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RESEARCH PAPER

Sublacustrine hyperpycnal channel-fan system in a large depression basin: A case study of Nen 1 Member, Cretaceous Nenjiang Formation in the Songliao Basin, NE China

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Abstract: Based on the integrated analysis of seismic, drilling and core data, a large channel-fan system of hyperpycnal flow origin was found in the Qijia-Gulong area of the Nen 1 Member of the Cretaceous Nenjiang Formation in the Songliao Basin. The hyperpycnal flow in this area, which originated from the edge of the basin and then passed the northern delta, formed a complete channel-fan system in the deepwater area. The channel-fan system comprises straight channels and meandering channels extending from north to south over a straight distance of more than 80 km with a width of 100–900 m, and distal fan lobes at the channel tip cover a maximum area of 20 km^2. This system, which is dominated by fine-grained deposits, contains massive sandstone, sedimentary structures of flow-water origin, and internal erosion surfaces; it also contains abundant continental organic clasts and exhibits evidence of bed-load and suspended-load transportation mechanisms. The hyperpycnite sequence contains pairs of coarsening-upward lower sequences and fining-upward upper sequences, reflecting the dynamic features of cycles in which floods first strengthen and then weaken. A new sedimentary model has been built for hyperpycnites in the Songliao Basin.

Key words: Songliao Basin; the Cretaceous; Nenjiang Formation; turbidity current; turbidite; hyperpycnal flow; hyperpycnites; sedimentary characteristics; sublacustrine channel-fan complexes

Introduction

Deepwater deposition has been one of the most active areas of exploration and research in the oil and gas industry. Research and exploration over the last two decades have shown that in addition to turbulence and mass transportation, which can give rise to large-scale deepwater reservoirs[1–4], hyperpycnal flow is another important geological agent that can transport shallow sediments over long distances to deepwater basins. However, hyperpycnal flows and their deposits, hyperpycnites, have not been investigated in detail[5–6]. Hyperpycnal flow refers to a high-density flow that forms due to estuarine fluid with a higher density than that of the surrounding water moving along the bottom of the basin[6–7]. In addition to ice melting, dam bursting, reservoir discharge, volcanic eruptions and other events, hyperpycnal flow is mostly triggered by seasonal floods[7]. A fluvial flood carrying massive sediments with greater density than that of the water body in the basin can flow for long distances along the basin bottom without being strongly affected by buoyancy[5].

In 1953, Bates[8] discovered this kind of flow and defined it as hyperpycnal flow. However, hyperpycnal flow was only highly valued and acknowledged by academics after the concept of hyperpycnal flow was re-defined in 1995 by Mulder and Syvitski et al.[9] Over the past two decades, the formation conditions, sedimentary characteristics and hydrocarbon exploration value of hyperpycnal flow have been some of the most active and popular topics of research in the field of deepwater sedimentation. In 2008, the American Association of Petroleum Geologists (AAPG) convened the Herderberg meeting in Argentina to discuss hyperpycnal flows and, specifically, hyperpycnites; later, AAPG published a special issue on this meeting in 2011[10]. The establishment of the theory of hyperpycnal flow marked new progress in deepwater sedimentological theory. Mulder et al.[5] strictly distinguished

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turbidites formed by extrinsic factors from hyperpycnal flow caused by non-excited floods and proposed that a deepwater sandbody could be formed by a continuous source-sink system, whereas hyperpycnal flow triggered by a fluvial flood might be a more ubiquitous and important deepwater geological agent. This distinction fundamentally changed the traditional understanding of the formation mechanism of deepwater sandbodies. Flood-generated hyperpycnal flows frequently occur in deepwater environments[9–11], giving rise to large-scale submarine (or sublacustrine) channel-fan complexes that usually form in the centers of basins[12–19]. The deposits formed by hyperpycnal flow are called hyperpycnites, and they represent the products of bed-load and suspension-load transportation mechanisms. The typical sedimentary features of a hyperpycnite include a coarsening-upward lower sequence and a fining-upward upper sequence appearing in pairs, indicating that the flood first strengthens and then weakens[5]. Because they contain large-scale sedimentary structures of flow genesis but do not contain soft-sedimentary deformation structures, hyperpycnites apparently differ from mass transport depositions (MTDs) and classical turbidites in terms of their formation mechanisms, sedimentary series and sedimentary characteristics[5–7].

In recent years, the exploration of deepwater sandbodies in continental basins of China has achieved several breakthroughs[20–22]. As for the study of the causes of deepwater sandbodies, there are new points such as landslide and mass transportation[23–25], sandy debris flow[26–28], hyperpycnal flow[29–30] and deepwater bottom current[31], which greatly enrich deepwater sedimentary theory of continental basins in China. Recently, some researchers discovered hyperpycnites in the Ordos and Bohai Bay basins[29–30], but little research has been performed on the flooding genesis of hyperpycnal flow and hyperpycnites. Therefore, here, using data from 15 exploration wells and 2 200-km^2 high-resolution three-dimensional seismic data, we re-examine the deepwater sandbodies of the first member of Cretaceous Nenjiang Formation in the lacustrine center of the Qijia-Gulong area in the Songliao Basin (SB) by analyzing their seismic sedimentology and their sedimentary structures and sequences in order to better understand and locate large-scale, high-quality deepwater reservoirs in the centers of lacustrine basins.

1. Sedimentary background

The Songliao Basin is a Mesozoic-Cenozoic large-scale superimposed sedimentary basin with a duplex structure in Eastern China[32–34]. Paleozoic Carboniferous-Permian metamorphic rocks and granites constitute the basement of the basin, and its sedimentary formations include those deposited during the Mesozoic (Jurassic and Cretaceous) and the Cenozoic (Tertiary and Quaternary).

The Cretaceous is the most important sedimentary formation in the basin. From bottom to top, the Lower Cretaceous strata include the Huoshiling Formation (K_1h), Shahezi Formation (K_1sh), Yingcheng Formation (K_1y), Denglouku Formation (K_1d) and Quantou Formation (K_1h); from bottom to top, the Upper Cretaceous strata comprise the Qingshankou Formation (K_2qn), Yaojia Formation (K_2y), Nenjiang Formation (K_2n), Sifangtai Formation (K_2s), and Mingshui Formation (K_2m). Based on the tectonic and geological characteristics of the depression of the basin, as well as the nature and burial depth of the basement and deep structures, the basin has been divided into five first-order structural units, namely, the central depression zone, the southeast uplift zone, the northern plunging zone, the western slope zone and the southwest uplift zone. In addition, the Qigu-Gulong Sag is located in the central depression zone.

The depositional period of the Nenjiang Formation was an important period in the development of the basin, which occurred at the end of the development of the intra-continental depression. During the depositional period of the first and second members of the Nenjiang Formation, large-scale subsidence and transgression occurred in the SB, causing the rapid expansion of the lacustrine area. Therefore, a vaster lacustrine basin was formed than that which formed during the depositional period of the Qingshankou Formation. The sedimentary fillings of this period mainly comprise mudstone in semi-deep to deep lacustrine facies. During the depositional period of the Nen 3 Member, due to the shrinking of the lacustrine area, an obvious regression sedimentary sequence formed; in this sequence, the delta is the major sedimentary type, especially the highly constructive delta of northern provenance that gradually prograded toward the south, reaching most parts of the basin[34].

The study area is located in the northern region of the Qijia-Gulong depression, where the Nen 1 Member, which is 0–100 m thick, mainly comprises black, gray-black mudstone interbedded with layers of sandstone and oil shale. During the depositional period of the Nen 1 Member, the northern water system was extremely developed, while the western, southern and eastern water systems were small in scale. The lacustrine facies was the main sedimentary filling type, and the sedimentary facies were dominated by delta and lacustrine facies (Fig. 1).

2. Sublacustrine channel-fan complex

The sublacustrine channel-fan complex in the Nen 1 Member discovered in the study area is located in the deepwater area of the northern prodelta. Seismic sedimentology has revealed that the delta front consists of three lobes that each have a birdfoot shape, in which dendritic channels are very clear (Fig. 2).

The sublacustrine channels extend from north to south, and some of the channels extend over a straight distance of more than 80 km, with a width of 100–900 m. These channels are characterized by multiple periods, long transportation distances, gradual decreases in width, and frequent migration. The channels can be divided into two types, i.e., straight and meandering channels. The sublacustrine fans at the ends of the channels are extremely developed, with a maximum area of 20 km^2.

Based on differences in their source-sink systems, the straight channels (Sc), meandering channels (Mc) and sub-