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Seismic geomorphology analysis of coal-bearing reservoirs using waveform classification: A case study from the Northern Malay Basin

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Abstract: The waveform classification is a machine learning method for pattern recognition, aims to classify areas of comparable waveforms, along a seismic horizon. It excels in mapping the subtle changes in seismic response and identifies facies and reservoir properties in greater detail compared to other seismic attributes. The waveform classification was applied to identify the stratigraphic architecture and the depositional elements of the coal-bearing Group E in the Northern Malay Basin. The studied interval is characterized by thin sand reservoirs, shale, and significant occurrence of coal beds. Although coal is a major source rock in the Northern Malay Basin and offers good marker horizons for structural seismic interpretation, it introduces uncertainty in seismic attributes analysis due to its masking effect on seismic data. The generated waveform classification maps revealed that the interval is deposited in a channel-dominated deltaic setting. Depositional elements such as distributary channels, distributary mouth bars, and subaqueous levees were identified on the maps. Well calibration indicated that the distributary channels and the distributary mouth bars are good sand reservoirs.

Keywords: Seismic attributes analysis, seismic geomorphology, waveform classification

INTRODUCTION

In recent years, machine learning has been introduced extensively to find solutions to a number of seismic interpretation problems. The Big Data issue is one of the seismic interpretation challenges. Interpreting a huge volume of seismic data that may contain a number of 3D surveys and different processing versions along with a large amount of well data is a very time consuming and difficult job. Machine learning has been developed to handle Big Data. Machine learning is also able to provide a good understanding of the relationship between diverse types of datasets at once. Machine learning algorithms are incorporated to learn from the data and produce reliable consistent results (Zhao *et al.,* 2015). Two kinds of machine learning techniques are used in seismic interpretation, supervised classification, and unsupervised classification. The latter is more popular in seismic interpretation and commonly applied to recognize geologic patterns in the data without prior information (Coléou *et al*., 2003).

A waveform is a portion of a seismic trace, consists of one or some reflections. Waveform classification is a machine learning method for pattern recognition aims to classify areas of comparable waveforms along a seismic horizon (Barnes, 2016). A waveform is a product of amplitude, phase, and frequency of a seismic trace. The change in the trace shape is attributed strongly to the changes in lithology, porosity, and pore-fill (Chopra & Marfurt, 2007). Unsupervised waveform classification was applied in this study to image and identify the geomorphological elements of the coal-bearing Group E in a field in the Northern Malay Basin.

The Northern Malay Basin is a gas-rich province with huge amounts of non-associated gas accumulations in Groups E, D, and B reservoirs. The seismic attributes imaging of Group E reservoirs is difficult and challenging. The interval is composed of thin sand reservoirs, a thick column of shale, and numerous coal layers. The sand reservoirs are generally very thin (a couple of meters) and bellow seismic vertical resolution. The prediction of lithology and fluid from seismic attributes is associated with many uncertainties due to the presence of coal beds. Coal seams produce very strong reflection similar to the gas sand. The presence of coal in the stratigraphic column of the Malay Basin is of great economic importance. It represents an important mature source rock, especially in the Northern Malay basin. The relatively low acoustic impedance contrast between the sand and shale in the young Tertiary basins such as the Malay Basin is luckily supported by the coal beds which provide very good marker horizons for structural seismic interpretation. In contrast, the occurrence of coal has a negative impact on the lithology and hydrocarbon prediction due to the masking effect of coal (Ghosh *et al*., 2010).

GEOLOGICAL SETTING

The Malay Basin is one of the major sedimentary basins in the Southeast Asia region. It is a Tertiary rift basin, located offshore Peninsular Malaysia (Figure 1).

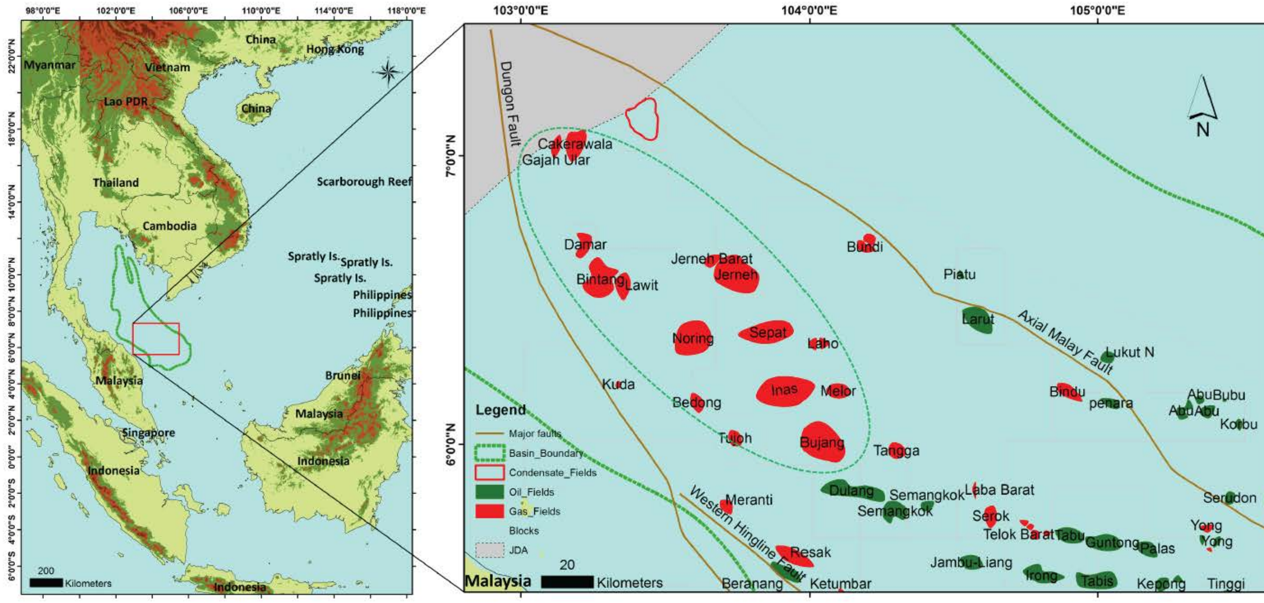

Figure 1: To the left is the location map of the Malay Basin. It is located offshore Peninsular Malaysia in the South China Sea. To the right is the location map of the study area. The field under investigation is located in the Bujang-Cakerawala gas-rich structural trend.

The geographical area of the Basin is approximately 500 kilometers by 200 kilometers. The Malay Basin is mature. It has undergone extensive exploration and production activities since the 1970s.

The initiation and development of the Malay Basin are related to the India-Asia collision during the late Eocene time (Madon & Watts, 1999). The basin was created by extensional activities along a shear zone in the Southeast Asia continental plate as a result of the collision between the Indian and the Eurasian Plate (Mansor *et al*., 2014).

The early rift phase of the Malay Basin is interpreted to be Late Eocene. The prominent E-W orientation of the half-grabens bounding faults compares to the NW-SE trend of the basin propose that the rifting has been caused by left-hand strike-slip movement (Madon, 1997). Based on a regional interpretation of recently acquired 2D seismic lines, the structural development of the Malay Basin was subdivided into four phases. These phases are pre-rift, syn-rift, fast subsidence, and compression. The late compressional phase is believed to have formed all the anticlinal traps in the Malay basin (Mansor *et al*., 2014).

The sedimentary fill of the basin is from Oligocene to Recent. The stratigraphy is subdivided into seismic stratigraphic groups named alphabetically from the older M to the younger A (Figure 2). The well-identified petroleum systems of the Malay Basin are two. One is holding a mix of gas and oil in the southern part and the other is gas-rich, dominating the Northern Malay basin (Madon *et al*., 1999).

The study area is located in the Northern Malay Basin where the petroleum system components comprise a mature source rock (coal and carbonaceous shale) of Group H and I that provides the hydrocarbon charge to reservoirs in E, D, and B groups. The hydrocarbon in the Northern Malay Basin is mainly gas, being trapped in the stratigraphically shallower units, E, D, and B. this is possibly due to the regional overpressure seal in the below Group F. These reservoir sequences are interpreted to be deposited in continental, coastal, and shallow marine environments (Madon *et al*., 2004).

The Middle-Upper Miocene Group E is characterized by an extensive occurrence of coal seams along with thin sand reservoirs. These sequences were deposited in a coastal plain environment. The fully-marine fauna are rare, suggests a confined marine environment (Madon, 2011). Studies on core samples from the Northern Malay Basin revealed that coal was originated from both freshwater and brackish environment. The fossil content and the bioturbated sandstone indicated that the sand reservoirs were deposited in a fluvio-deltaic setting (Ince *et al*., 2011).

WAVEFORM CLASSIFICATION

Classical seismic attributes such as RMS amplitude, reflection strength, and sweetness were applied to study the depositional elements and the lithological variation in Group E. Due to the presence of coal, the result of these attributes was not useful. An unsupervised waveform classification was carried out using a self-organizing map algorithm of Stratimagic® software to produce facies maps to help to interpret the depositional elements and to get information about the geological variability and seismic facies distribution within the studied interval. The result is totally data-driven. These seismic facies were linked to the geological facies that has been interpreted using well data and other attributes.

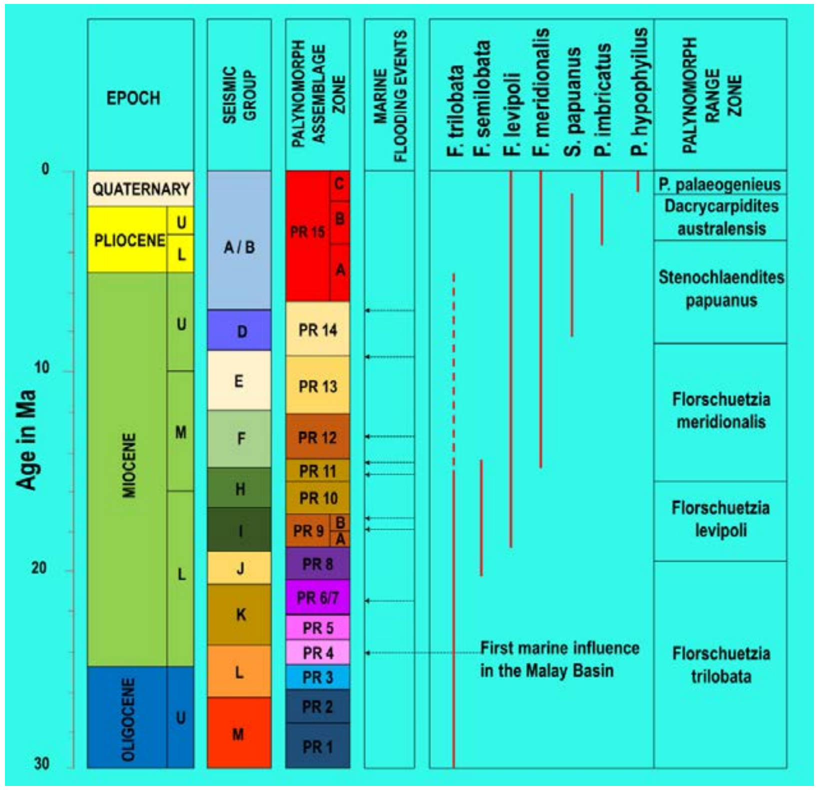

Figure 2: Stratigraphic column of the Malay Basin (Madon *et al.*, 1999).

Generally, the trace-base unsupervised classification is performed through two steps. As an initial step, the neural network algorithm examines and analyzes all the seismic traces within a predefined time window to generate template classes or groups based on a predefined number of classes (typically 5 to 20 classes) (Figure 4). The generated model classes are best representing all the waveforms within the defined time window. In the second step, the algorithm compares each waveform in the interval to the template classes and assign them to the template that provides the best correlation (Figure 3). Each resulting class is color-coded and displayed on a map (Chopra & Marfurt, 2007).

Waveform classification is sensitive to small errors in the guide horizon. Therefore, it requires accurate and carefully interpreted horizons. Four horizons (E, E7, E8, and E9M), within the upper part of Group E, were picked and mapped to be used as guiding horizons for the classification (Figure 5).

A self-organizing map (SOM) algorithm was used to carry out a trace-based unsupervised waveform classification along the four interpreted horizons. 10 ms below each horizon was defined as a time window to carry out the classification. The original amplitude seismic volume was used as input data for the analysis. Ten and eight number of classes and 100 iterations to perform the training of the self-organizing map was used.

Due to the many shortcomings related to the technique, the SOM waveform classification maps must be interpreted qualitatively with support from other available data. Lack

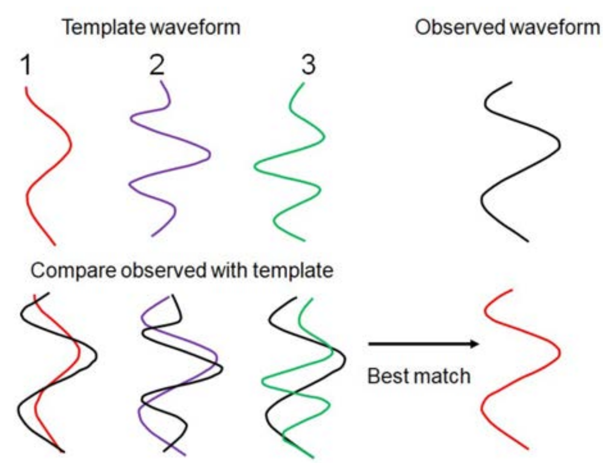

Figure 3: Waveform classification process matches observed trace shapes with a set of model traces and assigns each observed waveform to the most similar trace model (Barnes, 2016).

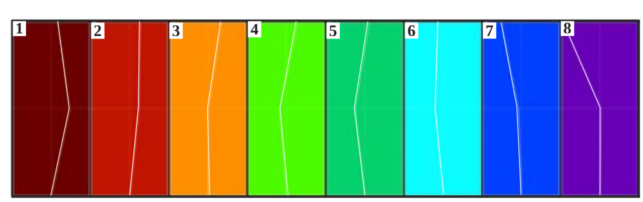

Figure 4: Color-coded model traces (templates) of the waveform classification.

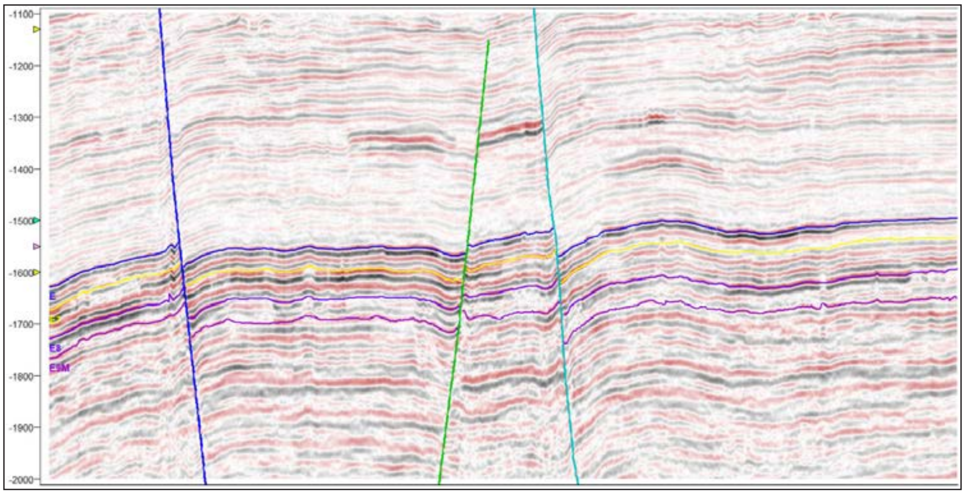

Figure 5: Interpreted horizons in the upper part of Group E. These horizons were used as guiding horizons for the waveform classification.

of a quantitative error measure is the main limitation of SOM (Roden *et al*., 2015).

SEISMIC GEOMORPHOLOGY

Seismic geomorphology is the study of depositional systems using maps extracted from 3D seismic. It is the seismic response of preserved landforms and features of a depositional element (Posamentier, 2005). Seismic geomorphology helps in interpreting depositional elements from attribute maps leading to the more precise prediction of lithological variations and reservoir quality. The seismic attribute maps can be obtained by surface slicing techniques such as time slicing, horizon slicing, and stratal slicing (Zeng, 2018).

Interpretation of geomorphological elements of a specific depositional system must be carried out based on many rules and guidelines such as the principles of seismic stratigraphy and sequence stratigraphy which are governed by outcrops observation and modern analogs (Zeng, 2018). This indicates that seismic geomorphology is largely model-driven, guided by geological observations and logic.

The carried out seismic geomorphology analysis in this study was mainly based on the generated waveform classification maps and well information within the depositional framework of Group E interval.

RESULTS AND DISCUSSION

The interpreted interval of Group E is characterized by sand and shale sequence along with numerous coal beds (Figure 6).

Due to the coal masking effect, the produce conventional seismic attributes such as RMS amplitude were not able to image the geology of the studied interval (Figure 7).

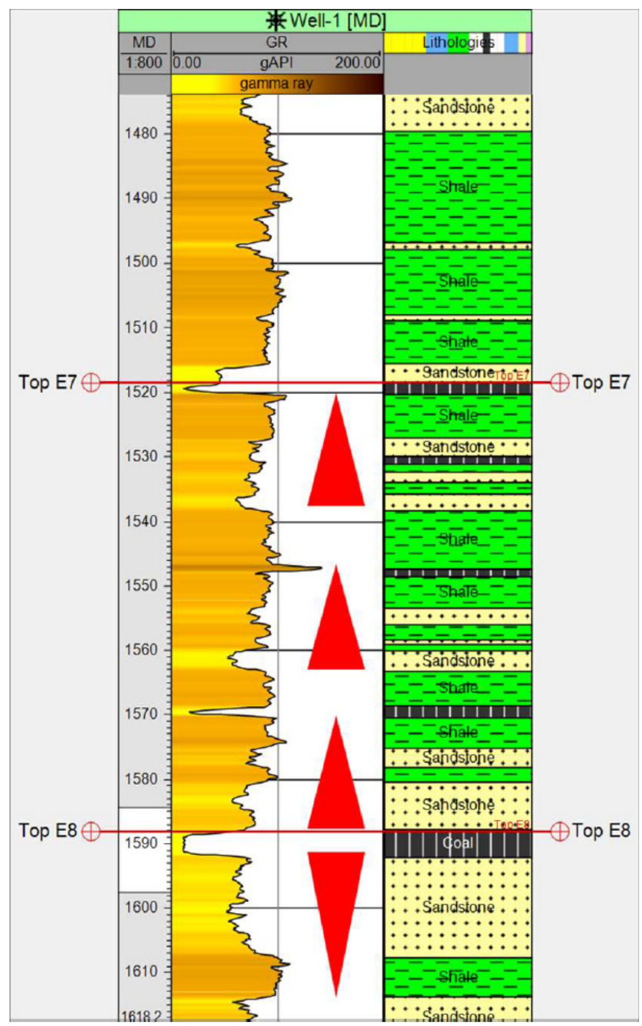

Figure 6: Well log display of the upper Group E interval showing sand, shale, and coal intercalation.

The seismic waveform carries information not only about amplitude but phase and frequency as well. The produced seismic facies maps were able to identify the depositional elements of the coal-prone Group E. The generated maps revealed many depositional elements related to a fluvio-deltaic setting. The interval is dominated by a fluvio-deltaic system. Many depositional elements such as distributary channels, floodplain, and distributary mouth bar were identified from the facies maps and confirmed by well data.

The waveform classification map of the E horizon was generated using 8 classes. The map shows a large SE-NW trending channel. The width of the channel is about 2 kilometers, in the upstream side and 500 meters on the downstream side. A continuous fan-like shape connected to the channel mouth is located in the NW corner of the map. This feature is interpreted as a distributary mouth bar. Well calibration indicated that class 8 and 7 are related to the sand lithology. Both the distributary channel and the distributary mouth bar were coded as class 8, confirming that they are sand-prone. A sheet-like feature in the southeastern part of the map is grouped under class 8 as well. It can be interpreted as another distributary mouth bar. Class 1 and 2 were interpreted as shale of the interdistributary fill (Figure 8).

Figure 9 showing a waveform classification map of E7-L. The Map reveals a channelized depositional system in this interval. Based on well calibration, the class 8 and 7 (light blue) was interpreted as sand. This sand interval has been penetrated by Well-1, Well-4, Well-5, Well-6, and Well-8. The interdistributary clay was encountered by Well-2, Well-

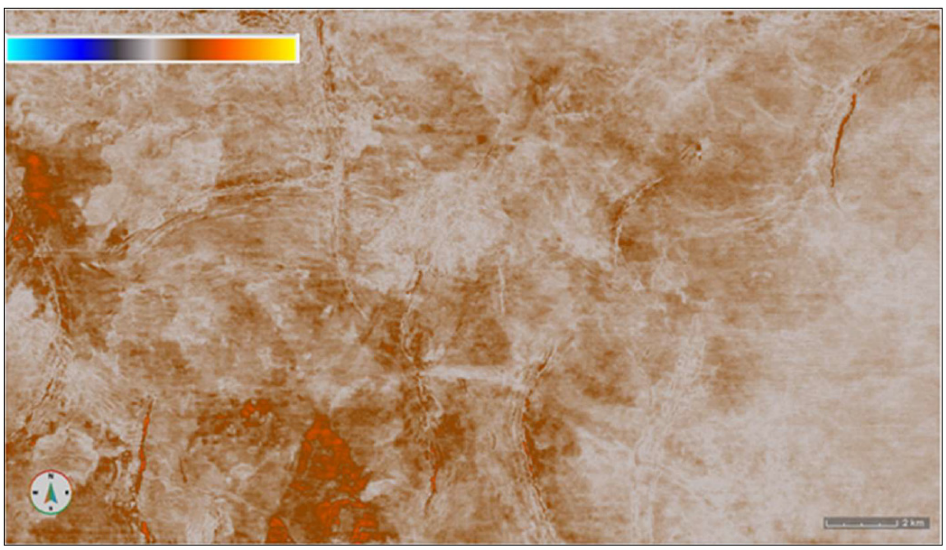

Figure 7: RMS amplitude map along E7 horizon. The strong reflection of coal dominates the seismic response and conceals the true geology.

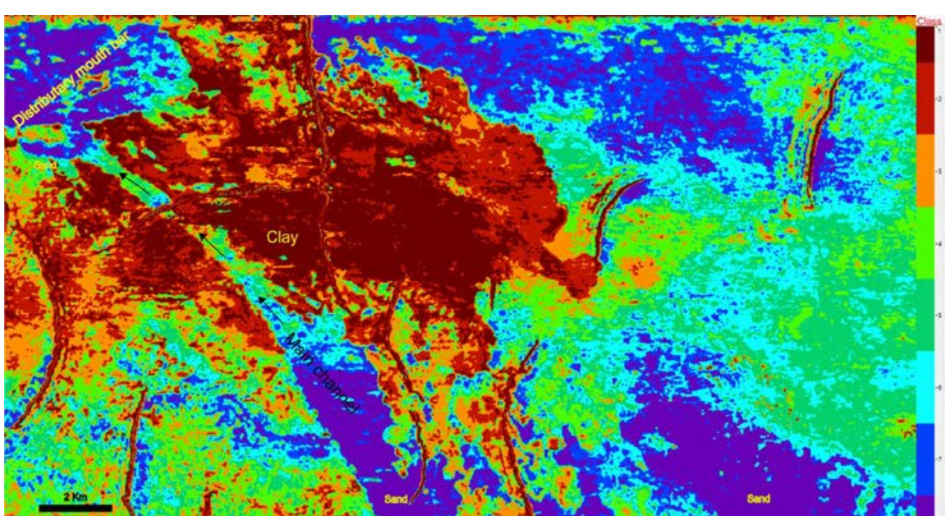

Figure 8: Trace-based Waveform classification map, generated by using 8 classes. The map showing the main channel and a distributary mouth bar in the NW corner.

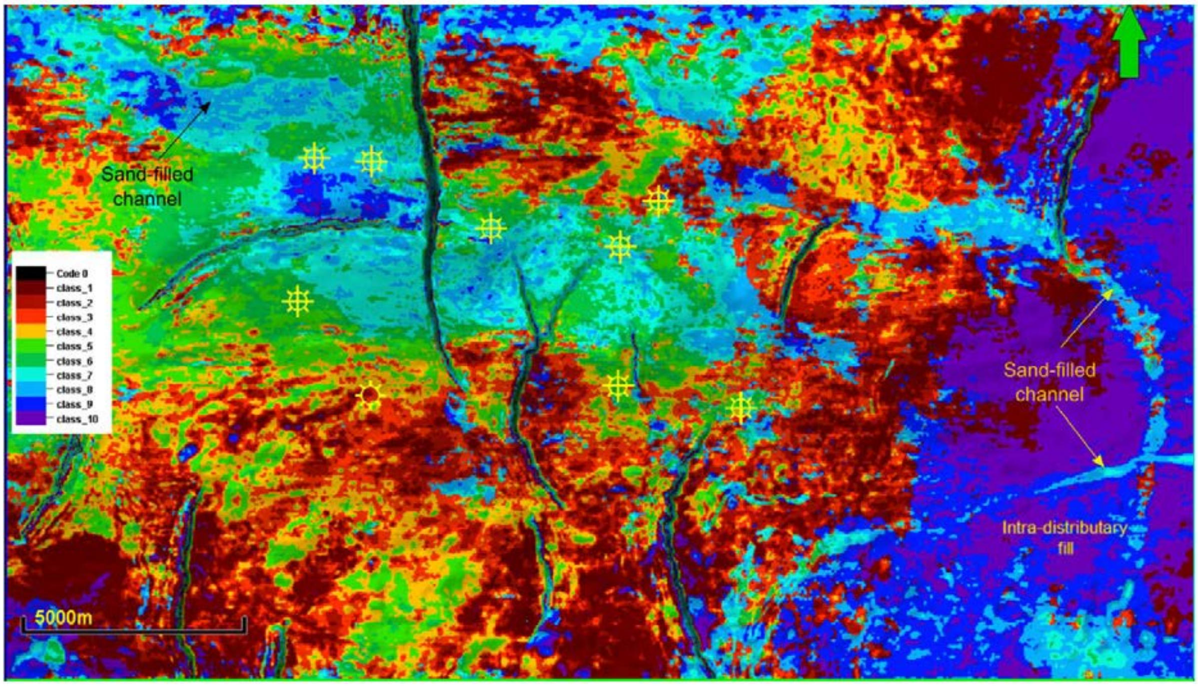

Figure 9: Trace-based Waveform classification map, generated by using 10 classes. The map showing an upper delta plain dominated by distributary channels. The channel-fill (class 8 = light blue) is interpreted as sand. This is indicated by well calibration.

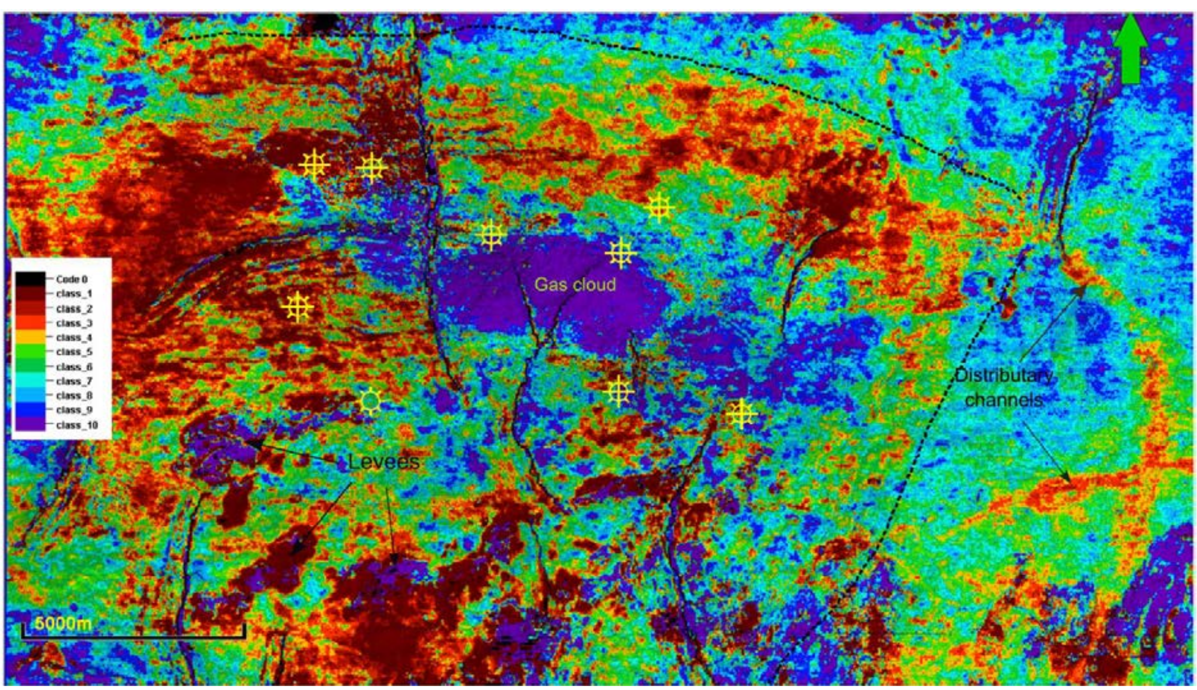

Figure 10: Trace-based Waveform classification map, generated by using 8 classes. The map showing a fan-like distributary mouth bar with elongated features interpreted as sub-aqueous levees.

3, Well-7, and Well-D The occurrence of the distributary channels in this interval is not dense and the interdistributary clay is dominant. Based on the stratigraphic position of the interval, the depositional setting was interpreted as a relatively distal upper delta plain.

Figure 10 is showing a trace-based waveform classification map of the E8 level. It exhibits a fan-like feature occupies the whole area of the map. Both the distributary channels located in the eastern part and the distributary mouth bar were categorized as class 3 and 4. Well calibration indicated sand lithology for those two classes. The radially spread elongated features were interpreted as subaqueous levees based on their geometrical configuration and the chaotic pattern on the seismic section. On the waveform classification map, these features were classified as class 8 together with the crestal part of the structure which is affected by the gas cloud. Both two features show a chaotic seismic pattern. The sub-aqueous levees are mud-dominated depositional element whereas the distributary mouth bar is a laterally continuous sand body, as indicated by wells.

The interpreted depositional elements on the waveform classification maps indicate that the studied interval was deposited in a river-dominated delta plain. This is supported by the fossil content of the interval. The distributary channels and the distributary mouth bars, as confirmed by wells, are sand-prone and considered good reservoirs.

CONCLUSION

Coal has significant importance as a source rock in the Northern Malay Basin. Most of the generated natural gases are from the coaly source rock. Due to the high acoustic impedance contrast between coal and sand/shale sequences, coal provides good marker horizons for structural seismic interpretation. Coal, on the other hand, introduces uncertainty to the seismic attribute analysis due to its masking effect. The sophisticated technique of the waveform classification was employed in this study to get rid of the coal effect. The generated waveform classification maps revealed that the interval is deposited in a channel-dominated deltaic setting. The interval is dominated by deltaic depositional elements such as distributary channels, distributary mouth bars, and subaqueous levees.

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