Sandstone diagenesis and its impact on reservoir quality of the Arenaceous Unit of Barail Group of an oilfield of Upper Assam Shelf, India

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The potential of a sandstone reservoir to produce hydrocarbons is intimately related to its diagenetic history. The Barail Group of rocks within the Upper Assam Basin is considered as one of the world's major deltaic deposits with known hydrocarbon potential. The Arenaceous Unit of the Barail Group constitutes a significant percentage of the known hydrocarbon reserves, but the heterogeneity of the distribution of the diagenetic properties in these reservoir sandstones makes the wide variation in crude oil production from well to well within the reservoirs. Precipitation of authigenic mica, chert, quartz overgrowth and crystallization of cementing material are some of the diagenetic changes responsible for porosity reduction. Moreover, the presence of clay minerals in the pore spaces and their bridging nature especially of illite makes certain reservoir horizons less productive. On the other hand, dissolution and replacement of framework grains, intragranular fracturing and floating type of texture enhance the porosity as well as permeability and make the reservoir sandstone highly productive.

Keywords: Arenaceous unit, diagenesis, reservoir quality, sandstone, Upper Assam Shelf.

THE Upper Assam Basin (Figure 1) is the earliest explored petroliferous basin of India. It represents the northeastern extremity of the Indian subcontinent encompassing an area of about 57,000 sq. km and forms the northeastern part of Assam–Arakan basin. Tectonically the Upper Assam Basin represents a structurally wrapped foreland basin between two convergent plate margins and came into existence during Early Cretaceous time. The basin is covered over a large part by shelf sediments that grade into geosynclinal facies, with the dividing line between the two facies occurring in the vicinity of Naga Thrust, the northwestern margin of Belt of Schuppen. Majority of the faults coupled with depositional environment played a major role in the accumulation and distribution of hydrocarbon in the region. During the last four decades, extensive exploration activities carried out by two national companies, Oil and Natural Gas Corporation Limited (ONGCL) and Oil India Limited (OIL), within Upper Assam Basin have resulted in discovery of a large number of new structures with potential hydrocarbon reserves. The generalized stratigraphy of the Upper Assam Shelf in the study area is given in Table 1 (ref. 14). The Barail Group of rocks, which receives special interest from the geoscientists, has been informally divided into two units: a lower Arenaceous Unit and an upper Coal-shale Unit in the present study area. The Arenaceous Unit contains significant quantities of oil reserves and is quite extensive in Assam Geological Province. Due to the wide aerial extent, depositional and diagenetic complexities, the reservoir characterization of the Barail reservoir sandstones is a major challenge. The diagenetic changes in these sands have severely affected the porosity distribution. It is also reported that the productivity varies significantly from well to well within the same reservoir. The main aim of our work is to find out the diagenetic history on porosity and permeability preservations, destruction, and enhancement that make certain horizons to be highly productive while the others are very poor. Keeping this view in mind 20 nos of drill core samples of the reservoir sands of the Arenaceous Unit have been collected from Nahorkatiya oilfield under Oil India Limited jurisdiction (Figure 1) for detailed thin section and Scanning Electron Microscope (SEM) study.

The thin section study indicates the rock to be mainly lithic greywacke type and less commonly of sublithic arenite to quartz arenite type (Figure 2; ref. 15). The modal analysis data are shown in Table 2. The sandstones are rich in concentration of quartz varying from 44.3% to 59.7%. They occur chiefly as monocrystalline quartz although polycrystalline grains are also recorded. The >3 crystal units of polycrystalline quartz is dominant over the 2–3 crystal units per grain variety. The grains are sub-angular to sub-rounded and show inclusions in certain samples. Both plagioclase and K-feldspar constitute an average of 1.33% in the sandstones. In certain cases, the sandstones are reported to be devoid of feldspars. It suggests a source of terrain with low relief and prolonged abrasion and a high rate of chemical weathering. Chert chiefly composed of microcrystalline and chalcedonic quartz, with subordinate mega quartz and minor impurities of clay, silt and pyrite makes up 4% to 8.7% of the sandstones. Mica makes up to 2.4% of the detrital fraction and includes both muscovite and biotite. Development of authigenic mica at the expense of argillaceous matrix is frequently observed in the sandstones. The metamorphic rock fragments are dominant over the igneous and sedimentary varieties. They are variable in size and angular to subangular with prominent grain boundaries. Majority of the metamorphic rock fragments are identified as schistose. Average percentage of rock fragments is 5.5%. Proportion of matrix, which constitutes 16–30% is mainly siliceous and argillaceous in nature, is higher in concentration than cements in certain samples. Cements are mainly ferruginous, argillaceous and siliceous in nature and comprise 2.3–16% of the sandstone.

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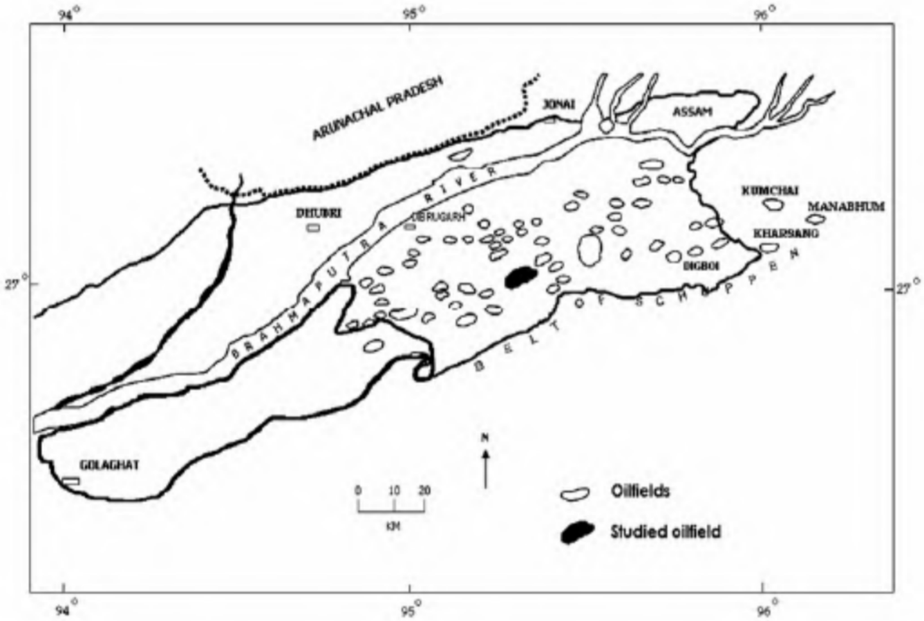

Figure 1. Location map of the study area.

Table 1. Tertiary succession of Upper Assam Shelf sediments (modified after Handique *et al.*[14])

	Lithostratigraphic units				
Epoch	Group	Formation		Thickness (m)	Major lithological types
Recent	–	Alluvium[1]			
Pliestocene	Dihing	Dhekiajuli[1]		1300–2000	Unconsolidated sands with clay and lignitic sands
Unconformity					
Pliocene Miocene	Dupitila	Namsang beds		0–1000	Poorly consolidated sandstone with clay and lignitic sands
Unconformity					
Miocene	Tipam	Girujan clays		100–2300	Mottled clay with sandstone lenses
		Tipam sandstones	Upper	300–500	Essentially arenaceous sequence
			Middle	100–200	Sand/shale alteration sequence
			Lower	100–200	Arenaceous sequence
	Surmas[2]	Not subdivided			Sandstone with shale and grit bands
Unconformity					
Oligocene	Barail	Not subdivided		500–1200	Upper part: Mudstone/sale with sandstone beds and coal bands (Argillaceous sequence) Lower part: Sandstone with shale bands (Arenaceous sequence)
Eocene[3]	Jaintia	Kopili alterations		280–500	Splintery shale with sandstone and fine-grained sandstone with coal bands
		Sylhet limestone	Prang Nurpuh Lakadong	350–450	Splintery shale with sandstone and limestone bands
	Therria			60–170	Sandstone, calcareous sandstone and limestone
Unconformity					
Precambrian granitic basement					

Compositional data of the sandstones are presented in Figures 3 and 4 (ref. 16). It appears from the figures that all the sediments are products of recycled orogen and quartzose recycled sources. Under different tectonic settings the rocks may be included into subduction complex of arc orogen, suture belts of collision

Table 2. Modal analysis data of the sandstones of the Barail Arenaceous Unit of Nahorkatiya Oilfield

Quartz				Feldspar			Rock fragments					Cement			
M(U)	M(NU)	2–3	>3	Plag.	K	Chert	Ig.	Met.	Sed.	Mica	Matrix	Ferr.	Arg	Sil.	Ca.
8	30	3	7	1.6	0	8	0	4	1.3	4.8	16	8.7	7.3	0.3	0
6.4	34.4	1.6	9.2	0.6	1	4.6	0	3.8	0	1.6	19	12.3	5.3	0.2	0
4.7	28.3	2	11.7	1.6	1.3	8.7	0.3	5.7	2.3	1.6	17	9.5	5	0.3	0
8	32.1	1.3	11.3	0	0	8	0	4.7	4.3	1.3	30	3.4	2.7	0	0
9.4	25	6	12.2	1.2	0	4	0.2	4	0.5	0	22	6	1.3	0	0
5.3	28.8	1.6	9.3	1	2.3	7	0.2	4.6	1.3	2.6	17.3	7.7	10.7	0.3	0
14	23.3	1	12	0	0	7.6	0	3.6	0	2.6	18.3	16.3	1.3	0	0
18	16.6	1.7	8	0	0	7.3	0.1	3	0	4.7	26	8.3	6.3	0	0
27.9	9.56	0.4	4	2.2	1.5	13.3	1.20	1.6	3	12	4.6	8.5	6.6	3.1	0
29.9	11.7	0.42	3.9	1.86	1.0	9.8	2.54	2.11	3.38	10.0	4.5	8.3	6.5	3.60	0
28.3	10.4	1.0	6.6	5.7	3.0	13.2	1.31	3.0	1.9	12.3	3.6	5.6	3.3	1.33	0
24.2	9.5	0.84	4.3	4.8	3.1	9.3	1.20	2.3	2.0	14.0	17.9	2.2	1.6	2.8	0
25.8	10.1	0.2	4.8	4.86	3.0	14.8	1.43	1.75	0.32	11.7	7.5	7.7	4.8	3.2	0
26.5	10.8	0.2	4.03	4.1	2.1	13.3	0.53	1.72	1.25	12.4	7.1	8.9	5.3	2.2	0
27.5	12.0	0.2	5.2	3.8	2.2	13.8	0.9	1.72	2.75	11.2	4.30	8.3	4.6	1.8	0
24.5	11.3	0.14	4.9	5.1	1.9	12.3	0.7	1.9	1.54	11.3	16.7	3.6	3.1	2.7	0
28.7	10.4	0.5	1.8	7.2	3.1	9.9	2.75	2.8	0.7	16.1	5.3	8.3	3.2	0	0
22.8	14.8	0.2	4.6	7.6	4.2	8.12	2.2	2.0	1.7	19.4	3.73	5.5	2.6	0.8	0
24.5	11.3	0.34	3.9	6.9	3.3	7.32	2.9	3.0	1.34	13.7	16.6	2.3	1.5	1.9	0
27.5	10.1	0.3	6.5	7.2	3.6	6.52	1.74	4.4	0.3	16.0	4.23	8.6	3.8	1.2	0

M(U), Monocrystalline quartz (undulose); M(NU), Monocrystalline quartz (non-undulose); 2–3, Polycrystalline quartz bearing 2–3 units; >3, Polycrystalline quartz bearing more than 3 units; Plag, Plagioclase feldspar; K, Potash feldspar; Ig., Igneous rock fragments; Meta, Metamorphic rock fragments; Sed., Sedimentary rock fragments; Ferr., Ferruginous cement; Arg., Argillaceous cement; Sil., Siliceous cement; Ca., Calcareous cement.

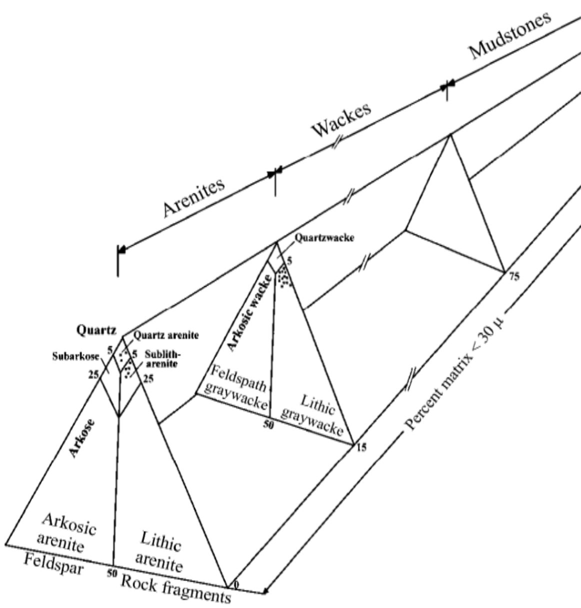

Figure 2. Classification of the sandstones (after Dott[15]).

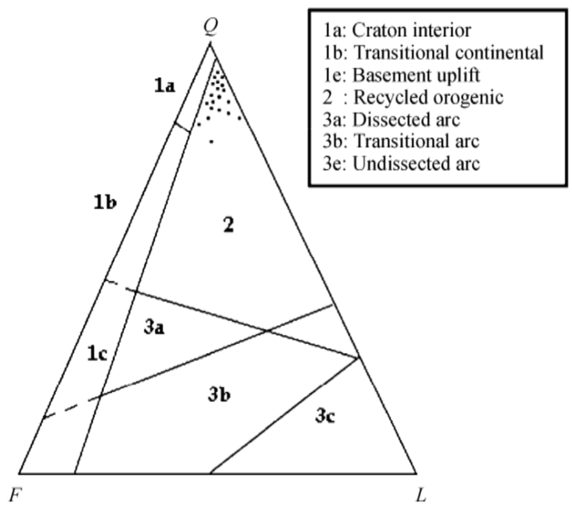

Figure 3. *Q–F–L* plot (after Dickinson and Suczeck[16]).

orogen and uplifted foreland fold-thrust belts[17]. Following the diamond diagram of Basu *et al.*[18], it is found that the sediments are derived from middle and upper rank metamorphic sources (Figure 5).

The physical and chemical environments experienced by sandstones produce an end product characterized by a specific suite of diagenetic features. The nature of this end product depends to a large degree on the initial mineralogical composition of the sands and the composition of the enclosing basin fill sediments. The important diagenetic changes observed under thin section study are sandstone compaction, precipitation of different types of cement, alteration and replacement of framework grains and nature of development of grain contacts. Compaction of the sediments started with burial and progressively increased with depth. Under more usual conditions, the point or tangential contacts of sandstones suggest early burial stage of diagenesis that on increased overburden load under deep burial stage come into closer contacts along long and concavo–convex grain boundaries and finally forms sutured contacts (Figure 6 *a*). The mechanical compaction of sediments is witnessed by bending of detrital mica flakes and fracturing of quartz grains (Figure 6 *b*). The long and concavo–convex contacts together with the precipitation of secondary chert represent the intermediate stage of diagenesis. The cementation is brought by chemical precipitation of pore solutions. All these cementing materials were precipitated under different pH conditions. The silica cement in the form of quartz overgrowth, precipitation of glauconites between the framework grains, the infiltration of ferruginous cements throughout the sandstones, and the post depositional accumulation of the patches of argillaceous materials within the framework grains (Figure 6 *c*) have a significant influence on the reservoir quality of the sandstone. The metamorphic rock fragments are squeezed to generate dispersed pseudomatrix (Figure 6 *d*). Authigenic development of mica at the expense of argillaceous cement and recrystallization of chert to quartz (Figure 6 *e*) may reduce porosity as well as permeability in the sandstones indicating the phyllomorphic or late stage of diagenesis. On the contrary, the corrosion, partial dissolution and replacement of the feldspar (Figure 6 *f*) and mica (Figure 6 *g*) grains by the cementing material enhance the porosity and permeability in the sandstones. Quartz replacement proceeds along the boundary of the grains (Figure 6 *h*). As a result, the replaced parts of the grains are occupied by replacing fronts. Such replacement processes enhance the reservoir quality.

With the help of SEM, mineralogy, texture and diagenetic sequences can be better elucidated, and porosity and permeability can be related to diagenetic features. In the present study, the commonly recorded clay minerals are kaolinite and illite. Kaolinte is widely distributed in the sandstones and is recorded as stacking of books pattern (Figure 7 *a*). The kaolinite 'books' can disaggregate into individual platelets or entire books can migrate into pore spaces thereby causing reduction in porosity and permeability. The irregular surfaces observed in the feldspar grains may be interpreted as to represent stages of growth of authigenic kaolinite. In most cases the chemical element needed for kaolinite formation, namely silicon and aluminum are thought to be derived from the leaching of some pre-existing minerals in the sandstones. K-feldspar and mica constitute the more probable Si and Al sources. Kaolinization that develops at the expense of extremely deformed and crushed feldspars clearly signifies the postdate compaction and belongs to the late diagenetic history. Authigenic growth of kaolinites reduces the permeability/porosity ratio. Moreover, the relative abundance of kaolinite indicates the dominance of fluvial influence in the depositional system. Flaky and fibrous illites found to grow in pore spaces often bridge the pores and offer a high resistance to fluid flow through the sandstone and thereby reduces permeability (Figure 7 *b*). The fibrous illite

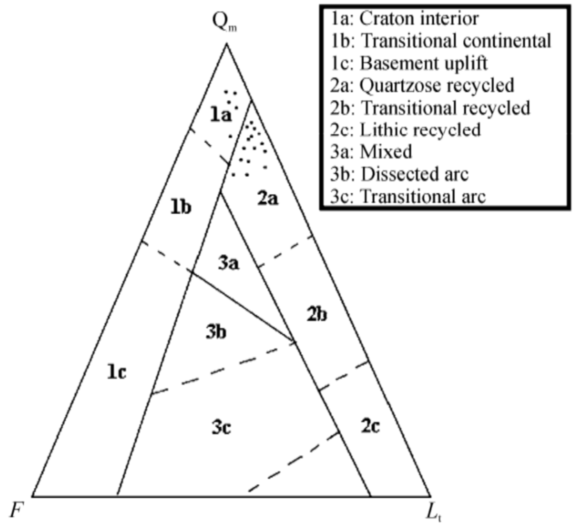

Figure 4. Q_m–F–L_t plot (after Dickinson and Suczeck[16]).

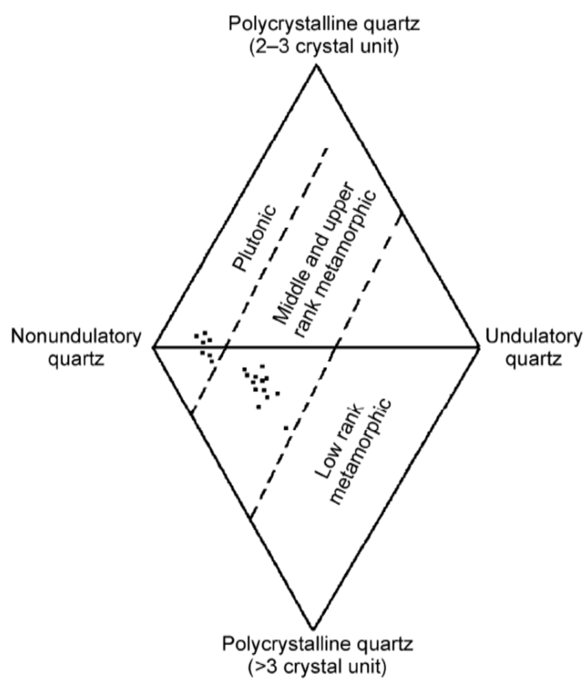

Figure 5. Diamond diagram showing provenance (after Basu *et al.*[18]).

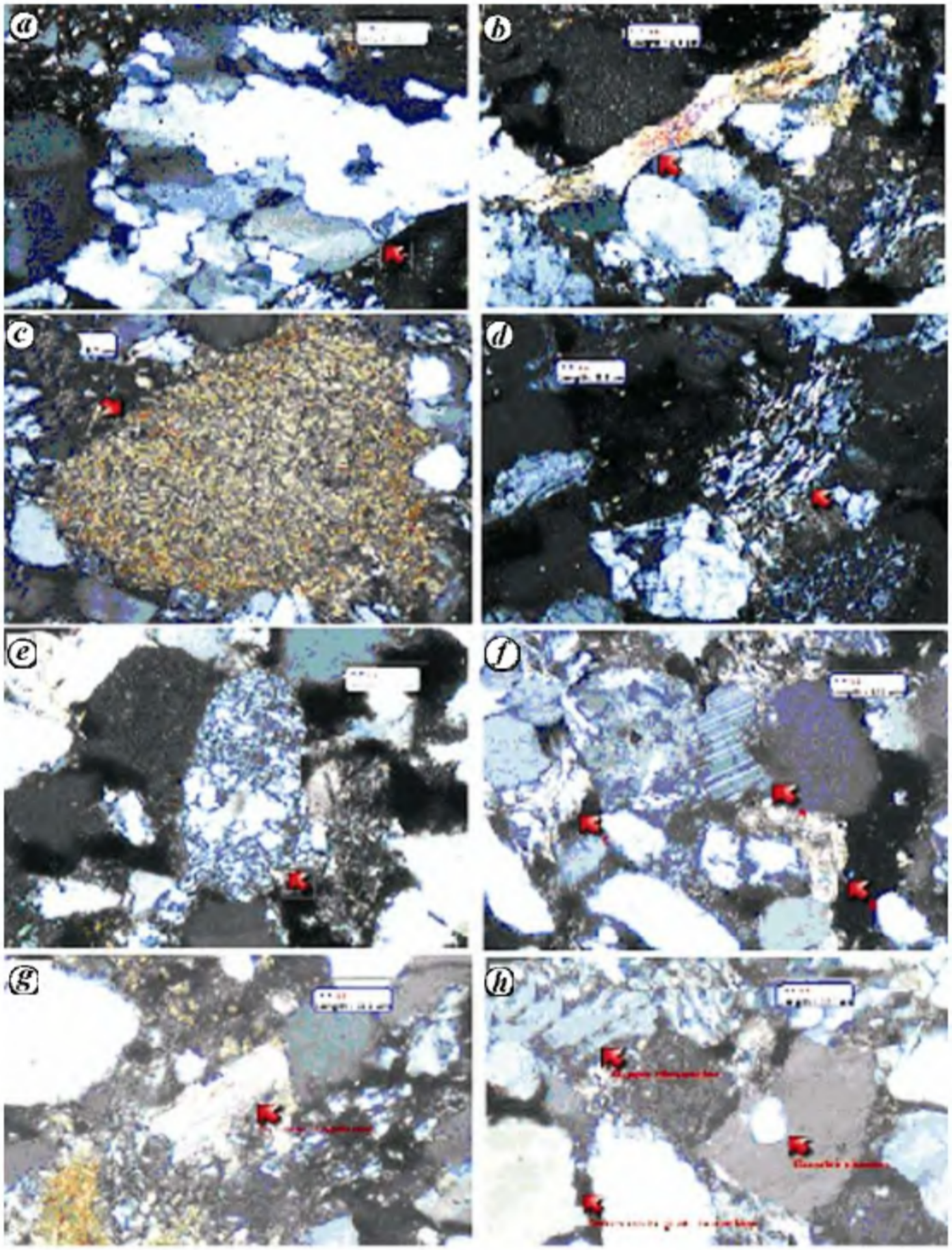

Figure 6. Rock thin section photomicrographs. ***a***, Sutured contacts (100×). ***b***, Bending of mica flakes (100×). ***c***, Post depositional accumulation of argillaceous material (100×). ***d***, Pseudomatrix (100×). ***e***, Recrystallization of chert to quartz (100×). ***f***, Dissolution of feldspar (100×). ***g***, Dissolution of mica (100×). ***h***, Corrosion and replacement of quartz along the boundary by argillaceous cement (100×).

acts as a fishnet in sandstone pores and creates permeability blocks, which significantly modifies the reservoir property. Guven *et al.*[6] reported the frequent occurrence of authigenic lathed illite in the pores of many sandstone reservoirs from the United States. Illite apparently develops under acidic condition. Presence of framboidal pyrite (Figure 7 *c*), dolomite (Figure 7 *d*) and quartz overgrowth (Figure 7 *e*) also reduces the porosity in the sandstones. On the other hand, partial dissolution of quartz (Figure 7 *f*) and both K-feldspar and plagioclase feldspar (Figure 7 *g*) enhance the porosity in the reservoir sandstone. In most of the cases, the quartz grains show intragranular

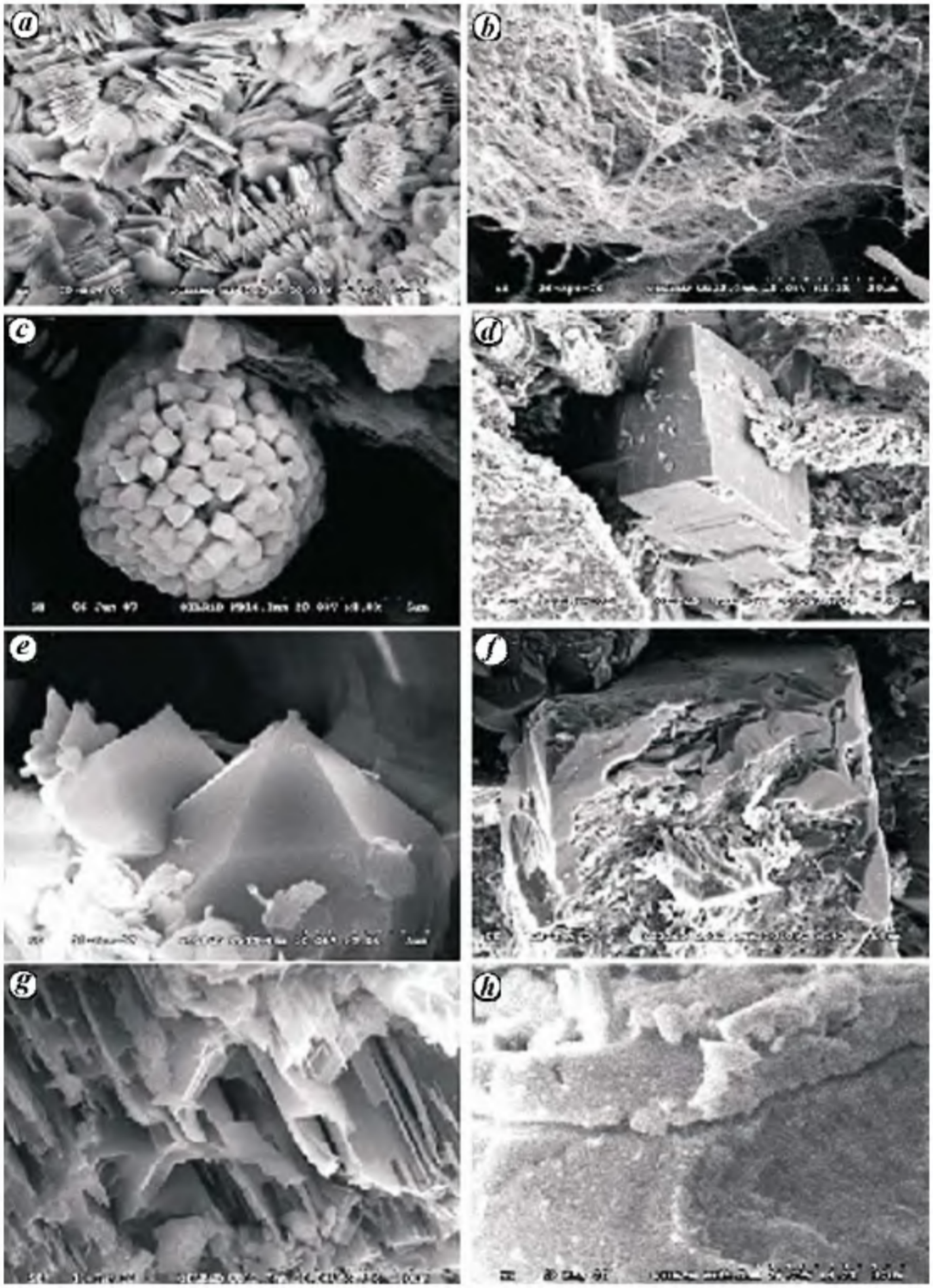

Figure 7. SEM photomicrographs. ***a***, Kaolinite (1500×). ***b***, Illite (1200×). ***c***, Framboidal pyrite (8000×). ***d***, Dolomite (700×). ***e***, Quatrz overgrowth (7000×). ***f***, Partial dissolution of quartz (700×). ***g***, Partial dissolution of K-feldspar (4500×). ***h***, Intra-particle fracture (4000×).

fracturing (Figure 7 *h*) and this post depositional effect obviously enhances the secondary porosity and permeability to make the sandstones highly productive.

Sandstones of the present study are moderately sorted to poorly sorted with floating type of texture. The progressive diagenetic alteration controls its reservoir quality. The petrography associated with SEM study reveals that the precipitations of cementing materials, authigenesis of secondary minerals like chert, mica and quartz overgrowth are some of the important diagenetic changes responsible for porosity reduction. Moreover, presence of kaolinites and fibrous nature of illite in the pore throats also play an important role in porosity reduction. Conversely development of intragranular fractures, corrosion, dissolution and partial replacement of the framework grains by cementing materials contribute towards the development and enhancement of secondary porosity and permeability. So, some of the diagenetic changes within the reservoir make certain horizons highly productive while others are less productive in spite of having good reserves. This heterogeneity in the distribution of diagenetic properties causes variation in crude oil production from well to well within the same reservoir. The study also reveals that the sandstones are derived from recycled orogenic provenance and are mainly the products of lower to middle metamorphic and less commonly of sedimentary and igneous sources.

1. Burley, S. D. and Kantorowicz, J. D., Thin section and SEM textural criteria for the recognition of cement-dissolution porosity in sandstones. *Sedimentology*, 1986, **33**, 587–604.
2. Dapples, E. C., Diagenesis of sandstones. In *Diagenesis in Sediments* (eds Larsen, G. and Chillinger, V. G.), Elsevier Publishing Company, Amsterdam, 1967, pp. 91–125.
3. Ehenberg, S. N., Relationship between diagenesis and reservoir quality in sandstone of Garn Formation, Haltenbanken, mid-Norwegian Continental Shelf. *AAPG Bull*., 1990, **74**, 1538–1558.
4. Folk, R. L., *Petrology of Sedimentary Rocks*, Hemphills, Austin, 1980.
5. Grim, R. E., *Clay Mineralogy*, International Series in Earth and Planetary Science, McGraw-Hill, New York, 1968, 2nd edn.
6. Guven, N., Smectites. In *Review in Mineralogy, Hydrous Phyllosilicates* (ed. Baily, J. W.), 1988, pp. 497–558.
7. Handique, G. K. and Mallick, R. K., Hydrocarbon exploration in Upper Assam Basin; problems and challenges. *Petrol. Asia J.*, 1990, **2**, 141–147.
8. Houseknecht, D. W., Assessing the relative importance of compaction processes and cementation to reduction of porosity in sandstones. *AAPG Bull*., 1987, **71**, 633–642.
9. Joshi, G. K., Shyammohan, V., Reddy, A. S., Singh, B. and Chandra, M., Reservoir characterization through log property mapping in Geleki field of upper Assam, India. In Proceedings of the 5th Conference & Exposition on Petroleum Geophysics, Hyderabad, 2004, pp. 685–687.
10. Kent, W. N., Hickman, R. G. and Dasgupta, U., Application of a ramp/flat fault model to interpretation of the Naga thrust and possible implications for petroleum exploration along the Naga thrust front. *AAPG Bull*., 2002, **86**, 2023–2045.
11. Pettijohn, F. J., *Sedimentary Rocks*, CBS Publishers and Distributors, New Delhi, 1984.
12. Rittenhouse, G., Pore space reduction by solution and cementation. *AAPG Bull*., 1971, **55**, 80–91.
13. Willson, M. D. and Pittman, E. D., Authigenic clays in sandstones: recognition and influence on reservoir properties and paleo-environmental analysis. *J. Sediment. Petrol*., 1977, **47**, 3–31.
14. Handique, G. K., Sethi, A. K. and Sarma, S. C., Review of tertiary stratigraphy of parts of upper Assam Valley. *Geol. Surv. India Spl. Publ*., 1989, **23**, 23–36.
15. Dott Jr, R. H., Wacke, greywacke and matrix – what approach to immature sandstone classification? *J. Sediment. Petrol*., 1964, **34**, 625–632.
16. Dickinson, W. R. *et al*., Provenance of North American Phanerozoic sandstones in relation to tectonic setting. *Geol. Soc. Am. Bull*., 1983, **94**, 222–235.
17. Dickinson, W. R. and Suczek, C. A., Plate tectonics and sandstone compositions. *AAPG Bull*., 1979, **63**, 2164–2182.
18. Basu, A., Young, S. W., Suttner, L. J., James, W. C. and Mack, G. H., Re-evaluation of the use of undulatory extinction and polycrystallinity in detrital quartz for provenance interpretation. *J. Sediment. Petrol*., 1975, **45**, 873–882.

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Lakadong limestone: Paleocene–Eocene boundary carbonate sedimentation in Meghalaya, northeastern India

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The Lakadong Limestone comprises the lowermost unit of the Sylhet Limestone Group which represents a major marine transgression during the Paleocene in the South Shillong Plateau. The tidal flat sedimentation took place in carbonate ramp platform environment. The carbonate facies of the Lakadong Limestone are rich in algae and larger foraminifera, which indicate that it is of a Late Paleocene (Thanetian)–earliest Eocene (Ilerdian) age. The Lakadong Limestone has yielded several taxa of algal–foraminiferal assemblages known from western Tethyan–Mediterranean realm indicating extension of the Neotethys Sea in the Shillong Plateau area, northeastern India. Carbon and oxygen isotopic signatures of the Lakadong Limestone have been obtained for the first time and indicate shallow marine depositional environment. The stable C and O isotope data corresponds to the marine Paleocene carbonate sediments and provides chemostratigraphy of the Lakadong Limestone well exposed in the Mawmluh Quarry near Cherrapunji. Petrographic study reveals that Lakadong Limestone is composed mainly of calcite, dolomite and smaller and larger microfossils. The microfacies identified include micrite, intramicrite, sparite, oosparite and intrasparite. The calcareous algal–foraminiferal assemblage recognized

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