Forward Modeling and Identification of Shallow Gas in the Seabed

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Methodology

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Forward modeling and identification of shallow gas in the seabed

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Abstract: The accumulation of shallow gas in the stratum will form high-gas bag and reduce the strength of soil, which will endanger the construction of marine engineering. So it is of great significance to find out the distribution of shallow gas in the work area. Shallow gas in soil will increase porosity and decrease formation sound velocity, which has absorption and attenuation effect on high frequency components of sound wave. Based on the drilling data around an oil platform in Bohai Bay, a formation model of shallow gas is established and the forward analysis is carried out, the result show that at the interface between the shallow gas and the formation, the phase of reflected wave reverses and the events at the lower part of the shallow gas is pulled down. The stratigraphic profile around the platform is investigated, and the amplitude, phase and frequency attributes of acoustic stratigraphic profile data are analyzed. The shallow gas reflection is identified by combining the features of weak amplitude clutter reflection, phase reversal, phase axis pull-down and high frequency missing, and the shallow gas reflection is columnar and the top to clay layer of the seafloor. The shallow gas is agglomerated and may come from the deep.

Key words: shallow gas; acoustic stratigraphic section; Seismic attribute; high frequency missing;

Foreword

Shallow gas in the submarine usually refers to the gas which is gathered in stratum at 1000m below the seabed. The character of shallow gas is small molecule, low density, low adsorption capacity and strong diffusion capacity and so on, which is easy to migrate and gather in the stratum. When the shallow gas accumulates in the formation, it changes the physical properties of the formation, the porosity increased, and the compaction degree and strength of the formation reduced[1-5]. So under the action of external load, the gas bearing stratum may creep, which resulting in foundation settlement or sliding. In addition, shallow gas with good cap rock will form a certain pressure air bag. Under these circumstances, if oil platform construction, drilling and other offshore engineering activities pierce the shallow gas cap, and under the action of internal pressure, shallow gas will gush out, which may lead to blowout accidents. Therefore, it is of great significance to identify the distribution characteristics of shallow gas in the work area for site selection and evaluation of offshore engineering construction.

There are two types of submarine shallow gas: One is biomethane shallow gas, and the main component is methane gas. Caused by the decomposition of methanogens for the bioclastic and organic matter in the formation, which form shallow gas mainly located in the shallow layer; The other is the shallow methane gas, which is a hydrocarbon caused by kerogen cracking in a high temperature and high pressure environment of 2000m below the sea floor, and usually form high pressure air bag with overpressure state[6-8]. Sometimes, the hydrocarbon also rises and migrates along the pores, fractures and fault and accumulates in the shallow strata forming shallow gas.

1. Acoustic detection technology

Acoustic detection technology is the main technology for detecting submarine shallow gas. The acoustic reflection characteristics of shallow gas are different due to the different accumulation patterns in the formation which caused by the shallow gas of different genesis. Sound waves are a form of energy transfer, the propagation

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velocity, spectrum composition and energy attenuation of sound wave will change in the medium with different intensity, structure and density.

The propagation equation of sound wave in water and stratum is as follows[9,10]:

$$\begin{cases} \rho \dfrac{\partial^2 u}{\partial t^2} = \dfrac{\partial \sigma_{xx}}{\partial x} + \dfrac{\partial \sigma_{xy}}{\partial y} + \dfrac{\partial \sigma_{xz}}{\partial z} + \rho F_x \\ \rho \dfrac{\partial^2 v}{\partial t^2} = \dfrac{\partial \sigma_{xy}}{\partial x} + \dfrac{\partial \sigma_{yy}}{\partial y} + \dfrac{\partial \sigma_{zy}}{\partial z} + \rho F_y \\ \rho \dfrac{\partial^2 w}{\partial t^2} = \dfrac{\partial \sigma_{xz}}{\partial x} + \dfrac{\partial \sigma_{yz}}{\partial y} + \dfrac{\partial \sigma_{zz}}{\partial z} + \rho F_z \end{cases} \tag{1}$$

Where, t is time; ρ is density of media; u, v, w are displacements in the direction of x, y and z; $\sigma_{xx}, \sigma_{xy}, \sigma_{xz}, \sigma_{yy}, \sigma_{yz}, \sigma_{zz}$ are stress; F_x, F_y, F_z are the external forces in the direction of x, y and z;

Three dimensional wave equation in homogeneous and isotropic ideal elastic medium expressed by vector as follows[10]:

$$\rho \frac{\partial^2 \boldsymbol{S}}{\partial t^2} = (\lambda + \mu)\mathrm{grad}\theta + \mu \nabla^2 \boldsymbol{S} + \rho \boldsymbol{F} \tag{2}$$

Where, F is external force vector and $\boldsymbol{F} = F_x \boldsymbol{i} + F_y \boldsymbol{j} + F_z \boldsymbol{k}$; S is Displacement vector and $\boldsymbol{S} = u\boldsymbol{i} + v\boldsymbol{j} + w\boldsymbol{k}$; $\mathrm{grad}\theta$ is gradient vector and $\mathrm{grad}\theta = \frac{\partial\theta}{\partial x}\boldsymbol{i} + \frac{\partial\theta}{\partial y}\boldsymbol{j} + \frac{\partial\theta}{\partial z}\boldsymbol{k}$; ∇^2 is laplacian operator; ρ is density of medium; λ和 μ are lame constant; t is time. Equation (2) could be rewritten as plane harmonic equation as follow:

$$p(x_i, t) = p_0 \sin\left(\frac{2\pi x_i}{\lambda} - \omega t + \phi\right) \tag{3}$$

Where, t is time; p is acoustic signal in time domain; p_0 is acoustic amplitude; λ is wavelength; ω is Angular frequency and $\omega = 2\pi f$; ϕ is phase shift. In the acoustic detection of stratum, the sound wave excited by transducer can be regarded as the superposition of several simple harmonic waves.

Different strata often have different physical properties, which leads to different wave impedance. When sound waves propagate to different formation interfaces, they will be reflected and transmitted. The energy of reflected sound wave is characterized by reflection coefficient R, as follows:

$$R = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1} \tag{4}$$

Where, ρ_1, v_1, ρ_2, v_2 are the density and sound velocity of the medium above the interface and the density and sound velocity of the medium below the interface. If the reflection coefficient is different between layers, the reflected sound energy is also different. Based on this, the stratigraphic interface and structure can be identified

2. Shallow gas forward modeling

If the shallow gas is accumulated in the formation, the porosity increases, which will affect the acoustic wave propagation speed and density of the formation. With the increase of porosity in the formation, the density of the formation decreases. However the formation sound velocity is related to porosity and water content, there exist the empirical formula as follows[11-13]:

$$v = 1981.7539 \times (0.9958 - 0.004n + 0.0002\omega) \quad (5)$$

Where, v is velocity of sound wave; n is porosity of formation (%); ω is water content (%);

Based on the data of a 120m engineering geological borehole in Bohai Bay(the coordinate of borehole is 38°29’28.6651”N,117°45’15.3138”E), the forward model of normal stratum is established. The drilling data are as follows as tabe1:

Table 1. Summary of borehole formation physical properties and sound velocity data

NO.	Depth of layer bottom/m	Sediment type	Water contact-%	Wet bulk density N/cm3	proportion	Porosity-%	Sounder velocity-m/s
1	2.4	Soft clay	55	16.5	2.7	62	1506
2	3.3	Medium dense silt	21	20.4	2.71	39	1671
3	14.5	Muddy clay	38	18.5	2.72	51	1588
4	16.7	Silty fine sand	26	19.3	2.69	45	1627
5	19.8	Hard silt	26	19.7	2.7	43	1643
6	22	Dense silt	23	20	2.72	42	1651
7	25.7	Dense silty fine sand	20	20.5	2.68	38	1684
8	28.8	Dense silt	28	19.1	2.68	46	1621
9	34.8	Hard clay	37	18.5	2.69	50	1594
10	40.6	Dense silt	23	19.6	2.71	44	1635
11	49.8	Silty clay	27	20.4	2.71	39	1674
12	55.7	Dense silt	26	19.6	2.7	44	1638
13	58.8	Hard clay	35	18.2	2.71	52	1575
14	61.7	Dense fine sand	24	19.2	2.7	46	1619
15	81.1	Hard silty clay	30	19.8	2.72	43	1644
16	91.7	Dense sandy silt	21	19.9	2.72	42	1645
17	106.6	Hard silty clay	20	20.5	2.72	39	1673
18	111.1	Dense silt	26	19.5	2.71	44	1631
19	120.3	Hard silty clay	21	20.5	2.71	39	1676

According to the sound velocity and wave impedance, the formation is divided into six layers, and the distribution of the strata is as follows as table2. The formation sound velocity and density of each layer are calculated by weighted average of each layer.

Table 2. Stratum division sheet

stratum	Representative stratum	Depth of layer botto-m	Formation thickness/m	Sounder velocity-m/s	Density-g/cm3
Layer-1	Soft clay	14.5	14.5	1573	1.81
Layer-2	Silty fine sand	25.7	11.2	1655	1.99
Layer-3	Hard clay	34.8	9.1	1603	1.87
Layer-4	Silt	49.8	15.0	1658	2.01
Layer-5	Dense silt	58.8	9.0	1616	1.91
Layer-6	Hard silty clay	120	61.2	1661	2.01

The data in Table 2 are used to build a two-dimensional stratigraphic model with a width of 2000m and a depth of 120m. The wavelet is Ricker wavelet with main frequency is 250Hz, bandwidth is 120Hz, and duration is 10ms. The stratigraphic model is shown in Figure 1.

According to the identified shallow gas conditions[3], shallow gas mostly exists in sandy soil. And the gas bearing formation's properties as follows: the water content is 7%, the saturation is 20%, the formation density is 1.49g/cm3, and the porosity is 49%, the formation sound velocity is 1588m /s.

For the shallow gas of biomethane, it is located in the formation 2-fine sand in the form of gasbag. For the pyrolysis methane shallow gas, it is set to migrate upward from the depth of the formation to the shallow formation, and exist in the formation 2, 3, 4, 5 and 6, in the form of gas column.

The forward acoustic stratigraphic profile is shown in Figure 1. There are six consecutive events in the section just as shown in Figure 2-a, corresponding to the interface between sea water and stratum and five stratum interfaces. The phase of reflection wave in events at the interface between stratum 2 and stratum 3 and between stratum 4 and stratum 5 are negative, indicating that the reflection coefficient of stratum here is negative. Combined with the formation model, there is velocity inversion in formation 3 and 5, which is less than the sound velocity in the upper layer. In Figure 2-b, because there is a shallow gasbag in formation 2, and the sound velocity of the shallow gas is less than that of formation 2, the reflected wave phase at the top interface of the shallow gas is negative, and the reflected wave phase at the bottom interface of the shallow gas is positive. Because the sound wave travels time in shallow gas is larger than that in the stratum, the reflection wave under the shallow gas is depressed downward in the same phase axis. In Figure 2-c, due to the existence of penetrating shallow gas column in the formation below stratum 2, the reflected wave phase at the shallow gas cap interface is negative, and the reflected wave at the side boundary is not clear.

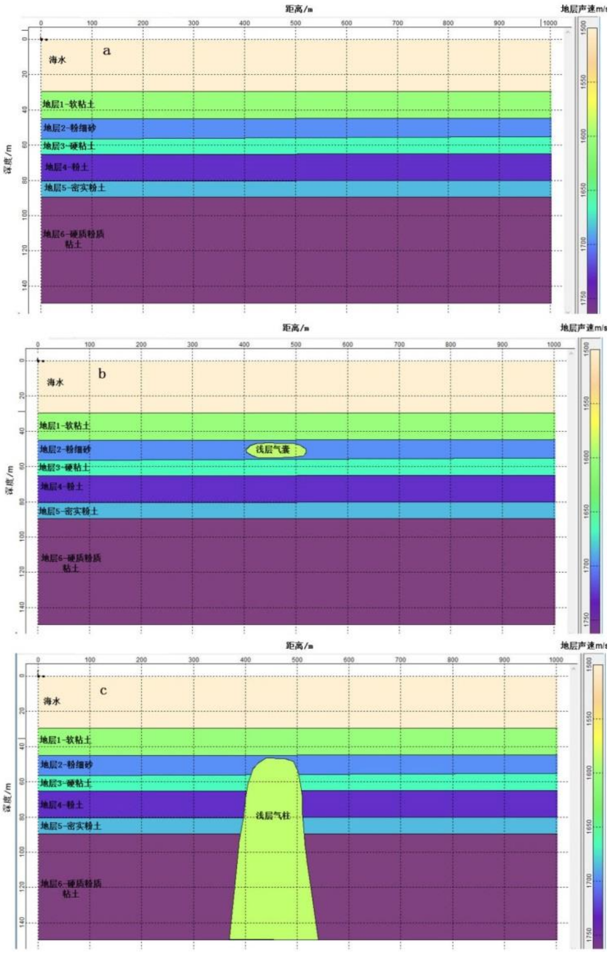

Fig.1 Stratigraphic model, where fig.1-a is normal stratigraphic model; fig.1-b is biomethane shallow gas model; c- pyrolysis shallow gas model

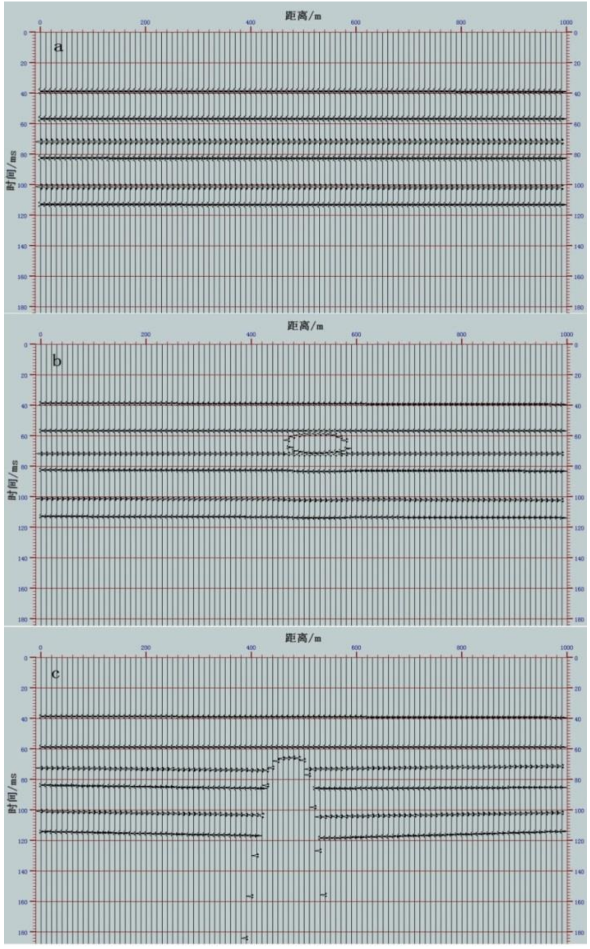

Fig.2 Forward acoustic stratigraphic profile, where fig.2-a is normal stratigraphic model; fig.2-b is biomethane shallow gas model; fig.2-c is pyrolysis shallow gas model

It can be seen that when there is shallow gas in the formation, the top boundary of the shallow gas in the acoustic stratigraphic section presents the reflection characteristics of opposite phase and the lower part phase axis of the shallow gas sags downward.

3. Analysis of measured seismic data

There is a lot of shallow gas in Huanghua sea area of Bohai Bay, and acoustic stratigraphic profile survey was carried out in the area around an oil platform. During survey, the shot source is electric spark, the excitation energy is 1000j, and the recording time is 400ms. There is a suspected shallow gas reflection in the acoustic stratigraphic section. Due to the selective absorption of different frequencies of acoustic waves by gas bearing formations, so there are three seismic attributes: the amplitude, instantaneous phase and instantaneous frequency of the acoustic stratigraphic section are analyzed to identify the shallow gas.

3.1 Amplitude characteristics

On the amplitude profile, the reflection characteristics are shown in Fig.3 and Fig.4. It can be seen in Figure 3 that there is a weak reflection area in the middle of the profile, which is suspected of shallow gas reflection. In this area, the reflected wave energy is weak, the events are discontinuous, the waveform is unstable, the reflection is disordered, and there is no obvious layered structure and obvious discontinuity with the normal events around. The events at the edge are obviously thicker and bend downward. This area is columnar, extending up and down, with a width of about 110m, and the top is about 15m away from the seabed. It can be seen in Fig.4 that there is a depression area of the events in the middle of the section, which almost runs through the whole section. While the events on both sides are not staggered and are still flush, which can eliminate the reflection caused by faults and is suspected to be the reflection contain gas which the events depression caused by the velocity reduction due to shallow gas in formation. The energy of the upper reflected wave is stable, and the events are continuous. However, the energy of the lower reflected wave is weak, and the events are no discontinuity, and the waveform is unstable. This area is columnar, extending up and down, with a width of about 40m, and the top is about 15m away from the seabed.

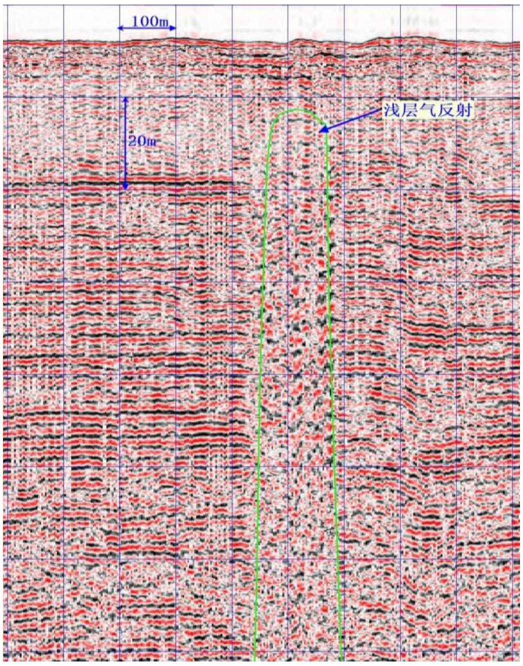

Fig.3 The acoustic profile in survey area profile1, and the seismic property is amplitude; the clutter reflection in the area bounded by green lines suspected shallow gas on amplitude profile

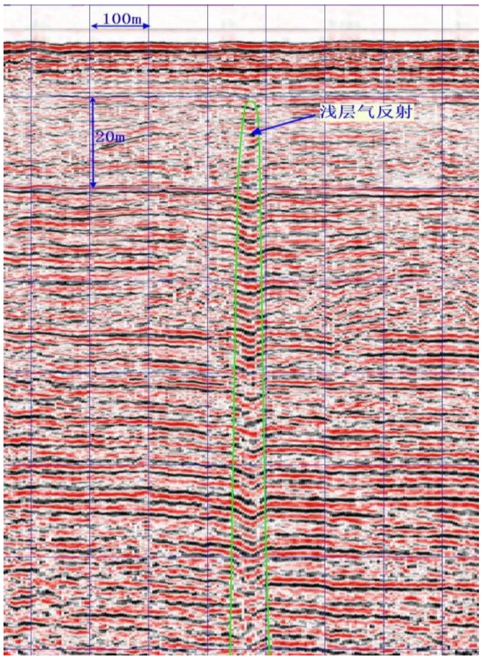

Fig.4 The acoustic profile in survey area profile2, and the seismic property is amplitude; Velocity drop in the area bounded by green lines on amplitude profile suspected caused by shallow gas

3.2 Phase characteristics

The instantaneous phase attributes of the amplitude profiles in Fig.3 and Fig.4 are calculated respectively, and the instantaneous phase profiles are shown in Fig.5 and Fig.6. It can be seen from Fig.5 that there is a phase disordered area in the middle of the profile, which is the same as the disordered reflection area on the amplitude profile. The area is cylindrical and with a width of about 40m, and the top is about 15m away from the seabed. In this region, there is no obvious layered structure, and compared with the surrounding events, the events are obviously thicker. At the top, the phase of the events are staggered and reversed.

It can be seen from Fig.6 that there is a depression area of the events in the middle of the section, which is columnar and about 40m wide and the top is about 15m away from the seafloor. This area is the same as the depression area of the events in the amplitude section. In the upper part of this region, although the events are concave, they are still continuous; In the lower part of this region, the events gradually becomes discontinuous, and the layered structure gradually becomes unobvious and disordered; At the top of this region, the events breaks and reverses.

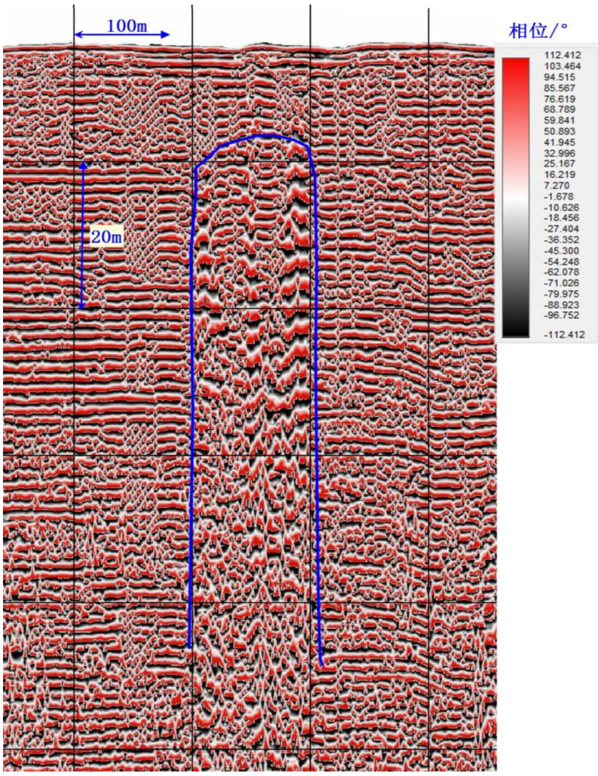

Fig.5 the acoustic profile in survey area profile1, and the property is phase for fig.3; Chaotic reflection region in the area bounded by blue lines, which indicate the present of shallow gas

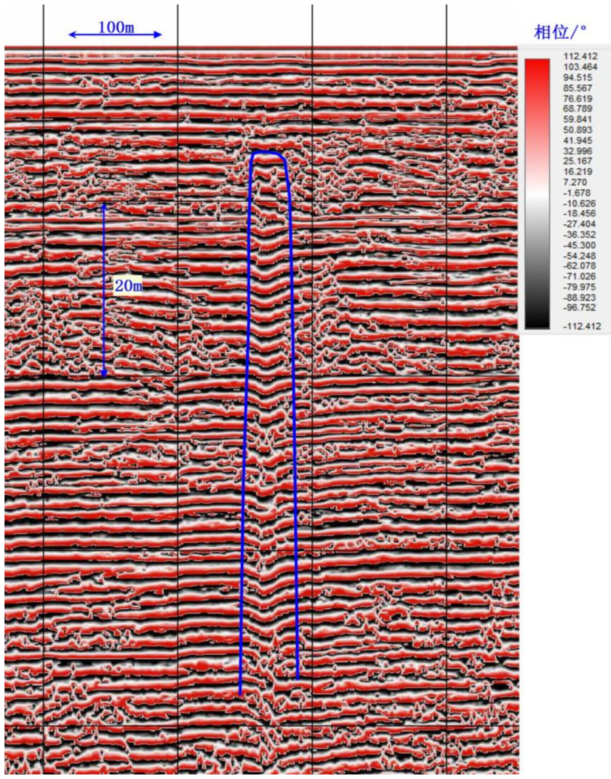

Fig.6 the acoustic profile in survey area profile2, and the property is phase for fig.4; Events drop-down region in the area bounded by blue lines, which is indicate the present of shallow gas

3.3 Frequency characteristics

Due to the increase of porosity and the decrease of sound velocity in gas bearing formation, it has a strong absorption and attenuation effect on sound wave[14-19]. The absorption coefficient of the formation can be expressed as:

$$Q = 2\pi\frac{E}{\Delta E} = 2\pi\frac{1}{1-\mathrm{e}^{-2\alpha\lambda}} = \frac{\pi f}{\alpha v}\ , \tag{6}$$

$$D_a = \mathrm{e}^{-\frac{\pi f}{Q}t} \tag{7}$$

Where, D_a is attenuation factor, f is acoustic frequency, t is acoustic travel time, v is acoustic velocity, α is absorption coefficient of medium.

It can be seen that the attenuation of sound wave is related to the frequency of sound wave. The higher the frequency is, the stronger the absorption and attenuation of sound wave are[20]. Therefore, the absence of high frequency in the frequency profile is the sufficient condition to judge the existence of shallow gas.

The instantaneous frequency attributes of the amplitude profiles in Fig.3 and Fig.4 are calculated, and the instantaneous frequency profiles are shown in Fig.7 and Fig.8. It can be seen from fig.7 that the instantaneous frequency of the whole section is between 50Hz and 500Hz, and the trend of upper high and lower part is low.

There is a frequency anomaly area in the middle of the profile, which is columnar and about 40m wide and the top is about 15m away from the seafloor. And this area is the same as the disordered reflection area on the amplitude profile. In this region, the high frequency component is missing, showing low frequency characteristics. The instantaneous frequency is about 100-150hz, and the instantaneous frequency in the surrounding area is generally greater than 200Hz.

It can be seen from Fig.8 that the instantaneous frequency of the whole section is between 50 Hz and 500 Hz, showing a trend of high frequency in the upper part and low frequency in the lower part. There is a frequency anomaly area in the middle of the profile, which is columnar with a width of about 40m and the top is about 15m away from the seafloor. And this area is the same as the concave area of the events on the amplitude profile. In this region, the high frequency component is missing, showing low frequency characteristics. The instantaneous frequency is about 150Hz ~ 200Hz, and the instantaneous frequency of the surrounding area is generally greater than 200Hz.

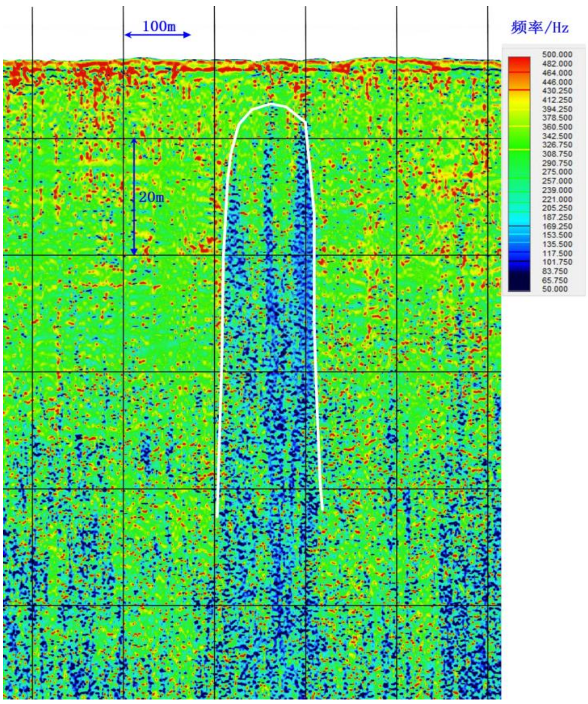

Fig. the acoustic profile in survey area profile1, and the property is instantaneous frequency for fig.3; Relative low frequency region in the area bounded by white lines, which indicate the present of shallow gas

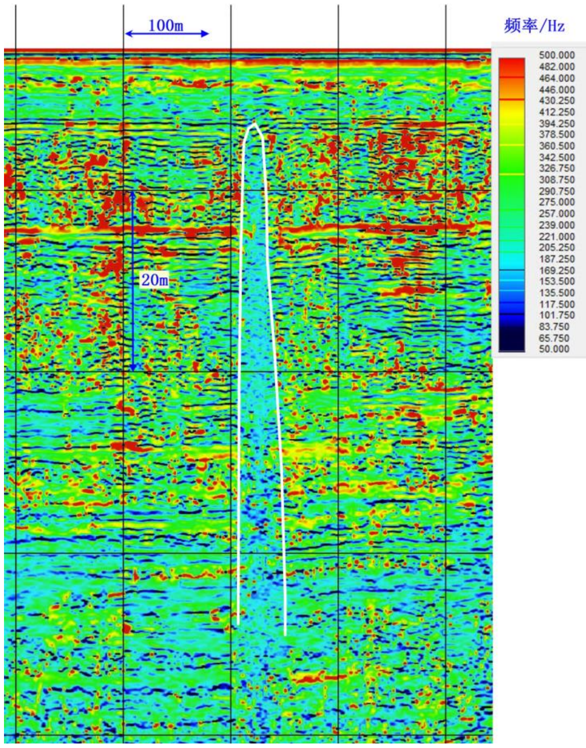

Fig.8 the acoustic profile in survey area profile2, and the property is instantaneous frequency for fig.4; Relative low frequency region in the area bounded by white lines, which indicate the present of shallow gas

From the above analysis, we can see that there is an abnormal region in amplitude, phase and frequency profile, and the shape and position are almost the same. It can be seen from the drilling data that the layer below 15m-120m of the seabed are mainly sand layer and a small amount of clay layer, which has strong permeability, while the layer below 15m of the seabed are mainly muddy clay, which is a good caprock. Therefore, considering the weak amplitude, disordered reflection, top phase inversion, pull-down of the events, high frequency missing and formation, the abnormal area can be basically determined as shallow gas reflection. The process is shown in Fig.9.

As can be seen from Fig.10, the shallow gas located at the end of a normal fault, and the buried depth of the top of the fault is 31-57m. According to the engineering geological drilling data, 15m below the seabed is mainly muddy clay layer, which is a good caprock. According to the survey data of the platform site in previous years, the shallow gas in the strata around the platform only appeared in the last 10 years. And the platform is located in the Yangerzhuang Zhaojiabao fault zone of Chengbei fault terrace. Zhaobei fault and Yangerzhuang fault, which have been developed for a long time, are not only boundary faults, but also oil and gas migration channels with unconformity. Oil and gas reservoirs are formed on both sides of fault and unconformity area. The buried depth of oil layer is 990-1985m, the porosity is more than 30%, the permeability is 1200-1700 × 10^{-3} μ m2, and the oil and gas migration is fast.

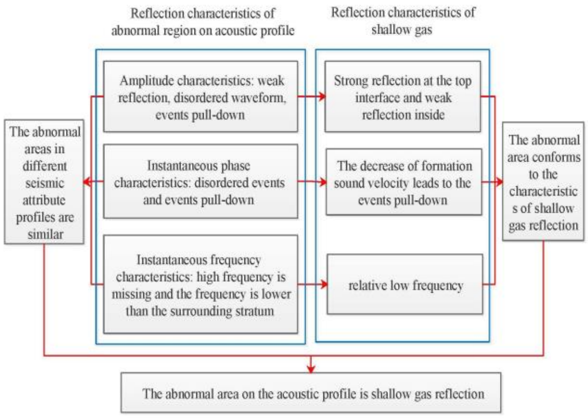

Fig.9 The method of identify shallow gas with acoustic profile

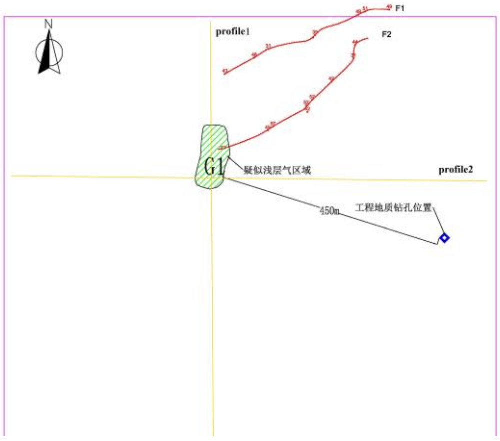

Fig.10 Distribution characteristics of shallow gas and faults; And profile1 is correspond to fig.3, fig.5, fig.7; profile2 is correspond to fig.4, fig.6, fig.8.

The shallow gas forming acoustic blank is considered to be the gas from deep rising to the shallow seabed along pores and fractures, the large-scale acoustic blank needs relatively more gas to be continuously supplemented in order to maintain its shape[21]. Therefore, it can be inferred that the abnormal area in the profile is shallow gas reflection, and it may come from the deep formation and migration upward along the fault. In recent years, with the increase of gas pressure, it has broken through the formation resistance and migrated upward to 15m below the seabed, until encountered the muddy clay layer, the gas pressure is balanced with the formation resistance, forming columnar shallow gas in the shallow formation.

4. Conclusion

Based on the actual drilling data, the stratigraphic model of the submarine shallow gas is established, and the forward simulation analysis of the submarine shallow gas is carried out. Because the sound velocity of gas bearing formation is lower than that of surrounding formation. Therefore, at the boundary between the shallow gas and the formation, the reflected wave phase reverses, and the events of the inner part and lower part of the shallow gas pull down.

The acoustic stratigraphic profile data around an oil platform in Huanghua sea area of Bohai Bay are analyzed in terms of amplitude, phase and frequency, and there is an abnormal area in the three attribute sections, and the location is the same, which is characterized by weak amplitude clutter reflection, top phase inversion and high frequency missing. Based on the above characteristics, it is considered that the abnormal area is shallow gas reflection.

Therefore, it can be used as a method to identify shallow gas by analyzing multiple attributes of acoustic stratigraphic section and synthesizing the attributes of amplitude, phase and frequency.

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Declaration：

Availability of data and material:

The engineering geological borehole data is from the actual borehole sampling in Bohai Bay, which is a full coring borehole. The drilling coordinates are 38°29’28.6651”N,117°45’15.3138”E; and the water depth is 3m, and the drilling depth is 120m. The date of drilling is 2020/11/14-2020/11/25.

The seismic data is from the actual geophysics survey in Bohai Bay, with a survey area of 1km×1km. the location of survey area surrounded by 4 points which is 38°29’45.3961”N，117°44’54.5349”E；38°29’45.1273”N，117°45’36.2801”E； 38°29’12.1228”N，117°45’35.9334”E； 38°29’12.3916”N，117°44’54.1935”E. the survey date is 2020/10/14-2020/10/19.

Competing interests：

The author(s) declare(s) that they have no competing interests。

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Authors' contributions：

Yang Xiaodi is responsible for most of the work of this paper, including data collection, data processing, results analysis and so on.

Chun Minghao is responsible for field engineering geophysical survey;

Luo Xiaoqiao is responsible for field engineering geological drilling;

Yao Zhiguang is responsible for field engineering geological drilling.

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Supplementary Files

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- engineergeilogicalboreholedata.xlsx