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Research paper

Lithofacies and origin of the Late Triassic muddy gravity-flow deposits in the Ordos Basin, central China

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ABSTRACT

Fine-grained sediments from the Late Triassic Yanchang Fm. in the Ordos Basin (central China) were studied by core analysis and geophysical logging. Part of the mudstones in this formation are stratified, part of them are unstratified; the various mudstones can be subdivided into eight types on the basis of their structures and textures. They represent a variety of environments, ranging from delta fronts and subaqueous fans to deep-water environments. Part of the sediments were reworked and became eventually deposited from subaqueous gravity flows, such as mud flows, turbidity currents and hyperpycnal flows that easily developed on the clay-rich deltaic slopes. The sediments deposited by such gravity flows show abundant soft-sediment deformation structures. Understanding of such structures and recognition of fine-grained sediments as gravity-flow deposits is significant for the exploration of potential hydrocarbon occurrences. Because fine-grained deposits become increasingly important for hydrocarbon exploration, and because the sediments in the lacustrine Yanchang Formation were deposited by exactly the same processes that play a role in the accumulation of deltaic and prodeltaic fine-grained sediments, the sedimentological analysis provided here is not only important for the understanding of deep lacustrine sediments like the Yanchang Formation, but also for a better insight into the accumulation of fine-grained prodeltaic deep-marine sediments and their potential as hydrocarbon source rocks and reservoir rocks.

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1. Introduction

The exploration of unconventional hydrocarbon occurrences has raised much interest in the transport and deposition of fine-grained lithified sediments such as shales, mudstones and siltstones (Schieber, 1994a; Schieber et al., 2007; Hovikoski et al., 2008; Bhattacharya and Maceachern, 2009; Aplin and Macquaker, 2011; Plint, 2014; Kostic, 2014). This has made clear that unconventional petroleum occurrences are present not only in marine deposits but also in lacustrine shales (Pollastro, 2007). It was commonly believed for a long time that fine-grained sediments can accumulate only from suspension in relatively deep, quiet water, but this view has been found incorrect already for several decades (e.g. Schieber, 1994b; Macquaker and Bohacs, 2007; Hovikoski et al., 2008; Ichaso and Dalrymple, 2009; Aplin and Macquaker, 2011; Ghadeer and Macquaker, 2011, 2012). It is now commonly accepted that mudstones with apparently monotonous lamination or with a massive character can have been deposited from gravity-induced flows that transported aggregate grains (e.g. Schieber, 1994a,b; Macquaker et al., 2007; Ghadeer and Macquaker, 2011; Plint, 2014). Flume experiments also show that mud with some 85% water can be eroded to form platy intraclasts (Schieber et al., 2010). In addition, mud aggregates transported as bedload can form part of current ripples if transported at current velocities comparable to those that transport fine sand (Schieber et al., 2007; Schieber and Southard, 2009). The last mentioned works emphasize that mud cannot only be transported and settle in quiet water, but – more importantly – also in high-energy environments if transported by gravity flows, i.e. turbidity currents, hyperpycnal flows or mudflows.

The relationship between gravity flows and their depositional

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characteristics is, however, still poorly understood (Sumner et al., 2009; Lamb and Mohrig, 2009; Talling et al., 2012; Pouderoux et al., 2012), especially for fine-grained deposits. A recent study has clearly pointed out the difficulties of recognizing microstructures and understanding the transport processes that resulted in mudstones (Plint, 2014). Bhattacharya and Maceachern (2009) provided a comprehensive review on the subject of mud transport in deltaic and shelf settings. Water-rich gravity-driven downslope flows, in which mud was supported by turbulence due to storm waves rather than by auto-suspension, have been documented from shelves (e.g. Ogston et al., 2000; Traykovski et al., 2000, 2007). Diagnostic criteria for the recognition of deposits of initially water-saturated muddy sediments in nearshore, tide-dominated and wave-dominated settings have been proposed by Ichaso and Dalrymple (2009) and MacKay and Dalrymple (2011). Wave-enhanced sediment gravity flows and their deposits, as well as beds with three distinctly different aspects (rippled, laminated and structureless) have been identified from ancient shelves (e.g. Macquaker et al., 2010; Plint, 2014).

Although modern examples of muddy gravity-flow deposits on continental shelves have been described extensively (Talling et al., 2007; Schieber et al., 2010; Plint et al., 2012; Plint, 2014; Talling, 2014), descriptions and interpretations of analogous ancient sediments are still scarce. In particular, Mesozoic deposits of water-rich flows on deltaic slopes and in deep lacustrine environments have rarely been documented. The main purpose of the present contribution is the description of Mesozoic lacustrine fine-grained gravity-flow deposits in the Late Triassic Ordos Basin and the reconstruction of their depositional mechanisms, also because of the importance of a good understanding of such deposits for hydrocarbon exploration. The present contribution is the last in a series of three, and completes the sedimentological investigation of the Yanchang Formation. The two earlier studies dealt with other aspects that are important in the context of hydrocarbon exploration in this formation, viz. recognition and genetic interpretation of the soft-sediment deformation structures in the fine-grained slurry deposits (Yang et al., 2016), and the influence of climate and tectonics on the origin of the sandy hyperpycnites (Yang et al., 2017). The reader is referred to the just-mentioned studies for details about those aspects.

2. Geological setting

2.1. Structural development and stratigraphy

The sediments under study belong to the Late Triassic Yanchang Formation, which forms part of the succession filling the Ordos Basin. This basin is the second largest sedimentary basin in China (Fig. 1A), covering 320,000 km^2, including the surrounding Cenozoic grabens. It is situated in the western part of the Sino-Korean Block, and is bordered by the Yinshan, Luliang, Qinling, Liupan and Helan Mountains (Fig. 1). Being situated on a stable Archean crystalline basement, it developed during the Mesoproterozoic. Sediments accumulated until (and including) the Tertiary, and reach a total thickness of, on average, 4–5 km (Zou et al., 2012; Yang and Deng, 2013).

During the Late Triassic, the paleocontinents in the south, which were one of the main source areas of the Yanchang Fm., were uplifted by the collision of the South China and the Sino-Korean Blocks (Weislogel et al., 2006; Dong et al., 2012); they were thrust to the north by intensification of the second episode of the Indosinian orogeny. The collision and thrusting downwarped the Ordos Basin, resulting in steep slopes on both sides: 3.5–5.5° in the south and 1.5–2.5° in the north (Fig. 1B) (Fu et al., 2013; Yang et al., 2017). Fast subsidence of the basement and deepening of the basin resulted in a transgression of the lake during the early Late Triassic. Sediment was supplied mainly from the Qinling, Liupan and Yinshan Mountains (Fig. 1).

The Yanchang Fm., the most important oil source of the basin, consists of detrital fluvial/deltaic/lacustrine sediments of 1000–1300 m thick. Its contact with the underlying Middle Triassic Zhifang Fm. is an unconformity in the marginal parts of the basin,

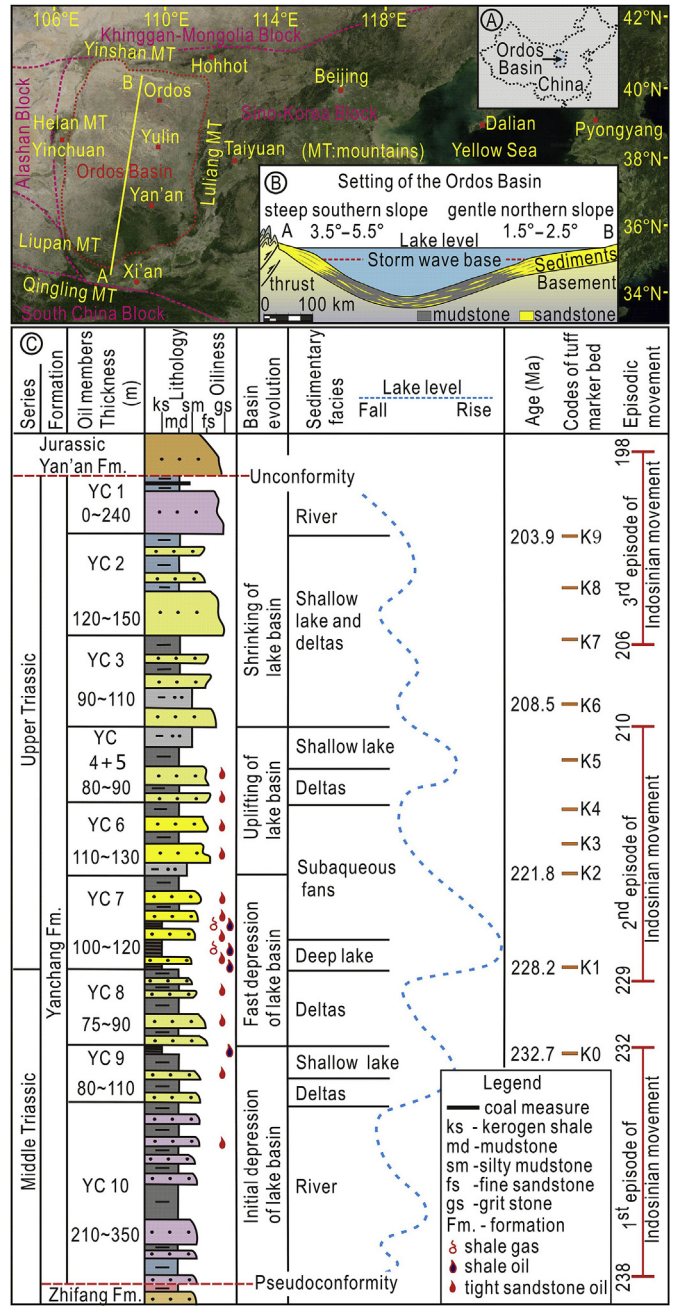

Fig. 1. Location (A), geological setting (B) and Triassic succession (C) of the Ordos Basin (from Yang et al., 2017). The main map shows the regional topography and the structural framework of central China, and the peripheral mountains of the Ordos Basin. The yellow line from A to B shows the location of the section sketched in (B). Inset map (B) shows the uplift of the Qinling Mountains, thrusts, downwarping and inclination of the Late Triassic basin. Figure (C) shows the Middle-Late Triassic strata, lithology and thicknesses of the 10 oil members, sedimentary facies, lake-level fluctuations, episodic tectonic movements, basin evolution and unconventional petroleum levels of the Yanchang Fm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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