Geodesy and Geodynamics 8 (2017) 347–355

Contents lists available at ScienceDirect

Geodesy and Geodynamics

journal homepages: www.keaipublishing.com/en/journals/geog; http://www.jgg09.com/jweb_ddcl_en/EN/volumn/home.shtml

Depositional setting analysis using seismic sedimentology: Example from the Paleogene Lishagang sequence in the Fushan depression, South China Sea

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ARTICLE INFO

Article history:
Received 27 July 2016
Accepted 8 May 2017
Available online 17 May 2017

Keywords:
Fushan depression
Seismic sedimentology
Seismic facies
Seismic attribute

ABSTRACT

The Fushan depression is a classic lacustrine rifted sub-basin in the Beibuwan Basin, South China Sea. The Paleogene Liushagang sequence is the main hydrocarbon-bearing stratigraphic unit in the depression. Using three-dimensional (3-D) seismic data and logging data, we analyzed depositional setting of the Liushagang sequence. We use wave impedance inversion to describe progradational directions of provenance and the general distribution of sand body. The seismic facies was analyzed by using the seismic sedimentology approach based on 3-D seismic data, and summed into eight types of seismic facies which could be well related to sedimentary facies. Seismic attributes with six objective sequence boundaries were extracted. Consequently, four provenance system of Liushagang sequence in the study area were confirmed by the corresponding relationship between the geologic information and the warm color and higher value area of seismic attributes: (i) the Hainan uplift provenance area in the south, (ii) the Linggao uplift provenance area in the west, (iii) the Yunlong uplift provenance area in the east and (iv) the northern provenance area. The seismic sedimentology used in this study may provide new insights into a better understanding of depositional setting in continental lacustrine rifted basins.

1. Introduction

In 1998, Zeng Hongliu firstly proposed a concept of "Seismic Sedimentology", marking the birth of this subject [1]. In 2004, Professor Zeng defined seismic sedimentology as a subject by using seismic data to study the sedimentary rocks and the formation process, with seismic petrology and seismic geomorphology composed the core content [2]. Later, Zeng Hongliu, Schlgaer, Lin Chengyan, Dong Chunmei, Zhu Xiaomin, et al. continually studied on the concept, method and technology of seismic sedimentology, which is gradually enriching and perfecting the theory system [3–7]. In recent years, domestic scholars carried out a lot of research on continental complex reservoir in China by using seismic sedimentology, and has achieved remarkable results [6–20] in petroleum exploration and development, but still in the development stage. For example, Dong Chunmei considered the 90° phase inversion-stratal, stratal slicing and frequency division interpretation as key technology in seismic sedimentology research [6]. Lu Yongchao classified logging constrained inversion, strata slice, attribute analysis and frequency division interpretation into main methods of seismic sedimentology [8]. With the continuous development of seismic technology, we should combine the basic principles of sedimentology and new geophysical technology, get further understanding of ancient sedimentary facies. Similar researches have been carried out in some adjacent sub-basins in the South China Sea. Based on the seismic data, Ma identify the seismic

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Peer review under responsibility of Institute of Seismology, China Earthquake Administration.

Production and Hosting by Elsevier on behalf of KeAi

http://dx.doi.org/10.1016/j.geog.2017.05.001
1674-9847/

characteristics about various sedimentary facies of the carbonate platform and different types of reef in the northern continental margin of the South China Sea [9]. Analysis of the drilling cores, well data and 3D seismic data was conducted to identify and interpret the sub-lacustrine fans which formed in a lacustrine succession as the low-stand fan in a sub-basin [10]. Zhu utilizing a high-quality 3D seismic data set, well logs and restored paleogeomorphology, systematically investigated the architecture and genesis of switched sequence stratigraphic units [11]. Also we have made some studies on the tectonic characteristics and structural styles by using seismic data in the Fushan depression [12], seismic sedimentology is applicable for researches of sedimentary system in the South China Sea area. With an increasing demand for petroleum resources in China, the Fushan depression has recently become a focal point for intensive petroleum exploration in South China Sea [21–23]. The Fushan depression is an extensional sub-basin formed during the Mesozoic and Cenozoic rifting located in the southeast of the Beibuwan Basin. However, the lack of spatial and vertical research of deep lacustrine deposition has seriously restricted the secondary exploration of the Fushan Oil Field. Therefore, a better understanding of the depositional system is helpful for further basin research and hydrocarbon exploration. However, traditional geological research based on logging data and 2-D seismic reflector data is hard to well understand the complex characters and distributions of the depositional environment. The best way to extend the well data to the entire investigation area and further study on previously identified area is by using 3-D seismic data. Given this, in this study, new log data, three-dimensional (3-D) seismic reflection data have been examined in the light of three main objectives: (i) using wave impedance inversion to describe progradational directions of provenance; (ii) combined with the actual situation, using better quality seismic sections to analysis major types of seismic facies which could be well related to sedimentary facies; (iii) extracting seismic attributes of six objective sequence boundaries, confirming provenance system of Liushagang formation in the study area.

2. Regional geological setting

The Fushan depression is a half-graben rifted sub-basin, located in the southeast of the Beibuwan Basin, South China Sea, with a total area of 2920 km^2. It is a “dustpan” shaped depression bounded by the Qiongzhou strait to the north, the Hainan uplift to the south, the Lingao uplift to the west and the Yunlong uplift to the east (Fig. 1 a, b) [21,23]. Accumulating sediments is supplied through braided river deltas mainly from the southern margin [24,25]. Using the sequence stratigraphic principles of Vail et al. [26], in combination with modern sedimentology techniques and sequence stratigraphic data (e.g. seismic reflection characteristics, cores, well logs and geological studies), the Paleogene unit of the Fushan depression is divided into three 2nd-order depositional sequences (SSQ1, SSQ2, SSQ3) (Fig. 1 c) which lasted approximately 41.5 Ma [27], the Liushagang sequence (SSQ2) can be further subdivided into three third-order sequences (SQELS3, SQELS2, SQELS1) (Fig. 1c). Based on the interpretation of wireline-log patterns, lithological combinations and 3D seismic successions, transgressive surface (ts) and maximum flooding surface (mfs) were recognized in the Liushagang sequence.

3. Material and methods

Seismic attributes analysis technique is a kind of interpretation automation technology by using 3D seismic data, which has been developed rapidly in recent years, and has been widely used in petroleum exploration. Seismic attribute analysis can provide an important reference value for the research of depositional system. By extracting seismic attributes, the distribution range of sedimentary sand bodies can be defined from the plane, which has important guiding significance in the study of sedimentary system. In different regions, different data conditions, there are significant differences in the response of various seismic attributes to the geological conditions. In this study we firstly build drilling in the calibration, comparing multiple seismic attributes and finally choose CCP2 attributes and variance amplitude attribute to study the distribution of sedimentary system (Fig. 2).

It is worth mentioning that marine sedimentary strata usually using RMS Amplitude as a seismic facies strata slice selection, but in our study, we found that CCP2 attribute is more applicable on the properties of such a continental rifted basin (Fig. 2).

4. Interpretation and results

4.1. Wave impedance inversion

Wave impedance inversion is a special processing and interpretation technique for seismic inversion of formation wave impedance (or velocity) by using seismic data. This technology began to emerge in the 1970s, which is mainly focused on stacked one-dimensional wave impedance inversion based on convolution model and has been booming since the 1980s. In 1983, Cooke introduced the generalized linear inversion method, which brought a new chapter of the wave impedance inversion technique [28]. In our research, we mainly used wave impedance profile to explain the distribution and trend of sand body, set the Bailian-Jinfeng Area as an example below:

Fig. 3a is a seismic inversion profile in southwest north to east direction of the SQEls1 formation in the Bailian area, within well data adding on the profile, we can clearly see that wave impedance level in longitudinal (colors of red, yellow, green, blue indicate wave impedance decreased gradually) is very consistent with the nature gamma curve level. It is worth mentioning that due to the precision imitation of wave impedance inversion, strong axis of high wave impedance represents a composite sand horizon but not a single sand layer, and in fact any kind of inversion method are difficult to achieve the true prediction of single sand layer. Overall, the high wave impedance (red, yellow and green) represents the sandstone, and the low wave impedance (blue) represents the mudstone. Therefore, we still can analyze the general distribution of the sand body based on the wave impedance profile.

Compared wave impedance inversion with seismic reflection profile, we can find that high wave impedance (sandstone) of SQEls1 is mainly distributed in the HST period whereas low wave impedance (mudstone) mainly distributed in the EST period (Fig. 3). The HST sand body developed from the Yunlong uplift and extended into the deep-lacustrine of Bailian area with thinning gradually. During the EST + LST period, the coarse clastic system is not well developed as the weaken of the provenance and supply distance.

4.2. Seismic facies analysis

Liushagang sequence belongs to the rifting stage of Paleogene, which experienced intense tectonic activities, especially large-scale episodic tectonic movement. The depositional background is characterized by a dustpan-like rifted lacustrine basin. Paleogeomorphology can be further divided into steep slope or steep faulted belt, the depression area, the gentle slope belt and some other tectonic-sedimentary belts. Our research combined with the actual situation, using better quality seismic sections, finally