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Research paper

Sequence stratigraphy and importance of syndepositional structural slope-break for architecture of Paleogene syn-rift lacustrine strata, Bohai Bay Basin, E. China

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ABSTRACT

Sequence stratigraphy and syndepositional structural slope-break zones define the architecture of the Paleogene syn-rift, lacustrine succession in eastern China's Bohai Bay Basin. Jiyang, Huanghua and Liaohe subbasins are of particular interest and were our primary research objectives. Interpretation of 3D seismic data, well logs and cores reveals: One first-order sequence, 4 second-order sequences, and ten to thirteen third-order sequences were identified on the basis of the tectonic evolution, lithologic assemblage and unconformities in the subbasins of Bohai Bay Basin. Three types of syndepositional paleostructure styles are recognized in this basin. They are identified as fault controlled, slope-break zone; flexure controlled, slope-break zone; and gentle slope.

The three active structural styles affect the sequence stratigraphy. Distinct third-order sequences, within second-order sequences, have variable systems tract architecture due to structuring effects during tectonic episodes. Second-order sequences 1 and 2 were formed during rifting episodes 1 and 2. The development of the third-order sequences within these 2 second-order sequences was controlled by the active NW and NE oriented fault controlled, slope-break zones. Second-order sequence 3 formed during rifting episode 3, the most intense extensional faulting of the basin. Two types of distinctive lacustrine depositional sequence were formed during rifting episode 3: one was developed in an active fault controlled, slope-break zone, the other in an active flexure controlled, slope-break zone. Second-order sequence 4 was formed during the fourth episode of rifting. Syndepositional, fault- and flexure-controlled slope-break zones developed in the subsidence center (shore to offshore areas) of the basin and controlled the architecture of third-order sequences in a way similar to that in second-order sequence 3. Sequences in the gentle slope and syndepositional, flexure controlled slope-break zones were developed in subaerial region.

Distribution of lowstand sandbodies was controlled primarily by active structuring on the slope-break zones, and these sandbodies were deposited downdip of the slope-break zones. Sand bodies within lowstand systems tracts have good reservoir quality, and are usually sealed by the shale sediments of the subsequent transgressive systems tract. They are favorable plays for stratigraphic trap exploration.

1. Introduction

Sequence stratigraphy was initially linked to accommodation changes caused mainly by rising and falling of global sea level, on passive continental margin environments. It was a useful tool for constructing isochronous stratigraphic frameworks, predicting reservoirs, and exploring for stratigraphic traps (Vail et al., 1977; Posamentier et al., 1988, 1992; Van Wagoner et al., 1990; Catuneanu et al, 2009), though it is recently being argued that the early 'solutions' attributed to key surfaces and architectures are likely to be non-unique (e.g., Prince and Burgess, 2013; Muto and

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Steel, 2014). Research and exploration during the last three decades have also demonstrated that sequence-stratigraphic methodology and some of the concepts developed for passive continental margin strata may also be applied to the study of rifted lacustrine basins (Shanley and McCabe, 1994; Strecker et al., 1999; Lin et al., 2001; Folkestad and Satur, 2008; Feng et al., 2013), even though they are not conditioned by global sea level. In the lacustrine basins, basin's tectonic movements and paleoclimate changes play an important role in sequence development rather than global sea level changes (Ravnas and Steel, 1998; Strecker et al., 1999; Zcchin et al., 2006; Feng et al., 2013, 2015), which is an important difference between the sequence stratigraphy of lacustrine basins and original Exxonian sequence stratigraphy. However, the application of sequence stratigraphy to the description of ancient rift basin infills has been somewhat limited, particularly with regard to the tectonic evolution of nonmarine continental rift basins, (Shanley and McCabe, 1994). For example, there are a host of large-scale extensional structural components that develop syndepositionally in rift basins. These components include faulted margins, border faults, uplifted basin flanks, deep troughs, intra-basin fault blocks and transfer zones (Withjack et al., 2002). Rift basins also develop folds or anticlines genetically associated with normal faulting, including fault-displacement folds, fault-propagation folds, forced folds, faulted-bend folds and drape folds or anticlines associated with paleostructures (Morey et al., 1990; Faulds and Varga, 1998; Withjack et al., 2002). Articles describing the application of sequence stratigraphy in rift basins include those focusing on the Suez rift basin, Egypt (Jackson et al., 2005), the UK's North Sea central graben (Howell and Flint, 1996), Norway's marine rift basins (Ravnas and Steel, 1998), the Erlian Basin, northeastern China (Lin et al., 2001), the Dongying depression (Ji and Zhang, 1996; Feng, 1999; Li et al., 2003; Feng et al., 2013) and the Bozhong depression (Dong et al., 2011) located in the Bohai Bay Basin, eastern China, and Southern Sudan's Muglad rift basin (D. Wu et al., 2015). Most of the previous work, however, focused on depositional systems and sequence architecture of small depressions within a large rift basin. In contrast, the controlling influence of active extensional structures on the sequence architecture of lacustrine rift basins have, to date, been less studied and reported, although Howell and Flint (1996), Jackson et al. (2005), and Magbageola and Willis (2007), provided exceptions.

Located in the eastern portion of the North China Craton (Fig. 1A), the Bohai Bay Basin is a very complex, large Mesozoic and Cenozoic continental rift basin containing substantial petroleum reserves. The boundaries between the Bohai Bay Basin and these basement blocks are a series of normal faults with a history of multiple episodes of tectonic movement. During the Cenozoic era, there were several distinct phases of rifting and subsidence in the Bohai Bay Basin (Allen et al., 1997), resulting in thick Paleogene, Neogene and Quaternary lacustrine deposits. Subduction rollback of the Pacific plate relative to the eastern margin of Asia is probably the most important tectonic control on the extension of Bohai Bay Basin (e.g., Watson, et al., 1987; Allen et al., 1997). Far-field effects of the collision between the Eurasia plate and the India plate is another possible tectonic driver (Wan, 2004). These structural controls and characteristics of Bohai Bay Basin provide an exceptional opportunity for understanding the role that active extension plays, as an influence on sequence stratigraphic architecture of lacustrine rift basins.

The Bohai Bay Basin has been explored and exploited for over forty years. As a result, large subsurface data sets including cores, stratigraphic paleontology, well logs and high-resolution 3D seismic data are available across much of the basin. These data provide the foundation for further research, and allow the current work to focus on (1) the detailed sequence stratigraphy and (2) on the controls that extensional structures exert on sequence stratigraphic architecture of the Bohai Bay rift basin.

1.1. Data acquisition

This study was based primarily on geological data from 1040 exploration boreholes and regional 3D seismic data covering approximately 11,500 km^2 in the Dongying and Zhanhua depressions of Jiyang subbasin, Qikou and Nanpu depressions of Huanghua subbasin and the West depression of Liaohe subbasin in Bohai Bay Basin (Fig. 1A). The seismic data was extracted from a series of surveys acquired between the years of 2000–2010. It was reprocessed and assembled into a single dataset for this study. Data with very high vertical resolution of 15–25 m (derived from a 35–40 Hz dominant-frequency seismic dataset and 3600 m/s average velocity) was judged to be sufficiently precise for the reconstructing the stratigraphic sequence framework within the regions of seismic coverage. Exploration well data (wireline logs, cores) was tied to the seismic data to complement and calibrate seismic interpretations in cases where the relatively low-resolution data was ambiguous. Well-log data were also used to interpret depositional systems on the basis of the shapes for spontaneous potential (SP) curves. Biostratigraphic and volcanic rock dating data of Chen and Peng (1985), Li et al. (1992), Yao et al. (1994), Feng (1994) was used to estimate the ages of strata and sequence boundaries.

1.2. The methods used in this study are set out below

First, three orders of unconformities and sequence boundaries were identified on seismic profiles using onlap surfaces or truncation surfaces, and in well-log data as surfaces of abrupt change in lithology or grain size. These interpretations served as a foundation for understanding the structural style and composite stratigraphic-sequence framework. After a regionally consistent seismic stratigraphic framework was constructed, biostratigraphic data was used to calibrate the seismic interpretations by age intervals. Stratigraphic 'orders' follow the order hierarchy of Embry, 1995 which is tectonic based.

Second, depositional systems and their cyclic repetition were established based on synthetic seismograms and interpretation of well-log data. At this stage, systems tracts were defined in the relation to maximum flooding surfaces appearing on seismic profiles as downlap surfaces, and as condensed sections characterized by organic-rich shale intervals in well logs motif.

Third, depositional systems and facies associations were delineated within the sequence frameworks previously established, by analyzing well logs and description of cores.

Fourth, slope-break zones controlled by syndepositional structures which influenced stratigraphic development of basin: extensional structural components, normal faults, syndepositional anticlines associated with normal faults and paleostructures were determined, and slope-break zones controlled by them were interpreted in the context of the sequence stratigraphic architecture.

Finally, the factors interpreted to control sequence development are addressed, along with their implications for stratigraphic traps. These discussions provide a framework for further exploration.

2. Geologic setting of Bohai Bay Basin

The Bohai Bay Basin is a Mesozoic and Cenozoic rifted lacustrine basin in Eastern China and has a total area of 200,000 km^2. Uplifted Precambrian basement blocks surround the Basin. These include the Taihang Mountains to the west, the Yanshan Mountains to the