

Multi-mineral potential of littoral placers of Sindhudurg District, Maharashtra, West coast of India

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Abstract

The present paper investigates the mineralogy of fluvial and coastal sediments, with special attention to the heavy mineral placers between Vijaydurg and Redi Point along the 105 km stretch of the coastal area of Sindhudurg District, Maharashtra. We present the distribution, depositional environment, mineralogy, geochemistry, replenishment and reserve potential of the heavy minerals. The heavy minerals (up to 98wt%, avg 27wt%) identified are opaque (ilmenite, magnetite, chromite), pyroxenes, amphiboles, rutile, tourmaline, kyanite, staurolite, zircon, garnet, epidote, sillimanite and olivine, while quartz and feldspar form the light fractions. It is observed that the concentration of heavy minerals is more in the supratidal zone as compared to intertidal zone. The provenances for the minerals are igneous, metamorphic rocks and recycled sediments of Pre-Cambrian Age along with Deccan Trap basalts.

Twelve sites were identified in which the inferred reserves of heavy minerals, ilmenite, magnetite and chromite were estimated on a conservative basis. In Area 1 (7 sites) the heavy minerals are 2.33 million tonnes (MT), ilmenite 0.55 MT, magnetite 0.98 MT and chromite 0.032 MT. In Area 2 (5 sites), the inferred reserves of heavy minerals are 0.031 MT, ilmenite 0.008 MT and magnetite 0.004 MT. In the future, these resources could be further explored and thus be useful to the mining industries.

Keywords: Placers, Littoral, Heavy Minerals, Provenance, Sindhudurg, Maharashtra, India

1. Introduction

Heavy mineral placers, commonly known as black sands, are sedimentary deposits of minerals (with density more than 2.9 g/cm^3) which get accumulated over a period of time with sand, silt and clay in the littoral zone and in the near shore areas of the ocean (Bradley et al. 2014). The strategic and commercially viable minerals include ilmenite, rutile, leucocene (titanium-bearing minerals), zircon and monazite (radioactive minerals) and others like garnet, sillimanite, magnetite and chromite (Rambabu Singh et al. 2020).

The heavy mineral concentrations in the littoral sediments depend primarily on the chemistry and tectonic-stratigraphic level of the rocks eroded from the hinterland areas or from the near shelf (Garzanti and Andò 2007). In addition to the source rocks, the formation and localization of the littoral placers is also controlled by drainage patterns, tectonic features, climatic variations and sea-level fluctuations during the Quaternary Era (Sutherland 1985). Heavy minerals could get concentrated by processes such as low rate of sediment supply and long periods of erosion (Roy 1999) that could lead to selective sorting of the sediments on account of waves and currents (Komar and Wang 1984; Garzanti and Andò 2019). The extent of the deposits depends on the circulation cells, which have unique mineral population, defined by the interaction between oceanographic processes, grain size and coastal configuration (Komar 2007; Garzanti et al. 2018).

Coastal placer minerals are a worldwide phenomenon including in India. In India, the occurrences of placer minerals are documented along Western and Eastern coasts, where sizeable deposits of onshore and offshore heavy minerals that formed under special circumstances and at specific locales have been reported. Along the West Coast heavy minerals are reported from Gujarat (Sakhawala and Shringarpure 1988; Dinesh et al. 2015), Maharashtra (Siddiquie et al. 1979, 1982; Gujar et al. 2010a,b; Iyer and Gujar 2014; Iyer et al. 2021); Goa (Kidwai and Wagle 1975; Patil 2007; Sreenivasa et al. 2014; Gujar et al. 2021); Karnataka (Chavadi and Nayak 1990; Hegde et al. 2006; Shalini et al. 2020), Kerala (Mallik et al. 1987; Nambiar and Unnikrishnan 1989; Prakash et al. 1991). Along the East Coast, placers are recorded at Tamil Nadu (Angusamy et al. 2005; Hentry et al. 2012; Nallusamy 2013; Kalyani et al. 2019; Dhinesh et al. 2020); Andhra Pradesh (Ravi et al. 2001; Rao et al. 2008; Reddy et al. 2012); Odisha (Acharya et al. 2009, 2015; Rambabu Singh 2020; Ghosal et al. 2020); West Bengal (Shirke and Chatterji 1959; Biswas and Roy 1976; Mallik 2005). In the recent book on Indian Placer Deposits (Dhana Raju 2021) the studies concerning only four Indian States are presented and these are Kerala, Tamil Nadu, Andhra Pradesh and Odisha. Unfortunately, information about the most important and rich deposits of ilmenite, magnetite and chromite placers along the Maharashtra coast is missing.

The present investigation is based on the earlier works of CSIR-National Institute of Oceanography (Goa, India) of late 1970's during which black patches in the littoral zone were demarcated from the study of aerial photographs (1:25,000 scale) of the entire Maharashtra coast (720 km). After ground truthing, these patches were confirmed to be of heavy mineral beach sand (Wagle et al. 1989). Maharashtra coast was divided into three zones depending upon the observed heavy mineral concentration, drainage patterns, hinterland geology and coastal geomorphic features. The three zones are Northern Zone (Arnala to Jaigad), Central Zone (Jaigad to Vijaydurg) and Southern Zone (Vijaydurg to Redi Point). The northern zone (along the Arnala coast) was studied for placer minerals (Iyer et al. 2021) and for the magnetic susceptibility (Badesab et al. 2017). Among these three zones, the central zone which hosts rich placer deposits has been investigated extensively and their offshore extension also was established (Siddiquie et al. 1982).

The southern zone with the second richest deposits was explored in detail under the CSIR Network Project of Capacity Building for Beach Placer Mining, initiated by the Planning Commission of India and executed through the Council of Scientific and Industrial Research (CSIR) from 2003-2008. The results of this study are presented for the first time in this paper in terms of placer mineral distribution, depositional environment, mineralogy, geochemistry, replenishment and probable reserve potential of the onshore placers occurring between Vijaydurg and Redi Point, along the Sindhudurg coast, Maharashtra, India (Fig. 1).

2. Methodology

2.1 Field Work

Prior to sample collection, a geomorphological map of the study area (**Fig. 2**) was prepared by referring to the land-use maps of Space Application Centre, Ahmedabad. Depending upon configuration and nature of the coastline, East-West sampling tracks were laid perpendicular to the beach at an interval of 500-700 m for the collection of samples. While spacing the sampling tracks, emphasis was placed to obtain maximum coverage of the area. This was done after accounting for the surficial spread of heavy minerals, positions of streams/rivers and physiographic features. These precautions were necessary in order to obtain unbiased sediment samples.

Sediments were collected using an acrylic tube of 40 cm length and 5 cm diameter from different physiographic domains namely low, mid and high-tide zones (foreshore/intertidal zone), berm and dune (backshore/supratidal zone) (**Fig. 2**). The sub-surface samples in the dry zone (beyond mid-tide level) and in the backshore were collected by using a shell-type hand auger. On an average, 1 m of sediment was recovered at intervals of 20 cm i.e., at levels of surface 0-20, 20-40,

40-60, 60-80 and 80-100 cm. Sampling was stopped when slumping of sand occurred due to water saturation, coarsening of sand and depletion of heavy minerals.

Sample positions were obtained by using a Global Positioning Fixing System (GPS), NAV-5000 PRO model which has an accuracy of ± 3 m. A total of 1,200 beach samples was collected along 110 sampling tracks. Twelve samples from the river bed (9 from River Gad and 3 from River Achara) were also collected with a Van-Veen grab from a flat-bottomed boat. In addition, 36 rock samples were collected from the hinterland formations to understand contribution of minerals to the coast. The drainage basin of these rivers (Achara and Gad) was selected because high concentrations of heavy minerals occur at their mouth and in the adjoining areas of these rivers. Rocks were collected between the coastline to base of the Western Ghat scarp (30-40 km in the hinterland) and within the catchment areas of the river Gad and Achara. The hinterland rocks include laterite, basalts, amphibolites, sandstones, quartzites, crushed conglomerates, phyllites, granite gneiss, schists and serpentinitised metamorphic rocks with chromite lenses. Eleven soil samples were also collected from hinterland lateritic formations to check for heavy minerals.

Beach topography profiling was carried out to determine the seasonal morphological changes between Achara and Talashil (Fig. 2), which are promising areas of placer deposits (Gujar et al. 2010a,b; 2011). The profiling was conducted at 10 locations during pre-monsoon, monsoon, post-monsoon and again pre-monsoon period from October 2004 to December 2005 by following standard survey method and using a Ceeducer DGPS System (Ganeshan 2006). Temporary bench marks were fixed on the shore and the vertical topographic level was determined using an auto level (Carl Zeiss make). The data helped to understand the trends of sediment erosion/deposition and replenishment of surficial placer minerals.

2.2 Laboratory Work

To cover the entire study area, samples were selected based on visual observation of significant presence of heavy minerals (black sand) and less of calcareous shells. Of the 1,200 samples, analysis of 1,090 (including 12 from the rivers Gad and Achara) was carried out for granulometric and heavy minerals separation by the methods of Folk (1968) and Hutchinson (1974). After drying each sample at 60 °C, 25 g were obtained after coning and quartering for further analysis. The samples were washed with distilled water and again dried at 60 °C. Diluted HCl (1:10, i.e., 10 ml concentrated HCl and 90 ml distilled water) was added to dissolve calcareous shells. After drying, the carbonate-free samples were sieved at 1/4 Φ interval in a ro-tap sieve shaker machine. The

granulometric data were used to compute the grain size statistical parameters by using GRANDISTAT computer programme (Blott 2000).

After sieving, the samples were divided into 4 fractions, viz. Fraction A was 500-250 μm as medium sand, Fraction B was 250-125 μm as fine sand, Fraction C was 125-63 μm as very fine sand and fraction D was 63-31 μm as coarse silt (Wentworth 1922). The heavy minerals in the coarse sands are very rare and even if present these are within the rock fragments, thus it becomes difficult to separate or mount them on glass slides (Garzanti and Andò 2019). Due to this difficulty, medium sand to coarse silt (500-31 μm) fractions were used for heavy mineral separation. The heavy mineral separation of these fractions was carried out by using bromoform of 2.9 g/cm^3 density (Milner 1962), because the dense grains of heavy minerals are more concentrated in the finer fractions.

The separated heavy minerals were washed with methyl alcohol and dried, then they were weighed and weight percentages were calculated for each fraction. Magnetite grains were separated from the heavy minerals by using a hand magnet. After the removal of magnetite grains, ilmenite grains were separated from the remaining heavy minerals by using an isodynamic separator (S. G. Frantz Isodynamic Separator Model L1). The current used to separate ilmenite was 0.22 and 0.4 amp for chromite (cf. Hutchinson 1974). After adding the weights of the separated heavies, magnetite, ilmenite and chromite from each fraction of samples, their percentages were computed with reference to the bulk sample, i.e., total weight of the sample taken for analysis (25 g). This absolute abundance percentage (Garzanti and Andò 2019) in the bulk sample is used for discussion, because the data analyzed by this method are required for the mining industry in India as per the project requirement of “Beach Placer Mining Capacity Building.”

The separated grains of ilmenite, magnetite and chromite were confirmed by using an X-Ray Diffraction unit (Philips Model 1840) and the peaks were identified by referring to JCPDS (1981). Glass micro-slides for transparent heavy minerals (fraction remaining after separating magnetite, ilmenite and chromite) retained in the very fine fraction (125-63 μm) were prepared using Canada Balsam. Twenty-one slides were prepared to identify transparent heavy minerals and their morphology and texture under transmitted slights using a Leica DMEP microscope.

The minerals on each slide were counted by point counting method following Galehouse (1971). A minimum of 300 to a maximum of 1,344 grains were counted on each slide and the counts of different minerals were converted into percentages and from these the characteristic heavy mineral assemblages were identified. The polished sections of detrital opaque grains of 21 samples were prepared on Bakelite stubs and their textural characters were identified under a reflected microscope.

In addition, 20 thin sections of hinterland rocks were also prepared and were studied for diagnostic textures and heavy mineral characters. Twenty samples (8 each of ilmenite and magnetite and 4 of chromite) from the prospective area were used to determine their chemical composition by using an ICP-OES, after following the standard procedures.

To estimate the reserve potential, the bulk density of heavy mineral sand was estimated and it is based on the average weight of the number of 100 cc samples from the prospective area. Considering the concentration of heavy minerals and their lateral extension, the dimensions of the prospective areas in the berm and dunes was calculated (only with respect to concentration zone of limited extent). The reserves were calculated for 1 m of sand thickness by using the following formula:

$$R = \frac{A \times T \times D \times C}{100}$$

R = Reserve in tonnes

A = Area in m²

T = Thickness of the deposit

D = Average bulk density of sand

C = Mineral Concentration

The bulk densities of the sediments were calculated area-wise and their values vary between 1.48 and 2.18 kg/m³, (avg 1.8 kg/m³).

3. Study Area: Geology, Geomorphology and Oceanographic Processes

The study area lies between 16°30' N latitude (Vijaydurg) and 15°43'N latitude (Redi Point) along the Sindhudurg district, west coast of Maharashtra (**Fig. 1**). A humid tropical climate (mean humidity 85%) prevails in most of the area while the temperature ranges between 16 and 36°C. The study area receives its annual rainfall from SW monsoon. During the exploration period (2003-2008), the rainfall in the study area was 2688 mm in 2003; 2607 mm in 2004; 3223 mm in 2005; 3410 mm in 2006; 3657 mm in 2007 and 3271 mm in 2008 (Mishra 2014). The study region is hilly and dissected by transverse ridges of the Western Ghats, and the ridges at several places extend as promontories into the Arabian Sea. The stratigraphy of hinterland includes those of Archean, Dharwar, Pre-Cambrian, Mesozoic and Quaternary age (Table 1; Fig. 3). The Archean and Dharwar are represented by phyllites, banded quartzite, chlorite schists, amphibolites, quartzites, granites,

granitic gneisses and staurolite schists. These rocks, at places, are intruded by dolerite, metadolerite and pegmatite (Anon 1976). The characteristic heavy minerals in these rocks include staurolite, kyanite, garnet, rutile, hornblende, zircon, sphene, magnetite, ilmenite, tourmaline and chromite.

The Kaladgi sandstones and quartzites lie unconformably over the Archean rocks and occur as detached in-lies separated from each other by outcrops of Deccan Trap and laterite. The heavy mineral composition of this formation includes ultra-stable heavy minerals like zircon, tourmaline and rutile and opaques (Sarkar and Soman 1984). Mesozoic and Tertiary rocks are represented by Deccan Trap basalts, which are overlain by laterite.

The shoreline is narrow (70-80 m) towards the south and progressively widens (200-250 m) towards the north and it consists of sandy beaches which are separated by rocky headlands or promontories/cliffs, river mouths, small creeks and broad estuaries (Fig. 4; Table 2). The beaches are either arcuate to semi-arcuate or straight and long (Fig. 4M) and have variable gradient. In the case of arcuate to semi-arcuate beaches, the gradients in the foreshore varies are low and moderate (2° - 7°), whereas straight beaches have moderate to steep (8° - 25°) gradients. The backshore (supratidal zone i.e., zone behind high tide line) is dominated by berm and vegetated sand dunes. Berms are narrow in width (20-80 m) and at most places two to five sand dune ridges of variable heights (1-4 m) occur parallel to the coast except in some areas (Fig. 4L).

Beyond the high tide line, at the base of the dune, beach rocks of different height occur at Kotharwadi, Kelye and Kolamb, and ranges between 3 and 3.5 m from the mean sea-level (Fig. 4 A). In addition to the depositional sea-level indicators, the coast also shows erosional features such as wave-cut platform, and sea-caves (Fig. 4 B, D) which are suggestive of emergence of the coast. On the other hand, the coast also preserves signatures of submergence like sand bar, offshore islands and estuaries (Fig. 4 C, N). The radiocarbon data of the beach rocks (Kelye $5,470 \pm 100$ years, Kotharwadi $1,900 \pm 80$ years and Kolamb $1,820 \pm 90$ years) point to formation during the period of Holocene sea-level fluctuations along the coast around 5,470 to 1,800 years BP (Anon, 2007).

The study area is drained by several minor rivers (length <100 km) and these, from the north to south, are Kelye, Devgad (also called Vadatar or Kharda), MithMumbari, Achra, Gad, Adari, Karli, Dungeshwar, Kelus, Dabholi and Talvandi (**Fig. 1**). Based on their geometrical properties, the major rivers Devgad, Achra, Gad and Karli are relatively longer (Karlekar 1981) (**Table 3**) and with large catchment basins as compared to other rivers. All the rivers join the Arabian Sea either in an east-west or northeast-southwest direction. The variations in lithology and structural features seem to

influence the longitudinal profiles of the rivers. Most of the rivers show sign of entrenchments (Dixit 1979).

The tidal range varies from 1 to 2 m and the predominant wave directions are from southwest, west-southwest, west and northwest (periods range from 5 to 14 seconds) (Reddy 1976; Gujar et al. 2011). The average breaking height of the waves differs from season to season (0.3 m in winter and 2-4 m during the monsoon). The waves break parallel to the coast and during monsoon the wave energy is high. The longshore current directions are variable but it is predominantly more towards the south. The transport paths get terminated in areas of spit bar, depositional foreland, shoals and promontories. Along the open straight beaches the wave height is high (>2 m), (whereas in arcuate and semi-arcuate bays it is less (<2 m)). The length of littoral, transport zone under uniform wave conditions is largely governed by the coastal configuration (Chandramohan et al. 1989).

In the study area, due to the indented coastline, convergence and divergence of wave orthogonal occur leading to the development of long transport path with individual sections/cells and heavy mineral concentrations. In addition, down-drift erosion and up-drift deposition along zones of convergence are present (Gujar et al. 2008). The long shore currents run parallel to the coast and are affected by the velocity and angle of the incoming waves and water from the long shore current moves on and off the beach which results in the formation of rip currents which flow perpendicular to the coast. The rip currents are generated due to variations in the near shore topography, presence of rock outcrops and islands along the coast cause massive sediment erosion of the surf zone. During period of high wave energy such currents are noticed at the lower reaches of Tondavali (**Fig. 2**) (Gujar et al. 2011).

4. Results And Interpretations

4.1. Sediment characteristics: The sediments dominantly contain sand and silt while the coarse fractions have placer minerals, quartz (fresh and iron stained) and feldspar. Pieces of laterite occur in the coarse and fine sand fractions. The calcareous material is comprised of broken shells, gastropods and benthic foraminifera like species of *Ammonia*, *Triloculia*, *Nonion*, *Quinqueloculia* and *Ephidium*. Carbonate content fluctuates in the different physiographic domains for e.g., in intertidal zone it is 8 to 12 wt% (avg 9.5 wt%) whereas in supratidal zone it is 3 to 5 wt% (avg 2.5 wt%). The carbonate content increases (12-19 wt%, avg 10.5 wt%) with depth below the beach surface. The observed variations can be attributed to the benthic production and the seasonal transport processes coupled with littoral currents and wave action. In the top 1 m sediment layer, the calcareous

materials occur as layers of variable thickness with limited lateral extent and show a negative relation with heavy mineral concentrations.

Granulometric analysis (**Table 4**) reveals the sand to be medium to fine grain and range in size between 1.43 and 2.97 Φ . The sorting values (i.e., standard deviation) vary between 0.31 and 0.83 Φ indicating the sediments to be moderately well sorted to well sorted. Skewness ranges from -0.04 to +0.74 and suggest symmetrical to finely skewed nature of sediments, while kurtosis ranges from 0.90 to 5.08 and point to platy- to mesokurtic nature of the sediments. On bivariate plots, the sediments depict three environments: beach (predominant), river and dune (Anon 2007).

4.2. Heavy minerals: The specific beach features and nature of distribution of heavy minerals are depicted (Fig. 4 A-P). The heavy minerals that occur in the dune cut, runnel, berm and along the river bank (**Fig. 4 F, E, O, L**) are opaque, pyroxenes (augite, hypersthene), amphiboles (hornblende), rutile, tourmaline, kyanite, zircon, staurolite, titanite, olivine, garnet, epidote, sillimanite and actinolite (Table 5), while the light fraction has mainly quartz and feldspar. The opaque includes fresh grains and weathered derivatives of ilmenite and magnetite. Interestingly, the occurrence of chromite is noticed for the first time as placer sand in this area along the Tondavali-Talashil zone, in the backshore and inter-tidal zone during the monsoon, and in the dune cut (Fig. 4 G, K, L, J) (Gujar et al. 2010a,b). Similarly, the spread of the heavy minerals in the intertidal zone is also noticed at Bhogwe (Fig. 4 H).

During the monsoon season, the heavy minerals are displaced from the beaches and get added due to high waves which are associated with strong winds and torrential rains. The sand on the beach is constantly in a labile phase and the waves reach up to the frontal sand dune ridges, thus resulting in the undercutting of dunes. This leads to the slumping of sediments and the laminations in the dunes are exposed (Fig. 4 K, P). Further, these sediments get transported seawards due to the strong retreating currents (Fig. 4 L). In some areas like Talashil significant deposits of heavy minerals up to 98 wt. % occur along the berm zone, which otherwise had a heavy mineral concentration around 47-52 wt % during fair season (Anon 2007).

We identified two areas in the study region that has variable concentration of heavy minerals: Area 1 (7 sites) has observable concentration with a notable spread of heavy minerals and Area 2 (5 sites) with visible concentration but limited spread of heavy minerals. Based on the analysis of 797 sediment samples, the range and average of heavy mineral concentrations from these two prospective areas are tabulated (**Table 6**). In certain areas, the percentage of heavy minerals ranges up to 98 wt% (avg 27 wt%) while in localized areas the concentration is up to 32 wt% (avg 12 wt%). Chromite

along Pirwadi to Tondavali is 0.61-6.99 wt% (avg 2.58 wt%) and along Tondavali to Talashil it is 0.12-12.35 wt% (avg 1.62 wt%) (**Table 6**). The accumulation of heavy minerals (ilmenite, magnetite, chromite) is consistent and substantially more in the backshore (berm and dune regions) in contrast to the intertidal zone. This fact is more noticeable between Pirwadi and Talashil (**Fig. 2**) (Gujar et al. 2010a). In addition, the heavy mineral concentration in the sediments of River Achara is much less (0.74- 0.79 wt%, avg 0.76 wt%) as compared to that of River Gad (13-34 wt%, avg 25 wt%).

4.3. Microscopy features: Polished detrital grains (Fig. 5 A-L) indicate ilmenite grains to be fresh and euhedral to sub-rounded in shape (Fig. 5 A, D, E, G). Minor alteration of ilmenite to sphene and leucoxene is noticed (Fig. 5 B, C, F) and some grains show sieve texture (Fig. 5 C). Fresh and weathered magnetite grains are also observed. The fresh magnetite grains are angular to sub-angular and they are mainly titanomagnetite (Fig. 5 H), which shows slight alteration to sphene along the margin (Fig. 5 I, J). This may be due to the selective dissolution of magnetite component of exsolution type and titanomagnetite by weathering (Ramdohr 1980). Chromite grains are sub-rounded to rounded and show the effect of transportation and have no intergrowth features (Fig. 5 K, L).

4.4. X-Ray Diffraction: X-Ray diffraction (XRD) analysis of separated fractions of ilmenite, magnetite, chromite and river bed sample was undertaken to identify the mineral phases (Fig. 6). Chromite is present as ferro chromite (FeCr_2O_4) and also as magnesio-chromite ($\text{Mg}_2\text{Cr}_2\text{O}_3$). The presence of chromite with other heavy minerals, mainly ilmenite, is also confirmed in the samples from River Gad (Fig.6). Ilmenite grains depict sharp unimodal peaks indicating their dominantly fresh nature. Similarly, most magnetite grains are fresh but the presence of bimodal peak suggests minor intergrowth/exsolution and alteration. This is also attested by ore microscopy observations.

4.5. Petrography: Transparent heavy minerals were identified in the thin sections of the hinterland rocks (Fig. 7 A-L). Basalt and dolerite outcrops in the study area occur along the eastern border with a few patches around Malvan (Fig. 3). In the thin section, the rocks show medium to fine grained opaques and olivine (Fig. 7 A). Amphibolites and schists are near KilleNivati (south of Malvan, Fig. 3) and these have abundant medium to fine grain opaques along with hornblende, zircon and colorless garnet (Fig. 7 H, I, J, F, K).

Kaladgi sandstones and quartzites are exposed in the bed of River Gad around Malvan and to its south in Bhogwe (Fig. 3). The sandstones and quartzites show anhedral to sub-rounded opaques,

along with zircon and kyanite (Fig. 7 D, B). Granite gneisses are also exposed near River Gad and these have euhedral colorless zircon.

Serpentinised metamorphic rocks are found near Janoli and Wagde (Iyer et al. 2010), and these have opaques, colorless euhedral and rounded garnet besides few chromite lenses (Fig. 7 C, E, L). Basalts contain laths of titanomagnetite, with few granular ilmenite. Inclusions in plagioclase of basalts include zircon and rutile. Laterite mainly contains zircon, magnetite, hematite, goethite and angular colorless garnet (Fig. 7 G).

4.6. Transparent minerals: The transparent detrital minerals (Fig. 8) are represented by amphibole (hornblende, actinolite), pyroxene (hypersthene, enstatite), kyanite, tourmaline, zircon, rutile, staurolite, titanite, olivine, garnet, epidote and a negligible amount of sillimanite.

Among the transparent detrital minerals, amphiboles are dominant (max 41%) and are found at Sukhalbhat, near Vengurla. The amphiboles are fibrous actinolite and mostly prismatic green hornblende with rounded edges while some grains are broken, and have dented rounded edges (Fig. 8). Pyroxenes are the second most abundant (8-15%) and occur in the Pirwadi-KilleNivati area. Prismatic hypersthene with broken edges are common (Fig. 8) whereas enstatite is rare. Zircons are present in all locations, except at Pirwadi and Tarkarli, with a maximum (31%) at Kalvibandar (near Nivati). Majority of zircon grains are light pink, brownish euhedral, rounded-broken, well-rounded with an outer growth and some have inclusions (Fig. 8). Tourmaline grains are less (up to 2%) and are of two types, brown and green. The grains are euhedral, broken and partly rounded and rounded grains (Fig. 8) and inclusions are common.

Rutile grains have a widespread occurrence and are deep red and foxy red in color, with higher concentration at Kalvibandar (3.5%). Rutile is present in euhedral, elongated broken and rounded forms (Fig. 8). Garnet grains occur in many locations (up to 25% at Bhogwe) and are colorless and pink. The grains are angular, corroded and rounded and show etching, pitting grooves and fractures (Fig. 8). Epidote grains are light green in color and broken as well as prismatic forms are noticed (up to 2% at Wagheshwari (near Vengurla) (Fig. 8). Kyanite grains are present in minor amount (max 1.6% at Sagartirth near Vengurla) and are prismatic and have sharp or round edge. Staurolite grains are yellow, sub-angular to sub-rounded and occur at Sagartirth (max 2.6%). Other grains are olivine (maximum 0.52%) and sillimanite (0.36%).

4.7. Chemical composition. Geochemical analysis of selected ilmenite, magnetite and chromite are tabulated in Table 7. The ilmenite in the study area has TiO₂ (38.89 – 50.69 wt%) and Fe₂O₃ (15.70 – 21.33 wt.%). Al₂O₃ ranges between 1.02 and 1.87wt%, SiO₂ 0.38 and 2.42wt%, CaO 0.27 and 1

wt% and V_2O_5 0.44 and 0.96 wt% and Cr_2O_3 is <0.45 wt%. Other elements like Ni, Zn are in negligible quantity.

The analysis of magnetite (Table 7) shows Fe_2O_3 to be between 31 and 48 wt% and FeO 17 and 24 wt%. The high values at locations 47, 48 and 97 (Fig. 2) are probably due to the presence of hematite. TiO_2 content in magnetite ranges between 14 and 24 wt% and V_2O_5 3.78 and 4.76 wt%. The chemical analysis and the microscopy studies confirm the occurrence of two types of magnetite in the study area, viz. pure magnetite and titano-magnetite with intergrowth of sphene and rutile.

Analysis of chromite grains (Table 7) depicts an appreciable content of Cr_2O_3 , which ranges between 32 and 47 wt%, Fe_2O_3 3.5 and 4.7wt%, FeO 19 and 22 wt% and MgO 12 and 14 wt% The chemical analysis confirms the presence of magnesio- and ferro-chromite that were revealed in the XRD profiles (Fig. 6).

4.8. Topographic profiles: The seasonal topographic profiles (Fig. 9 a-d) of the beaches between Pirwadi and Talashil (Fig. 2) for the 4 seasons (October 2004, March 2005, August 2005 and December 2005) show morphologic and variations in sediment volume. This stretch of ~12.5 km host rich deposits of ilmenite, magnetite and chromite (Gujar et al. 2010a).

With reference to the base profiles of the sediment volume for the entire period (from October 2004-December 2005), the most vulnerable areas for erosion are Tondavali and Pirwadi in a decreasing order of net erosion. Tondavali shows the highest erosion (-103%), while Pirwadi is (-18%) of the total sediments. In contrast, sediment deposition is noticed in Hirlewadi (+22%) and Talashil (2.5%). Overall, in the study area the width of the beaches remains more or less the same.

5. Discussion

5.1. Grain size analysis helps to classify unconsolidated material and also provides a clue about the sediment transport and depositional conditions. The sediments in the study area mainly consist of sand and silt. In the areas close to the cliffs and promontories, sandy sediments are absent but boulders and pebbles are noticed. This phenomenon which is common along the Maharashtra's coast may be due to convergence of high waves. The beach sediments (foreshore and backshore) are devoid of clay except at Morve where close to the cliff, olive brown sticky clay is seen. The presence of chlorite and kaolinite suggest their derivation from igneous and metamorphic rocks.

The medium to fine grained sediments are moderately well to well-sorted, symmetrically to finely skewed and meso- to leptokurtic in nature. The grain sizes suggest low to moderate energy conditions to prevail in the area, sorting indicates similar sediment size with low variance, while skewness points to a relatively high proportion of finer sediments. The kurtosis values (Table 4)

imply that a part of the sediment achieved their sorting elsewhere in a high energy environment and later mixed with sediments of another environment of moderate energy. The influence of beach, river and dune type of depositional environment is observed in the study area (Anon, 2007).

5.2. Heavy mineral concentrations in the study area ranges up to 98 wt% and consists of opaques, pyroxenes (augite, hypersthene, enstatite), rutile, kyanite, tourmaline, zircon, staurolite, titanite, olivine, garnet, epidote and amphibole (hornblende, actinolite) in variable proportions. The light fraction is dominated by quartz and feldspar. Opaques are represented by ilmenite, magnetite and their weathered derivatives. In addition to these two opaques, presence of chromite is noticed for the first time as a placer mineral along Talashil, near the mouth of River Gad (Gujar et al. 2010a).

The heavy minerals are concentrated in the supra-tidal zone (backshore, berm and dune) compared to the intertidal zone as well as around the mouth of the rivers in the study area. Their distribution pattern shows changes mainly during the monsoon season, when high waves (wave height 4-5 m and wave period 3-6 seconds), reach upto the frontal dunes (Karlekar and Thakurdesai, 2017). In addition to wave action and their strong retreating currents, the ephemeral monsoonal streams flowing in an E-W direction across the beach, carry water from hinterland during monsoon along with some loosened heavy minerals from dunes and they are redistributed in the backshore and intertidal zone (Fig. 4E). After the monsoon, during the fair season, the oceanographic conditions return to normal and when beach building resumes then these sands get further redistributed and occur mostly in the backshore.

Besides the waves, the long shore currents also play a significant role in the distribution of the heavy minerals. In general, the direction of the long shore current is southwards with transport rates of $1.9 \times 10^5 \text{ m}^3/\text{year}$ during most of the year, except the monsoon when it is variable (Chandramohan et al. 1993). In addition, the geomorphic features in the area, coastline configuration and beach gradient also influence, either collectively or individually, and thus affect the concentration pattern of the heavy minerals.

It is pertinent to state that the beach deposits cannot be assessed entirely in a holistic manner. Any estimate regarding the quality and quantity for a specific area will be true only for the period during which exploration was undertaken.

5.3. The XRD of the ilmenite shows sharp uni-modal peaks, while magnetites have bi-modal peaks (Fig. 6). This fact indicates that the ilmenites are fresh while magnetites are partly altered and this is confirmed by the ore microscopy studies.

5.4. The ore microscopy characterization of the grains indicates the transportation effect in the form of mechanical breaking (rounding) due to prolonged transportation or during the process of reworking. Sometimes even the effect of solution action is noticed in the form of etching along the border of the grains. Ilmenites are fresh and altered and some grains are angular to sub-angular to sub-rounded and even rounded (Fig. 5). The sieve texture is noticed in a few grains and the effect of minor alterations is along the border as well as within the grain matrix. These alterations probably resulted due to oxidation (Ramdohr, 1980) and removal of iron either during transportation (Fig. 5) or during the residential period in the depositional basin. During alteration grains with diffused borders are developed and these consist of isotropic Ti-rich rutile-leucoxene (Fig. 5).

Etching of the rounded magnetite grains suggest that this process took place in the depositional basin after transportation. With changes in the chemical environment, during the sedimentary cycle, alteration of titano-magnetites occur and the altered products include rutile±hematite, which further alter to sphene (Fig. 5). Chromite grains are fresh and altered and the transportation features are noticed in the form of partial rounding and breaking along the grain border (Fig. 5). The alteration along the border may be due to the change of geochemical conditions during transport and/or after deposition. Alteration of chromites could sometimes result in secondary phases such as ferrichromite (Ramdohr, 1980).

5.5. Transparent heavy minerals (Table 5) exhibit variety of textures (Fig. 8). The observed textures of minerals indicate that they are affected by transportation, physical sorting and mechanical abrasion. Prolonged transportation (from source to sink) and subsequent sorting under variable hydro-dynamic conditions after deposition affect the sediments. Mechanical abrasion during transport and reworking might have led to reduction in the size and rounding of the grains.

The predominance of opaques (Table 5), along with transparent minerals, after the removal of ilmenite and magnetite probably represent the alteration products of some of the heavy minerals and fine particles of laterite (Mislankar et al. 2005).

The transparent heavy minerals are angular, are etched along the border, have ragged edges and rounding due to attrition (Fig. 8). Based on angularity and rounding, the grains are of two types: angular to sub-angular and sub-rounded to rounded. The former type represents the grains received from the source rocks through fluvial transport and can be grains of first cycle. On the other hand, sub-rounded to rounded grains form due to prolonged transportation/recycling/resorting over a long period and are called as grains of second cycle.

In the present study, the ultra-stable minerals show partial or complete rounding. This suggests their derivation through many sedimentary cycles and longer residential period in the depositional site. Rounded tourmalines occur in the Kaladgi sandstones in the hinterland (Sarkar and Soman 1984; Gujar 1996). The euhedral zircons (Fig. 8) suggest their derivation from granites, whereas subrounded and rounded zircons may have been sourced from recycled Kaladgi sandstones, which in turn received zircons from the metamorphic rocks (Dharwar schist and gneiss). The overgrowth in zircon (Fig. 8) indicates the role of intrastratal solution activity in the area of deposition, either in the near shore or on the beach (Mislankar et al. 2005). The euhedral rutile grains (Fig. 8) suggest high grade metamorphic source rocks as their source whereas the pyramidal rutile grains are suggestive of their reworked origin. Garnets show effect of corrosion and etched border (Fig. 8). The sub-rounded garnets indicate the possibility of their transport from the source and then acquiring these features in the coastal areas.

Detrital heavy minerals in sedimentary environment are exposed to weathering, which is more intensive in the humid tropical climate, where the chemical reaction takes place at a faster rate (Andò et al. 2012). On the basis of the diagnostic textural features the weathering stages are divided into 5 categories: unweathered, corroded, etched, deeply etched and skeleton (Andò et al. 2012). The observed grains in the study area are fresh (unweathered, partially corroded and etched). This could be due to the supply of fresh grains from the hinterland and partially altered grains from the near shore area through shore ward transport or alteration within depositional basin.

The study area experiences semi-diurnal tides (2 episodes of equal high tide and 2 of equal low tide in 24 hours). Due to such alternate drying and wetting, the pH value of sediment fluctuates between 5.5 and 7.5 and sometimes it also reaches to 8.25 during summer (Braganza 2021). These parameters may cause chemical imbalance and may account for the observed textures. Further, the effect of salinity, dissolved oxygen, nitrate and phosphate levels and their seasonal variability in the littoral zone cannot be ruled out. These factors show seasonal fluctuations during monsoon and pre-monsoon. The salinity ranges between 23.6 and 37‰; dissolved oxygen 3.26-5.21 ml/l; nitrate 1.45-8.76 $\mu\text{mol/l}$ and phosphate 3.36-5.21 ml/l (Anon 2001).

The study also reveals 3 distinct mineral assemblages:

1. Tourmaline – amphibole - epidote and pyroxene.
2. Zircon – titanite –rutile and garnet.
3. Staurolite – kyanite.

The transparent heavy minerals and their assemblages in the study area clearly indicate the possibility of their derivation from the multi-source rocks.

The identified mineral assemblages when compared with the minerals identified in the thin sections of the hinterland rocks (Fig.7) indicates the possibility of their derivation from laterite, mafic and felsic igneous rocks, Kaladgi sandstones and high- grade metamorphic rocks. Green hornblende is considered to be derived from high grade metamorphic rocks while zircon confirms the sources to be granite, pegmatite and amphibolites. Angular and rounded colorless garnet is from serpentinised metamorphic rocks and laterite, kyanite from quartzite whereas disseminated opaques and olivine are from basalts and metamorphic rocks.

The ultra-stable minerals like green tourmaline appears to be sourced from pegmatite, quartzite, schists and Kaladgi sandstones. Chromite grains are derived from chromitites in the upper reaches of River Gad and rutile from the metamorphic rocks. Zircon, rutile and tourmaline are also present in the well-preserved lateritic profile in the upstream of River Gad in the hinterland (Nikam and Patil 2011). Some of these minerals occur along the river bed indicating their transport through River Gad to the depositional basin.

5.6. The ilmenite grains with TiO_2 between 39 and 50 wt% (avg 44 wt%) indicate these to be of moderate grade. In addition, Cr_2O_3 in ilmenites is low (0.01-0.45 wt%, avg 0.13 wt%). Magnetites with appreciable TiO_2 (14-24 wt%, avg 21 wt%) and chromite with Cr_2O_3 (32-47 wt%, avg 37 wt%) are of refractory grade.

5.7. A number of factors can be attributed for the erosional trends in the study area. Among them, the prominent factors are the rip currents, which are present in the lower reaches of Tondavali, wave dynamics like higher wave heights > 1.1 to 4 m, coastal configuration in Pirwadi which is semi-arcuate and Tondavali is nearly straight with few rocks in the surf zone and finally the beach gradients. On the other hand, the depositional trends at Hirlewadi and Talashil are due to the sediment transport by littoral currents.

In the absence of sufficient geochronological dates and information concerning recent tectonics and climatic change, it is difficult to provide an exact time frame for the formation and deposition of these placer deposits. Yet, on the basis of available dates and configuration of the present coastline, we postulate the time when the placers may have been deposited in the study area. Based on available data for the west coast of India, the sea-levels were slightly high during Late Holocene (Hashimi et al. 1995). This was corroborated by archeological investigations in coastal stretch of Northern Maharashtra which suggested that during Late Holocene the sea-level fluctuated

within short amplitude of 1-1.5 m, and these were related to phases of lateral transgression and regression (Deo et al. 2011). The C^{14} data of the beach rocks in the study areas have indicated the following dates (Anon 2007): (1) at Kelyewadi it is $5,470 \pm 100$ yr BP (2) at Kotharwadi it is $1,900 \pm 80$ yr BP and (3) at Kolamb it is $1,820 \pm 90$ yr BP.

The beach rock formation is between 3 and 3.5 m high, with reference to Mean Sea Level and is composed of medium to fine sands with broken shells and laminations of heavy minerals. This fact suggests that placer minerals accumulation along the coast occurred during the Late Holocene due to the progradation of the shore during the regression event and were subsequently modified by oceanographic processes. Such a movement of sediments by waves or during marine transgression may cause transport of heavy mineral-rich sediments from near-shelf to coast as also reported along the coast of Australia (Roy 1999).

6. Reserves Of Placer Minerals

Two prospective areas, along the studied 105 km stretch have been identified on the basis of the heavy mineral concentration and their extent. These areas are:

Area 1: Seven areas that have significant concentrations are Kotharwadi, Phansewadi, Padvanewadi, Pirwadi to Tondavali, Tondavali to Talashil, Bhogwe and PhalephondNivati.

Area 2: Five areas that have limited and localized concentrations are Kunkeshwar, Tarkarli, KilleNivati, Mochemad and Vengurla.

Out of these 12 areas the region between Pirwadi to Talashil is most promising for further exploration due to significant concentrations of ilmenite, magnetite and presence of chromite, and TiO_2 contents in ilmenite and magnetite. The dimensions of the areas covering heavy mineral rich zone were measured and calculated in the berm and dune zones in both the areas (Anon 2007).

Based on the formula given in Section 2.0 (Methodology) the inferred reserves of heavy minerals in Area 1 are 2.33 million tonnes (MT), ilmenite 0.55 MT, magnetite 0.98MT and chromite 0.032 MT. In Area 2, the inferred reserves of heavy minerals are 0.031 MT, ilmenite 0.008 MT and magnetite 0.004 MT.

As per the objectives of the CSIR Network Project the present work had involved only surficial sampling and hand auger sampling up to 1 m sand thickness from the surface of the foreshore and berm. Thus, the above reserves are calculated on a very conservative basis and as per the requirements of the mining industries.

7. Conclusions

The study of the onshore beach placers along the coast of Sindhudurg District, Maharashtra has revealed that the sediments are dominantly sandy, moderately well sorted to well sorted and symmetrical to finely skewed. The heavy mineral concentration ranges up to 98 wt% (avg 27 wt%) and the heavy minerals are opaques (ilmenite, magnetite and chromite); while transparent heavy minerals are pyroxene, amphiboles, rutile, zircon, staurolite, titanite, olivine, garnet, epidote and sillimanite. This mineral assemblage indicates their derivation from a mixed provenance of Igneous, Metamorphic rocks, recycled sediments of Pre-Cambrian Age and Deccan Trap Basalt. It is observed that ilmenite is of moderate grade, with TiO₂ percentage ranging between 39-51 wt%, having an average of 44 wt%. In addition to ilmenite, magnetites are titanomagnetites containing 14.31-22.98 wt% of TiO₂ and chromite can be valued as additional value products.

The inferred reserves of these heavy minerals to 1 m sand thickness are 2.33 MT in areas of significant concentration and extent and 0.031 MT in areas of limited concentration and extent. These deposits offer good prospects towards their economic exploitation and thus contribute in the enhancement of the resource base of the nation.

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- **Funding:** CSIR Network Project CMM 0023
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- **Code availability:** Not Applicable
- **Authors' contributions:** ARG, SDI, PGM and NVA carried out the field work and analysed the samples. GAP carried out the X-ray analysis. ARG and SDI wrote the manuscript.

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Captions to Figures

Fig. 1A. The study areas covered for onshore placer exploration.

Fig. 1 B. Topographic map of the Sindhudurg District.

Fig. 2. Representative map of part of the study area showing sampling locations and geomorphology between mouth of Achara and Gad rivers.

Fig. 3. Geology of the Sindhudurg District, Maharashtra (Anon, 2007).

Fig. 4. Field photographs of the study area.

A. Beach rocks, Kotharwadi; B. Sea cave, Kalambai (North of R. Kelye);

C. Sand Bar in Piyali river mouth, Morve; D. Wave-cut platform, Kunkeshwar;

E. Heavy minerals in a runnel, Kotharwadi; F. Heavy minerals in a dune cut, Tondavali; G. Heavy minerals in the backshore, Tondavali; H. Heavy minerals in the intertidal zone, Bhogwe; I. Southern view of beach depicting heavy minerals on the berm crest, Talashil; J. Raised beach with laminations of heavy minerals, Talashil. In the foreground are heavy minerals that have been eroded from the dune and deposited on the beach; K. Laminations of heavy minerals in a dune during monsoon occurring between BP 1 and BP 2, Talashil; L. Widespread distribution of heavy mineral in intertidal zone during monsoon, Talashil; M. View of Bhogwe beach from the southern end. N. Rocky island off Vengurla; O. Berm cut during monsoon, Phansewadi; P. Laminations of heavy minerals.

Fig. 5. Textural characters of detrital ilmenite, magnetite and chromite grains. (Bar scale for all photos $\text{---} 0.05 \text{ mm}$).

A. Fresh ilmenite grains; B. Altered ilmenite; C. Altered ilmenite with sieved texture; D. Fresh and altered ilmenite; E. Fresh ilmenite; F. Alteration of ilmenite to leucocene; G. Fresh and altered ilmenite; H. Fresh magnetite and titanomagnetite; I. Magnetite with etched border; J. Alteration of magnetite to sphene; K. Fresh and altered chromite; L. Partly altered chromite.

Fig. 6. X-Ray diffractogram of representative ilmenite, magnetite, chromite from the beach. XRD of river bed heavy minerals after removal of magnetite.

Fig. 7. Photomicrographs of heavy minerals in the thin section of hinterland rocks. (Bar scale for all photos $\text{---} 0.04 \text{ mm}$).

A. Disseminated laths of opaques and olivine in basalt; B. Kyanite in Quartzite; C. Colorless rounded garnet with opaques in serpentinised metamorphic rocks; D. Thick and oval shelled zircon in quartzite; E. Colorless angular garnet in metamorphic rock; F. Green hornblende with anhedral

opaques in metamorphic rock; G. Angular garnet in laterite; H. Colorless garnet and green hornblende in amphibolite; I. Rounded colorless zircon in amphibolites; J. Colorless, rounded outgrown zircon in amphibolites; K. Colorless angular garnet in amphibolites; L. Rounded chromite grains from chromite lens.

Fig. 8. Selected transparent detrital heavy minerals from the study area. (Bar scale for all photos ____ 0.05 mm).

Fig. 9. Representative beach profiles of the study area (a-d).

Captions to Tables

Table 1. Stratigraphic sequences, rock types and their associated characteristic heavy minerals.

Table 2. Geomorphic features and heavy mineral accumulation along some beaches in the study area.

Table 3. Details of geometrical properties of rivers from the study area.

Table 4. Range and average (within parenthesis) of grain size parameters of representative samples from prospective areas 1 and 2.

Table 5. Number percentage distribution of transparent heavy minerals from the study area (63-125 μm size fraction, n=no. of grains counted).

Table 6. Range and average (within parenthesis) of heavy mineral concentration in sediments from prospective Area 1 and 2. (value in parenthesis under column location indicates number of analysis).

Table 7. Geochemical analysis of ilmenite, magnetite and chromite from the study areas.

Fig 1 A

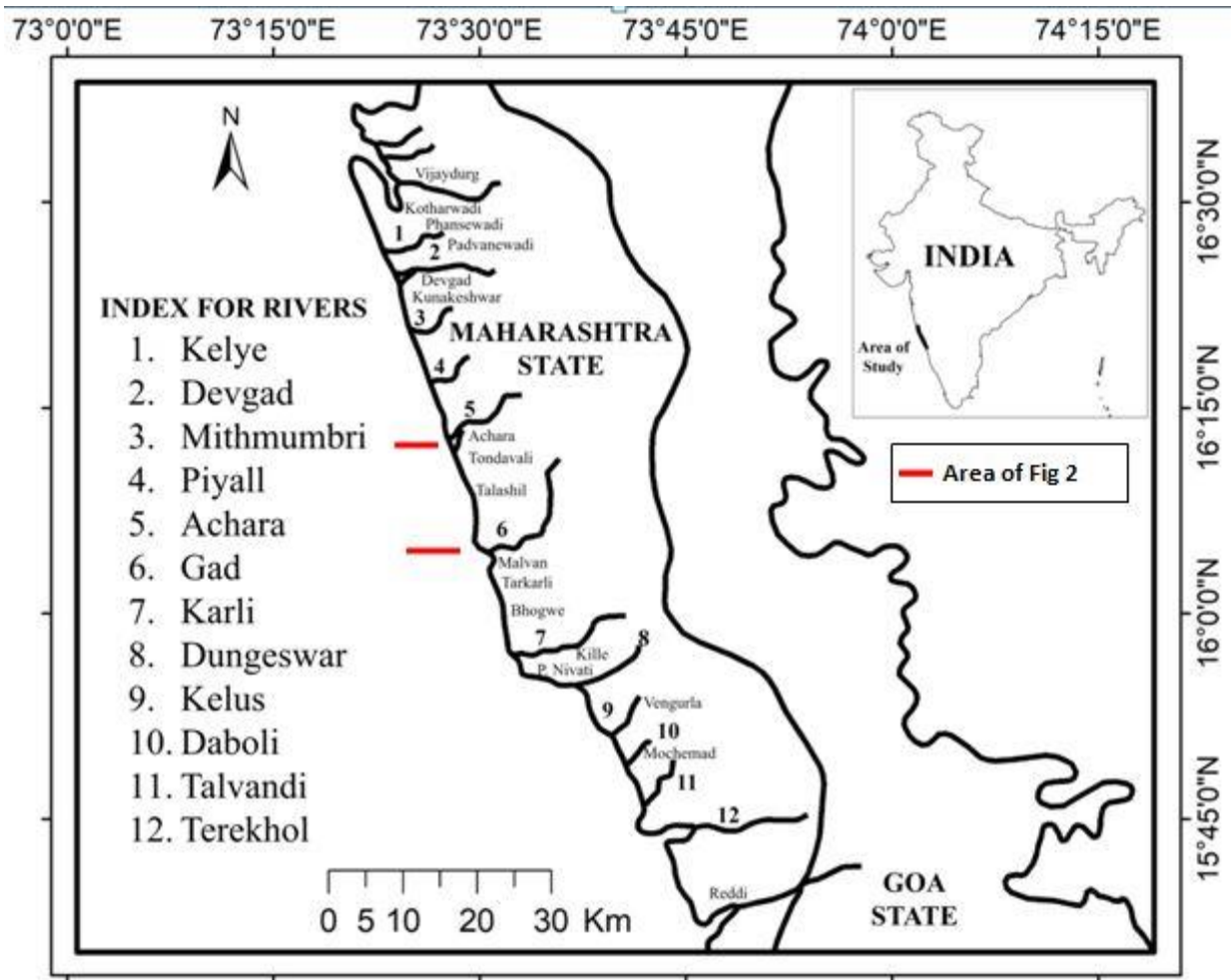
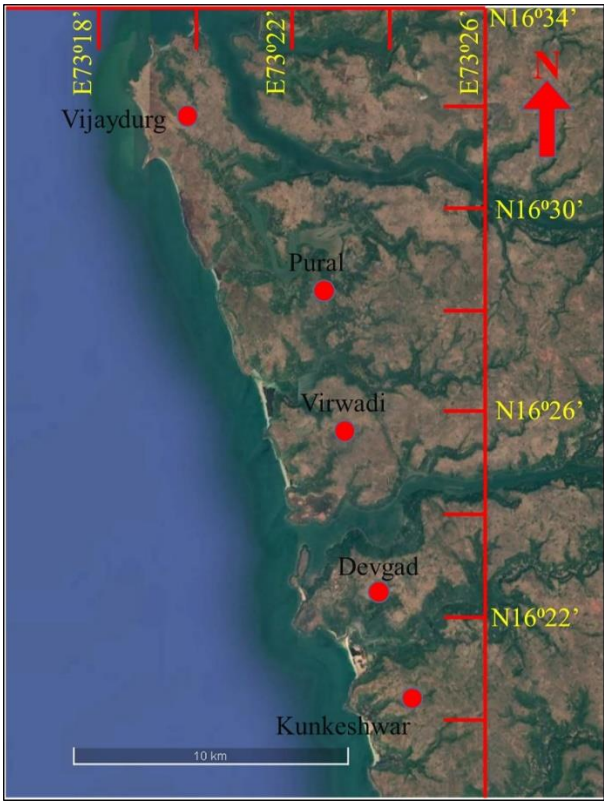
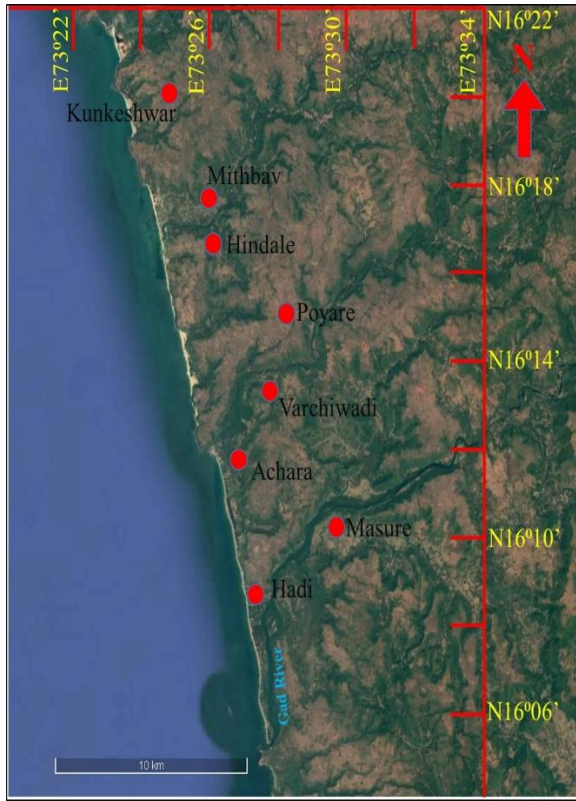


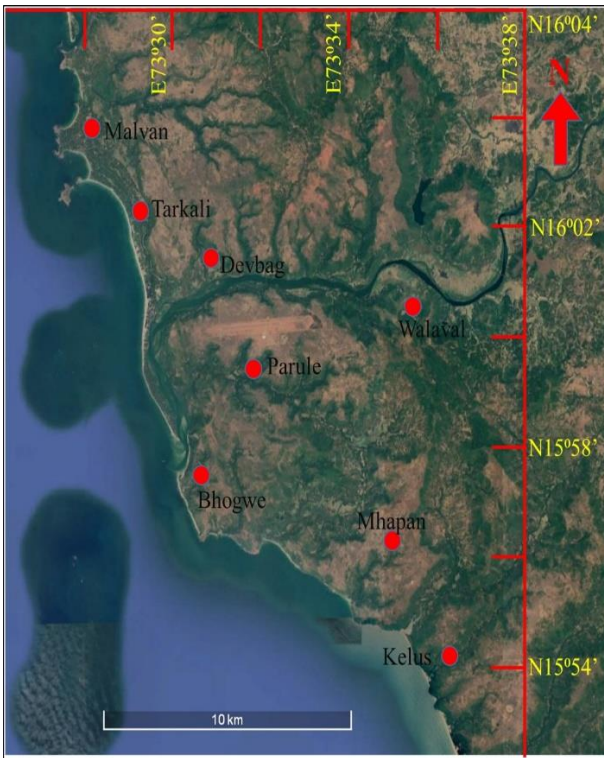
Fig 1 B



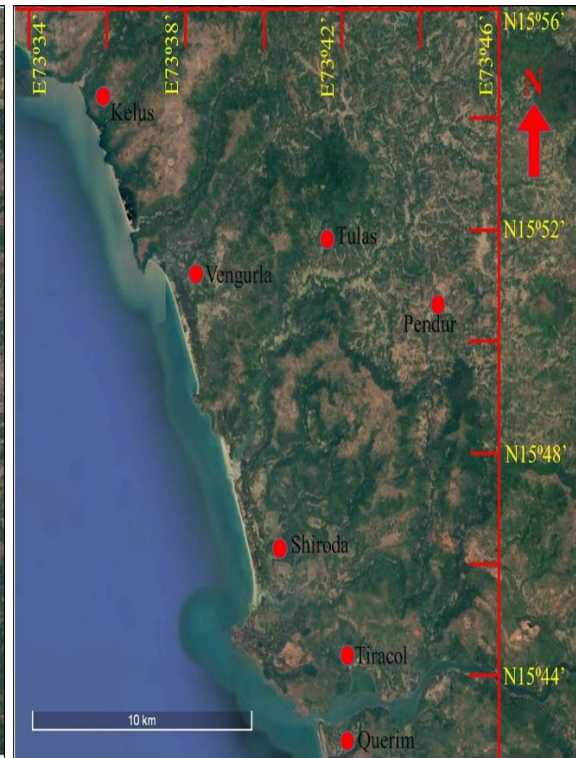
(i)



(ii)



(iii)



(iv)

Fig. 2

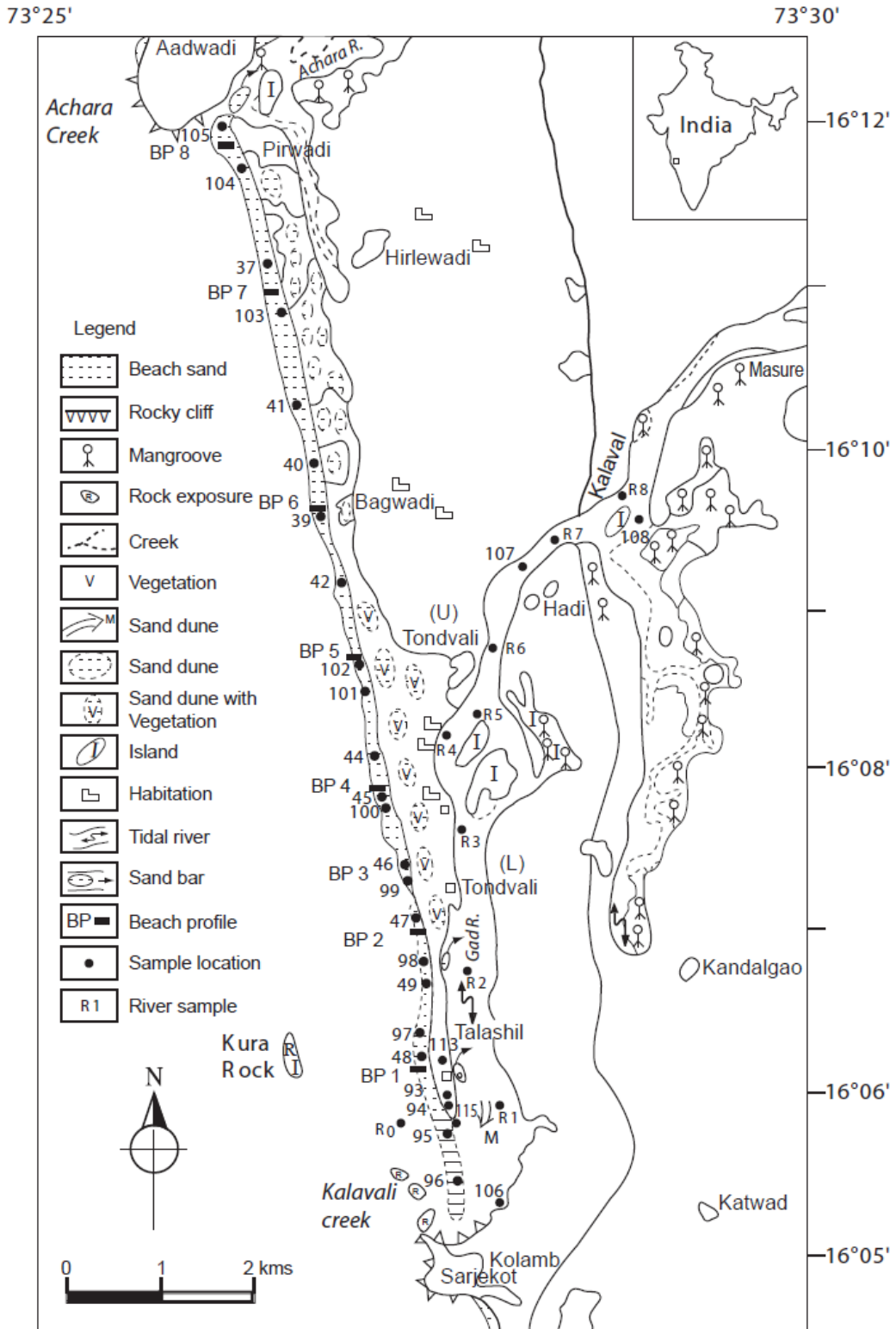


Fig. 3

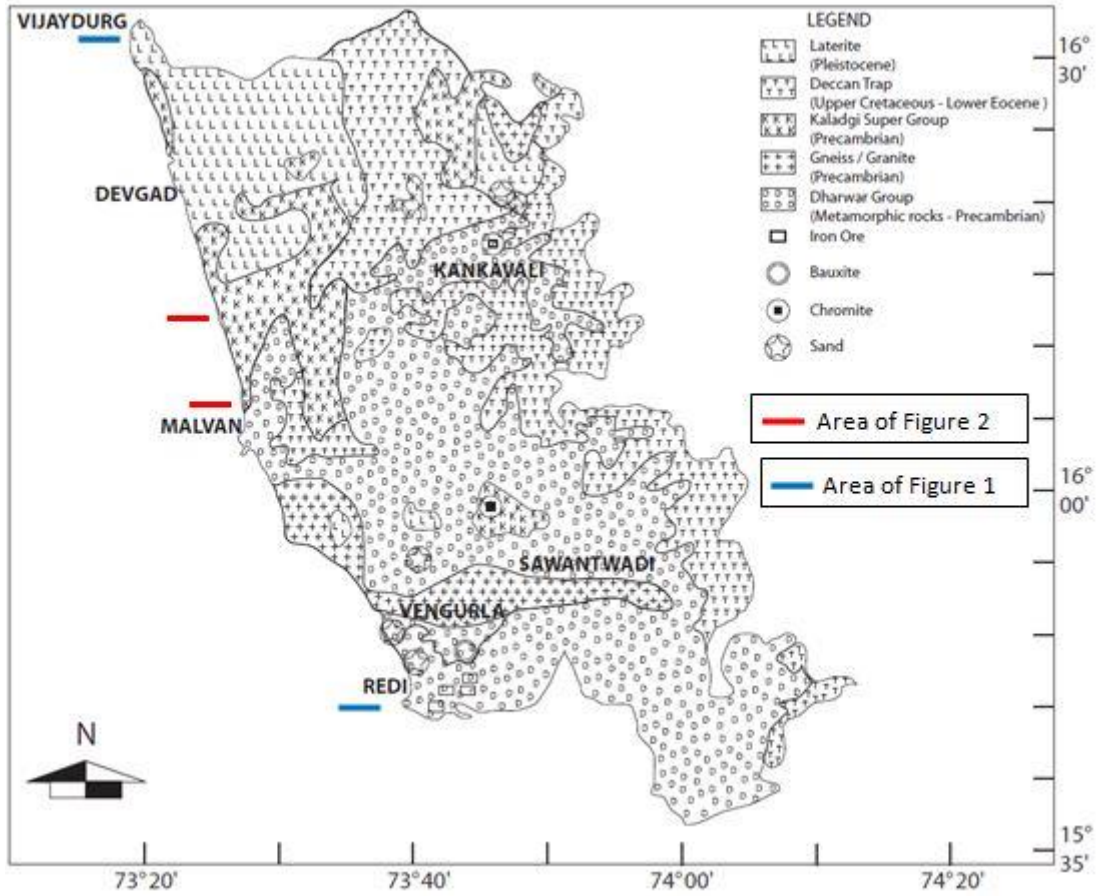


Figure 4

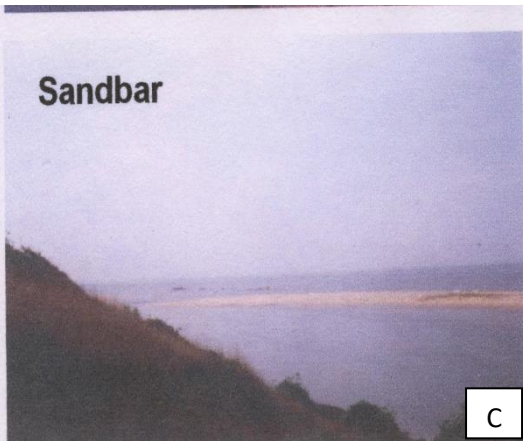


Figure 4



Figure 4



Figure 5

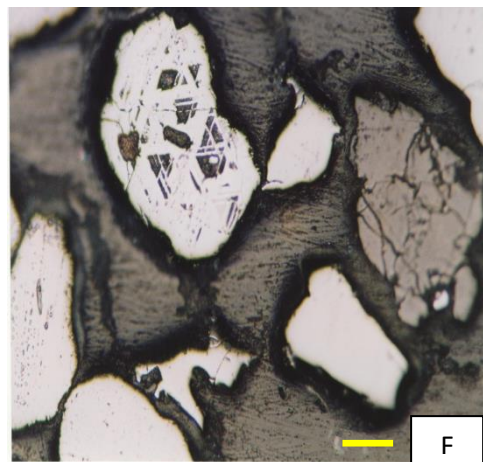
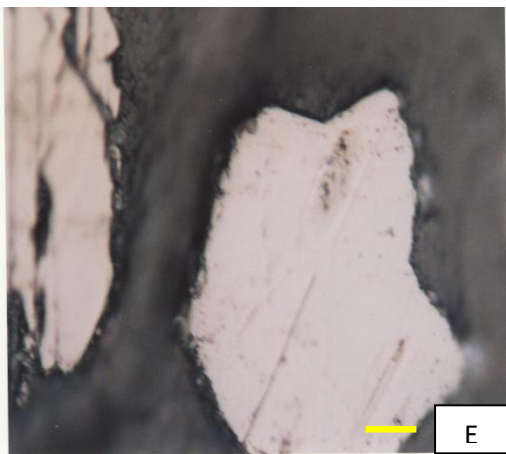
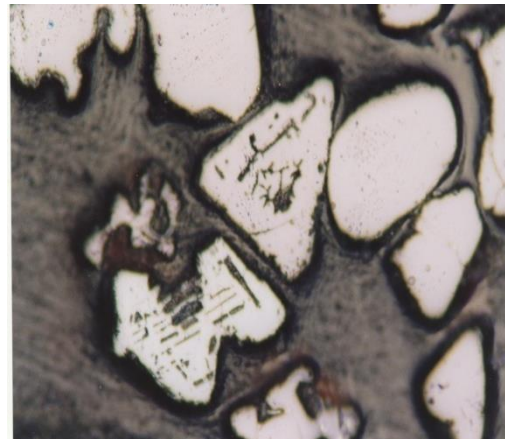
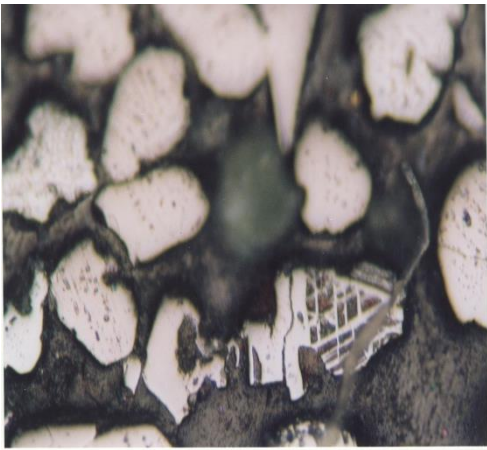
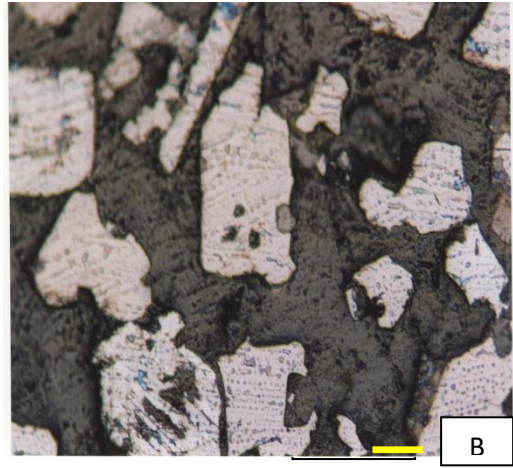
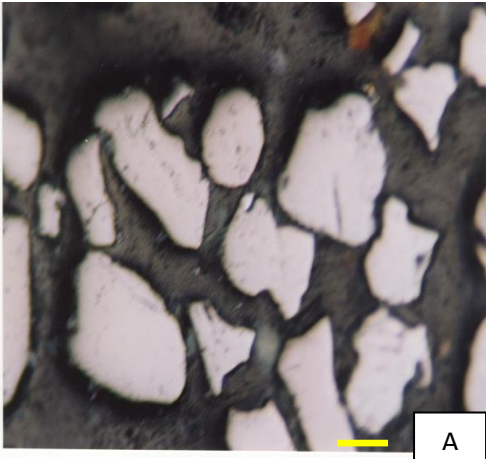


Figure 5

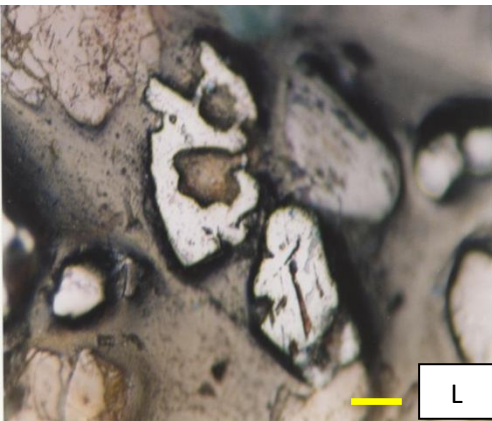
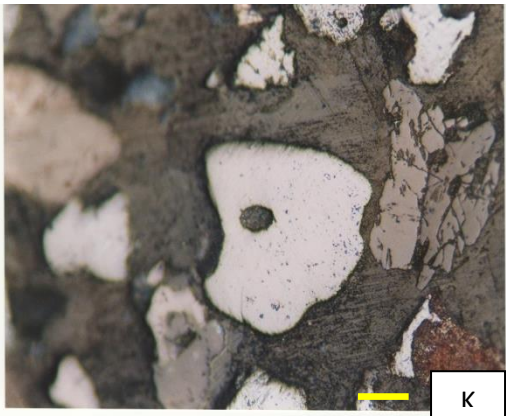
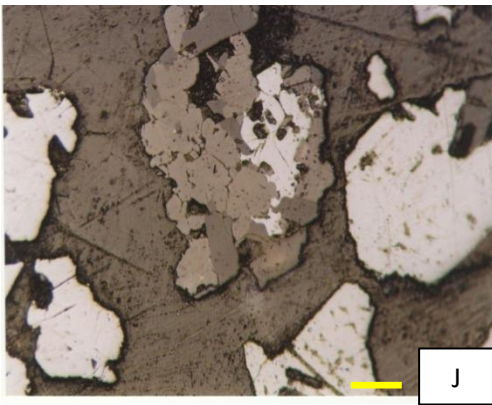
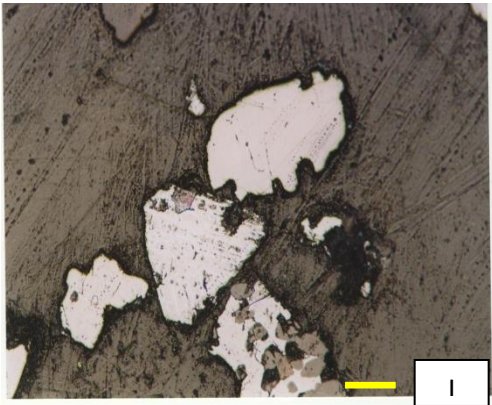
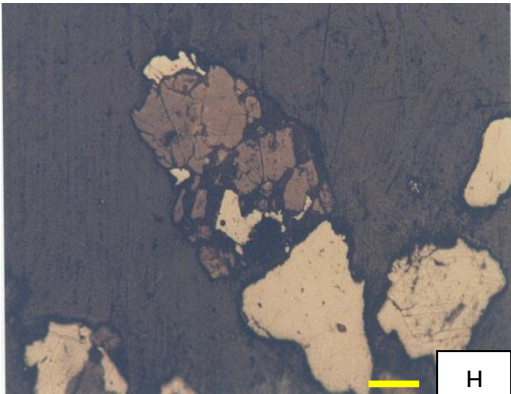
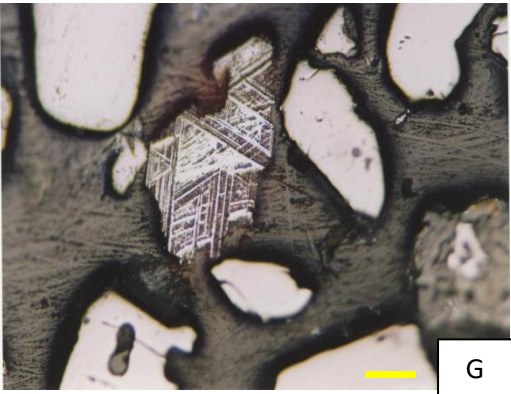


Figure 6

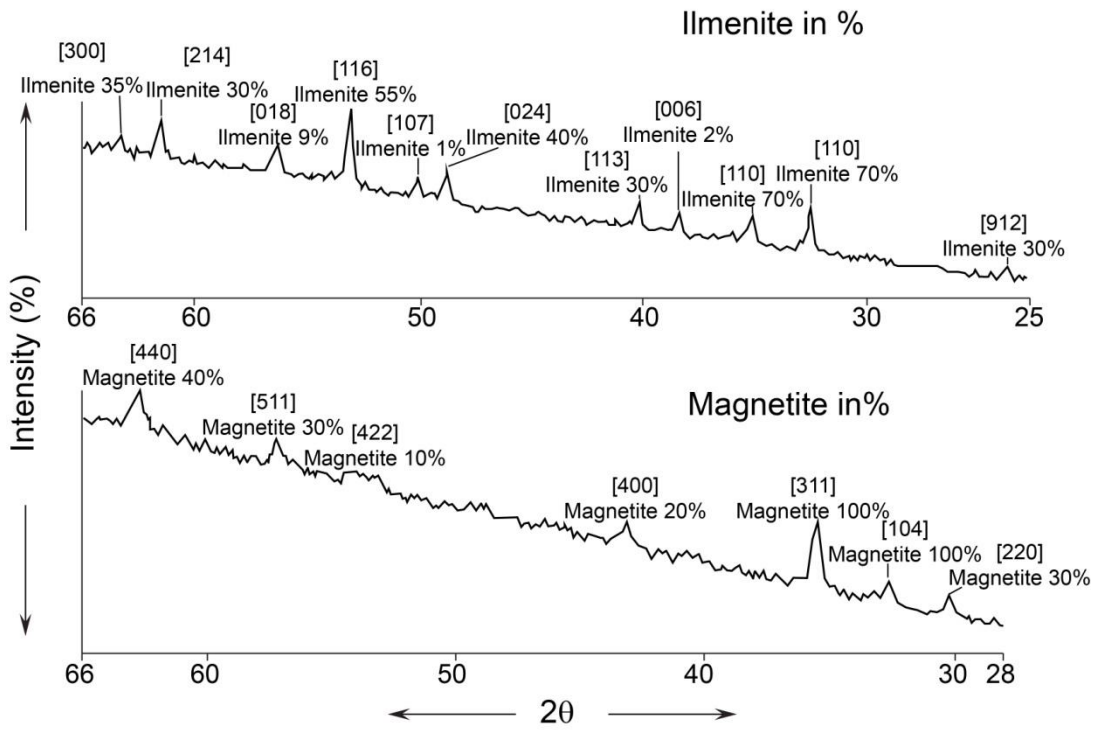


Figure 6

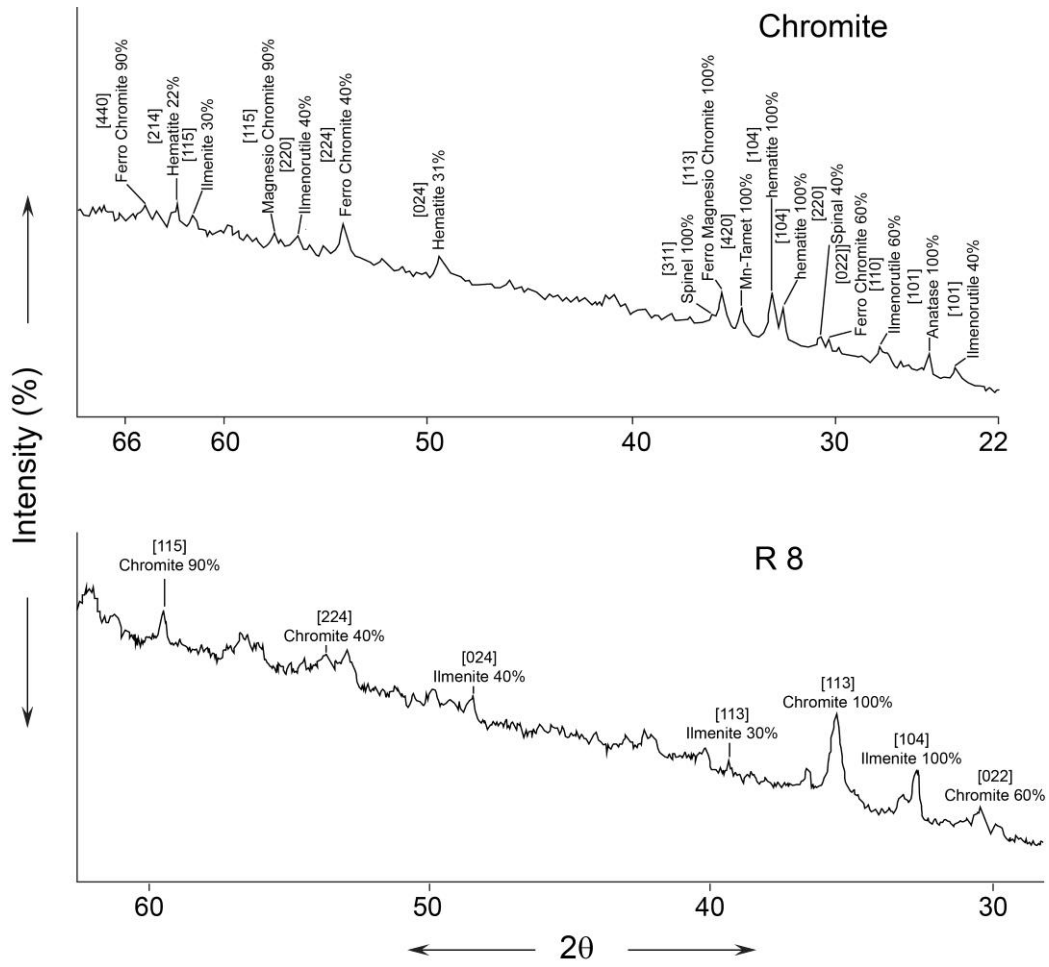


Figure 7

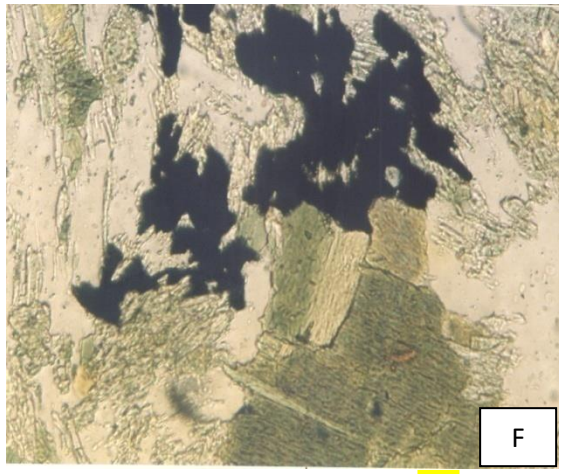
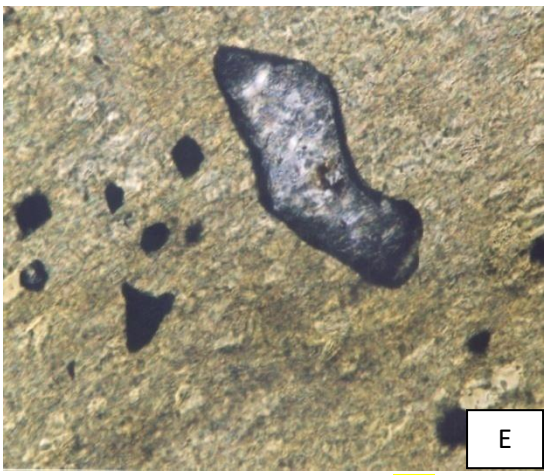
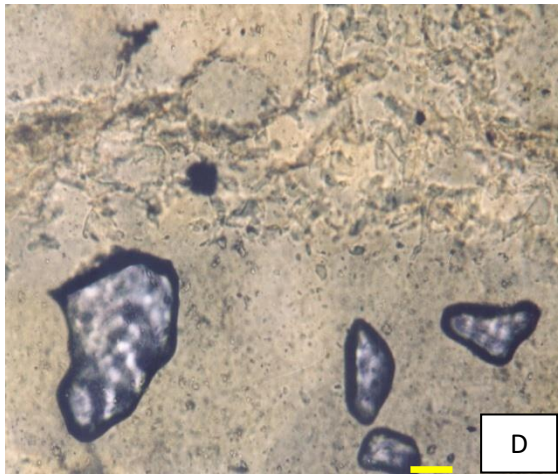
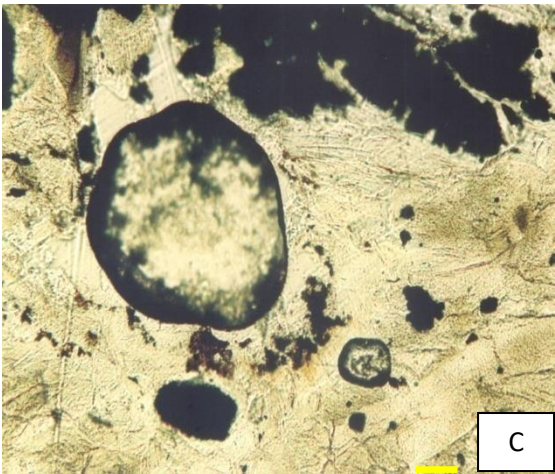
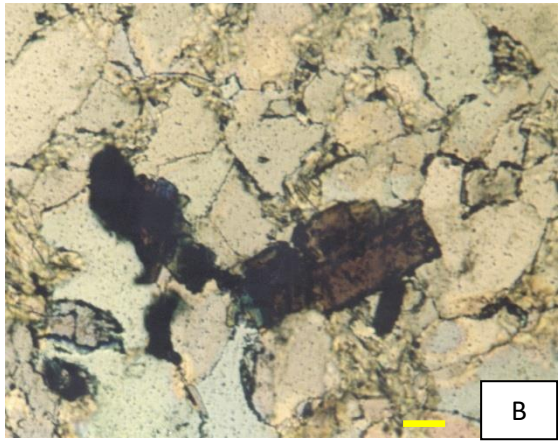
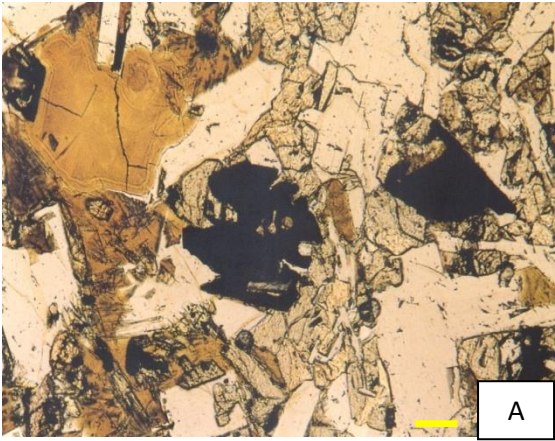


Figure 7

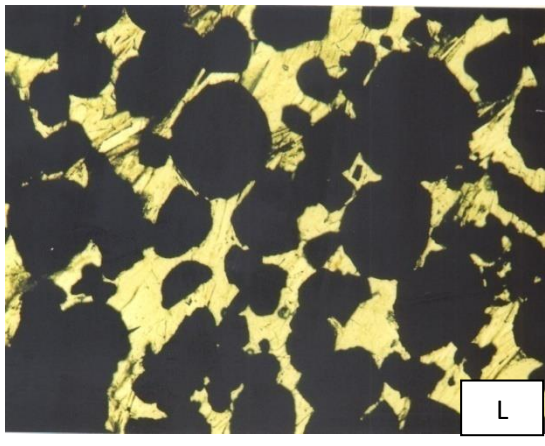
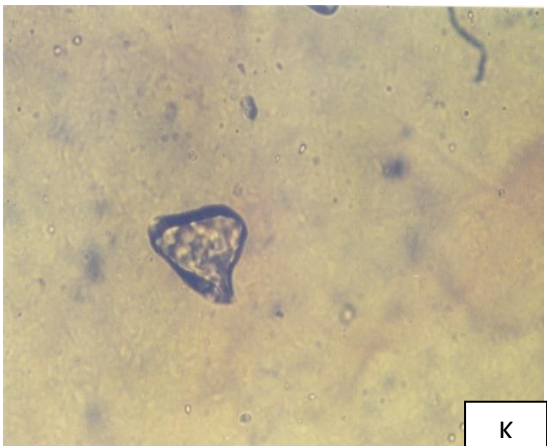
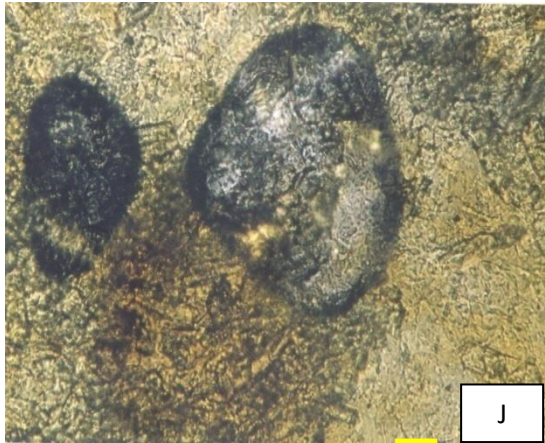
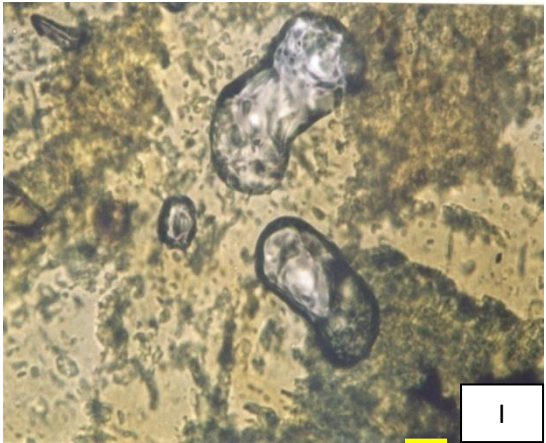
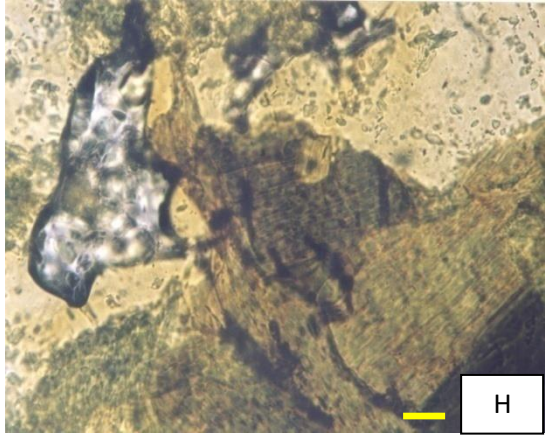
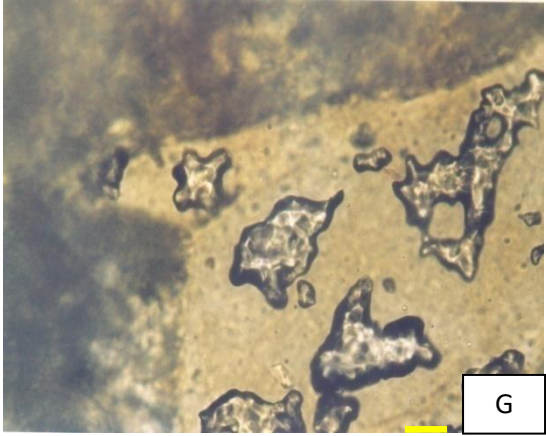
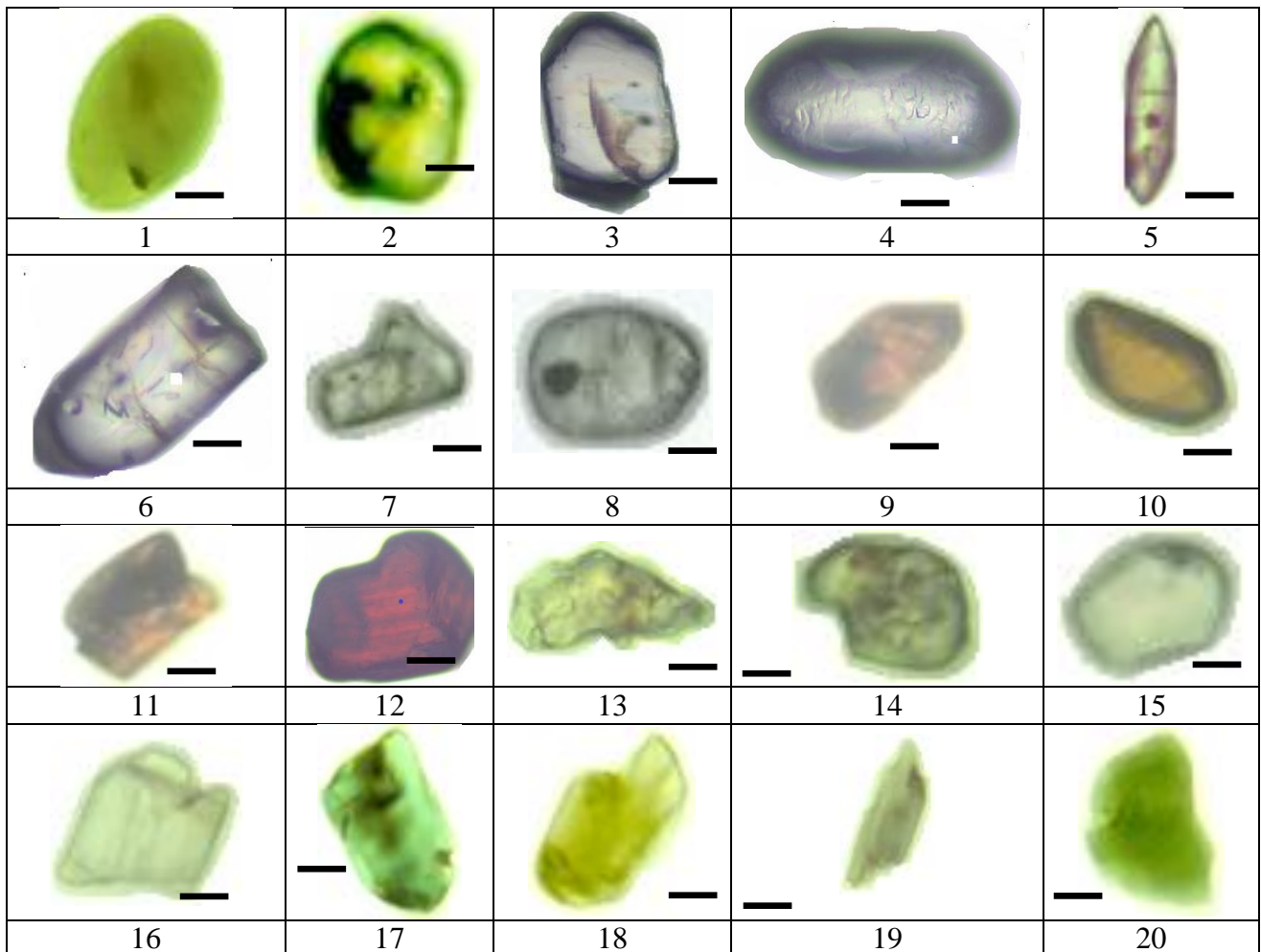


Fig 8

- 1.** Rounded Tourmaline, **2.** Sub-rounded Tourmaline, **3.** Euhedral Zircon, **4.** Sub-rounded Zircon, **5.** Euhedral Zircon, **6.** Broken Zircon, **7.** Zircon with outer growth, **8.** Rounded Zircon, **9.** Angular Rutile, **10.** Euhedral Rutile, **11.** Broken Rutile, **12.** Angular to sub-angular Rutile, **13.** Corroded Garnet, **14.** Sub-rounded Garnet, **15.** Sub-rounded Garnet, **16.** Broken Hornblende, **17.** Angular Hornblende, **18.** Broken Hypersthene, **19.** Angular Hypersthene, **20.** Sub-rounded Epidote.

Fig. 9

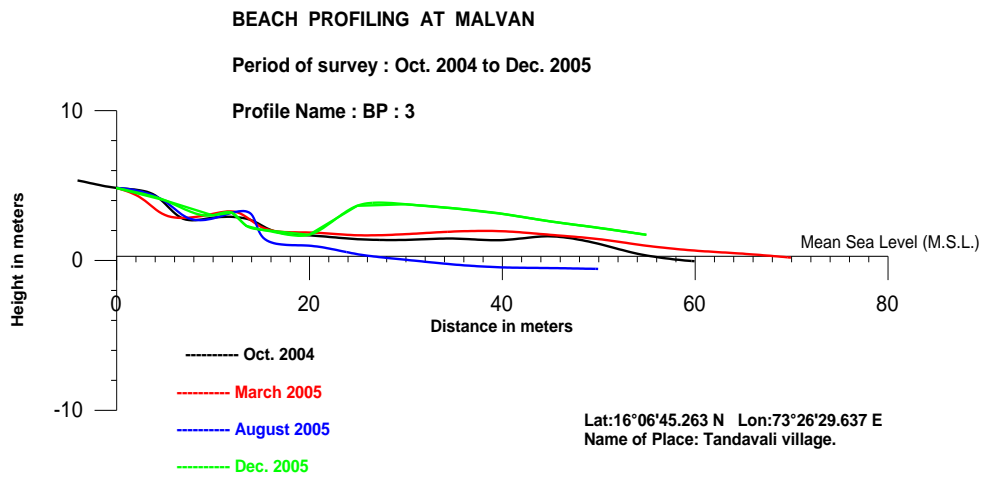
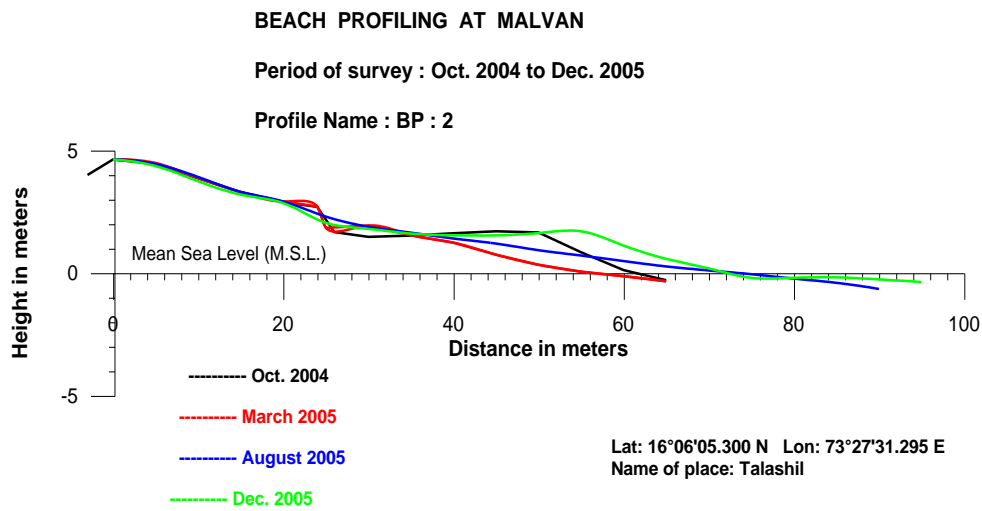
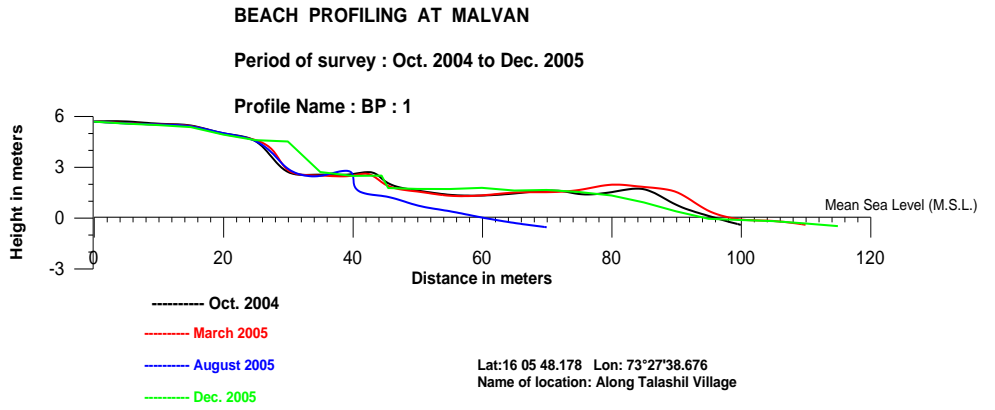
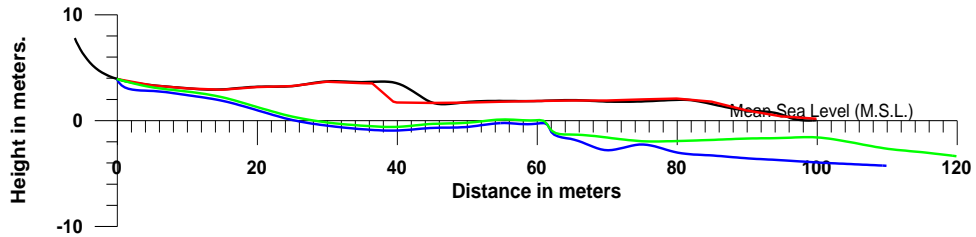


Fig. 9

BEACH PROFILING AT MALVAN

Period of survey : Oct. 2004 to Dec. 2005

Profile Name : BP : 4



----- Oct. 2004

----- march 2005

----- Aug. 2005

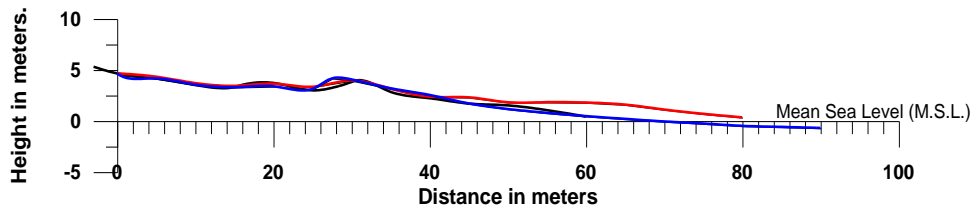
----- Dec. 2005

Lat:16°07'36.178 N Lon:73°27'18.734 E
Name of Place:Tandavali village.

BEACH PROFILING AT MALVAN

Period of survey : Oct. 2004 to Dec. 2005

Profile Name : BP : 5

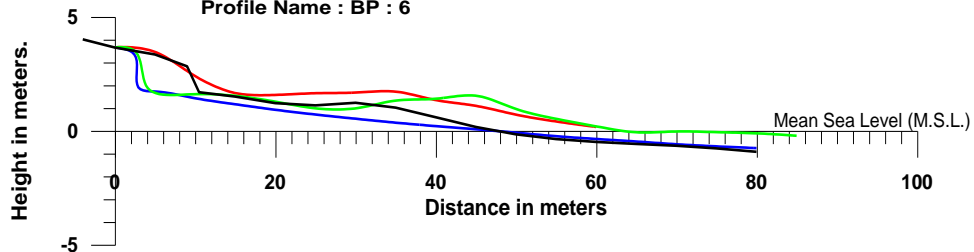


Lat:16°08'51.455 N Lon:73°27'02.171 E
Name of Place: Tandavali village.

BEACH PROFILING AT MALVAN

Period of survey : Oct. 2004 to Dec. 2005

Profile Name : BP : 6



----- Oct. 2004

----- march 2005

----- Aug. 2005

----- Dec. 2005

Lat: 16°09'29.178 N
Lon: 73°26'52.150 E
Village: Bagwadi

Fig. 9

Beach Profiling at two locations along Kotharwadi coast in different seasons.

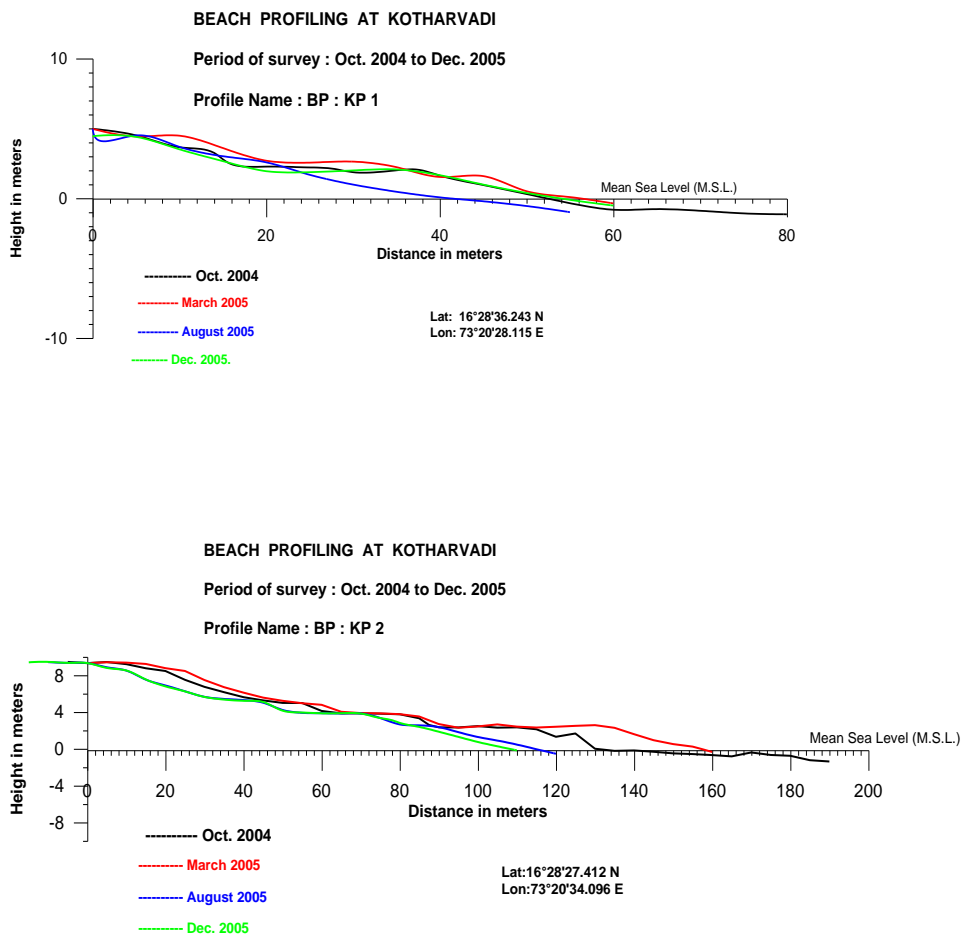
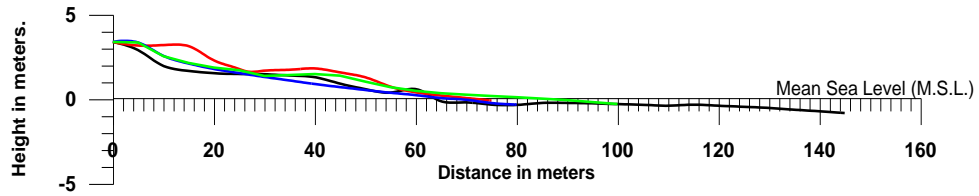


Fig. 9

BEACH PROFILING AT MALVAN

Period of survey : Oct. 2004 to Dec. 2005

Profile Name : BP : 7



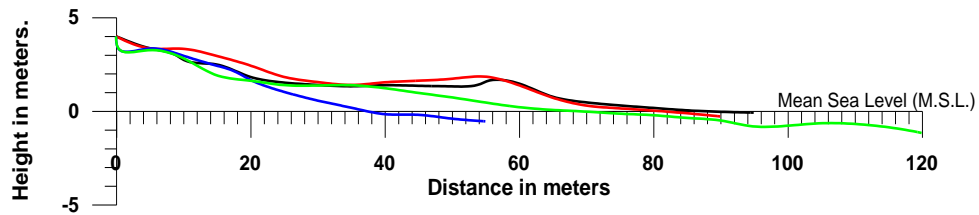
- Oct. 2004
- March 2005
- Aug. 2005
- Dec. 2005

Lat: 16°10'42.505 N
Lon: 73°26'30.127 E
Village: Hirlewadi

BEACH PROFILING AT MALVAN

Period of survey : Oct. 2004 to Dec. 2005

Profile Name : BP : 8



- Oct. 2004
- March 2005
- Aug. 2005
- Dec. 2005

Lat: 16°11'42.371 N
Lon: 73°26'14.464 E
Village: Pirvadi

Table 1

Stratigraphic sequence	Type of Rocks	Characteristic heavy minerals
Pleistocene to sub-Recent	Laterite	Ilmenite, hematite, goethite, garnet and zircon
Upper Cretaceous to Lower Eocene	Deccan Trap basalts	Ilmenite, magnetite titanomagnetite olivine, and augite
Pre-Cambrian	Kaladgi sandstones	Tourmaline, zircon, rutile, staurolite, kyanite, sillimanite, epidote, garnet, ilmenite, magnetite and pyrite
Archean & Dharwars	(Phyllite, quartzite, schists and intrusives like doletite gabbro, granite, pegmatite, aplite and quartz vein).	Tourmaline, staurolite garnet sillimanite, zircon, chromite and hornblende

Table 2

	LOCATION	ASSOCIATED GEOMORPHIC FEATURES	REMARKS
South Maharashtra (105 km strip). South of 16°30' N latitude.	Kotharwadi	Semi arcuate beach with three ridges of sand dunes, runnel and beach rock. (Fig 4 A, E)	Heavy mineral concentration 31 wt% (average).
	Kalambai	Straight beach backed by a hill with sea-caves, wave-cut platform in the north end and sea-stacks. (Fig 4 B)	Heavy mineral concentration <2 wt%
	Kelye	Arcuate beach with sand-bar in creek mouth. (Fig 4 C)	Heavy mineral concentration 9.12 wt% (average)
	Kunakeshwar	Straight beach backed by sand dunes. Wide wave-cut platform in the northern end. (Fig 4 D)	Heavy mineral concentration 20 wt % (average)
	Pirwadi-Tondavali	Straight beach backed by sand dunes ridges. (Fig 4 F)	Heavy mineral concentration 19.5 wt% (average).
	Tondavali	Straight beach backed by sand dunes ridges.	Heavy mineral concentration 7.5 wt% (average).
	Tondavali to Talashil	Straight beach backed by sand dunes and river Gad. Sandbar in the river mouth. (Fig 4 J K, I)	Heavy mineral concentration 58 wt % (average).
	Bhogwe	Straight beach backed by sand dunes. (Fig 4 H, M)	Heavy mineral concentration 11 wt % (average).
	Mochemad	Straight beach backed by Sand dunes, River mouth in the South	Heavy mineral concentration 8 wt % (average).

Table 3

River	Length (km)	Basin perimeter (km)	Basin area (km²)	Basin relief (m)
Kharda/Vadatar/ Devgad	51.84	118.08	444.41	---
Achara	44.67	98.11	263.37	145.45
Gad	74.51	181.32	973.62	681.81
Karli	75.84	149.12	817.15	---

Table 4**AREA 1**

Location	Median ϕ	Mean ϕ	Sorting ϕ	Skewness	Kurtosis	Sediment Class
Kotharwadi (n=5)	2.12-2.32 (2.21)	2.08- 2.38 (2.23)	0.48-0.60 (0.54)	-0.27- 0.74 (0.28)	3.4-5.08 (4.23)	Moderately well sorted fine sand
Phansewadi (n=17)	1.71-2.40 (2.03)	1.75- 2.81 (2.04)	0.44-0.60 (0.49)	-0.12- 0.71 (4.32)	2.60-4.14 (3.27)	Moderately well sorted to well sorted medium-fine sand
Padvanewadi (n=3)	1.43-1.57 (1.5)	1.43- 1.61 (1.51)	0.42-0.46 (0.44)	0.61-0.72 (0.66)	4.42-4.63 (4.5)	Well sorted medium sand
Pirwadi- tondavali (n=46)	2.10-2.72 (2.37)	2.18- 2.60 (2.40)	0.45-0.59 (0.51)	-0.17- 0.67 (0.25)	2.95-3.77 (3.50)	Moderately well sorted, to well sorted fine sand
Tondavali- Talashil (n=60)	1.66-2.32 (1.99)	2.17- 2.39 (2.27)	0.47-0.52 (0.49)	0.09-0.17 (0.13)	3.14-3.69 (3.41)	Moderately well sorted, to well sorted medium to fine sand
Bhogwe (n=5)	1.76-2.33 (2.07)	1.79- 2.36 (2.06)	0.44-0.52 (0.48)	-0.04- 0.14 (0.03)	0.95-1.21 (1.04)	Moderately well sorted to well sorted medium to fine sand
Phalephond- Nivati (n=50)	2.30-2.41 (2.36)	2.34- 2.35 (2.35)	0.47-0.65 (0.56)	-0.16- 0.18 (- 0.17)	0.97-1.25 (1.11)	Moderately well sorted to well sorted fine sand

AREA 2

Kunkeshwar (n=3)	1.52- 1.99 (1.72)	1.53- 2.04 (1.72)	0.44- 0.47 (0.46)	-0.12- 0.23 (0.05)	0.90- 1.05 (0.80)	Well sorted, medium sand
Tarkarli (n=7)	2.30- 2.74 (2.46)	2.30- 2.78 (2.49)	0.41- 0.54 (0.49)	-0.19- 0.16 (0.08)	0.98- 01.16 (1.02)	Moderately well sorted sand
Killenivati (n=30)	2.17- 2.41 (2.43)	2.18- 2.97 (2.43)	0.45- 0.72 (0.56)	-0.28-0.8 (0.02)	0.84- 1.09 (0.94)	Moderately well sorted fine sand
Mochemad (n=4)	2.57- 2.80 (2.72)	2.42- 2.80 (2.70)	0.31- 0.83 (0.48)	-0.39- 0.15 (0.12)	1.19- 1.68 (1.45)	Moderately well sorted to well sorted fine sand
Vengurla (n=6)	2.34- 2.67 (2.53)	2.31- 2.61 (2.53)	0.35- 0.48 (0.39)	-0.34- 0.14 (- 0.24)	0.86- 1.29 (1.0)	Well sorted fine sand

Table 5

Sample No.	Location	Opaque	Pyroxene	Amphibole	Kyanite	Tourmaline	Zircon	Rutile	Staurolite	Titanite	Olivine	Sillimout	Garnet	Epidote	Unidentified
K-8 Berm n= 485	Kotharwadi	87.83	5.56	0.82	0.20	0.82	0.20	1.23	1.85	-	-	-	1.23	0.20	-
9 Berm n = 724	Phanase wadi	84.6	5.8	3.45	0.82	1.38	0.27	0.27	1.24	-	0.27	-	0.14	0.14	1.51
13 Dune n = 1344	Phanase wadi	86.75	0.66	0.66	0.14	0.37	8.77	1.41	1.11	-	-	-	-	0.07	-
15 Dune n =477	Padwane wadi	90.98	2.09	2.93	0.42	0.42	0.42	0.21	1.25	-	-	-	0.83	-	0.42
17 Dune n = 939	Kunkeshwar	83.91	0.31	0.53	0.10	-	11.50	1.9	1.15	0.10	0.20	-	0.20	-	-
30 Berm n = 381	Morve	68.5	1.83	2.88	2.1	2.1	3.15	0.52	18.37	-	0.52	-	-	-	-
37 Dune n = 670	Pirwadi	46.56	15.52	34.02	-	1.94	-	-	1.34	-	0.15	-	-	0.44	-
44 Dune n = 357	Talashil	75.91	7.56	10.08	-	0.56	1.68	1.12	0.56	-	0.28	-	1.68	0.28	1.4
48 Dune n = 366	Talashil	83.33	4.1	1.36	0.27	0.54	6.28	1.09	0.54	-	-	-	2.45	-	-
54 Dune n = 669	Tarkarli	40.80	7.47	33.93	-	0.44	-	0.30	1.49	-	-	0.30	13.75	1.49	-

60 Berm n = 300	Bhogve	43. 58	12. 8	25. 64	0. 36	1. 1	3.2 9	-	2.5 6	-	-	0. 36	9.1 5	1. 10	-	-
61 Surf ace n = 443	Bhogve	32. 50	7.6 7	28. 66	-	0. 90	1.3 5	0. 90	0.9 0	-	0. 90	-	25. 73	0. 45	-	-
63 Berm n = 342	Nivati	35. 67	8.4 8	37. 71	1. 46	1. 46	1.7 5	-	2.6 3	-	-	-	9.3 5	1. 46	-	-
64 Berm n = 343	KilleNiv ati	58. 30	11. 95	15. 74	0. 87	0. 58	0.8 7	0. 87	1.4 5	-	0. 58	-	7.5 8	1. 16	-	-
70 Surfac e n = 300	Kalviban dar	72. 47	3.4 8	9.7 5	-	1. 04	31. 35	0. 69	0.6 9	0. 69	-	-	1.3 9	0. 34	-	-
71 Berm n = 548	Kalvi Bandar	73. 0	2.0 0	0.3 6	0. 36	-	16. 42	3. 46	1.8	0. 18	0. 36	-	1.6 4	0. 36	-	-
82 Dune n = 355	Wagesh wari	83. 38	1.9 7	4.2 2	0. 56	-	3.3 8	-	1.4 0	-	-	-	3.0 9	1. 97	-	-
83 Berm n = 346	Mochem ad	46. 24	2.0 2	40. 46	0. 29	2. 02	0.8 6	0. 60	1.4 4	-	-	0. 29	4.3 3	1. 44	-	-
86 Dune n = 611	Sagarthir th Beach	48. 77	1.1 4	19. 15	1. 63	1. 31	6.5 4	1. 47	2.6 1	-	0. 32	-	16. 09	1. 47	-	-
90 Surfac e n = 340	Sukalbha t	40. 88	1.4 7	41. 47	1. 17	1. 47	0.8 8	0. 58	1.7 6	-	0. 29	-	9.4 1	0. 58	-	-
91 Surfac e n = 621	Mahartal e	96. 6	0.3 2	1.9 3	0. 16	0. 16	0.1 6	0. 32	-	-	-	-	0.1 6	0. 16	-	-

Table 6**Area 1**

Location	Total Heavy Minerals	Ilmenite	Magnetite	Non-magnetite
Kotharwadi (27)	24.6-38.99 (31.80)	0.28-10.79 (08.53)	9.06-14.18 (11.62)	10.28-13.02 (11.65)
Phanasewadi (52)	3.63-29.45 (13.11)	0.31-7.65 (02.85)	0.91-7.40 (03.31)	2.41-14.39 (06.95)
Padwanewadi (23)	1.61-24.61 (13.13)	0.3-0.8 (0.55_	0.8-1.62 (01.21)	6.21-16.53 (11.37)
Pirwadi to Tondavali (169)	7.52-54.36 (19.05)	0.52-21.15 (05.12)	1.89-14.07 (06.50)	0.30-17.83 (4.85)
Tondavali to Talashil (223)	8.14-98.37 (58.08)	1.25-33.64 (13.39)	3.44-58.15 (28.56)	2.02-29.48 (14.51)
Bhogwe (30)	7.16-20.96 (11.81)	1.05-4.10 (2.32)	1.31-4.43 (2.45)	3.72-12.14 (7.04)
Phalephond Nivati (9)	2.64-80.87 (41.75)	0.27-43.07 (21.67)	0.1-3.95 (2.02)	2.01-33.85 (18.06)

Area 2

Location	Total Heavy Minerals	Ilmenite	Magnetite	Non-magnetite
Kunakeshwar (24)	1.61-31.67 (20.06)	0.3-2.05 (1.20)	0.24-8.27 (5.51)	1.35-23.14 (13.35)
Tarkarli (19)	2.30-25.31 (13.65)	0.33-6.35 (4.57)	0.34-5.29 (2.70)	1.62-13.67 (6.38)
KilleNivti (19)	5.14-10.0 (6.84)	1.0-2.63 (1.56)	1.11-3.12 (1.82)	2.81-4.22 (3.46)
Mochemad (9)	3.47-12.60 (8.03)	1.10-4.19 (2.64)	0.13-2.61 (0.37)	2.24-7.81 (5.02)
Vengurla (24)	1.0-26.51 (13.66)	0.1-11.02 (5.56)	0.04-1.40 (0.72)	0.68-14.09 (7.38)

Table 7

Ilmenite

Serial No	Area	Stn No.	TiO ₂	CaO	Cr ₂ O ₃	Fe ₂ O ₃	Feo	ZnO	V ₂ O ₅	NiO	MnO	MgO	Al ₂ O ₃	SiO ₂
1.	Kothar wadi	k-7	50.69	1.00	0.01	15.70	25.30	0.39	0.44	--	0.78	0.96	1.40	0.38
2.	Morve	32	48.60	0.27	0.44	16.30	26.15	0.11	0.92	0.08	1.05	1.84	1.21	2.10
3.	Talash il	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
4.	Talash il	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
5.	Talash il	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
6.	Talash il	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
7.	Talash il	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
8.	Bhogwe	61	38.89	0.48	0.07	20.00	33.26	0.29	0.66	0.08	1.20	0.36	1.29	2.21

Magnetite

Serial No.	Area	Station No.	TiO ₂	CaO	Cr ₂ O ₃	Fe ₂ O ₃	Feo	ZnO	V ₂ O ₅	NiO	MnO	MgO	Al ₂ O ₃	SiO ₂
1.	Kotharwadi	k-7	20.54	3.87	0.99	48.0	19.10	0.11	4.76	0.10	0.09	0.41	0.63	0.74
2.	Morve	32	23.98	3.70	0.10	35.19	23.0	1.62	3.78	0.15	3.78	0.08	2.50	1.45
3.	Talashil	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
4.	Talashil	47	14.31	ND	0.70	46.0	22.10	0.06	3.78	0.34	1.05	ND	0.85	0.90
5.	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
6.	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
7.	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
8.	Bhogwe	61	21.00	4.07	0.11	43.27	17.73	ND	4.23	0.16	4.18	0.12	3.02	1.30

Chromite

Serial No.	Area	Station No.	TiO ₂	CaO	Cr ₂ O ₃	Fe ₂ O ₃	Feo	ZnO	V ₂ O ₅	NiO	MnO	MgO	Al ₂ O ₃	SiO ₂
1.	Janoli	IIIb	0.05	2.25	33.62	3.54	22.34	0.03	0.12	0.34	0.76	12.61	14.96	5.32
2.	Talashil	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
3.	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
4.	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

Samples of ilmenite and magnetite are from Tondavali (stations 46, 47) and Talashil (87, 48, 47)

For chromite samples from Tondavali (46) and Talashil (97, 48, 47).

3 samples of ilmenite and magnetite are from Phalephondnivi (71) Kotharwadi (71) and Phansewadi (13)