

Identification of shallow water flow using multicomponent seismic and GPR attributes in the deepwater basin of the northern South China Sea

Yupeng Shen^{1,2*}, Tianxiao Tang¹, Ruifang Zuo¹, Zhe Zhang¹ & Yaqiong Wang³

¹School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, P.R. China

²Beijing Engineering and Technology Research Center of Rail Transit Line Safety and Disaster Prevention, Beijing 100044, P.R. China

³Key Laboratory for Bridge and Tunnel of Shanxi Province, Chang'an University, Xi'an 710064, P.R. China

*[Email: ypshen@bjtu.edu.cn]

Received 11 November 2018; revised 02 March 2017

China has been using large-scale ocean bottom cable (OBC) multicomponent seismic data in deepwater oil and gas exploration since May 2012. In the northern South China Sea, shallow-water flows and over-pressurized zones are major hazards in deepwater drilling projects. Thus, the accurate predrill seismic prediction of shallow-water flow sands is an important practical problem. In this paper, the exact velocity field of sound in deep water is calculated as a function of the density, temperature and pressure of the seawater. Models of various elastic parameters are established. Through drilling data and simulation of the full wave field, new Pp and Ps AVO phenomena of shallow-water flow at various effective pressures are developed. Methods based on multicomponent seismic attributes, such as weighted average frequency and sweetness, are established to predict and characterize shallow-water flow. By studying vertically oriented GPR signals and signals parallel to the well paths in the SWF region, we find a significantly increased polarity inversion and decreased amplitude in the SWF region as effective pressure increases. Methods based on multicomponent seismic attributes and characteristics of the GPR signals may aid in the identification of SWF in the deepwater basin of the northern South China Sea. This may help overcome limitations to research in this area.

[Keywords: deep water, velocity field, effective pressure, multicomponent, AVO, GPR, attributes]

Introduction

Shallow-water flow (SWF) of over-pressured, uncemented, and unconsolidated sands presents a challenge in drilling during oil and gas exploration in offshore areas where the water depth exceeds 500 m¹. It also poses a significant hazard to deepwater drilling and facilities. When these sands are drilled, water and sand may flow into the wells and cause accidents (Fig. 1). This problem cannot be overcome by increasing the mud weight because, if the mud weights are too high, the sands may fracture, leading to lost circulation and loss of well control². SWF was first identified in 1985. Since then, 70% of drilling operations in the Gulf of Mexico reportedly encountered SWF³ (Fig. 2). Millions of dollars were spent for prevention and repair of accidents resulting from SWF. Furthermore, SWF has been encountered in Norway, the South China Sea and other deepwater areas. Research and surveys indicate that SWF usually occurs in deepwater basins (water depths greater than 400 meters) with high deposition rates^{4,5,6,7}. The formation of shallow-water hazards

must meet three main conditions: first, the presence of loose, unconsolidated, large-porosity and permeable sedimentary sand; second, low permeability and effectively closed mud; and third, abnormally pressurized sand rock⁸.

The current method of identifying SWF involves predrill hazard studies utilizing conventional, high-

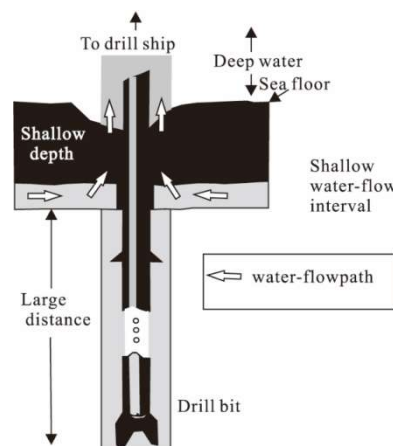


Fig. 1 — SWF hazard chart⁹

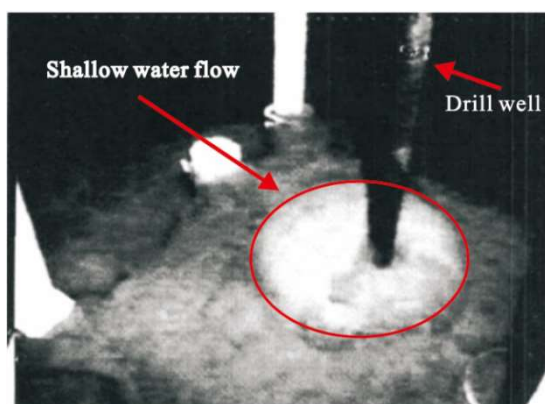


Fig. 2 — SWF photo in Gulf of Mexico^{10,11}

resolution seismic data to identify zones that might produce SWF¹². Based on laboratory studies, Prasad found that a high Poisson's ratio and shear wave velocity ratio could indicate shallow-water flows. Mallick and Dulla¹³ proposed the use of AVO and full-wave inversion methods to detect shallow-water flows. To obtain information about shear waves and increase the accuracy of predictions, Huffman studied the use of multicomponent seismic data to detect SWF. Huffman's research focused on the relationship between effective stress and V_p/V_s ¹⁴. However, the high incidence of SWF mitigation events in deepwater wells shows that existing geophysical techniques do not provide adequate resolution or accuracy¹³. Three main reasons cause these errors. First, the velocities (V_s) are difficult to obtain because log wells in early exploration are rare¹⁵. Second, we ignore changes in seismic wave velocity in deep water. Finally, velocity analysis is too imprecise in both streamer seismic data and multicomponent seismic data, especially in anisotropic rocks. These errors lead to failures in the interpretation of SWF from seismic profiles¹⁶.

To overcome these problems, in this article, we establish sedimentary models of the seabed by analyzing existing drilling data. The velocity field of deep seawater that follows from the physical properties of seawater is added to the models. We also establish electrical models at various effective pressures. By analyzing ground-penetrating radar (GPR) signals and multi-attribute seismic data, we present methods and workflows to identify SWF in the deepwater basin of the northern South China Sea. This study will assist in the use of upcoming ocean bottom cable (OBC) multicomponent seismic data and GPR data in wells to identify recent shallow-water flow hazards.

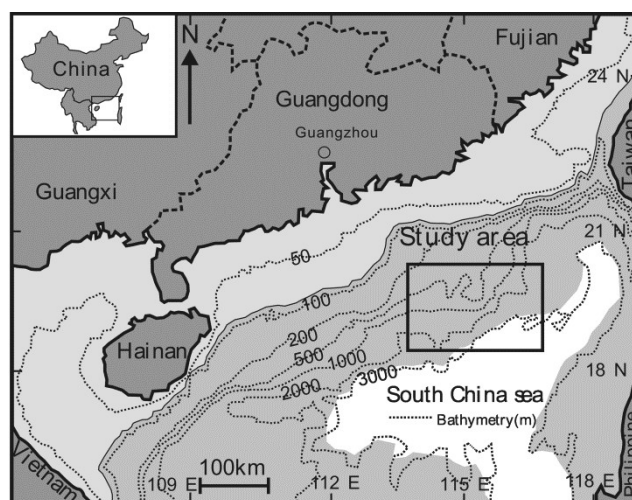


Fig. 3 — Schematic of the study area

Geological background

The deepwater area that this research focuses on occurs in the passive margin of the northern South China Sea. The water depth is 400–3000 m, and the depression area is 20,000 km² in size. The thickness of the Cenozoic sedimentary layer exceeds 11 km. This depression has the largest area and sedimentary thickness in the Pearl River Mouth Basin (Fig. 3).

In the Cenozoic Era, this area underwent three phases of tectonic evolution: rifting, thermal subsidence and a neotectonic stage. In the rifting stage, a sag prototype formed and linked faults developed in the seabed. This structural development provided access for deep cracking gas to migrate upward. During thermal subsidence, the sag developed a large number of ancient river channels that provided large-scale coarse sands to the sag with the fast speed of subsidence. Fan sediments with high porosity and permeability developed in the deepwater continental slope. This sediment may develop not only prime oil and gas reservoirs but also shallow-water flow. Deposition rates have been relatively high (4–25 cm/ka) since the middle Miocene. High deposition rates are an important condition of overpressurized formations³.

The study area is mainly a water fan system, which provides the primary material basis for the formation of shallow-water flows, the upper part of the low-permeability sediments, mainly marine Pliocene fine-grained sediments. These provide the sealing cap necessary for the formation of shallow-water flows, which can be described by the evolution of the real processes of burial and under-voltage waterways. The study area is mainly a deepwater fan system, which

provides the main material basis for the formation of shallow-water flows. The upper part of the research area comprises low-permeability sediments. It provides a sealing cap for the shallow-water flow.

Ethics statement

The authors state that no specific permissions were required for these locations or activities. The authors affirm that these field studies did not involve endangered or protected species.

Materials and Methods

Parameters for seawater

The velocity of seismic waves in a medium is the main factor affecting seismic data processing and interpretation. In deepwater oil and gas exploration, the sonic velocity of seawater varies with depth, pressure, salinity and temperature. Thus, it cannot be taken simply as 1500 m/s. Mackenzie gives a formula for the velocity in the deep sea. This formula is applicable to a maximum depth of 8000 m.

$$V(D, S, T) = 1448.96 + 4.591T - 5.304 \times 10^{-2} T^2 + 2.374 \times 10^{-4} T^3 + 1.340(S - 35) + 1.630 \times 10^{-2} D + 1.675 \times 10^{-7} D^2 - 1.025 \times 10^{-2} T(S - 35) - 7.139 \times 10^{-13} TD^3 \quad \dots (1)$$

Here, T , D , S , V are temperature (degrees Celsius), depth (m), salinity (‰ppt), and velocity (m/s), respectively. Using Mackenzie's formula, the UNESCO formula and CTD data, we build a model for sonic velocity in seawater (Fig. 2).

Elastic parameters of sediment

The formula for the relationship between density and depth of normal-pressure sand and mud rock in marine sediment was obtained from well logs in the study area:

$$\rho = 0.16D + 2071 \quad \dots (2)$$

Laboratory measurements of cores from the research areas show high porosity and permeability at high pore pressure. Table 1 shows the elastic parameters at different effective pressures.

Seismic full-wavefield modeling

According to survey data, velocity and pressure anomalies occur in the 200 meters under the sea-mud line. In the model, shallow submarine sediment exists from 1 to 150 meters under the sea-mud line. The lithology here is silty mudstone.

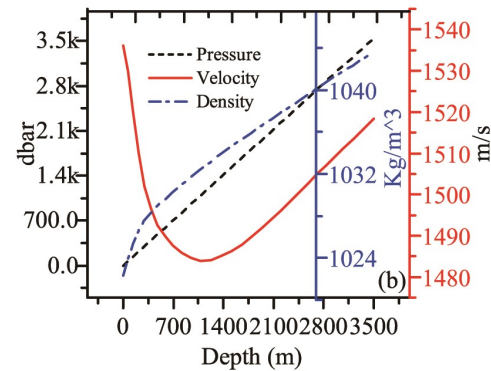


Fig. 4 — Velocity, density and pressure of seawater in the research area

Table 1— Elastic parameters in different effective pressure.

Effective pressure (PSI)	V_p (m/s)	V_s (m/s)	Density (g/cm^3)	Poisson's ratio
100	1540	320	1.51	0.477
150	1608	338	1.67	0.476
200	1734	359	1.73	0.477
250	1865	377	1.84	0.478
300	1998	385	1.96	0.481

The velocity of compressional waves (V_p) increases from 1600 m/s to 1900 m/s at these depths. According to Equation (2), the density here ranges from 2.22 to 2.35 g/cm^3 . At depths of 150-200 meters under the sea-mud line, cap rock exists with 2000 m/s V_p , 950 m/s V_s and 2.35 g/cm^3 density. In the range of 200-350 meters under the sea-mud line, the elastic parameters were set to those shown in Table 1. The velocity and density of bedrock at 350-600 meters under the mud line increases with depth. V_p and V_s increase to 2487 to 2512 m/s from 1142 to 1456 m/s, respectively. The density at this range is from 2.279 to 2.302 g/cm^3 . It is crucial that we consider the variations in sonic velocity in seawater according to the observed temperature and salinity data. This makes the velocity of the deep water in the model consistent with that in the real environment. Fig. 5 is a schematic of the model. Using the finite-difference wave equation to simulate a full wave field, a series of horizontal and vertical components of the seismic records were obtained.

GPR FDTD simulation

All the electromagnetic phenomena are described by Maxwell's equations on a macroscopic scale (JAG). These are first-order partial differential equations that express the relationship between the fundamental electromagnetic field quantities and their dependence on their sources:

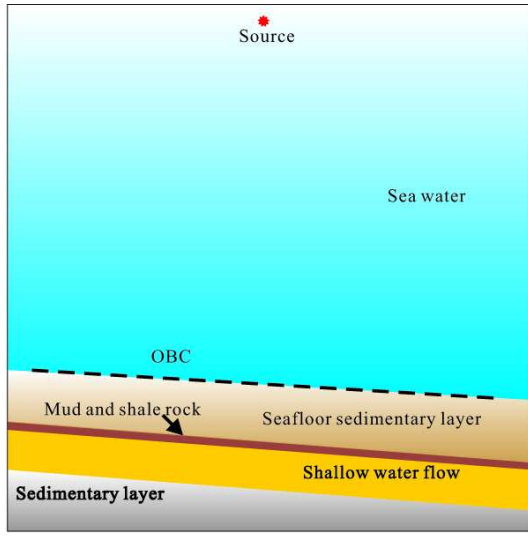


Fig. 5 — Schematic of the model

$$\begin{aligned}\nabla \times E &= -\frac{\partial B}{\partial t} \\ \nabla \times H &= \frac{\partial D}{\partial t} + J_C + J_S \quad \dots (3) \\ \nabla \cdot B &= 0 \\ \nabla \cdot D &= q_v\end{aligned}$$

Here, t is time (seconds) and q_v is the volumetric electric charge density (coulombs/cubic meter). We solve Maxwell's equations using the finite-difference time-domain (FDTD) to simulate the GPR response from a particular target or set of targets in 2D. The 2D FDTD algorithm is implemented in the (x - z) plane. The origin of the coordinate system is the lower left corner at (0,0). The smallest space that could be allocated to represent a specific medium is a 2D cell (Δx - Δz). It is important that for a given set of coordinates (x - z), the position of the electromagnetic field components are as follows:

$$\begin{aligned}E_z &: (x + \frac{\Delta x}{2}, z + \frac{\Delta z}{2}) \\ H_x &: (x + \frac{\Delta x}{2}, z) \\ H_y &: (x, z + \frac{\Delta z}{2})\end{aligned} \quad \dots (4)$$

where E_z , H_x and H_y are the electric and magnetic field components (Fig. 6). According to geometric parameters and the relative permittivities of SWF, limestone, seafloor sediment and the mud layer, we establish SWF electromagnetic models in parallel and vertical well paths (Fig. 7). Detailed parameters were set as shown in Table 2.

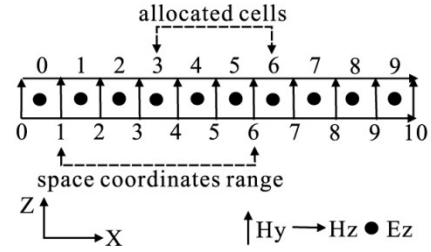
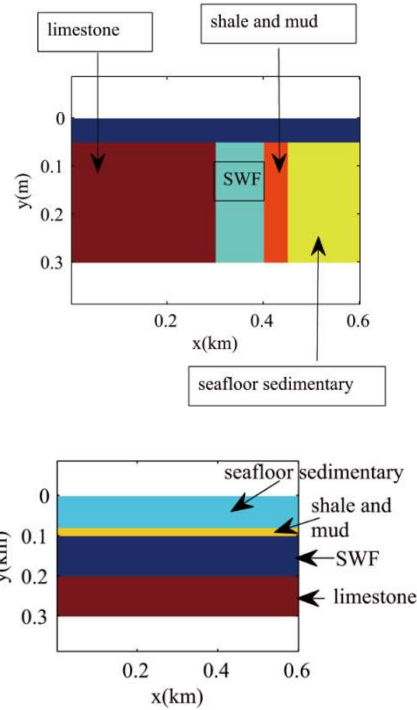
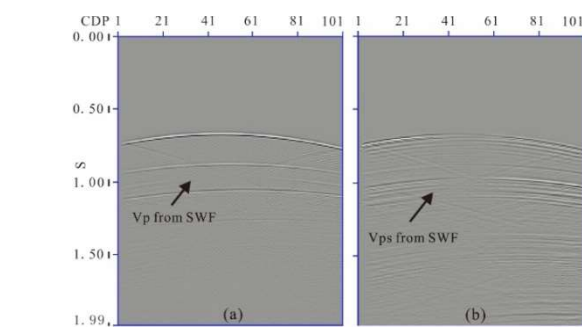
Fig. 6 — Schematic of the FDTD coordinate system and convention ($\Delta x = \Delta z = 1$).

Fig. 7 — Schematic of electromagnetic models

Results and Discussion

In the processing of seismic data with complex surface conditions, the correct identification and application of various waves are very important. Using the full wave field forward finite difference technique, theoretical models are simulated during the seismic data processing. In this technique, we consider the formation and propagation of various waves in the layer. The maximum amount of accurate seismic wave field information was obtained by using the details of the elastic parameters in the target area. The most important mathematical relationships between seismic attributes and physical properties of shallow-water flow were derived. Fig. 8 shows the vertical and horizontal components of the simulated seismic wave fields. The effective pressure is calculated according to the different physical

Table 2— Electrical parameters in different effective pressure			
SWF	Types	Relative permittivity ($\epsilon\gamma$)	Conductivity (σ)
	seafloor sedimentary	18	0.25
	shale and mud layer	12	0.002
	limestone	7	0.50
	Effective pressure(PSI)		
	100	20	0.08
	150	25	0.11
	200	30	0.14
	250	35	0.17
	300	40	0.20

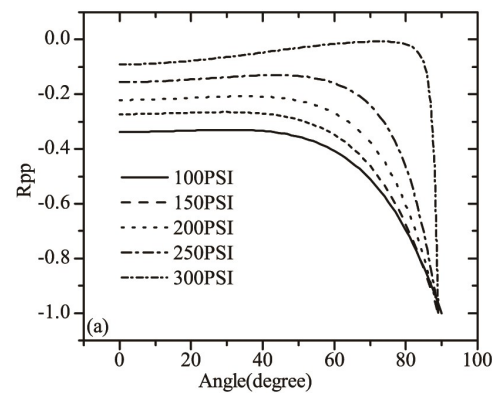


(a) V_p from the vertical component of the SWF;
 (b) V_{ps} from the horizontal component of the SWF.

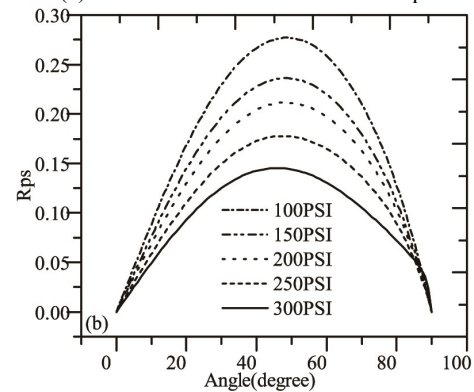
Fig. 8 — The vertical and horizontal components of the simulated seismic wave fields.

properties of shallow-water flow. Small effective pressure indicates that the internal overpressure is stronger and more likely to cause accidents. We analyze the shallow-water flow in the study area according to the characteristics of the AVO Pp- and Ps-wave curve shown in Fig. 9. In a large-offset acquisition of seismic data, at lower effective pressures, Pp shows a maximum reflection coefficient. The reflection point (which increases as the reflection coefficient increases) is near the offset. With increasing effective pressure, the reflection coefficients are smaller and the inflection points exist increasingly at long offsets. The lower the effective pressure of the Ps wave, the larger the gradient of the reflection coefficient increases with offset. The AVO influence is the most obvious. However, under different effective pressures, the inflection points exist at the same offset. By combining this information with multi-wave AVO laws, we are able to accurately determine the physical properties of shallow-water flow in the deepwater basin of the northern South China Sea.

After many calculations, we find that the weighted-average frequency (WAF) and sweetness attributes are applicable to the identification and classification of



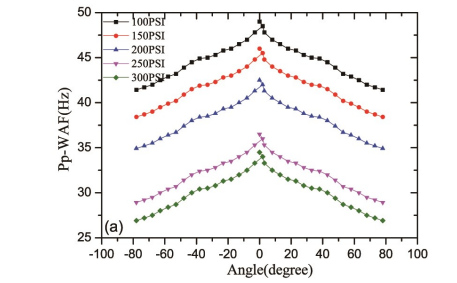
(a) Reflection coefficient curve for Pp.



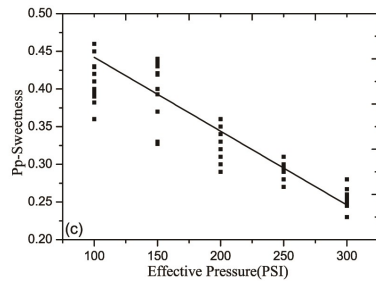
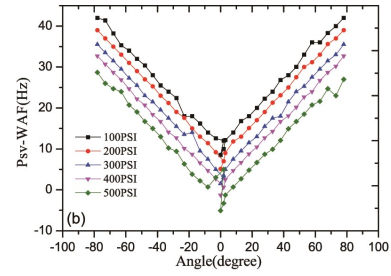
(b) Reflection coefficient curve for Ps.

Fig. 9 — AVO characteristic of the Pp- and Ps-wave curve.

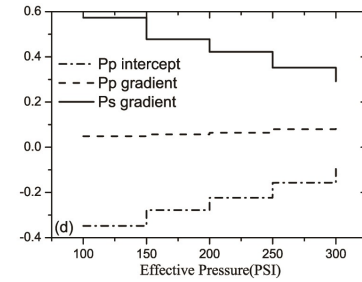
shallow-water flow problems. The WAF attribute is rarely affected by short wavelengths and facilitates analysis of shallow-water flow. Figs. 10(a) and 10(b) show the weighted-average frequency in Pp and Ps waves. The weighted-average frequency of Pp decreases with increasing offset and effective pressure of shallow-water flow. High values of weighted-average frequency indicate high-pressure environments in the shallow-water flow. In Fig. 10(b), we see that the trend of the weighted average frequency in the Ps wave is opposite that of the Pp wave. Furthermore, its value is lower than that of the



(a) Pp weighted-average frequency with offset

(c) The relationship between effective pressure and sweetness for Ps waves: $y=0.54-0.98e-4$.

(b) Ps weighted-average frequency with offset

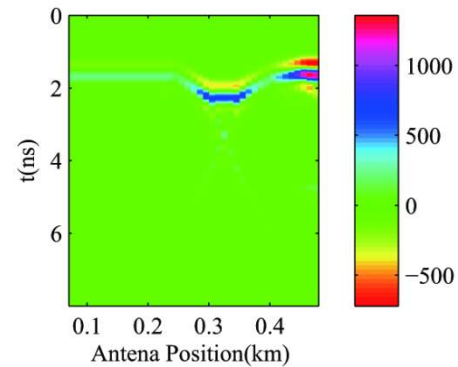


(d) AVO intercepts and gradient attributes at various effective pressures

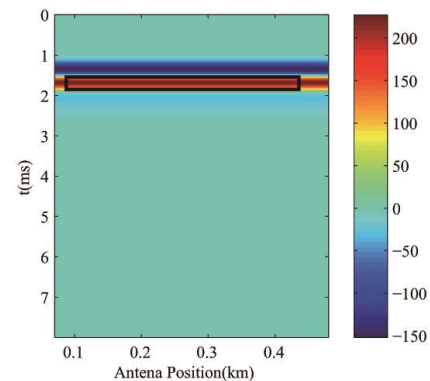
Fig. 10 — Multicomponent seismic attribute analysis

Pp wave. The lower the effective pressure (the larger the pressure inside the SWF), the greater the values of weighted-average frequency are in both Pp and Ps. Fig. 10(c) shows the relationship between effective pressure and sweetness in Ps waves. This relationship allows the use of artificial neural networks and inversions in shallow-water flow problems. Fig. 10(d) shows the AVO intercept and gradient attributes at various effective pressures of shallow-water flow. These various laws aid in the study of the characteristics of shallow-water flow.

Using the FDTD algorithm, we simulate the GPR wave electromagnetic profile data using 400-MHz high-frequency electromagnetic source wavelets. Because of the presence of a small amount of peripheral air parallel to the well path, a two-phase axis appears in the profile. The bottom phase represents the signal response to the stratum. Due to the presence of a high-relative-permittivity SWF region, the amplitude in the SWF region is large. The phase axis of the SWF region bends down. With increasing effective pressure, the bending of the phase axis increases. The amplitude in the SWF region also increases (Fig. 11(a)). Perpendicular to the well, we simulate the GPR wave electromagnetic profile data using 200-Hz ultra-low-frequency electromagnetic source wavelets. Because the relative permittivity increases suddenly, the polarity of the inversion amplitude appears in the SWF region. With increasing effective pressure, the intensity of the amplitude



(a) The GPR signal in the well-path-parallel direction. The black circle indicates the signal response to SWF.



(b) The GPR signal in the vertical direction. The black rectangle indicates the signal response to SWF.

Fig. 11 — GPR signals in electromagnetic models

inversion increases. The GPR signals in the SWF show significant anomalies and correlations with changes in effective pressure. This characteristic can be used as a supplement to multi-component seismic attributes for SWF recognition technology (Fig. 11(b)).

Conclusions

Shallow-water flow is a serious problem in deepwater oil and gas exploration. The deepwater area in the northern South China Sea has a geological environment conducive to the formation of shallow-water flow. With the development of OBC and OBS seismic data acquisition, methods for effectively using multi-component seismic data to predict and study shallow-water flow are areas of current research in this region.

To accurately simulate wave fields in various effective pressures in marine environments, we specify the velocity field in the deep sea to a new level of precision. Through computational analysis, new AVO phenomena in shallow-water flow at various effective pressures are obtained. We also extend and develop more multicomponent seismic attributes to predict and characterize shallow-water flow.

By studying the GPR signals in the vertical and well-path-parallel directions in SWF regions, we find that the amplitude of the GPR signals in SWF regions can be quite large. The phase axis in SWF regions bends down parallel to the path of the well. Because of the sudden increase in relative permittivity, a significantly increased amplitude of polarity inversion appears in SWF regions with increasing effective pressure. The GPR method can be used as a supplement to multi-component seismic attributes for SWF-recognition technology. These GPR signals, multicomponent seismic attributes laws and workflows can aid in the accurate and comprehensive study and solution of the shallow-water flow problem.

Acknowledgement

This research was financially supported by the National Natural Science Foundation (NSFC) under grants (No. 41772330 and No. 51578053) and the Fundamental Research Funds for the Central Universities (300102218505), whose supports are acknowledged.

References

- 1 Sun Y.B., The mechanism and prediction of deepwater geohazard in the northern of South China sea, China Academy of Sciences, *Institute of oceanology*, PhD thesis, Beijing, (2011),67-94.
- 2 Bruce B., Borel R. & Bowers G., Well planning for SWF and overpressures at the Kestrel well, *The Leading Edge*, 21(7), (2002),669-671.
- 3 Wu S.G. & Sun Y.B., Geophysical signature and detection of shallow water flow in the deepwater basin of the northern South China sea, *Chinese J. Geophys*, 53(7), (2010), 1681-1690.
- 4 Khakiev Z.H., Vladimir S. & Alexander K., GPR determination of physical parameters of railway structural layers, *Journal of Applied Geophysics*,106 (2014), 139-145.
- 5 Zhang J., Lin H. & Doolittle J., Soil layering and preferential flow impacts on seasonal changes of GPR signals in two contrasting soils, *Geoderma*, 213(2014), 560-569.
- 6 Galagedara L.W., Parkin G.W. & Redman J.D., Field studies of the GPR ground wave method for estimating soil water content during irrigation and drainage, *J. Hydrol*, 301(2005), 182-197.
- 7 Khakiev Z., Kislitsa K. & Yavna V., Efficiency evaluation of ground-penetrating radar by the results of measurement of dielectric properties of soils, *J. Appl. Phys*,112(12), (2012),117-126.
- 8 Alberty M.W., Hafle M.E. & Mingle J.C., Mechanisms of shallow waterflows and drilling practices for intervention, *SPE drilling & completion*, 14(02), (1999),123-129.
- 9 Hardage B.A., Remington R. & Roberts H.H., Gas hydrate—a source of shallow water flow, *The Leading Edge*, 25(5), (2006), 634-635.
- 10 Ostermeier R.M., Pelletier J.H. & Winker C.D., Dealing with shallow-water flow in the deepwater Gulf of Mexico, *The Leading Edge*,21(7), (2002),660-668.
- 11 Pelletier J.H., Ostermeier R.M. & Winker C.D., Shallow water flow sands in the deepwater Gulf of Mexico: some recent shell experience. *International Forum on Shallow Water Flows Conference*, held 6 October - 8 October, 1999 in League City, America, 6-9, 1999.
- 12 Liu H., Zhou G.J. & Burrows R., Lattice Boltzmann model for shallow water flows in curved and meandering channels, *International Journal of Computational Fluid Dynamics*, 23(3), (2009), 209-220.
- 13 Dutta N.C. & Dai J., Exploration for gas hydrates in a marine environment using seismic inversion and rock physics principles, *The Leading Edge*, 28(7), (2009) ,792-802.
- 14 Huffman A.R. & Castagna J.P., The petrophysical basis for shallow-water flow prediction using multicomponent seismic data, *The Leading Edge*, 20(9), (2001), 1030-1052.
- 15 Dutta N.C., Geopressure prediction using seismic data: Current status and the road ahead, *Geophysics*, 67(6), (2002), 2012-2041.
- 16 Lu S. & McMechan G.A., Elastic impedance inversion of multichannel seismic data from unconsolidated sediments containing gas hydrate and free gas, *Geophysics*,69(1), (2004), 164-179.