

Fan delta sedimentation in eocene of nanpu depression, northeastern china

Abstract

The Eocene Nanpu depression is located in the north part of Bohai bay basin and is an EW-trending depression, filled with associated coarse clastic deposits in the northern margin. Two fan delta systems have been recognized in the Eocene deposits of the depression. Transgressive fan delta and regressive fan delta systems were deposited when the basin was actively subsiding and uplifting. The transgressive fan deposits comprise proximal fan, middle fan and distal fan, and regressive fan delta can be divided into fan delta plain, fan delta front and prodelta subfacies. Detailed lithofacies studies have been carried out in the Eocene Nanpu depression. Ten lithofacies are present: massive conglomerate (Gm), massive or weakly to poor stratified conglomerate (Gms), stratified gravely sandstone (Gt), medium to very coarse-grained massive sandstone (Sm), coarse-grained trough cross-bedded sandstone (St), medium- to coarse-grained planar cross-bedded sandstone (Sp), pipple cross-laminated sandstone (Sr), very fine- to medium-grained sandstone with flat bedding (Sh), parallel laminated siltstone and claystone (Fl), massive mudstone (Fm). The origin, characteristics, distribution and spatial arrangement of the various lithofacies represent sediments distribution characteristics of different subfacies. Fan delta depositional systems developed good reservoir, and becoming one of the main oil and gas exploration targets. Therefore, the study of the fan delta sedimentary characteristics is of great value.

Keywords: shahejie formation, nanpu depression, fan delta, lithofacies, sedimentary model

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Introduction

The term “fan delta” was first introduced into the geological literature over five decades ago by Holmes. Fan deltas are common depositional systems in lacustrine and marine rift basin.¹⁻³ Now, fan deltas have begun to be recognized more widely in the rocks record and have become the focus of considerable geological interest.²⁻³

This is primarily because the sedimentary record of fan deltas proves to be of great value to basin analysis and to the reconstruction of basin margin sedimentary model. It normally also provide much information about the source-area evolution as well and an additional reason for studying fan delta deposits is that they can act as hydrocarbon reservoirs, due to their abrupt lithologic changes.⁴ A great deal of researches on the sedimentary characteristics of fan delta systems around the world have been made using different data and various methods. The purpose of this paper is to document and interpret two types of geologically young (Eocene) fan delta systems in Shahejie formation of Nanpu depression and make a contribution to the understanding of the wide range of different fan delta types and geological setting associated. The Eocene fan delta sandstone of Nanpu depression is one of the most important sets of oil and gas reservoir. According to core observations and descriptions combined with electrical properties and regional sedimentary background, two fan delta systems have been recognized. It is of great academic value to study the sedimentary characteristics of the Eocene fan delta of Nanpu depression. Furthermore, the study could guide the oil and gas exploration in this area and have broad implications for other similar basins.

Geological setting

Nanpu depression is located in northern Huanghua depression of

Bohai bay basin which experienced Mesozoic and Cenozoic fault block movement Figure 1 and it is a meso-cenozoic dustpan-like depression of faulting in north and overlapping in south on the north China platform basement.⁵⁻⁶ This depression is a characteristic oil & gas depression in Bohai bay basin where oil and gas resources is extremely rich, and the oil and gas accumulation is very complex.⁷ Nanpu depression is close to Laowangzhuang uplift and Xinanzhuang uplift in north, Matouying uplift and Boge-zhuang uplift in east, Shaleitian uplift in south, and Qikou depression in west, and it is bounded with Xinanzhuang fault, Boge-zhuang fault, Shabei fault and Jiandong fault respectively. Nanpu depression mainly developed Shichang, Linque, Liunan and Cao-feidian sub-depression, Gaosahngpu, Liuzan, Laoyemiao, south Boge-zhuang and east Xinanzhuang land structural belts and Nanpu No.1 to No.5 tectonic zones. Internal fracture is well developed and distributed in Gaoliu fault, Xinanzhuang fault and Boge-zhuang fault area, and it is related to the evolution process of Xinanzhuang structural belt in north-east trending and Boge-zhuang structural belt in north-west trending. Gaoliu fault is a syngenetic fault which is long-term inherited and developed.⁸

Regional geology and stratigraphy

The drilling in Nanpu depression reveals that the formation includes Eocene Shahejie formation, Dongying formation, Guantao formation, Minghuazhen formation, Pingyuan formation from bottom to top. Kongdian formation is lost, and Shahejie formation is lack of the forth member. Shahejie formation can be divided into three sections, and the third member is divided into five sub members. The second-third sub members are the main exploration target stratum, which can be divided into two third-order sequences called SQ2 (sequence 2) and SQ3 (sequence 3). SQ2 and SQ3 were subdivided into six forth-order sequences.

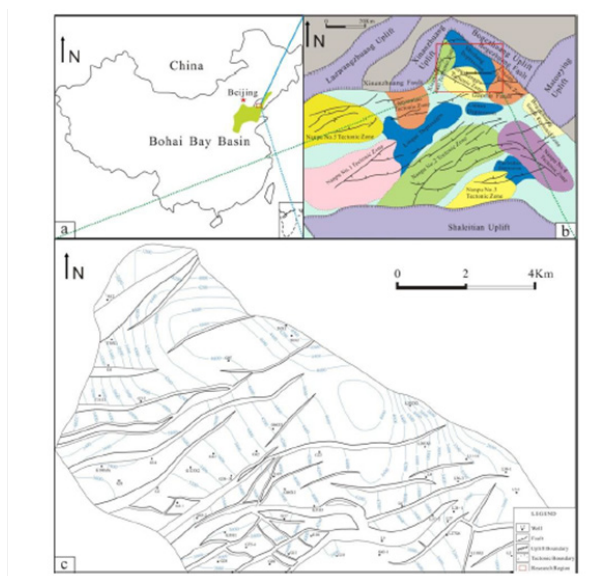


Figure 1 Location map of Gaoshangpu oilfield.

The SQ2 sequence is regressive system tract (RST). Sandstone thickness increases while mudstone becomes thin gradually, and the ratio of sand and mud increase. This system tract shows progradational characteristics and coarsening-upwards sequence. The two coarsening-upward sequences are corresponded to IV and V oil group of the third member of Shahejie formation respectively. The IV oil group developed grey and brown conglomeratic sandstone and coarse-medium sandstone with taupe gray mudstone, and the thickness of this stratum is about 105~235 meters. The V oil group developed light grey medium-coarse sandstone and taupe gray mudstone interbedding, and the thickness of this stratum is about 90~220 meters Figure 2.

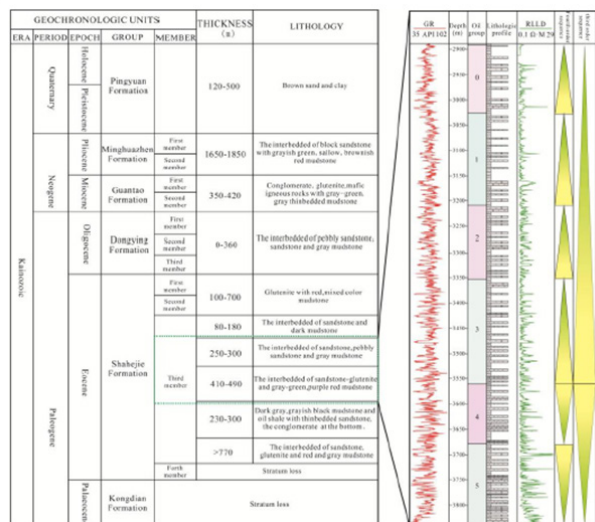


Figure 2 Kainozoic stratigraphy in Nanpu depression, Baohai Bay basin.

The main study unit and the lithologic character of G32-32 well (right)

The SQ3 sequence is a transgressive system tract (TST), in which sandstone thickness decreases while mudstone becomes thick gradually, and the ratio of sand and mud decrease. This system tract shows the retro gradation characteristics and fining-upwards sequence.

The two fining-upward sequences are corresponded to II and III oil group of the third member and 0 and I oil group of the second member of Shahejie formation respectively. The 0 oil group developed dark grey and taupe gray mudstone with thin siltstone and fine sandstone, and the thickness of this stratum is about 80~140 meters. The I oil group developed glutenite, conglomeratic sandstone, and medium-coarse sandstone with grey-green and taupe gray mudstone at bottom, dark grey and taupe gray mudstone with thin siltstone and fine sandstone at central section, and the thickness of this stratum is about 150~225 meters. The II oil group developed brown glutenite, coarse-medium sandstone and taupe gray mudstone interbedding, and the thickness of this stratum is about 110~155 meters. The III oil group developed brown and grey conglomeratic sandstone, coarse sandstone, fine sandstone and shaly sandstones with grey-green and taupe gray mudstone interbedding, and the thickness of this stratum is about 120~200 meters Figure 2.

Facies analysis

In this research, lots of work has been conducted to make successive core description. Sedimentary facies indicators such as rock constituent, rock texture, sedimentary structure are gathered. Then analysis has been made by combining logging information and geological data. A comprehensive understanding of sedimentary characteristics and sedimentary facies of Shahejie formation in Gaoshangpu oilfield is discussed below:

Provenance analysis

Provenance analysis is a very important part of basin analysis and it is significant for the analysis of sedimentary environments and ancient paleo geomorphology.⁹

There are various research methods on ancient provenance and paleo current analysis, such as lithic component analysis, compositional maturity analysis, heavy mineral analysis, dipmeter survey.¹⁰ In this study, two research approaches are chosen to investigate the veracious paleo current direction in Shahejie formation.¹¹

Heavy mineral analysis: Heavy minerals are an important sign of provenance. The ZTR index is often be used in heavy mineral analysis (The ZTR index refers to a ratio that is given by the content of stable heavy minerals / the content of transparent heavy minerals). The ZTR index is less than 0.1 of Well G4 in the northwestern study area; it is also less than 0.1 of Well G87, G66X5 and L11-16 in the northeastern study area. It ranges from 0.1 to 0.4 in the central portion of the area, and reaches values higher than 0.4 in the southwestern study area. The ZTR index increases from the northwest and northeast to the southwest Figure 3.

Compositional maturity: Clastic compositional maturity refers to the extent to which a clastic sedimentary rock approaches the most stable final product during the transformation process associated with its long-term weathering, transportation, and deposition [12]. In this study, we use $I_c = Q / (F + R)$ (Q, F and R are on behalf of the content of quartz, feldspar and rock debris respectively) to represent the compositional maturity of sandstone samples from the third member in Shahejie formation, then the content of quartz can represent compositional maturity, as quartz can keep away from weathering better than feldspar and rock debris, abrade less in the process of transport Figure 4. So, the compositional maturity of sandstones is lower in the northeast and northwest than in the southwestern study area. Specifically, the sediment in the study area came from northeast

and northwest during the third member of Shahejie formation. Analysis of compositional maturity and heavy minerals suggests that the sediment within the study area came mainly from the northeastern Baigezhuang uplift and the northwestern Xinanzhuang uplift.

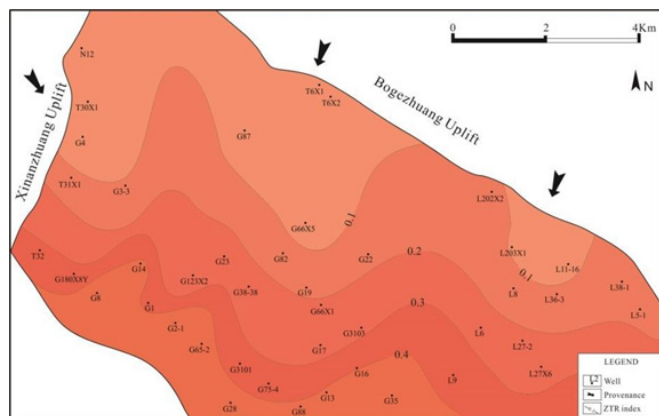


Figure 3 Contours of ZTR index in the third member of Shahejie formation.

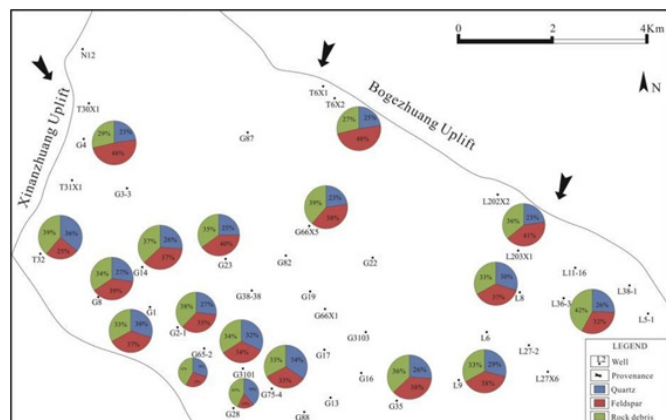


Figure 4 The content of quartz, feldspar and rock debris in the third member of Shahejie formation.

Table 1 Sedimentary composition of the sandstone in Shahejie formation fan delta system

Sample no.	Sample depth(M)	Detrital quartz	Detrital feldspar	Lithic grains	Matrix	Calcite cement	Dolomite cement	Clay mineral cement	Quartz overgrowth	Feldspar overgrowth	Porosity
G8X1	3824.7	32.1	25.7	34.9	0.9	0.9	0.9	3.7	0.9	0	0
G8X1	3825.8	32.1	24.8	35.8	0.9	0.9	0.9	2.8	0.9	0	0.9
G8X1	3827.5	31.80	26.2	35.5	0.9	0.9	0	3.7	0.9	0	0
G8X1	3829.9	26.5	22.1	39.8	0.9	5.3	0	1.8	0.9	0.9	1.8
G65-1	3222.6	31.4	19	39	8.6	0	1	0	0	0	1
G65-1	3237	29.8	29.8	28.1	11.4	0.9	0	0	0	0	0
G65-1	3272.6	26.7	28.4	31	6.9	0.9	0	0	0	0	6
G65-1	3304.7	24	20.7	38	3.3	12.4	1.7	0	0	0	0
G3X3	3082.9	31.8	19.1	40.9	0.9	0.9	0	1.8	0.9	0.9	2.7
G3X3	3986.8	18.5	28.7	46.3	1.9	1.9	0	1.9	0.9	0	0
G3X3	3987.8	20	25.2	41.7	0.9	4.3	0	2.6	1.7	0	3.5
G3X3	3988.2	19.6	28.6	42.9	0.9	3.6	0.9	2.7	0.9	0	0

Sedimentary composition analysis

Shahejie formation fan delta deposit a high proportion of conglomerate and conglomeratic sandstone in lithology profile. According to the samples of rock slices analyzed, the sandstones of Shahejie formation have low content of quartz and feldspar as well as high content of rock debris Figure 5. The types of the sandstones are mainly lithic arkose and feldapatic litharenite, with a small amount of arkose and litharenite. The content of quartz ranges from 17.1% to 37.1%, and 27.4% averagely. The content of feldspar fluctuates between 16.2-37.9% with 25.4% averagely. The content of debris ranges between 26.4-56.8%, and 38.4% averagely. Clastic particles are point-line contact, sorting is poor to moderate, psephicity is Subangular-subrounded, cementation type is pore cementation Table 1. In general, the content of stable components is less and sediment maturity is lower.

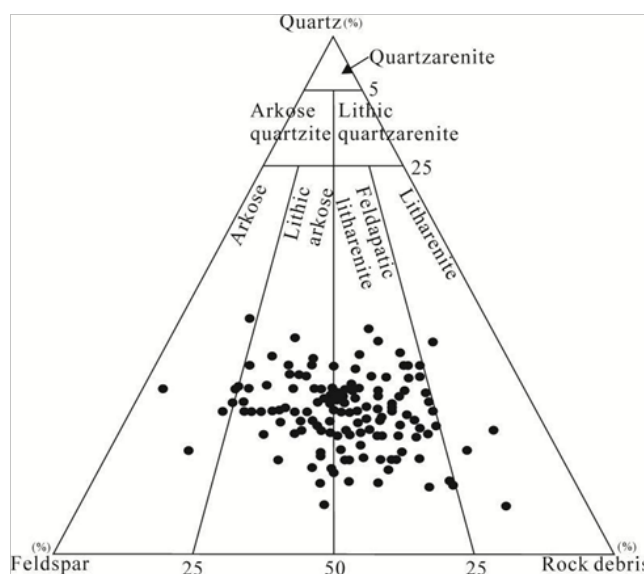


Figure 5 Lithology triangle figure of Shahejie formation in Gaoshangpu oilfield.

Table Continued...

Sample no.	Sample depth(M)	Detrital quartz	Detrital feldspar	Lithic grains	Matrix	Calcite cement	Dolomite cement	Clay mineral cement	Quartz overgrowth	Feldspar overgrowth	Porosity
G65-I	3206.9	27	22.6	34.8	2.6	0.9	0	0.9	0.9	0	10.4
G65-I	3215.4	22.3	27.7	39.3	1.8	0	1.8	0	0	0	7.1
G3104	3200.3	21.6	38.8	25.9	6.9	2.6	0	0	0	1.7	2.6
G3104	3202.6	19.3	38.5	33.9	2.8	0	0	0	0	0	5.5
G3104	3241.9	13	23.1	55.6	5.6	0	0.9	0.9	0	0	0.9
G3104	3242.7	26.70	30.5	38.1	1.9	0	0	0	0	2.9	0
G8	3903	25.5	34.9	32.1	1.9	4.7	0	0.9	0	0	0
G8	3904.9	22.70	32.8	28.6	1.7	8.4	0	0	3.4	0	2.5
G8	3905.8	25.2	33.3	31.5	0.9	5.4	2.7	0	0	0	0.9
G34	3139.9	34.9	35.8	21.7	1.9	2.8	0	0	0.9	0	1.9
G42	3229.3	27.3	40.9	21.8	2.7	4.5	1.8	0.9	0	0	0
G42	3229.4	26.6	41.3	23.9	1.8	2.8	1.8	0	0	0.9	0.9

Lithofacies analysis

The Shahejie formation sandstone can be informally divided into

several conglomerate, sandstone and clay stone units.¹² Ten lithofacies are recognized in the Shahejie formation fan delta system Figure 6.

Lithofacies	Gm	Gms	Gt	Sm	St	Sp	Sr	Sh	Fl	Fm
Lithology	Clast-supported conglomerate, ungraded to weakly graded, poorly sorted.	Matrix-supported conglomerate, ungraded to weakly inversely graded, poorly sorted.	Coarse- to very coarse-grained sandstone and graptolite; some intraformational clasts of claystone and siltstone.	Medium- to very coarse-grained sandstone, clast-supported, moderately to poorly sorted.	Medium- to very coarse-grained sandstone, moderately sorted, intraformational clasts of mudstone and siltstone.	Medium- to coarse-grained sandstone, moderately to well-sorted.	Very fine- to fine-grained sandstone interbedded with laminated siltstone and mudstone, well-sorted.	Very fine- to fine-grained sandstone, well- to poorly sorted.	Generally claystone with interbedded siltstone or sandstone.	Massive mudstone in dark grey colour.
Sedimentary structure	Massive.	Massive or weakly to poor stratified.	Trough cross-bedded sets; weakly stratified at set base; gravel cascading tile pattern.	Massive.	Small trough cross-bedded sets, rarely multistorey; pebble lags at set base.	Planar cross-bedded sets.	Dominantly ripple cross-laminated.	Flat bedded and horizontally laminated; common wavy lamination and isolated ripple forms.	Interbedded planar laminated or cross laminated.	Massive or weakly/poorly laminated.
Fossils	None	None	None	None	None	None	Rare, a small amount of plant roots fossils.	Rare	Low-density bioturbation, some foraminifera trace fossils.	Low-density bioturbation, some foraminifera trace fossils.
Contacts	Lower boundary is erosional and sharp with facies Fm; upper boundary is usually flat with facies Gm or Gt.	Lower boundary is erosional and sharp with facies Fm; upper boundary is usually flat with facies Gt.	Lower boundary is erosional and sharp with facies Fm; upper boundary is usually flat with facies St.	Lower boundary is sharp and flat with facies Gt or erosional with facies Fm; upper boundary is usually sharp with facies St.	Lower boundary is sharp and flat with facies Gt or erosional with facies Fm; upper boundary is usually sharp with facies Sp.	Lower boundary is sharp with facies Gt and St; upper boundary is usually sharp with facies Sr.	Lower boundary is sharp and erosional with facies Gt or Sp; upper boundary is usually sharp with facies Sh, Fl or Fm.	Both lower and upper boundaries are sharp or rarely gradational with facies Sr or Fl.	Lower boundary is flat with facies Sp, Sr or Sh.	Lower boundary is erosional or sharp with facies Sp, Sr or St; upper boundary is usually erosional with Gt.
Geometry	Massive.	Massive.	Thick, lenticular to tabular.	Lenticular.	Lenticular.	Lenticular to tabular.	Thin, discontinuous, lenticular or wedge-shaped.	Thin, sheet-like.	Thick.	Thin or thick, massive-shaped.
Environmental interpretation	Lag deposits, high hydrodynamic conditions.	Subaerial plastic debris flows.	Channelised lag and bedform deposits.	Subaerial hyperconcentrated flows.	Upper part of the lower flow regime.	Fluvial bedforms and bars, medium part of the lower flow regime.	Upper parts of bedforms and channel bars, traction and suspension deposits.	Lower and upper flow regime.	Waning flow deposits in overbank areas; flood deposits.	Flood plain distal to the main channel; prodelta deposits.

Figure 6 Summary of the characteristic features of the lithofacies types encountered in Shahejie formation of Nanpu depression.

Massive conglomerate (Gm) consists of clast-supported conglomerate with massive bedding, it is ungraded to weakly graded, poorly sorted and represents lag deposits or high hydrodynamic conditions. Massive or weakly stratified conglomerate (Gms) consists of matrix-supported conglomerate, ungraded to weakly inversely graded, poorly sorted, it presents sub aerial plastic debris flows.¹³ Stratified gravely sandstone (Gt) consists of coarse- to very coarse-grained sandstone with trough cross-bedded sets and weakly stratified at set base. Geometrically, Gt consists of thick lenticular to tabular shaped bodies on the transverse. The lower contact is erosional and sharp and upper boundary is usually gradational. This facies suggest relatively rapid sedimentation in fluvial channels from high velocity flows in the deepest part of the stream.^{14–16} Medium to very coarse-grained massive sandstone (Sm) consists of medium to very coarse-grained massive sandstone, clast-supported, moderately to poorly sorted.¹³ Coarse-grained trough cross-bedded sandstone (St) consists of medium- to very coarse-grained with small trough cross-bedded sets. Geometrically, this facies occurs as lenticular shaped bodies. The lower boundary is sharp and flat with facies Gt or is erosional with facies Fm of the underlying cycle and the upper contact is

usually sharp with facies Sp. Facies St is interpreted to form a fluvial or low-angle-inclined fronts of bars in the upper part of lower flow regime.^{13,17–20} Medium- to coarse-grained planar cross-bedded sandstone (Sp) consists of medium- to coarse-grained sandstone, sandstone arranged into lenticular or tabular, which are characterized with planar cross-bedding. The lower boundary of Sp is sharp with facies Gt or St and upper contact is sharp with facies Sr, or Fm. Facies Sp is interpreted to form medium parts of bed forms or channel bars. Ripple cross-laminated sandstone (Sr) consists of very fine- to fine-grained sandstone with siltstone lenses. The sandstone is thin lenticular or wedge-shaped bodies that contain ripple cross laminated and less amounts of small-scale planar. The cross strata in both facies Sp and Sr dip consistently in the same direction. This facies typically grades laterally and vertically into the finely laminated sediments of facies Sh and Fl. This facies likely represents the deposition of upper bars or in overbank areas.^{16,21,22} It may be also attributed to the slow sedimentation within largely inactive channels as fill deposits.¹⁹ Very fine- to medium-grained sandstone with flat bedding (Sh) consists of very fine- to fine-grained, flat bedded and horizontally laminated.^{28–30}

Sandstone, with thin and a sheet-like geometry. Lower and upper contacts of this facies are sharp or rarely gradational with facies Sr or Fl. This lithofacies suggests deposition as bar-top and sand sheets as high-energy sheet floods that spilled into a lower energy environment from channels during flooding of the main fluvial channel system. Parallel laminated siltstone and clay stone (Fl) consists of planar laminated clay stone units interbedded with siltstone to form shale horizons. Its lower boundary is flat with facies Sp, Sr or Sh. This facies contains low-density bioturbation and some foraminifera trace fossils. Units of this facies appear to possess sheet-like or rare lenticular geometries. Facies Fl is interpreted to represent the deposits of waning stage flood deposition, chiefly in overbank areas.²³ Massive mudstone (Fm) consists of massive mudstone with sandstone and

siltstone interbeds. It contains abundant bioturbation. The lower contact of this facies is erosional or sharp with facies Sp, Sr or St, whereas the upper contact is usually erosional with Gt. Units of this facies appear to possess thin or thick, massive-shaped geometries. Facies Fm is interpreted to represent deposition from flood plain distal to the main channel or prodelta.

Facies associations and depositional environments

The sedimentary microfacies can be identified by the combination characteristics of different types of lithofacies in the third member of Shahejie formation. Braided channel, front bar, underwater braided channel, channel bar, sand sheet, and interchannel bay microfacies can be identify in the study area Figure 7.

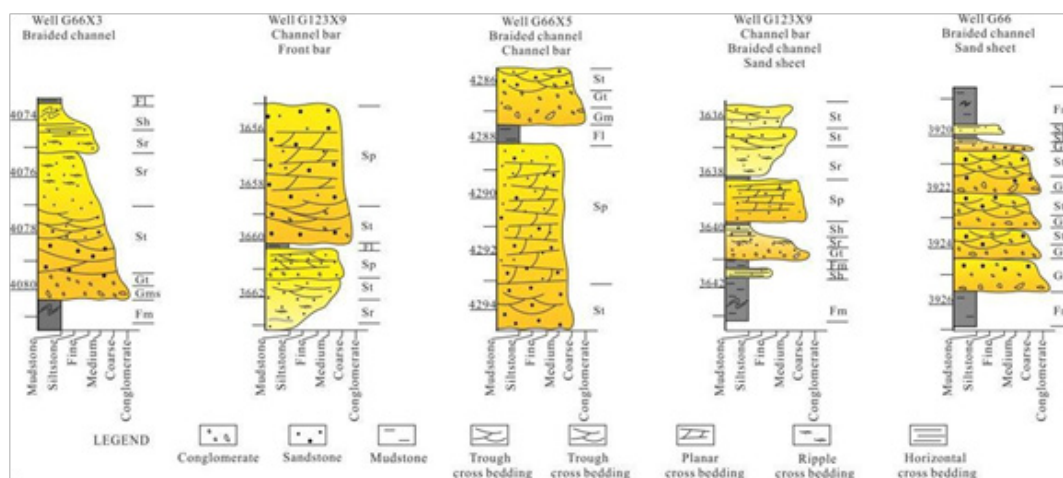


Figure 7 The combination characteristics of different types of lithofacies in the third member of Shahejie formation.

Braided channel: This facies association consists of poorly sorted massive conglomerates, indistinctly cross stratified conglomerate, medium to very coarse-grained massive sandstone, coarse-grained (facies Gm, Gt, Sm,) with intercalation of mudstone and thin-bedded siltstone or sandstone beds.^{24–27} It is characterized by erosively-based units that cut down into fine-grained clay stone or mudstone sediments (facies Fl and Fm) of the underlying cycle. These surfaces mark the beginning of each fining-upward fluvial cycle within the succession. The poor internal organization and the lack of well-developed grading in the conglomerates are suggestive of sub aerial emplacement of debris flows. These facies associations represent deposition on a debris-flow-dominated braided channel. This interpretation is based on the consistent erosional relationship with underlying mudstone deposits. Channel bodies are incised into underlying sediments and then it may infer that avulsion of the rivers to new sites involved variable levels of excavation of previously deposited alluvium.^{28–30}

Underwater braided channel: The underwater braided channel facies association consists of weakly stratified conglomerate, stratified gravely trough cross-bedded sandstone and medium- to coarse-grained trough cross-bedded sandstone (facies Gms, Gt, St). The basal surface is generally sharp and flat and erosive features are often observed. This deposits of the facies association were formed by bed load of gravel and sand into a water body. Because of this high-flow velocity and the fine grain size of the sediment, their bottom is mainly eroding into the underlying mudstone.^{31,32} Erosion surfaces and scours are common at the bottom of this facies association.

Front bar: Front bar is composed of stacked sets, arranged into coarsening-upward packages, and characterized by finer-grained cross-to horizontally-stratified sands (Sr, Sh), medium- to coarse-grained planar cross bedded sandstones (Sp) and very coarse-grained trough cross-bedded (St). Mottled or speckled silty-sandstone is usually developed at its bottom. Minor bounding surfaces separate sets and costs of facies St, Sp and Sr.³³ These elements represent the deposits of migratory dune-scale bed forms in fan delta front. Downstream reduction in the scale of the cross-bedded sets likely indicates downstream changes from dune- to ripple-scale bed forms, probably reflecting a local decrease in transport energy.²⁶ This interpretation is based upon their size and their orientation. The lens-, tabular- or wedge-shaped geometry of front bar might reflect the presence of straight-crested dunes deposited during high discharge events.³⁴

Channel bar: Channel bar is well developed in the succession that is identified as downstream accretion and lateral accretion elements. These microfacies are composed of medium- to coarse-grained sandstones arranged into trough cross-bedded, large-scale planar cross-bedded sets (facies St, Sp). Downstream accretion elements form the lower portions of the fining-upward cycles, either for the entire element or for individual units within a single element.²⁵ They are characterized by fining-upward packages composed of fine- to medium grained sandstones with siltstone interbeds in the upper parts. Low angle-inclined compound costs of planar cross-bedding are more abundant than trough cross-bedded sets and, within the inclined strata of these larger costs, smaller scale structures including ripple cross-

lamination and small-scale trough cross-stratification are developed. The downstream accretion units are interpreted to have been deposited under a constant flow regime during normal river discharge and likely represent a succession of mid-channel transverse bars within the central parts of a sinuous channel.^{26,35,36} The convex-up macro form bounding surfaces and lack of features otherwise indicative of lateral accretion suggest the lateral shifting of the down current-migrating sand dunes or channel bars.³⁴ The fining-upward grain size trend, the unidirectional dip direction of forests and internal bounding surfaces, and the downstream-dipping forests within these elements are together indicative of the downstream end of a channel bar.³⁷

Sand sheet: These discontinuous tabular thin sheets of fine-grained sandstone that are commonly inter-laminated (facies Sr and Sh). This microfacies is wide spread throughout the formation and its principal occurrence is in the upper portion of the fining-upward cycles and is laid down by nonchannelised flows.^{38–39} Their thin, discontinuous, sheet-like geometry, together with the small-scale of sedimentary structures and the fine-grained lithology suggests deposition as a bar-top or bar-flank,²⁵ which accumulated in the shallower parts of channels, terminal of fan delta front or middle fan, profan delta or distal fan.^{36,40–42} However, in places, the sand sheets are also deposited by overbank sheet flows rather than true sheet floods.³⁹ Alternatively, laminated sand sheets attributed to upper flow regime plane bed conditions may develop in shallow water on the upper parts of bars or low energy environment.^{43–45}

Interchannel bay: Interchannel area is characterized by fine-grained clay stone and mudstone with interbeds of siltstone and fine-grained sandstone. These microfacies can be traced laterally both parallel and perpendicular to channels and represent swamp deposits (facies Fl and Fm). The fine grain size and extensive, geometry of these elements indicates deposition over a wide area that was distal to the main channel.²⁷ Fine-grained units that show only weak palaeosol development are indicative of avulsion deposits that were subject to rapid sedimentation. The origins of grey and greenish-grey colours suggests a perennially water-logged, vegetated mudflat setting, indicative of an oxygen-poor environment.

Single-well facies analysis

Single well facies analysis is based on the study of the core section. The sedimentary microfacies types is recognized through the observation and description of rock mineral composition, mineral structure, sedimentary structure, the change of sediment rhythm, analysis and comparison to the core top and bottom contact relation, sedimentary sequence cycle.⁴⁶

Well G82 is located in the central of the research region. It is shown that fan delta was developed in third member of Shahejie formation. Distal fan subfacies and middle fan front subfacies were developed in I and III oil group while profan delta subfacies and fan delta front were developed in IV oil group. As a whole, the content of sandstones is more than mudstones. The coring section I oil group is composed of light grey mudstone, thin bed silty mudstone, pelitic siltstone with ripple cross bedding, fine sandstone with trough cross bedding, siltstone with ripple cross bedding, sandstone with planar bedding, pebbly sandstone with trough cross bedding, and an isomeric sandstone with cross bedding. III oil group is composed of glutenite with cross bedding and grey mudstone. The core section showing a variety of sedimentary microfacies, including braided channel, underwater braided channel, front bar, channel bar, sand sheet and interchannel bay microfacies Figure 8.

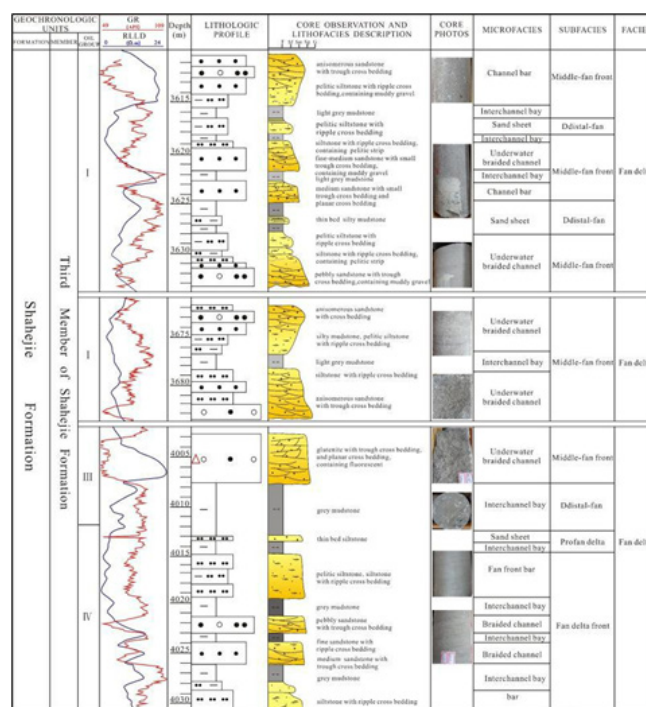


Figure 8 Single-well facies analysis of Shahejie Formation (Well G82).

Sedimentary model

Fan delta sedimentary model is used to describe and reveal the sedimentary environment and sedimentary characteristics of Shahejie formation in Nanpu depression of Bohaiwan basin, according to the characteristics of sedimentary environment, lithology and sedimentary structure analysis. In different microfacies of the fan delta, the hydrodynamic conditions are distinctive, and the characteristics of sedimentary facies sequence also have obvious differences.⁴⁷

Fan delta deposition is affected by two kinds of system tracts in the study area. The lower LST shows a coarsening-upward sedimentary sequence, and thickness of sandstone increased from bottom to top while the ratio of sandstone and mudstone increased gradually, the upper TST suggests a fining-upward sequence, and thickness of sandstone decreased from bottom to top while thickness of mudstone increased gradually. Sedimentary model can be divide into two types in Nanpu depression-transgressive fan delta and regressive fan delta. Transgressive fan delta can be identified three subfacies: proximal fan, middle fan and distal fan. Fan delta plain, fan delta front and profan delta subfacies can be identified in regressive fan delta.

When relative lake level drops, wave energy decreases and fluvial energy increases, the regressive fan delta is formed. Facies distribution is complete on plain with a coarsening-upward sequence. It can be divided into fan delta plain, fan delta front and front delta subfacies and it can also be identified as braided channel, front bar, interchannel bay and sand sheet microfacies further Figure 9. Fan delta plain is mainly composed of glutenite, coarse- to very coarse-grained sandstone, medium-grained sandstone and fine-grained sandstone in channel, grey, green and the variegated mudstone at interchannel area. The braided channel developed massive bedding, weakly trough cross bedding, spontaneous potential curve performed jagged box shape. The fan delta front deposits weakly stratified conglomerate, medium- to coarse-grained trough cross bedding or

planar bedding sandstone with gray-green mudstone and a small amount of inferior oil shale, spontaneous potential curve performed box shape, funnel-bell shape and finger shape. The fore-delta entered a lake and developed depression green, dark grey mudstone.

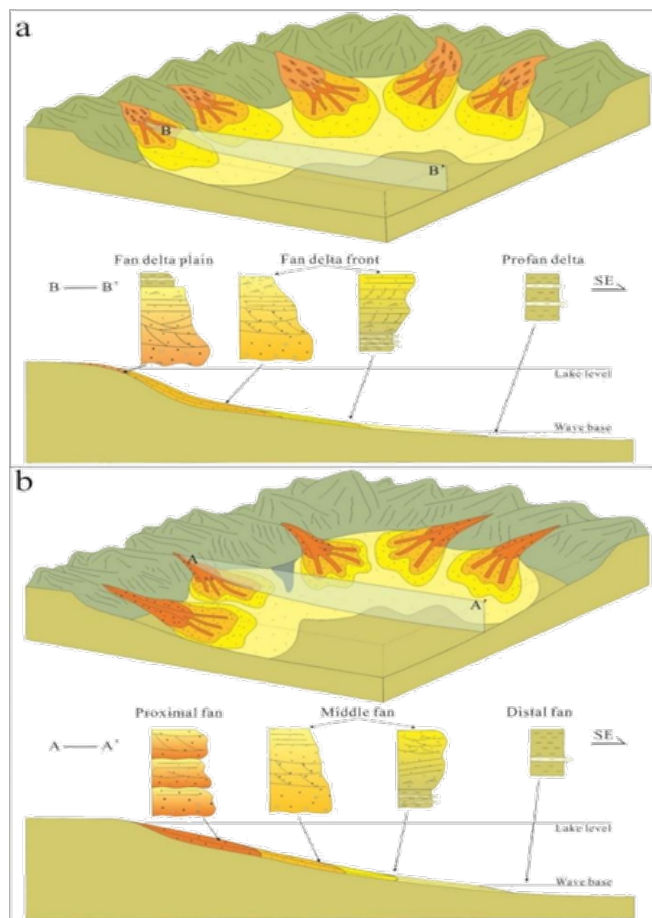


Figure 9 Sedimentary model of Shahejie formation in Nanpu depression.

Transgressive fan delta is a subaqueous depositional body formed during the transgression phase with a fining-upward sequence. This type of fan delta appears in the early filling stage of monocyclic basin or transgression phase of polycyclic basin. Based on the study of depositional environment, lithology, sedimentary sequence and lithofacies characters, it can be further divided into three sedimentary subfacies: proximal fan, middle fan and distal fan. Proximal fan is formed by intermittent water flow and braided channel sedimentation with conglomerate of poor sorting and layered property. It appears as imbricate conglomerate and gravelly sandstone with rough parallel bedding at the top and, sometimes, massive bedding and large trough cross bedding at the bottom. The lower boundary of proximal fan is usually erosional and sharp with underlying mudstone deposition. Underwater braided channel, channel bar, interchannel bay and sand sheet microfacies can be further identified. Middle fan formed the main part of the fan delta with highly-developed braided channel, which can be divided into undertaker braided channel, channel bar, sand sheet and interchannel bay microfacies. The clastic rocks of the middle fan braided channel are mainly medium- to very coarse-grained sandstone and rarely gravelly sandstones. Its sedimentary structure includes small trough cross bedding, planar bedding as well as an erosional basal surface at the bottom sometimes. The braided channel

extension towards basin forms the mid-fan front and changed into finer grains with better sorting and more cross bedding. The channel scouring decreased and wave energy increased. The interchannel bay is characterized by celadon to dark grey massive or weakly laminated mud with low-density bioturbation and thin sandstone with small-scale ripple bedding and deformational structures. Distal fan is formed in semi-deep lacustrine and the lithologies are mainly green or dark grey mud with low-density bioturbation.

Discussion and conclusion

The analysis of the samples of rock slices shows that the sandstones of Shahejie formation have low content of quartz and feldspar as well as high content of rock debris. The types of the sandstones were mainly lithic arkose and feldspathic litharenite with a small amount of arkose and litharenite. In general, the content of stable components is less and sediment maturity is lower. The textural maturity is relatively low by comparing the maturity of different samples, and deposits are transported nearly.

Core observation shows that the sedimentary structures have plenty types with various combining form, and are widely distributed. These types mainly include scour erosion surface, trough-shaped cross-bedding, parallel bedding, ripple bedding, graded bedding, lenticular bedding, horizontal bedding, massive bedding, and other sedimentary structures in Shahejie Formation, which reflects sedimentary characteristics of fan delta sediments.

The Shahejie formation Sandstone can be informally divided into several conglomerate, sandstone, clay stone and mudstone units. Ten lithofacies are present: massive conglomerate(Gm), massive or weakly to poor stratified conglomerate(Gms), stratified gravelly sandstone(Gt), medium to very coarse-grained massive sandstone(Sm), coarse-grained trough cross-bedded sandstone(St), medium- to coarse-grained planar cross-bedded sandstone(Sp), ripple cross-laminated sandstone(Sr), very fine- to medium-grained sandstone with flat bedding(Sh), parallel laminated siltstone and claystone(Fl), massive mudstone(Fm).

The comprehensive analyses of sedimentary and sequence-stratigraphic characteristic show that sedimentary model of the third member of Shahejie formation was a fan delta deposition formed in RST and TST environment. Two types of fan delta, transgressive fan delta and regressive fan delta, are identified through sedimentary environment, lithology and sedimentary structure and lithofacies identification. Regressive fan delta developed a coarsening-upward sequence under the control of the RST, which can be divided into fan delta plain, fan delta front and profane delta subfacies. Transgressive fan delta is formed at the transgression phase with a fining-upward sequence, and it can be further divided into three sedimentary subfacies: proximal fan, middle fan and distal fan.

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Conflict of interest

The author declares no conflict of interest.

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