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Diagenetic Environment of Oligocene Barail Sandstones, North-West of Kohima, Nagaland, India

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Abstract

Petrographies, Scanning Electron Microscopy (SEM) along with XRD analysis were used to thoroughly examine the physical and diagenetic characteristics of the Oligocene Barail siliciclastics exposed in the NW of Kohima town of Nagaland, India. The hard and compact sandstones of the study area are represented by very fine to medium sand fractions and belong to sublithicarenite/quartz arenite categories. Compaction effects, authigenesis and albitization, silica overgrowth, neo-morphic quartz, modified grain to grain contacts, bending of flaky minerals, and corroded grain boundaries are the diagenetic features observed in the Barail sandstones. Locomorphic and redoxomorphic diagenetic stages are common; while features showing phyllomorphic stage of diagenesis are less common. A progressive diagenetic regime has also been envisaged on the basis of various diagenetic signatures and stages. Preserved diagenetic features and stages suggest a depth range of 3 to 5 km and temperature above 150^{o}C. Chemistry of sea water, pH, increasing pressure and temperature were responsible for diagenetic modifications in the Oligocene Barail sandstones.

Keywords: Petrography, Diagenesis, Oligocene, Barail sandstone, Nagaland

Introduction

The geodynamic evolution of the Indo-Myanmar Ranges (IMR) is an outcome of the convergence of the Indian Plate against the Myanmar plates. The Naga Hills of the IMR represent the westernmost extent of the Indo-Myanmar collision, where large amount of Cenozoic sediments were deposited in the Assam-Arakan Basin (Imchen *et al.*, 2014). The Naga Hills which is NE-SW trending is composed of five distinct morphotectonic units from east to west, namely, Nimi Formation/ Naga Metamorphics, Naga Ophiolite Belt (NOB), Inner Fold Belt (IFB), Belt of Schuppen (BoS) and Jopi/ Phokphur Formation (Ghose *et al.*, 2010; Mathur and Evans, 1964). Cenozoic rocks except Disang rocks represent the Schuppen Belt whereas the Inner Fold Belt is represented by arenaceous Barail Group (Srivastava and Pandey, 2011; Srivastava and Kichu, 2021) and dominantly argillaceous Disang Group rocks as well as mixed Disang-Barail Transitional succession (Srivastava, 2002; Srivastava *et al*., 2004). Recently Srivastava *et al.* (2024) also studied the provenance of the Oligocene Barail sandstones exposed in and around Longsa village of Wokha District, Nagaland and suggested thatthe main depositional site was the North-East South-Westlinear depression created by the sub-ducting Indian plate and sediments were mainly supplied by the Shillong plateau/Karbi-Anlong Massif from the west and metamorphic sourcesfrom the east along with some of the sediments from the rocks formed under earlier tectonic regimes. However, sediment supply from the Shillong platueu/Karbi-Anglong massif has been questioned as the timing of upliftment of Shillong platueu/Karbi-Anglong massif are considered to be post Oligocene (Acharyya, 2007; Richa and Srivastava, 2024). The presence of invertebrate fossils and benthic foraminifers indicate a warm tropical-subtropical climate and shallow marine (neritic) depositional environment during the sedimentation of the Upper Disang Formation (Singh *et al*., 2024).

Diagenesis, in the broadest sense, encompasses all of the processes that act to modify sediment after deposition and maintaining equilibrium with the new regime (Burley *et al.*, 1985; Morad *et al.*, 2000; Worden and Burley, 2003; Worden *et al.*, 2018, Javed *et al.*, 2023). The net result of diagenesis is to achieve equilibrium with the diagenetic environment.These diagenetic processes bring about important physical, mineralogical, and chemical changes in the original assemblage. Changes taking place during the diagenesis are influenced by factors, such as the original sedimentary facies, depositional environment and pore water chemistry near the sediment-water interface (Chapelle *et al.*, 2000; Morad *et al.*, 2010; Worden *et al.*, 2018; Khanam *et al.*, 2021). It continues throughout burial and may extend into uplift stage when a sediment pile is uplifted after burial. According to Blatt *et al.*, (1980), diagenetic changes begin near the surface and continue up to deeper levels before metamorphism sets in. Burial time, temperature and subsurface water chemistry generally control the rate and type of diagenetic changes. Diagenesis takes place during burial at depths ranging from the depositional interface to perhaps

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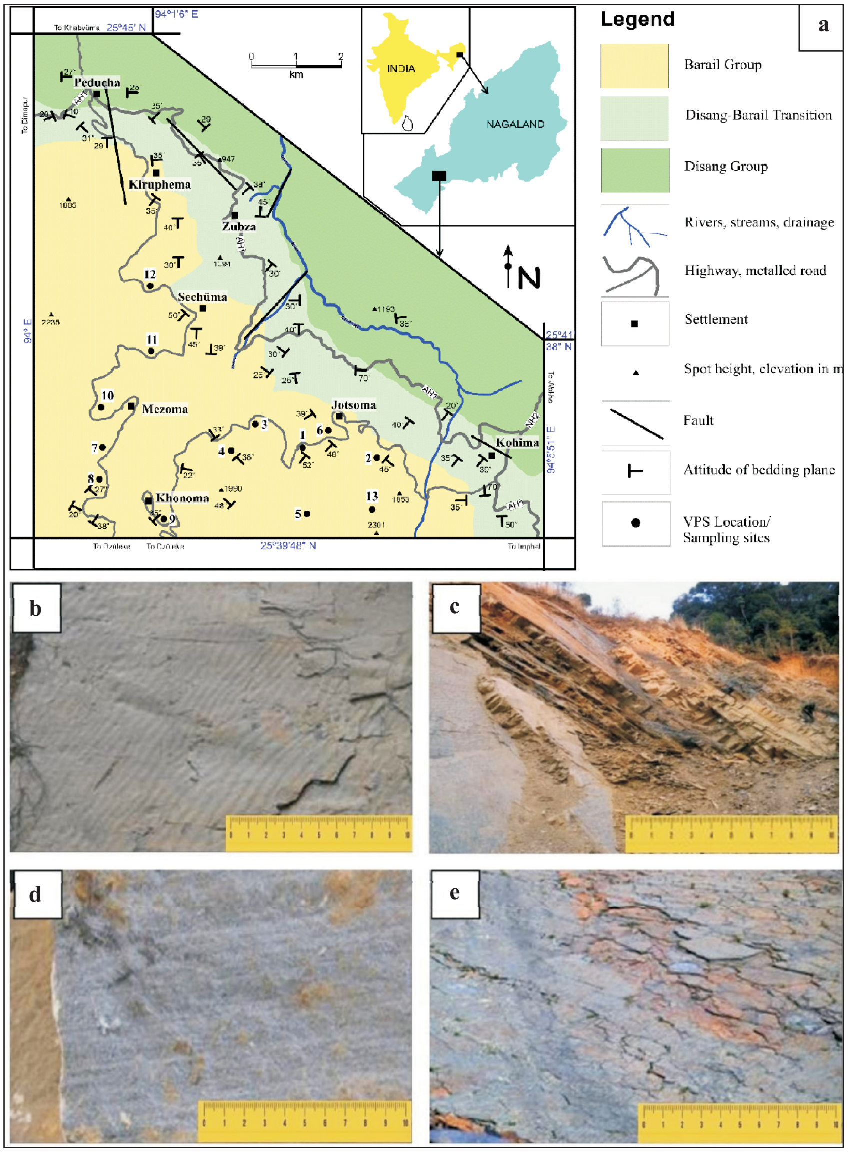

Fig.1. a) Geological map of the study area; field photographs showing b) Ripple marks; c) Channels; d) Plane laminations; e) Intensely bioturbated sediments

15km or more. Thus, the pressure-temperature conditions under which diagenesis occurs essentially extend from those characterized weathering to those that characterize metamorphism. There are no clear cut boundaries on either end of this scale, although diagenesis is commonly regarded to take place at temperatures below about 200-250°C and at pressure below 5 kb (Boggs, 2012).

In the present study an attempt has been made to identify the diagenetic features of the Barail sandstones and interpret them in terms of diagenetic environment and also to search for the probable source of cements. Petrography and SEM investigations have been used to study the early (near surface) and late (burial) diagenetic processes of a siliciclastic rock system, along with the resulting modifications due to the post-depositional processes.

Study Area

Present study area is a part of the Inner Fold Belt, comprising of well-developed Oligocene Barail sedimentary rocks, North-West of Kohima town and is characterised by multi-storeyed sandstone with intercalation of thinly bedded sandstone and shales. It is bounded between latitudes 25°36'00" N and 25°41'00" N and longitudes 94°00'00" E and 94°05'00" E of the topographic sheet no. 83 K/ (Fig.1a). Sedimentary structures encountered in the study area include symmetrical/ asymmetrical, bifurcating and interference ripples, plane/cross laminations, channels and some biogenic structures (Fig.1b-e). On the basis of the lithofacies analysis, grain size attributes primary sedimentary structures and trace fossils dominated by skolithos assemblages, a shallow marine depositional environment has been suggested by Kichu and Srivatava (2018). Srivastava and Kichu (2021) also suggested that the deposition of Barail rocks took place during dominantly regressive phases with minor fluctuations in response to the changing regional tectonics.

Methodology

Microscope is still the main instrument for identification of diagenetic features. However, Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD) and cathodoluminescence techniques have greatly enhanced our understanding of diagenetic processes and they have also helped in understanding the physico-chemical conditions which sediments had undergone. In the present study Leica DM 2700P has been used for identifying the diagenetic features and photomicrography. Eight (8) freshly broken Barail sandstone samples have been examined under SEM at the IIT, Gauhati, Assam. In addition, eight (8) samples have also been examined for their clay mineral contents. Both oriented as well as glycolated clay minerals slides were prepared and examined using XRD at Gauhati University.

Petrography

Sandstones of the study area, ranging in size from very fine to medium sand, are hard and compact in nature and have anaverage composition of Q: 90.23%, F:2.09%, and RF:7.65%. Quartz, represented by both undulatory and non-undulatory grains, is the dominant framework grain and is followedby rock fragments and feldspar.Cherts, schist and phyllites represent the lithic fragments. Feldspar is represented by both plagioclase and K-feldspar. Biotite, muscovite and chlorite are the flacky minerals observed in the thin sections.In the sandstones of the study area silica is the main cementing material. However, some iron cements have been observed. Yellowish/red coloured iron-oxides cements occur around the grains or asover-coating. Studied sandstones are matrix poor in nature. At places grain boundaries have been digested by the matrix (Fig. 2).

Diagenetic Features

Various diagenetic features observed in Barail sandstones include compaction, authigenesis and cementation represented by silica overgrowth, neo-morphic quartz, modified grain to grain contacts, bending of flaky minerals, albitization, matrix generation

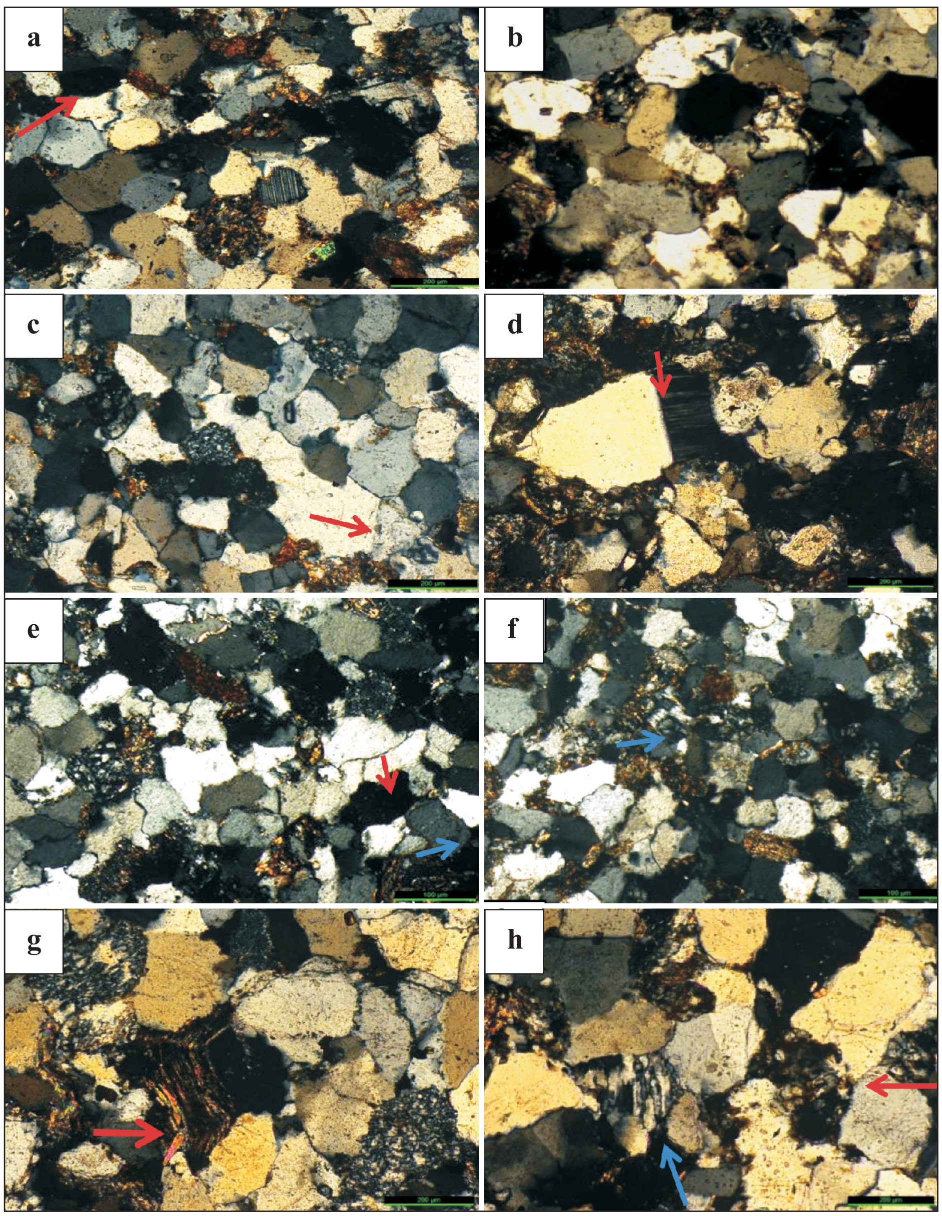

Fig.2. Photomicrographs showing **a.** Concavo-convex contacts and restoration of grain edges (arrow), **b**. Floating grain, **c**. Long and C-C contacts and other compaction effects, **d, f, h.** Albitized feldspar showing chess board like fabric, ***e, g.*** Bending of flaky mineral

and grain boundary digestion by matrix. For understanding the diagenetic conditions and environment microscopic properties, XRD data and SEM images were utilized. Two types of cements are observed in the present study: silica and iron cements. However, silica cement is the dominant cementing materials in the siliciclastics of the study area (ranges from 75 to 92 volume %; Table 1). Epitaxial overgrowths are common. Enlargement of quartz grains due to silica precipitation and thick rims of silica cement around detrital quartz grains are also common. Neomorphic quartz has also been noticed. In the present study, ferruginous (iron oxide) cement has been noticed as shapeless void fillers as well as coating on framework grains. Various diagenetic features are distinctly observed in the studied sandstones (Fig. 2-3).

Nature of the grain contacts gives an idea about the compaction history of the sediments.Concavo-convex contacts are dominantin the studied sandstones (Table 1). However, other grain contacts (floating, straight and sutured) have also been noticed though not very common. Dominance of concavo-convex contacts and low proportion of long and floating contacts suggest deep burial conditions. Compaction process is responsible for the pressure solution along the grain contacts. The resultant dissolution is responsible for the changes in the grain contacts which proceed from long to sutured contacts through the concavo-convex types. Presence of less number of straight and long contacts and dominance of the concavo-convex contacts suggest that the sediments have undergone chemical compaction processes also. Less number of sutured contacts in the studied sandstones suggests that the most of the compaction took place during the early stages of cementation (Ahmad *et al*., 2017).

Table 1: Percentage of various types of grain to grain contacts and volume percentage of cement types of Oligocene Barail sandstones, North-West of Kohima, Nagaland

Sample Number	Contact Types					Cement	
	Floating	Point	Long	Concavo convex	Suture	Silica	Iron
1	10	12	14	62	2	80	20
2	9.0	10	15	64	2	85	15
3	11	13	22	54	1	90	10
4	8.0	11	17	61	3	82	18
5	15	12	15	56	2	75	25
6	16	14	16	51	3	93	7.0
7	12	13	26	48	2	78	22
8	10	15	23	50	2	92	8.0
9	21	24	17	35	3	85	15
10	18	22	12	37	1	87	13

Quartz Overgrowth

Quartz overgrowth occurs both as syntaxial as well as

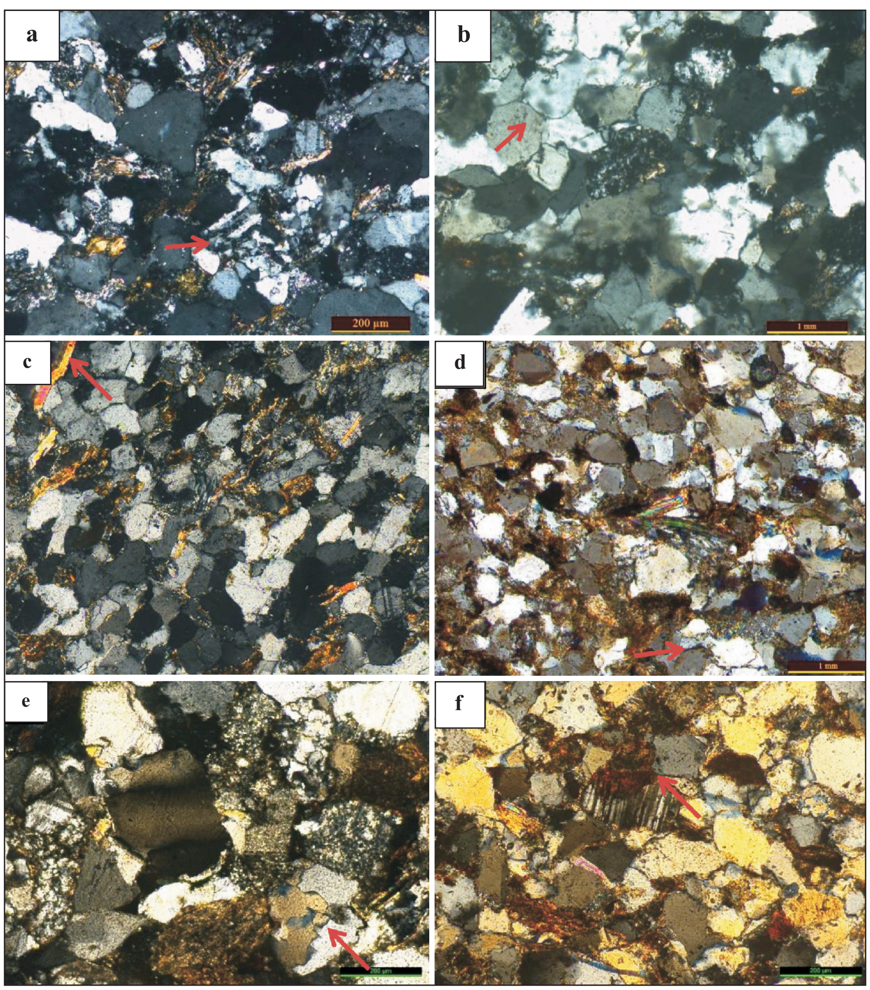

Fig.3. Photomicrographs showing **a.** Albitized feldspar, **b**. Cocavo-convex contact, **c**. Bending of flaky mineral, **d.** Corroded grain boundaries and restoration of edges, **e.** Suturing and matrix generation, **f.** Iron cement and dissolution of feldspar

epitaxial overgrowth on detrital quartz grains where the surfaces of the grains are free from any coating (Fig. 2a). Such overgrowths are less developed where quartz grains are held together by clay matrix (Heald and Lorese, 1974). Presence of authigenic quartz in the siliciclastics of the study area is considered as an indication of early diagenetic changes under eogenetic (shallow depth) marine conditions (Burley *et al.*, 1985). At places, small and sharply polyhedral aggregates of neo-quartz crystals, resembling metamorphic quartz, are observed that are developed at the stress points under early diagenetic conditions (Blatt *et al.*, 1980).

Albitization

Albitized feldspar is identified by their indistinct and diffused twinning in thin sections and presence of small blebs. Some albitized feldspar has vague, irregular complex twin lamella which does not pass through entire crystal. Some of them show chess board like fabric (Fig. 2f). Albitization generally progresses along the plane of weakness *i.e.* fracture and cleavage traces, where fluids could penetrate the crystal. Albitization occurs at temperatures of the order of 100-150°C (Boles, 1982; Surdam *et al.*, 1989) and also at temperatures as low as 70-100°C (Morad *et al.*, 1990). Presence of authigenic feldspar in the studied samples suggests increasing pressure and temperature (>100°C) in response to burial and thermal history. Presence of authigenic feldspar suggests a progression of pressure and temperature and so of burial and thermal history.

Cements

In the studied samples two main types of cements have been recognized: silica and iron cements, silica being the main cementing material (Table 1). Silica overgrowth is dominated by epitaxial growth. Rims of silica cement around detrital quartz grains and grain enlargement due to silica precipitation is common.

X-Ray Defractogram (XRD) Study and Scanning Electron Microscopy (SEM)

Both whole rock and clay fractions were analyzed for their clay and other mineral contents. The machine was set between 4° to 30° for the oriented samples while glycolated samples were run between 4° to 10°. Almost all the analyzed samples record the presence of kaolinite and montmorillonite. Illite was also recorded only in few samples. In addition to these, nimite (Na-rich chlorite), annite (mica group) dickite (kaoline group) and gibbsite (kaolinite byproduct) clay minerals were also observed (Fig. 4; Table 2). XRD analysis was carried out at the Guwahati University central

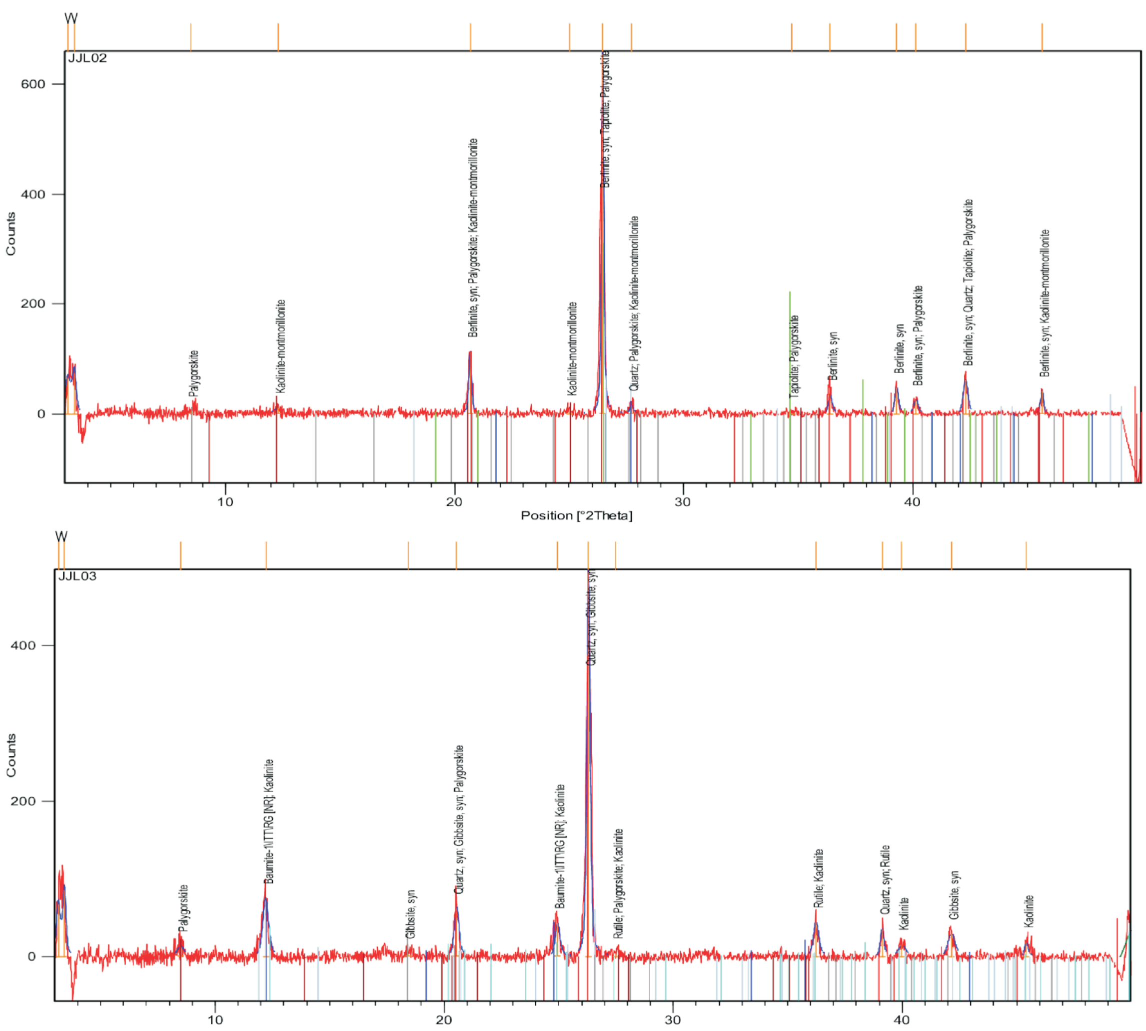

Fig.4. X-Ray Difractogram (XRD) showing identified clay minerals

Table 2: Various clay minerals recorded in the studied sandstone.

Sample No.	Minerals Identified
K1/17	Berlinite, Mannardite
K5/17	Kaolinite-montmorillonite, Annite (phyllosilicate) Quartz
L4-9	Kaolinite-montmorillonite, Quartz
M8/17	Wuestite , Rutile, Kaolinite-montmorillonite, Quartz
R4/14	Kaolinite-montmorillonite, Annite, Quartz
R4/17	Berlinite, Hollandite, Annite
R6/17	Berlinite, Heinrichite, Kaolinite-montmorillonite, Almandine
R33/16	Newberyite, Quartz, Nimite (Na-rich chlorite)

instrumentation facilities. Presence of Illite, Kaolinite, Neoquartz, dissolution of feldspar, pits on the grain surface and silica rims these are the identified features in the studied sandstone (Fig. 5) by the SEM analysis. The analysis was carried out at the IIT, Guwahati, Assam.

Illite

Illite has been reported from some of the samples. Decomposition of feldspar as well as degradation of mica; at least in the initial stages of weathering under alkaline conditions enriched with Ca^{2+} ions can produce illite. Transformation of kaolinite into illite is a common process as the quick mixing of fresh water sediments with those of marine favours the formation of illite as the later contains high concentration of K and Mg (Grim, 1968).

Kaolinite

Kaolinite which is common alteration product of K-feldspar under acidic condition favoured by a good drainage system is most abundant in these sediments. Formation of kaolinite has also been recorded in soils under a warm humid climate, where extensive

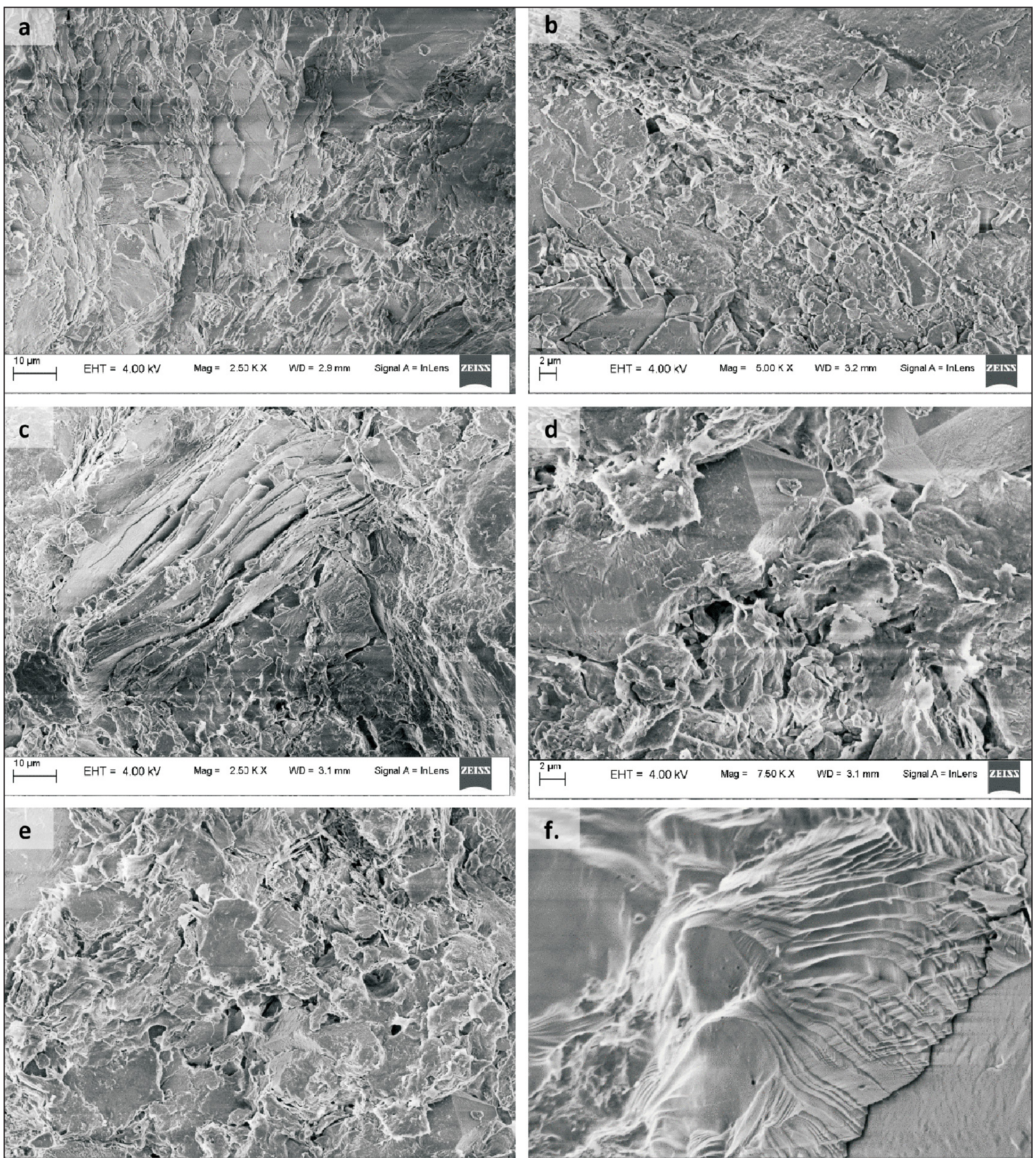

Fig.5. Scanning electron microscopic images showing a-b. Illite, c. Kaolinite, d. Neoquartz, e. Dissolution of feldspar, f. pits on the grain surface

leaching and acidic conditions predominate. In the present case Kaolinite is of authigenic origin as suggested by their form.

Montmorillonite

A member of smectite group, Montmorillonite, has been recorded in almost all the glycolated samples. Chemically, it is hydrated sodium calcium aluminum magnesium silicate and is commonly found as weathering products of ferromagnesian rocks such as basalts and gabbros. However, they can be formed under a variety of conditions.

Chlorite

Chlorite has also been recorded from a few samples only. It has magnesium and iron in its structures and is produced by the weathering of ferromagnesian minerals in such rocks as basalts and gabbros. Chlorites are found in low and medium rank metamorphic rocks and also in deeply buried sediments.

Discussion

Pressure, Temperature and Depth Regime

Precipitation of silica cements not only requires silica saturated water but also requires circulation of large volumes of water through the sediments. Silica cementation probably occurs during eodiagenesis and early mesodiagenesis. While studying the Cretaceous Travis Peak Formation of Texas (USA), Dutton and Diggs (1990) using isotopes data have opined that silica cements were precipitated between 55-75^{o}C temperature and a burial depth of 1 to 1.5 km. Surdam *et al.* (1989) suggest that quartz overgrowth can take place during early stages of mesodiagenesis and also between 160 and 200^{o}C during late mesodiagenesis. Diagenetic studies on Lower Cretaceous Arkoses of the Angora margin by Girard *et al.,* (1989), applying fluid inclusion experiments, reported a temperature range between 128 and 158^{o}C for the silica overgrowth in the studied sandstones. A temperature range of 90^{o}C and 118^{o}C was suggested by Walderhaug (1990) for overgrowth on sandstones from Norway offshore. Many workers suggest that the major mechanism of quartz precipitation may be the result of cooling of silica saturated solution. According to Boggs (2012), pH probably has little effect on silica precipitationunder normal diagenetic conditions but any process that enhances the silica concentration in pore waters must be above the concentration limit for silica to precipitate.

Albitization of feldspar in sandstones is very common phenomena in a sedimentary environment. It may take place either by direct precipitation or replacement by albite. It may also have an intermediate stage involving initial replacement of feldspar by calcite anhydrite which may be followed byalbitization. Boles (1982) while studying the Frio sandstone suggested that the albitization most probably in these sandstones has occurred between 2.5 km to 3.0 km with a temperature ranging between 110^{o}C to 120^{o}C. Sudram *et al. (*1989) has suggested thatalbitization occurs at temperatures between 100^{o}C-150^{o}C. Though Morad *et al.* (1990) on the other hand, suggested that the albitization may take place with a lower temperature regime between 70-100^{o}C. Studies done on the albitization of K-feldspar in sandstones show that the albitization of K-feldspar pre-ceded by a dissolution–precipitation mechanism. Most of the Na for Albitization is either supplied by pore water or by transformation of clay mineral. According to many the factors affecting the albitization of K-feldspar are rock permeability, temperature, Na+/K+ ratio and parent mineral dissolution. Milliken (1992) found while working with mudrocks and sandstones, suggested that approximately 56–68% of K-feldspar has been albitized in mudrocks which has proceeded through the dissolution–precipitation mechanism. Albitization also suggests progression of pressure, temperature and burial and thermal history.

Diagenetic Stages

Various diagenetic stages noticed in the studied sandstones include redoxmorphic, locomorphic and phyllomorphic stages. These stages are characterised by progressive appearance of certain features. According to Bjorkum and Gjelvik (1998) precipitation of iron oxide signifies the redoxomorphic stage. Silica overgrowth, modified grain to grain contacts, corroded detrital grain boundaries and alteration of feldspar represent the locomorphic stage (Borac and Friedman, 1981). Phyllomoprhic stage, though less common is represented by formation of authigenic mica.

Diagenetic Environment

Diagenetic features observed in these sediments are grouped into two categories: early and late diagenesis. Silica overgrowth around quartz grains suggests early diagenesis. Early diagenesis phase also includes precipitation of calcite and iron cements (Heald and Lorese, 1974). Fracturing, crushing, bending and warping of micaceous material around detrital quartz suggest the increasing depth of burial, under increasing pressure and temperature conditions *i.e.* late diagenesis (Sengupta, 1994; Srivastava *et al*., 2015; Singh and Singh, 1994).

Source of Cements

Silica Cement

Cementation in sandstones is the process by which mineral matter precipitates in the pore spaces binding the grains together and forming a sedimentary rock during diagenesis.However, probable sources for cements in sandstones are still a matter of debate. Whether a single source is supplying enough silica required for cementation or more than one source is responsible for the silica supply. It has been observed by many that the prime controlling factors for the amount of silica cement in sandstones are: framework composition; residence time in the “silica mobility window”; fluid composition, flow volume and pathways.

Sources which are considered by many include i) continuous overloading of the underlying argillaceous sediments ii) clay mineral transformation iii) compaction and pressure solution iv) reaction of feldspars, mafic minerals and volcanic glass with water.

In the present study based on the observations made through petrographic studies, SEM and XRD analysis and the diagenetic signatures in the Barail sandstones, following sources are considered for supply of silica cements.

1. Continuous overloading and compaction of dominantly argillaceous Disang sediments below the Barail sandstones (Srivastava *et al.*, 2004). 2. Reaction of K-feldspars, mafic minerals

and volcanic glass with water and origin of clay minerals (Hower *et al.,* 1976; Hawkins, 1978; Boles and Franks, 1979; Surdam and Boles, 1979;). 3.Transformation of clay minerals releasing silica; as with increasing depth smectite and kaolinite clay minerals are usually replaced by more stable illite and chlorite((Towe, 1962; Einsele, 2000). 4. Compaction and pressure solutions and percolating meteoric water saturated with silica (Dapples, 1979; Dutton and Diggs, 1990; Dutton, 1993; Walderhaug, 1994).

Iron Cement

Ferruginous (iron oxide) cement has been observed which are present as shapeless void fillers as well as coating on framework grains. Walker (1974) has opined that the weathering of iron rich minerals is a major source of iron cement. Presence of ferruginous cement also suggests an enhanced oxidation of meteoric water.The iron may have been released during the breaking of unstable iron-rich minerals under surface temperature and pressure conditions. Also, iron might have been transported into the basin by meteoric waters from the weathering of the adjacent rocks. Walker (1974) suggested that the dissolution of iron rich minerals such as pyroxene, hornblende, biotite, and magnetite grains are probably the main source of supply of iron.

Thus, from the above discussion it is clear that the type of sedimentary basin in which sand was deposited plays vital role to controls the cementation process. Sandstones of rift basins (arkoses) and collision-margin basins (litharenites) generally have only a few percent quartz cement; quartz arenites and other quartzose sandstones of intracratonic, foreland and passive-margin basins have the most quartz cement (McBride, 1989). So, another probable reason for the dominance of silica cement in the studied sandstones might be due to its compositional nature (quartz arenites) and tectonic setting (foreland).

Conclusions

Types of grain contacts, digestion of grain boundaries, siliceous overgrowth, neo-quartz, bending of flaky minerals, albitization are the diagenetic features preserved in these sediments. Preserved diagenetic features and observed clay minerals point towards; bothearly and the late stage of diagenesis. These also suggest that the sediments have been influenced by the chemistry of sea water and increasing depth. Mechanical compaction has resulted in reduction of porosity and also in modifying the grain contacts from straight to sutured through concavo-convex contacts; indicating a progressive diagenetic regime. Compaction has also been responsible for increased pressure and liberation of silica at grain contacts which later precipitated as cement and neomorphic quartz. Silica might have also come from clay mineral transformation and de-vitrification of volcanic glasses. Once the circulating water became supersaturated with silica, precipitation of the same would have been initiated.Solution activities along the fractures and/or the plane of weakness of resulted in the albitization. Based on the various diagenetic features preserved in the studied sandstones a temperature range between 80 to 150^{o}C and a depth regime of approximately 3-5km has been visualised.

Authors' Contributions

SKS: Investigation, Conceptualization, Methodology and Writing Original Draft. **AMK:** Investigation, Visualization. **AP:** Writing-Reviewing and Editing of Draft, **RAJ:** Investigation, Formal Analysis. **SY:** Investigation, Formal Analysis.

Conflict of Interest

Authors declare that there is no conflict of interests.

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