The Maximum Amplitude Weighted Integrated Energy Spectra: A New Gauge in Seismic Thin-Bed Interpretation

Eko Widi Purnomo & Deva Prasad Ghosh

Center for Seismic Imaging Universiti Teknologi Petronas Malaysia,
Building 16-02-06 Universiti Teknologi Petronas,
Bandar Seri Iskandar, 31750 Tronoh, Perak Darul Ridzuan, Malaysia
Email: ekowidi@hotmail.com

Abstract. Some combinations of seismic attributes are superior in detecting thin-bed thickness from 3D seismic data. However, their physical unit or meaning can be difficult to determine. Such attributes are considered as relative values. This paper introduces a newly developed relative-value attribute, which was identified to be more sensitive in detecting seismic thin-bed structures. The new attribute was developed based on seismic frequency shifting and amplitude decrease phenomena that occur when the seismic wave responds to a thinning bed structure. The new attribute is constructed by multiplying the integrated energy spectra with the relative maximum amplitude. Through a wedge model seismic test it was shown that the new relative-value attribute consistently gave more proportional and linear responses to the thin-bed thickness. The new attribute was examined in delineating a channel structure on the basis of public 3D seismic data from Stratton Field, Texas USA and the Group F Reservoir in the Malay Basin, Malaysia. The new attribute delineated the meandering channels featured in those two fields very well.

Keywords: *attribute-combination; channel; relative value attribute; seismic attribute; thin-bed; tuning.*

1 Introduction

As seismic profiling has problems in resolving bed thickness below a quarter wavelength, interpretation of channel structures from 3D seismic data is difficult [1-2]. Alternatively, seismic attributes can be used to detect and resolve such subtle structures. Seismic attributes can be used for either qualitative or quantitative interpretation of channel structures [3]. Amplitude and frequency, for instance, are seismic attributes that have sensitivity in detecting thin-bed thickness [4-11]. Widess [4] has shown that reflection amplitude and frequency change as bed thickness changes. It was found that at the zone below the tuning thickness (a quarter of a wavelength or less), the bed thickness has a linear relationship with the reflection amplitude and is inversely proportional to the peak spectral frequency. Based on instantaneous attributes and spectral

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decomposition, Taner, *et al.* [5] and Partyka [8] investigated the amplitude method of Widess [4] in predicting bed thickness.

Other robust attribute-based bed thickness detection methods have been proposed through derivation or combination of basic attributes (amplitude, frequency and phase). Marangakis, *et al.* [12] argued that as a consequence of wavelet differentiation, bed thickness can be predicted through the higher frequency shift. Therefore, bed thicknesses, including thin thicknesses, can be interpreted through their frequency domain signature. Marangakis, *et al.* [12] obtained integrated energy spectra as a function of frequency, later called INTENS, to accomplish bed thickness interpretation. Radovich and Oliveros [13] used a combination of instantaneous amplitude (reflection strength) and instantaneous frequency to sharpen the distinction between sand and shale based on impedance contrast. This combination is called sweetness. It can be expressed mathematically as instantaneous amplitude divided by the square root of instantaneous frequency. Another combination is INTENS with maximum and minimum seismic amplitude to predict thin-bed thickness [14].

This paper reviews INTENS and sweetness through a wedge model. A new attribute is then developed by combining relative maximum amplitude [4] and INTENS [11]. This new attribute is supposed to be a better indicator of thin-bed thickness as it provides better linearity and proportionality with regards to variations in bed thickness. 3D seismic data from two zones of interest, Stratton Field and the Group F Reservoir in the Malay Basin, were used to test the new attribute and compare it with sweetness. The significance of the results is discussed, as well as the potential contribution of seismic attributes for delineating thin-bed structures, especially channels, on the basis of 3D seismic data.

2 Theory and Methodology

2.1 Thin-Bed Seismic Amplitude

Seismically, a thin bed is defined as a bed whose thickness is less than $\lambda/4$, where λ is the predominant seismic wavelength. The seismic signature of thin beds was first studied in the seismic time domain by Ricker [15], Widess [4] and Kallweit and Wood [6]. A widely accepted thin-bed reflection formulation was proposed by Widess [4], which expresses that when two reflections are coming closer (the bed is becoming thinner), the wavelets of the two reflectors interfere with each other. The signature of such a bed is approximately equal to the differentiation of the two original wavelets. If s(t) is a seismic signature in the time domain, then the thin-bed signature can be expressed as

$$s(t)_d \approx A_d \sin 2\pi t / \tau \quad (1)$$

where t is the time relative to t_0 and τ is the predominant period of the wavelet. A_d is the maximum amplitude of $s(t)_d$ and can be approximated as

$$A_d \cong 4\pi Ab/\lambda_b \quad (2)$$

with b is the thickness of the bed, λ_b is the predominant wavelength corresponding to bed thickness b and the velocity of the bed, and A is the amplitude of the reflection when the bed is very thick (greater than twice λ).

2.2 Sweetness

This seismic attribute was developed by Radovich and Oliveros [13] with the goal of identifying thin shale and sandstone in clastic successions. Sweetness is constructed by combining two seismic attributes, i.e. instantaneous amplitude and instantaneous frequency. Mathematically it is derived by dividing instantaneous amplitude (also known as reflection strength or instantaneous envelope) by the square root of instantaneous frequency.

Instantaneous amplitude ($A_{instant}$) is the square root of the total energy of the seismic signal at time t and is defined as the total energy of the seismic trace at the corresponding time [5]:

$$A_{instant}(t) = \sqrt{x^2(t) + y^2(t)} \quad (3)$$

where x(t) is the seismic trace and y(t) is the seismic trace rotated -90°, also called quadrature or Hilbert transformed trace.

Instantaneous frequency ($F_{instant}$) is defined as the rate of change of the instantaneous phase.

If instantaneous phase θ at time t is defined as:

$$\theta(t) = \arctan\left[\frac{y(t)}{x(t)}\right] \quad (4)$$

then, the instantaneous frequency at time t is:

$$F_{instant}(t) = \frac{d\theta(t)}{dt} \quad (5)$$

Hence, sweetness can be obtained as:

$$\text{Sweetness} = \frac{A_{instant}}{\sqrt{F_{instant}}} \quad (6)$$

While the parent attributes are better in detecting thin-bed sand, sweetness is claimed to be better in giving net-pay estimation [10].

2.3 Integrated Energy Spectra (INTENS)

The relationship between bed thickness and seismic waves can be shown in the frequency domain (Fourier transform) of seismic wavelet S(ω) as follows:

$$S(\omega)=W(\omega)[1-\exp(-i\omega\Delta\tau)] \quad (7)$$

where W(ω) is the Fourier Transform of the seismic wavelet and Δτ is the bed thickness (two consecutive reflector spaces) in two-way travel time. Examining the amplitude spectrum of thin-bed seismic wavelets, Marangakis, *et al.* [12] found that there was a correspondence between the thicknesses of a bed and the peak frequency of the amplitude spectrum. The peak frequency of the amplitude spectrum is shifted to a higher value when the bed thickness becomes thinner. As a consequence of seismic wavelet differentiation (Widess [4]), the shifting of the peak frequencies is predictable through the frequency domain signature of the thin bed.

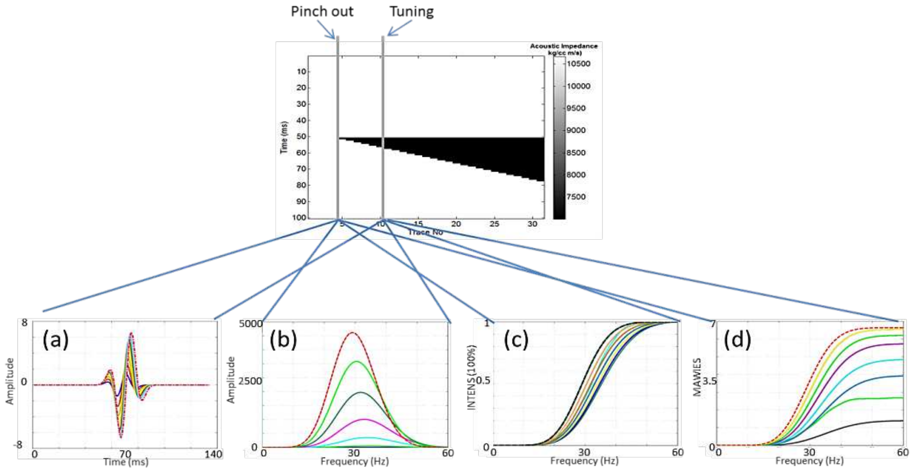

Figure 1 Thin-bed signatures: (a) seismic time-domain (amplitude), (b) amplitude spectrum, (c) Integrated Energy Spectra (INTENS), and (d) Maximum Amplitude Weighted Integrated Energy Spectra (MAWIES).

Integrated Energy Spectra (INTENS) is a form of frequency domain analysis, first introduced by Marangakis, *et al.* [12]. INTENS is suggested to be a sensitive detector of seismic thin-bed structures. INTENS is defined as integrated partial (normalized) energy spectra as a function of frequency. Mathematically, the INTENS of a set of time series data at frequency f is defined as:

$$E(f) = 100\,\frac{\int_{fl}^{f} A(f)A^{*}(f)df}{\int_{fl}^{fu} A(f)A^{*}(f)df} \quad (8)$$

where A(f) and A*(f) are the amplitude spectra of the time series data at frequency f and the conjugate, consecutively. fl and fu are the lowest and highest frequency range consecutively.

As a normalized energy spectrum INTENS is not only sensitive to layer thickness changes but is also stable in signaturing below seismic resolution thickness (Figure 1(c)).

2.4 Maximum Amplitude Weighted Integrated Energy Spectra (MAWIES)

A new attribute is proposed in order to obtain an attribute that correlates more proportionally and linearly to bed thickness variations. The new attribute is obtained simply by multiplying the integrated energy spectra (Eq. (8)) with the maximum amplitude (Eq. (2)). The new attribute can be expressed mathematically as

$$E_m(f) = A_d \text{ x } E(f) \tag{9}$$

where $E_m(f)$ is maximum amplitude weighted integrated energy spectra as a function of frequency, A_d is the maximum amplitude of the seismic waves, and E(f) is the INTENS in frequency f of the according seismic time series.

As explained in Section 2.3, INTENS E(f) successfully eliminates the unstability of the energy spectrum by normalizing the energy spectrum of a seismic wave, when the layer thickness becomes very thin (below one over eighth of the seismic wavelength). The result is that INTENS will provide a stable signature for the whole seismic range below the tuning thickness. However, there is a potential problem because INTENS signatures below the tuning thickness are very close to the signature of the tuning thickness. Some signatures even practically merge (Figure 1(c)). INTENS will have difficulty to separate signatures below the tuning thickness, particulary in the presence of noise, which is common in real seismic data. On the other hand, as identified by Widess [4] and Kalweith, *et al.* [5], the maximum amplitude has a strong linear relationship with the layer thickness in the zone where INTENS potentially has problems.

Combining both attributes gives a new response (signature) that will contribute a solution for a long-standing challenge in resolving thin-bed structures through their seismic response. Multiplication of INTENS with maximum amplitude makes INTENS's signatures weighted and move away or separable from the tuning thickness signature (Figure 1(d)). This means that the INTENS signature will have a higher resolution in detecting thin-bed structures and hence promise a better interpretation. Because the integrated energy spectra are weighted by the maximum amplitude, the new attribute is proposed to be named Maximum Amplitude Weighted Integrated Energy Spectra (MAWIES).

2.5 Wedge Model

The wedge model is a useful geological model to study seismic thin-bed structures. A wedge model has been built to test our method. The top and bottom reflection coefficients of the wedge model have opposite polarities, +0.2941 and -0.1579 respectively. The wedge thicknesses increase from 2 ms (5th trace) to 54 ms (last trace). The seismic model of the wedge is built by convolving the reflectivity of the wedge with a zero-phase Ricker wavelet with a dominant frequency of 25 Hz. The tuning thickness is about 13 ms at the 11th trace.

Figure 2(b) represents maximum amplitude response and INTENS at the dominant frequency versus wedge thickness. The three seismic attributes' thin-bed responses were also investigated for the purpose of comparison (Figure 2(c)). The investigation focused on the response of thicknesses from the tuning thickness to close-to-zero thickness (pinch out). As understood previously, due to frequency bandwidth limitations, the seismic time domain (Figure 1(a)) does not respond to changes in thickness. The amplitude spectrum (Figure 1(b)) has a more sensitive response except for near zero thickness. The peak amplitudes of near zero thickness are too small compared to the nearest thicker thickness, which potentially leads to interpretation difficulties. In contrast, the integrated energy spectra signature (Figure 1(c)) is capable of altering the near zero signature to the same order as the adjacent thickness. This is easy to understand, because the integrated energy spectra normalize the energy spectrum.

Figure 2(c) represents the instantaneous amplitude, instantaneous frequency response and sweetness response at the top of the wedge versus the wedge thickness of the wedge model. Examining the two graphs (Figure 2), it is found that when an attribute is sensitive to bed thickness changes, the attribute will be a good indicator for bed thickness identification. It is notable that instantaneous frequency has an inverse relationship with wedge thickness, where instantaneous frequency decreases when wedge thickness increases. INTENS is ambiguous when the bed thickness is below half of the tuning thickness. A rapid decrease of the maximum amplitude response, due to the decreasing layer thickness, causes an increasing trend of INTENS (Figure 2(b)). However, INTENS has a wider linear zone than maximum amplitude.

Figure 3 shows the plot of INTENS and MAWIES at the dominant frequency and maximum amplitude against layer thickness. It is shown that MAWIES has

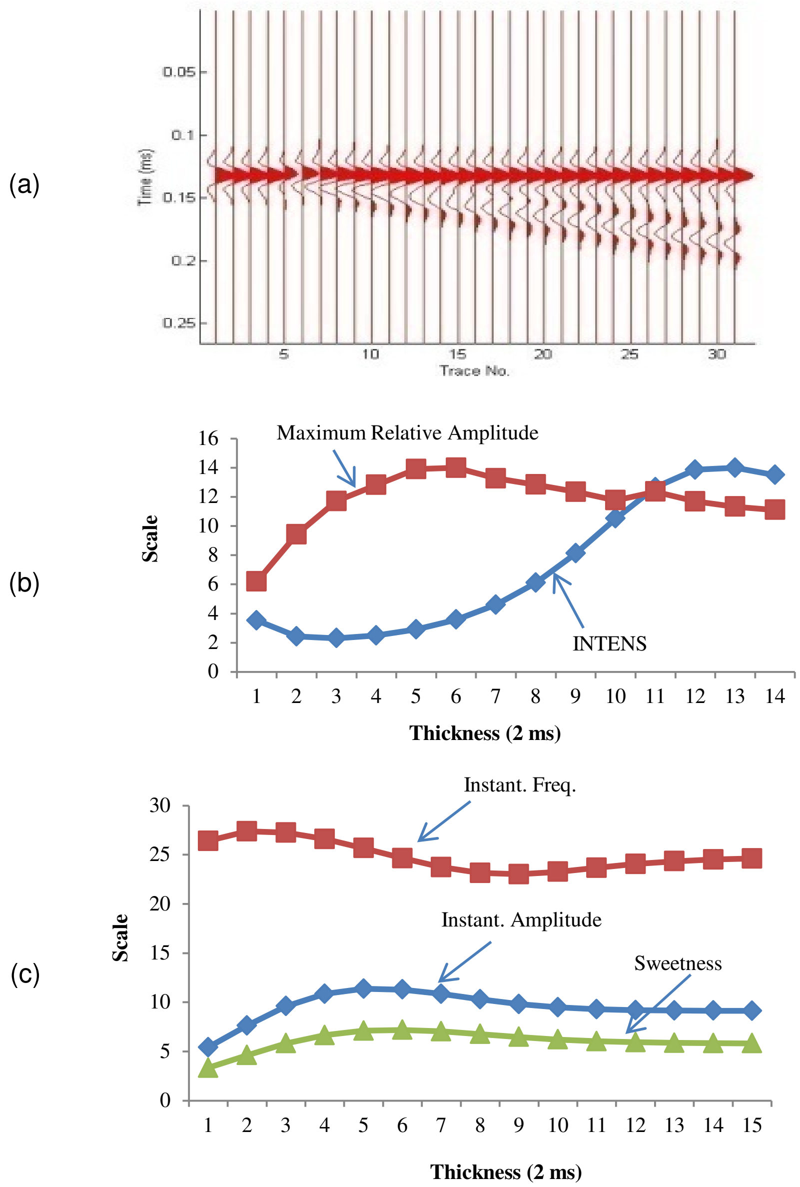

Figure 2 Seismic wedge model (a); maximum amplitude and INTENS response amplitude (b); instantaneous amplitude, instantaneous frequency and sweetness response (c). The tuning thickness is about 13 ms at the 11th trace of the seismic model (a).

a more linear and proportional response to bed thickness than the other attributes. Providing a wider linear zone is another advantage of INTENS and MAWIES compared to maximum amplitude. Qualitatively, thinning or thickening of a layer will be easier to identify from an INTENS or MAWIES map rather than from an amplitude map. As most layer thickness estimations are based on a linear relationship between seismic attribute and layer thickness, having a stronger linear relationship will increase the accuracy of the estimation. Availability of a wider range of linearity will extend the threshold that restricts the value of the attribute that is used for thickness estimation. More layer thicknesses can be accurately estimated.

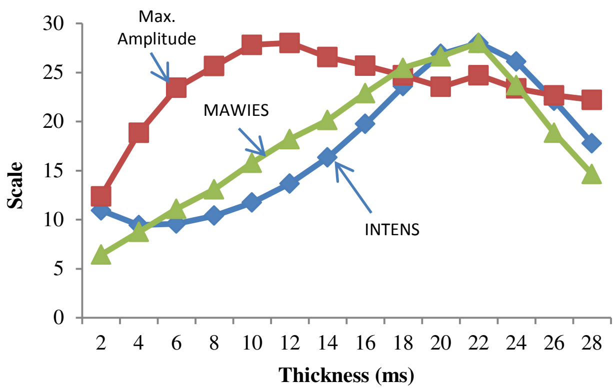

Figure 3 Wedge model response of maximum amplitude (rectangle line), INTENS (diamond line) and MAWIES (triangle line). The tuning thickness is about 13 ms.

The physical meaning of MAWIES may be difficult to determine. The only information is that the physical unit of the attribute is similar to that of amplitude. There are two seismic properties that change following changes in bed thickness, i.e. amplitude and peak frequency. A thinning layer stabilizes the amplitude near the tuning thickness and then linearly decreases to zero as the thickness becomes zero. At the same time, the peak frequency is shifted from low to high and decreases again after stabilizing. MAWIES combines the two different responses to a proper seismic signature for a thin-bed structure. Like sweetness, MAWIES can best be called a relative-value attribute.

3 Methodology Testing

3.1 Stratton Field Seismic Structure

Stacked 3D seismic data from Stratton Field, Texas USA were used to test the new attribute together with sweetness. The data are 3D migrated seismic data, comprising of 100 in-lines and 200 cross-lines in an interval of 55 ft and 3000 ms in depth with an interval of 2 ms. Imaging features below the seismic resolution are the challenge provided by these data. Some of the channels can be readily seen, particularly at shallow levels. A shallow, non-productive channel exists at about 840 ms depth. This channel is reported to differ only 2 ms from its surrounding traces [16].

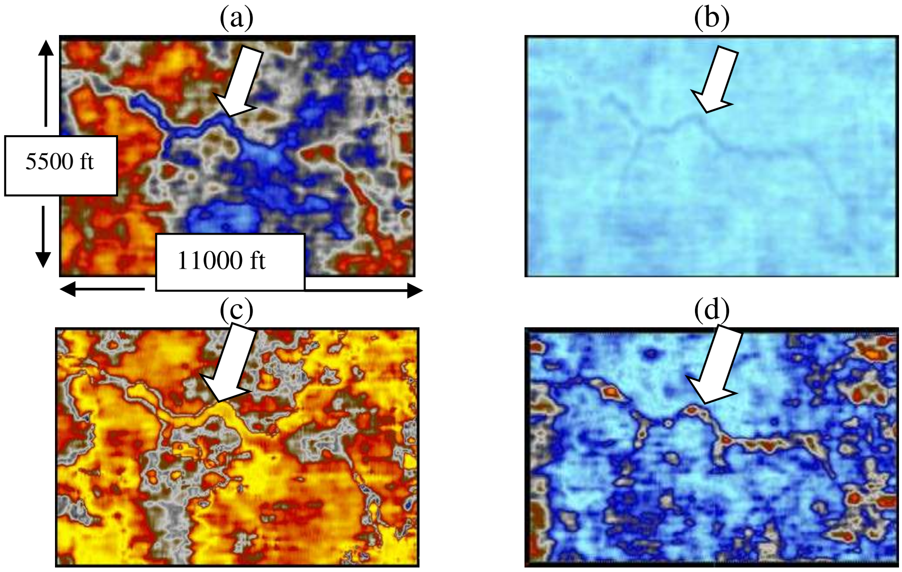

Figure 4 Time slice of amplitude (a), sweetness (b), INTENS (c), and MAWIES (d), showing the Stratton channel structure (white arrow) and its distribution. Note how color gradations appear on the body of the channel in the MAWIES image, showing variations in thickness, which do not appear in the INTENS image.

Figure 4 shows an image of the Stratton Field shallow channel derived from three different attributes. The channel can be easily identified by amplitude measurements on a time slice (Figure 4(a)).

The gentle dip in the channel’s bed is introduced by an amplitude phase change. Figure 4(b) shows how sweetness can clearly distinguish the channel from its surroundings. The INTENS image (Figure 4(c)) clearly shows some parts of the channel body. A more uniform color on the channel body of the INTENS image is suggested because INTENS fails to follow the thickess variation of the channel. Compared to the other three images, INTENS also fails to distinguish some parts of the channel body from its surroundings. It is suggested that this is because the thickness of the channel and its surroundings are similar in thickness, i.e. around the seismic tuning thickness. Figure 4(d) shows a firm image of the channel by MAWIES. Color variations indicate thickness variations along the channel. Major parts of the channel are thicker than its surroundings, as shown by its higher MAWIES or brighter color. It is shown that the channel structure can be better imaged laterally by sweetness and MAWIES. This is shown by the better lateral continuation of the channel imaged by both sweetness and MAWIES.

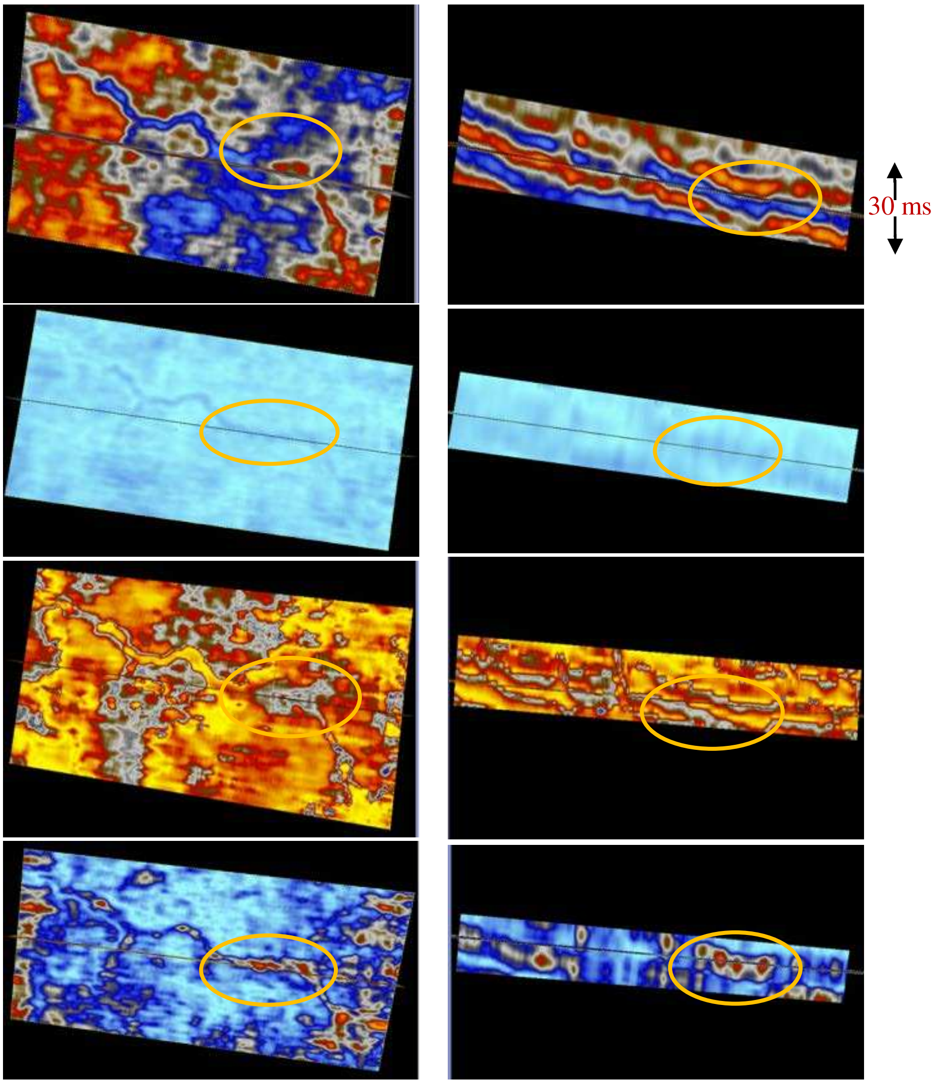

Figure 5 Time slice (first column) and cross section (second column) along the Stratton channel. Amplitude (1st row), sweetness (2nd row), INTENS (3rd row) and MAWIES (4th row). Ellipses identify the channel's body.

Figure 5 shows a cross section of the channel depicted in Figure 4. It is difficult to identify the channel body from the seismic cross section. It only shows a small change in amplitude, which may only be noticed by an experienced interpreter. The cross section of sweetness shows a clearer channel body image. The channel is easier to distinguish from its surroundings. Some experienced users have used sweetness to quantitatively estimate the relative net-to-gross ratio of a sand reservoir. However, it was mentioned that it is not possible to use sweetness for measuring sand thickness from logs [10]. As noted before, the cross section of INTENS does not show a clear image of the channel body. As INTENS's signatures of below the tuning thicknesses are practically identical to each other, their thicknesses are also estimated similarly or almost equal. In contrast, the cross section of MAWIES shows a very clear body channel. The channel can be clearly distinguished from its surroundings, either laterally or vertically. This indicates that INTENS's resolution is improved by MAWIES.

Variations in the sweetness, INTENS and MAWIES values, as shown in Figure 4 and Figure 5, represent variations in lithology (e. g. sandiness) and channel thickness. Thickness variations in a channel can be better detected by INTENS and/or MAWIES. Meanwhile, the impedance contrast with the surroundings will be better detected by sweetness. Different combinations of impedance contrast and thickness will give different effects in the detection performance of the three attributes.

3.2 Group F Reservoir Seismic Image

Sweetness, INTENS and MAWIES were tested to image the Group F Reservoir in the Malay Basin, Malaysia. The challenge was to delineate the channel geometry and flow direction as well as channel connectivity. The channel complex is located at a depth of about 1490 ms or 1613 m. An amplitude time slice clearly shows some parts of the channel(s). One appraisal (wildcat) well is available. The Group F Reservoir is reported to be predominated by shale with siltstone and minor sandstone. The average net sand thickness is reported to be very thin, 4 m, from a predicted gas column of 47 m. The porosity of the sand is 24%.

Figure 6 shows an image of the Group F Reservoir according to four attributes, including seismic amplitude. Some parts of the channel are clearly depicted by amplitude, sweetness, INTENS and MAWIES. The incomplete channel visualization is due to the thin thickness and a northward dip of the channel. There is no significant difference with what is shown in Fig 4. Again, sweetness and MAWIES provide stronger lateral channel visualization than the two other attributes. A well passing through a cross section of the amplitude, sweetness, INTENS and MAWIES cube is shown in Figure 7.

The cross section crosses the appraisal well in the inline direction. A gamma ray was inserted into the cross section. Although the four attributes cannot be compared directly with well-log data, it is shown that, structurally, the well-log data confirm the three-attribute cross section. Confronted with a well-log interpretation, the INTENS and MAWIES cross sections very clearly show a 5.5 m sand reservoir. The top of the reservoir is at a depth of 1609.5 m, associated with a 1508 ms time depth, while the base is at a depth of 1609.5 m 1615 m, associated with a 1512 ms time depth. A gas water contact (GWC), identified at a depth of 1622 m (1498 ms), was neither detected by INTENS nor by MAWIES. A sand series with an average thickness of 4 m inside a gas column of 47 m that extends from a depth of 1575 to 1622 m (1484 to 1492 ms time depth) was not clearly confirmed by any attribute. However a sequence of thick and thin layering could be imaged well by MAWIES.

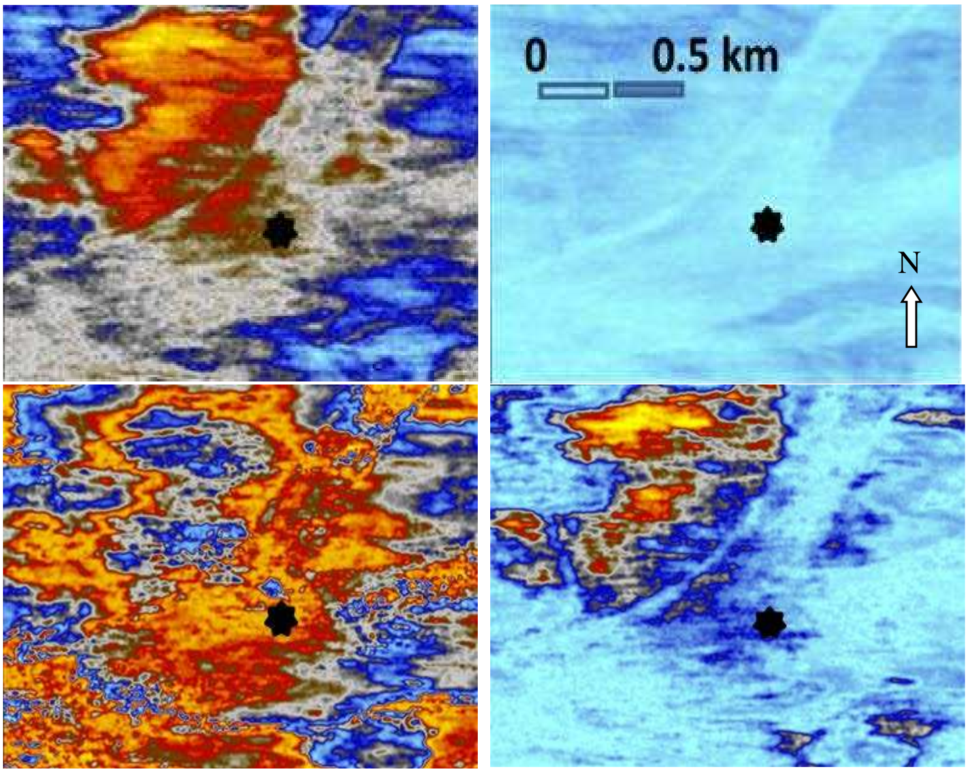

Figure 6 Time slice of amplitude (1st row, 1st column), sweetness (1st row, 2nd column), INTENS (2nd row, 1st column) and MAWIES (2nd row, 2nd column), showing the Group F Reservoir channel complex structure. The star indicates the location of an appraisal well.

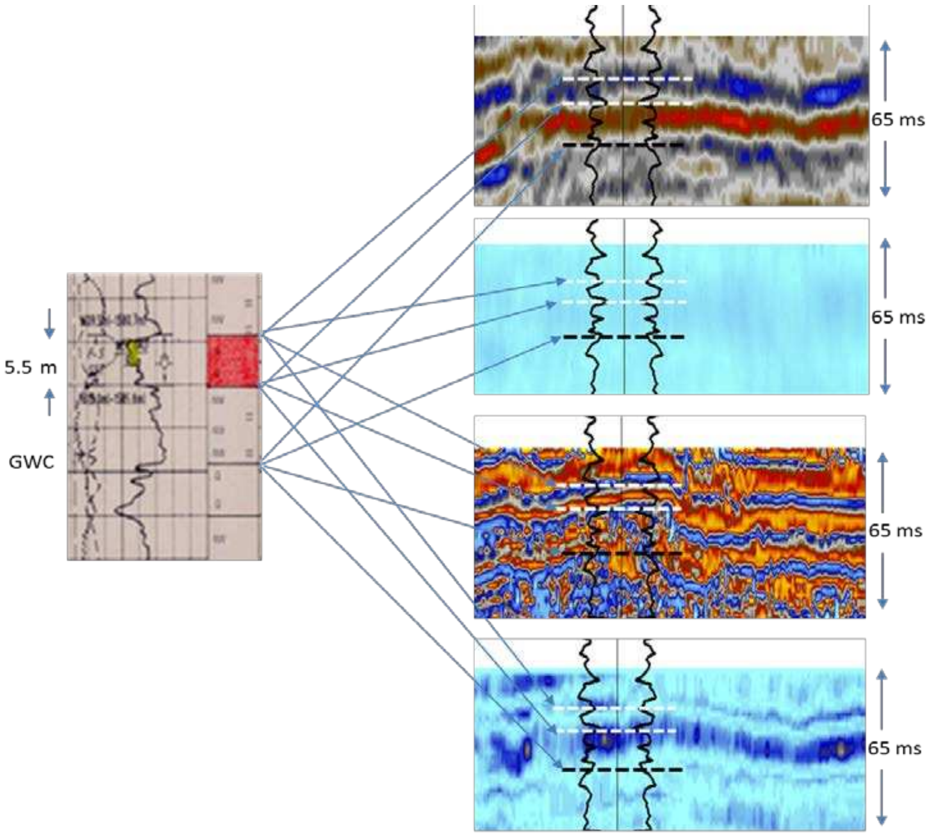

Figure 7 Cross section in inline direction across appraisal well B-1 in Figure 6. Consecutively for right column, from above to below: amplitude, sweetness, INTENS and MAWIES. The left column is a well interpretation, showing a 10 m interpreted sand reservoir. The two white dash lines indicate time depth corresponding to top and bottom of interpreted 10 m sand reservoir. The black dashed line is interpreted gas water contact (GWC).

4 Discussion

Sweetness was first derived for identifying sands in clastic succession using 3D seismic data. The sands were characterized by combining amplitude and frequency or acoustic impedance contrast. Sweetness is useful for detecting stratigraphic features such as sand-filled channels when those features can be distinguished from the background lithology by a combination of instantaneous frequency and instantaneous amplitude [10]. However, this study shows that sweetness does not always clearly image a thin-sand series, particularly in vertical direction. Sweetness had difficulty confirming the well-log data.

INTENS tries to image the thin bed in a different way, through the bed's energy spectra, which strongly correlate with the bed's thickness. The shifting of the peak frequency due to changes in bed thickness makes the energy spectra consistently detect every bed-thickness change. By integrating or normalizing the energy spectra, INTENS stabilizes the unstable very low energy spectra of very thin (one over eigth of the seismic wavelength) bed thicknesses. INTENS succesfully brings the whole seismic energy spectra signature below the tuning bed thickness to a detectable level. In ideal conditions (noise-free), all bed thicknesses can be resolved by INTENS.

INTENS faces a problem when resolving bed thickness in real conditions (noisy signal) because INTENS signatures of below tuning thickness are merged in practice. The resolvability of INTENS decreases for real data cases. MAWIES is proposed to overcome this problem. Attribute combination is the basis of our proposal. The strong linear relationship and steep gradient of maximum amplitude (also called relative maximum amplitude) to bed thickness of a short range of below tuning thicknesses is proposed to be combined with the INTENS signature. Multiplication of INTENS and maximum amplitude modifies the INTENS signature, following bed thickness changes according to the maximum amplitude trend. The strong gradient of the maximum amplitude makes the INTENS signatures of different thicknesses weighted with different values and separates them. Separation of INTENS signatures indicates increasing resolvability of INTENS. Maximum amplitude weighted integrated energy spectra, MAWIES, is proposed as the name for the new INTENS signature in which INTENS is weighted by the maximum amplitude to construct a new attribute.

A number of tests have shown that MAWIES is more powerful in detecting and resolving seismic thin bed thickness. Relative value may be the best way to define MAWIES because the physical unit is difficult to determine.

5 Conclusion

A new seismic attribute can be derived from previous basic attributes in order to obtain one that is more sensitive to changes in earth properties. However, the physical unit or meaning is sometimes difficult to determine. Such a derivative attribute can be seen as a relative value, while its physical meaning is still open for discussion.

A new attribute has been derived from previous bed-thickness-sensitive attributes. The new attribute is constructed by multiplying the integrated energy spectra (INTENS) with the maximum amplitude of the according seismic trace. Maximum amplitude weighted integrated energy (MAWIES) is proposed as the name of the new attribute. The attribute has better bed-thickness sensitivity and linearity of response than its parents (amplitude and INTENS). The new attribute is capable of delineating channels from 3D seismic data as well as sweetness does, or even better. Derived from energy spectra, the new attribute is supposed to be strongly correlated with bed thickness and a good tool for quantitative interpretation.

Confronted with well interpretation, MAWIES shows the capability of resolving a sand reservoir as thin as 5.5 m quite well. A thick and thin series of layers was also shown, which were in line with the well interpretation result. Further methods, e.g. inversion, may be the best way to quantitively observe the capability of MAWIES to estimate bed (thin-bed) thickness.

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