



Glaucinite from the Middle Eocene Sylhet Formation, Assam & Assam-Arakan Basin, India: implications for sequence-stratigraphic interpretation

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Abstract

The ubiquitous occurrence of glauconites in specific stratigraphic levels is observed within Sylhet Formation that belongs to an overall fining-up 2nd order transgressive systems tract (TST). The mixed siliciclastic-carbonate Sylhet Formation implies deposition in a tide affected marginal marine (deltaic) to inner-shelf carbonate ramp with episodic clastic supply from western hinterland by isolated proto-rivers during regressive phases. The glauconites indicate an open shallow marine environment with a low sedimentation rate, normal marine salinity and weakly reducing environments associated with transgression of relative sea-level. The glauconites occur mainly in three forms, viz. glauconite pellets/peloids, glauconite infillings within bioclasts and glauconite cements. The Sylhet glauconites represent a complete spectrum of maturity with presence of all four types, nascent, slightly evolved, evolved and highly evolved varieties and can be readily identified under petrographic microscope, XRD and SEM analysis. High resolution sequence stratigraphic analysis based on core and electrolog data on Sylhet Formation allows to subdivide the 2nd order TST into three systems tracts of 3rd order, (i) basal TST, represented by shale and limestone followed by (ii) a highstand systems tract (HST) incorporating sandstone, limestone and shale, and (iii) a TST at the top. The intervening 3rd order HST can be further subdivided into 4th order parasequence-sets separated by marine flooding surfaces. Electrolog correlation along dip and strike profiles reveal that the ubiquitous presence of glauconite-rich horizons corresponds to intervals of marine flooding events (MFE) of 3rd and 4th order sea-level change. The glauconites associated with MFE result in a condensed section with minimum sediment supply. Thus glauconitic horizons provide a key parameter to build the sequence stratigraphic architecture of Eocene sequence of Assam and Assam-Arakan Basin. The sources of K and Fe required for glauconitization are sea-water and detrital minerals respectively and are achieved by diffusion-nucleation-crystal growth process.

Introduction

Glaucinite occurs in forms of green clay aggregates in marine sedimentary rocks ranging in age from Late Paleo-Proterozoic to the Holocene. They are generally considered as a product of marine authigenesis indicative of low sedimentation rate (Odin and Matter, 1981; Dasgupta et al., 1990; Amorosi, 1994, 1995, 1997; Meunier and El Albani, 2007; Amorosi et al., 2007; Bandopadhyay, 2007; Banerjee et al., 2016). The Early to Middle Eocene Sylhet Formation, Assam & Assam Arakan Basin is characterized by abundant and ubiquitous occurrences of glauconites in some specific stratigraphic intervals. The present paper attempts to characterize the depositional significance of glauconite in a sequence stratigraphic perspective, as well as its influences of depositional environment and substrate within the Sylhet Limestone. The study is confined to Assam shelf (Upper Assam North and Upper Assam South) from Panidihing in north to Khoraghat in south (Fig.1). Such documentation of glauconitic horizons and their correlation with sequence stratigraphic surfaces will signify the extent of marine transgressions in the Assam & Assam Arakan Basin during the Middle Eocene time, which will provide important clues to sequence stratigraphic analysis of any basin and particularly the elucidation of hydrocarbon bearing sequences in a better way to characterize reservoirs.

Geological Background

The Assam & Assam Arakan Basin extends over large area of Northeast India, Myanmar and Bangladesh. Assam & Assam Arakan Basin is subdivided into three major tectonic blocks, based on tectonic evolution and major basement faults, viz. Upper Assam, North (UAN), Upper Assam South (UAS) of Assam Shelf and Assam and Assam-Arakan Fold Belt (AAFB). Assam Shelf is located between the Eastern Himalayan foothills and the Assam-Arakan Fold belt. Lithostratigraphically, the UAN and UAS blocks are similar due to their same paleoenvironment of deposition and tectonic setting; the two blocks are separated by a strike-slip fault, widely known as Jorhat Fault (Evans, 1932; Dasgupta and Biswas, 2000). The mixed siliciclastic-carbonate Sylhet

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Formation implies deposition in a tide affected marginal marine (deltaic) to inner-shelf carbonate ramp setting. The generalized lithostratigraphy of Basin is summarized in Table 1.

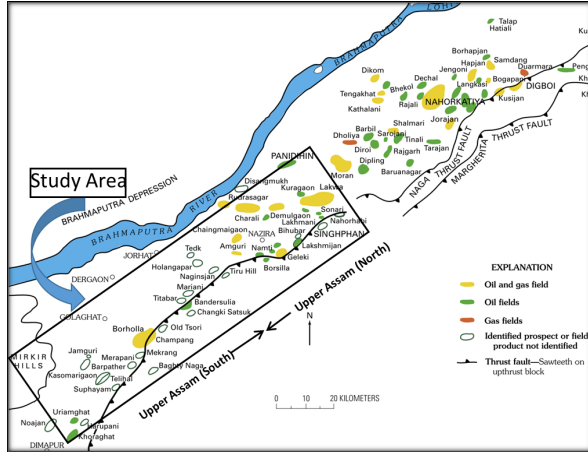


Fig.1: Location map of study area showing Upper Assam, North and South of Assam Shelf, Assam and Assam Arakan Basin showing different fields.

Assam & Assam Arakan Basin contains four 1st order sequences specific to four tectonic phases of the basin related to Gondwana intracratonic graben, Early Cretaceous rifts, Late Cretaceous to Oligocene passive margin pericratonic basin and post collision foreland basin system (Fig.2). The Late Cretaceous to Oligocene passive margin 1st order sequence has been divided into two 2nd order sequences separated by K/T boundary. The topmost 2nd order passive margin sequence of Paleocene to Oligocene age represents deposition over unconformity C-II-10 (KTB) when transgression entered in South Shillong during Early Danian after a hiatus of approximately 1Ma (Rastogi et al., 2007). Transgression entered to Assam Shelf around 58.7Ma and continued till 28.3Ma, which accumulated Tura, Sylhet and Kopilli formations and thus Sylhet Formation belongs to a 2nd order Transgressive systems tract (TST) (Rastogi et al., 2007).

Materials and Methods

The present work involves sedimentological analysis of glauconite samples collected from cores and cuttings from 30 wells from different fields of UAN and UAS blocks (Fig.1). Selected samples are analysed for clay and bulk mineralogy by X-ray diffractometer. SEM-EDAX analysis was carried out of samples to understand the composition, texture and clay mineralogy of glauconites. Basic electrolog data incorporating mainly four conventional logs; Gamma-Ray, Resistivity, Neutron and Density logs have been calibrated with lithology and the electrolog motifs were used for

regional correlation (68 wells along 12 dip, and 2 strike profiles) of different units present within the Sylhet Formation.

| Chrono-stratigraphy | Age* (Ma) | Thick-ness(m) | Lithology | Lithostratigraphy Group | Legend |
|----------------------|-----------|---------------|-----------|-------------------------|-----------------------|
| Quaternary | 2.0 | 600-1200 | | Moran | Alipuram |
| | 150-1900 | | Dhekajuli | | Shale |
| | 250-550 | | Namsang | | Siltstone, Silt |
| Neogene | 5.1 | 20-850 | | Tipam | Nazra Sandstone |
| | 11.3 | 50-850 | | | Gurjan Clay |
| Miocene | 14.4 | 100-550 | | | Lakwa Sandstone |
| | 200-400 | | | | Geleki Sandstone |
| Paleogene | 24.6 | | | Barail | Gravel, Conglomerate |
| | Upper | 40-500 | | | Rudrasagar Coal Shale |
| | Lower | 80-250 | | | Demulgaon Sandstone |
| | Upper | 40-350 | | | Disangmukh |
| | Lower | 100-450 | | | Kopilli |
| Eocene | 42.0 | | | Jaintia | Sylhet |
| | 50-120 | | | | |
| Paleocene | 50.5 | | | Tura | |
| | 59.9 | 10-35 | | | |
| Cretaceous? | 60.2 | | | | Coal, Lignite |
| | 65.0 | | | | Metamorphic |
| Precambrian Basement | | | | | |

Table1: Generalised stratigraphy of A&AA Basin (After Pandey et al., 1997).

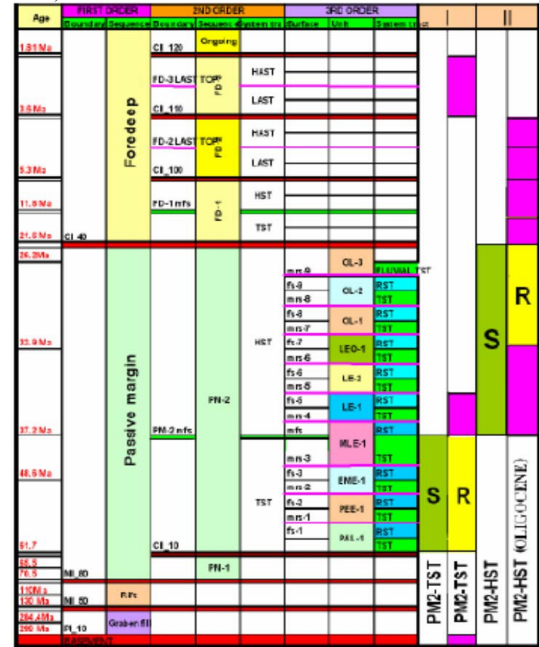


Fig.2: Sequence stratigraphic hierarchy of Assam and Assam- Arakan Basin (after Singh et al., 2011).

Occurrence and Maturity of Sylhet Glauconite

The glauconites occur mainly in three forms, viz. pellets/peloids, infillings within bioclast-pores and as glauconite cements. Glauconite pellets appear pale yellowish green to dark green and display dark to yellowish green interference colour (Fig.3a). The darker

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pellets exhibit slightly wrinkled surfaces, shiny appearance and deeply penetrating radiating cracks (Fig.3b). Euhedral pyrites, oxidized at places may occur disseminated within the glauconitic pellets (Fig.3c). The glauconite infilling predominantly occupies the chambers, canals and tiny pores in shell walls of benthic foraminifera (Fig.3d,e). Green stringers and blebs are also found within the intergranular spaces between framework grains in a few places (Fig.3f).

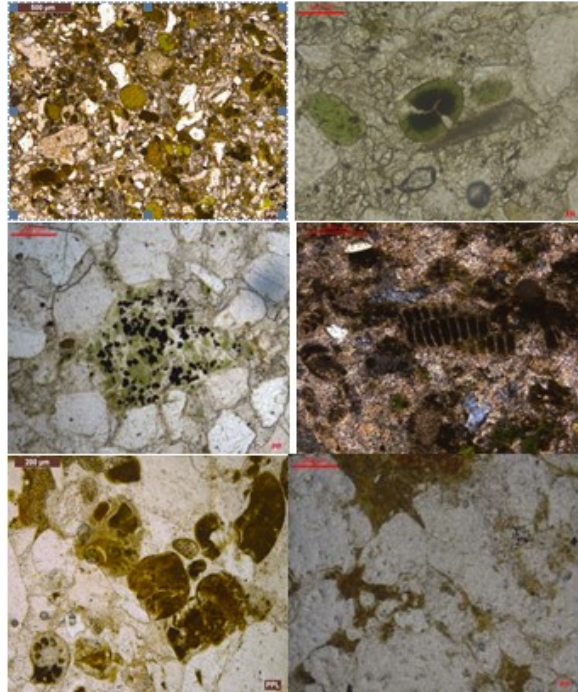


Fig.3: Occurrences of glauconite, (a) Arenaceous wackstone having fresh glauconite pellets, (b) Glauconite pellet is infilled by pyrite in the centre and replaced by calcite cement through cracks, (c) Glauconite pellet infilled with pyrite, (d) Arenaceous wackstone Fossils fragments, chamber filled with glauconite, (e) Speratised packstone, (f) Enlarged view showing quartz grains with glauconite as cement.

The XRD patterns of the clay fractions of samples from UAN and UAS blocks display the characteristic (001) reflections of glauconitic minerals at ~10Å (Bayliss et al., 1986). The maximum percentage of Glauconite occurs in samples of UAN and UAS blocks are 33% and 40% respectively (Fig.4). Glauconites are also identified in SEM by EDAX studies (Fig.5a,b,c,d). The relationship between K₂O-Fe₂O₃ weight percentage and maturation of glauconite has been explored from the SEM-EDAX analysis (Banerjee et al., 2016b, Fig.5). The change in K-Fe weight percentage in EDAX analysis is attributed to an increase of glauconite maturity.

The maturity of glauconite can readily be seen under polarizing microscope with different colours (pale

yellow, yellowish green, deep green and brownish green appearances). SEM-EDS studies clearly document that the infilling within the intra-particle pores of bioclasts mostly belong to nascent to slightly evolved glauconite (<6 wt% K), while the pellet belongs to slightly evolved to evolved glauconite (6-10 wt% K). SEM-EDS studies has confirmed presence of four different types of glauconites with increase in K percentage, viz. nascent (<4% K), slightly evolved (4-6% K), evolved (6-8% K) and highly evolved (8-10% K) glauconites (Fig.5; Odin and Matter, 1981).

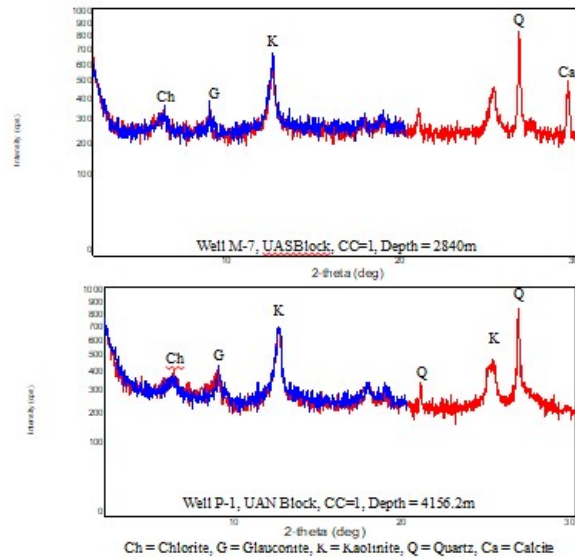


Fig.4: XRD data shows occurrences of glauconites in UAS and UAN Blocks.

High Resolution Sequence Stratigraphy and lower order units (3rd and 4th order)

Earlier detailed work on High Resolution Sequence Stratigraphic analysis (HRSS) based on core and electrolog data subdivided the 2nd order TST into 3 systems tracts of 3rd order (Chakrabarty et al., 2019). The basal transgressive systems tract (TST), represented by shale and limestone followed by highstand systems tract (HST) incorporating sandstone, limestone and shale, and finally a TST at the top (Fig.6).

On the basis of regional electrolog correlations (twelve dip profiles, 4 in UAN and 8 in UAS and 2 strike profiles) the bottom surface of Sylhet Formation is marked as MRS_3rd-2 that also represents top of underlying Tura Formation, while the top of Sylhet is marked as MFS_3rd_4. In between MRS_3rd-2 and MFS_3rd-4, there are another two 3rd order surfaces, MFS_3rd-3 and MRS_3rd-3, which divide the total Sylhet into three 3rd order systems tracts, viz. lower TST, middle HST and followed by upper TST (Chakrabarty et al., 2019).

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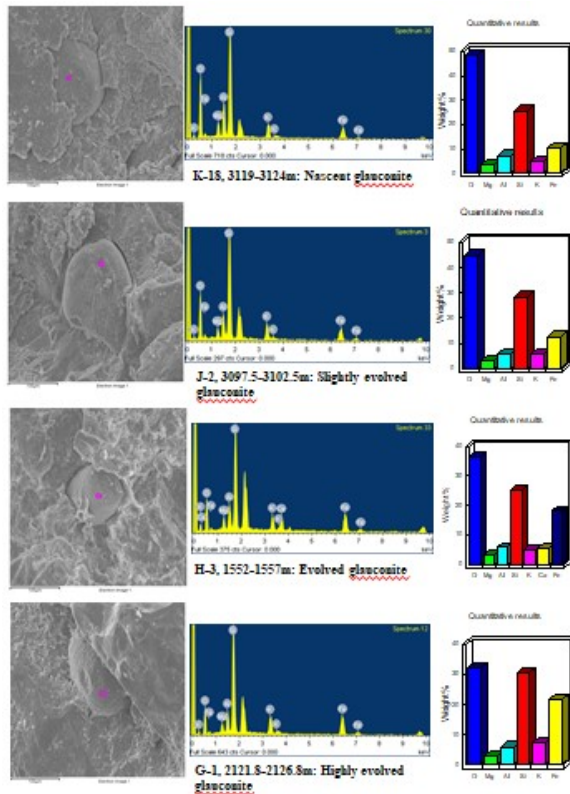


Fig.5: SEM-EDS analysis of glauconite grains from Sylhet Formation showing different degrees of maturity.

The 4th order units have been identified based on occurrences of three high frequency marine flooding surfaces that can be laterally correlated within the 3rd order basal TST and overlying HST in drilled wells of UAN and UAS blocks. These are designated as FS_4th-1 to FS_4th-3 from below. FS_4th-1 divides the basal 3rd order TST into one 4th order TST unit (bounded by MRS_3rd-2 and FS_4th-1) and one 4th order HST+TST full unit (bounded by FS_4th-1 and MFS_3rd-3). Bottom 4th order TST unit mainly consists of shale with minor sandstone interbeds, whereas the overlying 4th order unit consists mainly of coarsening upward limestone with shale. The marine flooding surfaces FS_4th-2 and FS_4th-3 divide the middle 3rd order HST into two 4th order parasequence-sets (full units) and one 4th order HST at the top (Fig.6). Each 4th order marine flooding surfaces can be laterally correlated from the basin margin to the interior (Fig.7a,b).

Glauconite in sequence stratigraphy

Abundant glauconite occurrence reflects marine transgression and associated sediment starvation facilitating marine authigenesis (Amorosi, 1997, 2012; Baum and Vail, 1988). It has been observed that the occurrences of Sylhet glauconites are maximum at 3rd

and 4th order MFS surfaces. Maximum glauconite abundance and maturity are characteristics of the condensed section (CS) and the associated surface of maximum sediment starvation, which occur near events of maximum flooding intervals. The occurrence of the glauconitic minerals with events of marine flooding is related to extremely slow sedimentation leading to glauconitization. In the recorded bed, fossil debris, pyrites and carbonate horizons are very commonly associated with glauconite (Fig.7a,b). Thus the occurrence of glauconites within the Sylhet Limestone provides a key parameter to build the sequence stratigraphic architecture of the Eocene sedimentation in A & AA Basin.

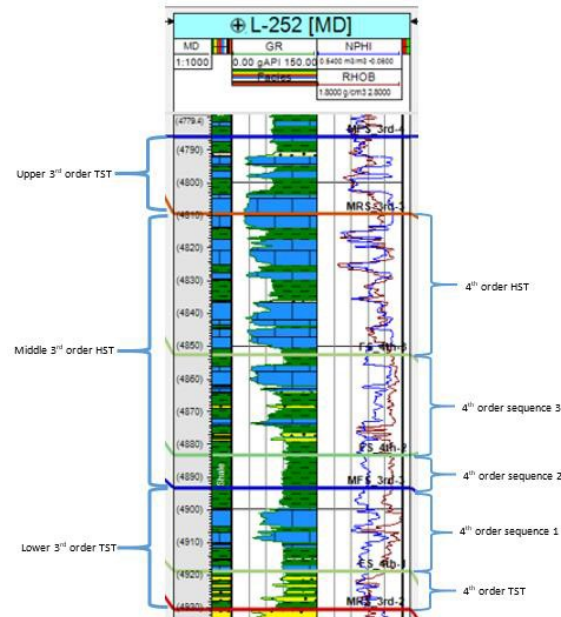


Fig.6: Key well showing electrolog with lithofacies depicting lower order sequence stratigraphic surfaces within the 2nd order TST (see text for detail subdivision).

Mechanism of Glauconite formation

The origin of glauconite is usually explained by three common theories, i.e., verdissement, layer lattice and replacement. The “verdissement theory” (Odin and Matter, 1981) involves precipitation of initial “glauconitic smectite” within the pores of bioclasts and faecal pellets, accompanied by continuous dissolution and recrystallization of the substrate. The “layer lattice theory” (Burst, 1958a,b; Hower, 1961) is based on the transformation of a degraded 2:1 layer silicate lattice (TOT clay) into an iron- and potassium-rich 2:1 layer silicate of the illite group with simultaneous increase of K₂O and TFe₂O₃ content. This is supposed to occur under reducing conditions. The 3rd theory regarding

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glauconitisation evidences pseudomorphic replacement of K-feldspars by glauconite.

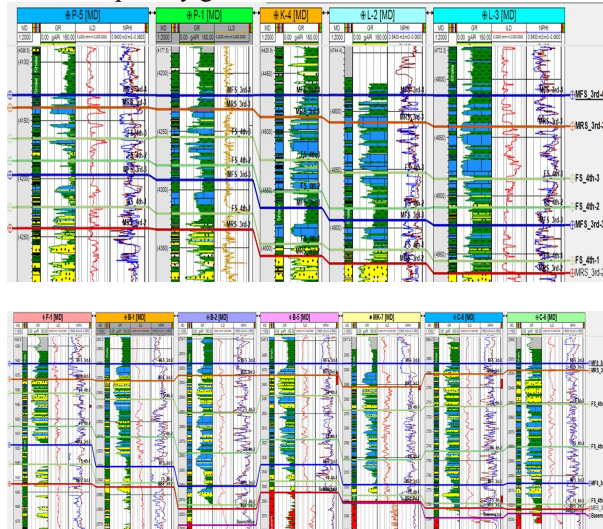


Fig. 7: (a) Electrolog correlation and lithofacies distribution along dip profile (UAN). (b) Electrolog correlation and lithofacies distribution along dip profile (UAS).

The glauconitisation process in Sylhet Formation may have formed differently as per the existing theories. The formation of green clays in marine environments, i.e. glaucony is made possible by the migration of K and Fe ions from sea-water or surrounding sediments to a given microsystem centred on organic debris (Meunier and Albani, 2007). The sources of K and Fe ions are sea-water and detrital minerals, respectively (Bansal et al., 2019). Iron mostly contained in Fe^{3+} state in detrital minerals (oxides, Fe-kaolinite), but it is required to be in soluble Fe^{2+} state for migration towards proto-green mineral pellet. Therefore, the micro-environment in which organic debris or bacterial activity imposes a reducing conditions is required (Fig.8). Framboidal pyrite is formed first in such microenvironments. In fact, in present study also, framboidal pyrites are well noticed and occur in profuse amount associated with glauconites, either within fossil chambers or pellets. Then, glauconites form by a nucleation-crystal growth process (Fig.8) (Gago-Duport et al., 2000).

Also, any modification of the porosity during the early diagenetic stage in cemented sandstones changes the composition of the glaucony (Strickler and Ferrell, 1990). The sandstone rich intervals in Sylhet Formation are characterised by presence of early calcite cementation (Shukla et al., 2019) that will lead to a significant porosity reduction. Consequently, the interruption of the diffusion paths due to compaction or cementation in sandstone rich horizons within Sylhet

Formation will result incomplete glauconitisation. This explains why glauconitisation is favoured by events of extreme slow sedimentation rate or events of marine flooding and condensation.

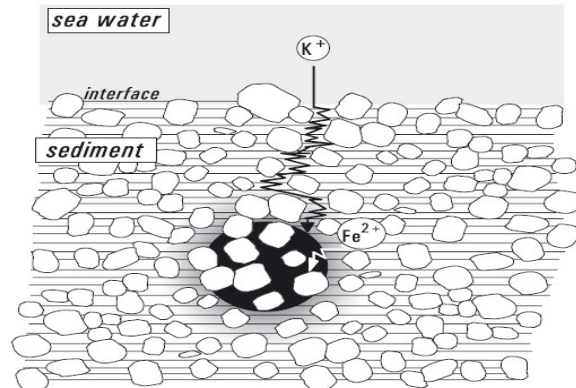


Fig.8: Schematic representation of mechanism of formation of green materials (glauconites) in a clay-rich marine substrate consists of shale/sandstone where organic debris are present (black area). K^+ diffuses from sea-water through the sediment-seawater interface while Fe^{2+} ions diffuse inside the reductive microenvironment centred on the organic debris (cf. Meunier and Albani, 2007).

Conclusions

This paper provides a systematic documentation of significance of glauconite-rich intervals within Early to Middle Eocene Sylhet Formation of the Assam and Assam-Arakan Basin. The significant findings and conclusions are:

- (a) The glauconite-rich horizons are restricted at specific stratigraphic levels within Sylhet Formation and it mainly occurs in three forms, viz. pellets, infillings within fossil chamber and cements/blebs.
- (b) The glauconites show different degrees of maturity that can be easily identified under microscope and SEM studies. The different stages of maturity of Sylhet glauconites are: nascent (<4% K), slightly evolved (4-6% K), evolved (6-8% K) and highly evolved (8-10% K). The nascent (immature) glauconites are characterised by low percentage of K and Fe concentration, whereas the mostly evolved glauconites are enriched in K and Fe. The more matured varieties are associated with silty shale facies.
- (c) High Resolution Sequence Stratigraphic analysis has shown that the ubiquitous and maximum occurrences of Glauconites are correlated with lower order (3rd and 4th order) Maximum Flooding Surfaces (MFS). It is a reliable indicator of low sedimentation rate that typically represent slow rates of clastic influx and thus maximum glauconite abundance and maturity are associated with surface of maximum sediment starvation, which occur at the events of marine flooding intervals and development of condensed sections.

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Therefore, glauconitic horizons provide a key parameter to build the sequence stratigraphic architecture of Eocene sequence in the Assam and Assam-Arakan Basin.

(d) Regional correlation along dip and strike profiles in UAN and UAS blocks have revealed existence of relatively matured glauconites towards landward part of the lower order (3rd and 4th order) MFS and are associated with exposure related surfaces.

(e) Sylhet glauconites are formed due to nucleation-crystal growth process with source of K^+ and Fe^{2+} from sea water and surrounding sediments respectively to a given microsystem centred on organic debris. The gradual K^+ chemical diffusion and simultaneous reduction of Fe^{3+} into a soluble Fe^{2+} state to migrate towards the proto-green mineral pellet slowly leads to glauconitization. Thus, the source of iron is limited to the micro-environment in which organic debris or bacterial activity impose reducing conditions.

(f) Complete glauconitization occurs at close contact with seawater for continuous exchange of K^+ . This means that exchanges with sea-water must be possible during the whole process and porosity/permeability of hosting sediment are decisive in the glauconitization process. When the porosity is blocked by early diagenesis calcite cementation, glauconitisation process is stopped due to stoppage of ion exchange that resulted immature/fresh glauconites to occur.

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