



# Research on the anisotropy of gas hydrate reservoirs in South China Sea

Xiangchun Wang<sup>1</sup> · Wuyunbateer Bai<sup>1</sup> · Yanpeng Zheng<sup>2</sup>

Received: 5 June 2020 / Accepted: 19 September 2020 / Published online: 27 September 2020  
© Springer Nature B.V. 2020

## Abstract

The leakage-type hydrate is filled in the fractures, with steep and directional dips characteristics and the reservoir is basically anisotropic. The fractures characteristics are the key factors for reserve estimation and making of the production plan, and it is also the challenge and difficulty of the seismic exploration. Here we use the existing data recorded from ocean-bottom seismometers in the northeastern slope of South China Sea to carry out the research on whether the hydrate reservoir has the seismic anisotropy characteristics, and the results show that the seismic anisotropy characteristics is very obvious. The thickness and position of HTI medium lies between the time of 1550 ms and 1600 ms. On the basis of HTI anisotropy, combined with the geological situation of the region, it is assumed that vertical fractures exist in the region and the leakage-type hydrate exists. Also the research on parameters extracted from the fracture strike is carried out. The symmetry axis and the fracture directions of fractures are estimated. The results show that 60° and 240° correspond to the fractures symmetry axis, and 150° and 300° are the fractures trend. The recognition is very important for the estimation of the gas hydrate's saturation.

**Keywords** Hydrate · Leakage type · Fractures · Anisotropy · Ocean-bottom seismometer

## Introduction

Natural gas hydrate is a new energy with huge reserves that has not yet been commercially produced (Sha et al. 2015a, b). As a crystalline compound of methane gas and water at a certain temperature and pressure, the important role of gas channeling system and migration mode in the gas hydrate reservoir has been concerned by many scholars. According to the controlling factors of gas migration, four kinds of gas hydrate accumulation are summarized, which are fault structure type, mud volcano type, stratum controlling type and structure stratum type (Milkov et al. 2002; Tréhu et al. 2004). Also there are some scholars (Fan et al. 2004; Su 2008) who divided gas hydrate deposits into two types of systems: diffusion type and leakage type according to the way of gas channeling.

South China Sea is located on the convergence zone of the Eurasian Plate, the Filipino Plate, and the Indian Ocean Plate. Owing to the interaction of these plates, the South China Sea evolved a marginal sea basin with a complex sedimentary structure and unique regional tectonic geological characteristics (Yang et al. 2014). Shenhu area is geographically situated in the central north continental slope of the South China Sea, between the Xisha Trough and Dongsha Islands. It structurally lies in Zhu II depression, Baiyun sag which is in the Pearl River Mouth Basin (Wu et al. 2009). From the towed streamer seismic data's migration profiles, it can be seen that there are many high angle faults in this area (Wang and Pan 2017). so it can be assumed that the region has some high angle fractures.

The gas hydrate of diffusion type is filled in the pores of sediments, the reservoir content is clay and silt, and the hydrate is distributed in the bottom of the layers. Leakage-type hydrate is a major hydrate type next to the diffusion type. Different from the diffusion type, the leakage type hydrate formation is generally steep due to the action of structural stress, and its distribution is related to the main stress of fault. The fault has directional characteristics and is similar to the fractures medium. It has obvious anisotropic characteristics in logging speed, resistivity and seismic

✉ Xiangchun Wang  
wangxc@cugb.edu.cn

<sup>1</sup> School of Geophysics and Information Technology, China University of Geosciences (Beijing), Beijing 100083, China

<sup>2</sup> Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266061, China

reflection (Lee and Collett 2009). The two types of gas hydrate both exist in the area of the northeast slope of South China Sea (Liang et al. 2017; Yang et al. 2017).

For large-scale fault structures, they are easy to be identified from seismic profiles, and the geometric parameters of fault are relatively easy to calculate. However, small and medium-sized fractures can not be identified directly from the seismic profiles, so how to identify small and medium-sized fractures and estimate their geometric parameters are key problems in the study of leakage hydrate.

OBS data has four components: a hydrophone component that only records P-wave, a vertical component that mainly records P-wave and two horizontal components that mainly record converted S-wave. During OBS exploration, shot points are distributed in three dimensions on the sea surface, with 360° coverage around OBS points, this is beneficial to all azimuthal study. Through the study of shear wave splitting in the Mid-Atlantic Ridge, the arrival time difference of fast and slow waves is independent of the length of ray path, azimuth and OBS position, and its anisotropy is mainly originated from a series of vertical and water filled fractures parallel to the rift direction developed in the shallow part of the oceanic crust (Barclay and Toomey 2003). Eleven four-component ocean-bottom seismometers (OBS), from an array of 21 OBS located on the northern headwall of the Storegga Slide were used to analyse the phenomenon of shear wave splitting in mode-converted shear waves (Stewart et al. 2002, 2003). Shear wave splitting in sediments is often attributed to the presence of aligned micro-cracks and fractures (Crampin 1987, 1993; Winterstein 1990; Crampin and Peacock 2005), which are commonly orientated normal to the direction of the minimum principal stress.

Before 2003, China had only completed 7 lines and 74 OBSs on the northern continental margin of the South China Sea (Zhao 2013). In 2004, Guangzhou Marine Geological Survey (GMGS) and the Institute of Marine Science of the University of Kiel in Germany cooperated to deploy OBS in the northern part of the South China Sea. For the first time, a giant carbonate rock formed by the “cold spring” spurt of hydrate in the northern of the South China Sea was discovered. In 2006, GMGS conducted an acquisition experiment using the OBS on the northern slope of the South China Sea. The OBS observation system was optimized, and the P and S wave’s velocities are obtained by a travel time inversion method. The relationship between the velocities and the hydrate are recognized (Sha et al. 2015a, b). In 2009, China conducted a three-dimensional (3D) seismic joint acquisition in the Shenhu area of the South China Sea for the first time. The multi-channel seismic data and OBS data were collected. The multi-channel seismic data was used to establish a geological model framework. The P- and S-waves of OBS were used for joint travel time inversion to obtain velocity information for better understanding the velocity

variation characteristics of the hydrate distribution region (Zhang 2014).

By now, there are not any research on the anisotropy analysis using the seismic data in this area. In this paper, we use the OBS data in the gas hydrate existing area of South China Sea to analyze the layer’s anisotropy, determine whether the small and medium-sized fractures exist, so we can identify the type of gas hydrate reservoir. Also we use the OBS data to carry out some quantitative research on the fractures trend extraction technique.

## Methods

Using OBS data, the anisotropy of a region can be studied, while using the drilling hole data, only the anisotropy of one point position can be achieved. So here we do the anisotropy research using the OBS data for the large area study.

### Radial and tangential energy variation with azimuth

When the S-wave passes through the anisotropic medium, it will split into fast and slow S-wave. The fast and slow S-wave have energy in both radial (R) and tangential (T) components, but they show different energy characteristics in azimuth gathers. Therefore, by analyzing the energy variation of R and T components in different azimuth gathers, we can judge whether the layers have anisotropic characteristics (Exley et al. 2010).

In order to determine the variation of radial and tangential energy with azimuth, the horizontal components data of OBS should be selected and used. The data should contain the information of 0° to 360° azimuth around each OBS. All traces of X and Y components of each OBS are rotated horizontally to obtain R and T components, and the rotation angle can be calculated by energy scanning method. The following formula is the rotation formula  $U_X$  and  $U_Y$  are the amplitudes of X and Y components.  $U_R$  and  $U_T$  are the amplitudes of R and T components.  $\theta$  is the rotation angle (Alford 2004).

$$\begin{bmatrix} U_R \\ U_T \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} U_X \\ U_Y \end{bmatrix}$$

If the layers are anisotropic, the time delay characteristics of the fast and slow waves in the R component is almost a sine event, the part with strong energy indicates the direction of the fast shear wave, and the part with weak energy indicates the direction of the slow shear wave. In the T component, polarity reversal occurs every 90°, it is divided into four sectors, each sector is 90°, the part of the strong energy is the maximum shear wave splitting direction, and the part

of the weak energy (approximately to zero) is the symmetry plane without shear wave splitting.

### Analysis of anisotropy by particle motions

In isotropic layers, the particle motions of S-wave on the horizontal plane is a straight line perpendicular to the R component movement, and there is no shear wave splitting phenomenon. In anisotropic layers, when the polarization direction of the incident shear wave is oblique to the fractures trend, shear wave splitting occurs, and the particle motion trajectory is elliptical. When the polarization direction of the incident shear wave is parallel to the fractures trend, no shear wave splitting occurs, and the particle motion trajectory is a straight line perpendicular to the R component. Therefore, the anisotropy of layers can be identified by particle motions trajectory.

The trajectory of a particle motion can be represented by a vector plot. Choosing the appropriate shot points to generate the particle motions trajectory can show the particles movements of the waves, and the level of ellipse polarization is determined by the anisotropy strength. This method can further confirm whether there is anisotropy in the layers and add more extra information (Exley et al. 2010).

### Quantitative estimation of fractures trend

The above-mentioned R and T energy variations with azimuth and particle motions trajectory can qualitatively analyze the anisotropy of the layers. Here we will study the method of quantitative detection of fractures trend. At present, there are many methods to determine the trend of fractures for fractured reservoirs, among which the most commonly used methods are energy ratio method, angle spectrum scanning method and fractures trend detection method based on Alford rotation.

Here we used the energy ratio method to quantitatively detect the fractures trend. The polarization direction of the fast shear wave is parallel to the trend of the fractures, so the problem of finding the trend of the fractures is to find the polarization direction of the fast shear wave. Firstly the R and T components data are stacked in a certain offset. When the polarization direction of the stacked R component is parallel to the fractures trend, the converted wave propagates at a faster speed in the fractures, and the fast shear wave energy is mainly observed in the R component, and the small or even zero slow shear wave energy is observed in the T component. At this time, the energy ratio of the R and T component is the largest. According to this principle, it can be detected that the azimuth angle with the largest energy ratio is the direction of fractures development.

$$A(\alpha) = \frac{\sum_{k=L}^M R^2(k, \alpha)}{\sum_{k=L}^M T^2(k, \alpha)}$$

In the above formula, L and M are the range of sampling points corresponding to the analysis window, R is the radial component, T is the tangential component,  $\alpha$  is the azimuth of the current azimuth gather, k is the sample point number, A ( $\alpha$ ) is the energy ratio of R and T components of the current azimuth, and when the ratio is the maximum, the corresponding azimuth is the trend of fracture development.

## Data processing

### Data

In this study, 10 OBS are freely dropped to the sea bottom from the sea surface at an interval of 500 m. 23 shot lines are arranged, the shot line spacing is 50 m. There are 685 shots on each shot line and the shot interval is 25 m. The data was collected by GMGS in 2015. The OBS used in the acquisition consists of three orthogonal velocity components and one hydrophone component. The source is an air gun source and the volume is 540 Cu. In. The colored straight lines in Fig. 1b are the 23 shot lines. The blue point in Fig. 1b is the position of one OBS. The acquisition geometry can achieve omni-directional coverage and can be used for azimuthal anisotropy research. In this paper, only the middle red OBS shown in Fig. 1b is presented.

The horizontal X and Y components of OBS data should be processed before they can be used in the following study. The processing steps include: relocation, denoising, linear NMO correction, horizontal component rotation and so on. And the quality of rotation is very important for the following anisotropic analysis.

### Horizontal component rotation

For OBS data, firstly the direct arrival wave is flattened by linear normal moveout (NMO) processing, and the converted shear wave near zero offset is flattened approximately. Here the rotation of energy scanning method is used to rotate the horizontal components. The maximum direct arriving wave energy in the R component is the constraint condition. Given the scanning angle, the X and Y components are projected into the R and T directions, and then the energy values of the R direction is calculated. When the R energy reaches the maximum value, the scanning angle is the rotation angle. Then using this rotation angle, the whole trace data is rotated.

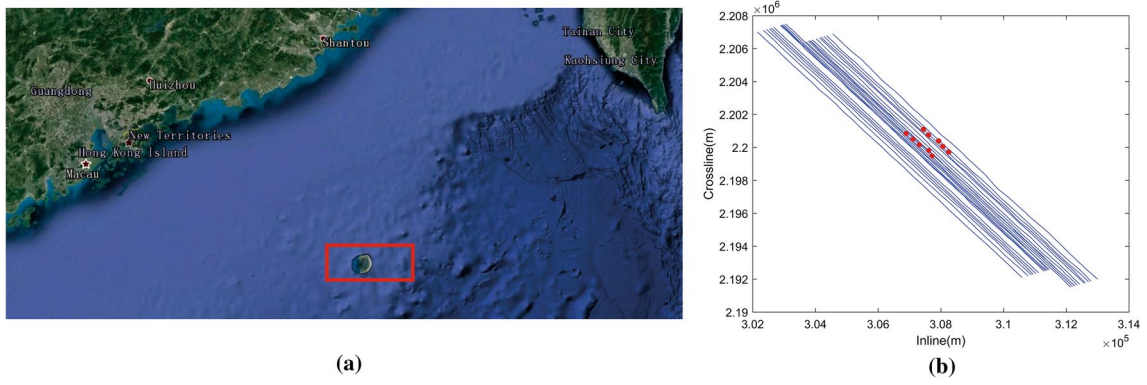


Fig. 1 The bathymetry map (a) and geometry of OBS exploration (b)

Fig. 2 Rotation of horizontal components. **a** is the X component, **b** is the Y component, **c** is the R component and **d** is the T component

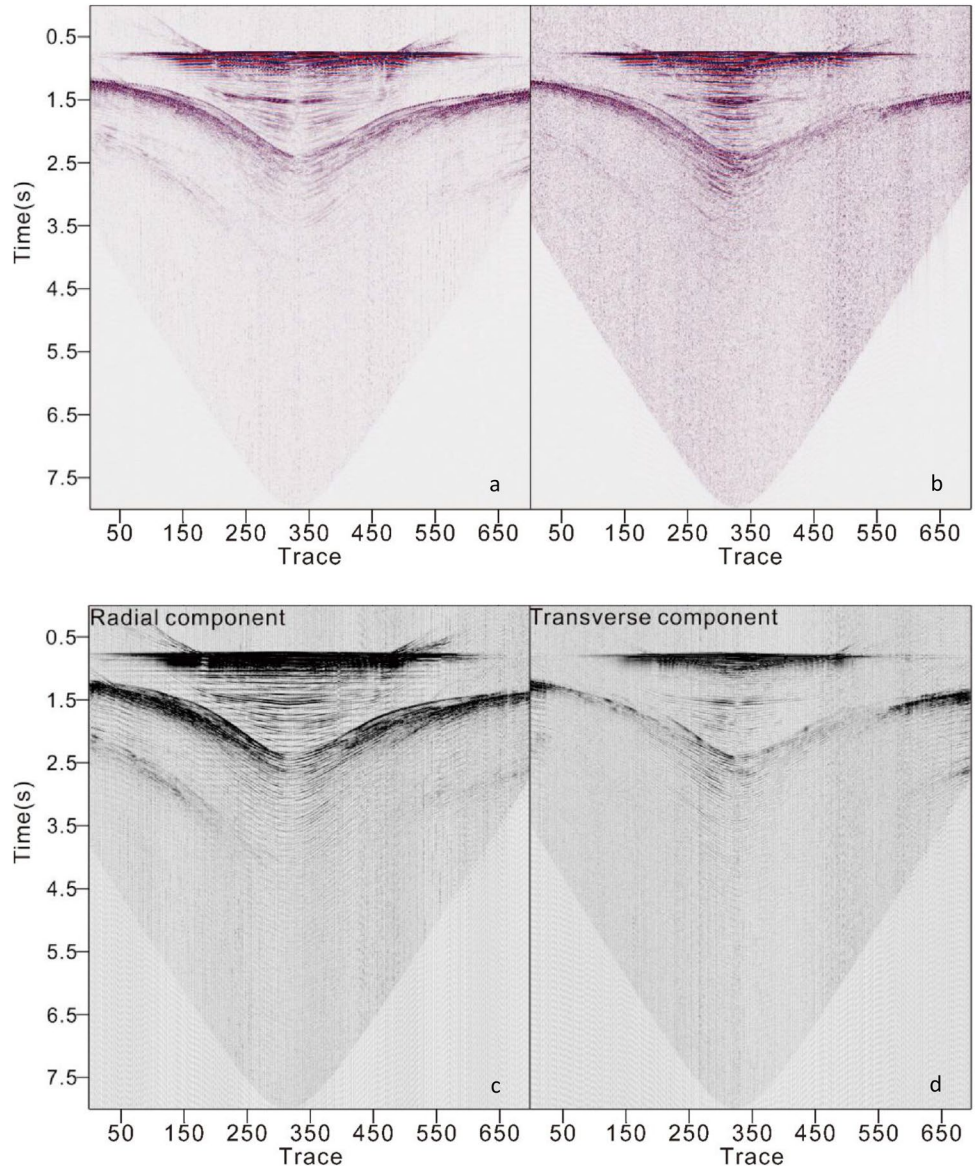


Figure 2 shows the wave field before and after the horizontal component rotation. Figure 2a, b are the X and Y component wave field, the energy of them is almost the same. Figure 2c and d are the R and T components wave field after rotation processing. The obvious strong event of the direct wave can be seen on the R component in Fig. 2c. And in Fig. 2d there is weak direct arriving wave event. Also the events of the reflected wave are more clear in the R component compared with the T component.

## Anisotropic analysis of OBS data

In this paper, on the basis of good horizontal component rotation processing, the anisotropy analysis using different offset data received by OBS is carried out. The method of observing the variations of stack amplitude energy with azimuth angles and the method of particle motion trajectory analysis are both used to do the qualitatively anisotropy analysis. Also the OBS data is used to carry out some quantitative research on the fractures trend extraction technique.

### Azimuthal stack

Based on the azimuthal anisotropy theory, the stack amplitude energy of the R and T components after the rotation of the horizontal component is observed with the variations of azimuthal angles. For this reason, shot points in the offset section can be divided into uniform stack segments according to the angle interval as shown in Fig. 3. The inner circle radius is 600 m and the outer circle radius is 900 m.

When the angle range is  $5^\circ$  and the offset range is 600 to 900 m, the stack profiles obtained are shown in Fig. 4. Here the T component profile has been gained for displaying reason, and the ratio of R and T actual amplitude energy is 6 to 10 times. In Fig. 4a, there is a sine shaped reflection wave event between 1500 to 1700 ms in  $0^\circ$  to  $180^\circ$  range. The trough of the event is about  $70^\circ$  and the peak of the event is around  $150^\circ$ . Because of the data's large phase difference in the  $180$  to  $360^\circ$ , the interference of the conversion wave is generated, resulting in the invisible events. In Fig. 4b, there are four empty amplitude energy bands at  $90^\circ$  interval on the events, the blank bands are at about  $60^\circ$ ,  $150^\circ$ ,  $240^\circ$  and  $330^\circ$  respectively, and the phase reversal phenomenon can be seen on the two sides of the empty band. Among which the phase reversal and blank band around  $60^\circ$  are particularly significant. According to the above analysis, the data in this area shows obvious HTI anisotropic characteristics, which can be used for fractures detection. The other 9 OBS data analysis also show the same results.

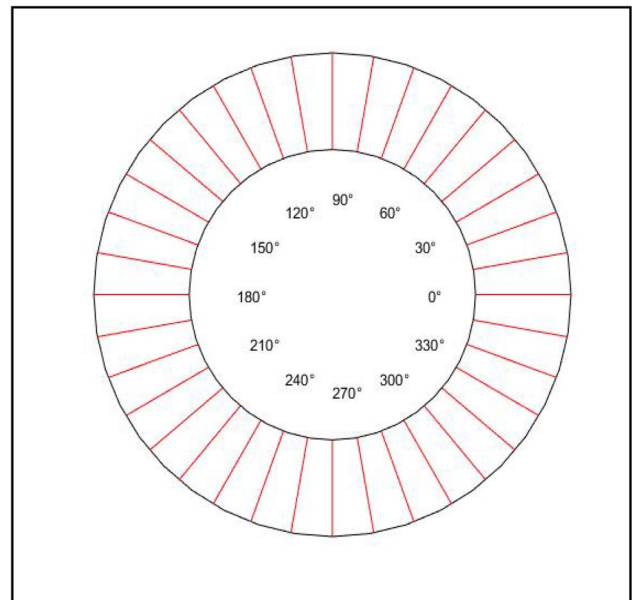


Fig. 3 Angle division map

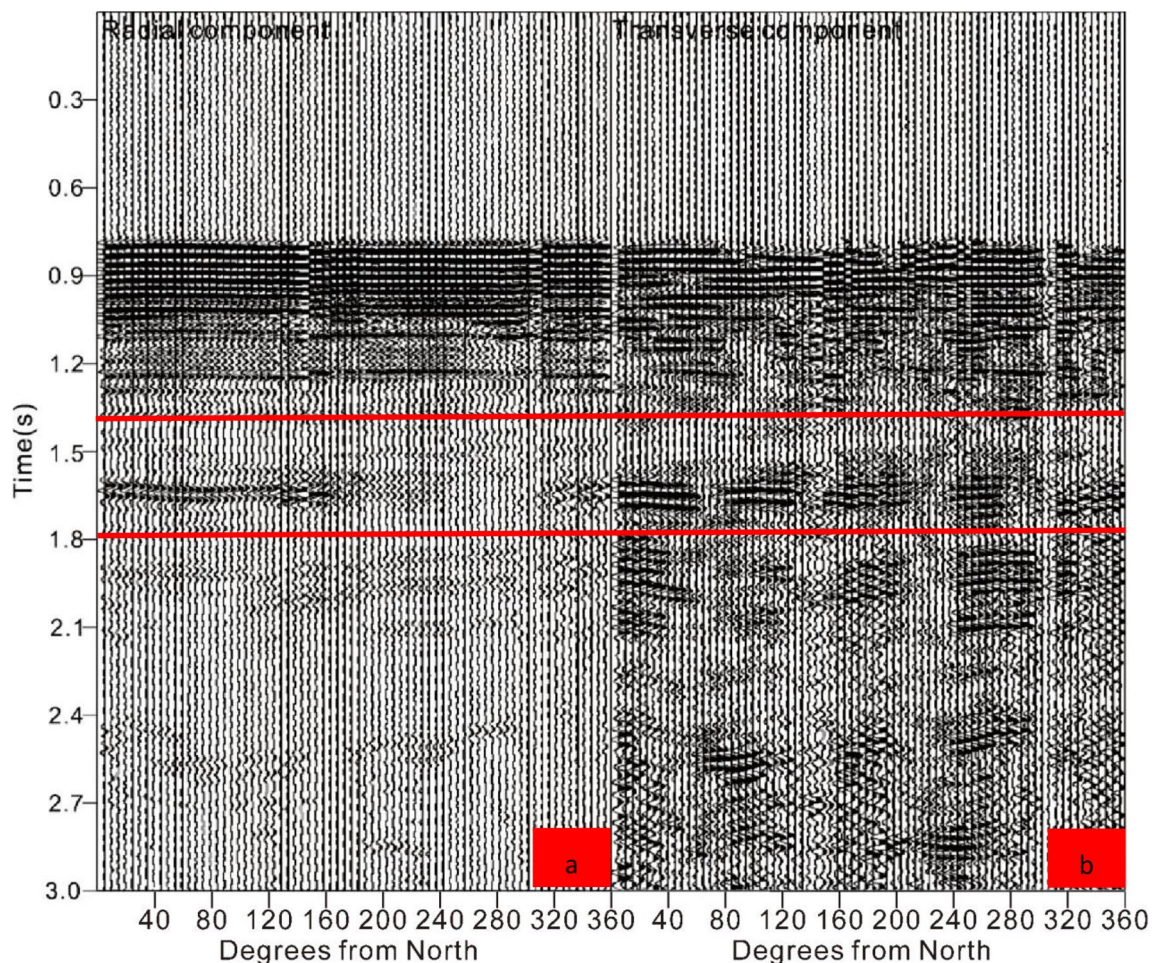
### Particle motion analysis

The particle motion analysis in this paper is based on the data of the stacked R and T components. In order to draw the trajectory, the channels in several directions are evenly selected, and the time length which can observe the shear wave splitting phenomenon is selected. According to the wavelet period, the time length is divided into a series of time windows, in each time window the motion trajectory is drawn.

In the 1400 to 1800 ms time length, 8 time windows whose length are 50 ms are selected to do the particle motion analysis. For the data's uneven coverage and some data's low ratio of signal to noise,  $30^\circ$ ,  $50^\circ$ ,  $60^\circ$ ,  $70^\circ$ ,  $80^\circ$ ,  $130^\circ$ ,  $150^\circ$ ,  $220^\circ$ ,  $240^\circ$ ,  $260^\circ$  and  $315^\circ$  channels are selected on the stacked profiles. R component is used as the vertical axis and T component is used as the horizontal axis to depict the particle motion, shown in Fig. 5.

It can be seen that there are elliptical and linear motion trajectory varying with the azimuth between the time of 1550 ms and 1600 ms, which can reveal the thickness and position of HTI medium. There is linear particle motion between 1550 and 1600 ms at  $60^\circ$ ,  $70^\circ$  and  $150^\circ$ , which can be considered as anisotropic trend and symmetric axis trend. At  $240^\circ$  and  $330^\circ$ , linear motion can not be seen due to the error of stack processing. Because of the accumulation of errors, the ellipse phenomenon which varies with the trend can not be obtained, and the fractures trend can not be identified by the long and short axis of the ellipse.

From the anisotropy identification of OBS, it can be seen that the peak and valley of R component, four blank bands



**Fig. 4** Azimuth stack of R and T components. **a** Azimuth stack of R component and **b** azimuth stack of T component

with  $90^\circ$  interval and phase reversal on both sides of T component prove the existence of HTI anisotropy, and the trend of anisotropy and symmetry axis can be obtained from the linear motion track of particles in  $60^\circ$  to  $70^\circ$  and  $150^\circ$  azimuth channels. The other 9 OBS data analysis also show the same results.

### Fractures trend prediction

On the basis of HTI anisotropy, combined with the geological situation of the region, it is assumed that the region is vertical fractures. The energy ratio method is used to quantitatively calculate the fractures trend.

We calculate the energy ratio of 72 channels in the time window between 1400 and 1800 ms, and get the results shown in Fig. 6. There are four significant peaks in the energy ratio, corresponding to 12, 30, 48 and 60 channels, and their corresponding azimuth angles are  $60^\circ$ ,  $150^\circ$ ,  $240^\circ$  and  $300^\circ$ . The four peaks correspond to the fractures trend and the symmetry axis. The results show that  $60^\circ$  and  $240^\circ$

correspond to the fractures symmetry axis, and  $150^\circ$  and  $300^\circ$  are the fractures trend. The other 9 OBS data analysis also show the same results.

### Conclusions and suggestions

The results show that the seismic anisotropy characteristics in the study area is very obvious. On the basis of HTI anisotropy, combined with the geological situation of the region, it is assumed that vertical fractures exist in the region and the leakage-type hydrate exists. The drilling hole data shows that there are high angle fractures filled with natural gas hydrate in the area. The final aim of this research is to estimate the saturation of hydrate. There are still many problems that need to be further studied. The most difficult thing is how to find an appropriate rock model that is suitable to leakage-type hydrate reservoirs. Only this difficulty is solved, methods of porosity and saturation estimation can be further studied. The data

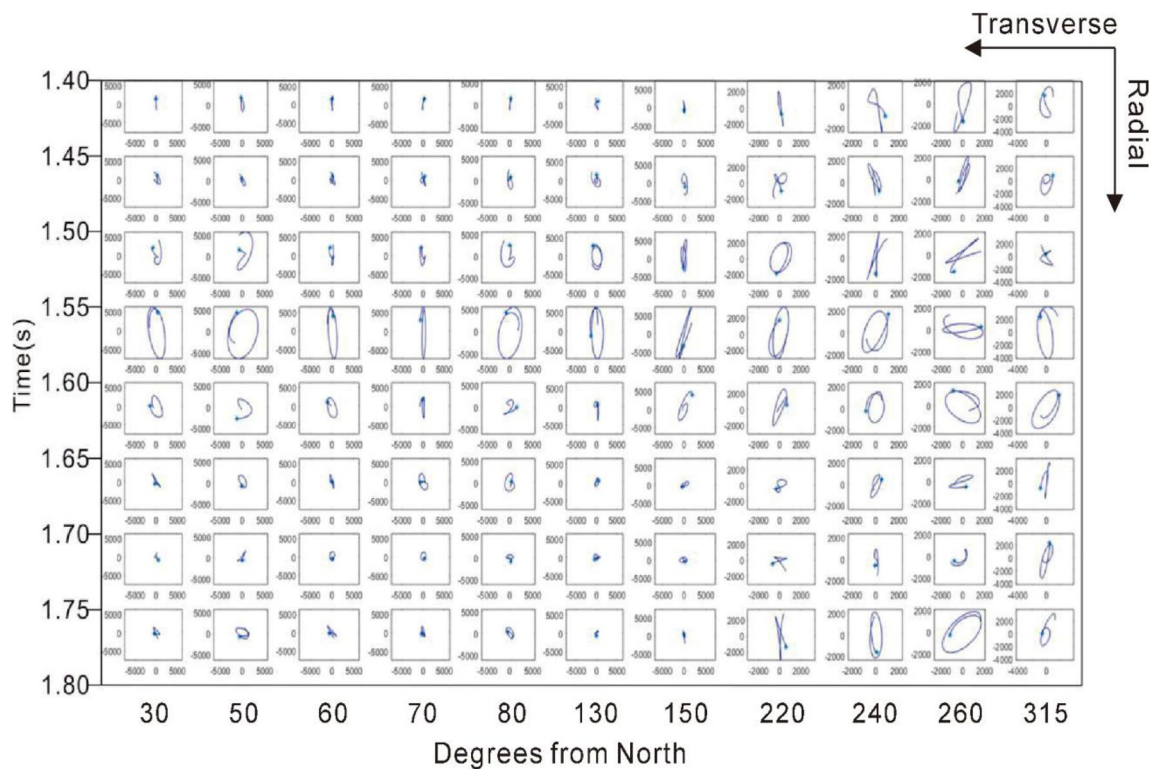


Fig. 5 Particle motion trajectory

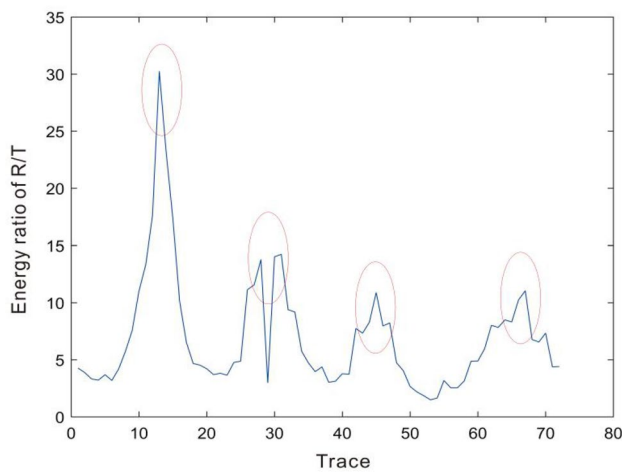


Fig. 6 Estimation of fracture azimuth by energy ratio method

processing should also be strengthened to guarantee the anisotropic analysis accuracy. For example, if the number of omnidirectional coverage of OBS data is insufficient, 5D interpolation method may be used to make shot points more dense and regular. This can increase the accuracy of anisotropy analysis. If the seabed terrain is not horizontal layered terrain, it has a great impact on the azimuth anisotropy analysis. Tilt correcting processing of OBS data

should be done to ensure the data's fidelity of X and Y component.

**Acknowledgements** This research was funded by the National Natural Science Foundation of China (No. 41874131), the Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology (No. MGQNL201811).

**References**

Alford RM (2004) Sheardata in the presence of azimuthal anisotropy: Dilly, Texas. SEG Technical Program Expanded Abstracts 2004. Society of Exploration Geophysicists, 183–186

Barclay AH, Toomey DR (2003) Shear wave splitting and crustal anisotropy at the Mid-Atlantic Ridge, 35°N. *J Geophys Res* 108(B8):2378

Crampin S (1987) Crack porosity and alignment from shear-wave VSPs, in shear-wave exploration. In: Danborn SH, Domenico SN (eds) Geophysical developments, SEG Special Publication, pp 227–251

Crampin S (1993) A review of the effects of crack geometry on wave propagation through aligned cracks. *Can J Expl Geophys* 29:3–17

Crampin S, Peacock S (2005) A review of shear-wave splitting in the compliant crack-critical anisotropic Earth. *Wave Motion* 41:311–330

Exley RJK, Westbrook GK, Haacke RR (2010) Detection of seismic anisotropy using ocean bottom seismometers: a case study from the northern headwall of the Storegga Slide. *Geophys J Int* 183:188–210

- Fan S, Liu F, Chen D (2004) The research of the origin mechanism of marine gas hydrate. *Natural Gas Geo Sci* 15(5):524–529
- Lee MW, Collett TS (2009) Gas hydrate saturations estimated from fractured reservoir at Site NGHP-01-10, Krishna-Godavari Basin, India. *J Geophys Res* 114(B07102):0148–0227
- Liang J, Fu S, Chen F, Su P, Shang J, Lu H, Fang Y (2017) Characteristics of methane seepage and gas hydrate reservoir in the northeastern slope of South China Sea. *Natural Gas Geosci* 28(5):761–770
- Milkov A, Sassen V et al (2002) Economic geology of offshore gas hydrate accumulations and provinces. *Mar Pet Geol* 19(1):1–11
- Sha Z, Liang J, Su P et al (2015a) Natural gas hydrate accumulation elements and drilling results analysis in the eastern part of the Pearl River Mouth Basin. *Earth Sci Front* 22(6):125–135
- Sha Z, Zhang M, Zhang G, Liang J, Su Y (2015b) Using four-component OBS data to reveal the distribution and velocity characteristics of gas hydrate in the north slope of the South China Sea. *Appl Geophys* 12(4):555–563
- Stewart RR, Gaiser JE, Brown RJ, Lawton DC (2002) Converted wave seismic exploration. *Meth Geophys* 67(5):1348–1363
- Stewart RR, Gaiser JE, Brown RJ, Lawton DC (2003) Converted wave seismic exploration. *Appl Geophys* 68(1):40–57
- Su Z (2008) Numerical simulation of Hydrate Distribution and leakage dynamics of marine natural gas. Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIGCAS)
- Tréhu AM, Long PE, Torres ME et al (2004) Three-dimensional distribution of gas hydrate beneath southern Hydrate Ridge: constraints from ODP Leg 204. *Earth Planet Sci Lett* 222(3–4):845–862
- Winterstein DF (1990) Velocity anisotropy terminology for geophysicists. *Geophysics* 55:1070–1088
- Wu N-Y, Yang S-X, Wang H-B, Liang J-Q, Gong Y-H, Lu Z-Q, Wu D-D, Guan H-X (2009) Gas-bearing fluid in flux sub-system for gas hydrate geological system in Shenhu Area, Northern South China Sea. *Chin J Geophys* 52(6):1641–1650 (in Chinese)
- Wang XC, Pan DY (2017) Application of AVO attribute inversion technology to gas hydrate identification in the Shenhu Area, South China Sea. *Mar Pet Geol* 80:23–31
- Yang R, Yan P, Wu N-Y, Sha ZB, Liang JQ (2014) Application of AVO analysis to gas hydrate identification in the northern slope of the South China Sea. *Acta Geophys* 62(4):802–817
- Yang S, Liang J, Lu J, Qu C, Liu B (2017) New understandings on the characteristics and controlling factors of gas hydrate reservoirs in the Shenhu area on the northern slope of the South China Sea. *Earth Sci Front* 24(4):1–14
- Zhang S (2014) Research on key technologies of multi-component seismic data imaging in OBS. Ocean University of China
- Zhao HB (2013) A study on the data processing methods of Ocean Bottom Seismograph(OBS). Chang'an University.

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.