenite, $FeO.TiO_2$ in nature involves the processes of oxidation and leaching whereby iron is progressively removed to give a residual product, essentially, TiO_2 (Rutile). ii) Ilmenite concentration is decreasing from NE Kalingapatnam coast and garnet concentration is increasing towards to SE Srikurmam (Yerraguddi). Mineral concentration of ilmenite (black, Kalingapatnam) and garnet (reddish, Yerraguddi) can clearly be seen from the morphological photographs (Fig. 2).

The correlation between the TiO_2 content with Al_2O_3 and ZrO_2 plotted for non magnetic heavy minerals (mostly sillimanite, rutile and zircon minerals) of Kalingapatnam to Yerraguddi coastal stretch including beach and dune sands are shown in Figs. 24 and 25.

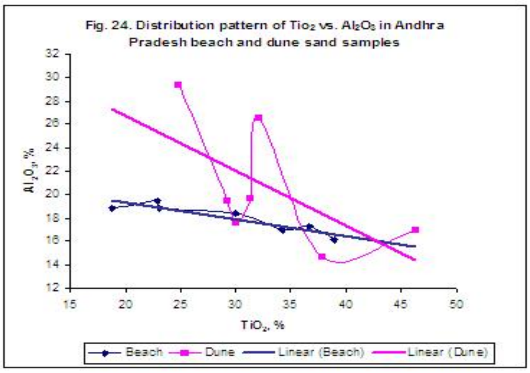


Figure 24. *Distribution pattern of TiO_2 vs. Al_2O_3 in Andhra Pradesh beach and dune sand samples*

It is observed from Fig. 24 that the Al_2O_3 content (mostly sillimanite mineral) increases, the TiO_2 content (mostly rutile mineral) decreases. The trend is more significant for dune sand. It is expressed in other way that, the correlation of sillimanite is more significant than the rutile mineral concentration.

Data seen from Fig. 25 where TiO_2 vs. ZrO_2 plotted indicate that the concentration of zircon and rutile in dune sand is almost constant and the TiO_2 vs. ZrO_2 is a straight line, whereas for beach sand the trend is different. The ZrO_2 is increasing with TiO_2 content. It indicates that the zircon mineral concentration increases with rutile concentration.

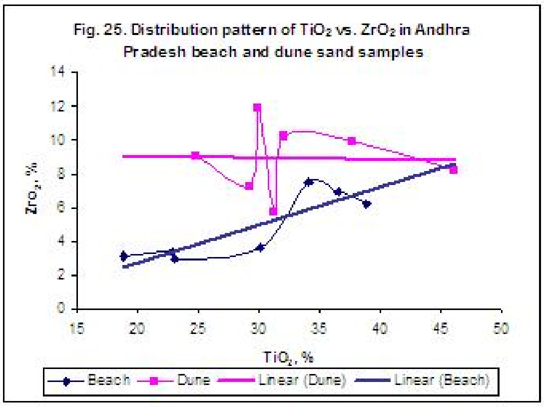


Figure 25. *Distribution pattern of TiO_2 vs. ZrO_2 in Andhra Pradesh beach and dune sand samples*

It is concluded from Figs. 23 to 25 that the correlation of TiO_2 with Fe_2O_3 in magnetic heavy minerals and TiO_2 vs. Al_2O_3 and ZrO_2 in non magnetic heavy minerals that ilmenite concentration decreases from NE Kalingapatnam coast to SE Srikurmam (Yerraguddi) where garnet concentration increases. It is also observed that sillimanite concentration is more significant than the rutile and zircon. It is also observed that sillimanite concentration is more significant than the rutile and zircon. Thus, the occurrence of minerals garnet, ilmenite, sillimanite, rutile and zircon are in order of abundance at this coast.

It is seen from Table 8 that light heavy mineral concentration (mostly sillimanite) is decreases in the beach sand from Kalingapatnam to Yerraguddi. The trend is different for dune sand. The concentration of light heavy minerals is significantly high in dune sand. It is also observed that the mineral concentration is marginally decreasing from Kalingapatnam to Yerraguddi.

The presence of very heavy minerals (VHM, such as garnet, ilmenite, rutile, zircon) in the beach sand indicates that from Kalingapatnam to Yerraguddi coastal stretch, the concentration of VHM are increasing where as in dune sand, the concentration of minerals are almost constant from Kalingapatnam to Yerraguddi.

It is concluded from these studies that these deposits contain economic minerals such as garnet, ilmenite, sillimanite, rutile and zircon with minor amounts of monazite and pyriboles in order of abundance. These individual minerals can be recovered by physical beneficiation methods for industrial applications.

d) Beneficiation studies to recover total heavy minerals

The physical properties of bulk sand sample are given in Table 10.

The data indicate that the d_{80} passing size of the bulk feed sample is 360 μm and the total heavy mineral content is 25%. The average density of the sample is 2.6 specific gravity.

Table 10. *Physical properties of bulk sand sample*

Details	Andhra Pradesh beach sand sample
Bulk density, gm/cc	1.65
True density	2.9
Porosity, %	43.1
Angle of repose, degree	16.2
d_{80} passing size, μm	360
THM, %	25
TMM, %	18.3

The modal analysis of the total heavy minerals of the bulk sample shown in Fig. 26 indicate that the sample contain 12.6% ilmenite, 56% garnet, 27% sillimanite, 0.4% zircon, 1.4% rutile and 2.5% other minerals. The results of spiral concentration summery of result are given in Tables 11 and 12. The flow sheet with material balance is shown in Fig 27.

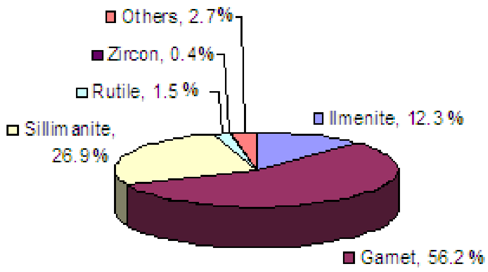


Figure 26. *Model analysis of THM of bulk sample*

Data shown in Tables 11 and 12 indicate that product 1 containing 99% THM could be achieved after two stage cleaner spirals and Products 2 and 3 containing 98.5% and 97.5% THM respectively could also be obtained from scavenging spirals. Data shown in Fig 27 indicate that the total product containing 98% THM with 22.7% yield and 89% recovery could be achieved.

Table 11. *Results of beneficiation studies*

a. Results of first Spiral concentration on feed sample

Details	Wt, %	Wt. dist, %	THM, %	THM dist.,%	THM Rec., %
Concentrate	59.0	59.0	40.0	23.6	94.0
Tailings	41.0	41.0	3.4	1.4	6.0
Total	100.0	100.0		25.0	100.0

b. Results of Second Spiral concentration on concentrate (Table a)

Details	Wt, %	Wt. dist, %	THM, %	THM dist.,%	THM Rec., %
Concentrate	65.9	38.9	59.0	23.0	92.0
Tailings	34.1	20.1	3.3	0.6	2.0
	100.0	59.0		23.6	94.0

c. Results of third Spiral concentration on concentrate (Table b)

Details	Wt., %	Wt. dist, %	THM, %	THM dist.,%	THM Rec., %
Concentrate	18.0	7.0	99.0	7.0	28.0
Tailings	82.0	31.9	50.2	16.0	64.0
Total	100.0	38.9		23.0	92.0

d. Results of fourth Spiral concentration on tailings (Table c)

Details	Wt., %	Wt. dist, %	THM, %	THM dist.,%	THM Rec., %
Concentrate	17.9	5.7	98.5	5.6	22.4
Tailings	82.1	26.2	39.7	10.4	41.6
Total	100.0	31.9		16.0	64.0

e. Results of fourth Spiral concentration on tailings (Table d)

Details	Wt, %	Wt. dist, %	THM, %	THM dist.,%	THM Rec., %
Concentrate	38.2	10.0	98.5	9.9	39.4
Tailings	61.8	16.2	3.4	0.5	2.2
Total	100.0	26.2		10.4	41.6

Table 12. *Summary of the beneficiation studies*

	Weight, %	THM, %	THM distribution, %	Recovery, %
Product 1	7.0	99.0	7.0	28
Product 2	5.7	98.5	5.6	22
Product 3	10.0	98.5	9.9	39.4
Reject 1	41.0	3.4	1.4	6
Reject 2	20.1	3.3	0.7	2
Reject 3	16.2	3.4	0.5	2
Total	100.0	25.0	25.0	100.0

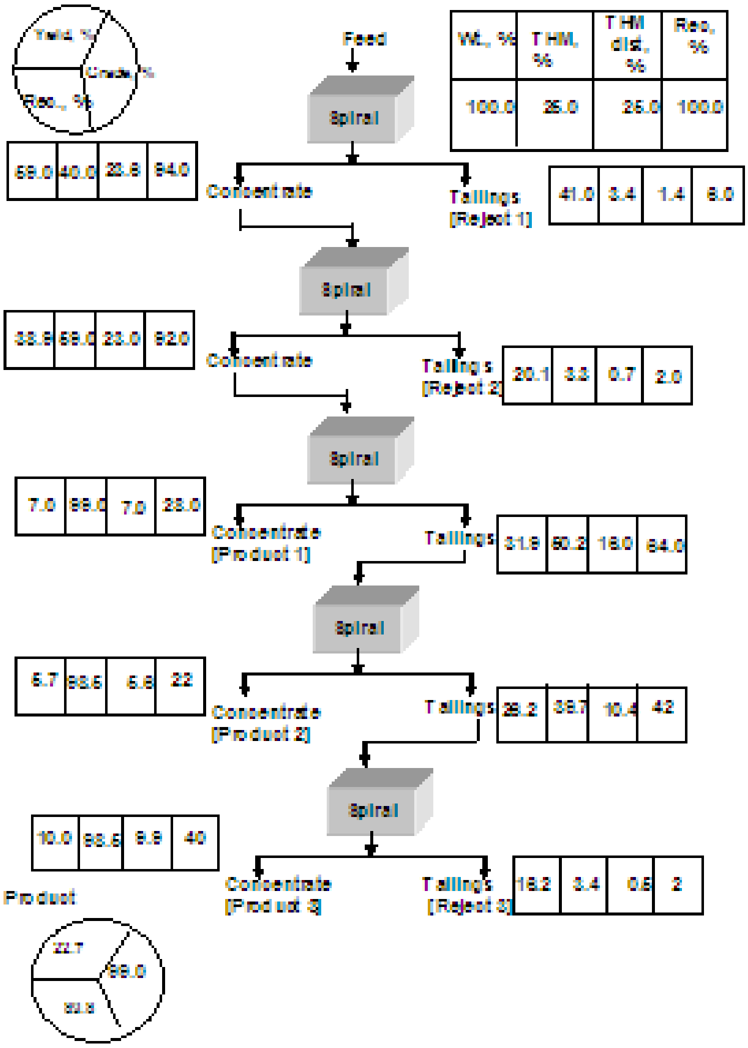


Figure 27. *The flow sheet with material balance on recovery of total heavy minerals from beach sand samples of Andhra Pradesh*

4. Conclusions

Based on the mineralogical, physical and chemical studies, the following conclusions are drawn from the study areas from Kalingapatnam, Komaravani peta, Vatsavalsa and Chinna Vatsavalasa and Yerraguddi in a coastal stretch of 20 Kms from NE side of Kalingapatnam town to SE side of Srikurmam in Srikakulam District, Andhra Pradesh, India.

- The maximum size frequency mode observed for beach and dune sand samples collected from Kalingapatnam to Yerraguddi varies from 300 µm to 100 µm, where as for heavy mineral concentration, the frequency mode follows 150 µm to 75 µm.
- The percentage of magnetic heavy minerals is significantly more compare to non-magnetic heavy minerals in all beach sand samples from Kalinga-patnam to Yerraguddi.
- As the particle size increases, true density of minerals is falling down for both beach and dune sand samples.
- Garnet concentration is increasing from Kalingapatnam coast to Yerraguddi for both beach and dune sand samples.
- It is observed that sillimanite mineral concentration is decreasing for beach sand and increasing in dune sand from Kalingapatnam coast to Yerraguddi.
- Titaniferrous minerals, ilmenite and rutile mineral concentration decreases from Kalingapatnam coast to Yerra-guddi for both beach and dune sand samples.
- Zircon concentration is almost constant in beach and dune sand samples from Kalingapatnam coast to Yerraguddi.
- Percentage of TiO_2 and ZrO_2 content decreases with increase in d_{80} passing size for both beach and dune sand.
- With increase of Fe_2O_3, the TiO_2 content is decreasing in the magnetic heavy minerals. While Al_2O_3 content increases, the TiO_2 content decreases for non magnetic heavy minerals.
- These deposits contain economic minerals such as garnet, ilmenite, sillimanite, rutile and zircon in order of abundance.
- The end product obtained by using sea water spirals containing 98% THM with 22.7% yield and 89% recovery could be subjected to mineral separation plant to recover individual heavy mineral concentrates.

5. Acknowledgements

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