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Research paper

Deep-lacustrine sandy debrites and turbidites in the lower Triassic Yanchang Formation, southeast Ordos Basin, central China: Facies distribution and reservoir quality

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ABSTRACT

The deep lacustrine gravity-flow deposits are widely developed in the lower Triassic Yanchang Formation, southeast Ordos Basin, central China. Three lithofacies include massive fine-grained sandstone, banded sandstone, and massive oil shale and mudstone. The massive fine-grained sandstones have sharp upper contacts, mud clasts, boxed-shaped Gamma Ray (GR) log, but no grading and Bouma sequences. In contrast, the banded sandstones display different bedding characteristics, gradational upper contacts, and fine-upward. The massive, fine-grained sandstones recognized in this study are sandy debrites deposited by sandy debris flows, while the banded sandstones are turbidites deposited by turbidity currents not bottom currents. The sediment source for these deep gravity-flow sediments is a sand-rich delta system prograding at the basin margin. Fabric of the debrites in the sandy debris fields indicates initial formation from slope failure caused by the tectonic movement. As the sandy debris flows became diluted by water and clay, they became turbidity currents. The deep lacustrine depositional model is different from the traditional marine fan or turbidite fan models. There are no channels or wide lobate sand bodies. In the lower Triassic Yanchang Formation, layers within the sandy debrites have higher porosity (8–14%) and permeability (0.1–4 mD) than the turbidites with lower porosity (3–8%) and permeability (0.04–1 mD). Consequently, only the sandy debrites constitute potential petroleum reservoir intervals. Results of this study may serve as a model for hydrocarbon exploration and production for deep-lacustrine reservoirs from gravity-flow systems in similar lacustrine depositional environments.

1. Introduction

Gravity flows are defined as the result of fluid-assisted mass wasting, and represent one of three fundamental mechanisms for sediment transport, especially for deep-water sandstone deposits (Postma, 1986; Haughton et al., 2009). Four types of gravity flows are commonly recognized: grain flows, liquefied flows, turbidity currents, and debris flows. Turbidity currents and debris flows are widely distributed and the most studied (*e.g.,* Middleton and Hampton, 1973; Shanmugam, 2000, 2015; Amy and Talling, 2006; Hodgson, 2009; Talling et al., 2012).

Forel (1885) was the first to recognize that dense, sediment-laden underflow produced by the Rhone River had created a subaqueous canyon in Lake Geneva, Switzerland, but little importance was assigned to this observation, until Daly (1936) proposed a similar origin for submarine canyons, and the name turbidity current was introduced by Johnson (1939). Yet, it was the work of Kueben (1951), and Kuenen and Migliorini (1950) that recognized turbidity currents as the agent most responsible for transportation of sediment into the deep sea settings, and that many sand-shale

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sequences previously interpreted as shallow water deposits were actually turbidites. Understanding of the mechanics of turbidity currents, and the models for submarine fans were refined further during the following decades (*e.g.,* Bouma, 1962; Normark, 1970; Mutti and Ricci Lucchi, 1972; Mutti, 1977; Walker, 1978; Shanmugam, 2000, 2002, 2016; Weimer et al., 2000; McHargue et al., 2011). Recently, the debris flow and its deposits have been recognized as part of the depositional dynamics in submarine fan settings (Shanmugam, 1996; Amy et al., 2005; Migeon et al., 2010). In general, a debris flow is characterized by a high sediment volume that suppresses turbulence (Talling et al., 2007). Consequently, grain-to-grain collisions, reduced excess particle density, and the yield strength of the sediment-water mixture replace fluid turbulence as the mechanisms for supporting sediment in the flow. Laminar, or only weakly turbulent flow, is produced, with deposition occurring through rapid halting (freezing) (Shanmugam, 2000; Talling et al., 2007, 2012). Understanding these relationships resulted in the identification of non-channelized, deep-water debris flows, which have been mistakenly interpreted as the turbidity current deposits using the channelized submarine fan model (Shanmugam, 2000; Zou et al., 2012). Even though deep lacustrine gravity flows have been recognized since Forel (1885), most studies have been outcrop based (*e.g.* Schofield et al., 2009; Sumner et al., 2009), and have treated the interval as a simple analog of turbidites (Kneller and Branney, 1995; Pang et al., 2009). In the Ordos Basin, the sandy debrites has been studied using core data (Li et al., 2011; Zou et al., 2012). Only limited data are available, there are few systematic studies of deep lacustrine gravity-flows using different kind data in the subsurface compared to other depositional settings.

Deep lacustrine facies are well developed within the Triassic Yanchang Formation in southern Ordos Basin, central China (Zou et al., 2012; Yang et al., 2014). It comprises mostly organic-rich mudstone and black oil shale, but also includes a deep lacustrine sandstone facies (Zou et al., 2008; Li et al., 2009), which has become a new exploration target in the southeast Ordos Basin, central China. This study integrates core, well logs, and seismic data to document the characteristics of deep lacustrine gravity flows, summarizes their depositional model, and proposes the potential mechanisms forming these gravity flows. Two types of gravity flows deposits, sandy debrites and turbidites, are both developed in the southeast Ordos Basin (Li et al., 2011; Zou et al., 2012). They exhibit distinctive differences in sedimentary structures, grain size, spatial distribution, well log signatures, and reservoir potential. Results of the study have important implications for hydrocarbon exploration and production in the south Ordos Basin, and can potentially be applied to similar deep-lacustrine settings elsewhere.

2. Geological setting

The Ordos Basin is an intracratonic basin located in north central China (Fig. 1A). The basin can be divided further into six tectonic units: the Yimeng Uplift, Western Thrust Belt, Tianhuan Depression, Yishan Slope, Jinxi Flexure Belt and the Weibei Uplift (Fig. 1B). The study site is located in the southern part of the basin across the Weibei Uplift and Yishan Slope (Fig. 1B). Faults and folds define the basin margins, but the strata in the principal part of the basin dip gently to the west (Zou et al., 2012). The Paleozoic-Mesozoic history of the Ordos Basin can be divided into three stages (Yang et al., 2005). From the early Cambrian to the early Ordovician, the south Ordos Basin occupied part of the broad passive margin of the North China block. The record of the first stage is dominated by shallow-marine and tidal-flat sediments (Sun et al., 1989). From the middle Ordovician to middle Triassic, the basin was surrounded by convergent margins, and the south Ordos Basin record of the second stage is mainly dominated by thin bedded marine sediments (Zhang, 1997; Yang et al., 2005); by the third stage, late Triassic, the collision and convergence of the North and South China blocks, and the collision of the Qiangtang block with the Eurasian plate transformed the Ordos basin into a complete intraplate basin, that experienced a transition from open marine facies to non-marine lacustrine facies (Yang et al., 2005; Zou et al., 2012; Fu et al., 2013).

The late Triassic Yanchang Formation in the Ordos Basin uncomfortably underlies the middle Triassic Zhifang Formation, and is uncomfortably overlaid by early Jurassic strata (Fig. 2). It is traditionally divided into ten stratigraphic sublayers: Chang1 to Chang10 (Fig. 2). The deposition of the Yanchang Formation, the south Ordos Basin records a complete cycle of a lake development (Li et al., 2009): initial formation and development stage (Chang 10–Chang 8), peaking stage (Chang 7–Chang 4 + 5), and declining stage (Chang 3–Chang 1). Well-developed fluvial, deltaic and lacustrine facies characterize the deposition of the Yanchang Formation (Zou et al., 2008). The Chang1 sublayer was eroded following uplift caused by Indo-Sinian tectonic movement in the study area (Yang et al., 2005). The focus of this study, the Chang 7 (C7) sublayer, comprises a deep lacustrine gravity-flow depositional system, and is composed of thick mudstone, oil shale, and sandstone (Chen et al., 2006; Pang et al., 2009; Zou et al., 2012). Yuan et al. (2015) suggested that the maximum water level was reached during the Chang 7 sublayer (Figs. 1B and 2), and the deepest part of lake was located along the counties of Huanxian-Wuhua-Huachi-Changwu-Xunyi in the southwest and the counties of Dingbian-Yan'an-Fuxian in the northeast (Pang et al., 2012, Fig. 1B).

3. Data and methods

Cores, well logs, and 3D seismic data were integrated to document the characteristics of gravity flows in the C7 sublayer in the south Ordos Basin. Cores from two wells were examined and described thoroughly to identify different component lithologies, sedimentary structures, and lithofacies (Figs. 3 and 4). The value and shape of gamma-ray log signatures for different lithofacies were summarized, categorized, and then applied to the remaining of 69 wells without core data in the study area. A high-resolution (25 Hz) 3D seismic survey of 968 km^2 was first calibrated and tied to wells using a synthetic seismogram to facilitate recognition of stratigraphic boundaries and faults. Identification of gravity-flows deposits based on core and well logs were calibrated on individual seismic lines to help mark the boundaries and distribution of each gravity flow, and the seismic traces of gravity-flow sediments were analyzed. The resulting depositional system, facies successions, and distribution of sediments were interpreted, and mapped using both well data and 3D seismic. Additionally, grain size distribution of samples from two wells were analyzed and compared.

4. Results

4.1. Lithofacies

Wells 56 and 38 were chosen to describe the features of the lithofacies of the C7 sublayer (Figs. 3 and 4). The study area is a new exploration area for studying the deep lacustrine reservoir in Ordos Basin. These two wells are the only cores available at the time when our study was conducted. These two-cored wells have continuous core data that display both sedimentary characteristics and depositional successions. In well 56, well log correlation shows that total thickness of the C7 sublayer is 132 m (from 726 to 858 m). It is