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An Investigation into Lithofacies of the Cretaceous Chishan Group in the Wubao Fault Zone of Gaoyou Sag, Subei Basin, China

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ABSTRACT

This study aims to identify favorable oil–gas reservoir facies in the Chishan group of the Wubao fault zone (Gaoyou sag, Subei basin, China) using the methods of outcrops and cores observation, granularity analysis, scanning electron microscope, log data, etc. The results suggest that the Chishan group in the studied area mainly develops desert sedimentary system, and contains five kinds of facies from bottom to top, namely dry salt lake, aeolian sand, intermittent river, fan delta, and salt lake facies; the Chishan group was divided two members according to the lithology and a sedimentary cycle of base-level. The lower member of the Chishan group in the Wubao fault zone contained dry salt lake, intermittent river, and aeolian sand facies. The upper member of the Chishan group in the Chenbao area consisted mainly of aeolian sand. The southwestern Zhousong area contained (from east to west) a succession of aeolian sand, intermittent river, fan delta, and salt lake facies. Among these facies, aeolian sand was divided into aeolian sand dune, interdune, and aeolian sand sheet three sub-lithofacies. In the aeolian sand dune, the sand dune was a typical micro-lithofacies and had a scattered distribution. The fan delta had a bead-like distribution along the main fault, in which mainly underwater distributary channel and sand bank were developed. The sand bodies of the sand dune, underwater distributary channel, and sand bank were all well developed, and had average porosity values of >20%, meaning that they were favorable oil–gas reservoirs. The interdune sediments were fine-grained and had low porosity and permeability. Hence the reservoir properties of the interdune sediments were poor, and they could represent either fluid interlayers of reservoirs or source beds.

Keywords: Typical Micro-lithofacies, Facies, Chishan Group, Wubao Fault Zone, Gaoyou Sag

INTRODUCTION

The Cretaceous Chishan group is an extensively developed desert sedimentary system in the Subei basin, China (Figure 1). The discovery of aeolian sandstone reservoirs of the Chishan group in the Chenbao oilfield, located in the Wubao fault zone of Gaoyou sag, has focused research attention on the sedimentary environment of the Chishan group in adjacent areas. Various authors have studied the sedimentary characteristics of the

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desert sedimentary system of the Chishan group, especially the aeolian sand in the Jiangsu and adjacent regions [1-4]. However, no detailed studies have been done on the sedimentary environment of the transition zone from the aeolian sand to the salt lake. The Wubao fault zone, located in the transitional zone, has an area of about 650 km^2, but has been drilled for hydrocarbon exploration over an area of only about 150 km^2. The Chishan group is found in the depression of Gaoyou sag, and is distributed mainly in the Wubao low uplift, situated in reversed stair-step fault blocks and in the fault-nose zone. In addition, the low uplift is located on the right side of a steep slope zone. Because the sedimentary environment is poorly understood and the division of sedimentary facies is not sufficiently detailed, effective guidance has yet to be provided regarding the exploitation of oil and gas in the Wubao fault zone. Combined with information from outcrops in the city of Jurong and from cores in the Wubao fault zone, this study analyzes the sedimentary types and characteristics of the Chishan group in the Wubao fault zone, and aims to inform the exploration and development of reservoirs of the Chishan group in the studied area.

Figure 1: Sketch map showing the sedimentary facies of the upper Cretaceous Chishan group in the Subei basin and neighboring areas (modified from Yue et al., 1999 [5])

Lithologic Characteristics

The Chishan group outcrops as a set of brick-red sandstones in Jurong. The lower part of the group comprises interbedded or rhythmically bedded brick-red or purple, fine-grained sandstone, siltstone, pebbly sandstone, calcareous clay rock and clay rock, rich in calcium. The upper part contains red-brown or purple lithic quartz sandstone, graywacke and siltstone, and locally contains elongate lenticular beds that differ from the surrounding lithology; the bottom of this part commonly contains fine gravels. The outcrops of the Chishan group are scattered, and the thickness of the group varies between 300 and 700 m [6-7]. Drilling of the Chishan group in the Wubao fault zone, in the area of the Wubao low uplift, indicates that the thickness of the group varies greatly from 151 m in Well zhou 14 to 811 m in Well zhou 38-2, with the thickness on average being about 400 m. The lithologic characteristics of the group in some wells are similar to those of outcrop sections, but in other wells, the top of the group shows gray or dark-gray, massive mudstone, silty mudstone intercalated with thin-layered siltstone, or fine-grained sandstone; the middle to lower part is composed of gray or dark-gray, massive, fine-grained sandstone, and medium-grained sandstone intercalated with gray or dark-gray argillaceous clumps or strips. The Chishan group in the Wubao fault zone comprises a sedimentary cycle of base-level shallowing and then deepening in higher stratigraphic levels (Figure 2), and is separated by a large Stokes surface in the aeolian sand or a marked erosion surface in the salt lake. Based on all the above, the Chishan group is divided into two lower and upper members.

Division and Characteristics of Facies

The Chishan group in the Subei basin consists of three sedimentary environments: alluvial fan, desert, and lake [2,5]. The Wubao fault zone is located in a zone of desert–lake transition (Figure 1). On the basis of the results of the previous investigations of the paleodesert deposits [8-11], and through a comparative study with the sections of the Chishan group in Jurong city, the Chishan group in the Wubao fault zone is subdivided into five facies from bottom to top, namely dry salt lake, aeolian sand, intermittent river, fan delta and salt lake facies. The aeolian sand dune, interdune, and fan delta are further subdivided into several micro-lithofacies. Their characteristics are as follows:

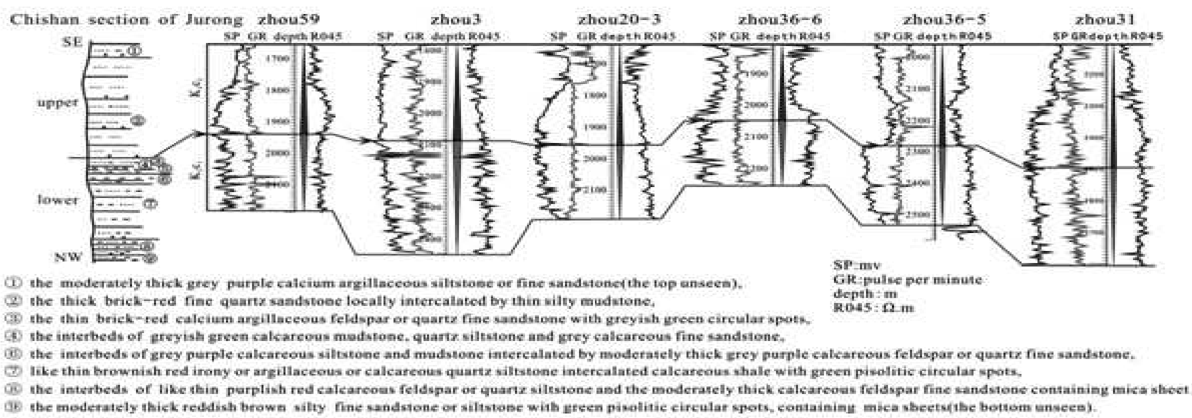

Figure 2: Correlation of the Chishan group in the Wubao fault zone and Jurong city

Dry Salt Lake

The dry salt lake is developed at the base of the Chishan group and has a thickness of about 10 m. The rock layer is dip-dyed by iron oxide and is mainly composed of gypsum-salt rock containing calcite, dolomite, magnetite, hematite, and limonite, with local zircon and other heavy minerals. The gypsum is mostly medium to coarse crystals, presenting microlaminations or stripes, which make the rock display a layered structure. The calcite is present as fine grains and the dolomite as powder crystal. All of the sediments described above are typical sediments and characteristics of a salt lake that formed during evaporation.

Aeolian Sand

Aeolian sand could be divided aeolian sand sheet, aeolian sand dune, and interdune in the current study.

Aeolian Sand Sheet

The aeolian sand sheet reaches a thickness of about 20 m in cores, and contains mainly siltstone and fine-grained sandstone. Parallel bedding is developed and horizontal laminae are observed in both outcrops and cores (Figure 3). The laminae become thicker upwards, and the interlamination is intercalated with thin layers of argillaceous siltstone and mudstone, which are laterally inconsistent and vary in thickness from 0.5 to 20 cm. The lower part of well log shows a finger, gradually changing upwards into a trend with only minor oscillations (Figure 4).

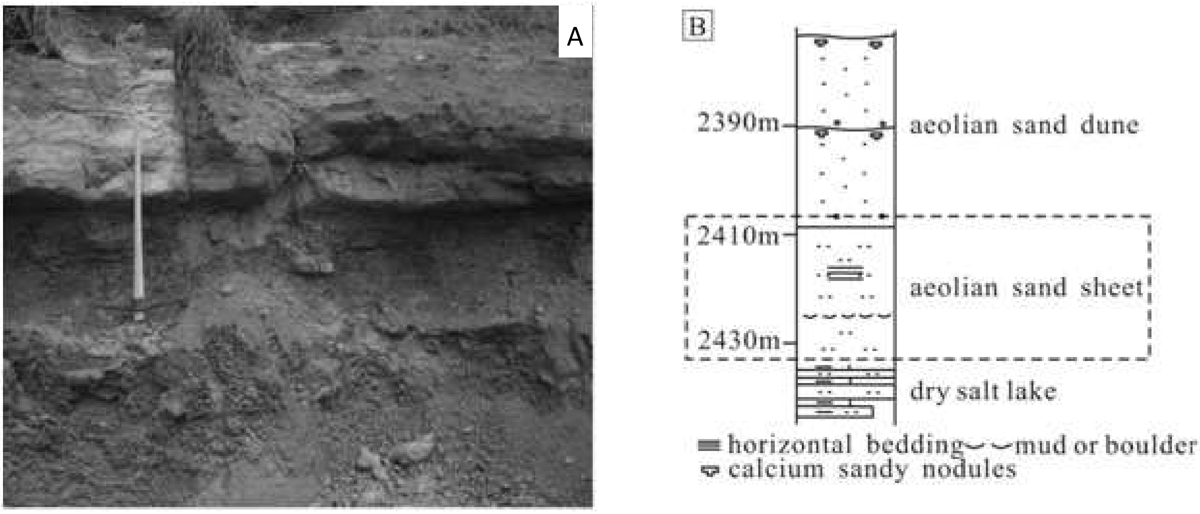

Figure 3: Features of the aeolian sand sheet: (A) Aeolian sand sheet of the Chishan section in Jurong; the pickax for scale is 80 cm; (B) Aeolian sand sheet of Well zhou 3.

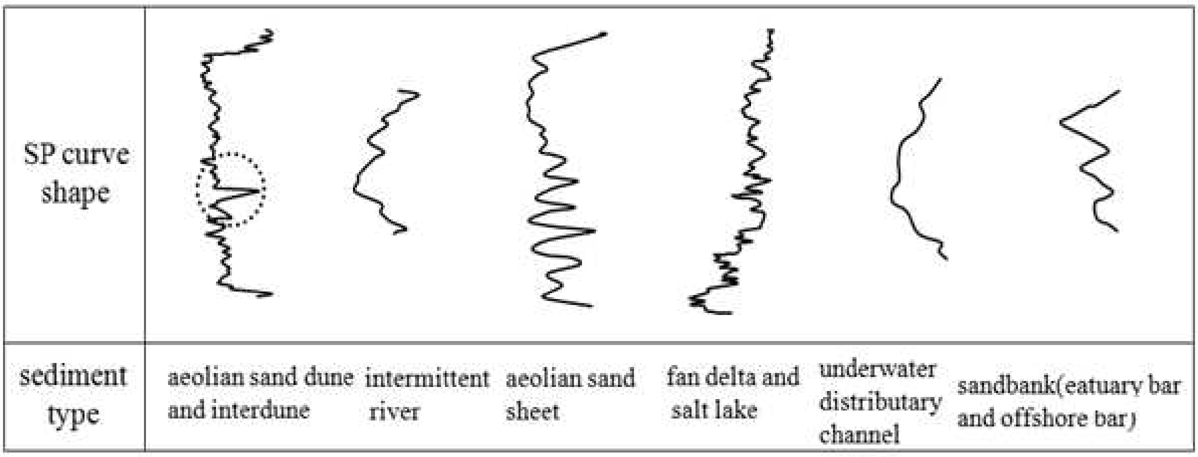

Figure 4: Features of electrofacies

The sub-lithofacies is located on the flat part of the transition between the desert edge and lake, where wind strength could have been weak, humidity has been relatively high, and the landscape could periodically have been first drowned and then exposed. The argillaceous siltstone and mudstone represent the sediments deposited during drowned, and the mudstone represents the dried clay exposed, which was later covered by thin sheets of sandy sediment.

Aeolian Sand Dune

The aeolian sand dune can be divided into the sand drift, sand cover, and sand dune. Of these, the sand dune is the main sedimentary type of this sub-lithofacies. The sand dune is the most typical and recognizable of the desert facies, and is widely distributed in the Subei basin, observed in both outcrops and cores. The thickness of the aeolian sand dune varies widely between 15 and 50 m in the Chenbao area and in the Chishan group sections in Jurong city, and reaches 50 m or more in the Zhousong area. The main lithology is brick-red or brownish-red, thick, fine-grained sandstone. Sand-grain surfaces are covered by an iron-rich membrane (hematite and limonite), known as “desert varnish” [1]. The packing of fine-grained sandstone is loose to moderate, but locally tight. The mineral components are quartz (60%-70%), subordinate lithic fragments, and feldspar, with minor dark-colored heavy minerals. Wind has produced conchoidal fractures, dish-shaped impact craters, v-shaped impact craters, direct impact ditches, and frost-like surfaces on quartz grains (Figure 5). The degree of mineral maturity is lower than that of modern desert sand.

The grain-size probability curves generally show three segments (Figure 6), which represent the saltation component, a small suspension component, and a small traction component. The inclinations of grain-size probability curves are in the range of 65 °-75°, which accounts for the tight distribution of sizes and good sorting. The roundness of sandstone particles is high in the Chishan group sections in Jurong city, but medium in cores. The rock is particle-supported and contacts with porous cemented. Mudstone matrix and cements are uncommon, both making up less than 7% of the rock volume, and there are many intergranular pores. Large-scale cross-bedding is developed in the aeolian sand dune, and biological remains and organism drill-holes are also found (Figure 7A–C). The dips of large-scale cross-bedding range between 26° and 35°, and the inclinations are bimodally distributed, between 80° and 145° and between 0° and 40°, in the Chishan sections in Jurong city. Combining the cross-bedding data with desert wind-direction data [12-13], the direction of the dominant wind is inferred to have been from the southwest.

Thin layers or stripes of well-rounded, coarse sand, and granular gravel are found on bedding surfaces (Figure 7D-E), and have the characteristics of ventifacts. In some sections, boundary surfaces of various dimensions cut through the beds; these are Stokes surfaces, which are the surfaces of aeolian sandstone representing erosion to the level of underground water. Gray calcareous spots and strips are found on these surfaces, and extend into the mudstone of the interdune. Sandstones are found above the Stokes surfaces but mudstones are placed below them (Figure 7F-G). These surfaces are unique to the aeolian sandstone. A layered structure is observed on the lee side of aeolian sand dunes, and may have been formed from the deferential sedimentation of a debris flow [11]. Our present investigation suggests that this feature is formed from the alternating effects of strong and weak wind, because its particle size distribution shows values that change abruptly, but not gradually (Figure 7H). All the aforementioned characteristics are typical of aeolian sand dunes, and such characteristics differentiate these sediments from those of other environments.

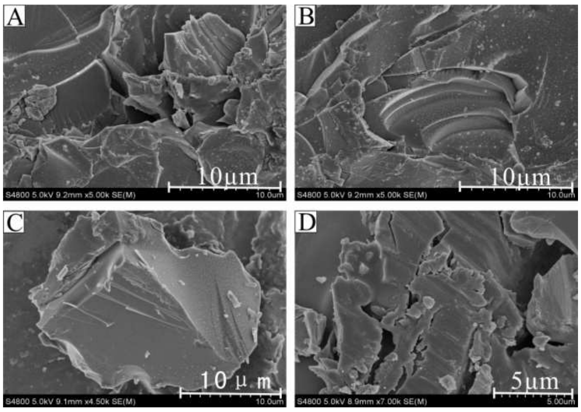

Figure 5: Scanning electron micrograph images showing the surface features of quartz grains; (A) Conchoidal fractures; (B) Dish-impact craters and frost-like surface; (C) V-shaped impact craters; (D) Direct-impact ditches.

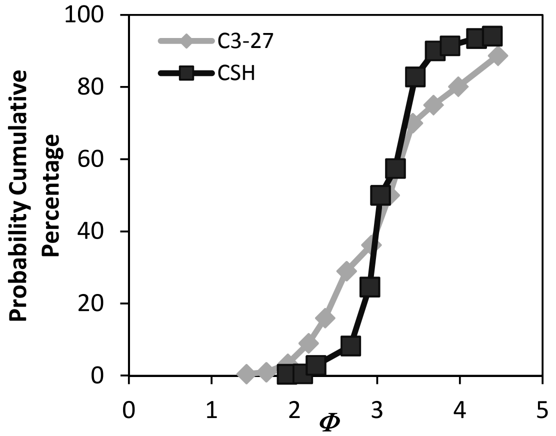

Figure 6: Probability accumulative curve of aeolian sand dune sediments. Sample CSH is from a member of the Chishan group in the Chishan sections (taken from Yue et al., 1999); sample C3-27 is from a member of the Chishan group in the Chenbao oilfield.

Interdune

The interdune can be divided into the wet interdune, dry interdune, and evaporative interdune. The wet interdune is developed mostly in the upper Cretaceous sediments of the Subei basin and represents the interdune depression that formed from ephemeral surface water derived either from fluctuations in the water table or from intermittent rain. The beds are purple mudstone to siltstone and are mainly thin (Figure 8A) or are lenses intercalated with thick sets of coarse-grained sandstone.

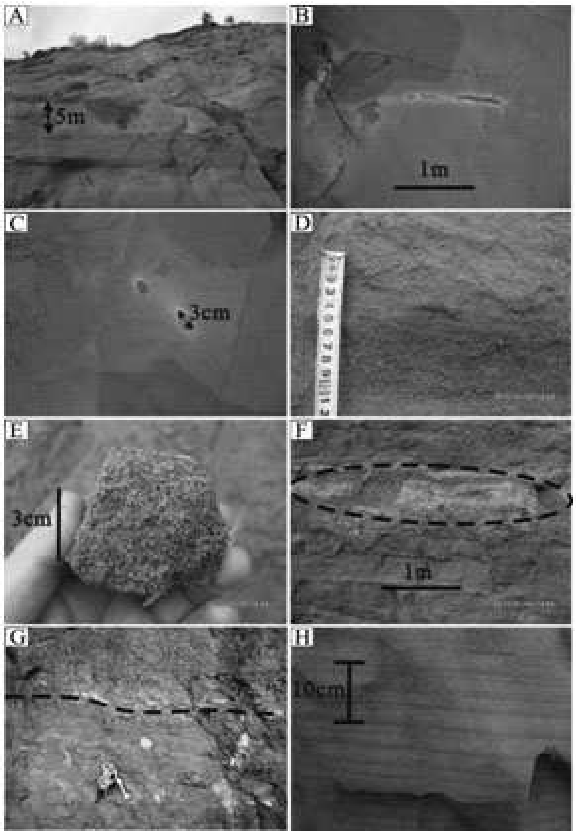

Figure 7: Features of aeolian sand dune sediments in the Chishan group in Jurong city; (A) Large-scale cross-bedding; (B) Biological remains on the lee side of sand dune; (C) Organism drill-holes on the lee side of sand dune; (D–E) Ventifacts; (F) A Stokes surface characterized by gray calcareous spots and strips; (G) Mudstone of the interdune into which the Stokes surface extends; (H) The layered structure on the lee side of an aeolian sand dune.

Ripple bedding and microscale horizontal bedding are observed in the Chishan sections in Jurong city (Figure 8B), and fractured fragments of clay and mud indicate intense evaporation thorough desiccation (Figure 8C). The mud fractures are mostly filled by aeolian sand, reflecting the typical sedimentary tectonics of a sand column or sand vein in a wet interdune (Figure 8D). The thickness of the wet interdune deposits ranges from several centimeters to more than 10 m, and they are irregularly distributed and limited in extent. The wet interdune is commonly overlain by sediments of the sand dune and is characterized by abnormal-amplitude finger logging, which contrasts strongly with the low-amplitude straight logging of sand dune sediments (Figure 4).

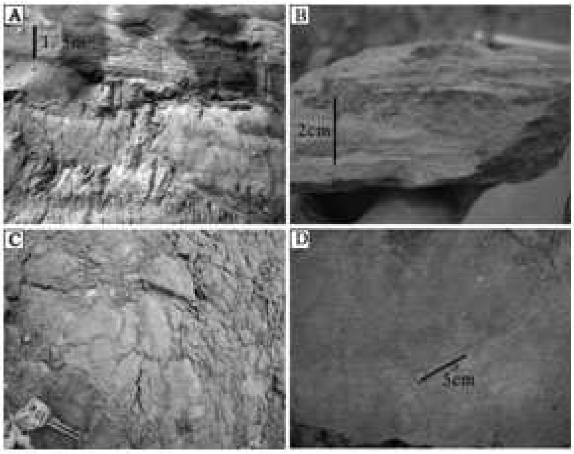

Figure 8: Sedimentary features of the interdune in the Chishan group in Jurong city; (A) Horizontal bedding of the interdune; (B) Ripple bedding of the wet interdune; (C) Shrunken mud fractures and dried clay fragments; The key for scale is 5 cm long; (D) Sand column or sand vein formed by younger aeolian sand filling fractures developed in mud.

Intermittent River

The intermittent river is found in both outcrops and cores, and the average thickness is about 10 m. The main lithologies are siltstone and fine-grained sandstone intercalated with mudstone, and the sediments are moderately to poorly sorted. The mineral components are predominantly quartz, with subordinate lithic fragments and feldspar. The grains are angular to subrounded. Both scour-fill and bioturbation structures are developed (Figure 9A, B), and both wave-bedding and small scale cross-bedding occur locally. Crumbly muddy gravels, pelitic strips, and calcium nodules are observed in cores (Figure 9C). All the aforementioned sediments are characteristic of intermittent river channel deposits.

Fan Delta

The fan delta is a large-scale facies found in both outcrops and cores, and attains a thickness of 100 m or more. The lithologies are gray, fine-grained sandstone, siltstone, and argillaceous siltstone.

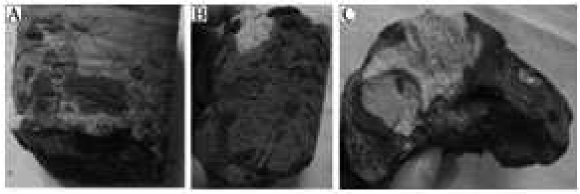

Figure 9: Sedimentary features of the intermittent river from Well zhou 3, 2231.75 m; (A) Scour in the riverbed; (B) Bioturbation; (C) Mud gravels and calcium nodules.

The mineral components are dominated by quartz (50-65%) with subordinate rock fragments (20-30%) and feldspar (15-25%), which reflects the higher rate of sedimentation compared with other facies and shorter transport distances of the sediments. The textural maturity of the sediments is low. The sediments are grain supported and contact with porous cemented, and they show moderate to tight packing. The cements are mainly dolomite and contain iron locally. Parallel bedding, ripple bedding, and convolute bedding are all widely developed (Figure 10A, C, and D), and graded bedding and reverse-graded bedding are observed locally (Figure 10E and D). Grayish-green, muddy gravels with particle sizes up to 3 cm containing irregularly shaped pyrite accretions are also found (Figure 10B).

Given the aforementioned characteristics, together with the small size of the drilled area (150 km^2) in the Wubao fault zone, the steep slope of the terrain (1.3-7.4%, calculated as the height difference between adjacent topographic contours, divided by the distance between the contours), and data from other studies [14-17], we suggest that these sediments belong to a fan delta adjacent to the aeolian sandstone, which was formed by an intermittent river running into a lake. In fact, these deposits are similar to the landward sedimentary facies (river and aeolian sand dune facies) of the Yallahs fan delta in the coastal area of southeast Jamaica. In accordance with the sedimentary characteristics of the Wubao fault zone, three micro-lithofacies can be distinguished within the fan delta: the underwater distributary channel, estuary dam, and far bar. The cores of the underwater distributary channel sediments are gray in color, show parallel bedding (locally graded bedding), and their logging curves are bell shaped. Both the estuary dam and offshore bar sediments consist of gray, fine-grained sandstone and siltstone, and their combined logging curves are funnel shaped and continuous. The amplitude of oscillations in the logging curves decreases downwards from the estuary dam to the offshore bar sediments (Figure 4).

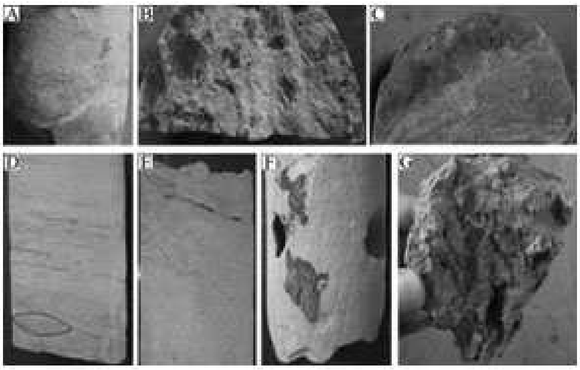

Figure 10: Sediments of the underwater distributary channel and estuary bar micro-lithofacies in the fan delta facies; (A) Parallel bedding in Well zhou 44-6, 1820.84 m; (B) Grayish-green, muddy gravels intercalated with sandstone, Well zhou44-6, 1822.3 m; (C) Ripple marks on the bedding surface, Well zhou 44-6, 1874.4 m; (D) Convolute bedding, Well zhou 44-6, 1822.1 m; (E) Graded bedding, Well zhou 44-6, 1822.3 m; (F) Pyrite accretions, Well zhou 44-6, 1826 m; (G) sandy mudstone, Well zhouxie 44-7, 1877.66 m.

Salt Lake

Salt lake sediments are gray or dark gray in color and are composed of gypsum, halite, dolomite, gypsiferous mudstone, and argillaceous glauberitic siltstone; glauconite is observed in siltstone. The cements are dolomitic and contain iron locally. High magnesium contents in some of the sediments indicate an affinity with sea water. Based on the above characteristics, we infer that the sediments belong to a terrigenous offshore salt lake environment.

Distribution of Facies and Typical Micro-lithofacies

Five facies, namely the dry salt lake, aeolian sand, intermittent river, fan delta, and salt lake, are found in the Chishan group in the Wubao fault zone of Gaoyou sag (Figure 11). The succession reflects a sedimentary cycle of base-level shallowing and then deepening in higher levels of the sedimentary column. On the basis of the sedimentary features observed in outcrops and cores, logging data, and relationships between lithology and electrical properties, the distributions of facies and typical micro-lithofacies are shown in Figure 12. The lower member of the Chishan group in the Wubao fault zone of Gaoyou sag comprises aeolian sand sheet, intermittent river, aeolian sand dune, interdune, and dry salt lake only around Well zhouxin 38-2. The thickness of the sand dune reaches 50 m or more, and the thickness of the sand sheet ranges from about 15 to 30 m. The upper member in the Chenbao area consists mainly of the aeolian sand dune, the thickness of which is 15 to 50 m, whereas the Zhousong area in the southwest of the Chenbao area contains the aeolian sand dune, interdune, aeolian sand sheet, intermittent river, fan delta, and salt lake from the east to the west. The distribution of sediments of the sand dune is relatively scattered, and it is developed only around wells zhou 12, zhou 3, and zhou 41-9, with a thickness reaching 50 m or more. The distribution of the fan delta is controlled by a reverse stair-step fault and shows a bead-like pattern along the trend of the main fault. In the fan delta front, the thickness of sandstone is 10 to 30 m, and the shale content increases upwards through the facies.

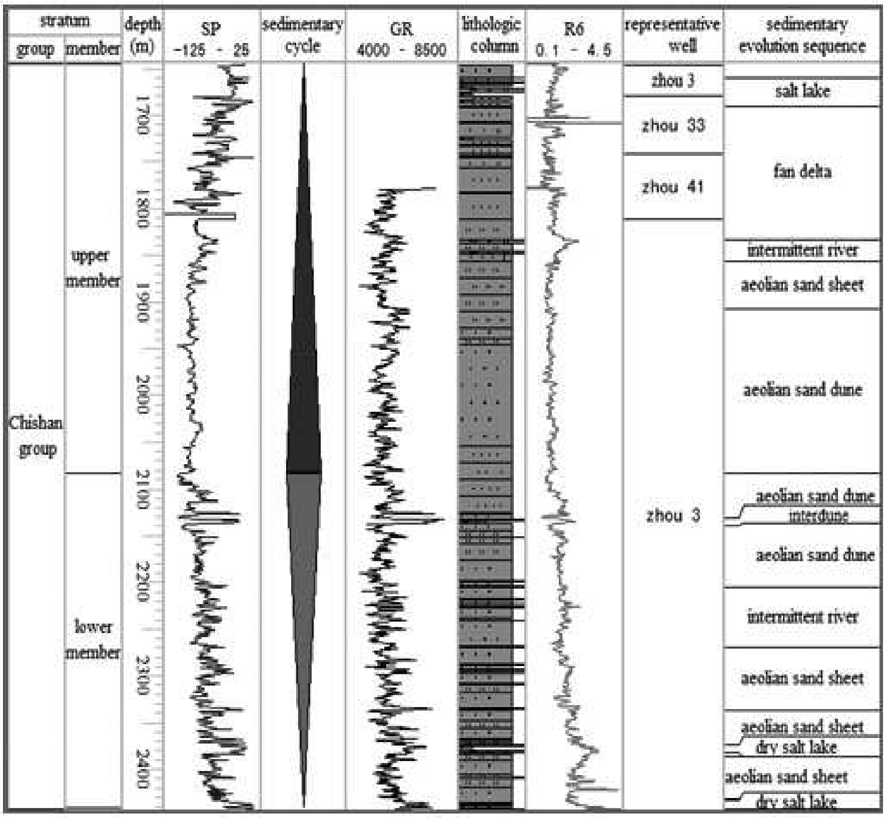

Figure 11: Sedimentary characteristics and inferred sedimentary environments of the Chishan group

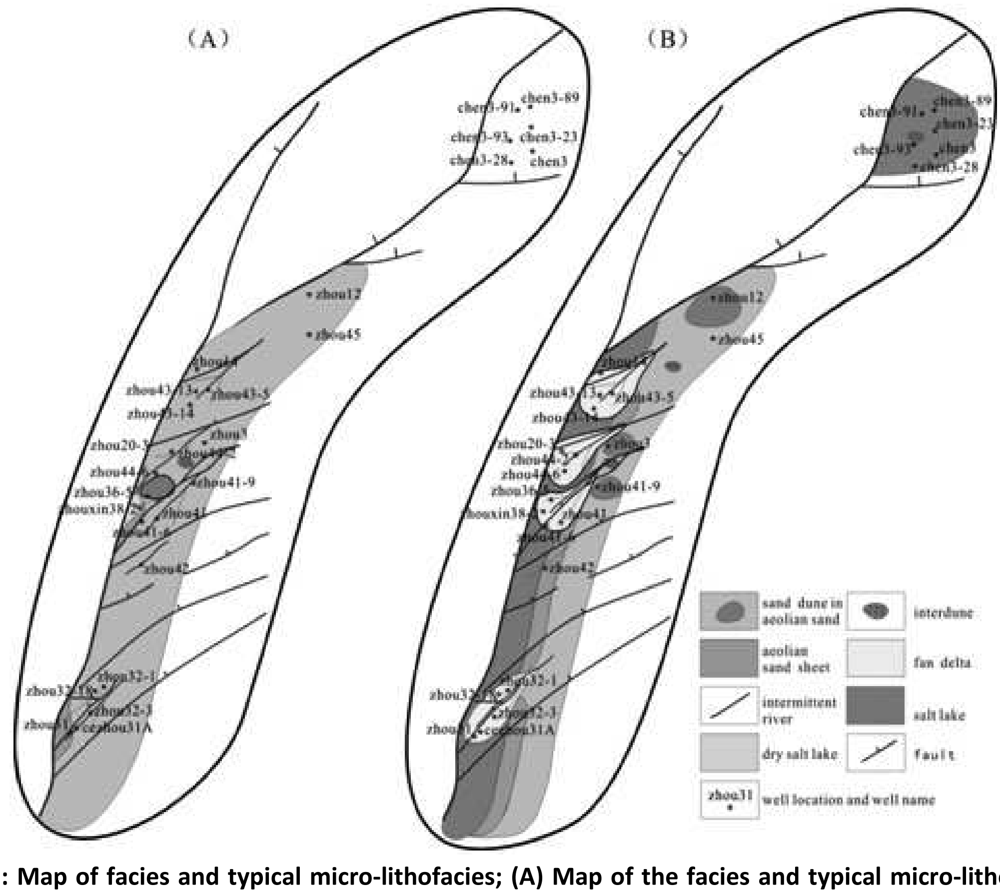

Figure 12: Map of facies and typical micro-lithofacies; (A) Map of the facies and typical micro-lithofacies of the lower member; (B) Map of the facies and typical micro-lithofacies of the upper member.

Geological Significance

Over the past two decades, oil and gas reservoirs related to paleodesert environments have been discovered in various locations both in China and elsewhere. Such reservoirs include large gas fields in Groningen in the Netherlands, Lehmann in England, and Unyielding in the North Sea [18]. Cretaceous desert sediments are widely distributed across China and are found in the Tarim, Ordos, Sichuan, Jianghan, and Subei basins. In 1997, the Chenbao oilfield was discovered in the Subei basin [19].

The key controls on hydrocarbon accumulation are the thickness of sandstone and the properties of reservoirs. The sediments of the interdune are fine grained, and the porosity and permeability are low; thus the reservoir properties of this sub-lithofacies are poor (Table 1). The sand dune, the underwater distributary channel, and the estuary bar are thick sedimentary bodies. In addition, the porosity of sandstone in the sand dune is about 20% on average, and in the underwater distributary channel and estuary bar about 30% on average. Furthermore, the permeability of these three sedimentary bodies is high (Table 1). Therefore, the sand dune, underwater distributary channel, and estuary bar are good reservoirs for hydrocarbon production, as confirmed by the oil production of wells Zhou44-6 and Zhou 3.

Table 1: Physical properties of samples of the Chishan group in the Wubao fault zone and Jurong city

Well	Sample depth (m)	Porosity (%)	Horizontal permeability (md)	Sedimentary environment	Outcrop sample	Porosity (%)	Horizontal permeability (md)	Rock density (g/cm^3)	Sedimentary environment
zhou 3	2031.65	19.6		Sand dune	1	11.86	9.52	2.34	Interdune
	2232.8	20.4							
zhou 44-6	1824.14	29	60.4	Underwater distributary	2	10.28	0.818	2.37	
	1825.29	31.6	72.5						
zhouxie 44-7	1874.3	26.8		Sand bank	3	26.97	155	1.88	Sand dune
	1876.96	37	587						
	1880.31	32.3			4	25.65	81	1.93	
	1881.31	32.4	311						
	1881.54	32.8	172		5	24.39	243	1.96	

CONCLUSIONS

The Chishan group in the Wubao fault zone contains five facies, namely dry salt lake, aeolian sand, intermittent river, fan delta, and salt lake, representing a sedimentary cycle of shallowing base level followed by deepening upwards through the sedimentary column. The sand dune is the predominant micro-lithofacies in the aeolian sand. The sandstone in the aeolian sand dune deposits shows typical aeolian features in terms of petrology, structure, quartz-particle surfaces, Stokes surfaces, large-scale cross-bedding, and layered structure. The fan delta is a new facies proposed in the studied area and is distinguished on the basis of facies characteristics, including the steep slope of the paleo-terrain, near-source deposition, rapid changes in depositional phase, the limited extent of the deposit, and the high gravel content of the sediment.

The lower member of the Chishan group in the Wubao fault zone contains dry salt lake, aeolian sand sheet, intermittent river, aeolian sand dune, and interdune. The upper member in the Chenbao area is mainly comprised of aeolian sand dune deposits, and in the southwestern Zhousong area contains the aeolian sand dune, interdune, aeolian sand sheet, intermittent river, fan delta, and salt lake. The sand dune micro-lithofacies has a scattered distribution. The distribution of the fan delta is tectonically controlled by reverse stair-step faulting and shows a bead-like pattern along the trend of the main fault.

The sand bodies of the sand dune, underwater distributary channel, and estuary bar are thick and have good porosity (average>20%) and permeability. These micro-lithofacies are favorable for oil and gas exploration. The sediments in the interdune are fine grained and the porosity and permeability are both low, on the basis of which the reservoir potential is judged to be low.

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