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Abstract: The Miocene Zhujiang Formation is the key horizon for oil and gas exploration in the Pearl River Mouth basin of northern South China Sea. With the help of core observation, seismic attributes and various analytical data, the sedimentary facies marks, distribution of sedimentary facies and depositional model of forced regression in the Miocene Zhujiang Formation of the Pearl River Mouth basin, northern South China Sea, have been studied. Forced regressive deposits were formed during the period when relative sea level ranged from highstand to lowstand and the sediments were forced to undergo progradation so that five sets of foreset delta deposits are developed in turn. In the early stage of forced regression, the normal delta where the delta plain, delta front and prodelta are not absent mainly developed. In the later stage of forced regression, the shelf edge delta with only the delta front and the prodelta, the longshore bar along the shelf break and the turbidite fan in the deep water of the slope area were developed. The favorable reservoir of forced regressive deposits are located near the upper boundary of the falling stage systems tract and the basal surface of forced regression, and they are the sand bodies of shelf edge delta, longshore bar and turbidite fan. The research results may provide guidance for reservoir prediction.

Keywords: forced regression, sedimentary characteristics, depositional model, Zhujiang Formation, Pearl River Mouth basin, northern South China Sea

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1 Introduction

In recent years, the theory of sequence stratigraphy has been enriched and improved continuously with a wide application in exploration and development of lithologic and stratigraphic reservoirs. Hunt and Tucker [1] identified the forced regressive wedge systems tract on the basis of the classical division of sequence stratigraphic systems tract (lowstand systems tract, transgressive systems tract and highstand systems tract) and described its sedimentary characteristics. Subsequently, Plint and Nummedal [2], and Catuneanu [3,4] developed the concept of forced regression wedge systems tract and pointed out that the falling stage systems tract (FSST) occurs during the descending stage of base-level when the shoreline is forced to regress. Generally, if $(\Delta V_s/\Delta t) > (\Delta V_a/\Delta t)$, regressive deposits occur (V_s is sediment supply, V_a is accommodation space and t is time). If $\Delta V_a/\Delta t > 0$ and $(\Delta V_s/\Delta t) > (\Delta V_a/\Delta t)$, normal regressive deposits occur. If $\Delta V_a/\Delta t < 0$ and $(\Delta V_s/\Delta t) > (\Delta V_a/\Delta t)$, forced regressive deposits occur. Because accommodation space is lost at this time, sediments are forced to deposit [5]. Definition of the FSST has attracted extensive attention, and a lot of research work has been carried out on forced regressive deposits [6–11]. Due to the shorter deposition time of the forced regression, several sets of progradational regressive sand bodies develop. The sand bodies are relatively thin and evenly distributed in an isolated and dispersed state. Therefore, the identification and description of forced regressive deposits are limited to a certain extent, and forced regressive deposits may be conformed with wedge-shaped deposits in lowstand systems tracts [12–15].

A set of foreset wedge deposits with large thickness and shelf-edge delta deposits were developed because the delta was pushed into the shelf margin and slope area about 21 Ma, as recorded in the Miocene Zhujiang Formation of the Pearl River Mouth basin (PRMB), northern South China Sea [16–19]. The foreset wedge deposits have been interpreted as a wedge or delta of the lowstand systems tract controlled by the shelf break zone [16–19]. During the 21 Ma period, a large sea level decline occurred in the PRMB, and the coastline retreated rapidly for several kilometers and fell below the shelf break, resulting in forced regression [12,20,21]. Chen et al. [22] and Yu et al. [23,24] interpreted the forced regressive deposits as previously mistaken for low stand wedge or low stand delta because of typical characteristics of forced regressive deposits such as a shelf-margin delta with high-angle oblique foresets, U-shaped incised valley perpendicular to the palaeoflow direction, foreset superimposed sets and shoreline migration trajectory. The division of the systems tract of forced regressive deposits and its sequence framework has been discussed, but there is no clear description of sedimentary characteristics and comprehensive conclusion for the depositional model.

In view of this, the sedimentary characteristics of a forced regressive deposits of the Miocene Zhujiang Formation have been analyzed using 3D seismic data and a large number of drilling and logging data. A depositional model of forced regression from the China Sea has been reconstructed to provide suggestive information for other cases around the world.

2 Geological setting

The PRMB which is located in the southern margin of South China and in the northern South China Sea is a Mesozoic and Cenozoic petroleum basin formed on the Caledonian, Hercynian and Yanshanian fold basement [25]. It can be divided into five large-scale first-order tectonic units with NE-SW strike, which are the northern fault terrace belt, the northern depression belt, the central uplift belt (including Shenhu uplift, Panyu low uplift and Dongsha uplift), the southern depression belt, and the southern uplift belt [26,27] (Figure 1a). During the Cenozoic, there were six tectonic events when basin development took place [21,28]. The study area is located in the south of Panyu low uplift which is in the central uplift belt and in the north-central part of Baiyun sag (Figure 1b). During the Cenozoic, the Wenchang, Enping, Zhuhai, Zhujiang, Hanjiang, Yuehai and Wanshan Formations were deposited in the study area from bottom to top [29,30]. The Shenhu, Wenchang and Enping Formations are characterized by depositions of fluvial-lacustrine sandstones, mudstones and coal. The lacustrine mudstones and coal layers in Wenchang and Enping Formations are the main hydrocarbon source rocks of the PRMB [29,30]. A large shallow shelf delta is developed in Zhuhai and Zhujiang Formations of the PRMB. The sandstone deposited at this stage accounts for about 50–60% of the volume of the rock and covers a large area, so it is considered to be the most important reservoir rocks in the PRMB [21]. The deep-water depositional systems dominated by argillaceous sediments are developed in the Hanjiang, Yuehai and Wanshan Formations of the PRMB [21,30]. According to the seismic reflection configuration characteristics of the PRBM, paleontological dating and the third-order relative sea level change curve, six third-order sequence boundaries and one maximum flooding surface in the Zhujiang Formation have been identified [20,22–24,31–33]. The Zhujiang Formation has been divided into five third-order sequences: SQ1, SQ2, SQ3, SQ4 and SQ5. The forced regressive deposits involved in this article are located in the FSST of SQ1 (Figure 1c).

3 Methods

Both multichannel 2D and high-resolution 3D seismic data used for this study were provided by Shenzhen branch of the China National Offshore Oil Corporation (CNOOC) (Figure 1b). The 3D seismic survey covered an area of approximately 3,100 km^2, with a bin size of 12.5 m^2 × 12.5 m^2 in the inline and crossline directions. The frequency bandwidth of the data ranges from 15 to 70 Hz with a dominant frequency of 50 Hz, and the sampling interval is 2 ms. The seismic velocity of the Zhujiang Formation is 3,500 m/s, and the vertical resolution is approximately 15 m. The vertical scale for all the seismic profiles shown in this article is two-way travel time. There are 22 wells involved in this study and all of them possess a complete suite of log and lithology data, including wells which also have core data (Figure 1b). Furthermore, 15 the wells have been drilled in the forced regressive deposits, from which 126 thin sections have been identified and 43 cases have been tested with laser particle analysis. The Langfang Branch Experimental Center of

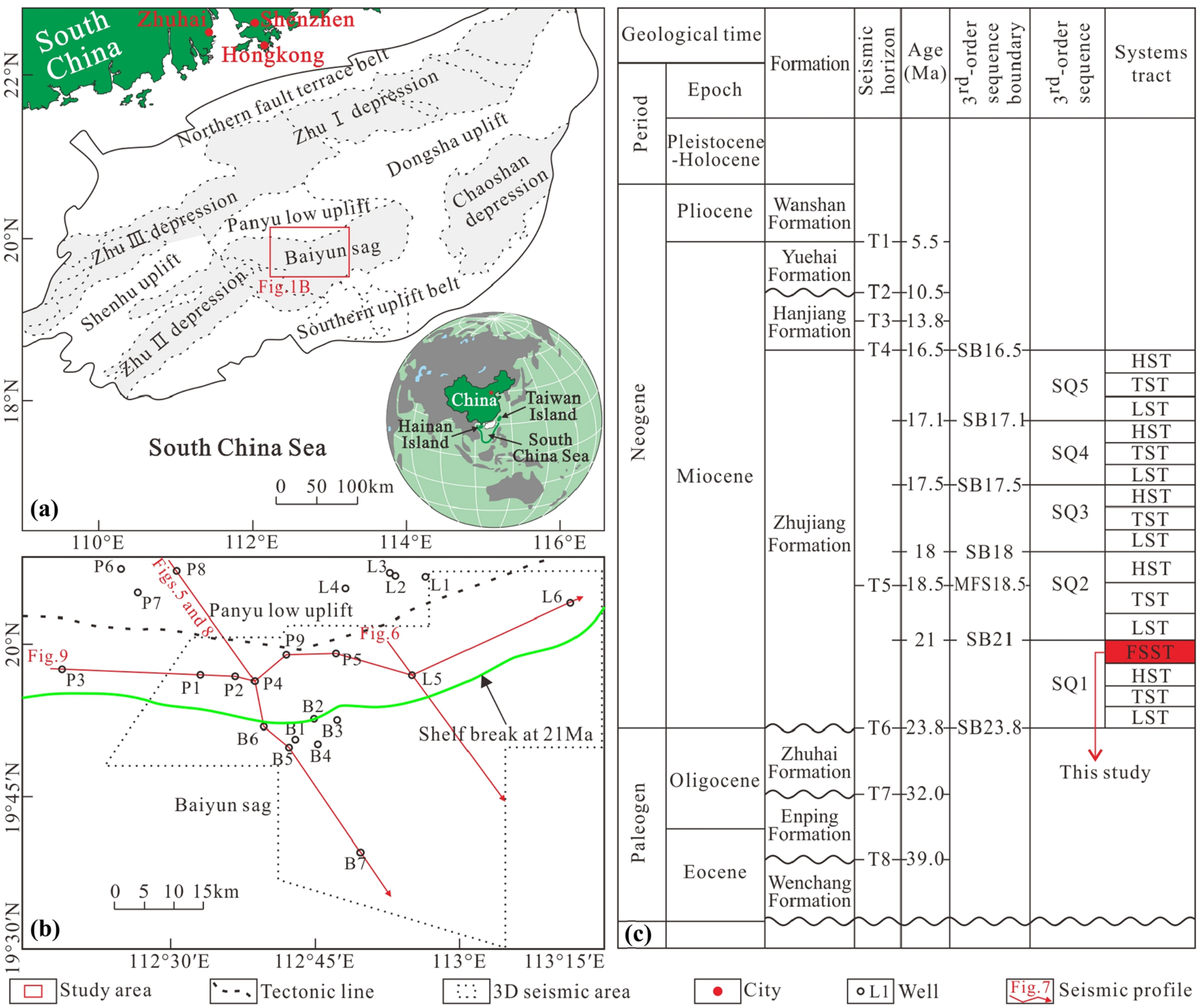


Figure 1: (a) Location map showing the tectonic compartmentalization of the PRMB in the northern South China Sea. (b) The study area located in the Panyu low uplift and Baiyun sag. Note that the forced regressive deposits mainly developed in the northern Baiyun sag. Shelf break at 21 Ma is modified from ref. [12]. (c) Stratigraphic systems of the Baiyun sag. The horizon marked by the red rectangle is the target horizon of this study. Modified after refs [22,23,31,32].

China Petroleum Exploration and Development Research Institute was commissioned to test all the samples mentioned above by Shenzhen branch of the CNOOC.

Grain size distribution characteristics, sedimentary structures, lithofacies and microfacies types of the forced regressive deposits can be determined. Second, aggradation direction and distribution range of the forced regressive deposits can be determined by detailed correlation of connecting-well sections and interpretation of seismic reflection configurations. Then, the distribution characteristics for the forced regression deposits can be determined and a depositional model of forced regression can be summarized.

4 Sedimentary characteristics of forced regression

4.1 Sedimentary facies' features

4.1.1 Petrological characteristics

Core observations from 6 core holes and identification of 126 thin sections together show that the clastic constituents of the forced regressive sandstone of the Zhujiang Formation in this area are mainly quartz and lithics. Rock types of the forced regressive sandstone are mainly

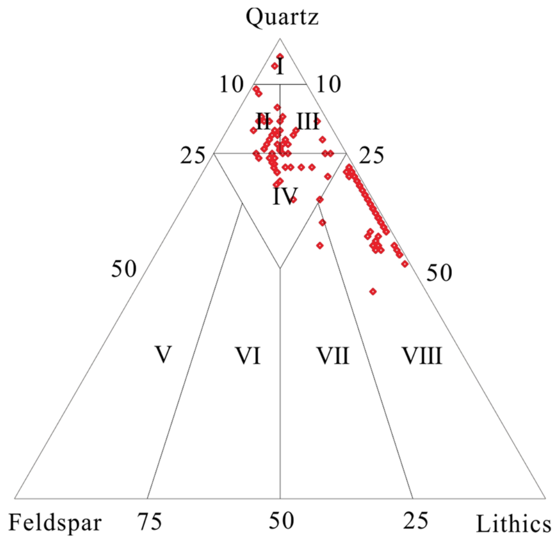


Figure 2: Diagram of sandstone compositional type of forced regressive deposits in Zhujiang Formation of Panyu low uplift and Baiyun sag. The data were collected from 7 wells, 126 thin sections. Note: I-quartz sandstone, II-feldspathic quartz sandstone, III-lithic quartz sandstone, IV-feldspar lithic quartz sandstone, V-feldspar sandstone, VI-feldspar sandstone with rock fragments, VII-lithic sandstone with feldspar, VIII-lithic sandstone.

feldspathic quartz sandstone, lithic quartz sandstone, feldspar detritus quartz sandstone and lithic sandstone (Figure 2). The content of stable minerals is relatively high and the compositional maturity is medium. The quartz content ranges from 45 to 96%, with an average of 69.25%. The quartz/(feldspar + lithics) ranges from 0.82 to 24%, with an average of 2.96%. The distribution range of rock grain size is relatively narrow, with medium sand grain size and poor to medium sorting. The grains are primarily sub-angular and sub-rounded. Weathering degree is moderate and sediment maturity is above middling.

4.1.2 Grain size distribution characteristics

Based on core observations, the grain size distribution characteristics were investigated and show that the lithology is mainly fine and medium sandstone, with a small amount of fine conglomerate, coarse sandstone and silt-stone, and most of the particles are greater than 0 Φ. The grain size accumulation probability curves of the forced regressive deposits are typical two segments or three segments (Figure 3), which are similar to that of the river sediments [34]. The grain size accumulation probability curves of distributary channel deposits in delta plain are mainly two segments (Figure 3a: 3355.07 m) and three segments (Figure 3a: 3359.07 m). The intercept point of saltation population and suspension population is between 1.8 Φ and 3.0 Φ. The content of suspension population is mostly between 15 and 35%, and the content of saltation population is above 65% (Figure 3a). Sedimentary characteristics of traction currents and relatively strong hydrodynamic conditions can be inferred because of a large number of saltation population and a small amount of rolling population. The grain size accumulation probability curves of subaqueous distributary channel deposits in delta front are mainly two segments (Figure 3a, 3372.02 m

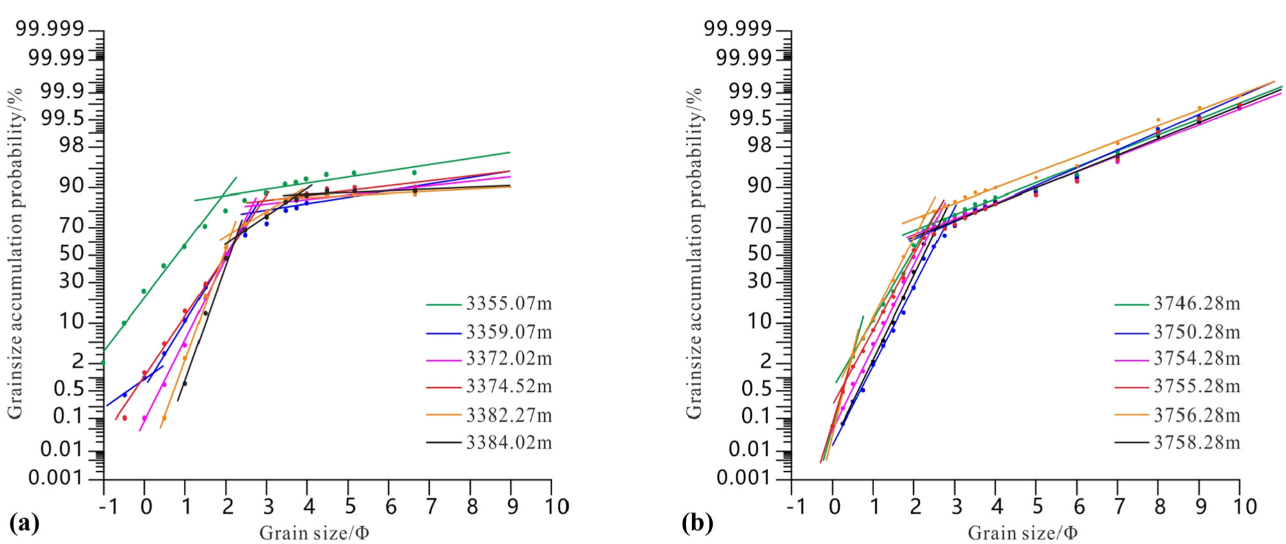


Figure 3: (a) Grain size accumulation probability curves of the forced regressive deposits in well P1. (b) Grain size accumulation probability curves of the forced regressive deposits in well B4.

and 3374.52 m, and Figure 3b, 3750.28, 3754.28, 3755.28 and 3758.28 m). The content of saltation population of the subaqueous distributary channel is mostly between 70 and 75% (Figure 3b). The suspension population of the subaqueous distributary channel are less and only account for about 25% (Figure 3b). Due to the complex hydrodynamic conditions in estuary area, the grain size accumulation probability curves of mouth bar are two segments with transition section and the transition section generally accounts for 10–15% (Figure 3a, 3382.7 and 3384.02 m). That is, when the river enters the sea, the flow velocity decreases and the carrying capacity decreases so that the sands influenced by the resistance of sea water accumulate rapidly. The grain size accumulation probability curves of sheet sand are two segments with double saltation population. The saltation population accounts for 70–80% and are well sorted (Figure 3b, 746.28 and 3756.28 m). It shows that sheet sand is influenced by two-way flow and indicates the sedimentary characteristics of repeated elutriation by wave.

4.1.3 Sedimentary structures

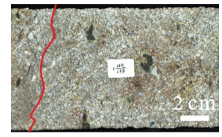
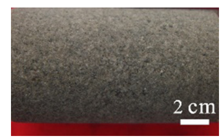
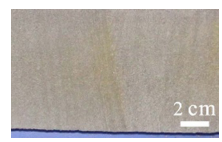
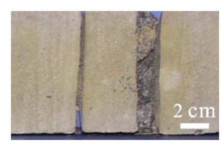
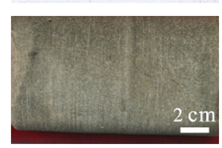
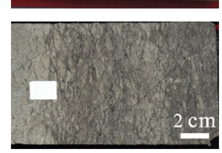
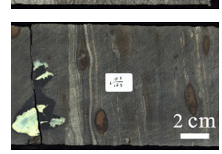
Through detailed core observation and description of six coring wells, a large number of typical sedimentary structures such as plant rhizome fossils, nodules, large-scale oblique bedding (trough cross bedding, tabular cross bedding and wedge cross bedding), small cross bedding, horizontal bedding, scouring structure, biological disturbance structure and contemporaneous deformation structure can be found in the forced regressive deposits (Table 1 core photo). Oblique bedding, parallel bedding and scouring structures indicate the strong hydrodynamic mechanism of a traction current. Above the scouring surface, there are gray-white elliptical fine gravels and gray-green flat claystone gravel which are formed by strong erosion under strong hydrodynamic conditions, indicating the channel sedimentary environment dominated by a high-energy traction current. The small-scale cross bedding which is not well developed in the study area reveals a sedimentary environment under the interaction of waves and currents. Horizontal bedding which are formed by deposition of suspended matter indicates a stable sedimentary environment with a weak hydrodynamic force [34]. The horizontal bedding is generally formed in interdistributary bays and prodelta, and occasionally can be found in the upper part of the abandoned channel deposits. Bioturbation structures are mainly developed in siltstone and mudstone. The original bedding characteristics are not clear due to strong bioturbation. Horizontal burrows are abundant, which represent a sedimentary environment with relatively deep water and weak energy [34]. The contemporaneous deformation structures which usually occur in the slope area under the shelf break of forced regressive deposits mainly include rumpled structures, slump structures, water escape structures and muddy strip deformation. It is an indication not only for the rapid accumulation of siltstone and mudstone but also for the instability of sedimentary body under rapid regression.

4.1.4 Lithofacies and lithofacies' associations

According to core observations and lithological statistics, its lithology mainly includes fine sandstone, siltstone, argillaceous siltstone, siltstone mudstone and mudstone. Conglomerate and medium-coarse sandstone are also relatively abundant. According to rock fabric, the lithofacies can be divided into 4 types: conglomerate, sandstone, siltstones and mudstone, and further divided into 11 subtypes. The specific characteristics and genesis are shown in Table 1.

Lithofacies is the sum of rock characteristics formed under certain energy conditions, also known as energy unit. It mainly reflects the hydrodynamic conditions in the process of sand body formation of each sedimentary genetic unit based on the characteristics of lithology and sedimentary structure. It is the basic material entity to understand the sedimentary environment and analyze the hydrodynamic conditions of sedimentary water [35–37]. Based on the analysis of the lithofacies characteristics, combined with the core description of the coring interval, six types of lithofacies' associations have been summarized (Figure 4): (1) the distributary channel microfacies are dominated by large oblique bedding and its lithology are mainly gravel-bearing coarse sandstones and medium sandstones. The thickness of the sand body is 15–30 m, and the mud gravel is visible at the bottom. The natural gamma-ray curve is of cylinder shape. The lithofacies are massive bedded conglomerate, trough cross bedded conglomerate, tabular cross bedded conglomerate and parallel bedded sandstone. (2) The floodplain microfacies are dominated by massive bedding and its lithology is mainly mudstone and argillaceous siltstone. The natural gamma-ray curve is linear shape and the lithofacies are massive bedded mudstone and horizontal bedded siltstone. (3) The subaqueous distributary channel microfacies are dominated by oblique bedded medium and fine sandstone. The grain size gradually becomes fine upward. The natural gamma-ray curve is cylinder or bell shaped.

Table 1: Lithofacies division of forced regressive deposits in Zhujiang Formation of the PRMB

Lithofacies types		Sedimentary characteristics	Core photo	Genetic interpretation
Conglomerate facies	Conglomerate facies of massive bedding (Gm)	Granule conglomerate with mixed grain size is arranged in orientation		Lag deposits at the bottom of the channel
	Conglomerate facies of oblique bedding (Go)	Granule conglomerate, tabular cross bedding or trough cross bedding, grain with directional arrangement		Filling deposits in large distributary channels
Sandstone facies	Sandstone facies of massive bedding (Sm)	Medium-fine sandstone, with graded bedding and most calcareous cements		Sediments accumulate rapidly in high-energy unidirectional flow
	Sandstone facies of oblique bedding (So)	Fine sandstone, tabular cross bedding or wedge cross bedding with uniform grain size		Formation of sand dune migration in high-energy unidirectional flow
	Sandstone facies of parallel bedding (Sp)	Fine sandstone with uniform grain size		High flow regime, shallow flow and rapid formation, mainly vertical accretion
	Sandstone facies of small cross bedding (Ssc)	Siltstone-fine sandstone with uniform grain size		Formation of sand dune migration in unidirectional medium-low energy flow
	Sandstone facies of deformation structure (Sd)	Siltstone-fine sandstone, argillaceous strip with rumpled structure and slump structure		Formed in the subaqueous instability environment of delta front
Siltstone facies	Siltstone facies of horizontal bedding (SIh)	Siltstone or argillaceous siltstone with argillaceous strip		Flat terrain conditions, products of low-energy unidirectional flow
	Siltstone facies of bioturbation (SIb)	Siltstone or siltstone-fine sandstone, heavily bioturbated		Relatively low flow regime or low hydrodynamic environment
Mudstone facies	Mudstone facies of massive bedding (Mm)	Gray or red-brown mudstone with iron nodules, charcoal chips and sandy strips		Formed in low-energy or shallow water environments such as floodplain
	Mudstone facies of horizontal bedding (Mh)	Gray-black or black mudstone with charcoal chips		Formed in low-energy environment of static water such as distributary bay

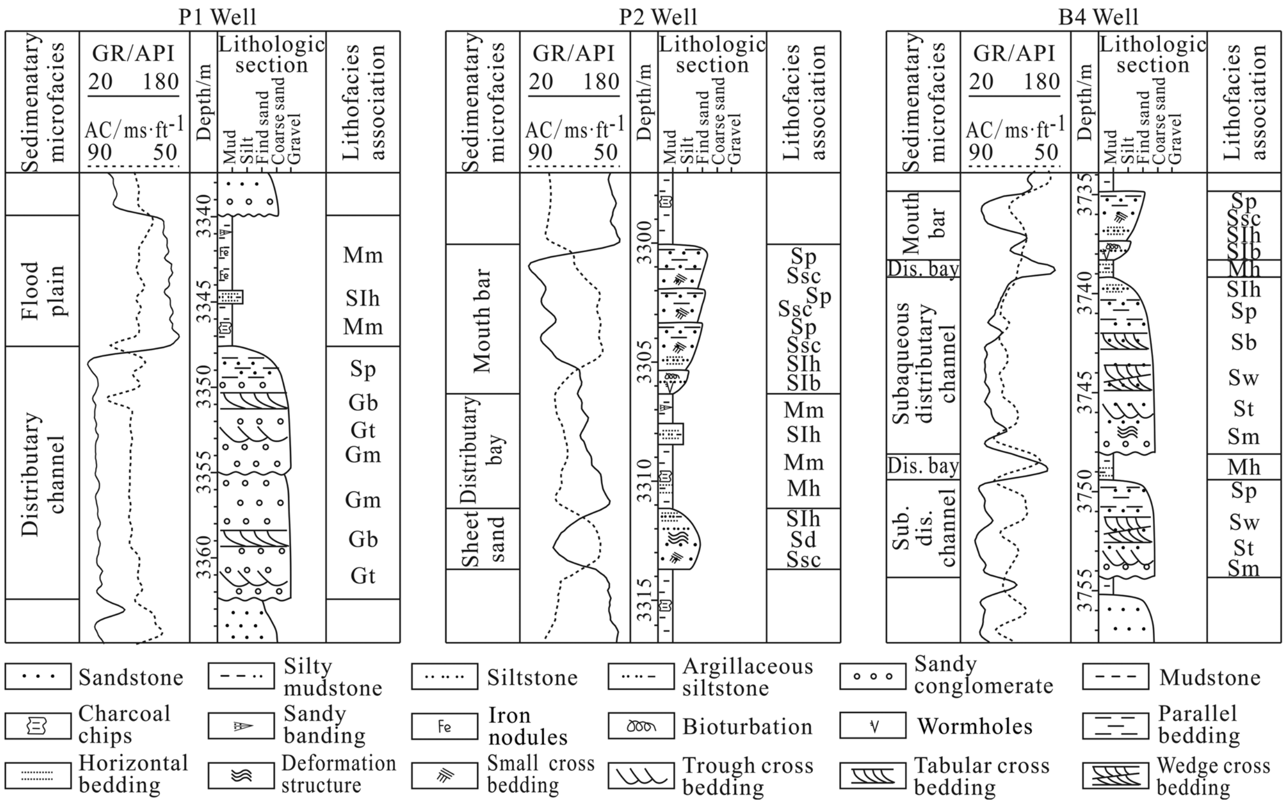


Figure 4: Lithofacies association of forced regressive deposits in Zhujiang Formation of Panyu low uplift and Baiyun sag. Abbreviations: Gm – conglomerate facies of massive bedding; Gt – conglomerate facies of trough cross bedding; Gb – conglomerate facies of tabular cross bedding; Sp – sandstone facies of parallel bedding; Sm – sandstone facies of massive bedding; St – sandstone facies of tabular cross bedding; Sw – sandstone facies of wedge cross bedding; Sb – sandstone facies of tabular cross bedding; Ssc – sandstone facies of small cross bedding; Sd – sandstone facies of deformation structure; SIh – siltstone facies of horizontal bedding; SIb – siltstone facies of bioturbation; Mm – mudstone facies of massive bedding; Mh – mudstone facies of horizontal bedding; Sub. – subaqueous; Dis. – distributary.

Lithofacies are massive bedded sandstone, trough cross bedded sandstone, tabular cross bedded sandstone, wedge cross bedded sandstone, parallel bedded sandstone and horizontal bedded siltstone. (4) The microfacies of the mouth bar whose grain size gradually coarsens from bottom to top are dominated by parallel bedded siltstone and fine sandstone. The natural gamma-ray curve is of funnel shape. Lithofacies are biologically disturbed siltstone, horizontal bedded siltstone, small cross bedded sandstone and parallel bedded sandstone. (5) The sheet sand microfacies are dominated by small cross bedded siltstone and fine sandstone. The natural gamma-ray curve shows egg shape. Lithofacies are small cross bedded sandstone, deformed sandstone and horizontal bedded siltstone. (6) The distributary bay microfacies are dominated by horizontal bedded mudstone and argillaceous siltstone. The natural gamma-ray curve is of linear shape. Lithofacies are horizontal bedded mudstone, massive bedded mudstone and horizontal bedded siltstone.

4.1.5 Seismic facies characteristics

Seismic facies are not only the 3D spatial seismic reflection units which are defined by specific external geometry, internal structural characteristics and top-bottom contact relations, but also the seismic responses of specific sedimentary facies or geological bodies [38]. The external geometry of the forced regressive deposits in the west of the study area is a mound according to the seismic profile (Figure 5). The thickness of the seismic facies unit of forced regression changes from thin to thick and then to thin in the palaeoflow direction. The seismic facies unit present a progradational reflection configuration in the palaeoflow direction (Figure 5). In the early stage of forced regression, the internal structure is characterized by low-angle S-type progradational reflections, and features indication of topset, foreset and bottomset beds can be identified (① and ② in Figure 5). In the later stage of forced regression, the internal structure is characterized by high-angle oblique progradational

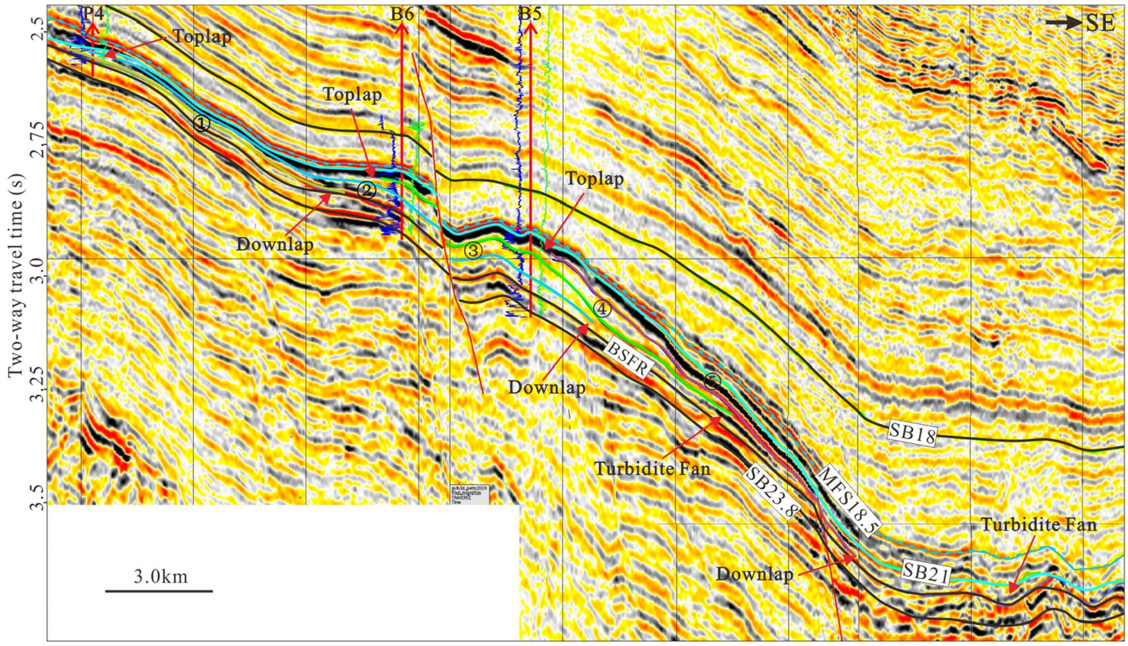


Figure 5: Seismic reflection characteristics of forced regressive deposits in Zhujiang Formation of the western Panyu low uplift and Baiyun sag. (location of section is given in Figure 1b). BSFR-basal surface of forced regression.

reflections, and lacks topsets and develops only foresets and bottomsets, showing the characteristics of the shelf-edge delta (③, ④ and ⑤ in Figure 5). The seismic termination for the top boundary of the forced regression (SB21) shows a toplap and the boundary is characterized by exposure and erosion of the sequence boundary.

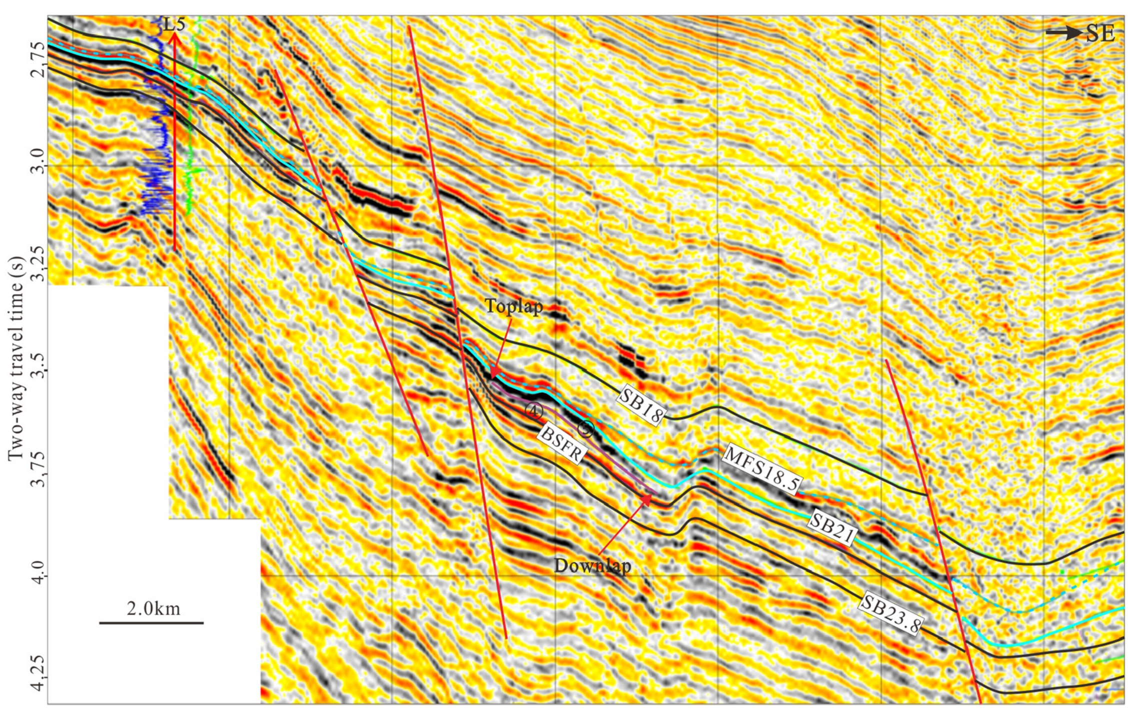


Figure 6: Seismic reflection characteristics of forced regressive deposits in Zhujiang formation of the eastern Panyu low uplift and Baiyun sag (location of section is given in Figure 1b).

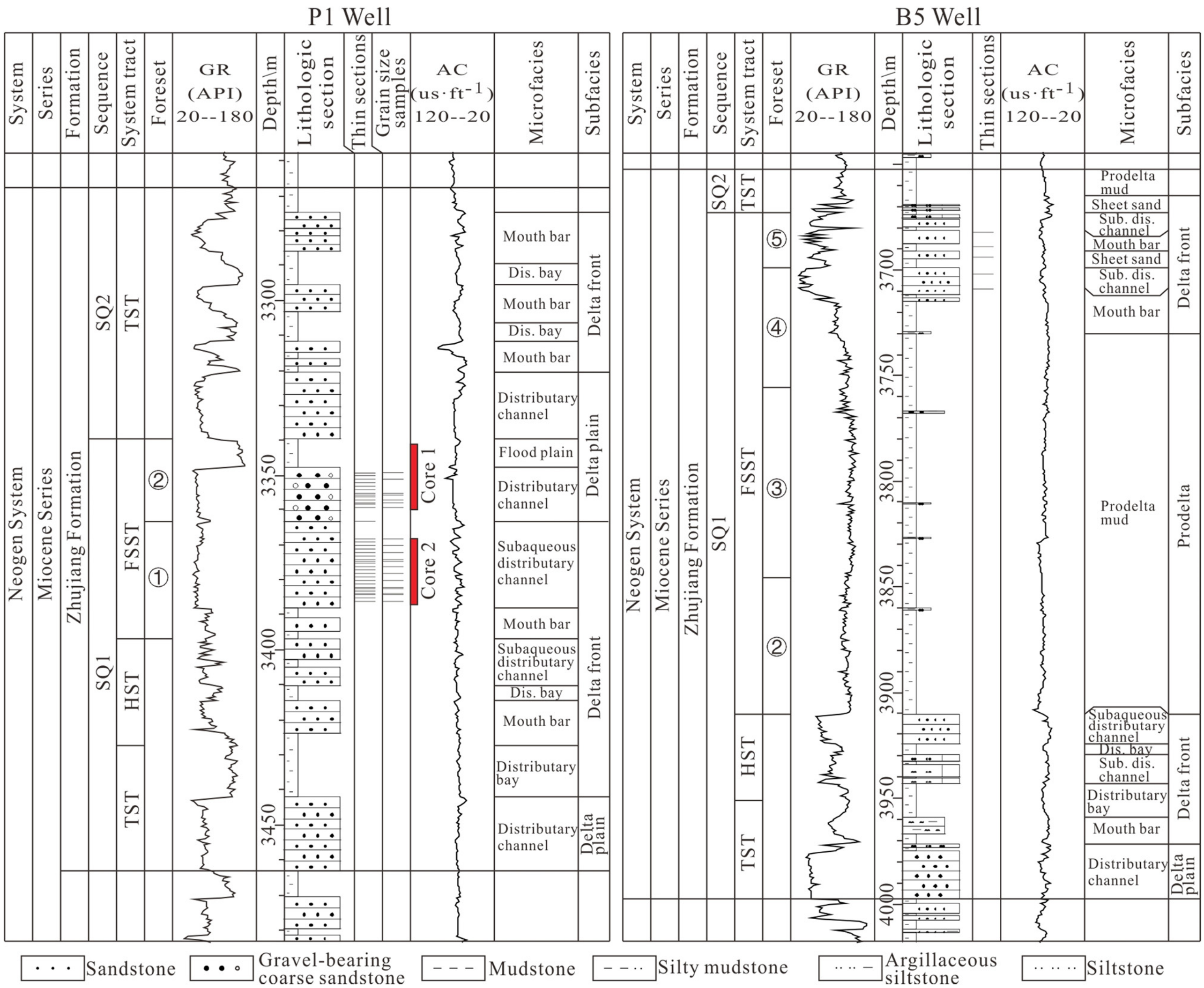


Figure 7: Sedimentary facies of forced regressive deposits in Zhujiang Formation of Panyu low uplift and Baiyun sag. Note the well P1 is above the shelf break at 21 Ma and landward, the well B5 is below the shelf break at 21 Ma and seaward.

However, the seismic termination for the basal surface of forced regression (BSFR) shows a downlap and the surface is characterized by stratigraphic integrity (Figure 5). The upper part of the forced regressive deposits has a high amplitude seismic reflection which infers delta plain and front sediments with a high sand content, while the middle-lower part presents disordered and low amplitude seismic reflections which infer prodelta sediments dominated by argillaceous sediments. In addition, high amplitude reflection structures can be seen at the bottom and its external geometry is fan type, which infers gravity flow turbidite fan deposition (Figure 5).

The external geometry of the forced regressive deposits is a mound in the east of the study area, but the internal reflection structure changes significantly (Figure 6). In the early stage of forced regression, due to the rapid decline in relative sea level, the depositional thickness is relatively thin, so the low-angle S-type progradational reflections are absent. Foresets are merged into a very thin layer, and the seismic resolution cannot be differentiated. In the later stage of forced regression, high-angle imbricate progradational reflections are seen, topsets are absent, and the bottomsets are not obvious. This is different in the sedimentary characteristics of the shelf-edge delta in the west part of the study area. The foreset is presumed to reflect longshore bar deposits because it is only 3 km long in the palaeoflow direction (Figure 6).

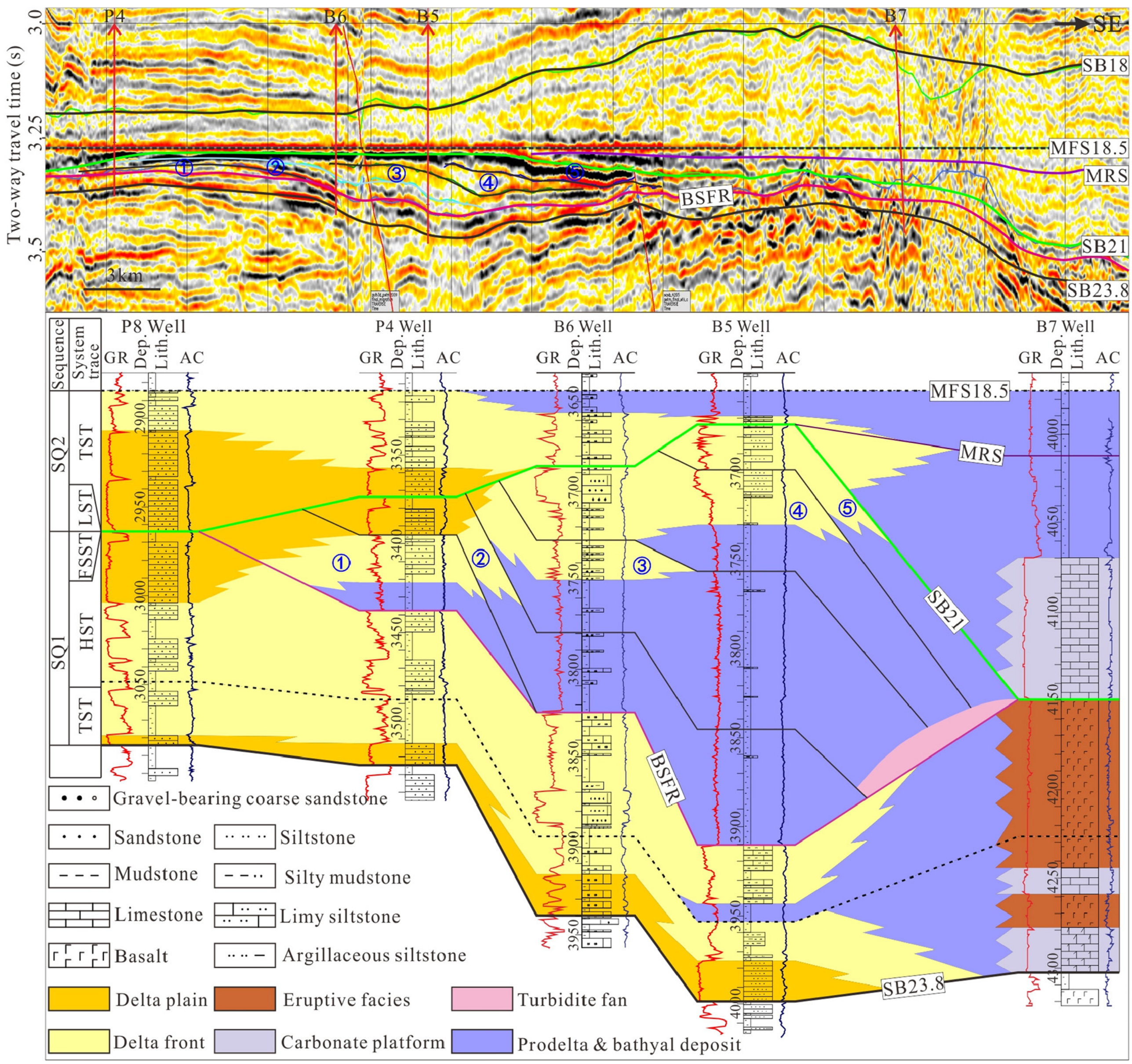


Figure 8: Sedimentary characteristics of cross-well correlation section in the palaeoflow direction (location of section is given in Figure 1b). FSST – falling stage systems tract, LST – lowstand systems tract, TST – transgressive systems tract, HST – highstand systems tract, BSFR – basal surface of forced regression, MRS – maximum regressive surface, MFS – maximum flooding surface, Dep. – depth/m, Lith. – lithology.

4.2 Sedimentary microfacies composition and sedimentary characteristics of cross-well correlation section

The information revealed by core observation of 6 wells, logging data of 22 wells and 3D seismic data is as follows. The forced regression deposits in the Zhujiang Formation are mainly shelf-margin deltas, followed by turbidite fan and longshore bar deposits. Because both the turbidite fan and longshore bar have not been met during drilling, sedimentary microfacies analysis has not been carried out and only seismic characteristics have been examined. Further, the typical subfacies of the shelf-margin delta are delta front and prodelta, while the delta plain which only exists in the early stage of forced regression is not well developed. The main microfacies types are distributary channel, floodplain, subaqueous distributary channel, mouth bar, sheet sand, distributary bay and prodelta mud (Figure 7).

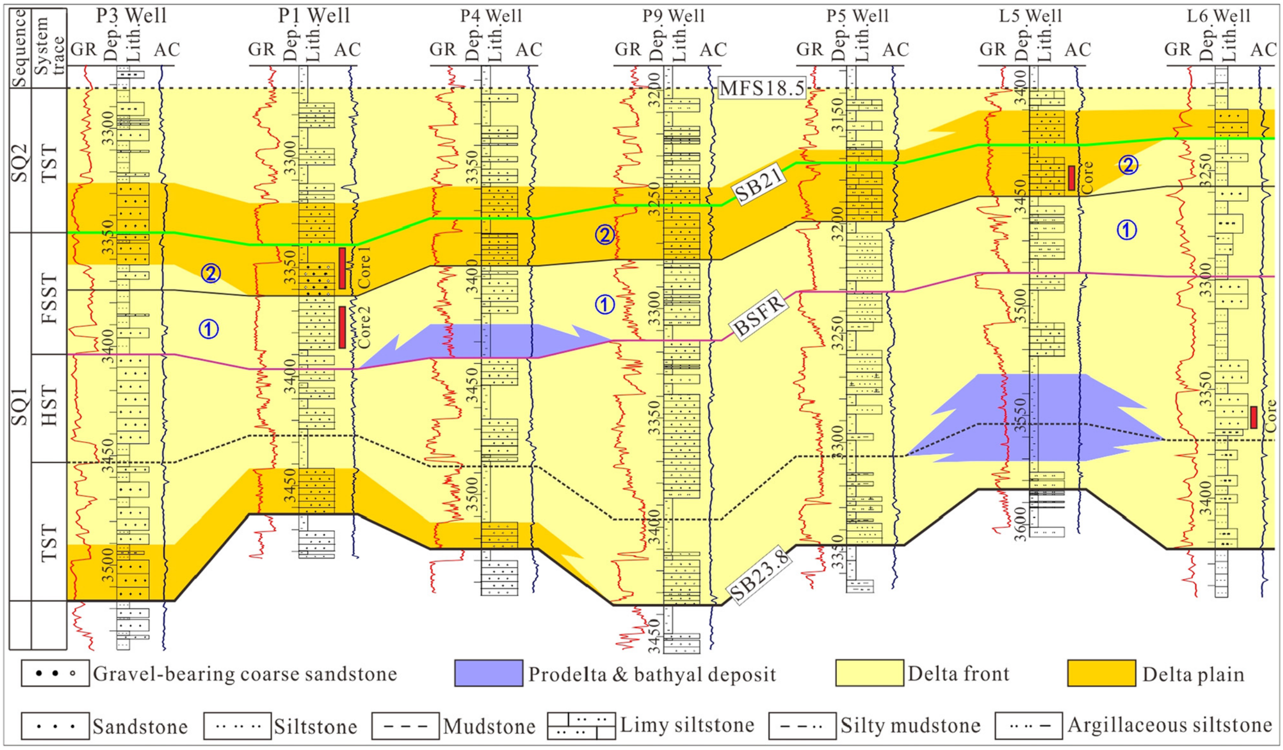


Figure 9: Sedimentary characteristics of cross-well correlation section which is perpendicular to the palaeoflow direction (location of section is given in Figure 1b). FSST – falling stage systems tract, LST – lowstand systems tract, TST – transgressive systems tract, HST – highstand systems tract, BSFR – basal surface of forced regression, MFS – maximum flooding surface, Dep. – depth/m, Lith. – lithology.

On the basis of analysis of sedimentary microfacies of single well and the identification and division of foresets in seismic profile, two well-connected sedimentary facies profiles (one parallel to the palaeoflow direction and the other perpendicular to it) have been compiled with the help of cuttings logging data and logging curve data. In the early stage of forced regression, delta plain, delta front and prodelta deposits are developed in turn in the palaeoflow direction and the seismic profiles are characterized by low-angle S-type progradational reflections (① and ② of Figure 8). In the later stage of forced regression, delta front and prodelta deposits are developed in the palaeoflow direction and seismic profiles present high-angle oblique progradational reflections. Turbidite fan high amplitude reflections are developed in the direction of downdip of the delta front (③, ④, and ⑤ of Figure 8). Perpendicular to the palaeoflow, the profile is located in the landward direction of the shelf break where it is relatively close to the source and its sediments are mainly formed in the early stage of forced regression (Figure 9). Two sets of foreset deposits were developed. Foreset ① is mainly a delta front in this profile, and prodelta is developed near the lower part of well P4 which is in the middle of the profile. Foreset ② is mainly a delta plain in the profile and is transitional to a delta front on both sides (Figure 9). During the 21 Ma period of Zhujiang Formation in the PRMB, 5 sets of foreset were developed, which showed the superposition process of 5 sets of shelf edge deltas retreating to the sea in turn.

4.3 Distribution characteristics of sedimentary systems via seismic attribute analysis

The root mean square amplitude attribute can differentiate the sand zone and shale zone, and is helpful for demarcating the transitional boundary of different sedimentary facies zones [36,39,40]. In order to confirm the existence of longshore bar perpendicular to the source area and further determine the distribution characteristics of shelf-edge delta and gravity flow turbidite fans, root mean square amplitude attributes are extracted 30 ms downward from the SB21 which is the upper interface of falling stage systems tract (Figure 10b), 30 ms upward from the basal surface of forced regression (Figure 10c), and top and bottom of the whole falling stage systems tract

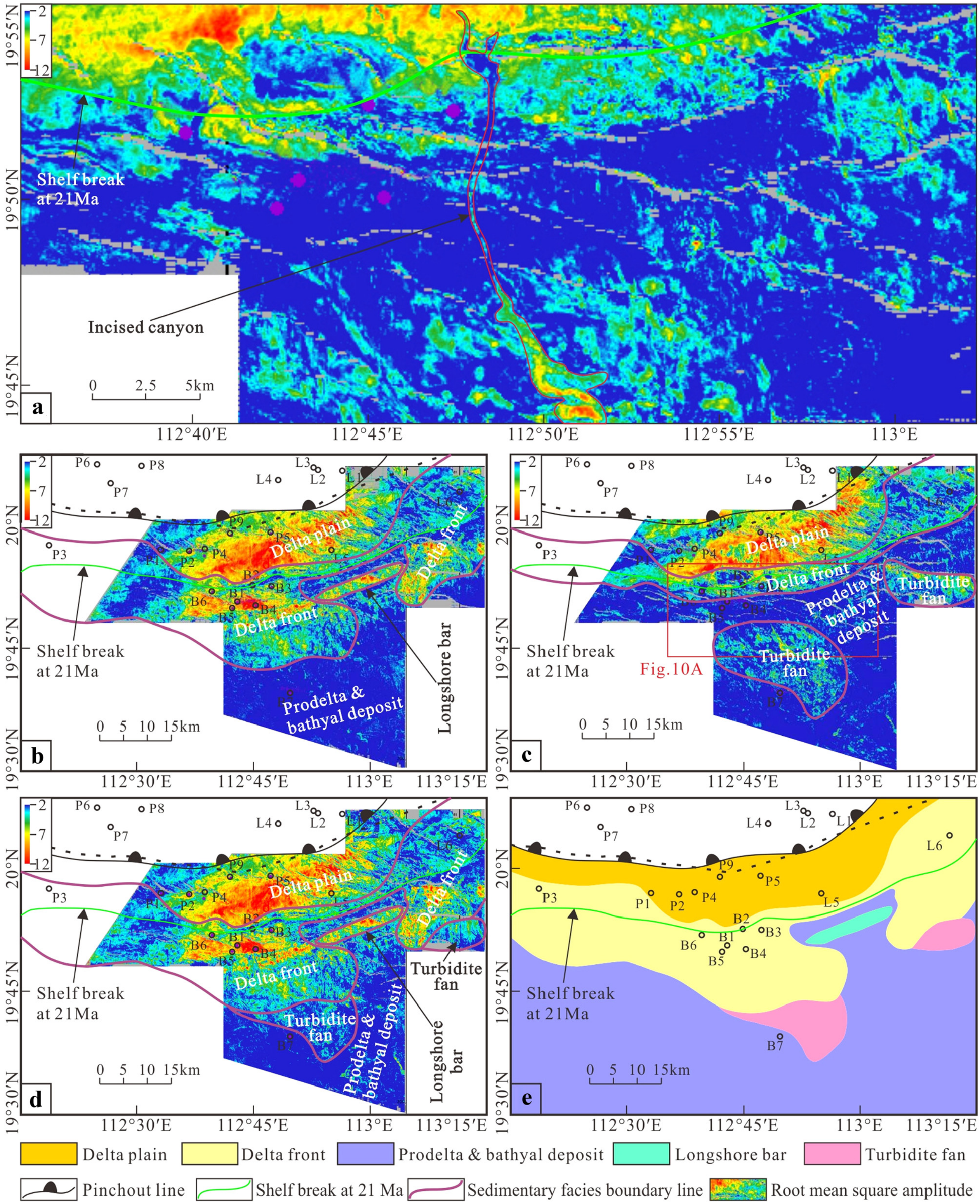


Figure 10: (a) Incised canyon developed in the slope area. Note the local amplification of root mean square amplitude attribute in (b). (b) Root mean square amplitude attribute extracted 30 ms downward from the SB21 which is the upper interface of falling stage systems tract. (c) Root mean square amplitude attribute extracted 30 ms upward from the basal surface of forced regression. (d) Root mean square amplitude attribute extracted from the falling stage systems tract. (e) Distribution characteristics of sedimentary facies in the falling stage systems tract.

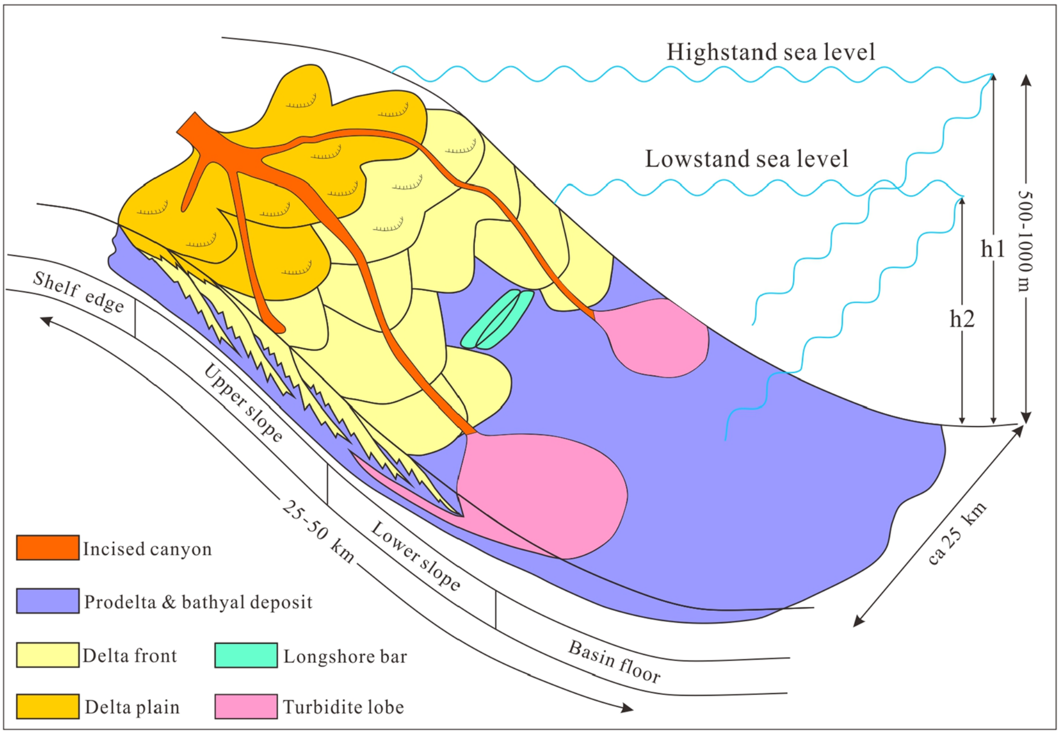


Figure 11: Depositional model of forced regression in the Miocene Zhujiang Formation of the PRMB, northern South China Sea.

(Figure 10d). It can be seen from Figure 10b that the root mean square amplitude is higher in the landward margin of the shelf break at 21 Ma, and the drilling reveals delta plain deposit. There are two large high amplitude lobe bodies and a long strip-shaped high amplitude anomaly (length 15 km, width 3 km) in the seaward margin of the shelf break at 21 Ma, and two shelf-edge delta fronts and longshore bar deposits are present. It can be seen from Figure 10c that the root mean square amplitude ranges from high to low at the landward margin of the shelf break at 21 Ma, which infers the sedimentary characteristics of the delta plain and delta front. There is a zone with a low amplitude in the seaward margin of the shelf break at 21 Ma. Where the two shelf-edge delta fronts develop, two lobate areas with relatively higher amplitudes are located. The place where delta plain sand bodies developed in the early stage of forced regression are linked to incised canyon channels (Figure 10a). The lower part of the foreset near the bottom of the forced regression deposit is the prodelta argillaceous deposit, while the upper part of the foreset near the top of the forced regressive deposit is the sand-rich delta front deposit, and the gravity flow turbidite fan deposit often develops in the front of the shelf-edge delta which is close to the center of the basin (Figure 10e).

5 Depositional model of forced regression

Based on the sedimentary background, development process, sedimentary characteristics and sedimentary facies types, a depositional model of forced regressive deposits can be established (Figure 11). (1) As relative sea level descends from highstand to lowstand, the sediment is forced to undergo progradation, and five sets of foreset delta deposits are developed in turn. (2) The forced regression is affected by a slow decline in sea level in the early stage, resulting in deposition of the delta plain, delta front and prodelta. (3) In the later stage of forced regression, due to a rapid decline in sea level, shelf-edge deltas with only delta front and prodelta and longshore bars constructed by waves are developed. (4) Gravity flow turbidite fans develop in a downdip direction on the front of the shelf-edge delta because of rapid sediment accumulation and instability. (5) The gravity flow turbidite fan communicates with the sand-rich source area in the delta plain in the edge of the continental shelf through an incised canyon channel. This model reveals the distribution role of sand bodies of the shelf-edge delta and longshore bar and the basal surface of forced regression (the sand bodies of the gravity flow turbidite fan). The sand bodies formed by the falling stage systems tract are directly covered on the shallow sea mudstone of the highstand systems tract, and then covered by the dark mudstone formed by the transgressive and highstand systems tract of the later sequence. It has favorable oil generation conditions, reservoir sites and caprock plugging, and is a favorable place for the formation of large oil and gas reservoirs.

6 Conclusion

The sedimentary characteristics and depositional model of forced regression of the Miocene Zhujiang Formation in the PRMB, northern South China Sea, were analyzed systematically with the help of core, slice and particle size analysis test data of 6 wells, logging data of 22 wells and 3D seismic data of about 3,100 km^2. The major conclusions of this study about forced regressive deposits are as follows:

(1) The forced regressive deposits of the Zhujiang Formation developed when relative sea level ranged from highstand to lowstand, and five sets of foreset delta deposits were developed in turn.
(2) In the early stage of forced regression, normal delta deposits of the topsets, foresets and bottomsets developed.
(3) In the later stage of forced regression, the shelf-edge delta, longshore bar and turbidite fan deposits were developed. Further, the shelf-edge delta developed only the delta front and prodelta but not the delta plain.
(4) The favorable reservoir sand bodies are located near the top and bottom interfaces of the sedimentary body. They are shelf-edge delta front sandstones, longshore bar sand bodies along the shelf break, and turbidite fan sand bodies on the lower slope.

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