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A Comparative Heavy Mineral Study of the Cenozoic Sediments of Assam and Siwalik Foreland Basins, Northeast Himalaya

Priti Rai[1], Biraj Borgohain[1], Nisha Chettri[1,2] and George Mathew[1*]

[1]Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai – 400 076, India
[2]Presently at Department of Geology, St. Anthony College, Shillong -793 001, India
[*]***E-mail:*** *gmathew@iitb.ac.in*

ABSTRACT

Heavy mineral assemblages of sedimentary units are used as an essential provenance constraint. The sedimentary successions of the southern Assam and Siwalik foreland basins were analyzed for their heavy mineral suits and provenance determination. Heavy minerals were identified using the petrological microscope, X-ray Diffraction (XRD) and Electron Probe Micro Analyzer (EPMA) analyses. The study demonstrates that heavy minerals weight percentage in the southern Assam basin is lower than that of the northeast (NE) Siwalik basin. In the Assam basin, the weight percentage of dense minerals varies from 0.08% to 1.31%; however, in the Siwalik sediments, it varies from 2.27% to 5.78%. The relative dominance of opaque minerals over transparent heavy minerals is observed throughout the Cenozoic rocks of Assam basin, except for the Tipam unit. At the same time, the Siwalik basin successions show a low percentage of opaque minerals and high amount of non-opaque heavies. Detritus in the Assam basin reveals a distinct change in the occurrence of heavy mineral assemblages (amphibole, aluminosilicates, staurolite and a high percentage of epidote, pyroxene and sphene) in the Mio-Pliocene unit (Tipam sandstone) compared to Barail and Surma older units, implying involvement of an additional orogenic source. This study suggests that NE Siwalik sediments were primarily derived from Himalayan rocks of the Siang window, while heavies in the detritus of the southern Assam basin exhibits a mixed provenance both from the eastern Himalaya, chiefly from Dibang and Lohit valley and Indo-Burman-Ranges (IBR).

INTRODUCTION

Adequate knowledge of the heavy mineral assemblages in sediments has always provided vital information for provenance reconstruction, as they divulge the nature of the source rocks from which they are derived (e.g., Mange and Maurer, 1992; Mange and Wright, 2007; Kripnner et al., 2016; Fossum et al., 2019). The study of heavy minerals in the foreland basin systems is useful to decipher composition, tectonic history and character of the provenance (Mange and Maurer, 1992; Najman, 2006; Zhang et al., 2017; Yang et al., 2019). The foreland basin deposits reflect events associated with the erosional history of the orogenic belts (Mange and Maurer, 1992). A variation in heavy mineral distributions illustrates that there may be distinct provenances (Krynine, 1942; Morton et al., 1992, 2003; Singh et al., 2004; Fossum et al., 2019). The analysis of heavy minerals has also been an effective means in the reconstruction of sediment's source, course of the ancient river systems and unroofing history of the orogeny (Uddin et al., 2007a). The heavier fractions of sediments have a wide occurrence of several minerals, including both non-opaque and opaque varieties. Among these mineral species, each mineral and association of some minerals are specific to rock types, and therefore heavy mineral analysis helps in the determination of provenance (Mange and Maurer, 1992; Morton and Hallsworth, 1999, Morton et al., 2003; Mange and Wright, 2007, and references therein; Fossum et al., 2019).

Although available literature indicates several studies related to heavy minerals reveals on the Siwalik deposits of western and central Himalaya (Sinha and Khan 1965; Sinha, 1970; Raju and Dehadrai 1962; Raju 1967; Chaudhri, 1972; Cerveny et al., 1989) and from Assam basin (Sinha and Sastri, 1973; Uddin et al., 2007a; Sarma and Chutia, 2013). However, sedimentary units of Siwalik from the eastern Arunachal Himalaya, and many parts of Assam basin are still lacking for a better insight towards the provenance history. In eastern Himalaya, Vogeli et al. (2018) analysed heavy minerals from Siwalik sediments along the Kameng section of western Arunachal Himalaya. Recently, Chutia et al. (2020) provide a very brief account on heavies from the Siwalik rocks of eastern Arunachal. Sinha and Sastri (1973) discussed the qualitative distribution of heavy mineral suits in lower Assam and Tripura state, whereas Uddin et al. (2007a) analysed associated heavy minerals of the upper Assam basin. Sarma and Chutia (2013) studied only the Tipam sandstone from Sita Kunda area, upper Assam for their heavy mineral suites. However, a comparative detail study of heavy mineral assemblages to understand the provenance history of these two sedimentary basins around northeast Himalaya still remains elusive.

The present study is focused on the heavy mineral assemblages from Siwalik and Assam basin sedimentary successions, using petrological microscope, powder X-ray diffraction and electron microprobe analyses. Heavy mineral suits from sedimentary units of the southern Assam basin (Barail Group, Surma Group, Tipam and Dupi-Tila/ Dihing) are compared with the heavies of the Siwalik deposits from eastern Arunachal Himalaya. The comparative heavy mineral study from the two sedimentary basins elucidates contrasting information towards their provenance and hence their paleo-drainage. The present work offers a preliminary insight into the possible existence of at least two major rivers in the NE Himalaya.

GEOLOGICAL SETTING

Siwalik Basin

The Neogene Siwalik foreland basin in northeastern Himalaya is located in front of the emerging Himalaya and comprises a thick sequence of Neogene sedimentary rocks (DeCelles et al., 1998; Ojha et al., 2009; Chirouze et al., 2012a). The Siwalik foreland basin encompasses sedimentary rock units deposited by the fluvial system between the middle Miocene and early Pleistocene (Syangbo and Tamrakar, 2013; Uddin et al., 2007b). In Arunachal Pradesh, Siwalik Group is regionally classified into three distinct Formations namely Dafla, Subansiri and Kimin units, respectively (Karunakaran and Rao, 1976; Rangarao, 1983; Kumar,1997). As a whole sedimentary sequence of Siwalik shows upward coarsening and thickening patterns (Rangarao, 1983; Kumar, 1997; Najman, 2006; Chirouze et al., 2013;

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Vogeli et al., 2018). The lower Siwalik (LS) unit, also known as Dafla Formation, mainly consist of fine to medium-grained sandstone, mudstone having intercalation of paleosols and silt-shale layers, deposited by a highly sinuous river system. The middle Siwalik (MS) (Subansiri Formation) is dominantly medium to coarse-grained, grey colour sandstone exhibiting characteristic salt and pepper texture (Chirouze et al., 2012a, 2012b). The presence of thick conglomerate beds interlayered with sandstone and infrequent mudstone layers form the upper Siwalik (US) succession, also called Kimin Formation. An extensive gravelly braided river system led to the deposition of Kimin facies (Chirouze et al., 2012a; Chirouze et al., 2013). The present study entails the Siwalik sedimentary units exposed in the Arunachal Pradesh area and contains the samples collected along the Jonai- Pashighat- Pangin road and Likabali-Garu road.

Assam Basin

The Assam basin, located in northeastern India, is juxtaposed with both the Himalaya and Indo-Burman Ranges (IBR). These active orogenic systems act as a significant contributor to the thick accumulation of detritus in the Assam basin (Uddin et al., 2007b). The evolution of the Assam basin is widely controlled by the tectonic features prevailing in its surroundings. The Himalaya is located to the north of the Assam basin, while IBR is in the east and southeast. NE Arunachal Himayala flanks the Assam basin in its north, Mishmi Hills to the northeast and Shillong Plateau in the west, Bengal basin and ridges of Assam-Arakan basin in the south (Fig. 1). Eastern Himalayan syntaxis plays a significant role in shaping the Assam basin and its sedimentation (Uddin et al., 2007a). The IBR resulting from Indian and Burmese plate collision consists of early Tertiary rocks, schists and ophiolites (Brunnschweiler, 1966; Curray et al., 1979; Sengupta et al., 1990).

The Paleogene units of Assam basin include Eocene Disang Group overlain by Oligocene Barail Group. In lower Assam and Bengal basin, the Sylhet and Kopili formations of Eocene age is equivalent to Disang Group, deep marine facies of upper Assam (Rangarao, 1983). A change in depositional environment from marine to deltaic was encountered at the time of deposition of Barail Group deposits. Barail Group has medium-grained sandstone, sandy siltstone and intercalation of coal seams (Rangarao, 1983). Surma Group (Miocene unit) rests unconformably over the Barail Group, comprises sandstone, siltstone and shale rock types (Evans, 1964; Raju and Mathur, 1995). This unconformity between Barail and Surma Group recognised by a sudden change in thickness of bed and attendance of conglomerate, considered as Oligocene/Miocene boundary (Rangarao, 1983). The following sequence is Tipam Group of late Mio-Pliocene age overlie the Surma Group deposits. Tipam Group is characterised by the occurrence of sandstone and clay layers, recognised as Tipam sandstone and Girujan clay, respectively (Sinha and Sastri, 1973; Uddin et al., 2007b; Ghosh et al., 2014). An unconformable relationship is surmised between the Tipam units and overlying Plio-Pleistocene and Pleistocene successions. The Tipam sandstone and younger units were deposited in a fluvial environment (Gupta and Biswas, 2000; Kent and Dasgupta, 2004). The younger units of Assam basin represented by the Dupi-Tila and Dihing formations consist chiefly pebble, cobble and boulder conglomerates along with friable sand and clay layers. Namsang beds overlie the Tipam Group in upper Assam, having similar characteristics as Dupi-Tila Formation (Gupta and Biswas, 2000). The Subansiri and Kimin sedimentary successions of Siwalik Group, Arunachal Pradesh, were correlated with the Tipam and Dihing units of Assam (Sekhose et al., 2016: Chutia et al., 2020). In the present work, samples were collected from the Haflong and along the Haflong-Silchar road (southern Assam basin, Fig. 1).

METHODOLOGY

The geological map of the study area with sample locations are shown in Figure 1. A total of 08 number of Cenozoic sedimentary samples were collected. Three samples were collected from Siwaliks of NE Arunachal Himalaya. Five samples collected from the sedimentary units of southern Assam (Haflong-Silchar region). The heavy mineral assemblages were identified based on semi-quantitative analysis using the petrological microscope. For both qualitative and quantitative assessment of the mineralogical assemblages in the collected samples, X-ray Diffraction (XRD) and EPMA were carried out for identification of the heavies at the Department of Earth Sciences, Indian Institute of Technology Bombay.

For the heavy mineral analysis, 63-120 µm sand fraction of the sample was sieved to obtain the maximum number of heavy mineral species. The chosen fraction of samples were washed several times with distilled water to clean it properly and dried in an oven. It was then treated with hydrogen peroxide (H_2O_2) to eliminate organic matters present in the samples. Thereafter, by cone and quartering method, approximately 10 gm of each sample has been taken, and heavy minerals separation was performed using Sodium Polytungstate heavy liquid having specific gravity 2.9. Post hand-magnet removal, the micro splitter has been used to obtain the representative fractions of collected heavy minerals and then mounted in epoxy. Epoxy mounts were observed under a petrological microscope to determine the different species of heavy minerals. Fleet method (Fleet, 1926) was used for counting all the grains present in the mount. More than 300 grains were counted from each sample (Table 1). Percentages of the various heavy mineral species were determined with respect to total non-opaque grains present in each sample. In contrast, the opaque portion is with respect to the whole counted grains. EPMA and XRD analyses were made for each sample to identify the mineral species. ZTR index has been calculated as defined by Hubert (1962) to get information on provenance characteristics of the sediments and its transportation history. Details of the heavy minerals (both opaque and non-opaque varieties) and ZTR index percentages in the samples is given in Table 1.

XRD analysis was carried out using an X-Ray PANalytical Diffractometer (Empyrean) with 2θ range set from 5° to 70° and a step size of 0.013°. X’Pert Highscore Plus software was used to process acquired data. The obtained data were compared with the ICSD-2013 database to recognise the different mineral phases. For EPMA analysis ~140-190 grains from each mount were analysed using CAMECA SX-FIVE electron probe micro-analyzer furnished with five wavelength dispersive spectrometers (WDS) for mineral composition. An acceleration voltage of 15 kV, 20 nA specimen current and beam size of 1 µm were used. To calibrate the instrument for each element, natural and synthetic standards were used. The X-PHI method was operated for the correction of matrix effects (Merlet, 1992).

RESULTS

NE Siwalik Basin

The samples from NE Siwalik basin indicate a considerable difference in abundance of heavy minerals than the southern Assam basin units. The weight proportions of heavies collected in lower Siwalik (Dafla Formation), middle Siwalik (Subansiri Formation) and upper Siwalik (Kimin Formation) vary from 2.27%, 2.81% and 5.78 % respectively. The amount of heavies is moderately high in Siwalik sediments than in samples of Assam basin. The normalized abundance of heavy mineral associations is shown in Table 1. Unlike Assam basin units, the Siwalik basin successions illustrate a meagre percentage of opaque minerals (< 10%) and moderately lower ZTR index. Opaque minerals percentage decreases towards the younger units of Siwalik deposits. An increasing trend in ZTR index exists from lower to upper

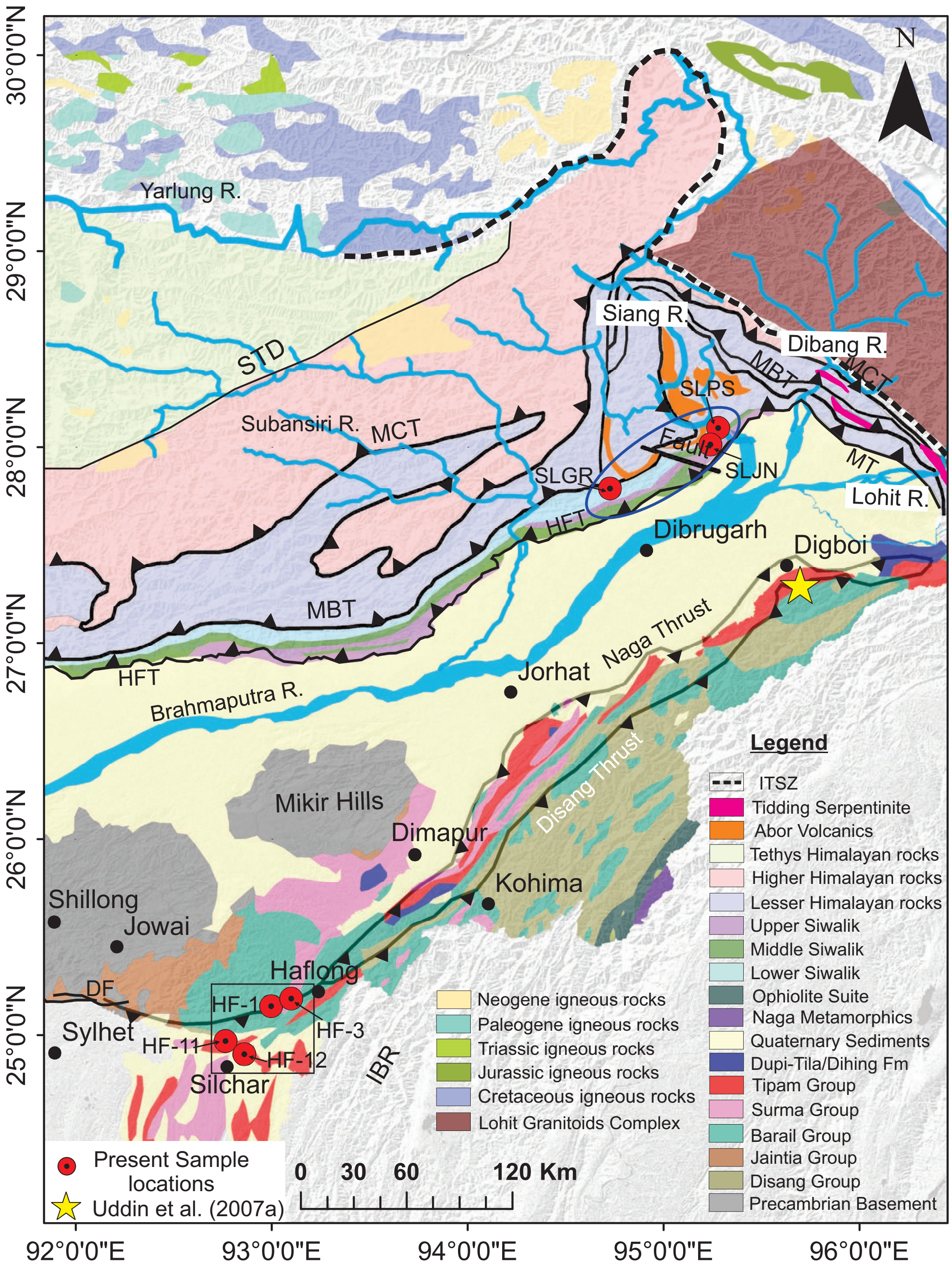

Fig. 1. Geological map of the study area and adjoining regions along with structural features (modified after GSI (1998, 2010); Biswas et al., 2007; Lang and Huntington, 2014; Rajkumar et al., 2019). Samples collected from the southern Assam basin are shown within the square and ellipse represents samples from the Siwalik basin. HFT- Himalayan Frontal Thrust, MBT- Main Boundary Thrust, MCT- Main Central Thrust, STD- South Tibetan Detachment, MT- Mishmi Thrust, DF- Dauki Fault, ITSZ- Indus–Tsangpo Suture Zone, IBR- Indo Burman Ranges.

Siwalik as ZTR index value in lower, middle and upper Siwalik units are 19.0%, 27.8% and 31.3%, respectively. The transparent dense minerals in Siwalik sediments are zircon, tourmaline, rutile, garnet, epidote, amphibole, pyroxene, sphene, aluminosilicates (andalusite, kyanite and sillimanite), mica and chlorite along with less proportion of chloritoid, apatite, staurolite and spinel (Table 1; Fig. 2). Furthermore, the presence of spinel (0.2%) is only observed in Subansiri Formation (middle Siwalik).

The counting results highlight that in the lower Siwalik unit (Dafla Formation), garnet is dominant (27.7%) among non-opaque heavy minerals, followed by epidote (19.8%), tourmaline (10.29%) and amphibole (7.7%). In the middle Siwalik, epidote is in major proportion (24.7%), but zircon (18.4%), garnet (8.4%) and pyroxene (8.8%) are also present in noteworthy amounts. Amphibole proportion is 27.4% in upper Siwalik (Kimin Formation) followed by tourmaline (22.7%), epidote (17.6%) and garnet (11.4%). The distribution of the ultra-stable minerals reveals that zircon is copious in middle Siwalik, while the tourmaline amount is high in upper Siwalik, but surprisingly, rutile has rare occurrence throughout the successive units of Siwalik. Among the aluminosilicates, kyanite and andalusite show presence in all the three Formations; however, sillimanite appears only in Dafla Formation. Epidote is quite high in Subansiri Formation but also consistent in the Dafla and Kimin formations. It is important to note that Siwalik basin samples have a high occurrence of garnet; however,

Table 1. Normalized percentage of heavy minerals in Assam and Siwalik basins.

	Assam Basin Samples					Siwalik Basin Samples		
Sample code	HF-1	HF-3(A)	HF- 3(B)	HF-11	HF-12	SLGR	SLPS	SLJN
Group/Formation	Barail Group	Surma Group	Surma Group	Tipam Sst	Dupi-Tila/ Dihing Fm	Dafla Fm	Subansiri Fm	Kimin Fm
Total number of grains	367	469	360	507	523	680	516	557
Total opaque minerals (as % of total heavy minerals)	54.2	43.5	39.7	19.9	55.5	8.1	5.2	4.3
Non-opaque heavy minerals (as % of non-opaque heavy minerals)								
Zircon	11.3	19.6	24.4	9.9	7.7	5.8	18.4	7.7
Tourmaline	6.5	17.4	12	11.3	23.2	11.2	8.2	22.7
Rutile	10.7	19.6	6.9	3.7	12.0	0.8	0.4	0.4
ZTR index	42.1	75.8	57.7	25.8	49.8	19.0	27.8	31.3
Garnet	1.2	-	0.5	2.2	-	27.7	8.4	11.4
Epidote Group	7.1	6.4	3.2	23.2	9.4	19.8	24.7	17.6
Sphene	0.6	-	-	5.7	9.4	4.5	5.5	0.9
Pyroxene	-	0.8	0.5	9.9	3.0	3.4	8.8	3
Amphibole	-	-	-	12.1	5.2	7.7	0.8	27.4
Staurolite	-	-	-	0.7	-	0.3	0.2	0.4
Kyanite	-	-	0.5	4.4	3.5	3.0	4.1	2.1
Andalusite	-	-	-	3.0	0.4	2.7	5.5	2.6
Sillimanite	-	-	-	1.0	1.3	1.1	-	-
Mica	32.1	25.3	24.9	2.7	13.7	5.0	3.1	1.7
Chlorite	20.8	3.8	21.7	6.4	3.4	3.0	7.2	0.8
Chloritoid	6.0	0.8	0.5	0.7	3.4	1.0	1.6	0.4
Spinel	-	3.8	2.8	0.5	0.9	-	0.2	-
Apatite	-	-	-	0.2	-	1.1	1.8	0.4
Monazite	2.4	-	-	0.2	-	-	-	-
Calcite	-	-	-	0.5	-	-	-	-
Dolomite	-	-	-	0.2	-	-	-	-
Serpentine?	-	-	-	-	-	1.0	-	-
Ep/Calcite	-	-	-	-	-	0.8	-	-
Others (Unknown)	1.2	2.6	2.3	1.5	3.4	0.2	1.0	0.6

in Assam basin, there is a sporadic and sparse supply of garnet. Siwalik detritus show minor presence of rutile in comparison to litho-units of the Assam basin. The representative heavy minerals identified from both the Assam and Siwalik basins are shown in Fig. 3.

Southern Assam Basin

The litho-units of the Assam basin reveals varying heavy mineral weight percentages, 0.64%, 0.23% 1.31% and 0.36% in Barail Group, Surma Group, Tipam sandstone and Dupi-Tila/Dihing Formations respectively. The data indicates Tipam sandstone with higher content of heavies than other units. The opaque mineral percentage varies from 54.2% in Barail Group, 43.5% and 39.7% in Surma Group, 19.9% in Tipam sandstone, and 55.5% in the Dupi-Tila/Dihing Formation. A decreasing trend is observed in the amount of opaque minerals percentage towards the younger units, except in the Dupi-Tila/Dihing Formation.

Heavy mineral analysis of the Cenozoic rocks of the Assam basin demonstrates opaque minerals dominance over the non-opaque heavies from the Barail and Dupi-Tila/Dihing units, while in other units non-opaque minerals are higher, specially in Tipam sandstone. The ZTR index is found to be reasonably high throughout the basin except for Tipam sandstone that has ZTR index marginally low (25.8%). In contrast, Surma Group is characterised by high (57.7% and 75.8%) ZTR index. Among the non-opaque minerals zircon, tourmaline, rutile, epidote, mica and chlorite are more abundant and diverse, while amphibole, pyroxene, chloritoid, sphene, garnet, staurolite, aluminosilicates (andalusite, kyanite and sillimanite), and spinel are in less amount. Monazite, apatite, calcite and dolomite are also present but have sporadic distribution (Fig. 2).

Heavy mineral assemblages of Barail Group (Oligocene unit) are dominated by opaque minerals. Among the transparent heavies, mica (32.1%), chlorite (20.8%) are dominant, apart from zircon (11.3%), rutile (10.7%) and epidote (7.1%). In the Surma Group, dense minerals, zircon, tourmaline, rutile, mica, chlorite, and epidote form the bulk of the heavies. Spinel is also observed in considerable quantity, while absent in Barail Group.

Tipam sandstone of the Assam basin exhibits diverse heavy mineral assemblages and contains almost all the minerals of the older units (Barail and Surma Group). It also contains pyroxene, amphiboles, aluminosilicates (kyanite, andalusite and sillimanite), staurolite, apatite and dolomite. They were absent in the older units, however, the later three heavies are present in low proportions (Table 1; Fig. 2). Epidote is the foremost (23.2%) heavy mineral in the Tipam sandstone along with amphibole (12.1%). The Dupi-Tila/Dihing Formation contains a high percentage of opaque minerals and a significant proportion of tourmaline, mica, rutile, epidote and sphene among the total transparent heavy minerals (Table 1).

It is intriguing to note that aluminosilicates, pyroxene, and amphibole heavies are rare in older rock units but present in significant amounts in the younger units, Tipam and Dupi-Tila/Dihing formations. Tipam sandstone encompasses plentiful amphiboles with different varieties, including hornblende, actinolite, tremolite, bluish-green

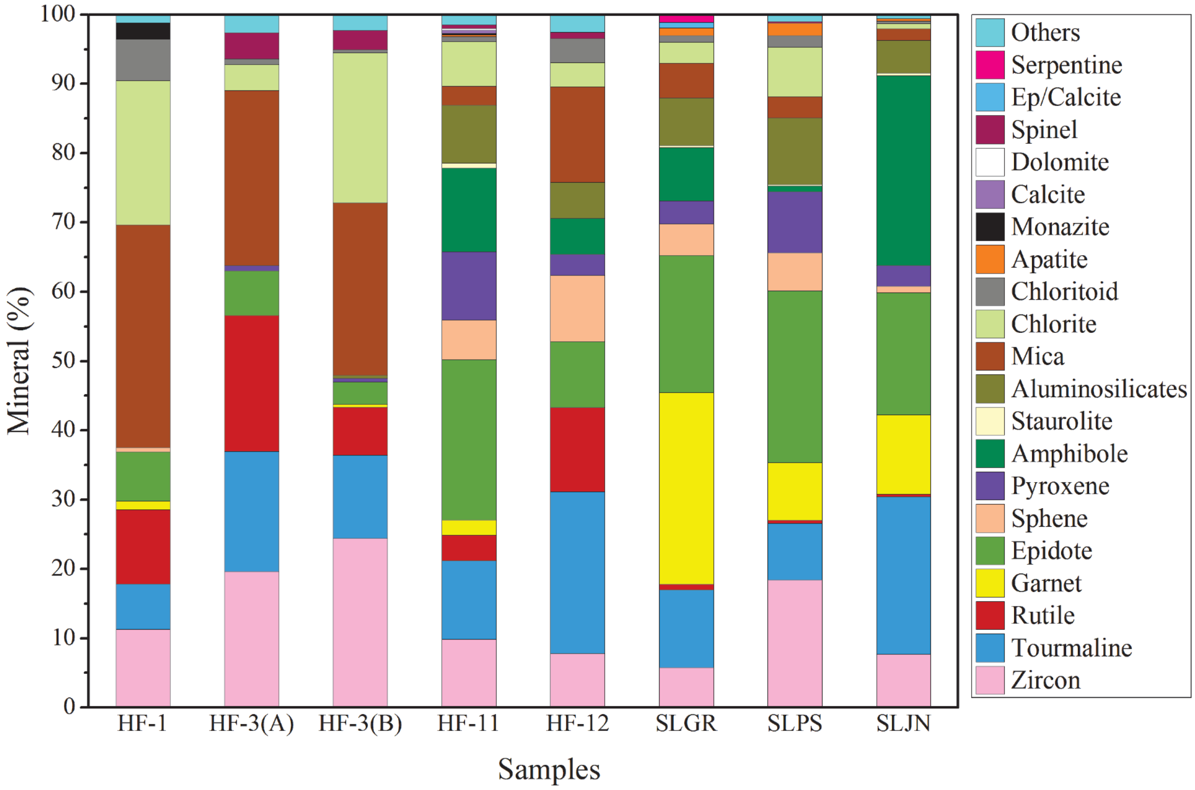

Fig. 2. Stack plots showing the percentage of various heavy minerals in the sedimentary units of Assam (HF-1, HF-3A, HF-3B, HF-11, HF-12) and Siwalik basins (SLGR, SLPS, SLJN).

hornblende. The maximum concentration of pyroxene is found in the Tipam sandstone with 9.9% of non-opaque heavy minerals. Amongst the ultra-stable heavy minerals, zircon demonstrates a higher value in the Barail and Surma groups. However, in the Tipam sandstone and Dupi-Tila/Dihing Formation, a moderate percentage of zircon and a more elevated amount of tourmaline are observed. Spinel is present in all units, except for the Barail Group sample. Another observation is the presence of sphene (titanite) in the Tipam and Dupi-Tila/Dihing units.

XRD and EPMA

XRD analysis reveals that many of the heavies are common in both the basins; however, the presence/ absence of some minerals is significant. It is noticeable that most of the minerals match with the counting data of the studied samples. However, only a few minerals were not detected by XRD analysis, which may be because of the low abundance of such minerals in the analysed fractions.

The presence of dolomite in Tipam sandstone was observed from counting as well as by XRD data. However, dolomite was not detected in Siwalik samples, both by counting and XRD analysis. XRD data reveal the presence of apatite mineral throughout the successive units of the Siwalik basin, in accordance with the semi-quantitative results. Additionally, the absence of garnet mineral in Dupi-Tila/Dihing unit from XRD data supports the microscopic observation. XRD data show that chromite, goethite, ilmenite and magnetite are the opaque minerals in the Assam basin. However, it reveals absence of the first three opaque varieties in Siwalik detritus and the presence of magnetite only from Subansiri Formation.

Most of the EPMA results are comparable with the data obtained from the quantifiable analysis of the heavies of Assam and Siwalik units. The semi-quantitative and EPMA analysis recorded apatite and dolomite only from the Tipam sandstone of the Assam basin. Furthermore, chrome spinel was discerned in all the successive units of the Assam basin. Microscopic observations also encountered spinel, apart from in the Barail Group. In Siwalik basin, the distribution of garnet, epidote and amphibole indicates a similar trend as observed from counting data. The high amount of garnet in the lower Siwalik obtained from counting data is corroborated by the EPMA. The finding of a significant amount of apatite grains from EPMA data in the detritus of Siwalik basin again supports the counting data. Staurolite detected by EPMA in the lower Siwalik could be taken as an index mineral for this unit, as recommended by Chaudhri (1972). EPMA data record monazite in lower Siwalik and upper Siwalik, but counting data show its absence throughout the Siwalik successions. Among opaque minerals, ilmenite, magnetite and titano-magnetite occur in both the basins; however, pyrite is observed only in Siwalik detritus. The identified heavy minerals by EPMA analysis, in successive litho-units of both Assam and Siwalik basins, are represented in Fig. 4.

DISCUSSION

The heavy mineral suites from both the foreland basins reveal that from Mio-Pliocene onwards, the complex rock types of the NE Himalaya seem to be the source of the detritus to the two basins. Several minerals hence are common in the stratigraphic units of both the basins, nonetheless, their abundance differs. However, the presence or absence of other heavies, ZTR index and opaque mineral percentage were found distinct for the basins. The southern Assam basin sedimentary units with a relatively higher ZTR index than NE Siwalik deposits and upper Assam deposits (Uddin et al., 2007a) indicate sediments have experienced post-depositional processes. It resulted in the removal of unstable minerals and the existence of ultrastable minerals (zircon, tourmaline and rutile) in abundance. The calculated ZTR index (< 75%) from the studied samples indicates that the detritus of both the foreland basins are mineralogically immature to sub-mature (Bassey et al., 2019). However, it is observed that the Assam basin detritus exhibit higher maturity than sediments of Siwalik basin.

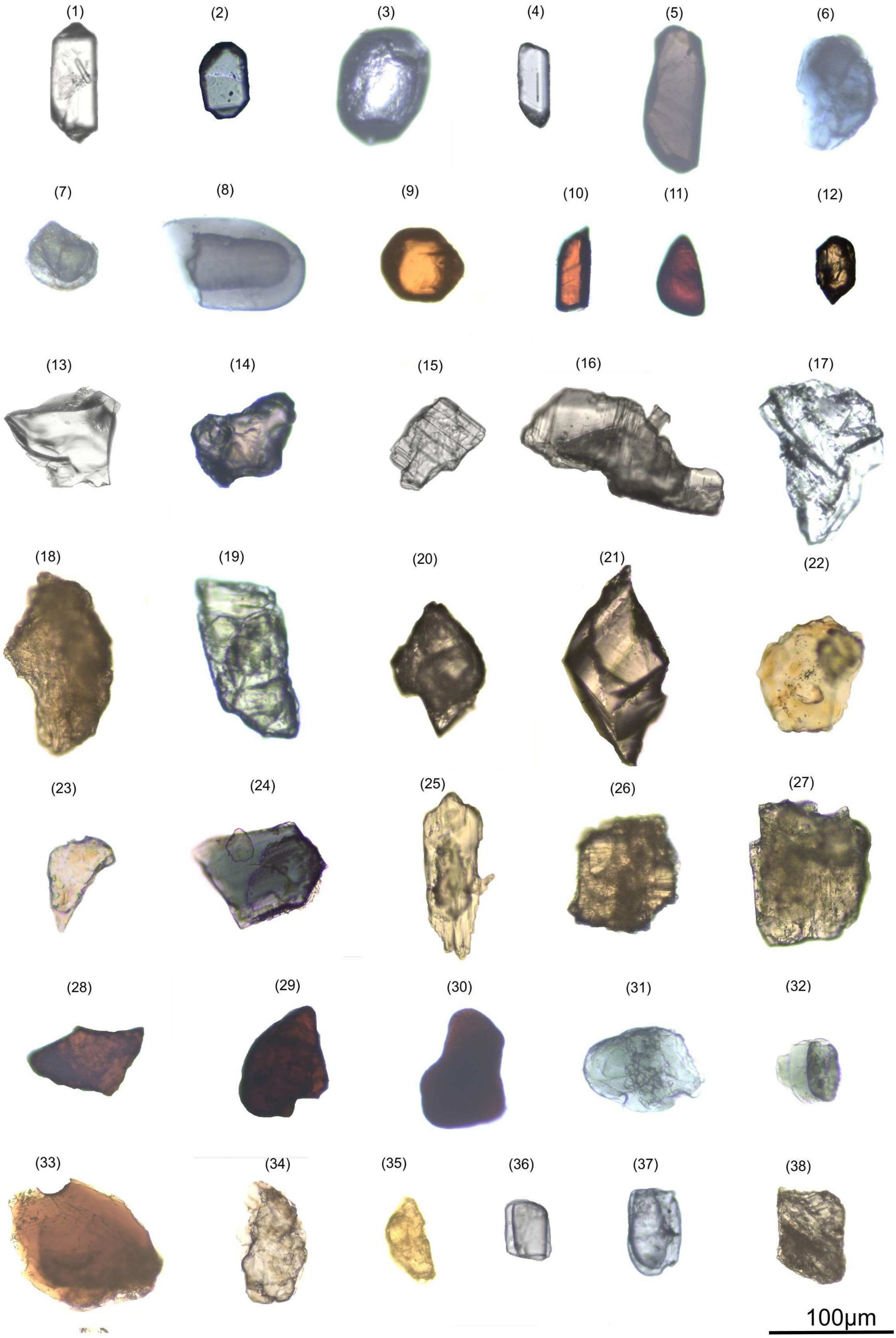

Fig. 3. Representative heavy minerals observed in studied samples of both the basins: Zircon (1-4), tourmaline (5-8), rutile (9-12), garnet (13-14), kyanite (15-16), andalusite (17), sillimanite (18), epidote (19), sphene (20-21), staurolite (22-23), bluish-green hornblende (24), actinolite (25), pyroxene (26-27), spinel (28-30), chloritoid (31), chlorite (32), biotite (33), monazite (34-35), apatite (36-37), dolomite (38).

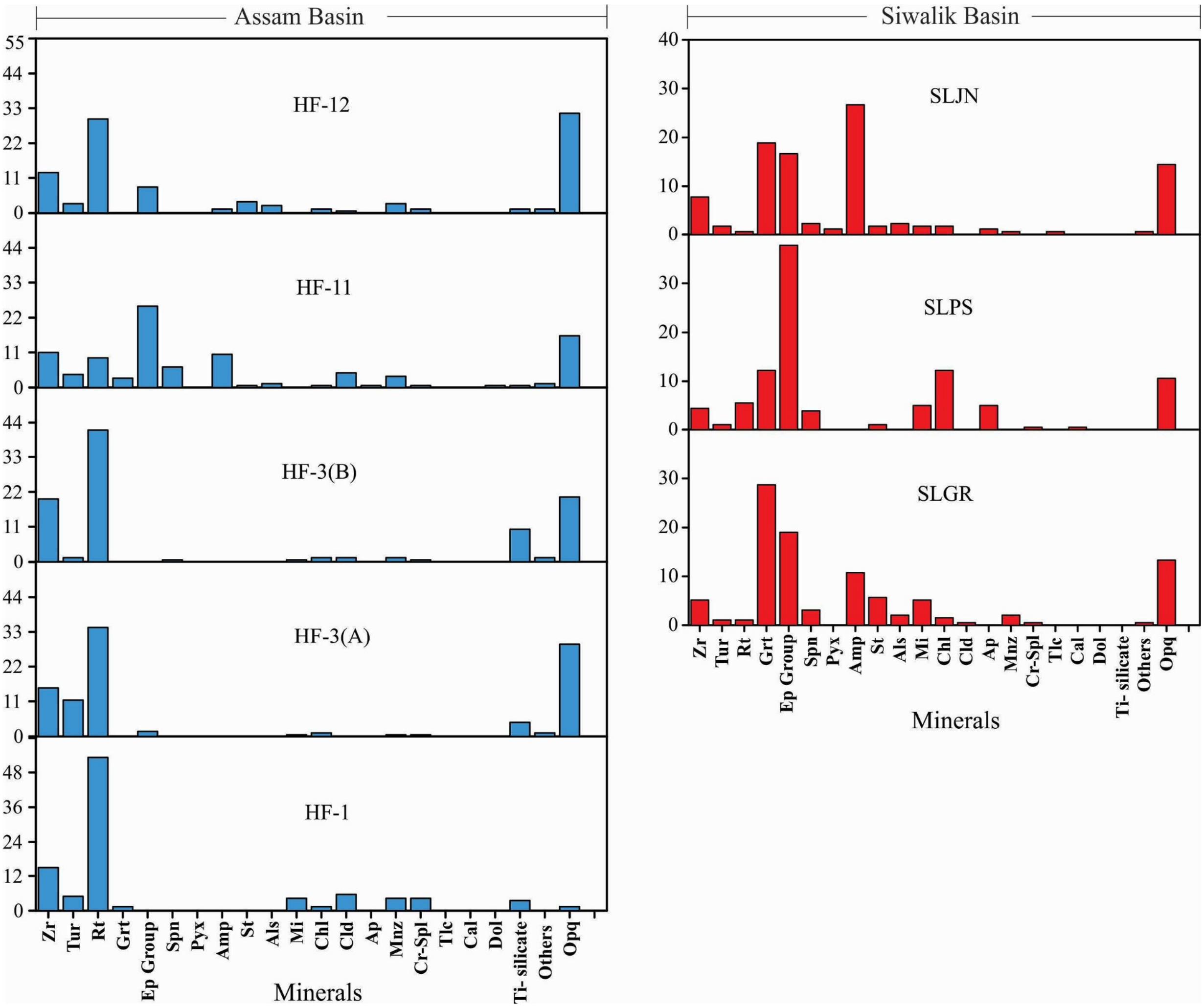

Fig. 4. Graphical representation of heavy minerals identified by EPMA in samples of Assam and Siwalik basins. Zr- Zircon, Tur- Tourmaline, Rt- Rutile, Grt- Garnet, Ep- Epidote, Spn- Sphene, Pyx- Pyroxene, Amp- Amphibole, St- Staurolite, Als-Aluminosilicate, Mi-Mica, Chl- Chlorite, Cld- Chloritoid, Ap- Apatite, Mnz- Monazite, Cr-Spl- Chrome-spinel, Tlc- Talc, Cal- Calcite, Dol- Dolomite, Ti-silicate- Titanium silicate, Opq- Opaque minerals. Mineral abbreviations after Whitney and Evans (2010).

NE Siwalik Basin

A significant quantity of epidote and garnet throughout the lower, middle and upper Siwalik units suggest a metamorphic provenance from the eastern Himalaya. The present work demonstrates the dominance of amphiboles in the upper Siwalik unit compared to lower and middle Siwaliks. Unroofing of the amphibolite rocks from the Higher Himalaya are accountable for the amphibole abundance in upper Siwalik (Table 1). The aluminosilicates in the Siwaliks, although sillimanite found only in lower Siwalik, suggest deep crustal rocks exhumation in the eastern Himalaya. The bluish-green hornblende in the Dafla Formation provides evidence for the erosion of arc ophiolites, as speculated by Uddin and Lundberg (1998). The Higher Himalayan rock type such as amphibolites, granites, and gneisses could also be suspects for the blue-green amphiboles (Amano and Taira, 1992). The blue-green hornblende, garnet, aluminosilicates and epidote form a zone of heavy minerals that indicates metamorphic rocks in the provenance.

The finding of staurolite and kyanite in the Siwalik sediments suggest Higher Himalayan rocks as the source. The prevalence of non-opaque over opaque heavy minerals is observed throughout Siwalik sequences in the present study. Pyroxenes are found in the ultramafic and intermediate igneous rock types, therefore owe its occurrence to such rocks in the source terrain (Mange and Maurer, 1992; Garzanti and Ando, 2007). Igneous and gneissic rocks host apatite, while sphene is considered as constituents of granite gneisses, schist, amphibolite and calc-silicate rocks (Mange and Maurer, 1992). Survival of apatite in all the samples of Siwalik basin and its non-existence in Assam sediments except Tipam unit indicates high discharge dominated transport of sediments in the Siwalik, thereby preserving apatite from easy dissolution. The present study suggests that heavy detritus in the NE Siwalik were chiefly derived from the N-S flowing rivers in NE Himalaya. Mainly by the Yarlung-Tsangpo-Siang river flowing through the Tibetan Plateau, incising deeply through the rapidly exhuming Namche Barwa syntaxial zone and further flowing down through the Paleogene deposits of the Siang window (Fig. 1).

Southern Assam Basin

The higher percentage of opaque minerals in the Oligocene (Barail Group) unit compared to younger sequences (Surma and Tipam) excluding Dupi-Tila/Dihing Formation. A decreasing trend in the opaque mineral percentage towards the younger formation in the southern Assam basin is in concordance with the observation of Uddin and Lundberg (1998) in the Bengal basin. A high percentage of opaque heavies and low diversity of non-opaque varieties in Barail Group indicates the dissolution of unstable mineral species and weathering in the source regions. The surprising enrichment of opaque over transparent minerals in Dupi-Tila/Dihing Formation indicates a more significant volume erosion of the basic-ultrabasic rocks in the source area (Uddin and Lundberg, 1998).

The presence of spinel from all the sedimentary units of the Assam basin (upper Assam, Uddin et al., 2007a) indicates source from the Tidding ophiolitic melange. Thus suggests that from Oligocene onwards, the orogenic belts acted as a source for the detritus. High-Al chromian spinel in peridotites is reported from Manipur ophiolite complex in the Indo-Myanmar orogenic belt (Singh, 2009). Similarly, chrome-spinels in the serpentinite of Tidding suture zone have been reported from the eastern Himalaya (Singh and Singh, 2011). The Dibang and Lohit rivers drain through the eastern Himalaya, providing detritus downstream (Fig. 1). In contrast, spinel bearing suture zone rocks are not exposed along in the distal ends of the Yarlung-Tsangpo river in Tibet and along the Siang river course through the Siang Antiform. No major river drains through Manipur ophiolites into the Assam basin to deposits its detritus. It is therefore, attributed that the chrome spinel presence in the southern Assam Basin solely to the Tidding suture zone exposed in the Dibang and Lohit valley (Misra, 2009; Salvi et al., 2020).

The heavy mineral suites of Tipam unit are very diverse, having almost all the minerals that are present in older deposits (Barail and Surma Group) along with other heavies lacking in the older units. This diversity in heavy mineral accumulations suggests orogenic fronts movement closer to the basin (Uddin et al., 2007a). The existence of varied heavy mineral assemblages in Tipam sandstone and Dupi-Tila/Dihing Formation than older rock units advise a different source having diverse lithologies. The input of aluminosilicates (kyanite, andalusite, and sillimanite) and epidote abundance in the Pliocene and Plio-Pleistocene rock units suggests additional source from low and high-grade metamorphic rocks. The Higher Himalayan crystalline seems plausible contributor of staurolite and kyanite in the Mio-Pliocene (Tipam) deposits.

Uddin and Lundberg (1998) and Uddin et al. (2007a) reported blue-green hornblende and sporadic occurrence of chromites from late Miocene units of Surma Group in the Bengal basin and the Tipam sandstone (upper Assam). They attributed the source to the ophiolitic rocks of suture zone as unroofing of Himalaya and Indo Burman Ranges (IBR). The present work finds the comparable observation from the Pliocene units (Tipam sandstone) of the Assam basin and corroborates the Himalaya and IBR as the provenance. According to Ando et al. (2014) and Bassey et al. (2019) the presence of blue-green hornblende indicates high-grade metamorphic rock (amphibolite rocks) in the source area, however, other researchers proposed Abor volcanic as a probable source (Srimal, 2005; Uddin et al., 2007a). The appearance of pyroxene in the Surma Group detritus and increase in their percentage towards younger units is in concordance with the observations of Uddin and Lundberg (1998) from the Bengal basin. Ultramafic and basic igneous rocks are the source for contributing pyroxene grains in the sediments of Assam basin (Mange and Wright, 2007; Garzanti and Ando, 2007)

The presence of blue tourmaline indicates pegmatitic rocks in the source and zircon points its origin from an acid igneous rock (Singh et al., 2004). Tourmaline bearing pegmatites described in litho-units of Lohit and Dibang valley could be the possible source rock for the presence of a substantial amount of tourmaline grains in southern Assam basin detritus (Gururajan and Choudhuri, 2003; Salvi et al., 2020). Monazite occurrence in Tipam sandstone reflects the contribution of granitic and gneissic rocks. The present contribution shows that throughout the successions, the quantity of garnet is meagre. Uddin et al. (2007a) report a higher percentage of garnet in successive units of upper Assam, which is ascribed to the adjacent metamorphic rocks of the eastern Himalaya. The dissolution of garnet during transportation could cause less perseverance in the detritus of the southern Assam basin (Morton and Hallsworth, 1994, 2007).

The Ilmenite abundance from southern Assam basin in the Tipam and Dupi-Tila/Dihing units suggests basic, acidic rocks and pegmatite sources. However, magnetite could be derived from igneous, sedimentary and metamorphic rocks (Meng et al., 2016). The rare occurrence of chromite in Tipam sandstone, detected by XRD analysis, indicates an igneous source (Blatt, 1967). Moreover, chromite in trace amount with blue-green hornblende infers again it origin from ophiolitic rocks (Uddin and Lundberg, 1998). Based on the heavy mineral assemblages from the southern Assam basin, it is suggested that the maximum detritus in both the Tipam and Dupi-Tila units seems to have been derived from the Dibang and Lohit valley in the NE Himalaya along with contributions from IBR.

Implications towards Paleodrainage

The mineralogical evidence portrays that during the Neogene and Pleistocene, the orogenic activities were significant in the eastern Himalaya and Indo-Burman ranges. The modern drainage patterns were then well developed, aiding in the transport of the detritus downstream. The present-day Brahmaputra river is the only major drainage in the Assam basin that originates from Tibet and flows through the NE Himalayan syntaxis. The major enigma, therefore, lies for the source of both Tipam and Dupi-Tila/Dihing fluvial deposits (Assam basin) that are stratigraphically comparable to Subansiri and Kimin formations of Siwalik foreland basin. It, therefore, casts uncertainty over the source for the fluvial deposits, both in the Siwalik and Assam foreland basins. Even if one accepts the work by Govin et al. (2018), wherein they advocate a single river (paleo-Brahmaputra) branching into two drainages from lower Pliocene. By ca. 2 Ma, paleo-Brahmaputra flowing east of the Shillong plateau got terminated due to uplift of the Plateau and westward advancement of IBR. The deposition of the Dupi-Tila/Dihing units along the entire Assam-Arakan range then remains elusive.

Although the results are not fully conclusive, it encourages to propose plausible origin of the major detritus from the Dibang and Lohit valley in the NE Arunachal Himalaya, provenance for the Assam basin. Therefore, the existence of two different rivers before the uplift-ment of Shillong plateau is speculated. One flowing north of the present plateau that might have deposited the Siwalik sediments and the other flowed through the Assam-Arakan basin depositing the sedimentary units in this foreland basin. This study predicts that the rivers may have merged later owing to the combined effect of plateau uplift and north-westward propagating IBR. Further work based on detrital zircon U-Pb dating of the sedimentary units along the Assam-Arakan foreland basin is in progress, which would eventually provide concrete evidence on the proposed existence of two drainage systems in the past.

CONCLUSIONS

Heavy mineral assemblages from the Cenozoic sediments of two different foreland basins, are comparatively diverse in terms of their profusion and also the existence and deficiency of some heavy minerals. Based on heavy minerals distribution, the study enables us with the following conclusions:

1) Heavy mineral weight percent is quite high in sedimentary suites of Siwalik basin as compared to Assam basin. A high proportion of the ZTR index and opaque mineral quantity in Assam basin samples than the Siwalik basin.
2) An abundance of garnet in Siwalik sediments relative to the Assam basin suggests its derivation from metamorphic rocks of Himalaya.
3) The enrichment of amphibole minerals in upper Siwalik suggests amphibolite rocks of Higher Himalaya as the source. Additionally, the existence of blue-green hornblende in both the foreland basins indicates amphibolite, gneisses and igneous rocks in the source area.

4) The occurrence of apatite throughout Siwalik basin detritus suggests its derivation from the gneissic/granitic rocks transported during high discharge. Its absence in Assam basin except for negligible presence in Tipam sandstone is possibly due to the hydraulic dissolution or acid leaching processes.
5) Spinel recorded in an unusual amount from Assam basin samples, however, less preserved in residues of Siwalik basin. Ophiolitic rocks of the Tidding suture zone from the Dibang and Lohit valley is proposed as a significant source for the derivation of spinel minerals in the detritus of the southern Assam basin.

The results from the present study infer eastern Himalaya as the primary source for sediments of the NE Siwalik basin. However, a mixed source both from IBR and NE Himalaya seems to have provided detritus into the southern Assam basin. Based on the comparative heavy mineral study of both the basins, it is proposed that two different drainages existed for the fluvial sedimentation in NE Siwalik and Assam foreland basins.

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