

Ilmenite, Magnetite and Chromite Beach Placers from South Maharashtra, Central West Coast of India

By

Anup R. Gujar, Nawso V. Ambre, Premchand G. Mislankar and Sridhar D. Iyer

Council of Scientific and Industrial Research

National Institute of Oceanography

Dona-Paula, Goa 403 004, India

Address for Correspondence

Dr. A. R. Gujar

Scientist

Geological Oceanography

National Institute of Oceanography

Dona- Paula, Goa 403 004, India

Email: agujar@nio.org

ABSTRACT

The heavy mineral placer deposits of the coastal sediments in south Maharashtra stretch for 12.5 km from Pirwadi in the north to Talashil in the south. The area is a sand bar represented by a narrow submergent coastal plain lying between Achara and Gad Rivers. The sediments in the area are mainly sands which are moderately well sorted to well sorted. The heavy mineral concentration in the surficial sediments ranges between 0.69 and 98.32 wt.% (28.73 wt.% in average). The heavy mineral concentration shows an increasing trend from north to south. The heavy mineral suite consists predominantly of opaque minerals (ilmenite, magnetite and chromite), garnet, pyroxene, amphibole, zircon, tourmaline, rutile, staurolite, etc. Ilmenite grains are fresh whereas magnetite grains show the effect of weathering and alteration. The chromite grains are rounded to sub-rounded with alteration at the margin of the grains. The surficial textures of the opaque minerals show mechanical breaking that indicates limited distance of transportation.

Ilmenite has TiO_2 in the range between 40.04 and 46.6 wt.%. Based on ore microscopy studies, the magnetite grains appear to be of two types: pure magnetite and titano-magnetite. Compositionally, the total magnetite fractions have Fe_2O_3 between 32 and 46 wt.%, FeO between 19.0 and 25 wt.% and TiO_2 between 14.3 and 23.9 wt.%. The chromite grains are an admixture of two varieties, ferro-chromite and magnesio-chromite. The chromite grains have 32.06 to 47.5 wt.% of Cr_2O_3 with total iron between 23.86 wt.% (4.73% Fe_2O_3 and 19.13% FeO) and 27.88 (4.36% Fe_2O_3 and 23.53% FeO) wt.% and MgO between 12 and 40 wt.%.

The observed variations in the distribution of heavy minerals in the area are found to be due to differences in the sediment supply, their sorting and oceanographic processes all of which result in a selective sorting of the sediments. The observed mineral assemblages of transparent heavy minerals (pyroxene, amphibole, tourmaline, kyanite, garnet, zircon and olivine) are suggestive of their derivation from a heterogeneous provenance comprising of igneous rocks, high grade metamorphic rocks and reworked Kaladgi sediments. The chromite grains appear to have been derived from ultrabasic rocks present in the upper reaches of Gad River. The inferred reserves of ilmenite, magnetite and chromite are 0.175, 0.395 and 0.032 million tons, respectively.

Keywords: - Beach placers, Ilmenite, Magnetite, Chromite, Sediment Supply, Selective Sorting, Provenance, Reserves, South Maharashtra, West Coast of India.

1. INTRODUCTION

Heavy mineral placer deposits containing variable proportions of ilmenite, magnetite, garnet, zircon, rutile, monazite, tourmaline, staurolite, sillimanite, kyanite etc. are reported from beaches as well as nearshore areas along the Indian coastline (Siddiquie et al., 1982, Rajamanickam, 1983; Gujar et al., 1988; Wagle et al., 1989; Gujar, 1995; Gujar et al., 2004; Angusamy et al., 2005). Under the National programme of Beach Placer Mining Capacity Building (2002-2007) an extensive exploration was taken up along South Maharashtra Coast, Central West Coast of India (Fig. 1). The site selected for the present research provides an ideal test area for evaluating the formation of beach placer deposits, as it is characterised by the required geologic conditions such as source (Igneous and high grade metamorphic rocks, Kaladgi sediments), liberation process (Chemical weathering process under humid tropical climate for decomposition and dispersion), transport routes (Gad and Achara rivers and their tributaries) and depositional basin/sink (Littoral zone between Pirwadi and Talashil bay).

The present work is based on a study of 91 surface and sub-surface sediment samples from 26 locations along the southern Maharashtra coast between Pirwadi (16°12'N latitude) and Talashil (16° 06'N latitude). This study first documents the occurrence of chromite in beach placers along the Indian coastline and also determines spatial and temporal distribution, mineralogy, geochemical aspects, transport history, seasonal variations, provenance and economic evaluation of the ilmenite, magnetite and chromite placer deposits.

2. STUDY AREA

The area under the present investigation is represented by a narrow submergent coastal plain lying between two rivers – Achara in the north and Gad in the south (Fig. 1). The offshore islands (Fig. 2) probably represent detached portions of the headlands due to erosion or tectonic activity. The coastal strip is about 90 m to 150 m wide with a moderate to gentle foreshore backed by a narrow berm and sand dune ridges of variable dimensions. The other significant morphological feature is a 'sand bar' at the mouth of river Gad (Fig. 2). This sand bar has beaches on its seaward limit and a tapering end on the river side and is oblique on the sea-side suggesting that the waves are an important agent in keeping the inlet open (Karlekar, 1981).

The drainage patterns of Achara and Gad Rivers are controlled by tectonic lineaments (Dixit, 1976). Although these two rivers appear to be graded, their tributaries remain ungraded and are still active. The river mouths are drowned, with about one third of their lower courses under tidal influence. In the hinterland, the steep sided river valleys are suggestive of an absence of widening which is an indication of recent development of drainage. Gad River has a steeper graded profile and with steep slope in the mid-profile as compared to Achara River (Dixit, 1976; Karlekar, 1981).

The sediment distribution in these two rivers differs characteristically. Gad River has a very narrow mouth. Upto Kalaval (Fig. 2) medium to fine sands are present but beyond this the sand is coarser and further upstream (for instance at Masure; Fig. 2) the grain size changes to coarse granules with pebbly sand. Achara River has a wide mouth compared to that of Gad River. The Achara River mouth has thick growth of mangroves whereas in Gad River mangroves occur only in the upstream area (Jagtap et al., 1994). The mangrove vegetation at the mouth of Achara River probably acts as a barrier for the entry of medium to fine sandy sediments and hence restricts the supply of sand to the coastal zone.

The hinterland area includes Precambrian, Mesozoic and Quaternary sequences, the characteristic heavy minerals of these are shown in Table 1. The Dharwar Group occupies a major part of the drainage area of the Gad river basin (Fig. 1). At places the sequence of the group has lateritic capping of variable thickness at different altitudes.

3. METHODOLOGY

The field programme consisted of collection of surficial and sub-surficial samples from the foreshore (inter-tidal) as well as in the backshore (supra-tidal) domains of the beach between Pirwadi and Talashil (Figs. 2 and 3). The samples were collected in a grid pattern at intervals of 500 to 800 m. The samples from foreshore (low-tide level and mid-tide level) were collected (0-20 cm level) using a transparent acrylic tube (5 cm diameter) and also from the surface. A shell-type hand auger was used for the collection of samples in the backshore zone (beyond the high-tide, berm and dune levels) and sub-surface samples at various levels (0-20, 20-40, 40-60, 60-80, 80-100 cm). Representative samples were collected from the river mouth to the upstream region using a Van-veen grab. A total of 91 samples were collected along 26 transects on the beach and 12 samples from the river bed (Fig. 2).

The sedimentological analysis was carried out following the standard procedures (drying, splitting, carbonate removal and sieving at $\frac{1}{2} \phi$ interval; Folk, 1968). The separation of heavy minerals was carried out in three size fractions, medium sand (500-250 μm), fine sand (250-125 μm) and very fine sand (125-62.5 μm) using bromoform (specific gravity 2.88). The separated heavy fraction was used for further separation of magnetite, ilmenite and chromite by hand magnet and isodynamic separator (S.G. Frantz, Model L-1) following the method by Hutchinson (1974). The separated mineral fractions were weighed and their weight percentages were determined. Representative non-magnetic fractions were studied under microscope to identify the transparent heavy minerals. Selected opaque fractions were analyzed by X-Ray diffractometer (Phillips PW 1840) for confirmation of the mineral phases and their chemical analysis was carried out using an Inductively Coupled Plasma - Optical Emission Spectrometer (ICP-OES). A few grains of chromite, magnetite and ilmenite were examined under the Scanning Electron Microscope (JEOL JSM-5800)

coupled with an Energy Dispersive System (EDS LINK) to identify their surface textural features and the chemical composition. FeO was determined by titration method as described by Shapiro (1978).

4. RESULTS AND INTERPRETATIONS

4.1 GRAIN SIZE PARAMETERS

The grain size parameters were computed by using $\frac{1}{2} \phi$ sieved sand fractions and a statistical programme package of Blott (2000). The nature of sediments in the study area is fine grained. The mean (Mz) values of Pirwadi ranges between 2.36 and 2.90 (avg. 2.58), Hirlewadi 2.43 and 2.84 (avg. 2.64), Bagwadi 2.29 and 2.81 (avg. 2.54), Tondavali 1.93 and 2.96 (avg. 2.21) and Talashil 2.13 and 2.75 (avg. 2.31) while the sample from Sarjekot has a value of 2.30. The sediment varies from moderately sorted to well sorted. The sediments of Pirwadi are well sorted (0.43 – 0.52 avg. 0.50), Hirlewadi sediments are moderately sorted (0.90 – 1.39 avg. 0.93) while sediments of Bagwadi (0.40 – 0.62 avg. 0.49), Tondavali (0.40 – 0.51 avg. 0.48), Talashil (0.34 – 0.58 avg. 0.44) and Sarjekot (0.69) are well sorted.

4.2 HEAVY MINERAL DISTRIBUTION

Heavy mineral concentration in the surficial sediments (0-20 cm) ranges between 0.69 and 98.32 % (avg. 28.73 %) (Table 2). The concentration of heavy minerals in the surficial sediments from inter-tidal zone (low tide to high tide zone) and supra-tidal zone (high tide to back dune zone) varies considerably; in the inter-tidal zone the concentrations are low (0.69 to 17.48 %, avg. 5.32 %) as compared to concentrations in the supra-tidal zone (7.52 to 98.32 %, avg. 44.51 %). The trends of the average heavy mineral concentrations in the surficial layers in the entire area (including inter-tidal and supra-tidal zones, Table 2) shows that at Pirwadi the concentration is 24.83% while the concentration lowers to 7.17% at Hirlewadi. Further south an increasing trend in the heavy mineral concentration is noted. For instance, at Bagwadi it is 8.16, Tondavali 23.09% and at Talashil it reaches to 53.40%. The Sarjekot area, further south of the mouth of river Gad, is not part of sand bar and has a concentration of 40.83%. In general, in the study area, from north to south, no definite trend in the concentration of heavy minerals in sub-surface sediments is observed but for samples at stations 105 and 98 (supra-tidal zones at Pirwadi and Talashil, respectively) and station 39 (inter-tidal zone, Bagwadi) where a down depth decrease in the concentration is observed.

The heavy mineral suite in the study area consists predominantly of opaque (ilmenite, magnetite and chromite), garnet, amphibole, zircon, tourmaline, rutile, staurolite, etc. An increase in the heavy mineral content with decreasing grain size is noticeable. Heavy mineral distribution in the supra-tidal sediments is characterized by discrete laminations with concentrations reaching upto 98.32 %. The heavy mineral lamina ranges in thickness from 2 mm to 150 mm and are separated by

white sands of variable thickness and laterally their continuity is noticed upto several meters (Figs. 4 A, B). Such depositional patterns are typical of beach placers and results from grain segregation due to selective sorting within the bed flow during wave backwash (Komar and Wang, 1984). Such laminations of heavy minerals are also noticed in the inter-tidal zone but these are of lesser thickness (2-5 mm) and limited lateral extent (10-15 m). The Gad River sediments exhibit a noticeable variation in the heavy mineral content (13.19 to 90.72 %, avg. 37.44 %). As indicated earlier in the description of the study area, the rivers are under tidal influence for about 15-20 km upstream. In this zone of tidal influence, the sediments are medium to fine grained but beyond the tidal influence zone in the upstream where the river gradient is steeper, the sediments become coarse to pebbly sands. The concentration of heavy minerals in this pebbly sand is patchy, which probably resulted due to lag entrapment within the interstices of pebbles and coarse sands. The probable reason for such an irregular distribution can be attributed to the local variations in the size of sands and pebble coupled with a drop in energy level at the nick point of fresh river water and zone of tidal influence.

The opaque in the beach sediments is represented by ilmenite, magnetite and chromite and their weathered derivatives. The ilmenite percentage varies between 0.03 and 33.64 % whereas magnetite ranges between 0.60 and 51.31 % and chromite between 0.05 and 10.09 %. The non-magnetic fraction (i.e., transparent heavy minerals like pyroxene, amphibole, garnet, zircon, rutile, staurolite, etc.) ranges between 0.31 and 29.48 %. The chromite is associated with ilmenite and spinel (Fig. 5) and although the concentration of chromite is low to moderate, this is the first reported occurrence of detrital chromite along the coasts of India's mainland.

X-ray diffraction (XRD) analysis of separated fractions of ilmenite, magnetite and chromite was carried out to confirm the different phases. Chromite is present as ferro-chromite (FeCr_2O_4) and also as magnesio-chromite (MgCr_2O_3) (Fig. 5). The presence of chromite with other heavy minerals, mainly ilmenite, is also confirmed in the samples from the Gad River (Fig. 6). Ore microscopic characterization of polished detrital grains revealed the following features.

Ilmenite: Fresh ilmenite dominates in the study area. The grains are sub-rounded to rounded, with occasional anhedral shape. A few grains show alteration effects along their margin and alteration product like sphene is observed. Some grains show sieve texture, replacement structure and intergrowth of rutile needles (Figs. 7A, B).

Magnetite: Magnetite shows the effects of weathering and alteration. The weathered products are likely to be hematite and sphene which are common along the cleavage planes (Figs. 7C, D). Magnetite is of two types, fresh and altered. The fresh magnetite grains are angular and sub-angular whereas the altered grains are mainly titanomagnetite that are altered to sphene along the margins. This may be due to the selective dissolution of magnetite component of exsolution type and titanomagnetite by weathering (Ramdhor, 1980).

Chromite: Chromite grains are sub-rounded to rounded and show the effects of transportation and have no intergrowth features (Figs. 7E, F).

SEM examination of the detrital ilmenite (Figs. 8A, B), magnetite (Figs. 8C, D) and chromite (Figs. 8E, F) shows features of mechanical breaking such as conchoidal to sub-conchoidal fractures, V-shaped impact depressions and irregular cracks and openings. All these features suggest that these grains are freshly derived and underwent limited transportation.

4.3 GEOCHEMISTRY OF ILMENITE, MAGNETITE AND CHROMITE

The geochemical analysis of the ilmenite, magnetite and chromite concentrates is shown in Table 3. The ilmenite in the study area has TiO_2 between 40.04 and 46.60 wt. % and the Fe_2O_3 content is between 18.05 and 21.33 wt. %. This probably indicates the presence of hematite in the structure of ilmenite. Al_2O_3 ranges between 1.02 and 1.76 wt. % and SiO_2 between 0.70 and 2.42 wt. %. The Cr_2O_3 content is less than 0.03 wt. % and CaO ranges between 0.27 and 1.44 wt. %. The other elements like Ni, Zn and V are in negligible quantity.

The analysis of magnetite grains shows Fe_2O_3 between 32 and 46 wt. % and FeO is between 19 and 25 wt. %. The observed high concentration at location 47 (Fig. 2) is probably due to the presence of hematite in that fraction. The TiO_2 content of magnetite ranges between 14.3 and 23.9 wt. % hence, titanium is probably present in the intergrown rutile, ilmenite and sphene. The compositional variation may be due to differential replacement of iron with titanium, such features are also noticed in the magnetite grains studied from the adjoining northern area (Gujar, 1996). Another important observation is the higher content of V_2O_5 (3.78 to 4.71 wt. %) in the magnetite. The chemical analysis and ore microscopic studies collectively suggest the possibility of occurrence of two types of magnetite in the study area: i) pure magnetite and ii) magnetite with intergrowth of rutile, ilmenite, and sphene i.e., titanomagnetite.

The analysis of chromite grains depict an appreciable content of Cr_2O_3 which ranges between 32.06 and 47.52 wt. % and with total iron ranging between 23 and 27 wt. %. The chemical analysis confirms the presence of magnesio- and ferro-chromite that were revealed by XRD. The concentration of MgO ranges between 12 and 14 wt. % and this may be due to a considerable replacement of iron by magnesium.

4.4 ASSOCIATED TRANSPARENT HEAVY MINERALS

Besides ilmenite, magnetite and chromite, the other heavy minerals include opaque, pyroxene, amphibole, kyanite, tourmaline, zircon, rutile, staurolite, olivine, garnet, epidote etc. (Mislankar et al., 2005). The ore minerals are mainly hematite grains that are angular to sub-angular in shape and show a high degree of alteration. Pyroxene (4.1 to 7.5 %) is represented by hypersthene, enstatite and augite. Among the pyroxene, hypersthene shows better rounding as compared to augite and these minerals do not show any effect of leaching probably due to their less residential period in the

depositional basin. The amphibole (1.32 to 10 %) is hornblende and actinolite. Hornblende is green, prismatic with rounded edges. The rounding of hornblende is possibly due to their limited transportation (Mislankar & Iyer, 1996; Mislankar & Gujar, 1996).

Tourmaline (0.05 to 0.2 %) and kyanite (0.10-2.1 %) are also present in the study area. Tourmaline occurs as prismatic or rounded or even as broken grains. Kyanite grains are prismatic, sharp edged and also rounded. Zircon (1.6 to 6.2 %) shows a higher percentage in the area and a majority of the grains are light pink or brown and are well- to sub-rounded in shape. A few anhedral grains are also present which indicate a fresh supply from zircon-bearing rocks. The rutile grains (1.09-1.12 %) are relatively fresh and show sub-angular to sub-rounded edges. Garnet grains (1.6 to 2.4 %) are mainly colorless with sharp edges that suggest a short transport. Olivine grains (upto 0.3 %) are rare and are with sub-rounded edges and are fresh.

5. DISCUSSION

As indicated earlier, the hinterland geological sequences include those of Precambrian, Mesozoic and Quaternary age and the heavy mineral assemblages of these are indicated in Table 1. The study area falls under humid tropical climate with an average rainfall of 3000 mm/year and chemical weathering is a dominant process that is responsible for the liberation of heavy minerals from the source rocks.

The study area receives the sediments through two rivers; Achara in the north and Gad in the south. The heavy mineral concentration in the sediments of the Achara river is less (0.74 -0.79 %, avg. 0.76 %) compared to that of the Gad river (13.19 to 34.32 %, avg. 24.84 %) (Table 2). This indicates that the supply of heavy minerals is predominantly from the Gad River, which flows through the area where the occurrence of chromite lenses of variable dimensions are also reported in the upstream near Kankavali (Chari et al., 1975) (Fig. 1).

As noted earlier, the nature of beach sediments in the area is fine grained. Higher heavy mineral concentration is noticed in these sediments which are well sorted whereas the sediments which are moderately or poorly sorted contain less heavy minerals.

The average density values of the opaque among i.e., ilmenite (4.5 - 5.0, avg. 4.75), magnetite (4.6 – 5.2, avg. 4.9) and chromite (Fe chromite 5.1 and Mg chromite 4.2, avg. 4.65) do not vary significantly and may result in minor variations in the settling of the grains during the process of selective sorting.

The beach gradient also shows variations in the study area. The area north of upper Tondavali has a moderate beach gradient (1:14 to 1:20) and the area between upper Tondavali and Talashil shows a relatively lower gradient (1:30 to 1:35). Wave refraction pattern (Jayakumar S. Personal communication, 2007) has indicated wave convergence in the area north of upper Tondavali and

wave divergence in the area south of upper Tondavali. Such an observed wave divergence has resulted in depositional conditions in the area south of upper Tondavali compared to the area north of upper Tondavali which comparatively shows more erosion and less deposition. Such variable condition also may result in a process of selective sediment sorting and appear to be responsible for the observed variation in the distribution of heavy minerals.

The above observations lead us to infer that the study area receives ilmenite, magnetite and chromite mainly from the hinterland which are dominated by Precambrian rocks. The observed mineral assemblage of transparent heavy minerals suggests derivation of these minerals from a heterogeneous provenance comprising of igneous rocks, high grade metamorphic rocks and reworked sediments derived from Kaladgi Group. Detrital chromite appears to have resulted from the chromite lenses of variable dimensions and the associated ultrabasic rocks, like serpentinite-talc-tremolite and hornblende schist, which are present in the upper reaches of the river Gad around Kankavali (Fig. 1). The chromite grains released from the rocks and from the lenses by weathering were transported down the Gad River to the depositional areas along with the other associated heavy minerals.

6. RESERVE EVALUATION

Although the presence of chromite is noted up to the northern boundary of the area i.e., Pirwadi but the main concentration is localized between stations 106 (southern most tip of sandbar) and station 42 (near upper Tondavali) (Fig. 2). The coastal zone in this area can be broadly divided into inter-tidal and supra-tidal zones. The inter-tidal zone is about 45 to 50 m wide. The supra-tidal zone as a zone between high tide and vegetated stabilized dunes is about 45-55 m wide (Fig. 3). Thus, the width of the area on very conservative scale is about 110 m. Since the work involved sampling up to 1 m sand thickness, the reserves were tentatively estimated and hence the reserves given are categorized as inferred.

In estimating the reserves, the following formula has been used.

$$\text{Reserve} = \frac{\text{Area} \times \text{Thickness} \times \text{Bulk density} \times \text{Concentration}}{100}$$

The bulk density was calculated by taking an average weight of 100 cc representative dry samples from the area and the number of weights was averaged. This average value (1.9 tons/m³) was taken for reserve estimation. On this basis, the inferred reserves (in metric tons) of ilmenite, magnetite and chromite are to the tune of 0.175, 0.395 and 0.032, million tons, respectively.

CONCLUSIONS

The investigation of beach placers between Pirwadi and Talashil situated on the central west coast of India has revealed that: 1) The sediments are sandy, fine grained, moderately well to very well

sorted in nature. 2) The heavy mineral concentration shows a variable distribution in the inter-tidal and supra-tidal zones, with higher concentration in the latter. 3) The heavy mineral distribution shows an increasing trend in the concentration from north to south. 4) The differences in the supply of heavy mineral from the two rivers (Achara and Gad) and associated oceanographic processes appear to be responsible for the observed variations in the heavy mineral concentrations. 5) The chromite grains, reported for the first time from this area, is significant and are associated with ilmenite and magnetite. 6) The inferred reserves of ilmenite, magnetite and chromite appear promising for exploitation of the beach placers.

ACKNOWLEDGEMENTS

We thank the Director Dr. Satish Shetye for permission to publish this work. We acknowledge the technical help rendered by G. Prabhu (XRD), V.M. Khedekar (SEM-EDS), and K. Chitari, Sham Akerkar and R. Uchil (drafting the figures) and Miss Celine D'silva for help in word processing. This work forms a part of the National Programme on “**Beach Placer Mining Capacity Building**” CSIR Network Project CMM0023. We are grateful to the Council of Scientific and Industrial Research, New Delhi for grants and the chairman and the co-ordinators of this network project for their constant encouragement and timely help. We profusely thank Dr. Y. Watanabe for valuable suggestions which considerably helped to improve the manuscript. We express our gratitude to Dr. Y. Kajiwara, Editor-in-Chief, for the encouragement to submit the revised version of the manuscript. This is NIO's contribution _____.

REFERENCES

- Anon. (1976) Geology of the Ratnagiri district, Maharashtra. Geol. Surv. India 125th Anniv. Publ., 1-8.
- Angusamy, N.J., Dajkumar Sahayam, J. Suresh Gandhi, M. and Rajamanickam, G. V. (2005) Coastal placer deposits of central Tamil Nadu, India. Mar. Geo-Resour. Geotech., 23, 137-174.
- Blott, S. (2000) Grain size distribution and statistics package for the analysis of unconsolidated sediments by sieving or by laser granulometer. Grandistat Version 4.0, 1-6.
- Chari, G.N., Marwar, S.A., Bobade, G.P., Kulkarni, G.A. and Bhagwatkar D. A. (1975) Ilmenite, Geology and Mineral resources of Maharashtra. Directorate of Geology and Mining Government of Maharashtra, Nagpur, 136-144.
- Dixit, K.R. (1976) Drainage basins of Konkan – forms and characteristics. Natl. Geographical Jour. India, 22, 79-105.
- Folk, R.L. (1968) Petrology of sedimentary rocks, Hamphil, Austin, Texas, 182p.
- Gujar, A.R. (1995) Morphogenetic controls on the distribution of the littoral placers along central west coast of India. Proc. Recent Researches on Geology along West Coast of India, 171-180.

- Gujar, A.R. (1996) Heavy mineral placers in the nearshore areas of South Konkan Maharashtra: their nature of distribution, origin and economic evaluation. Unpubl. Ph.D. Thesis, Tamil University, Thanjavur, 234p.
- Gujar, A.R. and Srinivas, K. (1991) Contributions from coastal laterites to the nearshore placers of central west coast of India. *Giornale di Geologia*, 53, 65-70.
- Gujar, A.R., Nagendernath, B. and Banerjee, R. (1988) Marine minerals: The Indian perspective. *Mar. Mining*, 7, 317-350.
- Gujar, A.R., Mislankar, P.G. and Ambre, N.V. (2004) Coastal placers of Konkan Maharashtra their distribution, mineralogy and geomorphic environment of formation. *Indian Jour. Geomorphology*, 9, 123-130.
- Hutchinson, C.S. (1974) Laboratory handbook of petrographic technique. John-Wiley and Sons, New York, 527p.
- Jagtap T. G., Untawale, A.G. and Inamdar, S.N. (1994) Study of mangrove environment of Maharashtra coast, using remote sensing data. *Indian Jour. Mari. Sci.*, 23, 90-93.
- Karlekar, S.N. (1981) A geomorphic study of South Konkan (between 16° and 17° N latitude and Sahyadrian crest and Arabian Coast). Unpubl. Ph.D. Thesis Univ. Pune, 193p.
- Kelkar, K.V. (1959) On some Archean rocks in southern part of Ratnagiri district. *Jour. Univ. Pune*, 10, 85-101.
- Komar, P. D. and Wang, C. (1984) Process of selective grain transport and formation of placers on beaches. *Jour. Geol.*, 92, 637-655.
- Mislankar, P.G. and Gujar, A.R. (1996) Heavy mineral distribution in the surficial sediments from the eastern continental margin of India and their implication on palaeoenvironment. *Indian Jour. Earth Sci.*, 23, 91-97.
- Mislankar, P.G. and Iyer, S.D. (1996) Origin of amphibole-rich beach sands from Tila-Mati, Karwar, central-west coast of India. *Jour. Geol. Soc. India*, 47, 499-502.
- Mislankar, P.G., Gujar, A.R. and Ambre, N.V. (2005) Transparent heavy minerals in the coastal sediments of south Maharashtra and their significance in delineating source and environment of transportation and deposition. In: *Proc. Development Planning of Coastal Placer Minerals*, V.J. Loveson, N. Chandrasekar and A. Sinha (eds.), Allied Publ., New Delhi, 29-39.
- Rajamanickam, G.V. (1983) Geological Investigation of offshore heavy mineral placers of Konkan Coast, Maharashtra. Unpubl. Ph.D. Thesis, Indian School of Mines, Dhanbad, 247p.
- Sahasrabudhe, Y.S. and Deshmukh, S.S. (1979) The laterites of the Maharashtra State. *Proceedings international seminar on lateritization processes*, Oxford-IBH, New Delhi, 209-220.
- Sarkar, P.K. and Soman, G.R. (1984) Heavy mineral assemblage from Konkan. *Kaladgi sediments. Proc. Indian Geol. Cong.*, Pune, 19-23.
- Shapiro, L. (1978) Rapid analysis of silicate, carbonate and phosphate rocks. Revised edition, *Bull. Geol. Surv. No. 1401*. U.S. Govt. Printing Office, Washington, D.C., 74p.
- Siddiquie, H.N., Rajamanickam, G.V., Gujar, A.R. and Ramana, M.V. (1982) Geological and geophysical exploration for offshore ilmenite placers off the Konkan coast, Maharashtra, India. *Proceedings of 14th Offshore Techno. Conf.*, Houston, Texas, 749-755.
- Wagle, B.G., Gujar, A.R. and Mislankar, P.G. (1989) Impact of coastal features on beach placers – A case study using remote sensing. *Proc. 21st Offshore Techno. Conf.*, Houston, Texas, 229-233.

LIST OF FIGURES

Fig.1. General geology and drainage of the study area. (Modified after Anon, 1976). Keys:

- 1 = Pleistocene laterite, 2 = Upper Cretaceous to Lower Eocene Deccan Trap basalt,
- 3 = Proterozoic Group, 4 = Precambrian Granite / Granitic gneiss, 5 = Archean / Dharwar Group, 6 = Chromite lenses, 7 = Dip direction, 8 = Approximate boundaries of the lithology.

Fig.2. Locations of sampling stations and geomorphology of the area between Pirwadi and Sarjekot.

Fig.3. Physiographic domains of the sites sampled in the study area.

Fig. 4. Concentrations of heavy minerals in surficial and sub-surficial sediments.

- A. Surficial enrichment of heavy minerals at Talashil. Note the concentration of heavy minerals occurring in the supra-tidal zone.
- B. Sub-surficial heavy mineral laminations exposed in a pit cutting at Talashil.

Fig. 5. X-ray diffractogram of ilmenite, magnetite and chromite (Tondavali station 46). The values in parentheses indicate interplanar spacing (hkl).

Fig. 6. X-ray diffractogram of heavy minerals after removal of magnetite from Gad River sample. The value in parentheses indicates interplanar spacing (hkl).

Fig. 7. Ore microscopy of ilmenite, magnetite and chromite grains. All images at x200.

- A. Angular to sub-angular grains of ilmenite.
- B. Altered ilmenite with sieve texture.
- C. Altered magnetite.
- D. Replacement of magnetite by sphene along the border.
- E. Rounded chromite with partial alteration.
- F. Chromite grains showing effects of transportation.

Fig. 8. Photomicrographs of ilmenite, magnetite and chromite grains. All images at x200.

- A. Angular grain of ilmenite.
- B. Ilmenite grain with impact v-marks.
- C. Angular grain of magnetite.
- D. Magnetite grain with v-marks and conchoidal fractures.
- E. Angular to sub-angular chromite grain with uneven fractures and impact depression.
- F. Sub-rounded chromite.

LIST OF TABLES

Table 1- Hinterland stratigraphic sequences and their associated characteristic heavy minerals.

Table 2- Distribution of heavy minerals, magnetite, ilmenite, chromite and non-magnetite fractions in surface and sub-surface samples (weight percent in total bulk samples).

Table 3 – Chemical composition of ilmenite, magnetite and chromite grain

Table 1

Stratigraphic Sequence	Type of Rocks	Characteristic Heavy Minerals	References
Pleistocene to Sub-Recent	Laterite	Hematite, Goethite	Anon (1976), Sahasrabudhe and Deshmukh (1979), Gujar and Srinivas (1991)
Upper Cretaceous to Lower Eocene	Deccan Trap Basalt	Ilmenite, Magnetite, Titano-magnetite, Olivine, Augite	Gujar (1996)
Proterozoic Kaladgi Group	Sandstones	Tourmaline, Zircon, Rutile, Staurolite, Kyanite, Sillimanite, Epidote, Garnet, Ilmenite, Magnetite Pyrite	Sarkar and Soman (1984)
Archean Dharwar Group	Phyllite, Quartzite, Schist, Dolerite, Gabbro, Granite Pegmatite, Aplite, Quartz vein	Tourmaline, Staurolite, Garnet Sillimanite, Zircon, Chromite	Chari et al. (1973), Kelkar (1959)

Table 2

Samples from Supra tidal Zone							
Sample No.	Sub-surface Level / cms	Heavy	Magnetite	Ilmenite	Chromite	Non-magnetic	Location / Physiographic Zone
106	0 – 20	40.83	12.02	13.21	0.40	15.20	Sarjekot [Berm]
	20 – 40	29.87	8.79	6.78	0.31	13.99	”
Average		35.35	10.39	9.99	0.35	14.59	
105	0 – 20	54.36	14.07	21.85	0.61	17.83	Pirwadi [Berm]
	20 – 40	13.70	3.81	3.66	0.37	5.86	”
	40 – 60	10.28	2.60	2.76	0.06	4.65	”
	60 – 80	5.76	1.55	1.28	-	2.93	”
	80 – 100	4.45	1.16	1.36	-	1.93	”
Average		17.71	4.63	6.18	0.34	6.54	
104	0 – 20	18.23	4.67	4.96	1.19	7.41	Pirwadi [Berm]
	20 – 40	17.01	4.05	6.34	0.12	6.55	”
	40 – 60	13.23	3.04	4.70	0.18	5.31	”
	60 – 80	7.56	2.30	2.60	0.10	2.56	”
	80 – 100	12.60	3.18	3.92	0.13	5.37	”
Average		14.12	3.44	4.50	0.34	5.44	
103	0 – 20	17.93	6.52	2.71	1.08	7.62	Hirlewadi [Berm]
	20 – 40	9.39	2.97	1.70	0.18	4.54	”
	40 – 60	11.04	3.43	2.15	0.18	5.27	”
	60 – 80	9.53	2.68	1.80	-	5.05	”
	80 – 100	12.35	1.10	0.82	-	10.42	”
Average		12.04	3.34	1.83	0.48	6.58	
102	0 – 20	16.14	6.02	2.40	1.18	6.54	Tondavali [Berm]
	20 – 40	7.97	2.38	1.47	1.00	3.11	”
	40 – 60	25.88	8.41	4.36	0.31	12.8	”
	60 – 80	17.62	5.68	3.16	0.42	8.36	”
	80 – 100	11.13	4.09	1.88	-	5.16	”
Average		15.74	5.31	2.65	0.72	7.19	
101	0 – 20	27.77	12.59	5.53	0.73	08.89	Tondavali [Berm]
	20 – 40	40.87	18.15	9.45	0.48	12.78	”
	40 – 60	14.98	2.19	1.49	-	11.30	”
	60 – 80	15.43	5.68	3.20	0.12	6.43	”
	80 – 100	14.19	5.45	2.90	0.12	5.72	”
Average		22.64	8.81	4.51	0.29	9.02	
100	0 – 20	08.14	3.44	1.48	0.12	3.10	Tondavali [Berm]
	20 – 40	08.83	3.30	1.44	-	4.09	”
	40 – 60	24.41	10.43	3.14	0.13	10.71	”
	60 – 80	20.87	7.90	3.69	0.11	9.17	”
	80 – 100	15.98	5.31	2.73	0.19	7.75	”
Average		15.68	6.07	2.49	0.12	6.96	

99	0 – 20	84.48	40.41	24.99	0.38	18.70	Talashil [Berm]
	20 – 40	86.03	44.23	17.8	4.56	19.41	”
	40 – 60	38.33	16.12	9.41	0.36	12.44	”
	60 – 80	89.13	44.78	28.00	0.60	15.75	”
	80 – 100	98.80	51.31	33.57	0.70	13.22	”
Average		79.35	39.35	22.73	1.32	15.90	
98	0 – 20	56.05	23.15	15.33	1.28	16.29	Talashil [Berm]
	20 – 40	48.52	15.17	8.39	0.05	24.91	”
	40 – 60	31.19	14.47	8.92	0.35	8.92	”
	60 – 80	30.35	14.51	7.53	0.33	7.98	”
	80 – 100	23.76	10.58	6.79	0.33	6.06	”
Average		37.97	15.57	9.35	0.46	12.83	
97	0 – 20	48.87	22.56	11.31	0.40	14.60	Talashil [Berm]
	20 – 40	41.26	13.45	9.72	0.33	17.76	”
	40 – 60	36.55	15.52	8.22	0.37	12.44	”
	60 – 80	33.09	13.79	7.28	1.72	10.30	”
	80 – 100	83.12	34.70	12.02	6.81	29.59	”
Average		48.57	20.00	9.71	0.72	16.93	
95	0 – 20	77.35	38.41	19.06	-	19.87	Talashil Berm
94	0 – 20	96.64	48.31	33.64	-	14.67	Talashil Dune
93	0 – 20	57.25	20.27	7.33	0.16	29.48	Talashil Dune
37	0 – 20	7.52	2.48	1.34	-	4.72	Hirlewadi HT
39	0 – 20	12.60	6.44	3.49	0.56	2.11	Bagwadi Dune
40	0 – 20	16.09	7.80	2.97	-	5.32	Bagwadi Dune
42	0 – 20	16.02	8.12	3.87	0.97	3.06	Bagwadi Dune
44	0 – 20	40.91	25.04	8.33	-	7.54	Tondavali Dune
45	0 – 20	46.44	22.90	8.90	6.58	8.06	Tondavali Dune
46	0 – 20	86.83	50.85	11.02	2.8	22.16	Tondavali Dune
47	0 – 20	82.35	45.51	12.93	-	23.89	Tondavali Dune
49	0 – 20	86.19	52.70	20.57	10.90	2.02	Talashil Dune
48	0 – 20	98.32	58.15	30.25	-	09.92	Talashil Dune
Samples from Inter tidal Zone							
96	0 – 20	15.68	6.72	1.25	-	07.70	Talashil Sea-side LT
41	0 – 20	9.70	1.89	0.52	0.30	6.99	Bagwadi LT
48	0 – 20	16.12	6.40	1.16	-	8.56	Talashil LT
49	0 – 20	17.48	7.31	3.34	0.46	6.37	Talashil LT
38	0 – 20	1.91	0.60	0.19	-	1.12	Pirwadi LT
37	0 – 20	1.89	0.61	0.16	-	1.12	Hirlewadi LT
39	0 – 20	2.64	0.85	0.70	-	0.87	Bagwadi LT
40	0 – 20	0.69	0.19	0.03	-	0.46	Bagwadi LT
44	0 – 20	3.07	1.32	0.41	-	1.60	Tondavali LT
45	0 – 20	2.10	0.95	0.18	-	0.43	Tondavali LT
46	0 – 20	3.85	1.56	0.46	-	1.96	Tondavali LT
47	0 – 20	4.15	2.43	0.59	-	3.13	Tondavali LT

42	0 – 20	2.03	0.94	0.78	-	0.31	Bagwadi LT
39	0 – 20	4.42	1.29	1.10	-	2.03	Bagwadi MT
	20-40	3.75	1.37	1.29	-	1.09	”
	40-60	1.70	0.87	0.11	-	0.72	”
Average		3.29	1.1	0.83	-	1.28	
40	0 – 20	1.28	0.43	0.05	-	0.80	Bagwadi MT
	20-40	1.66	0.53	0.23	-	0.99	”
	40-60	1.31	0.36	0.12	-	0.83	”
Average		1.41	0.44	0.13	-	1.28	
44	0 – 20	6.24	1.80	1.28	-	3.16	Tondavali MT
	20-40	2.23	0.93	0.24	-	1.06	”
	40-60	2.30	0.96	0.26	-	1.08	”
Average		3.59	1.23	0.59	-	1.76	
45	0 – 20	5.50	2.55	1.55	-	1.40	Tondavali MT
	20-40	3.14	1.45	0.79	-	0.90	”
	40-60	5.29	2.02	0.43	-	2.84	”
Average		4.64	1.99	0.92	-	1.71	
47	0 – 20	6.61	2.54	0.60	-	3.47	Tondavali MT
	20-40	5.46	2.12	0.65	-	2.69	”
	40-60	3.04	0.97	0.54	-	1.53	”
Average		5.03	1.87	0.59	-	2.56	
37	0 – 20	1.36	0.36	0.08	-	0.92	Hirlewadi MT
	20-40	2.00	1.26	0.21	-	0.53	”
	40-60	1.97	0.61	0.24	-	1.12	”
Average		1.77	0.74	0.17	-	0.85	

(HT= High Tide, LT= Low Tide and MT=Mid Tide)

Table 3

Ilmenite													
Area	Station No.	TiO₂	CaO	Cr₂O₃	Fe₂O₃	FeO	ZnO	V₂O₅	NiO	MnO	MgO	Al₂O₃	SiO₂
Tondavali [L]	46	40.04	0.95	0.01	19.96	31.32	0.29	0.73	0.09	1.38	0.39	1.64	2.20
Tondavali [L]	47	46.60	0.85	0.01	18.05	26.20	0.28	0.60	0.09	1.05	0.22	1.27	2.25
Talashil	97	41.63	0.77	0.03	21.33	28.00	0.29	0.89	0.10	1.43	0.48	1.87	2.01
Talashil	48	44.57	1.44	0.01	16.81	30.30	0.26	0.76	0.05	0.89	0.26	1.02	2.42
Talashil	113	41.01	1.00	0.45	20.02	29.92	0.26	0.96	0.11	1.26	1.75	1.76	0.70
Magnetite													
Tondavali [L]	46	22.86	5.30	0.02	32.80	19.10	1.49	4.71	0.20	4.40	0.06	2.20	1.85
Tondavali [L]	47	14.31	ND	0.70	46.0	22.10	0.06	3.78	0.34	1.05	ND	0.85	0.90
Talashil	97	22.00	5.62	0.02	32.40	24.10	2.58	3.85	0.16	3.95	0.05	1.39	1.02
Talashil	48	23.98	4.39	0.10	31.20	21.90	2.13	4.31	0.17	4.51	0.15	0.90	0.45
Talashil	113	21.00	5.05	0.04	37.52	22.00	1.75	4.65	0.19	4.38	0.09	1.86	0.86
Chromite													
Tondavali [L]	46	0.03	1.48	47.52	4.73	19.13	0.26	0.98	0.72	1.94	14.86	11.70	2.68
Talashil	97	0.79	3.75	34.76	4.36	23.52	ND	1.96	0.09	0.09	12.29	12.06	2.31
Talashil	48	0.48	3.86	32.06	4.32	21.32	0.42	2.46	0.15	3.35	13.16	10.86	3.60

(ND=Not determined) (L=Lower)

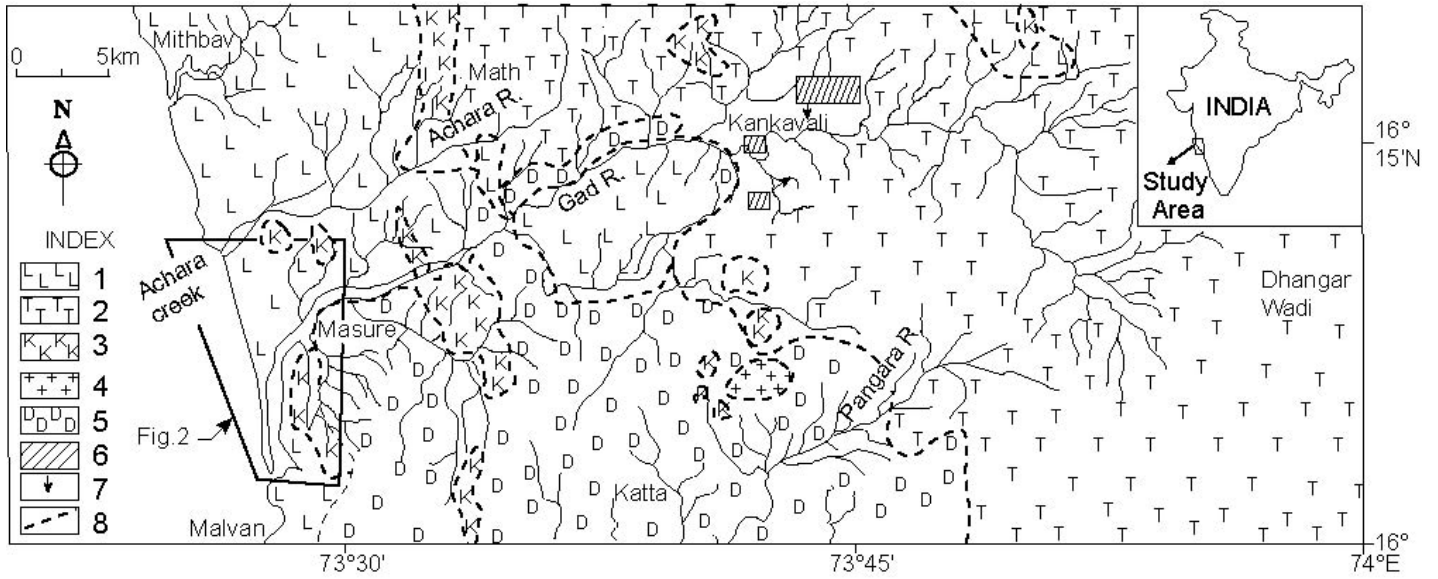


Fig. 1

73°25'E

30'

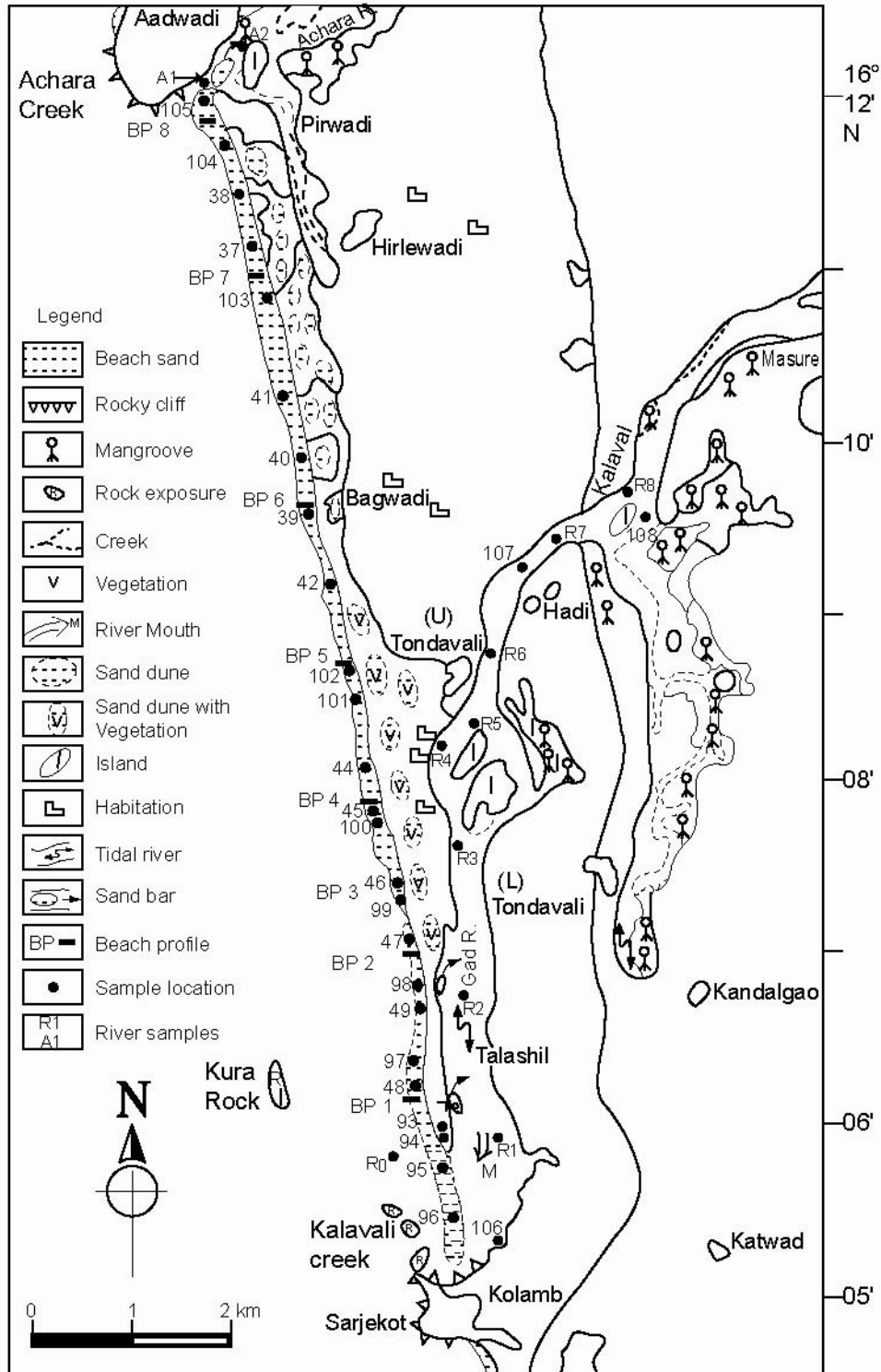


Fig.2

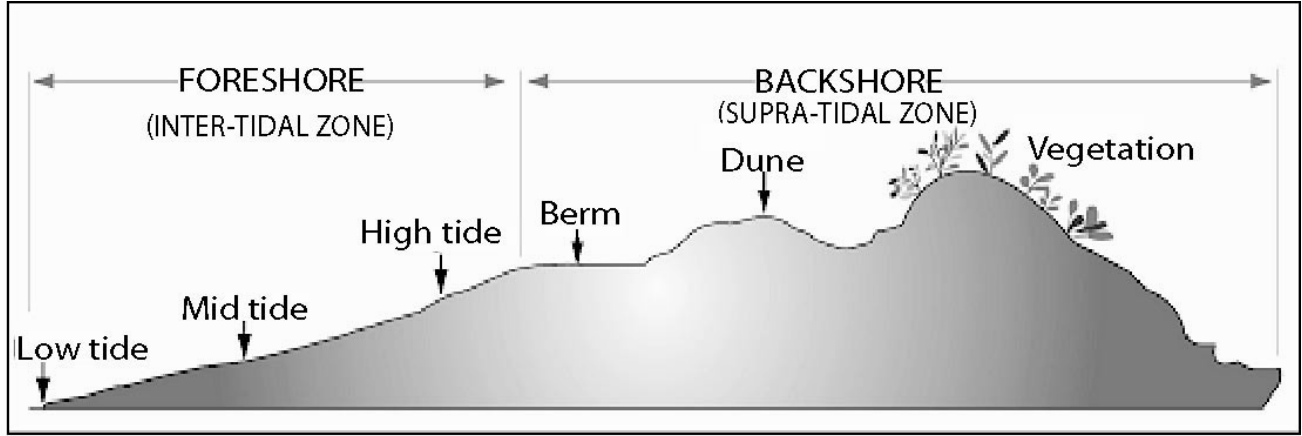


Fig. 3

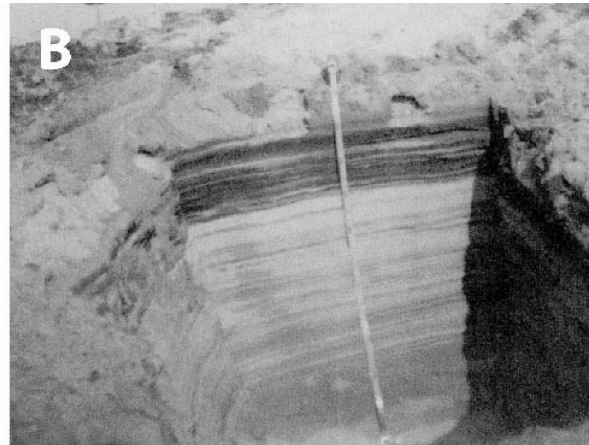


Fig. 4

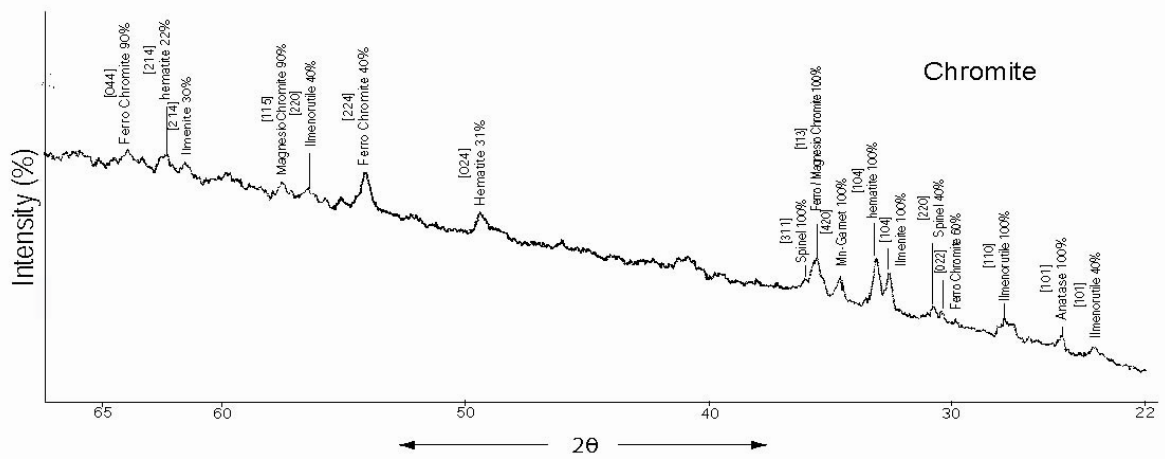
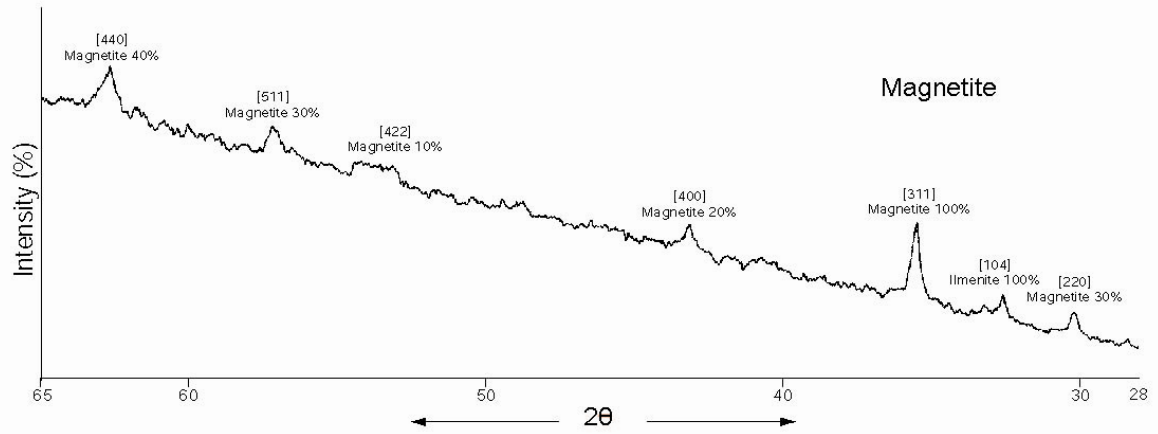
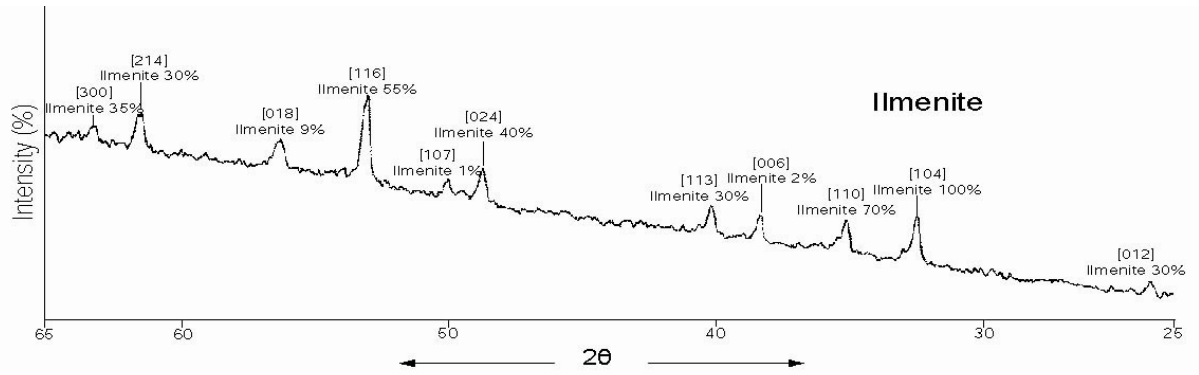


Fig.5

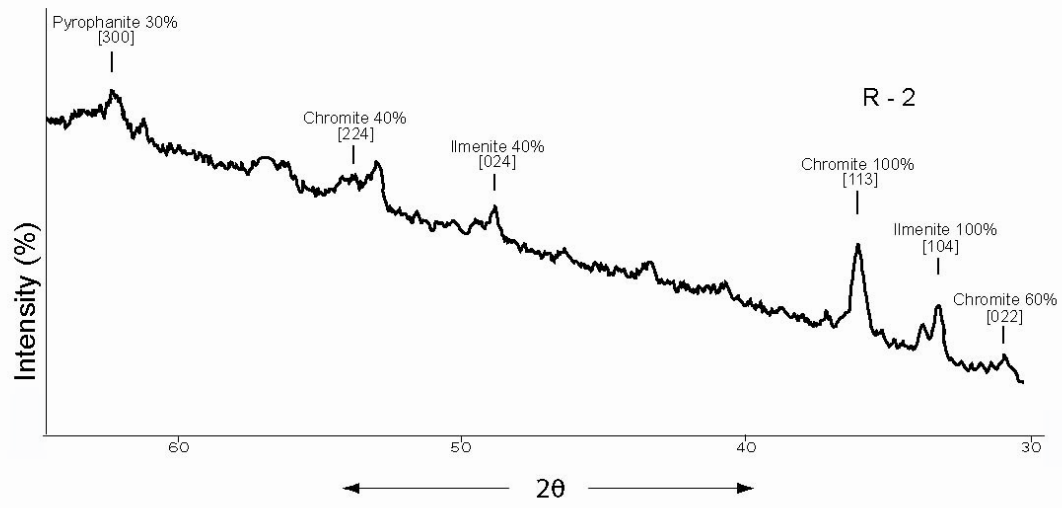
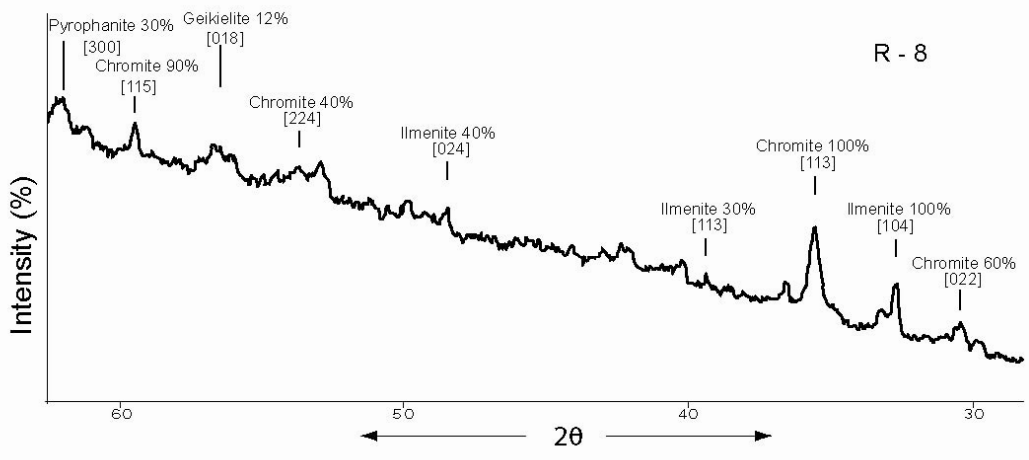
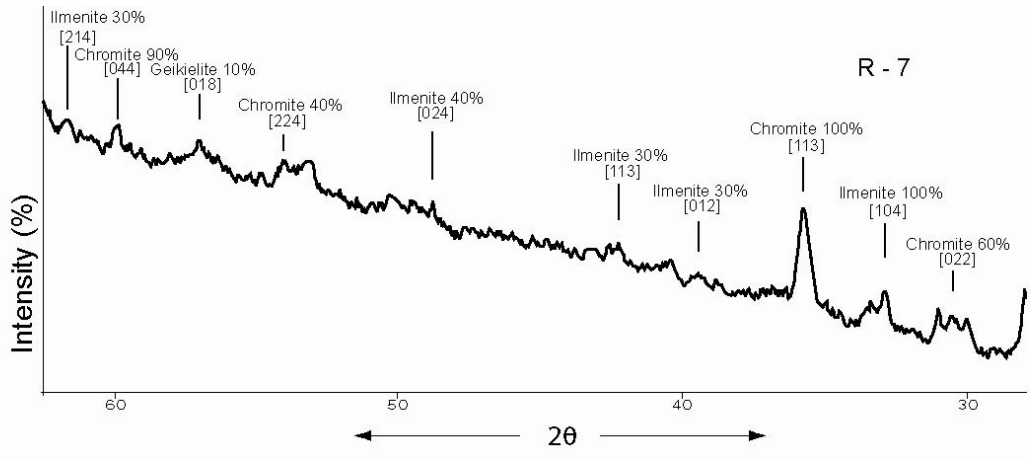


Fig. 6

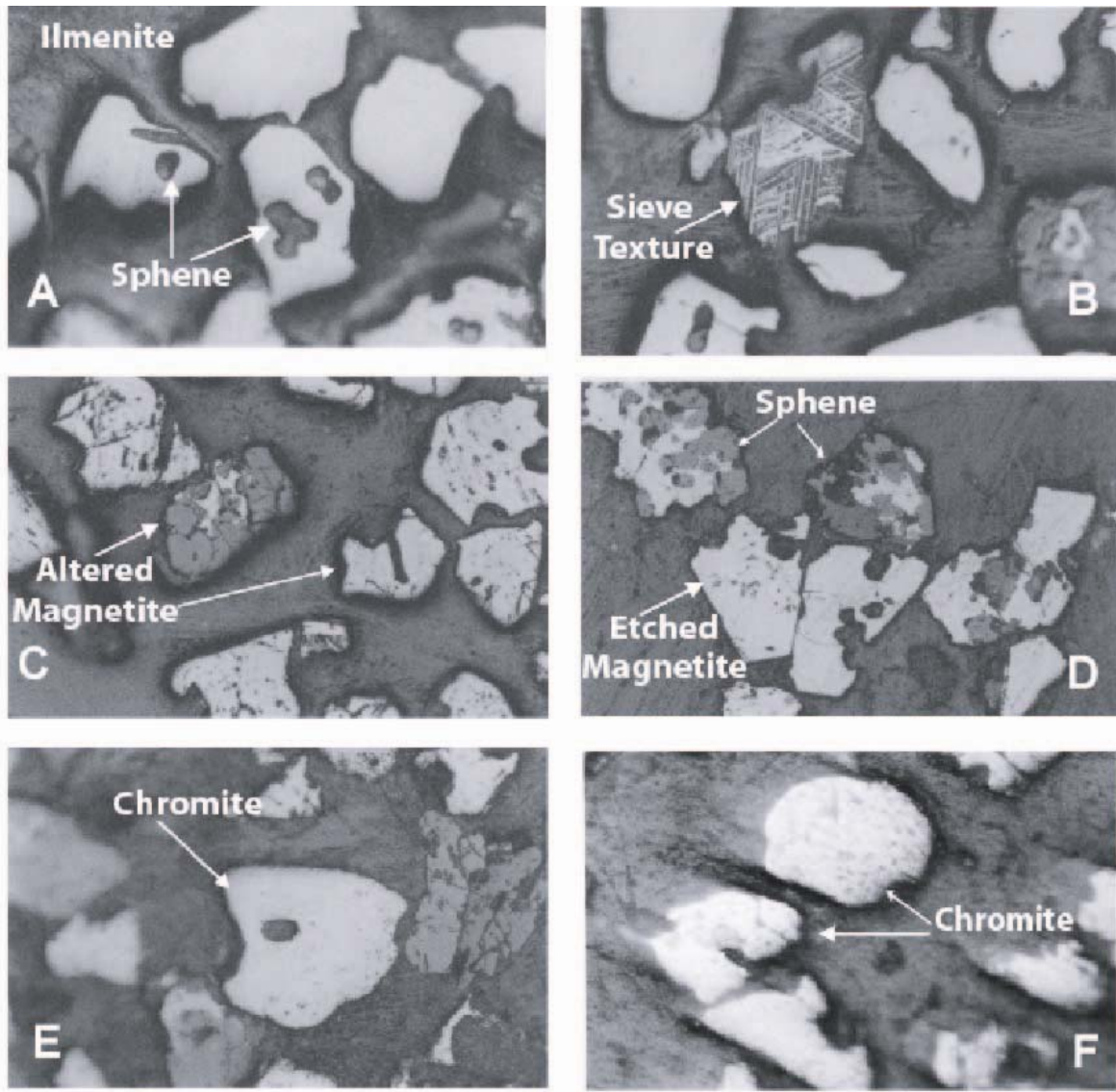


Fig. 7

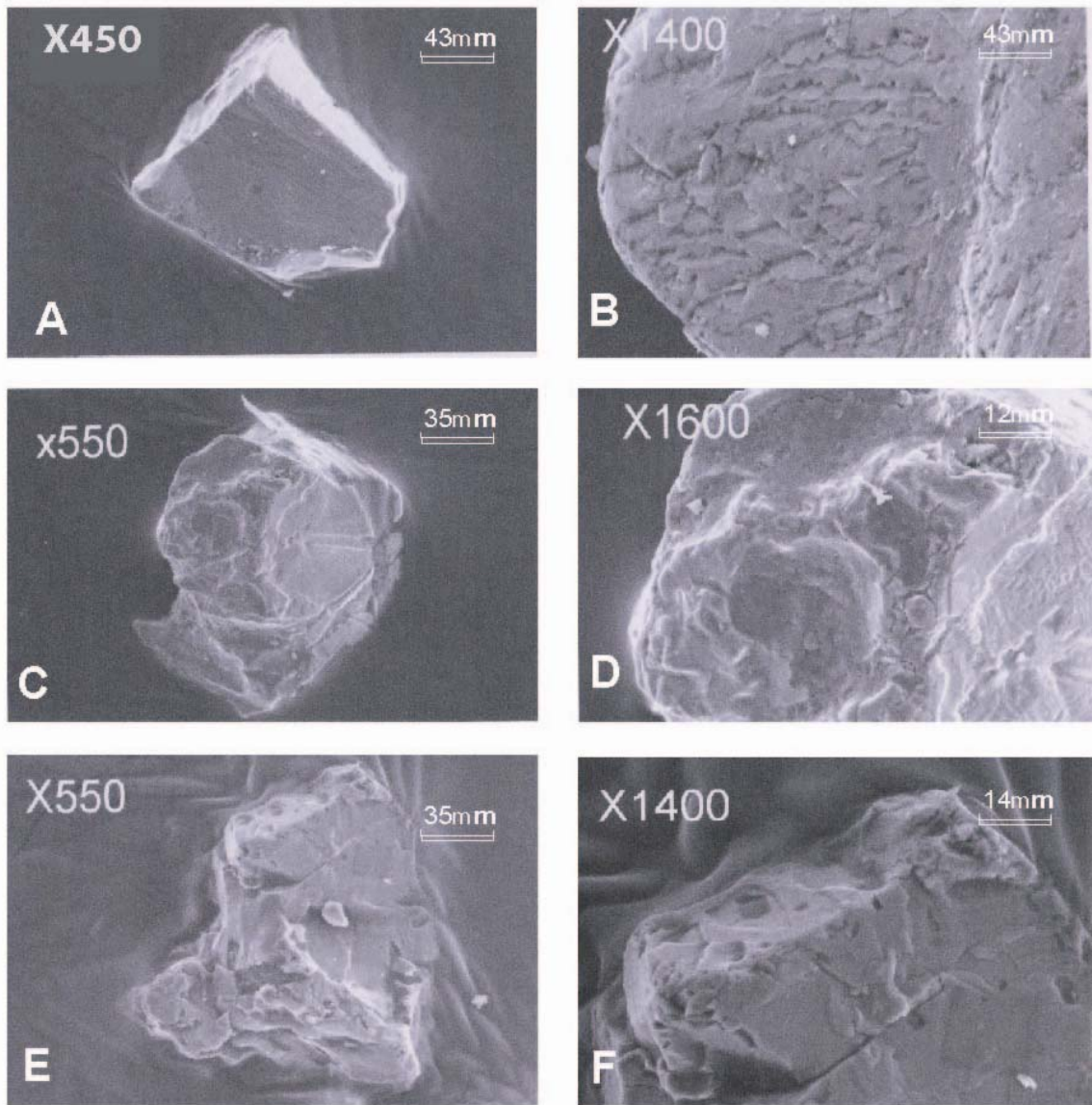


Fig. 8