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Using of stratal slicing in delineating delta-turbidite systems in Eocene Dongying depression, Bohai Bay Basin: Insights for the evolution of multi-source delta-turbidite systems in a fourth order sequence

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ABSTRACT

Delta-turbidite systems represent one of most significant targets for hydrocarbon exploration and development. Due to complex stratigraphic architecture of deltas and small scale of delta-fed turbidites, the prediction and characterization of them pose a challenge to successful exploration for hydrocarbons. Through seismic sedimentology approach, 3D seismic and borehole data were used to improve reservoir prediction of the delta-turbidite systems in the Eocene Shahejie Formation, eastern Dongying depression, Bohai Bay Basin, China. A highstand systems tract (HST) is recognized in the Eocene Shahejie Formation in eastern Dongying depression. It is composed of six fourth-order sequences (PSS5 ~ PSS10), each of which corresponds to a given period of delta progradation. Using stratal slicing of 90°-phase seismic data, mapping the fourth stage of delta development (PSS8), as an example, highlights the distribution and evolution of multi-source deltas and their associated thin-bedded turbidites within a fourth-order sequence. Interpretations of stratal slices indicate that the formation of delta-fed turbidites is closely related to base-level changes, sediment supply and syndepositional faults. Development of early larger-scale turbidites fed by north fan delta and Yongan delta suggests that enough sediment supply, rather than base-level falling, plays a more fundamental and critical role for turbidite formation. At the end period of a highstand fourth order sequence, the largest-scale turbidites developed in the front of Dongying delta are jointly driven by both rapid sediment supply and base level falling. This research also proves that the constraint of fourth-order sequences is necessary for ensuring the isochronism of stratal slices, which provide effective reservoir prediction of small-scale delta-fed turbidites and further insights into evolution of multi-source delta-turbidite systems.

1. Introduction

Seismic slicing technique has been widely used in depicting depositional systems to improve understanding sedimentary evolution (Brown et al., 1981; Posamentier et al., 1996; Schlager, 2000; Zeng et al., 2001; Carter, 2003; Davies et al., 2006; Hubbard et al., 2011) and to predict hydrocarbon reservoir distribution (Wood and Mize-Spansky, 2009; Zeng et al., 2011; Zhu et al., 2017). Seismic slicing provides a cost-effective method of imaging and visualizing both marine and lacustrine sedimentary bodies such as submarine channels and lobes (Posamentier and Kolla, 2003; Posamentier, 2004; Gee et al., 2007; Gong et al., 2013), submarine canyons (Gong et al., 2011), lacustrine deltas (Zhu et al., 2013, 2014; Dong et al., 2014, 2017) and lacustrine gravity flow channels (Liu et al., 2016).

Deltas and associated turbidites are one of important deposits in sedimentary basins (Heller and Dickinson, 1985; Mutti et al., 2003; Talling, 2014; Zavala and Arcuri, 2016), giving rise to huge sediment accumulations (Piper and Savoye, 1993; Sinclair, 2000; Girardclos et al., 2007; Lambiase and Cullen, 2013) and significant hydrocarbon reserves (Weimer and Pettingill, 2007; Liu et al., 2017a). Turbidites derived from the collapse of delta fronts are common in deep-water sites of lacustrine basins, and usually occur in the lower delta fronts and prodelta areas (Zavala and Arcuri, 2016). Compared to their counterparts in marine basins, lacustrine turbidites are more complex and smaller, because of more frequent base-level changes, multiple–source and limited sediment supplies, and the effects of tectonics and local

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topography (Bai and Zhang, 2004; Wang et al., 2013; Moernaut et al., 2014; Zhang and Scholz, 2015; Xian et al., 2013, 2017; Liu et al., 2017b). Resultantly, the interpretation and prediction of lacustrine thin-bedded turbidites using well data and conventional seismic stratigraphy approach pose a challenge to reservoir exploration. As an important approach in high-precision seismic imaging, stratal slicing requires seismic amplitudes to be extracted from a geologic time surface (Zeng et al., 1998a, 1998b; Hubbard et al., 2011). Sequence boundaries or systems tract surfaces (i.e., maximum flooding surfaces) are usually taken as geologic-time-equivalent reference seismic events (Zeng, 2010; Dong et al., 2014; Liu et al., 2015). However, it remains questionable as to whether stratal slicing should be constrained by sequence boundaries or systems tract surfaces, when applied to successions with clinoform geometries, such as deltaic clinothems as documented in this study. Driven by base-level changes and sediment supplies, multiple episodes of delta progradation within a depositional sequence generally yield different clinothems with complex stacking patterns (Helland-Hansen and Hampson, 2009; Catuneanu et al., 2009). This, in turn, suggests that stratal-slice analysis may not be applicable to delta-turbidte systems with complex clinoform geometries. Recently, great effect has been made to understand the distribution and evolution of delta-fed turbidite systems in the Eocene Dongying depression in the Bohai Bay Basin (e.g., Fang et al., 2003; Xian et al., 2016; Cao et al., 2017). The well-developed deltaic clinothems and concomitant turbidites provide a good opportunity to: (i) discuss how to improve reservoir prediction of deltas-fed turbidites with clinoform geometries and (ii) better understand the development of thin-bedded turbidites and their relationship to their associated deltas.

2. Geological background

The Dongying depression is known as a northeast-southwest–trending lacustrine rift basin, is located in the southeast Bohai Bay Basin, and occupies an area of approximately 5700 km^2 (Fig. 1A, B and C) (Feng et al., 2013). It is bounded to the north by the Chenjiazhuang Rise, to the eastby the Qingtuozi Rise, to the south by the Luxi Uplift and Guangrao Rise, and to the west by the Qingcheng Rise. It can be subdivided into five secondary tectonic zones, and from north to south, they are: (i) the northern steep slope zone, (ii) the Lijin sag, (iii) the central diapiric anticline zone, (iv) the Niuzhaung sag, and (v) the southern gentle slope zone. The eastern Dongying depression is located in the middle-east of the central diapiric anticline zone (Fig. 1C and D).

Tectonically, the Dongying depression experienced two main tectonic evolutionary stages, including a Paleogene synrift stage from 65.0 to 24.6 Ma and a Neogene thermal-subsidence stage from 24.6 Ma to Quaternary (Hu et al., 2001) (Fig. 2). The synrift stage can be further subdivided into an initial rift phase, a rift expansion phase, a deep subsidence phase, and a contractional phase.

Stratigraphically, the Paleogene Dongying depression is characterized by lacustrine depositional environments, and contain the Kongdian Formation, the Shahejie Formation, and the Dongying Formation (E_d). Thermal subsidence occurred after the deposition of E_d, and Dongying depression was then filled by widespread fluvial sediment deposits (Xiao and Chen, 2003) (Fig. 2).

The interpretation of sequence stratigraphic frameworks is based on regional tectonics, dynamic mechanisms, termination patterns in seismic reflection events, lithology and log data from wells, and changes in depositional systems. Two main supersequences were also recognized in the Dongying Depression, including a Paleogene synrift (65.0–24.6 Ma) supersequence and a Neogene post-rift (24.6 Ma to Quaternary) supersequence (Hubbard, 1988; Williams, 1993). The Paleogene synrift supersequence is composed of 4 s-order sequences (ESSQ1 through ESSQ4), each of which correlates to a major tectonic stages (Feng et al., 2013) (Fig. 2). The second-order sequence of ESSQ3 corresponds to the period of deep subsidence, and contains the 3rd Member and the lower sub-member of the 2nd Member of the Shahejie Formation. ESSQ3 was further classified into three third-order sequences (ESQ1 to ESQ3) (Fig. 2).

The ESQ2, the middle sub-member of the Shahejie Formation (E_s3^m), is the main focus of the present study. E_s3^m is comprised of dark gray mudstones and thin-bedded sandstones. During the deposition of E_s3^m, the lake area expanded and the lake-level rose, because of the intense rifting of border faults and humid climatic conditions, while the depositional center was located approximately in the north-central part of the depression (Li et al., 2005).

Three major deltaic (i.e., the north fan deltas, the northeast Yongan deltas, and the southwest Dongying deltas) were recognized in the middle sub-member of the third member of the Shahejie Formation (Fig. 1C). Among them, the Dongying delta is the largest deltaic system, and developed in the southeast Dongying depression at about 40 Ma. It is made up of clinothems, with thickness of 100 s m, and is shown to have abandoned due to structural inversion in the late Eocene (Fig. 2). Turbidity currents derived from delta-slope failures occurred frequently in the prodelta settings during the progradation of the Dongying deltas. The late Eocene Dongying depression was mainly filled by fluvial-delta systems, which cover an area of 4300 km^2.

3. Data and methodology

The primary data utilized in this study are 400 km^2 of 3D seismic data, tied to 60 boreholes. 3D seismic data have a frequency ranging from 0 to 80 Hz, with a dominant frequency of approximate 30 Hz, which, yields an estimated vertical resolution of 12.5 m. They have a 4-ms vertical sampling rate, and were processed to the zero phase. Seismic sedimentology approach integrated with sequence stratigraphy is used to investigate the distribution and sedimentary evolution of delta-turbidite systems in the HST of E_s3^m, Eocene Shahejie Formation.

3D seismic data were tied to boreholes utilized in this study using high-resolution synthetic seismograms, facilitating the recognition of stratigraphic boundaries. Well-log data were then used to identify the high-frequency sequence stratigraphic boundaries, which were employed to define fourth-order sequence stratigraphic frameworks and stratal architecture. After the construction of sequence stratigraphic frameworks, fourth-order sequences or parasequence sets (PSS) were identified within the E_s3^m, ESQ2. Stratal patterns and base-level changes were then inferred, on the basis of fourth-order sequence identification and seismic reflection configuration.

Seismic phase adjustments (Zeng and Backus, 2005a, 2005b) were used to calibrate the interpretation of thin-bedded turbidites on seismic profiles. Thin sandstones identified on well-log data were calibrated on individual seismic transects. Stratal slices were generated, using fourth-order sequence boundaries as the reference seismic horizons. Seismic facies analysis, coupled with well-log data interpretation, was used to investigate sediment distribution and the evolution of delta-turbidites in the southeast Dongying depression.

4. Fourth-order sequences and stratal patterns

The upper and lower boundaries of the third-order sequence of ESQ2 are termed "T_4" and "T_6" seismic horizons, respectively. Seismic horizons of T_4 and T_6 horizons are interpreted to be angular unconformities, which show truncation terminations below and onlap terminations above. Incision is seen to occur immediately above T_6, probably suggesting lowstand incised valley fills. Lowstand-transgressive and highstand systems tracts are, respectively, bounded at their bases by the initial and maximum flooding surfaces (Vail, 1991). In the study area, three systems tracts were recognized, based on the identification of the first flooding surface (FFS), maximum flooding surface (MFS), and the syndepositional fault-slope break zone (Lin et al., 2000). The distribution of the lowstand systems tract (LST) is controlled by the fault-slope break zone, which is seen to be restricted to the down-dropped block along the syndepositional faults. The transgressive