Seismic attributes add a new dimension to prospect evaluation and geomorphology offshore Malaysia

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Abstract

The Malay Basin is a mature Tertiary extensional basin with a later inversion regime in the Late Miocene. The general geology is simple “layer cake” seismically, with some compressive anticlinal inversion structures. The Borneo Basin, on the other hand, is tectonically complex, with steep dips, overthrust, and complex faulting. The rocks are unconsolidated, and geophysical techniques such as amplitude and other attributes should work well. In early years, seismic interpretation was based mostly on mapping structures. The advent of AVO and inversion technologies and pioneering geophysical work brought about increased usage of seismic attributes, solving various problems of geologic interpretation. In Southeast Asia, concentrated efforts since 2000 in seismic data acquisition and processing have resulted in significant improvement in data quality and hence success of attribute application. Seismic imaging and attributes meet challenges such as (1) inversion structural plays in the Malay Basin, (2) stratigraphic channels, (3) fractured basement, (4) deep high-pressure (HP) and high-temperature (HT) plays, (5) steep-dip/overthrust plays, (6) deepwater turbidite plays, (7) carbonate plays of Luconia Province, and (8) thin pay beds, often below seismic resolution, using spectral attributes. Various attributes can be applied to a widespread problem in prospect-maturation evaluation and reservoir characterization.

Introduction

The Malay Basin is a mature Tertiary extensional basin with a later inversion regime in the Late Miocene (Madon, 1999). The general geology is simple “layer cake” seismically, with some compressive anticlinal inversion structures. The Borneo Basin, on the other hand, is tectonically complex, with steep dips, overthrust, and complex faulting. The rocks are unconsolidated, and geophysical techniques such as amplitude and other attributes should work well. However, the earlier quantitative interpretation (QI) applications had limited success. A postmortem of these efforts underlies some key shortcomings:

1) The seismic data were adequate for mapping structures but were deemed not good enough for detailed amplitude interpretation.
2) Lack of a rock-property database and lack of dipole shear logs hindered hydrocarbon prediction from seismic.
3) Many of the pay beds were beyond seismic resolution

In early years, seismic interpretation was based mostly on mapping structures. The advent of AVO and inversion technologies and the pioneering work of Taner et al. (1979) brought about increased use of seismic attributes, solving various problems of geologic interpretation (Bahorich and Farmer, 1995; Partyka et al., 1999; Barnes, 2000; Marfurt, 2008). In Southeast Asia, concentrated efforts since 2000 in seismic data acquisition and processing have resulted in significant improvement in data quality and hence success of attribute application.

In this article, we will concentrate on how seismic imaging and attribute analysis are meeting some of these challenges. Exploration efforts and focused plays include (1) inversion structural plays in the Malay Basin, (2) stratigraphic channels, (3) fractured basement, (4) deep high-pressure (HP) and

Geologic applications	Algorithms
Structure Compressional anticline, faults	Dip/azimuth, semblance, Hilbert transform, crosscorrelation, coherency
Stratigraphic Unconformity Geomorphology (toplap, downlap, onlap) Fracture analysis	Amplitude Coherency Curvature, cosine of phase and instantaneous attributes dip/azimuth, curvature Seismic waveform
Seismic facies Pinch-out, unconformity, sinuosity	Impedance Strata slicing Sedimentology analysis Phase attributes

Table 1. Structure/geomorphological attributes.

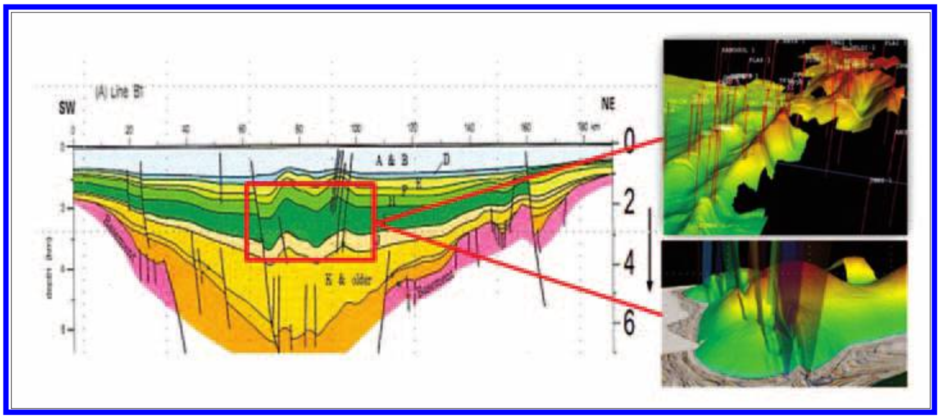

Figure 1. Malay Basin geologic cross section, with 3D seismic-visualization techniques. Note that most of the well (red lines) was drilled along the apex of the anticlinal structure where light transparencies on the 3D interpreted horizon represent high compressional-angle faults.

high-temperature (HT) plays, (5) Borneo Basin steep-dip/overthrust plays, (6) deepwater turbidite plays, (7) carbonate plays of Luconia Province, and (8) thin pay beds.

This article describes the various attributes to a widespread problem in prospect-maturation evaluation and reservoir characterization. Depending on their application, we classify the seismic attributes in three principal categories.

Class 1: Structure/geomorphology

The main objective is the mapping of the structure. Geomorphological analysis is an important aspect of stratigraphic plays, such as unconformity, pinch-out, toplap, downlap, and mapping. Geologic depositional-environment studies leading to seismic-facies analysis using seismic attributes are useful in reservoir modeling and delineation in locating sweet spots and reservoir efficiency and productivity (Ghosh et al., 2010b).

Table 1 shows the Class 1 attributes with their geologic application and algorithms (Ghosh et al., 2010b).

Structural attributes. A variety of structural styles reflects the tectonic history of our basin. They include basement-controlled normal fault with compressive-inversion anticlinal structures, as shown in Figure 1. Most of the hydrocarbon discoveries in the early 1970s were made by Esso, the principal operator in Peninsular Malaysia, and many of those fields are still producing, although in a declining mode (Ghosh et al., 2010b).

Figure 2 show the combination of two attributes such as amplitude and coherency into one display. This can improve the channel definition (coherency) and sweet spot. The final attribute is geologically realistic.

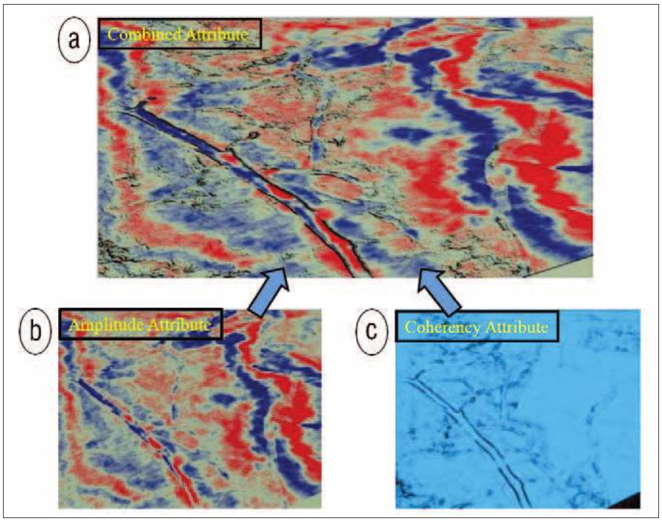

Figure 2. Multiattribute display of a channel complex combining (b) amplitude attribute highlighting sweet spots with (c) coherence attribute, the channel edges. (a) The final image gives a more realistic picture of the geology.

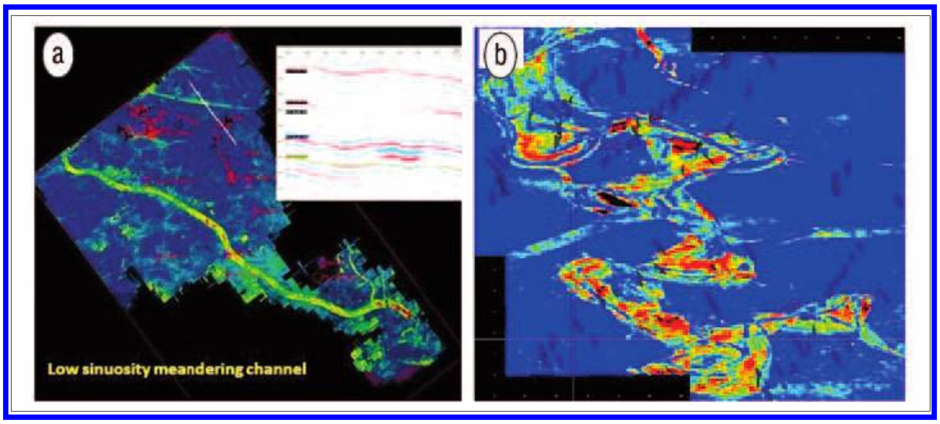

Figure 3. The high quality of modern 3D seismic data enables us to nicely image the channels that were missed on the old data set. Based on this analysis, we concluded that in the Malay Basin, there are basically two types of channel configurations. Many low sinusoidal channels are filled with clay or silt. The high sinusoidal channel contains sand in point bars with possible HC.

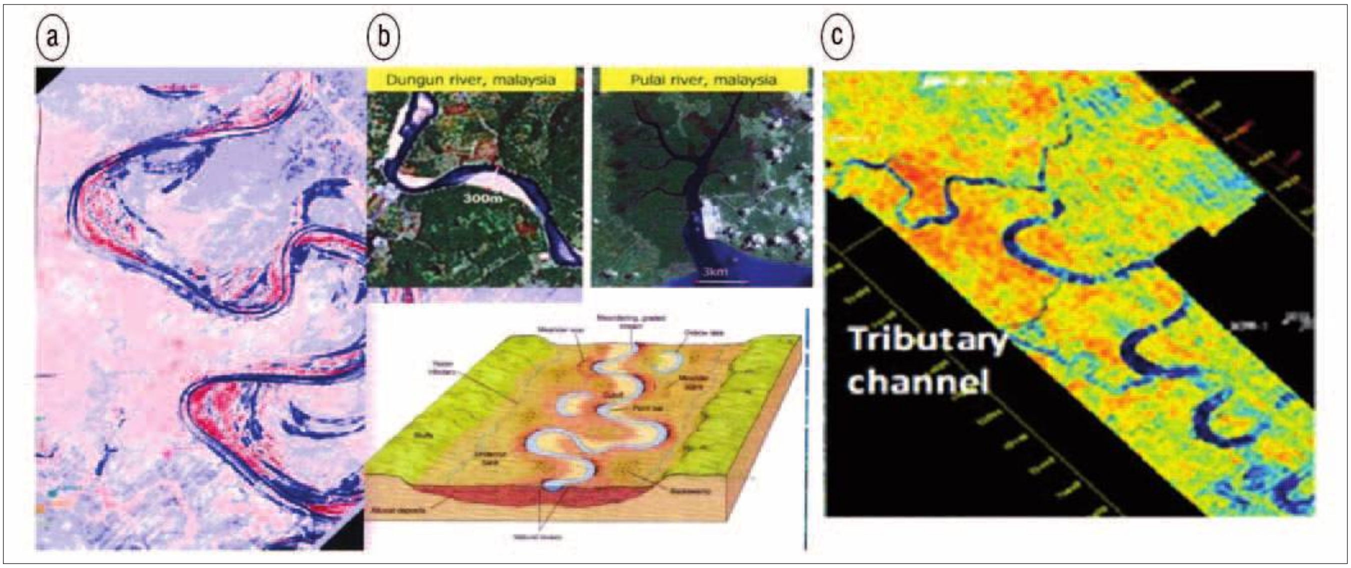

Figure 4. Channel characterization in 3D seismic: (a) time-slice seismic image of a shallow riverbed; (b) analogue and conceptual model; (c) prospect-level meandering-tributary clay-filled channel.

Geomorphological attributes — Stratigraphic channel play. High-resolution modern 3D seismic data with a final processed bin dimension of 12.5 × 12.5 m, with an enhanced frequency of 90 to 100 Hz at shallow levels and 50 to 60 Hz at prospect levels and improvement in imaging, were key features in producing well-imaged channels and quantifying channel properties regarding sinuosity, channel width, and thickness. In the Malay Basin, several channels have been identified, characterized, and used for exploration and field development. Figure 3 shows two types of channels: (1) low sinuosity with possible mixed infill of sand and shale and (2) high sinuosity, possibly sand filled (in point bar) where the locating hydrocarbon (HC) is high.

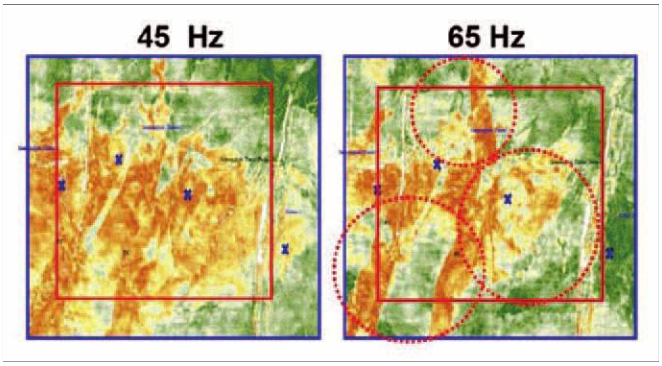

Figure 5. Spectral-decomposition result at optimal frequency of 65 Hz shows fine imaging of the channel under investigation.

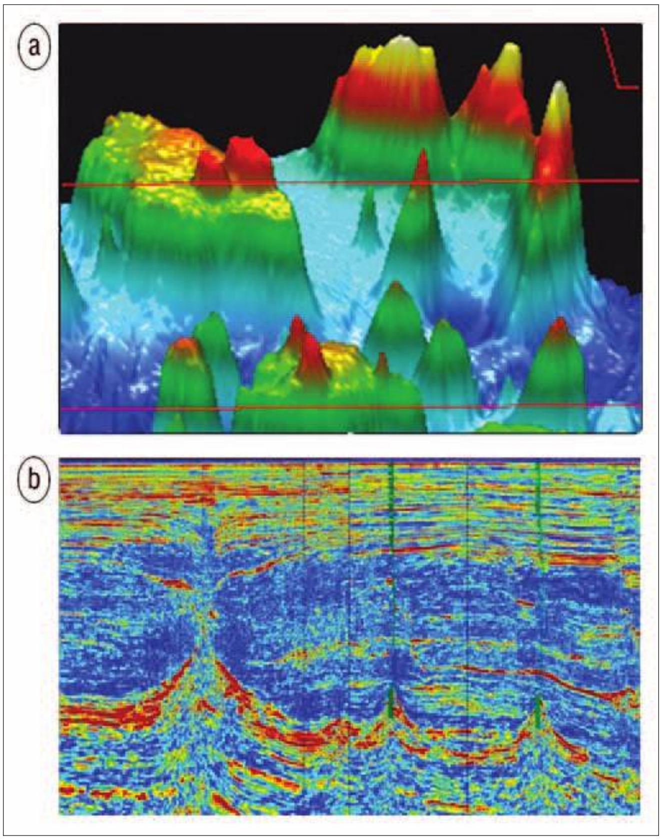

Figure 6. (a) 3D visualization and seismic section of part of the Luconia carbonate buildup. (b) Three pinnacle types of carbonate structures. Reddish brown represents the top of the carbonate, and blue refers to the top seal as shale. The two rightmost pinnacles were drilled successfully, resulting in a large gas column.

The amplitude-related attributes are adequate to analyze these channels in a regional sense for channels extending over large areas. On the other hand, for prospect evaluation and tying with well logs, we find spectral decomposition useful. The recorded data are interpreted best with attributes using geologic analogues and models, as shown in Figure 4. Spectral inversion further enhances the quality and details of the images and makes chasing stratigraphic play viable for exploration projects, as shown in Figure 5 (Ghosh et al., 2010b).

Geomorphological attributes — Carbonate play. The Central Luconia Province in Sarawak, East Malaysia, is a major site of carbonate buildup and contributes to a large percentage of Malaysian gas reserves. Prolific carbonate growth and development occurred in the Late Oligocene through Middle Miocene, with favorable warm tropical climatic conditions in shallow-marine environments. Depositional processes enhance lithologic and facies variations, leading to differences in acoustic properties. This is ideal for seismic attributes to produce noticeable differential responses that help to characterize carbonates.

Three-dimensional visualization (Figure 6a) has been found best to analyze some spectacular carbonate-buildup platforms, reefs, and pinnacles from Luconia. Figure 6b shows a three-pinnacle development, of which the largest one was not drilled because of the uncertainty of the sealing integrity of the overburden. The other two were drilled, and significant columns of gas were found (Ghosh et al., 2010b).

Attributes that help to further enhance these images and reveal internal architecture are coherency for mapping the edges of carbonate ridges, pinnacles, and reefs; waveform for facies mapping; and sweetness, amplitude, and acoustic impedance (AI)/elastic impedance (EI) for porosity mapping. Complex attributes such as envelope (reflection strength) and instantaneous phase and frequency in a pinnacle reef of a carbonate environment have shown positive information for lithofacies boundaries, potential heterogeneity, and reservoir quality, as shown in Figure 5.

In another prospect in Luconia, a sequence of attributes was applied, as shown in Figure 7. This included instantaneous phase and frequency and reflection strength in a prospect with pinnacle-reef carbonate buildup. This analysis yielded information about lithofacies boundaries, potential heterogeneity, and reservoir quality.

Use of the complex-attribute family has successfully confirmed the geology of interest. The bright amplitude response, as observed from the full-stack data on top of the carbonate, refers to a high-magnitude reflection strength (envelope) attribute. The high reflectivity indirectly indicates the composite response of the high acoustic-impedance contrast of shale and carbonate as well as the contribution of the gas-saturation influx. However, it seems that the envelope alone could not explicitly differentiate gas versus nongas reservoir responses. Further QI analysis is required.

We have applied the attribute analysis to a different environment, the Kujung Carbonates in the Madura Platform in Java, Indonesia. Sweetness and coherency (Figures 8a and

8b) were used in prospect evaluation in a qualitative manner, whereas impedance and coherency (Figures 8c and 8d) were more quantitative. The coherence attribute in time-slice format located the edges of the reefs. The smaller reefs were identified. As shown in Figure 8c, the seismic AI gave a nice distribution of porosity buildup. It was higher on the windward direction and patchy on the leeward direction, as expected.

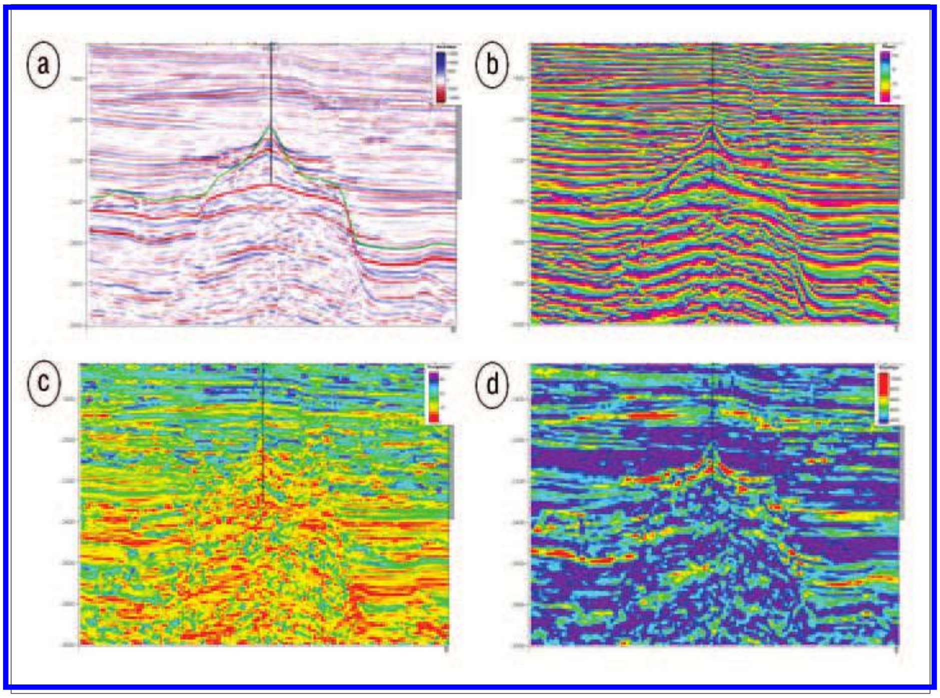

Figure 7. Luconia carbonate characterization obtained by using seismic-instantaneous attributes: (a) seismic section, (b) instantaneous phase, (c) instantaneous frequency, and (d) envelope.

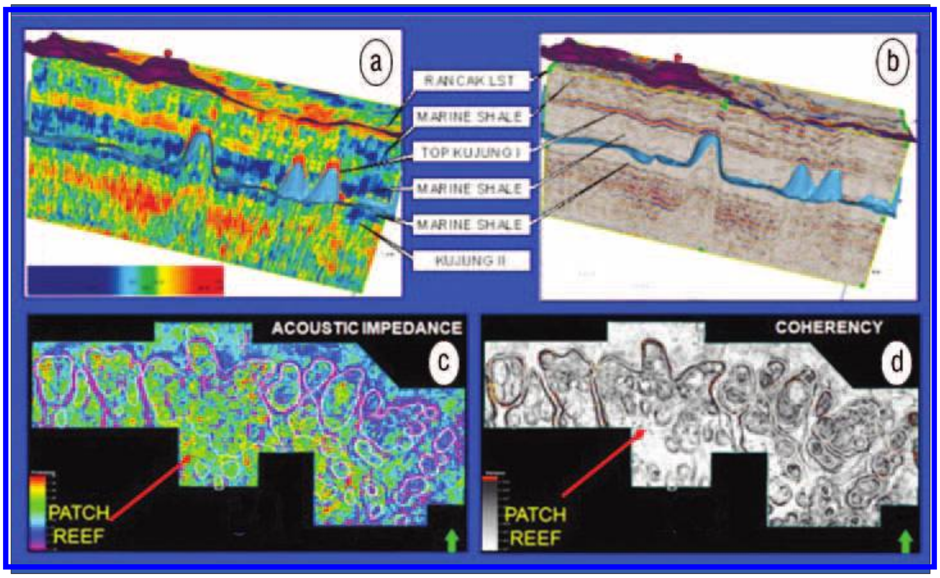

Figure 8. Carbonate bodies are best analyzed through (a) sweetness, (b) reflectivity, (c) impedance, and (d) coherency. The boundaries of the carbonate structure are defined better through coherency attributes and porosity buildup through AI.

Class 2: Spectral attributes

Spectral attributes are important in improving resolution in the Malay Basin, where thin beds play a critical role. Seismic velocity and dominant frequency result in a resolution of about 15 m at best (Widess, 1973), whereas from well logs at prospect evaluation, we often have a pay bed of about 1 to 5 m. Hence, enhancing resolution through spectral and seismic inversion has been useful.

Spectral attributes are not only important in detection of thin beds but also play a role in hydrocarbon prediction by zooming in on the "shadow" response of hydrocarbons (Castagna et al., 2003). Spectral attributes play a strong role in delineating the internal architecture of the reservoirs that require higher resolution and interpretability (Ghosh et al., 2010b). Table 2 shows Class 2 attributes, with applications and algorithms (Ghosh et al., 2010b).

Exploration in the Malay Basin has encountered pay sands juxtaposed with thin coal layers. Because of the Middle Miocene marshy environment, the reservoirs have significant layers of thin coal beds (Ghosh et al., 2010a). These coal beds dominate the response, as shown in Figure 9a. After we filter the higher spectral contents, the geology is now apparent in Figure 9b. The rising AVO is clearly evident at the reservoir level at low-frequency bandwidth, as shown in Figure 9c. However, if the hydrocarbon sands are thin and the same as coal, this technique will not work, and we then would revert to full elastic inversion, as discussed later.

E&P applications	Algorithms
Seismic resolution	Wavelet transform, cepstrum, instantaneous frequency and phase
Thin-bed tuning Channel characterization Thin coal bed removal	Spectral decomposition

Table 2. Spectral attributes.

Class 3: Fluid/lithology attributes

Tying amplitudes to the geology. To relate seismic amplitudes to geology, i.e., to lithology and/or pore fill, it is necessary to understand all the physical factors that influence seismic amplitudes. In the Malay Basin, the following factors affects seismic amplitudes: (1) quality of reservoir — net to gross, (2) thin pay beds, (3) high-quality wet sand, (4) coal and carbonaceous shales, and (5) anisotropic bounding shales. In this article, we will discuss with examples how each of these pitfalls is analyzed.

For an amplitude anomaly to be considered a direct hydrocarbon indicator (DHI), the amplitude is required to be interpreted in a geologic context such as (1) structural conformable amplitudes, (2) flat spot, (3) amplitude shutoff, (4) phase change, and (5) frequency dimming (Ghosh et al., 2010b).

Table 3 shows fluid/lithology attributes, with their QI applications and algorithms (Ghosh et al., 2010b).

Many successful drilling projects used the above hydrocarbon indicators. One such example is shown in Figure 10. The play is in East Malaysia. The prospects are a series of erosional domes called Buried Hill. A nearby well used as a reference was wet. An initial AVO modeling exercise revealed that gas and high-quality sand with brine show positive rising AVO Class 2 response, which

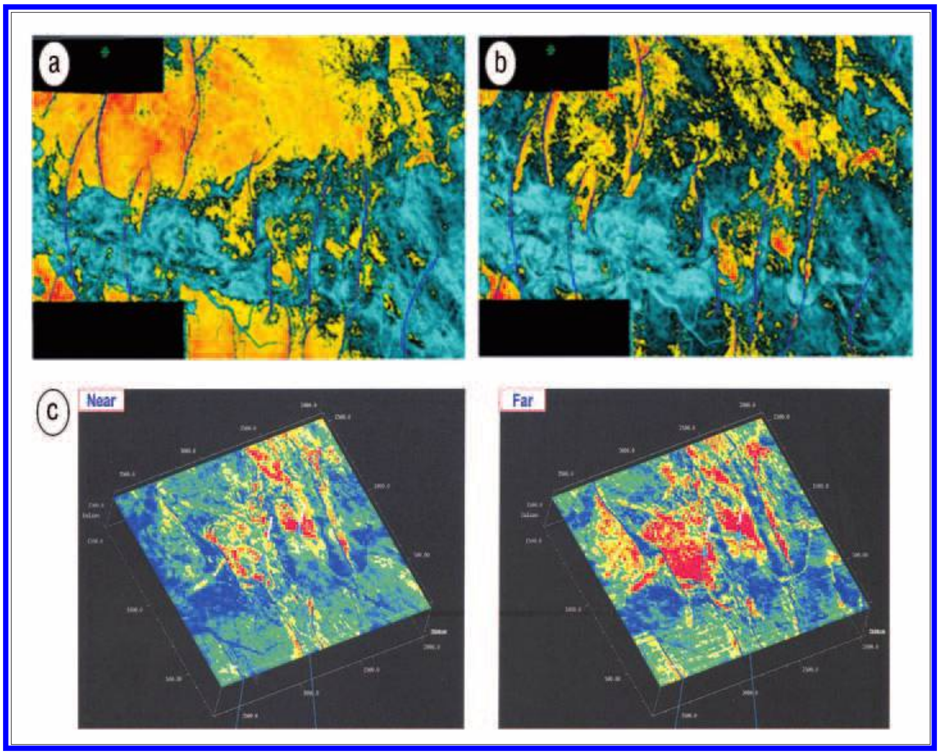

Figure 9. (a) Coal amplitude can mask the geologic information of interest because the response at zero offset is similar. (b) Because coal beds are relatively thin (2 to 5 m), they can be filtered spectrally, retaining the lower-frequency hydrocarbon response. (c) Coal-bed filtering leads to better AVO analysis at reservoir level.

QI applications	Algorithms
Quality of reservoir	Amplitude/impedance
HC prediction Lithology versus pore fill	AVO attributes: intercept gradient, envelope Elastic impedance (EI), V_P/V_S, Q_P/Q_S

Table 3. Fluid/lithology attributes.

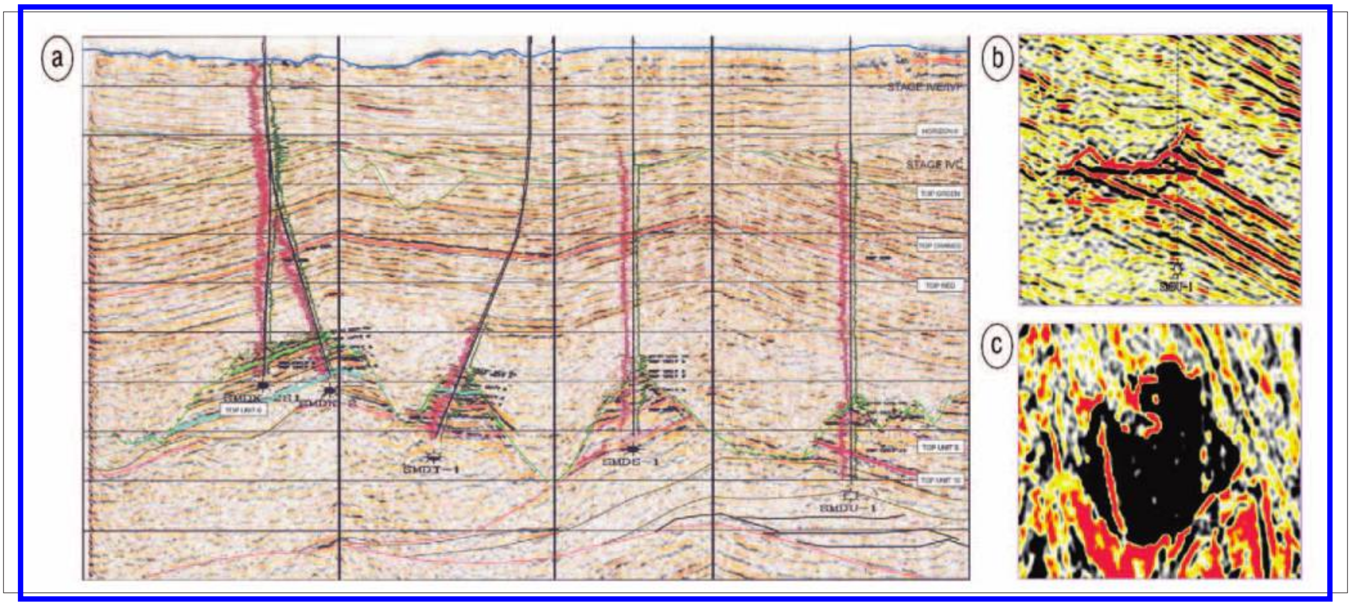

Figure 10. (a) Seismic cross section across four Buried Hill prospects with well trajectory. (b) Zoom of two of the prospects, showing the top of the reservoir as indicated. Red signifies hard impedance separating the reservoir from overlying shale. Clear hydrocarbon/water contact is shown (black represents soft impedance). Flat spot is in two dimensions. (c) 3D time slice highlighting two flat spots of the two reservoirs separated by a soft (red) event.

introduces uncertainty in hydrocarbon prediction. However, structurally conformable amplitudes (shown in red in Figure 10) and the existence of a clear flat spot (hard kick) indicated the presence of hydrocarbons, which was confirmed by drilling.

Amplitude: An indicator of sand quality. Figure 11, from an exploration venture in the Malay Basin, shows a far-offset amplitude display at a 20- to 30-Hz range that accentuated the hydrocarbon response. At the center of the channel, the well-found high-quality sand corresponding to a well-pronounced amplitude response. The logs confirmed good porosity and good net-to-gross (NTG) sand with good gamma-ray response. On the other hand, the amplitude response is spotty on the well drilled on the levee overbank, and that was confirmed by the gamma-ray response.

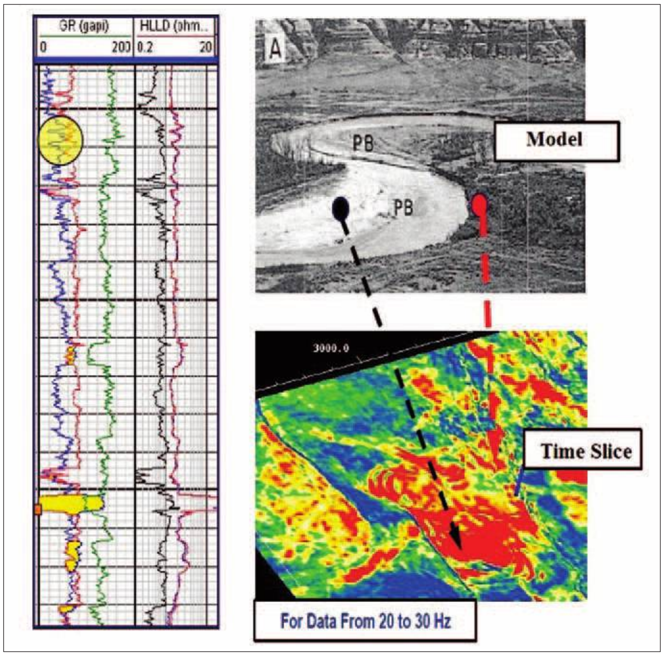

Figure 11. Amplitude as a good sand indicator and possibly a hydrocarbon indicator. The figure shows the model corresponding to the time slice of the amplitude attributes along well logs. Two wells were drilled; the well drilled at high amplitude showed good-quality sand point bar, whereas the low amplitude showed low-quality sand. A conceptual model of a channel-levee system is used to explain better-quality sand at the center, degrading to the overbank.

In this example, the amplitudes conform to the quality of sand. Both these locations found hydrocarbons. Good gamma-ray response of Sand A results in good amplitude response. Poorer amplitude would reflect to a ratty poor response, as marked as B in Figure 11.

Pitfalls: Soft shale-coal interference. AVO analysis is perfectly suitable to distinguish lithology such as bounding shale on hydrocarbon sand from hard shale on soft shale or coal. However, moving to the inversion domain, we can also remove thin-bed tuning, a critical issue in the Malay Basin. Further moving from the AI to EI domain, we can effectively separate sands from coal or shales because sands have a lower Poisson's ratio or V_P/V_S compared with shales.

Figure 12a shows discrimination of HC sands from coal/carbonaceous shale. In the AI domain, both have soft response and are not distinguishable. However, in the crossplot of AI versus EI, coal and shales have high V_P/V_S. Figure 12b show an example of this application in a field-development scenario. Because of the coal masking, the sweet hydrocarbon spot or the channels cannot be identified. However, after elastic inversion, the geology and the HC sweet spots are illuminated.

In view of the fact that most of the AVO responses are Class 2 types, we would require long cable length because the response is dominant at far offset. That is the main reason why AVO was not successful in the early years of exploration and production.

Conclusion

Attributes now form an integral part of prospect maturation, including risk and resource evaluation. They allow geoscientists to interpret faults and channels, recognize the depositional environment, and unravel the paleostructural history such as sequence boundaries, onlap, downlap, and unconformity. The combination of multiattributes and geologic concepts is a powerful tool for seismic interpretation and geomorphology interpretation that could lead to better

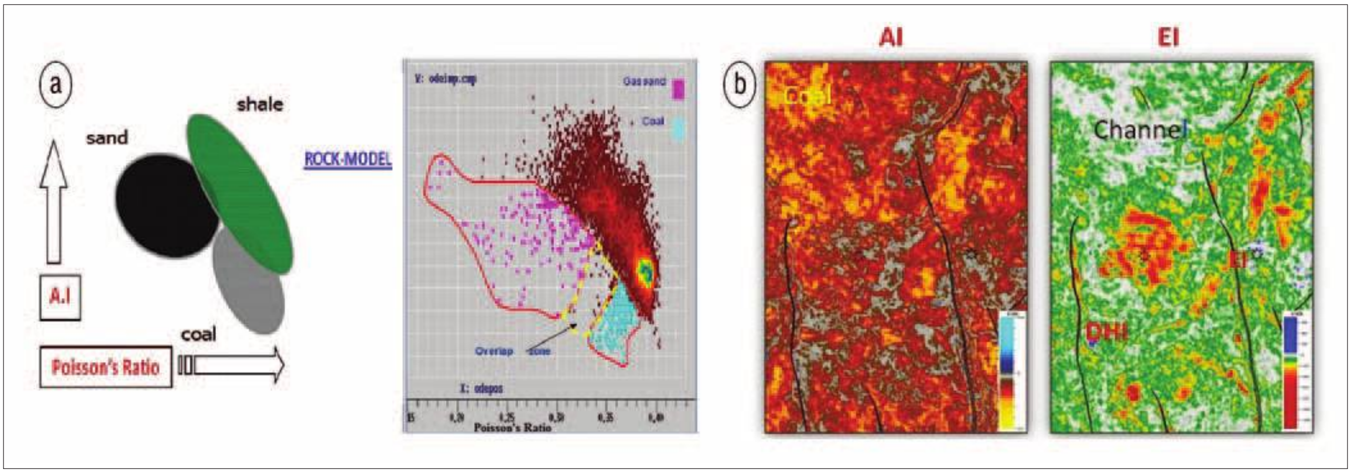

Figure 12. In the EI domain, gas sand (low σ) can be separated from coal (high σ) through elastic inversion. (a) Discrimination of sand, shale, coal, and HC in the EI domain. (b) The coal-layer masking effect is removed effectively in elastic inversion, which leads to discrimination of HC sand from shale and coal.

prospect identification and contribute to exploration success. Further attributes are used in reservoir modeling.

An attribute analysis requires high-quality data with a good signal-to-noise ratio. High-resolution 3D marine data acquired since 2000 in Southeast Asia have facilitated the successful use of attributes in our workflow. Further improvement in resolution is offered by the spectral attributes themselves by bringing in dormant and hitherto unrevealed geologic features. TLE

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