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Research paper

Reservoir quality variations within a sinuous deep water channel system in the Niger Delta Basin, offshore West Africa

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ABSTRACT

Submarine fan channel reservoirs exhibit strong heterogeneity not only on channel architecture but also on the qualities of reservoirs, which can exert direct control over the fluid flow and remaining oil distribution during oilfield development. However, the distribution of the variations in the reservoir quality within submarine fan channel systems is poorly understood. This paper, which takes the submarine fan channel reservoirs of the X oilfield in the Niger Delta Basin as an example, aims to study the variations in reservoir qualities and the controlling mechanisms within a sinuous deep-water channel system. The studies are based on the integration of core analysis, well-logging interpretation, seismic inversion and interpretation constrained by channel architecture.

The results show that variations in the reservoir quality within a sinuous deep-water channel system are primarily controlled by rock texture, lithofacies (association) and channel architecture under the circumstance of weak diagenesis. (1) The grain sorting and clay content mainly control the reservoir's porosity and permeability, respectively, while the relationship between grain size and the reservoir's properties is complicated because of the strong heterogeneity in the rock textures for different lithofacies. Cross-laminated fine sandstones have the highest porosity because of their good sorting, while massive medium to coarse sandstones have the highest permeability because of their low clay content. (2) Channel fillings are divided into four types (Type I – Type IV), which bear different reservoir qualities according to the lithofacies associations. Within a complete channel system, the channel fill types evolve progressively upward as the dominant gravity flow types evolve, which leads to the vertical differential distribution of porosity and permeability. (3) The relatively high porosity-permeability zones in the plane of a channel belt exhibit two patterns: multiple lenticular strips and single lenticular strips, which are controlled by the channel's architecture.

1. Introduction

Since the 1990s, submarine fan reservoirs have gradually become the focus of oil and gas exploration and development for the enormous potential of oil and gas resources (Mansurbeg et al., 2008). As the exploration of deep water resources progressed, great breakthroughs have been made in the Cambus Basin, Niger Delta Basin, Mexico Bay Basin and South China Sea Basin (Bruhn and Walker, 1997; Li et al., 2013; Mayall et al., 2006; McCaffrey and Kneller, 2001; Weimer and Link, 1991). In recent years, a large number of deep water oil-gas fields have been found in the Niger Delta Basin offshore West Africa, proving the enormous potential of deep water resources (Gao, 2007; Lin et al., 2013; Lonergan et al., 2013; Navarre et al., 2002; Seranne and Anka, 2005; Wang and Lü, 2009; Yu et al., 2012). However, as the deep water oilfields have been developed, many problems, such as uneven fluid flow and a disparity between injection and production, have been gradually exposed. These problems reflect that deep water reservoirs, especially turbidite channel reservoirs, are strongly heterogeneous, exerting important controls on the fluid flow and distribution of the remaining oil. Therefore, it is crucial for the adjustment of development schemes and the potential tapping of

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remaining oil to study the reservoir's heterogeneity within turbidite channel systems.

Deep water reservoir heterogeneity refers to the heterogeneity of both architecture and reservoir quality. Numerous results have been achieved for the former. Scholars have achieved deep and systematic understanding in terms of architecture hierarchies, channel migration patterns, superimposed sand body styles, scale, flow barriers, connectivity, etc. (Abreu et al., 2003; Beaubouef, 2004; Clark and Pickering, 1996a,b; Deptuck et al., 2003; Kolla et al., 2001; Labourdette, 2007, 2009; Posamentier, 2003; Prather, 2003; Slatt, 2000; Sweet and Sumpter, 2007; Weimer and Slatt, 2004; Wynn et al., 2007). In contrast, reservoir quality involves both porosity and permeability, which are controlled by both sedimentary and diagenetic factors (Ebdon et al., 1995; Johnson and Fisher, 1998; Schmid et al., 2004; Sun et al., 2007). Until now, a large amount of research on reservoir quality in continental and shallow water environments (e.g., detrital environments such as fluvial rivers, alluvial fans and deltas, and carbonate environments such as platforms and reef flats) has been carried out. In addition, a large amount of achievements have been made regarding sedimentary factors (rock texture, lithofacies, depositional facies and sedimentary sequences), diagenetic factors (compaction, cementation, and dissolution), and structural factors (faults and fractures) (Beavington-Penney et al., 2008; Hammer et al., 2010; Henares et al., 2014; Islam, 2009; Jeanne et al., 2012; Khidir and Catuneanu, 2010; Koehrer et al., 2010; Neilson and Oxtoby, 2008; Poursoltani and Gibling, 2011; Stimac et al., 2004; Sun et al., 2007; Taghavi et al., 2006; Vincent et al., 2010; Yangquan et al., 2005). However, research on reservoir quality for deep water reservoirs is relatively rare, and existing results mainly involve the following two aspects:

(1) Control of sedimentary factors on the reservoir quality. Submarine fan reservoirs develop complex types of lithofacies (association) and architectural elements. Using cores, well logging and outcrops, scholars have studied variations in reservoir quality for different lithofacies (association) and depositional facies (Brunt and McCaffrey, 2007; Lien et al., 2006; Mayall et al., 2006; Rotimi et al., 2014), which are mainly controlled by different rock textures (grain size, sorting, clay content, etc). Lien et al. (2006) noted that the grain size and total clay content have a major influence on the reservoir quality. In addition, sandstones with larger grain size and lower clay content have higher porosity and permeability for a given depth than finer grained, more clay-rich sandstones. However, Li et al. (2014) noted that porosity and permeability show no good correlation to the grain size and sorting.

(2) Control of diagenesis on the reservoir quality. Variations in reservoir quality for deep water reservoirs have been studied mostly in terms of diagenesis, involving the controls of compaction, authigenic minerals, and dissolution on turbidite reservoir quality (Li et al., 2014; Mansurbeg et al., 2008, 2012; Morad et al., 2000; Stonecipher, 2000; Shirley, 2008; Worden et al., 1997, 2000). Worden et al. (1997, 2000) noted that the compaction plays significant controls on reducing the porosity and permeability when the ductile grain content is much higher. Morad et al. (2000) noted the authigenic minerals, especially the silicate, clay and calcite cements, can reduce the physical properties dramatically when the cement content is much higher. And Mansurbeg et al. (2008, 2012) noted that the dissolution can enhance the reservoir quality greatly when the abundant unstable minerals (e.g., volcanic rock fragment, K-feldspar, calcite cements) are subjected to the modification of meteoric water or organic acid.

However, some aspects still need to be explored in depth: (1) Control of rock texture on the differential distribution of porosity and permeability for different turbidite lithofacies; (2) Control of the evolution of channel-fill types on the vertical differential distribution of porosity and permeability within a complete channel system; and (3) Control of the reservoir's architecture on the planar distribution of porosity and permeability in turbidite channel sand bodies.

Taking the submarine fan channel reservoirs of the X oilfield in the Niger Delta Basin (which bears rich core analysis, well logging and high-quality seismic data) as an example, this paper aims to study the variations in the reservoir quality of different turbidite lithofacies and the spatially differential distribution of reservoir quality within a sinuous deep water channel system and explore the controlling mechanisms of sedimentary factors on the variations in the reservoir quality.

2. Geological setting

2.1. Position and regional tectonic setting

The Niger Delta Basin is located in the gulf of Guinea in West Africa. The study area lies in the deep water zone in the southern part of the Niger Delta Basin, approximately 20 km from the northern port of Harcourt and with an approximate area of 1200 km^2. The present water depth of the study area is approximately 1300–1700 m, belonging to the lower continental slope of the basin floor setting (Fig. 1A).

Influenced by the gravity of the continental margin, the structural style of the Niger Delta Basin shows magnificent zonation, developing stretched, transitional, and crushed zones successively from north to south. These three structural zones are connected by the detached surface of deep water overpressured mudstone. The study area is located in the transitional zone of the Niger Delta Basin with a mostly developed mud diaper (Fig. 1B).

2.2. Formation and deposition

The Niger Delta Basin contains Cretaceous, Paleogene, Neogene and Quaternary formations progressing upward. Since the Paleocene, the Niger Delta Basin had entered into a stage of large scale sea-level fall and seaward delta deposition in the shallow water zone, resulting in a submarine fan deposition that developed largely in a deep water setting. According to the lithology, the stratigraphic formations since the Paleocene include the Akata formation, Agbada formation and Benin formation (diachronous formation) from the bottom up. The Akata formation, which contains thick marine mudstone rich in organic matter, is the main source bed of study area, with its main body thicker than 6 km. The Agbada formation contains fluvial and marine sands successively from north to south with thicknesses between 3 and 4.5 km. The Benin formation, whose lithology is mainly sand-conglomerate, contains fluvial and swamp deposition with thicknesses from 1 to 2 km. The Benin formation is connected with the underlying Agbada formation through a parallel unconformity (Corredor et al., 2005; Gao, 2007; Lonergan et al., 2013) (Fig. 2). The study area belongs to the Agbada formation from the Miocene, containing both submarine fan channels and lobe deposition (Navarre et al., 2002; Seranne and Anka, 2005; Wang and Lü, 2009; Yu et al., 2012). This paper mainly focuses on the submarine fan channel reservoirs.

2.3. Channel's architecture in the target interval

Two high sinuous channel systems, namely western channel system and eastern channel system, developed in the target interval (Fig. 3). The western channel system, which includes two branches (namely west branch and east branch) (Fig. 3A), developed earlier than the eastern channel system (Fig. 3B). The east