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Confined gravity flow sedimentary process and its impact on the lower continental slope, Niger Delta

LI Lei[1,2*], WANG YingMin[1], ZHANG LianMei[3] & HUANG ZhiChao[4]

[1] *College of Geosciences, China University of Petroleum, Beijing 102249, China;*
[2] *School of Petroleum Resources, Xi'an Shiyou University, Xi'an 710065, China;*
[3] *School of Resources & Geoscience, China University of Mining & Technology, Xuzhou 221008, China;*
[4] *Institute of Shanghai Offshore Oil & Gas Company, China Petroleum & Chemical Corporation, Shanghai 200120, China*

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There is active gravity flow sedimentation on the lower continental slope of Niger Delta. High-resolution 3-D seismic data enable a detailed study on the gravity flow deposition process and its impact. The lower continental slope of Niger Delta is characterized by a stepped complex topography, which resulted from gravity sliding and spreading during Miocene and Pliocene. Two types of accommodations are identified on the slope: ponded accommodation as isolated sub-basins and healed slope accommodation as connected tortuous corridors, where multi-scale submarine fans and submarine channels developed. Gravity flow deposition process is affected by the characteristics of gravity flows and the receiving basin. At the early stage, gravity flow deposition process was dominated by "fill and spill" pattern in the ponded accommodation, whereas it was confined to the healed slope accommodation during the late stage. On the lower continental slope of Niger Delta, complex slope topography controlled the distribution and evolution of the gravity flow, producing complicated gravity depositional patterns.

Niger Delta, confined gravity flow, accommodation, sedimentary process

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Study on the deep-water deposition process and its product is one of the most interesting fields in sedimentology [1]. Due to the lack of outcrop data and high cost of drilling, seismic interpretation has become one of the major approaches to studying deep-water deposits [2–6]. Processes such as salt (or mud) diapir, gravity sliding, and gravity extending produce numerous diapir and thrusting structures in the passive continental margin, forming complex continental slope topography [7–11]. The issue that the complex topography controls the sediment architecture and distribution has drawn great attention of geoscientists [10, 12–14]. Sediment supply, tectonism, and relative sea-level change are the three main controls in deep-water depositional system [15, 16]. However, as sediments reach the shelf margin or beyond, sediment delivery system and configuration of the receiving basin become the controlling factors of submarine fan morphology and lithofacies distribution.

The deep-water area of Niger Delta basin is one of the most important exploration provinces. The increasing exploration successes on the continental slope and the deep-water basin greatly promote scientific research on the deep-water deposits in this region [3, 4, 8, 14].

Many gravity-thrusting structures have been found on the lower continental slope, Niger Delta basin [8, 9, 11]. These structures are considered to have been controlling the depositional architecture and patterns of the submarine channels. According to Heinio and Davies [14], the growth folds per-

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*Corresponding author (email: lilei002@yahoo.com.cn)

pendicular to the channel-levee system caused knickpoint migration and also induced changes of submarine channel gradient and loading and erosional capacity of turbidity current. This paper focuses on the impact of basin configuration on deep-water gravity flow sedimentary process and its impact in the lower continental slope of Niger Delta.

1 Regional geologic setting

Niger Delta is located in the Gulf of Guinea on the margin of West Africa. It is bounded by the Cameroon volcanic belt to the east and 4000 m contour line and the Dahomey basin to the west. In the west Niger Delta, the width of the shelf ranges from 50 to 70 km with the shelf-break in a water depth of 150–200 m (Figure 1(a)). The relative sea-level drop and fast deposition rate since the Eocene have caused the building of the deep-water Niger Delta, which is one of the largest regressive deltas in the world. The Cenozoic Erathem of the deep-water Niger Delta is composed of Akata Formation and Agbada Formation (Figure 1(b)).

The study area is located at the toe thrust belts of the west Niger Delta with an average water depth of 1500 m (Figure 1(a)). The thrust belts induced by gravity sliding are characterized by a wide variety of thrust structural styles such as fault-bend folds and complex imbricate thrust series. The thrust faults cut through the Agbada Formation in many places and then merged downward into a detachment surface (Figure 1(b)). There are many piggy mini-basins in the back-limb of fault-related folds, which were caused by gravity sliding since the Eocene. Niger Delta exhibits complex slope and deep sea basin topography. Submarine canyons act as conduits transporting sediments from the shelf margin by gravity flows into the slope and deep sea plain. The complex seafloor topography has played an important role in controlling the gravity flow depositional processes and distribution of sediments.

2 Theory on confined gravity flow

Van Andel and Komar [17] used the word ‘ponding’ to describe a situation in which large volume of turbidity flows are fully confined by an area of enclosed bathymetry.

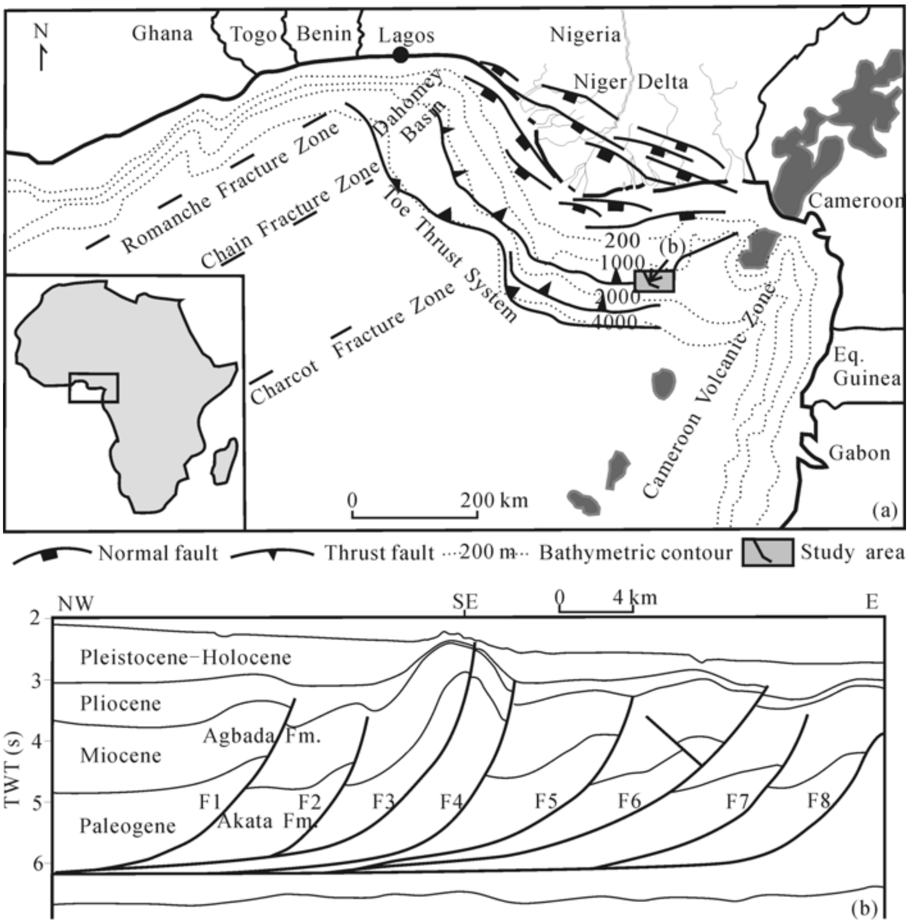

Figure 1 Schematic map showing the main sedimentary basins and tectonic features of Niger Delta and the structural framework of the study area. (a) Schematic map showing the main sedimentary basins and tectonic features of Niger Delta [9]; (b) sketch map showing the structural framework of the study area.

Pickering and Hiscott [18] proposed the concept 'contained turbidite' to refer to beds deposited from turbidity flows that are confined within a basin too small to allow multi-directional flows. Mutti and Normark [19] recognized four basic types of turbidite basins, emphasizing that the long-term stability of the receiving basin and the volume of sediments control the morphology and subfacies of submarine fans. Mutti and Normark [15] proposed that, along with eustasy and tectonism, the composition and volume of turbidity flows and the basin type and configuration are key factors in controlling the geometry and facies models of turbidite systems. Ross et al. [20] introduced a slope readjustment model, suggesting that depositional and erosional processes on continental slopes tend to maintain it in a steady and equilibrium state.

Kneller and McCaffrey [21, 22] demonstrated the effects of confined surface and salt diapir topography on turbidity flows based on flume experiment. Galloway [23] emphasized the important influence of sediment supply history and slope paleo-topography on the development of seven basic sedimentary facies in the slope and slope-base depositional systems. Prather et al. [13] showed that various seismic facies assemblages predominate in the fill history of Gulf of Mexico deepwater basins and related them to different types of accommodation. Prather [24] took a further step and simulated the fill and spill sequence of Gulf of Mexico intra-slope basins with numerical forward modeling. According to Prather [10], the distribution and quality of deep sea reservoirs are controlled by slope topography. Sheet sands tend to develop in ponded accommodation; cyclical alternation of channels, sheets, and mass transport complexes are common in healed slope accommodation, while sinuous ribbon-like channel sands are often found in stepped profiles. Smith [25] divided the depositional systems on topographically complex slopes into cascades of silled sub-basins and connected tortuous corridors lacking effective sills. According to Smith [25], filling styles and reservoir configuration are controlled by the volume of sediment supply, flow properties, the relative scale of the receiving basin, the relative rate of basin subsidence, and the infilling depositional processes.

3 Characteristics of receiving basin configurations, the lower continental slopes of Niger Delta

3.1 Topography of receiving basin

High-resolution 3-D seismic interpretation has become an important method in reconstructing the paleotopography at the time depositional systems were deposited [12]. From Miocene to late Pliocene, a series of thrust and fold belts were formed due to gravity sliding on the lower continental slope and in deep sea basin [8, 9, 26]. During late Pliocene, the development of gravity thrust faults (F1, F3, and F6) produced complex seafloor topography in the study area, with many mini-basins coming forth at the backlimb of the fault-related folds. Gravity sliding has weakened from Pleistocene to present. However, the topography of the continental slope is still affected by the early gravity thrusting faults, maintaining a mini-basin style (B1, B2, and B3) (Figures 1(b) and 2(a)). There are two uplifting belts in the study area, one in northwest direction and the other one in northeast direction. Between these two uplifting belts, mini-basins are connected by paths, forming cascades of silled mini-basins with lateral escaping paths (Figure 2(a) and (b)).

3.2 Slope equilibrium profile and accommodation types

Slopes can be divided into graded slope and above-graded slope on the basis of topography [10, 20]. Gravity structural movement tends to produce a rough surface and thus an above-graded slope, while deep-water deposition and erosion try to form gentle topography and consequently a graded slope. The slope equilibrium profile is a trend surface, where sediment deposition and erosion are in equilibrium. Spaces below this surface are accommodation where sediments transported by gravity flows are deposited, while strata above this surface tend to be eroded away. Erosion intensity is determined by the power of the gravity flows and properties of the slope. Areas above the slope equilibrium profile are potential erosion zones; in contrary, areas below the slope equilibrium profile are potential deposition zones (Figure 2(c)). Ponded accommodation and healed-slope accommodations, which make up the total accommodation, exist across the above-graded slopes (Figure 2(c)). The total accommodation is determined by the slope equilibrium profile and seafloor. Ponded accommodation lies within the 3-D enclosed topographic lows, which are identified by the points of maximum negative curvature [24, 27]. Effective ponded accommodation is a 3-D closure volume controlled by the lowest spill point. Healed slope accommodation is the volume difference between the total and the ponded accommodation (Figure 2).

4 Submarine sediment types and sedimentary facies

The thickness and distribution of gravity flow deposits are greatly controlled by the seafloor topography. As shown in Figure 3, sediments deposited from gravity flows are distributed mainly in the connected tortuous corridors. Three mini-basins (B1, B2, and B3) within the corridors hold most of the sediments (Figure 3(a) and (b)). The following seismic reflection characteristics can be observed from the seismic profile (Figures 2(b) and 3(c)–(f)): low amplitude-parallel to subparallel seismic reflections, high amplitude-mounded seismic reflections, seismic events overlap-

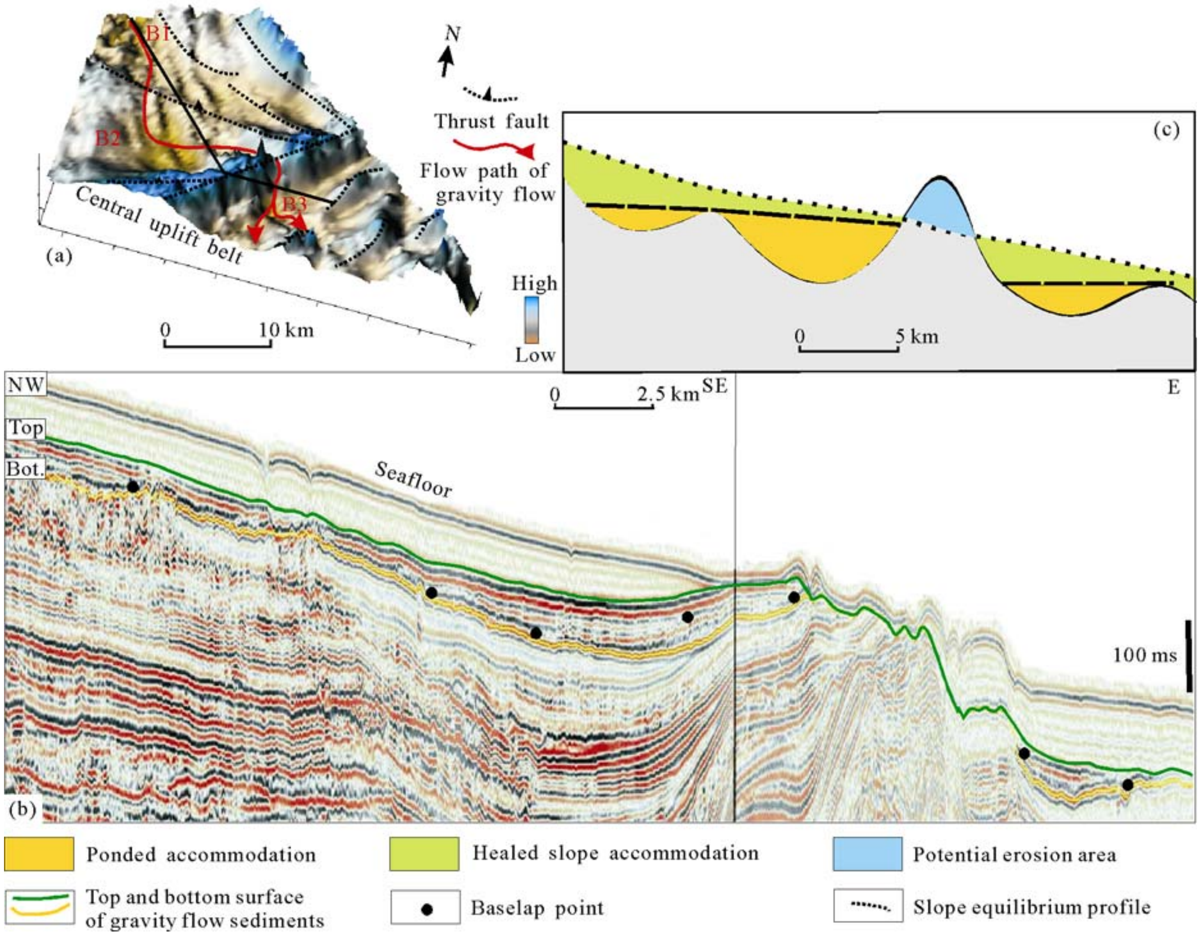

Figure 2 Slope topography of the study area in Pleistocene and typical seismic sections through the slope. (a) Slope topography and the tectonic features of the study area in Pleistocene; (b) typical seismic sections through the slope; (c) accommodation of above-graded slopes in the study area.

ping the margin of mini-basin and truncations. Low amplitude-parallel to subparallel seismic reflections are interpreted as hemipelagic mud; while mounded seismic facies are submarine fans, distributary channel-lobe complexes, and channel-levee complexes [2, 4, 6, 13]. Gravity flows deposits, which are characterized by high amplitude mounded seismic facies, are separated by hemipelagic mud with low amplitude, high-continuity reflections. Hemipelagic mud is deposited mostly during periods of gravity flows depositional quiescence.

5 Sediment processes of the confined gravity flows

5.1 Vertical evolution of the confined gravity flows

The gravity flow deposits on the basin margins often exhibit convergent-baselapping facies and convergent-thinning facies. Different seismic geometries indicate different sedimentary processes and record a variety of accommodation-filling successions [13]. High-resolution 3-D seismic reflections not only display the deep-water depositional elements including multi-submarine fan (lobe), erosional channel, but also reveal the depositional infilling history of different kinds of accommodations. Seismic events on the bottom of the three mini-basins (B1, B2, and B3) thin toward and baselap on the basin margins, which is typical of convergent-baselapping (Figure 2(b)). These reflection characteristics suggest that the capture of the gravity flow sediments occurred in these mini-basins and the depositional architecture is controlled by the volume and 3-D geometry of the mini-basins. Seismic events on the top of the three mini-basins thin toward the fold and have no distinctive baselapping facies. This is typical of the convergent-thinning facies, which reflects high gravity flow deposition ratio.

Most thrust faulting ceased in the study area since the Pleistocene, except for the gravity thrust faults in the central uplifting belt. The lower continental slope influenced by the early gravity thrusting maintained a series of mini-basins (B1, B2, and B3). Four stages of gravity flow have been recognized. At the first stage (Figure 4(a)), gravity flow deposition occurred only in mini-basin B1 because the volume of the gravity flow was less than that of the

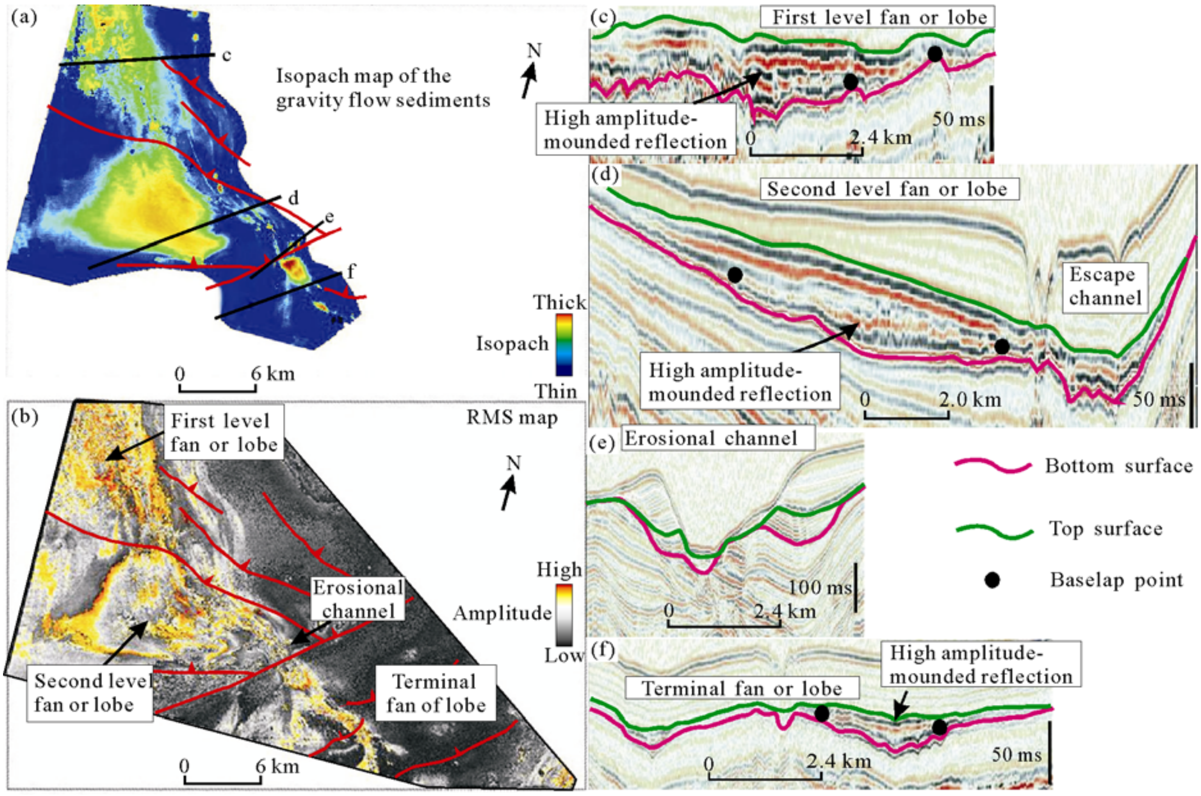

Figure 3 Plane features and seismic facies of submarine fan. (a) Isopach map of submarine fan and the tectonic features of the study area in Pleistocene; (b) Rms map (Bot-60 ms) highlighting the multi-submarine fan (lobe) and channel; (c)—(f) typical seismic sections showing submarine deposit elements.

mini-basin. This mini-basin was a ponded accommodation controlled by its lowest spill point. Submarine fans developed in mini-basin B1 showing a baselapping seismic reflection pattern (Figure 2(b)). At the second stage (Figure 4(b)), the volume of the gravity flow exceeded that of mini-basin B1. The gravity flow spilled from the mini-basin B1 to mini-basin B2 through the lowest spill point of the mini-basin B1. Sediments were accumulated in mini-basin B2 by progradation, showing a baselap seismic reflection pattern on the basin margin. Sediments on the base of mini-basin B1 are younger and finer than those in mini-basin B2. The baselap surface in the mini-basin B1 is also younger than that in the mini-basin B2. At the third stage (Figure 4(c)), gravity flow, which already filled ponded accommodation B1 and B2, started to deposit in the healed slope accommodation, which were induced by the slope topography and the density difference between gravity flow and seawater. Different from the “fill and spill” processes in the former two stages, gravity flow was deposited in healed slope accommodation, which are the connected tortuous corridors between mini-basins B1 and B2, showing convergent-thinning facies on the top of the uplift (Figure 2(b)). In the last stage (Figure 4(d)), localized erosion happened where the slope equilibrium profile lay below the central uplift. The gravity flows reached mini-basin B3 through the erosional V-shaped channel.

5.2 Plane evolution of the confined gravity flow

Due to the influence of the early northwest and northeast gravity thrust belts, the lower continental slope in the study area exhibits a stepped topography with connected tortuous corridors (Figure 5). Three mini-basins (B1, B2, and B3) controlled by their lowest spill points lie within the corridors, forming ponded accommodation. Without effective close volumes on a topographically complex slope, only the healed slope accommodation forms on the connected tortuous corridor.

Gravity flow deposition was confined in mini-basin B1 untill the volume of the gravity flow exceeds the effective accommodation of the basin, forming submarine fans (lobes). The submarine fan or lobe eventually filled the mini-basin B1 (Figure 5(a)). When the gravity flow volume exceeded the ponded accommodations, sediments bypassed the previously filled mini-basin B1 via the lowest spill point into the mini-basin B2 downslope, forming secondary level submarine fans (lobes) (Figure 5(b)). Under the control of continental topography and gravity flow hydrodynaminic conditions, healed slope accommodation developed above the ponded accommodation. Gravity flow deposition in healed slope accommodation shows patterns of channel or leveed-channel, which is affected by the geometry of connected tortuous corridors (Figure 5(c)). Erosion occurred where the central uplifting zone was above the equilibrium

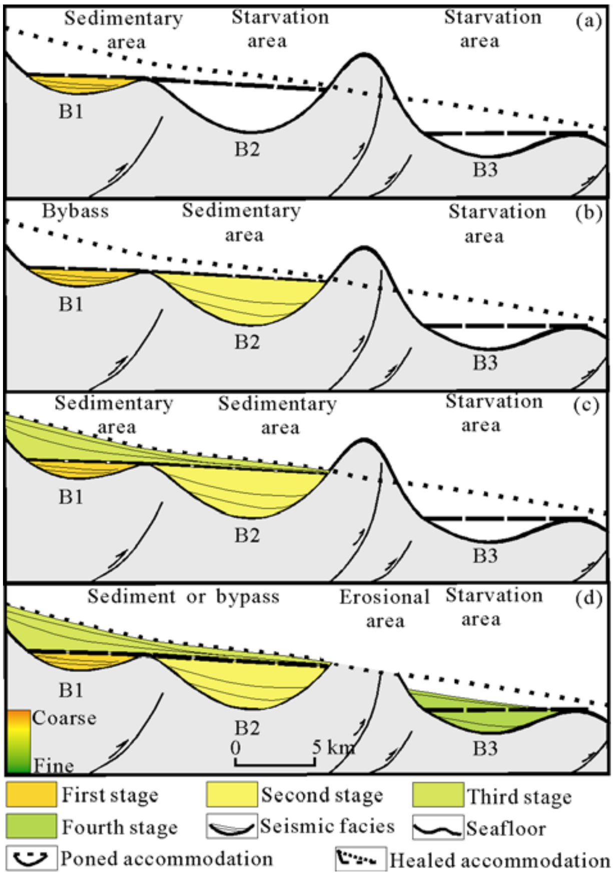

Figure 4 Profile illustrating the vertical evolution of confined gravity flow.

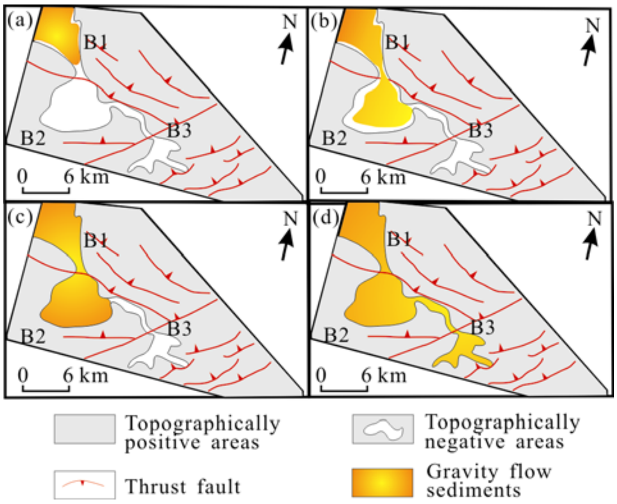

Figure 5 Schematic diagrams showing the plane evolution of confined gravity flow.

profile. The gravity flow cut through the weak rock zone into channels through which sediments were transported and deposited in mini-basin B3, forming terminal lobes (Figure 5(d)).

6 Conclusions

In this paper, we have discussed the gravity flow deposition process and its responses to complex topography by studying the lower continental slope, Niger Delta, with high-resolution 3-D seismic data. Three conclusions can be drawn from the interpretation of the shallow 3-D seismic data.

(1) The lower continental slope, Niger Delta, is characterized by stepped topography that is influenced by the gravity sliding or spreading from the Miocene to the Pliocene. Gravity flow sediments bypassed or deposited in the connected corridors and 3-D closed mini-basins within the corridors, forming multi-grade submarine fans (lobes) and submarine channels. Gravity flow deposition was dominated by “fill and spill” process in 3-D closed ponded accommodations in the early stage, while it was confined in healed slope accommodation in the late stage.

(2) The gravity flow deposition processes interpreted from 3-D seismic data are meaningful in predicting the distribution of gravity flow deposits and sediment quality. In areas with rich drilling data, further study should be done on the genetic type and distribution of the microfacies of the gravity flow depositional system.

(3) The topographically complex slope and deep-water plain are the primary factors that govern the gravity flow sedimentary processes and its distribution. It is unrealistic to accurately summarize and predict the gravity flow depositional system with any single model.

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