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Research paper

Integrated Approach to Delineate Meandering Channel Sands as Potential Stratigraphic Traps

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Abstract

After a half century of exploration, the Malay Basin, a mature hydrocarbon province in SE Asia, faces common challenge that most of the conventional structural reservoirs have been drilled out. As a result, the high-risk stratigraphic traps are considered as viable alternative to boost the dwindling oil reserves. In Y field, the discovery of Early Miocene Group I meander belt channel sands outside the low-relief anticlinal closure is seemed to have made substantial contributions to the later oil production. This sparks the inspiration to develop a practical workflow in visualizing the subtle, yet productive channel systems through integration of multidisciplinary datasets. Results have proven that the co-rendering of multi-attributes could effectively delineate the channel edges and reflection strength of sand bodies. Moreover, through the application of neural network techniques on the extracted waveform shape of seismic attribute, a supervised hierarchical lithofacies map was generated. This can help to create a better linkage between the seismic waveform patterns and lithological details of subsurface features. Wireline log analysis was also performed to verify the hydrocarbon potential of Group I sands. This integrated approach may adopted as a reliable best practice in near-field exploration program, especially in proving up the channel-sand stratigraphic play.

Keywords: *channel delineation; Malay Basin; seismic geomorphology; stratigraphic traps; waveform-based facies*

1. Introduction

The Malay Basin, a Tertiary oil and gas province, is located in the south of the Gulf of Thailand, between Vietnam and Malaysia. It is an elongated NW-SE intracontinental extensional basin (500 x 250km) and covers a total area of ca. 80,000km^2 [1, 2]. Since 1970's, exploration efforts in the Malay Basin were directed towards the more obvious structural traps such as compressional anticlines and fault-dip closures. However, to boost the dwindling oil reserves, therein, lies an urgent need to further explore on the yet-to-find resources in the mature Malay Basin. This has resulted in renewed interest by the petroleum industry to focus the "subtle" and higher risk stratigraphic play as the most viable solution to find additional reserves or resources to maintain production rate. However, not much studies have been carried out in identifying and drilling of stratigraphic traps in Malay Basin as compared to the structural traps. Since 1999, the drilling of stratigraphic traps was focused only on the NE flank of the basin, for instance channel plays in Bindu field [1].

The Y field, an oil-and-gas cluster field in SW part of Malay Basin, is established as a low-relief, NW-SE trending anticline. The N anticlinal closure accounts for most of the early production. The discovery of Early Miocene Group I meander channel systems in recent year resulted in a major boost in oil production in Y field. Hence, it is deemed worthy to carefully delineate the Group I meander channel systems in the form of prospective stratigraphic traps for future exploration drilling.

This accounts for the lack of research that discusses in detail the approaches in delineation and evaluation of deeper, older-aged than Oligocene-Miocene channel systems. Most research tend to focus on utilizing the technique of 3D seismic time-slice analysis to visualize the depositional elements of Pleistocene to Recent fluvial successions in northern Malay Basin, rather than the southern part [3, 4]. Through seismic geomorphological analysis, the details in terms of geometry, dimension, flow direction, sediment source, temporal and spatial distribution of channel systems can be predicted [5]. But then, to visualize and evaluate the prospectivity of the older fluvial succession, development of a series of practical and reliable workflow is necessary. This is because, from temporal-wise, the older channel systems might be more affected by compaction and erosion processes compared to recent systems and caused the geomorphological details to be hardly restored. Hence, the fundamental of stratigraphic reservoir identification would be how one could associate and integrate geology and geophysics knowledge more closely and effectively.

Moreover, from reservoir heterogeneity viewpoint, there are often noticeable variations in channel styles and scale. Oversimplified assumptions in channel styles and cross sectional dimensions could lead to the unreliable delineation of subsurface fluvial systems, erroneous reserve estimation resulting in a higher risk of drilling dry holes [6]. For this reason, all these key challenges warrant need to develop a more systematic and pragmatic approach, as the main objective in this study. The goal is to delineate the potential channel-sand stratigraphic traps within the Group I reservoir.

2. Geological Setting

Y field is located on the SW part of Malay Basin, c. 160km east from coast of Terengganu, with water depth of ca. 70m (Fig. 1A).

It was first discovered in 1974 by exploration well A-1. To date, a total of 110 development wells have been drilled. It has a NW-SE trending, low-relief asymmetrical anticline, with gentle structural dips of 1-3 degrees [7]. Dips towards SW tend to be relatively gentle compared to the NE. Multiple HC accumulations had been discovered throughout the Group H, I, J, K and L reservoirs. Group I sands are known to have the best reservoir quality among others and generally sourced from mixed lacustrine and fluvial-deltaic rock **[1]**. Besides, younger N-S trending normal faults are encountered only near the flanks of Y field and cut through intervals down to Group K reservoir. Fig. 1B shows the stratigraphic framework of the Malay Basin. The Group I sequence is possibly deposited within the subsidence phase of the basin with predominantly lower coastal plain deposits. In Y field, Group I reservoir were interpreted to be deposited in fluvial-deltaic environment, with interbedded fluvial-deltaic sandstone, coal seams, shale, and siltstone. In short, the less intense tectonic activity within Group I reservoir and the overall low-relief structures are the key considerations and encouragement for chasing the unconventional stratigraphic play within the Group I channel sands.

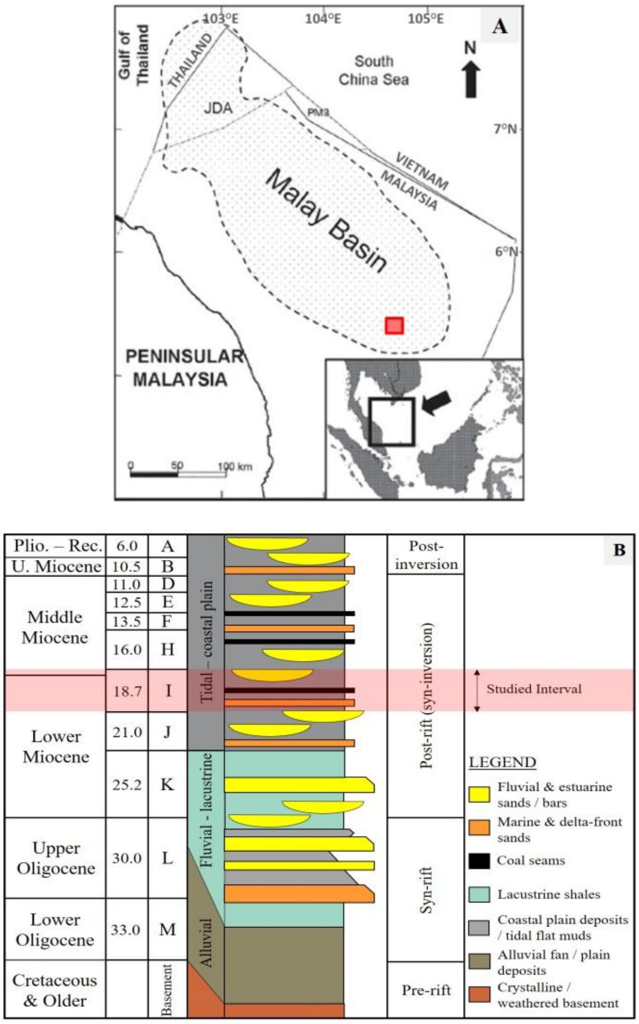

Fig. 1: (A) Location map of study area (redbox) (Modified from [8]). (B) Stratigraphic framework of Malay Basin. The studied interval (red), Lower-Middle Miocene Group I is interpreted to be deposited in tidal-coastal plain environment (Modified from [9]).

3. Dataset and Methods

A poststack 3-D seismic data (ca. 31 x 19km) and a total of 8 explorations wells were used for this study. This study will focus on delineating the Group I channel sands with the application of an integrated approach including seismic attributes, seismic facies and wireline log analysis (Fig. 2). Seismic intrepretation was mainly done by using PETREL®. Besides, seismic to well tie was performed using borehole checkshot data to cross-validate the intepreted horizons to their corresponding depths.

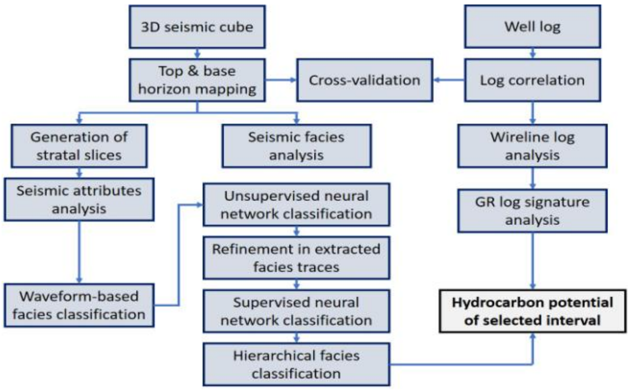

Fig. 2: The full integrated approach involved in this study.

Based on the interpreted horizons, 5 proportional stratal slices were created for further seismic attributes analysis [10, 11]. Three major groups of seismic attributes have been applied to delineate the channel geometries and evaluate the prospectivity of Group I channel sands, including the similarity, amplitude accentuating and instantaneous attributes (Table 1).

Table 1: List of seismic attributes used and its functions.

Groups of Seismic Attribute	Functions
Coherence / Semblance	Detects stratigraphic variations, faults & fractures
Amplitude accentuating attributes ▪ Sweetness	Enhances the DHI characteristics and aid in HC prediction and sweet spot identification
Instantaneous attributes ▪ Instantaneous amplitude	Reveals the lithological contrasts, gross porosity and DHIs

Next, on the targeted intervals of Group I succession, 2D arbitrary lines were generated to identify the reflection attributes, for instance, the reflection amplitude, geometry, continuity etc. The purpose of seismic facies analysis is to correlate the reflection attributes to the stratigraphic characteristics of targeted sequences (the Group I channel sand sequences) [12]. Other than that, waveform-based facies classification was introduced to generate facies maps based on the extracted seismic waveform shapes of selected seismic attributes, in this case is sweetness and instantaneous attributes [13]. Unsupervised facies classification is first applied by specifying the attributes and desired number of facies classes. Refinement is made by merging the facies traces to eliminate the similar facies, with reference to the calculated correlation matrix as well as the shape of the extracted traces. Supervised facies classification mapping is then performed using the neural network technique and user-defined parameters (refined facies traces) hierarchically.

Finally, lithostratigraphic correlation and standard wireline log analysis were performed to predict the HC occurrences. Gamma ray log signatures were assess to predict the overall depositional environments and the associated depositional facies at targeted intervals.

4. Results

4.1. Multi-Attributes Analysis

The co-rendering of multi-attributes could better visualize the Group I channel outlines, together with its potential porefills (Fig. 3). Semblance attribute works by capturing the similar seismic traces and is extremely useful for outlining of channel edges and faults identification. The mapping of channel edges is crucial especially for estimation of areal extent of reservoir channel-sand stratigraphic traps. On the other hand, the amplitude attenuating attributes and instantaneous attributes are relatively useful in identifying the variations in lithology as well as HC prediction. It is observed that these attributes can emphasize the distinct amplitude contrast of channel sands to the surrounding reflectors, indicating the likelihood of "sweet spots".

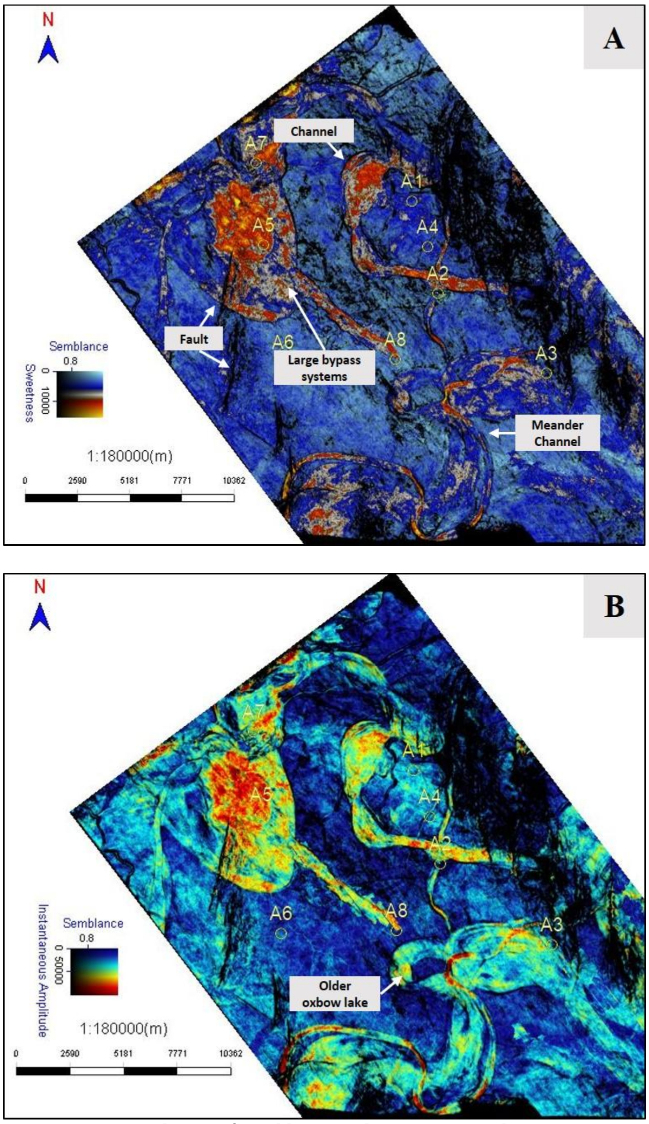

Fig. 3: (A) Corendering of semblance and sweetness attributes in Group I stratal slices. (B) Corendering of semblance and instantaneous attributes. Noted that channel edges and high reflection strength area are clearly shown. Geomorphological features such as oxbow lake can also be observed.

4.2. Seismic Facies Analysis vs Waveform-based Facies Analysis

Based on the 2D seismic section of arbitrary line created along well A-7 and A-5, total of 3 types of seismic facies were identified (Fig. 4). Table 2 demonstrates the types of seismic facies identified based on the selected reflection attributes.

Sometimes, it is hard to identify any erosional features within the traditional 2D seismic sections. Hence, waveform classification approach is performed for facies determination. Fig. 5 illustrates the extracted facies traces before and after the grouping of similar traces. The correlation values shown in Table. 3 indicate the level of similarity between each facies trace. After the merging of similar traces, neural network machine will simulate again with the refined facies traces. This step is required for generating a much more user-defined facies classification.

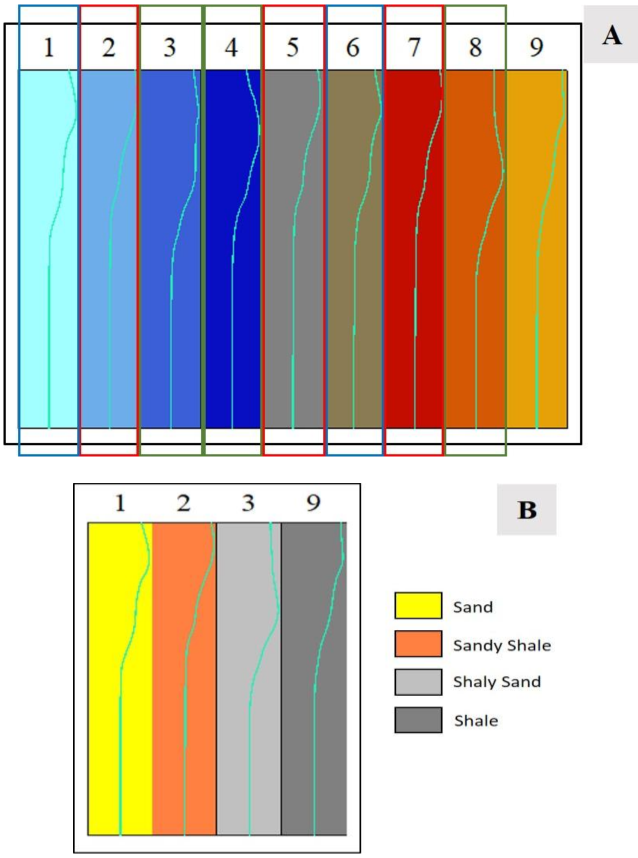

Fig. 5: (A) Extracted facies traces from sweetness and instantaneous amplitude attribute. (A) The default 9 facies classes created through unsupervised facies classification. Take note on the overlapping of similar traces. (B) The finalized 4 facies classes after merging.

The facies classes are being reduced to 4 main facies classes, which include, (i) sand; (ii) sandy shale; (iii) shaly sand; and (iv) shale. The meandering channels of interval I-35 are filled mainly with sands, and sandy shales along the edges of channels (Fig. 6). However, this kind of waveform-based classification rely mostly on the attributes that have been selected for calculation. Thus, improvements could be made by pre-defining the facies classes that one wishes to study in detail, and furthermore, sub-divide the respective facies classes into sub-classes. Therefore, the hierarchical waveform-based supervised facies classification map of interval I-35 is created with "sand" facies class being subdivided into 3 facies sub-classes, namely, (i) sandy heterolitic; (ii) good sand; and (iii) best sand (Fig. 7). This idea is reliable as it could provide the interpreter some information on the different sand distribution within the channels, together with cross-validation from wireline log analysis result.

Fig. 8 illustrates the lithostratigraphic correlation performed across N-S. Gamma ray (GR) log signatures were extracted to predict the associated log facies of each well. In well A-7, numerous stacked fining-upward, bell-shaped log motifs could be seen across the Group I sands. This suggests the presence of aggradational or progradational stacked fluvial point bars. Conversely, in well A-5, the intermittent presence of fining-upward channel sands within the coarsening-upward deltaic sequences implies possible sediment deposition in fluvial-deltaic environment. Meanwhile, the serrated log motif indicates the deposition of shale bed, possibly within the coastal plain areas. Based on the quick-look analysis, interval I-35 is characterized with low GR, neutron-density crossover and high resistivity values. This has confirmed the HC occurrence within the Group I-35 channel sands and validated the need to further evaluate the prospectivity of Group I channel sands.

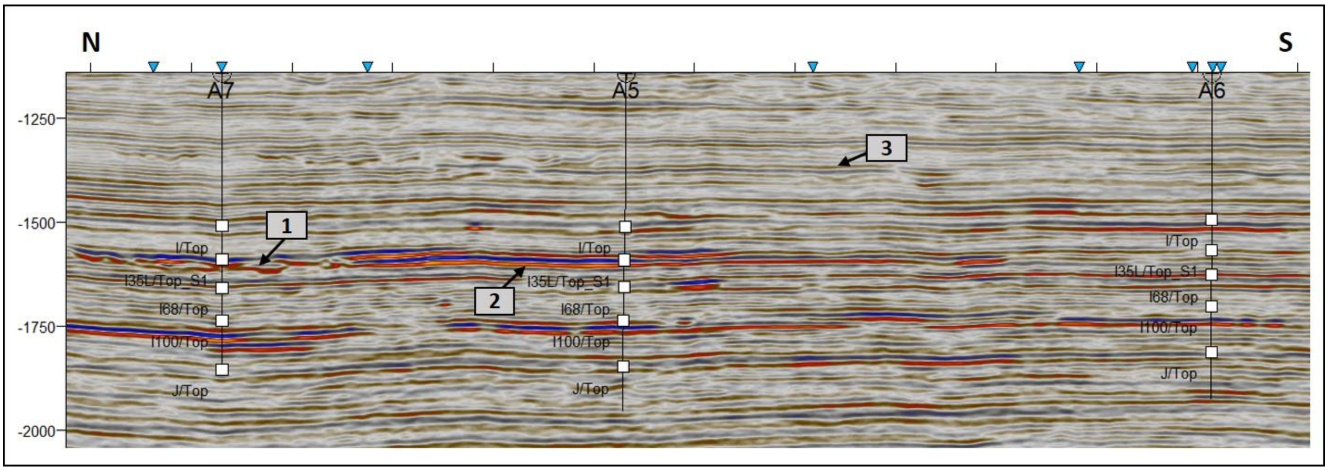

Fig. 4: Seismic facies analysis across well A-7 to A-6. Presence of scour-and-fill features along with discontinuous reflectors suggest the deposition of erosional-based channel sands. Laterally extensive, high reflective patterns may indicate the occurrence of massive sand bodies. Transparent, continuous reflectors, meanwhile reflect the deposition of shale bed.

Table 2: List of seismic facies identified based on the selected reflection attributes

Seismic Facies	Reflection Attributes		
	Continuity	Amplitude Strength	External & Internal Geometry
Type 1 (near well A-7)	Discontinuous	Low to moderate	Lenticular to channel-shaped, wavy to slightly chaotic
Type 2 (near well A-5)	High-continuity	Moderate to high	Sheet-form, parallel to subparallel
Type 3 (Background)	Semi- to high-continuity	Low to moderate	Sheet-form, subparallel to wavy

Table 3: Correlation matrix of 9 extracted facies traces. Merging is carried out based on the degree of correlation. High correlation value indicates high similarity across two facies classes.

Correlation Matrix									
	Facies 1	Facies 2	Facies 3	Facies 4	Facies 5	Facies 6	Facies 7	Facies 8	Facies 9
Facies 1	1.000	0.989	0.988	0.985	0.991	0.999	0.991	0.958	0.998
Facies 2	0.989	1.00	0.961	0.960	1.000	0.990	0.999	0.917	0.992
Facies 3	0.988	0.961	1.000	0.991	0.966	0.989	0.968	0.990	0.988
Facies 4	0.985	0.960	0.991	1.00	0.963	0.986	0.963	0.975	0.983
Facies 5	0.991	1.000	0.966	0.963	1.000	0.992	1.000	0.925	0.994
Facies 6	0.999	0.990	0.989	0.986	0.992	1.000	0.993	0.960	0.999
Facies 7	0.991	0.999	0.968	0.963	1.000	0.993	1.000	0.927	0.995
Facies 8	0.958	0.917	0.990	0.975	0.925	0.960	0.927	1.000	0.958
Facies 9	0.998	0.992	0.988	0.983	0.994	0.999	0.995	0.958	1.000

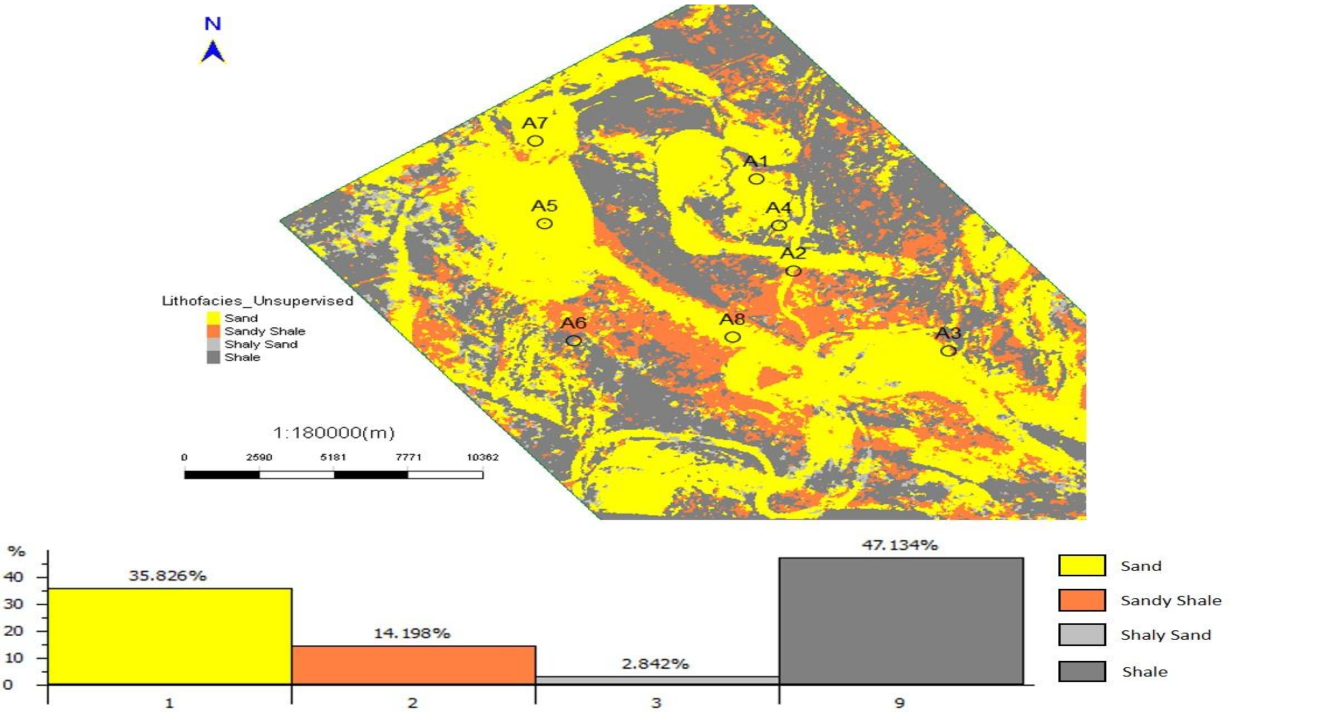

Fig. 6: Waveform-based supervised facies classification map of interval I-35 after the merging of facies traces. The channels are seemed to be filled dominantly by sand facies, with sandy shale along the channel edges. Sand and shale are the two most dominant facies in interval I-35.

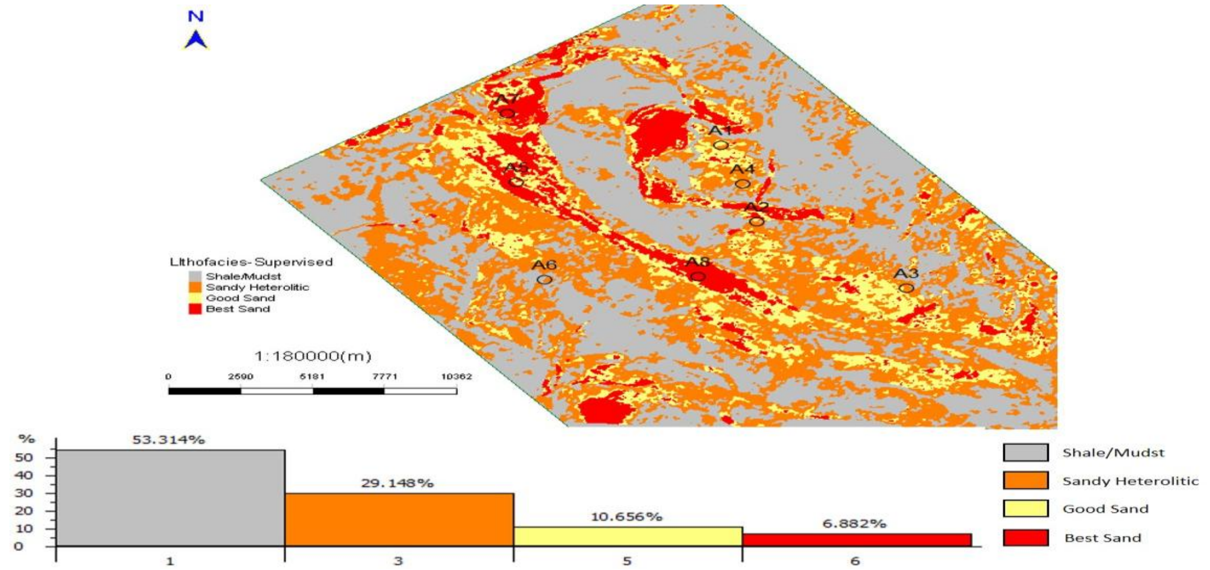

Fig. 7: Hierarchical waveform-based supervised facies classification map. The initially generated sand facies is being sub-divided into 3 facies classes in hierarchical order. "Best Sand" lithofacies is said to hold the best reservoir quality among all.

4.3. Well Log Correlation & Significance of GR Log Motif

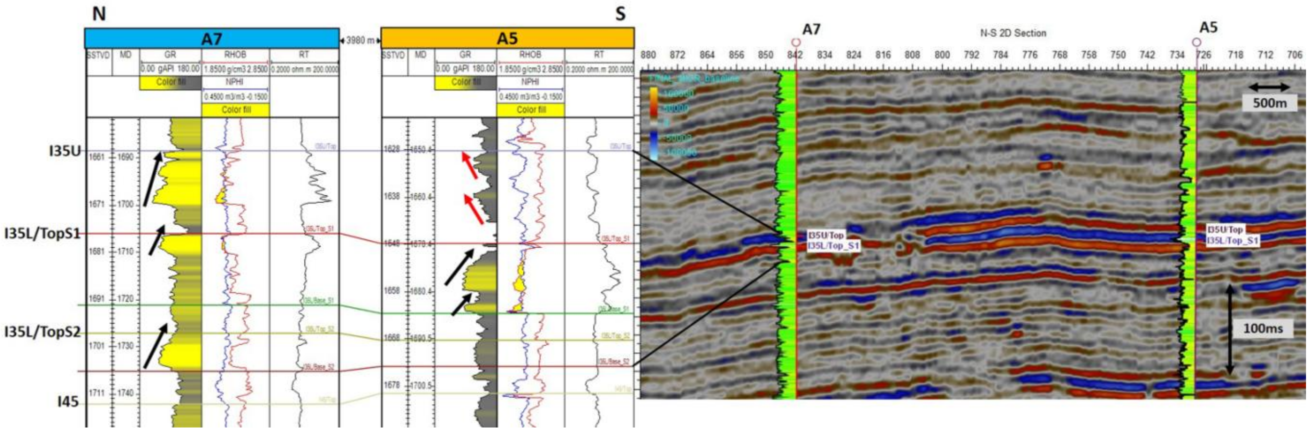

Fig. 8: N-S lithostratigraphic correlation across well A-7 and A-5 along with the associated 2D seismic facies and GR profiles. The target interval, I-35 is characterized by fining-upward (black arrow) meandering channels with coarsening-upward (red arrow) distributary mouth bar sections. From seismic facies aspect, A-7 shows chaotic, lenticular reflections, indicating channel sands; while A-5 shows continuous and high amplitude reflections, indicating the possible occurrence of massive sand bodies.

5. Discussion

With seismic attributes, one is able to ascribe the geological context to the observed patterns, features in seismic data and henceforth, establish a geological and geophysical (G&G) link for better reservoir characterization and thus lowering exploration risks and uncertainties. This is vital for channel delineation as it could reveal the "hidden and subtle" relationship, patterns, and geomorphological features in the seismic data which could otherwise be overlooked [14]. Application of multi-attributes are required to best workout the channels in multiple aspects, including the channel edges, fluid types, resolution, and reservoir quality etc. [15, 16].

Besides, the introduction of waveform-based facies classification also enables a detailed facies classification from the geophysical standpoint. Very often, the facies classification is performed using the geological means, involving the interpretation of core, log facies and modern analogue study. Yet, in this research, limited core information and sparsely-distributed exploration or appraisal wells result in greater difficulty in the process of facies determination. Thus, the waveform-based supervised facies classification, through the application of machine-learning neural network techniques on 3-D seismic data, has become the most viable alternative for facies discrimination.

Moreover, based on the wireline log analysis, it is observed that the channel sand packages are decreasing its dominance towards the S direction. This indicates that sediments were likely originated from the north, possibly branching off from the Mekong River, with a gradual decrease in depositional energy towards the south, thus the tail-end transportation much finer sands towads the south. Correlated with previous seismic waveform-based facies classification, well A-7 is proved to have been drilled within the best-quality aggradational fluvial point bar sands (Fig. 8).

From the viewpoint of stratigraphic trapping mechanism, Group I channel sands are nevertheless, the potential candidate for near-field exploration in Y field. This is due mainly to the few key reasons, which include:

- The overall low-relief, anticlinal structure of Y field. Anticlinal closures can only be seen near the N part. The centre and S part is relatively flattish, with no obvious closures (Fig. 9).
- At a later stage, Group I meandering channel system seemed to contribute to the overall oil production in Y field.

- The results of seismic attributes, seismic facies and wireline log analysis have proved the presence of HC-bearing channel sands within the Group I sequences.

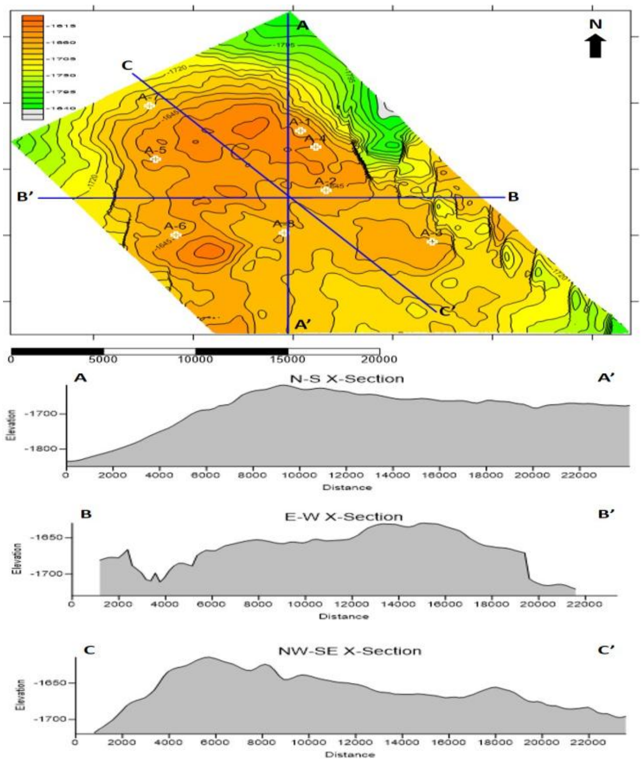

Fig. 9: Top depth map of I-35 and its associated cross-sections in different direction. Overall, structure of X Field is relatively gentle, especially near central and southern part. Elevation difference across the X field is relatively small, ranging within 50-100m. Anticlinal closures can be found within the depth of -1,645m.

6. Conclusion

The key highlights of this ongoing study, are:

1. The application of multiple groups or pairings of seismic attributes is effective in delineating the Group I channels from various aspects, including the channel outlines, lithological variations and HC prediction.
2. Traditional seismic facies analysis on 2D seismic section proves to be useful in Group I channel sands delineation with the aid of reflection attributes. Yet, it is only limited to the case where the seismic reflection configurations can be clearly defined.
3. Waveform-based supervised and hierarchical facies classification, with the application of neural network technique, can effectively discriminate the associated facies within the Group I channel systems from background shale. This geophysics-based approach is suitable for areas that have sparsely-distributed wells and limited core data available for facies determination.
4. Wireline log analysis, on the other hand, confirms the HC-bearing Group I channel sands based on the GR log signatures and quick-look analysis.
5. Group I-35 channel sands are interpreted, in this study, could be the one of the favourable candidate for future near-field exploration in the form of stratigraphic traps.

To conclude, the integration of multidisciplinary studies involving seismic attributes, seismic facies and wireline log analysis, could nonetheless, through weighing the comparative advantages, generate a much more reliable and systematic outcome, especially in visualizing the less discernible (subtle) channel-sand stratigraphic traps.

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