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# Petrography and heavy mineral studies of Miocene Bhuban siliciclastics in parts of Surma Basin, Northeast India

**Sujata Das*, Nagendra Pandey and Meghali Baruah**
Department of Earth Science, Assam University Silchar, Silchar-788011, Assam, India
sujatadas987@gmail.com

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## Abstract

*Miocene Bhuban Siliciclastics in parts of Surma Basin has been studied with respect to their modal composition and heavy mineral contents so as to document the tectonic provenance and paleoclimate. Mineralogically Bhuban siliciclastics has been characterized as Qt34 F15RF8 M7 MX17 Ct18 HM1 and thus qualify for clean (lithic to sub arkose) and wacke (arkosic wacke) sandstone types. Presence of undulatory quartz, recycled non-undulatory quartz, chert, physillite and feldspars (alkali & plagioclase) has been attributed to mixed source terrain comprising igneous, sedimentary and metamorphic rock types. Further occurrence of zircon, tourmaline, rutile and garnet suggests derivation from both felsic and mafic igneous rocks. Different shapes and sizes of heavy minerals including garnet, sillimanite, staurolite, kyanite, scapolite, glaucophane, phlogopite, sphene, wollastonite, chlorite, chondrodite and hedenbergite in Bhuban siliciclastics signifies overall regionally metamorphosed source rock with subordinate contributions from contact dolomitic marble and skarn deposits. Low ZTR value (15.15%) of Bhuban Siliciclastics is indicative of mineralogically immature nature of sediments. A semi-humid to semi-arid paleoclimateis is suggested with major contributions from the nearby Indo-Myanmar and the Himalayan orogens.*

**Keywords:** Petrography; Heavy Minerals; Bhuban siliciclastics; Surma Basin; Northeast India.

## Introduction

In the northeastern part of Bengal Foredeep there occurs a promising gas province of India and Bangladesh, named Surma basin (Figure-1A). Its eastern limit is defined by Chittagong-Tripura Fold Belt of Indo-Burma Range (IBR) while the basin remains open to the Bengal Foredeep in the south – west. To the north, the Dauki fault separates the Surma basin from the Shillong Massif[1]. A series of north – south trending anticlines and synclines characterize the eastern part of Surma basin owing to early-middle Miocene collision between the Indian Plate and the Burmese Plate[2]. The intensity of folding increases from west to east[3].

An area measuring 100sq. km between Bairabi (24˚23′59″N, 92˚52′13″E) and Kolasib (24˚23′11″N, 92˚67′6″E), Mizoram state has been targeted for the purpose of present investigation. The prime objective of the present study is to interpret the petrographic, heavy minerals and surface textural (SEM) attributes of Miocene Surma Group (Bhuban Formation) in terms of tectonic provenance, depositional setting and paleoclimate.

**Geology of the study area:** Surma basin comprises predominantly of Surma Group (Miocene) with subordinate Barail (Oligocene) and Tipam Group of rocks. The Surma Group of rocks occupies the major part of Mizoram Fold Belt (MFB), while the Barail rocks are restricted to the eastern part of the basin bordering Myanmar. The Surma Group of rocks has been divided into a lower Bhuban Formation and upper Bokabil Formation. Owing to the huge thickness of the Bhuban Formation (~5000m), it is further subdivided lithologically into Lower, Middle, and Upper divisions. The Lower and Upper Bhuban divisions are almost identical and may be characterized by alternating sandstone and shale sequences with addition of coarser sand in the later while the Middle Bhuban is predominantly argillaceous. In the study area the Bhuban Formation comprises of interbedded dark to light brown sandstones, shale and siltstones along with intraformational conglomerates and pockets of calcareous sandstones. It depicts westerly dip with amounts ranging between 9° to 80°. The regional stratigraphy of Mizo fold belt has been presented in Table-1.

## Methodology

All together 20 thin-sections were studied for their modal compositions as well as petrographic and diagenetic attributes[8,9]. For each thin section about 300–350 framework grains were counted using Leica DMLP POL 750 microscope at the Department. In addition, samples were also analyzed for their heavy minerals[10],[11]. Attempts have also been made to study the freshly fractured surfaces of representative rock samples using Scanning Electron Microscope (SEM) at CSIR-NEIST Jorhat, Assam.

**Table-1:** Stratigraphy of Mizo fold belt[6,7].

| Age | Group | Formation | Unit | Lithology |
|---|---|---|---|---|
| Recent | Alluvium | | | Silt, clay and gravel |
| Unconformity | | | | |
| Early Pliocene to Late Miocene | Tipam (+900m) | | | Friable sandstone with occasional clay bands |
| Conformable and transitional contact | | | | |
| Miocene to Upper Oligocene | Surma (+5950m) | Bokabil (+950m) | | Shale, siltstone and sandstone |
| | | Conformable and transitional contact | | |
| | | Bhuban (5000m) | Upper Bhuban (1100m) | Arenaceous predominating with sandstone, shale and siltstone |
| | | | Conformable and transitional contact | |
| | | | Midddle Bhuban (3000m) | Argillaceous predominating with shale, siltstone - shale alterations and sandstone |
| | | | Conformable and transitional contact | |
| | | | Lower Bhuban (900m) | Arenaceous predominating with sandstone and silty - shale |
| Unconformity | | | | |
| Oligocene | Barail (+3000m) | | | Shale, siltstone and sandstone |
| Lower contact not seen | | | | |

## Results and discussion

**Petrography:** Petrographic studies reveal that 60% of the Bhuban siliciclastics comprises of clean sand and 40% belong to the wacke category characterizing lithic arkose to sub-arkose and arkosic wacke respectively (Figure-2A & B).

**Lithic arkose:** An arkose classified as lithic arkose having a feldspar/ rock fragment ratio between 1:1 and 3:1[10]. An arkose with ≥ 10% rock fragments may also be considered as Lithic Arkose[12]. In the present context, the Bhuban Sandstones depict a composition that ranges from Lithic Arkose to Sub Arkose. Sub- Arkose a type of sandstone with 5-25% labile components of which feldspar exceeds rock particles[13]. In other words, a feldspathic sandstone having less feldspar than that of normal Arkose may be described as Sub – Arkose. Compositionally, the Lithic Arkose to Sub-Arkosic sandstones of Bhuban formations may be represented as $Qt_{37}\ F_{19}RF_{10}\ M_7\ Mx_6\ Ct_{20}HM_1$.

Among the framework grains Quartz (37%) is represented by its three varieties (non – undulatory > undulatory > polycrystalline) as most dominant followed by feldspar (19%, Plagioclase > K - feldspar) and rock fragments (10%, Metamorphic > Igneous >Sedimentary). Rock constituents other than framework grains include recrystallized mica (7%), matrix (6%), cement (20%) and heavy minerals (1%).

**Arkosic wacke:** Arkosic wackes contain more feldspar than rock fragments compared to normal wackes[16]. The term Arkose signifies the minimum limit of feldspar as 25% besides more feldspar than the rock fragments[15]. However, William et al.[16] considered the limit of feldspar as 20% or even less provided the content of feldspar is more than lithic grains. In the present context, the feldspar content was found to be 24%, rock fragment as 13% and quartz being 63% on an average. Compositionally, Arkosic Wacke sandstones of Bhuban formations may be represented as $Qt_{28}F_9RF_6M_8Mx_{32}Ct_{16}HM_1$.

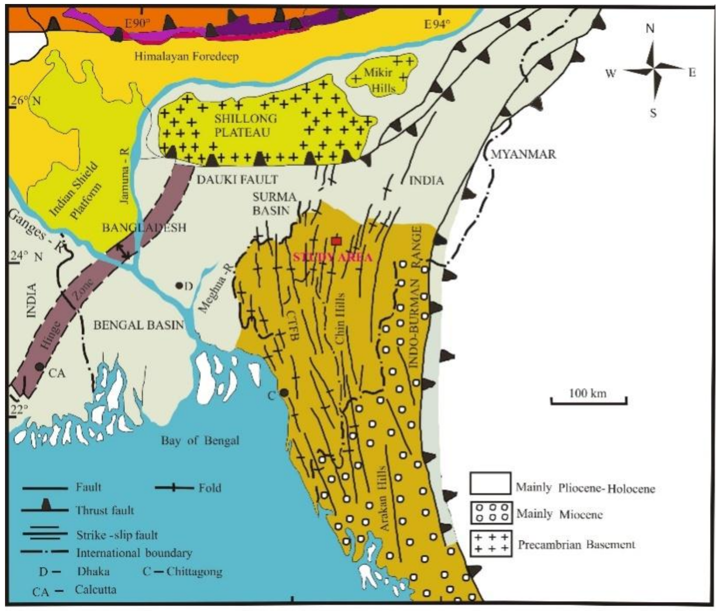
Among the framework grains Quartz (28%) is the most dominating framework constituent comprising all the three varieties i.e. non-undulatory > undulatory > polycrystalline followed by feldspar (9%, Plagioclase > K - feldspar) and rock fragments (6%, Metamorphic > Igneous >Sedimentary). Rock constituents other than framework grains include recrystallized mica (8%), matrix (32%), cement (16%) and heavy minerals (1%).

**Diagenesis:** Petrographic studies of Bhuban siliciclastics depict variety of diagenetic features resembling those of compaction, replacement and cementation. Features like bending and squeezing of the ductile grains such as micas (biotite and muscovite) and fracturing of grains (mostly quartz) have been attributed to mechanical compaction (Figure-3a). In contrast presence of concavo-convex grain contacts indicates effect of solution activity during early stage of diagenesis. The replacement of framework grains is volumetrically insignificant. Calcite appears as a product of partial to total replacement of feldspar grains (Figure-3d). At places detrital feldspars were found partially albitized, preferentially along cleavages (Figure-3b & 3f). During early stage of diagenesis silica cement occurs as authigenic overgrowths which led to euhedral overgrowths on detrital grains (Figure-3c). At places syntaxial overgrowth of quartz and authigenic clay have been followed by iron oxide precipitation (Figure-3b). In Bhuban siliciclastics two generations of calcite precipitation were observed i.e. early stage poikilotopic calcite and late stage fracture filling calcite (Figure-3d). Most of the detrital grains and clay minerals were replaced by early stage poikilotopic calcite cement (Figure-3d). Penetrations of replacing calcite in some cases are reaching the core of grains. In few samples psuedomatrix is abundant that ranges from 6.45% to 12.73% especially samples containing deformation bands. Pseudomatrix resulted from the physical compaction of lithic grains including volcanic, shale clasts and occasionally mica and feldspar grains (Figure-3d).

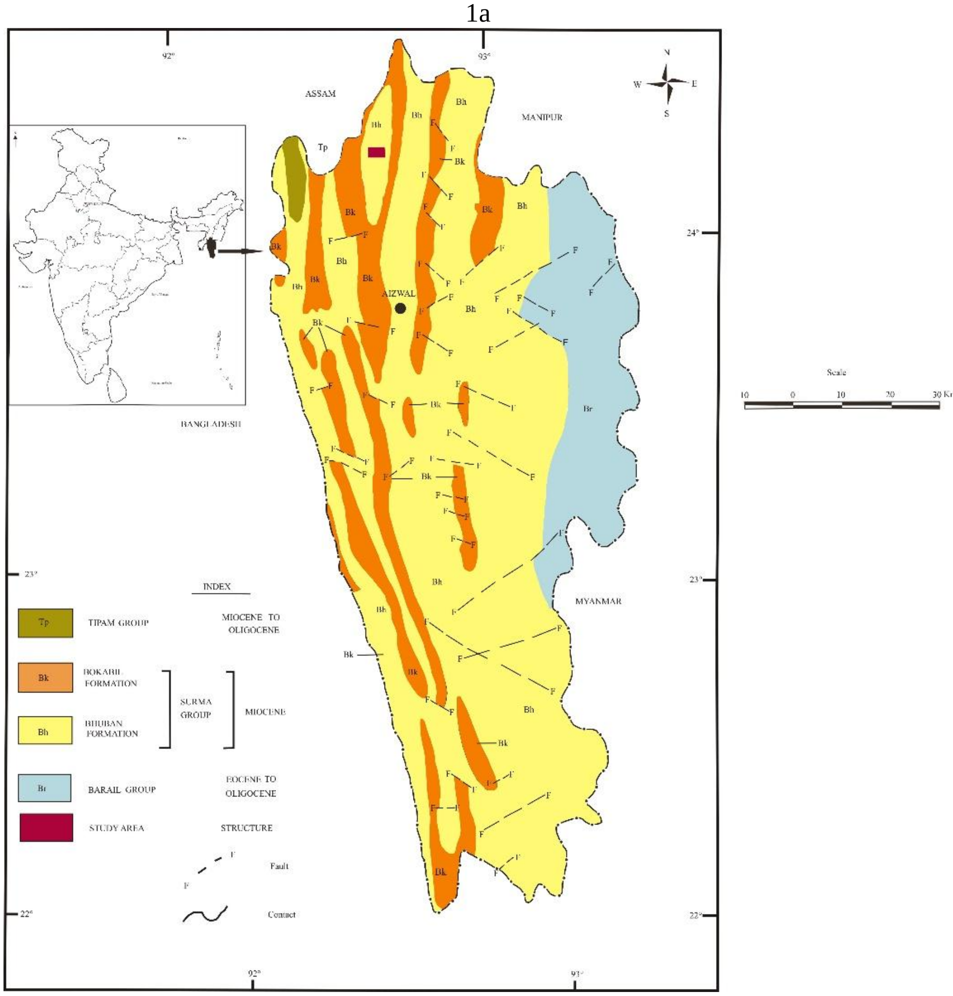
**Table-2:** Recalculated modal compositions (in %) of Bhuban Siliciclastics.

| Sample No. | $Q_tFL_t$ | | | QFR | | | $Q_mFL_t$ | | | $Q_t/F+R$ | $Q_P/F+R$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $Q_t$ | F | $L_t$ | Q | F | R | $Q_m$ | F | $L_t$ | | |
| PR 19/17 | 57.64 | 22.35 | 20 | 59.39 | 23.03 | 17.57 | 56.36 | 23.03 | 20.60 | 1.64 | 0.084 |
| RD 9/15 | 82.52 | 12.62 | 4.85 | 82.52 | 12.62 | 4.85 | 82.52 | 12.62 | 4.85 | 5.72 | 0.00 |
| SD 1/17 | 58.33 | 26.66 | 15.00 | 58.33 | 26.66 | 15.00 | 58.33 | 26.66 | 15.00 | 1.4 | 0.00 |
| SD 3/17 | 46.42 | 36.22 | 17.34 | 46.42 | 36.22 | 17.34 | 46.42 | 36.22 | 17.34 | 0.86 | 0.0 |
| SD 5/17 | 61.13 | 27.12 | 11.74 | 61.63 | 27.34 | 11.02 | 59.14 | 28.51 | 12.34 | 1.60 | 0.02 |
| SR 16/16 | 56.46 | 34.91 | 8.62 | 56.9 | 35.2 | 7.8 | 56.08 | 35.2 | 8.69 | 1.32 | 0.02 |
| SD 2/17 | 56.53 | 24.23 | 19.23 | 56.75 | 24.32 | 18.91 | 56.37 | 24.32 | 19.30 | 1.31 | 0.008 |
| SD 10/17 | 50.69 | 23.25 | 26.04 | 51.17 | 23.47 | 25.35 | 50.23 | 23.47 | 26.29 | 1.04 | 0.01 |
| PR 18/17 | 59.31 | 23.44 | 17.24 | 59.72 | 23.61 | 16.66 | 59.02 | 23.61 | 17.36 | 1.48 | 0.017 |
| PR 23/17 | 61.48 | 21.48 | 17.03 | 63.84 | 22.30 | 13.84 | 60.0 | 22.30 | 17.69 | 1.76 | 0.10 |
| RD 12/15 | 67.83 | 24.47 | 7.69 | 67.83 | 24.4 | 7.69 | 67.83 | 24.4 | 7.69 | 2.10 | 0.00 |
| RD 4/15 | 55.44 | 33.66 | 10.89 | 55.44 | 33.66 | 10.89 | 55.44 | 33.66 | 10.89 | 1.24 | 0.0 |
| RD 8/15 | 57.34 | 27.96 | 14.69 | 57.89 | 28.22 | 13.87 | 57.48 | 28.50 | 14.00 | 1.37 | 0.02 |
| PR 24/17 | 62.31 | 20.28 | 17.39 | 64.66 | 21.05 | 14.28 | 60.90 | 21.05 | 18.04 | 1.82 | 0.10 |
| SR 14/16 | 74.68 | 16.45 | 8.86 | 74.68 | 16.45 | 8.86 | 74.68 | 16.45 | 8.86 | 2.95 | 0.00 |
| RD 11/15 | 54.77 | 30.29 | 14.93 | 55 | 30.41 | 14.58 | 54.58 | 30.41 | 15 | 1.22 | 0.009 |
| PR 16/17 | 72.17 | 13.91 | 13.91 | 72.80 | 14.03 | 13.15 | 71.92 | 14.03 | 14.03 | 2.67 | 0.03 |
| PR 1/17 | 71.09 | 18.75 | 10.15 | 72.22 | 19.04 | 8.73 | 70.63 | 19.04 | 10.31 | 2.6 | 0.05 |
| PR 7/17 | 72.54 | 20.58 | 6.86 | 72.54 | 20.58 | 6.86 | 72.54 | 20.58 | 6.86 | 2.64 | 0.00 |
| PR 4/17 | 69.14 | 24.46 | 6.38 | 69.14 | 24.46 | 6.38 | 69.14 | 24.46 | 6.38 | 2.24 | 0.00 |

**Abbreviations:** Qm: Monocrystalline quartz; Qp: Polycrystalline quartz; Qt: Total Quartzose grains (Qm+Qp); F: Total feldspar grains; Lt: Total lithic fragments; L: Total unstable lithic fragments; Lv: Volcanic/metavolcanic lithic fragments; Ls: Sedimentary/metasedimentary lithic fragments; R: Rock Fragments.

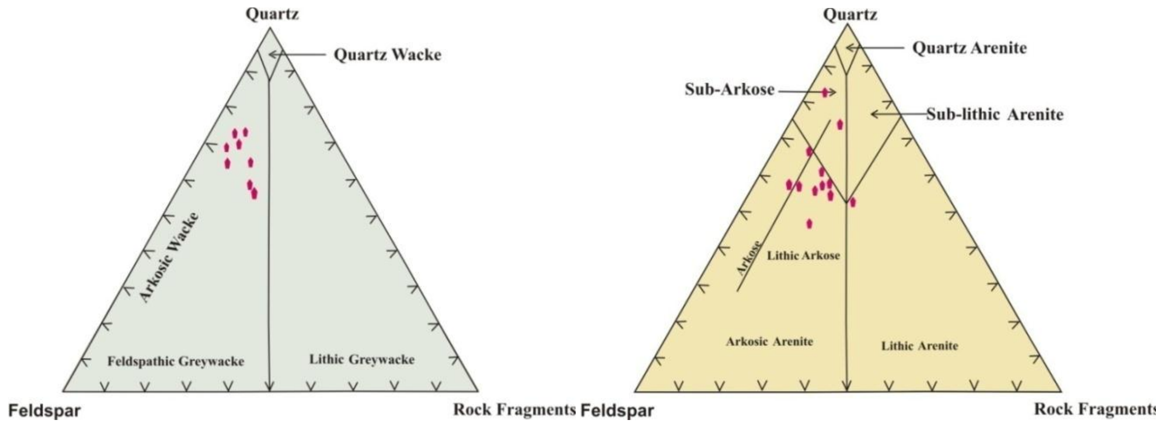



1a




1b

**Figure -1:** a. Regional tectonic map of Surma Basin[4]; b. Geological map of Mizoram showing location of the study area[5].




2a 2b

**Figure-2:** QFR Plot of Surma Sandstones: a ≥ 15% matrix[14]; b. ≤15% matrix[15].

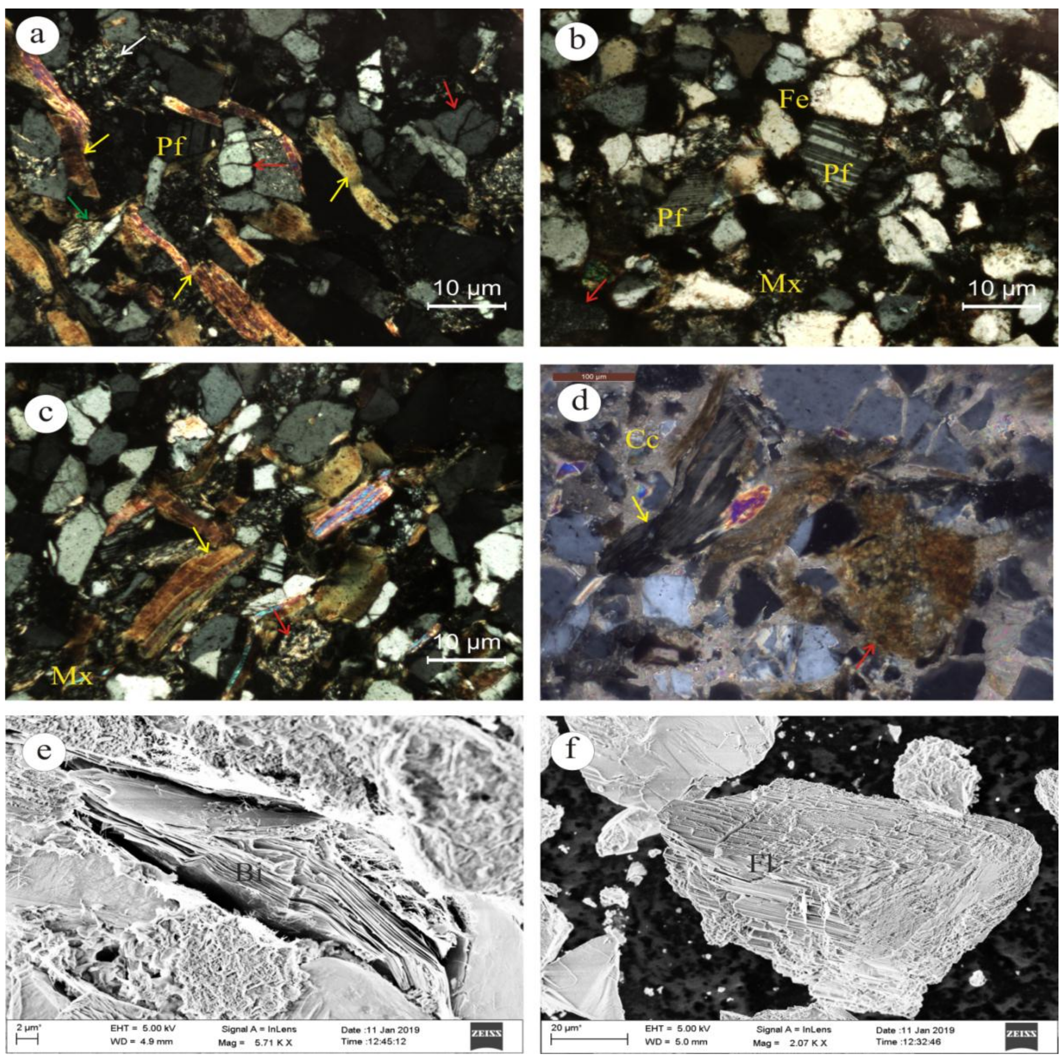



**Figure- 3:** Photomicrographs of Bhuban Siliciclastics showing a. Bending of mica flakes (yellow arrows), plagioclase feldspar (Pf), fractured quartz grains (red arrows), physillite (green arrow); b. Plagioclase feldspar (Pf), rock fragment converting into matrix (Mx), ferruginous cement (Fe), chert (red arrow); c. Biotite (yellow arrow), rock fragment converting into matrix (Mx), physillite (red arrow); d. Dissolution of rock fragment converting into matrix (red arrow), poikilotopic calcite cement (Cc), Dissolution of rock fragment (yellow arrow); e. *SEM image of dissolution of Biotite (Bi)*; f. *SEM image of Feldspar (Fl).*

**Heavy Mineral Analysis:** Bhuban siliciclastics present a cosmopolitan nature of heavy mineral suite. Both the opaque and non-opaque species are present in which the later dominates over the former. The non-opaque minerals are represented by transparent varieties including zircon, tourmaline (schorlite), rutile, epidote, kyanite, humite, staurolite, phlogopite, garnet, chlorite, biotite, hornblende, sphene, wollastonite, chondrodite, scapolite, sillimanite, hypersthene, and vesuvianite. The Iron – oxide has been considered as opaque heavy minerals (Figure-6). Table-3 and Figure-4 depict the percent distribution of heavy minerals and their graphical representation respectively. Table-6 presents the ZTR index of Bhuban siliciclastics calculated using the following formula as suggested by Hubert[13].

ZTR Index = [(Z + T + R) / Total non-opaque] * 100
Where, Z = Zircon, T = Tourmaline, R = Rutile

The Bhuban siliciclastics of the study area depict Zircon Tourmaline Rutile (ZTR) index as low as 15.15% (Table-4 and Figure-5) indicating a mineralogically immature to sub-mature character[10,15,17].

**Table - 3:** Relative abundance (%) of heavy minerals in Bhuban siliciclastics of the study area.

| Sample No. | Zr | Tr | Rt | Gt | Sp | Ky | Sl | St | Ep | Pl | Gl | Fl | Sc | Wl | Hm | Ch | Xe | Hb | Hd | Oq |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PR 19/17 | 0.78 | 3.91 | 5.47 | 3.13 | 2.34 | 10.96 | 1.3 | 9.13 | 16.18 | 0 | 0 | 0 | 7.57 | 1.04 | 15.13 | 3.39 | 0.52 | 0.26 | 0.54 | 18.79 |
| RD 9/15 | 2.67 | 2.67 | 3.05 | 18.7 | 0.76 | 0.76 | 0 | 8.77 | 5.33 | 2.67 | 0.76 | 0 | 4.19 | 2.29 | 2.28 | 0.38 | 0 | 0 | 0 | 44.65 |
| SD 1/17 | 7.14 | 2.84 | 1.42 | 31.42 | 2.85 | 0 | 0 | 1.42 | 1.42 | 0 | 0 | 0 | 37.14 | 0 | 2.84 | 2.85 | 0 | 0 | 0 | 8.57 |
| SD 3/17 | 3.47 | 3.47 | 2.3 | 32.81 | 2.7 | 0.38 | 0 | 1.15 | 0 | 0.77 | 0 | 0 | 27.79 | 0 | 11.19 | 0.77 | 0 | 0 | 0.38 | 12.74 |
| SD 5/17 | 9.28 | 7.64 | 3.81 | 4.37 | 1.63 | 0 | 0 | 3.82 | 5.45 | 1.09 | 1.63 | 1.63 | 25.68 | 0 | 9.28 | 0.54 | 1.09 | 0 | 1.63 | 21.31 |
| SR 16/16 | 4.22 | 4.57 | 2.11 | 37.67 | 0.35 | 1.05 | 0 | 6.69 | 8.09 | 6.69 | 1.4 | 0.7 | 3.16 | 0.7 | 2.11 | 0.7 | 0.7 | 0 | 0 | 14.43 |
| SD 2/17 | 6.93 | 11.88 | 5.93 | 3.46 | 1.48 | 0 | 0 | 0.99 | 5.94 | 2.47 | 1.48 | 0 | 1.98 | 4.45 | 49.99 | 0.99 | 0 | 0 | 0.49 | 1.48 |
| PR 23/17 | 1.73 | 3.45 | 4.03 | 55.57 | 0.38 | 0.96 | 0 | 3.26 | 4.42 | 2.11 | 0 | 0 | 0.38 | 0.57 | 1.15 | 0.19 | 0 | 0 | 0 | 21.7 |
| PR 22/17 | 2.77 | 5.55 | 5.55 | 11.11 | 5.55 | 5.55 | 0 | 2.77 | 27.77 | 5.55 | 0 | 0 | 5.55 | 0 | 5.55 | 2.77 | 0 | 0 | 0 | 13.88 |
| PR 16/17 | 4.62 | 6.48 | 4.62 | 4.62 | 13.88 | 2.78 | 0 | 0.92 | 9.25 | 0 | 0 | 0 | 20.37 | 0 | 15.74 | 0 | 0 | 0 | 0 | 14.81 |
| PR 18/17 | 2.41 | 9.17 | 2.4 | 0 | 7.24 | 5.79 | 0 | 5.31 | 12.55 | 2.41 | 0 | 0 | 8.69 | 0 | 0 | 17.86 | 0 | 0 | 0 | 26.08 |
| SR 13/16 | 2.45 | 3.26 | 2.74 | 28.61 | 2.17 | 2.99 | 0.27 | 2.74 | 9.25 | 1.36 | 0 | 0 | 13.35 | 3.26 | 14.71 | 1.63 | 0 | 0 | 0 | 10.62 |
| SD 12/17 | 6.45 | 6.45 | 3.22 | 17.74 | 6.45 | 3.22 | 0 | 1.61 | 11.33 | 4.83 | 0 | 0 | 12.9 | 4.83 | 4.83 | 0 | 0 | 4.83 | 0 | 11.29 |
| SD 11/17 | 2.9 | 9.2 | 0.98 | 3.28 | 1.64 | 3.94 | 0 | 10.52 | 22.36 | 3.61 | 1.31 | 0 | 15.13 | 0.98 | 9.53 | 0.32 | 0 | 0.98 | 0 | 11.84 |
| RD 4/15 | 5.04 | 2.52 | 3.36 | 55.46 | 0.84 | 0 | 0 | 0 | 0.84 | 0.84 | 0 | 0 | 9.24 | 0 | 4.2 | 2.52 | 0 | 0 | 0 | 15.12 |
| PR 1/17 | 4.3 | 6.45 | 4.3 | 19.35 | 4.3 | 3.22 | 0 | 4.3 | 13.97 | 2.15 | 0 | 0 | 8.62 | 0 | 12.9 | 1.07 | 0 | 0 | 0 | 15.05 |
| PR 4/17 | 3.6 | 4.5 | 2.7 | 12.61 | 8.1 | 1.8 | 0 | 1.8 | 9.9 | 3.6 | 0 | 0 | 18.91 | 0 | 11.71 | 1.8 | 0 | 0 | 0 | 18.91 |
| PR 7/17 | 5.17 | 6.03 | 3.44 | 12.93 | 5.17 | 2.58 | 0 | 3.44 | 7.75 | 4.31 | 0 | 0 | 24.13 | 0 | 12.06 | 1.72 | 0 | 0 | 0 | 11.2 |

**Abbreviations:** Zr: Zircon; Gr: Garnet; Tr: Tourmaline; Sp: Sphene; Ky: Kyanite; Sl: Sillimanite; St: Staurolite; Rt: Rutile; Ep: Epidote; Pg: Phlogopite; Gl: Glaucophane; Fl: Fluorite; Sc: Scapolite; Wl: Wollastonite; Hm: Humite; Ch: Chondrodite; Xn: Xenotime; Hb: Hornblende; Hd: Hedenbergite; Oq: Opaque;

**Table - 4:** ZTR percent distribution in Bhuban sediments (sample wise).

| Sample No. | Zircon | Tourmaline | Rutile | ZTR Index |
|---|---|---|---|---|
| PR 19/17 | 0.96 | 4.82 | 6.75 | 12.53 |
| RD 9/15 | 4.82 | 4.82 | 5.51 | 15.15 |
| SD 1/17 | 7.81 | 3.12 | 1.56 | 12.49 |
| SD 3/17 | 3.98 | 3.98 | 2.65 | 10.61 |
| SD 5/17 | 11.8 | 9.72 | 4.86 | 26.38 |
| SR 16/16 | 4.93 | 5.34 | 2.46 | 12.73 |
| SD 2/17 | 7.03 | 12.06 | 6.03 | 25.12 |
| PR 18/17 | 3.26 | 12.41 | 3.26 | 18.93 |
| PR 23/17 | 2.21 | 4.42 | 5.15 | 11.69 |
| PR 22/17 | 2.77 | 5.55 | 5.55 | 13.87 |
| PR 16/17 | 5.43 | 7.6 | 5.43 | 18.46 |
| RD 4/15 | 5.94 | 2.97 | 3.96 | 12.87 |
| SR 13/16 | 2.74 | 3.65 | 3.04 | 9.43 |
| SD 11/17 | 3.35 | 10.44 | 1.11 | 14.9 |
| SD 12/17 | 7.27 | 7.27 | 3.63 | 18.17 |
| PR 1/17 | 5.06 | 7.59 | 5.06 | 17.71 |
| PR 4/17 | 4.44 | 5.55 | 3.33 | 13.32 |
| PR 7/17 | 5.82 | 6.79 | 3.88 | 16.49 |

**Discussion: Tectonic Provenance and Depositional setting:** The tectonic provenance of Bhuban siliciclastic was inferred using the modal composition as suggested by Dickinsion & Suczek[18] and Dickinson et al.[19]. In a similar attempt the heavy mineral suites are divided into three categories i.e., GM (accessory minerals of felsic rock, i.e., zircon, tourmaline, staurolite, kyanite, zoisite, sillimanite, monazite & andalusite), MT (accessory minerals of basic metamorphic rock, i.e., epidote, amphibole & garnet) and MF (accessory minerals of mafic igneous rock, i.e., olivine, pyroxene & hornblende) in order to differentiate various depositional settings[20]. In the present context the heavy mineral suites of the Bhuban siliciclastics has been assigned to GM and MT categories and hence a passive continental margin set-up (Figure-7). In addition, use of QmFLt and QtFLt (Figure-8a & 8b) plots depict a recycled orogenic provenance and a mixed - transitional continental provenance respectively[19]. This observation is further substantiated by the presence of reworked heavy minerals in Bhuban siliciclastics.

**Palaeoclimate:** The log – log plot of Qt/ (F + R) vs. Qp/(F+R) was used to interpret the paleoclimate of Miocene Bhuban siliciclastics[21]. An arid to semi-arid climate has been indicated for the deposition of Bhuban sediments (Figure-9).

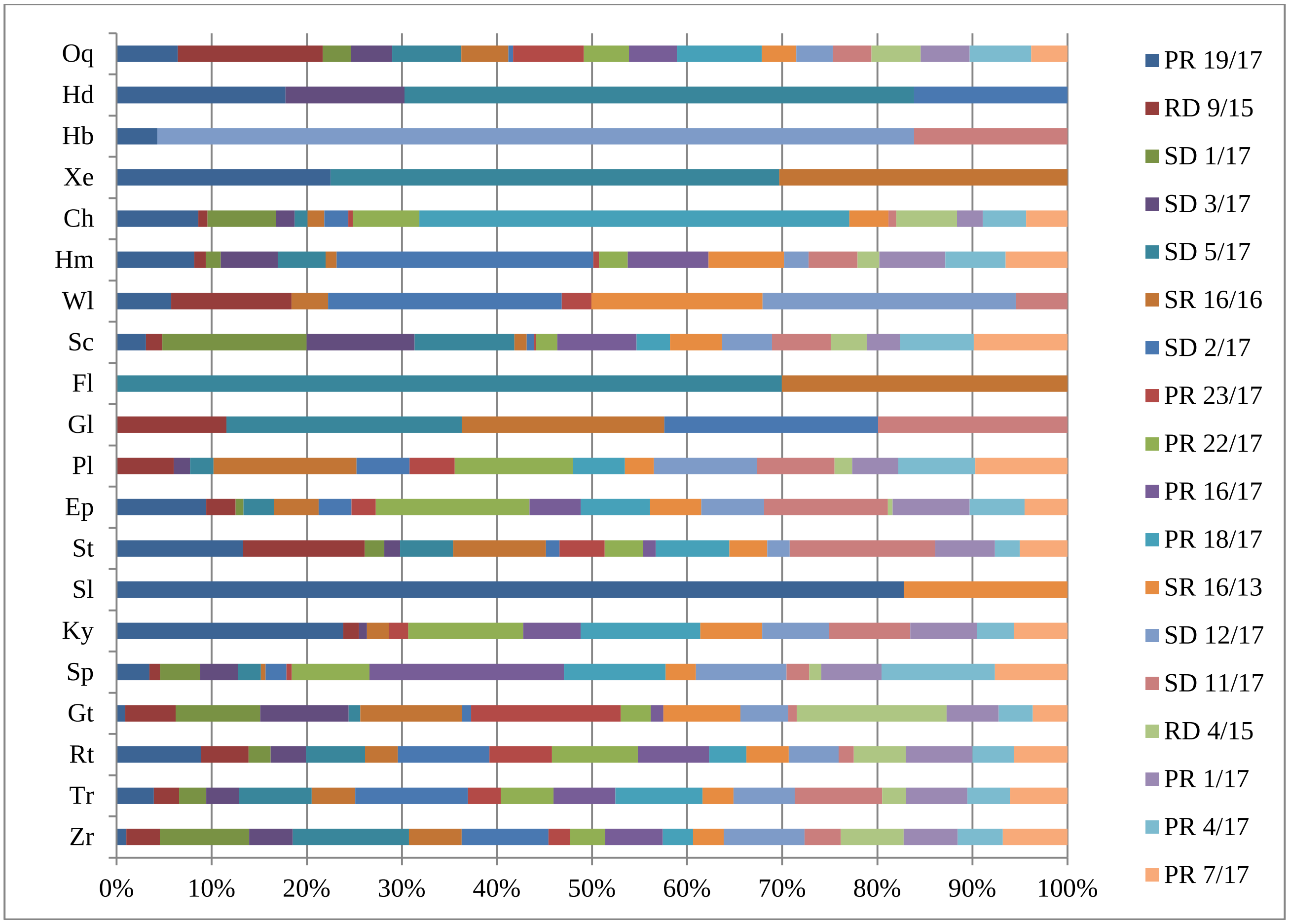



**Figure- 4:** Average distribution of heavy minerals in Bhuban Siliciclastics.

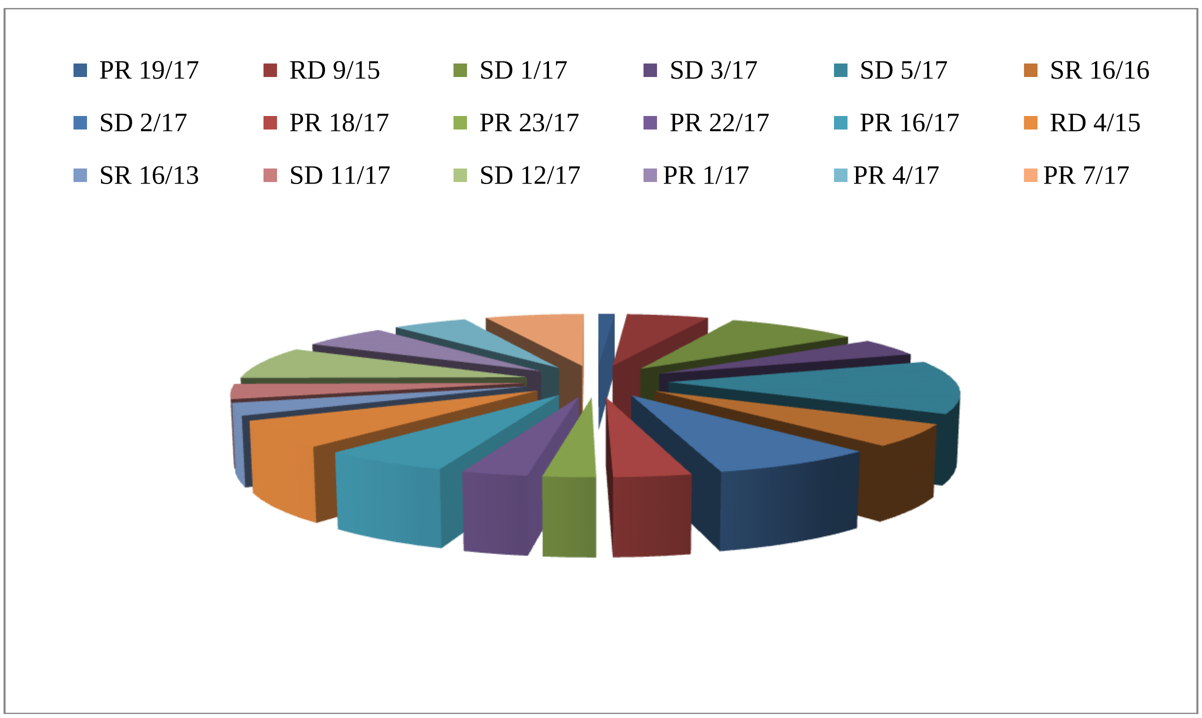



**Figure-5:** ZTR plot of Studied Bhuban Siliciclastics.

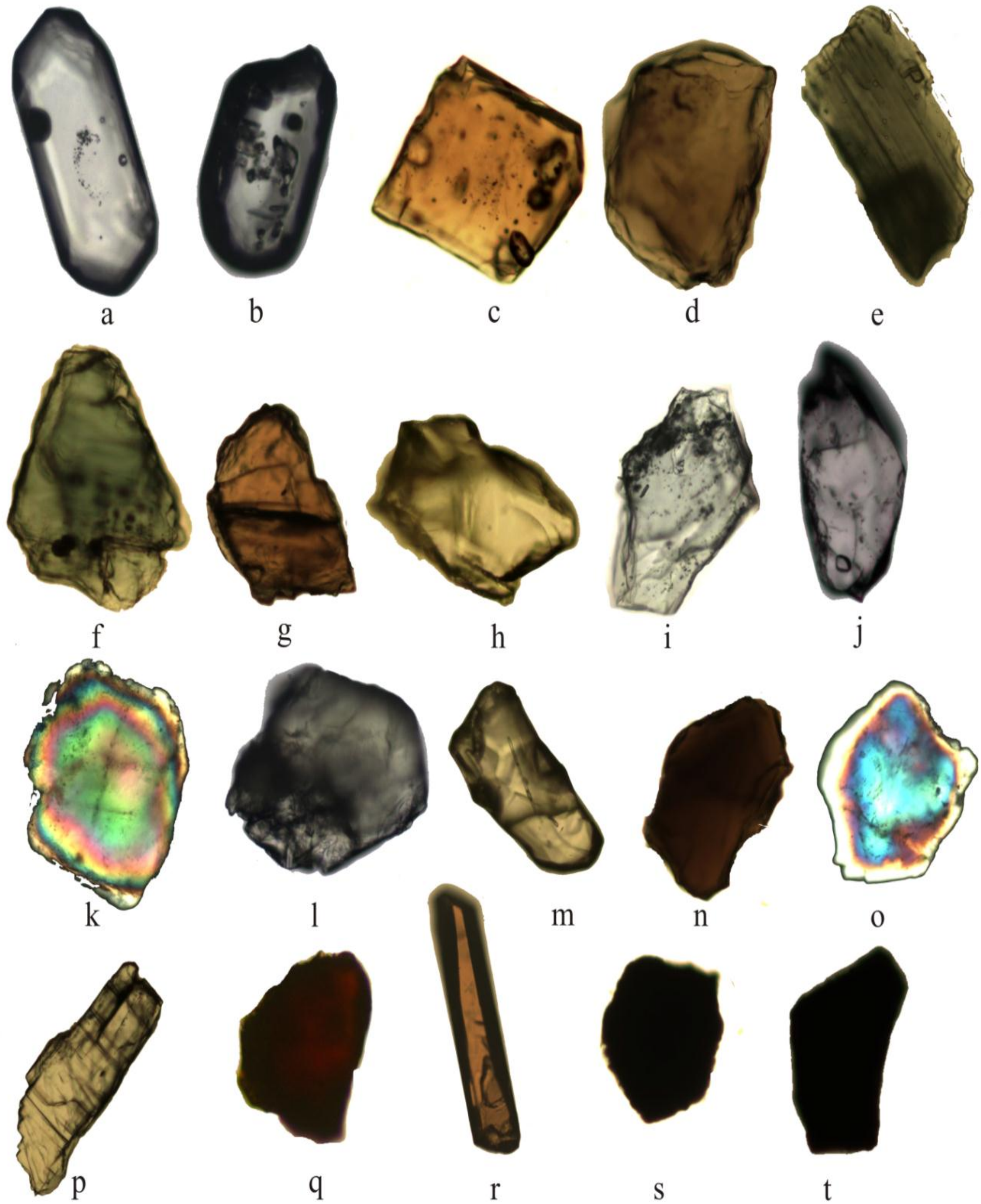



**Figure-6:** Photomicrographs of heavy minerals from Bhuban siliciclastics a. & b. Zircon; c. & d. Schorlite; e. Hornblende; f. Glaucophane; g. Staurolite; h. Humite; i. Wollastonite; j. Garnet; k. Clinohumite; l. Zoisite; m. Xenotime; n. Phlogopite; o. Scapolite; p. Kyanite; q. Rutile; r. Anatase; s. & t. Iron oxide.

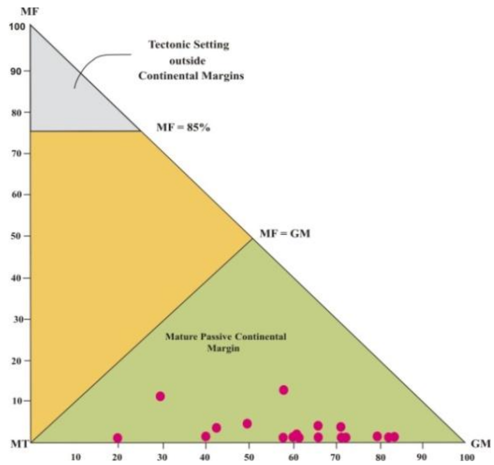
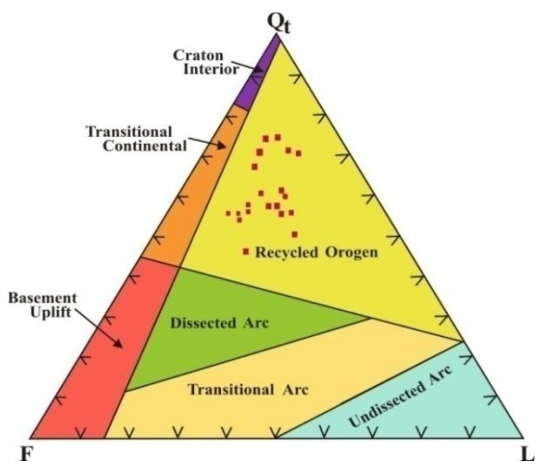
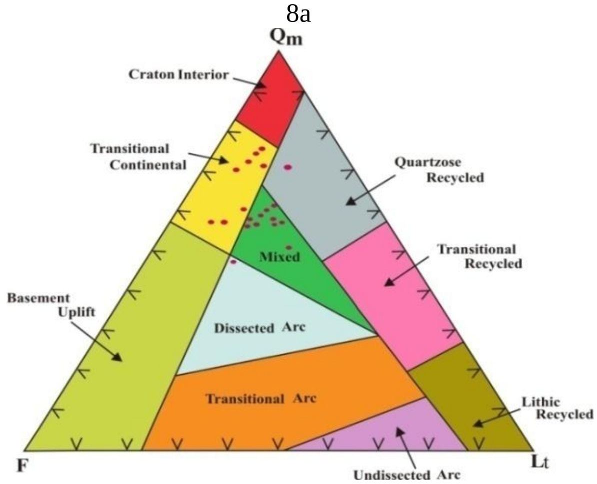



**Figure-7:** Plot of MF–MT–GM of heavy minerals showing a passive continental margin for the formation of Bhuban Siliciclastics[20].




8a




8b

**Figure–8:** a. QtFL plot of Miocene Bhuban siliciclastics showing the dominance of recycled Orogen Provenance[19]; b. QmFLt plot of Miocene Surma Sandstone showing that the Bhuban Siliciclastics are derived from mixed source terrain and Transitional Continental as well few from Quartzose recycled and dissected Arc[19]

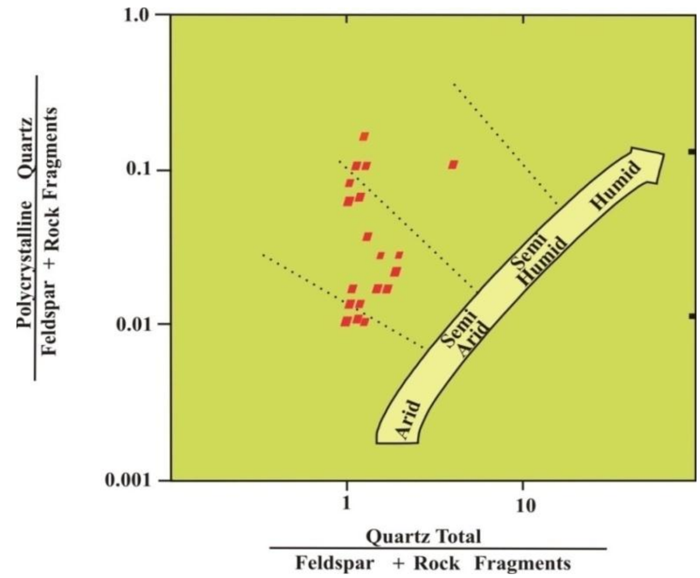



**Figure-9:** The bivariate log–log plot of Qt/(F+R) vs Qp/(F+R)[21].

## Conclusion

Based on the above observations and discussions the following inferences can be drawn in respect of Bhuban siliciclastics. i. Bhuban siliciclastics may be categorized as clean (lithic to sub arkose) and wacke (arkosic wacke) sandstones. ii. Presence of undulatory quartz, polycrystalline quartz, recycled non-undulatory quartz with rounded to sub rounded outline, quartz with abraded overgrowths, chert, physillite and alkali as well as plagioclase feldspars has been attributed to derivation from a mixed source terrain including medium-rank metamorphic, sedimentary and igneous source rock. iii. Dominance of metamorphic rock fragments in the Bhuban siliciclastics may be assigned to the nearby Indo-Myanmar and the Himalayan orogens. iv. Presence of cosmopolitan heavy mineral suite in conjugation with different shapes and sizes indicate a mixed source terrain. Further, presence of Garnet-Zircon-Tourmaline (var. schorlite)-rutile (var. anatase) indicates derivation from granitic and mafic igneous rocks. v. Occurrence of subhedral - euhedral staurolite-sillimanite-kyanite-chlorite-glaucophane-garnet (with inclusion) does indicate a regionally metamorphosed source terrain. vi. Presence of chondrodite-phlogopite-scapolite-wollastonite-sphene-hedenbergite signifies a contact dolomitic marble and skarn source rock. vii. Recycled abraded grains of zircon-tourmaline- rutile-glauconite-garnet suggests a sedimentary source terrain. viii. The ZTR index in respect of Bhuban Siliciclastics depicts a low value (15.15%) suggesting mineralogically immature sediments. vix. The Bhuban rocks seem to have been deposited in a semi-humid to semi-arid climatic condition.

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