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Slope of Spectral Amplitude: A Simple Yet Effective Hydrocarbon Indicator

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Abstract: Spectral decomposition has been developed and used for many years to help understand the subsurface condition. Numerous different approaches and specific applications of this methodology have been proposed and each of the approaches has its own advantages. The Slope of Spectral Amplitude is a new spectral decomposition-based methodology, which is developed based on the intrinsic seismic attenuation phenomenon affecting the seismic spectrum. The difference of spectrum will be characterized by Intercept and Gradient parameters. These parameters can be used to identify the presence of hydrocarbon from seismic data. Further extension of this concept, transformed the Intercept and Gradient result into Gas Probability data which indicates high probable gas occurrence. A good relationship between gas occurrences at the wells with the resulted Intercept, Gradient and Gas Probability data is shown through several examples presented in this study. These examples cover different seismic data environment and different intervals of analysis.
Keywords: Hydrocarbon indicator, Spectral decomposition, Seismic spectrum, Slope

Abstrak: Metode dekomposisi spektral telah cukup lama dikembangkan dan digunakan untuk kepentingan memahami kondisi di bawah permukaan. Dalam perkembangannya, muncul beberapa pendekatan maupun aplikasi yang berbeda dari metode ini, dimana masing-masing memiliki keunggulan tersendiri. Slope of Spectral Amplitude merupakan pengembangan baru dalam dekomposisi spektral, dimana metode ini dikembangkan berdasarkan fenomena atenuasi intrinsik dari sinyal seismik yang mempengaruhi perubahan spektrum seismik. Perbedaan spektrum tersebut dapat dikarakterisasi melalui dua parameter yakni Intercept dan Gradient. Kedua parameter ini selanjutnya dapat digunakan untuk mengidentifikasi keberadaan hidrokarbon dari data seismik. Konsep ini dapat dikembangkan lebih lanjut, dengan mengubah paramater Intercept dan Gradient menjadi data Probabilitas Gas yang akan mengindikasikan secara langsung kehadiran hidrokarbon (gas). Dari beberapa contoh yang disertakan dalam tulisan ini, terlihat korelasi yang baik antara hasil paramater Intercept, Gradient, dan Probabilitas Gas dengan kehadiran gas yang dikonfirmasi oleh data sumur. Contoh-contoh yang disertakan mencakup aplikasi metode pada tipe data seismik serta interval analisis yang berbeda.
Kata kunci: Indikator hidrokarbon, Dekomposisi spektral, Spektrum seismik, Slope

1 INTRODUCTION

For many years, seismic data has been heavily utilized in the oil and gas industry to understand the subsurface condition. From imaging the geological structure beneath the surface to identifying the possible accumulation of hydrocarbons trapped at certain depth and location. The latter objective can be achieved through numerous seismic-based methodologies, such as analysis from multiple seismic attributes, amplitude versus offset (AVO), seismic acoustic or elastic inversion, and many more.

Spectral decomposition is a signal-based analysis approach developed to answer the same challenge. With this methodology, a seismic signal can be decomposed into its frequency components. Throughout its development, numerous versions of spectral decomposition had been proposed. From using small time Fourier window (Partyka, Gridley, & Lopez, 1999), using a moving and scalable Gaussian window (Stockwell, Mansinha, & Lowe, 1996), to utilizing wavelet transform as its base of signal analysis (Castagna, Sun, & Siegfried, 2003; Sinha, Routh, Anno, & Castagna, 2005). The spectral decomposition is also applicable to different objectives, such as mapping thin-bed and geological discontinuity (Partyka et al., 1999), detecting hydrocarbon from low-frequency shadow below seismic anomaly (Castagna et al., 2003) and direct low-frequency anomaly at reservoir level (Goloshubin, Van Schuyver, Korneev, Silin, & Vingalov, 2006; Sinha et al., 2005).

In an area that has limitations in terms of data availability and quality (log data, multi-angle seismic data, etc.), complex (and costly) yet powerful seismic reservoir characterization methodologies such as seismic AVO and inversion may not be available or even applicable. Therefore, a simpler approach such as seismic attribute analysis (including spectral decomposition) offers an alternative solution that is easier to be accessed and applied, as the attribute analysis tool is usually embedded in most of the seismic interpretation software.

2 SLOPE OF SPECTRAL AMPLITUDE

As seismic wave traveled through subsurface formations, it loses energy due to many factors, such as spherical divergence, scattering, intrinsic absorption and reflection at formation interfaces. The amplitude and frequency content of the recorded seismic wave at the surface will be influenced by the condition of subsurface, such as lithology, formation thickness, and the fluid properties inside the formation. In the case of hydrocarbon-filled formation, Figure 1 shows the differences in seismic spectrum extracted from gas-filled formations (red box, red spectrum) and the non-gas formations (blue box, blue spectrum). From this figure, it is observed that the seismic wave tends to lose its high-frequency component (highly attenuated) in hydrocarbon (gas) filled formation. This phenomenon is suspected caused by the intrinsic attenuation of the hydrocarbon filled formation. This intrinsic attenuation was also addressed as one of the possible mechanisms which introduced low-frequency shadow beneath gas and condensate reservoirs (Ebrom, 2004)

The Slope of Spectral Amplitude approach is developed based on this intrinsic seismic attenuation phenomenon. The variation of the seismic spectrum which is affected by this high-frequency loss can be characterized by the slope of the spectrum. The difference can be represented by the Intercept and Gradient of the downward slope. A highly attenuated zone theoretically is expected to show a higher Intercept value and smaller (more negative) Gradient value, while the low attenuated zone is expected to show the contrary condition (Figure. 2).

The commonly known spectral decomposition methodology offers detailed seismic spectrum information for each time sample of the seismic signal (Figures. 3). Thus, it is an ideal methodology to analyze the slope of the spectrum differences on each time sample, for every seismic trace available in the seismic data, either 2D or 3D data. A specific spectral decomposition methodology called Generalized Spectral Decomposition is used in this paper. The signal decomposing process utilizes scaled and time-shifted wavelets with oscillating shapes (Aarre & Hoekstra, 2015).

The downward slope can be modeled using the following quadratic sinusoidal function:

$$y = I + (G.\sin^2 x) \tag{1}$$

Where y is the amplitude spectrum, I is the Intercept, G is the Gradient and x is the frequency. The function is similar to Shuey's 2-term approximation from Aki-Richard's formula. This approach is taken to mimic the conventional concept of AVO Intercept and Gradient, which fits quite well with the downward slope of the spectrum curve (Figure. 4). To estimate the Intercept and the Gradient, a simple mathematical substitution between two anchor points (with known y and x) is used in this approach. The first anchor point is at the top of the spectrum curve, and the second anchor point is at the downward slope. Due to limited resources, these anchor points are selected manually in a way that can produce a nice fit between the downward slope with the resulting curve from the quadratic sinusoidal function.

As explained earlier, the focus of this formula is the downward slope of the spectrum from its peak, which is affected by the presence of hydrocarbon. The amplitude spectrum from the Generalized Spectral Decomposition is positive (or zero in case of no amplitude) and the frequency range of the downward slope is also positive. Therefore, the resulting Intercept of the downward slope shall be positive (or zero in case of no amplitude) and the resulting Gradient of the downward slope shall be negative (or zero in case of no amplitude).

In full-scale calculation, 2D or 3D seismic time domain data will be used as the input. The typical Spectral decomposition attribute in most interpretation software can only generate iso-frequency (or common frequency) data at a certain frequency value. Thus, it is required to generate multiple iso-frequency datasets which cover the whole seismic bandwidth from low to high frequency (maximum at Nyquist). A spectral re-construction attempt from these iso-frequency datasets is then performed to achieve the commonly known spectrum curve representation (amplitude spectrum vs frequency plot). Anchor points in Intercept and Gradient estimation can be determined using several samples at wells as reference. At these points, the frequencies of the anchors are known. Therefore, the estimation of Intercept and Gradient can be extended to full-scale datasets (2D/3D) using the same quadratic sinusoidal function with the anchor frequencies (x) and the related iso-frequency datasets (y) as the input (Figure. 5)

It is known that the seismic frequency tends to decrease with the increase of depth and may also vary spatially. Therefore, ideally, the Intercept and Gradient estimation shall be limited at a certain time interval or area where the general frequency content is relatively consistent. If the methodology is intended to be applied to a large dataset, it is suggested to perform preliminary frequency analysis at different intervals (or areas) to confirm the frequency consistency. The inconsistency observed from the frequency analysis may result in separate applications of the methodology at certain time intervals or areas.

3 APPLICATION TO FIELD DATA

Based on the explanation from the previous chapter, it is clear by using the Slope of Spectral Amplitude methodology, Intercept and Gradient data from the spectrum can be generated using seismic data as input. The resulting Intercept and Gradient data can be used to identify the presence of hydrocarbon which attenuated the recorded seismic signal.

Figure 6 shows a comparison of a seismic line crossing several wells from the Shallow interval of Tunu Field (transition zone environment) in Mahakam Delta, with the Intercept and Gradient products from Slope of Spectral Amplitude. From the seismic data (A), it is observed the occurrence of several bright amplitude anomalies at well locations, which may indicate hydrocarbon presence. Some of these anomalies are then confirmed as gas hydrocarbon by the drilling result. Red dots depict the gas found from the well, and the blue dots mark where there was no gas found at the location, mostly water. Interestingly, the Intercept (B) and Gradient (C) data show clearer indications of gas-related anomalies, which will have higher Intercept value (positive) and lower Gradient value (negative). This example shows that the Intercept and Gradient from Slope of Spectral Am-

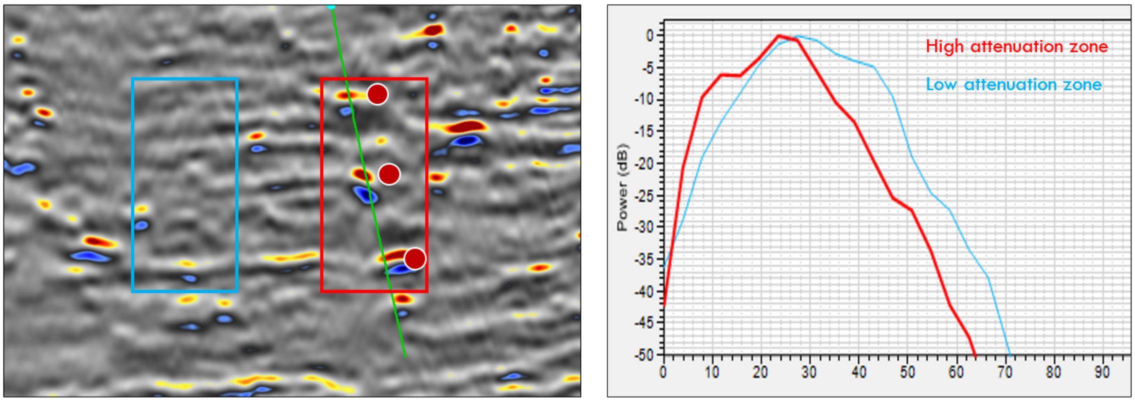

Figure 1. Seismic frequency spectrum differences (right) related to hydrocarbon and non-hydrocarbon presence (left).

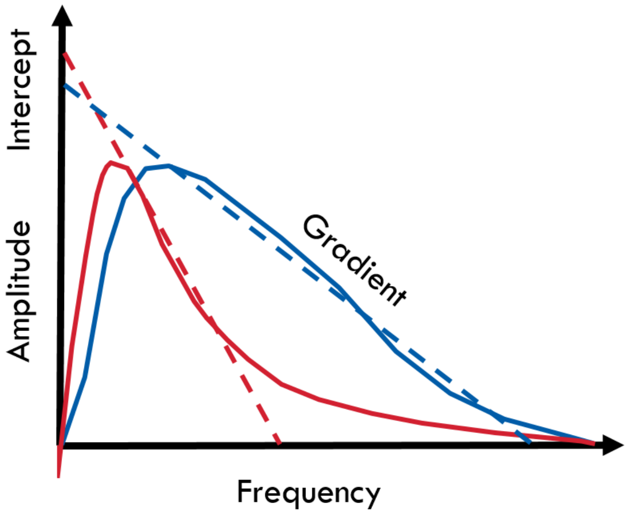

Figure 2. Attenuated seismic frequency spectrum characterized by Intercept and Gradient.

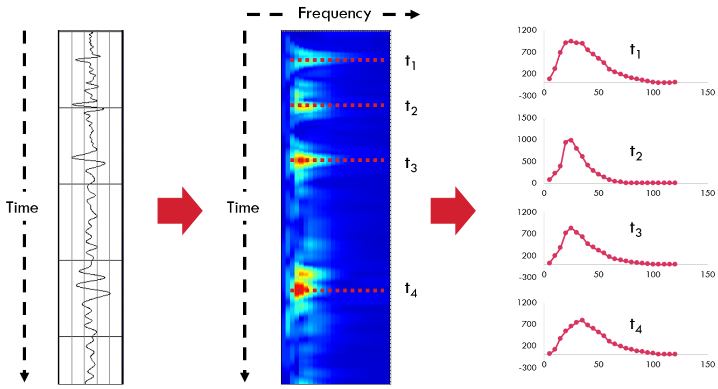

Figure 3. Spectral decomposition gives seismic spectrum details for every time samples

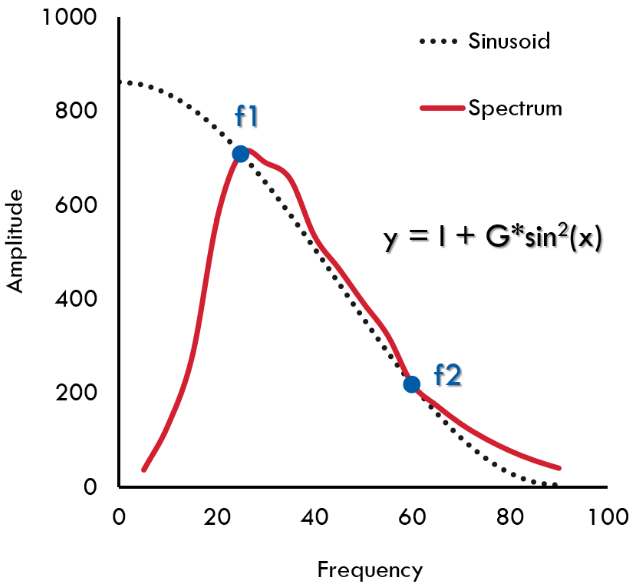

Figure 4. Intercept and Gradient estimation using quadratic sinusoidal function

plitude can detect and localize anomalies caused by hydrocarbon presence.

The application of Intercept and Gradient can be extended further, to achieve better discrimination of gas anomaly. The Intercept and Gradient can be extracted as logs at wells. From these logs, samples are taken at the gas and non-gas events (refer to the fluid interpretation result from well logs), which will serve as training data. The cross plot between Intercept and Gradient samples will be used to design a probability density function to separate the "gas cluster" from the background (Figure 7). Gas cluster is defined as cross plot area dominated by gas samples, which theoretically shall be located in high Intercept and low Gradient range. This process produces Gas Probability interpretation derived from the Slope of Spectral Amplitude methodology.

As an example, Figure 8 shows a seismic line at the Fresh Water Sand interval of the Sisi Nubi field (marine environment) in the Mahakam delta. Bright amplitude anomaly was observed at Horizon X, separated by faults. RMS amplitude map was then generated with a 50ms window using Horizon X as reference. Interesting channel-like features

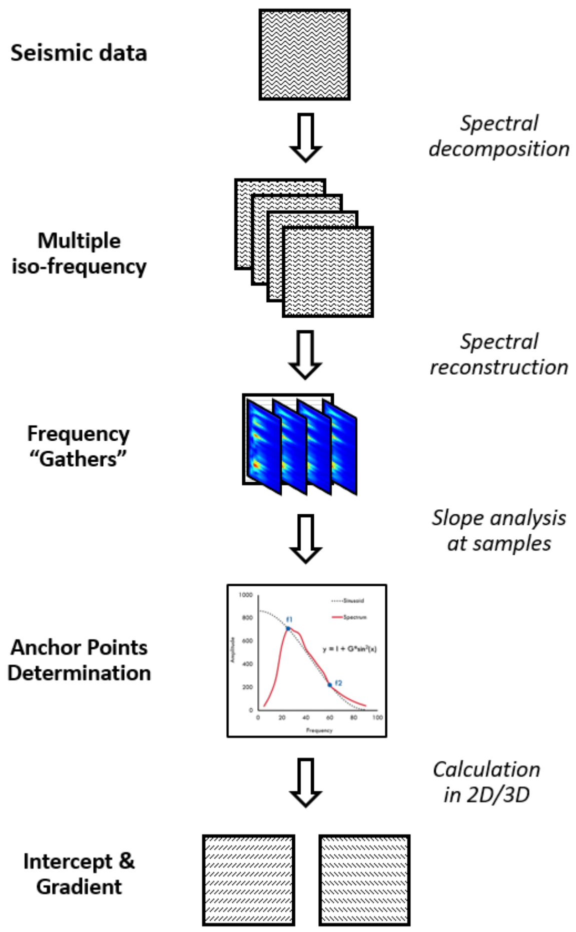

Figure 5. Slope of Spectral Amplitude workflow

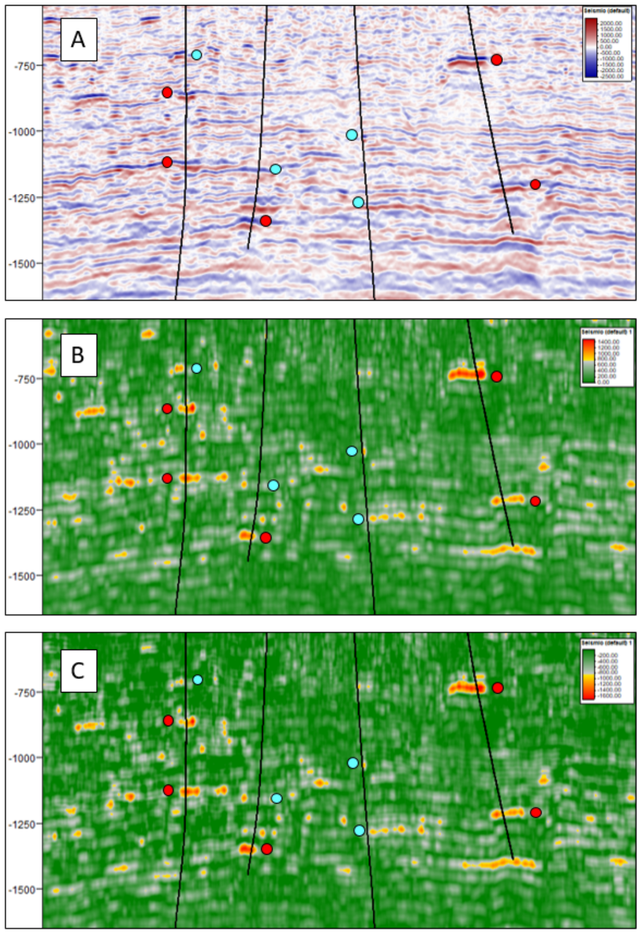

Figure 6. A) Seismic line from Shallow interval of Tunu field, crossing several wells. Black lines are the well trajectories. B) Intercept from Slope of Spectral Amplitude at the same line. C) Gradient from Slope of Spectral Amplitude at the same line. Red dots show where there is gas, blue dots show where there is no gas.

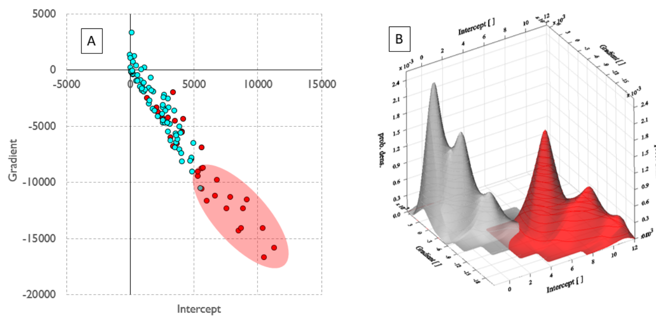

Figure 7. A) Cross plot between Intercept and Gradient at several well samples. Red dots represent gas samples; blue dots represent non-gas samples. Gas cluster is interpreted as red oval polygon. B) The simplified Probability Density Function (PDF) designed based on the Intercept and Gradient cross plot. Red surface represents the gas definition; grey surface represents the background (non-gas) definition.

were observed from the RMS amplitude map in the mid-panel between Fault A and Fault B (Figure 9). These features were confirmed as gas from the well result, marked as black dots. Gas was also found from several wells drilled on the west panel from Fault A, however, the amplitudes are not as strong as in mid-panel, even in some cases are minimal.

Using Slope of Spectral Amplitude methodology, Gas Probability data was generated. A Gas Probability map was then extracted as a surface attribute using a 50ms window based on the same horizon (Figure 10). The high probability anomaly has shown the same channel-like features in mid-panel with better definition. Moreover, the presence of gas in the west panel was better represented by this high probability anomaly.

4 CONCLUSIONS

Conventional seismic reservoir characterization is not always accessible and easily available to be performed, due to limited data availability, specific software requirement, additional cost, and longer time to be delivered. This study shows that a simple methodology based on spectral decomposition, Slope of Spectral Amplitude, offers a powerful aid to identify the presence of hydrocarbon from seismic data.

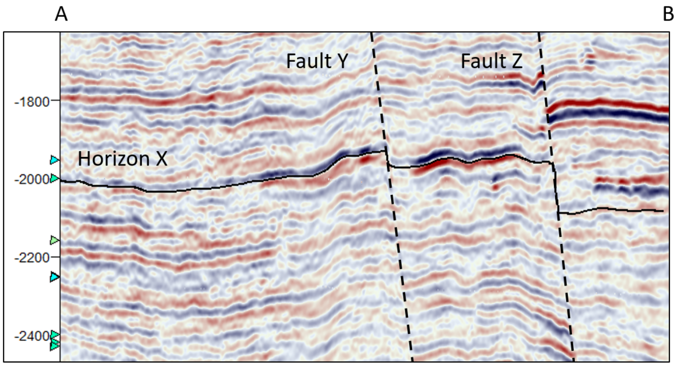

Figure 8. Seismic line from Fresh Water Sand interval of Sisi Nubi field, crossing two major faults. Bright amplitudes were observed at Horizon X location.

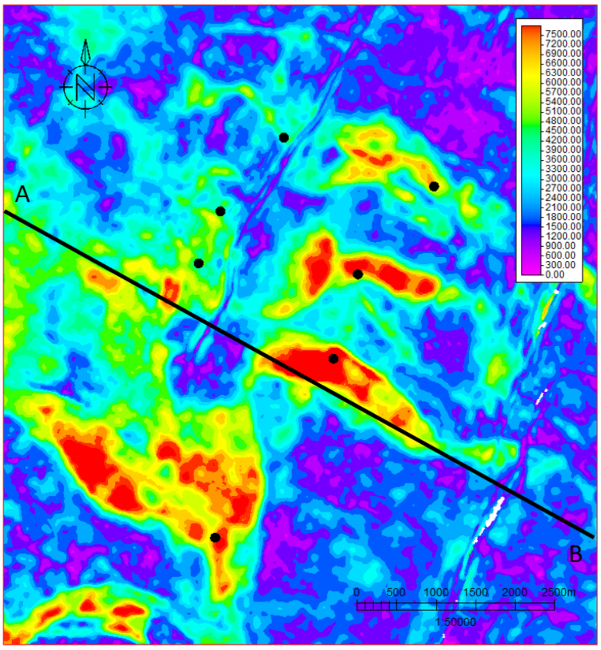

Figure 9. RMS amplitude map with 50ms window using Horizon X as reference. Black line shows the seismic line. Black dots represent gas found in wells.

The examples presented in this study show a good relationship between Intercept and Gradient generated from the methodology with the presence of gas anomalies. The further extent of the methodology in a form of Gas Probability data also shows the same benefit, which can be used for better identification and discrimination of possible hydrocarbon presence. Since the methodology relies on the frequency quality embedded in the seismic data as input, it is recommended to consider frequency factor since the early stage of seismic acquisition and processing.

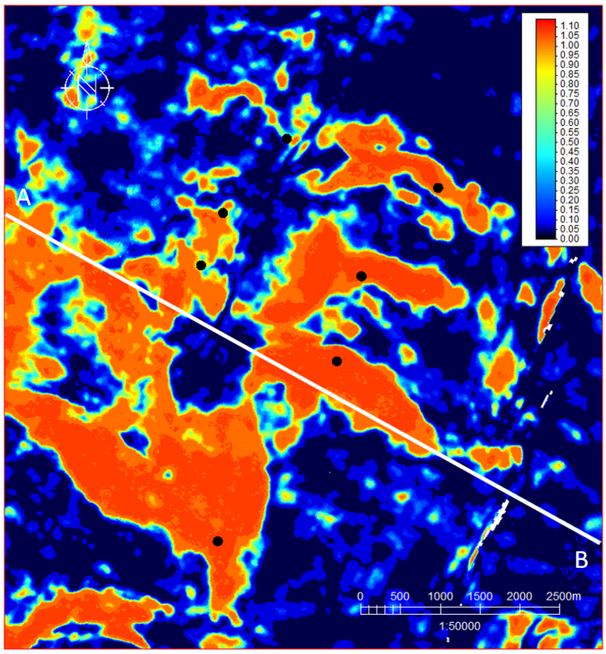

Figure 10. Gas Probability map with 50ms window using Horizon X as reference. White line shows the seismic line. Black dots represent gas found in wells.

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