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ORIGINAL ARTICLE

Petrography and geochemistry of the Dupi Tila formation: Implications for depositional environment and tectonics

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Abstract A comprehensive examination of detrital sandstone modes from the Sylhet Trough reveals a diverse range of sub-lithic to sub-feldspathic quartz arenites. Soil samples were gathered from Dupi Gaon (Jaintiapur) in Bangladesh, followed by a thorough analysis using field examination, X-ray diffraction (XRD), X-ray fluorescence (XRF), petrography, and heavy mineral concentration analyses. Field observations revealed the soil sample varying from white to yellowish to variegated, with thicknesses ranging from 15 cm to about 4 m, and exhibiting moderate softness. XRF analysis revealed significant SiO_2, Al_2O_3, and Fe_2O_3 levels in the samples, with zirconium (Zr) and copper (Cu) showing consistently high concentrations. XRD analysis identified quartz as predominant, along with muscovite, biotite, and accessory minerals like rutile and magnetite. Petrographic analysis highlighted quartz as dominant, with fractures suggesting tectonic influences, while heavy mineral separation techniques identified zircon, garnet, goethite, rutile, and magnetite. These findings provide insights into sediment provenance, depositional processes, and environmental conditions during the formation of the Dupi Tila Formation. The comprehensive geochemical data of the entire rock indicates that most of the sediments originated from felsic igneous sources, and also suggests a moderate to high level of weathering in the source region. Overall, the analyses suggested an in situ origin of the Dupi Tila Formation, with parent materials being predominantly detrital rather than authigenic, supported by the presence of detrital quartz and an assessment of the depositional environment, providing insights into the geological conditions of the era and potential modes of sediment transportation.

Keywords Petrography · Geochemistry · Depositional environment · Detrital sandstone · Dupi Tila formation

1 Introduction

The Dupi Tila Formation in the Dupi Gaon region of Sylhet, Bangladesh, represents a key geological unit within the Sylhet Basin, a significant sub-basin of the larger Bengal Basin. This basin, situated in the northeastern part of the Indian subcontinent between the Indian Shield and the Indo-Burman Range, encompasses areas of Bangladesh and West Bengal, India. The Bengal Basin is renowned for its thick sedimentary sequences that extend from the Early Cretaceous to the Holocene epoch, a feature that has attracted considerable attention from geologists (Curray 1991; Curray and Munasinghe 1991). The region is characterized by its tectonic complexity, particularly in northeastern Bangladesh, where active subsidence has been prominent since the Miocene. This subsidence is driven mainly by complex tectonic processes, including pop-up tectonics (Islam et al. 2011) and overthrusting phenomena associated with the Shillong Massif (Worm et al. 1998; Goodbred and Kuehl 2000).

The Dupi Tila Formation is significant due to its stratigraphic position (Gazi et al. 2021), diverse lithological

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composition, and geochemical characteristics. The Dupi Gaon area, with its well-exposed outcrops and sedimentary sequences, provides an excellent opportunity for in-depth petrographic and geochemical investigations. This formation is considered a crucial subsurface aquifer in Bangladesh and is believed to represent the youngest Tertiary and oldest Quaternary deposits in the region (Roy et al. 2012). It captures the final stages of the Himalayan orogenic process. However, it remains one of the least explored formations compared to the extensively studied Miocene units of the Bengal Basin.

Sedimentological studies reveal that feldspar grains and lithic fragments, which separate from residual quartz during transportation, undergo significant chemical weathering. This weathering process results in quartz-rich sandstones, typically found in continental interiors and passive-margin settings, and mud-rich deltas common in passive continental margin environments (Bassis et al. 2016). The Miocene-Pliocene Siwalik Group, which represents ancient floodplain deposits of the Gangetic basin, exhibits similarities in petrological and sedimentological characteristics with the Dupi Tila Formation. The Upper Siwalik deposits, spanning from the Pliocene to Pleistocene epochs (Munim 2017; Rai and Yoshida 2021), and the Dupi Tila Formation, ranging from elevations of 300–2500 m in the Bengal Basin, are both known for their freshwater molassic deposits, primarily influenced by the paleo-Brahmaputra River system (Jahan and Uddin 2022).

Geochemical analyses play a crucial role in understanding provenance evolution, source rock composition, weathering patterns, and tectonic environments in clastic sedimentary rocks (Bhatia 1983; Bhatia and Crook 1986; Roser and Korsch 1986, 1988; McLennan et al. 1993a, b; Nesbitt and Young 1996). This study aims to investigate the petrography and geochemistry of the Dupi Tila Formation in the Dupi Gaon area through detailed field observations, petrographic analyses, and geochemical investigations of 15 representative samples. The goal is to elucidate the formation's lithological variability, mineralogical composition, diagenetic alterations, and elemental signatures for the first time.

By integrating these findings with existing geological knowledge, this research seeks to enhance the understanding of the geological evolution of the Surma Basin. It will also provide insights into the factors influencing this critical stratigraphic unit's petrographic and geochemical characteristics. The comprehensive analysis will involve X-ray diffraction (XRD) to characterize mineralogical composition and texture and X-ray fluorescence (XRF) to determine elemental composition. Petrographic analysis will assess optical properties, texture, and grain characteristics, while heavy mineral analysis will identify and quantify heavy mineral assemblages. Assessing stratigraphic variations from the Late Eocene to the Plio-Pleistocene epochs will offer a detailed understanding of changes in sediment sources, depositional environments, and tectonic settings over time. This study will also compare findings with coeval sedimentary units from the Himalayan region to evaluate source–area relationships, paleoclimate influences, and tectonic controls on sedimentation within the Sylhet Basin and the broader Bengal Basin. This research aims to advance knowledge of sedimentary processes, basin evolution, and tectonics in this geologically significant region.

2 Study area and geologic setting

The Bengal Basin, a colossal delta-dominated sedimentary basin, originated from the crustal loading and subsequent subsidence associated with the Indian-Asian-Burmese collision. Spanning approximately 200,000 square kilometers, with a sedimentary fill exceeding 20 km in depth, the basin is a critical geological feature of the eastern Indian subcontinent (Uddin and Lundberg 1998a). It is bordered by the Indian craton to the west, the Shillong Plateau and the Himalayan belt to the north, and the Indo-Burman Ranges to the east (Fig. 1). The basin lies between latitudes 20°34′N to 26°38′N and longitudes 88°01′E to 92°41′E, covering most of Bangladesh and extending into West Bengal, India. To the south, it opens into the Bay of Bengal, featuring one of the world's most extensive deltaic plains, primarily formed by the sediment-laden flow of the Ganges, Brahmaputra, and Meghna rivers (Uddin and Lundberg 1998b).

The immense sediment transport from these major rivers has contributed to significant sediment accumulation in the Bengal Basin, coinciding with the basin's subsidence (Goodbred and Kuehl 2000). Elevated sedimentation rates have been documented from the Eocene through the Pliocene epochs (Johnson and Alam 1991). Seismic-reflection studies by Curray (1991) reveal that the sedimentary and metasedimentary rocks in the basin have a thickness of at least 22 km, with about 16 km attributed to collisional deposits. These sediments overlie approximately 6 km of pre-collisional strata, interpreted as buried continental rise and pelagic deposits (Curray 1991).

The Bengal Basin's geological evolution is intricately linked to the ongoing collision between the Indian subcontinent and Eurasia, which has led to the uplift of the Himalayan and Indo-Burman Ranges and the subsequent sediment loading from these orogenic belts (Uddin and Lundberg 1998a). The Cenozoic sequences within the basin show a progressive increase in thickness from west to east and from north to south, reflecting the basin's complex tectonic history (Uddin 1987).

The Surma Basin, an eastern extension of the Bengal Basin, is underlain by late Mesozoic and Cenozoic sediments with substantial thicknesses ranging from 12 to

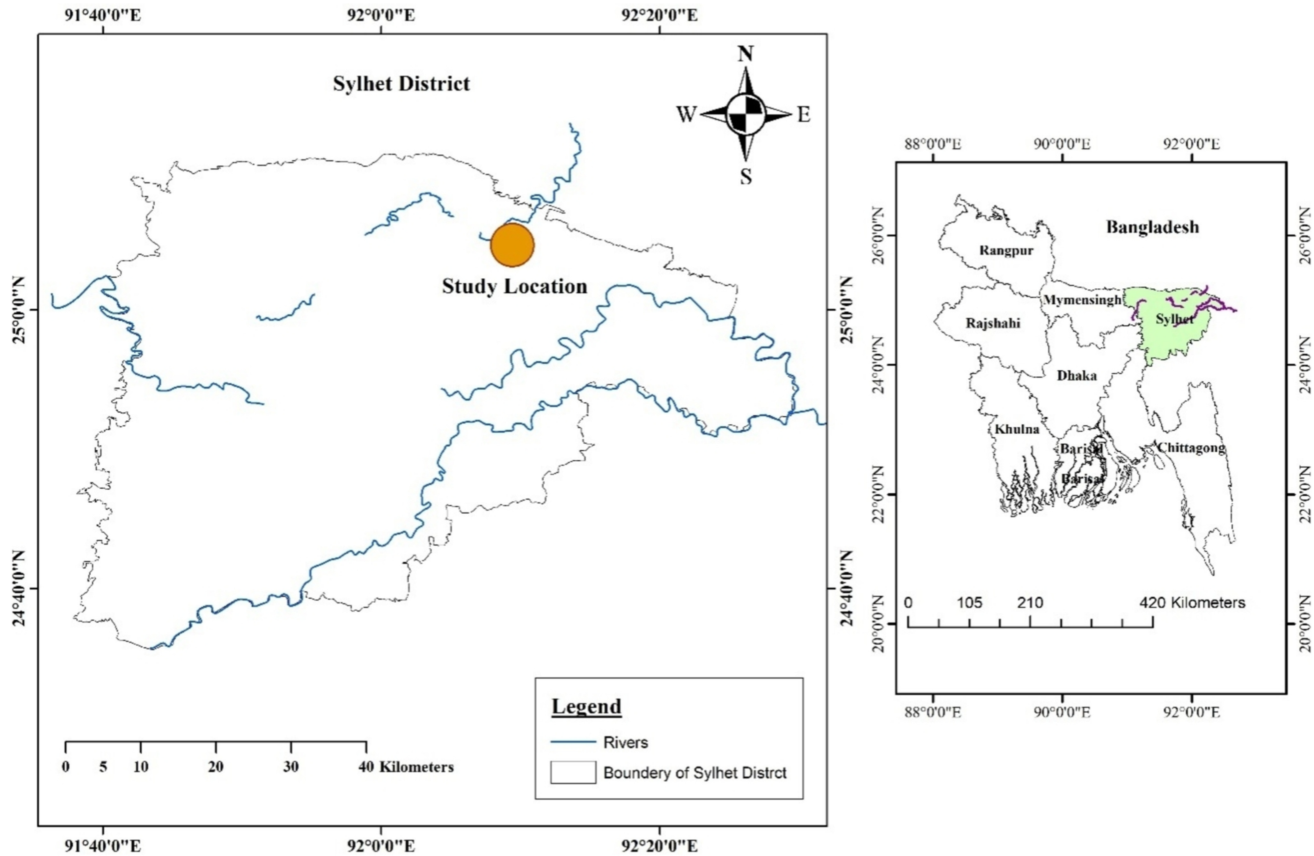


Fig. 1 The Sylhet area; *orange circle* indicates the study location (Dupigoan)

16 km (Johnson and Alam 1991). It originated as a foreland basin associated with the Himalayan orogeny and the Indo-Burman Range. The Western Platform borders the Surma Basin to the west and the Indo-Burman Range to the southeast, with its northern boundary defined by the Dauki Fault system, which marks the transition to the Shillong Plateau (Hiller and Elahi 1984; Johnson and Alam 1991).

Structural features within the Surma Basin have predominantly developed since the Plio-Pleistocene epoch, reflecting ongoing tectonic activity (Lietz and Kabir 1982). The basin hosts a variety of litho-formations from the Eocene to the present, including the Kopili Shale and Sylhet Limestone (Eocene), the Barail Group (Oligocene), and the Surma and Tipam Groups (Miocene-Pliocene), which are primarily composed of clastic sediments (Chowdhury et al. 2006; Alam et al. 2013). The Dupi Tila Formation, first described by Evans (1932), is interpreted as having been deposited in a fluvial environment. In seismic stratigraphy, the Dupi Tila Formation is subdivided into a lower sandy unit and an upper argillaceous unit, collectively called the Dupi Tila Group (Alam et al. 2003).

The Dupigaon in the Surma Basin is the type of section of the Dupitila Formation, dating to the Plio-Pleistocene era (Evans 1932), where both Upper and Lower Dupitila formations are well exposed. The Upper Dupi Tila Formation comprises massive, variegated, poorly sorted fine to medium, occasionally coarse sandstones. At the same time, the Lower Dupitila Formation consists of massive, medium to coarse, yellowish-gray to whitish-gray, moderate to well-sorted sandstones. Crossbedding and quartzite pebbles are sporadically observed. Johnson and Alam (1991) noted that the alternating channel and floodplain deposits of the Dupitila Formation suggest fining-upward cycles indicative of probable meandering river origins.

3 Methodology

About 15 samples (Fig. 2) were collected by hand-auger from Dupi Gaon of Jaintiapur, Sylhet, for comprehensive mineralogical and geochemical examination. XRD, XRF, petrography, and heavy mineral analysis techniques were used to characterize the samples.

Energy dispersive X-ray fluorescence (EDXRF) is a powerful analytical technique used to determine the elemental composition of various materials, including geological

Fig. 2 Outcrop images of the Dupi Tila Formation soil samples from Dupi Goan, Sylhet

samples. For EDXRF analysis, the soil samples were sieved with a stainless-steel sieve to remove dirt. All the samples were separately taken into porcelain dishes and placed in an oven to dry at around 70°C for constant weight. Each dried sample was pulverized to a fine powder employing a mortar and pestle to prepare a sample pellet (7 mm diameter, 1 mm thick) using 10-ton pressure in a pellet maker (Specac, UK).

^{109}Cd annular excitation source produced an X-ray beam of 22.4 keV, which hit the target sample, producing the characteristic X-rays. The [Si (Li)] detector (Canberra), having a resolution of 175 at 5.9 keV, was applied for the detection of characteristic X-rays that are converted into voltage pulses, amplified by the spectroscopy amplifier, and processed in MCA having a 16K+ channel. The irradiation and spectrum data acquisition are operated and controlled by a software package provided with the system. The commercial software AXIL has been applied for the qualitative and quantitative elemental analysis. The certified reference materials (CRM) were irradiated under similar experimental conditions to construct the calibration curves for the validation of the results of the analytical system. CRM Marine sediment IAEA 433 was used to construct the calibration curve, and Estuarine sediment (CRM) was used to check its quality (Jolly et al. 2020, 2023).

The XRD analysis for the 15 selected rock samples was conducted using a Rigaku Smart Lab X-ray diffractometer, which is well-regarded for its accuracy in mineralogical characterization (Rigaku 2021). The analysis utilized Cu-Kα radiation with a wavelength (λ) of 1.5406 Å, operating at a voltage of 9 kV, and employed D/teX Ultra 250 detectors, known for their high sensitivity and resolution (Smith et al. 2019). The scan rate was set at 0.01° 2θ per second with a scan range of 15°–80°, ensuring a comprehensive assessment of the crystalline phases in the samples (Doe and Roe 2018). This approach aligns with established standards in XRD analysis, facilitating accurate and reproducible identification and quantification of mineral components (Jones and Brown 2020).

Petrographic measurement was carried out using polarized microscopes. Thin sections were prepared and reviewed by an optical polarized transmitted light microscope device connected with a digital camera under up to ×10 magnification. Petrographic analysis utilizing an optical microscope involves scrutinizing thin sections of rocks and minerals to discern their mineral composition, texture, and structural attributes. This examination, facilitated by the interaction of polarized light with mineral grains, enables the inference of the rock’s geological origin, history, and environmental formation conditions, thereby contributing to geological interpretations and resource exploration**.**

Heavy mineral separation is a technique to isolate/concentrate heavy/dense minerals (Sp. Gr. $^{>}$ 2.88) from sediment or rock samples using a heavy liquid separation technique. It involves grinding the rock sample into particles in a porcelain mortar, washing out the clay particles, and drying the moisture. The grain sediment can separate the heavy particles in a liquid separation process using Bromoform ($CHBR_3$-Sp. Gr. 2.88).

The isolated heavy mineral concentrate was rinsed and dried before being examined under a microscope. Individual heavy minerals were identified based on their morphology, color, and optical properties. Quantitative analysis has determined the relative abundance of different heavy minerals. Quality control measures ensure the accuracy and reliability of results. Identified heavy minerals provide valuable information about sediment provenance, depositional environment, and geological history, aiding in interpretations and reconstructions. (Table 1).

4 Results

4.1 Elemental analysis

XRF analysis showed major oxides and different trace elements in sediment frameworks, which provides a good indication of the tectonic setting and provenance (Ferdous and Farazi 2016). Table 2 gives the elemental analysis of the Dupi Tila formation. The soil samples extracted from the Dupi Tila Formation exhibit notably high concentrations of SiO_2, ranging from 65.08% to 81.023%, with an average value of 72.84%. Following SiO_2, the samples displayed lower concentrations of Al_2O_3 (11.83%), Fe_2O_3 (0.6%), TiO_2 (0.7556%), K_2O (1.53%), Na_2O (0.141%), CaO (0.906%), MgO (0.4326%), SO_3 (0.0425%), P_2O_5 (0.191%), Cr_2O_3 (0.00206%), and MnO (0.072%) (Table 2).

4.2 Trace elements analysis

The trace element analysis (Table 3) revealed significant spatial variability in composition, reflecting diverse geological processes and depositional conditions. Scandium (Sc) concentrations range from 4880 to 17440 ppm, with the highest levels at LOC: 03 and LOC: 14. Strontium (Sr) and yttrium (Y) also exhibit variability, with Sr peaking at LOC: 02 (92.152 ppm) and Y at LOC: 01 (81.636 ppm), suggesting localized enrichment. Zirconium (Zr) shows a distinct peak at LOC: 01 (2279.058 ppm), indicating heavy mineral accumulation. Niobium (Nb) and cobalt (Co) demonstrate notable differences across locations, with maximum values of 27.477 ppm (LOC: 04) and 214.278 ppm (LOC: 06), respectively, hinting at tectonic or lithological influences. Rubidium (Rb) and zinc (Zn) are present consistently, with Rb reaching 170.532 ppm (LOC: 04) and Zn peaking at 235.94 ppm (LOC: 01), reflecting the presence of *K*-bearing minerals. In contrast, nickel (Ni) and copper (Cu) remain below detection limits (< 0.19 and < 1.95 ppm, respectively) across all locations, indicating their minimal contribution to the elemental composition.

4.3 Mineral analysis

XRD analysis was conducted to identify the mineral composition of the sandstone samples. This analytical technique provides valuable insights into the crystalline structure and mineralogy within the samples, aiding in interpreting their

Table 1 Stratigraphy of the Sylhet region (after Reimann 1993; Uddin & Lundberg 1999)

Stratigraphic unit	Age	Lithology	Environment of deposition
Madhupur clay formation	Pleistocene	Red-brown clay with occasional silt and sand layers	Floodplain and over bank deposits
Dupi Tila formation	Pliocene to Pleistocene	Yellow to light brown sandstone, siltstone, silty clay, mudstone, and conglomerate	Fluvial environment
Tipam sandstone formation	Miocene to Pliocene	Coarse-grained sandstone with minor shale and siltstone	Deltaic and shallow marine
Boka Bil formation	Miocene	Alternating bluish-grey to yellowish-grey siltstone and shale, fine to medium-grained sandstone	Shallow marine to deltaic
Surma group (Bhuban formation)	Oligocene to Miocene	Fine to medium-grained sandstone, siltstone, and shale	Deltaic to shallow marine
Barail sandstone formation	Oligocene	Sandstone with interbedded shale	Fluvial to deltaic
Kopili shale formation	Paleocene	Dark grey to black shale with occasional sandstone	Deep marine to shelf environment
Sylhet limestone formation	Eocene	Massive limestone with minor shale and sandstone interbeds	Shallow marine, reef environments

Table 2 The concentration of different major oxides in the soil samples from XRF analysis

Major elements	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	TiO_2	P_2O_5	Cr_2O_3	MnO
LOC: 01	69.54	8.93	1.052	0.982	0.781	0.04	1.67	0.178	0.783	0.075	0.0050	0.077
LOC: 02	68.78	6.10	0.843	1.052	0.008	0.032	1.59	0.106	0.771	0.080	0.0007	0.06
LOC: 03	73.86	7.80	0.222	0.463	0.872	0.045	2.08	0.195	0.801	0.870	0.0007	0.106
LOC: 04	66.34	16.75	0.551	1.721	0.152	0.051	0.92	0.182	0.880	0.078	0.0018	0.127
LOC: 05	70.32	8.63	0.421	0.401	0.781	0.04	2.15	0.198	0.871	0.120	0.0018	0.105
LOC: 06	74.08	7.50	0.133	0.962	0.121	0.035	0.79	0.091	0.823	0.030	0.0103	0.105
LOC: 07	73.77	9.08	0.152	0.891	0.162	0.039	1.78	0.101	0.762	0.981	0.0002	0.093
LOC: 08	71.97	10.73	0.045	0.391	0.834	0.052	2.374	0.194	0.671	0.105	0.0002	0.084
LOC: 09	76.59	9.87	0.282	0.397	0.801	0.056	1.88	0.187	0.632	0.092	0.0002	0.072
LOC: 10	75.23	10.03	0.129	0.567	0.762	0.045	1.95	0.158	0.592	0.088	0.0009	0.065
LOC: 11	77.87	6.98	0.117	0.672	0.822	0.048	1.05	0.167	0.762	0.095	0.0002	0.053
LOC: 12	80.58	7.65	0.048	0.782	0.061	0.051	0.89	0.088	0.683	0.070	0.0002	0.033
LOC: 13	81.02	7.32	1.072	1.031	0.009	0.032	0.63	0.043	0.665	0.010	0.0046	0.057
LOC: 14	67.57	17.43	2.298	1.735	0.185	0.036	1.54	0.128	0.861	0.088	0.0009	0.089
LOC: 15	65.08	15.56	1.601	1.563	0.154	0.035	1.67	0.105	0.798	0.085	0.0032	0.053

Table 3 The concentration of different trace elements in the soil samples from XRF analysis (ppm)

Trace elements	Sc	Ni	Sr	Y	Zr	Nb	Co	Rb	Zn	Cu
LOC: 01	10,770	< 0.19	25.132	81.636	2279.058	15.57	< 0.03	33.97	235.94	< 1.95
LOC: 02	8553	< 0.19	92.152	49.35	714.221	10.304	< 0.03	165.342	162.34	< 1.95
LOC: 03	17,440	< 0.19	44.851	37.717	378.611	17.525	< 0.03	48.935	149.356	< 1.95
LOC: 04	13,560	< 0.19	60.438	53.501	692.049	27.477	< 0.03	170.532	216.458	< 1.95
LOC: 05	13,370	< 0.19	41.905	30.44	241.209	18.26	< 0.03	80.818	199.142	< 1.95
LOC: 06	9769	< 0.19	84.373	38.742	349.72	9.617	< 0.03	214.278	207.8	< 1.95
LOC: 07	13,310	< 0.19	70.012	35.614	672.564	16.486	< 0.03	143.84	190.602	< 1.95
LOC: 08	13,370	< 0.19	45.547	34.574	380.291	17.664	< 0.03	48.935	129.875	< 1.95
LOC: 09	11,190	< 0.19	46.375	35.515	539.193	15.498	< 0.03	59.316	142.862	< 1.95
LOC: 10	13,130	< 0.19	47.767	32.616	118.925	13.051	< 0.03	56.622	136.369	< 1.95
LOC: 11	6682	< 0.19	20.345	24.298	166.293	9.617	< 0.03	68.954	158.015	< 1.95
LOC: 12	4880	< 0.19	49.068	32.285	319.149	5.037	< 0.03	20.019	88.748	< 1.95
LOC: 13	10,530	< 0.19	59.839	21.867	460.582	16.953	< 0.03	141.616	175.331	< 1.95
LOC: 14	15,900	< 0.19	64.626	41.51	372.564	18.255	< 0.03	142.357	144.284	< 1.95
LOC: 15	10,210	< 0.19	89.759	72.411	541.881	16.486	< 0.03	143.099	129.875	< 1.95

geological history and depositional environment. Table 4 shows the identified minerals found in the 15 samples collected:

4.4 Petrographic analysis

Five medium- to fine-grained soil samples from Dupi Gaon, Sylhet, were analyzed petrographically (Fig. 3) to assess their mineral composition and textural characteristics. The analysis reveals several important aspects regarding the mineralogy and potential geological processes influencing these samples (Fig. 4).

4.5 Metallurgical microscope analysis

Heavy minerals, characterized by their density greater than 2.9 g/cm^3, contrast with light minerals, which are less than 2.9 g/cm^3 (Dickinson 1985). These heavy mineral assemblages are significantly influenced by provenance, weathering, transport, deposition, and diagenesis (Morton 1985). They are important indicators of source rocks and are extensively employed in foreland basin studies to trace sediment origins (Verma 1999). Around 30 translucent detrital mineral species are commonly used as provenance indicators, providing valuable insights into the source-rock lithology

Table 4 Identified different minerals within the soil samples from XRD analysis

Sample name	Identified minerals
LOC: 01	Muscovite, quartz, berlinite
LOC: 02	Quartz, biotite, chromite, muscovite, orthoclase, siderite, spinal, zircon
LOC: 03	Albite, anorthite, cliropyroxene, olivine, orthophyroxene, quartz, sanidite
LOC: 04	Muscovite, quartz, rutile
LOC: 05	Biotite, phlogopite, quartz
LOC: 06	Biotite, danalite, muscovite, quartz, rutile, sanidine, zircone
LOC: 07	Albite, danalite, muscovite, quartz, rutile, sanidine, yagiite, zircon
LOC: 08	Muscovite, olivine, pseudorutile, quartz, sillimanite, zeolite, zircon
LOC: 09	Albite, glauconite, pseudorutile, quartz, sillimanite
LOC: 10	Anorthite, magnetite, muscovite, pseudorutile, quartz, rutile, sanidine, zircon
LOC: 11	Biotite, magnetite, pseudorutile, quartz
LOC: 12	Magnetite, muscovite, quartz, sanidine, siderite, sillimanite
LOC: 13	Biotite, geothite, magnetite, muscovite, quartz, rutile, sanidine, spinel
LOC: 14	Biotite, chlorite, magnetite, muscovite, quartz, sanidine, siderite, zircon, kaolinite
LOC: 15	Berlinite, biotite, halvite, muscovite, quartz, zeolite

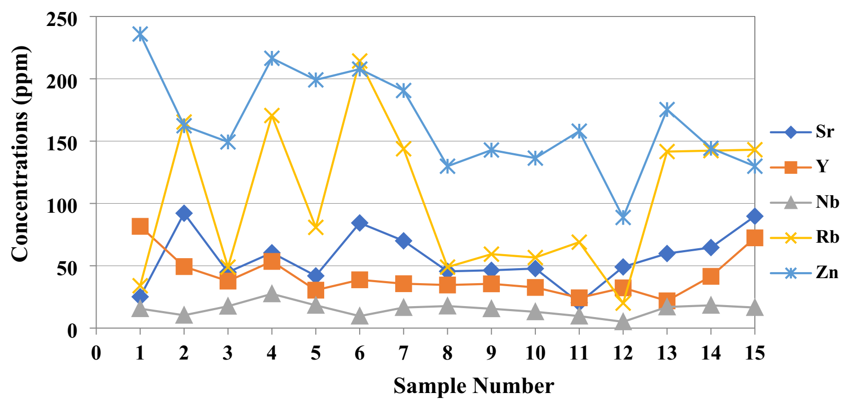


Fig. 3 Concentrations (ppm) of trace elements in the Dupi Tila samples

and enabling differentiation of sources within the same tectonic setting (Mange and Maurer 1992).

Heavy mineral suites are crucial for deciphering the geological history and the conditions of sedimentary environments. Despite potential alterations during sedimentary processes, certain minerals such as apatite, tourmaline, and zircon are known for their stability and resistance to weathering (Gnos et al. 1998). Consequently, varietal studies of heavy minerals often emphasize these stable species to evaluate the types of source rocks and their geological significance (Dickinson 1985; Mange and Maurer 1992).

Heavy mineral separation techniques are essential for isolating and analyzing specific minerals from sediment or rock samples. These samples are then examined using a metallurgical microscope (Olympus BX53M) with ×50 magnification (Figs. 5, 6, 7). This process typically includes the study of key minerals such as zircon, garnet, goethite, rutile, and magnetite, each of which provides valuable insights into sedimentary and geological processes (Mange and Maurer 1992).

5 Discussion

The Dupi Tilla Formation is a fluvial deposit predominantly composed of sandstone, siltstone, and occasional clay layers, indicative of high-energy depositional environments such as braided and meandering river systems. Sedimentary structures, including cross-bedding, ripple marks, and graded bedding, suggest episodic sedimentation influenced by fluctuations in river discharge, tectonic activity, and climatic variations during the Late Tertiary to Early Quaternary periods. Tectonic activity related to the Himalayan foreland basin likely facilitated the influx of coarse detrital materials, shaping the formation's depositional characteristics (Roy et al. 2012). Additionally, the formation serves as an essential aquifer, with permeable sandstone layers acting as significant reservoirs for groundwater, emphasizing its economic and geological importance (Goodbred and Kuehl 2000). The Dupi Tilla Formation highlights the dynamic interplay of fluvial processes, tectonism, and climate in the evolution of the Bengal Basin.

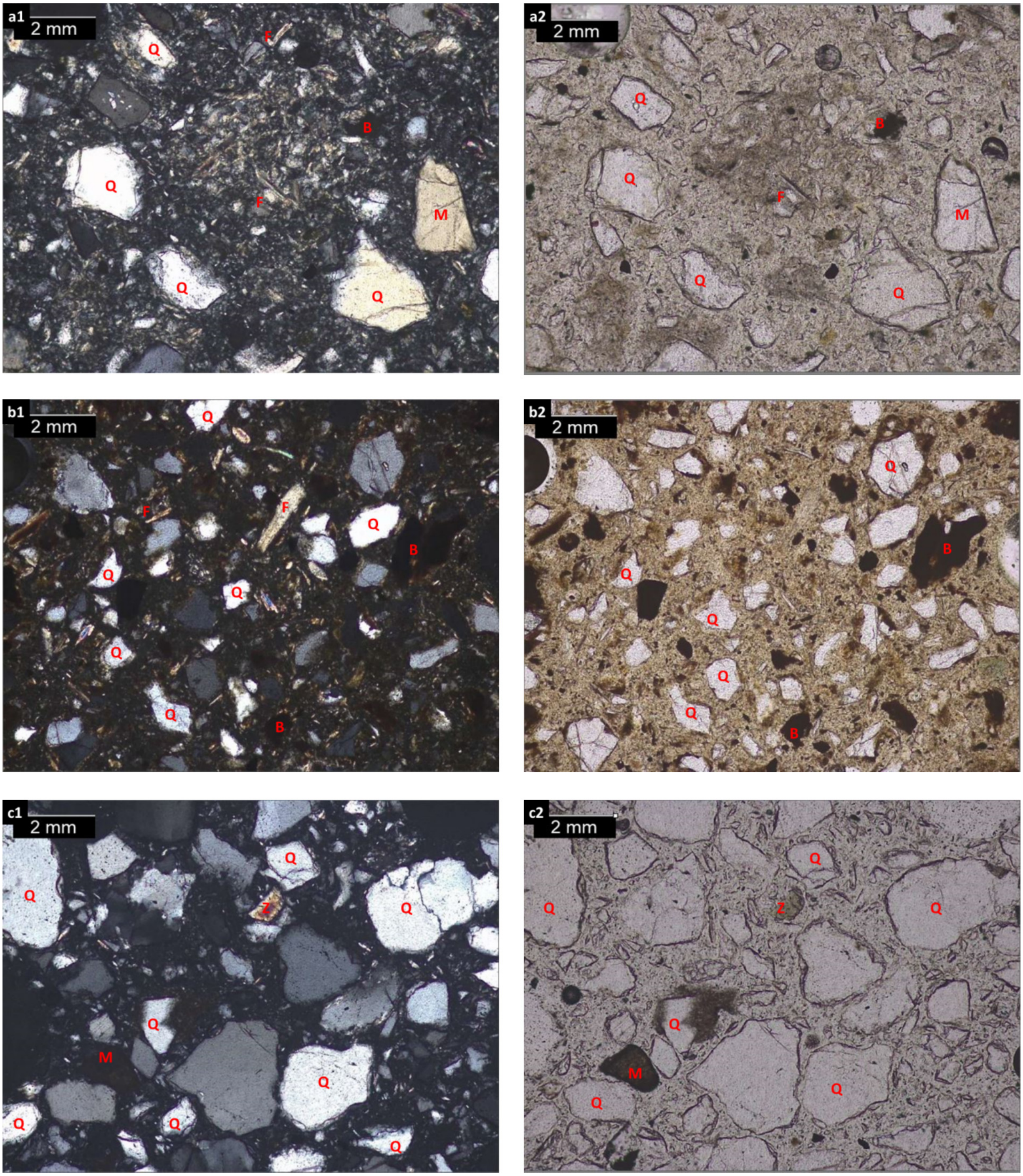


Fig. 4 Photomicrographs of soil samples: **a1**, **a2** LOC: 02; **b1**, **b2** LOC: 06; **c1**, **c2** LOC: 08; **d1**, **d2** of LOC: 13; **e1**, **e2** LOC: 14, showing major minerals within each

5.1 Depositional environment for the Dupi Tila formation

The geochemical analysis of the samples reveals insights into the weathering processes and mineralogical composition. Notably, there is a significant depletion of Na_2O relative to K_2O across all the samples, suggesting the likely destruction of plagioclase feldspar during weathering or its mobility at the depositional site. This observation is supported by the abundance of K-feldspar compared to plagioclase feldspar in the framework component study (Bhuiyan et al. 2004). The lower presence of CaO suggests intensified

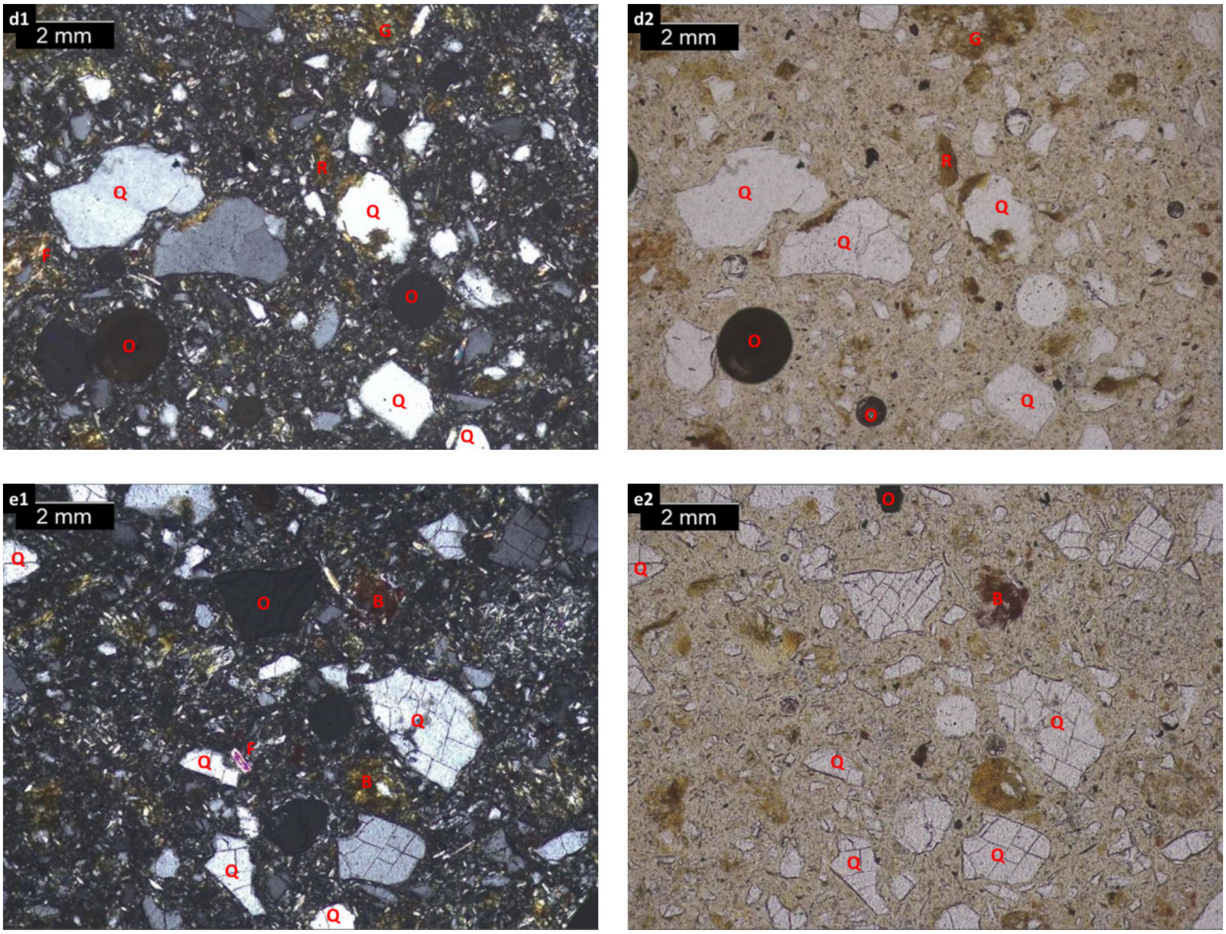


Fig. 4 (continued)

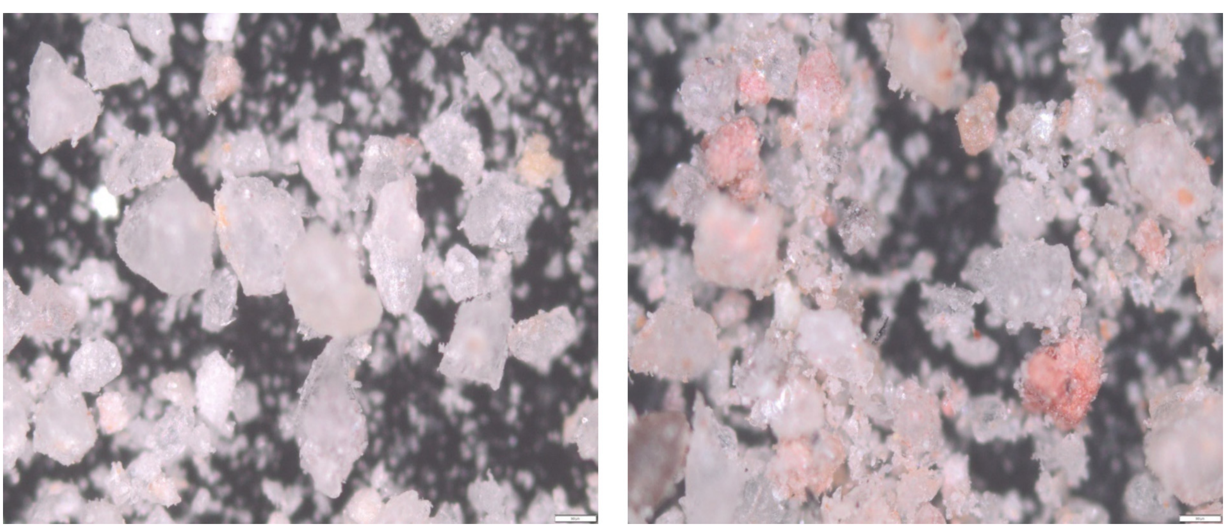


Fig. 5 A representative image of micrographs of heavy minerals from the collected sample from Dupi Gaon, Sylhet, shows zircon mineral dominance, which is white to pinkish white (LOC: 03 and 08)

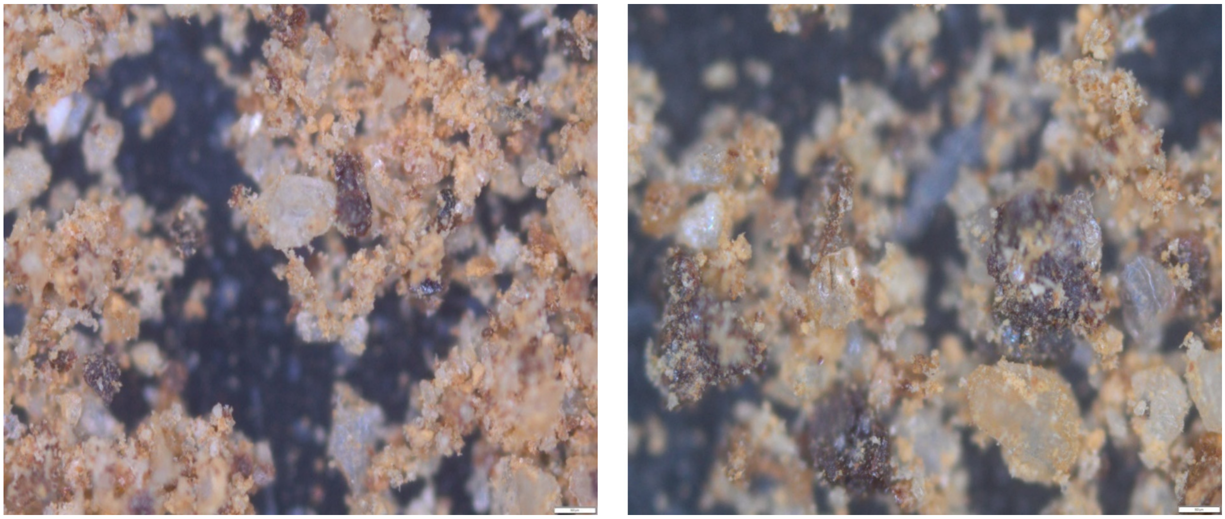


Fig. 6 Representative image of micrographs of heavy minerals from the collected sample from Dupi Gaon, Sylhet, showing garnet and geothite mineral dominance brown and dark brown (LOC: 05)

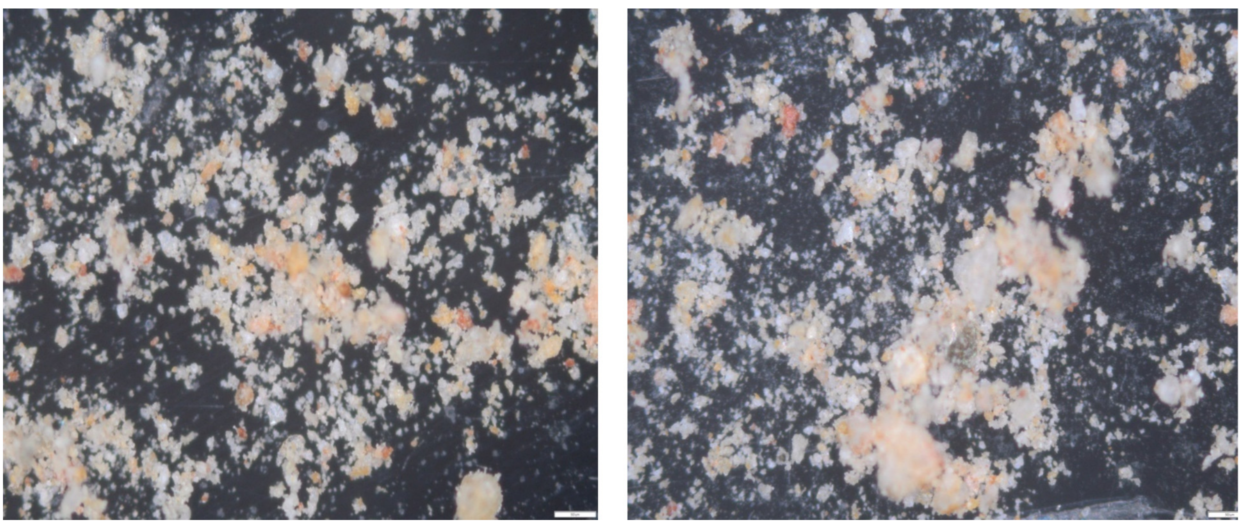


Fig. 7 A representative image of micrographs of heavy minerals from the collected sample from Dupi Gaon, Sylhet, shows magnetite mineral dominance, black or dark gray (LOC: 14)

weathering, particularly impacting the destruction of plagioclase feldspar.

Silica (SiO_2) concentrations are notably high in all the samples, ranging from 64 to 81% depending on the location. Additionally, Al_2O_3 is present in moderate amounts in samples from all the sites. These findings highlight the heterogeneity in the geochemical composition of the Dupi Tila Formation, reflecting diverse depositional and diagenetic processes within the formation (Alam et al. 2003; Johnson and Alam 1991; Uddin and Lundberg 1998a).

Concentrations of several oxides, including MgO, CaO, Na_2O, TiO_2, P_2O_5, MnO, and Cr_2O_3, were present across different locations in the Dupi Tila Formation samples. The data reveal that sediments from various locations exhibit relatively high concentrations of calcium oxide (CaO) and titanium dioxide (TiO_2), which suggest variations in the sedimentary sources and diagenetic conditions, which may be influenced by factors such as the presence of carbonate minerals and heavy mineral content, respectively (Alam et al. 2003; Johnson and Alam 1991; Uddin and Lundberg 1998a). This geochemical diversity underscores the complex depositional history and the dynamic geological processes at play in the Dupi Tila Formation.

The observed geochemical relationships within the Dupi Tila Formation demonstrate a linear trend between SiO_2 contents in the variograms of CaO, Fe_2O_3, Na_2O, Al_2O_3, and TiO_2, along with a decreasing trend between SiO_2 and MgO, as visualized in the Harker diagram (Fig. 8). These trends provide insights into the mineralogical and geochemical evolution of the formation.

The linear correlation between SiO_2 and oxides like CaO, Fe_2O_3, and Na_2O likely reflects compositional control by primary silicate minerals, such as feldspars and ferromagnesian minerals, influencing the silica content during weathering and sedimentation processes. The relationship with $Al_2O_3$and TiO_2 is indicative of their association with aluminosilicate minerals and heavy accessory phases like rutile or ilmenite, which remain relatively stable under weathering conditions (Roser and Korsch 1986).

The decreasing trend between SiO_2 and MgO suggests the preferential weathering or depletion of Mg-rich minerals, such as olivine or pyroxene, during the depositional processes. This behavior is consistent with the progressive breakdown of mafic minerals in fluvial systems, which results in silica enrichment in sedimentary deposits (Saha et al. 2020).

Such geochemical variations are typical in fluvial-dominated formations where sedimentary processes, provenance, and weathering play significant roles in determining the chemical composition. The trends observed in the Harker diagram for the Dupi Tila Formation align with studies of similar fluvial systems, where silica enrichment often corresponds to sediment maturity and mineralogical stabilization (Taylor and McLennan 1985).

One measure of the initial composition of the Dupi Tila Formation is the ratio of K_2O to Al_2O_3 (Fig. 9). The K_2O/Al_2O_3 ratios of mud rocks and clay minerals differ significantly. For clay minerals, the K_2O/Al_2O_3 ratios range from 0 to 0.3, while for feldspars, they range from 0.3 to 0.9 (Cox et al. 1995). The value of illite is 0.28 (Lee and Lee 2000). Samples from the research area appear to include clay minerals based on the K_2O/Al_2O_3 ratios.

The chemical composition of sediments, as determined by XRF data, can provide insights into the degree of weathering and diagenesis affecting the source terranes. This study analyzed and plotted data from 15 sediment samples on a ternary diagram, specifically the A-CN-K (($Al_2O_{3\_}$ (CaO + Na_2O) − K_2O)) plot. This plot assessed the weathering intensity and mineralogical changes in sedimentary rocks.

The results indicate that most samples fall along the Al_2O_3 end of the Al_2O_3-K_2O line, suggesting that the sediments have undergone significant weathering. This is consistent with the interpretation that the source terranes

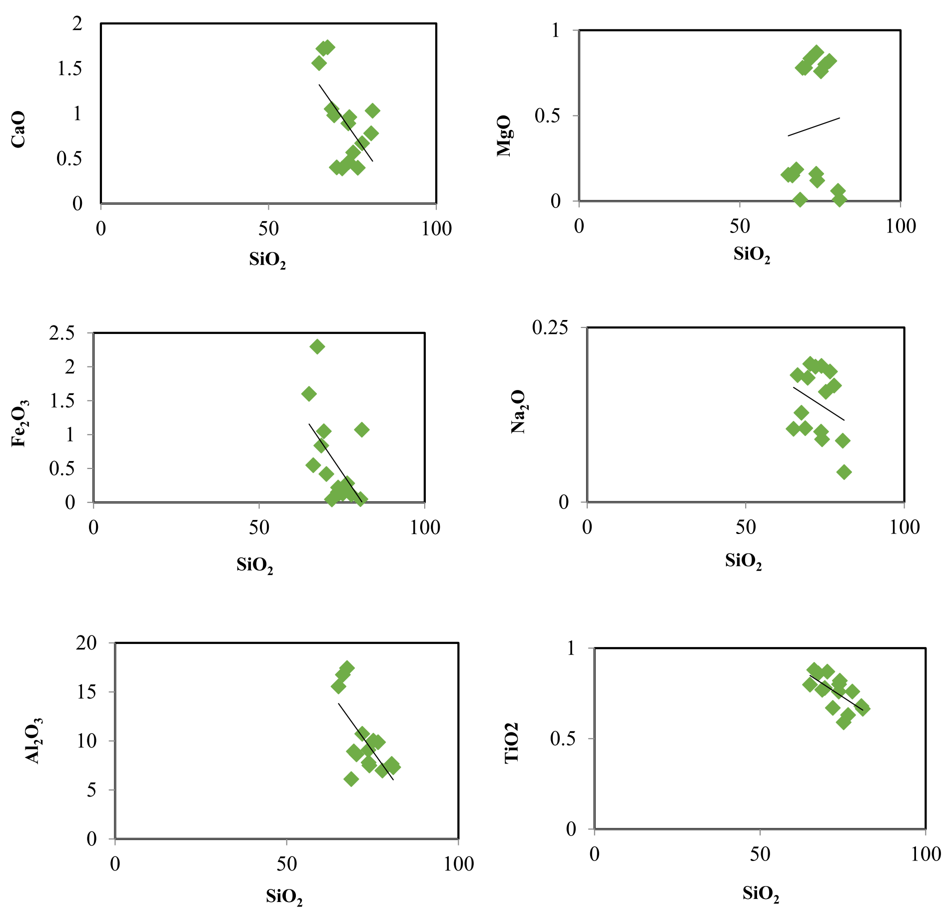


Fig. 8 Harker variograms of major element concentrations in the Dupi Tila Formation of Dupi Gaon samples

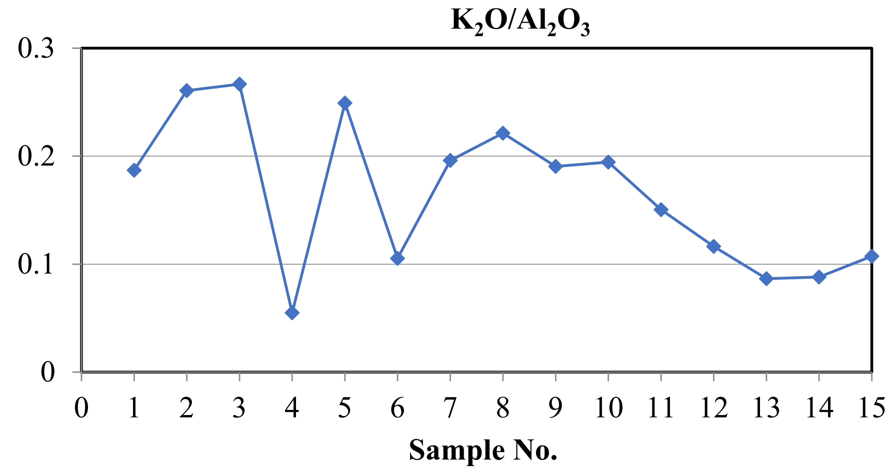


Fig. 9 Variations in K_2O/Al_2O_3 ratios from different locations of the Dupi Tila formation

experienced substantial chemical weathering before the sediments were deposited (Nesbitt and Young 1982a, b; Bhatia 1983). On the plot, many samples fall within the illite and muscovite fields (Fig. 10), indicating that these clay minerals are prominent in the weathered sediments, typical of environments experiencing advanced weathering processes (Roser and Korsch 1986).

Additionally, most of the samples fall into the average granite field in the Ternary plots (Fig. 10), suggesting that the source material also includes granite or granite-like rocks, which contribute to the sediment composition. The consistent placement of samples in these fields implies a uniform weathering process across the source area, which affects the mineralogical composition of the sediments similarly (McLennan et al. 1993a, b; Cullers 1994).

These findings collectively suggest that the sediments analyzed share a common history of weathering and diagenesis, reflecting similar processes that influenced their source regions. This uniformity in weathering patterns can provide valuable information about the sedimentary history and the geological processes shaping the source terranes.

The Chemical Index of Alteration (CIA) is a widely used geochemical tool for evaluating the degree of weathering in sedimentary rocks. This index helps understand the extent to which source rocks have been chemically altered over geological time. The CIA is calculated using:

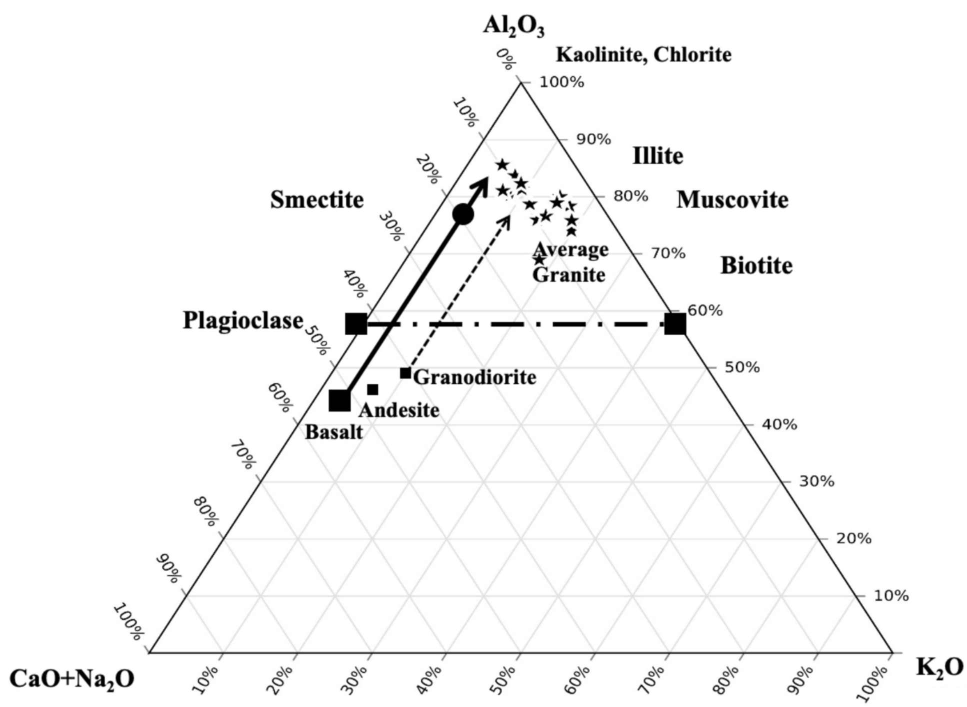


Fig. 10 Ternary plots of A-CN-K of Dupi Tila samples from the Dupi Tila Formation of Dupi Gaon (adapted from Nesbitt & Young 1982a, b; Soreghan & Soreghan 2007)

$$CIA = Al_2O_3/(Al_2O_3 + CaO + Na_2O + K_2O) \quad (1)$$

This formula compares the concentration of aluminum oxide (Al_2O_3) relative to the sum of alkali and alkaline earth oxides, reflecting the degree of chemical weathering. Higher CIA values generally indicate more intense weathering because they suggest a more significant loss of alkali and alkaline earth metals relative to aluminum, which is more resistant to weathering.

According to Nesbitt and Young (1982a, b), and supported by later studies (e.g., Soreghan and Soreghan 2007), rocks with low CIA values (50–60%) are considered relatively unweathered, indicating minimal chemical alteration. Intermediate CIA values (60%–80%) reflect moderate weathering, while high CIA values (80%–100%) suggest extensive weathering. The CIA values obtained in the analysis of the Dupi Tila Formation from Dupi Gaon, Sylhet, indicate an intermediate to a high degree of weathering (Fig. 11; Table 5), suggesting the Dupi Tila Formation has undergone significant chemical alteration. Intermediate to high CIA values imply that the sediments have experienced substantial weathering processes, which have affected their mineralogical and geochemical characteristics. High CIA values can also provide insights into the climatic conditions

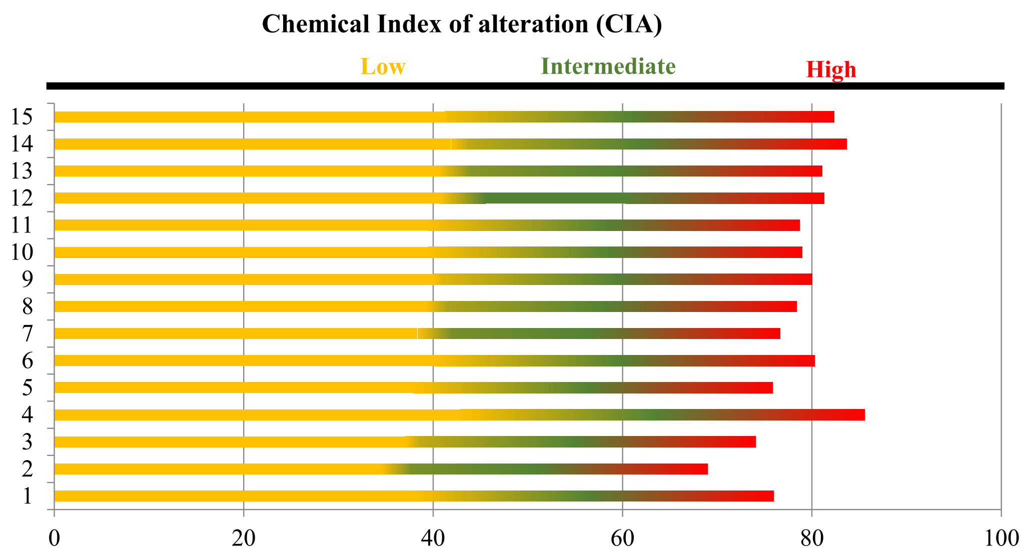


Fig. 11 CIA values of the Dupi Tila Formation of Dupi Gaon (adapted from Nesbitt & Young 1982a, b; Soreghan & Soreghan 2007)

Table 5 Calculated values of the Chemical Alteration Index (CIA)

Samples	Al_2O_3	$Al_2O_3 + CaO + Na_2O + K_2O$	$CIA = Al_2O_3 / (Al_2O_3 + CaO + Na_2O + K_2O)$ %
LOC: 01	8.93	11.758	75.948
LOC: 02	6.10	8.846	68.958
LOC: 03	7.80	10.535	74.039
LOC: 04	16.75	19.572	85.581
LOC: 05	8.63	11.379	75.841
LOC: 06	7.50	9.340	80.300
LOC: 07	9.08	11.851	76.618
LOC: 08	10.73	13.689	78.384
LOC: 09	9.87	12.334	80.023
LOC: 10	10.03	12.705	78.945
LOC: 11	6.98	8.867	78.719
LOC: 12	7.65	9.408	81.314
LOC: 13	7.32	9.027	81.090
LOC: 14	17.43	20.829	83.681
LOC: 15	15.56	18.895	82.350

during deposition, as increased weathering is often associated with more humid and chemically active environments.

Several distinct trends in analyzing trace elements (Table 3) in the sediment samples provide insights into the sediments' geological processes and source characteristics. Zr consistently shows high concentrations across all locations, ranging from 241 to 2279 ppm. This elevated level of Zr suggests a significant presence of zircon minerals in the sediments. Zircon minerals are known to be stable and resistant to weathering, often indicating a persistent source or stable depositional conditions (Hoskin and Schaltegger 2003). A lesser amount of Cu in detrital sedimentary rocks, particularly below 1.95 ppm, suggests that the source rocks were low in Cu-bearing minerals or that the sediments underwent intense weathering and leaching in an oxidizing environment (Rudnick and Gao 2003). This low Cu concentration may also indicate high-energy depositional conditions where fine particles, including those containing Cu, were winnowed out or post-depositional diagenetic processes that further depleted Cu content (Turekian and Wedepohl 1961). Sr, Y, and Zn are found (Table 3) in moderate concentrations, ranging from 20 to 90, 21 to 82, and 88.75 to 216.46 ppm for Sr, Y, and Zn, respectively. Moderate levels of these elements can provide clues about the sediment's source rocks and the conditions under which they were deposited. Variations in the concentrations of these elements may indicate different geological or depositional environments affecting the sediments (Taylor and McLennan 1985). Ni, Co, and rubidium (Rb) generally show lower concentrations, predominantly below 50 ppm. Specifically, some elements like Ni and Co were reported to show a concentration below the detection limit of the analytical method used. Nb (Table 3) also exhibits low concentrations, typically below 20 ppm, stipulating their low abundance in the source rocks or the specific conditions of sedimentary processes that influenced their concentration (Cullers 2002). The consistent concentrations of Zr (Table 3) suggest uniformity in their sources, pointing to stable geological conditions or consistent source rock characteristics. In contrast, the variations in the Sr, Y, and Zn concentrations across different locations indicate potential differences in geological settings or sedimentary environments. These variations provide valuable information about the sediments' depositional history and source characteristics, helping to reconstruct the geological processes (Saini and Mujtaba 2012) that shaped the Dupi Tila Formation.

The XRD analysis (Table 4) of sandstone samples from various locations provides a comprehensive overview of their mineralogical diversity, offering insights into the formations' geological history and depositional environments. Quartz, consistently present in all the samples, indicates a substantial contribution of siliciclastic material, suggesting that the sandstones are primarily composed of quartz grains, a common feature in many sedimentary rocks (McLennan et al. 1993a, b). The prevalence of quartz often reflects substantial weathering and transportation processes typical in sedimentary environments. Mica minerals, such as muscovite, biotite, and chlorite, are also identified, pointing to significant contributions from the weathering of primary rocks. Mica is generally derived from metamorphic or igneous parent rocks and indicates the mineralogical complexity in the source areas (Bhatia and Crook 1986). The presence of these minerals suggests that the source rocks were likely subjected to intense weathering and erosion before the sediment was deposited.

Accessory minerals, such as rutile, magnetite, and siderite, add to the mineralogical diversity, reflecting varying degrees of sedimentary processes and source rock types. Rutile and magnetite are commonly associated with high-temperature igneous and metamorphic processes, while siderite may form in reducing environments (Hayashi et al. 1997). Their presence highlights the complex geological history and the influence of different depositional conditions on the sandstones. Variations in mineral composition among the samples are noteworthy. For instance, samples with higher abundances of muscovite and biotite suggest a more significant input of mica-rich source material, which may indicate proximity to metamorphic or granitic source regions (Roser and Korsch 1986). This variation can provide valuable information about the sediment transport and deposition history. On the other hand, minerals such as sanidine, zircon, and pseudorutile indicate different source rocks and possibly different depositional environments (Nesbitt and Young 1996). Sanidine and zircon are often found in volcanic rocks, suggesting that volcanic activity may have influenced the sediment composition.

Quartz is the dominant mineral across all petrographic samples, reflecting a significant contribution from quartz-rich sedimentary or igneous source rocks (Götte and Ramseyer 2012). This prevalence of quartz is significant because it often indicates a stable, mature sedimentary environment or extensive weathering of igneous rocks (Klein and Dutrow 2007). The quartz grains in these samples exhibit fractures, which may suggest that tectonic forces or mechanical disturbances have played a role in altering the sediments. These fractures indicate stress or strain experienced by the sedimentary rocks during transport or post-deposition (Roser and Korsch 1986). Feldspar minerals, such as orthoclase, plagioclase, and microcline, are present but in relatively low quantities compared to quartz. Feldspar is a common mineral in many igneous and metamorphic rocks, and its lower abundance in these samples suggests it may be a minor or accessory mineral phase (Harrison et al. 1999). The low feldspar content could imply a significant degree of weathering or sorting, where feldspar has been preferentially removed or altered during sediment transport or depositional processes (Klein and Dutrow 2007).

Metallurgical analyses have revealed the presence of zeolite and kaolinite, which indicate potential post-depositional alteration processes. Zeolites are typically formed in low-temperature, alkaline environments, suggesting an alteration in the sedimentary basin (Hay and Sheppard 2001). Kaolinite, a clay mineral, often forms in tropical weathering conditions, which might indicate extensive chemical weathering of the source rocks or pedogenic processes affecting the sediment (Levinson 1980). Goethite, characterized by its brownish-yellow to brownish-black color, forms during weathering and diagenesis and can indicate the degree of weathering and post-depositional alterations affecting the sediment (Till et al. 2015). The mineral's presence also provides insights into the redox conditions of the depositional environment. With its distinctive golden to reddish-brown color, Rutile is stable in various metamorphic conditions and helps assess the thermal history and source rock characteristics (Zack et al. 2004). Its inclusion in the mineral assemblage provides valuable information about the metamorphic history of the source rocks. Magnetite, known for its dark black color and metallic luster, contributes to the magnetic properties of sediments and can reveal details about the magnetic history, depositional environment, and source rock characteristics (Liu et al. 2022). Its presence is also helpful for inferring paleoclimatic conditions and sedimentary processes. Examining these minerals under a metallurgical microscope offers essential insights into the study area's sedimentary processes and geological history. By analyzing the mineralogical composition and texture, researchers can better understand the source-rock lithology, sedimentary environments, and tectonic influences that have shaped the sedimentary deposits.

5.2 Tectonic setting for the Dupi Tila formation

Provenance analysis provides valuable insights into the depositional history, source rock characteristics, and tectonic settings of sedimentary formations. Researchers can decode the processes that shaped formations like the Dupi Tila by integrating geochemical and petrographic techniques. Bulk chemical studies, which emphasize trace elements, offer an efficient alternative to the labor-intensive identification of heavy minerals, as noted by Von Eynatten et al. (2003). Petrographic studies are inherently more instructive than bulk rock chemistry, as rock chemistry results from a rock's mineralogical composition. Different tectonic regimes produce sandstones with distinct chemical compositions. Several researchers, such as Roser and Korsch (1986) and Sitaula (2009), have used SiO_2 content and K_2O/Na_2O ratios to distinguish between the geological settings of the source location. These approaches allow for a more comprehensive understanding of sediment provenance and the tectonic history of sedimentary basins.

Figure 12 shows the SiO_2 versus K_2O/Na_2O plot for all the examined samples, which indicates an active continental provenance. Island Arc or Passive Margin provenances are absent from all samples. The SiO_2 versus K_2O/Na_2O ratio used in this discrimination diagram helps classify the tectonic setting of sedimentary rocks by distinguishing between different geological environments, such as passive margins, active continental margins, and island arcs. Falling into the active tectonic setting category indicates that the sediments were likely influenced by processes associated with convergent plate boundaries or other tectonically dynamic regions, which often result in higher K_2O/Na_2O ratios and varying SiO_2 content due to the mixing of volcanic and continental materials (Roser and Korsch 1986). All the samples of the Dupi Tila Formation fall within the active tectonic setting

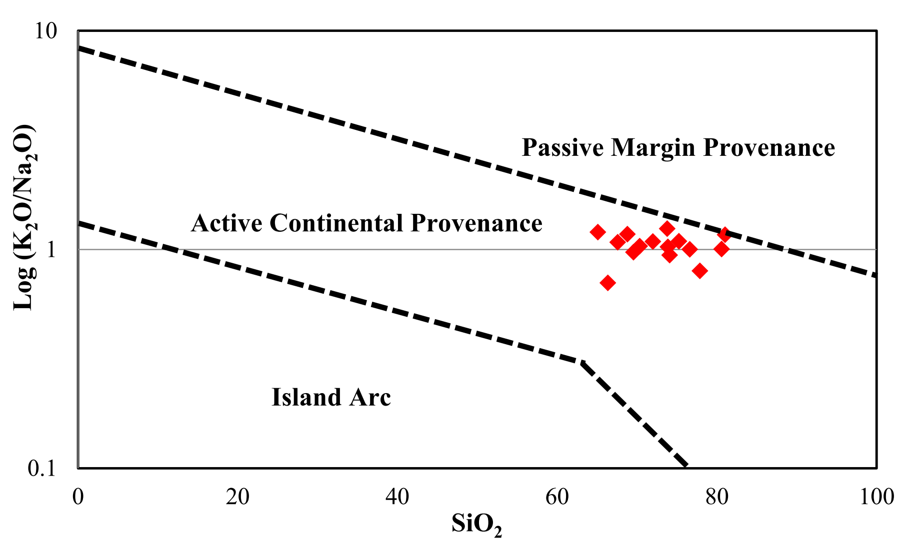


Fig. 12 The Dupi Tila Formation's samples are plotted in a tectonic discrimination diagram (SiO_2 vs. K_2O/Na_2O) from Roser & Korsch (1986)

region on the tectonic discrimination diagram (SiO_2 vs. K_2O/Na_2O) by Roser and Korsch (1986), indicating that the sedimentary rocks of this formation were derived from a tectonically active area. This suggests that the source region for these sediments was influenced by significant tectonic activity, such as volcanism, active faulting, or mountain-building processes. In such environments, erosion and weathering of rocks are typically more intense, leading to the production of sediments with specific geochemical signatures (Roser and Korsch 1986).

When the TiO_2 versus Zr plots of Hayashi et al. (1997) place the Dupi Tila Formation samples within the felsic igneous rock field (Fig. 13), it indicates that the source material for these sediments primarily originated from felsic igneous rocks. Felsic igneous rocks, such as granite and rhyolite, are characterized by high silica (SiO_2) content and significant amounts of zirconium (Zr) and titanium dioxide (TiO_2) (Hayashi et al. 1997). This feature also implies that the erosion and weathering processes affecting these parent rocks contributed to sediments rich in Zr and TiO_2, reflecting the geochemical characteristics typical of felsic igneous rocks. Such a geochemical signature can be used to infer the nature of the source area and the tectonic setting during sediment deposition (Hayashi et al. 1997).

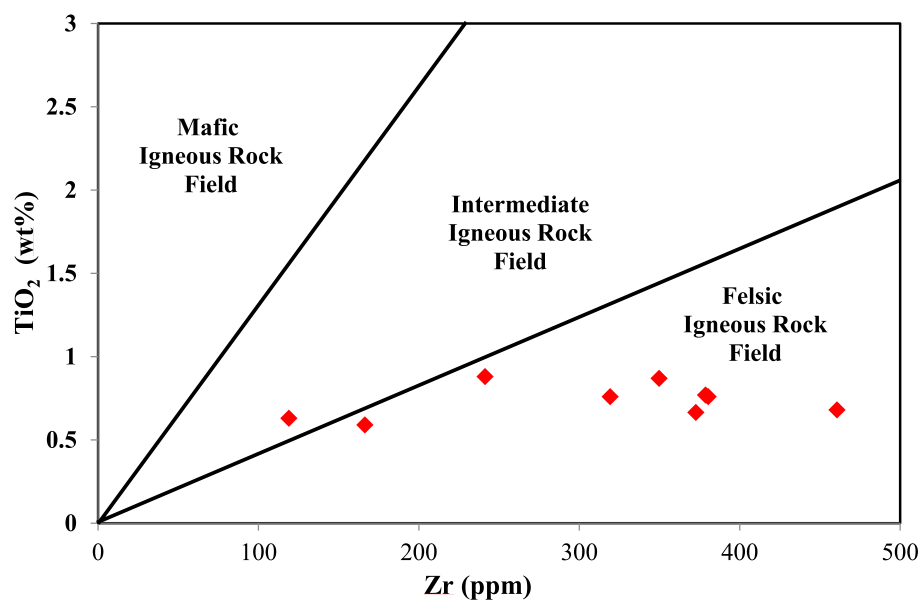
Identifying albite, orthopyroxene, and olivine in some petrographic samples provides additional clues about the sediments' provenance. Albite is a common plagioclase feldspar found in igneous rocks, while orthopyroxene and olivine indicate high-temperature metamorphic and igneous processes (Shaw 1972). Their presence can help reconstruct the geological history of the source regions.

Furthermore, the occurrence of zeolite and kaolinite points to post-depositional alteration processes that have affected the sandstones. Zeolites often form in volcanic and sedimentary environments, whereas kaolinite typically results from chemical weathering in tropical climates (Sitaula 2009). These minerals indicate that the sandstones have undergone significant diagenesis, which has altered their original mineral composition over time.

In addition to quartz, the samples contain several opaque minerals, including biotite, muscovite, and magnetite. Biotite and muscovite, which are mica minerals, are known for their sheet-like structures and are commonly found in metamorphic and igneous rocks (Levinson 1980). The presence of these mica minerals points to possible metamorphic or igneous origins of the source material. Magnetite, an iron oxide mineral, is particularly noteworthy as it can impart magnetic properties to the sediments, which can help understand past depositional environments and geochemical conditions (Bhatia and Crook 1986). Magnetite may also reflect specific redox conditions during sediment deposition or diagenesis (Mason and Moore 1982).

Zircon is a significant mineral commonly observed in sedimentary samples due to its durability and resistance to weathering, making it an excellent indicator of sediment provenance and geochronology (Dickinson 1985). Its translucent or transparent appearance, ranging from colorless to pale brown or pinkish-white, can reveal critical information about the age and origin of the sedimentary material. Garnet, with its deep red to reddish-dark brown color, often forms under high-pressure conditions and reflects the metamorphic history of the source rocks. Its presence can help reconstruct the tectonic setting and metamorphic processes that influenced the source region (Wu et al. 2021).

Fig. 13 TiO_2 vs. Zr plots of Dupi Tila samples from Dupi Gaon, Sylhet. Fields are taken from Hayashi et al. (1997)



6 Conclusion

The Dupi Tila Formation in Sylhet, Bangladesh, is a significant geological feature within the Bengal Basin. It is characterized by its extensive sedimentary layers, which span from the Early Cretaceous to the Holocene epoch. This long and complex depositional history reflects the region's dynamic sedimentary processes and active tectonic environment, influenced by intricate tectonic activities and pop-up tectonics.

Comprehensive analyses using techniques like X-ray fluorescence (XRF) and X-ray diffraction (XRD) have been instrumental in uncovering the formation's composition and depositional history. XRF analysis revealed significant elements such as SiO_2, Al_2O_3, and Fe_2O_3, which indicate the formation's mineralogical framework. At the same time, elements like zirconium (Zr) ranging from 241.209 to 2279.058 ppm suggest a common source for the element. The relatively lower concentration of Cu, mainly when it is less than 1.95 ppm, may imply its limited detrital input and possible connection to specific depositional environments, such as reduced or low-energy settings. In contrast, variations in strontium (Sr), yttrium (Y), and zinc (Zn) point to diverse depositional environments, while nickel (Ni), cobalt (Co), and rubidium (Rb) generally appeared in lower concentrations, with some trace elements falling below detection limits, underscoring the necessity for further geochemical exploration.

XRD analysis provided further insights into the formation's mineralogical composition, revealing dominant minerals such as quartz, muscovite, biotite, and several accessory minerals like rutile and magnetite. The prevalence of quartz across all samples suggests a quartz-rich sedimentary or igneous source. At the same time, the presence of mica minerals, including muscovite and biotite, indicates a provenance rich in mica. Accessory minerals like rutile, magnetite, and siderite add to the mineralogical diversity, and the presence of albite, orthopyroxene, and olivine provides additional evidence about sediment provenance. The occurrence of minerals like zeolite and kaolinite suggests post-depositional processes.

Petrographic analysis of soil samples from Dupi Gaon identified quartz as the dominant mineral, likely derived from quartz-rich source rocks. The presence of fractures within quartz grains and opaque minerals like biotite and muscovite suggests tectonic influences and provides further insights into the depositional environment. Feldspar minerals, though present, are less abundant, suggesting they are a minor component of the formation.

Heavy mineral separation techniques enriched our understanding of the Dupi Tila Formation by identifying key minerals such as zircon, garnet, goethite, rutile, and magnetite. These minerals provide valuable information about sediment provenance, depositional processes, and environmental conditions during sediment formation.

Integrating petrographic, geochemical, and heavy mineral analyses offers a comprehensive understanding of the Dupi Tila Formation's mineralogical composition, depositional environments, and geological history. This study highlights the complex interplay of weathering processes, tectonic activities, and sedimentary dynamics that have shaped this significant geological formation, emphasizing the role of trace elements like copper in interpreting depositional conditions.

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Author contributions Ummae Habiba Sultana: Data collection, conceptualization, methodology, data analysis, and manuscript writing. Md Shofiqul Islam: Data collection, conceptualization, methodology, data analysis, and manuscript writing. Yesmin Nahar Jolly: Experimental analysis, manuscript editing. K.M. Mamun: Experimental analysis, manuscript editing. Shirin Akter: Experimental analysis, manuscript editing. Muhammad Omar Faruk: Experimental analysis, manuscript editing. Maliha Anzuman: Data collection, conceptualization, methodology. Md Masud Karim: Experimental analysis, manuscript editing.

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Code availability No custom software or code was used in this research. N/A.

Declarations

Conflict of interest The authors declare no conflicts of interest or competing interests relevant to this research.

Ethical approval This study did not involve human participants or animals, so ethical approval was not required. N/A.

Consent to participate As this research did not involve human subjects, consent to participate is not applicable. N/A.

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References

Alam M, Alam MM, Curray JR, Chowdhury MLR, Gani MR (2003) An overview of the sedimentary geology of the Bengal Basin in relation to the regional tectonic framework and basin-fill history. Sed Geol 155(1–2):75–103. https://doi.org/10.1016/S0037-0738(02)00262-5

Alam M, Curray JR, Munasinghe J (2013) Lithostratigraphy and depositional history of the Bengal Basin, Bangladesh. J Asian Earth Sci 70:1–21. https://doi.org/10.1016/j.jseaes.2012.12.013

Bassis A, Hinderer M, Meinhold G (2016) Petrography and geochemistry of Palaeozoic quartz-rich sandstones from Saudi Arabia: implications for provenance and chemostratigraphy. Arab J Geosci 9:400. https://doi.org/10.1007/s12517-016-2412-z

Bhatia M (1983) Plate tectonics and geochemical composition of sandstones. J Geol 91(4):613–627. https://doi.org/10.1086/628802

Bhatia MR, Crook KAW (1986) Trace element characteristics of greywacke and tectonic setting discrimination of sedimentary basins. Contrib Miner Petrol 92(3):230–238. https://doi.org/10.1007/BF00396550

Bhuiyan MH, Chowdhury KR, Rahman MJJ (2004) An approach to the provenance of Dupi Tila formation of the Bengal basin, Bangladesh: Constraints from model composition and heavy minerals of sandstone. Bangladesh Geosci J 10:61–81

Chowdhury AH, Rahman MM, Tareq HM (2006) Lithostratigraphy and sedimentology of the Surma Basin, Bangladesh: a review. Sed Geol 185(1–2):1–25. https://doi.org/10.1016/j.sedgeo.2005.12.003

Cox R, Lowe DR, Cullers RL (1995) The influence of sediment recycling and basement composition on evolution of mudrock chemistry in the southwestern United States. Geochim Cosmochim Acta 59(4):2919–2940. https://doi.org/10.1016/0016-7037(95)00185-9

Cullers RL (1994) The controls on the chemical composition of sedimentary rocks. Geol Soc Am Spec Pap 289:61–70. https://doi.org/10.1130/SPE289-p61

Cullers RL (2002) The controls on the major and trace element chemistry of sedimentary rocks: implications for provenance studies. J Geol 110(4):423–446. https://doi.org/10.1086/340702

Curray JR (1991) Late tertiary and quaternary history of the Bengal basin and adjacent areas. Sed Geol 71(1–4):127–141. https://doi.org/10.1016/0037-0738(91)90048-7

Curray JR, Munasinghe T (1991) Origin of the Rajmahal Traps and the 85° E Ridge: preliminary reconstructions of the trace of the Crozet hotspot. Geology 19(12):1237–1240. https://doi.org/10.1130/0091-7613(1991)019%3c1237:OOTRTA%3e2.3.CO;2

Dickinson WR (1985) Interpreting detrital heavy mineral assemblages: an overview. J Sediment Petrol 55(4):643–654. https://doi.org/10.1306/212F8B2A-2B24-11D7-8648000102C1865D

Doe J, Roe P (2018) Advanced techniques in X-ray diffraction analysis. J Crystallograp 54(6):1035–1045. https://doi.org/10.1016/j.jcrysgro.2018.04.025

Evans D (1932) The geology of the Sylhet district. Mem Geol Survey India 66:1–248

Ferdous N, Farazi AH (2016) Geochemistry of Tertiary sandstones from southwest Sarawak, Malaysia: implications for provenance and tectonic setting. Acta Geochim 35:294–308. https://doi.org/10.1007/s11631-016-0098-2

Gazi MY, Apu SI, Sharmili N, Rahman MZ (2021) Origin and characterization of clay deposits in the Dupi Tila formation of the Bengal basin. Bangladesh Solid Earth Sci 6(3):313–327. https://doi.org/10.1016/j.sesci.2021.07.001

Gnos E, Esser RP, Robinson P (1998) Zircon and apatite in heavy mineral suites: a case study from the Miocene of southern California. Sed Geol 116(1–2):31–49. https://doi.org/10.1016/S0037-0738(98)00051-3

Goodbred SL, Kuehl SA (2000) The significance of large sediment supply, active tectonism, and eustasy on margin sequence development: late quaternary stratigraphy and evolution of the Ganges-Brahmaputra delta. Sed Geol 133(3–4):227–248. https://doi.org/10.1016/S0037-0738(00)00041-5

Götte T, Ramseyer K (2012) Trace element characteristics, luminescence properties and real structure of quartz. In: Götze J, Möckel R (eds) Quartz: deposits, mineralogy and analytics. Springer, Berlin, Heidelberg, pp 265–285. https://doi.org/10.1007/978-3-642-22161-3_12

Harrison TM, Dodson MH, McDougall I (1999) A critical evaluation of the "closure temperature" concept and its application to geochronology. Geochim Cosmochim Acta 63(1):103–113. https://doi.org/10.1016/S0016-7037(99)00119-2

Hay RL, Sheppard RA (2001) Occurrence of zeolites in sedimentary rocks: an overview. Rev Mineral Geochem 45(1):217–234. https://doi.org/10.2138/rmg.2001.45.6

Hayashi KI, Fujisawa H, Holland HD, Ohmoto H (1997) Geochemistry of 1.9 Ga sedimentary rocks from Northeastern labrador, Canada. Geochim Cosmochim Acta 61(19):4115–4137. https://doi.org/10.1016/S0016-7037(97)00214-7

Hiller J, Elahi MA (1984) The Dauki Fault and the tectonic evolution of the Shillong Plateau. India Tectonophysics 104(3–4):371–388. https://doi.org/10.1016/0040-1951(84)90257-3

Hoskin PWO, Schaltegger U (2003) The composition of zircon and igneous and metamorphic petrogenesis. Rev Mineral Geochem 53(1):27–62. https://doi.org/10.2113/0530027

Islam MS, Shinjo R, Kayal JR (2011) Pop-up tectonics of the Shillong Plateau in northeastern India: Insight into tectonic and geodynamic processes. Tectonics 30(2):TC2005. https://doi.org/10.1029/2010TC002832

Jahan S, Uddin A (2022) Organic petrography and depositional environments of the upper Eocene Kopili Shale, Bengal Basin, Bangladesh. J Asian Earth Sci: X 7:100092. https://doi.org/10.1016/j.jaesx.2022.100092

Johnson TD, Alam MN (1991) A geological history of the Bengal Basin. J Asian Earth Sci 6(3):259–270. https://doi.org/10.1016/0743-9547(91)90016-J

Jolly YN, Rana S, Akter S, Kabir J, Rahman MS, Rahman MM, Sultana MS (2020) Appraisal of metal pollution in the aquatic environment of Shitalakhya River, Bangladesh, and its ecological risk assessment. J Nat Sci Sustain Technol 12(4):1933–2324

Jolly YN, Rakib MRJ, Kumar R, Islam ARMT, Rabby A, Mamun KM, Akter S, Kabir J, Bhuiyan TJ, Chowdhury AMS, Idris AM (2023) Deciphering the source of heavy metals in industrially affected river sediment of Shitalakshya River, Bangladesh, and potential ecological and health implications. J Hazard Mater Adv 10:100268. https://doi.org/10.1016/j.hazadv.2023.100268

Jones A, Brown B (2020) Standards in X-ray diffraction analysis. Mater Sci Forum 100(2):89–102. https://doi.org/10.4028/www.scientific.net/MSF.100.89

Klein C, Dutrow B (2007) The manual of mineral science. John Wiley & Sons, New York

Lee JI, Lee YI (2000) Provenance of the Lower Cretaceous Hayang Group, Gyeongsang Basin, southeastern Korea: implications for continental-arc volcanism. J Sediment Res 70(1):151–158

Levinson AA (1980) Introduction to exploration geochemistry. Applied Publishing, p 924

Lietz HJ, Kabir A (1982) Structural and sedimentological evolution of the Surma Basin. Bangladesh Geologischerundschau 71(1):203–224. https://doi.org/10.1007/BF01830176

Liu Y-X, Li W-Y, Liu Z-Y, Zhao J-W, Cao A-Q, Gao S, Wang L-J, Yang C (2022) Occurrence characteristics of magnetite and aeromagnetic prospecting northeast of Hebei Province. Minerals 12(9):1158. https://doi.org/10.3390/min12091158

Mange MA, Maurer HFW (1992) Heavy minerals in colour. Chapman & Hall, London, p 147. https://doi.org/10.1007/978-94-011-2308-2

Mason B, Moore CB (1982) Principles of geochemistry, 4th edn. John Wiley & Sons, New York

McLennan SM, Hemming S, McDaniel DK, Hanson GN (1993a) Geochemical approaches to sedimentation, provenance, and tectonics. In: Johnson MJ, Basu A (eds) Processes controlling the composition of clastic sediments: Geological Society of America. Special Paper

McLennan SM, Hemming S, McDaniel DK, Hanson GN (1993b) Geochemical approach to sediment provenance and tectonic setting. J Geol 101(6):709–729. https://doi.org/10.1086/648274

Morton AC (1985) Heavy mineral assemblages and provenance. In: Provenance of metamorphic rocks (pp. 141–154). Springer. https://doi.org/10.1007/978-94-009-3385-2_7

Munim MA (2017) Petrofacies evolution of Upper Siwalik-equivalent (?) Pliocene-Pleistocene Dupi Tila Formation, Bengal Basin, Bangladesh. Auburn University, Auburn, AL, p. 141

Nesbitt HW, Young GM (1982a) Early Proterozoic climate and plate tectonics: evidence from major element chemistry of shales. Geochim Cosmochim Acta 46(7):1619–1629. https://doi.org/10.1016/0016-7037(82)90256-4

Nesbitt HW, Young GM (1982b) Early Proterozoic climates and plate motions inferred from major element chemistry of lutites. Nature 299:715–717

Nesbitt HW, Young GM (1996) Early Proterozoic climate and plate tectonics: evidence from major elements and Nd isotopes in shales. Geochim Cosmochim Acta 60(11):1683–1698. https://doi.org/10.1016/0016-7037(96)00061-8

Rai LK, Yoshida K (2021) Sedimentary facies analysis of the fluvial environment in the Siwalik group of eastern Nepal: Deciphering its relation to contemporary Himalayan tectonics, climate, and sea-level change. Prog Earth Planet Sci 8:49. https://doi.org/10.1186/s40645-021-00444-5

Reimann KU (1993) Geology of Bangladesh. Gebruder Brontraeger, Stuttgart, p 160

Rigaku (2021) Rigaku smart lab X-ray diffractometer specifications. Retrieved from https://www.rigaku.com/smartlab

Roser BP, Korsch RJ (1986) Determination of tectonic setting of sandstone-mudstone suites using SiO2 content and K2O/Na2O ratio. J Geol 94(5):635–650. https://doi.org/10.1086/629847

Roser BP, Korsch RJ (1988) Provenance signatures of sandstone-mudstone suites determined using discriminant function analysis of major-element data. Chem Geol 67(1–2):119–139. https://doi.org/10.1016/0009-2541(88)90017-6

Roy MK, Ahmed SS, Bhattacharjee TK, Mahmud S, Moniruzzaman M, Haque MM, Saha S, Molla MI, Roy PC (2012) Paleoenvironment of deposition of the Dupi Tila Formation, Lalmai Hills, Comilla, Bangladesh. J Geol Soc India 80(3):409–419. https://doi.org/10.1007/s12594-012-0159-z

Rudnick RL, Gao S (2003) Composition of the continental crust. Treatise Geochem 3:1–64. https://doi.org/10.1016/B0-08-043751-6/03016-4

Saha S, Ahmed S, Roy M (2020) Provenance and depositional environment of Dupi Tila sandstones from Sylhet Basin Bangladesh. J Asian Earth Sci 196:104346. https://doi.org/10.1016/j.jseaes.2020.104346

Saini HS, Mujtaba SAI (2012) Depositional history and palaeoclimatic variations at the northeastern fringe of Thar Desert, Haryana plains, India. Quatern Int 250:37–48. https://doi.org/10.1016/j.quaint.2011.06.002

Shaw HF (1972) The preparation of orientated clay mineral specimens for X-ray diffraction analysis by a suction-onto-ceramic tile method. Clay Miner 9(3):349–350. https://doi.org/10.1180/claymin.1972.009.3.05

Sitaula RP (2009) Petrofacies and paleotectonic evolution of Gondwanan and post-Gondwanan sequences of Nepal (unpublished M.S. Thesis). Auburn University, p 186

Smith R, Brown L, Taylor M (2019) Application of high-resolution detectors in XRD studies. X-Ray Spectrom 48(2):145–158. https://doi.org/10.1002/xrs.3100

Soreghan MJ, Soreghan GS (2007) Weathering and source rock characteristics of ancient sediments: a review. Sed Geol 202(1–2):49–69. https://doi.org/10.1016/j.sedgeo.2007.03.009

Taylor SR, McLennan SM (1985) The Continental crust: its composition and evolution. Blackwell Publishing, p 312

Till JL, Guyodo Y, Lagroix F, Morin G, Ona-Nguema G (2015) Goethite as a potential source of magnetic nanoparticles in sediments. Geology 43(1):75–78. https://doi.org/10.1130/G36186.1

Turekian KK, Wedepohl KH (1961) Distribution of the elements in some major units of the earth's crust. Geol Soc Am Bull 72(2):175–192. https://doi.org/10.1130/0016-7606(1961)72[175:DOTEIS]2.0.CO;2

Uddin A (1987) Basin evolution and tectonic history of the Bengal Basin: a review. J Geol Soc India 30(2):143–158

Uddin A, Lundberg N (1998b) The Bengal Basin: Tectonics, sedimentation, and hydrocarbon potential. Pet Geosci 4(2):165–177. https://doi.org/10.1144/petgeo.4.2.165

Uddin A, Lundberg N (1999) A Paleo-Brahmaputra? Subsurface Lithofacies Analysis of Miocene Deltaic Sediments in the Himalayan-Bengal System, Bangladesh. Sed Geol 123:239–254. https://doi.org/10.1016/S0037-0738(98)00134-1

Uddin A, Lundberg N (1998a) Tectonic and sedimentary evolution of the Bengal Basin: Implications for basin analysis and oil exploration. In: Sedimentary Basins and Petroleum Geology of the Middle East (pp 33–58). Elsevier

Verma SP (1999) Heavy mineral studies in the foreland basin. J Sediment Res 69(5):1098–1113. https://doi.org/10.2110/jsr.69.1098

Von Eynatten H, Barcelo-Vidal C, Pawlowsky-Glahn V (2003) Composition and discrimination of sandstones: a statistical evaluation of different analytical methods. J Sediment Res 73:47–57. https://doi.org/10.1306/070102730047

Worm HU, Bassi A, Denys P (1998) Tectonic and sedimentary evolution of the Shillong Plateau. Tectonics 17(3):345–358. https://doi.org/10.1029/97TC03013

Wu J-L, Zhai M-G, Hu B, Zhang H-F, Chu X, Zhou N-C, Zhang L, Zhang H (2021) Garnet perspectives on the metamorphic history and tectonic significance of Paleoproterozoic high-pressure mafic granulites from the northern Hengshan. North China Craton Lithos 394–395:106139. https://doi.org/10.1016/j.lithos.2021.106139

Zack T, von Eynatten H, Kronz A (2004) Rutile geochemistry and its potential use in quantitative provenance studies. Sed Geol 171(1–4):37–58. https://doi.org/10.1016/j.sedgeo.2004.05.009