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Mechanism of diagenetic trap formation in nearshore subaqueous fans on steep rift lacustrine basin slopes—A case study from the Shahejie Formation on the north slope of the Minfeng Subsag, Bohai Basin, China

Wang Yanzhong[1]*, Cao Yingchang[1], Ma Benben[1], Liu Huimin[2], Gao Yongjin[2] and Chen Lin[3]

[1] School of Geosciences, China University of Petroleum, Qingdao, Shandong 266555, China
[2] Geological Science Research Institute of Shengli Oilfield, SINOPEC, Dongying, Shandong 257015, China
[3] Western New Prospect Research Center of Shengli Oilfield, SINOPEC, Dongying, Shandong 257015, China

Abstract: Diagenetic traps in conglomerate in nearshore subaqueous fans in the steep slope zones of rift basins have been important exploration targets for subtle reservoirs in eastern China. However, the mechanism of how those traps were formed is not clear, which inhibits further exploration for this type of reservoir. In order to solve the problem, we take as an example nearshore subaqueous fans in the upper part of the fourth member of the Shahejie Formation (Es_4^s) on the north slope of the Minfeng Subsag in the Dongying Sag. Combining different research methods, such as core observation, thin section examination, scanning electron microscope (SEM) observation, fluid-inclusion analysis, carbon and oxygen isotope analysis of carbonate cements, and analysis of core properties, we studied the genetic mechanisms of diagenetic traps on the basis of diagenetic environment evolution and diagenetic evolution sequence in different sub/micro-facies. Conglomerate in Es_4^s in the north Minfeng Subsag experienced several periods of transition between alkaline and acidic environments as "alkaline–acidic–alkaline–acidic–weak alkaline". As a result, dissolution and cementation are also very complex, and the sequence is "early pyrite cementation / siderite cementation / gypsum cementation / calcite and dolomite cementation——feldspar dissolution / quartz overgrowth——quartz dissolution / ferroan calcite cementation / ankerite cementation / lime-mud matrix recrystallization / feldspar overgrowth——carbonate dissolution / feldspar dissolution / quartz overgrowth / pyrite cementation". The difference in sedimentary characteristics between different sub/micro-facies of nearshore subaqueous fans controls diagenetic characteristics. Inner fan conglomerates mainly experienced compaction and lime-mud matrix recrystallization, with weak dissolution, which led to a reduction in the porosity and permeability crucial to reservoir formation. Lime-mud matrix recrystallization results in a rapid decrease in porosity and permeability in inner fan conglomerates in middle-to-deep layers. Because acid dissolution reworks reservoirs and hydrocarbon filling inhibits cementation, reservoirs far from mudstone layers in middle fan braided channels develop a great number of primary pores and secondary pores, and are good enough to be effective reservoirs of hydrocarbon. With the increase of burial depth, both the decrease of porosity and permeability of inner fan conglomerates and the increase of the physical property difference between inner fans and middle fans enhance the quality of seals in middle-to-deep layers. As a result, inner fan conglomerates can be sealing layers in middle-to-deep buried layers. Reservoirs adjacent to mudstones in middle fan braided channels and reservoirs in middle fan interdistributaries experienced extensive cementation, and tight cemented crusts formed at both the top and bottom of conglomerates, which can then act as cap rocks. In conclusion, diagenetic traps in conglomerates of nearshore subaqueous fans could be developed with inner fan conglomerates as lateral or vertical sealing layers, tight carbonate crusts near mudstone layers in middle fan braided channels as well as lacustrine mudstones as cap rocks, and conglomerates far from mudstone layers in middle fan braided channels as reservoirs. Lime-mud matrix recrystallization of inner

*Corresponding author. email: wangyanzhong1980@163.com
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fan conglomerates and carbonate cementation of conglomerates adjacent to mudstone layers in middle fan braided channels took place from 32 Ma B.P. to 24.6 Ma B.P., thus the formation of diagenetic traps was from 32 Ma B.P. to 24.6 Ma B.P. and diagenetic traps have a better hydrocarbon sealing ability from 24 Ma B.P.. The sealing ability of inner fans gradually increases with the increase of burial depth and diagenetic traps buried more than 3,200 m have better seals.

Key words: Nearshore subaqueous fan, diagenetic trap, genetic mechanism, Dongying Sag, rift basin, lacustrine basin

1 Introduction

Lacustrine rift basins are one of the most important petroliferous basin types in China. There are almost 300 Meso-Cenozoic continental lacustrine rift basins in continental and offshore areas in eastern China, covering a total area of more than 2×10^6 km^2 (Xian et al, 2007). As the process of hydrocarbon exploration matures, it approaches a stage of exploring for subtle reservoirs in eastern China (Li, 2003). Nearshore subaqueous fans on steep slopes tend to form lithologic or structural-lithologic reservoirs as the spatial relations among sources, reservoirs and seals are very good (Sui et al, 2010). Recently, there has been a great breakthrough in hydrocarbon exploration in nearshore subaqueous fans (mainly conglomerates or sandy conglomerates) on steep slopes of rift basins in eastern China. A series of lithologic reservoirs in nearshore subaqueous fans have been discovered in many basins, such as the Bohai Bay Basin, the southern part of the North China Basin, the Erlian Basin as well as the Ural Basin in eastern China. More than ten hydrocarbon production bases have been built up one after another recently (Cao et al, 2008; Cao et al, 2009). However, the mechanism of trap formation in those conglomerates and sandy conglomerates is still unclear, which makes exploration activities much more difficult and risky. For example, an exploration well (Fengshen1) on the north steep slope of the Dongying Sag was very successful with a production of more than 50 t per day oil and more than 1×10^5 m^3 per day gas from conglomerate layers in the fourth member of the Shahejie Formation, Eocene (Es_4), while two adjacent wells (Fengshen2 and Fengshen3) drilled subsequently failed. Fengshen2 is a dry hole, and Fengshen3 has a low gas production of 2.64×10^4 m^3 per day. This phenomenon is not uncommon in hydrocarbon exploration in conglomerate layers formed by nearshore subaqueous fans in China (Zhong et al, 2008).

At present, reports have mainly focused on sedimentary classification, delineation, diagenesis and diagenetic environment evolution and hydrocarbon accumulation on steep slopes of those rift basins (Sui et al, 2010; Sui, 2003; Pu et al, 2013; Kong, 2000; Yan et al, 2005; Sun, 2003; Bi, 2002). Few have mentioned the mechanisms of diagenetic trap formation in those conglomerates. The Dongying Sag is a typical case of a hydrocarbon-rich rift basin in eastern China. From 2005, hydrocarbon exploration aimed at the conglomerates formed in nearshore subaqueous fans in Es_4^s in the north Minfeng Subsag. A great breakthrough has been made which has turned into a stage of diagenetic trap exploration. For example, Yong936 obtained a daily oil production of 7.6 t at a depth of 3,793 m to 3,808 m, and Yan222 obtained a daily oil production of 17.7 t at a depth of 3,985.8 m to 4,194.6 m. 41.88 million tons of proved original oil in place (OOIP) was registered to the relevant authorities in the Yong920 block in Es_4^s on the north steep slope of the Minfeng Subsag in 2010. Sui et al (2010) discussed accumulation models of lithologic reservoirs in conglomerates of nearshore subaqueous fans. They believe that sedimentary differences among inner fan, middle fan and outer fan subfacies control the difference in diagenesis, and further exert influence on heterogeneity by controlling evolution processes, which makes it possible to form lithologic reservoirs in conglomerates at depths of 3,200 m or deeper. Then they summarized the model of lithologic reservoir formation as “outer fan for migration, middle fan for accumulation, inner fan for sealing” (Sui et al, 2010). However, the matrix of inner fan conglomerates in the north Minfeng Subsag is mainly sand-sized particles with less fine particles or clay. Under these circumstances, whether inner fan conglomerates can act as seals only by compaction at depth or not should be studied. At the same time, hydrocarbon distribution is very complex in conglomerates deposited in middle fan braided channels with formation of many dry layers. Therefore, taking conglomerates of the nearshore subaqueous fans in Es_4^s in the north Minfeng Subsag as an example, based on further research into the characteristics and differences of reservoir diagenesis and porosity and permeability among different sub/micro-facies in nearshore subaqueous fans, the mechanism of diagenetic trap formation in conglomerates needs to be clarified. This is significant for exploration and development of diagenetic trap reservoirs in conglomerates of nearshore subaqueous fans on the steep slopes in rift basins.

2 Geological setting

The Dongying Sag is a sub-tectonic unit in the southeastern part of the Jiyang Depression of the Bohai Bay Basin, East China (Fig. 1(a)). It is a Mesozoic-Cenozoic half graben rift-downwarped basin with lacustrine facies directly deposited on Paleozoic bedrocks (Yuan and Wang, 2001). The Dongying Sag is bounded to the east by the Qingtuozi Salient, to the south by the Luxi Uplift and Guangrao Salient, to the west by the Linfanjia and Gaoqing Salients, and to the north by the Chenjiazhuang-Binxian Salient. The NE-trending sag covers an area of 5,850 km^2. It is a half graben with a faulted northern margin and a gentle southern margin. In plan, this sag is further subdivided into several secondary structural units, such as the northern steep slope zone, middle uplift belt, and the Lijin, Minfeng, Niuzhuang trough zones, Boxing subsags, and the southern gentle zone (Zhang et al, 2006; Jiang et al, 2014) (Fig. 1(b)). The Minfeng subsag, which lies in the northeastern part of the Dongying Sag, is adjacent to the Chenjiazhuang Salient in north, to the Central Uplift in south, to the Qingtuozi Salient in east and to the Lijin Subsag in west (Wan et al, 2010) (Fig. 1(b)). The northern part of the Minfeng Subsag is a steep slope bounded by the Chennan listric fault. The depo-center of the subsag is near the Chennan fault. The Palaeogene of the Dongying Sag can be divided from bottom to top into three formations: the Kongdian, Shahejie and Dongying Formations. The Shahejie Formation can be further divided into four members; the top member (Es_1), the upper member (Es_2), the lower member (Es_3) and the bottom member (Es_4). Es_4 comprises two parts, the upper part of Es_4 (Es_4^s) and the lower part of Es_4 (Es_4^x) (Fig. 1(c)). When Es_4^s was deposited, the Dongying Sag experienced an early depression developing stage with a dry climate, which led to a small water body with high salinity. Terrigenous clastic sediments were carried by seasonal floods to deep lakes, and large-scale conglomerate deposits of nearshore subaqueous fans accumulated on the downthrown side of the Chennan fault. Conglomerate layers were thick with strong heterogeneity. At the same time, they were close to lacustrine source rocks and gypsiferous mudstones (Sui et al, 2010) (Fig. 1(d)). The reservoir rocks consist mainly of conglomerates, pebbly sandstones, pebble-bearing sandstones, sandstones and dark-gray mudstones. The gravels and cobbles, supported by a marl matrix, are mainly limestone or granitic gneiss with angular to sub-rounded shapes. Sandstones are mainly lithic arkose or feldspathic lithic sandstones. The content of quartz ranges from 10% to 47%, with an average value of about 42%. The feldspar content varies between 10% and 43% (average 31%). The detritus content is 8%-62% with an average of 26%. The detritus consist of various composition types, but mainly of metamorphic fragments. The detrital grains are moderately-to-poorly sorted with sorting coefficient varying between 1.6 and 2.3. Cements are mainly carbonate and siliceous, and cement content varies from 3% to 28% with an average of 9.2%. The matrix content is 3%-15% with an average value of 5%.

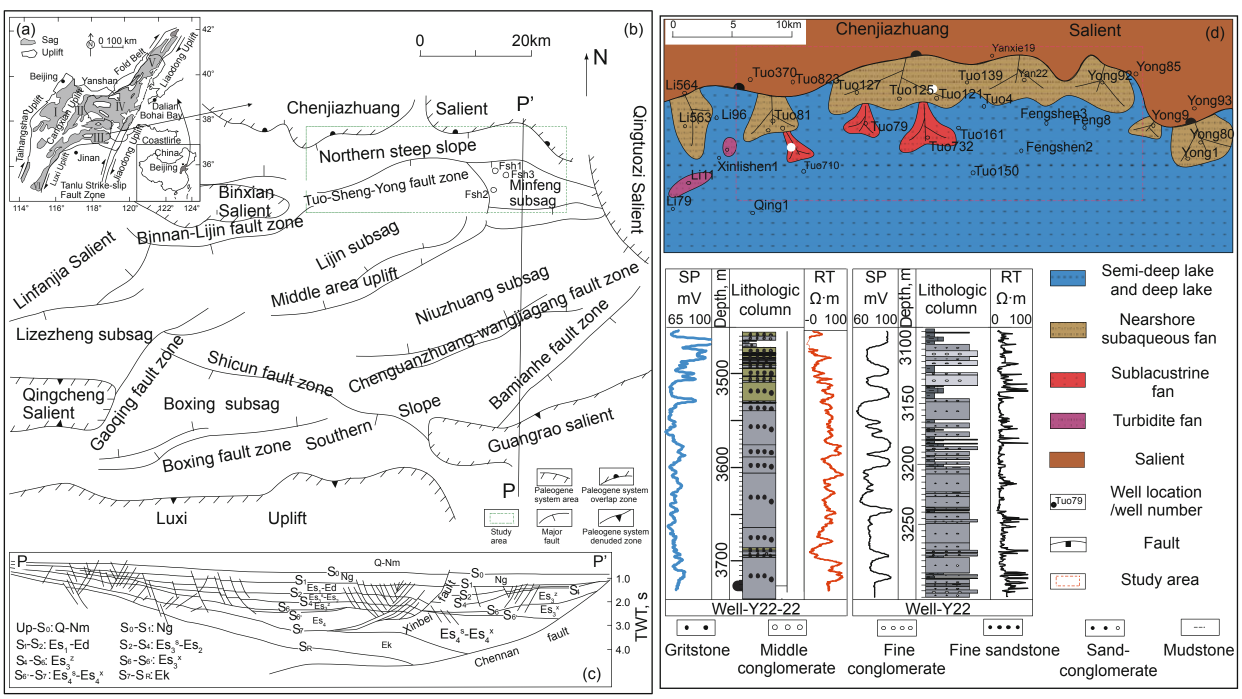


Fig. 1 Location, structure and sedimentary facies of the northern steep slope zone in the Dongying Sag, Bohai Bay Basin, East China

3 Characteristics of diagenesis

Conglomerates have experienced complex diagenetic processes of multi-stage dissolution, multi-stage cementation and complex metasomatism. Generally, compaction is intense, and the contact types are mainly point-line, line and sometime concave-convex, and suture. Chemical cements are mainly carbonate minerals and overgrowth quartz with some pyrite, overgrowth feldspar and anhydrite. Carbonate minerals include mainly ferroan calcite, ankerite, siderite, calcite, and dolomite. Metasomatism occurs mainly among carbonate cements. Sometimes quartz overgrowth is replaced by carbonate minerals, anhydrite or pyrite. Recrystallization can be found in the matrix, but mainly occurs in lime-mud. Dissolution mainly occurs among feldspars and carbonate cements, and locally among quartz particles and silica overgrowths. According to sedimentary characteristics and hydrodynamic conditions, nearshore subaqueous fans can be divided into three sub-facies: inner fan, middle fan, and outer fan. The difference of sedimentary characteristics in different sub/micro-facies leads to the differences in burial diagenesis (Sui et al, 2010).

3.1 Diagenesis in inner fans

Inner fan facies are dominated by major channels, with huge bed thickness of poorly-sorted matrix-supported conglomerates. There is a high proportion of matrix which is composed of lime-mud and sandy clastics. In order to study the mineral composition of conglomerates, samples were selected aiming at relative finer parts from cores. Diagenesis was analyzed in detail using cast thin sections. Intense compaction is the main feature of diagenesis in inner fans (Plate I(a)). When the matrix is lime-mud, recrystallization occurs. The degree of recrystallization increases with depth and even leads to particles being replaced at some depths (Plate I(b)). Cements also can be found in inner fans, but they occur at a relatively low frequency. Cement minerals are mainly carbonates, which usually fill pores or fractures (Plate I(c)). Statistics show that the content of carbonate cements is generally low, normally no more than 5%. Dissolution is weak and only occurs in feldspar particles and carbonate cements (Plate I(d)). The porosity in inner fans is mainly micropores in the matrix and dissolution pores. A small number of primary intergranular pores can be found at shallow depths, while few can be found in deeper buried layers because of strong compaction and recrystallization of the matrix (Plate I(e), (f)). As a result, porosity and permeability are poor in inner fans.

3.2 Diagenesis in middle fans

3.2.1 Diagenesis of middle fan braided channel subfacies

The lithology of middle fan braided channels is mainly gravel sandstones, gravel-bearing sandstones, middle-to-fine sandstones and siltstones. On the whole, the conglomerates of braided channels are medium sorted, with a lower content of matrix and moderate thickness. Lacustrine mudstones are generally deposited among multi-stage middle fans. Dissolution can be found in quartz and rock debris, but mainly among feldspar particles and carbonate cements (Plate II(d), (e)). Cementation minerals are mainly carbonate and quartz (Plate I(h); II(a), (b), (c)), with a little pyrite and gypsum (Plate II(b), (f)). Both primary intergranular pores and early secondary dissolved pores are severely filled in intensively cemented but weakly dissolved reservoirs (Plate II(d)). While in those weakly cemented reservoirs, primary pores are well preserved with strong dissolution.

The cement content of carbonate in braided-channel conglomerates varies according to the distance from the nearest mudstones. Cement content is commonly higher and dissolution is weaker in conglomerates close to mudstones (Fig. 2(a)) than those conglomerates far from mudstones (Fig. 2(b)). By relating the carbonate cement content of middle and outer fan to the distance between conglomerates and mudstones, we can see that carbonate cement content of conglomerates is generally more than 10%, if the distance is less than 0.52 m. But when the distance reaches 0.52-1.2 m, carbonate cement content varies between 5% and 10%. If the distance reaches 1.2 m, carbonate cement content is less than 5% (Fig. 3).

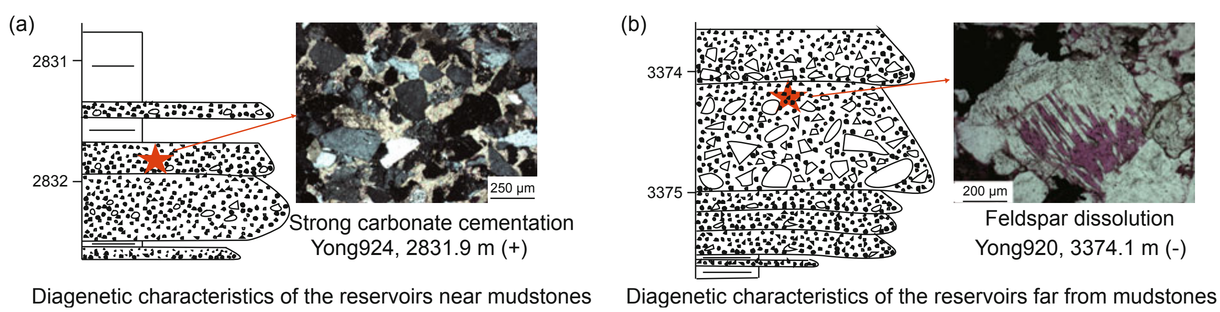


Fig. 2 Diagenetic characteristics of conglomerates in middle fan braided channels in Es_4^s in the north Minfeng Subsag, Dongying Sag

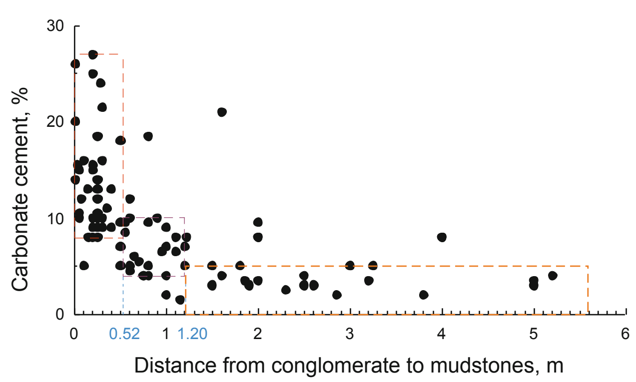


Fig. 3 The relationship between carbonate cement content and the distance between conglomerates and mudstones in braided channels in the north Minfeng Subsag

3.2.2 Diagenesis in interdistributaries in middle fan subfacies

The lithology of middle fan interdistributaries is mainly fine-grained sedimentary rocks, such as interbedded sandstones, siltstones, and mudstones. Sometimes, there are pebbly sandstones. Sandstones are poorly sorted with a high percentage of matrix. Diagenesis includes cementation and metasomatism. Cementation is strong and cement content is usually more than 10%. The cements are mainly carbonates, overgrowth quartz and a small amount of pyrite. Dissolution of feldspars and carbonate cements are two key types of dissolution, but both are relatively weak.

3.3 Diagenesis in outer fans

The lithology of outer fan subfacies is mainly thick mudstones, thin argillaceous siltstones, thin sandstones and some thin pebbly sandstones. Diagenesis is similar to that in middle fan interdistributaries. Two main types of diagenesis are cementation and metasomatism. Cements are mainly carbonates and are usually more than 10%. Quartz overgrowth is relatively intensive, and sometimes two generations of quartz overgrowth can be observed. Some pyrite can also be observed. Dissolution of feldspar and carbonate cements is relatively weak, even though they are the only two types of dissolution.

4 Diagenetic evolution sequence

4.1 Cementation and dissolution sequence

Based on the study of diagenesis, the cementation and dissolution sequence of conglomerate reservoirs in Es_4^s in the north Minfeng Subsag has been established by comprehensive analysis of the shape of authigenic minerals, replacement-crosscutting relationships, dissolving-filling relationships, homogenization temperatures of fluid-inclusions, and isotope analysis of carbon and oxygen among carbonate cements.

Carbonate cements in the research area are mainly calcite, dolomite, ferroan calcite and ankerite. Siderite cement can be found locally. Granular or lumpy siderite cements are the result of early stage diagenesis. This kind of cement can only be found locally because of the low content in rocks (Deng et al, 2004) (Plate I(g)). The formation of calcite and dolomite is relatively earlier than that of ankerite and ferroan calcite as calcite and dolomite are usually replaced by ankerite (Plate I(h)) and dolomite is replaced by ferroan calcite. On the basis of petrological studies, carbonate cements from eight conglomerate samples in Es_4^s were selectively analyzed for carbon and oxygen isotopes (Table 1). The $\delta^{18}O_{PDB}$ value of Es_4 lacustrine dolomite rocks in the Dongying Sag ranges from –1.502‰ to +0.331‰, with an average value of –0.854‰ (Liu, 1998). Assuming that the water temperature at the lake bottom is 10 °C, the calculated $\delta^{18}O$ value of lake water ranges from –35.25‰ to –33.48‰, with an average value of –34.6‰ by using dolomite-water fractionation factors of Matthews and Katz (1977). The value can be considered as the initial $\delta^{18}O$ values of pore fluid during early burial. Precipitation temperatures of carbonate cements were calculated by using $\delta^{18}O$ composition (Matthews and Katz, 1977; Coplen et al, 1983; O'Neil et al, 1969) (Table 1): Precipitation temperatures of calcites and dolomites are between 63 °C and 81 °C. As a result, those calcites and dolomites can be assumed to be a result of early stage diagenesis; the precipitation temperature of ferroan calcite and ankerite is about 122 °C, and those minerals are the result of late stage diagenesis. The content of ankerite cements from one sample at the depth of 3,756.3 m in Yong928 well is up to 70% with a precipitation temperature of 81 °C. From the reasoning above, we can conclude that the ankerite might have been formed by replacing earlier carbonate cements.

Table 1 Isotopic composition of Es_4^s conglomerates in the north steep slope zone of the Minfeng Subsag

Well	Depth, m	Strata	Carbonate minerals	Carbonate cement, %	$\delta^{18}O_{PDB}$, ‰	$\delta^{13}C_{PDB}$, ‰	Temp., °C $\delta^{18}O_{PDB}$=-34.6‰
Yong92	2972.72	Es_4^s	80%Ca+20%An	10.00	-13.33	2.29	66
Yong924	2866.80	Es_4^s	40%Ca+40%Do+20%An	8.00	-12.96	2.07	____
Yong925	2730.51	Es_4^s	90%Do+10%An	0.10	-13.46	3.18	81
Yan23	3672.85	Es_4^s	100%Do	26.00	-10.74	5.65	63
Yong920	3370.90	Es_4^s	90%An+10%Ca	10.00	-18.38	-2.10	123
Yong928	3756.30	Es_4^s	70%An+30%Do	7.00	-13.48	0.68	81
Yanxie21	3045.40	Es_4^s	40%An+30%Fc+30%Ca	6.00	-14.59	1.43	____
Yong924	2892.01	Es_4^s	20%Fc+80%An	8.00	-18.32	1.97	12

Notes: the formula used in calculating calcite mineral temperature is $1000\ln \alpha_{calcite\text{-}water}=2.78\times10^6/T^2-2.89$ (O'Neil et al, 1969), the formula used in calculating dolomite mineral temperature is $1000\ln \alpha_{dolomite\text{-}water}=3.06\times10^6/T^2-3.24$ (Matthews and Katz, 1977), and $1000\ln \alpha_{carbon\text{-}water}=\delta^{18}O_{carbonate}-\delta^{18}O_{water}$

The isotopic composition of carbon in carbonate cement can be used to determine its source (Curtis, 1978; Fayek et al, 2001; Dutton and Loucks, 2010). In general, carbonate precipitated in bacterial fermentation zones has the most positive $\delta^{13}C$ values, which can be as high as +15‰, while carbonate precipitates with organic carbon from decarboxylation of organic matter in source rocks have the most negative $\delta^{13}C$, which can be as low as –20‰ (Curtis, 1978). The $\delta^{13}C_{PDB}$ values of Es_4 lacustrine carbonate in the Dongying Sag range from –5.48‰ to 6.30‰ (Liu, 1998). Early dolomites and calcites of Es_4^s in the north Minfeng Subsag exhibit a relative wide range of $\delta^{13}C$, from 2.07‰ to 5.65‰. During the Es_4^s deposition period, carbonate minerals in mudstones could be dissolved by CO_2 generated by bacterial action, with $\delta^{13}C$ values between +3‰ and +10‰ (Liu, 1998). Therefore, carbonate minerals in adjacent mudstones may also be an important carbon source for carbonate cements in reservoirs. Ferroan calcite and ankerite formed at a late stage have relatively negative $\delta^{13}C$ values ranging from –2.1‰ to 1.97‰, which probably represent a mixture of carbon from decarboxylation of organic matter or from carbonate from dissolution in source rocks (Dutton and Loucks, 2010; Zeng et al, 2006). Therefore, carbonate cements in middle and outer fan conglomerates on the north steep slope of the Minfeng Subsag are mostly from carbonate minerals dissolved by organic acid from decarboxylation of organic matter in adjacent mudstones at a late period, and relatively small amounts are from carbonate minerals in adjacent mudstones dissolved by CO_2 during eodiagenesis. During the period of decarboxylation of organic matter, the transition from smectite to illite/smectite (I/S), as well as gypsum dehydration in mudstones, would release significant amount of metal ions, such as Ca^{2+}, Mg^{2+} and Fe^{2+}, into adjacent conglomerates. The maximum concentration of metal ions is at conglomerate-mudstone contact interfaces, and the value gradually reduces with the increase of distance from conglomerate to mudstones. As a result, relatively extensive cementation occurs along conglomerate boundaries and leads to severe damage to existing pores. Decrease of porosity along conglomerate boundaries makes it difficult for hydrocarbon to migrate to the inner part of conglomerate bodies. Moreover, the chance of being reworked by later entering acid fluids is also reduced. When cementation is weak inside the conglomerate, hydrocarbon has the opportunity to accumulate, which can prevent further diagenesis from happening later. As a result, a large amount of porosity can be preserved. Owing to the process mentioned above, the phenomenon of strong cementation at conglomerate-mudstone interfaces reducing in the interior of the conglomerate is very common in Es_4 conglomerate layers. Some previous studies also show that diagenetic evolution of mudstones has a great influence on pore evolution in sandstones near the sandstone-mudstone interface area (Zhong et al, 2004; Cao et al, 2014; Qi et al, 2006; Zhang et al, 2009; Dutton et al, 2002; Dutton, 2008; Nyman et al, 2014; Wolela, 2012; Day-Stirrat et al, 2010). According to Zhong et al (2004), when deeply buried sandstone layers (>2,500 m) are interbedded with mudstone layers, cementation in those sandstones near sandstone-mudstone interfaces is stronger than that in the inner parts of sandstones, which results in porosity and permeability of sandstones near interfaces being worse than their internal counterparts. Qi et al (2006) believes that there are tight calcareous crusts in contact zones between sand lenses and calcareous mudstones, which leads to low porosity and permeability in sandstones.

There are two preconditions for carbonate recrystallization: 1) proper temperature and pressure (Deng et al, 2004; Hartig et al, 2011; Qi, 2006; Guo et al, 2009); 2) existence of exotic alkaline thermal fluids with enough calcium (Hartig et al, 2011; Kang, 2007; Zhu et al, 2008; Liu et al, 2008). According to Heydari and Wade (2002), carbonate recrystallization begins at temperatures of 50 °C - 75 °C and continues to a depth over 4,000 m. Lime-mud matrix recrystallization in inner fans needs participation of exotic fluids, as pore water in inner fans had already been mostly discharged at shallow depths by continuous compaction. As a result, it is reasonable to believe that lime-mud matrix recrystallization in inner fans happened at the same period as carbonate cementation occurred because of the involvement of exotic alkaline fluids. According to Wang (2010), decarboxylation of organic acids and dehydration of gypsum happened between 32 Ma B.P. and 24.6 Ma B.P. at a temperature of 85 °C - 130 °C. The combined effects of those two events led to the conglomerate formations being alkaline. In an alkaline environment, a large amount of cations, such as Ca^{2+}, Mg^{2+} and Fe^{3+} entered middle fans and inner fans, and carbonate cementation and lime-mud matrix recrystallization took place respectively. With the increase of burial depth, the degree of lime-mud matrix recrystallization in inner fans increases gradually and the content of minerals undergoing recrystallization also increases. In deep layers, the degree of recrystallization deepens, while the content of minerals undergoing recrystallization increases only slightly (Plate I(b), (e), (f)).

Quartz overgrowth is replaced by carbonate (Plate II(a)), which implies that quartz overgrowth occurs earlier than carbonate cements. However, multi-stage quartz overgrowth may indicate that quartz also experienced overgrowth at a later time (Plate II(c)). Because carbonate cementation and quartz dissolution both take place in an alkaline environment, that means they may happen at the same diagenetic process. The phenomena of carbonate cements filling feldspar-dissolved pores (Plate II(d)) and dissolution of carbonate cements (Plate II(e)) indicates that reservoirs have experienced two stages of acid dissolution: the early stage of feldspar dissolution and the late stage of carbonate cement dissolution. In an acidic environment, SiO_2 is one of the products of feldspar dissolution, which then precipitates as quartz overgrowth. In this study, the average homogenization temperature of brine inclusions in quartz overgrowth is 110 °C - 118 °C and the average homogenization temperature of oil inclusions is 91 °C, while the average homogenization temperature of oil inclusion in feldspar-dissolved pores is 87 °C (Table 2). According to the burial history of the Fengshen1 well (Song et al, 2009), quartz overgrowth was formed at about 36 Ma, which indicates that feldspar dissolution and early stage quartz overgrowth occur at the same time.

The phenomenon of quartz overgrowth being replaced by anhydrite cements (Plate II(b)) indicates that anhydrite was formed later than the first stage of quartz overgrowth, but it is difficult to determine whether it was later than the second stage of quartz overgrowth. Both gypsum layers in Es_4^x

Table 2 Homogenization temperatures of fluid-inclusions of reservoirs in Es_4^s in the north zone of the Minfeng Subsag

Well number	Depth, m	Horizon	Host minerals	Types	Number of inclusions	Average homogenization temperature, °C
Yan22-22	3403	Es_4^s	Quartz overgrowth	Brine	1	110
Yan22-22	3403	Es_4^s	Quartz overgrowth	Brine	1	115
Yong928	3757.1	Es_4^s	Quartz overgrowth	Brine	1	111
Fengshen1*	3684.9	Es_4^s	Quartz overgrowth	Brine	6	118
Fengshen1*	3684.9	Es_4^s	Quartz overgrowth	Petroleum	4	76
Fengshen1*	3684.9	Es_4^s	Feldspar-dissolved pore	Petroleum	2	87
Yong921*	2789	Es_4^s	Quartz overgrowth	Petroleum	2	91

*Notes: from Geological Science Research Institute of the Shengli Oilfield and gypsum-bearing mudstones in Es_4^s dehydrated at high temperature. The dehydrated water with high concentration of Ca^{2+} and SO_4^{2-} was released into Es_4^s conglomerates, forming late stage anhydrite. However, during the Es_4^s deposition period, the north Minfeng Subsag was in an alkaline reducing environment in a deep body of water. So, it indicates that the primary formation water was alkaline (Wang, 2010), which meets the requirement of gypsum precipitation during syngenesis and eodiagenesis. Therefore, anhydrite should have formed by dehydration at high temperatures in conglomerates at the early stage of diagenesis.

From the phenomena of quartz overgrowth and carbonate cements being replaced by pyrite (Plate II(g)-(h)), it is reasonable to believe that some pyrite cements are formed late even though the formation of spherulitic pyrite cement in the early stage cannot be excluded (Plate II(f)).

Combining different research results, we believe that the diagenetic evolution sequence of conglomerate in Es_4^s in the north Minfeng Subsag consists of four stages: 1) early pyrite cementation, siderite cementation, gypsum cementation, calcite cementation, dolomite cementation; 2) feldspar dissolution, quartz overgrowth; 3) quartz dissolution, ferroan calcite cementation, ankerite cementation, lime-mud matrix recrystallization, feldspar overgrowth, anhydrite cementation; 4) carbonate dissolution, feldspar dissolution, quartz overgrowth, pyrite cementation.

4.2 Differences of diagenetic evolution among different subfacies

On the basis of comprehensive analyses of burial history, thermal evolution of organic matter, dehydration of gypsum layers, transformation of clay minerals and the history of hydrocarbon accumulation, Wang (2010) believed that reservoirs in Es_4^s on the north steep slope of the Minfeng Subsag experienced diagenetic environment alternation between acidity and alkalinity. The coexistence of gypsum-bearing mudstones and deep water source rocks implies that when Es_4^s was deposited, the salty lake environment was alkaline and reducing. As a result, conglomerates were primarily filled with alkaline formation water. From the time of Es_4^s deposition to 42.5 Ma B.P. (the early period of the deposition of Es_3^x), organic matter were not mature enough and the conglomerates were still filled with weakly-alkaline fluids. From 42.5 Ma B.P. to 32 Ma B.P., it was an acidic environment caused by the conversion of organic matter to organic acids. From 32 Ma B.P. to 24.6 Ma B.P., hydrocarbon charging happened, as well as decarboxylation of organic acids and dehydration of gypsum, the combination of those processes led to alkaline formation water. From 24.6 Ma B.P. to 6 Ma B.P., the strata were uplifted at first and then subsided. During the uplifting period, organic matter generated organic acids causing the formation water to become acidic. From 6 Ma B.P. to present, the second hydrocarbon charging took place. At about 2 Ma B.P., gypsum layers in Es_4^s entered a large-scale dehydration stage again, and made the formation fluids weakly alkaline. The formation fluids in Es_4^s still remained weakly alkaline to the present time (the value of pH is 7-8.5) (Wang, 2010). With the analysis of the diagenetic environment, it is clear that under certain diagenetic environments, sedimentary differences among different sub/micro-facies of nearshore subaqueous fans result in significant differences in the degree of completion of diagenesis (Fig. 4).

Inner fan conglomerates of nearshore subaqueous fans have low primary porosity, poor sorting, and high matrix content. Compaction was the main diagenesis type which had continually reduced the porosity before 42.5 Ma B.P.. From 42.5 Ma B.P. to 32 Ma B.P., dissolution occurred caused by organic acids. Because the dissolution was relatively weak, the porosity kept reducing because porosity increase caused by dissolution was much less than the porosity decrease caused by compaction. From 32 Ma B.P. to 24.6 Ma B.P., the temperature of the top of Es_4^s increased from 85 °C to 105 °C, and the temperature of the bottom of Es_4^s increased from 120 °C to 130 °C. Meanwhile lots of alkaline water from dehydration of gypsum at the top of Es_4^x made the formation water alkaline. During this period, high formation temperatures and exotic alkaline fluids led to lime-mud matrix recrystallization in inner fan conglomerates, which resulted in an increase of calcium carbonate, as well as replacement of particles by calcium carbonate and the inner fan conglomerates getting denser. From 24.6 Ma B.P. to present, compaction and recrystallization in inner fans were continuously strengthened, but dissolution remained weak. As porosity and permeability in inner fans got worse and worse, the inner fans could act as lateral seals (Fig. 5).

The primary porosity of middle fan braided channel reservoirs far from mudstones is high. 42.5 Ma B.P. ago, diagenesis had been mainly compaction and weak cementation of pyrite, gypsum, siderite, calcite and dolomite, which reduced the porosity continuously. From 42.5 Ma B.P. to 32 Ma B.P., strong feldspar dissolution and quartz overgrowth took place and porosity and permeability improved significantly. From 32 Ma B.P. to 24.6 Ma B.P., ferroan calcite and ankerite cementation and quartz dissolution occurred under alkaline conditions. However, the first hydrocarbon charging occurred during this period. Cementation was inhibited and reservoir porosity was well preserved at this stage. From 24.6 Ma B.P. to 6 Ma B.P., the second stage acid dissolution took place, which caused further improvement in porosity and permeability of reservoirs. From 6 Ma B.P. to present, hydrocarbon accumulation occurred again and the porosity and permeability of reservoirs only changed slightly.

The primary porosity was moderate in middle fans near mudstones (braided channel reservoirs and interdistributary reservoirs) and outer fans. 42.5 Ma B.P. ago, diagenesis types were compaction and cementation of pyrite, gypsum, siderite, calcite and dolomite, which made porosity poorer and poorer. From 42.5 Ma B.P. to 32 Ma B.P., feldspar dissolution and quartz overgrowth took place, as a result porosity increased. From 32 Ma B.P. to 24.6 Ma B.P., strong ferroan calcite and ankerite cementation resulted in the intergranular primary pores and the secondary dissolved pores being filled tightly. So the reservoir porosity was reduced to an extremely low degree and porosity and permeability of reservoirs were very poor. From 24.6 Ma B.P. to 2 Ma B.P., formation water was

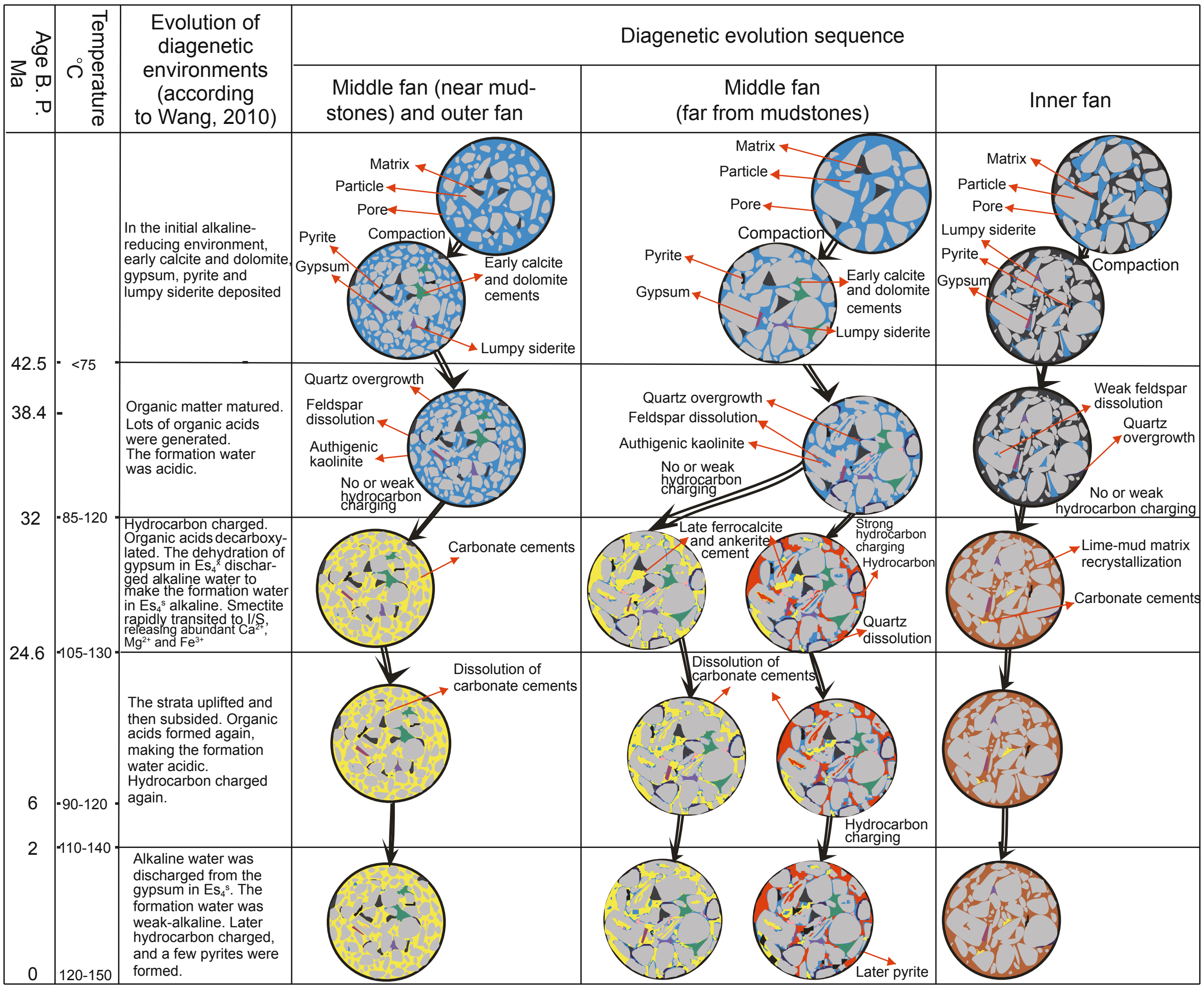


Fig. 4 Diagenetic evolution and fluid composition in Es_4^s in the north steep slope zone of the Minfeng Subsag

acidic. However, it was very difficult for acidic fluids to flow into reservoirs with poor permeability, which resulted in weak dissolution and only a slight increase in porosity. From 2 Ma B.P. to present, the reservoirs with poor porosity and permeability were mainly ineffective.

5 Mechanism of the formation of diagenetic traps in nearshore subaqueous fans

The concept of diagenetic trap was used by W. D. Lowry and H. Wilson, which was vividly called "frozen reservoir" at that time. Many studies of the mechanisms of diagenetic trap formation have been published by scholars across the world, and it is believed that tight sealing layers (upwards or lateral) formed by diagenesis are necessary for the formation of diagenetic traps (Yan, 1987; Wang, 2003; Zhang et al, 2005). They have also proposed several genetic mechanisms, such as thermal convection (Yang et al, 2007; Kuang et al, 2008), physical and chemical differences of fluid, tectonic activities (Cant and Zhang, 1986), interbedding with mudstones (Zhong et al, 2004; Si et al, 2008), existence of fractures (Yan, 1987), burial depth and differential subsidence (Wang, 2003; Cant and Zhang, 1986; Si et al, 2008), and differences of sedimentary fabrics (Sui et al, 2010). According to the theory of caprocks, layers with poor porosity and permeability can prevent hydrocarbon in reservoirs from escaping (Li, 1994). That is to say hydrocarbon cannot migrate through diagenetic seals when the migration dynamic cannot overcome the minimum difference of displacement pressure between sealing layers and reservoirs. The displacement pressure difference between diagenetic tight sealing layers and reservoirs is influenced by two main factors: 1) absolute values of porosity and permeability of diagenetic tight layers and 2) the difference of porosity and permeability between tight sealing layers and reservoirs. The sealing ability of diagenetic tight layers and the formation of diagenetic traps are controlled by those two factors.

Inner fan conglomerates of nearshore subaqueous fans in Es_4^s on the north steep slope of the Minfeng Subsag mainly experienced compaction, lime-mud matrix recrystallization and weak dissolution. As a result, the porosity and permeability of inner fan conglomerates kept reducing. In middle-to-deep layers buried deeper than 3,200 m, lime-mud matrix recrystallization resulted in a rapid reduction of porosity and permeability in inner fans, which led to the formation of diagenetic tight layers. Porosities of inner fan conglomerates are lower than the threshold of effective reservoirs. There are only dry conglomerate layers in middle-to-deep layers buried deeper than 3,200 m (Fig. 6(a)). Because of acid dissolution and inhibition of cementation by

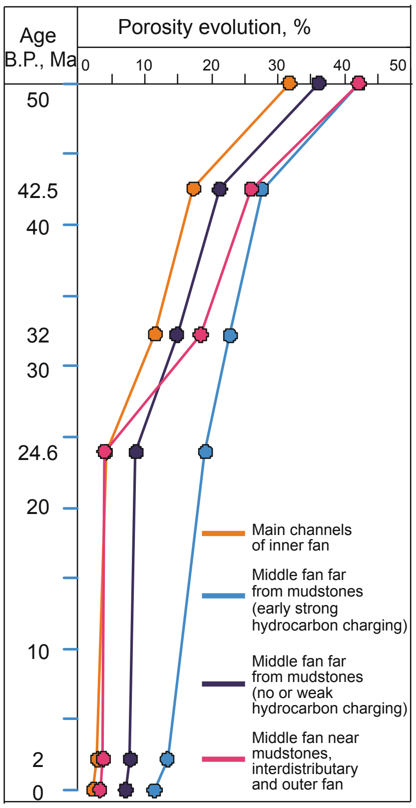
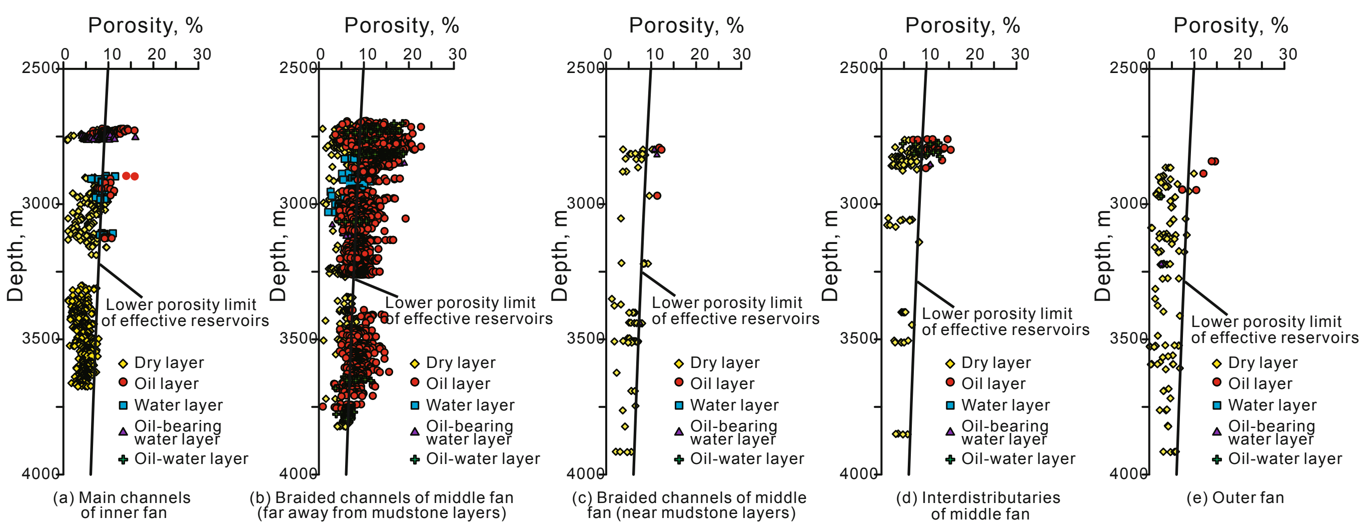


Fig. 5 Porosity evolution of different subfacies in nearshore subaqueous fans according to Wang et al (2013)

hydrocarbon charging, a great number of primary pores are preserved in the reservoirs far away from mudstone layers and secondary pores are developed. Those conglomerates have higher porosity and permeability, and can be effective hydrocarbon reservoirs. As a result, abundant oil or water can be found in those layers, whether they are shallow or deeply buried (Fig. 6(b)). Porosity and permeability are poorly developed in reservoirs adjacent to mudstone layers because of intense cementation, whether they are deposited in middle fan braided channels, in middle fan interdistributaries or in outer fans. Only a few oil layers are found in shallow depths, less than 3,000 m, and all of the layers are dry when they are buried deeper than 3,000 m (Fig. 6(c), (d), (e)). From the section map of Es_4^s in the north Minfeng Subsag, it is obvious that inner fan conglomerates layers adjacent to middle and outer fan mudstone layers are mainly dry layers, while oil or water bearing layers mostly develop in conglomerate reservoirs far away from mudstone layers in middle fan (Fig. 7).

Comprehensive analysis shows that with an increase in burial depth, deterioration in porosity and permeability of inner fan conglomerates and enlargement of physical property differences between inner fans and middle fans led to an increase of the sealing ability of inner fan conglomerates. Thus inner fan conglomerates can act as seals when their burial depth reaches middle depth. Conglomerates adjacent to middle fan mudstone layers and those in middle fan interdistributaries can be good cap rocks with tight cement



Notes: porosity and oiliness data are from 17 wells, including 1,120 samples from core analysis and 2,113 from logging interpretation. The lower porosity limits of effective reservoirs are from Wang (2010)

Fig. 6 Relationship of porosity and oiliness on the basis of sedimentary microfacies and depth (Es_4^s samples in the north steep slope zone of the Minfeng Subsag)

crusts at top or bottom of sand bodies caused by intense cementation. Lacustrine mudstones interlayered with multi-period fans can also be good cap rocks. Conglomerates far away from middle fan mudstone layers can be oil and gas bearing reservoirs of moderate to good quality.

In conclusion, diagenetic traps in conglomerates can develop as follows: Inner fan conglomerates can act as lateral or vertical seals, tight carbonate crusts near mudstone layers in middle fan braided channels and lacustrine mudstones among multi-period fans as cap rocks, and conglomerates far from mudstone layers in middle fan braided channels as reservoirs. There are two types of diagenetic traps. One type

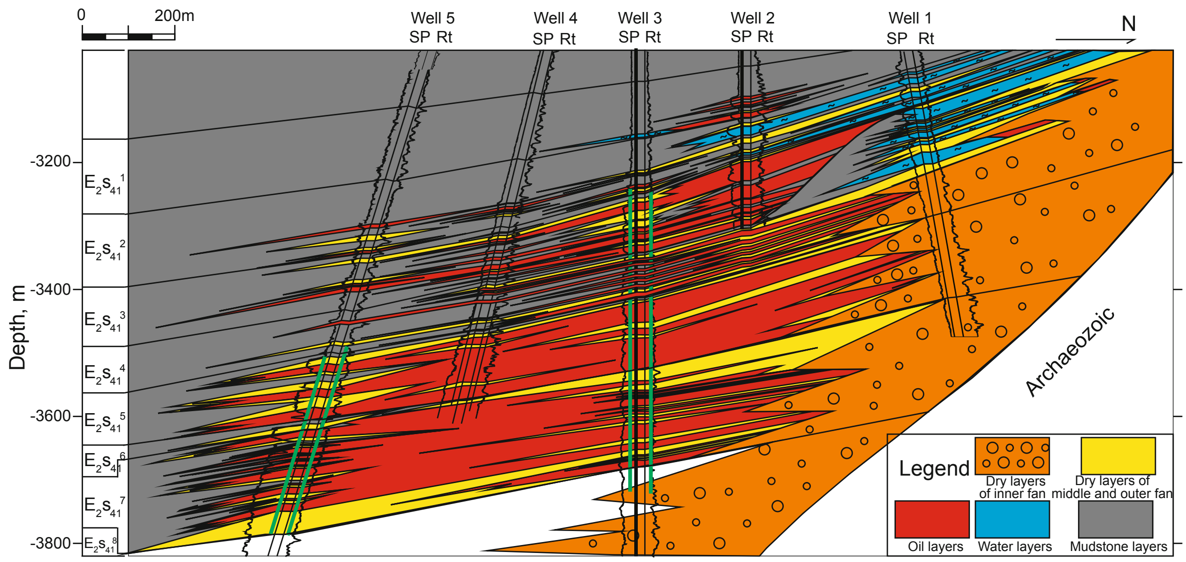


Fig. 7 Reservoir section map of Es_4^s in the north Minfeng Subsag (according to Geological Science Research Institute of Shengli Oilfield, modified)

is with inner fan conglomerates of the same period acting as lateral seals and tight carbonate crusts near mudstone layers and lacustrine mudstones acting as cap rocks (Fig. 8 type II). Another type is with inner fan conglomerates of the same period acting as lateral seals, but inner fan conglomerates of a later stage, tight carbonate crusts near mudstone layers in middle fans, and lacustrine mudstones acting as cap rocks (Fig. 8 type I). Under regression sequence conditions, inner fan conglomerates may lie directly over early middle fan conglomerates and act as cap rocks. In both of these types of diagenetic traps, the displacement pressure differences are enormous whether they are between mudstones and middle fan conglomerates or between tight carbonate crusts and middle fan conglomerates far from mudstone layers. So the absolute porosity and permeability of inner fans and the difference of porosity and permeability between inner fans and middle fans control the quality of seals in diagenetic traps.

We found that the lithological association of conglomerates (or conglomerate-sandstones) in inner fans and pebbly sandstones in middle fans determined the quality of seals in diagenetic traps. We calculated the maximum height of oil columns sealed by the difference of displacement

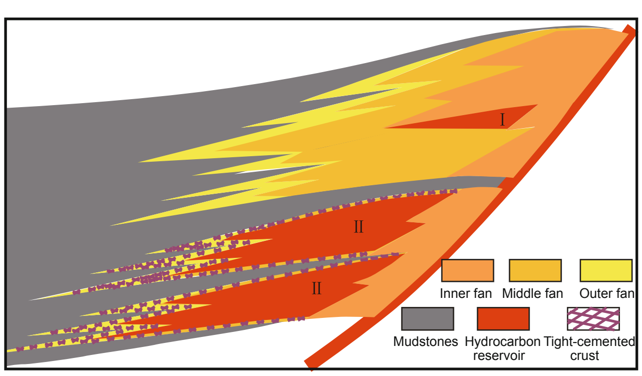


Fig. 8 Sketch map showing genetic mechanisms of diagenetic traps in nearshore subaqueous fans in Es_4^s in the north Minfeng Subsag

pressure between conglomerates (or conglomerate-sandstones) and pebbly sandstones, and made a comparison with the actual oil column heights in Es_4^s in the north Minfeng Subsag (Fig. 9). The figure shows that inner fans buried less than 2,200 m can hardly seal petroleum; from 2,200 m to 3,200 m, the sealing ability of inner fans increases gradually with the increase of burial depth, and this depth interval belongs to the transition zone of sealing ability; the sealing ability of inner fans buried more than 3,200 m reaches a maximum value, and conglomerates at this depth are the best objectives to explore for lithological traps. As shown in the section map of Es_4^s in the north Minfeng Subsag (Fig. 7), the scale of oil reservoirs in nearshore subaqueous fans is relatively small in shallow layers buried less than 3,200 m. Also, oil reservoirs get smaller in scale along with the depth being shallower when they are buried less than 3,200 m. In layers deeper than 3,200 m, the scale of oil reservoirs in nearshore subaqueous fans is relatively large, and the scale of oil accumulation gets larger with the increase of depth. This phenomenon shows that the quality of lateral seals is low in nearshore subaqueous inner fan reservoirs in shallow formations (less than 3,200 m). As a result, even though there are effective reservoirs, it is difficult for them to accumulate oil (or just small scale diagenetic hydrocarbon traps are formed) if there were no structural traps. But in deep formations, there are effective lateral seals for nearshore subaqueous inner fan reservoirs, diagenetic hydrocarbon traps can be formed by the lateral sealing of inner fans.

In conclusion, lime-mud matrix recrystallization of inner fan conglomerates and carbonate cementation of conglomerates adjacent to mudstone layers in middle fan braided channels took place from 32 Ma B.P. to 24.6 Ma B.P., thus the formation of diagenetic traps is from 32 Ma B.P. to 24.6 Ma B.P. and diagenetic traps have better seals after 24 Ma B.P.. In depth, diagenetic traps buried from 2,200 m to 3,200 m have relatively weak seals and diagenetic traps buried more than 3,200 m have relatively good seals.

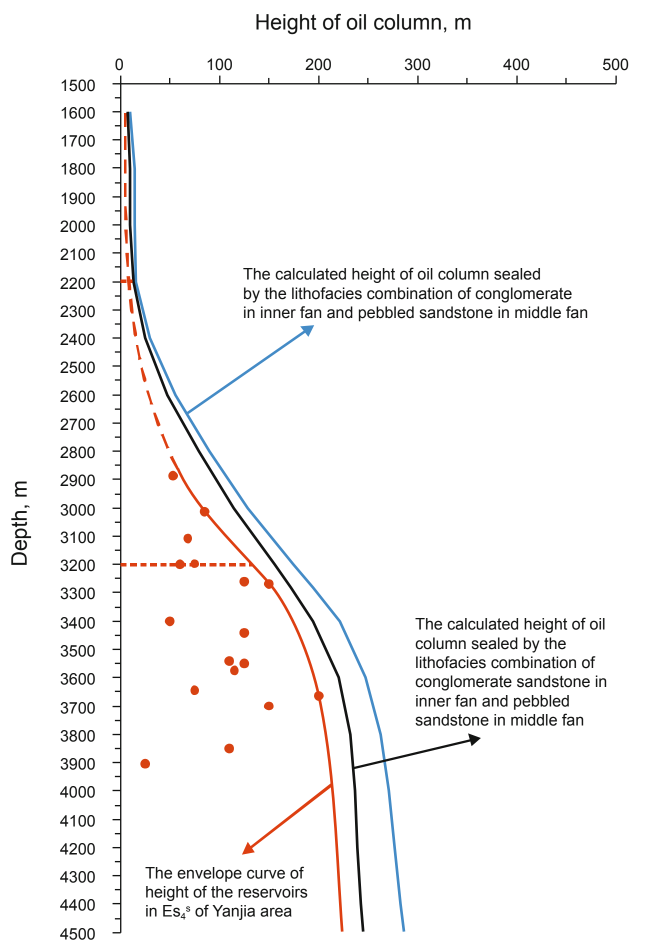


Fig. 9 A contrast between the calculated maximum height of oil columns sealed by inner fan and middle fan lithofacies and the actual height of hydrocarbon reservoirs in Es_4^s in the north Minfeng Subsag (the data of actual height of reservoirs from the Geological Science Research Institute of Shengli Oilfield, SINOPEC)

6 Conclusions

1) The difference in sedimentary characteristics in different sub/micro-facies of nearshore subaqueous fans in the north steep slope zones in rift basins controls diagenetic characteristics. Conglomerates of nearshore subaqueous fans in Es_4^s in the north Minfeng Subsag of the Dongying Sag experienced a diagenetic environment of "alkaline–acidic–alkaline–acidic–weak alkaline" and a cementation and dissolution sequence of "early pyrite cementation / siderite cementation / gypsum cementation / calcite and dolomite cementation → feldspar dissolution / quartz overgrowth → quartz dissolution / ferroan calcite cementation / ankerite cementation / lime-mud matrix recrystallization / feldspar overgrowth → carbonate dissolution / feldspar dissolution / quartz overgrowth / pyrite cementation". Inner fan conglomerates mainly experienced compaction and lime-mud matrix recrystallization, with weak dissolution in the process of burial evolution. So the porosity and permeability of inner fan conglomerates kept reducing and lime-mud matrix recrystallization results in a rapid reduction in porosity and permeability of inner fan conglomerates in middle-deep layers. Because two stages of acid dissolution reworked the reservoirs and the existence of hydrocarbon inhibits cementation, the reservoirs far away from mudstone layers in the middle fan braided channels developed a great number of primary pores and secondary pores in middle-to-deep layers, and can be regarded as effective reservoirs of hydrocarbon. Reservoirs adjacent to mudstone layers in middle fan braided channels, reservoirs in middle fan interdistributaries and outer fan reservoirs have undergone intense cementation and metasomatism.

2) Diagenesis differences in different sub/micro-facies control the formation of diagenetic traps. With an increase in burial depth, the decrease of porosity and permeability of inner fan conglomerates and the enlargement of the physical property difference between inner fan and middle fan facies enhance the sealing ability of inner fans. Thus, conglomerates in inner fans can be sealing layers. The tight carbonate crusts near mudstone layers in middle fan braided channels as well as lacustrine mudstones can be cap rocks. The conglomerates far from mudstone layers in middle fan braided channels can be reservoir rocks. Therefore, diagenetic traps in conglomerates can be developed as "inner fan conglomerates as lateral or vertical sealing layers, tight carbonate crusts near mudstone layers in middle fan braided channels and lacustrine mudstones as cap rocks, and conglomerates far from mudstone layers in middle fan braided channels as reservoir rocks".

3) Deep diagenetic traps in conglomerates of nearshore subaqueous fans in the steep slope zones in rift basins are close to source rocks. Some conglomerates have the ability to seal hydrocarbon from further migration and some have the ability to form reservoirs. Due to the existence of tight carbonate-cemented crusts, middle fan conglomerates with thicknesses of more than 2 m can be favorable targets for hydrocarbon exploration.

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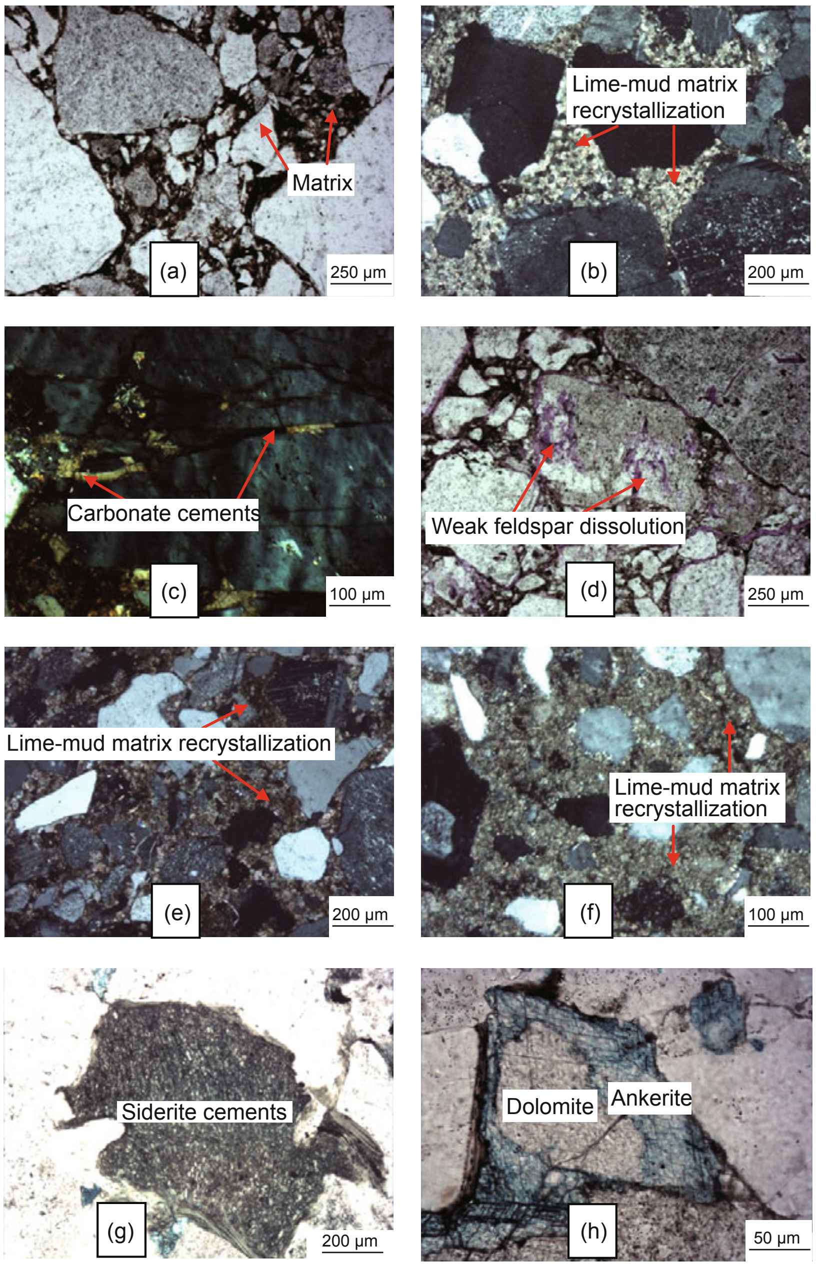
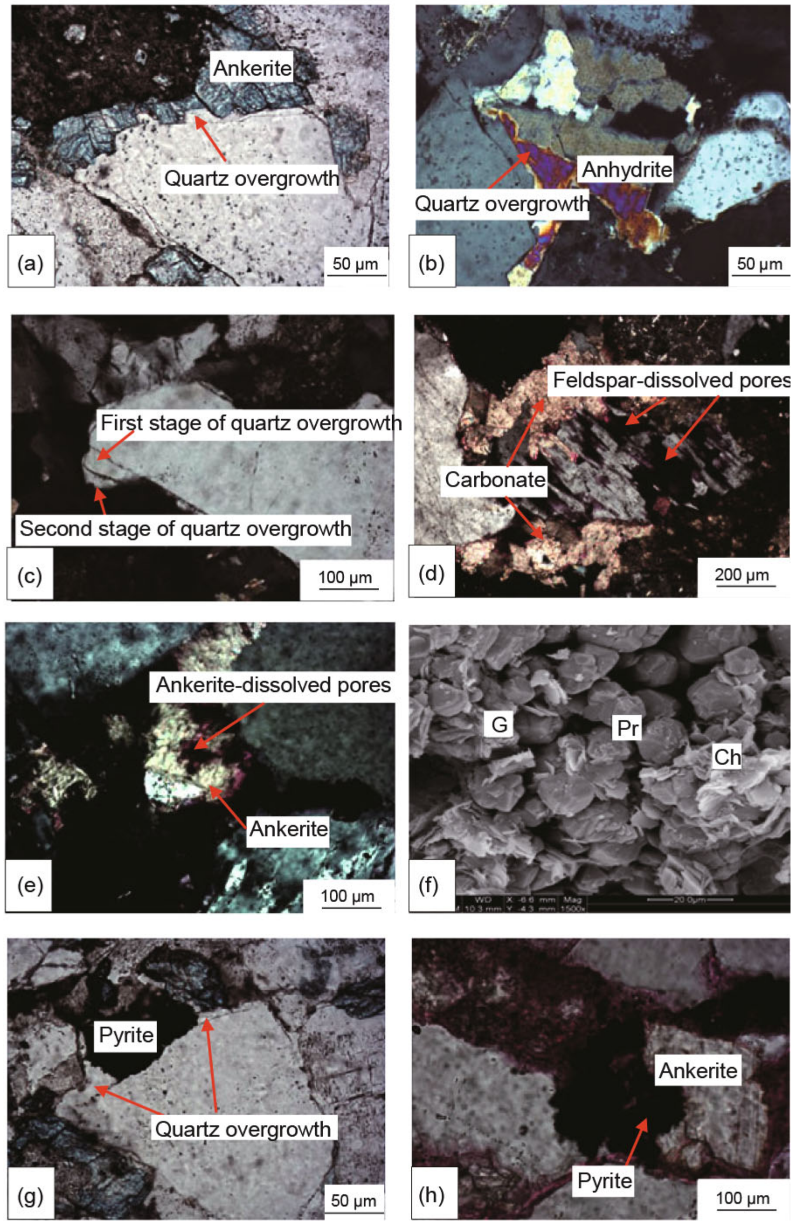
Plate I



(a): Yong920 well, 3585.5 m, (-), high matrix content, strong compaction. (b): Fengshen10 well, 4320.5 m, (+), strong lime-mud matrix recrystallization. (c): Yan227 well, 3840.1 m, (+), carbonate cements filling compacted cracks of particles. (d): Yong920 well, 3585.5 m, (-), weak feldspar dissolution. (e): Yong930 well, 3994.8 m, (+), lime-mud matrix recrystallization. (f): Fengshen10 well, 4320.5 m, (+), lime-mud matrix recrystallization. (g): Yanxie21 well, 3137.7 m, (-), siderite cements. (h): Yan 22-22 well, 3431.5 m, (-), ankerite replacing dolomite

Plate II



(a): Yan22-22 well, 3431.5 m, (-), ankerite replacing quartz overgrowth. (b): Yong924 well, 2846.61 m, (+), anhydrite replacing quartz overgrowth. (c): Yan22-22, 3499.5 m, (+), two stages of quartz overgrowth. (d): Yan22 well, 3239.1 m, (+), carbonate filling parts of feldspar-dissolved pores. (e): Yanxie21 well, 3053.65 m, (+), ankerite cements dissolution. (f): Yanxie21 well, 3137.7 m, spheroidic pyrite (Pr) cements and anhydrite cements. (g): Yan22-22 well, 3431.5 m, (-), pyrite replacing quartz overgrowth. (h): Yong920 well, 3374.1 m, (-), pyrite replacing ankerite

(Edited by Hao Jie)