

# Study on Characterization and Sedimentary Environment of Tidal Sand Ridges

Run Zhao<sup>1,2</sup>, Ganggui Zhang<sup>1,2</sup>, Yupeng Wu<sup>1,2</sup>

<sup>1</sup> School of Earth Sciences and Engineering, Xi'an Shiyou University, Xi'an Shaanxi, 710065, China

<sup>2</sup> Shaanxi Key Lab of Petroleum Accumulation Geology, Xi'an Shaanxi, 710065, China

## Abstract

As an important marine sedimentary geomorphic unit, the spatial distribution characteristics of tidal sand ridges hold significant guiding significance for oil and gas resource exploration and coastal zone management. This study systematically sorts out the morphological characteristics, sedimentary structures, and formation-evolution mechanisms of typical tidal sand ridges at home and abroad. Through comparative analysis, it is found that relevant research mainly focuses on two aspects: the statistical characterization parameters and sedimentary facies division of continental shelf sand ridges, as well as hydrodynamic-sedimentary coupling simulation and 3D geological modeling. Based on the integration of multi-source data, a multi-dimensional characterization system is proposed, which includes morphological parameters (aspect ratio, slope aspect angle), sedimentary sequences (grain size rhythm, ichnofossil assemblage), and hydrodynamic responses (tidal current rose diagram, vortex intensity). The applicability of this system is verified by previous comparative studies on tidal sand ridges in the offshore area of the Yangtze River Estuary and the North Sea.

## Keywords

Tidal Sand Ridges; Genetic Mechanism; Hydrodynamics; Numerical Simulation.

## 1. Introduction

Large-scale linear sand bodies develop in the shallow sea areas of the continental shelf. Most of their extension directions are parallel to the direction of tidal currents. These are sedimentary landforms formed under the influence of multiple factors such as tides and topography, and are called tidal sand ridges. Scholar T. Off (1973) first proposed the concept of "tidal current ridge" [1], laying a foundation for subsequent research. Later, Swift (1977), Caston (1972), and other researchers conducted studies on the submarine sand ridges in the Mid-Atlantic Continental Shelf of North America and the southern North Sea [2, 3], further deepening the understanding of the concept of tidal sand ridges. In China, Liu Zhenxia, Xia Dongxing, and others (1983) took the lead in researching tidal sand ridges [4], and comprehensively summarized the sand ridges distributed in the East China Sea, Bohai Sea, Yellow Sea, and other regions, providing substantial support for the study of tidal sand ridges.

Tidal sand ridges not only reflect coastal evolution and the impact of human activities on the environment but also respond to climate changes. They possess high physical properties and maturity, and a wide distribution range. They can form an excellent reservoir-caprock assemblage with the surrounding fine-grained sediments of the continental shelf, making them favorable exploration targets for lithologic oil and gas reservoirs and high-quality oil and gas reservoir facies belts [4]. They also contain abundant marine sand resources.

The sedimentary architecture of tidal sand ridges is mainly influenced by factors such as tidal dynamics, sediment supply, and water depth. Studies have shown that the internal architecture

of tidal sand ridges includes foresets along the main flow direction, lateral accretion layers, and parallel bedding at the top. Their formation process and evolution mechanism are complex and diverse. The identification of these architectural units is crucial for the application of tidal sand ridges in oil and gas reservoirs. Observations on the characteristics of tidal sand ridges in modern tidal environments provide a reference for reconstructing paleoenvironments. Research on the Xihu Sag indicates that tidal sand ridges develop in tectonically controlled tidal flat environments, exhibiting complex sequences and sand body distribution patterns. Using numerical simulations and flume experiments, researchers have reconstructed the sedimentary process of tidal sand ridges and revealed changes in the morphology of sedimentary bodies under different flow conditions. For example, changes in river discharge and tidal amplitude have a significant impact on the morphology of sand ridges in tide-dominated deltas; increased tidal amplitude leads to flattening of bars and an increase in their area. Under the combined action of rivers and tides, sediments in tidal sand ridges and dunes are gradually transported and deposited in deep-water areas, forming a variety of sand body structures. Studies have also found that the sedimentary process of tidal sand ridges is not only controlled by hydrodynamics but also influenced by topography and water depth. This phenomenon has also been confirmed in the research on the Kepingtage Formation in eastern Tazhong, indicating a close relationship between tidal sand ridges and high-quality reservoirs.

## 2. Definition and Characteristics of Tidal Sand Ridges

### 2.1. Formation Background of Tidal Sand Ridges

Sand ridges are mostly distributed in the subtidal zone under the influence of strong tidal action. In a tidal-dominated shallow marine environment, which includes supratidal, intertidal, and subtidal zones, tidal sand bars are distributed in the intertidal zone, while tidal sand ridges are distributed in the subtidal zone and shallow seabed areas. This is because in restricted topographic conditions such as estuaries, bays, and straits, the energy of tidal currents increases due to the venturi effect, leading to the development of tidal sand ridges in the subtidal zone [5].

The development of tidal sand ridges is mainly affected by the sea-level rise rate, sediment source supply, seabed topography, and tidal hydrodynamics. They are special geomorphic features and sedimentary types formed under the repeated action of strong hydrodynamic forces such as tides, and are usually associated with muddy sediments on the continental shelf. Therefore, they exhibit uniqueness in terms of geomorphic features, sedimentary components, and structures.

When identifying tidal sand ridges, the extension direction of their long axis can be used as a criterion: it usually forms an acute angle to a parallel relationship with the main direction of tidal currents, and the migration direction of tidal sand ridges forms an acute angle with the paleocurrent direction. Thus, in the field, the progradation direction of sand bodies can be used to distinguish tidal sand ridges.

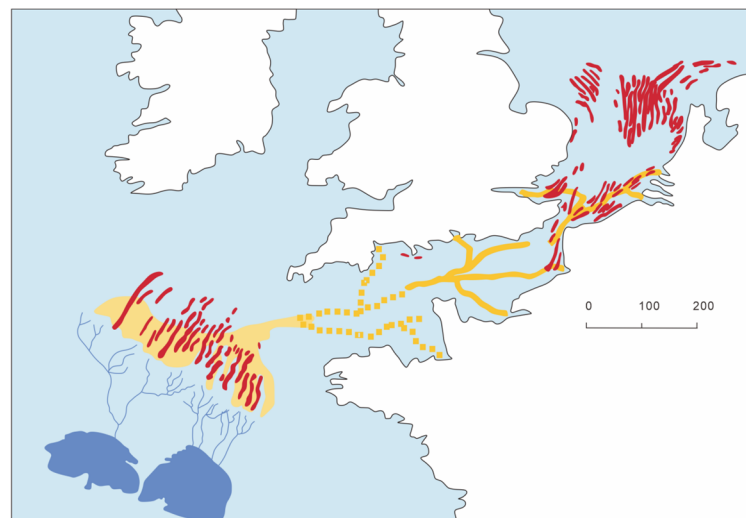
### 2.2. Distribution of Tidal Sand Ridges

Current research on tidal sand ridges mainly focuses on modern sediments, emphasizing the discussion of their formation conditions, scale, and characteristics of sedimentary structures. The study of sedimentary structures provides excellent guiding significance for identifying continental shelf sand ridges in ancient stratigraphic records.

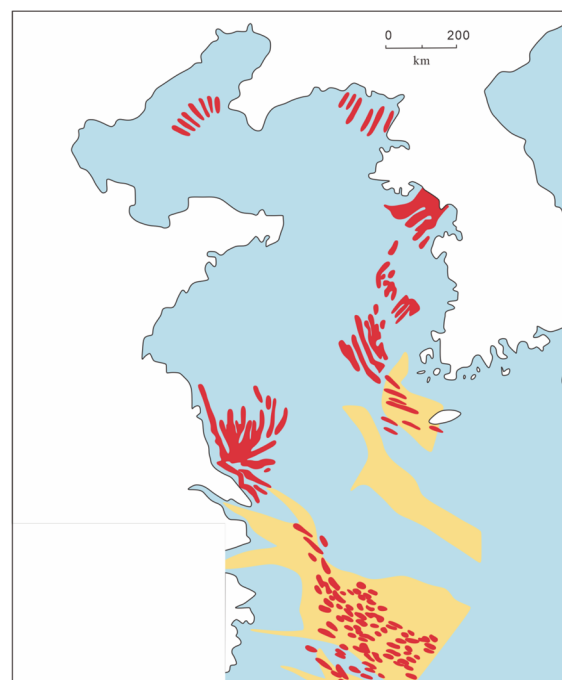
Most modern sand ridges are distributed in coastal areas with strong hydrodynamic forces, and are distinguished from other tidal sediments by their unique sedimentary structures. The sand bodies of sand ridges are nearly parallel to the main direction of tidal currents; therefore, the strike of sand ridge crests and the distribution of sand ridge groups can be used to determine

the paleocurrent characteristics and sedimentary environment characteristics of their location, which plays an important role in restoring paleogeomorphology and paleogeographic conditions.

China has an extremely extensive coastline, with a large area of shallow continental shelf seas in the east, making it one of the regions with strong tidal action in the world. Consequently, tidal sand ridges are distributed in most coastal areas, including the East China Sea, South Yellow Sea, Bohai Sea, Fujian shallow sea, off the Minjiang Estuary, Jiangsu Jianggang, Cezi Waterway of the Zhoushan Archipelago, and the Taiwan Strait. Internationally, they are also distributed on the continental shelf margins affected by strong tidal currents in coastal areas such as the Celtic Sea of the Atlantic Ocean, Gyeonggi Bay of South Korea, Combaya Bay in western India, and the Siderno Strait in southern Italy.



**Figure 1. (a)** (Cited and modified from Reynaud J Y, Dalrymple R W. Shallow-marine tidal deposits [J])

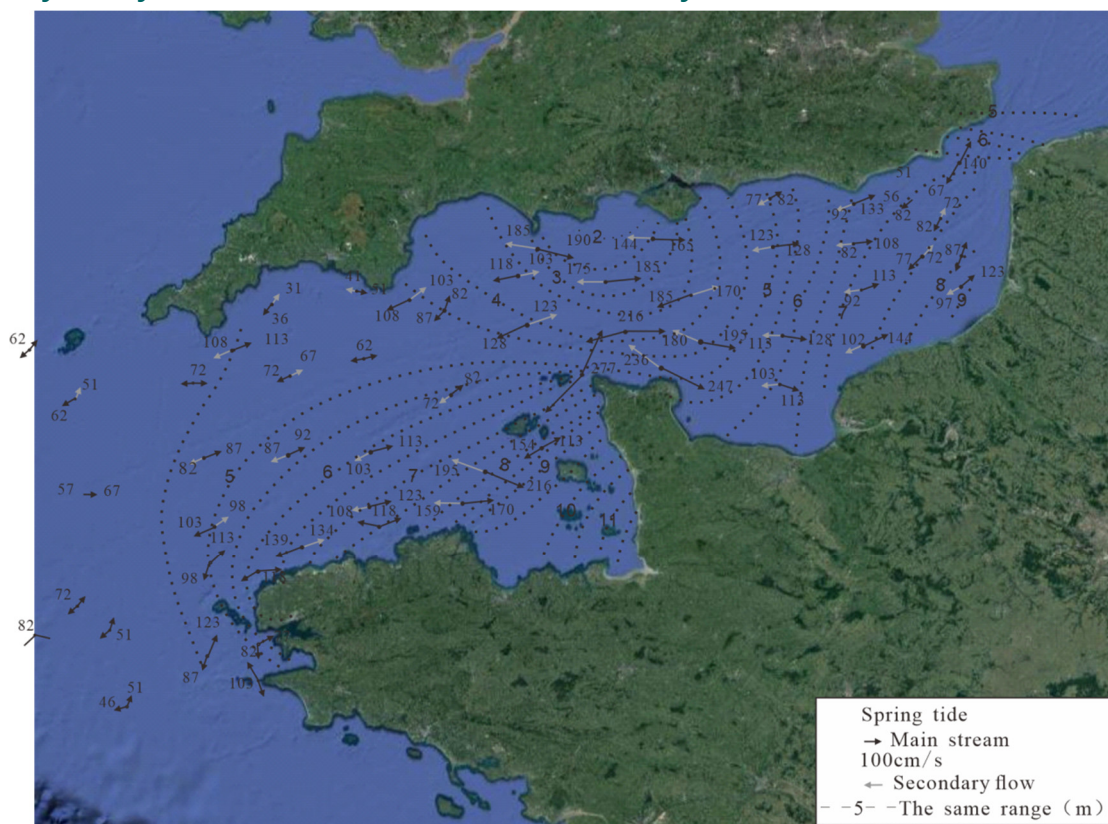


**Figure 1. (b)** (Cited and modified from Reynaud J Y, Dalrymple R W. Shallow-marine tidal deposits [J])

Figures 1a and 1b are distribution maps of major sand ridges on the Western European Continental Shelf, Yellow Sea, and East China Sea.

Most modern sand ridges were formed during the Late Pleistocene of the Quaternary and the Holocene transgression period. The Quaternary sea-level rise promoted the development of offshore sand ridges, accompanied by coastal erosion and reformation. For example: tidal sand ridges in the East China Sea and the Celtic Sea were formed during the post-glacial sea-level rise period [6]; tidal sand ridges off the Minjiang Estuary in Fujian were formed due to transgression after the Late Pleistocene [7]; analysis of seismic data and core data shows that the continental shelf sand ridges in Gyeonggi Bay of South Korea were formed during the Holocene transgression period [8]; and the continental shelf sand ridges in New Jersey, USA, were mainly formed at the end of the Late Pleistocene and during the Holocene transgression period.

### 2.3. Hydrodynamic Characteristics and Activity of Modern Tidal Sand Ridges



**Figure 2.** Main Tidal Currents in the English Channel

Tidal current is the main dynamic force shaping sand ridges. Liu Zhenxia and others used a hydromechanical perspective to verify that the formation of sand ridges is related to circulation; the flow velocity in the troughs of the tidal sand ridge area is greater than that at the ridge crests. The secondary longitudinal and transverse circulation is the direct dynamic force shaping submarine sand ridges. When the tidal current reaches its maximum velocity, the circulation velocity is also high, which can thus initiate sediment movement. Sediments converge and settle at the center of the trough where the flow velocity is the highest, strongly eroding the trough bottom; at the same time, they diverge and rise to both sides, and the eroded sediments are thrown to the two flanks in a saltation mode, continuously increasing the ridge-trough relief.

The condition for sand ridge development is a reversing tidal current with a maximum velocity ranging from 1 knot to 3.7 knots. When the maximum tidal current velocity exceeds 3.7 knots, erosion dominates, and the tidal current erodes sediments, making it difficult for sediments to form stable bodies; when the maximum tidal current velocity is between 1 and 3.7 knots,

deposition dominates—sediments are deposited when the tidal current velocity is 0 and transported when the velocity reaches the maximum; in addition, when the tidal current velocity is irregular, the deposited sand ridges will shift to one side.

The figure 2 below shows the main surface tidal currents in the English Channel. In the channel topography, the venturi effect is most significant, increasing the tidal current energy and leading to the development of tidal sand ridges in the subtidal zone.

Whether modern tidal sedimentary sand bodies can exist stably can also be judged based on the sediment incipient velocity. Since there are multiple calculation methods, the incipient velocity formula (1) proposed by Zhang Ruijin (considering the cohesive force between particles) and the incipient velocity formula (2) for coarser-grained sediments proposed by Shamov can be used:

$$U_c = \left(\frac{h}{D}\right)^{0.14} \left(17.6 \frac{\rho_s - \rho}{\rho} D + K \frac{10 + h}{D^{0.72}}\right)^{\frac{1}{2}} \quad (K = 6.05 \times 10^{-7}) \quad (1)$$

$$U_c = 1.14 \sqrt{\frac{\rho_s - \rho}{\rho} g D} \left(\frac{h}{D}\right)^{\frac{1}{6}} \quad (2)$$

Where:  $U_c$  is the incipient velocity (m/s);  $g$  is the gravitational acceleration ( $m/s^2$ );  $\rho$  is the water density ( $kg/m^3$ );  $\rho_s$  is the sediment density ( $kg/m^3$ );  $h$  is the average water depth (m);  $D$  is the median grain size of sediment (mm).

Sand ridges can be classified into active sand ridges, quasi-active sand ridges, and degenerate sand ridges based on their activity. The activity of sand ridges is related to various factors dominated by tidal current velocity, and the presence of sand wave superposition on sand ridges is also an indicator for judging the activity of sand ridges.

Sand ridges are widely distributed in marine areas. Generally speaking, tidal sand ridges developed in sea areas with water depth shallower than 30 m or 70 m are active sand ridges. Due to the shallow water depth and strong dynamic forces such as tidal currents, the average near-surface peak velocity of spring tides is generally greater than 70 cm/s (1 knot); they are often superimposed with topographies such as sand waves and sand dunes; and their cross-sections are asymmetric, which is due to the tendency of continuous sediment migration. For example, the maximum tidal current velocity of the tidal sand ridges in the Liaodong Shoal is 1.3–2.3 knots, which can drive sediment deposition, and sand dunes are superimposed and developed on the sand ridges.

When the tidal current velocity decreases to a level that cannot initiate the sandy sediments on the seabed (basically less than 1 knot), the tidal sand ridges are in a degenerate state and are called degenerate sand ridges. Their cross-sections are relatively smooth, and there is no sand wave superposition on the sand ridges. The offshore sand ridges on the margin of New Jersey, USA, are degenerate sand ridges because transgression increased the water depth of the sand ridges, reducing the influence of coastal tidal currents and stopping the growth of the sand ridges. The sand ridges in the eastern coastal area of the North Sea are located in relatively deep sea areas, with minimal influence from tidal currents, and are also degenerate sand ridges [9].

Liu Zhenxia and others [7] argued that the hydrodynamic conditions in the environment where some sand ridges develop are weakening, but they can still initiate the sandy sediments on the seabed. These sand ridges are in the developmental process between active sand ridges and degenerate sand ridges and are classified as quasi-active sand ridges. For example, the tidal sand ridges in the East China Sea (excluding the Yangtze Shoal): there is no sand wave superposition on these sand ridges, but the tidal current environment is above 1 knot, which can transport fine sand or medium-fine sand on the seabed. Therefore, they are still affected by tidal currents and other forces and are quasi-active sand ridges.

### 3. Sedimentary Structures and Grain Size Characteristics of Sand Ridges

#### 3.1. Sedimentary Structures of Sand Ridges

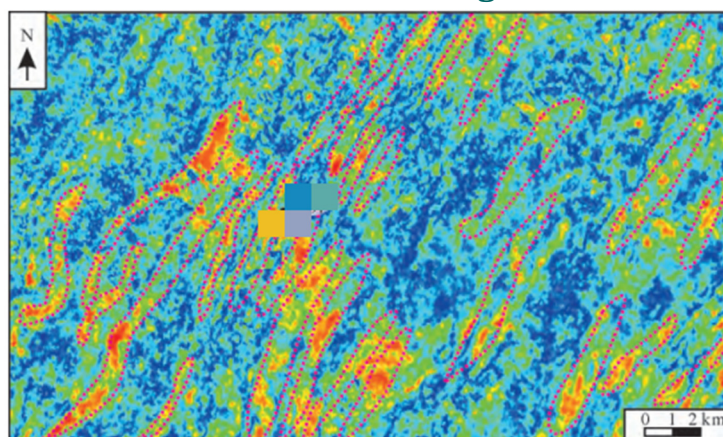
Affected by strong tidal current action, tidal channels develop between some adjacent sand ridges, with relatively thin clay layers. In addition, sand waves are superimposed and developed on active sand ridges. Typical tidal sediments are developed: under tidal conditions, ordered cross-bedding (S-type cross-bedding, composite cross-bedding), herringbone cross-bedding (bidirectional cross-bedding), bidirectional current ripples, rhythmic bedding with alternating sand and mud layers, and lenticular-wavy-flaser bedding are usually formed. On this basis, sand ridges are mostly developed with sedimentary structures reflecting strong hydrodynamics, such as tabular cross-bedding and scour surfaces [9].

The length of tidal sand ridges is generally 10–100 km, with a maximum of over 100 km; their height ranges from 10 to 70 m; they develop in shallow continental shelves with water depths varying from 0 to 60 m. Their plan view morphologies include parallel or finger-like shapes, and affected by the reciprocating action of tidal currents, the sand bodies are nearly parallel to the main direction of tidal currents. The ridge crests are straight or curved, exhibiting unique planar distribution characteristics. Their width is generally positively correlated with their height—the higher the sand body, the greater the width.

For active sand ridges, due to the gradual enhancement of hydrodynamics, the upper part is mainly dominated by large-scale cross-bedding, while the lower part develops some lenticular bedding, parallel bedding, small-scale cross-bedding, ripple bedding, herringbone cross-bedding, etc. Bioturbations such as plant fossils and burrows are developed at the top and bottom. In degenerate sand ridges, due to the gradual reduction of hydrodynamic conditions, large-scale cross-bedding is developed in the middle and lower parts, and small-scale cross-bedding, parallel bedding, etc., are developed in the upper part (Figure 7).

A series of sand dunes migrating along the main tidal current direction are formed by flood or ebb tides. On the cross-section of the dunes, there are a series of cross-bedded sandstones with foresets inclined toward the flow direction, bounded by thin muddy drapes or erosion and reworking surfaces. The thickness of the laminae changes periodically, with numerous reactivation surfaces inside. Sand dunes are usually associated with sand ridges.

#### 3.2. Grain Size Characteristics of Tidal Sand Ridge Sediments



**Figure 3.** Amplitude Map of Sand Ridges in the Pinghu Formation of the Xihu Sag. The sand ridges are strip-shaped with obvious amplitude response.

(Source: Wu J P. Discovery and significance of tidal sand ridges in the Pinghu Formation of the Xihu Sag [J]. *Acta Sedimentologica Sinica*, 2018, 34(07): 924-929.)

A summary of previous studies shows that the sediments of tidal sand ridges are generally sandy, with some attached argillaceous sediments, and their grain sizes range from fine sand to coarse sand. The grain size characteristics of sediments are mainly determined by the sediment source area. Due to the strong hydrodynamic conditions, the sorting of sediments is good, and they exhibit a unique reverse cyclic structure. The grain size of modern sand ridges is mainly counted through sampling in sedimentary areas. Since sand ridges are mostly distributed in mud-rich sedimentary backgrounds such as continental shelves and estuaries; when alternating sand-mud deposition occurs, there is also a large acoustic impedance difference between internal rock layers. Therefore, on seismic sections, sand ridges show strong amplitude reflection.

#### 4. Conclusion

Tidal sand ridges are mostly developed in areas such as estuaries, deltas, or continental shelves; they are a special type of geomorphic sediment formed under the repeated action of tidal hydrodynamics with a velocity of 1–3.7 knots, and are often associated with muddy sediments. Due to the relatively high tidal current velocity, they have a unique reverse cyclic configuration, develop large-scale bedding with associated bioturbation, and are dominated by sandy sediments. They have good oil-generating potential and are therefore often explored as common oil and gas reservoirs.

In China, tidal sand ridges are widely distributed in the East China Sea—the continental shelf of the East China Sea has a large area of continental shelf sand ridges. A large number of radial sand ridges are also distributed along the coast of Jiangsu. Sand ridges are also distributed in the coastal areas of Fujian and the Qiongzhou Strait, but their scale is relatively small. Most of the sediment sources of these sand ridges come from the two major rivers, the Yangtze River and the Yellow River.

#### References

- [1] Off, T., 1973. Rhythmic Linear Sand Bodies Caused by Tidal Currents. *Am. Assoc. Pet. Geol. Bull.* 2:324-337.
- [2] Trentesaux A, Stolk A, Berné S. Sedimentology and stratigraphy of a tidal sand bank in the southern North Sea[J]. *Marine Geology*, 1999, 89(1-4): 273-272.
- [3] Wu Z, Jin X, Zhou J, et al. Comparison of buried sand ridges and regressive sand ridges on the outer shelf of the East China Sea[J]. *Marine Geophysical Research*, 206, 38: 187-198.
- [4] Tong, C.L., Wang, H.Q., Qin, M.G., et al., 2022. Surface Sediment Characteristics and Sedimentary Environment Division of Tidal Sand Ridges at the Eastern Entrance of the Qiongzhou Strait. *Journal of Applied Oceanography*, 41(04): 727-737.
- [5] Zhao, X.F., Lü, Z.G., Zhang, W.L., et al., 2008. Nearshore Tidal Deposits of the Xujiahe Formation in the Anyue Area, Sichuan Basin. *Natural Gas Industry*, (04): 4-18+134.
- [6] Liu, Z.X., Tang, Y.X., Wang, K.Y., et al., 1997. Characteristics of Tidal Dynamic Geomorphology in the Eastern Bohai Sea. *Journal of Yellow Sea and Bohai Sea Marine Science*, (01): 7-21.
- [7] Liu, Z.X., Xia, D.X., 1997. Discussion on Hydrodynamic Problems of Tidal Sand Ridges. *Journal of Yellow Sea and Bohai Sea Marine Science*, (04): 23-29.
- [8] Cao, L.H., Hou, Z.M., Zhuang, Z.Y., et al., 2010. Characteristics and Genesis of Seabed Topography at the Southeastern Margin of the Yangtze Shoal. *Marine Geology Letters*, 27(09).
- [9] Wu, J.P., 2018. Discovery and Significance of Tidal Sand Ridges in the Pinghu Formation of the Xihu Sag. *Acta Sedimentologica Sinica*, 34(07): 924-929.