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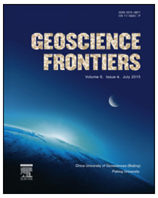

Research paper

Paleotopographic controls on facies development in various types of braid-delta depositional systems in lacustrine basins in China

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ABSTRACT

Braid-delta depositional systems are widely developed in most continental basins in China. Research indicates that, for different types of braid delta, the facies sequence and association, which are critical to the prediction of the distribution of reservoirs, differ greatly. This study illustrates the differences in braid-delta depositional systems in terms of sedimentary characteristics, associated systems and reservoir distributions using three typical paleodeltas in western China: the Zhenbei delta of the upper Triassic Yanchang Formation in the Ordos Basin, the Yuanba delta of the upper Triassic Xujiahe Formation in the Sichuan Basin and the Jimsar delta of the upper Permian Wutonggou Formation in the Junggar Basin. A stratigraphic framework was established using seismic data, logs and cores by choosing stable mud sections as regional correlation markers and, topographies of these deltas were reconstructed based on the decompaction and paleobathymetric corrections. Based on both the paleotopography of these deltas and the differences of their sedimentary facies, these braided deltas can be classified into two systems: steep-gradient braid-delta-turbidite system and low-gradient braid-delta-lacustrine system. Moreover, the low-gradient braid-delta-lacustrine system can be further divided into interfingered and sharp contact sub-types according to the contact relation between the delta sands and lacustrine muds. This study shows that the paleotopography of basin margins strongly controls the accommodation as braid deltas prograde into lacustrine basins and, influences the location of the shoreline in response to changes in the lake level. Furthermore, paleotopography plays a significant role in facies and reservoir distribution which is important for petroleum exploration and development.

1. Introduction

Braid deltas were previously classified as fan deltas (McGowen, 1971; Bates and Jackson, 1980; Galloway and Hobday, 1983; Nilsen, 1985). However, there are significant differences between braid deltas and fan deltas, such as their mechanisms of generation, geomorphic features and sedimentary environments. McPherson et al. (1987) described separately and after than most of researchers agree that braid deltas are formed by the progradation of braided fluvial system into a standing body of water, are composed primarily of laterally coalesced fluvial sands and gravels and are interbedded with finer-grained marine or lacustrine deposits (McPherson et al., 1987; Dunne et al., 1988; Soegaard, 1990; Xue and Galloway, 1991). Recent studies demonstrate typical characteristics of braid deltas in different depositional settings, such as their original geomorphology, sediment supply and the reworking processes (Eriksson et al., 1995; Hamlin et al., 1996; Macnaughton et al., 1997; Lemons and Chan, 1999; George, 2000; Zou et al., 2010).

There are different views about the controlling factors of braid-delta deposition in basin margins. For example, Lemons and Chan (1999) noted that under relatively stable tectonic conditions, basin paleotopography is an important contributor to depositional systems in continental basins. Other studies equate the depositional system of braid deltas with that of common deltas (Li et al., 2001; Shao et al., 2005; Zhu et al., 2008). There have been relatively few studies comparing the deposition of braid deltas developed in different basin margins, which caused some debate in

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depositional systems and reservoir distributions within these types of deltas (Posamentier and Allen, 1993; Shanley and McCabe, 1994; Lemons and Chan, 1999; Yagishita and Takano, 2005; Zhang et al., 2008; Zou et al., 2010; Zhu et al., 2013).

So far, the debate about lacustrine braid deltas has mainly focused on the following concepts: (1) May braid deltas form when braided fluvial systems prograde into lakes (Dunne et al., 1988)? (2) May braid deltas develop three sets (topset, foreset and bottomset), similar to common deltas (Guo, 2012; Zhu et al., 2013)? (3) May turbidite systems develop in a foredelta (Posamentier and Allen, 1993; Lemons and Chan, 1999; Zhu et al., 2013)? (4) What are the differences in the vertical sequence and facies in different types of braid delta and what are the main controlling factors (Lemons and Chan, 1999; Li et al., 2001; Shao et al., 2005; Zhu et al., 2008; Zou et al., 2010)? Therefore, the Zhenbei delta in the upper Triassic Yanchang Formation in the Ordos Basin, the Yuanba delta in the upper Triassic Xujiahe Formation in the Sichuan Basin and the Jimsar delta in the upper Permian Wutonggou Formation in the Junggar Basin provide an excellent opportunity to study these issues.

The purpose of this study is to document the influence of the paleotopography of basin margins and to compare the properties of depositional systems in different styles of braid deltas. The tectonics, climate, sediment flux, lake level and basin paleotopography of these depositional systems provide a model for hydrocarbon reservoir exploration of lacustrine subsurface deposits where many of these controlling parameters are generally unknown or poorly understood.

2. Geological setting

The Ordos, Sichuan and Junggar basins are the most important continental basins in western China (Fig. 1). The Ordos and Sichuan basins are in the western margin of the North China plate and the Yangtze plate, respectively. The tectonic movements of these basins are controlled by regional uplifting and subsidence (Chen et al., 2001; Zhang et al., 2007). The Ordos Basin and Sichuan Basin fully evolved into lake basins due to the regional collisional tectonism and related intra-plate deformation in the late Triassic (Fig. 2). The Junggar Basin, located in the eastern part of the Junggar–Kazakhstan plate, is bounded by the Altai orogenic belt to the north and the Tianshan orogenic belt to the south. Two tectonic stages had been effective in this basin: a rifting stage in the Permian and a sagging stage from the Triassic to the late Eocene (Han et al., 2001; Lu et al., 2008). During late Permian, Junggar Basin underwent a rift-sagging transition period and was dominated by lacustrine deposition (Fig. 2).

The Zhenbei delta of the upper Triassic Yanchang Formation developed as a result of both sediment supply from the southwest and the west of the Ordos Basin and unactivated faults and folds. This delta occupies an area of nearly 8×10^3 km^3 (Wei et al., 2003; Chen et al., 2009).

The Yuanba delta of the upper Triassic Xujiahe Formation is situated in the north part of the Sichuan Basin and formed on a surface with gentle structural deformations where fewer faults developed. It covers an area of approximately 1.7×10^3 km^3. Its feeder systems are mainly from the north and the northeast of the Sichuan Basin (Jiang et al., 2007).

The Jimsar delta of the upper Permian Wutonggou Formation lies in the southeast of the Junggar Basin and has an area of approximately 1.3×10^3 km^3. It was fed from the southwest of the Junggar basin. Seismic reflections have shown that there is little change in the thickness of the Wutonggou Formation as it dips toward the west (Guo, 2012).

3. Paleotopography reconstruction

The paleotopography of the basin margins and its significance on the paleogeography of sedimentary basins has recently been a popular topic in sedimentary geology and basin analysis. It has also proven to be a useful tool in paleogeographic analysis and reservoir prediction (Plint and Wadsworth, 2003; Posamentier and Kolla, 2003; Deptuck et al., 2007; Green, 2009; Lin et al., 2009; Glørstad-Clark et al., 2010; Pandey et al., 2010; Liu et al., 2012).

Paleotopography, as used here, refers to the angle and length of the depositional surface (which is also called ramp) on which each paleodelta was deposited. The process of reconstructing the paleotopography of the ramp is illustrated as case study of the Zhenbei delta by including stratigraphic correlation, restoration for erosion, decompaction and paleobathymetric correction.

3.1. Stratigraphic correlation

Accurate correlation of stratigraphy is the basic requirement for paleotopography reconstruction. The most reliable correlation markers are widespread within a mudstone section, deposited during lacustrine flooding period (Xue and Galloway, 1993; Shanley and McCabe, 1994; Fanti and Catuneanu, 2010).

The upper Triassic Yanchang Formation, between the boundaries of Ch6 and Oil shale, can be divided into two units, the Ch6 unit and Ch7 unit, which are separated by stable mud (Ch7). Each unit can be further divided into several subunits by the inter-mud (Fig. 3).

3.2. Method of paleotopography reconstruction

(1) **Restoration for erosion.** There are many methods for restoration of eroded strata (Wyllie et al., 1956; Magara, 1976; Kumar, 1979; Henry, 1996; Lin et al., 2009; Liu et al., 2012). Extended seismic reflection configuration method has been widely applied for its simplicity and efficiency. The erosion was estimated from the seismic reflection configuration and from well log comparison, using the principle of the similar thickness trends in adjacent strata.

During the late Triassic, the Ordos Basin was a stable craton depression. The Yanchang Formation was a sequential deposition in this area. There was no unconformity or erosion in the study units; therefore, restoration for erosion could be ignored.

(2) **Decompaction correction.** We did not simply flatten Ch6 and calculate the thickness of the unit between Ch6 and Oil shale, because the thickness and ratio of sand to mud differs from the delta plain to lake in delta systems, which cause great differences in the degree of compaction at the different regions. Therefore, a decompaction correction is necessary to calculate the original thickness from data at the present burial depths.

Under normal compaction conditions, the relationship between porosity and burial depth of a deposit can be expressed by an exponential function (Athy, 1930; Perrier and Quiblier, 1974):

$$\varphi = \varphi_0 e^{-ch} \tag{1}$$

where φ is the porosity at burial depth h, φ_0 is the depositional porosity and c is the compaction coefficient.

Based on measured porosity data from 60 wells, curves that reflect the relationship between porosity and burial depth were formulized for various lithologies.

Mudstone:

$$\varphi = 0.5947e^{-0.000762h} \tag{2}$$

Sandstone: