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Applications of seismic techniques to gas hydrates prediction*

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Abstract: Based on the sensitivity of geophysical response to gas hydrates contained in sediments, we studied the prediction of gas hydrates with seismic techniques, including seismic attributes analysis, AVO, inverted velocity field construction for dipping formations, and pseudo-well constrained impedance inversion. We used an optimal integration of geophysical techniques results in a set of reliable and effective workflows to predict gas hydrates. The results show that the integrated analysis of the combination of reflectivity amplitude, instantaneous phase, interval velocity, relative impedance, absolute impedance, and AVO intercept is a valid combination of techniques for identifying the BSR (Bottom Simulated Reflector) from the lower boundary of the gas hydrates. Integration of seismic sections, relative and absolute impedance sections, and interval velocity sections can improve the validity of gas hydrates determination. The combination of instantaneous frequency, energy half attenuation time, interval velocity, AVO intercept, AVO product, and AVO fluid factor accurately locates the escaped gas beneath the BSR. With these conclusions, the combined techniques have been used to successfully predict the gas hydrates in the Dongsha Sea area.

Keywords: Geophysical data, special processing, gas hydrates, BSR, prediction.

Introduction

Gas hydrates, one important replacement energy, is a kind of cage-like solid crystalline of water-enveloping gas formed under certain temperatures and pressures (Kvenvolden, 1988; Wu et al., 2004). Gas hydrates usually exist in the permafrost horizon of onshore and inner continental shelf in Polar Regions and in the sediments of the outer shelf break and continental rise in deep seas (Zhang et al., 2003).

The research data from home and abroad show that the seismic response of gas hydrates are weak wedge-shaped reflections. The reflection from the bottom of the gas hydrates is characterized by a bottom simulating reflection (BSR) (Markl et al., 1970; Ewing and Hollister, 1972) which is oblique to formation boundaries and with opposite polarity to the seafloor reflection. There are two viewpoints about the genetic mechanism of the BSR. One regards the BSR as an interface between hydrates and free gas (Katzman et al., 1994) and the other believes that the BSR is the interface between hydrates and sediments filled with water (Hyndman and Davis, 1992). No matter what the mechanism, it is commonly believed that the BSR corresponds to the bottom interface of the gas hydrates. At present, the BSR is an effective method to indicate gas hydrates directly. However, gas hydrates have been found in regions without a BSR (Holbrook et al., 1996).

Furthermore, the BSR, as the key indicator of

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hydrates, cannot be used alone to determine the existence of free-gas. Therefore, we focus on the comprehensive analysis of geophysical information to exactly locate the abundance zone of the gas hydrates and free-gas based on the disciplines of seismic waves and impendence.

Based on the research discussed in this paper, the combination of all attributes has proven to be an effective method to detect gas hydrates. These attributes include interval velocity, relative impedance, absolute impedance, AVO, reflectivity amplitude, instantaneous phase, instantaneous frequency, and the energy half attenuation time. This paper first illustrates the methods to process and extract these attributes and then comprehensively evaluates the geological interpretation of each attribute. The purpose of this paper is to find the common area from all the interpretations in order to reduce ambiguity and increase reliability.

The seismic techniques and theories to predict gas hydrates

The main flow-chart of seismic techniques to predict gas hydrates is shown in Figure 1.

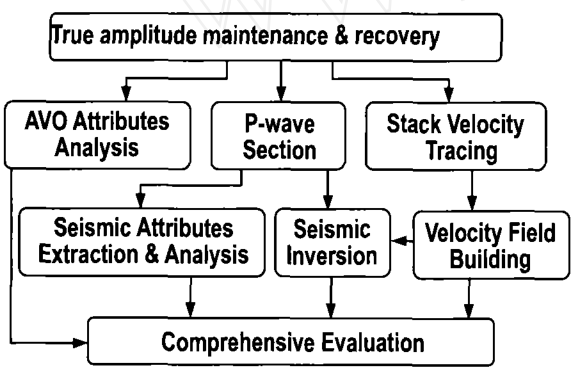

Fig. 1 A flow-chart to predict gas hydrates.

Seismic attributes extraction and analysis

The characteristics of seismic signals reflect the physical character of rocks and their variations which are the comprehensive response of lithology, physical properties, fluid properties, and etc. The extraction process of seismic attributes separates the geometrical shapes of the seismic waves and the kinematic and statistic information from prestack or poststack seismic data using mathematic transforms. Some of the information is sensitive to the rock surrounding the reservoir and some is sensitive to the pores fluid properties within the reservoir.

Seismic attribute analysis highlights and interprets the target by means of these properties. The processing tests show that some attributes are effective in identifying and predicting gas hydrates. These attributes include instantaneous amplitude, instantaneous phase, instantaneous frequency, and energy half attenuation time. Instantaneous amplitude (reflection strength) emphasizes the variation of the amplitude envelope using colors. The velocity and density of the hydrates formation is higher than that of depositional formations filled with free-gas or water. Therefore, the reflection from the bottom interface of the hydrates formation will show positive polarity if the wavelet polarity from seismic data is negative or negative polarity if the wavelet polarity is positive. This interface is the BSR discussed above. Based on this feature, instantaneous amplitude can be used to identify the BSR.

Instantaneous phase focuses on the continuity of the seismic waves and ignores the amplitude information. The BSR is oblique to the depositional formation; therefore, due to the reflection interference, sometimes the BSR boundary is not clear. In this case, instantaneous phase can be used to reduce the interference and to highlight the BSR.

Instantaneous frequency is the frequency value of a sample point, which reflects the absorbency of a formation, and can be used to predict the paleo-depositional environment. Since high absorbency leads to rapid attenuation of the high frequency components; a low instantaneous frequency anomaly will appear at regions where free gas is enriched. Based on this feature, instantaneous frequency, together with other techniques, can be used to estimate the regions filled with free-gas and their enrichment.

AVO analysis technique

The linear approximation of Zoeppritz's function for AVO (Amplitude Versus Offset) analysis technique is the main method for predicting the presence of natural gas (Gao et al., 2006; Sun et al., 2004). The intercept of a linear AVO function is the P-wave section which generally shows normal incidence and zero offset. The slope of an AVO section reflects the gradient variation of P-wave amplitude with offset and is related to Poisson's Ratio. Since the Poission ratio is the fuction of the ratio between S-wave and P-wave velocity (Vs/Vp), the slope section is sensitive to Vs/Vp.

Based on the fact that high volume gas affects the Vs/Vp ratio, slope sections can be used to indicate gas-saturated layers. The product of intercept and slope is referred to as a hydrocarbon indicator section, which is useful in predicting oil and gas since it will enlarge the absolute value and improve the resolution. The fluid factor reflects fluid properties. When the pore is filled with water, the liquid factor is zero and when the pore is full of oil and gas, the fluid factor is negative. Furthermore, the more negative, the more likely that it is filled with gas. This observation can be used to predict the fluid. We can also use AVO attribute crossplots from seismic inversion to determine whether the sediments contain gas hydrate or free gas (Zhang et al., 2005).

A formation filled with gas hydrates is generally uncompacted or poorly compacted, which is normal for depths 200 - 600 m beneath the sea floor on the outer continental shelf slope. Therefore, this kind of free-gas reservoir has low acoustic impedance and belongs to the third lithologic combination (Type III) described by Rutherford and Williams (1989) and was cited broadly. The AVO intercept and slope of this lithologic combination are all negative and the product section will show a prominent positive anomaly even though the gradient is small. In the fluid factor section, the value is zero if the formation is water-saturated and negative if the formation is gas-saturated. Based on these features, we can predict the region filled with hydrate and free-gas.

True amplitude maintenance and recovery is necessary in the processing (Wang et al., 2005), which can be fulfilled through geometric spreading correction, Q compensation, surface-consistent amplitude processing, deconvolution, multiple suppression, moveout correction, static correction, and an integral correction of residual amplitude which reflects the variation of offset with time based on statistics (Zhang, 2006). Various AVO attributes are processed and obtained on the basis of a detailed seismic processing flow.

Velocity field building technique

Velocity is a key parameter for detecting hydrates and free-gases, since the velocity of hydrates is higher than the velocity of surrounding rocks. The stacking velocity will reverse due to the velocity reduction if the underlying layer is filled with free-gas (Ecker et al., 2000). In the velocity spectrum (Figure 2), a high stacking velocity layer is shown between 1.9 sec and 2 sec, which may indicate the enrichment of hydrates.

Beneath this layer, between 2.1 sec and 2.2 sec, there must be a free-gas layer since the velocity is reversed. The velocity field can be built with stacking velocity, if there are no acoustic logs, dipole transverse wave logs, or VSP information. However, the resolution is low without constraints from logs. One way to solve this problem is to improve the processing and interpretation precision of the stacking velocity by decreasing the distance between spectra locations to 250 m to increase lateral resolution and by increasing the number of samples in shallow layers, especially 200-600 m below the sea floor (since hydrates are developed below this depth). Another method is to improve the precision of interval velocities obtained from stacking velocity. The traditional method to obtain interval velocity is to convert stacking velocities after dip correction into root-mean-square velocities and then calculate the interval velocity using the Dix formula. This method can only apply to homogeneous or horizontal layered media and the offset is not too long.

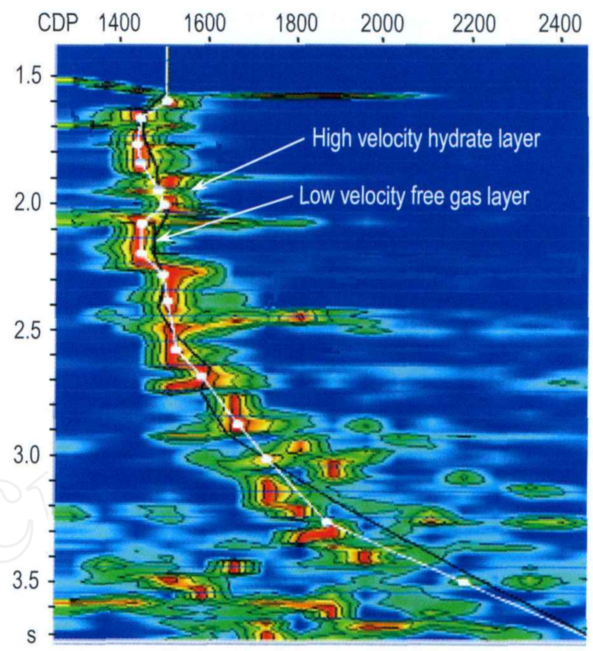

Fig.2 The velocity spectrum

Generally, hydrates are found on the continental slope and rise in the deep sea and are oblique to the normal sedimentary formations. In this situation, if the traditional method is used to calculate interval velocity, the error would be very large since the assumptions of the traditional method are unsatisfactory. When the dip is over 30 degrees, the velocity error calculated from the traditional model iteration method is very large and when the dip is larger than 60 degrees, it is impossible to trace the rays. To solve this problem, the normal wave ray tracing method can be applied to calculate interval velocity. This method is not limited by steep structure and large dip formations and thoroughly considers the effects from interference and diffraction. With this method, the travel path of seismic waves, including the integral effects from reflection, refraction, and transmission, can be fully simulating, even in the regions with abrupt velocity variation and large fault slip. Finally, a stacking velocity which is consistent with the seismic record is obtained to ensure the precision of interval velocity.

Impedance inversion

The relative and absolute impedances are calculated by sparse spike inversion constrained by pseudo-wells. Since velocity is sensitive to gas hydrates (Liu et al., 2005; Zeng et al., 2003), the pseudo-wells are built from velocity information. The advantage of sparse spike inversion is that reflectivity coefficients can be extracted from seismic data directly. The resolution, signal-to-noise ratio, and reliability of the inversion are dependent on the quality of seismic data. Therefore, the seismic data used in inversion must have a wide frequency band, low noise, and high fidelity. P-wave sections obtained from AVO processing are used to invert for impedance instead of stacked migrated sections in this study.

The inversion of the hydrates region uses the interpreted information from the sea floor, BSR, and key deeper layers to build structural models and to control the low frequency part of the model. Since the velocity information is in the time domain, for convenience, we build pseudo-wells in the time domain and extract a wavelet close to the well to prepare for the inversion to absolute impedance. Generally, to calculate absolute impedances, the density of hydrates is chosen to be 0.9 k/cm3. The inversion results are constrained with trend lines built from the pseudo-wells. Finally, the frequency information lower than 15 Hz is added to constrain the sparse impulse inversion and then the absolute impedance section which can indicate the distribution of hydrates and free-gases is obtained.

Prediction schemes for gas hydrates using geophysical techniques and effectiveness analysis

The study area is located in north-east Taixinan Basin. The depositional formations are higher to the north-west than the south-east and the basin is divided into east and west sections by a sea-floor trench. Highly rough sea-floor topographic relief and highly developed formation folds provide a good tectonic environment for the gas hydrates accumulation.

Figure 3 shows a stacked section after migration in the Nanhai Sea area. There is a BSR between 2050 and 2230 traces which is smeared. Therefore, the evidence is not clear enough to infer if this layer is filled with hydrates or free-gases. Figure 4 shows an instantaneous amplitude (reflection strength) section. A strong reflection similar to that of the sea floor is clearly identified between 1800-2400 ms which may be interpreted as a BSR. This reflection is about 200-300 ms below the strong reflection of the sea floor. Also, there is a weak reflection between the BSR and the reflection from the sea floor which is different than the original seismic section. The instantaneous phase section in Figure 5 shows that all reflectors are equivalent. A clear interface 250 ms beneath the sea floor penetrates the sedimentary layers but is parallel to the sea floor. The instantaneous frequency section in Figure 6 does not show a strong reflection interface but a large low frequency area beneath the BSR is clearly identified. At the same location, a low anomaly is shown in the energy half attenuation time section which may indicate a free-gas saturated region.

AVO attributes are also sensitive to hydrates and free-gas and will reveal the degree of enrichment and distribution of hydrates and free-gas. The high energy anomaly in the AVO intercept section shows a large P-wave velocity difference between the top and lower layer which indicates that hydrates may be enriched in the top layer and free-gases may be enriched in the lower layer. Moreover, the larger the anomaly at the BSR interface, the more hydrates and free-gas in this region. The positive anomaly is clearly shown in the AVO gradient and intercept product section which indicates a gas-saturated layer with lower than surrounding velocities. Another AVO attribute, the fluid factor, is

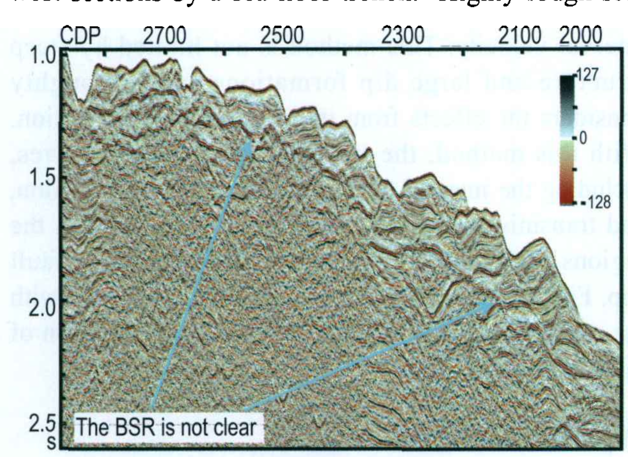

Fig. 3 Migrated section.

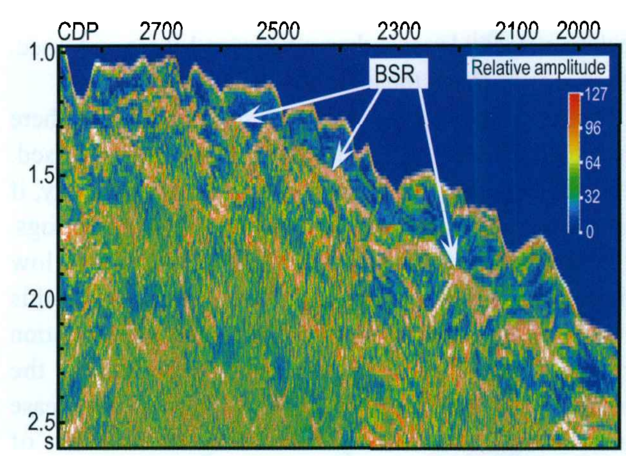

Fig. 4 Instantaneous amplitude section .

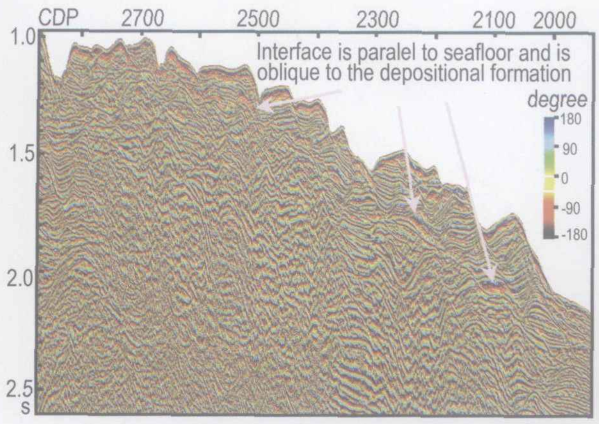

Fig. 5 Instantaneous phase section.

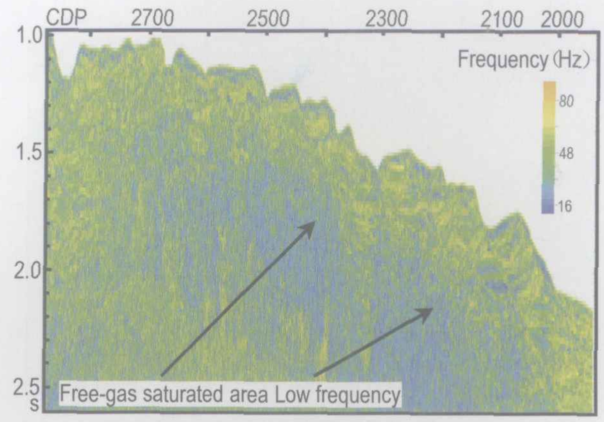

Fig. 6 Instantaneous frequency section.

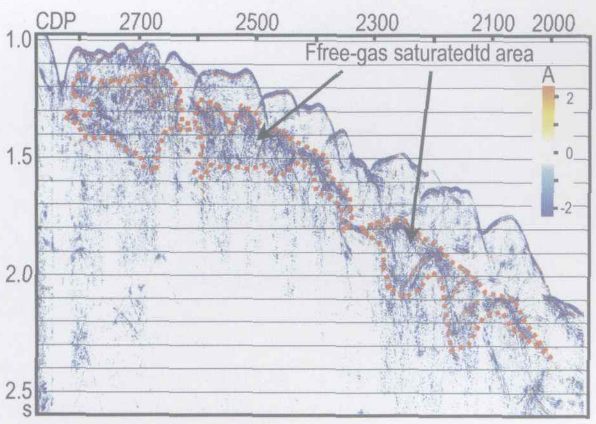

Fig. 7 Gradient and intercept product section.

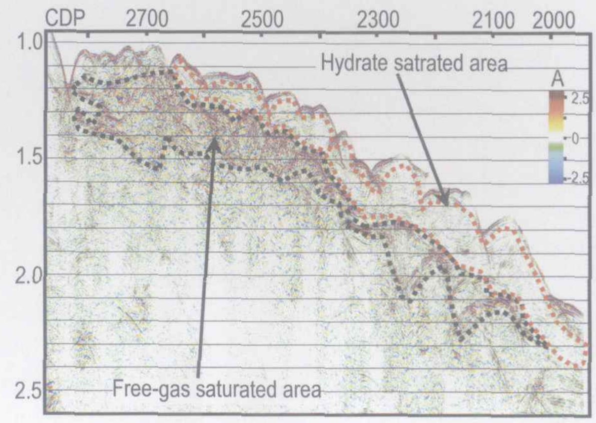

Fig. 8 Fluid factor section

shown in Figure 8. Strong negative reflections indicate the gas-saturated layers and weak reflections indicate hydrate-saturated or water-saturated layers.

Figure 9 shows a relative impedance section. The region 250 ms below the sea floor exhibits a weak relative impedance region over the strong BSR reflectors which correspond to the reflection strength and intercept sections. This region shows high velocities in velocity section (Figure 10) with velocity in the range of 1600 - 2200 m/s and a high anomaly in the absolute impedance section (Figure 11) which may indicate the existence of hydrates. The region between 1800-2000 ms and traces 2100-2250 below the BSR shows low velocity in the velocity section, low impedance in the absolute impedance section, negative anomaly in the fluid factor section, high absorbency in the instantaneous frequency

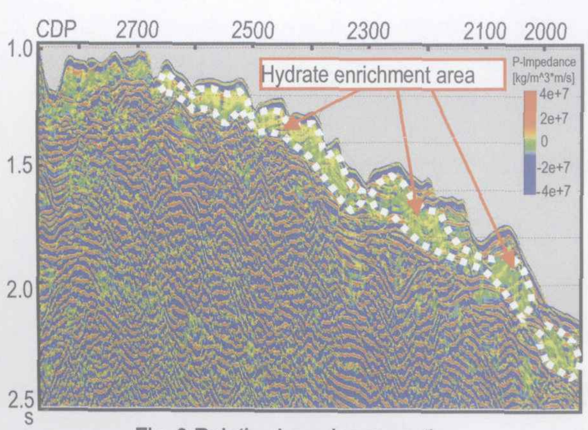

Fig. 9 Relative impedance section.

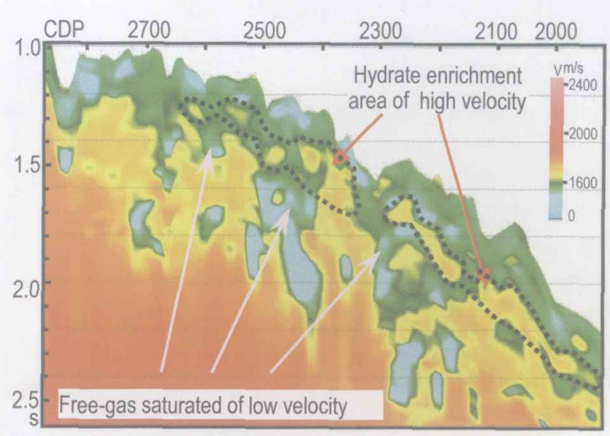

Fig. 10 Velocity section.

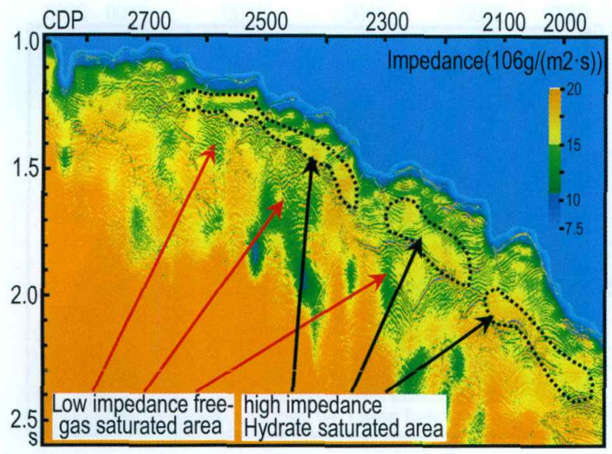

Fig. 11 Absolute impedance section.

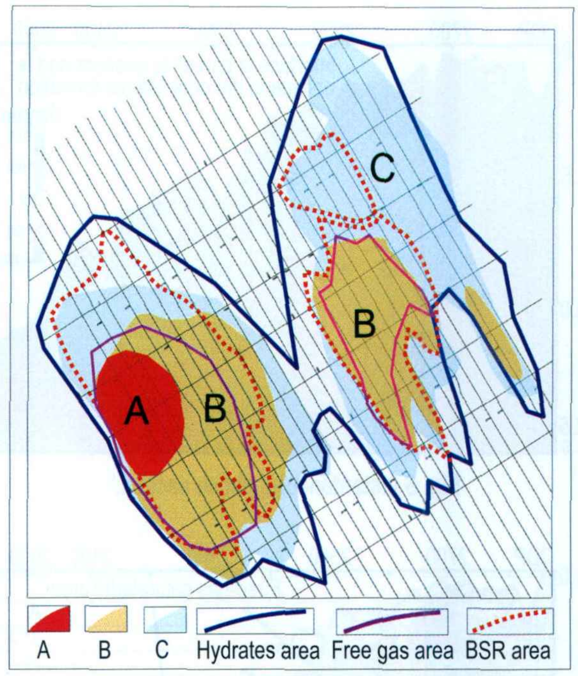

Fig. 12 Comprehensive evaluation map.

section, and low anomaly in the energy half attenuation time section. All the information indicates that this region is a free-gas enriched region.

We studied thirty-four seismic sections in the study area. Eleven absolute impedance sections show high impedance anomalies above the BSR and while six of them show seismically transparent mass distributions. One section shows a weak anomaly in the absolute and relative impedance sections. Eight seismic sections show some low anomaly zones in the relative and absolute impedance sections, low anomalies in the instantaneous frequency section, a rapid attenuation in the energy half attenuation time section, and high values in the fluid factor section. This study shows that a single technique cannot identify the existence of hydrates or free-gas accurately. However, the integrated application of AVO, interval velocity, instantaneous phase, instantaneous frequency, instantaneous amplitude, and impedance sections can identify the distribution of hydrates from different aspects which improves the reliability of prediction and decreases the drilling risk.

Based on the integrated studies, the study area was classed into three regions: regions A, B, and C (Figure 12). All attributes indicate gas hydrates in region A which is located level 800 to 1500 meters, below sea. The characteristics are strong BSR, regular weak reflectors, low fluid factor, and seismically transparent zone in the relative impedance section above the BSR, high frequency absorption and high fluid factor under the BSR, high impendence, and interval velocity greater than 1800 m/s. Some of the attributes for gas hydrates are observed in region B, including a weak BSR reflector and no visible high frequency absorption. There is no clear BSR reflector in region C with few attributes indicating the presence of gas hydrates.

Conclusions

Effective seismic attribute methods are integrated into a set of reliable predictors for gas hydrates. Based on the comprehensive study results, we conclude:

(1) Instantaneous amplitude, instantaneous phase, interval velocity, relative impedance, absolute impedance, and AVO intercept are valid techniques for identifying the BSR (bottom simulating reflector).

(2) Hydrates are enriched in regions with a clear BSR, weak seismic reflections, high interval velocity, low relative impedance, and high absolute impedance.

(3) The combination of instantaneous frequency, energy half attenuation time, interval velocity, AVO intercept, AVO intercept and gradient product, and AVO fluid factor helps to locate free-gas accurately.

(4) The Dongsha Sea area was classed into three regions based on the comprehensive attribute evaluation. Region A, the hydrates and free-gas enriched area, is regarded as the main target for the next exploration and exploitation cycle.

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随频率和入射角度的变化所反映出的反射和透射的特征，并且改变BSR上下层介质中水合物含量和游离气含量，进一步研究波在介质分界面上的反射和透射特征与流体饱和度的关系。对模型计算发现第一类纵波和横波对频率的变化不敏感，速度改变不大；而第二类纵波受频率的影响较大，速度变化范围较大；随着水合物和游离气含量的变化，各种反射和透射波都会随之改变，变化的范围和幅度说明了波对介质组分变化的敏感性。
关键词： 天然气水合物，似海底反射层，双相介质、反射系数，透射系数，饱和度

9. 地球物理技术在天然气水合物预测中的应用// Applications of seismic techniques to gas hydrates prediction, 刘彦君[1]，刘喜武[2]，刘大锰[1]，王燕津[3]，赵迎新[3]，Applied Geophysics, 2008, 5(1), 67 – 73
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摘要： 本文基于天然气水合物发育区特有的构造沉积特征对各种地球物理响应的敏感性，研究了地震属性、AVO分析、陡倾角地层反转速度场建立、及伪井约束波阻抗反演等地震技术在天然气水合物预测中的应用及其效果。通过多信息联合分析与融合策略，优化集成有效地球物理技术，形成一套可靠的天然气水合物探测技术与流程。实际表明：综合分析反射强度、瞬时相位、层速度、相对波阻抗、绝对波阻抗、及AVO截距剖面等特征资料是识别天然气水合物底界似海底反射（BSR）的有效手段；综合应用地震、相对波阻抗、绝对波阻抗、层速度等剖面的特征可提高天然气水合物识别的有效性；而瞬时频率、能量半衰时、层速度、AVO截距、AVO乘积、AVO流体因子等剖面特征的有效组合能更准确有效地识别BSR以下的游离气。文中所总结的一套预测天然气水合物的优化组合地球物理技术在我国南海海域中已取得良好效果。
关键词： 地震属性，特殊处理，天然气水合物，BSR，预测

10. 利用大地电磁资料对玄武岩成像的可行性// Feasibility of using magnetotelluric for sub-basalt imaging at Kutch, India, Dhananjai Pande[y1,3], Lucy MacGregor[2], Martin Sinha[3], Satish Singh[4], Applied Geophysics, 2008, 5(1), 74 – 82.
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摘要： 磁大地电流法（MT）已成为有助于地下盐和地下玄武岩地震成像的有利方法之一。本文印度卡奇地区（这个地区玄武岩覆盖了中生代沉积岩）。并讨论了利用MT方法作为这样地质背景地区勘探工具的可能性。我们的结果突出了由侵入薄层玄武岩引起的磁大地电流响应的差别。本文讨论的关键问题是在这样的地质背景条件下MT方法能够或不能提供什么。首先我们利用了具有代表性的电阻率—深度模型和研究区的井资料计算了视电阻率和相位响应曲线，然后对这些结果的对比分析，评估了利用MT对Kachchh地区地下火成岩沉积成像的合理性。 最后，通过对这个地区野外观测的MT资料一维反演证实了我们的讨论。
关键词： 地下玄武岩成像，德干圈闭，卡奇，磁大地电流。