Microfacies characteristics and depositional evolution of typical wave-dominated littoral deposits – A case of Carboniferous ‘Donghe sandstones’ in Hudson Oilfield, Tarim basin, NW China

W L Li\textsuperscript{1,2,3}, S Y Gao\textsuperscript{1}, X D Tian\textsuperscript{1}, C H Han\textsuperscript{1}, G H Wei\textsuperscript{1} and H M Xu\textsuperscript{2}

\textsuperscript{1}National Marine Data and Information Service, Tianjin 300171, China
\textsuperscript{2}China University of Petroleum, Beijing, Beijing 102249, China

E-mail: qrange@163.com

Abstract. Hudson Oilfield, which located in the northern Uplift of Tarim Basin, is considered to be the largest whole-shaped oilfield in China, and the extensive Carboniferous ‘Donghe sandstones’, one of the most important marine sandstones units for oil and gas exploration in Tabei Uplift, constitutes the main reservoir. However, not all this sandstones are with good physical properties, and hence, the sedimentary characteristics and depositional evolution is believed to be critical to prediction of reservoir. It is determined that wave-dominated clastic littoral deposits with no barrier are the main depositional environment based on the modern sedimentary theory and related data analysis including ancient landform characteristics. And transitional zone, shoreface, foreshore, backshore and dune are considered as the five sub-environments. Through data of high resolution dipmeter logging and imaging logging, different sedimentary structures and other facies marks observed from cores of research regions are demarcated, and thirteen microfacies are further identified. Based on the detailed microfacies types, the evolution process of Carboniferous ‘Donghe sandstones’ can be divided to four main periods, in which, early highstand systems tract (HST) deposits in Period 1-2, and late HST deposits in Period 3-4.

1. Introduction

Hudson Oilfield which located in northern Tabei Uplift plays a significant role in Tarim Basin with its abundant oil and gas resources. A major breakthrough is made for the first time in marine clastic rock reservoirs of Tarim Basin since well Donghe 1 attained high capacity oil-gas flow in 1989. In 1998, the discovery of ‘Donghe sandstones’ reservoirs in HD area attracted widespread attention of geological workers [1-4], and it became the main exploration target and oil-producing stratum in Tarim Basin.

The Carboniferous ‘Donghe sandstones’ of Hudson Oilfield is a set of lithic quartz sandstone with color of grey, higher compositional and textural maturity, extensive distribution and good reservoir property. It’s the most favorable strata in large stratigraphic-lithologic trap of Tabei Uplift. However, there are more controversies in research of sedimentary microfacies and evolution characteristics, some scholars regarded ‘Donghe sandstones’ as the composite sands under the background of regression with complex distribution of punctate or massive [5], some scholars thought ‘Donghe sandstones’ are the basal sands which deposited in the transgression process during the period from late Devonian to early Carboniferous with characteristics of ‘fill-up’[3, 6-8], and still some scholars...
took it for the deposits of wave-dominated or tide-dominated delta, with the distribution features of local concentrated [9]. The insufficient knowledge of sedimentology could not effectively guide the reservoir evaluation and prediction, which could not meet the requirement of production objects, thus, it is of important significance to study the relationship of sedimentary facies and oil and gas distribution by analyzing the sedimentary characteristics, faices distribution and evolution of ‘Donghe sandstones’.

This paper aims to provide a reference for oil and gas exploration and favorable reservoir facies prediction on the basis of sedimentary and depositional evolution research.

2. Geological setting

Situated in Shaya country, Akesu, Xinjiang Province, and bordered by Tarim Basin to the north, Hudson Oilfield has a distance of 20km from the village with the same name. It locates in Hudson structure belt of Manjar Depression which has sag tectonic framework since early Paleozoic. In late Ordovician, Silurian, and Devonian, Manjar Depression was the sedimentary center of the entire basin, and in the process of geological evolution, it generally showed a relatively stable feature of sag. The Hudson structure belt showed as an anticlinal structural belt with low amplitude, and developed in a nose-like uplift, extending southward from the Lunnan low bulge in Tabei Uplift (Figure 1). From the oily construction perspective, it’s a typical inner-sag uplift which having a favorable accumulation conditions [10,11].

![Figure 1. Location of Hudson Oilfield in Tarim Basin, NW China.](image)

The Carboniferous stratum in Hudson Oilfield rests on the Silurian stratum with an unconformity at the base, meanwhile, the above unconformity with the overlying Permian stratum is present. The sedimentary strata are divided into sections of Donghe sandstones, Breccia, middle mudstone, standard limestone, upper mudstone, sandy mudstone and limestone from the bottom up [3,4], among which, the section of ‘Donghe sandstones’ is the target strata.

A set of fine-grained quartz sandstones with color of grey white makes the Carboniferous ‘Donghe sandstones’ section, which is wave-dominated littoral deposits with high textural and compositional maturity. Generally, it deposits like a belt along the coastline and presents a trend of onlap with thickness reduction southeastward [7]. On natural potential and natural gamma curves for ‘Donghe sandstones’, micro gear boxes with a value range of 12-20mv and 27-45 API presents respectively; for deep resistivity curve, it shows like a step from top to bottom with a value of 0.3-5 Ω•m, and for acoustic time curve, a wave shape appears with value of 65-75 us/ft.
3. Data and methods
The data used to analyze the microfacies and evolution mainly concentrated on cores, including sample analysis and test, and well logs. In consideration of the vertical resolution of 3-D seismic data, it was used for reference only. In general, the data and methods used in this paper to analyze the microfacies characteristics and depositional evolution involved three steps. (i) on the basis of the stratigraphic sequence framework with high resolution established by former scholars, cores from 11 cored wells were described in detail for lithology, sedimentary structures and depositional environment, and logging data of non-cored wells and various sampling analysis and test data were used to recognize the microfacies features. (ii) aiming at the classified microfacies types and characteristics, the core data were used to demarcate the logging data to establish the logging chart of sedimentary analysis for cored well, and then the non-cored well. From points to plane and body, a sedimentary model is summarized, which contained all the characteristics that presented. (iii) the sedimentary model provided a basis for further depositional distribution and evolution studies, and under this constrains, the distribution in plane and evolution rules in vertical were simulated. Thus, the depositional process of ‘Donghe sandstones’ in Hudson region is reappeared to improve the cognition on deposition.

4. Results
4.1. Depositional environment and lithofacies
The sedimentary environment of Carboniferous ‘Donghe sandstones’ in Hudson Oilfield are considered as wave-dominated clastic littoral deposits with no-barrier in combination with the study of rock types, sequence, sedimentary structures, grain size, fossil assemblages, trace elements and characteristics of clay minerals. The littoral system in Hudson area are made up of a number of sub-environments, each of which is characterized by individual and complex lithofacies, include: 1) the transitional zone, 2) shoreface or the sub-tidal zone, 3) foreshore or the intertidal zone, 4) backshore, 5) dune. According to the characteristics of geomorphic elements, hydrodynamic conditions and sediments, they are further subdivided into thirteen distinct micro-environments (finer lithofacies association below the level of sub-environments) (Table 1).

| Lithofacies Associations     | Hydrodynamic Conditions | Lithology                                   | Typical Sedimentary Structures                      |
|------------------------------|-------------------------|---------------------------------------------|-----------------------------------------------------|
| Transitional zone            | Mud                     | Swell                                       | Pelitic siltstone, silty mudstone                    |
| Storm sands                  | Storm wave              | Fine-grained sandstone                      | Hummocky cross-stratification                       |
| Shoreface                    |                        |                                        |                                                     |
| Lower sands                  | Lift wave               | Upper fine-grained sandstone with            | Hummocky cross-stratification, minor wavy lamination, |
| Longshore bar                | Break wave              | mudstone and siltstone interbeds            | wave rip cross-lamination                           |
| Longshore trough             |                        | Fine- to medium-grained sandstone           | Tabular and wedge-shaped cross-stratification, low-angle |
| Upper sands                  | Breaking wave           | Fine sandstone                              | inclined bedding                                   |
| Rip-channel channels         | Rip current             | Upper fine- to lower medium-grained sandstone| Trough and tabular cross-beds, minor planar lamination, |
|                              |                         | Fine sandstone                              | and swaly cross-stratification                      |

Table 1. Sedimentary summary of facies associations in the studied succession.
| Lithofacies Associations | Hydrodynamic Conditions | Lithology | Typical Sedimentary Structures |
|-------------------------|-------------------------|-----------|-------------------------------|
| Foreshore               | Beach sands             | Surf wave | Medium-grained sandstone, gravel Fine sandstone Swash cross-stratification, wedged-shaped cross-stratification Parallel bedding and small ripple bedding |
|                         | Trough                  |           |                               |
| Backshore               | Berm                    | Storm wave/Wind | Fine- to medium-grained sandstone | Landward-dipping parallel bedding, high-angle landward-dipping cross bedding |
|                         | Beach ridge             |           |                               |
| Dune                    | Beach runnel            | Wind      | Ostracum debris               | Cross bedding, low-angle oblique bedding, parallel bedding Low-angle cross bedding and small-scale ripple bedding Trough cross-stratification |
|                         | Dune                    |           | Fine-medium sandstone, well-sorted and rounding |

4.1.1. Transitional zone. The transitional zone environment is defined as the area between storm wave base and fair-weather wave base, where the dominant process is storm wave (Figure 2). Mud and stormy sands are the common lithofacies association.

Mud is formed under normal weather conditions and is reflected in sediments which consist of layers of mudstone and silt mudstone. Bioturbation structures are abundant in Mud sediments.

Storm sands dominated by storm wave mainly consists of fine sands and is interbedded with Mud sediments. The typical sedimentary structure is hummocky cross-bedding (Figure 2(a), Table 1).

4.1.2. Shoreface deposits. The shoreface environment, also called the subtidal zone, is confined to the area seaward of the land from low tide mark to fair-weather wave base (Figure 2). The deposition processes are dominated by wave energy, which decreases as water depth increases. From water base to the land, water body’s energy is increasingly stronger and the sediments are finer grained with less bioturbation. In Hudson area, five interrelated microfacies group are analyzed: lower sands, longshore bar, longshore trough, rip-current channels and upper sands (Figures 2(b), 2(c), 2(d), 2(e); Table 1).

Lower sands mainly develops in lower shoreface deposits, which occur seaward of the break in the shoreface slope at the shoreline sediment prism. The wave energy here is relatively low, and it begins to affect the seabed. Shoaling wave is the main wave type. Under the effort of swash, small ripple bedding and seaward-dipping, low-angle horizontal bedding are formed. Rock types include: fine-, medium- and girt-grained sands.
Figure 2. Typical stratification in different sedimentary environments of wave-dominated littoral deposits in Hudson area. a. Typical hummocky cross stratification in transitional zone, well A1, 5069.4 m; b. Trough cross-stratification, well A2, 5073.45 m; c. Low-angle inclined bedding, well A3, 5086.5 m; d. Wavy lamination, well A3, 5082.8 m; e. Wave-dominated cross bedding, well A2, 5073.7 m; f. Swash cross-stratification in core, well A2, 5087.4 m; g. Wedged-shaped cross-stratification in core, well A4, 5080.9 m; h. Parallel bedding, well A5, 5063.3 m; i. Ripple bedding, well A2, 5070.4 m; j. Outcrops of trough cross-stratification in dune deposits; k. Trough cross bedding in core, well A6, 5226.8 m.

Longshore bar, which dominated by break wave, mainly develops in middle shoreface environment. The development state of longshore bar is strongly influenced by wave energy. Under strong energy, a number of bars would develop, while weak, one or even no bar occurs. In the shape, it shows that it is an asymmetrical ridge whose seaward limb has a mild stratigraphic dip and landward limb has a deep one. Sediments consist of fine- to medium-grained sands. Depositional structures are relatively complex, mainly include: tabular and wedge-shaped cross-stratification, low-angle inclined bedding (Table 1).

Longshore trough, associated with longshore bar, is located at the landward side of it in middle shoreface environment. Sediments which are mainly fine sands has a finer granularity compares to longshore bar. Small current ripple, sometimes large current ripple and wave ripples exist in this environment.

Rip-current channels mainly exist in middle or upper shoreface environment, controlled by rip currents. Sands of the rip-current channels have a fine or medium granularity. Depositional structures include: trough-shaped cross bedding, low-angle oblique bedding and parallel bedding.

Upper sands mainly develop in the upper shoreface and are closely associated with foreshore deposits. Some studies have placed upper shoreface in the same bracket as foreshore, because they are situated in the high energy surf zone just seaward of foreshore and landward of the breaker zone. It represents the shoreface-foreshore transition zone. Textures range from fine sands to gravel, and generally a coarser granularity exists here. The predominant upper sands depositional structures are
swash, through or wedge-shaped cross stratifications, which are thought to indicate the multidirectional current flow in this surf zone. Parallel bedding may also be common.

4.1.3. **Foreshore deposits.** Because of process-oriented sedimentological studies in area with a wide range of tides, wave energy, and nearshore morphology [12,13], characteristics of foreshore deposits are quite well known. The foreshore environment, which is termed ‘the intertidal zone’ or ‘beach’ in some studies, is defined as the area from mean low water to mean high water. It’s usually marked by a sharp change in slope, both at the base and at the top of the beachface [14]. The dominant process in foreshore deposits is wave swash, which runs up the foreshore and occasionally overtops the berm during high tides. Wave swash forms the distinct subparallel to low-angle, seaward-dipping, planar lamination, which occur as wedge-shaped sets in most beach deposits (Figures 2(f), 2(g); Table 1). In the mass, fine- and silt-fine sandstones give priority to lithology of foreshore deposits. Results indicate that the reservoir is mainly quartz sandstones which have high absolute values on quartz content and high compositional and textural maturity. The log response is as follows: the GR curve is serrated box- or bell-shaped in performance. Beach sands and Trough are two common types of foreshore deposits.

Compositions of beach sands are mainly fine, well-sorted sandstones, and gravel can also be found. Sometimes, there are abundant and various biological debris and local heavy minerals enrichment. Typical flush cross stratification (Figures 2(f), 2(g); Table 1), the distinct subparallel to low-angle, seaward-dipping, planar laminations which occur as wedge-shaped sets [15,16] are the obvious results of wave swash. Through is given priority with silt- and fine-sandstones sedimentary, with a form of planar laminations. Parallel bedding and small ripple bedding generally develop in this environment.

4.1.4. **Backshore deposits.** Backshore environment belongs to beach deposits in some studies, and is also called backshore-dune deposits with dune deposits in others [14]. Here, it’s individually discussed. It locates between lower bound of Aeolian dune and mean high water, belongs to supratidal zone, and is only submerged under water during super storm surge and extra high tidal. As a result, it is affected by wave and weak water flow, while wind is also an important factor. Backshore environment includes: Berm, Beach ridge and Beach runnels.

Berm generally situates at the junction of foreshore and backshore, and is the transitional zone between slow terrain area in backshore and steep terrain area in foreshore. Sediments are mainly fine- and medium-grained sands. Landward-dipping parallel bedding exists (Figure 2(h); Table 1), and furthermore, high-angle landward-dipping cross beddings are also present at the bottom.

Backshore beach includes Beach ridge and runnels, are mainly made up of normal and storm deposits. Wind dominates the fair-weather sediments, which carries the sediments of foreshore and leading edge of backshore. As the declining of wind, the sediments deposited. For this reason, they have high textural and compositional maturity. A number of sediments carried by storm wave forms storm wave deposits, which has the condition of poorly sorted and gravel mixed. And the scour is obvious at the bottom of sediments. In the aspect of logging response, it shows funnel or juggled funnel for the GR curves of berm, while box or juggled box for backshore beach. And values of GR at the bottom of storm wave deposits often mutate. Generally, runnels of backshore beach are made up of fine-grained sands, and low-angle cross bedding and small-scale ripple bedding are the main structures (Figure 2(i)). By contrast, ridges which appear single or packaged usually include coarse sands, gravel or shell fragments. Scour surface and parallel exist at the bottom; cross bedding and low-angle oblique bedding exists at the top (Table 1).

4.1.5. **Dune deposits.** Coastal dunes are meant to be the meal above the sea level, which are transformed from sands by wind, with a shape of long ridge or crescent and 10 km in width. Dune has a simple composition, which is mainly made up of quartz sands and lacks of argillaceous substances and fossils. It is characterized by trough cross-stratified sets, up to 2 m in thickness, which are
predominantly wind-generated depositional results. Series of strata and lamina has a large thickness, up to 40 degrees (Figures 2(j), 2(k); Table 1).

4.2. Sedimentary model
Before ‘Donghe sandstones’ deposits, it showed the characteristics of plunging to the southwest and uplift to the northeast in the aspect of paleotopography at Hudson area. During late Devonian to early carboniferous epoch, ‘Donghe sandstones’ overlapped the underlayer from southwest to northeast, with an outstanding feature of filling and leveling up. Blocked by the Tabei uplift, the sea stranded for a long time around the ancient uplift. Coarser sediments supply continuous injected, and it formed shoreline deposits with no-barrier under the background of slower slope (Figure 3(a)).

In the transgressive-regressive cycle of HST, the relative change of accommodation space controlled the forming of superposed sands. Below the transition surface, the transgressive environment developed, and the superposed sands retrograded landwards, while regressive environment developed above the transition surface, sands prograde to form the littoral beach and bar (Figure 3(b)).

![Figure 3. Simplified block diagram illustrating the various sub-environments in littoral facies.](image)

4.3. Depositional evolution
The Carboniferous ‘Donghe sandstones’ in Hudson oilfield is only characterized with highstand systems tract (HST), which is denudated on the top. Four periods has been experienced for deposition, and among which, early HST deposits in period 1-2 (Figure 4), while late HST in period 3-4 (Figure 5).
Figure 4. Lithological division of Period 1-2, Hudson area. a. Period 1, the relative sea level initially rose; b. Period 2, the main raise stage of relative sea level.

The relative sea level initially raise occurred in the first period, and foreshore and backshore deposits distributed landwards in this area, with small-scale transgression onlap to the coastal zone. In this stage, only part of the marginal facies develops because of the edge location of Hudson region. The onlap deposits appeared from southwest to northeast, and the shoreline gradually moved back to the northwest. The foreshore beach is made up of beach sands (divided into bar and beach) and trough, which is mainly influenced by water erosion and is with higher maturity on architecture and composition. Backshore is classified by beach dam and backshore beach (ridge and runnel), and facies distributed paralleling to the shoreline (Figure 4(a)).
Figure 5. Lithological division of Period 3-4, Hudson area. a. Period 3, the initially descent period of the relative sea level; b. Period 4, the main decline stage of relative sea level.

In the second period, it came to the main raise period of the relative sea level, large-scale shoreface appeared in the southwestern, while the distribution of foreshore and backshore moved landwards. To the end of the second period, the ingestion and distribution range of shoreface deposits reached the maximum, and facies belt of shoreline spread along the ancient coastline band. Parasequence I came to an end, meanwhile, it gradually evolved into the deposits period of Parasequence II after a short and stable deposit which controlled by a phase of flooding. Upper sands, lower sands and rip current channel are not distinguished in this evolution (Figure 4(b)).

The original falling of relative sea level occurred in third period, when the facies belt got to migrate seaward (NW). In this stage, stratigraphic units formed the prograding parasequence when the late HST shoreline prograded. On the top, part of the deposits was eroded, with a smaller thickness. The thickness changing features in horizontal are similar to Parasequence 1, with a larger deposits thickness in the northwest and smaller one in the east (Figure 5(a)).

The relative sea level mainly fell in the fourth period, and the facies belt continued to move seaward, together with the erosion moving landward. In the northeastern and southeastern, the erosion areas can be found. To the end of this period, the relative sea level fell to the maximum depth, and the distribution of shoreface, foreshore and backshore reduced. The extent of facies migration seaward got a peak, and at the same time, the erosions achieved a maximum area with only small part of ‘Donghe sandstones’ remained in the western (Figure 5(b)).

4.4. Comparison to ones in previous studies
The cognition that interpreting the sedimentary model of ‘Donghe sandstones’ in Hudson area to composite sands under the background of regression with complex distribution of punctate or massive, or wave-dominated or tide-dominated deltas [5-9, 17-21] cannot cover all the depositional features or contradiction presented in study area, like the cross stratification that occurred frequently, the
occurrence of oblique oil-water surface, failed water injection, etc. Table 1 summarized the resulting microfacies scheme and part of the characteristics of individual sub-environments, and various microfacies constituted the recognition features and guided the future heterogeneity research. Compared to the sedimentary model established in previous studies, wave-dominated littoral deposits with no-barrier fit better to the Hudson area, and the reservoir controlled by facies can be easier to classify. In it, the bar and beach sands in shoreface and foreshore environments, which formed in a strong hydrodynamic environment, have relatively higher maturities and constitute favorable reservoirs.

5. Conclusions
Typical wave-dominated littoral depositional system developed in Carboniferous ‘Donghe sandstones’ in Hudson area. Transitional zone, shoreface, foreshore, backshore and dune are widely distributed in this area. Quartz sandstones of storm sands in transitional zone, longshore bar, and beach sands are considered as the favorable reservoirs.

The Carboniferous sandstones deposits in Hudson has experienced four main periods, which only develops highstrand systems tract (HST). In the first period, water intruded from southwest and made facies belt onlap towards northeast; to the second, a larger ingestion formed the pattern that shoreface deposits distributed surround the ancient shoreline made an element dominant; to the third, seawater shoaling accelerated the migration of facies belt towards southwest; and in the fourth period, the seawater continue to decline, only in western part of study area that ‘Donghe sandstones’ can be found.

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