Research Article

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Sedimentary succession and recognition marks of lacustrine gravel beach-bars, a case study from the Qinghai Lake, China

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Abstract: The present is the key to the past. Based on the dissection of modern beach-bars in the Qinghai Lake, Qinghai-Tibet Plateau, China, including two profiles parallelly to the shoreline, two profiles vertically to the shoreline and one plane-view profile, the sedimentary succession and recognition marks of lacustrine gravel beach-bars have been summarized. Vertically, the lacustrine gravel beach-bars develop with the "ABC" succession. The A interval, the B interval, and the C interval respectively correspond with the gravelly sand facies, the well-sorted gravel facies, and the graded sand facies. The lacustrine gravel beach-bars is composed of several combinations of the "ABC" succession, such as "ABAB", "ABCABC", "BCBC". The main recognition marks of lacustrine gravel beach-bars is the following: the bottom contact is distinct and with the "ABC" succession; and the lacustrine beach-bars develop the swash bedding and sheet-like parallelly to the lakeshore. These viewpoints have significant contributions to the reconstruction of paleoenvironments and paleoshorelines and to the reservoir interpretation within lacustrine beach-bar clastic bodies.

Keywords: Qinghai Lake, Beach-bar, Lacustrine, Gravel beach-bars, Delta front

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1 Introduction

Lacustrine beach-bars are widely spread in modern lakes, but they, especially gravel beach-bars, have rarely been found in ancient lakes [1–3]. In all probability, many ancient lacustrine beach-bars were not correctly identified or were mistakenly interpreted as delta fronts. Because previous researchers hold that lacustrine beach-bars are characterized by siltstones, sandstones, conglomerates with thin mudstone units, and the presence of well-developed sedimentary structures, such as swash bedding, parallel bedding. ripples, terrestrial plant debris and vertical burrows [4–7], which suggests that beach-bars were deposited in a relatively shallow water environment under the influence of strong hydrodynamics [8, 9]. These sedimentary characteristics are similar to the sedimentary characteristics of delta fronts [10, 11]. How to distinguish between lacustrine beach-bar sediments and delta front sediments? This is a key question.

Previous studies on lacustrine beach-bars have not received enough attention. The highlighted point is that the beach-bars are generally attributed to the shore-shallow lacustrine, which is between the lake level and the wave base [4, 12, 13]. This point ignores the influence of waves on sediments when the form of waves varies with the water depth and the landform. And previous researchers did not systematically summarize the sedimentary characteristics and key identification marks of beach-bars in the different wave zones, and the particular sedimentary succession is not established.

Recently, the beach-bar reservoir play has also become an attractive exploration target of the Bohai Bay basin, of Erdos basin, and of Junggar basin [14–17]. The beach-bar reservoirs are discovered primarily in structure-lithologic, litho-stratigraphic or stratigraphic traps, which are ideal for hydrocarbon accumulation [5, 17–19]. How to correctly identify ancient beach-bar sediments is great significance to the exploration and development of hydrocarbon. Meanwhile, this is also significance to the reconstruction of paleoenvironments and paleoshorelines.

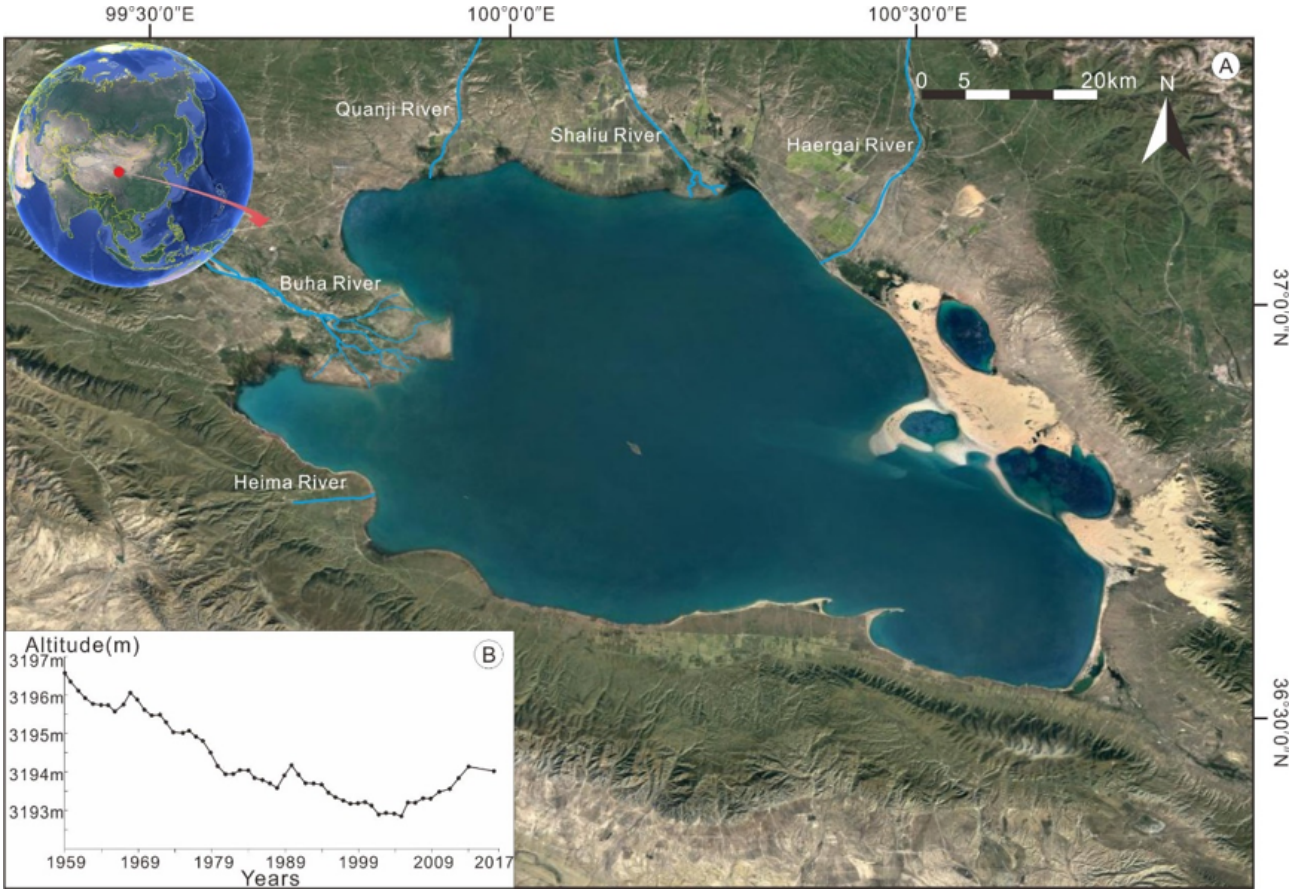

Figure 1: (A) Map showing Location of the Qinghai Lake of Qinghai-Tibet Plateau. China. The map was created with 91 Satellite Map Assistant. Image data: Google, DigitalGlobe. (B) Map showing lake-level oscillations of the Qinghai Lake from 1959 to 2017.

In this study, based on the present lacustrine beach-bar of Qinghai Lake, China, the sedimentary characteristics of lacustrine gravel beach-bars in the different wave zone have been summarized, and the sedimentary succession and depositional model have been built, and the key identification marks have been found.

2 Study area

Qinghai Lake (36°32' to 37°15' N, 99°36' to 100°46' E), the largest closed-basin lake in China, is situated at an altitude of 3194m above the sea level on the northeastern Qinghai-Tibetan plateau (Figure 1A), with a surface area of about 4260 km^2 and a catchment area of about 29660 km^2 [20]. The maximum water depth is approximately 33 m, and its average depth is approximately 21 m. Five rivers, Buha, Quanji, Shaliu, Haergai and Heima, discharge into the Qinghai Lake basin (Figure 1A), and the inflowing water is mainly from the Buha, Shaliu and Hargai rivers, which contribute 42.6%, 15.3%, and 15.0% of the total water volume, respectively [21, 22]. From 1958 to 2017, the Lake level gradually declined from 3196.5m to 3194m (Figure 1B) [23–25]. Beach-bars are widely developed along the coast of the Qinghai Lake (Figure 1A). The total length of beach-bars is about 162km.

3 Method

The present is the key to the past. Based on the field investigation of the Qinghai Lake, two gravel beach-bars have been researched in which the four profiles were measured, including two parallelly to the shoreline and two vertically to the shoreline. And the plane-view change of sedimentary characteristics of beach-bars was measured. A total of 73 beach-bar samples were collected from the gravel beach-bars in the Qinghai Lake, China. The grain size distribution was measured by a Malvern 3000 laser diffraction instrument at the State Key Laboratory of Petroleum Resources and Prospecting, China. The sorting and mean grainsize

Figure 2: Lithofacies of gravel beach-bars in the Qinghai lake.

are based on Folk (1966) equation[23-25], where:

$$\sigma_1 = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6}$$

$$Mz = \frac{\phi_{16} + \phi_{84} + \phi_{50}}{3}$$

here, σ_1 is the sediment sorting, and Mz is the mean grain-size, and φ_x is the grain diameter (in phi units) at the cumulative percentile value of x. Other parameters were measured on the field sites.

4 Lithofacies

Based on the study of several beach-bar profiles, it is found that the gravel beach-bar is composed of three lithofacies, gravelly sand, well-sorted gravel, and graded sand.

4.1 Gravelly sand facies

The gravelly sand facies is characterized by poor-sorted gravelly sand (Figure 2). The sand is 1 to 2mm in grain size. The gravel accounts for 10% to 30% of this facies. The gravel, generally 2 to 30mm in grain size, are well-rounded, and float in the sand parallelly with the bedding surface. The grainsize accumulation probability curve has two sub-populations with a relatively low gradient (Figure 2 and 3). The grainsize accumulation probability curve has two sub-populations with a relatively low gradient and the mean grain size is 1 to 4mm. The sorting is 1.5 to 3 (Figure 3).

4.2 Well-sorted gravel facies

The well-sorted facies is characterized by well-sorted gravel with massive bedding (Figure 2). The gravel account for 80% to 90% of this facies. The gravel, generally 6 to 50mm in grain size, are well-rounded. The basal contact with the wave asymmetric zone gravelly sand is abrupt. The grainsize accumulation probability curve has two sub-populations with a relatively high gradient (Figure 2 and 3). The grainsize accumulation probability curve has two sub-populations with a relatively high gradient, and the mean grain size is 4 to 16mm. The sorting is 0.5 to 1.2 (Figure 3).

4.3 Graded sand facies

The graded sand facies is characterized by well-sorted sand with normally graded bedding (Figure 2). The sand is 0.5 to 2mm in grain size. The gravel accounts for 5% to 10% of this facies. The gravel, generally 2 to 4mm in grain size, is well-rounded. Vertically, the sediments gradually change from fine gravel to fine sand upwards. Laterally, the sediments gradually change from fine gravel to fine sand landwards. The basal contact with the breaker zone gravel is gradual. The grainsize accumulation probability curve has two sub-populations with a relatively high gradient (Figure 2 and 3). The grainsize accumulation probability curve has two sub-populations with a relatively high gradient, and the mean grain size is 0.4 to 2mm. The sorting is 0.4 to 0.9 (Figure 3).

4.4 Distributional characteristics of facies

Among the above three types of lithofacies, Gravelly sand facies is the thickest, the single layer is mostly 20cm-40cm in thickness (Figure 3). The Well-sorted gravel facies is the second. The single layer is mostly 10cm-20cm in thickness (Figure 3). the thickness of graded sand facies is the thinnest, mostly a few centimeters to ten centimeters (Figure 3).

On the profile parallelly with the shoreline, the lateral continuity of all types of facies is generally well and is ex-

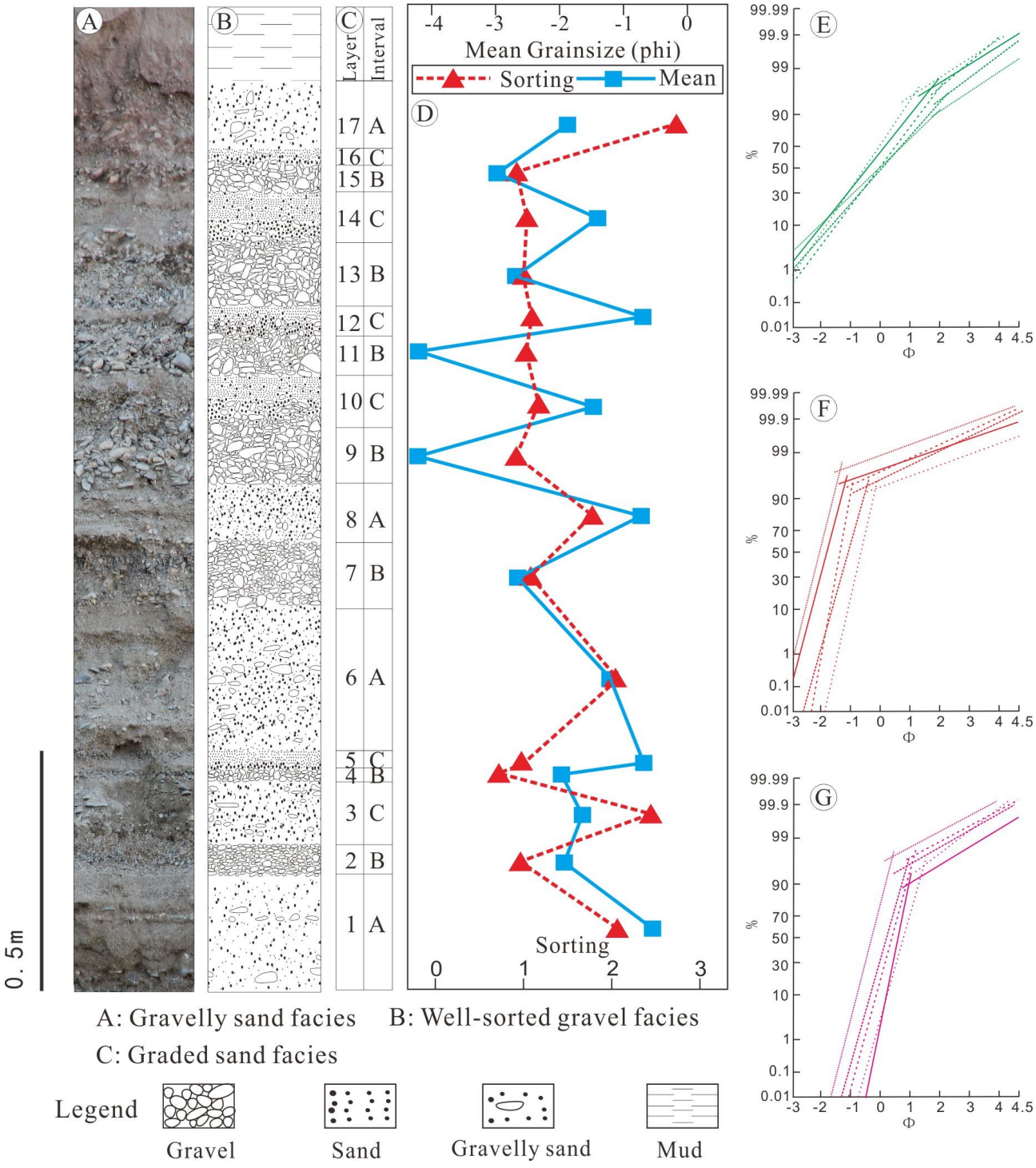

Figure 3: (A) Column photography of gravel beach-bars in the Qinghai Lake, Qinghai-Tibet Plateau, China; (B) Column sketch of the gravel beach-bars; (C) Partition of the gravel beach-bars, "A" is the gravelly sand facies, "B" is the well-sorted gravel facies, "C" is the graded sand facies; (D) Grainsize parameters of the gravel beach-bars; (E) Grainsize accumulation probability curve of gravelly sand facies; (F) Grainsize accumulation probability curve of well-sorted gravel facies; (G) Grainsize accumulation probability curve of graded sand facies.

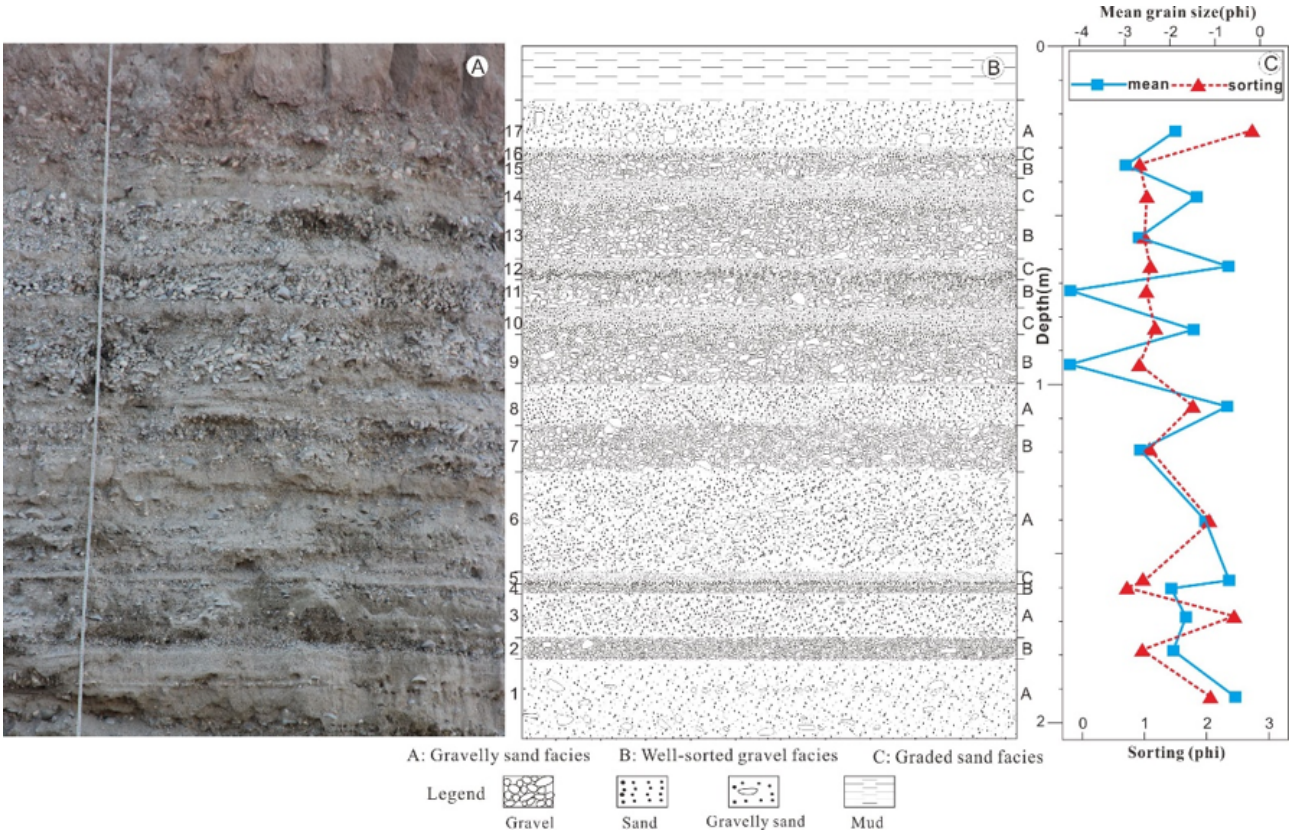

Figure 4: Beach-bar profile parallelly with the shoreline. (A) Photography of gravel beach-bars in the Qinghai Lake, Qinghai-Tibet Plateau, China; (B) Column sketch of the gravel beach-bars; (C) Grainsize parameters of the gravel beach-bars.

tended to ten meters. The formations are horizontal and parallel to each other (Figure 4).

On the profile vertically with the shoreline, the lateral continuity of all types of facies is generally poor and extends about two meters. Moreover, the formation is obviously inclined to the lake with a slope of between 4° and 8° (Figure 5).

5 Hydrodynamic characteristics in the different wave zones

The division of wave zone is the basis of the depositional model and the sedimentary succession. In order to comprehend the origin of three types of lithofacies above and the differences of every part of the beach-bars, the hydrodynamic characteristics and sedimentary characteristics in the different wave zone have been analyzed. The wave zone can be divided into three parts, wave asymmetric zone, wave breaker zone, and wave surfing zone (Figure 6).

5.1 Wave asymmetric zone

The wave asymmetric zone is located between the wave base and the wave breaker zone. The wave asymmetric zone is similar to the shoaling zone. The wave starts to touch the lake bottom so that the wave shape begins to be asymmetric, but not be broken (Figure 6). The breadth of wave asymmetric zone is 20m to 40m, and the depth is 1m to 3m. The wave energy is relatively weak, and only the sand can be transported, but the intermittent storm wave can deposit some gravel in this zone.

5.2 Wave breaker zone

The wave breaker zone is located between the wave asymmetric zone and the wave surfing zone. As the water depth becomes shallower and the water depth is less than the wave height, the wave will be turn up and broken, and dive into the lake bottom (Figure 6). The breadth of wave breaker zone is less than 1m, and the depth is about 1m. The wave height is biggest in all wave zones, and the en-

Figure 5: Beach-bar profile vertically with the shoreline. (A) Column photography of gravel beach-bars in the Qinghai Lake, Qinghai-Tibet Plateau, China; (B) Column sketch of the gravel beach-bars.

ergy is strongest. Only the gravel can be deposited in this zone.

5.3 Wave surfing zone

The wave surfing zone is located between the wave breaker zone and the shoreline. Resulting from the effect of inertia, the wave continues to move landwards after the wave is broken (Figure 6). The wave height is smallest in all wave zones. The energy is weakest in all wave zones, and the wave energy gradually decreases landward. The breadth of wave surfing zone is 1m to 2m, and the depth is less than 0.5m. The sediments are obviously finer than the sediments of the wave breaker zone. Resulting from the gradual decrease of wave energy landward, the graded bedding is produced.

6 Depositional model and depositional succession

6.1 Depositional model

Through the investigation of the forming beach-bars along the shoreline, it is found that the three lithofacies above are formed respectively in the different wave zone (Figure 7). The depositional model has been built, and the beach-bars can be divided into three parts (Figure 8).

The gravelly sand facies form in the wave asymmetric zone. In current Qinghai lake, there is gravelly sand in the wave asymmetric zone. The gravel is 0.5*3cm to 1*5cm, and scatter in the sand. In normal weather (the wind scale is less than 6 level), the gravel in the wave asymmetric zone is stationary, not transported, indicating that the normal waves cannot transport these gravel. These gravel are transported by the storm wave. In other words, the gravelly sand facies is consist of sand formed by the normal wave and gravel formed by the storm wave, so the sorting is poor.

The well-sorted gravel facies form in the wave breaker zone. In current Qinghai lake, it is found that the wave is turned up and dive into the lake bottom, and the sediments are stirred and deposited quickly in front. A narrow bar, tens centimeters in width, has been formed along the shoreline, which is consist of gravel. This is the well-sorted gravel facies.

The graded sand facies form in the wave surfing zone. In current Qinghai lake, it is found that the wave continues to move to the land after the break of waves, but the

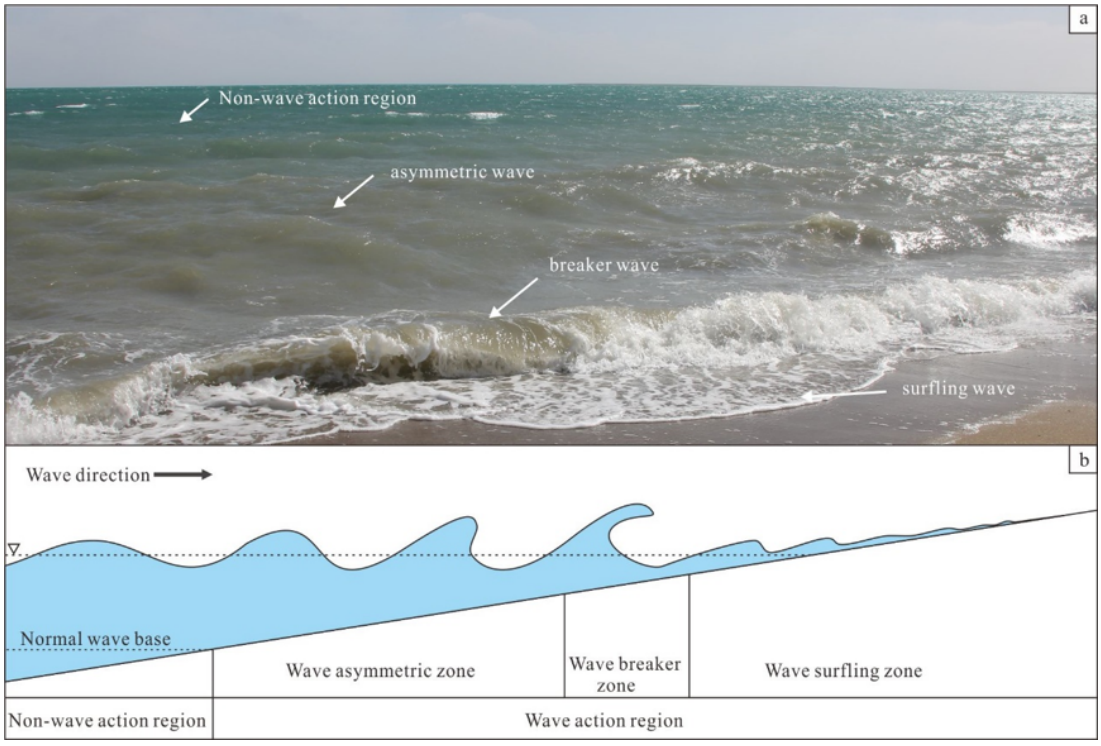

Figure 6: (A) Photography of waves in the Qinghai Lake; (B) Division of wave zone.

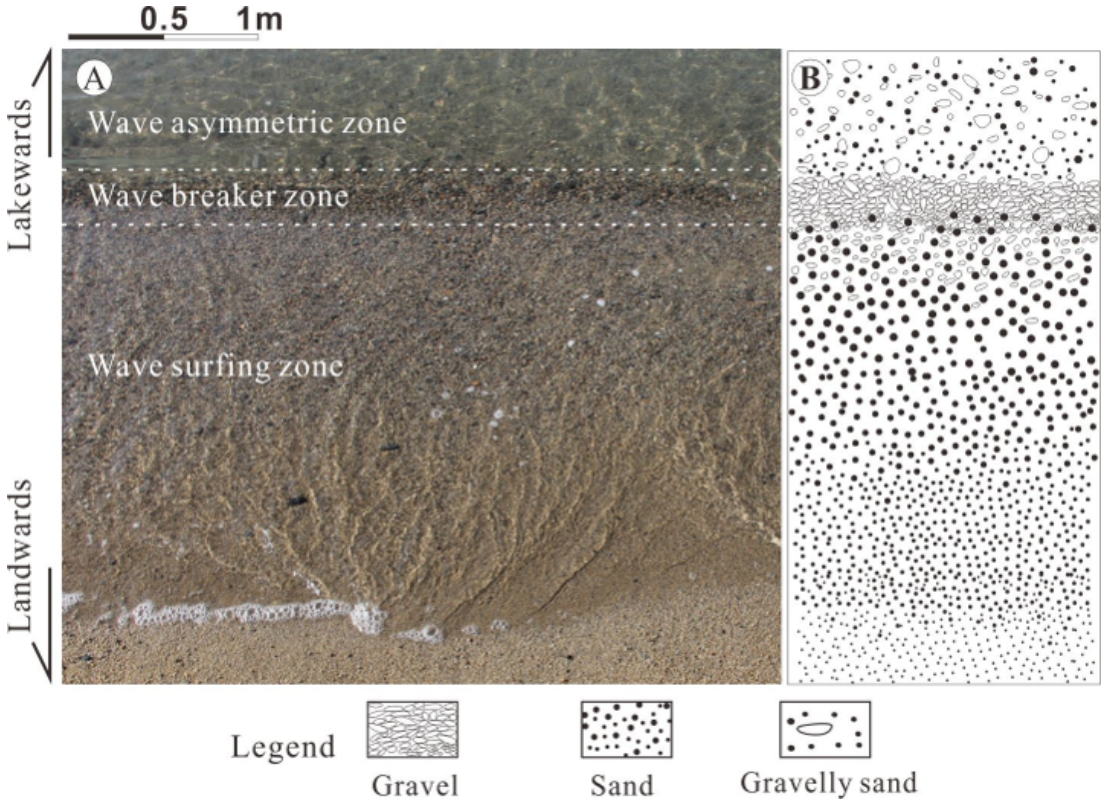

Figure 7: (A) Photography of forming beach-bars in the Qinghai Lake, Qinghai-Tibet Plateau, China; (B) Sketch of forming beach-bars in the Qinghai Lake, Qinghai-Tibet Plateau, China.

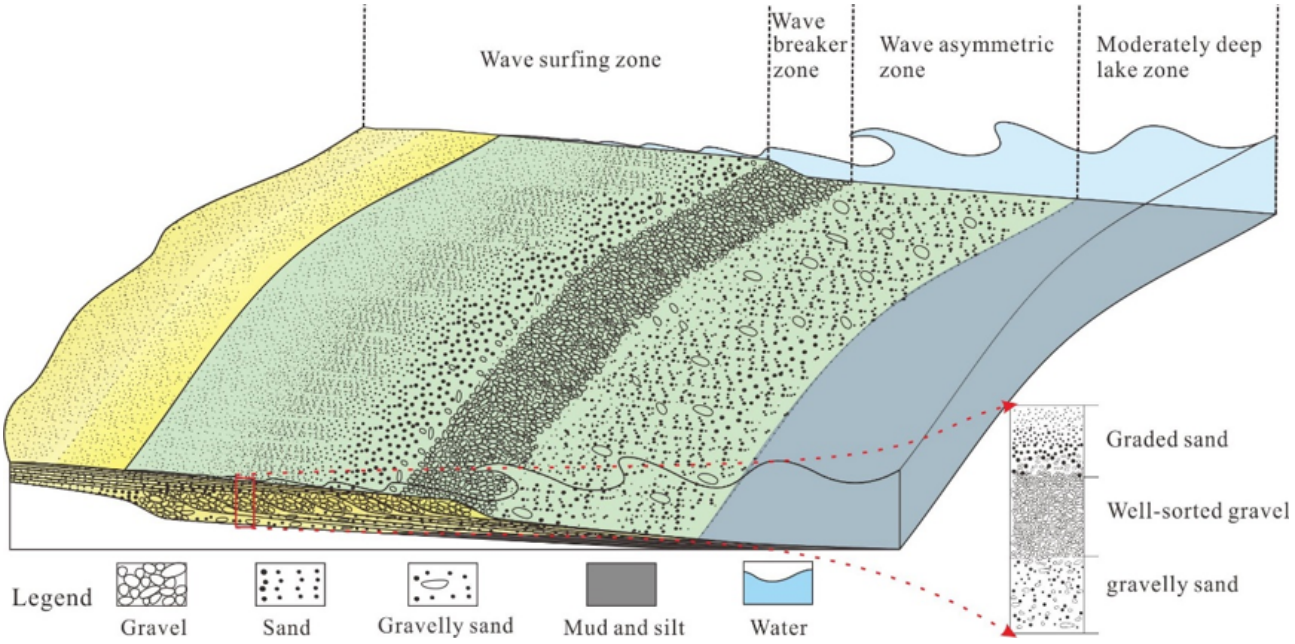

Figure 8: Depositional model of lacustrine gravel beach-bars.

energy is gradually decreasing. The grain size of sediment changes obviously. The coarse sand gradually changes into fine sand landward.

6.2 Depositional succession

In the normal setting, the shoreline gradually migrates towards basins due to sedimentation, a whole gravel beach-bar succession can be formed. This succession can be divided into three intervals, from bottom to top: the gravelly sand facies, the well-sorted gravel facies, and the graded sand facies. If A interval, B interval, and C interval represent the gravelly sand facies, the well-sorted gravel facies, and the graded sand facies, respectively, the beach-bar depositional succession can be called the "ABC succession" (Figure 9). The lacustrine gravel beach-bars is composed of several combinations of the "ABC" succession, such as "ABAB", "ABCABC", "BCBC", and so on (Figure 3).

A interval, the bottom of the sedimentary succession, is dominated by coarse sand and gravel, which are subrounded, poor-sorted, massive, and the gravel oriented floating in the coarse sand (Figure 9). The thickness of A interval is the largest in the succession, generally 20cm to 40cm, because the wave asymmetric zone generally is tens meters in width. The small amplitude change of lake level does not cause facies change, so a relative thick A interval is formed.

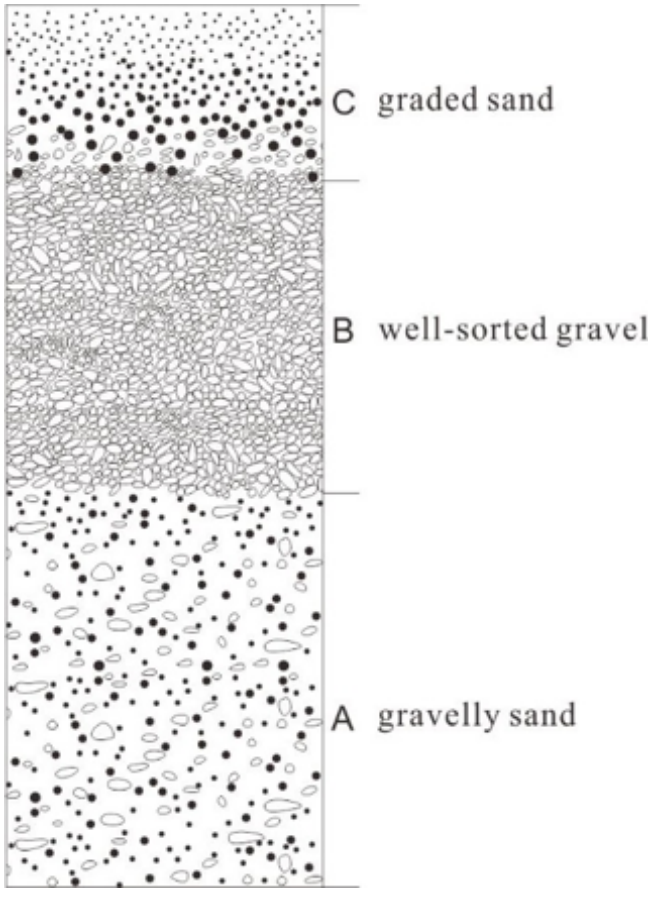

Figure 9: Depositional succession of lacustrine gravel beach-bars.

B interval, the middle of the sedimentary succession, is dominated by gravels, which are sub-round, well-sorted, and massive bedding (Figure 9). The contact between A interval and B interval is generally distinct. The thickness of B interval is usually 10cm to 20cm in thickness.

C interval, the top of the sedimentary succession, is dominated by coarse sand, which is well-sorted and normally graded bedding (Figure 9). The contact between B interval and C interval is generally gradual. The thickness of C interval is usually 5cm to 10cm in thickness. B interval and C interval are relatively thin and frequently changed in the succession, because the wave breaker zone and the wave surfing zone are relatively narrow and the small amplitude change of lake level cause facies changes.

7 Identification marks

The differentiation between the beach-bar and the delta front in ancient formation is greatly important for the reconstruction of paleoenvironment and the exploration of hydrocarbon reservoirs. The differences between the delta front and the beach-bar have been summarized in the present study.

7.1 Difference between the mouth bar and the beach-bar

The beach-bar is often developed on the side of deltas, because most beach-bar sediments are from the delta. The sediments of deltas are transported by the coastal current, and deposit beside the delta. Therefore, the beach-bar are usually associated with the mouth bar.

The difference between the mouth bar and the beach-bar is as follows:

1. Difference in the contact relationship of lithologic bottom
   The bottom contact of mouth bars is gradual (Figure 10). In the delta front environment, sediments are transported from the land to the lake. As the water depth becomes larger, the sediments become thinner, so the bottom interface of mouth bars is usually gradual. The mouth bar sand gradually changes to the distal bar silt, and the distal bar silt gradually changes to the lacustrine mud.
   The bottom contact of beach-bars is distinct (Figure 10). The beach-bar is distributed in the wave asymmetric zone, the wave breaker zone and the wave surfing zone, and the general trend of hydrodynamic is to transport the sediments to the land. The sediment of each wave zone can directly cover the lacustrine mud.
2. Difference in the depositional succession
   The beach-bar develop the "ABC" succession vertically, and the beach-bar shows a fine-coarse-fine succession from bottom to top (Figure 9 and 10). The mouth bar shows a fine-coarse succession from bottom to top (Figure 10).
3. Difference in the sedimentary structure
   The beach-bar is generally developed with swash bedding and the overbank sediment. The mouth bar is mainly developed with trough cross bedding.
4. Difference in the distribution of sediments
   The beach-bar sediments are generally parallel to the lakeshore, while the mouth bar sediments are generally vertical to the lakeshore.

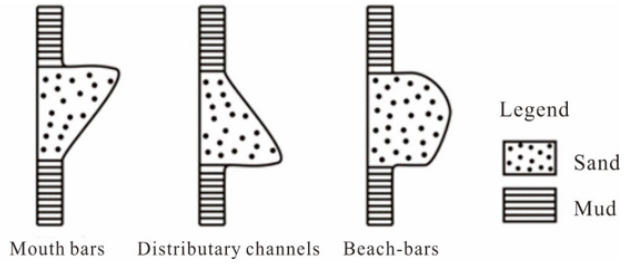

Figure 10: Differences between beach-bars, mouth bars and distributary channels.

7.2 Difference between the distributary channel and the beach-bar

The difference between the beach-bar and the distributary channel is mainly the bottom contact relationship, the depositional succession, the sedimentary structure, and the distribution of sediments.

1. Difference in the contact relationship of lithologic bottom
   The bottom contact of beach-bars is distinct (Figure 10), showing a flat surface. The bottom contact of distributary channels is distinct (Figure 10), showing an uneven surface. The river action causes the washing surface.
2. Difference in the depositional succession
   The beach-bars have the "ABC" succession vertically, and the beach-bar shows a fine-coarse-fine succession from bottom to top (Figure 10). The distributary channel shows a coarse-fine succession from bottom to top (Figure 10).

3. Difference in the sedimentary structure
   The beach-bar is generally developed with swash bedding and without the washing surface. The distributary channel is mainly developed with cross bedding with the washing surface.
4. Difference in the distribution of sediments
   The beach-bar sediments are generally sheet-like parallelly to the lakeshore, while the distributary channels are generally strip-like vertically to the lakeshore.

8 Discussion

These viewpoints of gravel beach-bar deposits developed in the lacustrine basin differ from the previous research of beach-bars [4, 6, 27–30].

Jiang etc. [4] and Hongwen etc. [6] hold that the lacustrine beach-bars are characterized by sandstones interbedded with thin mudstone units, and the presence of well-developed sedimentary structures, such as swash bedding, parting lineation, parallel bedding, ripples, terrestrial plant debris and vertical burrows. Peng etc. [28] established the physical criteria for recognition of lacustrine beach-bars, which include many quantitative parameters of beach-bar. Zhu etc. [17] established four depositional models of lacustrine beach-bars, beach-bars in open shallow lake, beach-bars in turning of shoreline, beach-bars beside deltas and beach-bars in ridges of deep lake. However, both of them neglected the effect of different wave zone to sediments. Although the lake waves are not as big as the sea waves, the effect of different wave zone to sediments is still obvious. Our study shows that the lake waves are obviously divided into three parts, wave asymmetric zone, wave breaker zone, and wave surfing zone (Figure 6). The different wave zones have different sedimentary characteristics (Figure 8 and 10).

At present, no one has proposed the particular depositional succession of lacustrine beach-bars. Most beach-bar researches pay their attention to the summary of lithology, texture, sedimentary structure, distributional pattern [4, 6, 29], or the applied research of lacustrine beach-bars[16, 30-34]. Through our study on the several beach-bar profiles in the Qinghai Lake, the lacustrine gravel beach-bars are composed several particular depositional successions, the "ABC" succession (Figure 9). The gravel beach-bars can present various combinations, such as "ABABAB", "ABCABC", "BCBCBC" etc. (Figure 3 and 4).

The sedimentary environment of lacustrine beach-bars is similar to the sedimentary environment of lacustrine delta fronts [4, 35, 36]. It is difficult how to distinguish between lacustrine beach-bar sediments and delta fronts sediments in ancient basins. Through our study, the particular identification marks have been proposed. In terms of the bottom contact relationship, the beach-bars are distinct, and the delta fronts are gradual. In terms of the depositional succession, the beach-bars have the "ABC" succession, and show a fine-coarse-fine succession from bottom to top. The delta fronts have not the special succession, and show a fine-coarse succession from bottom to top. These new viewpoints are greatly important for the recognition of lacustrine beach-bar.

9 Conclusion

The depositional model of lacustrine gravel beach-bars has been established. From lake to land, the lacustrine gravel beach-bars can be divided into three parts, the wave asymmetric zone, the wave breaker zone, and the wave surfing zone. The wave asymmetric zone is dominated by poorly sorted sand and gravel. The wave breaker zone is dominated by gravel with massive bedding. The wave surfing zone is dominated by sand with graded bedding. Vertically, the lacustrine gravel beach-bars develop with the "ABC" succession. The A interval, the B interval, and the C interval respectively correspond with the gravelly sand facies, the well-sorted gravel facies, and the graded sand facies. The lacustrine gravel beach-bars is composed of several combinations of the "ABC" succession, such as "ABAB", "ABCABC", "BCBC".

The difference between the lacustrine beach-bar and the delta front is mainly the bottom contact relationship, the depositional succession, the sedimentary structure, and the distribution of sediments. The bottom contact of lacustrine beach-bars is distinct. The lacustrine beach-bars develop with the "ABC" succession, and shows a fine-coarse-fine change from bottom to top. The lacustrine beach-bars develop the swash bedding. The beach-bar sediments are generally sheet-like parallelly to the lakeshore.

These viewpoints have significant contributions to the reconstruction of paleoenvironments and paleoshorelines and to the reservoir interpretation within lacustrine beach-bar clastic bodies.

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