A Novel Method for Analyzing Sandbar Distribution in Shelf-Type Tidal Deltas Using Sediment Dynamic Simulation

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Abstract: Shallow marine shelf sedimentation is a hot and difficult topic in today’s reservoir sedimentology research, and it is widely present in the world. The shallow marine shelf sedimentation is not only affected by complex hydrodynamic effects such as tides and waves, but also controlled by bottom tectonic features, forming a complex and varied sedimentation pattern. During the Middle Jurassic period, the northern part of West Siberian Basin was characterized by a shallow marine shelf sedimentary environment. In the central region of this basin, a typical tectonic uplift zone developed, forming a tectonic background of “one uplift zone between two depressions”. Simultaneously, the dominant influence of tides in the shallow marine shelf environment facilitated the formation of a typical shelf-type tidal delta sedimentation system in the Jurassic strata of the northern part of West Siberian Basin. This sedimentation constitutes a significant natural gas reservoir, and it is important to investigate the sedimentary evolution of shelf-type tidal deltas and to clarify the internal structure and distribution of sedimentary sand bodies and interlayers in shelf-type tidal deltas, which is the basis for the fine development of this type of reservoir. This paper takes the Jurassic strata in the Y region of northern part of West Siberian Basin as the research object, and conducts numerical simulation based on sedimentary dynamics for the shelf-type tidal delta sedimentation formed under the tectonic background of “one uplift zone between two depressions”. In addition, tidal amplitude and initial water level were selected for different hydrodynamic factors to study the main controlling factors of shelf-type tidal delta sedimentation. The simulation results show that tidal amplitude is positively correlated with three-dimensional configuration characteristic parameters of the sedimentary sand bodies, and the development of tidal bars becomes more and more limited as the initial water level increases. This paper systematically investigates the sedimentary evolution of shelf-type tidal delta under the tectonic background of “one uplift zone between two depressions” by the sedimentary dynamics method, which deepens the understanding of the shelf-type tidal delta sedimentation process and provides a new thinking for the development of this sedimentary reservoir type (School of Geosciences China University of Petroleum (East China)).

Keywords: shelf-type tidal delta; sedimentary dynamics; numerical simulation; Delft3D

1. Introduction

The hydrodynamic conditions of shallow marine shelf-type tidal deltas are complex and diverse, including tides, currents, and storm-induced waves [1], and shelf-type tidal delta deposition is a complex depositional system formed under the joint influence of tidal action and paleo-uplift tectonics. The shelf-type tidal delta is a special kind of shallow marine shelf deposition that is mainly developed in the broader continental shelf, shallow sea water in the coastal zone environment, and it is a kind of sedimentary landform formed...
by the strong influence of tidal action [2]. The sediments of shelf-type tidal deltas are mainly imported by the fluvial system and interact with periodic tidal currents, forming a series of complex morphological sedimentary sand bodies on the shelf, and its sedimentary sequences often show obvious tidal rhythmic laminations and interbedded laminar structures [3]. The formation process of shelf-type tidal deltas involves a number of links such as fluvial sand transport, tidal current dynamics, sediment resuspension and redeposition [4], and their depositional systems usually include components such as distal bars, intermediate plains, and frontal subfacies, where the distal bar portion is often shown to be branching channels and sheet sand bodies due to the action of strong tidal currents, and the frontal subfacies may develop tidal pads, tidal channels, and tidal sand ridges and other geomorphological units [5,6]. However, in sedimentary geology, there are fewer literature records on shelf-type tidal delta deposition formed due to tectonics [1], and there is a lack of systematic understanding of the internal structure and distribution of sand bodies and interlayers in shelf-type tidal delta deposition, which is needed to clarify the sedimentary evolution law, to determine the spreading characteristics of the sand bodies, and to provide guiding ideas for the research of the exploration and development of oil and gas in this kind of sedimentary reservoir. As such, study on shelf-type tidal delta deposition has become a hot and difficult problem nowadays.

Commonly used methods to study ancient sedimentation include ancient sedimentary record analysis, modern sedimentary example dissection, flume physics experiments, and numerical simulation [7]. Seismic data would be limited by a lack of drilling wells, resulting in less information available for research [8]. Modern sedimentary example dissection depends on the practicalities of outcrops; sometimes rock outcrops can provide the two-dimensional structure of sediments but not enough information on internal three-dimensional structure [9]. Physical simulation is mainly carried out through flume experiments for sediments, and it can provide reliable results [10]; however, physical simulation is limited by many conditions, such as small study size and limited run time [11]. The utilization of numerical simulation as an efficient tool in sedimentary dynamics primarily relies on the hydrodynamic approaches to investigate sediment transport and geomorphological evolution [12]. Numerical simulation is highly actionable and applicable to a wide range of hydrodynamic scenarios, and can provide strong evidence for the study of morphodynamic and stratigraphic patterns arising from sedimentary erosion at different spatial and temporal scales [13]. To date, numerous numerical simulation methods of sediment dynamic have been developed, which can be classified into various categories based on different principles and criteria. [14]. This study employs a sediment dynamics numerical simulation model grounded in hydrodynamic equations. It is the numerical simulation of sedimentation–erosion based on the Naiver–Stokes equations, which allows the recovery of the detailed processes of sediment transport and lithofacies distribution and it is appropriate for modelling the evolution of sediment environments over short timescales measured in millennia [15]. In 2016, Chatzirodou [16] used Delft3D software to simulate a deep-water shelf in the Nestor Channel, Scotland, UK, and the model revealed the interactions between the sand bodies and the complex three-dimensional tidal structures; in particular, how channel currents formed during rising tide periods and tidal jets formed during ebb tide periods can affect the sediment’s movement and morphology changes. In 2018, Tristan Salles [17] used the numerical simulation method to study the millennial-scale sedimentary evolution of a shallow marine shelf. In the same year, Van de Lageweg [18,19] applied sedimentary dynamics modelling in a land–marine transition zone environment; the research quantifies the role of factors such as fluvial flow, waves, tides, and mud supply in the geometry and sedimentary structure of funnel-shaped basins along the fluvial–marine transition zone region based on a sedimentary dynamics method. In 2020, Nnafie [20] analyzed the evolution of the natural morphodynamics of tidal sand ridges on the shelf and the response to human intervention based on numerical simulation of sedimentary dynamics, and carried out a simulation study of the dynamic process of large sedimentary sand bodies formed under strong tidal influence in a shallow marine
shelf environment by Delft3D. These studies exemplify that the Delft3D software is a reliable and widely used tool for the analysis of shelf environments and tidally driven sedimentary dynamics problems.

2. Region Setting

The West Siberian Basin is the largest hydrocarbon-bearing basin in the world, with an area of about 3.5 million square kilometers and a huge potential for hydrocarbon resource development [21]. The study area is the Y area on the uplift zone in the northern part of the West Siberian Basin, as shown in Figure 1a, and its Jurassic stratigraphic system shows a good potential for gas deposits. Shallow marine facies deposits were widely developed in the northern part of West Siberian Basin during the Jurassic period [22], and in the center of the northern part of the basin, a significant paleo-uplift zone was formed due to long-term tectonic movements and crustal uplift [23,24]. This uplift zone serves as an important geological tectonic line, bisecting the vast northern part of Western Siberian Basin into two relatively low-lying depressions, thus constituting a typical tectonic pattern of “one uplift zone between two depressions” [23–26].

![Figure 1.](image)

Georgiy Shemin [22] in 2019 carried out a detailed Jurassic paleogeography study in the northern part of West Siberian Basin, mapping the litho-paleogeography of the Jurassic strata (Figure 1b). In Vym time, the northern part of West Siberian Basin was in an extensive shallow marine shelf environment, with depths ranging from 25 to 100 m. The study area is located in a region where sandstones and siltstones dominate the sediments, accompanied by the development of some mudstones, in which sandstones generally account for more
than 50% of the sediments, and sandy and muddy interbedded sediments with a thickness of up to 260 m have been deposited. The shelf uplift zone below sea level was under the joint control of tides and paleo-tectonics [22], which resulted in the formation of shelf-type tidal delta deposition under the tectonic background of “one uplift zone between two depressions”. Under the tectonic background of “one uplift zone between two depressions”, the gently sloping zone extending to both depressions not only received a large amount of sediments from the Ural Mountains and the Taimyr region, but also deposited mud and sand from the two oceans under the strong influence of tides, which ultimately formed the complex shelf-type tidal delta depositional system [2].

3. Methods

The simulation software used in this study is the open-source software Delft3D version 4.04.01, which is a high-resolution numerical simulation system for dynamic flow of sedimentary sands based on continuous profiles for hydrodynamic–stratigraphic numerical simulations [27]. Its FLOW module is suitable for predicting hydrodynamic and sedimentary geomorphological evolution in semi-enclosed coastal areas such as coastal areas, estuaries, shallow marine shelves, and lagoons [28,29]. Fluid and sediment transport are discretized on a 3D curvilinear finite-difference grid and solved using the alternate-direction implicit format ADI method [29]. In this paper, Delft3D software is used to carry out numerical simulation of the depositional process of shelf-type tidal deltas formed by the Jurassic strata in the study area, so as to determine the main controlling factors for the distribution of sand bodies and their internal configuration in the “one uplift zone between two depressions” shelf-type tidal delta.

3.1. Establishment of Basic Model

In this paper, the target strata in the study area correspond to the Jurassic Vym time strata. The geological conceptual model topography is set up with reference to the litho-paleogeographic map of the Vym time in the northern part of West Siberian Basin mapped by Georgiy Shemin. The horizontal surface area of the model corresponds to the area of the paleogeographic map (Figure 1a), which is 1500 km long and 1200 km wide, as shown in Figure 2. According to the litho-paleogeographic map, the ocean boundary is set in the north, east, and northwest of the model to provide tidal action, and the Harmonic tidal force type is adopted, that is, the tide with a period of 12 h and amplitude of 6 m. In the Ural Mountains, the Taimyr region, and the Siberian craton, river boundaries are set.

![Figure 2. Three-dimensional conceptual model plan of the study area.](image-url)
3.2. Basic Model Parameter Setting

The research of modern depositional systems, especially the modern continental shelf depositional system, can provide a reference for the hydrodynamic and sediment parameters of the numerical simulation model of the “one uplift zone between two depressions” shelf-type tidal delta [30–37]. The area of the model grid is set to 3 \( \times \) 3 km\(^2\). During the Jurassic period, the study area was in an extensive shallow marine shelf environment, the shelf uplift zone, lying below sea level, and was concurrently influenced by the synergistic controls of tidal forces and paleotectonic activities [22]. In this context, the height value of the highest point of the uplift zone in the model is defined as 0 m in the Z axis of the model, and the initial water level of the sea in the model is set as 1 m. Semi-diurnal tidal control was adopted, the tidal frequency is 12 h/time, and the tidal height was set to 6 m. The wave frequency is 25 s/time, and the wave height is set to 1 m. The fluvial discharge is set to 3000 m\(^3\)/s, and the amount of sediment carried by the river is 0.525 kg/m\(^3\). The sediment types are divided into two types, non-cohesive sandy sediment and cohesive muddy sediment. The non-cohesive sandy sediments are divided into coarse grain size and fine grain size. The content ratio is coarse sand:fine sand:mud = 1:1:1, the simulation time is 150 days, every 10 days is recorded as 1 step, the simulation discrete time step is 1 min, the morphological scale factor H is set to 100, and the results can be obtained for up to 500 months of sedimentary evolution. At the same time, the morphological scale factor does not have any effect on the formation of the sedimentary morphology of the shelf tidal delta [38], as shown in Table 1. In the simulation of Delft3D software, the tidal amplitude and wave height vary automatically with time in a single period, and the input parameters represent the absolute values of the maximum and minimum within a period. Fluvial discharge serves as an auxiliary hydrodynamic force, maintained at a constant rate throughout the simulation. The initial water level height means the water level at the beginning moment of the simulation, and it is subsequently allowed to fluctuate in response to the evolving hydrodynamic conditions as the simulation progresses.

<table>
<thead>
<tr>
<th>Parameter Settings</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of Study Area</td>
<td>1500 ( \times ) 1200 km(^2)</td>
</tr>
<tr>
<td>Size of Single Grid</td>
<td>3 ( \times ) 3 km(^2)</td>
</tr>
<tr>
<td>Time Step</td>
<td>1 min</td>
</tr>
<tr>
<td>Initial Water Level</td>
<td>1.0 m</td>
</tr>
<tr>
<td>Tidal Amplitude</td>
<td>6.0 m</td>
</tr>
<tr>
<td>Wave Height</td>
<td>1 m</td>
</tr>
<tr>
<td>Fluvial Discharge</td>
<td>3000.0 m(^3)/s</td>
</tr>
<tr>
<td>Sediment Grain Size</td>
<td>130(\mu) m(^3)/s</td>
</tr>
<tr>
<td>Coarse Sand:Fine Sand:Mud</td>
<td>1:1:1</td>
</tr>
<tr>
<td>Maximum Water Depth</td>
<td>176 m</td>
</tr>
<tr>
<td>Morphological Scale Factor</td>
<td>100</td>
</tr>
</tbody>
</table>

3.3. Main Controlling Factor Analysis Model Parameter Setting

In order to clarify what factors are mainly in control of the sand bodies’ development in the shelf-type tidal delta, the tidal amplitude and initial water level were selected for two univariate analyses and the values of the tidal amplitude and the initial water level are referenced by research of modern depositional systems, mentioned in Section 3.2 of this paper. In order to study the influence of the two factors on the sedimentation in depth, the range of values of the two factors in this paper is slightly larger than the reference range of research of modern depositional systems. Two different cases are selected for each factor on the basis of the basic model, and a total of five models were simulated. Tidal factors are as follows: high tide, 10 m; medium tide, 6 m (base); and low tide, 2 m. The water level factors are as follows: high water level, 45 m; medium water level, 15 m; and low water level, 1 m (base), as shown in Table 2.
Table 2. Main controlling factor analysis parameters.

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Factor</th>
<th>Case</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGHWATER</td>
<td>Initial Water Level (m)</td>
<td>High Water Level</td>
<td>45</td>
</tr>
<tr>
<td>MIDDLEWATER</td>
<td>Medium Water Level</td>
<td>Low Water Level</td>
<td>15</td>
</tr>
<tr>
<td>BASE</td>
<td>Low Water Level</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>HIGHTIDE</td>
<td>Tidal Amplitude (m)</td>
<td>High Tide</td>
<td>10</td>
</tr>
<tr>
<td>BASE</td>
<td>Medium Tide</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>LOWTIDE</td>
<td>Low Tide</td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

4. Results

4.1. Analysis of Basic Model Results

Figure 3 shows the simulated erosion and sedimentation in the northern part of West Siberian Basin at simulation time step = 15. Marine boundaries are set in the northwestern, northern, and northeastern parts of the study area, and the local high part of the uplift zone and the east and west sides of the target study area are the main sources of sand supply, and in the shallow marine shelf area, the study area is adjacent to the sources and the high-current-shear-stress area, forming sand body deposits. In the semi-deep-water and deep-water shelf area, the currents are far away from the sources and only receive mud supply from the east and west sides and the northern ancient ocean. The shelf uplift zone in which area Y is situated, as shown in Figure 3b, has a stronger sedimentary erosion in the north than in the south. Sedimentary sand bodies are more developed in the north, and sand sheets are widely distributed in the study area, on which some tidal bars are developed, and the sedimentary sand bodies are in the form of sand–mud thin interbedded structures. Tidal channels are distributed on both sides of the uplift zone, dividing the sand bars. The results of the simulation show that the distribution of sand bodies is similar to the conclusions obtained from the paleogeographic study of Kontorovich, A.E. [25,26], which verifies the reliability of this simulation.

Figure 3. Results of basic model: (a) cumulative erosion and sedimentation of basic model; (b) cumulative erosion and sedimentation of target study area.

Figure 4 shows the simulation results of the erosion and sedimentation distribution in the target study area during the simulation time. Due to tidal action, sediment accumulation occurs, and as the simulation time grows, the sheet sand bodies gradually increase in length and width, and tidal channels appear in some areas; as the bars continue to be deposited, they begin to move towards the center of the basin, and the rate of deposition slows down.
At the marine boundary in the northwestern part of the study area, various bars and tidal channels are developed. In the early period of the simulation, when step = 1, there is sediment accumulation in the study area, although tidal channels are not obviously developed, but there is a trend; in the middle period of the simulation, when step = 8, the basic morphology of the tidal bars and tidal channels in the study area is initially visible, and in the late period of the simulation, when step = 15, the development of the tidal bars and tidal channels becomes particularly significant.

![Figure 4. Process of basic model study area simulation: (a) cumulative erosion and sedimentation of basic model at step 1; (b) cumulative erosion and sedimentation of basic model at step 8; (c) cumulative erosion and sedimentation of basic model at step 15.](image)

Especially in the study area, it can be observed that under the strong influence of the tidal channels, strip-shaped bar structure with separation characteristics is gradually formed. The type of sand bar is mostly dominated by northwest-trending bars, and statistical results show that the average length of the tidal bar is 11.83 km, the average width is 4.2 km, and the average thickness is 0.77 m. A large number of thin sand sheets are developed on both sides of the uplift zone, with the simulation going on, where sand sheets become more developed and expanded, and statistical results show that the average length of the sand sheets is 14.83 km, the average width is 12.60 km, and the average thickness is 0.77 m.

4.2. Analysis of Tide Model Results

Tidal amplitude is one of the important factors affecting the development of bars in the shelf depositional system. The rest of the parameters are fixed to carry out simulations with different tidal amplitudes, which are set to be a low tide with 2 m amplitude, a medium tide with 6 m (basic model) amplitude, and a high tide with 10 m amplitude.

4.2.1. Analysis of Sediment Distribution

As shown in Figure 5, comparison of the models with different tidal amplitudes shows that, compared to the basic model for the medium tide, the bars develop slowly at low tide, but the sediment thickness is greater, little sediment is reworked, and tidal channels are developed along both sides of the uplift zone. At high tide, the tidal modification is stronger, the bars and tidal channels are more developed, and the bar morphology is heavily eroded and redeposited. As tidal amplitude increases, tidal bars grow faster and tidal channels are more developed; the greater the tidal amplitude, the wider the range of tidal influence, the greater the number of bars, and the more complex the morphology.
4.2.2. Analysis of Flow Velocity Distribution

As shown in Figure 6, at low tide, deposition occurs only at the ends of the channel of the uplift zone, with less tidal action, and the water flows in the channel during rising tide, resulting in the formation of a bar at that location. At medium tide, the oscillation of water flow caused by tidal action is significantly enhanced, and multiple tidal channels develop on both sides of the northern side of the uplift zone under the impact of rising tidal currents. At high tide, the tidal action is the strongest, and the water flow in the channel meets with the tidal current to form a vortex current, resulting in the rapid formation of bars on both sides of the uplift zone.

Figure 5. Changes in cumulative erosion and sedimentation of shelf-type tidal delta with different tidal amplitude: (a) low tide model at step 8; (b) low tide model at step 15; (c) medium tide model at step 15; (d) medium tide model at step 8; (e) high tide model at step 15; (f) high tide model at step 15.

Figure 6. Changes in velocity of shelf-type tidal delta with different tidal amplitude: (a) study area at low tide; (b) zoom in on study area at low tide; (c) study area at medium tide; (d) zoom in on study area at medium tide; (e) study area at high tide; (f) zoom in on study area at high tide.
4.2.3. Analysis of Sand Bodies

According to the simulation results, as shown in Table 3, the three-dimensional configuration characteristic parameters of the sand bodies for each tidal amplitude model were counted. At low tide, the average length, average width, and average thickness of the sand bodies decreased to different degrees compared to the medium tidal amplitude model used as the basic model. The average length of the tidal bars decreased by 21.13%, the average width by 9.78%, and the average thickness by 10.57%, while the average length of the sand sheet decreased by 7.42%, the average width by 16.19%, and the average thickness by 29.87%. On the other hand, at high tide, the three-dimensional configuration characteristic parameters of the sand bodies increased significantly compared to the basic model. The average length of the tidal bars increased by 26.63%, the average width by 23.09%, and the average thickness by 19.28%, while the average length of the sand sheet increased by 34.05%, the average width by 7.30%, and the average thickness by 27.27%. The simulation results show that the tidal energy effect has the greatest influence on the length of the deposited sand body, and with the increase in tidal amplitude, there is a trend of advancing towards the northern ocean of the study area, indicating that the tidal amplitude is one of the main factors controlling the sedimentation in the study area.

Table 3. Three-dimensional configuration characteristic parameters of the sand bodies with different tidal amplitude.

<table>
<thead>
<tr>
<th>Tidal Amplitude</th>
<th>Average Length/km</th>
<th>Average Width/km</th>
<th>Average Thickness/m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tidal Bar</td>
<td>Sand Sheet</td>
<td>Tidal Bar</td>
</tr>
<tr>
<td>Low tide (2 m)</td>
<td>10.33</td>
<td>13.73</td>
<td>4.61</td>
</tr>
<tr>
<td>Medium tide (6 m)</td>
<td>11.83</td>
<td>14.83</td>
<td>5.11</td>
</tr>
<tr>
<td>High tide (10 m)</td>
<td>13.48</td>
<td>19.88</td>
<td>6.49</td>
</tr>
</tbody>
</table>

Analyzing the relationships of the three-dimensional configuration characteristic parameters of tidal bars, as shown in Figure 7, the values of the length-to-width ratio of the tidal bars ranged from 1.15 to 5, and the values of the length-to-thickness ratio ranged from 0.62 to 2.33. Tidal amplitude is positively correlated with the length, width, thickness, length-to-width ratio, and length-to-thickness ratio of tidal bars.

![Figure 7](image)

**Figure 7.** (a) Tidal bars’ length-to-width ratio distribution map with different tidal amplitude; (b) tidal bars’ length-to-thickness ratio distribution map with different tidal amplitude.

4.2.4. Analysis of Interlayers

As shown in Figure 8, at low tide, the length of the interlayers ranges from 8 to 25 km, the thickness of the interlayers ranges from 1.0 to 2.5 m, and the length of the interlayers is concentrated at 18.73 km; at medium tide, the length of the interlayers ranges from 4 to 18 km, the thickness of the interlayers ranges from 0.3 to 0.6 m, and the length of the interlayers is concentrated at 9.16 km; at high tide, the length of the interlayers ranges from 2 to 12 km, the thickness of the interlayers ranges from 0.1 to 0.3 m, and the length of the interlayers is concentrated at 5.94 km. The statistical result shows that the interlayers are
widely developed at low tide; at medium and high tide, the development of the interlayers is limited and the thickness is thinner. With the increase in tidal amplitude, the length of the interlayers tends to become shorter, and the thickness of the interlayers gradually becomes smaller.

![Figure 8. Distribution of interlayer length with different tidal amplitude.](image)

After the above analysis, we know that three-dimensional configuration characteristic parameters of the sand bodies all increase with the increase in the tidal amplitude, and the larger the tidal amplitude, the more bars are eroded and redeposited. The larger the tidal amplitude, the larger the average length and average width, the thicker average thickness of the tidal bars, and the larger the length-to-width and length-to-thickness ratios of the bars; the larger the tidal amplitude, the larger the length and width, the thicker the thickness of the sand sheets; the tidal factor is positively correlated with the above parameters. The interlayers are widely developed at low tide with a large number, and the length and thickness of the interlayers are large. The development of interlayers is limited at medium and high tide with a decreasing number, while the length and thickness of the interlayers decrease with the increase in tidal amplitude.

4.3. Analysis of Initial Water Level Model Results

The initial water level is also one of the important factors affecting the shelf tidal delta depositional system, and different initial water levels produce very different results in the sedimentary numerical simulation. Simulations in different initial water level conditions are carried out with remaining parameters fixed; the initial water level is set as 1 m for low water level (basic model), 15 m for medium water level, and 45 m for high water level, with the bottom of the channel in the uplift zone as the 0 m water level surface. A simulation is carried out in different initial water level conditions.

4.3.1. Analysis of Sediment Distribution

As shown in Figure 9, the low water level model (basic model) has formed tidal bars and tidal channels at the study area in the early stage of the simulation, but the segmentation is not clear enough, and the development of tidal bars and tidal channels is obvious in the later stage of the simulation, with the development of distinctly segmented bars under the tidal action in the study area. The medium water level model has formed a large area of sand sheets in the early stage of the simulation, and there is a slight development of the tidal channels but not the development of tidal bars. In the later stage of the simulation, large sand sheets are further developed in the study area, and a small number of tidal bars and tidal channels are developed near the area. In the high water level model, the tidal bar and tidal channel are not developed in the whole simulation process, and only part of the sand sheets are developed. Comparison of the different water level models shows that from the tidal delta to the shallow-water shelf to the deep-water shelf, the cutting of the channel becomes weaker and weaker, and the concentration of the sand bodies becomes less and less, and the thickness becomes thinner and thinner.
of the different water level models shows that from the tidal delta to the shallow-water shelf to the deep-water shelf, the cutting of the channel becomes weaker and weaker, and the concentration of the sand bodies becomes less and less, and the thickness becomes thinner and thinner.

Figure 9. Changes in cumulative erosion and sedimentation of shelf-type tidal delta with different water level: (a) low water level model at step 8; (b) low water level model at step 15; (c) medium water level model at step 15; (d) medium water level model at step 8; (e) high water level model at step 15; (f) high water level model at step 15.

4.3.2. Analysis of Flow Velocity Distribution

As shown in Figure 10, at low water level, the current oscillation caused by tidal action is obvious, and in the north side of the uplift zone, many tidal channels and tidal bars are developed on the east and west sides of the study area under the impact of rising tidal currents. At medium water level, the flow velocity in the study area does not change significantly under the same tidal action, and only a small number of tidal bars and tidal channels are developed on the west side. At high water level, the uplift zone is in deep water and less affected by tidal action, the flow oscillation in the study area is not obvious, and neither tidal bar nor tidal channel is developed.

Figure 10. Changes in velocity of shelf-type tidal delta with different water levels: (a) study area at low water level; (b) zoom in on study area at low water level; (c) study area at medium water level; (d) zoom in on study area at medium water level; (e) study area at high water level; (f) zoom in on study area at high water level.
4.3.3. Analysis of Sand Bodies

According to the simulation results, as shown in Table 4, the three-dimensional configuration characteristic parameters of the sand bodies for each water level model were counted, and the low water level model (basic model) can be used as a control group for comparison. When the initial water level increases to 15 m, the length and width of the deposited sand bodies show a decreasing trend, while the thickness of the tidal bars increased and the thickness of the sand sheet decreased. The average length and average width of the tidal bars decreased by 5.07% and 12.13%, respectively, and the average thickness increased by 5.23%. The depositional condition in the study area changes drastically when the water level increases significantly up to 45 m. At high water, the study area is at a lower depth below the water’s surface, and tidal bar is not developed. Only large, thin sand sheets are developed, and the length of the sand sheet increases substantially. The simulation results show that the development of sedimentary sand bodies is more and more limited as the water level rises and the whole study area is gradually submerged deeper and deeper below the water’s surface. The simulation results under different water levels with other parameters kept constant are quite different, indicating that the water level is also one of the main controlling factors of sedimentation in the study area.

Table 4. Three-dimensional configuration characteristic parameters of the sand bodies with different water levels.

<table>
<thead>
<tr>
<th>Water Level</th>
<th>Average Length/km</th>
<th>Average Width/km</th>
<th>Average Thickness/m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tidal Bar</td>
<td>Sand Sheet</td>
<td>Tidal Bar</td>
</tr>
<tr>
<td>Low water level (1 m)</td>
<td>11.83</td>
<td>14.83</td>
<td>5.11</td>
</tr>
<tr>
<td>Medium water level (15 m)</td>
<td>11.23</td>
<td>13.55</td>
<td>4.49</td>
</tr>
<tr>
<td>High water level (45 m)</td>
<td>-</td>
<td>49.21</td>
<td>-</td>
</tr>
</tbody>
</table>

Analyze the relationships of the three-dimensional configuration characteristic parameters of tidal bars, as shown in Figure 11, the values of the length to width ratio of the tidal bars ranged from 1.5 to 5, and the values of the length to thickness ratio ranged from 0.6 to 3.36. Initial water level is positively correlated with the length, width, and length to thickness ratio of tidal bars and it is negatively correlated with the thickness and length to width ratio of tidal bars.

Figure 11. (a) Tidal bars’ length-to-width ratio distribution map with different water levels; (b) tidal bars’ length-to-thickness ratio distribution map with different water levels.

4.3.4. Analysis of Interlayers

As shown in Figure 12, at low water level, the length of the interlayers ranges from 4 to 18 km, the thickness of the interlayers ranges from 0.3 to 0.6 m, and the length of the interlayers is concentrated at 9.16 km; at medium water level, the length of the interlayers ranges from 6 to 40 km, the thickness of the interlayers ranges from 0.5 to 1.8 m, and the length of the interlayers is concentrated at 23.88 km; at high water level, the length of the
interlayers ranges from 12 to 50 km, the thickness of the interlayers ranges from 1.0 to 3.0 m, and the length of the interlayers is concentrated at 31.43 km. From the statistical results, it shows that at low water level, the interlayers are developed with thin thickness; at medium and high water level, the interlayers are more developed and become thicker.

![Figure 12](image)

**Figure 12.** Distribution of interlayer length with different water levels.

After the above analysis, we know that at low water level, sedimentary sand bodies on the uplift zone are more developed, forming shelf-type tidal delta deposition. The development of tidal channels is obvious, as well as the development of strip-shaped bars with clear divisibility under its action. At medium water level, the development of sand bars is limited and it is easier to form dispersed and spreading thin sand sheets, with only a few tidal bars and tidal channels developed. At high water level, a deep-water shelf is formed, so that sand deposits do not easily to develop. Sedimentation is dominated by remotely suspended and slowly settling mud, with no tidal bar or tidal channel developed, and only a large area of thin sand sheets formed. With the increase in water level height, the length of the interlayers tends to become longer, and the thickness of the interlayers increases.

### 5. Discussion

This study has conducted extensive research on parameter selection during the preliminary model construction phase and has carried out multiple simulation experiments to adjust the modeling parameters. To validate the rationality of the models built in this research, this section compares the simulation results of the series of models with the parameters of the Jurassic strata sand bodies in the study area, as shown in Table 5.

**Table 5.** Comparison of study area’s actual conditions and numerical simulation.

<table>
<thead>
<tr>
<th>Model</th>
<th>Hydrodynamic Condition</th>
<th>Statistical Result of Tidal Bars</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tide/m</td>
<td>Water Level/m</td>
</tr>
<tr>
<td>Study area</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Base 1</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Base 2</td>
<td>4.5</td>
<td>1</td>
</tr>
<tr>
<td>Base 3</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Base 4</td>
<td>7.5</td>
<td>5</td>
</tr>
</tbody>
</table>

Extensive simulation experiments were performed to establish a basic model that best represents the characteristics of the study area. Table 5 presents a comparison of typical simulation outcomes with the actual parameters of the sand bodies in the study area, and the three-dimensional configuration characteristic parameters of simulated sand...
bodies of the Base 1 model show the highest degree of congruence with the real conditions. Subsequent random fine-tuning of the Base 1 model’s parameters led to a decline in the degree of congruence between the simulation results and the actual conditions of the study area. In this study, based on existing data from the study area, we present the sedimentary facies map of the Jurassic Vym time in the study area. As shown in Figure 13, a comparative examination of the map of cumulative erosion and sedimentation from the Base 1 model and the sedimentary facies map of the Jurassic Vym time in the northern study area reveals obvious similarities. Both illustrations show the prominent development of tidal bars atop sand sheets. Notably, these tidal sand bars, under the partitioning influence of tidal channels, have evolved into a diverse array of morphologies, thereby testifying to the model’s capability in replicating complex depositional patterns akin to those observed in natural settings. This visual correlation reinforces the notion that the model simulates the tide-dominated dynamic processes in a shallow marine shelf environment during Jurassic Vym time, including the intricate interplay between sedimentation and erosion forces giving rise to the varied forms of tidal bars. The comparison shows the optimality of the Base 1 model’s parameter settings and further validates the Base 1 model’s similarity with the depositional characteristics of the Vym time strata. Therefore, the Base 1 model is adopted as the basic model in this paper, serving as a platform for subsequent univariate analyses.

Figure 13. Comparison between the actual conditions and numerical simulation in study area: (a) sedimentary facies map of the Jurassic Vym time in the study area; (b) cumulative erosion and sedimentation simulation result of basic model.

6. Conclusions

The present study utilizes numerical simulation of sedimentary dynamics to investigate the distribution of sand bodies and interlayers in the target strata in the study area, and to provide prediction and guidance for the development of oil and gas reservoirs. In addition, we carry out numerical simulation with two factors, namely model tide and water level, and establish a numerical evolution model of sedimentary dynamics under the control of the two factors. By comparing the morphology and three-dimensional configuration characteristic parameters of sand bodies under different single-factor conditions, the shelf-type tidal delta depositional system with mixed fluvial and tide is quantitatively
studied. The sedimentary numerical simulation can obtain the following insights about the main controlling factors of the development of the sedimentary sand bodies and interlayers. Based on numerical simulation of sedimentary dynamics, models adopt conceptual paleogeographic topography in this study, with tidal hydrodynamics as the main role. The analysis of the results shows that the tide and water level as the main controlling factors all have a significant influence on the development of tidal bars, sand sheets, and the length and width of tidal channels and interlayers in the location of the study area.

1. The tidal amplitude effect is the factor that produces the greatest impact on the shelf tidal delta; the average length, width, and thickness of tidal bars and sand sheets increase with tidal amplitude, and the three-dimensional configuration characteristic parameters are positively correlated with tidal amplitude.

2. The effect of initial water level height on the development of shelf-type tidal delta sand bodies shows that the development of tidal bars, sand sheets, and tidal channels is limited with the increase in water level from a low water level to medium water level, and only a large area of thin sand sheets is formed under a high water level, indicating that the development of sediment is more appropriate in the low water level, namely the shallow-water shelf condition. Sand bodies do not easily form in a deep-water shelf.

3. Quantitative characterization of the distribution of interlayers in the bars shows that the tidal amplitude and initial water level have a strong influence on the morphology of the interlayers. In this case, the tidal amplitude is negatively correlated with both the length of the interlayers and the thickness of the interlayers, and the initial water level is positively correlated with both the length and the thickness of the interlayers.

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Conflicts of Interest: The authors declare no conflicts of interest.

References


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