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3D Seismic Sedimentology of Nearshore Subaqueous Fans – A Case Study from Dongying Depression, Eastern China

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1. Introduction

The nearshore subaqueous fan, also known as the steep bank sublacustrine fan (Zhao, 2000), or submarine fan (Catuneanu et al., 2002; Richard & Bowman, 1998; Takahiro & Makoto, 2002), is the fan-shaped sedimentary accumulation of sand–conglomerate body located in the footwall of major fault in rift basins (Zhang, J.L & Shen, 1991; Zhang, M. & Tian, 1999), and commonly composed by three sub- facies including a root sub-fan, a mid sub-fan and a marginal sub-fan. Its formation and development are controlled by basin boundary conditions, paleotopography, tectonic evolution, the nature of the provenance, paleoclimate, paleocurrent and other factors (Lu, 2008; Xie et al., 2004; Yan et al., 2005). In the Bohai Bay Basin, eastern China, a nearshore subaqueous fan system of Paleogene age is widely developed in the lower Es4 Formation in Paleogene in the northern Dongying Depression (Fig.1). Analyses found that the mid sub-fan is the main part of the fan, characterized by the pebbly sandstones, conglomerates and block sandstones in the braided channel microfacies, intra-channel microfacies and leafy sandbody microfacies (Gao et al., 2008; Song, 2004; Yan et al., 2005). Oil and gas exploration in the Dongying Depression has demonstrated that the sand–conglomerate developed in the mid sub-fan is the effective oil and gas reservoir. Due to a deep burial (>3500m), multi staged sub-fan development, and small seismic impedance differences, however, to describe and predict the distribution of the effective sand–conglomerate reservoir in the nearshore subaqueous fan is difficult. Studies have also found that conventional 3D seismic data with industry-standard and seismic acoustic impedance inversion data from ac+den loggings could not distinguish the effective sand–conglomerate reservoir from sand–conglomerate sedimentary body (Song, 2004).

Seismic sedimentology is the use of seismic data to study sedimentary rocks and processes by which they form (Zeng et al., 2001, 2004). Since its first introduction in 1998 (Zeng et al., 1998), the concept has been applied in the identification of paleorivers, the sedimentary facies and sedimentary environment evolutions of carbonate platform and the slope fans with many good results (Carter, 2003; Chen.& Meng, 2004; Crumeyrolle et al., 2007; Darmad et al., 2007; Gee & Gawthorpe, 2007; Handford & Baria, 2007; Ling et al., 2005; Lin et al., 2007; Liu, B.G. & Liu, L.H., 2008; Nordfjord et al., 2005; Posamentier & Killa, 2003; Prather, 2003; Sullivan et al., 2007; Schwab et al., 2007; Wang et al , 2004; Wu et al, 2005; Zeng et al., 2003, 2004, 2007; Zhang et al., 2007), but rarely used to study nearshore subaqueous fans. In this paper, we took the nearshore subaqueous fan in the Dongying Depression as a case, and used the pseudo-acoustic 3D seismic inversion method on characteristic logs to reconstruct 3D seismic sedimentological structures of the nearshore subaqueous fans including the distribution of the effective sand-conglomerate reservoirs and the temporospatial evolution of individual nearshore subaqueous fan system.

Over the years, six exploratory wells were drilled into the lower Es4 Formation in the northern Dongying Depression and four of them encountered commercial oil and gas. The logging data from all six wells yield good coverage with 0.125 m or 0.25 m sampling spacing. An industry- standard 3D seismic data of 600 km^2 acquired in 2005 was processed using high-fidelity prestack time migration technique with 25m × 25m track spacing, 1ms sampling interval, 25HZ dominant frequency and 10-60Hz effective frequency bandwidth in the target formation.

2. Characteristics of the nearshore subaqueous fan in the northern Dongying Depression

The Dongying Depression is a typical sub-structural unit in the Bohai Bay Basin, Eastern China, surrounded by a series of uplifts, including the Luxi Massif in the south, Chenjiazhuang Uplift in the north, Qingtuozi Uplift in the east, Binxian Uplift and Qingcheng Uplift in the west (Fig.1). As a rift basin, the Dongying Depression is

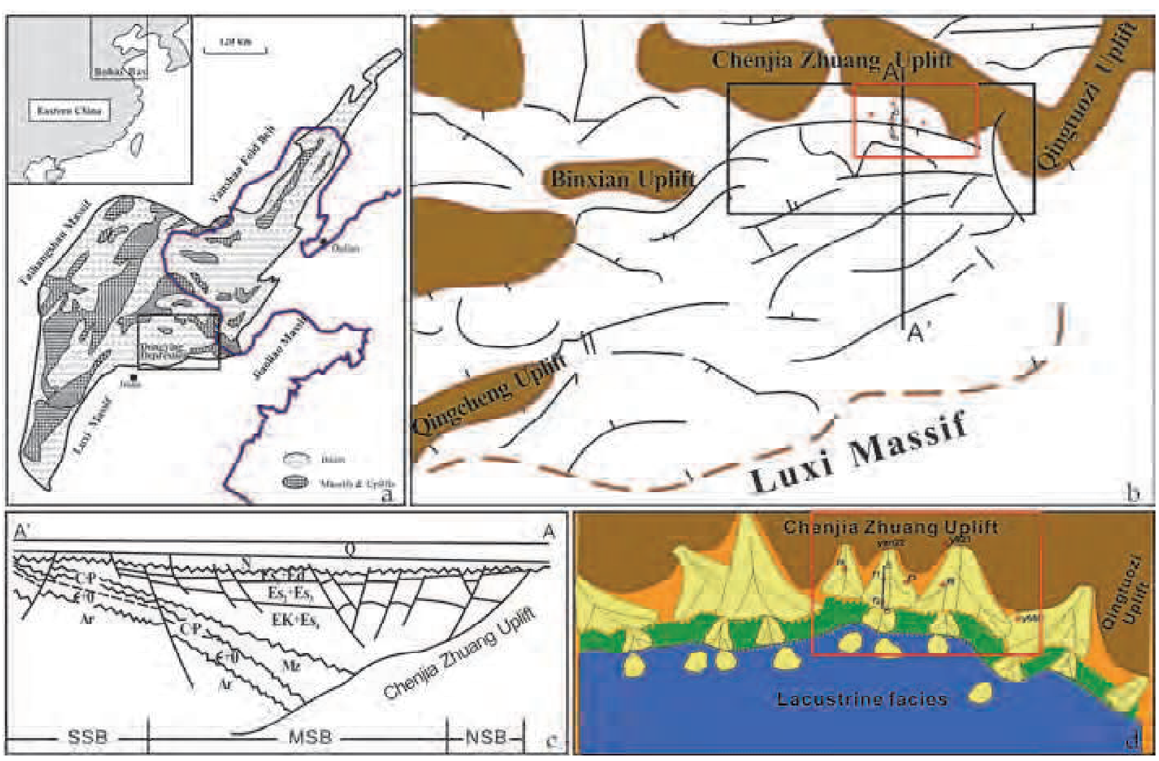

Fig. 1. Location and distribution of sedimentary facies of the lower Es4 Formation in the northern Dongying Depression, Bohai Bay Basin, Eastern China. 3D seismic area is marked by Red box.

characterized by a structural style of half-graben with a northern faulting and southward overlaping. The Depression can be divided in to three structural belts: a northern steep belt (NSB), a middle sag belt (MSB) and a southern slope belt (SSB) (Fig.1c). During the lower Es4 Formation in the early Paleogene, under the controlling of the northern Chenjiazhuang boundary extensional fault, many nearshore subaqueous fans developed in the footwall of the Chenjiazhuang major fault along the northern steep belt and extending into the deep and semi-deep lacustrine facies of the middle sag belt (Fig.1d) with sources mainly from the northern Chenjiazhuang Uplift (Gao et al., 2008; Xie et al., 2004; Yan et al., 2005) (Fig. 1). The burial depth of these subaqueous fans now reaches more than 3500m.

Facies analyses shows that the Dongying nearshore subaqueous fan consists of three sub-facies including a root sub-fan, a mid sub -fan and a marginal sub -fan (Gao et al., 2008; Song, 2004; Yan et al., 2005). The root sub-fan is composed by one or more major channel

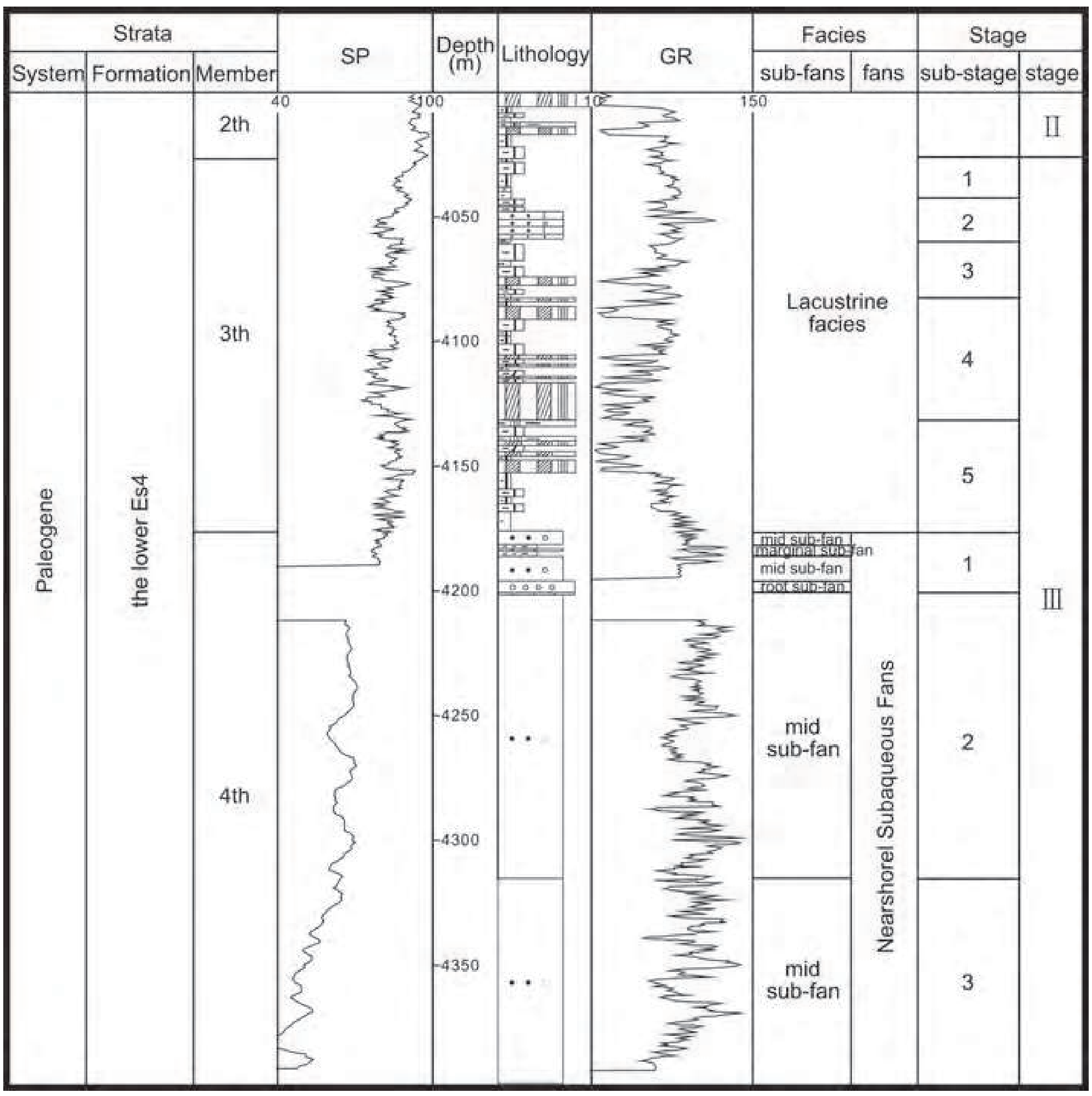

Fig. 2. The single-well facies analysis of well f8 shows that the 4th member of the lower Es4 Formation is a nearshore subaqueous fans with three sub-facies (modified from Gao et al., 2008; Song, 2004; Yan et al., 2005).

sediments and the main lithology includes gray matrix-supported conglomerates, sandy conglomerates and black shales. The mid sub-fan, which is the main part of the nearshore subaqueous fan and forms the effective reservoir in the study area, is characterized by braided channels with braided channel microfacies, intra-channel microfacies and leafy sandbody microfacies. The main lithology of the mid sub-fan includes pebbly sandstones, conglomerate and block sandstones, with thickness varying between 1 and 55 m. The marginal sub-fan consists of siltstones, muddy siltstones and mudstone interbedding rocks (Fig.2). According to well stratigraphic cyclicities and 3D seismic reflection features, the lower Es4 Formation can be divided further into 5 members, standing for 5 individual nearshore subaqueous fans with several sub-facies (Fig. 2).

In general, 3D seismic reflection profiles of the nearshore subaqueous fan are characterized by wedge-shaped, mound-shaped or lenticular-shaped systems, and sub-fans can be further identified. On the synthetic seismograms record calibration, the root sub-fan is characterized by weak reflection, non-reflection or chaotic reflection, the mid sub-fan is characterized by weak to moderate intensity amplitudes, sub-parallel, weak continuous reflection, and the marginal sub-fan is characterized by continuous medium frequency, moderate to low intensity amplitudes. The deep lacustrine facies in the sag belt is characterized by either weak reflection or non- reflection. However, to identify the sub-facies of the nearshore subaqueous fan using the 3D seismic section is difficult (Fig.3).

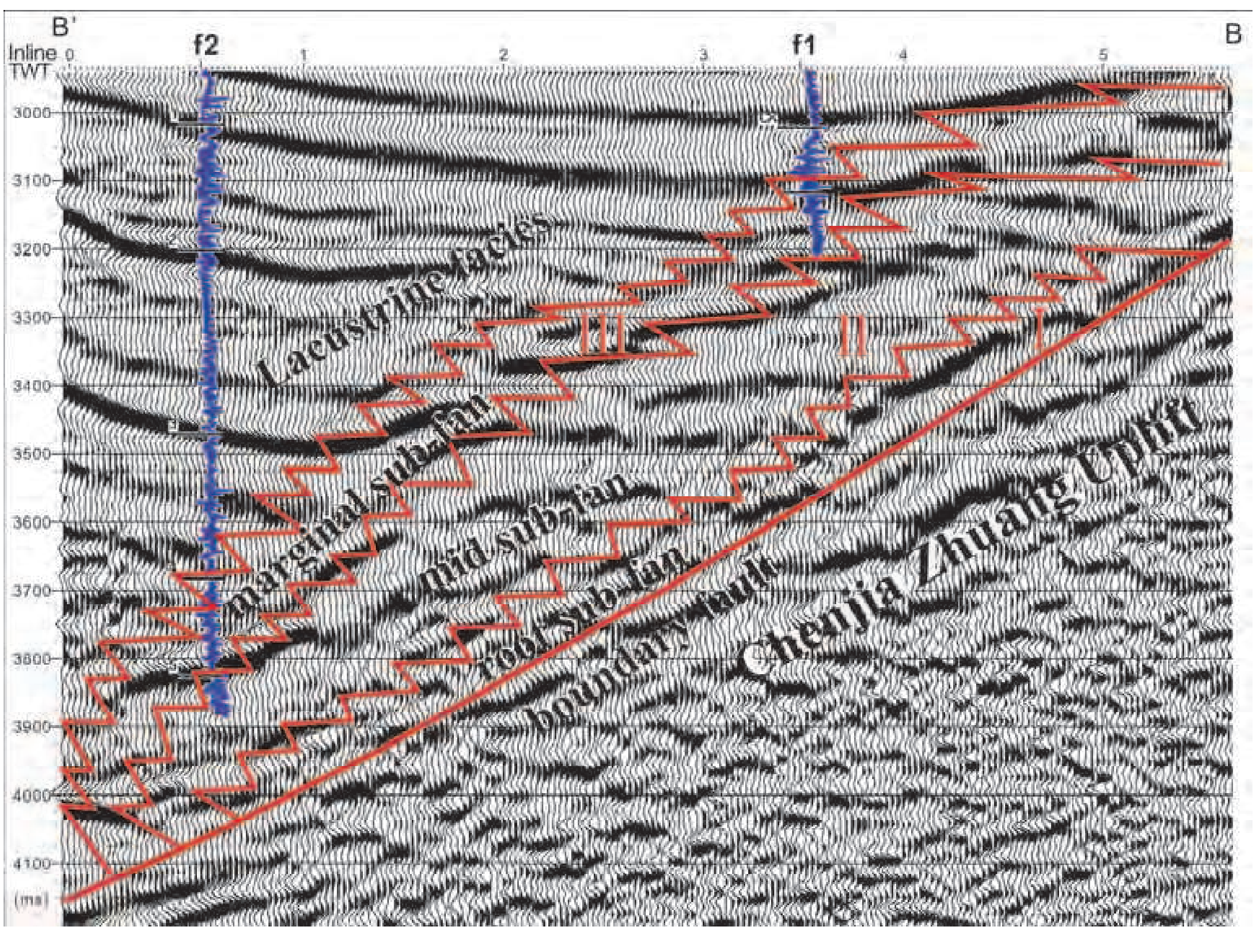

Fig. 3. 3D seismic reflection characteristics of the nearshore subaqueous fans along line B'B (see Line location in Fig.1)

3. The pseudo-acoustic 3D seismic inversion based on Logs reconstruction

3.1 Methodology

The pseudo-acoustic 3D seismic inversion method different from the conventional 3D seismic impedance inversion method not only in working through logs reconstruction, inversion, interpolation and extrapolation, but also adding or replacing characteristic curves to the density logs or, more commonly, velocity logs in order to achieve the ability to identify the reservoir from the surrounding rock in the case of small impedance difference (Shen & Yang, 2006; Zhang et al., 2005). The potential reservoir may show no direct relationship with the seismic reflection but can be distinguished from different lithological changes.

The velocity and the time-depth relationship after logs reconstruction may change so deviations between seismic reflection horizon and synthetic seismogram calibration's horizon should be established to reflect these changes (Luo et al., 2006). The pseudo-acoustic seismic inversion results based on logs reconstruction may be not accurately reveals the corresponding lithological changes of the target layers. To solve this problem, the zero Mean-Based logs reconstruction techniques, which keeps the original time-depth relationship unchanged, can be applied. The principle is to set the characteristic curves or logs involved in seismic inversion to a mean of 0, that is $\Sigma Ai = 0$ (Ai is characteristic curve sample values of target layers). Adding or subtracting the normalized curve and acoustic characteristics curve, then properly magnifying the normalized characteristics curve in order to highlight lithology information. This process can be expressed as:

pseudo-acoustic curve = acoustic logs ± characteristic curves × K,

while K stands for the curve amplification factor.

As the characteristic curves keep the information of the target layer, and the velocity curves of the upper and lower target layers are kept unchanged, so the original time-depth relationship will remaine unchange (Luo et al., 2006).

The implementation process of this method includes the following: ①selection of the characteristic curves; ②standardization of the characteristic curves; ③normalization and reconstruction of the pseudo-acoustic curve; ④seismic wavelet extraction and the establishment of the initial model; ⑤ pseudo-acoustic seismic inversion.

3.2 The pseudo-acoustic 3D seismic inversion based on logs reconstruction

1. Selection of the characteristic curves

To select the characteristic curves of the target layers, quantitative and semi-quantitative correlations through statistical analysis are established between different lithologyies (such as the conglomerate in the fan-root, sand–conglomerate in the mid-fan, mudstone, gypsum-salt rock in the marginal-fan), effective reservoir (such as gas sand–conglomerate in the mid-fan), logs (such as acoustic time (ac), natural gamma (gr), neutron porosity (cnl), spontaneous potential (sp), and logging parameters that correspond to different lithology types in different fans.

The results show that single logs parameter cannot identify the different lithologies in different fans, but combinations of any two of logging parameters (ac, gr or sp) can effectively indentify them to some extent. Further analysis also show that any two logs parameter's combinations between ac, gr, and sp could distinguish the effective and ineffective sand –conglomerate reservoir with a thicknesses greater than 6 m (Fig.4). Therefore, we can use any two logs combination between ac, gr, and sp as the characteristic curves.

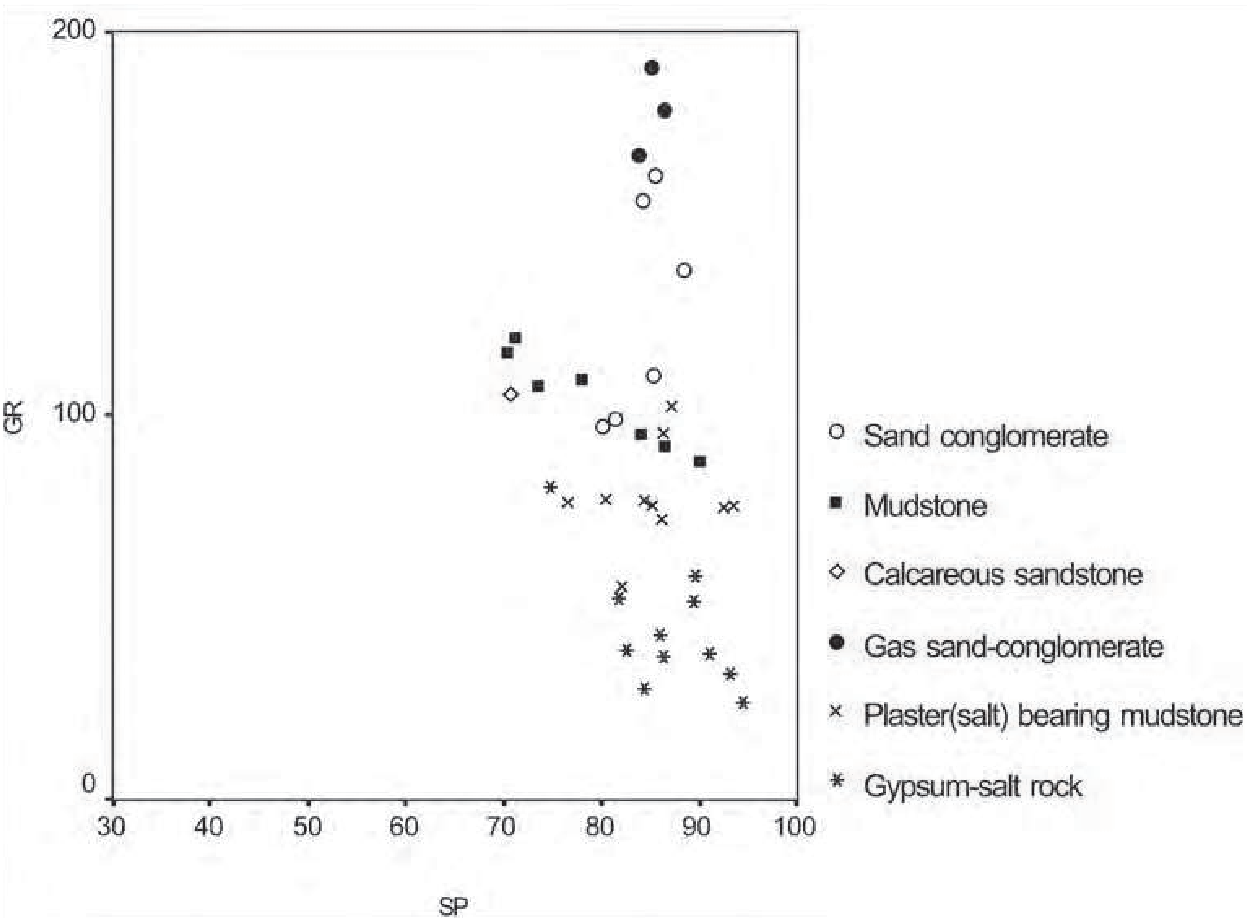

Fig. 4. Statistical analysis between the different lithology, logging parameters of gr and sp and effective reservoir with a thicknesses of > 6 m in wells f1,f2,f3,f8.

2. The standardization of the characteristic curve

In order to eliminate the systematic error caused by different measuring apparatuses and time, the characteristic curves need to be standardized by depth correction, environment correction, mudstone baseline correction, outliers removal, wave filtering and so on.

3. Normalization and the creation of the pseudo-acoustic curve

In order to avoid the systematic error caused by differences in dimension and value range, the characteristic curves need to be normalized before creating the pseudo-acoustic curve. Firstly, the natural gamma (gr) and spontaneous potential (sp) logs will be normalized by regulating the numerical range to the [0 ,1] ,and conducting the [0 ,100] amplification process before summing them for a GS (gr+sp) curve. Then, the asonic logging curve (ac) is processed for the treatment filter values that exceed 100 in order to remain the low-frequency information and eliminate high-frequency information of ac. Finally, the pseudo-acoustic curve GS is obtained by adding the characteristic curve (GS) to the filtered ac. It is clear that the pseudo-acoustic curve GS contain not only the high frequency information of both gr and sp, but also the low frequency information of ac, thus the ability to identify lithologies and strata is greatly improved.

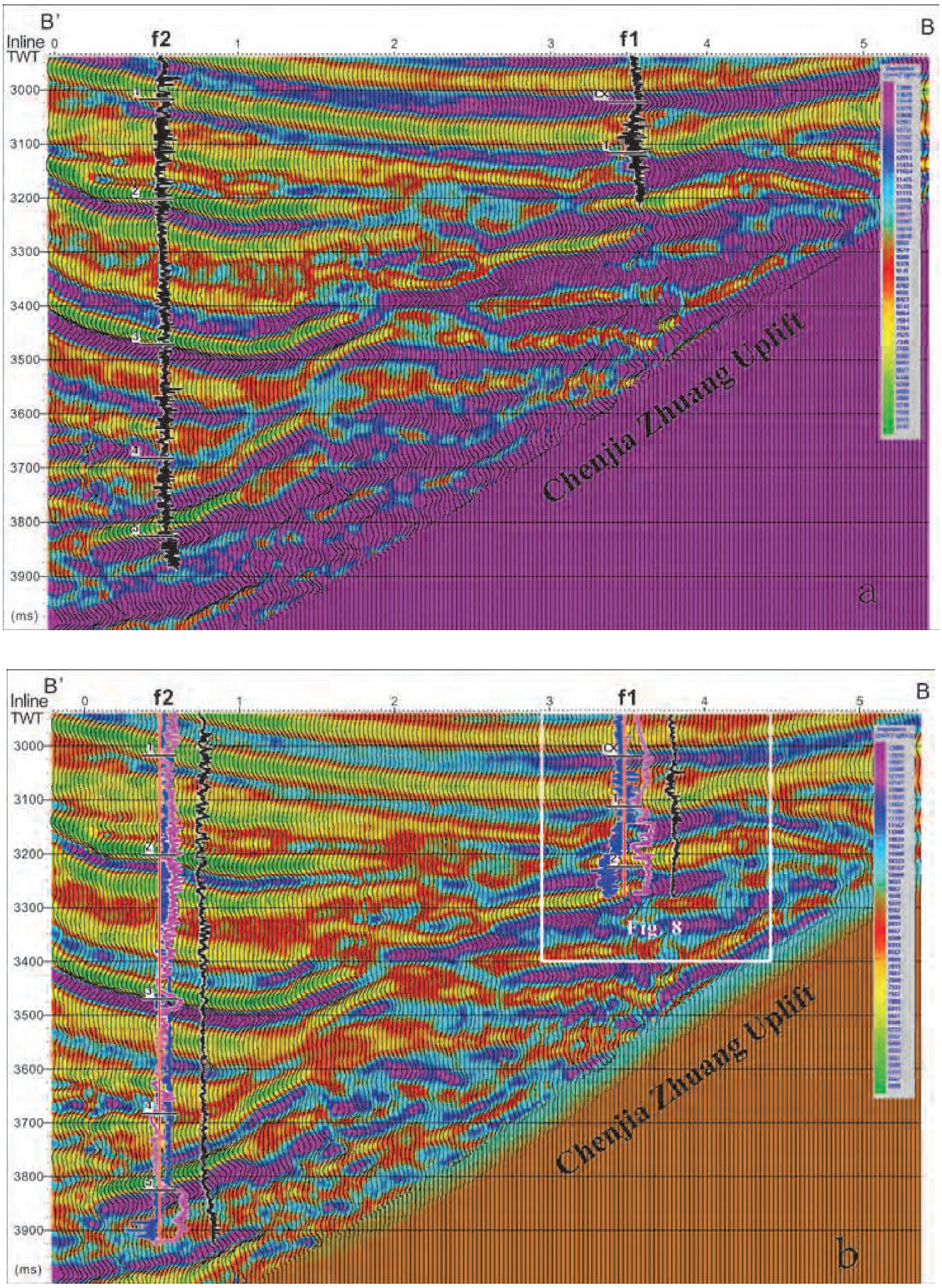

Fig. 5. Comparison between results using different 3D seismic inversion parameters.
a. Conventional 3D seismic inversion data using ac+den loggings; b. Pseudo-acoustic (GS) 3D seismic inversion data based on gr + sp Logs reconstruction

4. Seismic wavelet extraction and initial model creation

Establishing a reasonable initial geological model is the key for getting a good pseudo-acoustic seismic inversion. In fact it is a process of deciphering interpolation and extrapolation of well data under the constraints of the geological concept; the quality of the seismic inversion results are largely dependant on the initial model, which is decided by previous geological knowledge. In order to acquire a good model of impedance inversion, we not only replace the sonic logging curve (ac) by the GS logging curve and by extract Ricker wavelet from the target layer, but also combine the available well information based on the synthetic seismograms calibration and test runs repeatedly.

5. Pseudo-acoustic 3D seismic inversion

On the Strata5.2 inversion software platform, the GS, the GS pseudo-acoustic 3D seismic inversion data are obtained by calculation after importing the GS. The results show that 3D seismic inversion data based on gr+sp logs reconstruction is better than the conventional 3D seismic inversion using ac+den loggings to distinguish the internal structure of the nearshore subagueous fans (Figs. 5, 6)

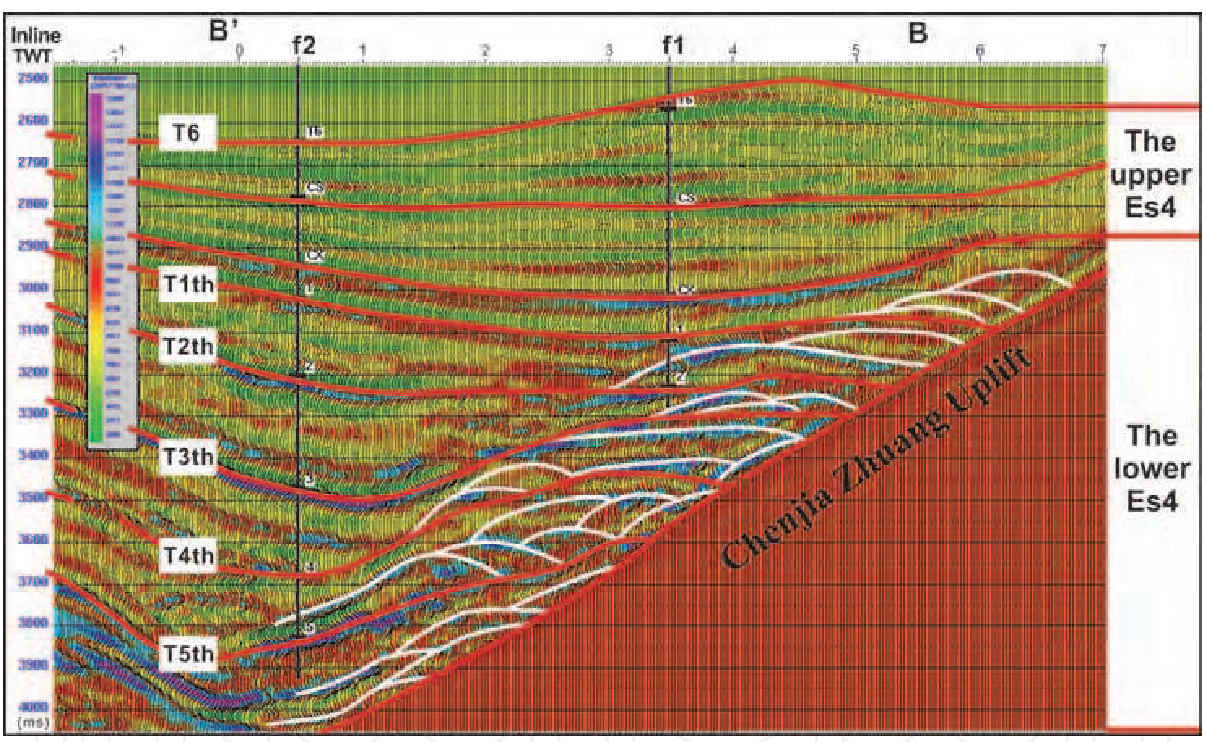

Fig. 6. 3D seismic reflection characteristics of the internal structure in the nearshore subaqueous fans based on GS 3D seismic inversion data along line B'B (see Line L location in Fig.1)

4. 3D seismic sedimentology analysis of nearshore subaqueous fans

4.1 Evolution characteristics of seismic palaeogeomorphology of nearshore subaqueous fans

By using the GS pseudo-acoustic 3D seismic inversion data coupled with calibration of the synthetic seismograms, the internal sub-facies in each member of the lower Es4 Formation can be identified and the temporospatial evolution of the nearshore subaqueous fans can be extrapolated (Fig.6). The analysis finds that each member of the lower Es4 generally consists of 2-5 sub-facies (Fig.6). The time for high frequent sub-facies development is during deposition of the 4th member of the lower Es4 Formation, which includes at least 5 sub-facies. Fig.7 shows the instantaneous frequency level slices of sub-layers' bottom boundary of the lower Es4 Formation as characterized by a low frequency in the main channel in the fan-root, a middle-low frequency in the mid-fan and a high frequency in the marginal-fan. These results clearly reveal the paleogeographic characteristics and different temporospatial evolution stages of sub-facies in the nearshore subaqueous fan system.

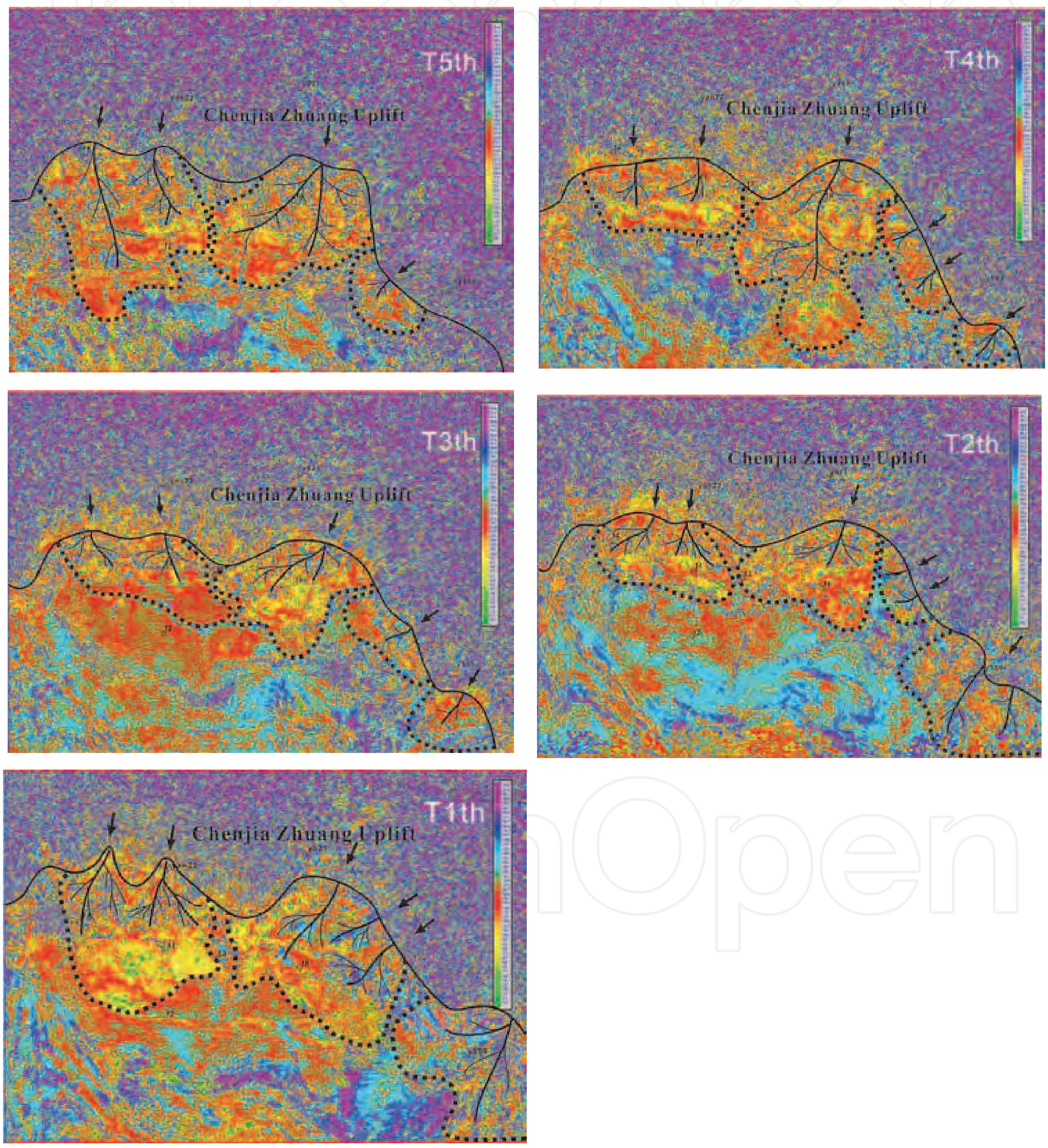

Fig. 7. The instantaneous frequency level slices of sub-layers' bottom boundary of the lower Es4 Formation reflect the paleogeographic characteristics and space-time evolution of different sub-layers

4.2 The distribution characteristics of effective reservoir in nearshore subaqueous fan

The synthetic seismogram calibration results show significantly higher dimension values of 12000-15500 in the GS pseudo-acoustic 3D seismic inversion for the effective sand-conglomerate reservoir but lower dimension values<12,000 for the ineffective reservoir in the lower Es_4 Formation (Fig.8). Accordingly, quantifying the thickness and the distribution of the effective sand-conglomerate reservoir in the lower Es_4 Formation can be relatively easy (Fig.8).

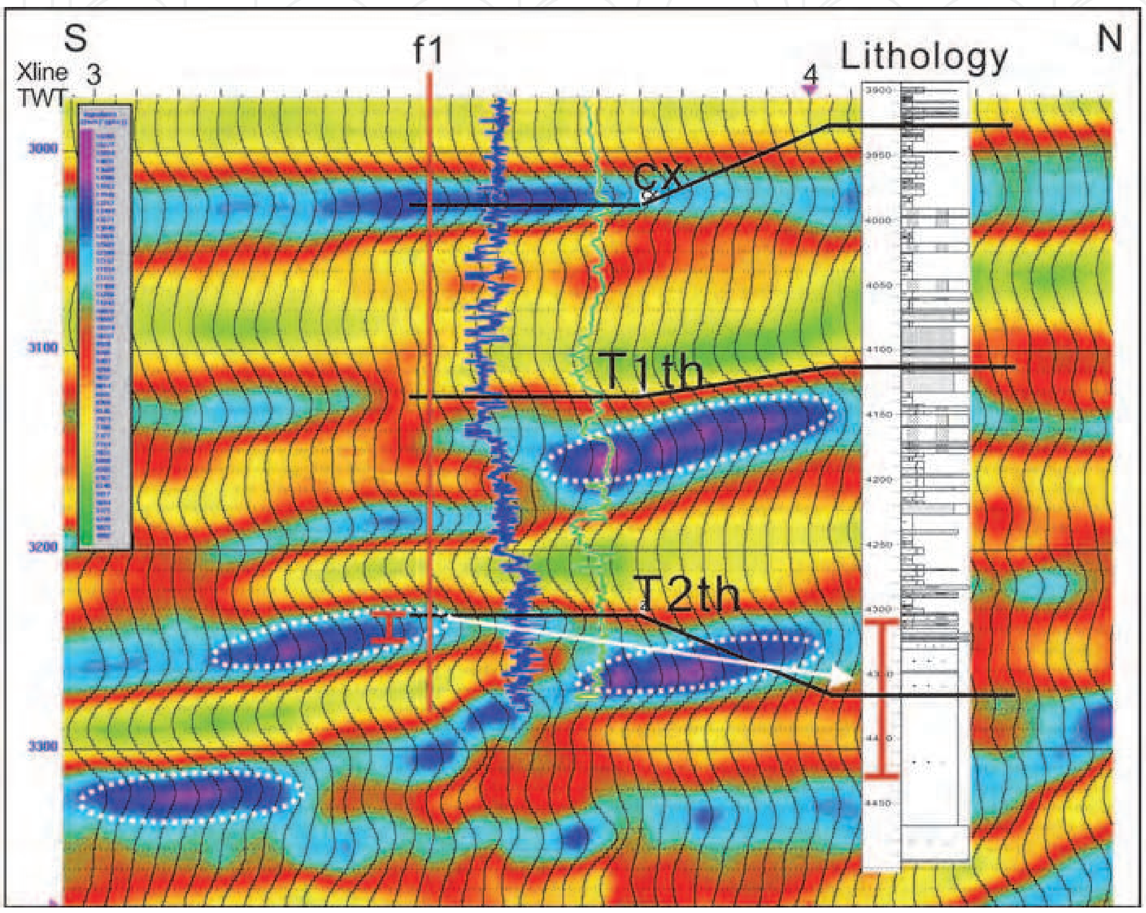

Fig. 8. The effective reservoirs range of values in the GS 3D seismic inversion data for the blue zone (see location in Fig.5b)

5. Conclusions

1. Nearshore subaqueous fans of Paleogene age are well developed in the lower Es4 Formation of the Dongying Depression, in the Bohai Bay Basin, eastern China. Research and oil and gas exploration in the northern Dongying Depression have demonstrated that the sand–conglomerate in the mid sub-fan is not only the main part of the nearshore subaqueous fan, but also the effective oil and gas reservoir in the region.
2. Statistical analyses on different lithology and effective reservoir and logging parameters show that the acoustic (ac), natural gamma (gr), spontaneous potential (sp) can be used as characteristic curves for seismic inversion calculation. Any combinations of two logs can distinguish the effective from the ineffective sand –conglomerate reservoirs with a thicknesses greater than 6 m.

3. Compared with the conventional 3D seismic inversion, the pseudo-acoustic 3D seismic inversion based on characteristic logs reconstruction greatly improves the ability to identify internal seismic sub-facies. Several internal sub-facies in each member of the nearshore subaqueous fan in the lower Es4 Formation have been identified.
4. The pseudo-acoustic 3D seismic inversion technique based on logs reconstruction reveals the 3D seismic sedimentological characteristics of nearshore subaqueous fans including the internal sub-facies structure and various temporospatial evolution stages in different sub-facies. The distribution of the effective sand-conglomerate reservoirs can be better quantified by using this method than the conventional 3D seismic impedance inversion.

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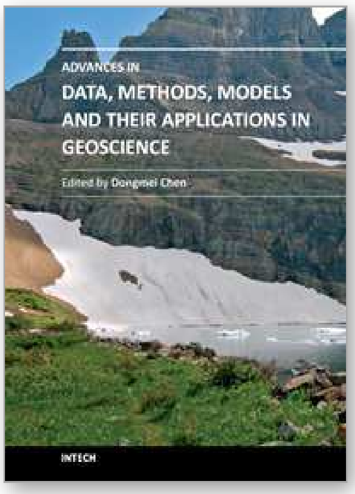

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With growing attention on global environmental and climate change, geoscience has experienced rapid change and development in the last three decades. Many new data, methods and modeling techniques have been developed and applied in various aspects of geoscience. The chapters collected in this book present an excellent profile of the current state of various data, analysis methods and modeling techniques, and demonstrate their applications from hydrology, geology and paleogeomorphology, to geophysics, environmental and climate change. The wide range methods and techniques covered in the book include information systems and technology, global position system (GPS), digital sediment core image analysis, fuzzy set theory for hydrology, spatial interpolation, spectral analysis of geophysical data, GIS-based hydrological models, high resolution geological models, 3D sedimentology, change detection from remote sensing, etc. Besides two comprehensive review articles, most chapters focus on in-depth studies of a particular method or technique.