Petrography and diagenesis of the Upper Palaeocene–Lower Eocene rocks of Nahorkatiya oilfield, Assam

P. Borgohain[1], S. Hazarika[2,*], G. B. Gilfellon[3] and M. P. Gogoi[2]

[1]Department of Applied Geology, Dibrugarh University, Dibrugarh 786 004, India
[2]Department of Geology, Sibsagar College, Joysagar 785 665, India
[3]Oil India Limited, Duliajan 786 602, India

The Upper Palaeocene–Lower Eocene rocks in Nahorkatiya oilfield of Upper Assam consist of sandstones with variable colours, compactness, particle size, porosity and permeability alternating with shales. Diagenesis has played a major role in determining the reservoir quality of these sandstones. The thickness of these sandstones is less (2–3 m in certain cases), but their productivity is high. These sandstones contain large secondary pores and intragranular fractures which have developed mainly due to the activity of interstitial solutions and tectonic effects. Authigenic growth of secondary minerals in the intergranular spaces and in certain cases the development of overgrowth cause reduction in permeability, which finally leads to the significant loss in production. Permeability is also lost due to the presence of clay minerals such as kaolinite, illite and chlorite, which tend to swell significantly in the presence of water. All of these clays are present in varying proportions within the Upper Palaeocene–Lower Eocene reservoir sandstones.

Keywords: Diagenesis, oilfield, petrography, rocks.

THE Upper Assam basin is a well-known petroliferous sedimentary basin of India. It is bounded in the north by the Eastern Himalayas, in the east by the Misimi Massif, in the south by the Naga–Patkai Hills and in the west by the Mikir Hills and Shillong Plateau (Figure 1)[2]. A thick pile of sediment ranging in age from Cretaceous to Pleistocene has been deposited in the basin. Since the successful completion of Digboi oilfield in 1989, extensive exploration activities have been carried out by two national companies, Oil and Natural Gas Corporation Limited and Oil India Limited, within the Upper Assam basin, which has resulted in the discovery of a large number of new structures with potential hydrocarbon reserves. Major success was achieved in 1953, when the Nahorkatiya structure was encountered with commercial oil deposit. Till 1990, most of the production in this basin was coming from Oligocene and Miocene formations. A major breakthrough came in 1990, when for the first time commercial oil was discovered in the Early Eocene rocks in Upper Assam. In spite of having lower thickness, the productivity from these sandstones is high.

The modal analysis data are presented in Table 1. The sandstones are rich in quartz, with concentration varying from 75% to 80%. It occurs chiefly as monocrystalline quartz, although polycrystalline grains have also been recorded. The > 3 crystal units of polycrystalline quartz are dominant over the 2–3 crystal units per grain variety. The thin-section study indicates the rock to be mainly quartz arenite to sublitharenite and less commonly quartzwacke type (Figure 2)[2]. The grains are sub-angular to sub-rounded and show inclusions in certain samples. Feldspars are few in the sandstone. In certain cases the sandstones are reported to be devoid of feldspar. It may be assumed that this is because of prolonged abrasion or a high rate of weathering of the source sediments. Moreover, the source area constitutes middle and upper rank metamorphic rocks, which contribute little or no feldspar to the sandstone in the present study. Chert is chiefly composed of microcrystalline and chalcedonic quartz, with subordinate mega quartz and minor impurities of clay, silt and pyrite. Mica makes up to 2–4% of the detrital fraction and includes both muscovite and biotite. The authigenic micas are developed at the expense of argillaceous cement and matrix in the sandstone. The metamorphic rock fragments are dominant over the igneous and sedimentary varieties. They are variable in size and shape. Majority of the metamorphic rock fragments are identified as schist and gneiss. The matrix consists of both detrital as well as authigenic grains of siliceous and argillaceous materials. Cements are mainly siliceous, ferruginous and calcareous, along with other cementing materials like glauconite and dead hydrocarbons. The dead hydrocarbon as cementing material is occasionally observed. It consists of completely dried-up residual hydrocarbons which tend to bind mineral particles together (Figure 3 *a*). Glauconites are reported mainly in the upper part of the sequence. In certain cases it is recorded in compressed and flattened form occurring as cementing material (Figure 3 *b*). Presence of glauconite indicates a shallow marine environment of deposition. The calcareous cements are reported mainly in the upper part of the rock sequence, resembling a carbonate-producing area of deposition.

Mineral compositional data of the sandstones are plotted in Figure 4 *a* and *b*, following from Dickinson *et al.*[3]. It appears from Figure 3 that all the sediments are the products of craton interior, recycled orogen and quartzose recycled sources. The sediments derived from cratonic interior provenance are characterized by the dominance of quartz and minor presence of feldspar, and it indicates probable low relief cratonic sources that had undergone prolonged transport across continental surfaces having low gradients. High quartz-to-feldspar ratio represents collision-derived fold thrust belt and distant uplifted

*For correspondence. (e-mail: swapnil.hazarika@gmail.com)

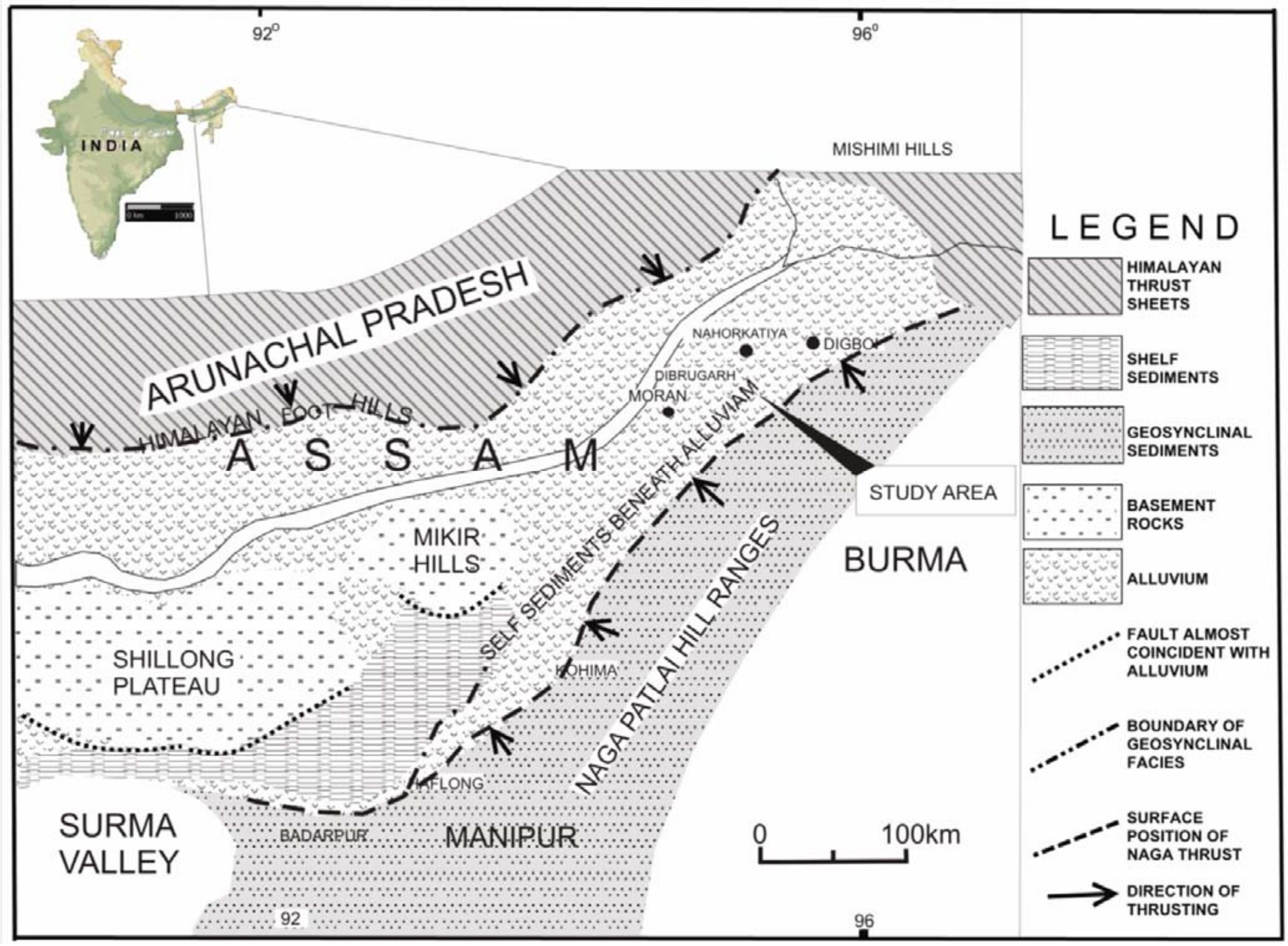

Figure 1. Geological map of Upper Assam with major tectonic elements (after Mallick[1]).

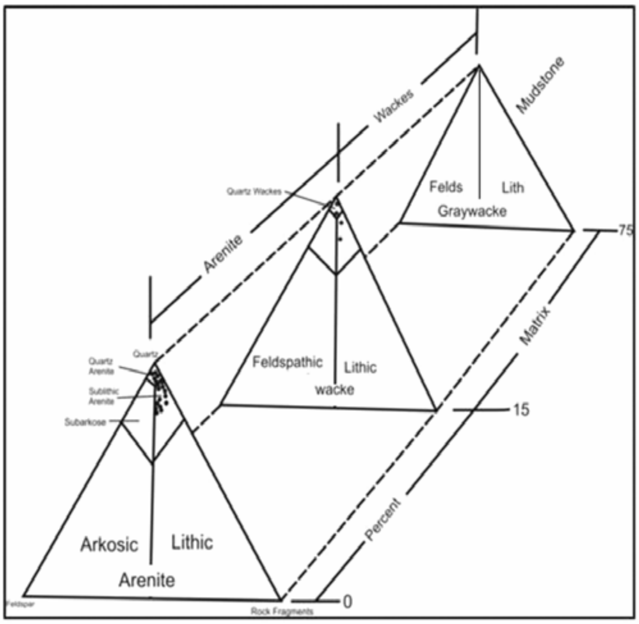

Figure 2. Classification of the Lakadong sandstone in the study area (after Dott[2]).

cratonic blocks as their sources. To discriminate the provenance of quartz, the percentages of monocrystalline quartz together with those of polycrystalline quartz are plotted on the diamond diagram of Basu *et al.*[4]. It is found that the sediments are derived from plutonic to middle rank metamorphic sources (Figure 5)[4].

The important diagenetic changes that have been observed are grain compaction leading to pressure solution effect, authigenic development of minerals and overgrowths, alteration and replacement of framework grains, precipitation of cement, development of intragranular fracture due to differential compaction, etc. The point and tangential grain contacts suggest early burial stage of diagenesis that on increased overburden load under deep burial stage comes into closer contacts along long and concavo-convex grain boundaries and finally forms sutured contacts (Figure 3 *c*). Mechanical compaction is witnessed by bending of detrital mica-flakes (Figure 3 *d*) and fracturing of quartz grains (Figure 3 *e*). The long and concavo-convex contacts (Figure 3 *f*) together with precipitation of secondary chert (Figure 3 *g*) represent the intermediate stage of diagenesis. Silica cement in the

Table 1. Modal analysis data of the hydrocarbon-bearing Lakadong Member of the study area

Sample	Depth (m)	Quartz				Feldspar		Rock fragment			Cement				Chert	Mica	Glauconite	Matrix
		MNU	MU	2–3	> 3	K	PL	Ig	Sed	Met	Ar	Cal	Fe	Si				
OL-1	3466.00	6.79	9.68	3.83	0.0	0.0	0.0	0.8	0.0	1.0	0.0	50.79	0.0	0.0	27.11	0.0	0.0	0.0
OL-2	3468.00	18.51	12.08	6.39	9.51	1.10	1.02	2.04	3.0	0.8	0.0	10.16	4.51	0.0	2.29	8.51	2.65	17.3
OL-3	3470.30	9.90	8.5	3.70	0.0	1.90	1.99	1.0	2.0	1.2	0.0	55.2	0.95	0.0	9.3	0.6	0.0	4.1
OL-4	3474.00	30.42	9.56	15.82	10.8	0.0	0.0	1.0	3.5	1.2	0.0	17.8	4.88	0.0	0.0	1.33	0.8	2.9
OL-5	3465.05–3465.10	30.8	15.2	4.2	1.2	0.0	1.2	0.6	1.8	0.2	1.8	18.6	0.6	0.4	2.6	1.4	16.2	3.2
OL-6	3510.25–3510.30	29.5	2.7	0.0	0.0	3.1	0.0	0.0	0.0	3.1	0.0	35.70	0.0	0.0	0.0	0.0	0.0	25.9
OL-7	3467.20–3467.30	30.3	5.3	1.1	7.4	2.7	0.0	0.0	4.3	2.1	3.7	0.0	6.4	2.7	1.6	0.0	0.0	32.4
OL-8	3469.25–3469.30	46.0	10.7	5.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.0	1.3	0.0	0.0	0.0	12.7
OL-9	3506.50	11.66	19.44	13.18	17.8	0.0	0.0	0.0	0.0	0.0	13.6	0.0	0.0	0.0	0.0	0.0	0.0	25.2
OL-10	3510.30	11.70	52.60	14.80	4.36	0.0	0.12	0.0	0.0	0.0	3.69	0.0	0.0	0.3	0.0	0.0	0.0	0.0
OL-11	3534.80–35.4.90	36.4	10.4	4.2	2.2	0.0	0.0	1.2	2.4	0.2	0.0	24.4	1.6	0.0	4.2	0.4	0.0	12.4
OL-12	3538.40–3538.45	32.2	8.4	3.2	0.2	0.0	0.0	0.8	1.8	0.0	0.0	20.4	3.6	0.0	6.8	0.6	0.0	14.6
OL-13	3536.80–3536.84	33.6	23.6	10.8	3.6	0.0	0.0	1.2	3.2	0.2	0.0	1.0	0.0	6.2	0.0	0.6	0.0	15.4
OL-14	3530.45–3530.50	35.1	3.2	3.1	4.7	2.2	1.7	0.0	0.0	0.0	0.0	0.0	3.9	0.0	0.0	0.0	0.0	46.0
OL-15	3533.00–3533.10	55.6	7.9	3.2	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.0	6.3	7.9	3.2	0.0	0.0	14.3
OL-16	3536.84–3536.89	42.2	11.6	0.0	0.0	0.0	5.6	3.2	0.0	1.2	0.0	6.4	0.0	10.8	0.0	0.0	0.0	18.6
OL-17	3518.63	40.2	4.4	0.0	2.8	0.8	1.6	0.0	0.0	0.0	0.0	28.4	7.4	1.8	2.2	0.0	0.0	10.4
OL-18	3474.05–3474.10	32.4	7.4	1.0	2.4	3.4	1.8	0.0	8.4	0.0	0.0	19.4	2.2	0.0	1.4	0.8	10.4	16.4
OL-19	3472.95–3473.00	38.8	10.4	0.4	0.0	2.0	0.0	0.0	0.0	0.0	0.0	30.8	1.4	2.0	0.0	0.0	0.0	12.2
OL-20	3472.45–3472.50	40.8	8.4	0.4	0.0	2.0	0.0	0.0	0.0	0.0	0.0	30.8	1.2	2.1	0.0	0.0	0.0	14.4

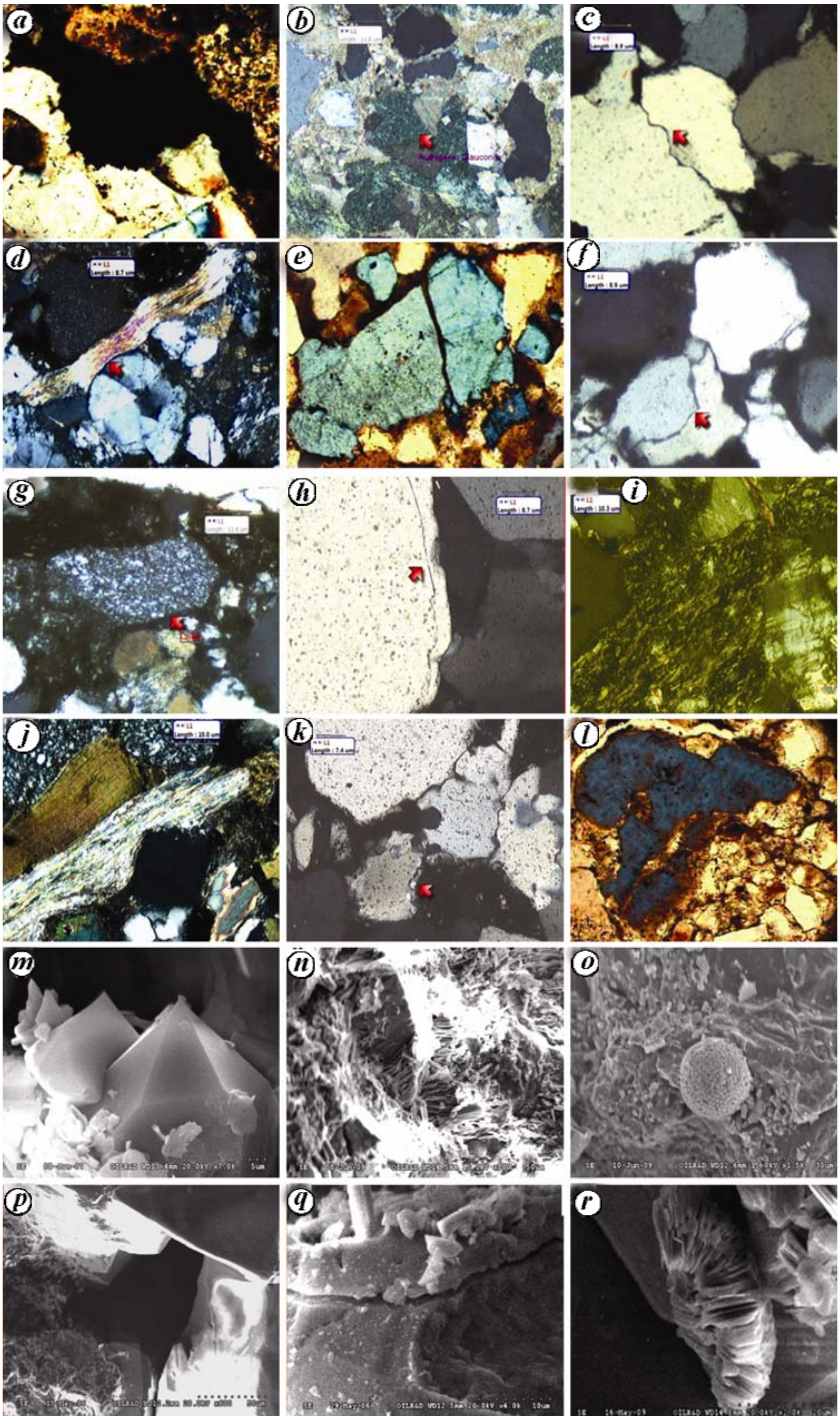

Figure 3. ***a***, Residual hydrocarbons; ***b***, Glauconites as cementing material; ***c***, Sutured contact between quartz grains; ***d***, Bending of detrital mica-flakes; ***e***, Fracturing of quartz grain; ***f***, Concavo-convex contact between quartz grains; ***g***, Precipitation of secondary chert; ***h***, Silica as quartz overgrowth; ***i***, Argillaceous materials within the framework grain; ***j***, Development of authigenic mica; ***k***, Corrosion in quartz grains; ***l***, Partial dissolution of quartz grains; ***m***, Overgrowth on quartz; ***n***, Dissolution of feldspar; ***o***, Framboidal pyrite; ***p***, Inter-granular pore; ***q***, Intragranular micro-fractures; ***r***, Stacking of books pattern of kaolinite. (Magnification = 100×).

form of quartz overgrowth (Figure 3 *h*), precipitation of glauconites between the framework grains, infiltration of ferruginous cement throughout the sandstone and post-depositional accumulation of patches of argillaceous materials within the framework grains (Figure 3 *i*) have significantly reduced the reservoir quality of the sandstone. The low-grade metamorphic rock fragments are squeezed to generate dispersed pseudo matrix. Authigenic development of mica (Figure 3 *j*) at the expense of argillaceous cement and recrystallization of chert to quartz may reduce porosity as well as permeability, indicating phyllomorphic or late stage of diagenesis. On the contrary, corrosion (Figure 3 *k*), partial dissolution and replacement of quartz, feldspar and mica grains by the cementing material enhance the porosity and permeability in sandstone (Figure 3 *l*). Quartz replacement proceeds along the boundary of the grains. As a result, the replaced parts of the grains are occupied by the replacing fronts. The SEM study reveals that many of the feldspar grains have undergone partial dissolution resulting in the formation of secondary pores (Figure 3 *m*), whereas some of them are observed to have been partly altered to clay. Such replacement processes enhance the reservoir quality.

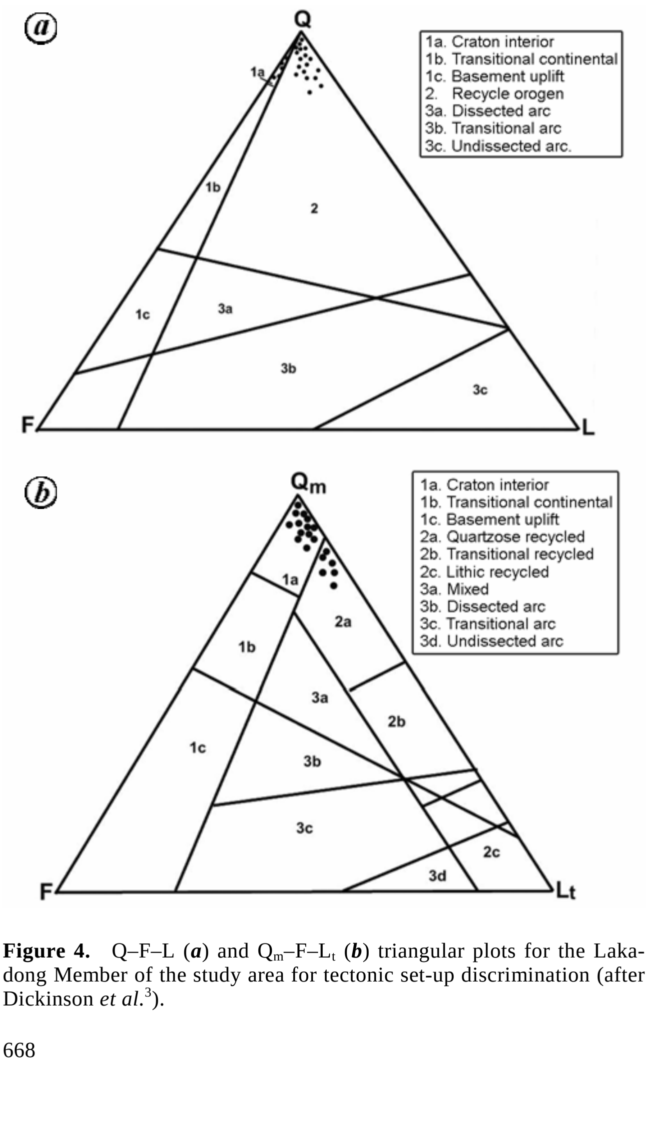

Figure 4. Q–F–L (***a***) and Q_m–F–L_t (***b***) triangular plots for the Lakadong Member of the study area for tectonic set-up discrimination (after Dickinson *et al.*[3]).

Overgrowths on quartz (Figure 3 *n*) grains are developed in open primary and secondary pore spaces, thus reducing porosity and permeability, as well as cementing mineral particles together. Opaque pyrite crystals are generally identified as black patches in thin sections of rocks. Moreover, SEM study also suggests the presence of framboidal pyrites occurring individually or in clusters (Figure 3 *o*). Some of these framboids are observed to be partly broken, with their euhedral crystallites dispersed within the rock. When pyrite crystals occur in clusters, they are observed to partly or wholly occupy pore spaces in the sandstone. Haematite occurring as cementing material is seen to partly or wholly occupy pore spaces. Quartz grains showing intergranular pore geometry of various shapes and sizes (Figure 3 *p*) enhance porosity and permeability to make the sandstones highly productive. On the other hand, some of the intragranular microfractures (Figure 3 *q*) in the sandstones are observed to be completely healed by clay minerals.

The commonly occurring clay minerals in the sandstone are kaolinite, illite, chlorite and minor smectite. SEM study shows wide occurrences of kaolinite in stacking of books pattern (Figure 3 *r*). This may be allochthonous or autochthonous in origin. Irregular surfaces observed in the feldspar grains may represent stages of growth of authigenic kaolinite. In most cases the chemical elements needed for kaolinite formation, namely silicon and aluminium are possibly derived from leaching of some pre-existing minerals. Kaolinization that develops at the expense of extremely deformed and crushed feldspar clearly signifies post-date compaction and belongs to

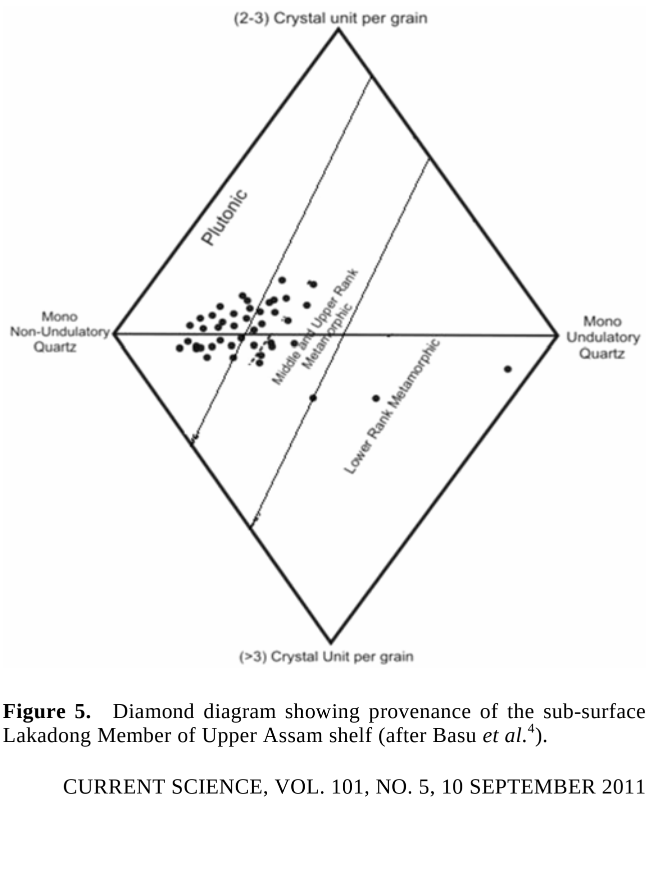

Figure 5. Diamond diagram showing provenance of the sub-surface Lakadong Member of Upper Assam shelf (after Basu *et al.*[4]).

the late diagenetic history. Authigenic growth of kaolinites reduces the permeability/porosity ratio. Flaky and fibrous illites are found to grow in pore spaces offering resistance to fluid flow through the sandstone and thereby reduce permeability. Presence of hairy illite in sandstone pores increases the micro porosity and pore tortuosity, and thereby decreases permeability.

The sandstones of the present study are mainly quartz arenite to sublitharenite and less commonly study. Petrographic associated with SEM study investigation that certain diagenetic changes like precipitation of secondary minerals, quartz overgrowth and precipitation of various cementing materials are some of the important factors responsible for porosity reduction in certain oil-producing horizons of the Upper Palaeocene–Lower Eocene rocks of Nahorkatiya oilfield. Moreover, presence of kaolinites and fibrous nature of illite in the pore throats also reduces porosity and permeability. Conversely, development of intra-particle microfractures, dissolution and partial replacement of the framework grains by cementing materials are some of the important diagenetic changes which contribute towards development and preservation of secondary porosity. So, these diagenetic changes may be responsible for making certain oil-bearing horizons highly productive, whereas others are less productive in spite having good reserves. Also, the sandstones of the present study are found to be the products of craton interior, recycled orogen and quartzose recycled sources, and are mainly derived from plutonic to middle rank metamorphic sources.

1. Mallick, R. K., Characterization and hydrocarbon resource evolution of Lower Eocene source rocks in Upper Assam Basin, using well logs. Reprints of published papers, Department of Petroleum Technology, Dibrugarh University, July 2001.
2. Dott Jr, R. H., Wacke, greywacke and matrix – what approach to immature sandstone classification? *J. Sediment. Petrol.*, 1964, **34**, 625–632.
3. Dickinson, W. R. *et al.*, Provenance of North American Phanerozoic sandstones in relation to tectonic setting. *Geol. Soc. Am. Bull.*, 1983, **94**, 222–235.
4. 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.
5. Burley, S. D. and Kantorowicz, J. D., Thin section and S.E.M. textural criteria for the recognition of cement-dissolution porosity in sandstones. *Sedimentology*, 1986, **33**, 587–604.
6. 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.
7. Folk, R. L., *Petrology of Sedimentary Rocks*, Hemphills, Austin, 1980.
8. Grim, R. E., *Clay Mineralogy*, International Series in Earth and Planetary Science, McGraw-Hill Book Company, New York, 1968, 2nd edn.
9. Guven, N., Smectites. In *Review in Mineralogy, Hydrous Phyllosilicates* (ed. Baily J. W.), 1988, pp. 497–558.
10. Handique, G. K., Sethi, A. K. and Sarma, S. C., Review of Tertiary stratigraphy of parts of Upper Assam Valley. *Geol. Surv. India Spec. Publ.*, 1989, **23**, 23–36.
11. Handique, G. K. and Mallick, R. K., Hydrocarbon exploration in Upper Assam basin; problems and challenges. *Pet. Asia J.*, 1990, **2**, 141–147.
12. Houseknecht, D. W., Assessing the relative importance of compaction processes and cementation to reduction of porosity in sandstones. *AAPG Bull.*, 1987, **71**, 633–642.
13. 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 and Exposition on Petroleum Geophysics, Hyderabad, 2004, pp. 685–687.
14. Norman, K. W., 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.
15. Pettijohn, F. J., *Sedimentary Rocks*, CBS Publishers and Distributors, New Delhi, 1984.
16. Rittenhouse, G., Pore space reduction by solution and cementation. *AAPG Bull.*, 1971, **55**, 80–91.
17. 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.

ACKNOWLEDGEMENTS. We thank the authorities of Oil India Limited, Duliajan, Assam for providing subsurface samples and laboratory facility for SEM analysis. We also thank the University Grants Commission, New Delhi for funds. Views expressed in this paper are those of the authors only.

Received 11 December 2010; revised accepted 1 August 2011

Phylogenetic studies in Indian scleractinian corals based on mitochondrial cytochrome *b* gene sequences

S. Senthil Kumar*, Ajay Gaur* and S. Shivaji†

Laboratory for Conservation of Endangered Species,
Centre for Cellular and Molecular Biology, Uppal Road,
Hyderabad 500 007, India

Phylogenetic relationships within and among three genera of the family Acroporidae, namely *Acropora*, *Montipora* and *Astreopora* were examined based on mitochondrial cytochrome *b* (690 bp) gene sequences with special emphasis on Indian scleractinian corals. Analyses using mitochondrial DNA sequences highlight the usefulness of a molecular approach for examining the phylogenetics, evolution and diversity of corals. The analysis based on various algorithms, including neighbour joining and maximum parsimony along with network analysis clearly establishes the monophyly of *Acropora* and *Montipora*. The average

*Equal contribution.
†For correspondence. (e-mail: shivas@ccmb.res.in)