Du et al. Journal of Palaeogeography (2020) 9:25
https://doi.org/10.1186/s42501-020-00074-w

Journal of Palaeogeography

ORIGINAL ARTICLE Open Access

A near-shore clastic-carbonate mixing mode in a continental rift basin (early Oligocene, eastern Shijiutuo Uplift, Bohai Bay Basin, China): sedimentology, reservoir characteristics and exploration practice

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Abstract

A comprehensive sedimentary and reservoir analysis was conducted based on seismic, well logging, core and relative test data, taking Members 1 and 2 of Shahejie Formation of the early Oligocene in the steep slope belt, eastern Shijiutuo Uplift (STU), Bohai Bay Basin (BBB) as a case. The study indicates that a near-shore mixed fan deposit formed in the study area and developed characteristics and pattern of a high-quality reservoir. The mixed clastic-carbonate rocks constitute Members 1 and 2 of Shahejie Formation which developed along the steep slope belt and is named as a near-shore mixed fan. The mixed fan of the study area is mainly composed of microfacies of proximal channel, mixed deposited channel, mixed clastic beach, mixed bioclastic (grain) beach, with vertical multi-stage superimposition feature, and basically a similar shape as modern near-shore fans. It constitutes a new depositional type developing in the steep slope belt of a characteristic and complex lacustrine rift basin in the study area. This mixed fan in the steep slope of eastern STU is controlled by comprehensive factors including tectonics, clastic material supply, climate, palaeogeomorphology and hydrodynamic conditions. The reservoir quality of Members 1 and 2 of Shahejie Formation of eastern STU is, however, actually controlled by the sedimentary environment and diagenesis processes. Coarse-grained mixed rocks of near-shore fans, rich in bioclastics, can form excellent reservoirs, characterized by resistance to compaction, easy to dissolution, little influenced by burial depth and high production of oil and gas, which enable them become key exploration targets of medium-deep strata of BBB. Analyses of high-quality reservoir, its controlling factors and the oil and gas exploration implications of the near-shore mixed fan developing in the study area give a deeper insight into discussions of the same type of mixed rocks of other lacustrine rift basins worldwide.

Keywords: Early Oligocene, eastern Shijiutuo Uplift, Bohai Bay Basin, Continental rift basin, Mixed carbonate-siliciclastic fan, High-quality reservoirs

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1 Introduction

Terrigenous clastics and carbonate rocks are separated as two systems in traditional sedimentary researches, which consider that infilling of terrestrial materials will inhibit deposition of carbonate rocks and therefore clastic rocks and carbonate rocks deposit in an opposite tendency. In most cases, these two types of sediments will not mix with each other which has led to insufficient attention being paid to mixed sediments (also known as mixosedimentite in China). Mixed deposition, however, has been testified as a very common phenomenon in nature (e.g. Bruckner 1953; Mount 1984, 1985; Dorsey and Kidwell 1999). Mixed deposition, belonging to a transitional type between carbonate deposition and terrestrial clastic deposition, refers to a special mixing deposition of terrestrial clastics and carbonate grains or marls (e.g. Bruckner 1953; Maxwell and Swinchatt 1970; Button and Vos 1977; Campbell 2005; Dix & Dix and Parras 2014). In a broad sense, it refers to the interbedding and interlayering in a strata profile due to the frequently alternating of terrestrial clastics and carbonate rock deposits, i.e., mixed deposited series. In a narrow sense, mixed deposition refers to the compositional mixing of terrestrial clastics and carbonate rocks, i.e., the mixture of component and texture forming the typical product of mixed sediments.

Researches on mixed sediment have been carried out since this phenomenon has been noticed in the 1950s (e.g. Bruckner 1953), and studies of mixed sediment have been gradually increasing over the last half-century. Researchers identified this special depositional phenomenon in different sedimentary environments including continental and marine setting and some achievements have been acquired (e.g. Mount 1984, 1985; Dorsey and Kidwell 1999; Brooks et al. 2003; Coffey and Read 2004; Longhitano et al. 2010; Morsilli et al. 2012; Anan 2014; Sarkar et al. 2014; Chiarella et al. 2017; Rivera et al. 2018; Moscardelli et al. 2019). Research processes of mixed sediments generally include i) the budding stage (before 1980s) (e.g. Bruckner 1953; Maxwell and Swinchatt 1970; Button and Vos 1977), ii) concept stage (division and origin mechanism study stage (1980s–1990s)) (e.g. Mount 1984, 1985; Yose and Heller 1989; Yang and Sha 1990), iii) main controlling factor and sedimentary pattern study stage (1990s-early twenty-first century) (e.g. Sanders and Pons 1999) and iv) comprehensive developing stage (early twenty-first century-present) (e.g. Brooks et al. 2003; Coffey and Read 2004; García-Hidalgo et al. 2007; Longhitano et al. 2010; Mata and Bottjer 2011; Morsilli et al. 2012; Anan 2014; Chiarella et al. 2017; Rivera et al. 2018; Moscardelli et al. 2019). Since the 1990s, detailed analyses have been made on mixed sediment in different areas in China (e.g. Yang and Sha 1990; Wang et al. 2001). These studies mainly focus on mixing depositional mechanism, main controlling factors of mixed sediment (event of sea level change, tectonic rise and fall, storm flow and turbidite flow and climate change). Different sedimentary patterns of mixed deposition in different sedimentary environments were established. Meanwhile, the concept of sequence stratigraphy was used to analyze the sedimentary pattern of mixed sediment (e.g. Sanders and Pons 1999). Since year 2000, more comprehensive studies of mixed sediment have been carried out. Much more attention has been paid to the developing process of mixed sediment within a sequence stratigraphic framework (e.g. Brooks et al. 2003; Coffey and Read 2004; García-Hidalgo et al. 2007; Longhitano et al. 2010; Morsilli et al. 2012; Anan 2014; Chiarella et al. 2017; Rivera et al. 2018; Moscardelli et al. 2019). Furthermore, the study of sedimentary environments of mixed sediment is no longer restricted to marine or marine-continental transitional facies, with attention being paid now to continental environments as well including back-arc foreland basin (e.g. Li et al. 1997; Sanders and Hofling 2000), orogenic belt (e.g. Parcell and Williams 2005). Detailed discussions regarding the main controlling factors of mixed sediment concluded that more comprehensive factors such as monsoon and climate are involved (John et al. 2003), as well as sea level change, tectonic factors etc. Chinese scholars began to pay attention to mixed sediment of continental lacustrine basins, which broadened its study domain (e.g. Jiang and Sha 1995; Luo et al. 2004; Dong et al. 2007; Zhang and Si 2007; Dong et al. 2011; Feng et al. 2011; Song et al. 2013).

The study of mixed sediments transfers from theory to practice, especially the study of mixed sediment reservoir, which has attracted a lot of interest in oil and gas implications of mixed sediments (e.g. Monstad 2000; Ma and Liu 2003; Moissette et al. 2010; Chiarella et al. 2017; Abdelkarim et al. 2019; Moscardelli et al. 2019; Leila et al. 2020).

However, there are apparently geographical limitations in the study of the depositional process and mechanism pattern of mixed sediments and relevant patterns are difficult to apply to a broad range. For example, mixed sediments of terrestrial clastics and carbonate rocks were found in the Bohai offshore area, which is a special case of complex continental lacustrine rift basins. Exploration indicates that this type of mixed sediments with thick reservoir, good physical property and high oil production ability has important implications, but its mechanism is difficult to be interpreted using patterns proposed by previous researchers. Further study is necessary regarding the mechanism of the thick bed, high production-type reservoir of this complex continental rift basin.

This study, in combination with drilling and logging, core observation and laboratory analysis data, taking

Members 1 and 2 of the Shahejie Formation of eastern steep slope of STU, BBB as an example, investigates the deposition and reservoir characteristics of the mixed sediments reservoir and discusses the sedimentary origin and main controlling factors of a high-quality reservoir. This study aims at providing a deeper insight into oil and gas exploration and drilling well deployment.

2 Geological setting

The Bohai Bay Basin, located in the eastern North China Plate, is a Meso-Cenozoic superimposed rift basin dominated by the Cenozoic and developed on the base of Paleozoic North China Craton. It is surrounded by Yanshan fold uplifting belt, Liaodong-Jiaodong uplifting area, Luxi Uplift and Taihangshan Uplift, while inside the basin the first-order tectonic units include Liaohe Depression, Bozhong Depression, Changwei Depression, Jiyang Depression, Huanghua Depression, Linqing Depression, Jizhong Depression and Cangxian Uplift, Xingheng Uplift, Chengning Uplift and Neihuang Uplift (Fig. 1) (Tian et al. 2009; Zhou et al. 2010). The basement rocks of the BBB are composed of Archean Taishan Group and Paleoproterozoic orogenic granite, and the cap rock comprises the Neoproterozoic and Paleozoic platform deposits succeeded by the fold-rift basin deposits of the Meso-Cenozoic. The Mesozoic Triassic deposit was only found in Jizhong Depression, Linqing Depression and Huanghua Depression in the western basin; the Middle-Lower Jurassic expanded to Jiyang Depression; the Upper Jurassic-Lower Cretaceous was found in the entire basin and the Upper Cretaceous only occurred in the western basin (Tian et al. 2009; Zhou et al. 2010). The Cenozoic, dominated by lacustrine clastics, was deposited basin-wide and developed Kongdian (E1-2 k, 65 ~ 50.5 Ma), Shahejie (E2s, 50.5 ~ 34 Ma), Dongying (E3d, 34 ~ 23 Ma), Guantao (N2g, 16 ~ 5.3 Ma), Minghuazhen (N1m, 5.3 ~ 1.8 Ma) and Pingyuan (Qp, 1.8 Ma ~ present) formations respectively. The basin depositional center shifted from around the basin to the BBB (e.g. Glider et al. 1999; Hsiao et al. 2004; Schellart and Lister 2005; Liu et al. 2015, 2017, 2020).

The Shijiutuo Uplift (STU) is tectonically located in the northeastern part of the BBB, and is bounded by Qinnan Sag in the north, Bozhong Sag in the south, Nanpu Sag in the west connecting with Bogezhuang Structural High, pitching towards Bozhong Sag in the eastern part and opposite to Liaozhong Sag. The total area of STU is about 1350 km^2, extending in approximate E-W direction (Fig. 1). The Cenozoic of the structural high area mainly consists of Neogene and Quaternary, and the Cenozoic of the sag area is complete, developing the Paleogene Kongdian, Shahejie and Dongying formations, the Neogene Guantao and Minghuazhen formations in an ascending order (Fig. 2) (Liu et al. 2017, 2018, 2020; Tian et al. 2019). Sequence deposition of the Paleogene is characterized by alluvial facies developing in an early period, lacustrine facies in the middle period and fluvial facies in the late period. A unit of gypsum developed in the early-middle period of Member 4 of Shahejie Formation indicating a high-salinity lacustrine basin setting, whereas normal lacustrine facies developed in the later period. During the main rifting period of the basin, a set of thick deep lake-semi-deep lake mudstones developed with local near-source coarse clastics as important hydrocarbon source rocks. A fan delta dominated the early period of Members 1 and 2 of Shahejie Formation and shallow lacustrine dominated the late period, with locally developed carbonate rocks. Semi-deep thick mudstone dominated Member 3 of Dongying Formation with locally developed delta. A large-scale delta developed in Member 2 of Dongying Formation. The lake area shrank quickly during the deposition of Member 1 of Dongying Formation with development of delta plain and fluvial facies (Liu et al. 2017, 2018, 2020).

This study involves the eastern part of STU (also called 428 Structural High) and its adjacent area which is surrounded by Qinnan Sag and Bozhong Sag respectively in a long strip E-W direction. It has excellent hydrocarbon accumulation prospects with abundant oil source and good transportation conditions in a resting mountain and facing sag background. Earlier workers considered that the sand-rich reservoir did not develop in the Paleogene of this area which restricted exploration progress. Focused researches of sedimentary systems guided by source-to-sink system theory have been conducted in recent years, and the near-source, sand-rich reservoir of Members 1 and 2 of Shahejie Formation and Dongying Formation was gradually identified and became important exploration targets. Many new oil and gas fields were found and hydrocarbon accumulations found in the study area are mainly from reservoir of Members 1 and 2 of Shahejie Formation.

3 Data and methods

The data include: nine drilling wells, representing in total 67.92 m of cumulative core length from 4 drilling wells, 409 slices for analysis, other laboratory test analysis (1836 samples, analysis including physical property, grain type, scanning electron microscopy, inclusion, elements, cathodoluminescence, electronic probe and whole-rock) and a 3-D seismic survey. The 3-D seismic data, covering 800 km^2 area, have a 2-m vertical sampling rate and were processed to zero phase. It was displayed as normal polarity with a dominant frequency of~25 Hz, with a vertical resolution of about 10–15 m.

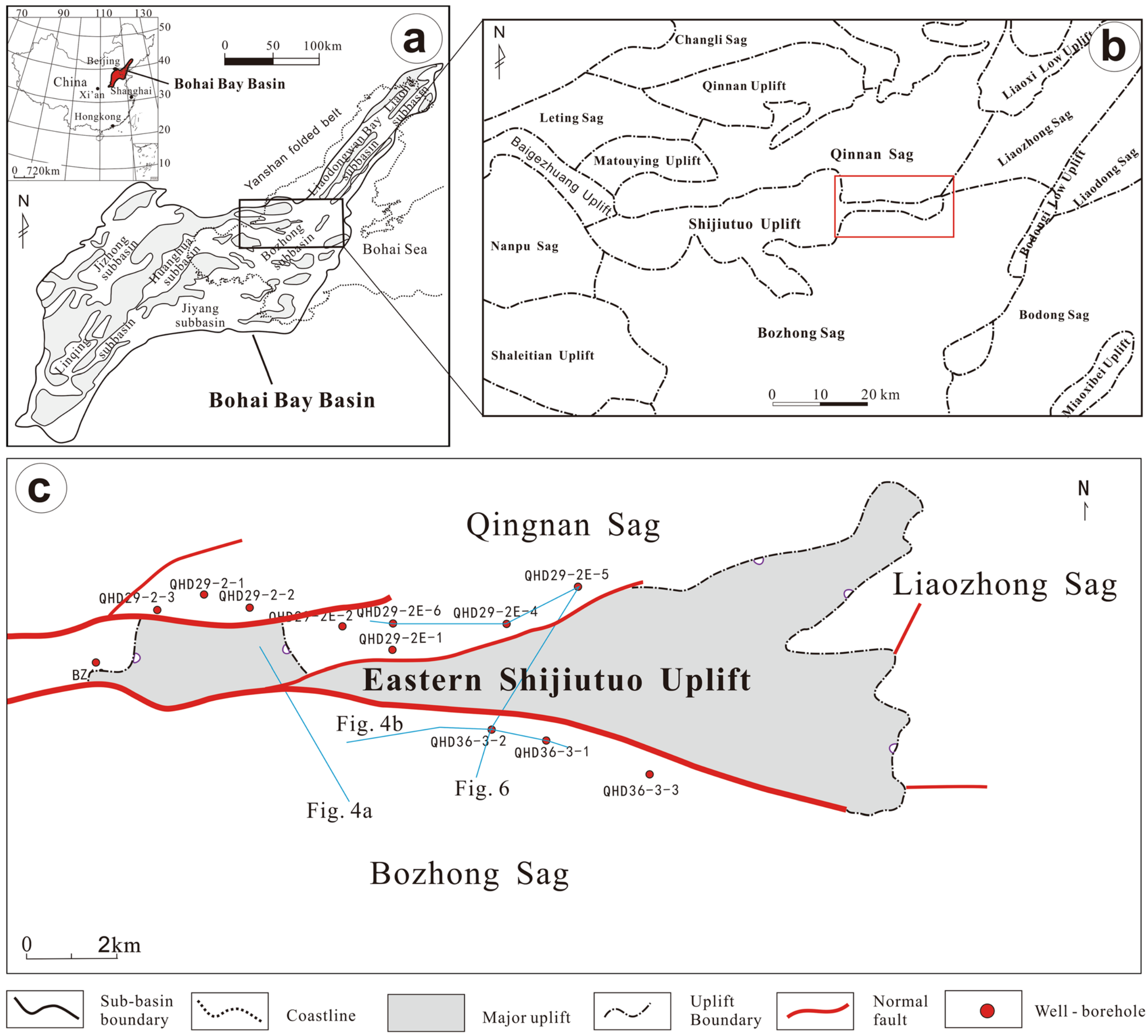

Fig. 1 Tectonic location map of the study area. a-Geographic location of the BBB and sub-basin divisions (from Liu et al. 2017; Liu et al. 2020). Black rectangle is the range of STU and its neighbouring area; The inset map of China is referring the standard map available on the official website of Ministry of Natural Resources of China: http://bzdt.ch.mnr.gov.cn/); b-Tectonic unit subdivision and planar distribution of STU and its neighbouring area (from Liu et al. 2017). Red rectangle is the area of this study; c-Tectonic characteristics of the eastern part of STU during Eocene-Members 1 and 2 of Shahejie Formation period

Drilling well and well logging data were combined to establish the regional stratigraphic framework and seismic stratigraphic interpretation is carried out through synthetic seismogram calibration providing a basis for regional sedimentary facies analysis and prediction of depositional system distribution. Slice and geochemistry data, as supplementary evidence, were mainly used for analyzing sedimentary environments and sedimentary facies.

4 Typical characteristics of mixed sediments

Mixed sediments of the study area are dominated by terrigenous clastics, with content of 40%–70% and abundant bioclastic and oolitic carbonate grains. Controlled by the active boundary fault, a single unit of mixed sediments has a thickness of 2–8 m and vertically developing as transgressive and aggradation successions. Stacking thickness is larger, rock types are complicated and characteristics of well logging facies and seismic facies are different compared to conventional clastic rocks and carbonate rocks.

4.1 Petrologic characteristics

Mixed sediments are complicated due to the special mixing depositional pattern. Some researches have been conducted regarding how to distinguish mixed

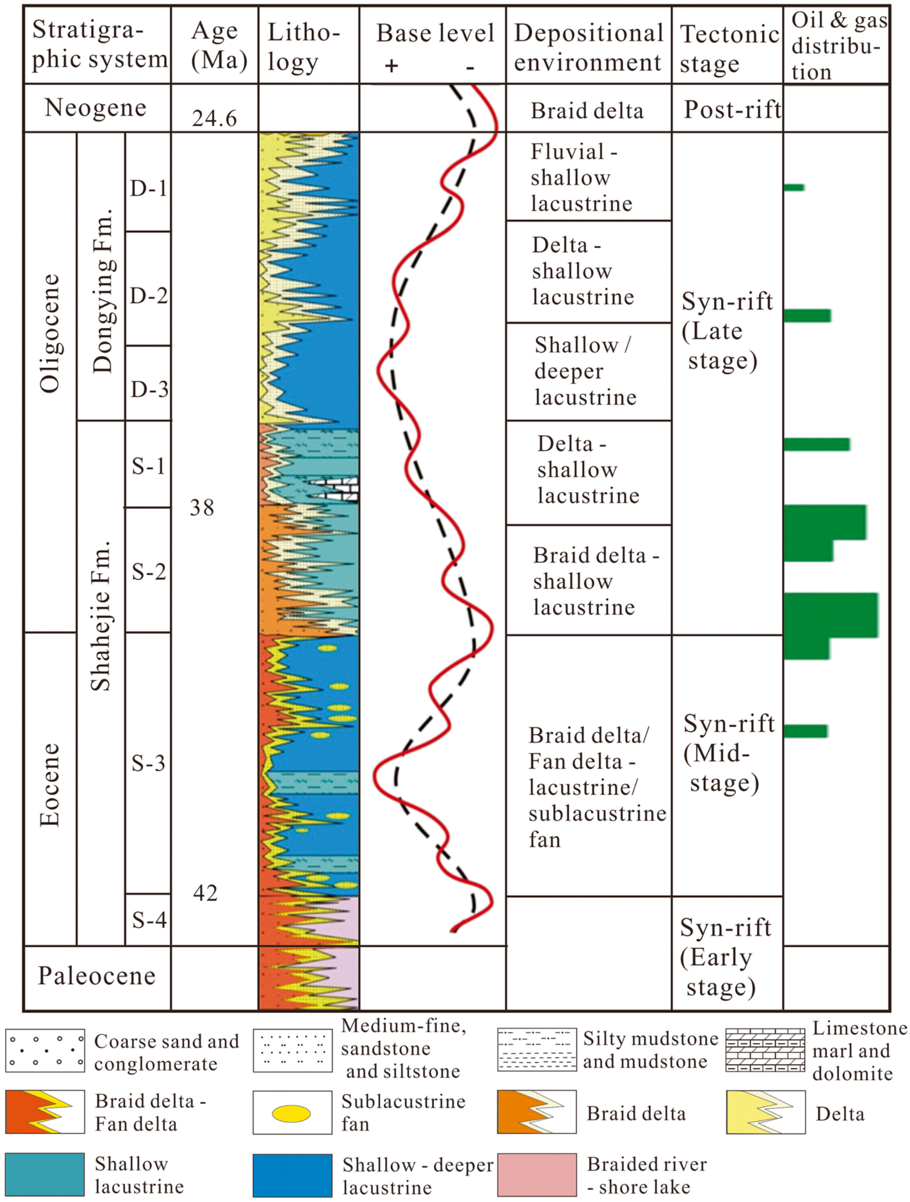

Fig. 2 Lithostratigraphy and sequences of the STU. The lithological data and interpretations are based mainly on a combination of data from the wells in the eastern part of STU. The tectonic stages and sedimentary environment are modified after Liu et al. (2017). Compilation of base-level curve is according to analysis of lithofacies associations, black dotted line indicating fluctuation of base level of the third-order sequence cycle and red solid line indicating base-level rise and fall of the fourth-order cycle. D-1 = Member 1 of the Dongying Fm.; D-2 = Member 2 of the Dongying Fm.; D-3 = Member 3 of the Dongying Fm.; S-1 = Member 1 of the Shahejie Fm.; S-2 = Member 2 of the Shahejie Fm.; S-3 = Member 3 of the Shahejie Fm.; S-4 = Member 4 of the Shahejie Fm.

sediments from normally deposited sedimentary rocks. However no unified classification criteria have been accepted yet (e.g. Yang and Sha 1990; Zhang 2000; Brooks et al. 2003; Coffey and Read 2004; García-Hidalgo et al. 2007; Anan 2014; Wang et al. 2014; Chiarella et al. 2017; Rivera et al. 2018; Moscardelli et al. 2019). In this investigation, we utilized a classification constituted by terrigenous clastics, biocarbonate grains and chemogenic carbonates as three components to reflect the original texture origins.

The steep slope belt of STU mainly developed mixed sediments dominated by externally sourced clastics with lithofacies of bioclastic-bearing sandy conglomerate. This lithofacies is of obvious gravel texture in macroscale (Fig. 3a) with the main component of fine gravel felsic grains or medium-fine gravel igneous debris, poor

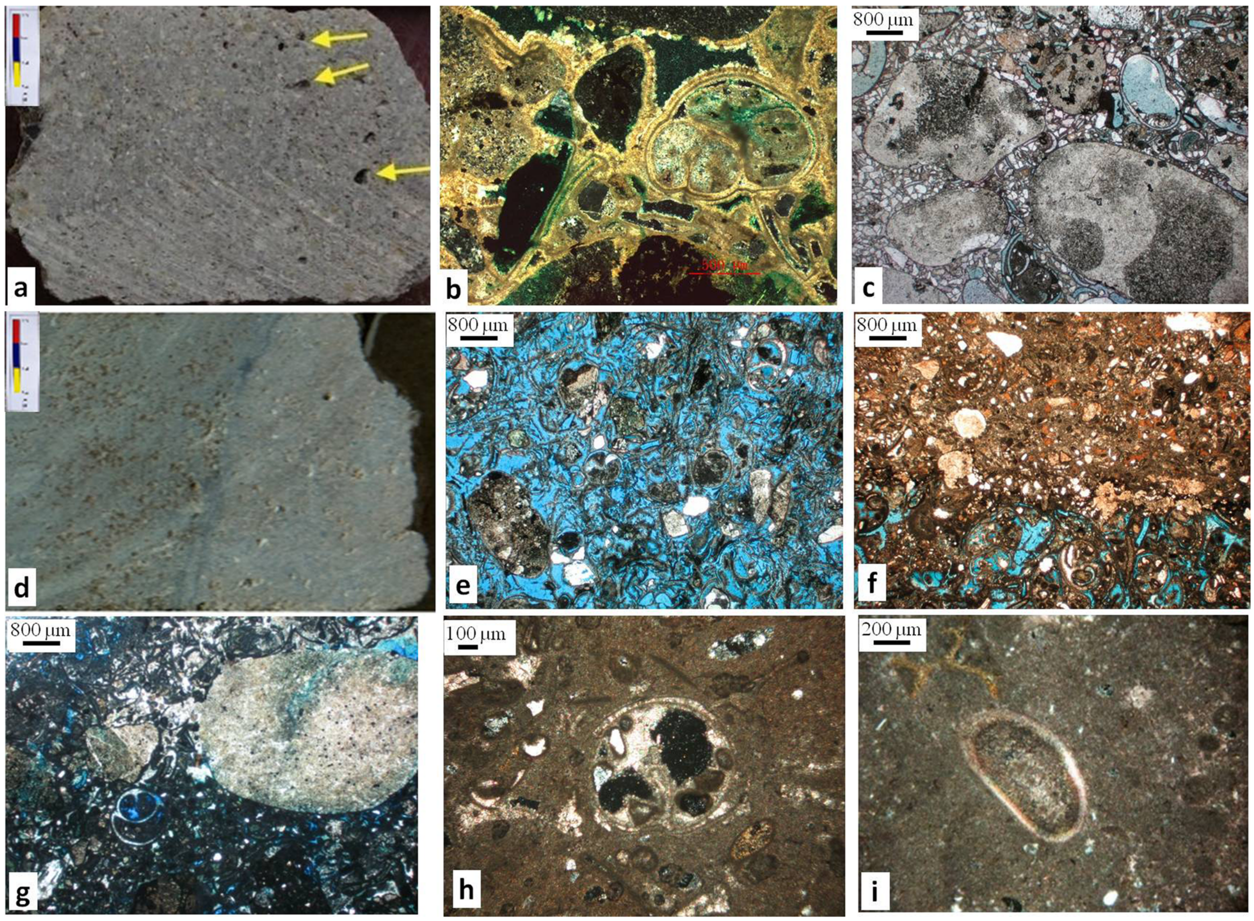

Fig. 3 The lithological characteristics of the mixed sediment lithofacies of Members 1 and 2 of Shahejie Formation, the steep slope belt, eastern STU. **a** and **d** Core photos, arrows in **a** are biological dissolution pores; **b**, **c**, **e**, **i** Photomicrographs, **b**-Cross-polarized light, **c**, **e** and **i**-Plane-polarized light. **a** Well QHD29-2E-5, 3386.14 m, core sample, sandy conglomerate. Biological dissolution pores can be found on the surface; **b** Well QHD29-2E-5, 3384.88 m, dolomitic grains bearing epidermis oolitic fine conglomerate, with complete gastropods fossils; **c** Well QHD36–3-2, 3771.96 m, bioclast-bearing sandy conglomerate; **d** Well QHD36–3-2, 3777.00 m, core specimen, bioclastic dolomite, developing biological cavity and bioclastic dissolution pores; **e** Well QHD36–3-2, 3765.16 m, terrestrial clastic bioclastic dolomite; **f** Well QHD36–3-2, 3776.94 m, quartz-bearing bioclastic dolomite; **g** Well QHD29-2E-5, 3358 m, epidermis oolitic bioclast-bearing dolomite; **h** Well QHD36–3-2, 3777.15 m, oolitic-bearing bioclastic micrite dolomite; **i** Well QHD29-2E-2, 3223.51 m, sandy micrite bearing dolomite

sorting and some degree of roundness. Well-rounded bioclasts are present among the grains. Micro-lithofacies indicate that bioclasts are dispersed among clastic grains and well preserved (Fig. 3b-c), which reflected a mixed deposition of near-source terrigenous clastics being transported quickly to the in situ organic bank.

Sandy bioclastic facies developed as a secondary type which was characterized by biological dissolution pores present in hand specimen and a few terrigenous clastics distributing among fossil shells (Fig. 3d). Microscopic investigation shows the domination of bioclastic composition with completely preserved fossils, complicated terrigenous clastics including both basaltic igneous debris and felsic grains dispersedly distributing among shells with relatively good sorting and roundness (Fig. 3e-f). This lithofacies was inferred as a mixed deposition with the in situ fossils when terrigenous clastics from other places were transported to the in situ organic bank (coquina) controlled by hydrodynamics.

Sand-bearing or bioclast-bearing micritic limestone lithofacies developed as well (Fig. 3h, g). Its main micro composition is chemical carbonate, which was produced as substrate and dominated by micrite. Other components include bioclasts and terrigenous clastics. Shells were relatively well preserved and a few terrigenous clastic grains, e.g., feldspar and quartz were dispersed throughout the substrate with poor sorting and general roundness. This lithofacies with micritic matrix reflects a relatively low-energy sedimentary environment.

4.2 Well logging characteristics

Mixed deposition is a special transitional type between clastic rock and carbonate rock, which forms mixed sediment with a complicated lithology and various complex well logging responses. Mixed sediments with different rock components are shown by obvious overlapping features in well logging responses and there are no obvious boundaries in well logging responses among different types of mixed sediments. Overall, mixed sediments are characterized by obviously high electrical resistivity, with high velocity (low acoustic time) compared to normal clastic rocks, due to the high content of carbonates. Meanwhile, there is usually an abrupt contact between mixed sediments and the underlying strata and a gradational contact between mixed sediments and the overlying strata. Well logging curves of the mixed sediment dominated by bioclastics are characterized by low GR, low density and high electrical resistivity and high velocity due to its high content of bioclasts (Fig. 5), good reservoir property and low density of skeletal particles; whereas well logging curves of mixed sediments dominated by terrigenous clastics, similar to conventional sandy conglomerates, are characterized by low GR, medium electrical resistivity, medium-high density, medium-high velocity due to the bioclastics and carbonates which obviously improved the reservoir property (Fig. 5).

4.3 Seismic reflection characteristics

Mixed sediment of the study area, belonging to a nearshore fan, was inferred to form in a special setting which was reconstructed by the environment after the formation of the fan. The fan that developed in an early period was not destroyed completely by later-period reconstruction and thus showed similar reflection characteristics on seismic profiles with an overall obvious wedge shape and locally obvious internal progradational texture (Fig. 4a). Mixed sediment of the study area, indicated by an amplitude obviously higher than peripheral normal deposition, is different from normal fan delta, which is possibly due to its high carbonate content, high density of the rock and an apparently different wave impedance, compared to the overlying normal lacustrine deposit. This was testified by the model forward result (Fig. 4b).

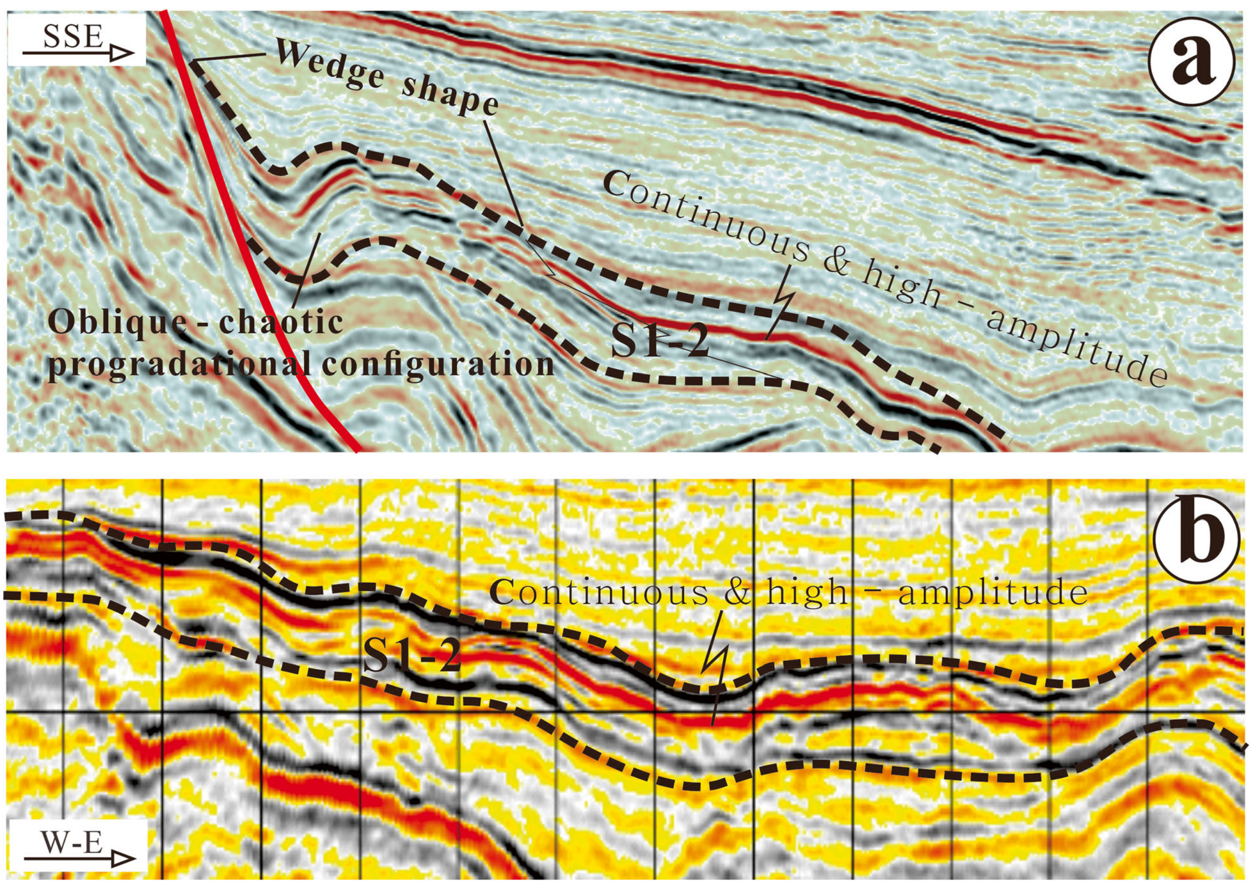

Fig. 4 Seismic reflection features of mixed deposition. **a**-Seismic reflection features parallel to the provenance direction. Obvious seismic forward reflection can be seen near basin synsedimentary fault, with medium-strong amplitude; **b**-Seismic reflection features vertical to the provenance direction. Obviously high continuity, high-amplitude reflection can be found. Location of seismic lines are shown in Fig. 1

5 Characteristics of depositional systems and origin patterns

This mixed deposition of terrigenous clastics and bioclastics with a fan delta shape developing in local provenance steep slope belt, along with fan delta, is named as near-shore mixed fan in this study. It has specific characteristics in depositional features and origin patterns.

5.1 Division and characteristics of depositional systems

Near-shore mixed fan is divided into near-shore mixed fan root, near-shore mid mixed fan and near-shore distal fan subfacies. Microfacies of proximal channel developed in mixed proximal fan, microfacies mixed channel, mixed clastic bank and mixed bioclastic (grain clastics) bank developed in near-shore mixed mid fan.

5.1.1 Near-shore mixed proximal fan

Near-shore mixed proximal fan subfacies, developed along the near-shore steep slope belt and controlled by the near-shore fan (fan delta) system, was dominated by proximal mixed channel microfacies which usually formed channel sandy conglomerates mainly composed of coarse-grained sandy conglomerates. Vertically it was characterized by fan delta plain distributary channel deposition almost without bioclastics. Roundness and sorting of sandy conglomerate was poor and thickness was large.

5.1.2 Near-shore mixed mid fan

Near-shore mixed mid fan, the main body of the entire mixed fan, developed in the front end of near-shore mixed proximal fan towards the lacustrine basin which is the most characteristic mixed deposition. Obviously influenced by the fan delta system, its terrigenous clastic content was high with locally developed bioclasts. Vertically a large set of mixed rock dominated by terrigenous clastics intercalated with thinner mixed rock dominated by bioclastics. Clastic particles with relatively poor roundness and sorting intercalating with bioclastics was the typical identification marker of mixed deposition. Near-shore mixed mid fan can be subdivided into microfacies of mixed channel, mixed grain bank and mixed bioclastic bank according to differences in lithofacies and sedimentary characters (Figs. 5 and 6).

Mixed channel microfacies, characterized by channel sandy conglomerate deposition vertically, shows normal bedding overall, dominated by low content of bioclastic sandy conglomerate and was dispersedly distributed among coarse-grained sandy conglomerates (Figs. 5 and Fig. 6a-f).

Mixed clastic bank microfacies was dominated by sandy grain limestone which was mainly composed of intraclast-like epidermis oolites mixing with coarse-grained sandy grains. The formation of oolite and its mixing with clastic grains reflected strong tidal reconstruction and vertically mixed grain bank developed as the intercalation in mixed channel sandy conglomerate (Figs. 5 and 6g-i).

Mixed bioclastic bank microfacies mainly developed in hiatus of fan delta deposition, with weak influence from provenance area, well developed fossils mixed with clastic grains which was resulted by wave action (Figs. 5 and 6j). It was thinner vertically and superimposed with other microfacies.

5.1.3 Near-shore mixed distal fan

Near-shore mixed distal fan subfacies developed in the front of mixed fan. Similar as fan delta front, clastics content was higher and carbonate grains like bioclasts were less with fine lithology and small thickness.

5.2 Distribution characteristics of near-shore mixed fan

5.2.1 Vertical sequence characteristics

Near-shore mixed fan of the study area concentrated in Members 1 and 2 of Shahejie Formation. From bottom to top, a normal lacustrine deposit association of mixed proximal fan, mixed mid fan and mixed distal fan (Fig. 7) developed, which indicated lake level rise and transgression of fan body as a whole and coincided with the regional depositional regularity of Members 1 and 2 of Shahejie Formation in BBB. The fan body mainly developed in a deep valley of the downthrown side of a fault during lowstand systems tract period. Only two drilling wells in the study area drilled it, reflecting a mixed proximal fan subfacies with lithology of mottled tuffaceous breccia or sandy conglomerate interbedded with brownish-red or greenish-grey mudstone of near-shore quick deposition. The mixed fan body developed widely during the transgressive systems tract period which was drilled by drilling wells of the study area. Sedimentary facies was dominated by mixed mid fan and different types of mixed lithofacies developed, and the reservoir property was good. The scale of the fan body obviously was reduced during the highstand systems tract period and mixed distal fan and normally deposited lacustrine mudstone were intersected by drilling wells.

5.2.2 Distribution characteristics in plan view

Depositional system distribution in plan view of the Members 1 and 2 of Shahejie Formation was compiled using drilling well and 3-D seismic data combining with forward model and sedimentary simulation results. The results indicated that two sub-uplifts occurred in the eastern part of STU, the various types of slope break belts formed by paleo-channels and steep slope belt developing there constituted a good passage system and

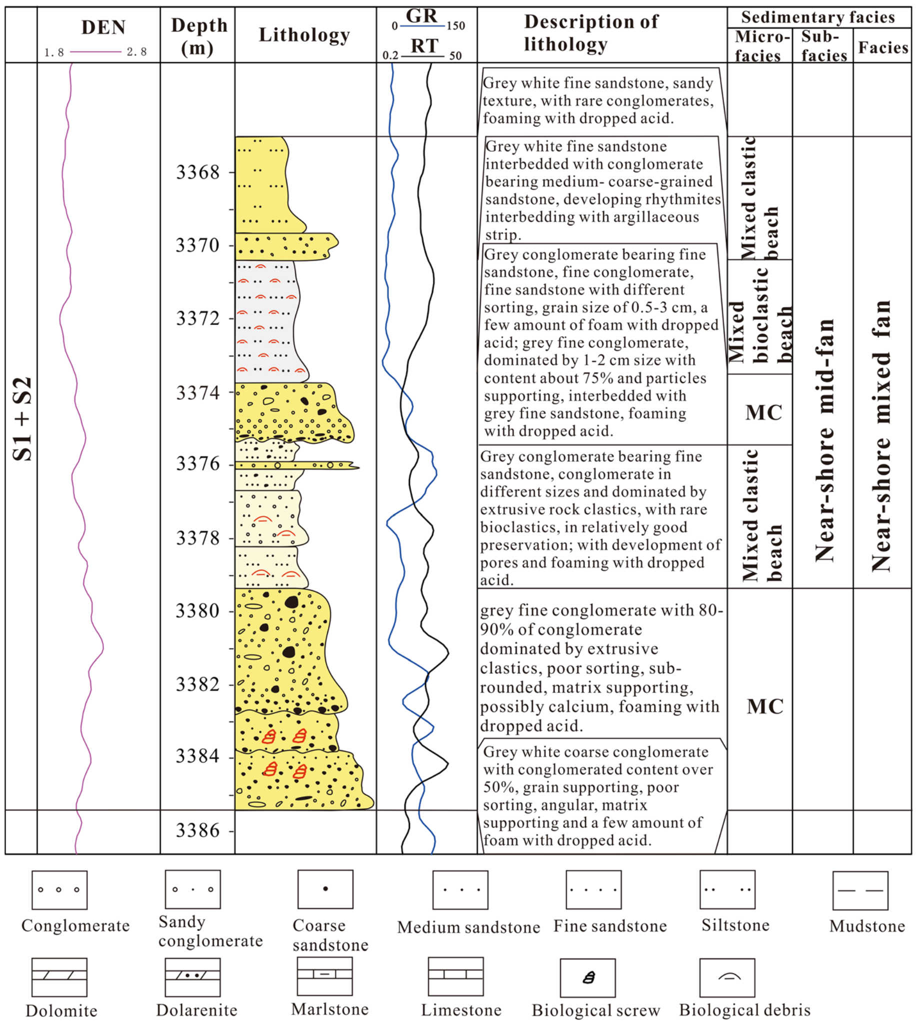

Fig. 5 Comprehensive column of core interval from Well QHD29-2E-5 of the eastern part of STU. Log signature shows an upward-fining, normal cycle character. MC–Channel of mid fan; S-1 = Member 1 of the Shahejie Fm., S-2 = Member 2 of the Shahejie Fm., DEN-density logging, GR-gamma logging, RT-medium electrical resistivity logging

mixed fans with near-shore steep slope fan delta background were formed in the downthrown sides of boundary faults on the south and north sides (Fig. 8). Mixed fans were of small scale in plan view, the area of a single fan was about 7–12 km^2 but was significantly different at different locations. The eastern sub-uplift, with a large provenance area, strong boundary fault activity and larger accommodation space, formed a thicker mixed fan body. The largest thickness of mixed fan body which was drilled by was 240 m, e.g., in Well QHD9-2E-4. The western sub-uplift, however, with small area, weak boundary fault activity or transferring as fault transferred slope and correspondingly small accommodation space, formed the mixed fan with a small area and thickness, e.g., Well QHD29-2E-6.

6 Discussion

6.1 Pattern of near-shore mixed fan

A great deal of case studies indicate that mixed deposition is common in modern time and throughout geological history which develops in a wide variety of environments (e.g., Mount 1984, 1985; Dorsey and Kidwell 1999; Brooks et al. 2003; Coffey and Read 2004; Longhitano et al. 2010; Morsilli et al. 2012; Anan 2014; Chiarella et al. 2017; Rivera et al. 2018; Moscardelli et al. 2019). Regarding basin type, mixed deposition can develop in under-compensated saline basins, fresh water lacustrine basins, active continental marginal basins, back-arc inland basins, whereas regarding local sedimentary environments, it develops in shore-shallow lake, shoreland, bay, shallow shelf, deep slope etc. Different

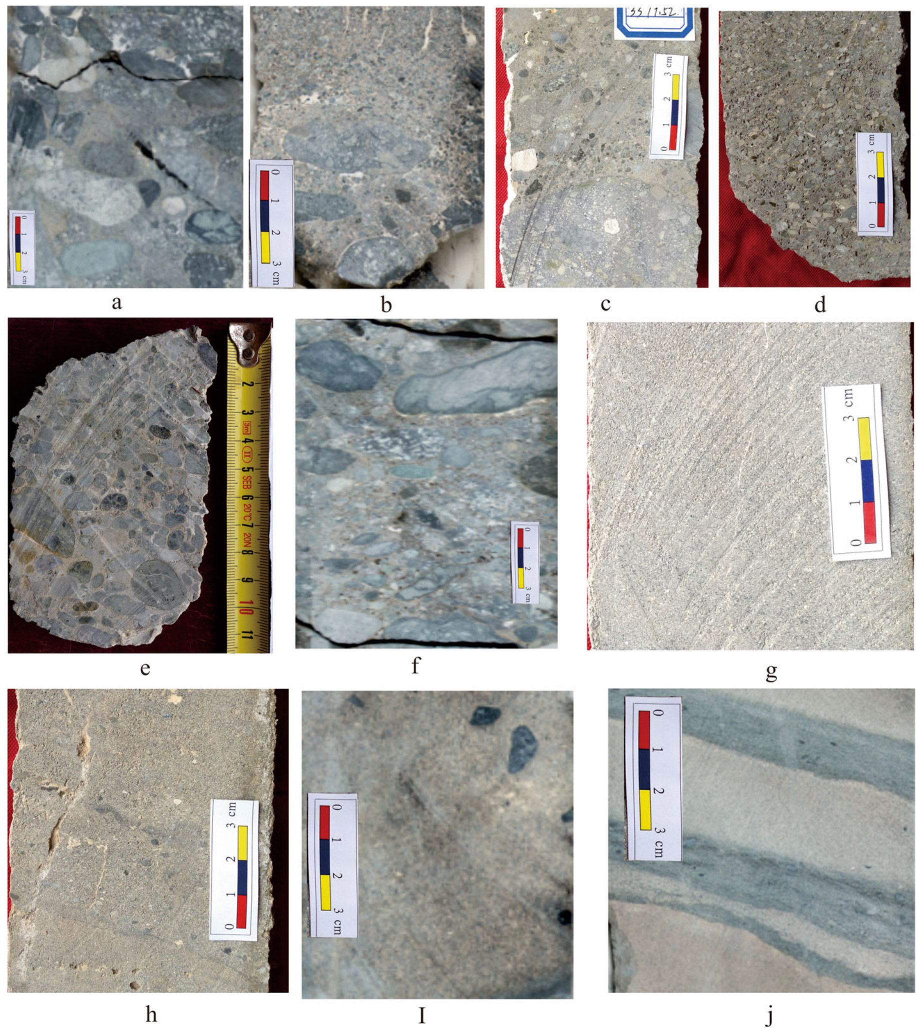

Fig. 6 Typical core characteristics of Well QHD29-2E-5 in the eastern part of STU. The depth of the core photograph is consistent with the depth shown in Fig. 5. **a**-3374.30 m, gravel-bearing fine sandstone; **b**-3375.52 m, scouring surface is present at the bottom; **c**-3379.52 m, a sharp contact between fine sandstone and gravel-bearing fine sandstone; **d**-3380.48 m, fine conglomerate with conglomerate content reaching 80%; **e**-3382.52 m, fine conglomerate, occasional bioclasts; **f**-3385.04 m, grey coarse conglomerate; **g**-3367.1 m, grey fine sandstone; **h**-3369.37 m, grey medium-coarse-grained sandstone, developing fracture; **i**-3376.55 m, fine sandstone, blistering with dropped acid; **j**-3372.68 m, argillaceous strips

types of mixed deposition develop in different sedimentary environments.

The boundary fault in the northern side of eastern STU was active in the Paleogene with a large displacement. The neighbouring steep belt was favorable for developing near-shore fan delta. Meantime, the climate was relatively arid during the deposition of Members 1 and 2 of Shahejie Formation, water body was of relatively high salinity favoring the growth of organisms and precipitation of carbonate components. Near-shore mixed fan developed in the above-mentioned backgrounds associated with the deposition of fan delta.

The steep slope belt mainly developed fan delta deposits and proximal channel microfacies developed when abundant clastic materials were supplied to the uplift. Lithology was dominated by sandy conglomerate and pebble-bearing coarse-grained conglomerate, indicating obvious near-shore coarse clastics feature. A few gastropods occurred, mixing with in situ delta sandy grains and formed mixed clastic bank dominated by terrigenous clastics; when provenance supply reduced, clastics interruption became weaker, which was not enough to restrict biological action. Its lithology was dominated by bioclast-bearing sandstone; whereas mixed bioclastic bank dominated by sand-bearing bioclastic limestone formed during the intermission of provenance supply in a quiet and clear water body favorable for the prosperous growth of gastropods and ostrocods. Meanwhile, bioclasts and sandy clastic sediment mixed thoroughly due to the wave reconstruction (Fig. 9). Mixed channel

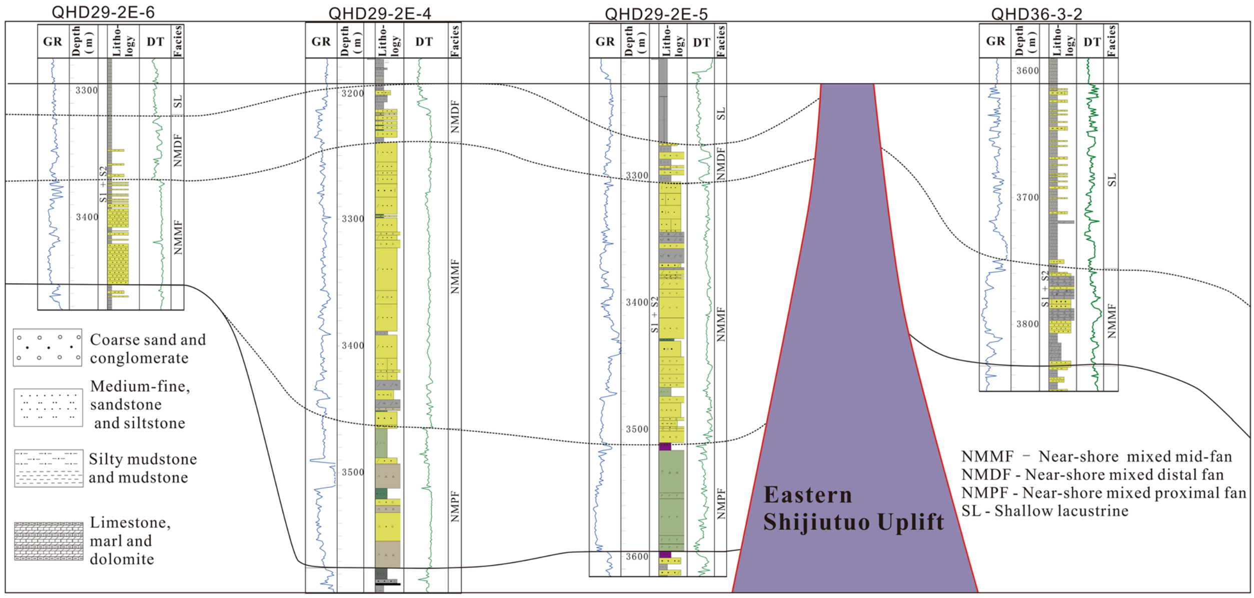

Fig. 7 Vertical succession of typical mixed fans and correlation across drilling wells of the eastern part of STU. The STU, as an uplift, provided abundant source materials for the near-shore mixed fan during the early Oligocence. GR-gamma logging, DT-acoustic logging. Section location is shown in Fig. 1

sandbody with abundant bioclastics and mixed clastic bank dominated by sandy clastics formed due to the scouring reconstruction of bioclastic bank of intermission period by fan body when provenance supply increased again (Fig. 9).

A larger accommodation space can be maintained due to the continuous activity of more active boundary faults along the steep slope belt. The near-shore mixed fan of multi-stage developed as an aggradation succession vertically with a larger superimposed thickness and associated with fan delta which displayed as a wedge shape of near-shore fans (Fig. 9).

6.2 Reservoir characteristics of near-shore mixed fan

Mixed deposition has important implications in oil and gas exploration. Near-shore mixed deposition associated with delta, near-shore mixed deposition in subaqueous uplifting areas and algae mixed deposition can form excellent continental mixed oil and gas reservoir (e.g., Monstad 2000; Brooks et al. 2003; Longhitano et al. 2010; Morsilli et al. 2012; Chiarella et al. 2017; Moscardelli et al. 2019; Moscardelli et al. 2019; Leila et al. 2020).

The burial depth of near-shore mixed fan of Members 1 and 2 of Shahejie Formation along the eastern steep slope belt of STU is generally over 3000 m with an average depth of 3500 m and relatively better reservoir property (Fig. 10). The average porosity is 19.7%, with a maximum value of 40.1%; the average permeability is $168.40 \times 10^{-3} \mu m^2$ with a maximum value of $2350.4 \times 10^{-3} \mu m^2$ according to core analysis results of 374 samples. Reservoir property is significantly different among different microfacies. Mixed organic banks show the best reservoir property, with an average porosity of 29.3%, and a maximum value of 40.1%, and an average permeability of $408.13 \times 10^{-3} \mu m^2$ and a maximum value of $2350.4 \times 10^{-3} \mu m^2$; Mixed clastic banks have good reservoir property, as well, with an average porosity of 17.8% and a maximum value of 29.5%, with an average permeability of $27.0 \times 10^{-3} \mu m^2$ and a maximum value of $340.1 \times 10^{-3} \mu m^2$. Mixed valley has relatively poor reservoir property, with an average porosity of 14.3% and a maximum value of 18.8%, and an average permeability of $8.0 \times 10^{-3} \mu m^2$ and a maximum value of $113.5/767.5 \times 10^{-3} \mu m^2$. The proximal channel has the poorest reservoir porosity, with an average porosity of 3.99%–11.7%, a maximum value of 7.72%, and an average permeability of $0.23 \times 10^{-3} \mu m^2$, and a maximum value of $3.25 \times 10^{-3} \mu m^2$.

Difference of sedimentary microfacies is the most important factor controlling reservoir property with similar burial depth, tectonics and diagenesis setting. Mixed bioclastic bank has the best reservoir property having a large quantity of bioclasts, skeletal cavities and dissolution pores, whereas mixed bioclastic bank, terrestrial clastics being reconstructed by wave and intergranular clay matrix reducing greatly after washing, has increasing sorting and rounding degree of grains. Meanwhile, due to having some bioclasts, it still preserves relatively good reservoir property during deep burial stage. The

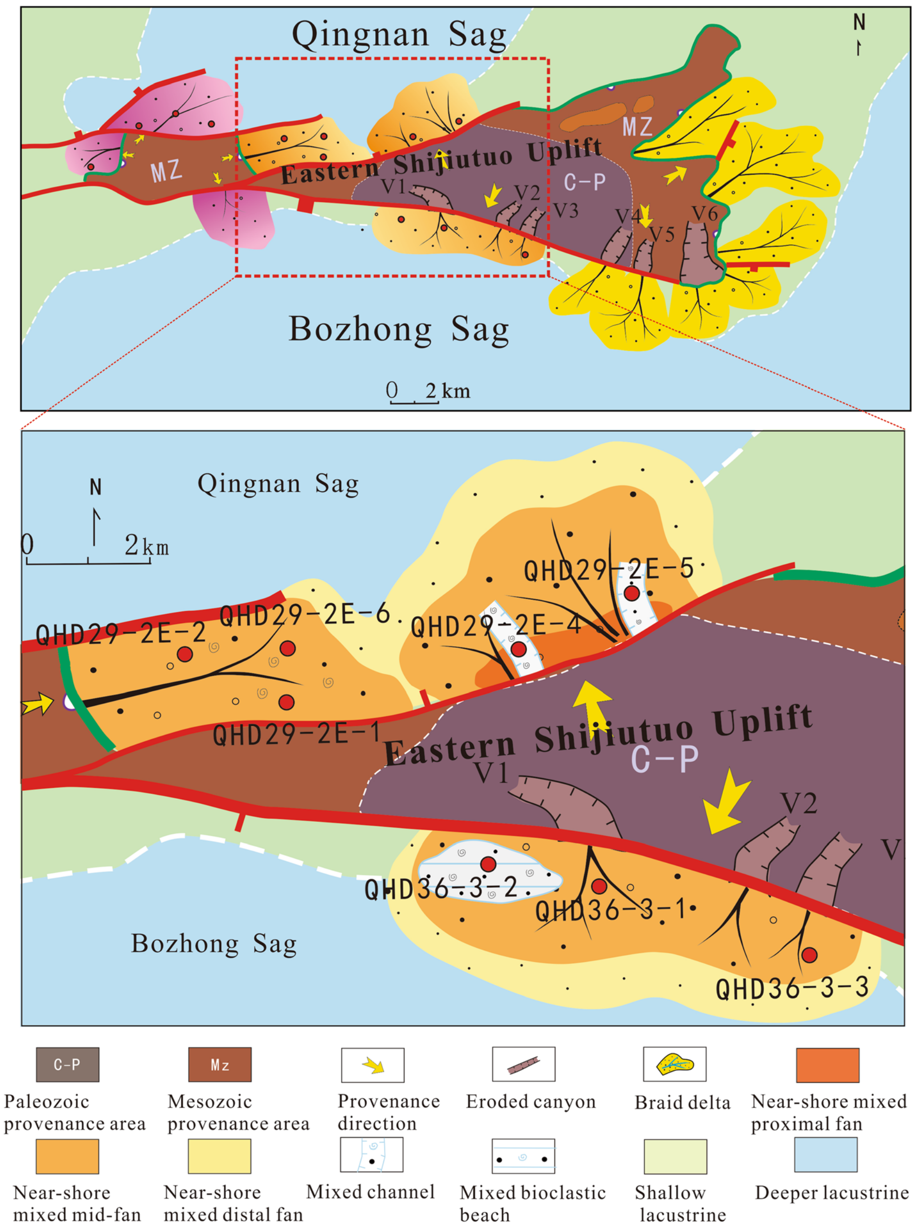

Fig. 8 Distribution map of depositional systems of Members 1 and 2 of Shahejie Formation in eastern STU. Lithology of the basement provenance of STU is mainly Mesozoic rhyolite, andesite and Paleozoic sandstone which respectively provided abundant terrestrial sediments for the north and south sagging areas of the uplift

reservoir property of mixed channel was improved to some degree due to the mixing of some bioclasts, although without wave reconstruction. Proximal channel, located at the proximal fan as a near-shore traditional mixed deposition, has the poorest reservoir property with poor sorting and roundness and high intergranular matrix content.

6.3 Main controlling factors of high-quality reservoir

Different types of mixed deposition can be formed influenced by comprehensive factors including clastic materials supply, climate and water environment, sea (lake) level change, palaeogeomorphology conditions, tectonic movement and hydrodynamic conditions (e.g., Monstad 2000; Moissette et al. 2010; Chiarella et al. 2017; Abdelkarim et al. 2019; Moscardelli et al. 2019; Leila et al. 2020). The reservoir quality of mixed sediments of Members 1 and 2 of Shahejie Formation, eastern part of STU is jointly controlled by sedimentary environment and diagenesis. To illustrate this better, key diagenesis events were analyzed, diagenesis evolution succession was reconstructed and origins and main controlling factors of mixed high-quality reservoir were determined through analyses of rock slices,

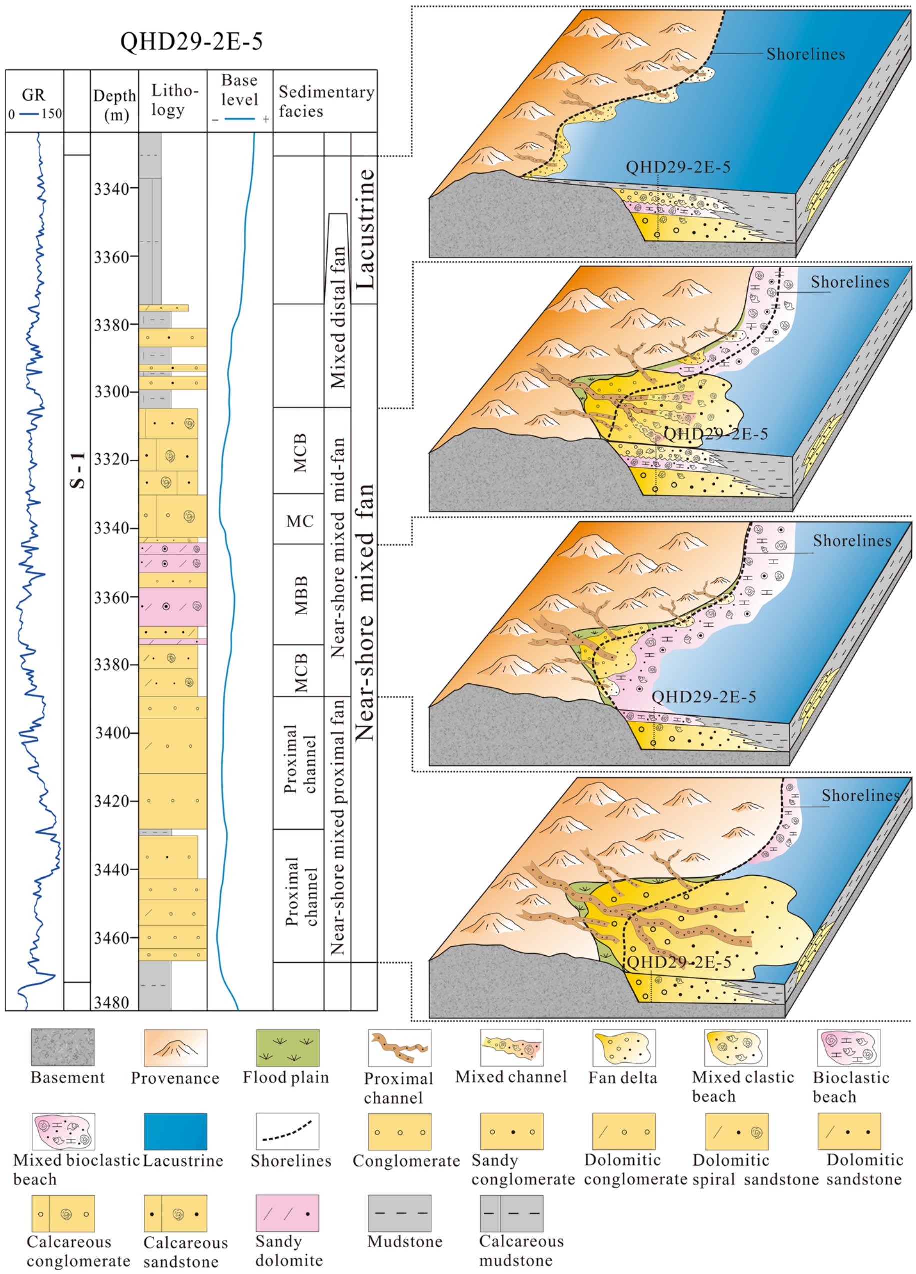

Fig. 9 Depositional origin pattern of near-shore mixed fan. During the deposition of Member 1 of Shahejie Formation, lake shoreline shifted towards the basin margin from bottom to top and scale of the mixed fan gradually reduced; whereas carbonate-clastic mixed deposition mainly developed in mid fan of near-shore mixed fan setting. MCB–Mixed clastic beach. MC–Mixed channel. MBB–Mixed bioclastic beach

scanning electron microscopy, electronic probe, cathodoluminescence, isotope, inclusion test etc.

1) Coarse grain size and rich in bioclasts as the basis of forming high-quality reservoir

Exploration indicates that relatively coarse-grained mixed sedimentary rocks with good pore texture, development of primary and secondary pores, usually have good reservoir property. Meanwhile, higher bioclastic content in rocks is more favorable for dissolution at penecontemporaneous period and formation of a large quantity of skeletal cavities and mould dissolution pores. Statistics indicate that reservoir property of mixed sediments has a positive correlation with bioclastic content (Song et al. 2013). Coarse-grained sedimentary facies rich in bioclastics is therefore the basis of forming high-quality reservoir.

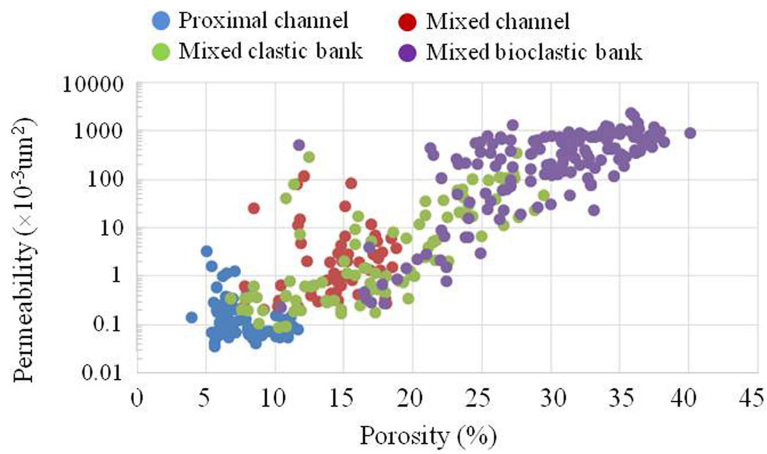

Fig. 10 Reservoir characteristic diagram of near-shore mixed fan in the study area

2) Formation of cladding in early period and dolomitization favorable for preserving primary pores

Cladding texture develops widely in mixed sediments of the study area, micrite dolomite cladding growing closely on the surface of grain clastics and a layer of foliated rim cement developing outside of the cladding. Electronic probe and carbon and oxygen isotope analyses indicated that the cladding, formed in a high salinity environment and possibly influenced by fresh water leaching, can be divided into organic and inorganic origins. Traces of microbial activity found in scanning electron microscope photos of cladding indicated that the formation of cladding was related with microbial activity (Song et al. 2013); Meanwhile particles continued to rotate under tractive current effect, wrap adsorbed materials surrounding the particles and gradually form a shell. The formation of the cladding can be speculated as: i) depositional period of Members 1 and 2 of Shahejie Formation, with high salinity and shallow water body, particles rolled and stirred under strong hydrodynamic conditions which was easy to form the cladding, and dolomitization occurred under arid condition; ii) dolomitization reduced with injection of atmospheric fresh water and continuous rolling led to the formation of a new cladding layer outside of the originally formed cladding. This process repeated until the grain gravity was larger than the influence of buoyancy and hydrodynamic force and the grain began to precipitate and dropped down on the lake bottom, being buried, deposited and preserved there (Fig. 11).

Studies indicate that cladding is mainly formed in syngenic-early period of diagenetic A stage (Li et al. 1997; Song et al. 2013). Microscope of slices shows that cladding texture is destroyed and breaks with compaction in late period, indicating that cladding texture is formed before compaction of the late period. Meanwhile, a lower formation temperature, i.e. between 38 and 66 °C through temperature measurement of inclusions in the cladding and formation temperature calculated by oxygen isotope values through laser isotope analysis, indicated that it was formed in an earlier period. Cladding texture formed in the early period and dolomitization can restrain compaction in the late period and restrain the growth of imbedded crystal cement, as well as which protected primary pores, and was favorable for forming high-quality reservoir.

3) Reconstruction of reservoir by hydrothermal fluid of late period

Generally multi-stage cementation and dissolution of a different degree occur in late period diagenesis process after the formation of high-quality reservoir in the early period, which will reconstruct the reservoir furthermore and influence reservoir property. The reservoir of the study area was significantly influenced by deep hydrothermal fluids resulting from multi-stage activity of deep fractures. An obvious vertical vein observed from hand specimens of core is the direct proof of hydrothermal fluid activity. Carbon and oxygen isotope analyses indicated that there were no significant differences in carbon isotope values between the vein and surrounding rocks, suggesting a normal primary lacustrine carbonates range (− 2%–6%); whereas oxygen isotopes were obviously different and values of the internal fluid passage show an obviously negative bias than the surrounding rocks (Table 1). The occurrence of pyrite with large quantity, some pyrites in complete crystal form of autotype-semi-

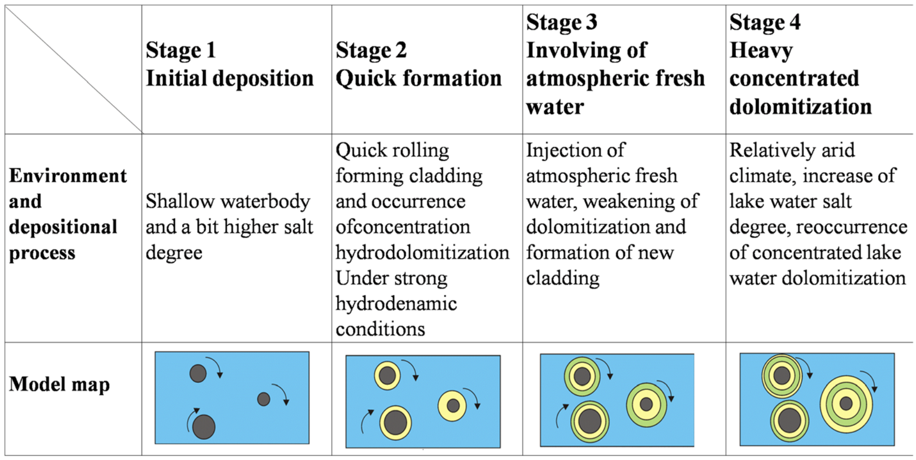

Fig. 11 Diagram showing the formation process of grain cladding in early period

autotype, some pyrites being cut by micro fractures of tectonic movement in late periods, indicated that the pyrites were developed and formed in a relatively early period and were influenced by fractures to some degree. The ratio of Co/Ni in pyrite has specific origin implication. Ratio of Co/Ni larger than 1 measured by electron probe (Fig. 12) suggested a possible hydrothermal origin for the pyrite.

CO_2 is common in hydrocarbon accumulations of drilling wells in the study area, reaching high as 50% in some wells. Analyses indicated that a large quantity of CO_2 forms an acidic fluid environment, which is quite favorable for dissolution and for the reconstruction of the reservoir. Furthermore, dissolution of bioclasts and dolomite cement, dissolution of feldspar is very common in the study area and dissolution of albite and potassium feldspar occurs with higher percentage of dissolved albite than potassium feldspar. Statistics indicate that the reservoir property of hydrocarbon accumulations with CO_2 is obviously better than other reservoirs of neighbouring areas, which furthermore explains the positive reconstruction of CO_2 in forming a high-quality reservoir.

Table 1 Correlations of carbon and oxygen isotopes between hydrothermal fluid and surrounding rocks

No.	Character	δ^{18}O‰ V-PDB	δ^{13}C‰ V-PDB
1	Vein	−7.01	2.56
2	Surrounding rocks	− 1.25	1.93
3	Vein	−5.59	2.17
4	Surrounding rocks	0.13	2.59

6.4 Oil and gas exploration examples

The Shahejie Formation of the study area has been regarded as lacking effective reservoir for a long period, which led to no progress. In the early period of the 13th Five Year Plan Project, instructed by the "source-to-sink system" theory, it is understood that a local small-scale provenance area like the eastern part of the STU has the possibility of developing thick sand-rich reservoir and fine reservoir researches were conducted (e.g. Liu et al. 2017).

Multiple thick contiguous fan bodies (proved to be mixed fans later) were found along the steep slope belt of the eastern STU. Six wells were drilled, targeted at Members 1 and 2 of Shahejie Formation and 5 of them acquired high-yield oil and gas, except one failure of exploration caused by failed strata identification due to seismic data problem. Among them, oil and gas interval of Members 1 and 2 of Shahejie Formation from a single well is larger than 200 m in Well QHD29-2E-4 and daily production of oil and gas over one thousand tons which refreshed the records of oil interval thickness and tested production of a single well of BBB.

The proven reserves of near-shore mixed fan of Members 1 and 2 of Shahejie Formation in eastern 29-2E tectonic unit exceeds 50,000,000 oil barrels, crude oil density of 0.83–0.87 g/cm^3, ground oil viscosity of 4.37 ~ 5.33 mPa·s (50 °C) and the hydrocarbon accumulation type is tectonic-lithologic complex type in a near-shore steep slope thick mixed fan setting (Fig. 13). This is the first subtle hydrocarbon accumulation with commercial value in Paleogene of BBB having instruction implications for exploration in similar areas.

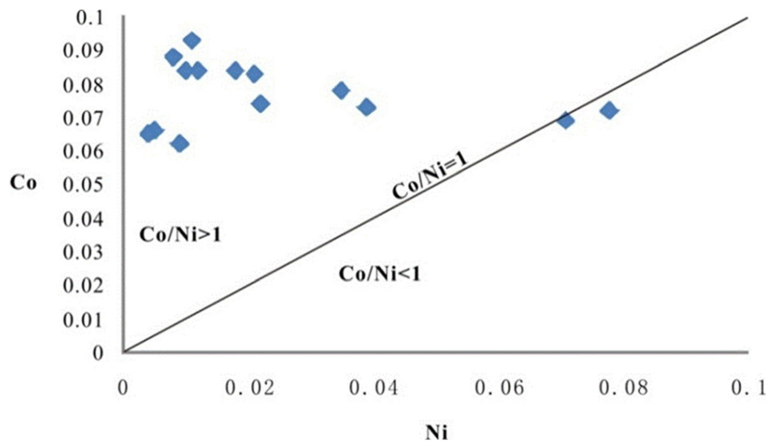

Fig. 12 A scatter diagram of cobalt and nickel content of pyrite in Well QHD29-2E-5 in eastern STU

7 Conclusions

Near-shore mixed fans developed in Members 1 and 2 of Shahejie Formation of eastern part of STU, BBB, which are dominated by thick sandy conglomerate lithofacies rich in bioclastics. Typical characteristics include mixed channel microfacies developing in near-shore mixed fan and some mixed clastic bank and mixed bioclastic bank microfacies. Overall, the reservoir is of good quality, different microfacies having some difference: mixed bioclastic bank as the best reservoir, mixed clastic bank as the second one, and mixed channel has the poorest quality. However, with some quantity of bioclastics, the reservoir quality was improved to some degree and proximal channel was the poorest one. Key factors forming high-quality reservoir include being rich in bioclasts, cladding and dolomitization and hydrothermal fluids of the late period and CO_2 can improve the reservoir quality as well. Near-shore mixed fans, with good reservoir quality and high-yield of oil and gas, are favorable for forming tectonic-lithologic traps with quick facies variations, which are favorable areas for mid-deep exploration in BBB.

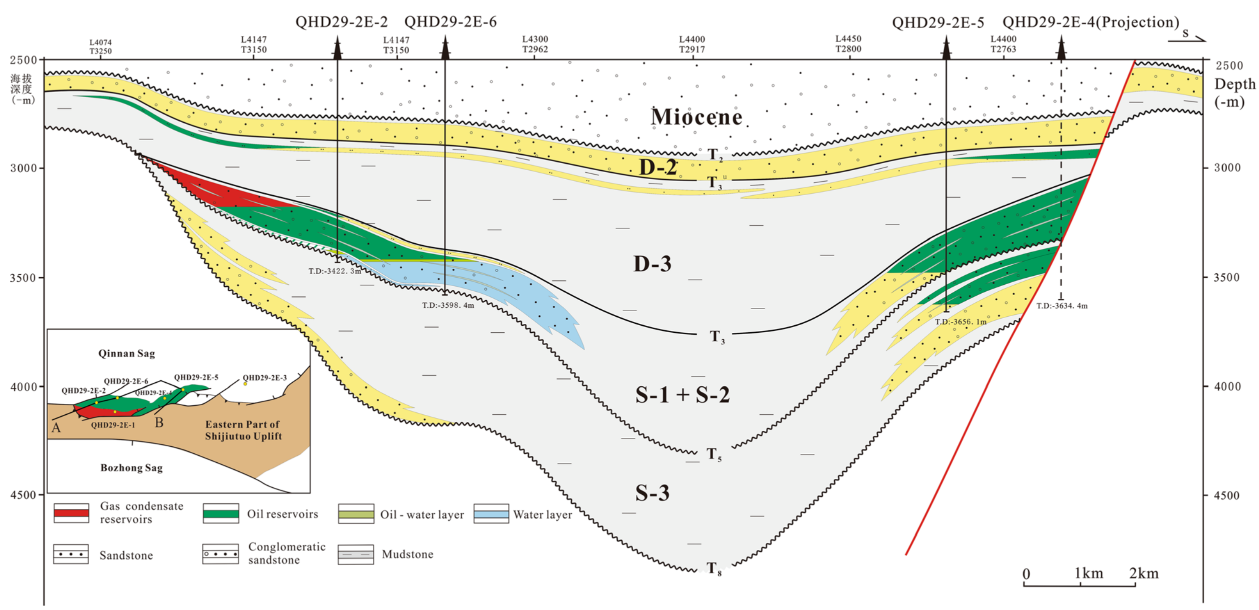

Fig. 13 Oil and gas accumulations pattern of Members 1 and 2 of Shahejie Formation in QHD29-2E tectonic unit of steep slope belt, STU. D-2 = Member 2 of the Dongying Fm.; D-3 = Member 3 of the Dongying Fm.; S-1 = Member 1 of the Shahejie Fm.; S-2 = Member 2 of the Shahejie Fm.; S-3 = Member 3 of the Shahejie Fm.

Abbreviations
BBB: Bohai Bay Basin; STU: Shijiutuo Uplift

Acknowledgements
We would like to thank the National Science and Technology Major Project (Exploration Technologies for Offshore Subtle Oil/Gas) (project no.:2016ZX05024003 and 2016ZX05024-003-003) and the Fundamental Research Funds for the Central Universities for support. We thank two anonymous reviewers and Prof. Ian D. Somerville for their helpful suggestions on an early manuscript.

Authors' contributions
HL and XFD conceived and designed the study. XFD, XBH and ZQS collected the materials. ZQS, WX, and CZ performed the laboratory investigations. HL and XFD analyzed the data. XFD and HL wrote the paper. All authors read and approved the final manuscript.

Funding
This study is supported by National Science and Technology Major Project (2016ZX05024003).

Competing interests
The authors declare that they have no competing interests.

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Received: 18 May 2020 Accepted: 25 August 2020
Published online: 22 September 2020

References

Abdelkarim, A.A., O.M. Abdullatif, L.O. Babalola, M.H. Makkawi, and M.A. Yassin. 2019. High-resolution lithofacies and porosity modeling of the mixed siliciclastic-carbonate deposits of the Burdigalian dam formation, eastern Saudi, Arabia. *International Journal of Earth Sciences* 108: 155–172.

Anan, T.I. 2014. Facies analysis and sequence stratigraphy of the Cenomanian-Turonian mixed siliciclastic-carbonate sediments in West Sinai, Egypt. *Sedimentary Geology* 307: 34–46.

Brooks, G.R., L.J. Doyle, B.C. Suthard, S.D. Locker, and A.C. Hine. 2003. Facies architecture of the mixed carbonate/siliciclastic inner continental shelf of west-central Florida: Implications for Holocene barrier development. *Marine Geology* 200: 325–349.

Bruckner, W.D. 1953. Cyclic calcareous sedimentation as an index of climatic variations in the past. *Journal of Sedimentary Petrology* 23 (4): 235–237.

Button, A., and R.G. Vos. 1977. Subtidal and intertidal clastic and carbonate sedimentation in a macrotidal environment: An example from the lower Proterozoic of South Africa. *Sedimentary Geology* 18: 175–200.

Campbell, A.E. 2005. Shelf-geometry response to changes in relative sea level on a mixed carbonate–siliciclastic shelf in the Guyana Basin. *Sedimentary Geology* 175: 259–275.

Chiarella, D., S.G. Longhitano, and M. Tropeano. 2017. Types of mixing and heterogeneities in siliciclastic-carbonate sediments. *Marine and Petroleum Geology* 88: 617–627.

Coffey, B.P., and J.F. Read. 2004. Mixed carbonate–siliciclastic sequence stratigraphy of a Paleogene transition zone continental shelf, southeastern USA. *Sedimentary Geology* 166: 21–57.

Dix, G.R., and A. Parras. 2014. Integrated diagenetic and sequence stratigraphy of a late Oligocene–early Miocene, mixed-sediment platform (Austral Basin, southern Patagonia): Resolving base-level and paleoceanographic changes, and paleoaquifer characteristics. *Sedimentary Geology* 307: 17–33.

Dong, G.Y., H.D. Chen, and Y.B. He. 2007. Some problems on the study of the mixed siliciclastic-carbonate sediments. *Advances in Earth Science* 22 (9): 931–939 (in Chinese with English abstract).

Dong, Y.L., X.M. Zhu, and S.J. Hua. 2011. Genetic types and evolutionary model of mixed clastic-carbonate deposits in the lower part of the Sha-1 Formation, the Huanghua Depression. *Oil & Gas Geology* 32 (1): 98–106 (in Chinese with English abstract).

Dorsey, R.J., and S.M. Kidwell. 1999. Mixed carbonate-siliciclastic sedimentation on a tectonically active margin: Example from the Pliocene of Baja California Sur, Mexico. *Geology* 27: 935–938.

Feng, J.L., K. Hu, and J. Cao. 2011. A review on mixed rocks of terrigenous clastics and carbonates and their petroleum-gas geological significance. *Geological Journal of China Universities* 17 (2): 297–307 (in Chinese with English abstract).

García-Hidalgo, J.F., J. Gil, M. Segura, and C. Dominguez. 2007. Internal anatomy of a mixed siliciclastic-carbonate platform: The late Cenomanian–Mid Turonian at the southern margin of the Spanish central system. *Sedimentology* 54 (6): 1245–1271.

Glider, S.A., P.H. Leloup, and V. Courtillot. 1999. Tectonic evolution of Tancheng-Lujiang (Tan-Lu) fault via middle Triassic to early Cenozoic paleomagnetic. *Journal of Geophysical Research* 104 (B7): 15365–15390.

Hsiao, L.Y., S.A. Graham, and N. Tilander. 2004. Seismic reflection imaging of a major strike-slip fault zone in a rift system: Palaeogene structure and evolution of the Tan-Lu fault system, Liaodong Bay, Bohai, offshore China. *AAPG Bulletin* 88: 71–97.

Jiang, M.S., and Q.A. Sha. 1995. Research advances in the mixed siliciclastic-carbonate sedimentary systems. *Advance in Earth Sciences* 10 (6): 551–554 (in Chinese with English abstract).

John, C.M., M. Mutti, and T. Adatte. 2003. Mixed carbonate-siliciclastic record on the north African margin (Malta)-- coupling of weathering processes and mid Miocene climate. *Geological Society of America Bulletin* 115: 217–229.

Leila, M., A. Moscariello, M. Kora, A. Mohamed, and E. Samankassou. 2020. Sedimentology and reservoir quality of a Messinian mixed siliciclastic-carbonate succession, onshore Nile Delta, Egypt. *Marine and Petroleum Geology* 112: 104076.

Li, X.H., W.J. Liu, and R.C. Zheng. 1997. Hybrid facies and mechanism of the formation of the mixed Devonian carbonate-siliciclastic sediments in the Longmen Mountain area, Sichuan. *Sedimentary Facies and Palaeogeography* 17 (3): 1–9 (in Chinese with English abstract).

Liu, H., J. Meng, and S. Banerjee. 2017. Estimation of palaeo-slope and sediment volume of a lacustrine rift basin: A semi-quantitative study on the southern steep slope of the Shijiutuo uplift, Bohai Offshore Basin, China. *Journal of Asian Earth Sciences* 147: 148–163.

Liu, H., A.J. van Loon, J. Xu, L.X. Tian, X.F. Du, X.T. Zhang, and D.L. Chen. 2020. Relationships between tectonic activity and sedimentary source-to-sink system parameters in a lacustrine rift basin: A quantitative case study of the Huanghekou Depression (Bohai Bay Basin, E China). *Basin Research* 32: 587–612.

Liu, H., Q.L. Xia, I.D. Somerville, Y. Wang, X.H. Zhou, C.M. Niu, X.F. Du, and X. T. Zhang. 2015. Palaeogene of the Huanghekou sag in the Bohai Bay Basin, NE China: Deposition-erosion response to a slope break system of rift lacustrine basins. *Geological Journal* 50: 71–92.

Liu, H., Q.L. Xia, and X.H. Zhou. 2018. Geologic-seismic models, prediction of shallow-water lacustrine delta sandbody and hydrocarbon potential in the Late Miocene, Huanghekou Sag, Bohai Bay Basin, northern China. *Journal of Palaeogeography* 7 (1): 66–87.

Longhitano, S.G., L. Sabato, M. Tropeano, and S. Gallicchio. 2010. A mixed bioclastic–siliciclastic flood-tidal delta in a microtidal setting: Depositional architectures and hierarchical internal organization (Pliocene, southern apennine, Italy). *Journal of Sedimentary Research* 80: 36–53.

Luo, S.S., K.Y. Liu, and Y.B. He. 2004. Mixed sedimentary characteristics and mode of terrigenous clastics and carbonate in Es4 of Bonan depression. *Journal of Jianghan Petroleum Institute* 26 (4): 19–21 (in Chinese with English abstract).

Ma, Y.P., and L. Liu. 2003. Sedimentary and Diagenetic characteristics of Paleogene lacustrine "Hunji" rock in Beach District, Dagang. *Acta Sedimentologica Sinica* 21 (4): 607–613 (in Chinese with English abstract).

Mata, S.A., and D.J. Bottjer. 2011. Origin of lower Triassic microbialites in mixed carbonate-siliciclastic successions: Ichnology, applied stratigraphy, and the end-Permian mass extinction. *Palaeogeography, Palaeoclimatology, Palaeoecology* 300: 158–178.

Maxwell, W.G.H., and J.P. Swinchatt. 1970. Great barrier reef: Regional variation in a terrigenous-carbonate province. *Geological Society of America Bulletin* 81 (3): 691–724.
Moissette, P., J.J. Cornée, B. Mannaï-Tayech, M. Rabhi, J.P. André, E. Koskeridou, and H. Méon. 2010. The western edge of the Mediterranean Pelagian platform: A Messinian mixed siliciclastic-carbonate ramp in northern Tunisia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 285: 85–103.
Monstad, S. 2000. Carbonate sedimentation on inactive fan-delta lobes: Response to sea-level changes, Sant-Llorenc del munt fan-delta complex, NE Spain. *Sedimentary Geology* 138: 99–124.
Morsilli, M., F.R. Bosellini, L. Pomar, P. Hallock, M. Aurell, and C.A. Papazzoni. 2012. Mesophotic coral buildups in a prodelta setting (late Eocene, southern Pyrenees, Spain): A mixed carbonate–siliciclastic system. *Sedimentology* 59: 766–794.
Moscardelli, L., J. Ochoa, I. Lunt, and L. Zahm. 2019. Mixed siliciclastic-carbonate systems and their impact for the development of deep-water turbidites in continental margins: A case study from the late Jurassic to early Cretaceous Shelburne subbasin in offshore Nova Scotia. *AAPG Bulletin* 103: 2487–2520.
Mount, J.F. 1984. Mixing of siliciclastic and carbonate sediments in shallow shelf environments. *Geology* 12 (7): 432–435.
Mount, J.F. 1985. Mixed siliciclastic and carbonate sediments: A proposed first-order textural and compositional classification. *Sedimentology* 32: 435–442.
Parcell, W.C., and M.K. Williams. 2005. Mixed sediment deposition in a retroarc foreland basin: Lower Ellis Group (M. Jurassic), Wyoming and Montana, U.S.A. *Sedimentary Geology* 177: 175–194.
Rivera, H.A., J.P. Le Roux, L.K. Sanchez, J.E. Marino-Martinez, C. Salazar, and J. C. Barragan. 2018. Palaeoredox conditions and sequence stratigraphy of the Cretaceous storm-dominated, mixed siliciclastic-carbonate ramp in the eastern Cordillera Basin (Colombia): Evidence from sedimentary geochemical proxies and facies analysis. *Sedimentary Geology* 372: 1–24.
Sanders, D., and R. Hofling. 2000. Carbonate deposition in mixed siliciclastic-carbonate environments on top of an orogenic wedge (late Cretaceous, northern calcareous Alps, Austria). *Sedimentary Geology* 137: 127–146.
Sanders, D., and J.M. Pons. 1999. Rudist formations in mixed siliciclastic-carbonate depositional environments, upper Cretaceous, Austria: Stratigraphy, sedimentology, and models of development. *Palaeogeography, Palaeoclimatology, Palaeoecology* 148: 249–284.
Sarkar, S., N. Chakraborty, A. Mandal, S. Banerjee, and P.K. Bose. 2014. Siliciclastic-carbonate mixing modes in the river-mouth bar palaeogeography of the upper Cretaceous Garudamangalam sandstone (Ariyalur, India). *Journal of Palaeogeography* 3 (3): 233–256.
Schellart, W.P., and G.S. Lister. 2005. The role of east Asian active margin in widespread and strike-slip deformation in East Asia. *Journal of the Geological Society* 162: 959–972.
Song, Z.Q., Y.F. Chen, and X.F. Du. 2013. Research on mixed sedimentary characteristics and reservoir of second member of Shahejie Formation, A Area, Bohai Sea. *Offshore Oil* 33 (4): 13–18 (in Chinese with English abstract).
Tian, L.X., H. Liu, C.M. Niu, X.F. Du, B. Yang, X.D. Lan, and D.L. Chen. 2019. Development characteristics and controlling factor analysis of the Neogene Minghuazhen Formation shallow water delta in Huanghekou area, Bohai offshore basin. *Journal of Palaeogeography* 8 (1): 19.
Tian, L.X., H. Yu, X.H. Zhou, W. Peng, and Y. Wang. 2009. Major control factors of petroleum accumulation in Huanghekou sag. *Xinjiang Petroleum Geology* 30: 319–321 (in Chinese with English abstract).
Wang, G.Z. 2001. Mixed sedimentation of recent reefoid carbonates and terrigenous clastics in the north continental shelf of the South China Sea. *Journal of Palaeogeography* 3 (3): 48–49 (in Chinese with English abstract).
Wang, J.Q., B. Liu, and P. Luo. 2014. Classification and genesis of Sinian mixosedimentite from northwest margin of Tarim Bain, China. *Journal of Chengdu University of Technology (Science & Technology Edition)* 41 (3): 339–346 (in Chinese with English abstract).
Yang, C.Q., and Q.G. Sha. 1990. Sedimentary environment of the middle Devonian Qujiang formation, Qujiang, Yunnan Province: A kind of mixing sedimentation of terrigenous clastics and carbonate. *Acta Sedimentologica Sinica* 8 (2): 59–65 (in Chinese with English abstract).
Yose, L.A., and P.L. Heller. 1989. Sea-level control of mixed-carbonate-siliciclastic, gravity-flow deposition: Lower part of the Keeler canyon formation (Pennsylvanian), southeastern California. *Geological Society of America Bulletin* 101: 427–439.
Zhang, J.L., and X.Q. Si. 2007. Mixed siliciclastic—carbonate sediment in rift lacustrine basin——A case on the upper part of the fourth member of the Eogene Shahejie Formation in Jinjia area, Dongying depression. *Geological Review* 53 (4): 448–454 (in Chinese with English abstract).
Zhang, X.H. 2000. Classification and origin of mixed imentite. *Geological Science and Technology Information* 19 (4): 31–34 (in Chinese with English abstract).
Zhou, X.H., Y.X. Yu, L.J. Tang, D.Y. Lv, and Y.B. Wang. 2010. Cenozoic offshore basin architecture and division of structural elements in Bohai Sea. *China Offshore Oil and Gas* 22: 285–289 (in Chinese with English abstract).

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