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Research Article

Depositional Environment of Shallow-Marine Sandstones from Outcrop Gamma-Ray Logs, Belait Formation, Meragang Beach, Brunei Darussalam

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Abstract: The outcrop of shallow marine sandstone, Belait formation at Meragang Beach, Brunei Darussalam have long been regarded as tide-, wave- and storm-dominated environment that reveals the reservoir heterogeneities and variation in sand body geometry. Intensive outcrop study methods were available from previously conducted work on Belait Formation. But for this study the priority was to acquire gamma-ray profile at 5-10 cm scale by using Digital Total GR Count Detector and re-logged of Sedimentological log (in cm) of 311.8 m thick outcrop to describe the depositional environment and sedimentary facies architecture. The sediments deposited in a tide-dominated environment mostly interpreted in all cycles which were characterized by sub-depositional environment which includes; tidal channel, muddy tidal flat and mixed tidal flat sub-environment with sedimentary facies of planner cross-bedding, trough cross-bedding, herringbone cross-stratification, wave ripples and thin parallel lamination with coal fragmented bed and carbonaceous material. The gamma-ray profile for tide dominated environment shows different shapes; block left-boxcar, bell shape, funnel shape and irregular trend. In wave- and storm-dominated are wave ripples, thin parallel lamination with mud drapes, large planner cross-bedding, trough cross-bedding, highly bioturbated (skalithos) sandstone and hummocky cross-stratification. Whereas, the gamma-ray profile shows different shapes; left-boxcar, right-boxcar, funnel shape and irregular trend and in storm-dominated it show only left-boxcar with no sharp edges on top and bottom. This approach combines excellent data quality to interpretate different depositional environment and its impact on sandstone quality which implies that the outcrop gamma-ray log can use to characterize the rock deposited in different depositional environment in different facies. It also reveals that the changes in gamma-ray profile with in the sandstone depend upon the environment in which the sandbody deposited that reveal in reservoir heterogeneities in subsurface well correlation.

Keywords: Depositional environments, facies, gamma-ray log, shallow-marine sandstone

INTRODUCTION

The gamma ray and its change in trend in different depositional environment with respect to facies distribution are useful for the characterization of reservoir analogues and to improve the understanding of subsurface well log correlation. There are numerous reservoir analogue studies across the world that attempt to characterize outcrop in order to understand the reservoir archecture and rock properties of different depositional environment (Liu *et al*., 1996; Beaubouef, 2004; Yoshida *et al*., 2004).

Outcrop gamma-ray logging and facies description is an applicable tool that can provide invaluable information on the thickness of sand body, geometry, grain size, lithology, shale sand cut-outs and depositional environment. They are most useful when combined with core or image log data, biostratigraphic information and other well log (Rider, 1996). In addition to that, outcrop gamma-ray logging with a hand hold tool has become a widely used routine for stratigraphic analysis (Myers and Bristow, 1989; Slatt *et al*., 1992; Parkinson, 1996) for correlating between outcrops and documenting changes in variations in grain sizes and sedimentary environment (Myers and Bristow, 1989; Rider, 1990; Cant, 1992) and for the identification of Para sequences and sequence stratigraphic analysis (Van Wagoner *et al*., 1990; Ketzer *et al*., 2002). Data from such studies are generally used to improve 3D geological models of hydrocarbon reservoirs from similar environments (Ballin *et al*., 1997; Dalrymple, 2001; Pringle *et al*.,

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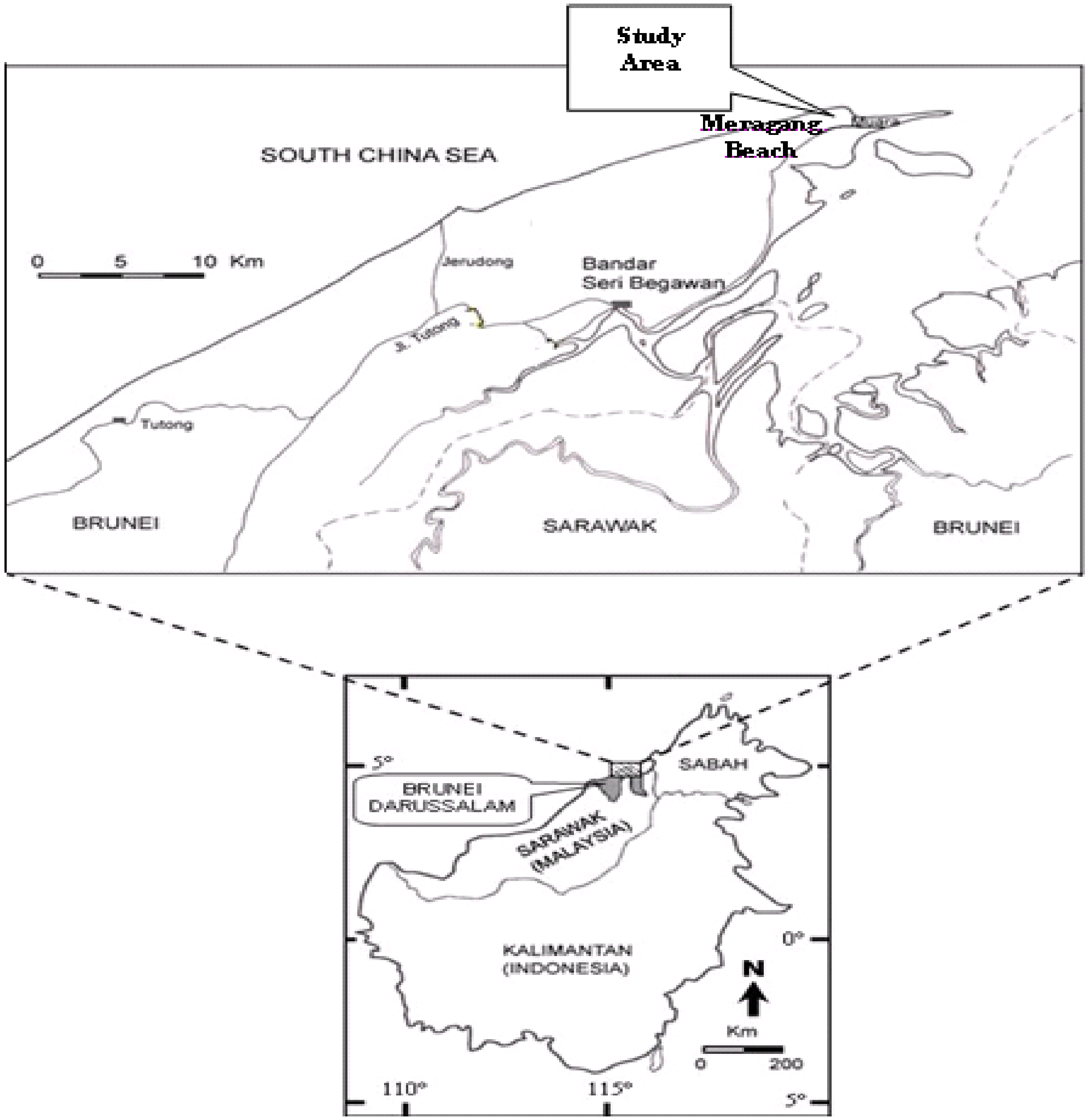


Fig. 1: Location map of the study area at Meragang Beach

2004), as a subsurface data limited by well spacing and 3D seismic resolution. Engineers upscale these geological models for reservoir simulation in order to model fluid flow and plan for hydrocarbon extraction with optimum design of production and injection wells (Andrews *et al*., 2004).

This study documents the facies distribution and outcrop gamma-ray log profile in shallow marine tide-, wave- and storm-dominated depositional environment sandstone of South Brunei, Muara District along Meragang Beach (Fig. 1). The study area consist of 311.8 m thick outcrop, which sub-divided into thirteen cycles, separated with thick mudstones and comprises with interbedded sandstone and shale, dipping from 60º-80º NW and strike towards NE.

Our study is at small scale to compare the gamma-ray log with three different depositional environments (tide-, wave- and storm-dominated) sandstone. The advantage of the Meragang beach outcrop is that, it is possible to walk along many of the exposure and can

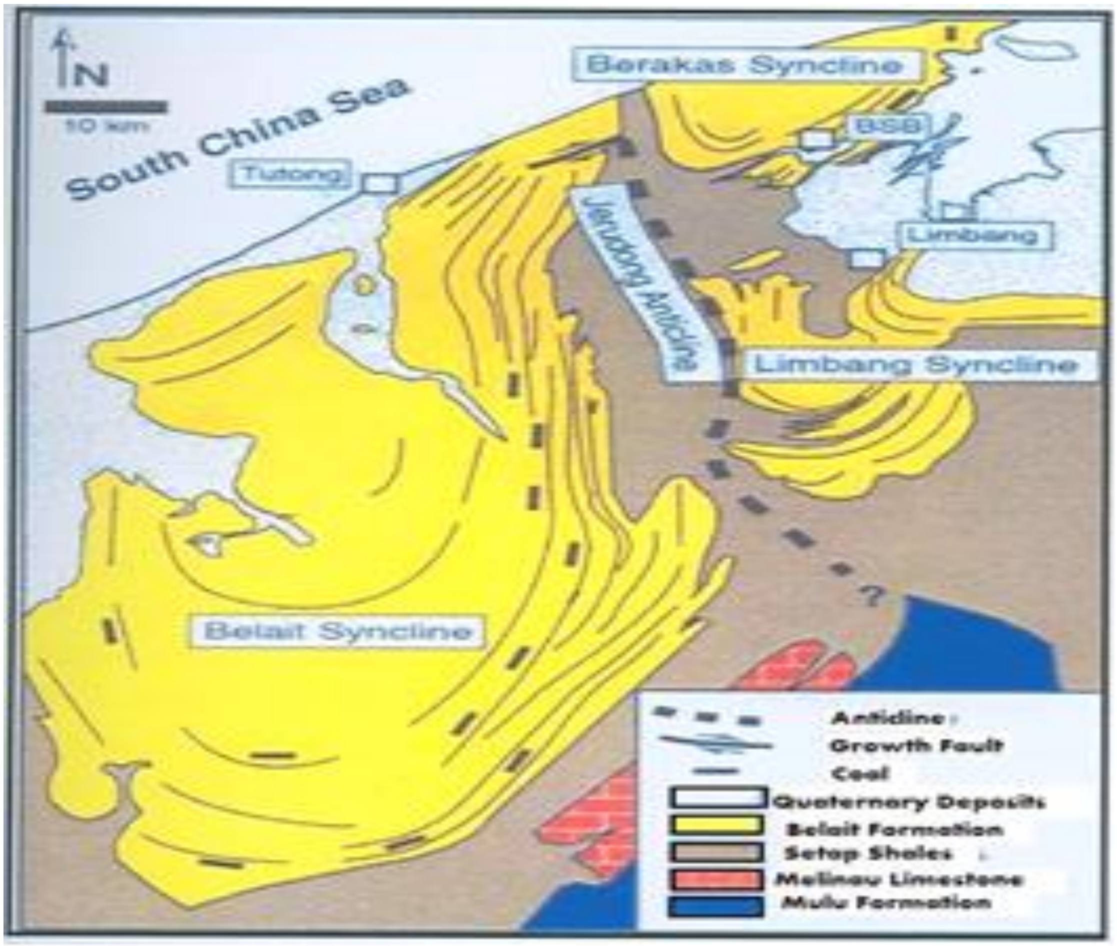


Fig. 2: The map shows the central Brunei and the geology of the Belait and Berakas Syncline (James, 1984)

construct the Sedimentological logs, sample collection and gamma-ray log. This allows the accurate measurement of logs to several laterally extensive bedding planes in outcrop, reservoir facies studies and mode of depositional environment in understanding with gamma-ray profiles (shapes).

GEOLOGICAL SETTING

Brunei Darussalam occupies a central position of central and Southern Borneo, bounded by the South China to Northwest, the Sulu Sea and Celebes Sea to the East and the North-East part of Sundaland to the South (Fig. 2) with in zone of lithospheric deformation. The Proto-South China Sea subdected below Borneo, where the Crocker Rajang mountain belt is the dominant structure formed. This mountain belt is highly complex deformed belt, runs from South-Central Sarawak to Northern Sabah. It consists of Lower Cretaceous & Tertiary, especially Eocene rocks which were formed by the subducted oceanic crust and accretionary prism of the Proto-South China Sea (Schreurs, 1996).

Structurally, the Brunei Darussalam is dominated by two synclines; the Berakas Syncline and the Belait Syncline, separated by Jerudong Anticline (Fig. 2). The study area lies in Berakas Syncline is bounded by the North-South Jerudong Anticline to the West, the Northeast and the Bandar Seri Begwan fault to the South. The older cycle occurs in the Southern part, Lumpas area, middle Miocene occupied by the Belait Formation and the youngest cycle is present in the Northern part, near the coastline, late Miocene-Pliocene, occupied by the Liang Formation (Sandal, 1996) Whereas, in between the Lumpas and the coastline, prominent ridge is formed by the Belait Formation. The Belait Formation interfingers with the setap Formation in the Western and Southern parts of the Belait Syncline. The Belait Syncline was develop in the Middle Miocene to Late Miocene and the folds are primarily a make-up of the setap shale and Belait Formation (Sandal, 1996) (Fig. 3).

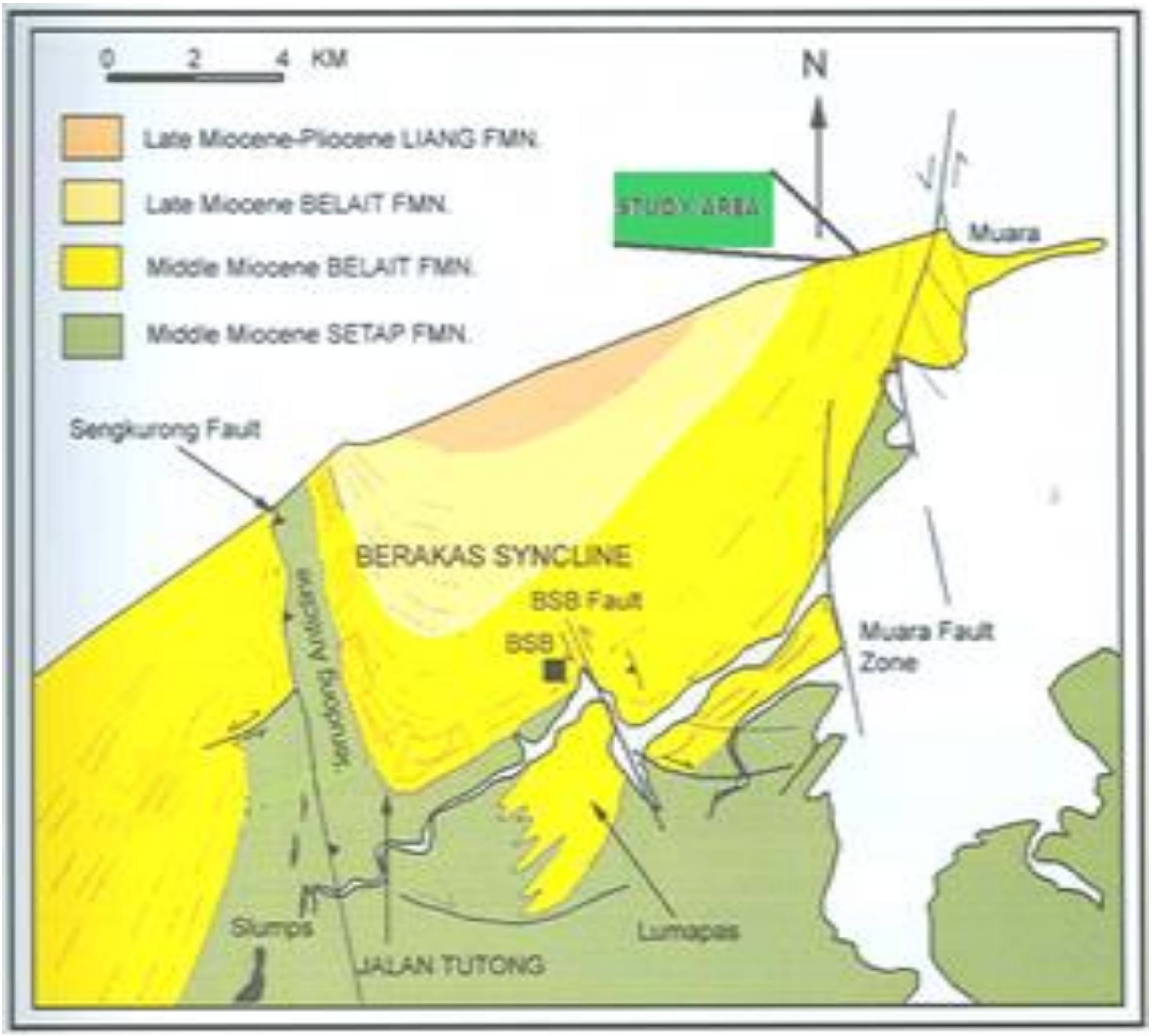


Fig. 3: The structural trend of Berakas Syncline, Jerudong Anticline and Bandar Seri Begawan (BSB) faults (Morleya *et al*., 2003)

The study area is projected to be a part of the middle Miocene Belait Formation which is time equivilant to the Miri and Setap formations in Malaysia. The middle Miocene Belait Formation is composed mainly of thick inter-bedded sandstone and clay stone. The sandstone was deposited in shallow marine environment (Sandal, 1996). This formation can reach more than 6 km of the total thickness.

DEPOSITIONAL SETTING

In term of depositional setting the studied outcrop is a modern example of the tide-dominated deltas within structurally controlled coastal embayment. This is suitable analogue for the tidal succession of the Belait Formation Previously, it was studied the Belait Formation was deposited in two depositional setting; tide- and wave-dominated environment setting (Lambiase *et al*., 2001). Tidal-dominated environment includes tidal channel, tidal bar and tidal flat sands and are associated with brakish water mudstone, tidal flat mudstone, coal fragments and coaly shale. The tidal channel and bar sands are generally contain clean and fine- to medium-grained size sandstone. The sand-rich modern facies near the mouth of the modern tidal channel are (1-1.5 m) thick and pinch out laterally (Lambiase *et al*., 2001). The sandstone is thin bedded, fine-to medium-grained sandstone with common mud drapes and lamination, current ripples and trace fossils.

Wave-dominated environment sandstones were previously interpreted as shoreface sands, which were extensively bioturbated, associated with beach, offshore

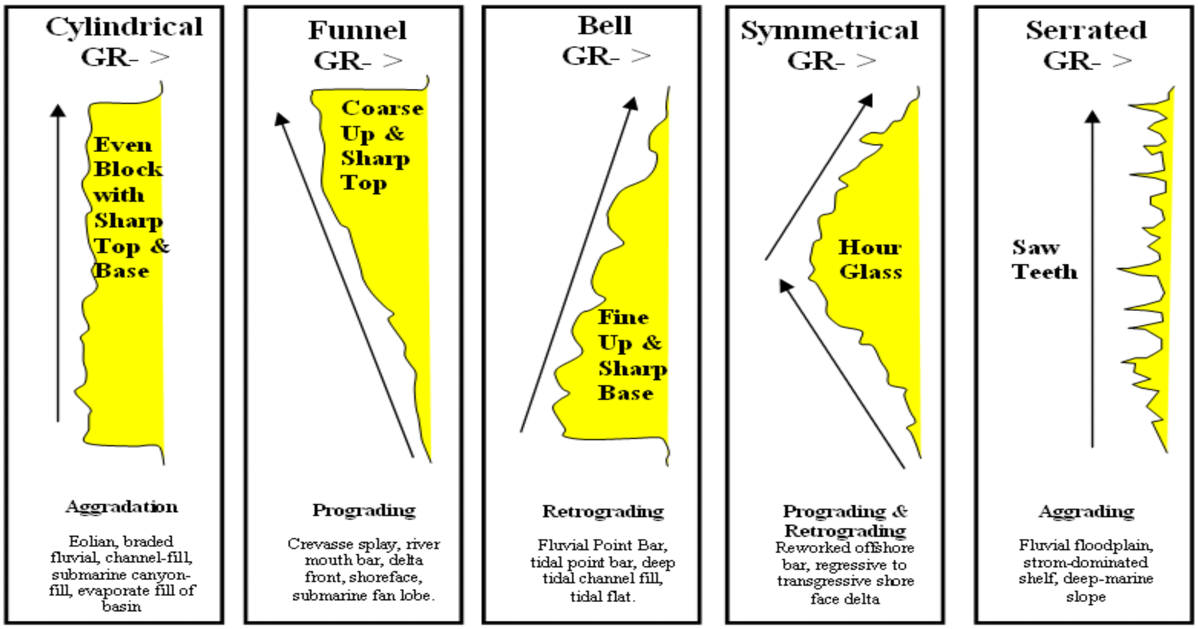


Fig. 4: The direct correlation between facies and a variety of other log shapes relative to the sedimentological relationship (Cant, 1992)

transition and shelf deposits in wave-dominated environment sandstones accumulated on the marine coastal quite far from the deltaic river mouth. The sandstone of shoreface is much cleaner then the sandstone which occurs close to a fluvial system. Where supported mud is high the sand is well-sorted and fine- to medium-grained. It has common wave ripples, wavy bedding and trough cross-bedding. In storm-dominated environment sandstone dominated by hummocky cross-stratification, parallel lamination and low angle trough cross-bedding as well as swaly cross-stratification was interpret.

METHODOLOGY

This study documents the use of outcrop Digital Gamma-ray Count and sedimentological logs for facies description to characterize depositional environment of the shallow marine Middle Miocene, Belait sandstone formation. Intensive outcrop study methods were available from previously conducted work by students of University Brunei Darussalam, for sedimentological log studies and reservoir potential on the Belait Formation (Morleya *et al*., 2003). In this study the priority was to acquire gamma-ray profiles (at scale of 5-10 cm) and re-logged of sedimentological log (at scale in cm's) of 311.8 m thick outcrop to identify the change in gamma-ray profile with comparison of different depositional environment (tide-, wave and storm-dominated environment). The gamma-ray measurements were taken at different interval depending on the variation of the lithology. A 5-10 cm scale was the general interval rate. A 20-30 cm scale was used for large cycle with no varying lithology, while, a 1-5 m scale was used for long shale section. A normal gamma-ray of 40-55 cps (a value closely figured in exposed shale section) was applied onto the gamma-ray log.

Visually checking the GR readings on the LCD display of the detector was practiced, as a method to check whether the acquired readings from the interval were within the expected limits. When the readings had exceeded the limit, a repeat measurement was made. A real anomaly would repeat while a false one would probably not (Hellenburg, 1998). The detector at the time of usage was factory calibrated. Digital detectors do not suffer from logging motion errors as the analog systems would.

From the gamma-ray log responses, measured during this study, specifically the log trend/patterns, an electrofacies approach will be developed and applied for discriminating depositional environment of the various outcrops. Electrofacies, as described by Cant (1992) (Fig. 4) are characterized and grouped into subpopulations which would provide a method for estimating the lithologic characteristics of the formation, ultimately to distinguish itself from its surroundings.

The acquired Gamma Ray total counts from the handheld detector generated an ASCII file as output, which could be downloaded to a PC via a USB cable.

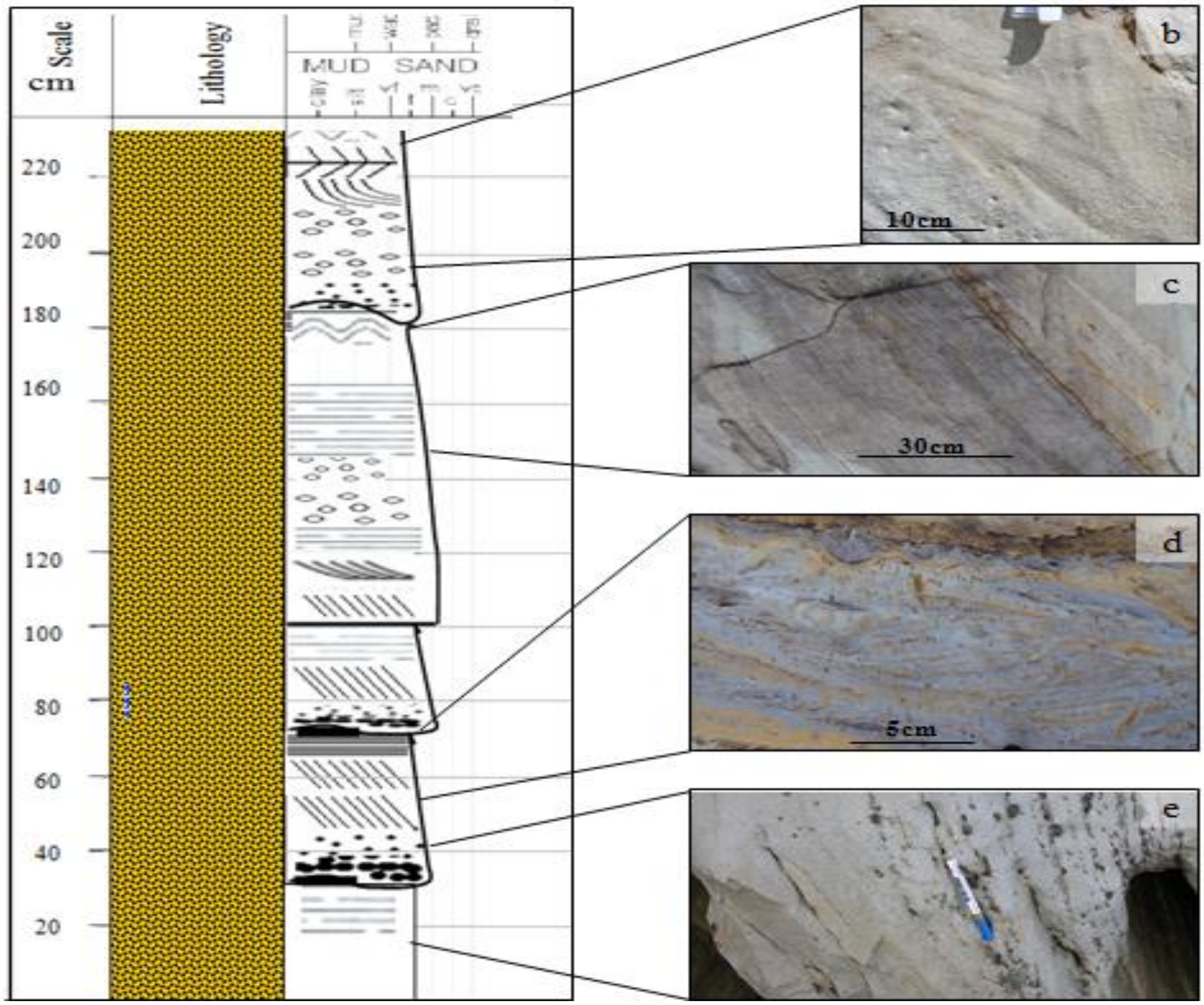


Fig. 5: a) Sedimentological log of tide-dominated environment which is characterized by b) herringbone cross-stratification, c) wave ripples, d) planner cross-bedding and e) thin parallel lamination that contain mud drapes and mud interaclasts

The numeric ASCII file was loaded and by manual graphical method (using grapher software) to produce the gamma-ray curves in counts per second (cps) cycle in a log format. Whereas, Adobe Photoshop and office word were used to generate and illustrate the sedimentology log and finally the gamma-ray log generated from IP was integrated into the sedimentology log presentation.

FACIES DESCRIPTION IN TERM OF DEPOSITIONAL ENVIRONMENT

The facies of Meragang Beach outcrop were described in terms of depositional environments. We describe the studied outcrop at Meragang Beach by detailed description of the facies, documenting all the characteristics of its lithology, texture, sedimentary structures and traces fossil which can aid in determining the processes that were dominated during time of deposition and thus, depositional environment interpretation. The characteristics of the recognized facies in the studied outcrop were resulted in determination of three dominant processes i.e. tide-, wave- and storm-dominated depositional environment. Each of these depositional environments has a unique combination of processes of sediment supply and relative change in sea-level and the products of these processes. Here the recognized facies are described in term of depositional environment.

Tide-dominated environment: The sediments deposited in a tide-dominated environment were characterized by different sub-depositional environment which includes; tidal channel, muddy tidal flat and mixed tidal flat sub-environment. The recognized tide-dominated sub-environment was based on the nature the mudstone and sandstone bodies. The tide-dominated sedimentary structures that include planar cross-bedding, trough cross-bedding, herringbone cross-stratification, wave ripples and thin parallel lamination with coal fragmented bed and carbonaceous material (Fig. 5). These structures were found in muddy tidal,

Fig. 6: a) 1 m thick tidal channel sandstone has mud intraclasts and erosional surface at top and base (pen for scale); b) the herringbone cross-stratification at the top of tidal channel about 15 cm thick; c) bioturbated fine-grained sandstone pointed by hammer, having wave ripples at the top channel; d) pinching out of tidal channel sandstone (having mud intraclasts) into the thick medium-grained sand body of upper shoreface with mud drapes (coin for scale)

mixed tidal and tidal channel sub-environment. The proportion of sediments preserved in each of the tide-dominated sub-environment is controlled by the variation in energy of the tidal current and the type of sediments which was available for transportation.

Tidal channel sub-environment: Tidal channel sub-environment occurs throughout the studied outcrop. The sandstone deposited in tidal channel is (0.8 to 4 m) thick and predominately consist of clean, fine- to medium-grained sandstone with trough cross-bedding, planner cross-bedding, wave ripples, herringbone cross-stratification contain mud intraclasts, mud drapes and carbonaceous material. The trace fossils (skalithos), coal clasts and thin lamination were occurred seldom.

The tidal channel sandstone deposited, which is about 2.5 m thick, predominately consists of very fine- to medium-grained sandstone with four channelized sets. The base of each tidal channel is marked by an erosive surface that cuts downward into sandstone having mud intraclasts (1-3 cm). The mud intraclasts are rounded and elongated (Fig. 6a) which overlain by a fining-upwards sandstone interval with planner cross-bedded with an angle of 30º-45º. Mostly all tidal channel base shows mud drapes with planner cross-bedding and parallel thin lamination structures. In some rare case, tidal channel sandstone was identified with the structure of herringbone cross-stratification, which was about 15 cm thick with an angle of 40o from the bedding plain (Fig. 6b). The herringbone cross-stratification is the characteristic of tidal sedimentation, but is not found in all instances.

The tidal channel sandstones also which occurs with three vertically amalgamated channels. The sandstone at the top of each channel composed of small wave ripples and small bioturbated sandstone large traces fossils (which was some what simple straight tube of skalithos) about 1-2 cm in length (Fig. 6c). Some of the channels deposited are pinching out into thick sand body of upper shoreface sandstone (Fig. 6d).

Muddy tidal flat sub-environment: The sediments deposition in muddy tidal flat in the studied outcrop are characterized by area of inter-tidal mudflats that are covered at high tide and exposed at low tide at the time of deposition. Generally, in the outcrop where muddy tidal flat sediment was deposited are characterized by thin bedded (2-10 cm) fine- to occasionally medium-

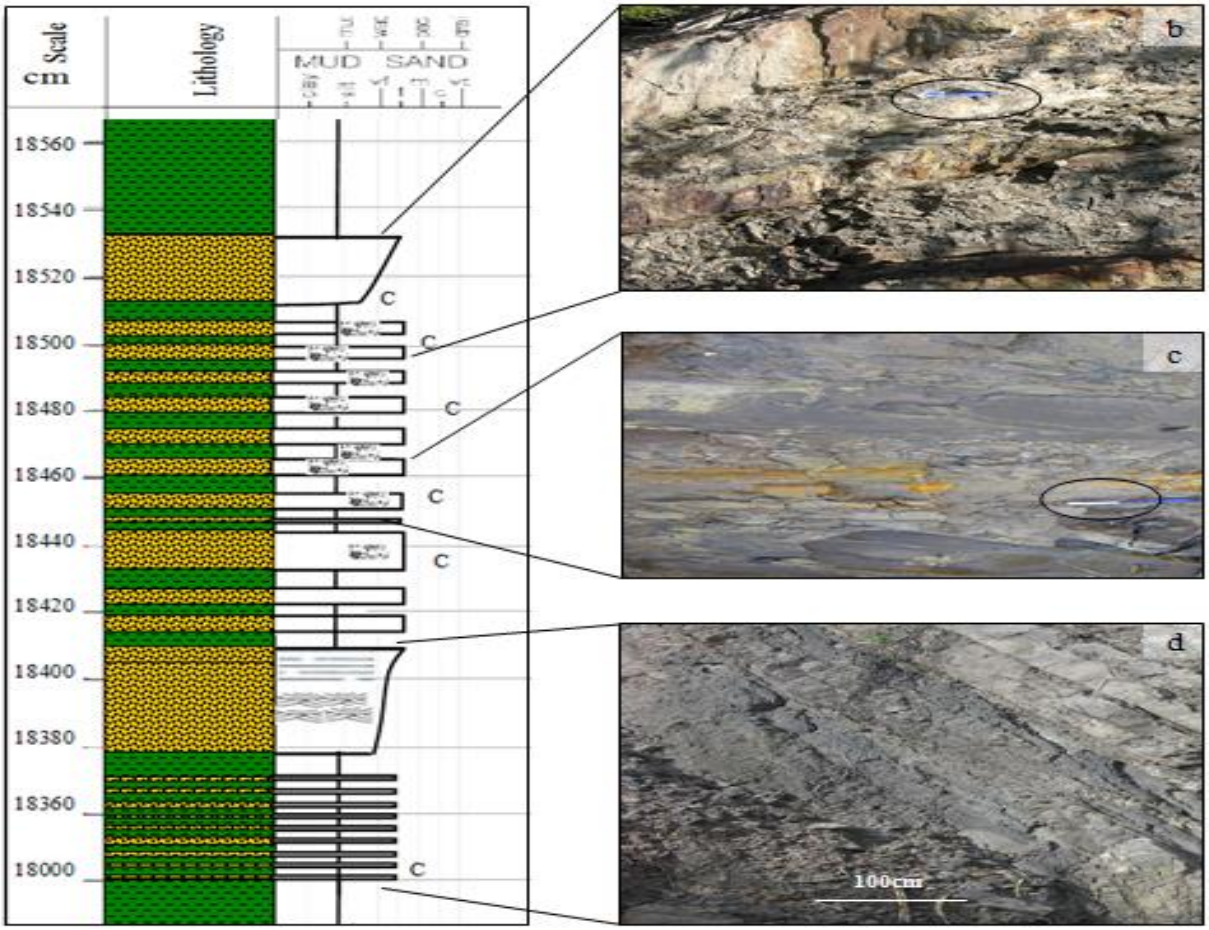


Fig. 7: a) Sedimentlogical log of muddy tidal flat sediment b) thin bedded fine to occasionally medium-grained sandstone and mudstone c) very fine-sandstone and mudstone and d) thick muddy deposited (2-10 cm)

Fig. 8: The photo of muddy tidal flat consists of interbedded sandstone and mudstone with no structure identified due to weathered rock

Fig. 9: The photo of muddy tidal flat with sand-mud intercalation mostly covered by thick recent vegetation

Fig. 10: The photo shows the muddy tidal flat in middle of cycle 12 with small wave ripples

grained sandstone that intercalated with mudstone (Fig. 7). Individual muddy tidal flat generally is less than 3 m thick of interbedded very fine-grained sandstone and mudstones (Fig. 8 and 9). Sedimentary structures include thin lamination with carbonaceous material, small wave ripple and current ripple (Fig. 10).

Mixed tidal flat sub-environment: The mixed tidal flat are deposited when the fluvial and marine influence both act in short period of time to deposit sediments. The mixed tidal flat in the studied outcrop is sandy to silty sandstone, intercalated with muddy to fine-grained sandstone. The structures identified in this sub-environment are small wave ripples and parallel thin lamination with coal fragments. (Fig. 11), planner cross-bedding (Fig. 12) and rarely small scale trough cross-bedding about 0.5 cm in length and width (Fig. 13). The mixed tidal flat are mostly underlain by the muddy tidal flat or offshore mudstone and overlain by the tidal channel.

Wave-dominated environment: In the studied outcrop succession, wave-dominated sequence is generally coarsening upward from very fine- to coarse-grained sandstone. The thickness of wave-dominated depositional sandstone varies from 1-5 m in upper shoreface to lower shoreface. Generally, the structures identified in wave-dominated sandstone from lower shoreface to upper shoreface were wave ripples, thin parallel lamination with mud drapes from 0.1 to 0.5 cm, planner cross-bedding (about 5 to 40 cm thick), wave ripples in small scale to large scale, trough cross-bedding (3-60 cm thick) and highly bioturbated (skalithos) sandstone (2-25 cm in length), Fig. 14.

Storm-dominated environment: In the studied outcrop Hummocky Cross-Stratification (HCS) was one of the characteristics that are distinctive in form as compare to other depositional environment sandstone. It was consisting of rounded mounds of sandstone from 0.2 to 1 m thick swaly part with normally fine-to medium-grained sandstone. This HCS was not seen in shoreface deposits above fair-weather wave base, so this characteristic form of cross-stratification was found

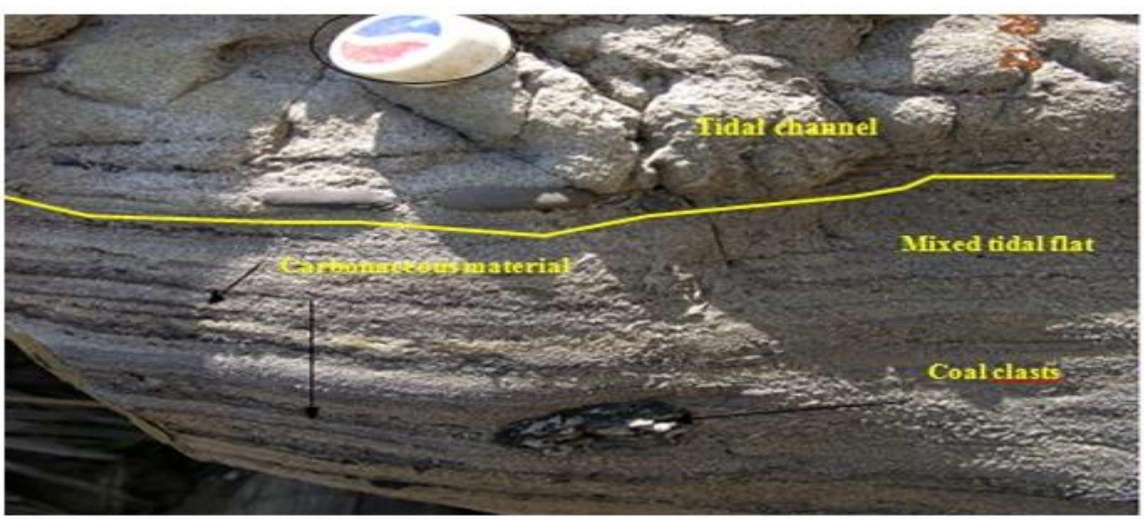


Fig. 11: This photo shows the thin laminated and coal fragment lamination mixed tidal flat with fine- to medium-grained sandstone in cycle 7 and the line shows that the mixed tidal flat overlain by tidal channe

Fig. 12: The photo shows the mixed tidal flat in cycle 13 with carbonaceous material, planner cross-bedding and water seepage

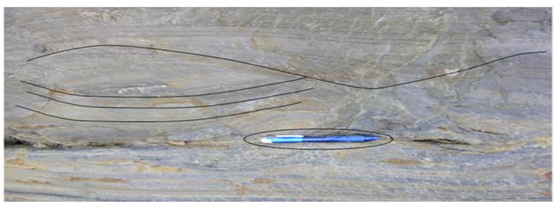


Fig. 13: The photo shows trough cross-bedding that was observed in mixed tidal flat, underlain and overlain by thin lamination of silty mud with well-sorted sandstone grains

in lower shoreface and upper shoreface of storm-dominated environment. The structures identified were dominated by HCS (0.8 m thick), (Fig. 15), trough cross-bedding (20 cm thick), (Fig. 16), wave ripples, thin lamination and tangential cross-bedding about 10º with overlain bed (Fig. 17). The storm-dominated environment sandstone is underlain by offshore mudstone and overlain by muddy tidal flats or tidal channel.

GAMMA RAY (GR) TREND AND DEPOSITIONAL ENVIRONMENT

Gamma ray trend in tide-dominated environment: The GR trends, in the studied outcrop of tide-dominated environment are characterized by different shapes including; blocky left-boxcar shape, funnel-shape coarsening upwards trend, bell-shape fining upward and irregular trend. Under the acquired sampling rate, the trend is spiky over the alternating channel top and base. The tide-dominated depositional environment in terms of GR trend is sub-divided into tidal channel, muddy tidal flat and mixed tidal flat.

Gamma ray trend in tidal channel: The gamma ray trend in tidal channel sand bodies shows three different shapes, i.e. funnel shape (coarsening upward) trend shows that the GR value gradually decreasing upward

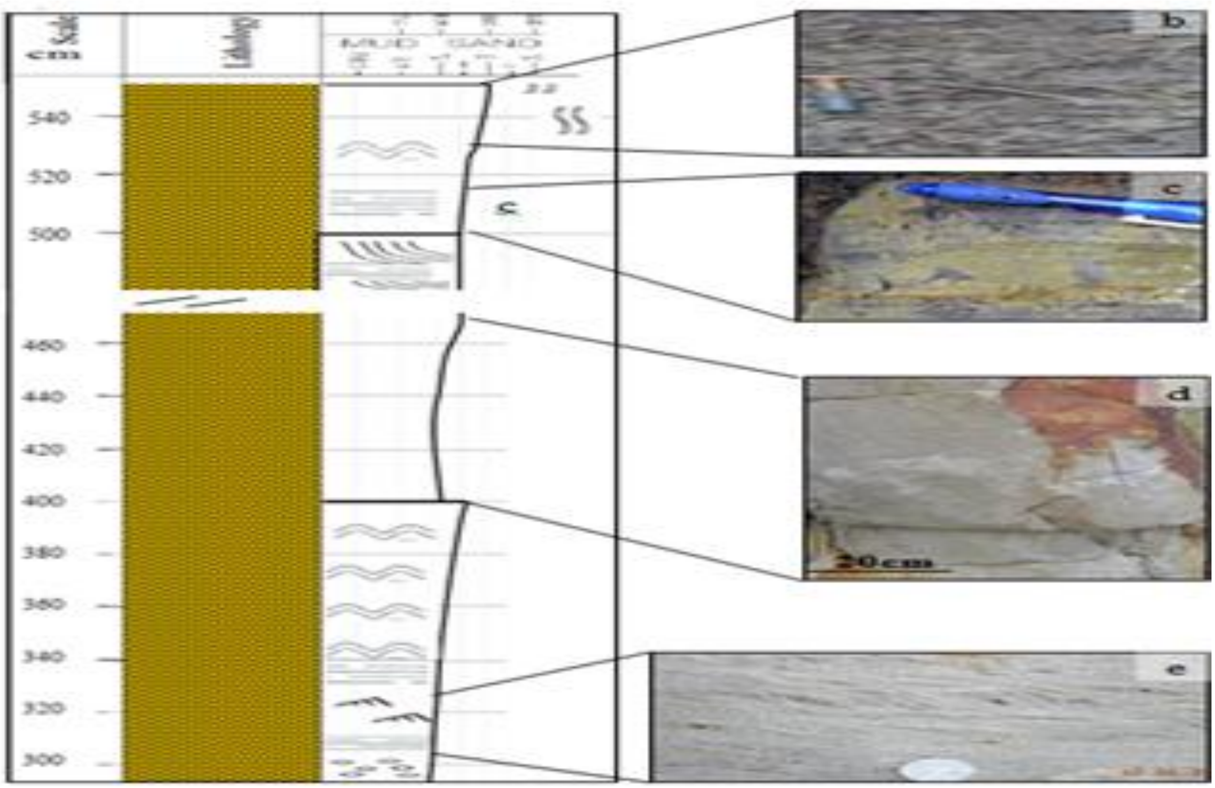
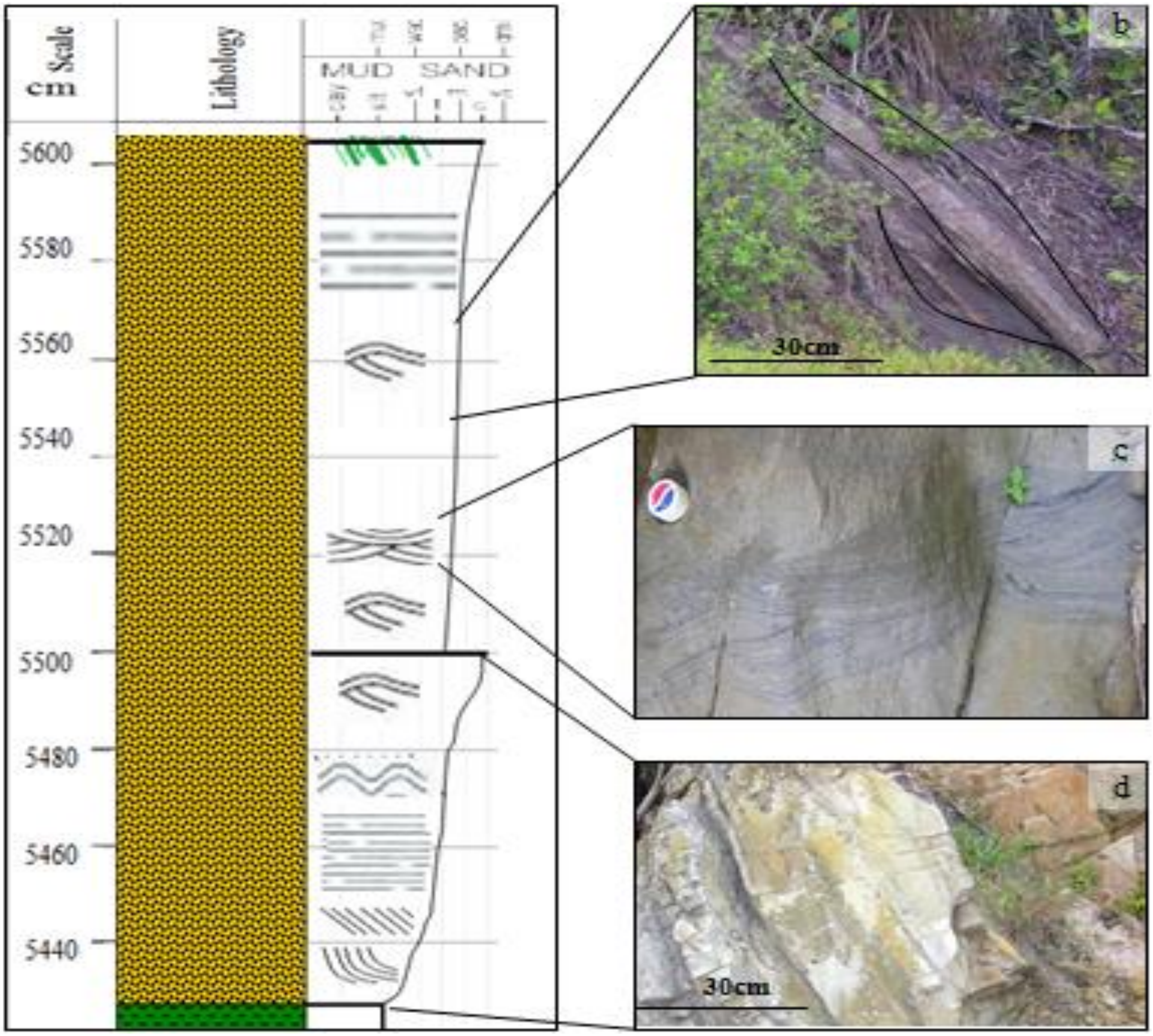


Fig. 14: a) Sedimentological log of wave-dominated environment sandstone with b) bioturbation, c) thin parallel lamination with carbonaceous material d) weathered oxidized sandstone and e) wave and current-ripples structure



15: a) The 6 m thick sandstone sequence shows the storm-dominated environment which underlain by tidal channel and overlain offshore mudstone. The structures identified were a) HCS, b) trough cross-bedding and c) HCS, wave ripples and parallel thin lamination

Fig. 16: The photo shows the HCS about 0.8 m think in cycle 3 covered by recent vegetation, overlain by muddy tidal flat and underlain by offshore mudstone. This characteristic was only observed in sandstone deposited in lower shoreface and upper shoreface

Fig. 17: The photo show the trough cross-bedding in storm-dominated environment (20 cm in length and 8 cm in width) with fine-grained sandstone

with progradational parasequences and ranges from 10-25 cps. (Fig. 18a), bell shape (fining upward) trend shows tidal retrogradational parasequences sets, that the GR gradually increasing upward. The bell shape is

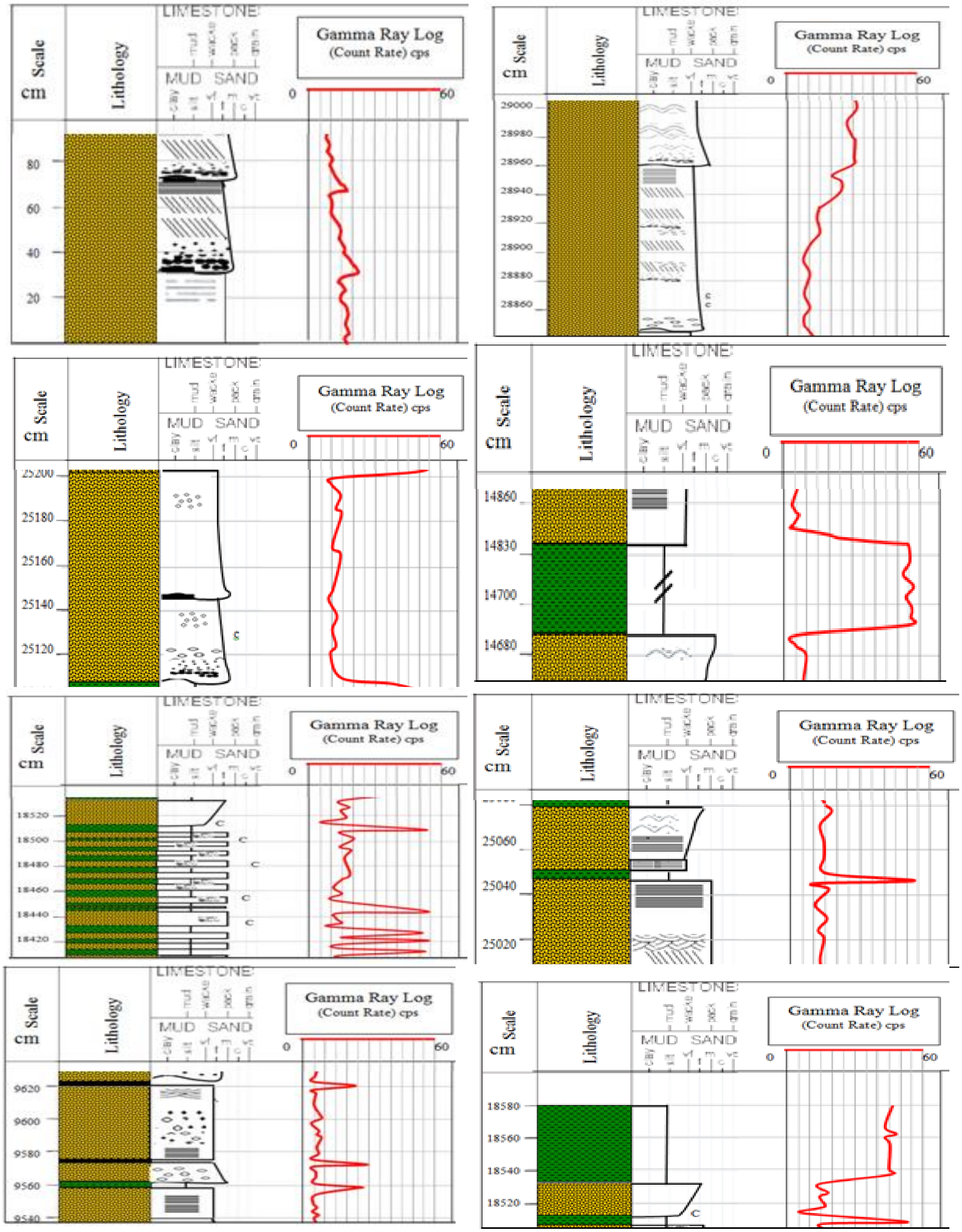


Fig. 18: The logs shows a) gradually decreasing GR trend (coarsening upward, funnel shape) of tidal channel sand bodies b) gradually increasing upward GR trend (fining upward, bell shape) of tidal channel sandstone c) blocky left-boxcar GR trend of tidal channel sandstone d) right-boxcar GR trend/shape of muddy tidal flat sub-environment e) irregular (serrated) GR trend/shape of muddy tidal flat sub-environment f) bow-shaped GR trend in mixed tidal flat sub-environment g) irregular, serrated GR trend in mixed tidal flat sub-environment h) left boxcar GR trend with internal irregularities in mixed tidal flat sub-environment

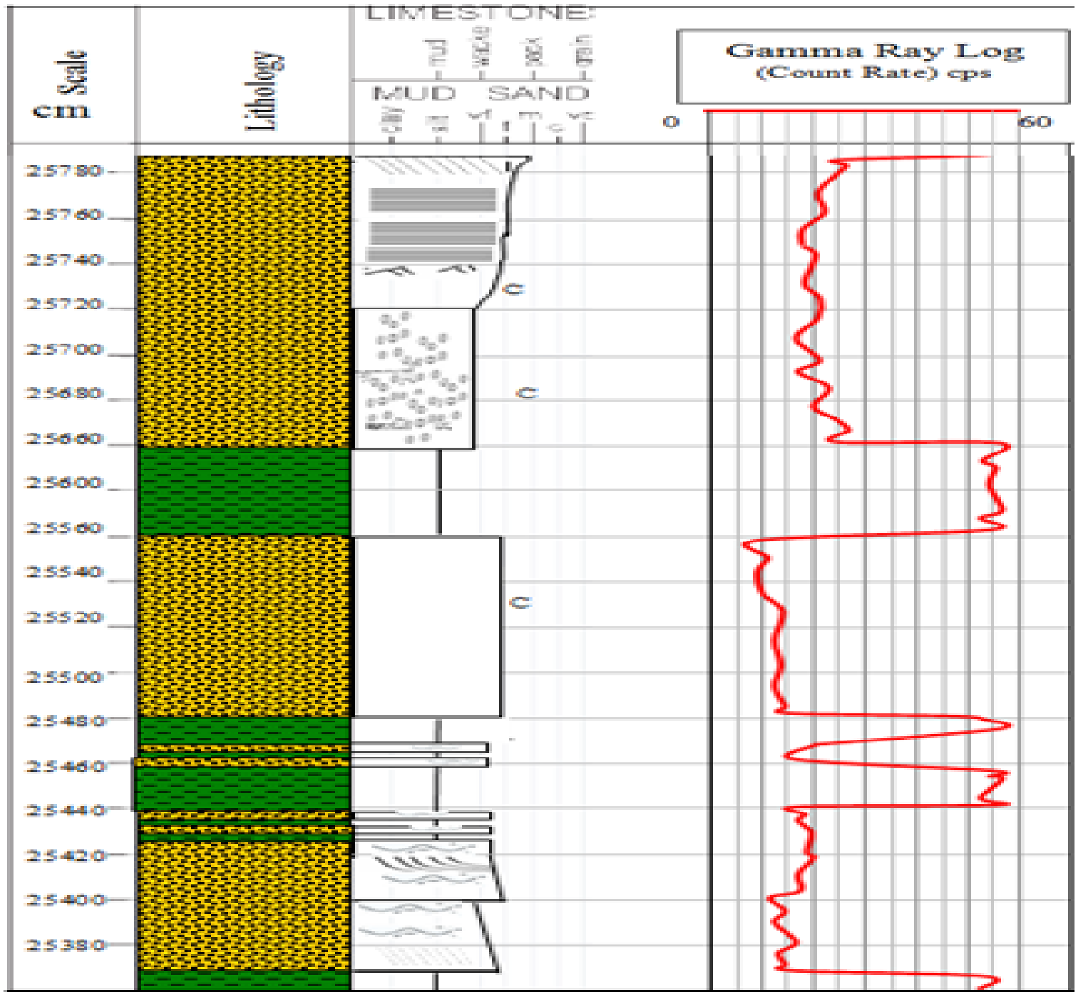


Fig. 19: The log shows the example of left boxcar GR trend with internal irregularities in wave-dominated environment of shoreface (upper shoreface to lower shoreface)

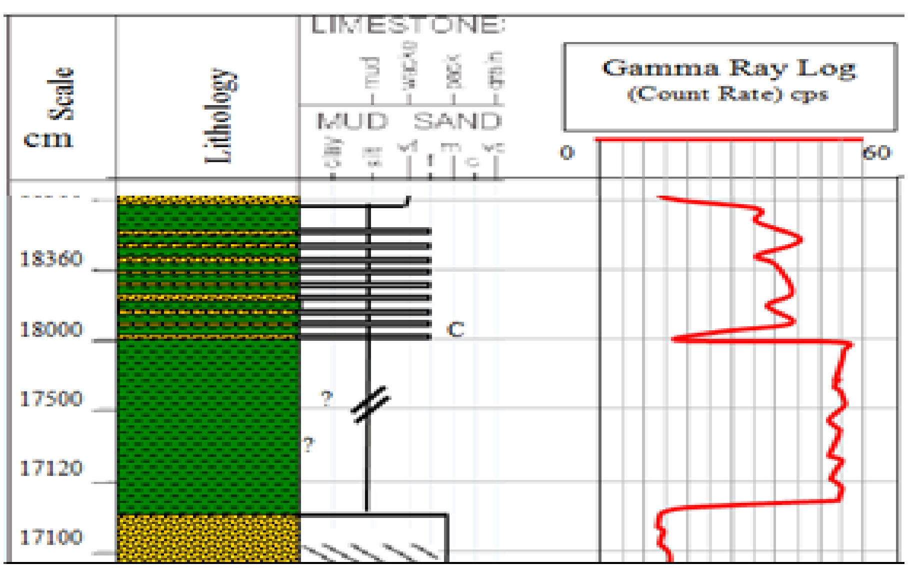


Fig. 20: The log shows the example of right boxcar GR trend with very small internal irregularities in wave-dominated environment of offshore mudstone and offshore transition. This trend is observed though out the cycles

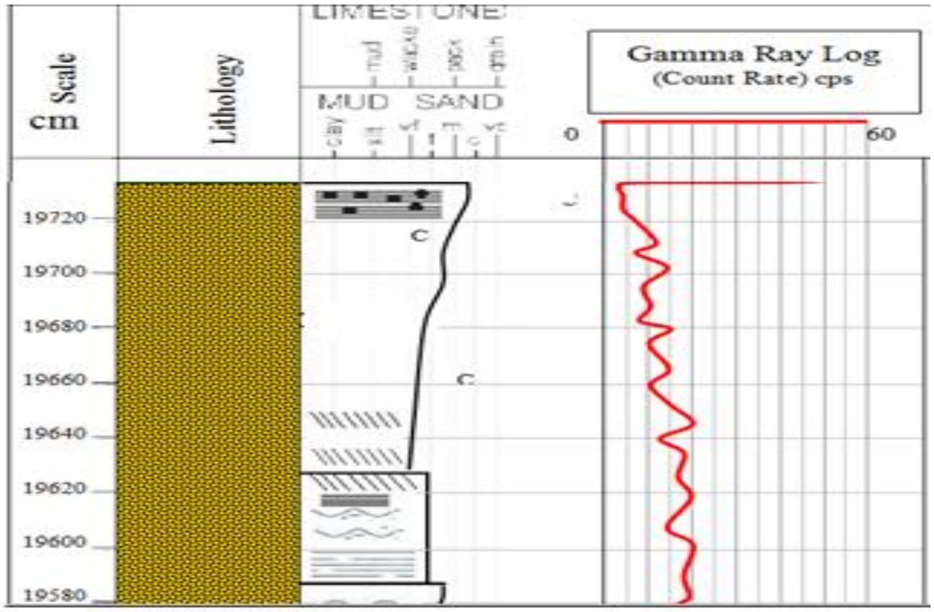


Fig. 21: The log shows the example of gradually decreasing GR trend (coarsening upward, funnel shape) in wave-dominated sandstone of lower shoreface

observed in the tidal channel sand bodies with GR ranges from 5-35 cps (Fig. 18b). Blocky left-boxcar trend reflects the tidal aggradational sandstone bodies which usually show low gamma ray value with sharp upper and lower end due to erosional bases truncate the underlying mudstones cause the sharp basal boundary (Fig. 18c).

Gamma ray trend in muddy tidal flat: The GR trend in muddy tidal flat in the studied outcrop shows two different trend/shape; i.e., right boxcar and irregular serrated trend. Right Boxcar (RB) trend represents high GR reading, having sharp boundaries and no internal irregularities. For instant, in muddy tidal flat this trend is observed (Fig. 18d) with GR value ranges between 50-57cps. Whereas Irregular (serrated) trend represents GR with a serrated trend, usually at intermediate GR reading, is observed in muddy tidal flat (Fig. 18e), with GR values fluctuate from alternating high and low value (10-50 cps).

Gamma ray trend in mixed tidal flat: The GR trend in mixed tidal flat sub-environment shows three different trends i.e. bow-shaped, irregular (serrated) and left boxcar. Bow-Shape represents the GR trend with one or more sharp right pecks. For instant this shape of mixed tidal flat is observed (Fig. 18f) with high value of GR (40-55 cps). The Irregular (serrated) trend represents GR in mixed tidal flat which does not exhibit any systematic changes in either ends of the base line. This trend is observed in the mixed tidal flat (Fig. 18g) with GR value ranges from 5-30 cps. Whereas left boxcar trend reflects the same trend as in tidal channel sand bodies, but in mixed tidal flat the GR value fluctuates with in the trend with small sharp right peaks (Fig. 18 h). The GR value varies in the between 10-40 cps.

Gamma ray trend in wave-dominated environment: The GR trends in the studied outcrop of wave-dominated environment are geometrically complex pattern as compare to the tide- and storm-dominated environment, owing to the occurrence of variable which is influence by the variation in shale content by inferring a relationship in grain size changes. The principal GR trend observed in wave-dominated environment are left boxcar, right boxcar, funnel shape and irregular trend.

The left boxcar trend represents low GR reading (4-10 cps) with some internal irregularities or changes. For instant, massive sandstone layers are seen in shoreface sandstone (upper shoreface, middle shoreface and lower shoreface) which shows left boxcar trend (Fig. 19). The right boxcar trend represents high GR reading, sharp boundaries and with very small internal irregularities or changes.

This GR trends are clearly seen in offshore mudstone and offshore transition (Fig. 20) with GR value ranges from 45-57 cps. The funnel shape (coarsening upward trend) represents GR gradually increasing upward trend, which is similar to that of tidal channel coarsening upward trend. This trend is observed from lower shoreface to upper shoreface (Fig. 21). Whereas irregular (serrated) trend represents the fluctuated GR reading with high and low values, from 20-50 cps in offshore transition and rare variation

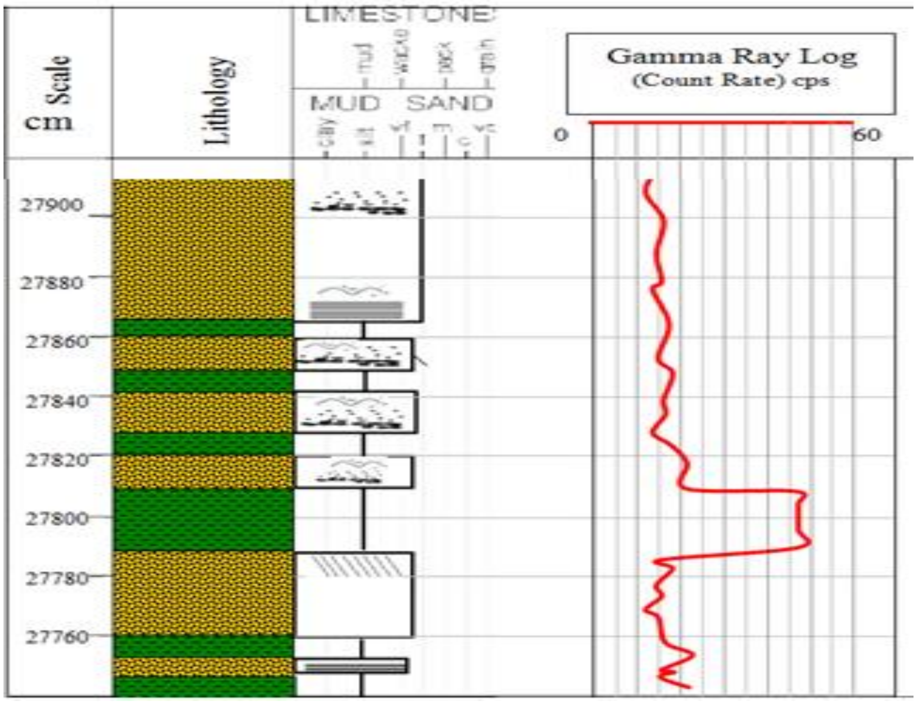


Fig. 22: The log shows the example of irregular, serrated GR trend of offshore transition and upper shoreface sandstone

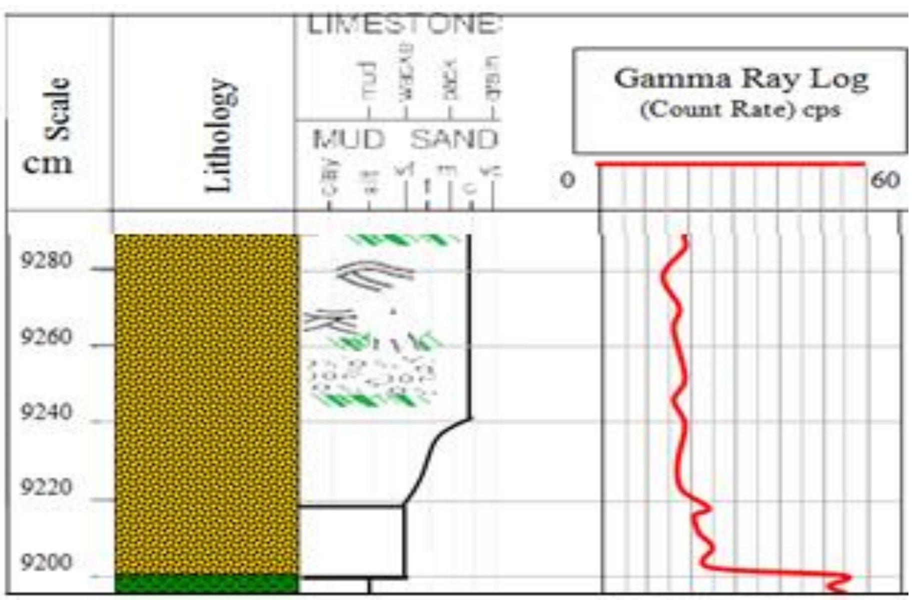
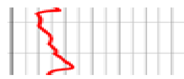
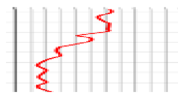
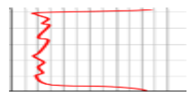
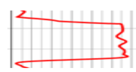
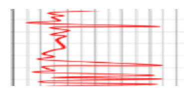
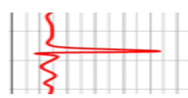
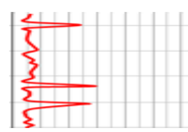
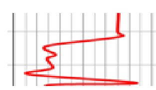
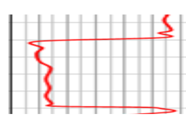
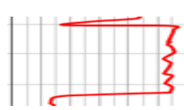
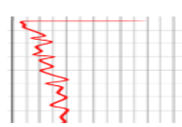
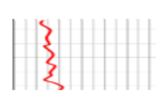
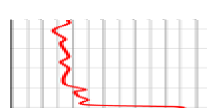


Fig. 23: The log shows the example of left boxcar GR trend having less sharp edges with storm-dominated environment of lower shoreface

GR from upper shoreface to lower shoreface (4-20 cps) (Fig. 22).

Gamma ray trend in storm-dominated environment: The storm-dominated sandstone is characterized only with left boxcar GR trend. This trend, (as compare to left boxcar trend in tide and wave-dominated environment) shows no sharp edges on the top and bottom. The GR value fluctuates between 10-30cps (Fig. 23).

Table 1: Summary of gamma-ray trends and depositional environments

Depositional Environment		GR Trends	GR Shape (examples) 0 — 60	Average GR value	Litho logy and Facies	Figure #
Tide-dominated	Tidal channel	Coarsening upward/funnel shape		10-25 cps	Sandstone with poorly sorted grains having mud intraclasts, planner cross-bedding and erosional base.	18a
		Fining upward/bell shaped		05-35 cps	Fine grain at the base with mud drapes and carbonaceous material fallowed by very fine-grained with planner cross-bedding and thin lamination	18b
		Blocky left boxcar		5-10 cps	Equally distributed grain with fine- grained coal fragmented thin lamination with small mud drapes	18c
	Muddy tidal-flat	Right boxcar trend		50-57 cps	Highly vegetated/mudstone having silt size particles with no internal structure	18d
		Irregular/serrated trend		10-50 cps	Very fine to silty-grained size particles with thin laminated muddy coal fragmented intercalation with silty sand	18e
	Mixed tidal-flat	Right bow-shape		Varies	Forms in between sand bodies with medium- to coarse-grained. Within bow shape there is no internal structure, only muddy deposit	18f
		Irregular/serrated trend		5-30 cps	Thin laminated bed with uniform intercalation of sandstone and mudstone having small scale trough cross-bedding, mud drapes and mud intraclasts	18g
		Left bow-shape		40-55 cps	Mostly unidentified structures with very fine- to fine-grained sandbody in between thick muddy deposit	18h
Wave-dominated	Upper shore face to lower shore face	Left boxcar trend		4-10 cps	Deposited with very fine- to medium grained sand bodies with thin lamination, wave ripples, planner cross-bedding, ripple marks and small scale trough cross-bedding	19
	Offshore mudstone and offshore transition	Right boxcar trend		45-57 cps	Mostly vegetated and having silty size to clay size particles with no internal structures	20
	Lower shore face	Coarsening upward/funnel shape		10-20 cps	Very fine-to coarse-grained sand bodies with small scale wave ripples fallowed by low angle planner cross-bedding and coal laminated moderately sorted grains	21
	Offshore transition and upper shore face	Irregular/ serrated trend		20-50 cps 04-20 cps	Mostly muddy offshore deposits with few small scale thin laminated wave ripples	22
Storm-dominated	Lower middle shore face	Left boxcar trend		10-30 cps	Very fine-to very coarse-grained moderately sorted hummocky cross-bedding, trough cross-bedding and water wet sand with mud drapes	23

DISCUSSION

The GR log is commonly used by the geologist to distinguish different sedimentary environments as the fining and coarsening upward cycles are often related to changes in grain-size and clay contents (Cant, 1992). However, this grain-size relationship is often highly variable and rarely straight forward (Rider, 1996). In order to test the relationship between grain-size, lithology and total gamma-ray count measured in the Belait sandstone formation, we study the detailed section of each depositional environment (tide-, wave- and storm-dominated). When plotted as adjacent vertical profiles, grain size and GR reveal a broadly similar character as with the sedimentological logs of each of three depositional sandstone (Fig. 18-23), with a general relationship of increasing grain-size with decreasing GR (decreasing total count rate, cps).

In the studies outcrop the log shapes are geometrically complex log patterns, which occur in all lithologies, bearing many forms/shape/trends and occurring at varies scales (Table 1). The principle shapes in the studied outcrop take the form of the bell (fining upward), funnel (coarsening upward) blocky (cylinder) and irregular (serrated). With GR log being an indicator of clay contents; its log shape is influenced by the variation in shale content by inferring a relationship in grain-size change, where increasing shale from clean sands corresponds to decrease in grain size (Rider, 1996). However, this is not always the case, for instant, coarse sand containing shale; rip-up mud clasts may give a high GR reading (Fig. 18a).

Interpretation of the depositional environment in the study area is made based on facies architecture and the GR electrofacies analysis to evaluate and investigate whether significant geological information, especially depositional environment, can be determined from the GR response (Table 1).

Usefulness of GR log trends/ shapes in depositional environment: The building of vertical succession for electrofacies or GR log shapes can be interpreted in terms of possible depositional environments. The electrofacies, therefore, consists of a set of log trends/shapes indicating succession of sedimentological facies and depositional environments. The gamma ray logs and lithological columns of the study area are classified into three depositional environments with seven basic log trends. This shows centimeter by centimeter correlation of the lithology and log trends.

Funnel shape: When the GR values decreases upward consistently from maximum value, usually indicating decreasing shale content, it forms funnel shape or coarsening upward trend. This shape related to a transformation from shale to shale-free lithologies due to upwardly increasing depositional energy (not always). For instant, in the studies outcrop, this shape are formed in tide-dominated (tidal channel) and wave-dominated (lower shore face to shoreface) environment (Table 1). Although the shape is same, but facies are different that is favorable to each of the depositional environment. The base of tidal channel sand bodies deposited mud interaclasts with erosional base poorly sorted sandstone which gives high GR (<25 cps) count as compare to low-energy upward increasing planner cross-bedding, which results in decrease GR (>10cps) count to form funnel shape (Fig. 18a). Whereas, in lower shoreface of wave-dominated sand body, GR value gradually decreases (10-20cps) from small scale wave ripples to moderately-sorted coal fragmented large scale sandstone at low energy deposit result with same funnel shape.

Bell shape: This shape formed by the increasing upward consistently from a minimum GR values usually indicate an increasing in shale content. For instant, bell shape or finning upward trend are formed in tide-dominated (tidal channel) which corresponds to a retreating shoreline-shelf system with decreasing energy. This can related to a gradual upward change in the clay minerals due to lithological changes shifting from sand to shale, or upward thinning of sand beds (Fig. 18b).

Blocky left boxcar: It is a low GR cycle, usually within high GR zone, which has a relatively constant gamma reading. In the studied outcrop it forms in all of the depositional environment i-e. Tide-dominated (tidal channel), wave-dominated (upper-lower shoreface) and storm-dominated (lower middle shoreface). In tidal channel this shape reflects the tidal aggradational sand bodies which usually show low GR values with sharp upper and lower end due to erosional bases truncate the underlying mudstones cause the sharp basal boundary with in cross-bedding structures (Fig. 18c). In wave-dominated environment left boxcar shape represents low GR reading (4-10 cps) with some internal irregularities as compare to tide-dominated tidal channel sandstone. For instant, in wave-dominated environment, massive sandstone layers with wave ripples graded upward into small current ripples and thin laminated beds are recognized in upper shoreface to lower shoreface under below fair weather condition, shows left boxcar shape/trend (Fig. 19). Whereas, in storm-dominated environment, this trend shows no sharp edges on the top and bottom with GR bit higher (10-30 cps), as compare to tide- and wave-dominated left boxcar trend.

Right boxcar: It is a high GR usually in shelly formation, which has a relatively gamma reading. The boundaries with the overlying and underlying reading are abrupt. It formed in tide-dominated (muddy tidal-flat) mudstone, having no internal irregularities and GR ranges from 50-57 cps. Whereas, in offshore mudstone it form sharp boundaries with very small internal irregularities or changes as compare to tidal channel sandstone. The GR trend of this shape are clearly seen in wave-dominated offshore transition and offshore mudstone, ranges from 45-57 cps. In addition to that, in term of facies, it forms with rare small wave ripples,

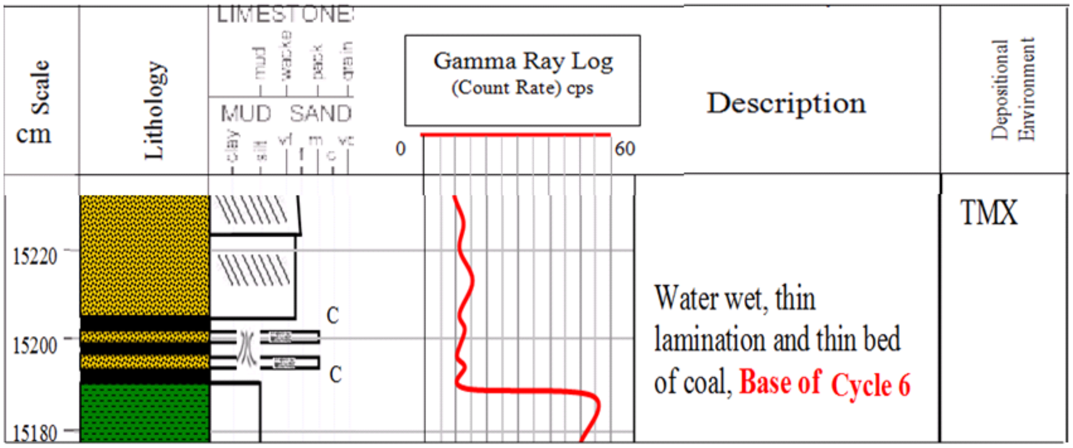


Fig. 24: The log shows the GR log reading over the thin sandstone beds of cycle 6 of the Meragang outcrop which is less than 5 cm and does not able to describe the change in GR trend

mostly in very low energy or with no internal structure with clay size particles (Fig. 18d and 20).

Irregular trend: This trend represents the fluctuated GR reading with high and low values. For instant, this trend was formed in tide-dominated (muddy tidal flat); usually at intermediate GR reading fluctuating from alternating high and low values (10-50 cps) with thin laminated sand mud intercalation having rare planner cross-stratification. Whereas, in mixed tidal flat the GR doesn't exhibit any systematic changes in either end of the base line (Fig. 18e), but GR fluctuating is smaller (5-30 cps) than muddy tidal flat with medium-grained tabular cross-bedding and thin stratification of coal (Fig. 20). This trend also forms in offshore transition and upper shoreface of wave-dominated environment with GR ranges from 20-50 cps and 04-20 cps with in small wave ripples and mud interaclasts. This concludes that the main difference between the tide- and wave-dominated depositional environments is the fluctuating GR values.

Bow shape: This shape is developed by a cleaning upward overlain by dirtying-up trend of similar grain-size and with no sharp breaks between the two, shows left box shape. The opposite of this, the trend is right bow shape. In the studied area this bow shape is seldom. However, this trend form in tide-dominated (mixed tidal flat) environment with one or more sharp left or right peaks. The GR range is in between 40-55 cps with no internal sedimentary structures.

LIMITATION

Gamma ray reading in the studied outcrop was taken at the interval of 5-10 cm, which was the minimum range of instrument that can give the variation between changes in sedimentation. Those, beds which were less than 5 cm were not able to describe the change in GR trend through this instrument. For instant, in some of the succession the interbedded sandstone and mud were about 1-3 cm thick deposited mixed tidal flat and muddy tidal flat sandstone (Fig. 24), here it's quite difficult to identify the depositional environment through GR log trend. So it is not realizable in case of less than 5 cm.

CONCLUSION

Detailed sedimentological study and gamma ray log analysis of the Meragang Beach Outcrop provides an improved need to our understanding of tide-, wave- and storm-dominated environment and its lithological distribution with in the framework in order to predict the reservoir heterogeneity in terms of sandstone quality. The impact of gamma ray log trends on each depositional environment leads to the following conclusions:

- The depositional system and facies distribution suggested that the studied outcrop sandstone deposited in tide-, wave- and storm-dominated environment
- The gamma ray trend in each depositional environment shows different shape/trend that may be similar with in two depositional environments i.e., in tide-dominated environment; blocky left boxcar, funnel shaped, bell shaped, right boxcar and irregular, in wave-dominated environment; left and right boxcar, funnel shaped and irregular and in storm-dominated environment only left boxcar
- The changes in gamma-ray profile with in the sandstone depend upon the environment in which the sand body deposited that reveal in reservoir heterogeneities in subsurface well correlation.

The outcrop gamma-ray is limited to measure above 5 cm beds with portable gamma-ray logging tool otherwise it may loses the accuracy to differentiate the lithology and its radioactive minerals.

Key for Sedimentological logs:

	Wave ripples large scale		Hummocky cross-stratifications (HCS)
	Current ripples	SW	Swaley cross-stratifications (SWC)
	Tangential cross-beddings (TCB		Planar laminations
C	Small coal fragments		Planner cross-bedding (PCB)
	Highly bioturbated		Small bioturbation
	Pebble quartz		Low-angle trough cross-bedding (TCB)
	Erosional base		Herringbone cross-stratification (HCS)
	Small lanticular wave ripples		Large high angle trough cross-bedding (TCB)
	Coal thin bed		Large fragment of coal with in thin parallel lamination
	Mud drapes		Mud intraclasts
	Thin parallel lamination		Mud cracks

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