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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.


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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 (Ieridan) 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 chemosтратigraphy 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 microfossies identified include micrite, intramicrite, sparite, oosparite and intrasparite. The calcareous algal–foraminiferal assemblage recognized

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in the Lakadong Limestone includes coralline algae (Lithophyllum, Dasycladaceae) and larger forams (Alveolina, Miscellanea, Rotalia, Ranikothalia, miliolids, Dentaloides, Textularia, Discocyclina and Nummulites). Some microfish remains are also present. The sedimentary structures indicate tidal influence in carbonate reef environment.

Keywords: Algae, foraminifera, Lakadong Limestone, Meghalaya, Paleocene, Shillong Plateau, stable isotope chemostратigraphy.

This communication deals with the carbonate sedimentation facies, depositional environment, and carbon and oxygen isotope signatures of the Paleocene–early Eocene Lakadong Limestone (older of the two members of the Lakadong Formation). Lakadong Limestone is well exposed in a limestone quarry at Mawmluh (lat. 25°15’25”N, long. 91°42’47”E) near Sohra, South Shillong Plateau (Meghalaya), northeastern India (Figure 1).

The Lakadong Limestone is considered mainly Paleocene (Thanetian) in age but also extends into early Ieridion in some sections, e.g. Therissa. It is the lowermost unit of the Sylhet Limestone Group established by Dasgupta (Table 1). The Lakadong Limestone in the East Khasi Hills and Jaintia Hills was deposited during the Paleocene marine transgression. A detailed lithological log of the Lakadong Formation exposed in the Mawmluh Quarry is presented in Figure 2 showing the major facies variations and fossiliferous horizons. The Lakadong Formation is made up of two lithounits, the older Lakadong Limestone and the younger Lakadong Sandstone (Figures 2 and 3). The sedimentary structures, trace fossils and carbonate facies indicate that the Lakadong Limestone was deposited in the shallow carbonate ramp environment (Figure 3 b–o). The conformably overlying Lakadong Sandstone shows conditions favourable for deposition of coal beds and carbonate shales in a reducing environment (Figure 3 a).

In Mawmluh Quarry (MQ), the exposed part of Lakadong Limestone is about 44 m thick (Figure 2). We studied it systematically for the carbonate microfossils, depositional environment, and carbon and oxygen stable isotope chemostратigraphy. Petrographic thin sections of the Lakadong Limestone reveal its bioclastic (algal–foraminiferal) nature. It is composed mainly of calcite, dolomite, and smaller and larger microfossils. The X-ray diffraction analysis (XRD) has confirmed the presence of dominantly carbonate minerals calcite and dolomite (Figure 4). However, minor peaks of quartz, mica and clay minerals are also present. The microfossics identified include micrite, intramicrite, sparite, oosparite and intrasparrite (Figure 5). The algal–foraminiferal assemblage recognized in the Lakadong Limestone includes coralline algae, Lithophyllum and Dasycladaceae and larger foraminifers, e.g. Miscellanea sp., Rotalia sp., Ranikothalia sp., miliolids, Dentaloides sp., Textularia sp., Alveolina sp., Discocyclina sp. and Nummulites sp. (Figure 5). The presence of some microfish remains was noticed for the first time in the disaggregated matrix of the Lakadong Limestone. The taxonomic details of the algal–foraminiferal assemblage and other fossils are not provided here as these are either available from earlier publications and references therein or need substantiation before documentation. The microfossils recorded from the base to the top in the stratigraphic sequence are discussed with special reference to their depositional environment and microfacies.

The lower part of the Lakadong Limestone has yielded a diverse microfossil assemblage comprising larger foraminifers, e.g. Glomalveolina primaeva, Miscellanea sp., Rotalia sp., Dentaloides sp., Textularia sp., miliolids and some smaller benthic foraminifers. Apart from foraminifers bivalves, gastropods (large turritellids), burrow holes and calcareous algae have also been found. Jauhi et al. reported similar assemblage from the Lakadong Limestone of the Therissa section exposed ~8 km northeast of Mawmluh, the present study area (Figure 1).

Figure 1. Geological map of the South Shillong Plateau, Meghalaya showing location of the Mawmluh Quarry (study area) and Therissa (after Ghosh’). 1. Alluvium; 2. Kopili Formation; 3. Sylhet Limestone; 4. Therissa Formation; 5. Langpar Formation and Um Sohryngkew Formation; 6. Sylhet trap; 7. Archaean; 8. K/T section; 9. Um Sohryngkew River.
According to them, the lower part of the Lakadong Limestone can be regarded as representing the Shallow Benthic zones (SBZ) 3 and 4 of Serra-Kiel et al., which are equivalent to the planktonic foraminiferal zone P4 of Pearson et al. and correspond to the latest Paleocene. The present study supports the findings of Jauhari et al.

About 6 m thick zone in the middle part of the Lakadong Limestone (sample nos MQ6–MQ8) is apparently barren and has not yielded any fauna or flora so far. Moreover, it is also very low in carbon content. This zone corresponds with the sample number 91/LKD/DR6 (from Therria section) of Jauhari et al., who also marked it as devoid of fossils.

The upper part of the Lakadong Limestone (sample numbers MQ9–MQ14) has yielded Discocyclina sp., Rotalia sp., Miscellanea miscella, Ranikathiala nutalli, miliolids, smaller benthic foraminifera, and rich algal remains, including Distichoplax biserialis (Figure 5f) and Lithophyllum sp. Jauhari et al. assigned the upper part of the Lakadong Limestone to SBZ 5 and 6, which are equivalent to the planktonic foraminiferal Zone P5 and correspond to the latest Eocene (Ieridian). The present study corroborates the biostratigraphic age (latest Paleocene to earliest Eocene) suggested for the Lakadong Limestone by Jauhari et al.

The microfossils association of bivalves, small gastropods, algae and foraminifera suggest that Lakadong Limestone was deposited in shallow marine conditions with tidal influence as evidenced by the close association of high energy reworked clasts, ooids, intraclasts and broken shell fragments with algae and foraminifera (Figure 5a–f). The Lakadong Limestone carbonate microfossils reveal that it was deposited in the inner carbonate ramp setting. The 44 m thick algal–foraminiferal limestone is characterized by grainstones, boundstones, packstones and wackestones. Algal facies indicate deposition in carbonate reef environment.

Jauhari et al. based on their work in the Therria section suggested that the lower part of the Lakadong Limestone belongs to Thanetian transgressive cycle. In Therria (Figure 1), the lower part of the Lakadong Limestone is Thanetian in age (Late Paleocene) and the upper part is early Ieridian (early Eocene). Typical early Ieridian species, e.g., Miscellanea miscella and Ranikathiala nutalli are present in the upper part. Late Paleocene–Early Eocene (late early Thanetian to early Ieridian) age is indicated by the foraminiferal association for the whole Lakadong Limestone based on a comparison with the standard Paleogene larger foraminiferal biozones. The Lakadong Limestone of the MQ section (present study) supports the presence of SBZ 3–4 and 5–6 of Serra Kiel et al. (Figure 5).

The stable carbon and oxygen isotope chemostatigraphic of the Lakadong Limestone has been attempted for the first time. The carbon and oxygen isotopic variations in the samples collected from the base (MQ0, oldest) to the top (MQ14, youngest) are discussed and given in Table 2. C and O isotope values obtained from the Lakadong Limestone are shown in Figure 6. In the lower part of the Lakadong Limestone exposed in the MQ section (sample numbers MQ0–MQ4) $^{13}$C ratios vary from –0.093‰ (PDB) to 1.31‰ (PDB) and $^{18}$O ratios vary from –7.87‰ (PDB) to –9.25‰ (PDB) or 21.32‰ (SMOW) to

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Lithological log of the Lakadong Formation, Mawmluh Quarry, South Shillong Plateau showing sedimentary facies, sedimentary structures and fossiliferous horizons.

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**Table 1.** Stratigraphy of the Sylhet Limestone Group, Shillong Plateau (after Dasgupta)

<table>
<thead>
<tr>
<th>Formation</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kopili Formation</td>
<td>Late Eocene</td>
</tr>
<tr>
<td>Prang Formation</td>
<td>Middle Eocene</td>
</tr>
<tr>
<td>Unmatlah Formation</td>
<td>Early Eocene</td>
</tr>
<tr>
<td>Lakadong Formation</td>
<td>Late Paleocene–Early Eocene</td>
</tr>
<tr>
<td>Therria Formation</td>
<td>Late Paleocene</td>
</tr>
<tr>
<td>Langar Formation</td>
<td>Early Paleocene</td>
</tr>
</tbody>
</table>

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Figure 3. Field photographs of the Lakadong Formation exposed in Mawmluh Limestone Quarry near Cherrapunji. a, Panoramic view showing the Lakadong Formation; b, Dolomite between benches RL 1290 and 1297; c, Dolomite between RL 1297 and 1304, note the two carbonaceous shale bands in the upper part of the section; d, Limestone beds between RL 1304 and 1312, in this part of the section (thickness ~ 8 m) trace fossils along as well as across the bedding are common and foraminifers occur in a 2 m band ~1.5 m from the base; e, Close up of shaly limestone beds rich in trace fossils between RL 1304 and 1312; f, Recrystallized limestone with foraminifers and molluscs in the upper part of the Lakadong Limestone between RL 1312 and 1320; g, Hand specimen of dolomitic limestone between RL 1285 and 1290 showing microfossils, mainly algae; h, Hand specimen of dolomitic limestone between RL 1285 and 1290 showing the abundance of microfossils; i-l, Hand specimens of shale and shaly limestone from the middle and upper parts of the Lakadong Limestone showing abundance of trace fossils; m, Close up of limestone packed with foraminifers and algae from the upper part of the Lakadong Limestone between RL 1312 and 1320; n, Close up of weathered limestone full of foraminifers and algae from the topmost part of the Lakadong Limestone between RL 1320 and 1328; o, Longitudinal section of a large turritellid preserved in recrystallized limestone in the upper part (RL 1312–1320) of the Lakadong Limestone.
22.74‰ (SMOW). In the middle part of the Lakadong Limestone (sample nos MQ5–MQ9), δ¹³C isotope ratios range from 0.46‰ (PDB) to 1.59‰ (PDB) and δ¹⁸O isotope ratios vary from −7.90‰ (PDB) to −14.24‰ (PDB) or 16.62‰ (SMOW) to 22.80‰ (SMOW). Sample numbers MQ6–MQ8 do not contain any foraminifera and are low in carbon. In the upper part of the Lakadong Limestone (sample nos MQ10–MQ14), δ¹³C isotope ratios vary from −0.13‰ (PDB) to 1.94‰ (PDB) and δ¹⁸O isotope ratios are in the range between −7.41‰ (PDB) and −10.30‰ (PDB) or 20.24‰ (SMOW) and 23.49‰ (SMOW). Present δ¹³C and δ¹⁸O isotope data of the Lakadong Limestone from the MQ section are comparable with the normal marine values of the limestone and indicate a shallow marine depositional environment. It correlates well with the global Paleocene stable carbon and oxygen isotopic data indicating similar depositional environment and isotope chemostratigraphy\(^{10,11}\). For example, the Paleocene beds of the Liburnia Formation, NW Adriatic–Dinaric platform (Slovenia) are open shelf subtidal marine limestone and their δ¹³C values range from 2.3‰ to 0.1‰ (PDB)\(^{12}\). A recent study from the post Cretaceous–Paleogene (K/Pg) boundary Santa Elena borehole from the Chicxulub impact crater\(^{11}\) has shown that δ¹³C values range from 1.2‰ to 3.5‰ (PDB) and δ¹⁸O values from −1.4‰ to −4.8‰ (PDB). The Paleocene marine carbonate cores from the North Pacific Ocean also show similar carbon and oxygen isotope ratios\(^{14,16}\).

The oxygen isotope ratios of the Lakadong Limestone from Meghalaya are more negative when compared with the Chicxulub crater and may be related to local palaeogeographic conditions. The δ¹⁸O values from Santa Elena core are more or less similar to the Deep Sea Drilling Program (DSDP) hole in the North Pacific Ocean\(^{11}\). The Cretaceous–Paleogene (K/Pg) boundary marine carbonates from the Padriciano section in the North Adriatic platform have shown highly depleted δ¹³C values (−3.62‰ to −10.01‰ PDB) and the δ¹⁸O values range from −3.85‰ to −5.47‰ (V-PDB)\(^{15}\). C and O isotopic study of the Lakadong Limestone suggests that the water temperature ranged approximately between 27°C and 30°C.

The calcareous–algal foraminiferal assemblage of the western Tethyan realm in the Mediterranean region (Adriatic platform in Italy and Slovenia) is correlated with the eastern part of the Neotethys in Turkey, Greece, Pakistan and Meghalaya\(^{3,12,13}\).

The sedimentary facies and calcareous algae of the Lakadong Limestone indicate slow rate of sedimentation and shallow water environment in a carbonate ramp. The symbiotic relationship between the coralline algae and

### Table 2. Results of δ¹³C and δ¹⁸O analysis of the Lakadong Limestone, Mawmluh Quarry section, Meghalaya

<table>
<thead>
<tr>
<th>Sample</th>
<th>δC męr (%)</th>
<th>δO męr (%)</th>
<th>δO SMOW (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MQ0</td>
<td>0.46</td>
<td>−7.95</td>
<td>22.67</td>
</tr>
<tr>
<td>MQ1</td>
<td>0.95</td>
<td>−9.25</td>
<td>21.32</td>
</tr>
<tr>
<td>MQ2</td>
<td>−0.93</td>
<td>−8.17</td>
<td>22.44</td>
</tr>
<tr>
<td>MQ3</td>
<td>1.31</td>
<td>−8.22</td>
<td>22.64</td>
</tr>
<tr>
<td>MQ4</td>
<td>0.73</td>
<td>−7.87</td>
<td>22.74</td>
</tr>
<tr>
<td>MQ5</td>
<td>0.75</td>
<td>−7.90</td>
<td>22.72</td>
</tr>
<tr>
<td>MQ6</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>MQ7</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>MQ8</td>
<td>0.46</td>
<td>−14.24</td>
<td>16.62</td>
</tr>
<tr>
<td>MQ9</td>
<td>1.59</td>
<td>−8.06</td>
<td>22.80</td>
</tr>
<tr>
<td>MQ10</td>
<td>1.94</td>
<td>−7.62</td>
<td>23.24</td>
</tr>
<tr>
<td>MQ11A</td>
<td>0.52</td>
<td>−10.24</td>
<td>−</td>
</tr>
<tr>
<td>MQ12</td>
<td>0.79</td>
<td>−7.41</td>
<td>23.22</td>
</tr>
<tr>
<td>MQ13</td>
<td>1.83</td>
<td>−7.14</td>
<td>23.49</td>
</tr>
<tr>
<td>MQ14</td>
<td>−0.13</td>
<td>−10.30</td>
<td>20.24</td>
</tr>
</tbody>
</table>

**Figure 4.** X-ray diffraction pattern for Lakadong Limestone from the Mawmluh Quarry, showing the calcite peak.
Figure 5. Photomicrographs of fossil assemblage (mainly algal–foraminiferal) recorded from the Lakadong Limestone, Mawmluh Quarry, South Shillong Plateau, Meghalaya. a, Recrystallized turritellid mollusc (bioclastic and intrasparite microfacies); b, Glomalveolina primaeva in recrystallized sparry cement; c, Discocyclina sp.; d, Coralline algae Lithophyllum sp. with fragments of foraminifera Rotalia sp.; e, Fragment of coralline algae; f, Algae Distrochotax birnarealis; g, Coralline algae Lithophyllum sp.; h, Miscellania sp.; i, Milolid showing recrystallization (bioclastic microfacies); j, Glomalveolina sp. in micritic facies.
foraminifera has been observed in the microfacies analysis (Figure 5c, d and g). Lakadong Limestone is characterized by the presence of Standard Micro Facies (SMF 16–18) belonging to mainly algal biopartite (Figure 5a and d–g). The biostratigraphic data suggest a Paleocene–Eocene (P/E) boundary sedimentation and Paleocene transgression in the Lakadong Limestone.

The conformably overlying Lakadong Sandstone (Figures 2 and 3a) was deposited in the mud flats and marshes protected from tidal waves. The carbonaceous shales and coal beds of the Lakadong Sandstone were deposited in coastal swamplike environment in restricted basin during the early Eocene. In the western Himalaya, the coeval Kakara–Subathu succession represents deposition in transgressive marine basin during the Late Paleocene–early middle Eocene period. In northeastern India, apart from Meghalaya, marine early Tertiary fossiliferous sediments have been recorded from Assam, Arunachal Pradesh and Nagaland. Possibly an embayment extended from Turkey and Greece through Pakistan towards Meghalaya, Assam, Arunachal Pradesh and Nagaland in the northeastern region of India. It was a shallow eastern Neotethys Sea extending in the Himalaya as evidenced by the algal–foraminiferal, other invertebrate and vertebrate fauna, sedimentary structures and facies, and the newly generated carbon isotopic data from the northeastern region of India. In the northwest Himalaya, the Subathu Sea shrank and shallowed during the early Eocene due to the northward drift of the Indian plate and finally vanished in early middle Eocene. Similar palaeobiological assemblages from the Mediterranean region of Europe, Afro–Arabian, Central Asian and Himalayan regions suggest that the Indian plate was very close to the Eurasian plate during the Paleocene–Eocene boundary time before collision. The collision and post collision phase (middle Eocene, 49 Ma) have been recently discussed by Sahni and Prasad based on vertebrate fauna. Basin architecture of the south Shillong Plateau, Meghalaya suggests that the northward movement of the Indian plate from late Cretaceous to Oligocene represents passive margin setting that continued until the collision of Indian plate with Eurasian plate. The Neothepys Sea regressed from the northern margin during the middle Eocene time and was restricted in the eastern and western margins. The subsequent palaeoclimatic changes followed the collision and uplift of the Himalayas.

Stream profiles as indicator of active tectonic deformation along the Intra-Foreland Thrust, Nahan Salient, NW India

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Stream profiles along five major streams from the Nahan Salient in the Western Sub-Himalaya were investigated with special emphasis on reactivation/active tectonics of the Intra-Foreland Thrust (IFT). Each of the stream profiles is observed to consist of two to three segments of different stream gradients. Each segment comprises a ‘stream reach’ and is marked by a distinct stream-length (SL) gradient index. SL index curves drawn for the five streams show anomalous increase in its values at the contact of two stream reaches. These distinct anomalies are found associated with the surface exposure of IFT in the field. Likewise low mountain front sinuosity (1.1 to 2.4) and low valley width to height ratios (0.1 to 0.33) also reflect active tectonic deformation along the IFT due to reactivation. The present stream profile approach is simpler, easier and faster to locate sites of fault related reactivation.

Keywords: Intra-Foreland Thrust, Nahan Salient, reactivation, stream long profiles, SL value.

The Sub-Himalayan belt in the NW India is marked by the sinuous trace of the Main Boundary Thrust (MBT) giving rise to areas that are concave towards the foreland, known as reentrants, and areas that are convex towards the foreland, known as salients. The present study was carried out in the largest salient of NW India, i.e. the Nahan Salient (Figure 1). The Nahan Salient is located in between the Kangra and the Dehradun reentrants lying in its northwest and southeast respectively. The salient and the reentrants are marked by thrusts running parallel to sub-parallel to the Himalayan Frontal Thrust (HFT) in the NW–SE direction.

It is commonly believed that the Himalayan front has sequentially migrated southwards giving rise to new thrusts1–3. It is also believed that the newly formed thrusts are the focus of tectonic convergence as seen in the case of HFT at a number of places, all along its strike4,5. Consequently, many or almost all of the thrusts/faults that lie to the north of the HFT may have, at some time in the geological past, ceased to absorb the convergence of the Indian and Eurasian plates and were rendered inactive. In

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