

Provenance, tectonic setting and paleoenvironment of the Tura Sandstone Formation, Northeast India: An integrated approach

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Received: 7 March 2025 / Revised: 23 June 2025 / Accepted: 10 July 2025 / Published online: 24 August 2025

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Abstract The Upper Paleocene–Lower Eocene Tura Formation, encountered in most oil wells of the Upper Assam Shelf, India, rests non-conformably over the Precambrian granitic basement. Its type section is well exposed in the West Garo Hills of Meghalaya, India. Petrographic and geochemical analyses of the sandstones have been employed to determine their provenance, tectonic setting, and prevailing paleoenvironmental conditions. The Tura sandstones are mainly classified as quartz arenite, sublitharenite, and some subarkosic types. Geochemical data, including trace elements and rare earth elements (REEs), indicate that the sandstones were predominantly derived from felsic sources. Tectonic discrimination diagrams suggest that the sandstones were deposited in an active margin setting. The sandstones were derived from source areas that experienced semi-humid to humid climatic conditions with moderate to intense degrees of chemical weathering, as indicated by paleoweathering indices such as the Chemical Index of Alteration (CIA: 79.10), Chemical Index of Weathering (CIW: 84.20), and Index of Compositional Variability (ICV: 7.67).

Keywords Tura Formation · Petrography · Geochemistry · Provenance · Tectonic setting · Paleoenvironmental conditions

1 Introduction

Understanding the provenance, paleoenvironmental conditions, and tectonic setting of sedimentary formations is fundamental to reconstructing the geological evolution of sedimentary basins worldwide. In recent decades, the integration of petrographic and geochemical approaches has proven to be a powerful method in deciphering sediment dispersal pathways, source area compositions, and basin-forming tectonics in a wide range of settings (Zelilidis et al. 2015; Marvelis et al. 2023). This multidisciplinary strategy has broad applicability in global sedimentary geology, especially in underexplored or structurally complex terrains. From their outset, the petrography and geochemistry of rocks and sediments have been primary tools for understanding sediment sources, tectonic contexts, weathering trends, and paleoenvironmental conditions, including paleoclimate, paleoweathering, and paleoredox (Gogoi et al. 2025).

The Tura Formation of Upper Paleocene–Lower Eocene age is a prolific clastic sedimentary unit within Northeast India. This formation comprises predominantly sandstones that have been deposited in various types of geological settings (Sahariah et al. 2020). The Tura Formation is disposed both in the Garo Hills of Meghalaya and within the Upper Assam Basin; however, its occurrences in spatially different geographical contexts have not been investigated so far. In the Garo Hills, the Tura Formation is exposed at the surface because of the tectonic uplift and erosion processes that have removed the overlying younger sediments, revealing the older Tura Formation rocks at elevations of 700 to 800 m

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11631-025-00812-8>.

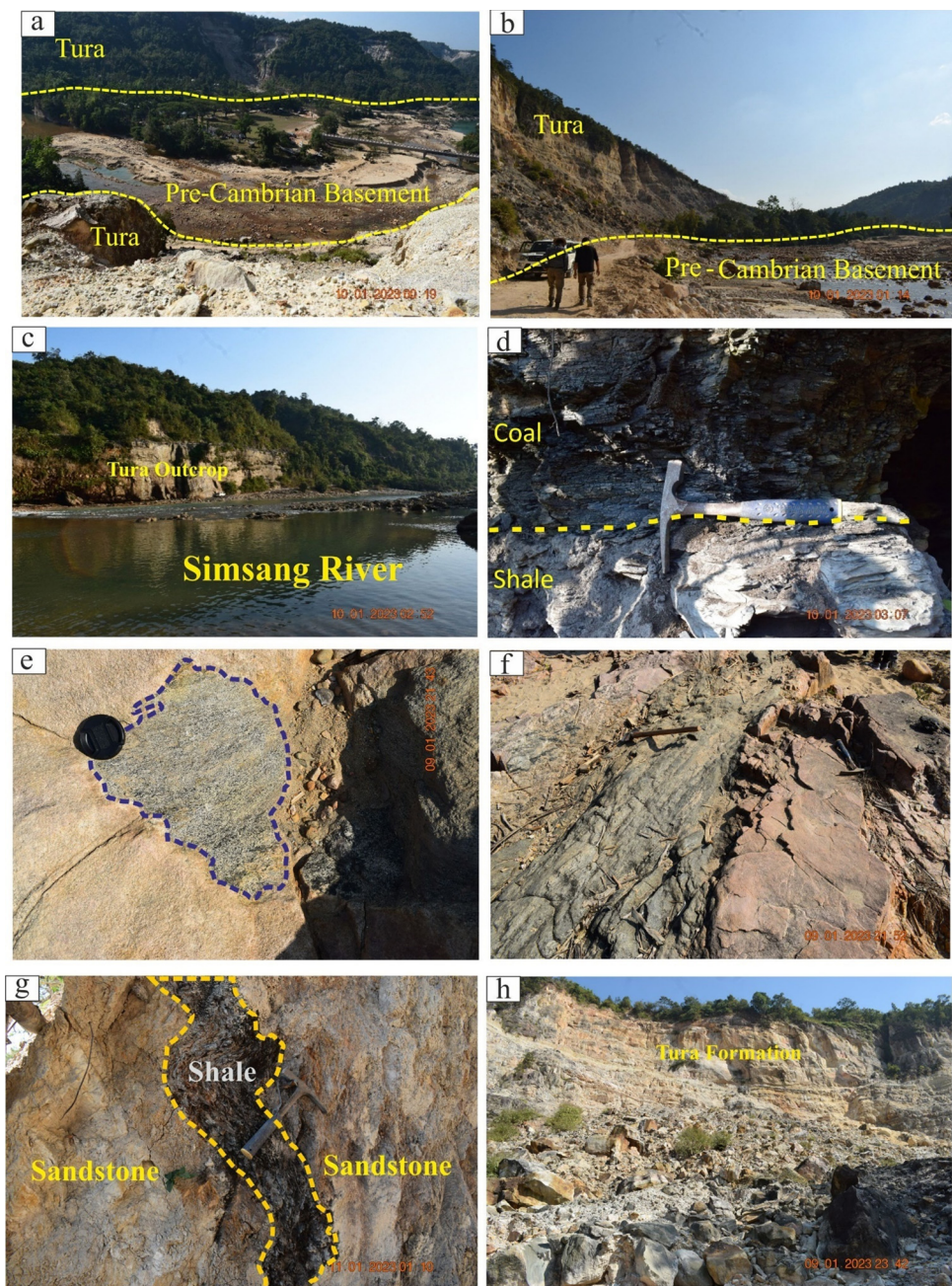
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Fig. 1 Field photographs showing a), b) Tura outcrop and Pre-Cambrian Basement; c) Tura outcrop along with Simsang River; d) Alteration of coal and shale; e) Intrusive contact showing a finer-grained intrusion cutting through the host rock; f) Pre-Cambrian granitic basement rock; g) Sandstone interbedded with shale; h) Exposure of Tura Formation outcrop



(Fig. 1h). Moreover, in the Upper Assam Basin, the Tura Formation lies buried at depths of about 3000 to 4000 m because of prolonged subsidence (Evans 1964; Kumar et al. 2024). This downward shift may be driven by tectonic compression from the Himalayas and the adjacent belt, causing the formation to be gradually covered by overlying younger sediments (Valdiya 1980; Najman 2006). Earlier researchers attempted to explain the sedimentological and reservoir properties of Tura Formation in the Upper Assam Shelf (Sahariah et al. 2019, 2020; Morang et al. 2011). However, there has been no petrographic or geochemical study of Tura Formation in Garo Hills, Meghalaya, which is exposed on

the surface. Previous studies suggest that the Tura sandstones were derived from a felsic igneous source and deposited under anoxic conditions (Sahariah et al. 2020).

Recent advances in sandstone geochemistry have significantly improved the understanding of sediment provenance and tectonic settings. The integration of major, trace, and rare earth element (REEs) compositions with petrographic analysis enables the characterization of source rock types, weathering intensity, and depositional environments. Geochemical indices such as the Chemical Index of Alteration (CIA), Chemical Index of Weathering (CIW), and Plagioclase Index of Alteration (PIA)

are commonly used to infer paleoweathering trends and source area conditions (Tobia and Shangola 2019; Ahmad et al. 2022). Trace element ratios including Th/Sc, Cr/Th, and La/Co have proven effective in distinguishing felsic to intermediate provenance (Noori et al. 2016; Sahraeyan and Bahrami 2012). REE patterns, particularly light REE (LREE) enrichment and negative Eu anomalies, have been employed to fingerprint specific crustal source terrains (Ahmad et al. 2022). Furthermore, tectonic discrimination diagrams based on major and trace element data have been instrumental in differentiating among tectonic settings such as passive margins, active continental margins, and island arcs (Tobia and Shangola 2019; Noori et al. 2016). These geochemical methods are especially valuable in regions where surface exposures are limited or deeply buried, offering a reliable toolset for reconstructing sedimentary histories.

This research seeks to investigate whether sandstones from the Garo Hills and Upper Assam Basin share a common source and depositional history, thereby establishing a correlation between the two regions. As no definitive scientific data have previously been available to confirm this connection, this study is a pioneering effort to fill this knowledge gap. Through detailed petrographic and geochemical analyses, the study aims to elucidate the tectono-sedimentary evolution of the region and establish compositional similarities between the sandstones of the Garo Hills and Upper Assam Basin. The outcomes will assist in deducing the sediment dispersal patterns, provenance features, and paleoenvironmental conditions that controlled the deposition of the Tura Formation in these areas. The current work emphasizes the provenance, tectonic setting, and paleoenvironmental conditions of the Tura Formation through a comprehensive study of the petrographic and geochemical characteristics of the Garo Hills and Upper Assam Basin.

2 Geological setting of the study area

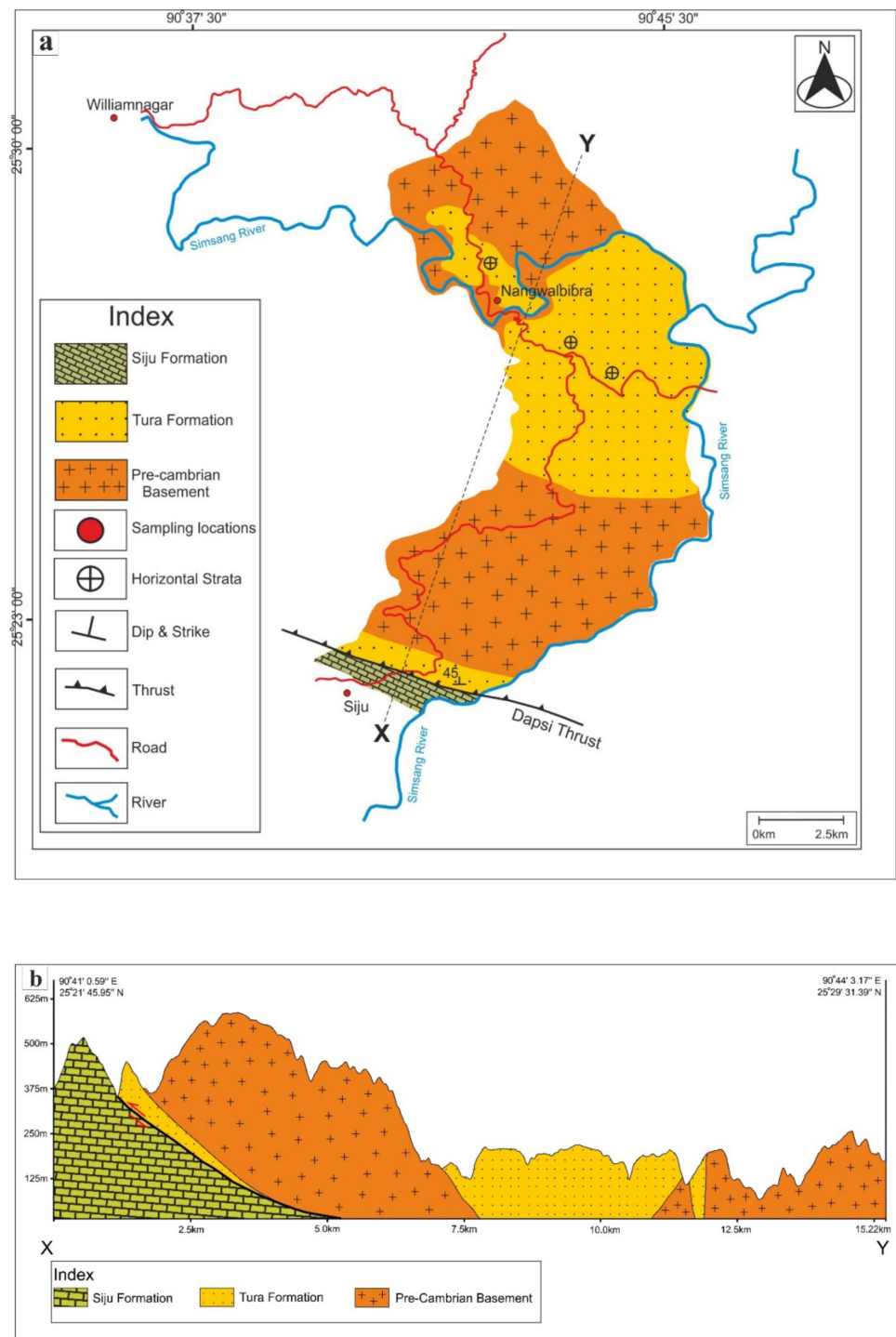
The Tura Formation is a prominent sedimentary succession from the Upper Paleocene–Lower Eocene epoch exposed in the Garo Hills of Meghalaya and Upper Assam Basin in Northeast India, which provides essential insight into the tectonic and sedimentological evolution of the Shillong Plateau and its surrounding regions. Situated non-conformably upon the Precambrian basement (Table 1), the Tura Formation displays lithological analogies to sedimentary sequences documented in oil wells all over the Upper Assam Shelf (Evans 1964; Ghosh et al. 2019). Hence, the outcrops of the Garo Hills are important for regional geological research as they provide sections of the Tura Formation that are relatively unaltered and may reveal information about ancient depositional environments, sources of sediments, and tectonic influences (Bilham and England 2001).

The southern part of the Garo Hills, Meghalaya, is occupied by a thick Palaeocene–Eocene sedimentary sequence, unconformably overlying the Precambrian Basement Complex. The western part of the Garo Hills of Meghalaya plateau is bounded by Dapsi Fault to the south, Jamuna Fault to the west, and Brahmaputra fault to the North (Choudhury et al. 2012). The Tura Formation of Garo Hills consists of medium- to coarser-grained and gritty, dirty white, yellow and reddish, clayey, non-feldspathic, frequently current-bedded sandstone intercalated with gray shale (Fig. 1g) and alternate bands of sandstone and coal (Fig. 1d). This formation is widely developed in the north and south of Tura Range. The thickness of the Tura Formation is variable and is fairly dispersed in the Garo Hills, on the NNE and southern flank of the Tura Range. Moving toward the south, Tura sediments are bounded by two Pre-Cambrian granitic basement rocks in the Williamnagar-Siju Road section (Fig. 2a). Along with the road section, towards the Siju roads, the Siju

Table 1 Generalized stratigraphic succession of the Garo Hills, Meghalaya (after Chakraborty and Baksi 1972)

Age	Stratigraphic units	Lithology	Thickness (m)
Miocene	Angartoli Formation	Fine-grained, non-feldspathic, micaceous sandstone, bluish siltstone and sandy shales	–
	Boldamgiri Formation	Coarse-grained, gritty, feldspathic, ferruginous sandstone with carbonaceous shale	–
Oligocene	Kherapara Formation	Fine-grained alterations of thinly bedded sandstone and shale, thickly bedded sandstone and carbonaceous shale	–
Late Eocene	Rewak Formation	Thinly bedded, shale and carbonaceous shale, ferruginous, current bedded sandstones with molluscan fauna and coal streaks	450–500
Middle Eocene	Siju Formation	Banded alternations of arenaceous, hard foraminiferal limestones with pyrite, carbonaceous shales, Marl with molluscan fauna, massive limestones	100–160
Palaeocene–Eocene	Tura Formation	Medium to coarse-grained and gritty, clayey, dirty white, yellow and reddish, non-feldspathic, current bedded sandstone with intercalations of gray shale, carbonaceous shale, siltstone, lithomargic clay and coal	189–250
Precambrian	Basement Complex	Granite and granitic gneisses	–

Fig. 2 a) Transect geological map along Williamnagar- Siju Road section; b) Profile section showing disposition of Williamnagar- Siju Road section



Formation is overlain by the Tura Formation (Table 1), and it encounters the Dapsi Fault. The generalized stratigraphic succession of Tura Formation in West Garo Hills, Meghalaya, is shown in Table 1.

The Upper Assam Basin is situated in a unique geotectonic framework in the northeast part of India and is bounded by the Arunachal Himalayas in the north, the Mishmi block in the east, Naga Hills in the south, and

Mikir Massif in the west (Fig. 3). The basin has been affected by three phases of tectonic deformations during inter-plate convergence between the Indian and Eurasian plates (Sahoo and Gogoi 2011). The Upper Assam Basin is a composite foreland basin located between the eastern Himalayan foothills and the Assam Arakan thrust belt (Sahoo and Gogoi 2011). Its structural geometry is influenced by surrounding mountain belts, including the

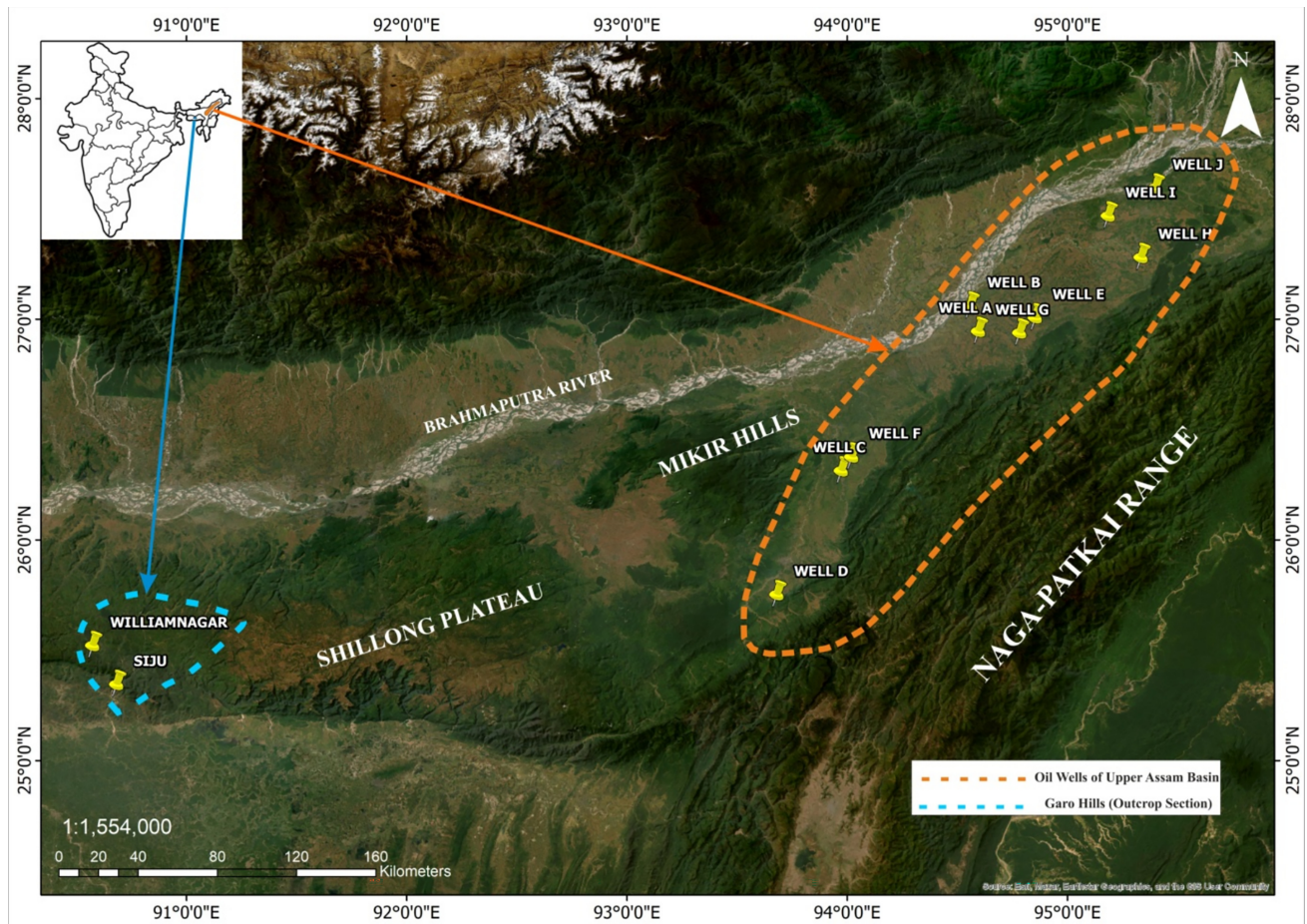


Fig. 3 Location map showing Upper Assam Basin (UAB) and Garo Hills

Himalayan orogenic belt and Mishmi thrusts (Kumar et al. 2024). Tectonic subsidence analysis reveals four stages of development, with slow subsidence during the Paleocene-Eocene, a gradual increase through the Oligocene, and rapid acceleration in the Miocene and post-Miocene periods (Kumar et al. 2024). Stratigraphically, the Tura Formation is considered of Early Eocene age (Table 2), and it is the oldest sedimentary sequence in Assam Shelf and unconformably overlies the Precambrian granitic basement (Sahariah et al. 2019). The bottom part of Tura Formation consists of alternate beds of sandstone and shale, poorly consolidated whitish gray, light brown to reddish brown, medium- to coarse-grained, friable sandstone with scoured base intermixed with ferruginous clay clast.

3 Materials and methods

Thirty-one representative Tura sandstones sample were considered for petrographic analysis, including both outcrop samples (9 nos) and subsurface samples (22 nos), for

the present study. Subsurface core samples were collected from ten wells in Upper Assam Basin, and sampling points from one of the well areas were marked, as shown in Fig. 4. The size of the core sample is 4 inches (length) × 4 inches (diameter); the representative samples are collected from a drilling core box of 9 ft length. Regarding the core age, all core samples are of Upper Paleocene-Lower Eocene age (Tura Formation of Upper Assam oil fields), which lies above the Precambrian basement rock. Thin sections were prepared for both outcrop (9 nos) and subsurface samples (22 nos) by impregnating the samples with Araldite, and then they were examined petrographically under a Leica-DM750P Trinocular Polarizing Microscope equipped with a CCD camera and Leica Application Suite (LAS) software. Five hundred points were counted under the thin section for modal analysis by the method of Gazzi-Dickinson (1966) (Table 3). The point counting was performed at the Department of Petroleum Technology, Dibrugarh University, using a polarizing microscope (Leica-DM750P).

For geochemical analysis, twenty-five (24) representative Tura sandstones sample were collected, including outcrop

Table 2 Generalized stratigraphic succession in North Assam Shelf (after Rajkhowa et al. 2019)

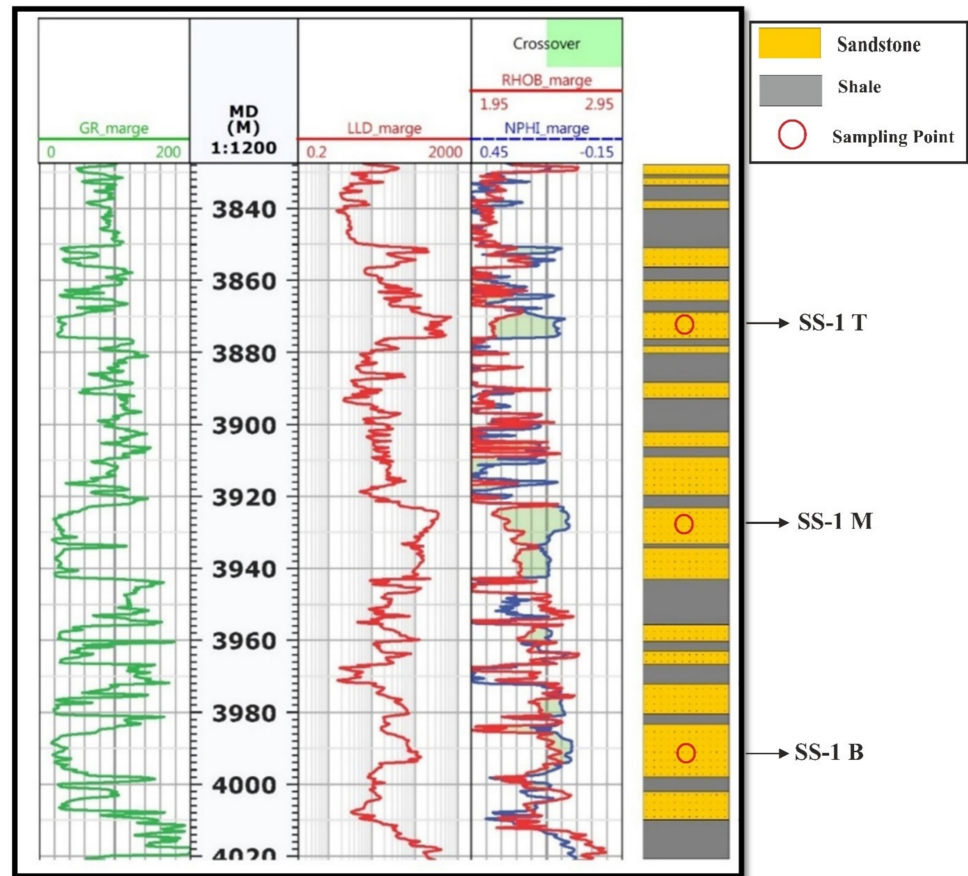
Age	Group	Formation		Lithological description
Recent-Pleistocene		Alluvium		Unconsolidated sands with gravel, silt and minor clays
~~~~~Unconformity~~~~~				
Pleistocene - Pliocene	Moran	Dhekiajuli		Thickly bedded sands with minor clays
		Namsang		Intercalated sands and mottled clay
~~~~~Unconformity~~~~~				
Pliocene-Miocene	Tipam	Nazira Sst		Predominantly sandstone with minor clays
		Girujan		Mottled and variegated clays with intercalations of silt/sandstone beds
		Lakwa Sst	TS-1	Massive sandstone with clay/shale alternations
			TS-2	
			TS-3	
		Geleki Sst	LCM/TS-4	Mainly clay/claystone inter-bedded with channel sands
			TS-5	Massive sandstone with claystone/shale alternations with minor calcareous matter in the lower part
			TS-6	
		Safrai		Conglomerate/grit with sandstone shale alternations
~~~~~Unconformity~~~~~				
Oligocene-Late Eocene	Barail	Rudrasagar (BCS)		Carbonaceous shale and coal with alternations of sand & shale
		Demulgaon (BMS)		Dominantly sandstone with intercalations of minor shale
		Disangmukh		Carbonaceous shale and sand alternations
Late Eocene-Late Paleocene	Jaintia	Kopili		Dominantly shale with sandstone beds
		Sylhet		Mainly limestone with shale/sand alternations
		Tura		Weathered granitic wash, fine to coarse grained sand with kaolinite clay, coal and shale
~~~~~Unconformity~~~~~				
Precambrian	Granitic Basement			Granite and Gneissic Complex

samples (9 nos) and subsurface samples (15 nos). Major oxide, trace element, and rare earth element (REE) analyses were carried out through x-ray fluorescence spectroscopy (XRF) and high-resolution inductively coupled plasma mass spectrometry (HR-ICP-MS) at the National Geophysical Research Institute (NGRI), Hyderabad, India. Major oxide concentrations were measured with a Philips MagiX PRO PW2440 XRF instrument. Sample pellets were prepared using boric acid and compressed with a hydraulic press before the main oxides were measured. To determine the loss on ignition (LOI), 5 g of each sample was heated to 800 °C in muffle furnace and both the initial and final weights were recorded (Rollinson 1993).

For trace and REE analysis, the rock samples underwent wet chemical dissolution based on the method of Satyanarayanan et al. (2018). A 0.05 g sample aliquot, combined with a 7:3 mixture of HF-HNO₃ acids and internal standards, was placed in Savillex® screw-top vessels. After mixing

thoroughly, the vessels were tightly sealed and heated at 140 °C for 48 h. Following this, the containers were opened, and the contents were evaporated to near dryness at 200 °C with HClO₄ to remove any remaining HF. The resulting mixture was dissolved in 1:1 HNO₃ and diluted to 250 mL with Milli-Q® deionized water before being stored in HDPE bottles. Procedural blanks were prepared to minimize errors from handling and reagents, and data were validated using geological reference samples. The analysis was conducted with AttoM® HR-ICP-MS (Nu Instruments, UK). Calibration was carried out using the international reference Sandstone sample (GSR-4) and precision and accuracy for major, trace and REE analyses were confirmed to be within < 2% relative standard deviation (RSD).

Fig. 4 Typical well log from showing lithological variation with sampling point



4 Results

4.1 Petrography of sandstones

The thin section analysis reveals that the Tura sandstones are classified as quartz arenite to sublitharenite with a few samples falling in the subarkose field (Fig. 5). The Tura sandstones from both outcrop and subsurface samples are predominantly composed of quartz, with monocrystalline quartz being more abundant than polycrystalline quartz. Modal analysis data are presented in Table 3. The monocrystalline quartz variety comprises both non-undulatory, with concentrations ranging from 41.68% to 54.79% (average 46.33%), and undulatory types, with a concentration varying between 36.80% and 53.53% (average 50.24%), with the latter variety being comparatively dominant (Fig. 6a). Volumetric percentages in the range of 0.00%–5.04% (average 1.62%) for 2–3 units and 0.00%–7.94% (average 1.83%) for > 3 units per grain are recorded for the polycrystalline quartz (Fig. 6b). Sheared or stretched metamorphic quartz (Fig. 6j) and recrystallized metamorphic quartz are typical among the polycrystalline variations. Plagioclase feldspar (Fig. 6h) and K-feldspar or microcline (Fig. 6c) are two types of feldspar minerals observed, ranging from 0.00% to 2.20% (average

1.10%) and 0.00% to 2.10% (average 0.54%), respectively. K-feldspar is more prevalent than the plagioclase feldspar observed in both outcrop and subsurface samples. The mica grains mostly dominated by muscovite followed by biotite were found in very small amounts, averaging only about 0.56%. The mica shows a kink-bending nature due to stress deformation (Fig. 6i). Volumetric percentages of rock fragments having igneous, sedimentary (Fig. 6e), and metamorphic origins with gneissic and schist fragment varieties have been reported, ranging from 0.00% to 4.58%. Most of the grains have been interlocked by cementing material (average 1.33%) of siliceous type with ferruginous (Fig. 6c), argillaceous (Fig. 6k), and calcareous (Fig. 6h) kinds also acting as binding agents. Calcareous cement dominates more in subsurface samples than in outcrop samples. Matrix resulting from the recycling of sediments within the grain boundary is also present, making up around 0.00% to 10% of the rock volume. Table 3 provides the corresponding percentages of all detrital minerals.

The Tura sandstones under study are generally fine to medium size, with occasional coarser grains. It is well cemented and exhibits moderate to good sorting. The grain shapes range from sub-angular to sub-rounded (Fig. 6d), with a few well-rounded quartz grains present. Other detrital

Table 3 Volumetric weight percentage of framework grains of Tura sandstones

Sample area	Well no. with depth (m)	Sample no.	Quartz		Feldspar				Cement		Rock fragments				Matrix	Mica	Chert	Other	
			MNU	MU	P 2-3	P > 3	PLAG	K-FLD	ARG	FER	SIL	CALC	IGN	SEDI					MET
Subsurface of UAB	WELL-A (3928-4029)	SS-1 T	40.00	26.00	0.00	0.00	1.24	1.01	0.00	0.42	0.00	27.76	0.00	0.00	0.00	0.00	0.00	3.57	
		SS-1 M	32.00	45.00	0.00	0.00	0.00	1.00	10.00	6.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	5.00
		SS-1 B	32.62	36.21	1.51	2.02	1.00	2.00	0.00	0.00	0.00	20.64	0.00	0.00	0.00	0.00	0.00	0.00	4.00
		SS-2 T	35.60	44.40	0.00	0.00	0.00	0.00	2.00	10.00	2.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	4.00
	WELL-B (3674-3759)	SS-2 B	33.80	41.10	0.12	0.00	0.00	0.00	0.00	0.00	0.00	18.78	0.00	0.00	0.00	0.00	1.00	0.00	5.20
		SS-3 B	28.00	46.00	1.50	2.80	1.20	2.80	12.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	3.70	0.00	0.00
		SS-4 T	37.08	42.25	0.00	0.00	0.00	0.00	11.79	1.50	0.04	0.00	0.00	3.11	0.00	1.23	3.00	0.00	0.00
		SS-5 T	43.00	32.00	1.00	2.00	0.66	2.44	10.22	2.67	1.11	0.00	0.00	0.00	2.00	1.00	1.90	0.00	0.00
	WELL-E (4965-5113)	SS-6 T	34.28	43.21	0.00	1.20	2.12	0.10	7.68	2.89	0.00	1.98	0.00	0.00	2.57	2.97	1.00	0.00	0.00
		SS-6 M	43.76	35.80	0.01	0.22	0.00	2.61	10.10	5.50	0.00	0.00	0.00	0.00	0.00	0.00	2.00	0.00	0.00
		SS-6 B	31.01	40.05	0.00	0.00	0.00	0.00	10.43	2.62	1.70	0.00	0.00	0.00	1.01	13.18	0.00	0.00	0.00
		SS-7 T	39.00	41.00	0.00	0.00	0.00	0.00	2.38	10.46	1.18	0.00	0.00	0.00	0.00	4.98	1.00	0.00	0.00
	WELL-G (3556-3645)	SS-7 M	35.50	42.00	0.00	0.00	0.00	0.00	9.70	1.72	1.40	0.00	0.00	0.00	0.00	7.00	0.00	2.68	0.00
		SS-7 B	35.50	42.00	0.00	0.00	0.00	0.00	9.70	1.72	1.40	0.00	0.00	0.00	0.00	7.00	0.00	2.68	0.00
		SS-8 T	27.23	38.77	0.00	0.00	1.51	1.09	1.20	0.00	0.00	18.80	0.00	0.00	0.00	1.40	0.00	0.00	10.00
		SS-8 B	34.50	36.30	0.00	0.00	0.00	0.00	0.00	0.00	3.00	6.00	0.00	0.00	0.00	0.00	0.00	0.00	20.20
	WELL-H (3472-3474)	SS-9 T	38.46	46.00	0.00	0.00	0.00	0.00	0.00	4.72	8.82	0.00	0.00	0.00	0.00	0.00	2.00	0.00	0.00
		SS-9 M	36.00	40.00	0.00	0.00	0.00	0.00	4.70	5.40	2.90	0.00	0.00	0.00	0.00	10.00	0.00	1.00	0.00
		SS-9 B	39.60	44.40	0.00	0.00	0.00	0.00	0.00	6.00	4.00	0.00	0.00	0.00	0.00	4.00	2.00	0.00	0.00

Table 3 (continued)

Sample area	Well no. with depth (m)	Sample no.	Quartz		Feldspar			Cement		Rock fragments				Matrix	Mica	Chert	Other
			MNU	MU	P 2–3	P > 3	PLAG	K-FLD	ARG	FER	SIL	CALC	IGN				
Garo Hills	WELL-J (3955–3960)	SS-10 T	41.70	32.30	0.00	0.00	0.00	0.00	12.00	5.00	0.00	0.00	0.00	0.00	8.00	1.00	0.00
		SS-10 M	35.26	45.21	0.00	0.00	0.00	0.00	7.36	5.13	0.00	2.14	0.00	0.00	4.90	0.00	0.00
		SS-10 B	30.38	35.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	34.62	0.00	0.00	0.00	0.00	0.00
			37.76	35.88	0.91	1.20	0.00	0.00	10.14	2.11	0.00	0.00	0.00	0.00	2.00	5.00	0.00
	OS-1		35.72	42.28	1.36	2.19	0.00	0.00	6.67	11.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	OS-2		25.45	32.86	1.03	0.66	2.42	5.12	0.00	0.00	0.00	0.00	0.00	0.00	32.46	0.00	0.00
	OS-3		33.14	45.33	0.40	1.13	1.52	4.15	13.22	1.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	OS-4		44.60	37.40	0.00	0.00	0.00	0.00	15.00	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	OS-5		29.38	37.20	2.12	3.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	27.76	0.00	0.00
	OS-6		39.87	45.03	0.00	0.00	0.00	0.00	10.00	0.00	0.00	0.00	0.00	4.00	0.00	1.10	0.00
	OS-7		36.50	46.50	0.00	0.00	0.00	0.00	9.50	0.00	0.00	0.00	0.00	2.50	0.00	0.00	0.00
	OS-8		22.20	41.00	0.71	3.02	2.32	5.75	0.00	25.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	OS-9																

*NU: monocrySTALLINE non-undulatory; MU: monocrySTALLINE undulatory; P2–3: polycrySTALLINE quartz with 2–3 grains per quartz; P > 3: polycrySTALLINE quartz with > 3 grains per quartz; Plag: plagioclase; K-Fld: potash feldspar; ARG: argillaceous cement; FER: ferruginous cement; SIL: siliceous cement; CALC: calcareous cement; IGN: igneous rock fragment; SEDI: sedimentary rock fragment; META: metamorphic rock fragment; T: top; M: middle; B: bottom; SS: subsurface sample; OS: outcrop sample; UAB: Upper Assam Basin

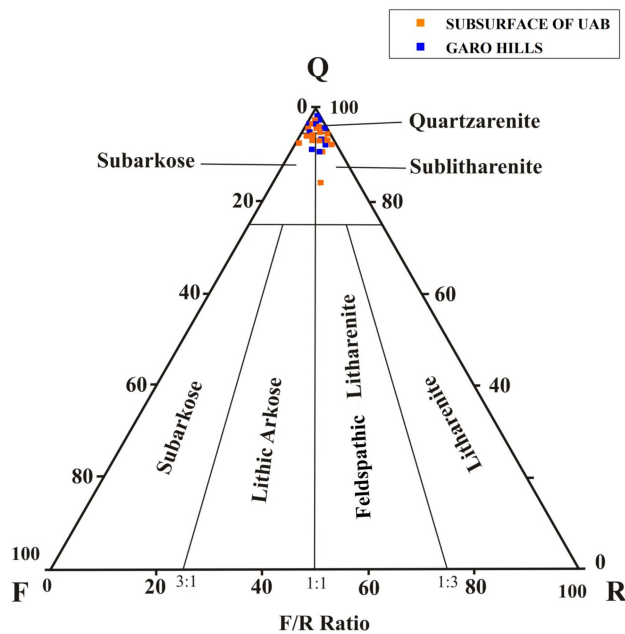


Fig. 5 Sandstone classification after Folk (1980) (*UAB: Upper Assam Basin)

minerals such as chlorite, muscovite, biotite, and calcite are found in smaller quantities. Glauconite (0%–20%) is also recorded (Fig. 6 g). Glauconite grains appear either fresh greenish or oxidized to varying extents, observed in subsurface samples. Dissolution of feldspar is recorded (Fig. 5k); this is due to the post-diagenetic effects of sandstones. The framework of the Tura sandstones is well supported by substantial calcareous cement, iron cement, argillaceous cement, and a minor amount of matrix.

4.2 Geochemistry of sandstones

4.2.1 Major oxides

The major oxides identified in the Tura sandstones are SiO_2 , Al_2O_3 , TiO_2 , Fe_2O_3 , MnO , Na_2O , K_2O , MgO , and CaO , with weight percentages shown in Table S4. The major oxide composition (in wt%) of the Tura sandstones is dominated by SiO_2 , which ranges from 6.11 to 95.87 wt% (average 70.09 wt%). This is followed by intermediate components such as Al_2O_3 , ranging from 1.72 to 32.11 wt% (average 13.32 wt%), Fe_2O_3 (0.37–17.88 wt%, average 3.56 wt%), CaO (0.14–38.22 wt%, average 3.00 wt%), K_2O (0.01–3.89 wt%, average 0.73 wt%), TiO_2 (0.09–2.77 wt%, average 0.68 wt%), and MgO (0.00–2.89 wt%, average 0.28 wt%). Minor oxides include Na_2O (0.02–1.00 wt%, average 0.17 wt%), MnO (0.00–0.26 wt%, average 0.02 wt%), and P_2O_5 (0.00–0.62 wt%, average 0.06 wt%). Compared to the average composition of the Upper Continental Crust (UCC) as

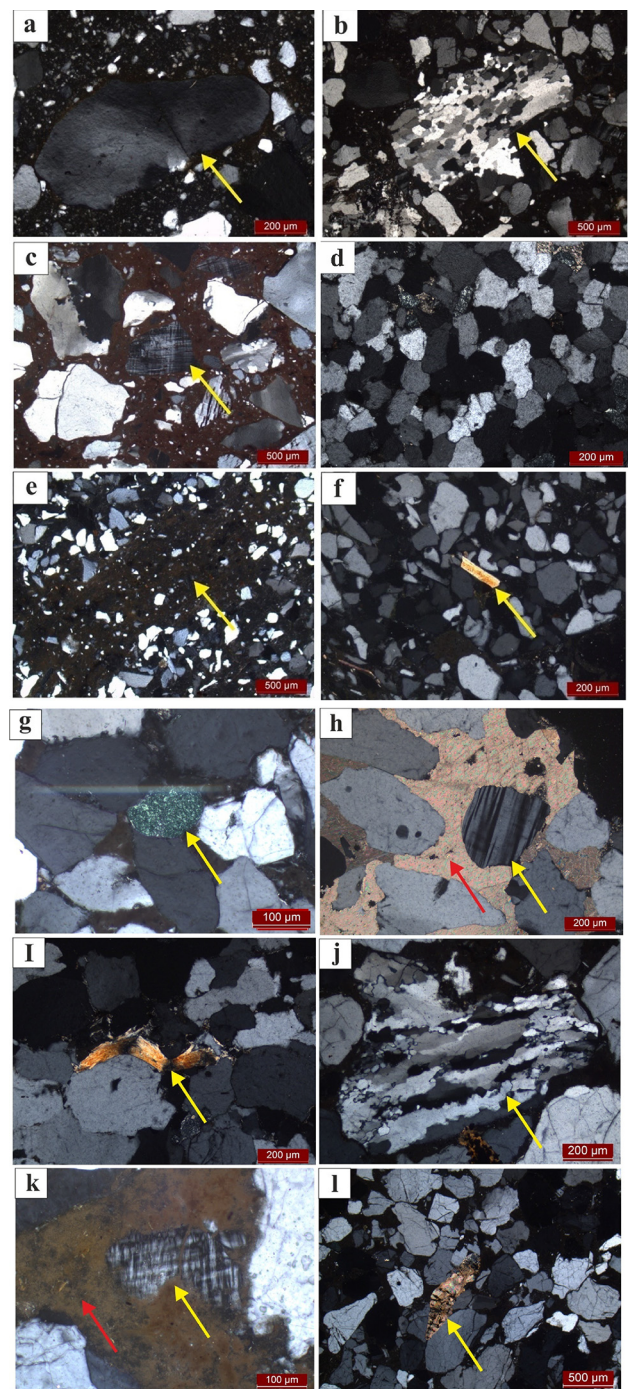


Fig. 6 Photomicrographs of outcrop samples: a) Undulatory monocrystalline quartz (yellow arrow); b) Polycrystalline quartz (yellow arrow); c) K-feldspar or microcline floated in ferruginous cement (yellow arrow); d) Quartz arenite showing sub-angular to sub-rounded; e) Sedimentary rock fragments disintegrated and weathered distributed within the framework grains (yellow arrow); f) Mica (yellow arrow); Photomicrographs of subsurface samples: g) Glauconite (yellow arrow); h) Plagioclase feldspar (yellow arrow), calcareous cement (red arrow); i) Kink mica (yellow arrow); j) Stressed metamorphic quartz (yellow arrow); k) Feldspar dissolution (yellow arrow), argillaceous cement (red arrow); l) Isolated patches of calcite cement (yellow arrow)

reported by Rudnick and Gao (2003), the sandstones exhibit enrichment in SiO_2 , Al_2O_3 , Fe_2O_3 , MgO , and CaO , whereas TiO_2 , Na_2O , K_2O , Al_2O_3 , MnO , and P_2O_5 show relative depletion (Fig. 7a).

Pearson's coefficient correlation variations of major elements (e.g., SiO_2 , TiO_2 , and K_2O) against Al_2O_3 reveal the link between the types of minerals and the distribution of major elements (Bauluz et al. 2000; Maravelis et al. 2023) (Table S6). Al_2O_3 exhibits a moderate positive correlation with TiO_2 ($R=0.58$) and a weak positive correlation with K_2O ($R=0.004$), while it shows a negative correlation with SiO_2 ($R=-0.42$). Al_2O_3 is chosen as a reference oxide because aluminum is relatively immobile and less affected by weathering, diagenesis, and metamorphism (Bauluz et al. 2000). The positive correlations suggest enrichment of these oxides because of their association with rock fragments and/or clay minerals, whereas the negative correlation with SiO_2 may reflect alteration or leaching processes during sedimentation (Nagarajan et al. 2007).

4.2.2 Trace elements

The trace element concentrations of Tura sandstones are shown in Table S5. All the trace element values were normalized using upper continental crust (UCC) values of Taylor and McLennan (1985) (Fig. 7b). Among the trace elements, the large ion lithophile elements (LILEs) are enriched, with average concentrations of Sr at 63.43 ppm and Ba at 277.93 ppm, except Rb at 25.77 ppm. The enrichment of Ba may be due to the presence of K-feldspar and barite occurrence, which was established by petrographic observations. High-field-strength elements (HFSEs) such as Th (13.45 ppm on average) and U (2.61 ppm) underwent depletion, except for Zr, which has a relatively high average concentration of 432.03 ppm. Due to the presence of detrital zircons derived from felsic source rocks, Zr has a high concentration (average 432.03 ppm). Similarly, transitional elements like Sc (6.65 ppm on average), Co (3.64 ppm), as Cu (15.53 ppm), Zn (15.39 ppm), V (52.69 ppm), Cr (35.53 ppm), and Ni (14.30 ppm) are also depleted. These transitional elements are found in lower concentrations compared to the Upper Continental Crust (UCC) values reported by Taylor and McLennan (1985).

The types of minerals that occur in sedimentary rocks control the distribution of major and trace elements, and Pearson's correlations of trace elements versus Al_2O_3 can provide additional information (Maravelis et al. 2021) (Table S6). Analysis of Al_2O_3 and trace elements reveals moderate positive correlations with Th ($R=0.68$) and U ($R=0.55$), suggesting their possible association with aluminous phases such as clay minerals (Taylor

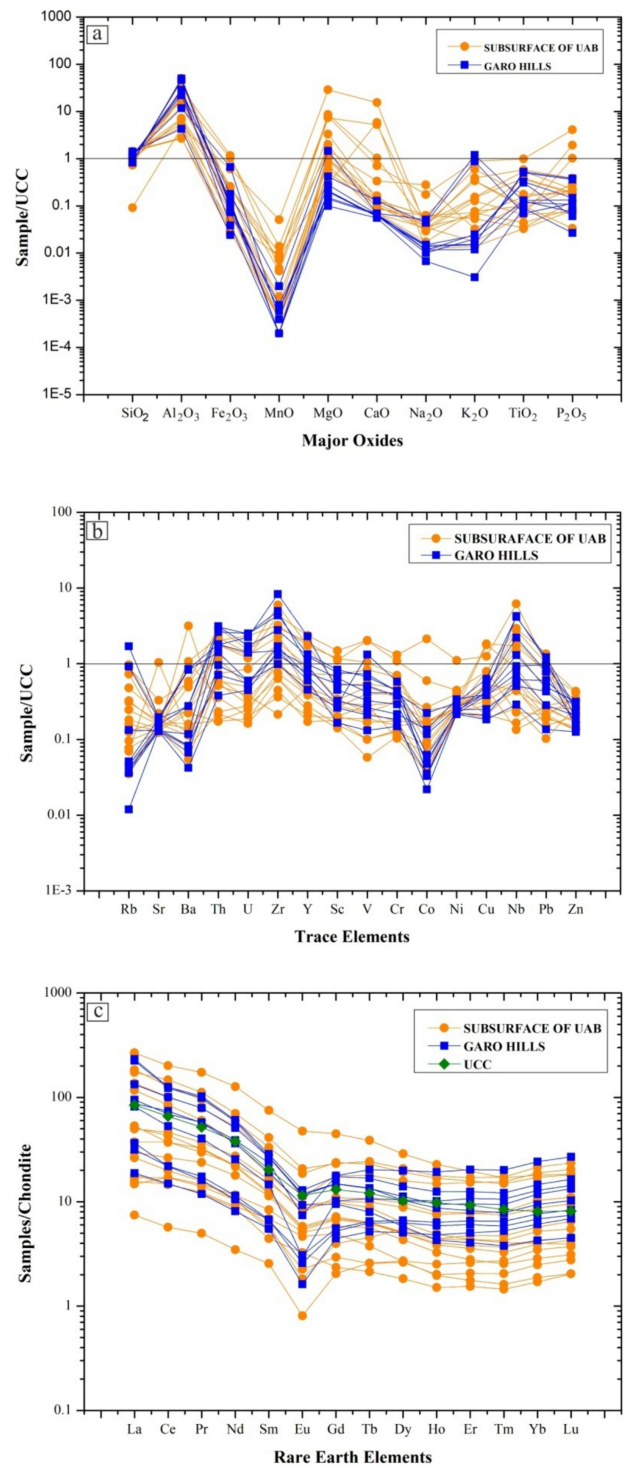


Fig. 7 a) UCC normalized plot for major oxides (Taylor and McLennan 1985); b) UCC normalized multi-element plot (Taylor and McLennan 1985); c) Chondrite normalised REE patterns (Taylor and McLennan 1985) of the Tura sandstones (*UAB: Upper Assam Basin)

and McLennan 1985; Cullers 1994). Moderate to weak positive correlations are observed with Hf ($R=0.38$), Zr ($R=0.34$), Sc ($R=0.35$), Y ($R=0.26$), V ($R=0.22$), and Cr ($R=0.20$). Weak or negligible correlations are noted with Rb ($R=0.08$), Ni ($R=0.01$), and Co ($R=0.008$), while Ba ($R=-0.14$), Sr ($R=-0.19$), and Cu ($R=-0.06$) exhibit negative correlations, suggesting their variable mobility during weathering or diagenesis (Nesbitt and Young 1982). However, the negative correlations with Ba ($R=-0.14$), Sr ($R=-0.19$), and Cu ($R=-0.06$) could reflect dilution effects due to quartz input or removal by diagenetic fluids (Bhatia and Crook 1986; Nesbitt and Young 1982).

4.2.3 Rare earth elements

Rare earth element (REE) concentrations of Tura sandstones (Table S5) are shown as chondrite normalized patterns (Fig. 7c). REEs shows light rare earth elements (LREE: La–Gd) and heavy rare earth elements (HREE: Tb–Lu) in which LREE is enriched over HREE. The sandstone REE contents range from 0.27 ppm to 59.14 ppm, with an average of 9.89 ppm, which is lower than the average UCC (Taylor and McLennan 1985). The LREE/HREE ratio ranges from 3.18 to 17.00 (average 9.03). The chondrite normalized ratio $(La/Yb)_N$ ranges from 2.15 to 20.52 (average 9.09), $(La/Sm)_N$ ranges from 1.76 to 8.40 (average 4.35), and $(Gd/Yb)_N$ ranges from 0.59 to 2.64 (average 1.35). These values are similar to the UCC values (Taylor and McLennan 1985). The Eu anomaly $[(Eu/Eu^* = (Eu)_N / [(Sm)_N \times (Gd)_N]^{1/2})]$ of the samples ranges from 0.24 to 1.01 (average 0.58).

5 Discussions

5.1 Provenance

Trace element and rare earth element (REE) geochemistry provides a valuable reflection of the source rocks for clastic sedimentary rocks (Gogoi et al. 2024; Borgohain et al. 2020; Quasim et al. 2023). Therefore, the geochemical composition of source rocks can be correlated with sediment geochemistry to trace their origins. To understand the nature and origins of these source rocks, several ternary and bivariate plots are utilized, including the La–Th–Sc plot (Zhang and Zhang 2008), Sc vs Th/Sc (Schoenborn and Fedo 2011), Y/Ni vs Cr/V (Mongelli et al. 2006), Th $\times$ 10–V–Ni (Bracciali et al. 2007), Zr/Sc vs Th/Sc (McLennan et al. 1993), and additional bivariate plots using specific trace and REE ratios. Intermixing of Y/Ni and Cr/V provides source characteristics where Y/Ni represents granitic rocks and Cr/V represents ultrabasic rocks (Mongelli et al. 2006). The bivariate plot Y/Ni vs Cr/V of the studied samples indicates the source is close to a granitic field (Fig. 8c). A similar felsic and/or

silicic source rock inference can be derived from ternary plots Th*10–V–Ni (Bracciali et al. 2007) (Fig. 8e). Moreover, source intermixing of granite and granodiorite, acidic and intermediate rocks can be portrayed from plots of Sc–La–Th (Zhang and Zhang 2008) (Fig. 8a), Sc vs Th/Sc (Schoenborn and Fedo 2011) (Fig. 8b), and Zr/Sc vs Th/Sc (McLennan et al. 1993) (Fig. 8d). Based on the above whole-rock geochemical characterization of the Tura sandstones, it can be inferred that the source of sediments is predominantly granitic/felsic/silicic rocks.

The chondrite-normalized rare earth element (REE) patterns and the nature of the europium (Eu) anomaly provide significant insights into the provenance of the source rocks (Armstrong-Altrin 2009; Absar and Sreenivas 2015; Maravelis et al. 2023), while mafic sources generally exhibit lower LREE/HREE ratios and lack a pronounced Eu anomaly (Cullers 2000). In the present study, the Eu anomaly (Eu/Eu^*) values range from 0.24 to 1.01, with an average of 0.58, indicating predominantly negative Eu anomalies (Table S5). Such values are characteristic of felsic igneous source rocks, which typically display LREE-enriched patterns and negative Eu anomalies because of feldspar fractionation (Cullers 1994; Rollinson 1993).

5.2 Tectonic setting

From the petrographic analyses, the proportions of the detrital framework grains are plotted on different ternary diagrams, demonstrating the intimate relationship between detritus sediment composition and tectonic setting (Ingersoll 1978; Dickinson and Suczek 1979; Dickinson 1985; Decelles and Hertel 1989). The composition of sandstones originating from different source regions is influenced by plate tectonics, as noted by Dickinson and (Suczek 1979). To differentiate various source terrains, such as continental blocks, magmatic arcs, and recycled orogens, they introduced the QFL (where Q represents total quartz, F is total feldspar, and L refers to lithic fragments) and QmFLt (where Qm stands for monocrystalline quartz, F represents total feldspar, and Lt includes lithic fragments and chert) ternary discrimination plots. When recalculated data from the point-counting method (Table 3) are plotted on these QFL and QmFLt diagrams, it suggests that the sandstones investigated in the present study originated from a craton interior setting, but few samples, particularly the subsurface ones in QmFLt diagrams, were derived from a quartzose recycled setting (Fig. 9a and 9b), which is classified as part of a continental block and recycled orogen. The sediments likely came from the stable regions of a craton or from shield and recycled platform sediments (Dickinson and Suczek 1979; Dickinson 1985). The presence of undulose extinction in monocrystalline quartz indicates that the minerals are mostly derived from metamorphic rocks, whereas non-undulose

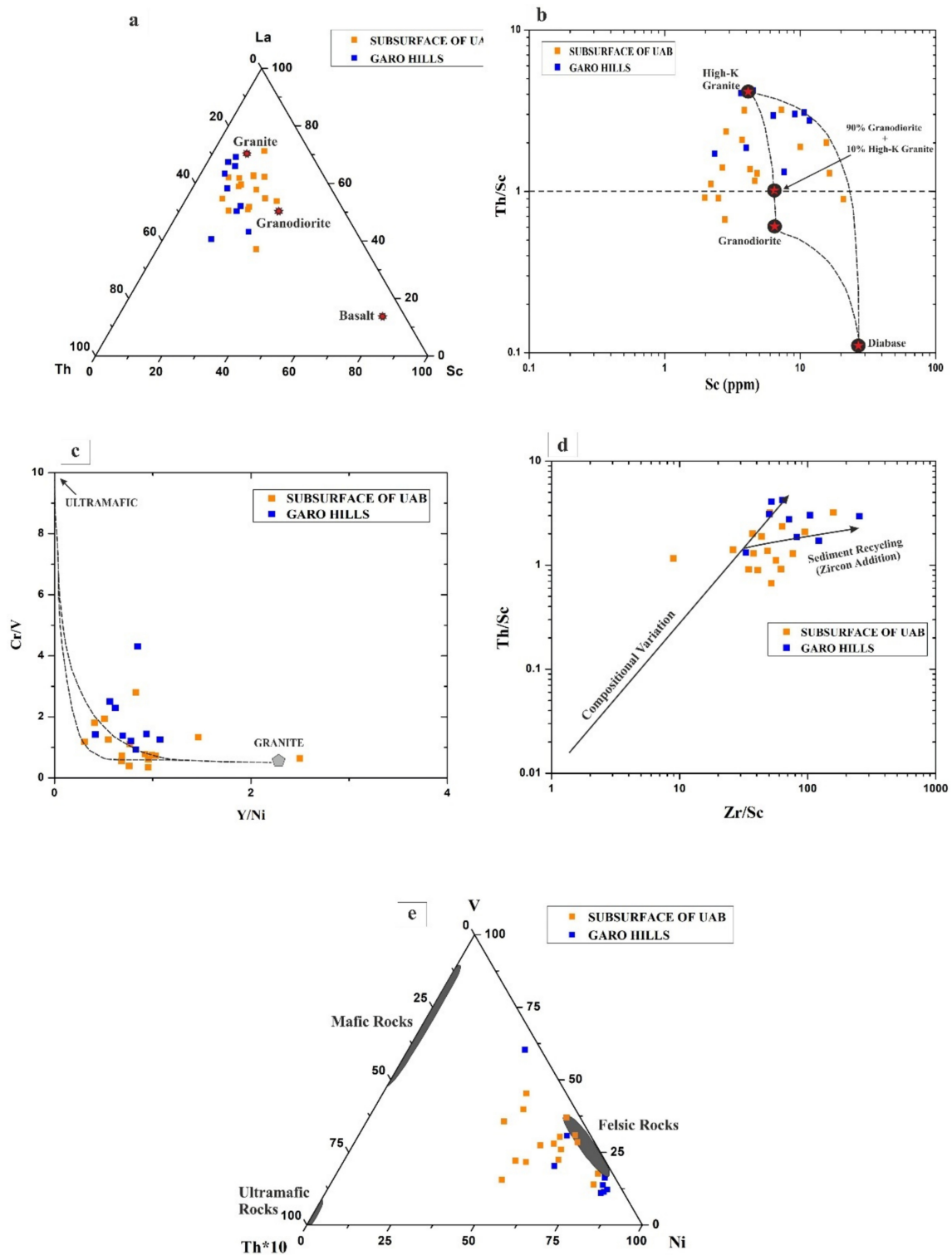


Fig. 8 Geochemical Provenance plots: a) ternary plot of La-Th-Sc after Jinliang and Xin (2008); b) bivariate plot of Sc vs Th/Sc after Schoenborn and Fedo (2011); c) bivariate plot of Y/Ni vs Cr/V after Mongelli et al. (2006); d) ternary plot of Th × 10-V-Ni after Bracciali et al. (2007); e) bivariate plot of Zr/Sc vs Th/Sc after McLennan and Hanson (1993) representing the source of Tura sandstones (*UAB: Upper Assam Basin)

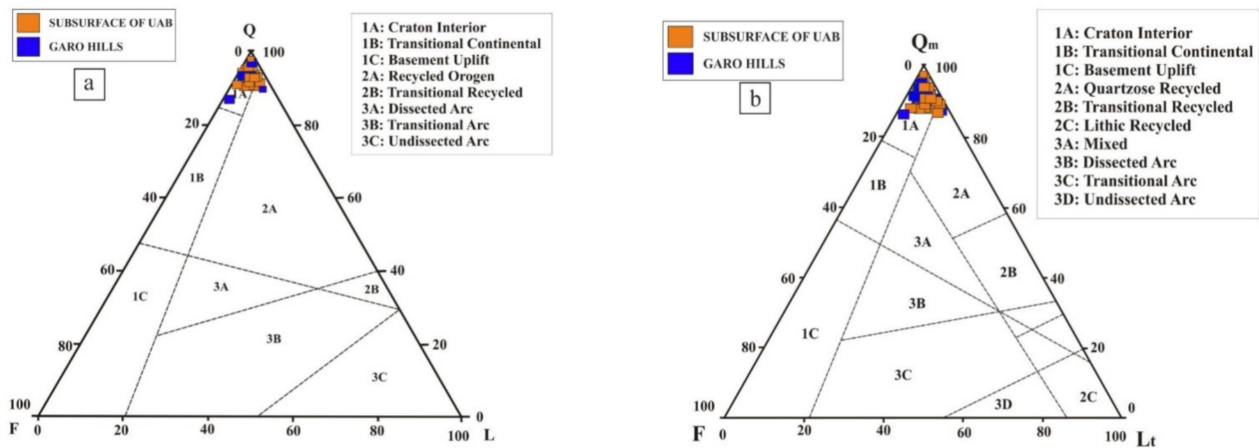


Fig. 9 a) QFL (Q- Quartz, F-Feldspar and L-Rock Fragment) ternary tectonic setup discrimination diagram (Dickinson and Suczek 1979) for Tura sandstones; b) QmFLt (Qm-Monocrystalline quartz, F-Feldspar and Lt-Rock Fragment + Chert) ternary tectonic setup discrimination diagram (Dickinson and Suczek 1979) for Tura sandstones (*UAB: Upper Assam Basin)

extinction suggests igneous sources (Basu et al. 1975). Its high abundance suggests sources from weathered granites or high-grade metamorphic rocks. The monocrystalline quartz tends to dominate in sediments derived from stable cratonic interiors, granitic terrains, and mature continental settings (Dickinson and Suczek 1979). Moreover, the quartz-rich nature of the sandstone, as indicated by major oxide discriminant functions (Roser and Korsch 1988), supports the idea that the terrigenous detritus was derived from a low-relief interior part of the craton.

Tectonic settings of source sediments have been extensively examined through the geochemical properties of sedimentary rocks (Bhatia 1983; Bhatia and Crook 1986; Gu et al. 2002; Roser and Korsch 1988; Toulkeridis et al. 1999). Globally, the discrimination plots introduced by these researchers have been widely applied across various sedimentary basins. Verma and Armstrong-Altrin 2016 developed an advanced multidimensional discrimination method using isometric log-ratio (ILR) transformations of ten major elements, later enhanced by incorporating six trace elements (Cr, Nb, Ni, V, Y, Zr), to construct two linear discriminant functions, i.e., $DF(A-P)M$ and $DF(A-P)MT$, with 87%–97% and 84%–86% success rates for active and passive margins, respectively, significantly outperforming traditional bivariate plots, which only achieved 0%–30% success rates. In Fig. 10a (using $DF(A-P)M$), most detrital samples fall clearly within the active margin field, with just a few plotting in the passive margin domain. while Fig. 10b (using $DF(A-P)MT$, which includes trace elements) shows every sample plotting consistently within the active margin field, clearly indicating an active margin origin.

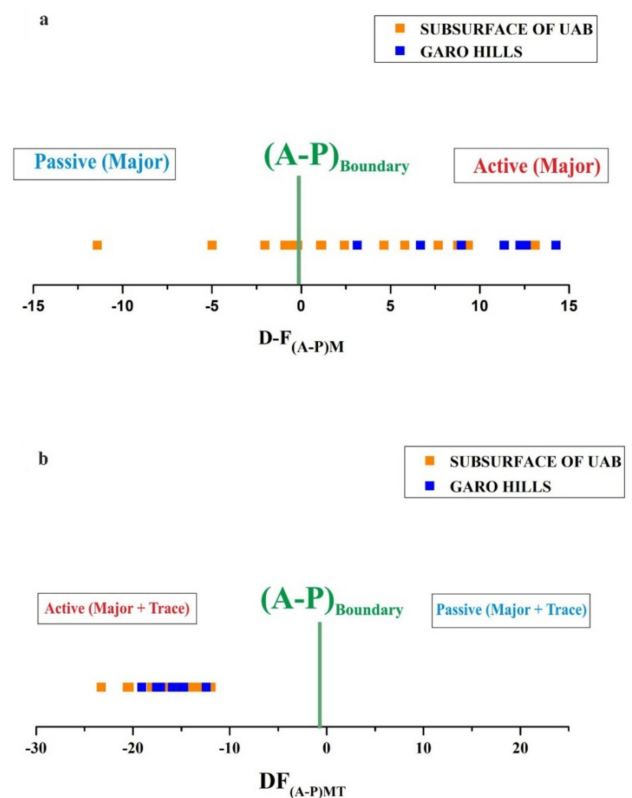


Fig. 10 a) Major element based multidimensional discriminant function diagram for Tura sandstones (Verma and Armstrong-Altrin 2016); b) Combined major and trace element based multidimensional discriminant function diagram for Tura sandstones (Verma and Armstrong-Altrin 2016) [* UAB: Upper Assam Basin]

5.3 Paleoclimate and Paleoweathering

The functions of quartz, feldspar, and rock fragments are influenced by changing climatic conditions (Suttner and Dutta 1986; Gogoi et al. 2025). As climate changes, their respective proportions tend to change. Large proportions of quartz with subordinate proportions of feldspar and quartz indicate humid climatic conditions (Suttner et al. 1981). The average relative percentages of quartz, feldspar, and rock fragments of the Tura sandstones are 95.02%, 3.46%, and 1.52%, respectively. A semi-quantitative weathering index ($WI = C \times R$, where WI is the weathering index, C represents climate, and R stands for relief, Grantham and Velbel 1988) combined with a bivariate plot of $\ln(Q/F)$ vs. $\ln(Q/R)$ (Weltje 1994) provides insights into the climate, topography, and sediment source characteristics. Based on the three-fold classification of climate and relief (Fig. 11a), the Tura sandstones fall within fields 1, 2, and 4 of the weathering indices. These fields indicate that the sediments experienced moderate to severe weathering and originated from areas ranging from low plains to moderate hills, where humid to sub-humid climates were dominant. The bivariate log/log plot of $Q_T/F + RF$ versus $Q_P/F + RF$ (Fig. 11b), constructed in accordance with the framework proposed by Suttner and Dutta (1986), offers valuable constraints on the paleoclimatic conditions prevailing during sandstone formation. Most of the samples plot within the domain typically associated with humid climatic settings. This distribution suggests that the sandstones were largely derived and deposited under conditions of elevated chemical weathering, consistent with a humid weathering regime. Such climatic conditions likely promoted the breakdown of unstable minerals and enhanced the compositional maturity of the detritus, contributing to the observed modal trends (Suttner and Dutta 1986). These findings align with other sedimentological and geochemical indicators, pointing toward a humid depositional environment during the time of sediment generation and transport.

Siliciclastic sediments undergo significant changes in their mineralogy and composition due to chemical weathering at their source (Fedó et al. 1995; McLennan 1993; Nesbitt and Young 1989). Several indices have been introduced to assess the extent of weathering (Ejeh 2021; Long et al. 2012; Nesbitt and Young 1982, 1989; Parker 1970; Potter et al. 2005). One such index is the Chemical Index of Alteration (CIA), proposed by Nesbitt and Young (1982), which has been widely used to gauge the degree of rock weathering. The CIA is calculated using molecular proportions with the formula: $CIA = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$, where CaO^* represents the amount of CaO in the silicate portion of the sample ($CaO^* = \text{molar proportion of total } CaO - \text{molar proportion of } P_2O_5$). When $CaO^* < Na_2O$, CaO^* is directly used; otherwise, $CaO^* = Na_2O$ (McLennan et al. 1983; Oyebanjo et al.

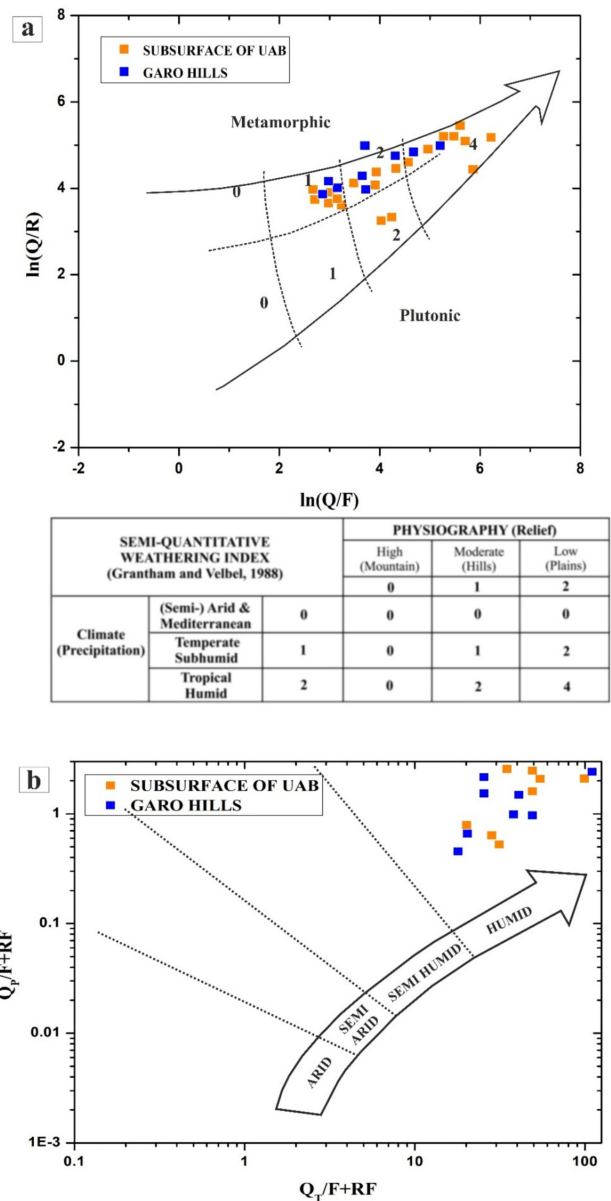


Fig. 11 a) Semi-Quantitative Weathering Index (Weltje 1994 and Grantham and Velbel 1988) showing tripartite subdivision of climate and relief for sandstones of Tura Formation; b) Log/log bivariate plot of $(Q_{Total}/F + RF)$ vs. $(Q_P/F + RF)$ discriminating paleoclimatic conditions for sandstones of Tura Formation (Suttner and Dutta 1986) (*UAB: Upper Assam Basin)

2018; Chi et al. 2021; Ma et al. 2023). The CIA also acts as a paleoclimate indicator. Higher values suggest more intense chemical weathering, typically associated with humid climates, while lower values indicate less alteration, often linked to cooler or drier conditions. Specifically, CIA values in the ranges of 50–60, 60–80, and 80–100 correspond to low, moderate, and intense degrees of weathering, respectively, indicating climates from arid to humid conditions (Fedó et al. 1995; McLennan 1993; Nesbitt and

Young 1982). Moreover, the CIA can give insight into the type of source rock, with values ranging from 30–45 for fresh basalts, 45–50 for fresh granites, and granodiorites and 70–80 for average shales (Fedo et al. 1995; Nesbitt and Young 1982).

The CIA values of the samples studied range from 7.00 to 99.33 (average 79.10) (Table S7), showing that the sediments were subjected to moderate-intense mechanical breakdown and chemical changes ranging from cold/arid to hot/humid (Nesbitt and Young 1982). The CIA is frequently used to assess weathering; nevertheless, a significant drawback is the remobilization of K during the sedimentation and metamorphic processes. Harnois (1988) proposed an alternative parameter called the Chemical Index of Weathering (CIW) to minimize this issue. This method avoids the use of K_2O as K content may be regarded as a diagenetic feature as K-bearing minerals can be formed while entering a solution or be adsorbed on clay minerals through an ion exchange process (Harnois 1988). CIW can be calculated (using molecular proportions) as $CIW = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O)] \times 100$. The CIW values of the studied sandstones range from 7.01–99.48 (average 84.20) (Table S7), indicating sediments derived from sources suffering moderate to intense degree of weathering.

Nesbitt and Young (1984) proposed A–CN–K (A: Al_2O_3 , CN: $CaO^* + Na_2O$ and K: K_2O) ternary diagram for determining source area weathering. The A–CN–K diagram is useful for evaluating fresh rock compositions and examining their weathering trends due to the upper continental crust (UCC), which is mainly dominated by plagioclase feldspar and K-feldspar rocks and clay minerals (Fedo et al. 1995). The horizontal line with a CIA value of 50, parallel to the CN–K axis, depicts the natural feldspar composition, also known as the feldspar joint. This line serves to restrict the initial composition of source rocks (Fig. 12a). In the present study, the degree of weathering of the studied sandstones ranges from moderate to intense chemical weathering (Fig. 12a). During moderate chemical weathering, feldspars convert to muscovite, illite, and smectite, while intense chemical weathering leads to the formation of kaolinite. In general, the intensity of chemical weathering increases when there is a decrease in tectonic activity and/or warm and humid conditions prevail in the source region (Jacobson et al. 2003).

To understand the maturity of source detritus of clastic sedimentary rocks, Cox et al. (1995) proposed the Index of Compositional Variability [$ICV = (Fe_2O_3 + K_2O + Na_2O + CaO + MgO + MnO + TiO_2) / Al_2O_3$]. Non-clay silicate minerals typically have lower amounts of Al_2O_3 compared to clay minerals and generally exhibit higher ICV values (Cox et al. 1995). Compositionally immature clastic sedimentary rocks tend to contain more nonclay silicate minerals and, therefore, display higher ICV values. In contrast,

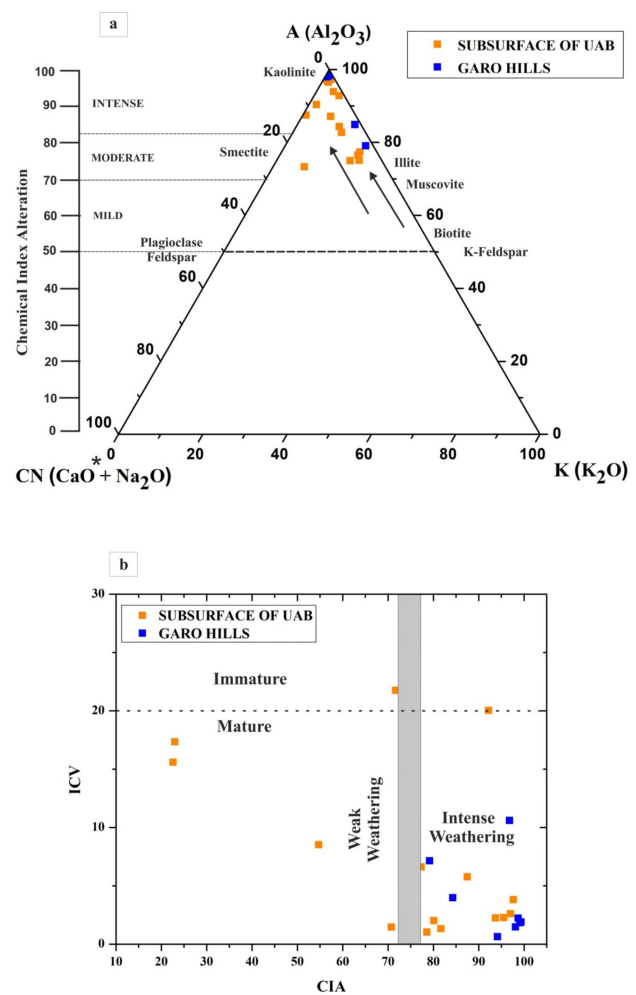


Fig. 12 a) A–CN–K (Nesbitt and Young 1989) ternary diagram to evaluate the composition of parent rock as well as their weathering trend of Tura sandstones; b) ICV vs CIA (Potter et al. 2005) depicting nature of source rock composition (*UAB: Upper Assam Basin)

more mature sediments, which have a higher clay mineral content, exhibit lower ICV values (Cox et al. 1995). During weathering, the ICV value decreases because of conversion of feldspar to aluminum-bearing clays (Cox et al. 1995). An interrelation between CIA and ICV (Fig. 12b), Long et al. (2012) depicts the presence of both immature ($ICV > 1$) and mature ($ICV < 1$) sediments as source, experiencing a low to moderate degree of weathering. The ICV of studied samples of the Tura Formation ranges from 0.67 to 50.91 (average 7.67), suggesting that the clay mineral content is high in highly weathered Tura sandstones. This is also supported by the bivariate plot of CIA versus ICV for the studied sandstone samples, suggesting that most of the samples are immature and have undergone moderate to intense weathering, as shown in Fig. 12b.

6 Conclusions

Based on the petrographic and geochemical analysis of the Tura sandstones (both outcrop and subsurface sandstones), the following conclusions regarding provenance, tectonic setting, and paleoenvironmental conditions can be reached.

- Based on the petrographic analysis, the Tura sandstones are characterized by higher proportions of quartz grains, predominantly of monocrystalline quartz (both non-undulatory and undulatory), followed by polycrystalline quartz (including both 2–3 units and > 3 units types). K-feldspar is more abundant than plagioclase feldspar. These sandstones are mainly classified as having quartz arenite, sub-litharenite, and some subarkose in their composition and are derived from recycled orogenic provenances. Furthermore, calcareous cement is prevalent in subsurface samples, suggesting stable burial conditions that favored carbonate precipitation during diagenesis. In contrast, outcrop samples lack calcareous cement, likely because of meteoric weathering and leaching, leading to its dissolution.

- Based on geochemical analysis, the sandstones are primarily derived from felsic igneous sources, suggesting that the source region is likely associated with the Shillong Plateau basement rocks. Consequently, the sandstones of the Tura Formations from both the Garo Hills, Meghalaya, and the Upper Assam Basin are likely to have originated from a common source. The observed REE signatures further support a dominant contribution from felsic lithologies in the source areas.

- From the paleoenvironmental viewpoint, petrographic and geochemical data suggest prevalence of hot and humid paleoclimatic conditions in the source areas. The sediments derived from these areas underwent moderate to intense degrees of chemical weathering before the deposition took place in the basin.

Acknowledgements The authors thank DST-SERB (under Core Research Grant), file No. CRG/2021/007514, for the financial support to carry out the work. The authors thank Oil and Natural Gas Corporation Limited (ONGCL), Sibasagar and Oil India Limited (OIL), Duliajan, Assam, India, for providing core samples and well log data. The authors also acknowledge National Geophysical Research Institute (NGRI), Hyderabad, India, for giving permission to carry out the XRF and HR-ICP-MS analyses of the rock samples in the laboratories. The authors thank the Department of Petroleum Technology, Dibrugarh University, Assam, India, for providing laboratory facilities for petrographic studies.

Author Contributions Pradip Borgohain, Devojit Bezbaruah Anurag Bharadwaj, and Yadav Krishna Gogoi prepared the main manuscript text; Pradip Borgohain, Devojit Bezbaruah, Yadav Krishna Gogoi, Anurag Bharadwaj, Bishal Singh, Garima Konwar, Dipankar Sainia, and Mondip Sarma conducted the field work; Pradip Borgohain,

Devojit Bezbaruah, Anurag Bharadwaj, and Yadav Krishna Gogoi performed the petrographic analysis; Pradip Borgohain, Devojit Bezbaruah, Anurag Bharadwaj, Yadav Krishna Gogoi, and Bubul Bharali carried out the interpretation of the geochemical analysis; Anurag Bharadwaj and Yadav Krishna Gogoi prepared the figures. All authors reviewed and approved the final version of the manuscript.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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