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Sources and transport of the heavy minerals in some Gondwana basins of extra-peninsular eastern India

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Abstract: The present endeavor is concerned with analyses of heavy mineral distributions entombed within the sandstones of some extra-peninsular Gondwana basins located in Singrimari, Meghalaya; Elephant Flat, Arunachal Pradesh and Kalijhora, West Bengal. Around 60% of the heavy minerals are similar in all the study areas with the common mineral species being zircon, garnet, opaque minerals, tourmaline, rutile, epidote, kyanite, staurolite and titanite. Compared to Singrimari and Kalijhora, Elephant Flat suite hosts more varieties. Heavy mineral indices indicate the sandstones of the study areas to be somewhat mineralogically mature. Hydraulic separation and transportation length influenced variation in the physical attributes of heavy minerals between Singrimari and that of Kalijhora and Elephant Flat. The heavy minerals were contributed from a southern Precambrian terrain and accumulated in a mature continental passive margin setting. Source rocks of the study areas were closely associated in space ± time and were a mélange of ultrastable and metastable minerals. It is considerably probable that contributions of detritus from the denuded Precambrian Eastern Ghats Supergroup were very high. The fluviatile Singrimari Gondwanas were closer to the provenance and the drainage network extended further north wherein the Kalijhora and Elephant Flat Gondwana rocks were deposited under marine shoreline influence.

Keywords: Heavy minerals, Gondwana sandstones, Extra-peninsular India, provenance, statistical tests

Introduction

Clastic sedimentary rocks are windows to myriad facts of the geological past. Their analyses help one to have an understanding of the pre-depositional setup, nature of provenance, influence of relief and climate, weathering, tectonic setting of depositional basins, diagenetic stages etc (Dickinson, 1985; Suttner and Dutta, 1986; Boggs, 2009). Although sparse, heavy minerals which are a key component of siliciclastic sedimentary rocks play a discriminatory role in this regard.

Heavy mineral study is one of the oldest fields of endeavour in sedimentary petrology (Hubert, 1962; Mange and Maurer, 1992; Ramasamy and Karikalan, 2010). Quantitative treatment of heavy minerals was pioneered by Artini in 1898 and 1950s onward heavy minerals in sands and sandstones were mostly studied in detail (Von Andel, 1959). Application of advanced analytical techniques and mathematical treatment of data attracted a lot of workers towards heavy mineral studies. Although certain heavy mineral species can be selectively destroyed during transportation and diagenesis, the remaining ones carry a lot of ingredients to reflect their source as well as let one know about the tectonic history of provenance, erosion, weathering, transport path, dispersal pattern, deposition and post-depositional changes (Morton, 1985a; Lindholm, 1987; Silva and Vital, 2000; Mishra and Tiwari, 2005; Hota and Maejima, 2009) thereby contributing a lot towards basin analysis, delineation of sedimentary petrologic province and correlation.

Formation of Gondwanaland south of the supercontinent Pangaea, deposition of Gondwana rocks with the onset of Permo-Carboniferous along rifts (palaeo-sutures) were some of the most important events that took place in the geological past of our Earth. Continued rifting and subsequent breakup of Gondwanaland along the pre-existing tracks of weaknesses influenced land-sea distribution on Earth as what we see today. Gondwana Supergroup today can be found in many now separated locales. Making efforts towards understanding tectono-sedimentary evolution of Gondwana Supergroup and correlation studies as such have been a global obsession amongst geologists since long.

In the present endeavour heavy minerals from three extra-peninsular Gondwana locales exposed in and around Singrimari, Meghalaya; Elephant Flat, Arunachal Pradesh and Kalijhora in West Bengal of India have been considered for detailed petrographic investigations and subsequent statistical analyses. Objectives of the present attempt revolve around elucidation of the heavy mineral suites and their variations apart from determination of provenance in particular and correlation in general.

Geology of the study areas

The geological setup of Singrimari exudes a litho-association similar to the ones found in and around many Gondwana exposures of peninsular India, the Elephant Flat and Kalijhora exposures reflect the influence of Himalayan geodynamism (Fig. 1).

The Singrimari area lies at the western most tip of the Assam-Meghalaya Plateau where a Gondwanide sedimentary blanket of roughly 20 sq. km. (Table 1, Fig. 2) spreads over an eroded Precambrian basement, (Baruah and Das, 2001). Sedimentation here started with a southerly pinching basal coarser sandstone having pebbles towards the base. This buff-brown, friable-compact fining upward unit shows pinching and swelling and minor westerly slipping step faults apart from hosting carbonaceous shale. This unit shows two truncated cyclothems and a northward palaeocurrent direction, (Baruah and Das, 2012). Carbonaceous shales bear

Figure 1: Location of the three study areas in and around Singrimari, Meghalaya; Elephant Flat, Arunachal Pradesh and Kalijhora in West Bengal of India; Source: Google Earth image.

AGE	LITHOTYPES
Recent	Alluvium ~~~~~~~Unconformity~~~~~
Jurassic?	Basic Intrusives - Dolerite ~~~~~~~Unconformity~~~~~~ Fine grained sandstones bearing sedimentary pebbles at the base towards north, laystone, siltstone.
Permo-Carboniferous	~~~~~~~~~~hiatus~~~~~~~~~ Pebbly sandstones with layers of carbonaceous shale having specks of coal - Jhama (?). Shales bear palaeofloral remnants and are mylonitised at certain patches ~~~~~~~Unconformity~~~~~
Precambrian	Quartzofeldspathic gneiss - granite gneiss, calc-silicate gneiss, amphibolite, migmatite, granite, vein rocks - quartzofeldspathic (pegmatite in certain cases) and quartz vein.

Table 1: Lithostratigraphy of Singrimari area

palaeofloral remnants of Gondwanide affinity. Following a hiatus from here, the next sedimentation resulted in northerly pinching sandstone. Hosting sedimentary pebbles of the nature of the basal sandstones towards the base (Fig. 5A), this upper unit is buff-pink, friable-compact and fine-very fine grained. It entombs minor claystones and Fe-laminations which exudes a seasonal increment like look. The whole sedimentary column is intruded by dolerite intrusives. A highly extensive drainage network shed recent alluvium to sporadically cap the older lithounits. Overall, the sedimentary exposures which trends N10°E-N30°E with low dip towards west looks to be the easternmost fringe of a Gondwana basin where intermittent channel shifting, subsidence partially aided by tectonic play took place.

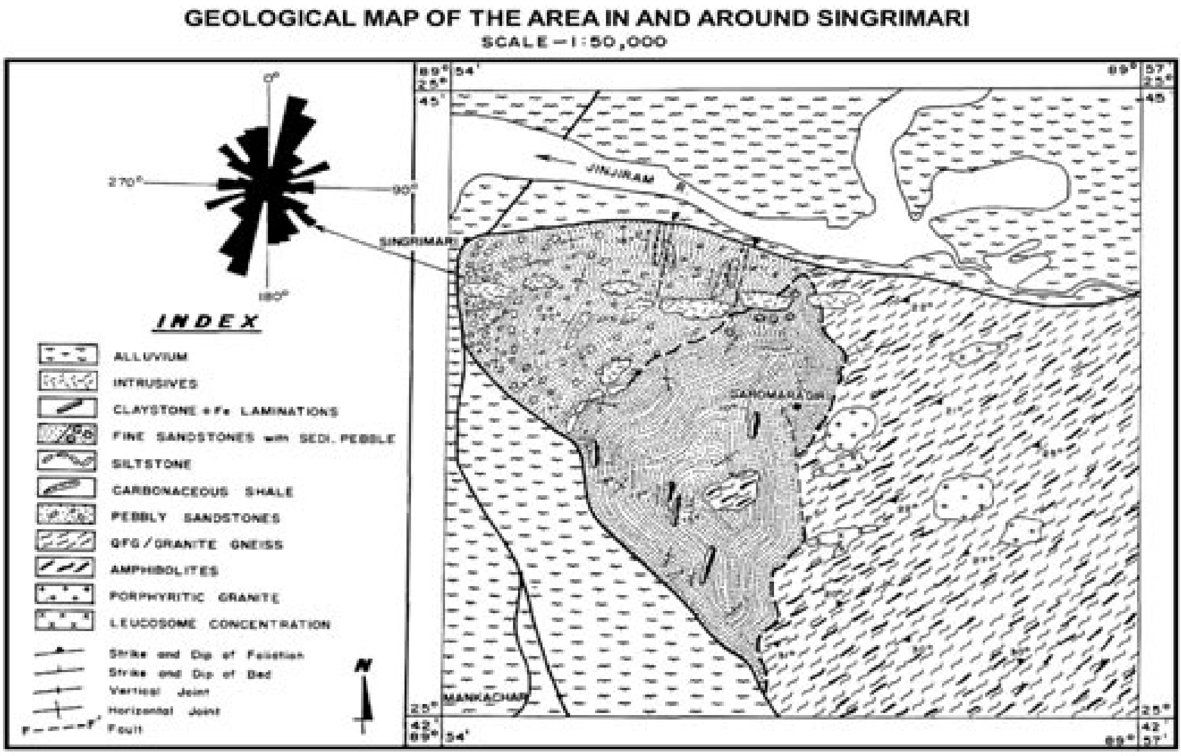


Figure 2: Geological map of the areas in and around Singrimari, Meghalaya (after Baruah and Das,

AGE		LITHOTYPES
Tertiary		Fine grained, white and ferrugenous sandstones
		~ ~ ~ ~ ~ unconformity ~ ~ ~ ~ ~
	Upper Unit	Massive micaceous sandstone interbedded with carbonaceous shale, shale, shaly sandstone, ferrugenous sandstones, Coarse and gritty sandstone shale and coal, Plant fossils: Vertibraria, Schizoneura, Taenopteris
North ↓		
Permo-Carboniferous	Lower Unit	Hard, massive, coarse grained sandstones criss crossed by quartz veins; Black sandstones and shale (interlayered). Shales host plant fossils; Black, buff fine grained sandstones
		~ ° ~ ° ~ ° Crushed zone ° ~ ° ~ ° ~
		Hard shale Crushed coal quartzitic sandstone
		~ ~ ~ ~ ~ unconformity ~ ~ ~ ~ ~
Precambrian		Slate, Phyllite, Quartzite.

Table 2: Synthesised lithostratigraphy of Elephant Flat area

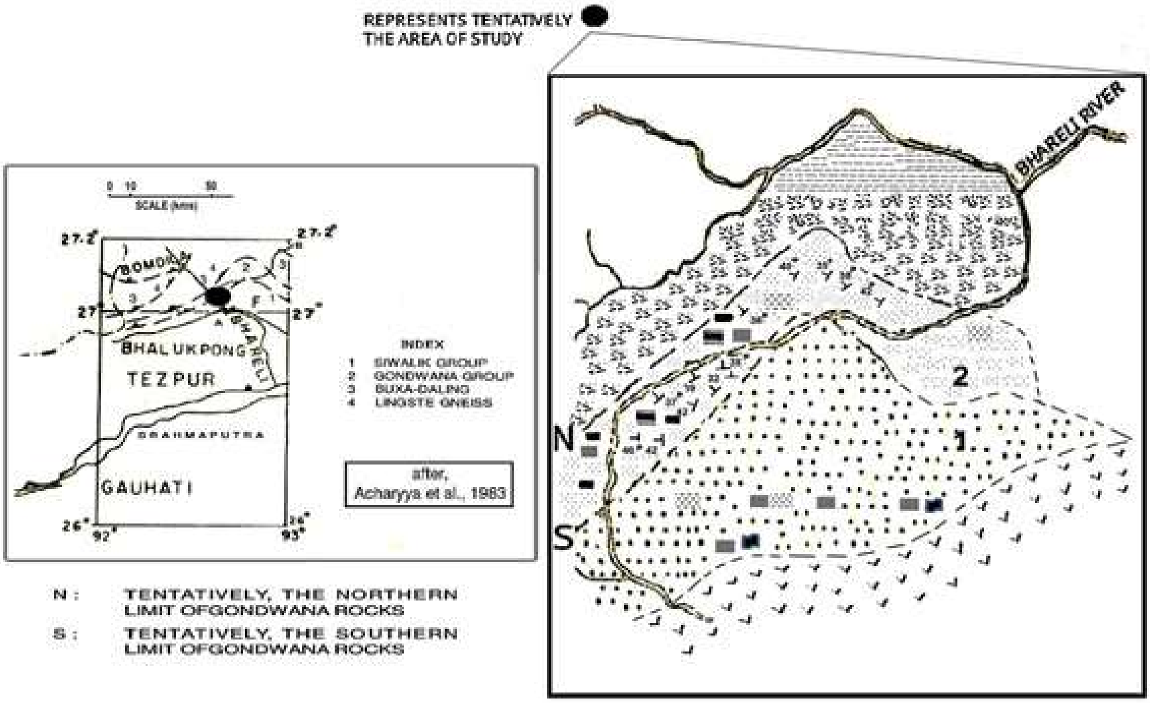


Figure 3: Geological map of the areas in and around Elephant Flat, Arunachal Pradesh (modified after Acharyya et al., 1983)

About 14 kms. North of Bhalukpung point on way to Bomdila, Gondwana rocks are exposed in and around Elephant Flat area between Pinjuli Nala and Sessa Nala from south to north (Baruah, 2007). Tertiary (Siwalik Group of rocks) and Precambrian rocks mark the southern and northern limits. E-W trending Himalayan thrusts (MBT) traverse the area consequently affecting the normal stratigraphic sequence (Table 2, Fig. 3). The area is sandstone dominated with varieties being buff-, grey- and black coloured, gritty-, and medium to fine grained. These arkosic to quartzitic arenaceous varieties are inter-layered with minor shaly sandstones, silty shale, shale, carbonaceous shale, lenses of coal (Fig.5B).

Coal in particular is crushed and shows high reflectance owing to tectonic jerks. Repetition of the litho assemblage: sandstone - shale - coal, colour variations are indicative of either seasonal influence or tectonic control. Dominance of black, recrystallised, fine and massive sandstones increases towards north. Plant fossils like Vertibraria, Glossopteris and Schizoneura confirm their age to be Lower Gondwana. The rock units dip towards north with the amount of dip varying between 30° to 60°. Occasionally vertical beds are also seen in these rocks which strike ENE-WSW to NE-SW. Kalijhora in Darjeeling Himalayas hosts Gondwana rocks (known as Rishi Group here) sandwiched between Precambrian Dalings towards north and Siwalik rocks towards south in a roughly ENE-WSW to WNW-ESE trend in the vicinity of the MBT (Table 3, Fig. 4). The exposed rocks mostly comprise of sandstones which are relatively more compact than the Siwalik sandstones. The arenaceous units are found as buff, grey, dark grey coloured and a little bit recrystallised. Grey sandstones along the river bed hosts variable calcareous ingredients. Carbonaceous shale, sandy shale, coal are some of the other litho units (Fig. 5C). At places coal exudes an anthracitic look owing to thrusting. Unlike Elephant Flat area which is also a part of the Himalayan framework, Kalijhora is devoid of fossils.

At least two prominent deformational phases are evident. Across the Kalijhora on its either bank, sandstone beds are dipping oppositely (Fig. 5D). The beds on the northern bank show a moderate north-westerly dip while those on the southern bank show a moderate southerly dip reflecting the existence of a larger antiform with east-west axial planar trend and a moderately westerly plunging fold axis. Consequent to D_1 a weak bedding parallel foliation developed in the sandstones. Subsequent to formation of F_1 folds, NE-SW trending F_2 folds developed. The area is also affected by dextral shearing reflected best by the carbonaceous shale and coal. This whole sequence underwent brittle deformation later (Basu, 2013; Kar et al., 2017).

AGE	GROUP	LITHOTYPES
Recent		Alluvium
		~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~unconformity~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
Tertiary	Siwalik	Medium grained sandstone, carbonaceous shale intercalated with sandy shale, silt, minor marl and pebbly sandstones, conglomerate: Repetitive sequence
	↓ North	~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ thrusted ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
		Fine to medium sandstone, sandy shale, shale, minor coal, pebbly sandstones, conglomerate
		~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ unconformity ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
Permo-Carboniferous	Gondwana (Rishi)	Fine to medium grained buff coloured sandstones Grey coloured intercalated with slaty Shale, carbonaceous shale and coal; minor gritty sandstones; few sandstones exude a calcareous look Grey to dark grey recrystallised sandstone
		~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ unconformity ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
Precambrian	Daling	Massive quartzites Intercalations of foliated quartzites and phyllites

Table 3: Synthesised lithostratigraphy of Kalijhora area

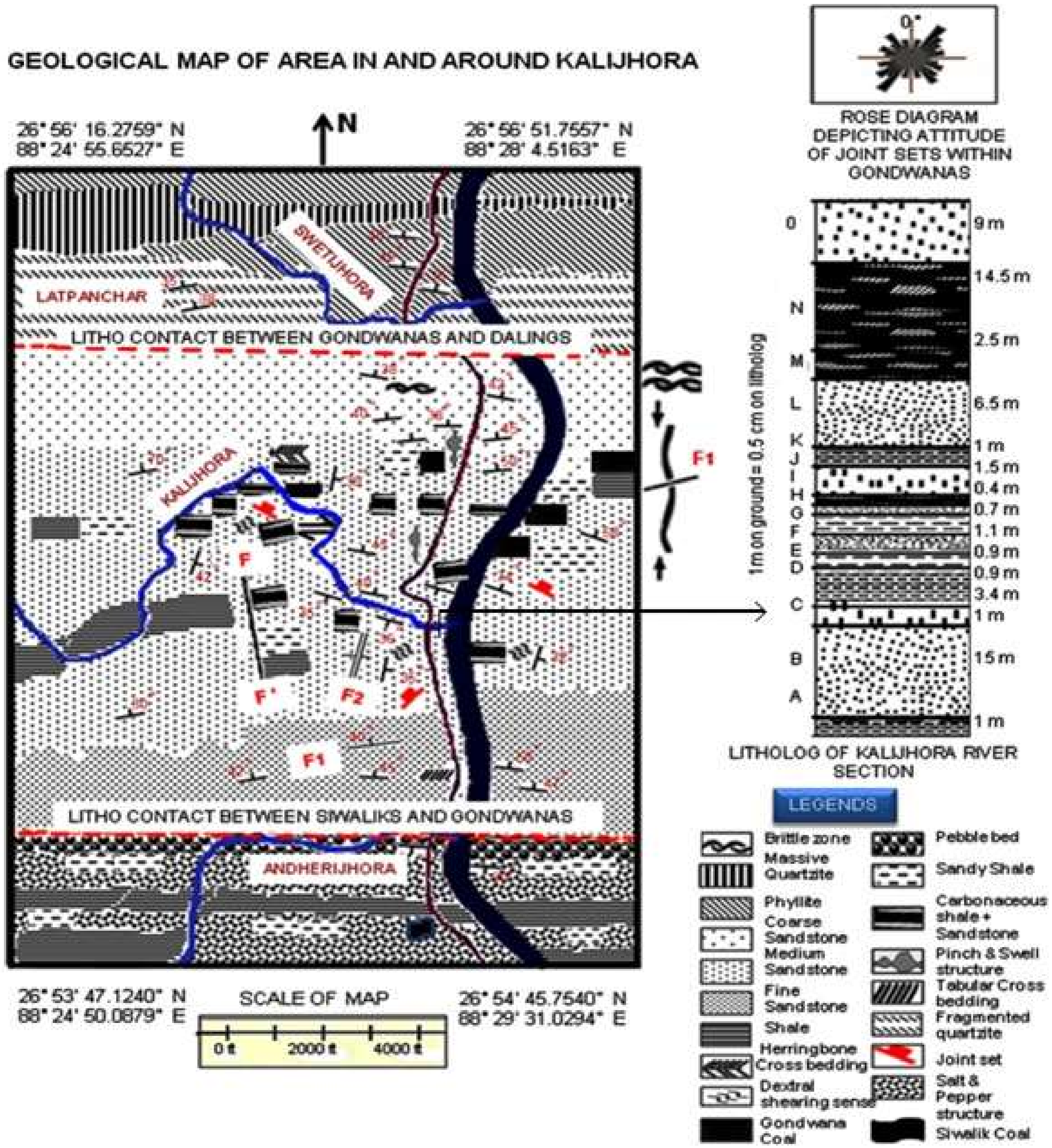


Figure 4: Geological map of the areas in and around Kalijhora, West Bengal (after Kar et al., 2017)

5a

5B

5C

5D

Figure 5: (A) Photograph shows traces of a current-bedding within the basal pebbly sandstone; Locality: south-east of BSF Camp, Singrimari; (B) Photograph shows alternations of fine grey sandstone, carbonaceous shale and coal; Locality: south of Elephant Flat proper, (Baruah, 2007); (C) Photograph shows alternations of sandstone and coal; Locality: Kalijhora; (D) Photograph shows sandstones being warped into an antiform with lensoidal presence of coaly matter at the core; Locality: North bank of Kalijhora river, (Kar et al., 2017).

Methodology

Sand fractions from 0.250 mm to 0.0625 mm (medium to very fine grained) have been considered for analyses. Representative samples have been put to "Funnel Separation" method (Krumbein and Pettijohn, 1938). 84 representative thin-sections were considered for petrographic studies. Based on field findings Singrimari sandstones were classified as upper and lower (basal). Around 100 counts were made per section to substantiate the suite characteristics of the heavy minerals following Lindholm (1987). Common heavy mineral parameters like ZTR, shape index and density index were calculated following Hubert, 1962 and Flores and Schideler, 1978 apart from analysing reciprocal relationships of selected ultrastable – metastable heavy minerals.

The multivariate data of the heavy minerals were put to some statistical tests like correlation matrix analyses, principal component analyses and cluster analyses (Davis, 2002). Mutual sympathetic and antipathetic relationships amongst the heavy minerals were figured out by correlation coefficients. All statistical analyses have been performed to have a better understanding of the heavy mineral assemblages, inter-relationship amongst different mineral species and the source rocks. SPSS-20 was used for all statistical analyses.

Results

Heavy minerals and their variability not only indicate the nature of source rocks but also the influences of sedimentary cycle processes. The heavy mineral assemblage of the study areas comprise of both transparent and opaque varieties (Table 4, Fig. 6) as listed below:

The Singrimari suite comprise of zircon + garnet + opaque minerals + tourmaline + rutile + chloritoid + epidote + kyanite + staurolite + titanite + apatite. Transparent heavy minerals constitute 32.12% of Upper Sandstones and 60.27% of the Basal Sandstones.

The Elephant Flat suite hosts zircon + rutile + garnet + opaque minerals + tourmaline + epidote + titanite + cordierite + actinolite + staurolite + kyanite + brookite + biotite. Both actinolite and biotite exudes strong leaching. Transparent heavy minerals constitute 39.75% of the total.

The Kalijhora suite comprise of zircon + tourmaline + rutile + kyanite + staurolite + epidote + garnet + chloritoid +

opaques + titanite + apatite. Transparent heavy minerals have a 93.18% share of the lot.

Although spatially separated, the heavy mineral finds in the study areas have a lot of similarity amidst minor perceptible differences and a comparative account of observations is stated herewith:

Zircon grains in all the study areas occur in a variety of forms right from prismatic, subhedral to euhedral types with well defined crystal faces through sub-rounded forms to rounded forms. The grains are colourless, gray to pale brownish, show straight extinction and pale high order interference colour and contain opaque and non-opaque inclusions. The brownish varieties sometimes show ferruginous encrustations while the gray varieties show more of minute opaque inclusions. Primary growth forms like parallel (with common base) and twinned crystals are rare compared to secondary growth which includes overgrowth, outgrowth and multiple growths. Overgrowths are seen on prismatic ('sawfish' type) as well as pyramidal faces. Necked zircons and those showing geniculate twinning are rare. Zircons with zircon inclusions are also seen. Size wise zircons from the Upper Sandstones (7.3% to 24.3%) of Singrimari are finer and unimodal compared to the Basal Sandstones (10.1% to 27.03%) which show extreme bimodality. Zircons of Elephant Flat area (12.12% to 29.16%) show unimodality similar to Upper Sandstones of Singrimari. Zircons from Kalijhora area (32.28% to 45.54%) are mostly medium grained and bimodal.

Tourmaline grains in all the study areas are prismatic and angular to sub-rounded. Tourmalines are identified by their characteristic pleochroism from light brown to dark brown and light green to dark green. The varieties are dominantly brown followed by some colourless ones and a few in Singrimari and Kalijhora are with bluish tinge. Tourmalines in Elephant Flat show partings. The abundance of tourmalines varies from 1.04% to 5.19% in case of Upper Sandstones and 1.35% to 3.25% in case of the Basal Sandstones of Singrimari. In Elephant Flat tourmaline grains vary from 0% to 6.4%. Tourmalines are most abundant in Kalijhora after zircon and they vary from 30.54% to 44.81.

Rutiles are identified by their peculiar 'blood red' colouration. The grains are mostly sub-angular to sub-rounded in form and distinct prismatic and pyramidal terminations are seen in some cases. Under reflectance, the grains show vitreous lustre. Faint striations slightly oblique to the prismatic faces are seen in all the study areas. The percentage of rutiles varies from 1.1% to 5.04% in case of the Upper Sandstones and 1.1% to 3.28% in case of the Basal Sandstones of Singrimari. Rutiles are most abundant in the Elephant Flat suite after zircon and it varies from 2.08% to 18.25%. Rutiles in Kalijhora range from 0% to 6.66%.

Garnets are sub-angular to sub-rounded, reddish brown and mostly anhedral in all the areas. The grains are isotropic to feebly anisotropic and show small opaque inclusions. Garnets are most abundant in the Singrimari suite after zircon and pitted surfaces in certain grains are seen. Pitted surfaces are common in Singrimari and Kalijhora. In Elephant Flat and Kalijhora garnets are relatively less. The percentage of garnets varies from 1.7% to 19.5% in case of the Upper Sandstones and 18.2% to 35.2% in case of the Basal Sandstones. In Elephant Flat percentage of garnets vary from 0% to 8.2% while in Singrimari it ranges from 0% to 9.18%.

Kyanites Characterized by transverse fractures kyanites are seen as bladed, platy and elongated grains with irregular terminations in all the study areas. They occur as colourless to pale green colour. The grains show inclined (~30°) extinction angle and a higher order interference colour of blue, pink and yellow. The percentage of kyanites vary from 1.4% to 3.4% in case of the Upper Sandstones while it case of the Basal Sandstones of Singrimari it is found only in one sample showing a quantity of 2.1%. In Elephant Flat the percentage of kyanites vary from 0% to 1.5%. Kyanites are rare in Kalijhora. Only two samples mark their presence and abundance varies from 0% to 1.63%.

Epidotes range from colourless ones to those with the characteristic pistachio green colour and shiny surfaces. The grains have mostly irregular boundaries and are sub-angular in form. The grains show straight extinction and, brilliant green to purplish and red interference colours. The percentage of epidotes varies from 0.9% to 15.5% in case of the Upper Sandstones and 1.75% to 6.5% in case of the Basal Sandstones in Singrimari. Epidotes in Elephant Flat exhibit themselves as small chips and vary from 0% to 6.02%. In Kalijhora percentage of epidote varies from 0% to 12.85%.

Staurolites in all the study areas are light yellow to straw yellow in colour, angular to sub-angular, shows parallel extinction and low birefringence. The grains mark themselves as irregular with hackly fracture. The percentage of staurolites in Singrimari varies from 1.25% to 3.25% in case of the Upper Sandstones while in case of the Basal Sandstones it ranges from 1.03% to 2.04%. In Elephant Flat a few staurolites with inclusions of quartz and opaque minerals are seen. The percentage of staurolite here varies from 0% to 2.01%. In Kalijhora the percentage of staurolites varies from 0% to 9.54%.

Opaques are sub-rounded to anhedral in all the study areas and are most dominant of all the minerals stated above. Under reflected setup, certain grains show black, reddish and rarely bluish reflectance. EPMA studies of heavy opaques of Singrimari and Elephant Flat were done. Magnetite is found to be dominant in Singrimari while it is poor in Elephant Flat. In Singrimari the percentage of opaque minerals varies from 50.1% to 80.2% in case of the Upper Sandstones and, 24.1% to 49.25% in case of the Basal Sandstones. Opaques average 58.43% in Elephant Flat while it is lowest in Kalijhora amounting to only 6.64% on average.

Titanites Although low in abundance, titanites are encountered in all the study areas. The grains are identified by their rhombohedral nature, very high relief, dark marginal rim, light yellow colour with dusky tinge and symmetrical extinction. The grains show white to light yellow interference colour. In Singrimari the percentage of titanites varies from 0.6% to 2.4% in case of the Upper Sandstones, while in Basal Sandstones it ranges from 1.01% to 4.02%. Titanites vary from 0% to 2.5% in Elephant Flat while it ranges from 0% to 13.97% in Kalijhora.

Apatites grains are found only in Singrimari and Kalijhora. These grains are colourless to straw green in colour, sub-angular, show parallel extinction and low birefringence. The colourless grains show prismatic habit more clearly than the straw green type grains which mark themselves as sub-angular. Overall, these grains are not so common. The percentage of apatite in Singrimari varies from 1.03% to 1.2% in case of the Upper Sandstones while in case of the Basal Sandstones it ranges from 2% to 2.2%. The percentage of apatite in Kalijhora varies from 0% to 2.57%.

Chloritoids are identified by features like dark greenish to black colour, sub-angular to sub-rounded forms and a translucent border surrounding an opaque core. The typical scaly flakes or wisps are not clearly visible. The grains show nearly straight extinction when aligned along its longer dimension. Pleochroism is strong. However, the dark body colour of the grains blanket the clarity of these characteristics. In Singrimari the percentage of chloritoid varies from 1.09% to 6.1% in case of the Upper Sandstones whereas in case of the Basal Sandstones it ranges from 1.05% to 4.9%. In Kalijhora it varies from 0% to 6.27%. Chloritoids are not found in Elephant Flat.

A few minerals like cordierite, actinolite, brookite and biotite have been found only in Elephant Flat area.

Cordierite is sparse in terms of abundance and is marked by its subhedral, sub-rounded, slightly prismatic nature, light yellow colour with dusky tinge, and straight extinction when oriented parallel to their prismatic and longer dimension. The grains show white to light yellow interference colour. Sub-conchoidal fracture is seen. The percentage of cordierites varies from 0% to 2.84%.

Actinolite expresses itself as fibrous green elongated, subhedral to anhedral grains. Their cleavages are distinct. They are lower in abundance compared to the other minerals. The grains show inclined extinction of around 7° and exhibit green interference colour. Leaching is clearly seen in the actinolites and as a result, specks of iron are seen to be smeared in and around the actinolite grains. In fact, a few actinolites are themselves seen to be secondary after pyroxenes. The pyroxenes in this case are distinguished by their deeper green colour, higher relief and distinct cleavages. Evidences of transition from pyroxene to actinolite are seen. In this case, the two phases can be distinguished by the differences in relief and colour contrast. The percentage of actinolites varies from 0% to 4.56%.

Brookite is a rare entity and is identified by its high relief, light yellowish brown, slightly translucent, prismatic and tabular expression. Faint striations are seen parallel to the longer dimension of the grain and partial extinction is seen parallel to the striations. Many small opaques specks are seen as inclusions. The percentage of brookite varies from 0% to 1.5%.

Biotites are characterised by their brown colour, hexagonal and flaky habit. The biotites are marked by opaque minerals and rutile as inclusions. Biotite exhibits leaching and evidences of their secondary origin after amphiboles. The percentage of biotites varies from 0% to 5.39%.

Heavy Minerals and few Indices	**Singrimari (Upper)**	**Singrimari (Basal)**	**Elephant Flat**	**Kalijhora**
	Average of **19** Representative Samples	Average of **11** Representative Samples	Average of **30** Representative Samples	Average of **24** Representative Samples
Zircon	14.34	29.18	21.26	38.95
Tourmaline	1.23	0.95	2.19	38.1
Rutile	1.26	1.38	8.27	1.41
Kyanite	0.38	0.31	0.13	0.04
Staurolite	0.36	0.86	0.19	1.69
Epidote	4.12	4.3	1.72	6.65
Garnet	7.19	18.57	4.09	1.56
Chloritoid	2.75	2.46	Abs.	0.34
Opaque	68.48	39.8	58.43	6.64
Titanite	0.45	1.82	0.49	3.93
Apatite	0.05	0.45	Abs.	0.5

Cordierite	Abs.	Abs.	0.54	Abs.
Actinolite	Abs.	Abs.	0.78	Abs.
Brookite	Abs.	Abs.	0.08	Abs.
Biotite	Abs.	Abs.	1.84	Abs.
ZTR Index	59.45	55.8	44.1	84.18
Bl+El	20.46	36.54	33.22	83.27
Sm. Equant	11.66	23.74	6.53	9.9
Shape Index	2.07	1.74	5.92	8.41
Sm. Transparent	32.12	60.27	39.75	93.18
Density Index (O/NO)	2.28	0.68	1.55	0.07

Table 4: Average abundance and few indices of heavy minerals in the three study areas

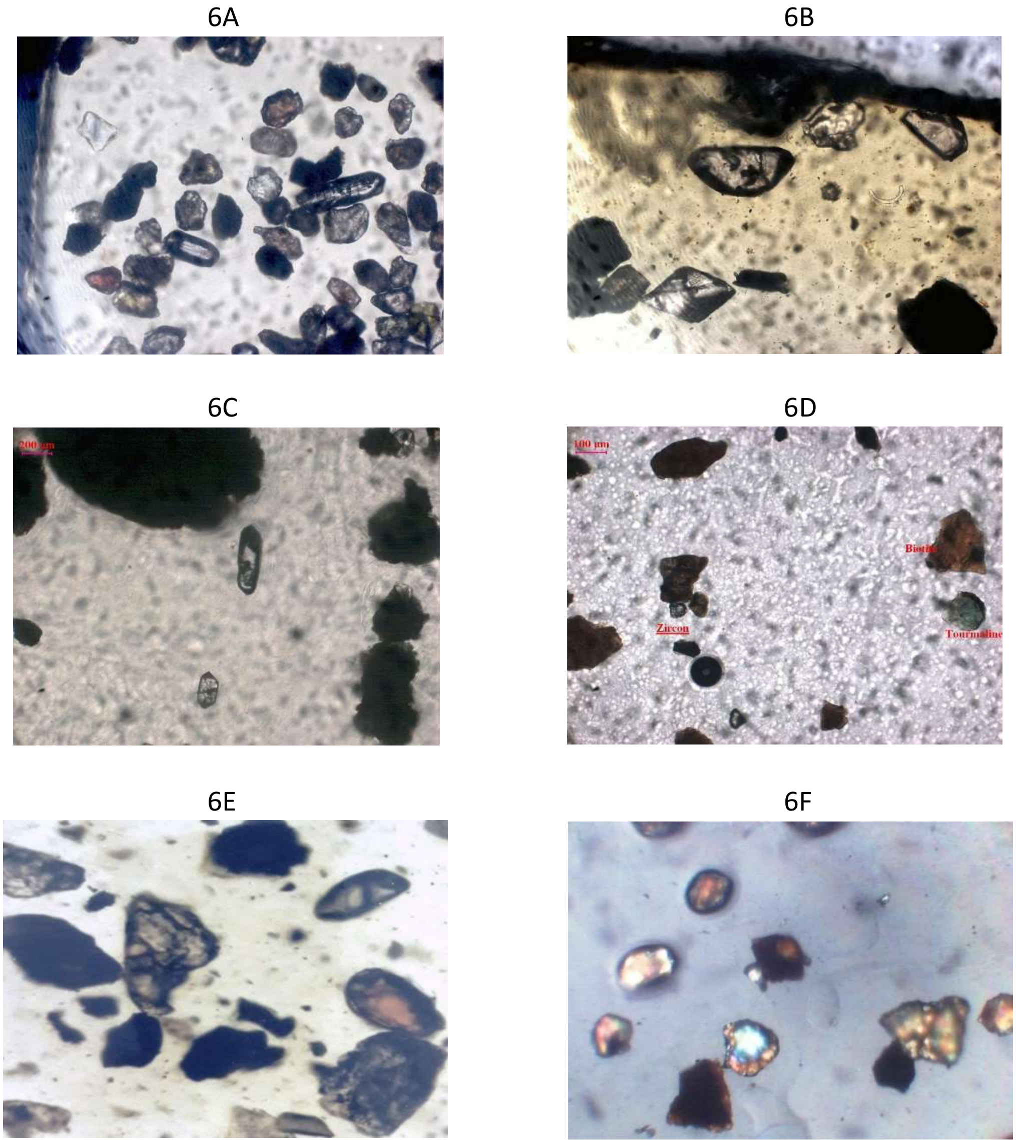


Figure 6: Photomicrographs showing (A) euhedral zircon, rutile, garnet , epidote and opaque grains in Singrimari sandstones; (B) Zircon, sphene and garnet grains in Singrimari sandstones. Magnification: 100X; (C) Two varieties of zircon: authigenic and nearly euhedral in Elephant Flat sandstones; (D) Garnet, biotite (leached), tourmaline, zircon in Elephant Flat sandstones; (E) Nearly euhedral zircon, sub-rounded tourmaline, garnet and opaque minerals in Kalijhora sandstones and (F) Zircon, epidote and rutile in Kalijhora sandstones. Magnification: 100X.

Heavy mineral indices: a few implications

While source rocks contribute the heavy minerals, their concentration are influenced by factors like nature of terrain, sediment influx from hinterland, energy conditions, weathering, length and nature of transportation, geomorphology as well as tectonic setup. Even marine action and coastal geomorphology influences heavy mineral concentration, (Cheepurupalli et al., 2012). Certain heavy mineral indices like ZTR, Shape index, Density index, reciprocal relationships between selected heavy minerals helps one to have a better understanding on many afore mentioned factors.

The summation of quantitative percentage of zircon, tourmaline, and rutile amongst the transparent, non-micaceous and detrital heavy minerals is an indication of mineralogical maturity of the sediments (Hubert, 1962). In the present case ZTR index is moderately high in Singrimari and Elephant Flat while it is extremely high in Kalijhora. ZTR index is commonly found to be high in beach or littoral zone depositional environments mostly due to long transportation distances from provenance and the prevailing high energy environment.

Shape Index is the ratio of bladed and elongated minerals like zircon, tourmaline, rutile, kyanite, actinolite etc to equant minerals like garnet and epidote while density index is the ratio of opaque heavy minerals to transparent heavy minerals. Analyses of shape index results show the values to be relatively higher in Elephant Flat and Kalijhora compared to Singrimari indicating dominance of bladed and elongated minerals in these two areas. Density index values do not vary much. However contribution from opaque sources was more in Singrimari towards the later stages of the sedimentation process. Hydraulic separation by density may have played some role in enhancement of bladed and elongated minerals in the Kalijhora and Elephant Flat areas as high density minerals settle more rapidly than the low density ones, (Prothero and Schwab, 2004). Selective decomposition of heavy minerals had taken place during transportation or in post depositional stages.

With an objective to have an idea about the nature of source rocks and their stability, reciprocal relationships between six selected minerals namely zircon, tourmaline, rutile, garnet, epidote and staurolite (Table 5) were calculated and analysed. Amongst the ultrastable minerals the dominance of zircon is high to very high in all the study areas. Tourmaline / garnet and tourmaline / epidote ratios is Elephant Flat and Kalijhora areas reveal the dominance of ultrastable minerals over metastable ones. The ratio metastable / ultrastable heavy minerals also reveal similar features. Relatively the share of ultrastable minerals is more in the Kalijhora and Elephant Flat compared to Singrimari. This may be due to the influence of provenance, recycling or changes coming into effect during transportation or post-depositional events. Proximity to the

Study areas	Zircon / Rutile	Zircon / Tourmaline	Tourmaline / Garnet	Staurolite / Garnet	Tourmaline / Epidote	Metastable / Ultrastable
Singrimari (Upper)	11.38	11.66	0.17	0.05	0.30	0.69
Singrimari (Basal)	21.14	30.72	0.05	0.05	0.22	0.75
Elephant Flat	2.57	9.71	0.54	0.05	1.27	0.19
Kalijhora	27.62	1.02	24.42	1.08	5.73	0.13

Table 5: Reciprocal relationships of selected heavy minerals in the three study areas

provenance has influenced the presence of more metastable grains in Singrimari compared to Elephant Flat and Kalijhora areas, (Fig. 7).

Compositions of clastic sedimentary rocks have been used as a tool to decipher tectonic setting in various ways, (Bhatia, 1983; Roser and Korsch 1986, Nechaev and Isphording, 1993). The discrimination diagram of Nechaev and Isphording (1993) used in the present case (Fig. 8) is a right angled triangle with the apices being coded as MF, MT and GM. MF represents heavy minerals like pyroxene, hornblende and olivine derived from mafic magmatic rocks. MT denotes common constituents of basic

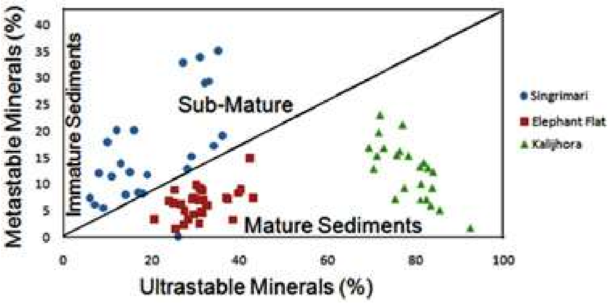


Figure 7: Relationship between ultrastable and metastable heavy minerals of the study areas, (after Pettijohn, 1957).

metamorphic rocks like amphiboles, garnet and epidote while GM stand for accessory minerals of granite and sialic metamorphic rocks like zircon, tourmaline, staurolite, kyanite, andalusite, monazite and sillimanite. Plots from all the study areas are found to cluster within the field of mature continental passive margin, a feature also corroborated by petrographic and geochemical findings, (Kar et al., 2017). Such settings are characterised by minerals which are dominantly derived from granites and sialic metamorphic rocks, reworked zones as well as deeply weathered zones which are tectonically less perturbed.

Statistical Analyses

Geological endeavours depend to a large extent on observations in which there is a large portion of uncertainty, (Davis,

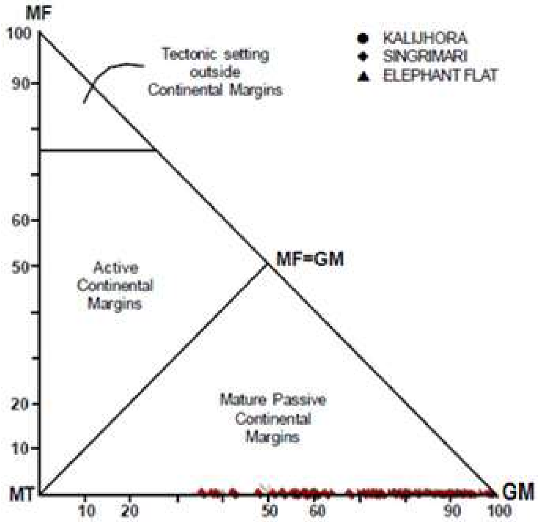


Figure 8: Tectonic discrimination diagram showing inter-relationship of the MF-MT-GM suites of heavy minerals from the study areas, (after Nechaev and Isphording, 1993).

2002). Application of statistics scales down the levels of uncertainty to an appreciable extent. A few statistical analytical procedures like bivariate correlation, principal component analysis and cluster analysis have been applied in the present case to arrive at a logical conclusion. It may be mentioned that although in petrographic procedures Singrimari heavy minerals were grouped into two: upper and basal, the groups have been merged into one for statistical analysis as it was found that there is more than 90% similarity in the nature of both the distributions.

Correlation Matrix Analysis

Detailed analyses of correlation matrix of the Singrimari heavy mineral assemblage (Table 6A) at 5% significance level show that the bivariate relationship between zircon-staurolite, zircon-garnet, zircon-apatite, zircon-sphene, staurolite-apatite and garnet-sphene are strongly significant. In Elephant Flat (Table 6B) epidote-brookite relationship is strongly significant while rutile-epidote, rutile-garnet and staurolite-cordierite relationships are moderately significant. Similarly in Kalijhora (Table 6C), bivariate relationship between rutile-kyanite and chloritoid-sphene are strongly significant while those between tourmaline-opaque and zircon-kyanite are moderately significant. Such relationships could be due to the fact that the source rocks responsible for contributing these minerals as found in the three study areas were closely associated in space ± time. Furthermore, a strong to moderate retrogressive relationship exists between zircon-opaques, garnet-opaques and sphene-opaques in all the study areas suggesting that supply of opaque minerals were from sources that had very less zircon, garnet and sphene. Correlation analyses considering |r| >0.5 (c.f., Hota et al., 2002) also supports these observations.

		ZIR.	TOUR	RUT.	KYA.	STAU.	EPI.	GAR.	CHLO	APA.	OPAQ	SPH.
Correlation	ZIRCON	1.000	.027	-.046	-.152	.350	-.043	.556	-.012	.393	-.895	.498
	TOUR	.027	1.000	-.183	.027	.184	-.135	-.239	-.298	.028	.128	-.182
	RUTILE	-.046	-.183	1.000	-.110	-.154	-.097	.145	-.065	-.210	-.070	.111
	KYANITE	-.152	.027	-.110	1.000	-.213	-.032	-.144	-.009	-.127	.134	-.160
	STAUR	.350	.184	-.154	-.213	1.000	-.073	.239	-.077	.533	-.367	-.037
	EPIDOTE	-.043	-.135	-.097	-.032	-.073	1.000	-.060	-.168	.031	-.079	.045
	GARNET	.556	-.239	.145	-.144	.239	-.060	1.000	.053	.022	-.828	.628
	CHLO	-.012	-.298	-.065	-.009	-.077	-.168	.053	1.000	.023	-.055	-.133
	APATITE	.393	.028	-.210	-.127	.533	.031	.022	.023	1.000	-.271	-.177
	OPAQUES	-.895	.128	-.070	.134	-.367	-.079	-.828	-.055	-.271	1.000	-.606
	SPHENE	.498	-.182	.111	-.160	-.037	.045	.628	-.133	-.177	-.606	1.000
Sig. (1-tailed)	ZIRCON		.444	.404	.212	.029	.411	.001	.476	.016	.000	.003
	TOUR	.444		.167	.443	.165	.239	.102	.055	.441	.251	.167
	RUTILE	.404	.167		.281	.208	.304	.222	.367	.133	.356	.279
	KYANITE	.212	.443	.281		.129	.433	.224	.482	.252	.240	.199
	STAUR	.029	.165	.208	.129		.351	.102	.344	.001	.023	.424
	EPIDOTE	.411	.239	.304	.433	.351		.376	.187	.436	.338	.406
	GARNET	.001	.102	.222	.224	.102	.376		.391	.455	.000	.000
	CHLO	.476	.055	.367	.482	.344	.187	.391		.451	.386	.243
	APATITE	.016	.441	.133	.252	.001	.436	.455	.451		.074	.174
	OPAQUES	.000	.251	.356	.240	.023	.338	.000	.386	.074		.000
	SPHENE	.003	.167	.279	.199	.424	.406	.000	.243	.174	.000	

Table 6A: Matrix of correlation between heavy minerals of Singrimari Gondwana

		ZIR	TOU	RUT	KYA	STA	EPI	GAR	COR	ACT	BRO	OPA	SPH	BIO
Correlation	ZIR	1.000	.040	.096	-.050	.059	-.225	.237	.037	-.013	-.004	-.605	.224	-.108
	TOU	.040	1.000	-.297	.061	.021	-.340	-.142	.249	-.041	-.072	.009	-.131	-.067
	RUT	.096	-.297	1.000	.024	-.296	.428	.477	-.132	-.291	.308	-.701	.125	.212
	KYA	-.050	.061	.024	1.000	.313	-.108	.076	.153	-.192	-.087	-.055	.112	-.057
	STA	.059	.021	-.296	.313	1.000	-.275	-.138	.447	.025	-.099	.088	-.009	-.047
	EPI	-.225	-.340	.428	-.108	-.275	1.000	-.237	-.418	-.149	.521	-.126	.098	.199
	GAR	.237	-.142	.477	.076	-.138	-.237	1.000	.169	-.157	-.185	-.613	.323	.138
	COR	.037	.249	-.132	.153	.447	-.418	.169	1.000	-.036	-.171	-.122	-.122	.099
	ACT	-.013	-.041	-.291	-.192	.025	-.149	-.157	-.036	1.000	-.151	.064	.169	-.014
	BRO	-.004	-.072	.308	-.087	-.099	.521	-.185	-.171	-.151	1.000	-.190	-.168	.156
	OPA	-.605	.009	-.701	-.055	.088	-.126	-.613	-.122	.064	-.190	1.000	-.437	-.362
	SPH	.224	-.131	.125	.112	-.009	.098	.323	-.122	.169	-.168	-.437	1.000	.298
	BIO	-.108	-.067	.212	-.057	-.047	.199	.138	.099	-.014	.156	-.362	.298	1.000
Sig. (1-tailed)	ZIR		.416	.306	.396	.378	.116	.104	.423	.472	.491	.000	.117	.284
	TOU	.416		.055	.375	.457	.033	.226	.093	.414	.352	.482	.246	.363
	RUT	.306	.055		.449	.056	.009	.004	.243	.060	.049	.000	.255	.130
	KYA	.396	.375	.449		.046	.286	.345	.210	.155	.324	.386	.278	.382
	STA	.378	.457	.056	.046		.071	.233	.007	.447	.301	.323	.482	.403
	EPI	.116	.033	.009	.286	.071		.103	.011	.216	.002	.254	.303	.145
	GAR	.104	.226	.004	.345	.233	.103		.186	.203	.164	.000	.041	.233
	COR	.423	.093	.243	.210	.007	.011	.186		.426	.184	.260	.261	.302
	ACT	.472	.414	.060	.155	.447	.216	.203	.426		.213	.368	.187	.471
	BRO	.491	.352	.049	.324	.301	.002	.164	.184	.213		.157	.187	.205
	OPA	.000	.482	.000	.386	.323	.254	.000	.260	.368	.157		.008	.025
	SPH	.117	.246	.255	.278	.482	.303	.041	.261	.187	.187	.008		.055
	BIO	.284	.363	.130	.382	.403	.145	.233	.302	.471	.205	.025	.055	

Table 6B: Matrix of correlation between heavy minerals of Elephant Flat Gondwana sandstones

		ZIR	TOU	RUT	KYA	STA	EPI	GAR	CHL	OPA	SPH	APA
Correlation	ZIR	1.000	.086	-.016	.398	-.214	-.475	-.040	.031	-.380	.146	-.124
	TOU	.086	1.000	-.068	.111	-.411	-.273	.003	-.289	.382	-.493	.113
	RUT	-.016	-.068	1.000	.574	-.012	.188	-.341	-.195	.022	-.256	-.222
	KYA	.398	.111	.574	1.000	-.106	-.286	-.063	-.055	-.039	-.185	-.159
	STA	-.214	-.411	-.012	-.106	1.000	-.065	-.255	-.134	-.192	.199	-.114
	EPI	-.475	-.273	.188	-.286	-.065	1.000	-.118	-.175	-.165	-.326	.275
	GAR	-.040	.003	-.341	-.063	-.255	-.118	1.000	-.104	.100	-.194	-.164
	CHL	.031	-.289	-.195	-.055	-.134	-.175	-.104	1.000	-.150	.520	-.137
	OPA	-.380	.382	.022	-.039	-.192	-.165	.100	-.150	1.000	-.472	-.038
	SPH	.146	-.493	-.256	-.185	.199	-.326	-.194	.520	-.472	1.000	-.082
	APA	-.124	.113	-.222	-.159	-.114	.275	-.164	-.137	-.038	-.082	1.000
Sig. (1-tailed)	ZIR		.344	.470	.027	.157	.010	.427	.443	.033	.248	.282
	TOU	.344		.376	.303	.023	.099	.494	.085	.033	.007	.300
	RUT	.470	.376		.002	.479	.190	.051	.180	.459	.113	.148
	KYA	.027	.303	.002		.312	.088	.386	.399	.428	.194	.228
	STA	.157	.023	.479	.312		.382	.115	.266	.184	.175	.298
	EPI	.010	.099	.190	.088	.382		.291	.207	.220	.060	.096
	GAR	.427	.494	.051	.386	.115	.291		.314	.321	.182	.222
	CHL	.443	.085	.180	.399	.266	.207	.314		.242	.005	.262
	OPA	.033	.033	.459	.428	.184	.220	.321	.242		.010	.431
	SPH	.248	.007	.113	.194	.175	.060	.182	.005	.010		.352
	APA	.282	.300	.148	.228	.298	.096	.222	.262	.431	.352	

Table 6C: Matrix of correlation between heavy minerals of Kalijhora Gondwana sandstone.

Principal Component Analysis (PCA)

Principal Component Analysis is a sophisticated multivariate statistical technique which transforms a number of possibly correlated variables into a smaller number of variables called principal components. PCA helps to analyse interrelationships between several variables concurrently. It is a way of identifying patterns in data and expressing the data in such a way as to highlight their similarities and differences without much loss of information (Davis, 2002). Only those principal components which are statistically significant and greater than unity (1) are used for geological interpretation.

Heavy Minerals	**Component**				
	1	2	3	4	5
Eigenvalues	3.284	1.856	1.287	1.128	1.060
Percentage of total variance	29.852	16.872	11.696	10.257	9.636
Cumulative percentage of total variance	29.852	46.724	58.420	68.677	78.313
ZIRCON	**.873**	.165	-.035	-.030	.164
TOURMALINE	-.155	**.517**	-.539	-.384	.175
RUTILE	**.063**	-.507	-.066	-.358	-.492
KYANITE	-.281	-.077	-.014	.066	**.796**
STAUROLITE	.453	**.675**	.045	-.108	-.179
EPIDOTE	.009	-.045	-.263	**.892**	-.167
GARNET	**.838**	-.290	.026	-.082	.086
CHLORITOID	.006	-.123	**.877**	-.034	.120
APATITE	.334	**.721**	.264	.170	-.137
OPAQUES	-.966	**.040**	-.006	-.051	-.128
SPHENE	**.679**	-.469	-.282	.018	.104

Extraction Method: Principal Component Analysis; 5 components extracted.

Table 7A: Matrix of five components for the 11 heavy minerals of Singrimari Gondwana sandstones

In case of Singrimari (Table 6A) five principal components which are greater than unity account for a cumulative percentage of total variance of 78.313. The principal component – 1 includes minerals like zircon, rutile, garnet and sphene while principal component – 2 includes tourmaline, staurolite, apatite and opaques. Chloritoid, epidote and kyanite make up lone representations as principal components – 3, 4 and 5.

In case of Elephant Flat (Table 6B) six principal components which are greater than unity account for a cumulative percentage of total variance of 78.213. The principal component – 1 includes minerals like rutile, epidote and garnet while principal component – 2 includes staurolite and cordierite. While principal component – 3 is marked by kyanite, principal component – 4 is represented by actinolite, opaques, sphene and biotite. Tourmaline and brookite marks principal component – 5 while zircon marks principal component – 6.

In case of Kalijhora (Table 6C) six principal components which are greater than unity account for a cumulative percentage of total variance of 86.825. The principal component – 1 includes minerals like tourmaline, garnet and opaque while principal component – 2 includes zircon and kyanite. While principal component – 3 is marked by rutile, staurolite and epidote, principal components – 4, – 5 and – 6 are marked by apatite, sphene and chloritoid respectively.

It is interesting to note that in Elephant Flat and Kalijhora areas, staurolite is almost equally loaded to two principal components and the association of staurolite and sphene is common in both the areas.

Heavy Minerals	**Component**					
	1	2	3	4	5	6
Eigenvalues	2.946	2.339	1.462	1.250	1.135	1.035
Percentage of total variance	22.662	17.996	11.249	9.614	8.729	7.964
Cumulative percentage of total variance	22.662	40.658	51.906	61.521	70.249	78.213
ZIRCON	.330	.486	-.196	-.404	.221	**.548**
TOURMALINE	-.336	.288	.159	-.329	**.455**	-.211
RUTILE	**.849**	-.085	.226	-.121	-.149	-.084
KYANITE	-.042	.321	**.482**	.322	-.416	.246
STAUROLITE	-.355	**.427**	.359	**.426**	.090	.404
EPIDOTE	**.466**	-.720	.140	.221	.047	.144
GARNET	**.579**	.541	-.064	-.139	-.311	-.301
CORDIERITE	-.209	**.623**	.395	.116	.272	-.233
ACTINOLITE	-.220	.041	-.677	**.288**	**.280**	.122
BROOKITE	.349	-.502	.399	-.054	**.443**	.265
OPAQUE	-.847	-.427	-.018	**.080**	-.229	-.106
SPHENE	.454	.303	-.432	**.464**	-.065	.131
BIOTITE	.430	.023	.047	**.539**	.413	-.425

Extraction Method: Principal Component Analysis; 6 components extracted.

Table 7B: Matrix of six components for the 13 heavy minerals of Elephant Flat Gondwana sandstones

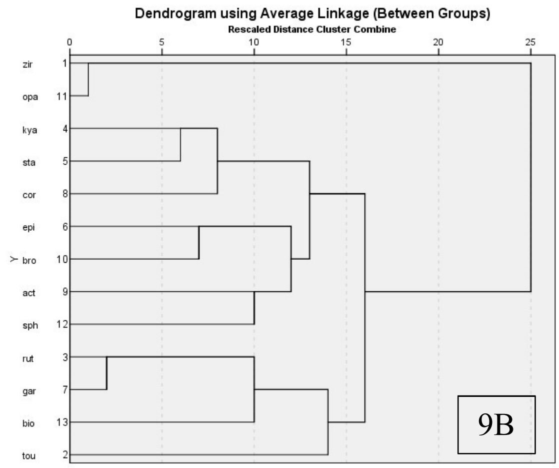
Heavy Minerals	Component					
	1	2	3	4	5	6
Eigenvalues	2.417	2.040	1.754	1.240	1.063	1.037
Percentage of total variance	21.975	18.549	15.947	11.269	9.661	9.424
Cumulative percentage of total variance	21.975	40.524	56.471	67.739	77.400	86.825
ZIRCON	-.192	**.761**	-.123	.386	-.098	-.271
TOURMALINE	**.692**	.250	-.350	.206	.343	-.008
RUTILE	.260	.325	**.813**	-.100	-.079	.243
KYANITE	.200	**.758**	.396	.030	-.090	.044
STAUROLITE	-.397	-.226	**.380**	-.413	**.379**	-.513
EPIDOTE	.158	-.683	**.461**	.248	-.398	.149
GARNET	**.188**	-.014	-.547	-.304	-.661	-.231
CHLORITOID	-.593	.102	-.248	-.015	.000	**.677**
OPAQUE	**.641**	-.091	-.243	-.432	.339	.303
SPHENE	-.891	.072	-.140	.032	**.143**	.095
APATITE	.141	-.419	-.054	**.724**	.219	-.071

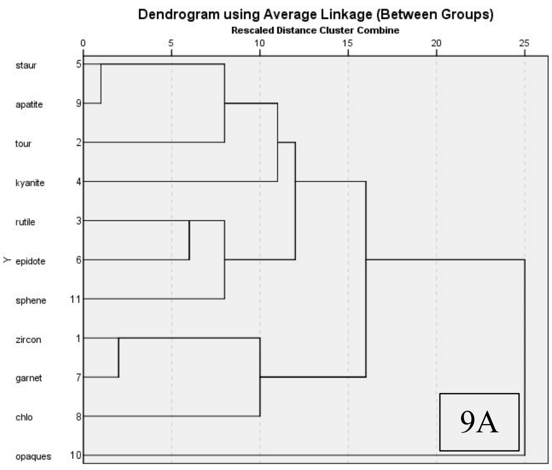
Extraction Method: Principal Component Analysis; 6 components extracted.

Table 7C: Matrix of six components for the 11 heavy minerals of Kalijhora Gondwana sandstones

Cluster Analysis

Cluster analysis is a sort of baffling assortment technique designed to create groups, clusters or associations which are homogenous and distinct from other groups, (Davis, 2002). The process attempts to deduce lineage amongst components of a distribution and it is regarded as an efficient way of displaying complex relationships among many objects. In the present case dendograms





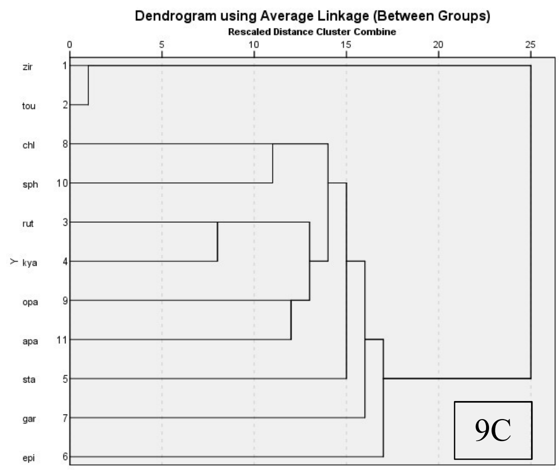


Figure 9A-C: Dendogram of heavy minerals from Gondwana sandstones of Singrimari, Elephant Flat and Kalijhora.

(Figures 9A, B and C) of distance matrix clustered by average linkage between groups were prepared)

Analyses of the dendograms reveal clusters which are found to match to a large extent with the principal component analysis findings. The major groups which can be related to provenance are enlisted herewith. In Singrimari three major clusters in the form of staurolite-apatite-tourmaline, rutile-epidote-sphene and zircon-garnet-chlorite are reflected from the dendogram. Elephant Flat is marked by clusters like kyanite-staurolite-cordierite and rutile-garnet-biotite. Chloritoid-sphene-rutile-kyanite and rutile-kyanite-opaques make up the two significant heavy mineral clusters in Kalijhora.

Discussion

Heavy minerals from all the three study areas bear both opaque and non-opaque varieties. While garnets are more dominant after opaques and zircons in the Singrimari suite, rutile occupies the similar status in the Elephant Flat suite. Zircon and tourmaline are very high in Kalijhora where opaque minerals are least compared to the other two areas of study. The overall composition may however be affected by allied processes during various phases of a sedimentary cycle like palaeoweathering, transportation, deposition and diagenesis (Morton and Johnsson, 1993).

Parallel growths in zircon indicate igneous genesis and is attributed to their survival during mechanical transportation. These grains are also considered as characteristic of anatectic, autocthonous or, metasomatic granitic rocks, (Poldervaart, 1955). The presence of sub-rounded zircons indicates a reworked source while tectonic impacts are reflected by the broken grains. Authigenic overgrowths seen are mostly due to post-depositional changes. Overgrowths and authigenesis is more in Singrimari and Kalijhora suites compared to the Elephant Flat assemblage. Zircons of basal sandstones of Singrimari and Kalijhora exhibit bimodality while upper sandstones of Singrimari and Elephant Flat shows distinct unimodality and these may be related to nature of source rocks. Further, it is seen that the abundance of opaque and transparent heavy mineral components of Upper Singrimari unit and Elephant Flat does not differ much from each other. The higher presence of garnets in the Singrimari suite and rutile in the Elephant Flat indicate influx from crystalline gneisses and schists and acid igneous rocks. Rutile and garnet are indicative of metamorphosed argillaceous sediments too, (Force, 1980). Garnets may be a product of breakdown of chlorites in the lower grade and mica in the higher grade as well as contributions from garnet rich metasedimentary rocks. The existence of etched garnets suggests etching during burial, (Grzebyk and Leszczynski, 2006). The presence of larger grains of rutile particularly in the Elephant Flat indicates contributions from granitic pegmatites. The presence of brown variety of tourmaline is indicative of metamorphic provenance, (Blatt et al., 1972) while epidote may be derived from acid igneous rocks, (Heinrich, 1956). Bluish tourmaline is generally contributed from pegmatites. Titanite is an indicator of gneissic and schistose provenance as well as late stage igneous derivatives. The association of garnet, staurolite and epidote also hints about a metamorphic source in the same way as does garnet, chloritoid, staurolite and titanite. Contribution of opaque sources was more in Singrimari deposits towards the later stages of the sedimentation process. Hydraulic separation by density may have influenced distribution of opaques in the Kalijhora and Elephant Flat compared to Singrimari. The presence of actinolites, rutile, opaque oxides hint at the presence of some basic / mafic source rocks. Overall, these heavy minerals may be linked to reworked sediments, low and high rank metamorphic rocks, sialic and minor mafic igneous rocks typically seen in a Precambrian terrain. Post depositional diagenetic as well as stress related changes are also seen.

ZTR index in the present case is moderately high in Singrimari and Elephant Flat while it is extremely high in Kalijhora and hints at relatively higher mineralogical maturity. High ZTR values in Kalijhora support its nearness to shoreline. Higher proportions of opaque minerals and the presence of more heavy mineral species have masked the ZTR values of Elephant Flat area. Analyses of shape index indicate dominance of bladed and elongated minerals in Elephant Flat and Kalijhora compared to Singrimari. This could have been possible due to hydraulic separation and longer distance of Elephant Flat and Kalijhora from the provenance. Study of reciprocal relationships show dominance of ultrastable minerals in Kalijhora and Elephant Flat compared to Singrimari and this was due to proximity of Singrimari area to the provenance as well as recycling or changes coming into effect during transportation as well as due to post-depositional events.

Analysis of plate tectonic settings following Nechaev and Isphording (1993) shows affinity towards mature continental passive margin. This finding is further corroborated by petrographic and geochemical findings. Such settings are characterised by minerals which are dominantly derived from granites and sialic metamorphic rocks, reworked zones as well as deeply weathered zones. Effects of uplift were probably more in the Elephant Flat suite compared to the Singrimari and Kalijhora areas. This is reflected by the presence of vulnerable species within the Elephant Flat sandstones.

Correlation matrix analyses of progressive and retrogressive relationships between different heavy minerals indicated that source rocks of the three study areas were closely associated in space □ time. Principal component analyses have helped to understand the different statistically significant heavy mineral assemblages in each of the study areas in order of their dominance and the same could be linked up with the possible source rocks. While five principal components dominate Singrimari assemblage, six components dominate Elephant Flat and Kalijhora. Cluster analyses with the help of dendograms reveal clusters that match to a large extent with the principal component analysis findings. In Singrimari three major clusters have been found while Elephant Flat and Kalijhora are marked by two significant heavy mineral clusters. Scrutiny of PCA and cluster analyses results show the heavy mineral suites to comprise of ultrastable and metastable minerals. This suggests derivation of the sediments from different lithologies. Close association of ultrastable and metastable minerals may be due to high stability and preservation potential of certain species and equal degree of mineral stability for others (Pettijohn, 1984). Garnet is seen to be a part of the Principal Component-1 in all the three study areas. It is possible that khondalites which are integral components of the East Ghats Supergroup and where garnet is a major constituent contributed these minerals.

On a regional scale, western part of the present day region of the Bay of Bengal was a landmass before the breakup of the Pangea. The Ninety-east Ridge which formed a water divide between India and Australia and the adjacent landward regions that now lie in the Bay of Bengal and west Australia basins, like the Wharton Basin, formed the catchment regions. These areas flourished with thick growth of vegetations and contributed to the main source of Gondwana coal deposits found in India and Australia, now preserved in fault bounded grabens, (Desikachar, 1977). Continued tensional stress during Permian times caused criss-cross rift basins like the Eastern Lesser Himalayan rift, Purnea-Rajmahal-Galsi rift, Kuchma rift etc in Eastern India which were connected to each other and also important depocentres for Gondwana sedimentation, (Biswas, 1999). These Permo-Triassic formations occur extensively in all the basins and show uniformity in many attributes, (Chakraborty et al., 2003). Many studies also emphasize the existence of Pan-African sutures in Australia and Antarctica with implications that the different crustal blocks of eastern Gondwanaland had closer co-existence around 500 m.a. ago, (Chatterjee et al., 2007). The Eastern Ghats belt exhibits strong Pan-African imprints. It is certain that the Gondwana sedimentation was a global tectono-sedimentation phenomenon and the initial tectonic instability of the whole setup was later ameliorated by crustal maturity. Judging by the occurrences of Lower Gondwana rocks in the Peninsula, it appears that these isolated outcrops were deposited in valleys of sluggish rivers which drained the land to the south and discharged the same into the Tethys at north, (Dutta, 1976). In context with the present study it may be stated that the fluviatile Singrimari Gondwanas (Baruah, 2007) were closer to the provenance and the drainage network extended further north wherein the Kalijhora and Elephant Flat Gondwana rocks were found deposited under marine shoreline influence. Under these circumstances it is highly probable that contributions of detritus from adjacent denuded Precambrian terrains particularly the Eastern Ghats Supergroup were very high.

Conclusions

Based on afore stated findings and discussion, the following points may be forwarded as conclusions:

1. Heavy minerals from all the three study areas bear both opaque and non-opaque varieties. The Singrimari suite comprise of heavy minerals like zircon + garnet + opaque minerals + tourmaline + rutile + chloritoid + epidote + kyanite + staurolite + titanite + apatite. The Elephant Flat suite hosts zircon + rutile + garnet + opaque minerals + tourmaline + epidote + titanite + cordierite + actinolite + staurolite + kyanite + brookite + biotite while the Kalijhora suite entombs zircon + tourmaline + rutile + kyanite + staurolite + epidote + garnet + chloritoid + opaques + titanite + apatite.
2. Elevated ZTR values indicate the presently analysed sandstones to be somewhat mineralogically mature. High ZTR values in Kalijhora support its nearness to shoreline.
3. Bladed, elongated and ultrastable minerals are dominant in Elephant Flat and Kalijhora compared to Singrimari. This could have been possible due to hydraulic separation and longer distance of transportation of Elephant Flat and Kalijhora sediments from the provenance.
4. The heavy minerals show affinity towards mature continental passive margin and may be linked to source rock types like reworked sediments; low and high rank metamorphic rocks, sialic and minor mafic igneous rocks which are typically seen in a Precambrian terrain.
5. Statistical tests like correlation matrix analyses, principal component analyses and cluster analyses indicate the source rocks of the three study areas to be closely associated in space □ time and a mélange of ultrastable and metastable minerals.
6. Prior to breakup of Pangea, the Ninety-east Ridge formed a catchment region which flourished with thick growth of vegetations and contributed to the main source of Gondwana coal deposits found in India and Australia. It is highly probable that contributions of detritus from the adjacent denuded Precambrian terrains particularly Eastern Ghats Supergroup were very high. Some contributions may also have been from distant sources located in the Trans-Antarctican mountains,
7. The fluviatile Singrimari Gondwanas with a northward palaeocurrent direction, (Baruah and Das, 2012) were closer to the provenance and the

drainage network extended further north wherein the Kalijhora (Kar et al., 2017) and Elephant Flat Gondwana rocks were deposited under marine shoreline influence.

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