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Discussion on lithology data conversion methods in studies of seismic sedimentology

Seismic sedimentology is a new interdisciplinary in oil and gas exploration, and consists of two branches: seismic lithology and seismic geomorphology. The current prevailing seismic lithology method is 90º phase conversion technology, which transforms seismic data to lithology data for the purpose of direct interpretation of seismic events, acting like interpreting logging data. Based on premise of zero-phase wavelet of seismic data, with the geological formations of thin sandstone layers and simple vertical composition of sandstone and mudstone with great impedance contrast, the results of seismic events transformed by 90º phase conversion method correspond to lithology interfaces, and have the capability of effectively distinguishing sandstone from other different lithologies. However, continental sedimentary basins face several geological difficulties, such as diversity of depositional types, fast changeable sedimentary facies, great variable sandstone thickness, complex diagenesis and diagenetic sequence. These problems result in velocity of sandstone from acoustic logging or seismic survey less than velocity of incumbent mudstone, moreover these abnormal velocity discrepancies vary with sediment types and buried depth, which bring great difficulties for utilizing seismic data to predict sedimentary lithology and identify sandstone formations especially thin layers. Therefore, 90º phase conversion technology has limited applications, and cannot guarantee its accuracy for predicting unconventional oil and gas reservoirs. In this paper, we discusses several conversion methods of seismic data to lithology data, including 90º phase conversion, trace integration, post-stack inversion (for example, colour inversion and logging constrained inversion) and pre-stack inversion technology. We focused on the advantages and disadvantages of these techniques as well as their feasibility and applicable conditions, so that the optimal method matching strata slice is able to be selected to describe subsurface geomorphology. These lithology data conversion methods, can greatly improve the lithology discrimination ability and lithology data resolution, which would benefit extensive application of seismic sedimentology, especially at the areas with complex lithology and tight hydrocarbon reservoirs in continental sedimentary basin.

Keywords: *Seismic sedimentology, 90º phase conversion, colour inversion, post-stack inversion, pre-stack inversion, seismic lithology.*

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Introduction

In recent years, with the rapid development of seismic exploration technology and widely application of high-precision 3D seismic exploration, it has become possible to obtain sedimentary environment information from the seismic data, such as sedimentary units, lithology, facies, geometry, internal structure and geological information. Sequence stratigraphy can predict reservoir location among the three sequence stratigraphic frameworks and it plays an important role during the exploration. However, it cannot meet the demand for accurate prediction of reservoirs distribution, especially for the time domain horizon slicing of deposition interface in the high level of exploration areas. The term of seismic sedimentology was first used by Zeng (1998) in the paper of "Stratal slicing, Part II, Realistic 3D seismic stratigraphy"[1]. Since then, the concept of seismic sedimentology gradually become familiar by scientific researchers, and caused widespread concern and research. Seismic sedimentology is a new idea and method which was applied for oil and gas exploration in recent years. It is a new subject which studied sediment environment distribution and deposition system evolution based on high-precision 3D seismic data and geophysical techniques. And it is also the inheritance and development of seismic stratigraphy, sequence stratigraphy and high resolution sequence stratigraphy [2-5]. However, seismic sedimentology is still not a mature theory due to seismic resolution and limited research methods. So it lacks systematic study though seismic sedimentary facies, lithology identification research have been extensively used in recent years. Therefore, seismic sedimentary is both of challenge and opportunity; there are advantages and broad prospects, on the other hand, the appropriate technical methods are not matured yet [6].

Seismic sedimentology has two important branches: seismic lithology and geomorphology. There are a lot of research on seismic geomorphology from domestic and foreign experts, such as channel, incised valley, subsurface waterway, deep water fans and so on. But it is not mature about study and application of seismic lithology, which has less literature and elaborate introduction [7]. Based on seismic processing technology, seismic lithology technology transforms seismic data to a lithological volume, so that a seismic trace can be seen as a lithologic curve [8] by adjusting the amplitude. The main method of seismic lithology currently is 90^{o} phase shift technologies. It is a method which shift phase of seismic data –90^{o} so that the main peak of reflected waves centered in the middle of thin layers in order to overcome the shortcomings of the zero phase wavelet. Finally, the goal is to convert the seismic data to lithological volume for the consistent performance of seismic traces and well loggings. When these improvements are applied to the actual data, the relationship is established between seismic events and lithology unit of thin layers, and it becomes easier to distinguish sandstone and mudstone and more consistent between seismic events and lithological well loggings. But the virtues of interpretation like these do not exist among other methods.

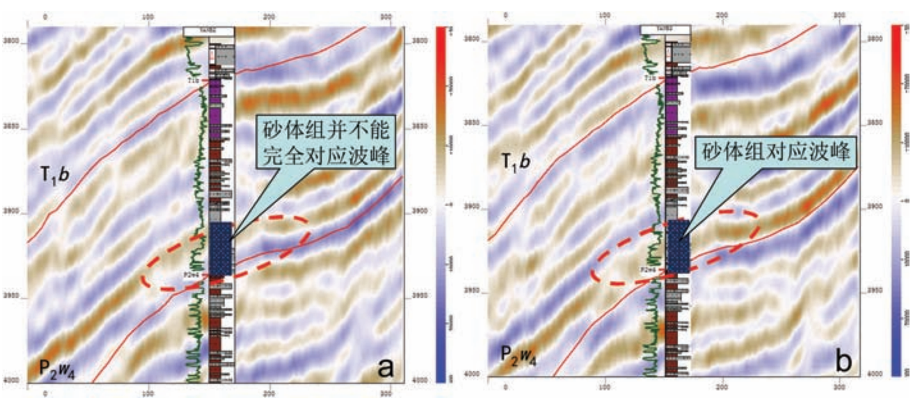
However, there are many geological problems in continental sedimentary basins, such as many depositional system types, changeable facies, different sand thickness, complex diagenesis and diagenetic sequence. So this will be velocity of sonic logging of sandstone which is less than that of overload mudstone. Meanwhile, the relationship of these velocities changes which are subjected to the lithology type and depth of deposition, so it brings great difficulties [11] for application of seismic data to predict sedimentary system and identify sandstone. Liu Lihui, et al proposed the concept of seismic lithology in 2013 [7]; the requirement of seismic lithological volume is amplitude of seismic data is related to lithology. So it means the value of amplitude of seismic data can indicate lithology. However, the simple use of 90^{o} phase shift technology cannot achieve the function of distinguishing lithology, because there are several problems when converting seismic data to lithological data. In this paper, we discuss in-depth several methods of lithology transforms, such as 90^{o} phase shift, trace integration, post-stack inversion (including coloured inversion and logging constrained inversion, etc.) and pre-stack inversion technologies, and contrast the advantages and disadvantages of these techniques and applicable conditions, in order to search the matching methods to strata slice technology for description of palaeogeomorphology.

1. The phase-shift and trace integration technologies

In the current conditions, 90^{o} phase shift technology is the most simple and economic method of converting seismic data to lithologic data. The peaks and troughs of zero phase data volume is corresponding to the formation interface, but there is no causal relationship between the phases of seismic stratigraphy and lithology, so it is difficult to build established relationship between seismic data and lithology loggings. The reservoir is often thin, poor continuant, narrow and great changeable phase band in continental deposits. Especially for thin layer, reflection amplitude is a combination of the responses of several thin layers, which is the mix of reflections from both top and bottom interfaces, therefore, there is no direct correspondence between seismic events and sandstone, and zero phase seismic data is not suitable for interpret thin sandstone layers.

90^{o} phase shift technology is a method which shift phase of seismic data to –90^{o} for changing the main lobe of the reflected wave to the centre of thin layers, in order to overcome the disadvantages of zero phase waves. Therefore, seismic phases after 90^{o} phase shift is corresponding to formations rather than interfaces of top and bottom, and interfaces are corresponding to zero phases, so the events of seismic reflections are corresponding to formations, and seismic phases have a litho-stratigraphic meaning. Therefore, seismic traces are similar to impedance data and it is easier to interpret these data. For example, it is comparable to original seismic data and data after 90^{o} phase shift. Fig.1a is original seismic data; Fig.1b is seismic data after 90^{o} phase shift. At the position of CDP150, the sandstone of interest is not located at peak in the original seismic data, however, after 90^{o} phase shift, the sandstone of interest is located at peak and it is easier to interpret these data.

However, it cannot always be guaranted that seismic data are zero phases because of the influence of the seismic processing to time lags, amplitude and phases. Therefore, we



a. original seismic data; b seismic data after 90^{o} phase shift

Fig.1 Comparison of original seismic data and data after 90^{o} phase shift

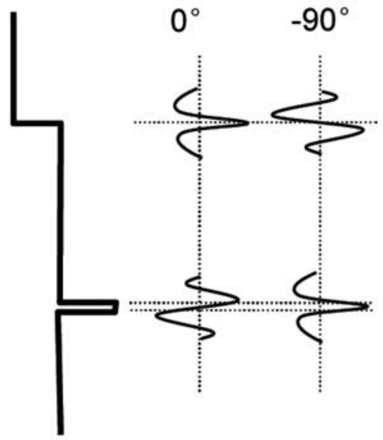


Fig.2 0º, –90º wavelet corresponding to single and double interfaces

need to estimate the phase of seismic data of interest first, then apply 90º phase shift. As shown in Fig.2, when it is the ideal conditions of theory, zero phase wavelet corresponding to single interface is symmetrical and the max energy of it is greater than non zero phase wavelet; and if it is –90º phase wavelet with reverse symmetric display, its max energy is less than non –90º phase wavelet, in fact, it can be considered as the waves from two overlapped thick layers. For the model of two overlapped thin layers, the corresponding zero-phase wavelet is reverse symmetrical, and its max energy is less than non –90º phase wavelet; if it is –90º phase wavelet, the waveform is symmetrical, and its max energy is greater than non –90º phase wavelet; in fact, it can be considered as the waves from two overlapped thin layers.

The concrete workflow is: we use multi-channel scanning method to estimate phase, first, define a step length of phase, then modify seismic data by different phase shift steps, finally, obtain the optical phase shift based on the criterion of waveform similarity or maximum energy. Both methods are carried out within a short time window, and Seismic phase spectrum consists of phase spectrum of the reflection coefficient sequences and the wavelet. The addition and subtraction of the normal phase spectrum is equivalent to the phase adjustment of wavelet. So here, we scan and convert seismic phase by the Hilbert transform. In Fig.3, it is residual phase estimated from 9 wells, the average is 4.9º, therefore, we should shift phase of seismic data by –94.9º instead of –90º, in order to keep the actual effect of conversion of -90º.

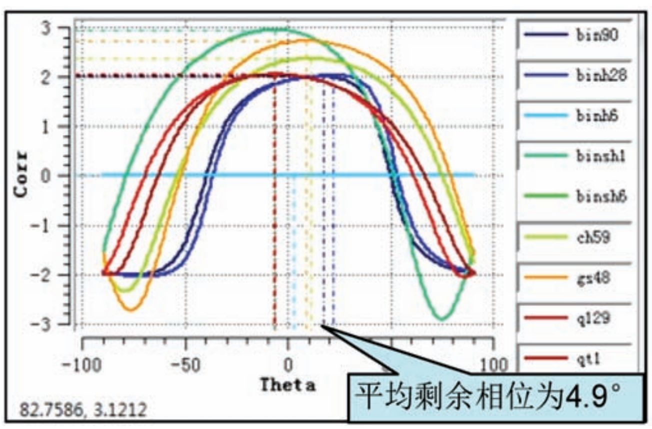


Fig.3 The residual phases estimated from 9 wells

In theory, the seismic trace can be represented by the mathematical model:

$$S_i = r_i * w_i \quad ... \quad (1)$$

where S_i, r_i, w_i stand for seismic trace, reflection coefficient sequence and seismic wavelet respectively.

The seismic trace integration is expressed as:

$$\sum_{i=1}^{n-1} S_i = \frac{1}{2} w_n * \log(Z_n / Z_1)(Z_n \text{ is wave impedance}) \quad ... (2)$$

The formula (2) shows that seismic trace integration is equal to a filter to impedance logarithm after normalization. In the case of thick layers, seismic trace integration can show impedance only through a filter. Because of this "filtering" effect, compared to the 90º phase shift, its resolution and description ability to thin layers decrease.

Therefore, we should try preferably 90º phase shift technique rather than seismic trace integration technology for lithology data volume conversion in the cases of regions with the absence of well or less well or incomplete loggings. The 90º phase shift technology has a fast calculation speed, no limit of wells and horizons, which is not subjected to wells and models, resulting in a good interpretation of thin sandstone.

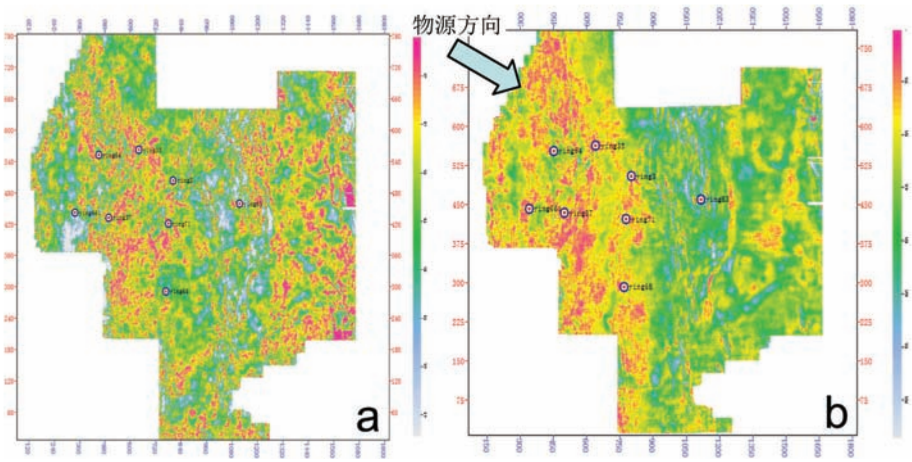
But 90º phase shift technology also has the following disadvantages: (1) it does not improve the resolution of seismic data; (2) application conditions are subject to the thickness of the reservoirs. Seismic data only have the ability to distinguish the top and bottom interfaces and thickness of the geological body within the ability of resolution. So we should try to apply lithology data conversion methods with the high resolution as far as possible.

2. The post-stack inversion

We discuss the application of seismic lithologic data conversion by coloured inversion and constrained inversion.

Coloured inversion is a kind of inversion algorithms which is less dependent on wells. It belongs to impedance inversion constrained by well loggings in the frequency domain in the view of algorithm. The core step of coloured inversion is the match of the spectrum of seismic data and well impedance. Therefore, there is no extraction process of wavelet and no need of original model. Its vertical resolution is higher than the method of sparse pulse inversion, but lower than model inversion. However, coloured inversion is a popular term, which refers to a coloured band range in chromatographic theory. It features for its objective, concise, and particularly suitable for predicting lithologic traps with lateral change and geological phenomenon of fault and deposition.

Coloured inversion process can be summarized as: (1) spectrum analysis of impedance of well logging; (2) spectrum analysis of seismic data; (3) matching operator design between spectrum of seismic data and well data; (4) matching



a. the result of 90º phase shift b. the result of colored inversion

Fig.4 The result of 90º phase shift and coloured inversion of F1 section (RMS)

operator application to seismic data. So, the result of coloured inversion is loyal to original seismic data, and it matches well data as a whole, which can be seen an attribute with the meaning of inversion and has a slightly higher resolution than 90º phase shift technology.

Fig.4 is the result of 90º phase shift and coloured inversion of F1 section (RMS). Based on geological background, sedimentary patterns and geochemical evidence, provenance direction is northwest. The prediction of effective sand thickness of 8 wells from coloured inversion was thick in this area (> 10m), which matches the results of the well loggings. Therefore the seismic geomorphology maps (Fig. 4b) can be one of assistance for portraying sedimentary microfacies maps.

However, some scholars excessively use well logging constrained inversion, even Gammar ray constrained inversion to convert seismic data to lithology data volume for the purpose of high resolution. Though the results are clearly corresponding to lithology, the inversion data is greatly subjected to initial model, therefore, the boundary of sediment will be blurred and the description of sediment cannot be accurate. Therefore, the reasonable geologic model is the key. It is misleading in practice of unduly emphasizing high resolution in model-based seismic inversion method. Since this method starts and ends with models, so it has the same resolution as well logging in theory, and the real problem is to see that how to reduce the multiplicity of solutions. On the other hand, it is not right to unduly emphasize the most likely similarity between well

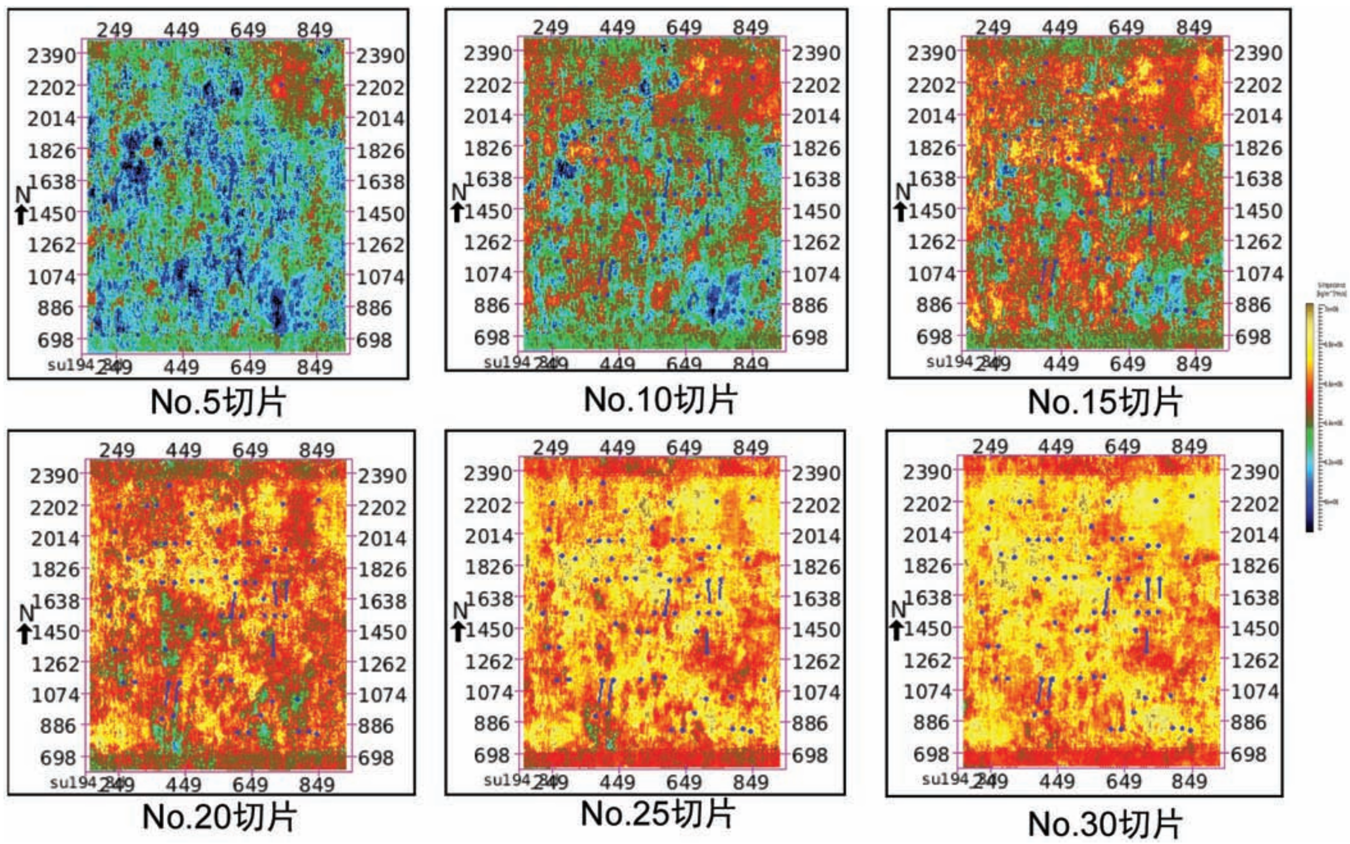


Fig.5 S-wave impedance slicing of multi-wave pre-stack simultaneous inversion

logging and inversion result at well location. Because the first step of establishing the initial model is logging data correction in order to match synthetic records and seismic data at well location, then create model from corrected well logging. In fact, we do not make big changes of model near the well location, so this comparison is not meaningful; it is easy to mislead. Only when the seismic data resolution is high enough, it is possible to explain the finer horizons and close to the initial model, therefore, we will obtain greater range of effective frequencies, and reduce the possibility of multiplicity of solutions. So, in the case of seismic data with low frequency, we should use logging constrained inversion prudently. We recommend apply pre-stack or post-stack to increase seismic solution first, and then use coloured inversion for lithology data conversion.

3. Application and Prospect of pre-stack simultaneous inversion in seismic sedimentology

With the development of exploration, the type of oil and gas reservoirs in the most oil fields has been changed from structure reservoir to lithology reservoir, and the thickness of reservoirs is more and more thin, so it demands more beyond 90º phase shift or post-stack inversion. Pre-stack simultaneous inversion, based on AVO theory, applies P-wave or S-wave at different angles of incidence to obtain lithological parameters volumes, such as elastic impedance, P and S wave impedance, density, Poisson's ratio, shear modulus, Lame coefficient. It can reduce the possibility of multiplicity of solutions by analyzing both reservoir lithology and physical properties.

It has not been reported in either domestic or international literatures that pre-stack simultaneous inversion was applied in seismic sedimentology. For the reason of S-wave data, we can get S wave impedance and Poisson's ratio from pre-stack simultaneous inversion, which can describe lithology distribution with high resolution. Therefore, we can choose these two elastic parameter volumes to match stratigraphic slice for description of palaeogeomorphology. If it is lucky to have PP + PS limited-offset data, we can obtain high accuracy and high resolution S-wave impedance and Poisson's ratio data by pre-stack PP + PS joint inversion simultaneously. Based on the study of stratigraphic slicing on elastic parameter volumes, we can distinguish lithology in complex and tight sandstone areas, which is not solved by 90º phase shift or post-stack inversion.

Fig.5 is the S-wave impedance slicing of multi-wave pre-stack simultaneous inversion. It shows the distribution of main sandstone resulting from stratigraphic slicing of elastic parameter volume. According to the seismic waveform clustering geostatistical results, combined with sedimentary facies at well locations and S-wave impedance slicing from multi-wave pre-stack simultaneous inversion, we can predict accurately distribution of sandstone and sedimentary microfacies.

Conclusions

(1) Seismic sedimentology consists of two branches: Seismic lithology and seismic geomorphology. Seismic geomorphology concerns strata slicing, focusing on the interpretation of the time slice and sedimentary; seismic lithology concerns attributes, focusing on technologies and providing lithology data volume.

(2) Coloured inversion is preferred to 90º phase shift technique for lithological data conversion. If seismic data has low main frequencies, we should firstly improve the resolution of seismic data, and then use coloured inversion for lithology volume conversion.

(3) When pre-stack limited offset data exist, we should give priority to the pre-stack simultaneous inversion and even pre-stack PP + PS joint simultaneously inversion for high resolution elastic parameter volumes, such as S-wave impedance and Poisson's ratio. Based on the study of stratigraphic slicing on elastic parameter volumes, we can distinguish lithology in complex and tight sandstone areas, which is not solved by 90º phase shift or post-stack inversion.

References

1. Zeng, H., Henry, S. C. and Riola, J. P. (1998b): "Stratal slicing: part II: real seismic data." *Geophysics*, 1998b ,63(2):514-522.
2. Zeng, H. and Kerans, Charles (2003): "Seismic frequency control on carbonate seismic stratigraphy: A case study of the Kingdom Abo sequence, west Texas." *AAPG Bulletin*, 2003, 87(2): 273-293.
3. Zeng, H.: "Seismic Sedimentology in China: A Review." *Acta Sedimentologica Sinica*, 29(3): 417-426.
4. Posamentier, H., et al. (1996): Imaging elements of depositional systems with 3-D seismic data: a case study. in 17th Annual Conference, SEPM Foundation, Gulf Coast Section. 1996.
5. Posamentier, H. W. (2002): Seismic geomorphology and depositional systems of deep water environments; observations from offshore Nigeria, Gulf of Mexico, and Indonesia. in 64th EAGE Conference & Exhibition. 2002.
6. Dong, Chun-mei, Zhang, Xian-guo and Lin, Cheng-yan (2006): "Discussion on several issues about seismic sedimentology." *Oil Geophysical Prospecting*, 2006, 41(4):405-409.
7. Liu, Lihui, Chen, Shan and Ni, Changkuan (2013): "Application of prestack coloured inversion technology in seismic lithology." *Geophysical Prospecting for Petroleum*, 2013, 52(2): 171-176.
8. Zeng, H. L. and Hentz, T. F. (2004): "High-frequency sequence stratigraphy from seismic sedimentology: applied to Miocene, Vermilion Block 50, Tiger Shoal area, offshore Louisiana." *AAPG Bulletin*, 2004, 88(2): 153-174.
9. Zeng, Hongliu and Milo, M. Backus (2005): "Interpretive advantages of 90º-phase wavelets: Part I - Modelling." *Geophysics*, 2005, 70(3):C7-C15.
10. Zeng, Hongliu and Milo, M. Backus (2005): "Interpretive advantages of 90º-phase wavelets: Part II - Seismic applications." *Geophysics*, 2005, 70(3):C17-C24.
11. Zhu, Xiaomin, Li, Yang and Dong, Yanlei, et al. (2013): "The program of seismic sedimentology and its application to Shahejie Formation in Qikou depression of North China." *Geology in China*, 2013, 40(1): 152-162.