



Provenance and depositional setting of the Disang Group exposed in the north-easternmost part of Assam-Arakan Basin, India: insights from petrography and clay mineralogy

Dimple Moni Kachari¹ · Chaitra Dhar Taye² · Ananya Chutia¹

Received: 9 May 2024 / Revised: 26 June 2024 / Accepted: 28 July 2024
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2024

Abstract

The present study attempts to investigate the provenance, tectonic setting, paleoclimate, and diagenetic history of the Disang Group using an integrated approach of field investigation, petrography, and clay mineralogy. It has been observed that the Disang Group in the study area chiefly consists of shales with subordinate amounts of sandstone, siltstone, chert, and limestone. Dicotyledon fossil leaf impression in sandstone has also been observed during the study. Petrographic analysis of sandstones has shown that they are fine to medium-grained, poorly to moderately sorted, with sub-angular to sub-rounded grains, and classified mainly as wacke with minor arenite. They were derived mostly from low to middle and upper rank metamorphic source rocks in variable climatic conditions from arid to humid, and the source areas were of low to moderate relief. Tectonic discrimination diagrams have suggested craton interior and recycled orogen provenance. The occurrence of clay minerals like chlorite, illite, and smectite-montmorillonite has implied weathering in a cold, arid climate. The diagenetic processes involved were of early to late stages. The limestones are olistostromal deposits and are classified as micrite. The presence of thick shale beds and chert indicates a deep marine environment whereas rip-up clasts and fossil leaves are indicative of their deposition in a shallower part of the basin. Thus, there must have been a change in the environment from deep marine to shallow marine during the deposition of the Disang Group under study.

Keywords Disang Group · Petrography · Clay mineralogy · Limestone · Chert · Fossil leaf · Provenance · Tectonic setting

1 Introduction

Clastic sedimentary rocks can reveal a wealth of information about the geological past. To understand the provenance, tectonic setting, transportation history, and associated environment of deposition of clastic sedimentary rocks, the study of detrital framework composition plays a crucial role (Ahmad et al., 2019; Bordoloi et al., 2022; Chutia et al., 2020, 2022; Dickinson, 1985; Dickinson & Suczek, 1979; Ingersoll & Suczek, 1979; Javed et al., 2023a; Khan & Khan, 2015; Khan & Sarma, 2023; Khan et al., 2020; Mahanta et al.,

2019; Quasim et al., 2017a, 2017b). Petrographic analyses reveal the processes associated with provenance, environment of deposition and transportation of clastic materials (Dickinson, 1985; Dickinson & Suczek, 1979; Ingersoll & Suczek, 1979; Rao et al., 2018). On the other hand, it also helps in understanding the diagenetic processes that sediments have undergone during and after burial. Diagenesis involves modification of sediment both in terms of texture and composition, resulting from various processes such as compaction, recrystallization, dissolution, replacement, authigenesis and cementation (Tucker, 2001), which in turn affects the porosity and permeability in sandstones, therefore, directly influencing their potentiality as hydrocarbon reservoirs (Ajdukiewicz & Lander, 2010; Bhuyan et al., 2022; Bordoloi et al., 2023; Javed et al., 2023b; Morad et al., 2000; Worden & Burley, 2003). Clay mineralogical study could be considered as a helpful tool in estimating physical, chemical and climatic conditions of the depositional basin and provenance (Adatte et al., 2002; Chamley, 1997; Keller, 1956). Carbonates contain a wide range of textures,

✉ Ananya Chutia
ananyachutia@gmail.com

¹ Department of Geology, Cotton University, Guwahati, Assam 781001, India

² Department of Geology, Jagannath Barooah University (Formerly Jagannath Barooah College), Jorhat, Assam 785001, India

structures, and fossils that can reveal crucial details regarding palaeoecological conditions, ancient marine ecosystems, and the evolution of life forms, particularly marine organisms through time (Boggs, 2006). Cherts are biogenic sediments that have been deposited primarily on oceanic plates from the Archean to the present day (Murray et al., 1991; Perry & Lefticariu, 2014; Zhang et al., 2020). Their study provides various aspect of earth's history such as palaeogeography, palaeo-oceanographic circulation patterns, and plate tectonics (Boggs, 2006).

Disang Group represents the oldest rocks in the Paleogene sequence of Assam Arakan Basin which emerged as a result of subduction of Indian plate beneath Burmese plate. A number of studies on the Disang Group of Manipur and Nagaland have been performed by Geological Survey of India (GSI, 2011 and references cited therein). The Disang's of Manipur (Devi, 2022; Lokho et al., 2020; Singh & Meera, 2013; Singh et al., 2015, and others) and Nagaland (Gogoi et al., 2021; Imchen et al., 2014; and others) have been studied by previous researchers based on their lithology,

petrography, and fossil occurrences. However, except few reports of GSI, the Disang rocks in the study area located at the northeastern fringe of the basin have received less attention. Earlier studies suggested that they are deep water turbidite deposits and the shales exhibit high maturity but poor hydrocarbon generation potential (Baruah et al., 2007; Bhattacharya, 2017; Gogoi & Sarmah, 2013; Gogoi et al., 2023). The sandstones are sublithic arenite and lithic wacke type derived from igneous and metamorphic sources in a recycled orogen tectonic setting (Phukon et al., 2010; Gogoi & Sarmah, 2021 and Gogoi et al., 2023).

In this paper, we present thorough investigations on lithological, petrological, and clay mineralogical approaches to delineate the provenance, tectonic setting, palaeoclimate, palaeoenvironment, and diagenetic history of the Disang Group exposed along the Khonsa-Changlang road section in the southeastern part of Arunachal Pradesh. This study will help to better understand the northeastern fringe extension of the Disang Basins. A location map of the study area is presented in Fig. 1.

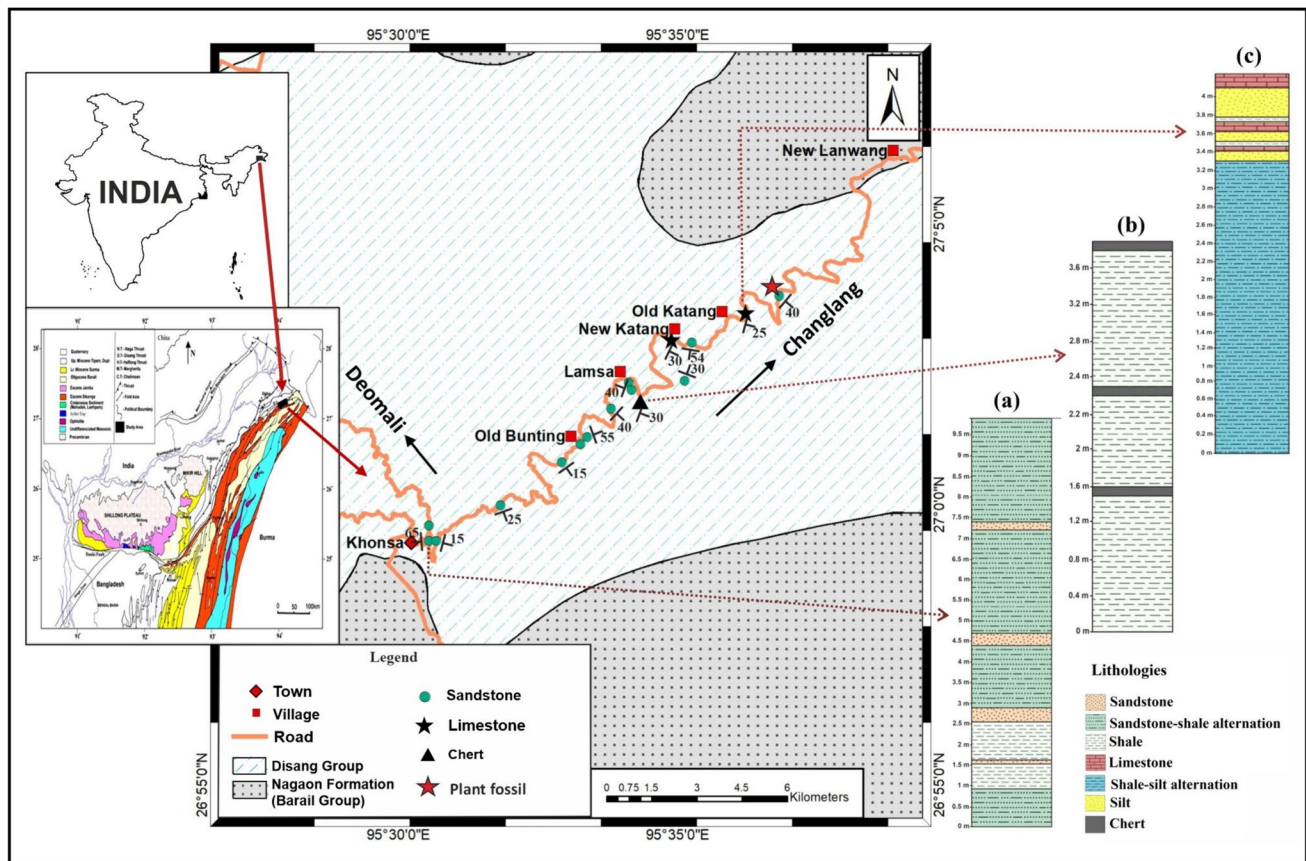


Fig. 1 Geological map of study area (Dasgupta & Biswas, 2000); (a–c) Lithocolumns of three measured sections of Disang Group

2 Geological background

The Cenozoic sediments of the Naga-Patkai belt extend north-eastward in the Tissa and Tirap valleys and Changlang district of Arunachal Pradesh, Nagaland, Manipur, a small portion of Dima Hasao and extends up to Chin Ranges of Myanmar (Devi, 2022; Singh & Kushwaha, 2008; Singh et al., 2017). The flysch-type sediments deposited in this basin during Eocene are represented by Disang Group which later became shallow due to sediment filling, faulting and thrusting. The term 'Disang' was first proposed by Mallet (1876) for a group of monotonous splintery shales with sandstones towards top exposed in Disang river section of Upper Assam. Mathur and Evans (1964) have used chronostratigraphic terms for shelf and geosynclinal facies and named the base of the Cenozoic sequence of Upper Assam as Disang Series. Nagappa (1959) recorded arenaceous foraminifera from the upper part of Disang and suggested a late Eocene age while Evans (1964) found nummulites from the sandy shale of Disang and also suggested a late Eocene age. Krishnan (1968) regarded the Disangs as geosynclinal lithological facies which is well developed to the east and southeast of the Haflong-Disang Thrust in Nagaland, Manipur and beyond. In the study area, the Naga-Patkai ranges are divided into two structural belts, viz., the Inner Fold belt and the Outer belt. These two structural components are separated by the Disang thrust. The Outer belt is characterized by a series of intricate overthrusts in an imbricated pattern running from Haflong to the Mishmi front over a distance of roughly 250 km, with a narrow 20–25 km wide tectonic zone known as the Belt of Schuppen (Evans, 1964). It consists of subflysch-molasse sediments from the Barail Group as well as post-Barail sediments. The Outer belt is divided from the northwestern Upper Assam valley by the Naga Thrust, and it is bordered by the Haflong-Disang Thrust to the east and southeast. The Inner Fold belt lying to the east of Disang Thrust, also designated as the Patkai Synclinorium exposes extensive deposits of Disang and Barail Group of rocks (Dasgupta & Biswas, 2000). These rocks were deposited in a linear flysch trough in accretionary prism complexes under an arc-trench system of the Indo-Myanmar orogen. According to Gogoi and Sarmah (2013), these strata have been folded into a number of north-easterly plunging folds that swerve to the east–west and then to the NW–SE trend. In Tirap district, the compressional tectonism has produced the Nampong anticline, a regional isoclinal anticline that plunges towards the east-northeast (Acharyya, 2010, GSI, 2010).

Sinha and Chatterjee (1982) divided the Disang Group into two members, viz., Lower and Upper Disangs. The Lower Disang is dominated by shales, whereas the Upper

Disang maintains a coarsening upward sequence with an increase in sand-shale ratio, adhering to the gradual shallowing of basin through time. Disang Group is conformably overlain by the arenaceous sedimentary unit of the base of Barail Group, called 'Nagaon Formation'. The contact between Disang Group and overlying Nagaon Formation is gradational and hence, is difficult to ascertain in the field. According to Evans (1932), the sediments of the Disang Group are deep water deposits which are equivalent to the Upper Cretaceous and Eocene shelf deposits of the south Shillong Plateau and Upper Assam valley. Kumar (2004, unpublished thesis) reported that the Disang sediments were laid down during Eocene time in a deep marine environment near an arc-trench system. The Indo Burma Ranges in the study region is annexed to the eastern end of the Himalayas, where it is bordered by NW–SE trending Mishmi Thrust; bringing continental arc filled Paleogene flysch sediments into contact with the Namdapha Crystalline Complex and Tilung Formation of Precambrian age (Majumdar & Chetia, 2016). The stratigraphic classification of GSI (2010) in southern Arunachal Pradesh has been used in the present study (Table 1).

3 Methodology

To understand the nature of rock exposures and their lithological association, geological field investigation has been carried out along the Khonsa-Changlang road section. During the study, various sedimentary attributes such as thickness of individual litho-unit, texture, sedimentary structures, etc. were recorded and fresh samples were collected for laboratory investigation. Laboratory methods in this study include petrography and clay mineralogy. For petrography, thin section of sandstone, limestone and chert have been prepared and observed under petrological microscope at the Department of Geology, Cotton University, Guwahati. For modal analysis of sandstones, at least 400 points per sample were counted using the conventional point counting method (Dickinson, 1970; Gazzi, 1966; Ingersoll et al., 1984) where the sand-sized grains have been counted as separate mineral phase rather than the host rock fragments. Different triangular plots of sandstone are used to infer provenance, tectonic setting and paleoclimate. The textural and mineralogical constituents of limestones have been identified and classified according to Folk (1959, 1962). The clay mineralogical composition of the sandstones was determined by X-ray diffraction (XRD) technique at the Department of Instrumentation and USIC, Gauhati University. Slurry slides containing fine clay fraction of the sandstones were prepared and analyzed on an Empyrean diffractometer system using Cu-K α radiations. The previously published data of Tucker (1988) have been used as a reference to recognize

Table 1 Stratigraphic succession of southeastern Arunachal Pradesh, NE India (modified after GSI, 2010)

Age	Group	Formation	Description
Pleistocene to Recent			Alluvium and high level terraces
Pliocene		Dihing	Boulder beds and sand
		Namsang	Coarse pebbly sandstone
Mio- Pliocene	Naharkatia	Girujan	Variegated clays, minor sand
Miocene		Tipam/Gandhigram	Greenish grey micaceous sandstones, minor lenses of coal
Unconformity			North of Disang Thrust (platform facies) South of Disang Thrust (geosynclinal facies)
Oligocene	Barail	Tikak Parbat	Sandstone and coal Greyish green sandstone with intercalation of greenish shale
		Bargolai	Sandstone, clay and minor coal seams
		Nagaon	Hard well bedded sandstone
Eocene	Disang		Dark grey shales with interbands of hard, fine grained, flaggy, sandstone and fossil leaf within sandstone. Limestone and chert are also present within shales
Tilung thrust			
Proterozoic		Tilung	Quartz-chlorite/mica schist with intercalation of quartzite
Namdapha thrust			
Proterozoic		Namdapha crystalline complex	Biotite granitoid gneiss

the diffractograms. The fossil leaf has been traced based on the morphology and venation of the preserved portion and correlated them with existing taxa.

4 Results

4.1 Description of lithology

The Disang Group is well exposed along the Khonsa-Changlang road which are composed primarily of thick layers of shale with subordinate amounts of sandstone, siltstone, limestone and chert. The sandstones are compact, hard, grey to dark grey coloured and medium to fine grained. The shales are dark grey to black, splintery and exhibit fine laminations. An exposure with a thickness of around nine (9 m) metres has been observed near Khonsa town (heading towards Changlang road) consisting of thin sandstone beds interbedded within thick shale beds (Fig. 2a). At many places, the rhythmic nature of sandstone-shale alternation has been observed (Fig. 2b). Limestone occurs at two places along the road section-one after crossing New Katang village and other, after crossing Old Katang village. The limestones are reddish, fine grained, highly fizzy and occur as patches and also as thin to thick bands (5–30 cm) within the shales (Fig. 2c). After crossing Lamsa village, an exposure consisting of thin chert beds within the thick shales have been observed (Fig. 2d). The chert beds are grey in colour and about 10 cm thick. Spheroidal weathering is very common

in the Disang shales (Fig. 2e). Another important finding is the fossil leaf within the sandstones near Old Katang village (Fig. 2f). Earlier, the existence of limestone, chert, and fossil leaves were uncovered within the Disang Group in Tirap district of Arunachal Pradesh (Vaz and Durairaj, 1980–81, unpublished GSI report). However, no extensive studies on this limestone, chert beds, and fossil leaves have been undertaken so far. It is noteworthy that, prior to this, no study has been conducted on these findings so far. Rip up clasts and carbonate concretions have also been recorded from the studied sandstones (Fig. 2g–h). To understand the depositional environment, three lithocolumns have been prepared, based on available field data (Fig. 1a–c). Lithocolumns (a) and (b) show characteristics of deepwater setting, involving deposition of biogenic (chert) and terrigenous (sandstone and shale) material through suspension fall-out within the water column, and slow lateral advection processes, producing clay and silt sized particles. Lithocolumn (c) comprising of limestone, shale and silt points toward deposition in a shallower part of the basin. It is evident from the lithocolumns that there has been a change in the depositional environment from deep water to shallow water (towards Changlang).

4.2 Description of the fossil leaf

Poorly preserved leaf impressions were observed in some of the sandstones of the studied region. Identification has been made based on the morphology and venation of the

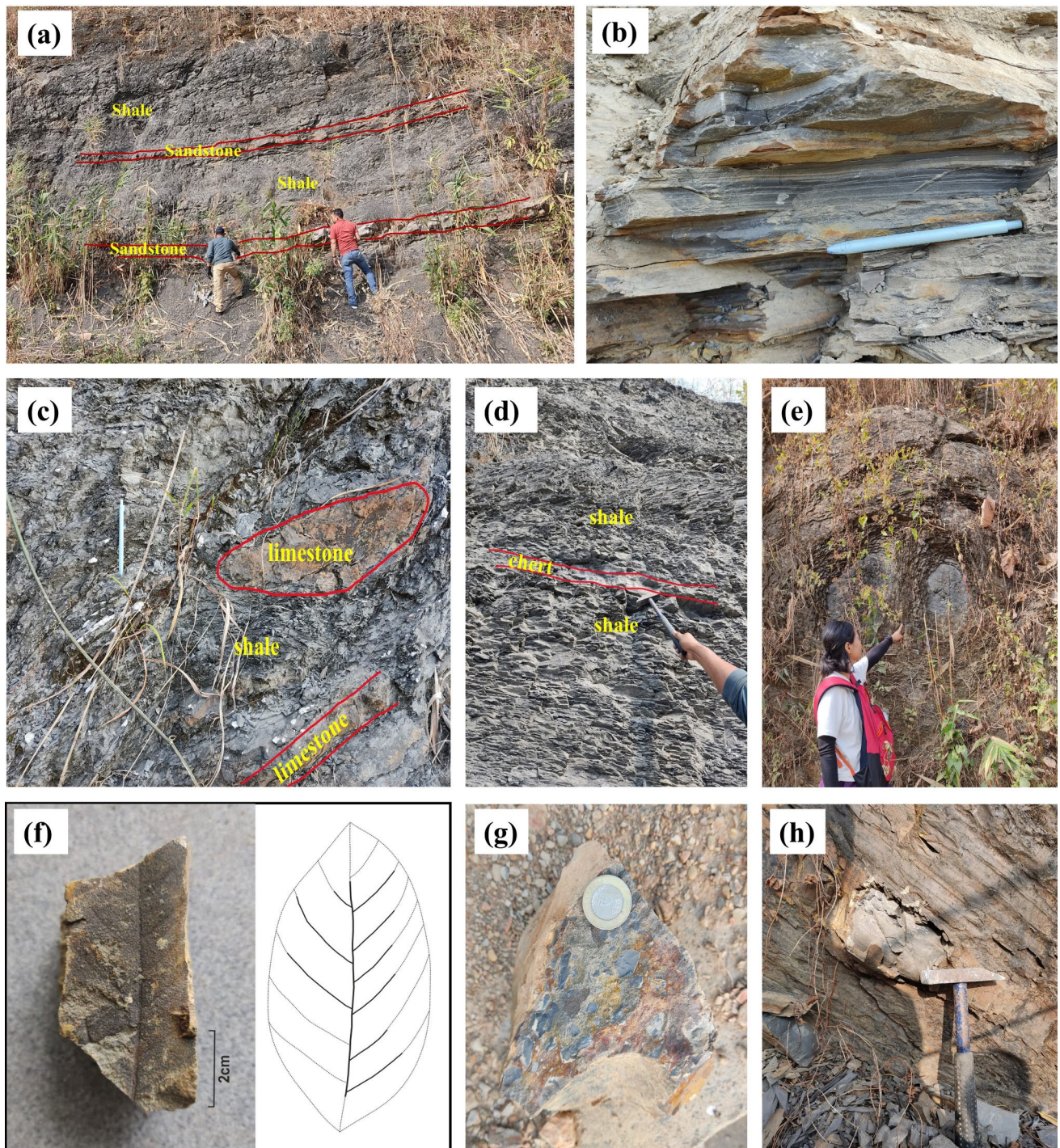


Fig. 2 Field photographs of the Disang Group: **(a)** Thin sandstone beds within thick shale beds; **(b)** Rhythmic sandstone-shale Alternations; **(c)** Limestone occurring as patches and beds within the Disang

shales; **(d)** Occurrence of thin chert bands within splintery shales; **(e)** Spheroidal weathering of the shales; **(f)** Plant fossil; **(g)** Rip up clasts within sandstone; and **(h)** Carbonate concretion within sandstone bed

leaves and correlated them with existing taxa. Morphologically, the leaf appearing asymmetrical, elliptic, texturally chartaceous, with a preserved length of lamina of about 6 cm and width of about 3.5 cm (Fig. 2f). The leaf is incomplete with apex, base and margin broken; the venation is pinnate

and eucamptodromous; primary vein is moderately thick and straight; and five secondary veins are visible on one side of the lamina. These features indicate that the fossil is a dicotyledon leaf. It shows close resemblance to *Dicotylophyllum asymmetricum* species reported from the Upper

Disang Group of late Eocene age in Manipur (Guleria et al., 2005). However, thorough paleontological research in this region may eventually shed light on interpreting paleoclimate conditions.

4.3 Petrography

Results of the petrographic analysis of sandstone, limestone and chert have been discussed below:

4.3.1 Sandstones

The Disang sandstones are fine to medium grained, poorly to moderately sorted and sub angular to sub rounded. The framework grains of these sandstones are quartz, feldspar, rock fragments and mica. The result of modal analysis depicts the contents of individual detrital constituents (Table 2). Quartz being the dominant mineral, constitutes 86.3–97.7% and is present as both monocrystalline and polycrystalline forms (Fig. 3a and b). Monocrystalline quartz (60.2–76.3%) dominates over polycrystalline quartz (14.4–25.3%) with non-undulatory monocrystalline quartz exceeding the proportion of undulatory quartz. The quartz grains are mostly poorly to moderately sorted and sub angular to sub rounded, although a few rounded quartz grains is also observed in some samples (Fig. 3a). Feldspars are mostly plagioclase and orthoclase with few microcline grains (Fig. 3b and c). The proportion of feldspar ranges from 1.1 to 8.3%. Rock fragments constitute 0.6–5.8% with mostly

sedimentary and metamorphic fragments (Fig. 3d and e). Very few igneous rock fragments are found (Fig. 3f). Mica occurs as specks or bent flakes and constitutes 0.3–6.9% of the detrital framework grains (Fig. 3g and h). Muscovite is found to be more abundant than biotite. Small quantities of chert grains varying from 0.3 to 2.0% are also seen in most sandstone samples (Fig. 3h).

The detrital grains are bound together by different types of cement and matrix. The cement and matrix percentage varies from 11.8 to 46.0% and 12.0 to 28.3%, respectively (Table 2). The cement types are argillaceous, ferruginous, siliceous and calcareous (Figs. 3i–k and 4e). The authigenic clay minerals are the main cementing materials in the sandstones and they occur as pore-filling and pore-lining rim cement. The calcareous cements often show patchwork cleavage and they are seen between the grains (Fig. 3k). Argillaceous, ferruginous, siliceous and calcareous types of matrixes are common (Fig. 3l). The diagenetic minerals are thought to have been formed due to the alteration, dissolution of the framework grains and recrystallization of other minerals.

4.3.2 Carbonates and chert

The limestones are composed mostly of calcium carbonate in the form of micrite and sparry calcite. However, a few terrigenous admixtures such as quartz and mica have also been observed (Fig. 3m). The major constituent is micrite,

Table 2 Results of modal analysis of the sandstones of Disang Group

Sample no.	Qt (%)	F	L (%)	Qm (%)	NUM	UM	Lt%	P2–3	P>3	Qp (%)	M	Mic	C	Chert
D1	90.35	7.82	1.83	69.81	71.88	22.84	17.97	4.58	13.22	16.15	18.50	6.90	14.09	0.55
D5	95.93	2.44	1.63	70.64	73.08	15.38	23.74	10.17	11.87	22.11	12.00	0.33	46.00	0.67
D7	86.30	8.34	5.36	60.18	60.01	29.60	26.37	8.96	13.80	21.01	18.67	4.00	19.67	1.67
D10	95.67	1.44	2.89	75.80	66.67	25.97	22.16	6.42	12.83	19.27	12.25	1.25	16.75	0.50
D11	96.67	1.43	1.90	76.27	55.73	30.21	21.09	13.30	5.42	19.18	21.25	0.75	25.25	0.25
D12	97.72	1.14	1.14	71.56	50.00	34.21	26.52	13.95	11.63	25.38	20.67	0.33	20.00	0.33
D13A	93.41	1.16	5.43	72.19	63.26	26.51	26.07	9.13	10.79	20.65	21.00	1.25	11.75	1.50
D13B	91.09	3.14	5.76	64.27	67.38	24.11	31.04	6.90	18.97	25.27	18.67	3.33	12.67	0.67
D14	96.25	1.25	2.51	75.49	60.99	26.95	22.24	11.12	7.84	19.73	21.00	1.33	24.67	0.00
D15A	95.24	2.16	2.60	74.88	62.31	27.64	21.50	9.09	9.55	18.90	25.25	1.75	14.25	1.00
D15B	88.43	6.36	5.20	68.73	59.56	35.30	21.10	4.57	11.12	15.90	23.00	2.67	14.67	1.00
D18	95.60	3.77	0.62	73.25	66.66	21.02	19.90	11.19	9.21	19.28	28.33	1.33	17.00	0.33
D21	87.26	6.95	5.79	61.02	60.53	28.42	28.94	9.29	15.93	23.15	17.25	2.75	13.25	2.00
D23A	92.44	4.89	2.67	74.72	65.26	28.42	17.07	5.77	8.65	14.40	24.00	3.75	15.50	0.50
D23B	89.66	5.17	5.17	64.16	55.80	32.60	27.54	10.10	12.98	22.37	23.75	2.75	13.75	1.75
Average	92.80	3.83	3.37	70.20	62.61	27.28	23.55	8.97	11.59	20.18	20.37	2.30	18.62	0.85

Qt total quartz, F feldspar, L lithic fragments, Qm monocrystalline quartz, Qp polycrystalline quartz, NUM non-undulose monocrystalline quartz, UM undulose monocrystalline quartz, Lt total lithic fragments, P2–3 polycrystalline quartz with 2–3 crystal units per grain, P>3 polycrystalline quartz with >3 crystal units per grain, C cement, M matrix, Mic mica

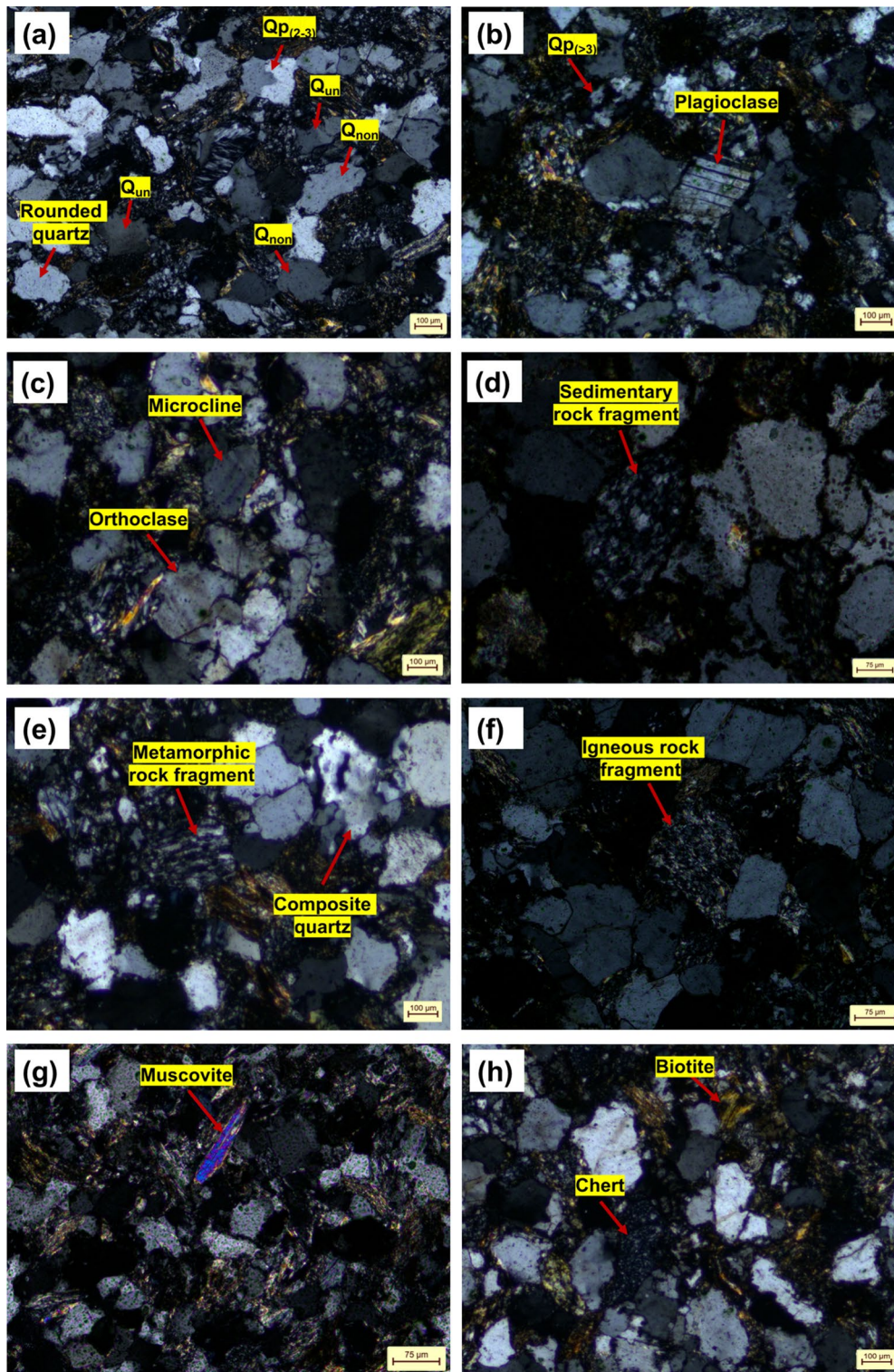


Fig. 3 Representative photomicrographs of Disang Group of rocks: (a) Non-undulose and undulose quartz, polycrystalline quartz with 2–3 crystal units and rounded quartz; (b) Polycrystalline quartz with > 3 crystal units and plagioclase; (c) Microcline and orthoclase; (d) Sedimentary rock fragment; (e) Metamorphic rock fragment and composite quartz grain with sutured intercrystalline boundaries (met-

amorphic origin); and (f) Igneous rock fragment; (g) Muscovite; (h) Biotite and chert; (i) Argillaceous cement; (j) Ferruginous cement; (k) Poikilotopic calcite cement; (l) Argillaceous and ferruginous matrix; (m) Micrite, quartz & recrystallization of micrite to sparite in limestones; and (n) Chert with a quartz vein

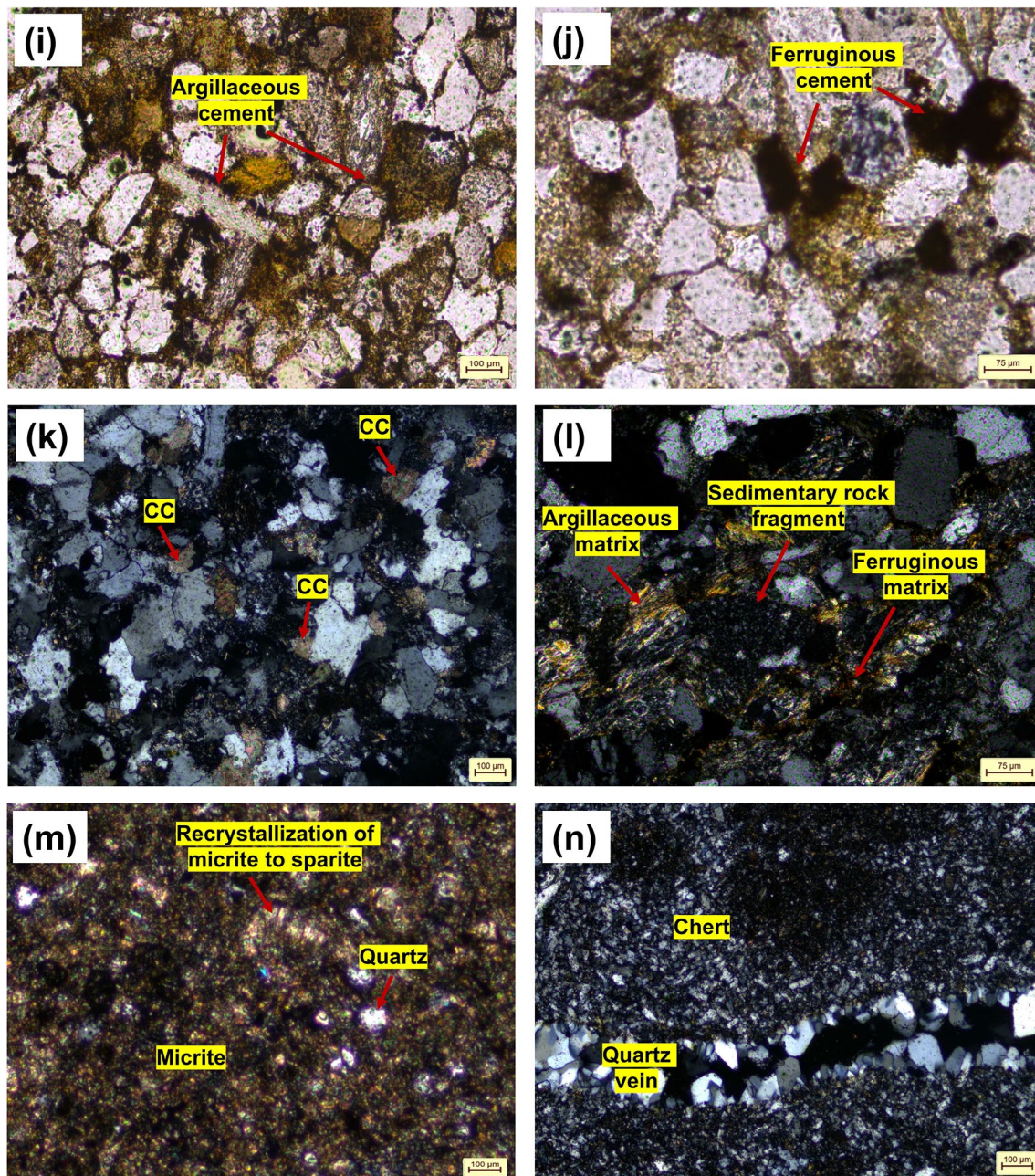


Fig. 3 (continued)

although some of them have been recrystallized to sparite during neomorphism. Chert consists of silica in the form of microcrystalline quartz. Well-developed quartz veins are present within a homogenous matrix consisting of equant subhedral quartz grains (Fig. 3n).

4.4 Clay mineralogy

XRD analysis have been carried out from sandstone samples to identify the presence of clay and non-clay minerals. Different types of clay minerals such as chlorite, illite, muscovite, montmorillonite and mixed layer clays such as smectite-montmorillonite, chlorite-montmorillonite and mica-montmorillonite

have been identified in the diffractograms. Chlorite is the most dominant clay mineral in all the samples identified by its 3.54 Å and 4.72 Å peaks. Other clay minerals like illite showing 4.47 Å and 10.06 Å; and smectite-montmorillonite with 4.5 Å and 5.01 Å are also present. The non-clay minerals include mostly quartz along with albite, calcite, dolomite, siderite, aragonite, muscovite, pyrite and gypsum (Fig. 5a–d).

5 Discussion

To classify the studied rocks and determine the provenance, tectonic setting, palaeo climate and diagenetic history of the Disang Group, following interpretations have been made based on sandstone petrography and clay mineralogical study. Occurrences of fossil leaf and carbonate rock have also been incorporated to describe the provenance and palaeoclimate.

5.1 Detrital composition and classification of sandstone

Classification schemes for sandstones are based on the relative abundance of major detrital (quartz, feldspar and rock fragments) and matrix content. To classify the sandstone under study, the ternary diagram of Dott, 1964 (modified by Pettijohn, 1984) has been used. They have been classified as arenite and wacke based on their matrix content. Barring two samples (having matrix content of 12.0 and 12.3%) most of the samples are of wacke type (having matrix content of 17.3–28.3% (Table 2). They are classified as quartz wacke, arkosic wacke, lithic greywacke and quartz arenite (Fig. 6) by employing the ternary diagram of Dott, 1964 (modified by Pettijohn, 1984). According to Dickinson et al. (1983), tectonic settings as well as climate, relief, transport mechanisms, depositional environment, and diagenetic changes control sandstone composition. Thus, these factors may produce different sediment characteristics, leading to variations in the texture and composition of sandstones even within the same formation.

To classify the limestones of the present study, Folk's classification scheme (1959, 1962) has been employed and are designated as micrite since they contain micrite as the dominant constituent. On the other hand, chert is composed mostly of silica in the form of microcrystalline quartz, with few quartz veins.

5.2 Provenance and tectonic settings

The petrographic study has revealed that the studied sediments are composed of higher proportions of monocrystalline quartz, a smaller amount of polycrystalline quartz and a minor amount of feldspar, and rock fragments. The abundance of monocrystalline non-undulatory quartz indicates a plutonic provenance, whereas the presence of undulatory quartz is indicative of metamorphic provenance for the studied sandstones (Basu, 1985; Basu et al., 1975). To determine the provenance, two types of diamond diagrams after Basu et al. (1975) and Tortosa et al. (1991) have been used and they indicate that the sandstones were derived from low- to middle- and upper rank metamorphic sources such as slates, schists, and gneisses (Fig. 7a and b).

Dickinson and Suczek (1979) and Dickinson (1985) have established that different types of provenances can simultaneously contribute detritus to a sedimentary basin. Tectonic discrimination diagrams are usually applied to show the relationship between sandstone composition and major provenance types, such as stable cratons, basement uplifts, magmatic arcs, and recycled orogens (Dickinson et al., 1983). In the Qt-F-L diagram, the sandstones of Disang Group plot in craton interior and recycled orogen field, and in Qm-F-Lt diagram, they fall in quartzose recycled field (Fig. 8a and b). Craton interior provenance may have contributed sediments to the cratonal flank of the Assam-Arakan foreland basin and recycled orogen provenance may have contributed sediments directly into the foreland basin next to the orogenic belt.

5.3 Implications on palaeoclimate

The palaeoclimatic condition of the Disang sandstones has been investigated using Q-F-R ternary plot (Suttner et al., 1981); bivariate plot of $QP/(F+RF)$ vs $QT/(F+RF)$ (Suttner & Dutta, 1986); semi-quantitative weathering index (Grantham & Velbel, 1988); and $\ln(Q/R)$ vs $\ln(Q/F)$ plot (Weltje, 1994). The Q-F-R plot suggests that the sandstones were derived from metamorphic sources in a humid climatic condition (Fig. 9a). The invariant log/log plot between $QP/F+R$ and $QT/F+R$ of the climate discrimination diagram also suggests the prevalence of humid climate (Fig. 9b). In the weathering index: $WI=C \times R$ (WI—weathering index, C—climate and R—relief) and $\ln(Q/R)$ vs $\ln(Q/F)$ plot, majority of the samples plot in field 2 and 4, indicating low to moderate relief and weathering in a tropical-humid climate (Fig. 9c).

The presence of chlorite in the sandstones indicates a cold or possibly arid climate, as they are destroyed in warm and humid climates (Einsele, 1992). Illites are formed by mechanical weathering in high relief areas with cold and/or dry climate (Ghandour et al., 2003). Illite and chlorite are more abundant in ancient sediments than modern sediments

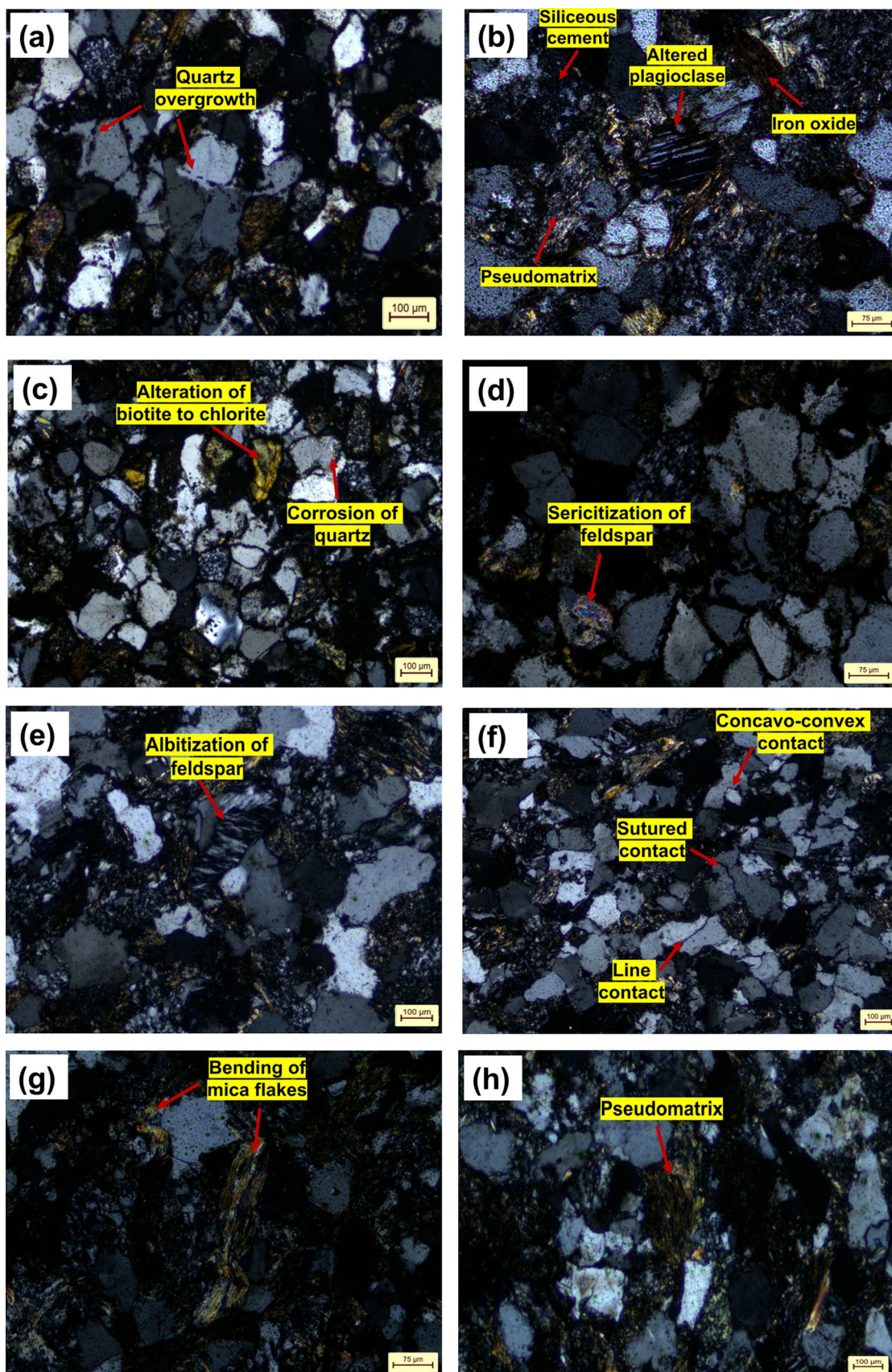


Fig. 4 Representative photomicrographs of Disang Sandstones: (a) Quartz overgrowth; (b) Altered plagioclase, pseudomatrix, siliceous and iron oxide cement; (c) Alteration of biotite to chlorite and corrosion of quartz; (d) Sericitization of feldspar; (e) Albitization of feldspar; (f) Line, concave–convex and sutured contacts; (g) Bending of mica flakes; and (h) Production of pseudo matrix

(Grim, 1951). They are present in soils of arid region under temperate and higher latitudes where leaching is not severe. Mixed layer clays are formed mainly through the leaching of pre-existing illite and mica. The alteration of chlorite to mixed layer mineral chlorite-montmorillonite and smectite to smectite-montmorillonite indicates weak hydrothermal action or long-continued weathering (Tomita et al., 1980). Montmorillonite is believed to be particularly abundant in arid climates with alkaline soils with extreme wetting and drying conditions (Prothero & Schwab, 2014).

The presence of high percentage of micrite reflects deposition in a setting where current or wave energy was insufficient to winnow away the fine matrix (Folk, 1962). Moreover, cherts, particularly those associated with Phanerozoic deep marine environments, are common in sedimentary sequences of orogenic belts (Hesse, 1988; Jones & Murchey, 1986). The identified plant fossil (*Dicotylophyllum asymmetricum?*) also indicates a moist tropical environment at the time of deposition of the leaves (Guleria et al., 2005). However, geochemical proxies will help in a better understanding of the environmental conditions.

5.4 Diagenetic history

The major diagenetic processes identified from petrography of the Disang sandstones include formation of authigenic minerals, dissolution of feldspar, cementation and mechanical compaction. Authigenic growth of quartz and feldspar are common during near-surface diagenetic changes of siliceous sediments which is caused by the interaction of minerals with interstitial pore fluid (Sengupta, 2007). In the studied sandstones, silica cement occurs as syntaxial overgrowth around quartz grains (Fig. 4a) and also as microcrystalline quartz in the pore spaces (Fig. 4b). Corrosion at the boundary of some of the detrital quartz grains is due to dissolution (Fig. 4c). Iron oxide has stained the majority of argillaceous cement and detrital grains, which indicates that ferruginous cement was formed during the early stages of diagenetic development while oxygen was present (Fig. 4b). The alteration of feldspar into sericite material gives a dusty appearance, where complete replacement produces clay mineral pseudomorphs (Fig. 4d). This feldspar alteration has taken place at the site of weathering during diagenesis either on burial or subsequent upliftment. Calcite occurs as poikiloplastic cements (Fig. 3k) filling the pore space and replaced the detrital grains, which are formed during early diagenesis.

Albitization of feldspar and chloritization of biotite have also been observed within the studied sandstones (Fig. 4c and e). On the other hand, effects of mechanical processes are significant during diagenesis at greater depths which includes fracturing, crushing and squashing of detrital grains and wrapping of mica flakes around quartz grains (Sengupta, 2007). In the present study, the observed long contacts (Fig. 4f) of quartz grains correspond to early stage of diagenesis, whereas the concavo-convex and sutured contacts (Fig. 4f) represent comparatively later stage of diagenesis at greater depths (Estupiñan et al., 2010; Quasim et al., 2021). The bending of mica flakes (Fig. 4g) and plastic deformation of lithic fragments forming pseudo matrix (Fig. 4b and h) are also the results of later stage of diagenesis.

The only diagenetic process identified in the studied limestones is aggradational neomorphism, which involves recrystallization of pre-existing micrite to sparite. Such process is thought to have taken place through dissolution and recrystallization of high magnesian calcite and aragonite in the presence of water during early to shallow burial diagenesis (Tucker & Wright, 1990). The presence of quartz veins in chert shows evidence of late-stage, post-depositional processes.

5.5 Probable depositional environment

The Disang Group has been considered as flysch type deep-water deposits by Mathur and Evans (1964). The wide areal extent and enormous thickness of dark grey to black splintery shale indicate that they were deposited in deeper marine water condition (Potter et al., 1980; Ramteke and Chowdhury, 1984–85, unpublished GSI report). The occurrence of thin sandstone beds within the shales signifies rapid deposition and occasional shallowing of the basin. The rhythmic nature of sandstone-shale alternations represents deposition under fluctuating energy conditions (Fig. 2b). Formation of carbonate rocks is favoured by increasing temperature and reduced pressure. Therefore, they are more readily formed in warm, shallow water, mostly in a neritic environment. The fine-grained limestones indicate their deposition in quiet water condition (Fig. 2c). The scattered limestone found as pocket deposits within the Disang Group in Manipur and Nagaland has been classified as olistostromal/exotic (Acharyya, 2010; Devi and Duarah, 2015; Devi et al., 2016; Guruaribam et al., 2021; Mitra et al., 1986; Prithiraj et al., 1992). Similar limestone pockets have been identified in the south-eastern region of Arunachal Pradesh, which can likewise be designated as olistostrome/exotic deposits. These limestone olistostromes were initially formed in a shallow, neritic environment and later transported to the basin and emplaced within the shales of Disang Group by gravity flows and submarine slides (Singh et al., 2015). It is believed that the Naga-Manipur Ophiolitic Complex, an

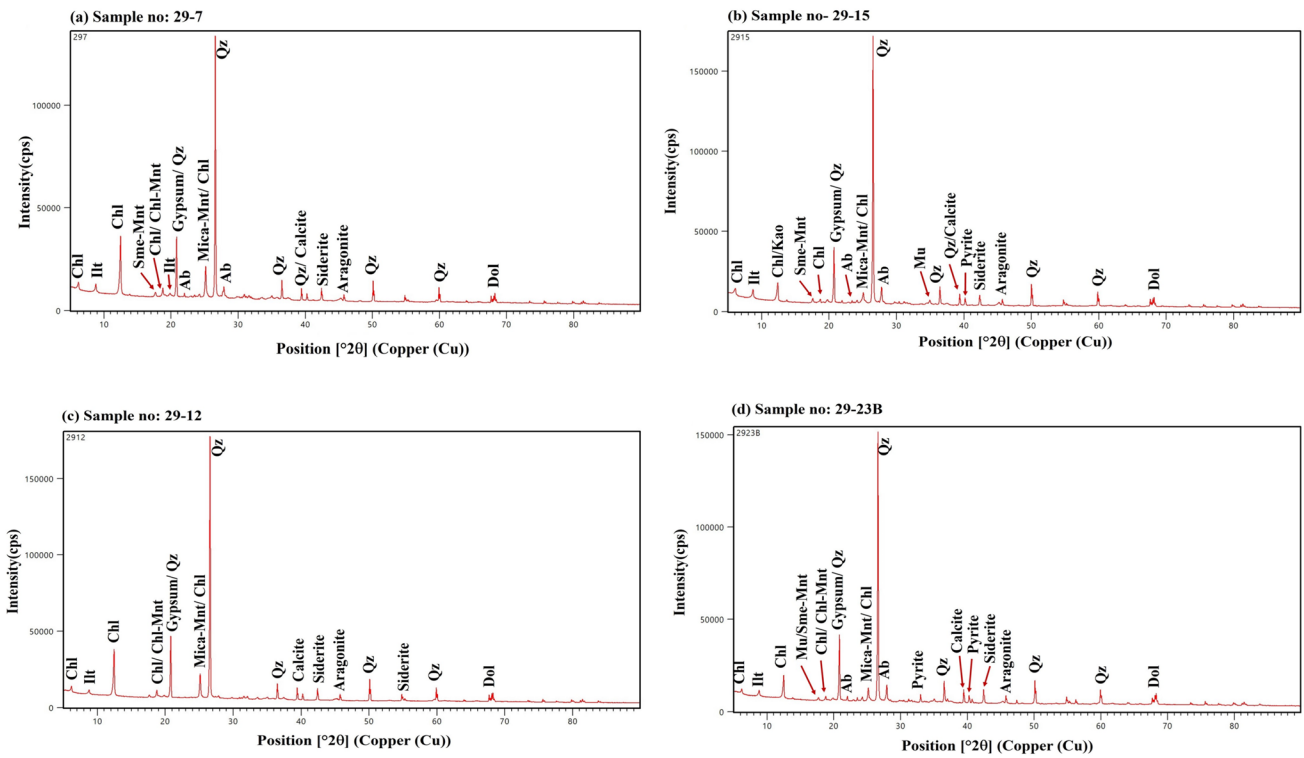


Fig. 5 X-Ray diffractograms of sandstones of Disang Group

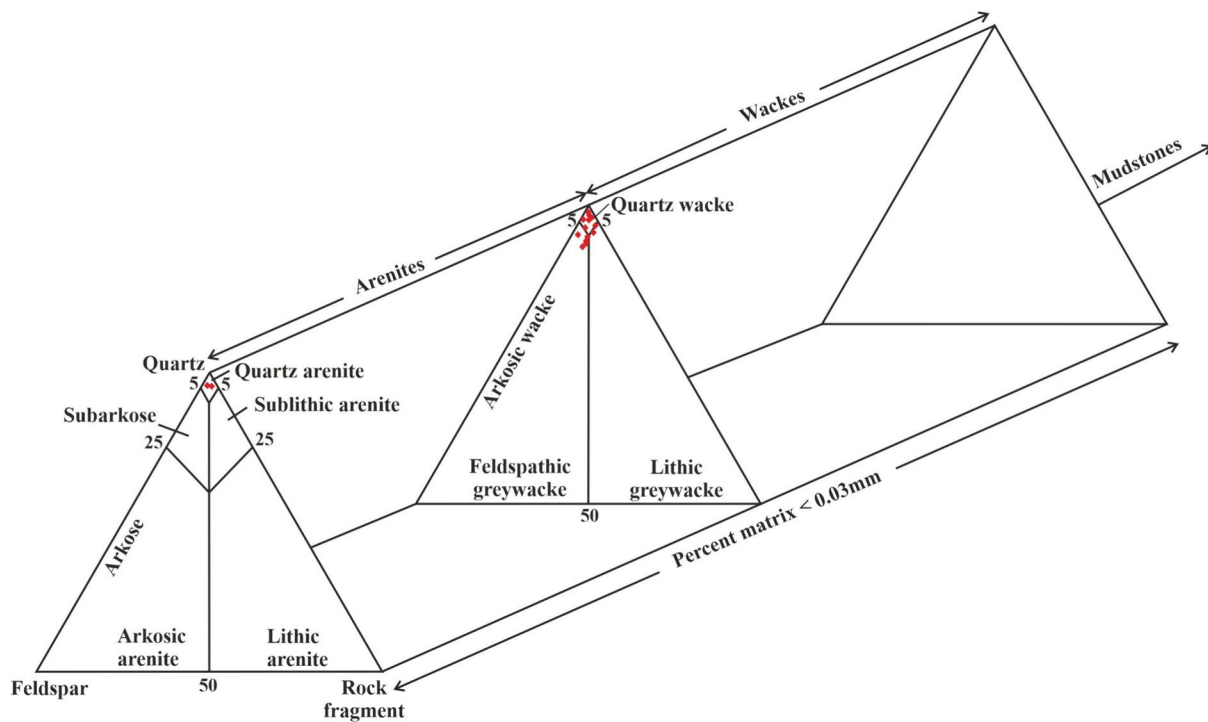


Fig. 6 Classifications of the sandstones of Disang Group (after Dott, 1964, in Pettijohn, 1984)

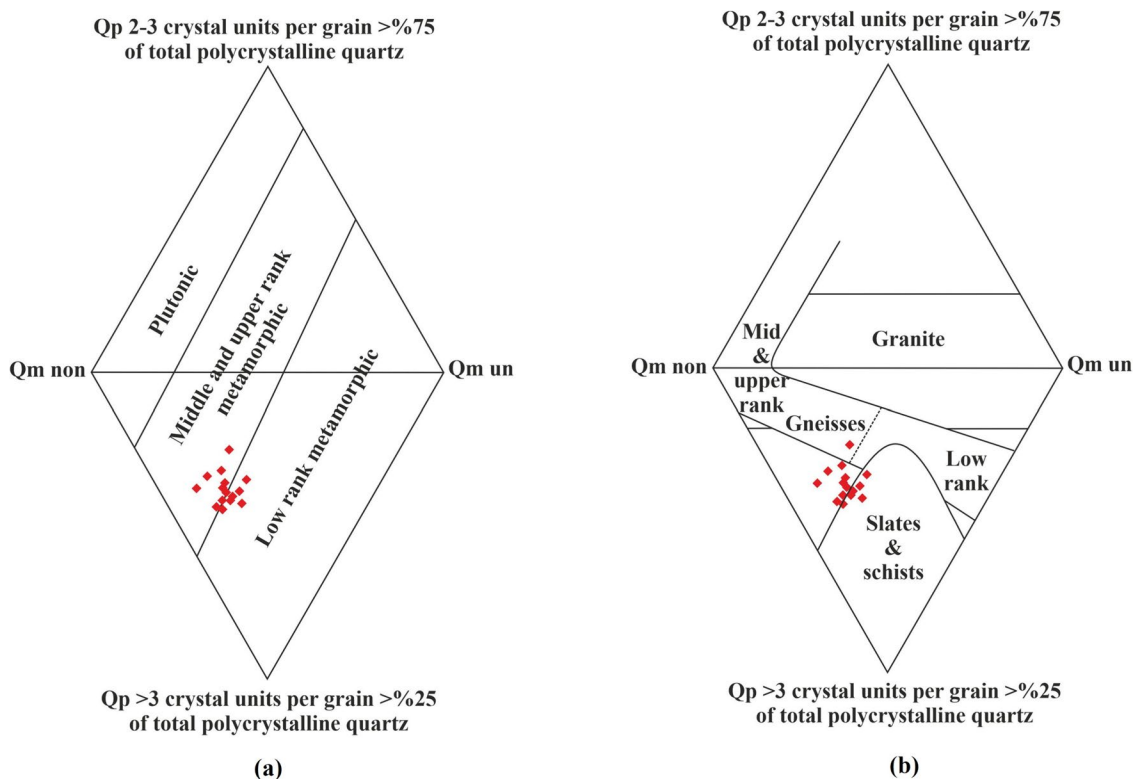


Fig. 7 Diamond diagram of Disang Sandstones (a) After Basu et al. (1975); and (b) After Tortosa et al. (1991)

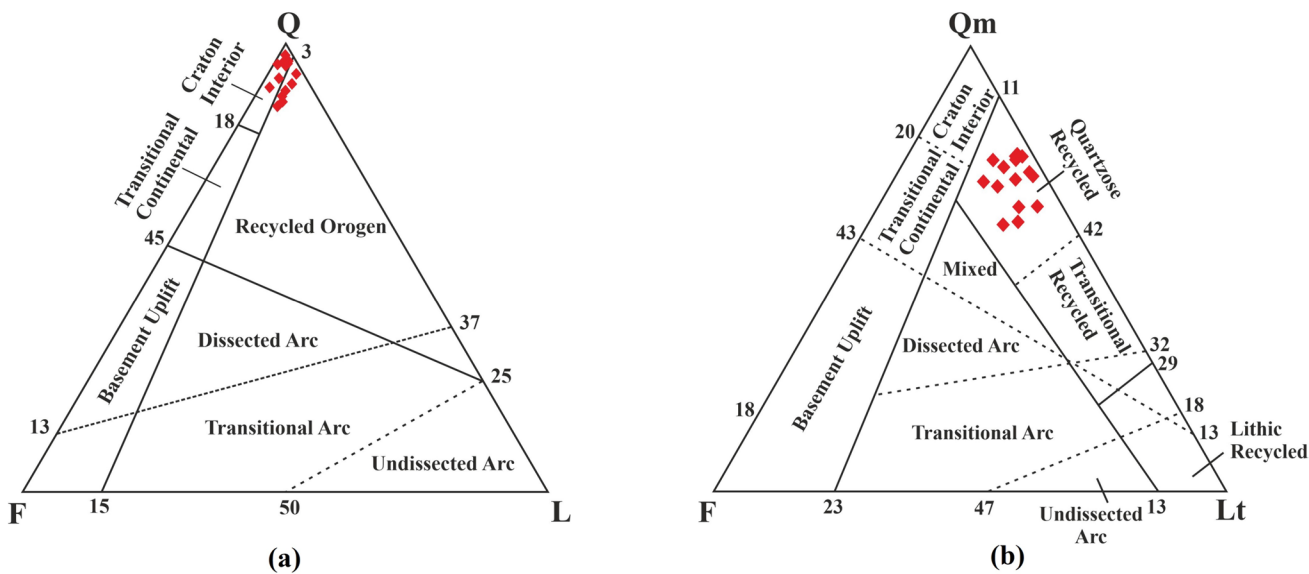


Fig. 8 (a) QtFL, (b) Q_mFL_t triangular plot of Disang Sandstones (after Dickinson et al., 1983)

accretionary prism complex exposed to the eastern side of the Indo-Burma Ranges and formed during the subduction and obduction episode of India and Burma plates, is most likely the source of these deposits (Acharyya et al., 1989; Bhattacharjee, 1991; Guruaribam et al., 2021; Mitchell,

1993). Olistostromal material in subduction zone tectonic setting includes deformed sediments and native, extrabasinal, or exotic rocks of different ages, generally older and more consolidated than intrabasinal components, which are sourced from the accretionary wedge front and/or wedge-top

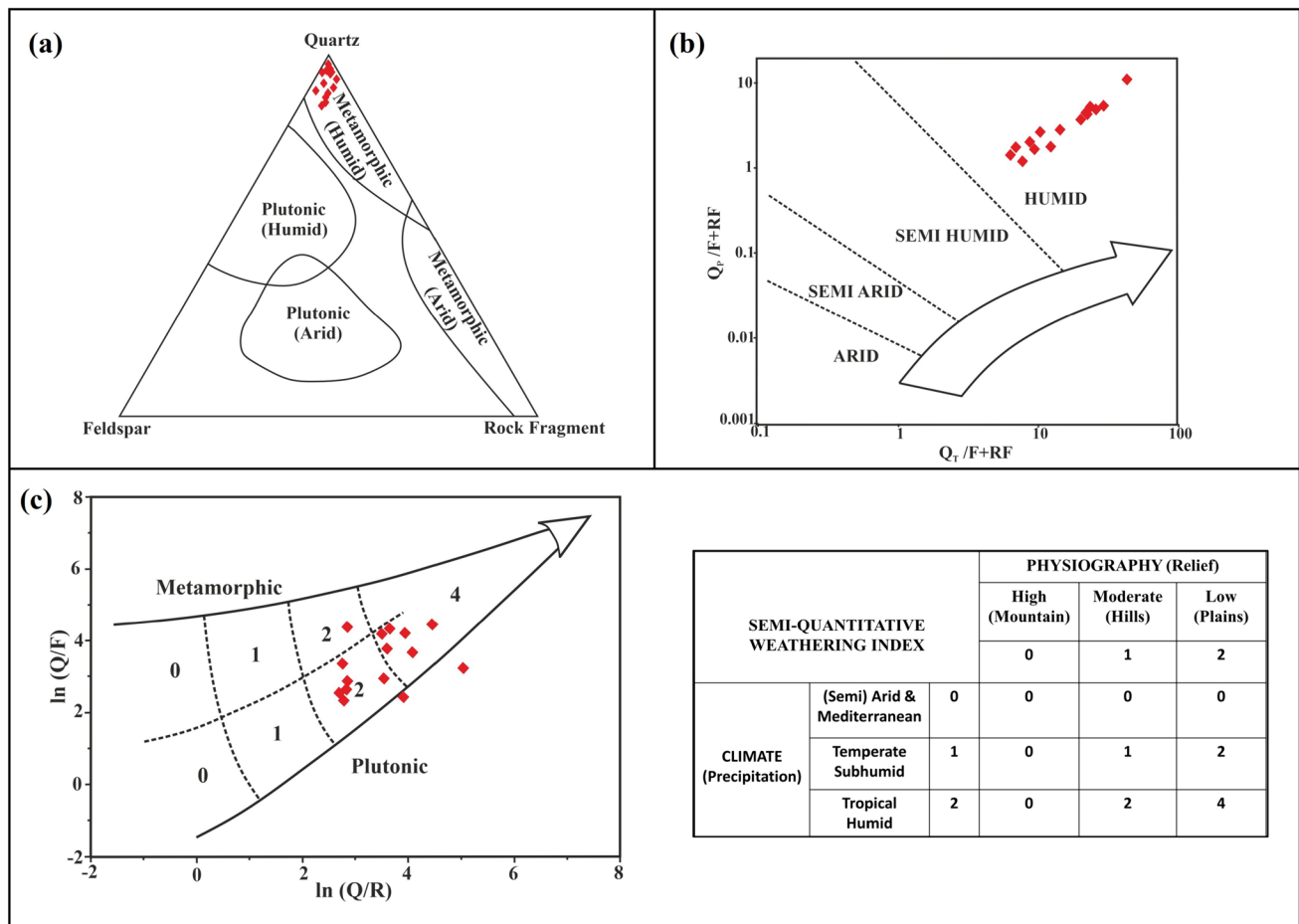


Fig. 9 **a** QFL ternary plot (after Dickinson & Suczek, 1979); **b** Bivariate log–log plot (after Suttner & Dutta, 1986); and **c** Semi quantitative weathering index (Grantham & Velbel, 1988) and $\ln(Q/R)$ vs $\ln(Q/F)$ plot (Weltje, 1994)

basins (Festa et al., 2016). Chert beds typically occurring within deepwater shale sequences (Fig. 2d) are produced when silica-rich organic oozes deposited on the deep-sea floor are recrystallized (Prothero & Schwab, 2014). No evidence of organic remains has been observed in the studied chert thin section. They could have been completely dissolved and recrystallized (Weaver & Wise, 1974). Mud rip-up clasts within sandstones that are transported by high energy currents, are interpreted as a product of storm reworking of surficial or shallowly buried muds that had become sufficiently cohesive to withstand disaggregation during erosion (Macquaker & Gawthorpe, 1993; Plint, 2014; Schieber et al., 2010). The appearance of dicot leaf fossil devoid of any twig, seed, or aquatic elements points to the allochthonous nature of the plant material which must have been transported to the site of deposition by river or current action (Guleria et al., 2005). The thick shale beds with thin sandstone and chert beds were deposited in a deep marine environment while carbonates, fossilized leaf

(Dicotylophyllum asymmetricum?), and rip up clasts were deposited in a much shallower part of the basin.

The limestone pockets (olistostromal bodies), as well as rhythmic alternations of siltstones, shales and fine-grained sandstones occurring in different parts of Manipur and Nagaland are designated as Upper Disang Formation (Chatopadhyay and Roy, 1977, unpublished GSI report; Devdas and Gandhi, 1985, unpublished GSI progress report; GSI, 2011; Mitra et al., 1986; and reference therein). On the other hand, fossils such as Dictyoconoides sp. from the Middle Eocene have been found in Nagaland (Sinha & Chatterjee, 1982), and Dicotylophyllum asymmetricum from the late Eocene in Manipur (Guleria et al., 2005), and assigned as Lower and Upper Disang, respectively. Thus, it is assumed that the present investigated rocks of north-easternmost part of Assam-Arakan Basin might probably represent the north easternmost extension of Upper Disang Formation of Disang basins (Table 3). Moreover, the change in the depositional environment from deep to shallow marine may

Table 3 Stratigraphic succession of Disang Group of rocks of Manipur, Nagaland and Arunachal Pradesh (modified after GSI, 2010, 2011)

Description of the lithology		
Arunachal Pradesh (GSI, 2010)	Nagaland (GSI, 2011) (Palaeogene Inner Belt)	Manipur (GSI, 2011)
Barail Group (Oligocene)		
Not specified	Not specified	Contact gradational: boundary containing patchy conglomerate at places
Disang Group: Dark grey shales with interbands of hard, fine grained, flaggy, sandstone and fossil leaf within sandstone. Limestone (olistostrome) and chert are also present within shales (reported in this study) (Eocene)	Disang formation: Grey, khaki grey, black splintery shales with silty interbands, lensoidal sandstones (6–8 m thick) and rhythmites (Upper Cretaceous to Eocene)	Upper Disang Formation: Shale, siltstone, graywacke with rhythmite, olitrostome with fossils and slices of ophiolitic rocks (Middle to Upper Eocene) Lower Disang Formation: Shale, graywacke with rhythmites and minor sandstone bands (Upper Cretaceous to Lower Eocene)
Tilung thrust	Not specified	Tectonic contact

indicate the existence of the Lower Disang Formation which can be established only after more extensive investigation.

6 Conclusion

Based on the present detailed study, the following conclusions about the Disang Group are drawn:

- It is composed mainly of shales with subordinate sandstone, limestone, and chert.
- The sandstones are dominantly of wacke with minor arenite types, and the limestones are of micritic type.
- The sandstones were derived from low to middle and upper rank metamorphic source rocks in a craton interior and quartzose recycled tectonic setting.
- Both tropical humid and arid climates prevailed during weathering in the source region. However, firm conclusion will be obtained only after a thorough geochemical study.
- There was a change in the depositional environment from deep marine to shallow marine.

Acknowledgements We extend our sincere gratitude to Cotton University for providing ample laboratory facilities to carry out the present work and Department of Instrumentation & USIC, Gauhati University, Guwahati for providing their XRD lab facility. We also gratefully acknowledge the anonymous reviewers and the editorial team for their constructive suggestions. One of us is extremely grateful to University Grants Commission (UGC) for the financial assistance in the form of the UGC-JRF Fellowship/2021/201610124633.

Author contributions All of the authors participated in the geological fieldwork, sample collection, and laboratory studies. The first author, DMK, performed laboratory analysis, data interpretation, writing, and editing of the original draft. CDT is involved in the conceptualization, supervision, and revision of the manuscript. AC coordinated the

laboratory analysis, data interpretation, writing, and editing of the manuscript. The papers were read and approved by all of the authors.

Funding Author Dimple Moni Kachari has received financial support from UGC-JRF for pursuing Ph.D having order number UGC-JRF Fellowship/2021/201610124633.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare that they have no competing interests in this manuscript.

Consent for publication Not applicable.

Ethics approval and consent to participate Not applicable.

References

- Acharyya, S. K. (2010). Tectonic evaluation of the Indo-Burma-Andaman mobile belt and the nature of its linkage with the Indian Continent. *Journal of Indian Geological Congress*, 2, 41–59.
- Acharyya, S. K., Ray, K. K., & Roy, D. K. (1989). Tectono-Stratigraphy and emplacement history of the Ophiolite assemblage from the Naga Hills and Andaman Island arc, India. *Journal of the Geological Society of India*, 33, 4–18.
- Adatte, T., Keller, G., & Stinnesbeck, W. (2002). Late Cretaceous to Early Paleocene climate and sea-level fluctuations: The Tunisian record. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 178, 165–196.
- Ahmad, F., Quasim, M. A., Ahmad, A. H. M., Ghaznavi, A. A., Khan, Z., & Albaroot, M. (2019). Factors influencing detrital mineralogy and tectono-provenance of fort member Sandstone, Jaisalmer formation, Western Rajasthan, India. *Journal of the Geological Society of India*, 93, 392–398.
- Ajdukiewicz, J. M., & Lander, R. H. (2010). Sandstone reservoir quality prediction: The state of the art. *American Association of Petroleum Geologists Studies*, 94, 1083–1091.
- Baruah, P. K., Meghali, G., Bhuyan, S., & Barah, R. M. (2007). Sedimentology and petroleum prospect of Eocene-Oligocene Disang

- and Barail Group of the Patkai hills of Assam Arakan folded belt, NE India. *Journal of Applied Geochemistry*, 9(1), 74–90.
- Basu, A. (1985). Influence of climate and relief on composition of sand release at source areas. In G. G. Zuffa (Ed.), *Provenance of arenites* (pp. 1–18). Reidel.
- Basu, A., Young, S. W., Suttner, L. J., James, W. C., & Mack, G. H. (1975). Re-evaluation of the use of undulatory extinction in detrital quartz for provenance interpretation. *Journal of Sedimentary Petrology*, 45, 873–882.
- Bhattacharjee, C. G. (1991). The ophiolites of northeast India—A subduction zone ophiolite complex of the Indo-Burman orogenic belt. *Tectonophysics*, 191, 213–222.
- Bhattacharya, S. W. (2017). Assessment of shale gas potential in Disang shale of upper Assam basin. *International Journal of Engineering Research and Applications*, 7(11), 30–33.
- Bhuyan, D., Borgohain, P., & Bezbaruah, D. (2022). Diagenesis and reservoir quality of oligocene Barail Group of Upper Assam Shelf, Assam and Assam Arakan basin, India. *Journal of Asian Earth Science*, 7, 1–13.
- Boggs, S., Jr. (2006). *Principles of sedimentology and stratigraphy* (4th ed., p. 662). Pearson Education Inc.
- Bordoloi, A., Chutia, A., & Taye, C. D. (2023). Reservoir characterization and rock eval pyrolysis of clastic sedimentary rocks in the Geku Formation, Arunachal Pradesh, North-eastern India. *Journal Indian Association of Sedimentologists*, 40(1), 43–54.
- Bordoloi, A., Chutia, A., Taye, C. D., & Gogoi, M. P. (2022). Petrography and geochemistry of Palaeogene sandstones of Geku Formation, Yinkiong Group, Arunachal Pradesh, NE India: Implications on provenance and tectonic setting. *Journal of Sedimentary Environments*, 7(4), 691–709.
- Chamley, H. (1997). Clay mineral sedimentation in the ocean. Soils and sediments In H. Paquet & N. Clauer (Eds.), *Z* (pp. 269–302). mineral-ogy and geochemistry. Springer.
- Chutia, A., Gogoi, M. P., Taye, C. D., & Bordoloi, A. (2022). Petrography and clay mineral study of Siwalik Group, East Siang District, Arunachal Pradesh : Implications for tectonic setting and depositional environment. *Indian Journal of Geosciences*, 76(4), 371–384.
- Chutia, A., Taye, C. D., Daimari, J., & Chutia, D. (2020). Petrography and clay mineralogical study of the Siwalik Group of rocks exposed along Pasighat-Mariyang road section, East Siang District, Arunachal Pradesh, Northeast India. *Journal of Geological Society of India*, 95(3), 263–272.
- Dasgupta, A. B., & Biswas, A. K. (2000). *Geology of Assam* (p. 169). Geol. Soc.
- Devi, K. R., & Duarah, B. P. (2015). Geochemistry of Ukhrul limestone of Assam-Arakan subduction basin, Manipur, Northeast India. *Journal of Geological Society of India*, 85, 367–376.
- Devi, K. R., Singh, W. I., Kumar, D., & Duarah, B. P. (2016). Petrography of Upper Cretaceous Eocene limestone deposits of Ukhrul district, Manipur, India: Implication to depositional environment. *Journal of Himalayan Geology*, 37(2), 165–175.
- Devi, S. R. (2022). Weathering and source rock characteristics of the upper Disang sedimentary rock of the Indo-Myanmar Ranges, NE India. *Journal of the Indian Association of Sedimentologists*, 39(1), 86–95.
- Dickinson, W. R. (1970). Interpreting detrital modes of greywacke and arkose. *Journal of Sedimentary Petrology*, 40, 695–707.
- Dickinson, W. R. (1985). Interpreting provenance relations from detrital modes of sandstones. In: G. G. Zuffa (Ed.), *Provenance of arenites: NATO ASI series* (Vol. 148, pp. 333–361). Springer.
- Dickinson, W. R., Beard, L. S., Brakenridge, G. R., Erjavec, J. L., Ferguson, R. C., Inman, K. F., Knepp, R. A., Lindberg, F. A., & Ryberg, P. T. (1983). Provenance of North American Phanerozoic sandstones in relation to tectonic setting. *Geological Society of America Bulletin*, 94(2), 222–235.
- Dickinson, W. R., & Suczek, C. A. (1979). Plate tectonics and sandstone compositions. *AAPG Bulletin*, 63, 2164–2182.
- Dott, R. H. (1964). Wacke, greywacke and matrix-what approach to immature sandstone classification? *Journal of Sedimentary Petrology*, 34, 625–632.
- Einsele, G. (1992). *Sedimentary basin: Evolution* (p. 628). Springer.
- Estupiñan, J., Marfil, R., Scherer, M., & Permanyer, A. (2010). Reservoir sandstones of the Cretaceous Napo Formation U and T members in the Oriente Basin, Ecuador: Links between diagenesis and sequence stratigraphy. *Journal of Petroleum Geology*, 33, 221–245.
- Evans, P. (1932). Explanatory notes to accompany a table showing the Tertiary succession in Assam. *Trans. Min. Geol. Met. Inst. Ind.*, 27, 168–248.
- Evans, P. (1964). The tectonic framework of Assam. *Journal of the Geological Society of India*, 5, 80–96.
- Festa, A., Ogata, K., Pini, G. A., & Dilek, Y. (2016). Origin and significance of olistostromes in the evolution of orogenic belts: A global synthesis. *Gondwana Research*, 39, 180–203.
- Folk, R. L. (1959). Practical petrographic classification of limestone. *Bulletin of the American Association of Petroleum Geologists*, 43, 1–38.
- Folk, R. L. (1962). Spectral subdivision of limestone types. *Bulletin of the American Association of Petroleum Geologists, Memoir*, 1, 62–84.
- Gazzi, P. (1966). Le Arenarie del Flysch Sopraretaceo dell' Appennino Modenese: Correlazionicon il Flysch di Monghidoro. *Mineralogica Et Petrographica Acta*, 12, 69–97.
- Ghandour, I. M., Masuda, H., & Maejima, W. (2003). Mineralogical and chemical characteristics of Bajocian-Bathonian shales, G. Al-Maghara, North Sinai, Egypt: Climatic and environmental significance. *Geochemical Journal*, 37(1), 87–108.
- Gogoi, B. K., & Sarmah, R. K. (2013). Geochemical characteristics of shale of Disang Group, Tirap District, Arunachal Pradesh. *International Journal of Scientific and Technology Research*, 2(11), 186–192.
- Gogoi, B. K., & Sarmah, R. K. (2021). Tectonic setting and provenance of eocene sandstones of Disang Group, Tirap District, Arunachal Pradesh. *Journal of the Indian Association of Sedimentologists*, 38(1), 5–12.
- Gogoi, M. P., Borgohain, P., Gogoi, Y. K., & Bezbaruah, D. (2023). Petrography, diagenesis and hydrocarbon source potential of the Barail and Disang Group of rocks in parts of the Naga Schuppen belt and inner fold belt of Assam-Arakan Basin. *Journal of the Geological Society of India*, 99(7), 906–916.
- Gogoi, M., Mathur, N., Kumar, T. S., Walling, T., & Phukan, S. (2021). Geochemical characterization of shales of the Eocene Disang Group, Kohima Syncline, India: Inferences to hydrocarbon potential and depositional environment. *Petroleum Research I*, 6, 42–56.
- Grantham, J. J., & Velbel, M. A. (1988). The influence of climate and topography on rock fragment abundance in southern Blue Ridge Mountains, North Carolina. *Journal of Sedimentary Petrology*, 58, 219–227.
- Grim, R. E. (1951). The depositional environment of red and green shales. *Journal of Sedimentary Petrology*, 21, 226–232.
- GSI. (2010). Geology and mineral resources of Arunachal Pradesh, Geological survey of India. *Miscellaneous Publication*, 30(IV), 1–60.
- GSI. (2011). Geology and mineral resources of Manipur, Mizoram, Nagaland, and Tripura, Geological survey of India. *Miscellaneous Publication*, 30(4), 1–104.
- Guleria, J. S., Rajkumar, H. S., Mehrotra, R. C., Soibam, I., & Rajkumar, K. (2005). Palaeogene plant fossils of Manipur and their palaeoecological significance. *Palaeobotanist*, 54, 61–77.

- Guruaribam, V., Singh, Y. R., & Singh, A. K. (2021). Age and depositional environment of carbonate exotics associated with the Disang group of Assam-Arakan Basin, Northeast India: Constraints from microfossils and geochemistry. *Carbonates and Evaporites*, 36, 46.
- Hesse, R. (1988). Diagenesis# 13. Origin of chert: Diagenesis of biogenic siliceous sediments. *Geoscience Canada*, 15(3), 171–192.
- Imchen, W., Thong, G. T., & Pongen, T. (2014). Provenance, tectonic setting and age of the sediments of the upper Disang Formation in the Phek district, Nagaland. *Journal of Asian Earth Sciences*, 88, 11–27.
- Ingersoll, R. V., Bullard, T. F., Ford, R. L., Grimm, J. P., Pickle, J. D., & Sares, S. W. (1984). The effect of grain size on detrital modes: A test of the Gazzi–Dickinson point-counting method. *Journal of Sedimentary Petrology*, 54, 103–116.
- Ingersoll, R. V., & Suczek, C. A. (1979). Petrology and provenance of Neogene sand from Nicobar and Bangal Fans, DSDP sites 211 and 218. *Journal of Sedimentary Petrology*, 49, 1217–1228.
- Javed, A., Khan, K. F., & Quasim, M. A. (2023a). Petrography of the Bajocian Sandstone of Joyan Member, Jaisalmer Basin, Western Rajasthan: Implications for provenance and basin evolution. *Journal of the Geological Society of India*, 99, 73–87.
- Javed, A., Khan, K. F., Quasim, M. A., & Asjad, S. (2023b). Diagenetic characteristics and their implications on the reservoir potential of Bajocian Sandstone, Jaisalmer Basin, western Rajasthan, India. *Geosystems and Geoenvironment*, 2(4), 100219.
- Jones, D. L., & Murchey, B. (1986). Geological significance of paleozoic and mesozoic radiolarian chert. *Annual Review of Earth and Planetary Sciences*, 14, 455–492.
- Keller, W. D. (1956). Clay minerals as influenced by environments of their formation. *Bull. Am. Petr. Geol.*, 40, 2689–2710.
- Khan, T., & Khan, M. S. (2015). Clastic rock geochemistry of Punagarh basin, trans-Aravalli region, NW Indian shield: Implications for paleoweathering, provenance, and tectonic setting. *Arabian Journal of Geosciences*, 8, 3621–3644.
- Khan, T., & Sarma, D. S. (2023). Clastic rock geochemistry of the Sirohi Basin, Aravalli Craton, NW India: Implications for paleoweathering, provenance and geodynamics. *Geosystems and Geoenvironment*, 2(1), 100105.
- Khan, T., Sarma, D. S., & Khan, M. S. (2020). Geochemical study of the Neoproterozoic clastic sedimentary rocks of the Khambal Formation (Sindreth Basin), Aravalli Craton, NW Indian Shield: Implications for paleoweathering, provenance, and geodynamic evolution. *Geochemistry*, 80(1), 125596.
- Krishnan, M. S. (1968). *Geology of India and Burma*. Higginbotham (P) Ltd.
- Lokho, K., Aitchison, J. C., Whiso, K., Lhoupenyi, D., Zhou, R., & Raju, D. S. N. (2020). Eocene foraminifers of the Naga Hills of Manipur, Indo-Myanmar Range (IMR): Implications on age and basin evolution. *Journal of Asian Earth Sciences*, 191, 1–13.
- MacQuaker, J. H. S., & Gawthorpe, R. L. (1993). Mudstone lithofacies in the Kimmeridge clay formation, Wessex Basin, Southern England: Implications for the origin and controls of the distribution of mudstones. *Journal of Sedimentary Petrology*, 63, 1129–1143.
- Mahanta, B. N., Sarmah, R. K., & Goswami, T. K. (2019). Elucidation of provenance, palaeoclimate and tectonic setting of the Gondwana sandstones of Arunachal Himalayas: A petrographic approach. *Journal Geological Society of India.*, 94, 260–266.
- Majumdar, D., & Chetia, B. K. (2016). Clay mineralogy and provenance of Disang Shales in NE Tethys Basin, India. *IOSR Journal of Applied Geology and Geophysics*, 4(4), 1–8.
- Mallet, F. R. (1876). On the coal field of Naga hills, bordering the Sibsagar and Lakhimpur districts. *Geological Survey of India Memoirs*, 12(2), 1–95.
- Mathur, L. P., & Evans, P. (1964). Oil in India. In: *International geological congress. 22nd Session India* (p. 85).
- Mitchell, A. H. G. (1993). Cretaceous-Cenozoic tectonic events in the western Myanmar (Burma) Assam region. *Journal of Geological Society of London*, 150, 1089–1102.
- Mitra, N. D., Vidhyadharan, K. T., Gaur, M. P., Singh, S. K., Mishra, U. K., Joshi, A., Khan, I. K., & Ghosh, S. (1986). A note on the olistostromal deposits Manipur. *Records of the Geological Survey of India*, 114(4), 61–76.
- Morad, S., Ketzer, J. M., & De Ros, L. F. (2000). Spatial and temporal distribution of diagenetic alterations in siliciclastic rocks: Implications for mass transfer in sedimentary basins. *Sedimentology*, 47, 95–120.
- Murray, R. W., Buchholtz ten Brink, M. R., Gerlach, D. C., Ruth, G. P., III., & Jones, D. L. (1991). Rare earth, major, and trace elements in chert from the Franciscan Complex and Monterey Group, California: Assessing REE sources to fine-grained marine sediments. *Geochimica Et Cosmochimica Acta*, 55, 1875–1895.
- Nagappa, Y. (1959). Foraminiferal biostratigraphy of the Cretaceous-Eocene succession in India, Pakistan and Burma Region. *Micro-paleontology*, 5(2), 145–192.
- Perry, E. C., & Lefticariu, L. (2014). Formation and geochemistry of Precambrian cherts. *Treatise on Geochemistry*, 9, 113–139.
- Pettijohn, F. J. (1984). *Sedimentary rocks* (3rd ed., p. 628). CBS Publishers and Distributors.
- Phukon, S., Hazorika, S., & Sarmah, R. K. (2010). Study of petrography and dispersed organic matter of Disang-Barail group of rocks in Deomali-Hukanjuri area, Tirap, District, Arunachal Pradesh, India. *Journal of Indian Association of Sedimentologists.*, 29(1), 37–49.
- Plint, A. G. (2014). Mud dispersal across a Cretaceous prodelta: Storm-generated, wave-enhanced sediment gravity flows inferred from mudstone microtexture and microfacies. *Sedimentology*, 61, 609–664.
- Potter, P. E., Maynard, J. B., & Pryor, W. A. (1980). *Sedimentology of shale*. Springer.
- Prithiraj, Ch., Mishra, P. K., & Sahni, A. (1992). Late and terminal Cretaceous foraminiferal assemblages from Ukhrul, Mélange zone, Manipur. *Current Science*, 62(6), 478–481.
- Prothero, D. R., & Schwab, F. (2014). *An introduction to sedimentary rocks and stratigraphy* (3rd ed., p. 410). W.H. Freeman and Company.
- Quasim, M. A., Ahmad, A. H. M., & Ghosh, S. K. (2017a). Depositional environment and tectono-provenance of Upper Kaimur Group sandstones, Son Valley Central India. *Arabian Journal of Geosciences*, 10, 4.
- Quasim, M. A., Khan, I., & Ahmad, A. H. M. (2017b). Integrated petrographic, mineralogical, and geochemical study of the Upper Kaimur Group of rocks, Son Valley, India: Implications for provenance, source area weathering and tectonic setting. *Journal of the Geological Society of India*, 90, 467–484.
- Quasim, M. A., Khan, S., Srivastava, V. K., Ghaznavi, A. A., & Ahmad, A. H. M. (2021). Role of cementation and compaction in controlling the reservoir quality of the Middle to Late Jurassic Sandstones, Jara dome, Kachchh Basin, western India. *Geological Journal*, 56, 976–994.
- Rao, N. K., Dora, M. L., Baswani, S. R., Malpe, D. B., & Deshmukh, M. S. (2018). Petrography and geochemistry of the Proterozoic sandstones of Somanpalli Group from Pomburna area, Eastern Belt of Pranhita-Godavari Valley, central India: Implications for provenance, weathering and tectonic setting. *Journal of Earth System Science*, 127, 90.
- Schieber, J., Southard, J. B., & Schimmelmann, A. (2010). Lenticular shale fabrics resulting from intermittent erosion of water-rich

- muds: Interpreting the rock record in the light of recent flume experiments. *Journal of Sedimentary Research*, 80(1), 119–128.
- Sengupta, S. M. (2007). *Introduction to sedimentology* (2nd ed., p. 314). CBS Publishers and Distributors.
- Singh, Ch. G., & Kushwaha, R. A. S. (2008). Petrographic analysis of Tertiary Sediments between Imphal and Moreh, Manipur. *Journal of the Indian Association of Sedimentologists*, 27, 23–34.
- Singh, Y. R., & Meera, N. (2013). Source rock palynology of Disang sediments of Imphal valley, Manipur. *Journal of Earth Science*, 1, 239–246.
- Singh, Y. R., Singh, B. P., & Devi, S. R. (2017). Source rock characterization, diagenesis and depositional environment of the upper Disang formation from Gelmoul area of Southern Manipur, NE India. *Journal of the Indian Association of Sedimentologists*, 34(1&2), 1–7.
- Singh, Y. R., Singh, B. P., & Jianguo, L. (2015). Hydrocarbon potential of the Paleogene Disang Group, Manipur region, India—A palynological approach. In S. Mukherjee (Ed.), *Petroleum geosciences: Indian contexts* (pp. 191–204). Springer Geology.
- Sinha, N. K., & Chatterjee, B. P. (1982). Notes on the Disang Group in parts of Nagaland and its fossil fauna. *Records of the Geological Survey of India*, 13(4), 50–52.
- Suttner, L. J., Basu, A., & Mach, G. H. (1981). Climate and origin of quartz arenites. *Journal of Sedimentary Petrology*, 51(4), 1235–1246.
- Suttner, L. J., & Dutta, P. K. (1986). Alluvial sandstone composition and paleoclimate, I. Framework mineralogy. *Journal of Sedimentary Petrology*, 56(3), 329–345.
- Tomita, K., Masato, K., Masahiko, Y., & Noboru, O. (1980). A regularly interstratified mineral of chlorite-montmorillonite in an altered andesite from Kinzan, Kagoshima Prefecture. *J. Japan. Assoc. Min. Petr. Econ. Geol.*, 76, 213–220.
- Tortosa, A., Palomares, M., & Arribas, J. (1991). Quartz grain types in Holocene deposits from the Spanish Central System: Some problems in provenance analysis. *Geological Society, London, Special Publications*, 57, 47–54.
- Tucker, M. E. (1988). *Techniques in sedimentology* (p. 394). Blackwell Scientific Publications.
- Tucker, M. E. (2001). *Sedimentary petrology: An introduction to the origin of sedimentary rocks* (3rd ed., p. 262). Blackwell science Ltd.
- Tucker, M. E., & Wright, V. P. (1990). *Carbonate sedimentology*. Blackwell Scientific Publications.
- Weaver, F. M., & Wise, S. W., Jr. (1974). Opaline sediments of the southeastern coastal plain and horizon A: Biogenic origin. *Science*, 184, 899–901.
- Weltje, G. J. (1994). Provenance and dispersal of sand-sized sediments: Recognition of dispersal pattern and sources of sand-sized sediments by means of inverse modelling techniques. *Geologica Ultraiectina*, 121, 208.
- Worden, R. H., & Burley, S. D. (2003). Sandstone diagenesis: The evolution of sand to stone. *International Association of Sedimentologists, Blackwells, Oxford*, 4, 3–44.
- Zhang, H., Fan, H., Wen, H., Zhu, X., & Tian, S. (2020). Oceanic chemistry recorded by cherts during the early Cambrian Explosion, South China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 558, 109961.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.