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Discovery of Deep-water Fan System in Pearl River Mouth Basin, South China Sea

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Introduction

Pearl River Mouth Basin (PRMB), located at the northern continental margin of South China Sea, is a Cenezoic passive continental margin rift basin with acreage of 175000km^2. In the northern part of the basin, sets of stacked shelf delta/strand arenaceous-pelitic depositions of highstand and transgression systems tract were developed due to abundant detritus supply of paleo-Pearl River and frequent eustatic changes. These sandstones already became the most important pay zones of PRMB. Up till now, more than 100 exploration wells have been drilled, approximate 6×10^8 tons OOIP have been discovered in neritic shelf (Zhu 1 Depression). Today, with 12 oil fields yielding an annual oil production of more than ten million tons for 5 straight years, PRMB has already become an important offshore oil-producing base. The success of exploration confirms that PRMB is a Cenozoic basin with great petroleum potential. However, the Baiyun Sag at Zhu 2 Depression, the largest sub-basin with the thickest sediments and the greatest potential in hydrocarbon generation, has not achieved any important discoveries due to deep water and sparse exploration. In recent years, sequence stratigraphic studies have been performed in PRMB. A large number of stacked lowstand deep-water fan systems are found in Baiyun Sag with water depth ranging between 500 and 2000m. The discovery of deep-water fan systems creates a new region for petroleum exploration in PRMB.

1. General Geology

PRMB can be divided into three tectonic units. The North Depression Belt consists of Zhu 1 and Zhu 3 sub-basins; the Central Uplift Belt is made of Shenhu Massif, Panyu Low Uplift and Dongsha Massif; and the South Depression Belt consists of Zhu 2 and Chaoshan Sub-basins. The Tertiary formation includes the Upper and Lower Tertiary sequence, which is separated by seismic reflection event T7 interpreted as unconformity interface. In Early Tertiary, there existed a number of strongly separated rifts, in which deposited the fluviolacustrine facies of Wenchang and Enping Formation. The thickness of these formations, the main source rocks of the basin, is generally about 3000 m. Among the rifts, the Baiyun Sag is the largest sub-basin with acreage of 13300km^2, and the thickness of Lower Tertiary sedimentary rocks is over 5000m. The Upper Tertiary formation is post-rifting marine facies deposition, which is consisted of Zhuhai-Zhujiang, Yuehai and Wanshan Formations.

The North Depression Belt and Central Uplift Belt evolved into a broad and flat shelf since the Nanhai Movement and erosional truncation (T_7 unconformity). While in the southern part of the basin, which is at the dip direction of the paleo-Pearl River, Baiyun Sag evolved into slope or abyssal basin controlled by persistent geothermal subsidence, and formed an ideal depositional place for lowstand systems tract during sea level falling. The thickness of Upper Tertiary marine sediment (6000 m) is about two times as thick as Zhu 1 Depression's. This explains the persistent subsidence and formation of depositional sequential accommodation space within Baiyun Sag, and it also tells the story about how a great amount of detrital matters of paleo-Pearl River accumulated in the deep-water Baiyun Sag.

2. Discovery of Deep-water Fan system

The Deep-water fan system of South China Sea, generally speaking, implies the Upper Tertiary deep-water sediments distributed over the vast offshore regions of the sea. The major part of deep-water fan system is the transitional zone between paleo-shelf and slope, distributed at Zhu 2 Depression of PRMB. The deep-water fan system is densely distributed in a belt within an area of 150×45Km. . Currently, the water depth is 200~2000 m.

The discovery of deep-water fan system was based on three large-scale seismic surveys conducted since 1979. In 1999, through re-understanding and re-interpretation of sequence stratigraphic framework and characteristics of deep-water sedimentation, based on high-resolution, high-fidelity, and high ratio of information to noise seismic data processing, it finally led to the discovery of a possible brand-new type of trap, of which reservoirs are sandstones within the deep-water fan system.

2.1 Identify the sequence stratigraphy

Sequence identification is the basis for the sequence stratigraphic research. The key marks for the identification and division of sequence stratigraphy are based mainly on these existences: downward transfusion of coastal onlap (sea level falling), basin-ward transfusion of sedimental facies, rejuvenation of river (incised valley and its filling), and shelf break (growth faulting, basin-floor fans, slope fans, slump bodies, …). Beside these, more complementary signs are also useful for the identification of sequence stratigraphic boundary.

A systematic bio-stratigraphy and sedimentary environment study, of 50 wells located in Zhu 1 Depression, had been conducted several years ago. As part of the study, the high-precision quantitative examination of paleo-biology established the bio-chronologic framework; meanwhile, the paleo-environmental analysis discovered the existences of sea level cyclic changes. The research of sequence identification, based on high-resolution seismic profiles, found that there were 7 Sequence boundaries from 21 Ma to 10.5 Ma, a good concordance in eustatic changes with global events discovered. This establishes an important foundation for the discovery of incised valley, and further for the systematic study of the lowstand systems tract in Baiyun deep-water Sag, Zhu 2 Depression.

2.2 Discovery of incised valley

The analysis of typical high-resolution seismic profiles shows that the related sedimental units of lowstand systems tract, developed at the south of seismic line 87EC2435 in Baiyun deep-water Sag, include important units such as incised valley, basin-floor fan (mound seismic reflection configuration), slope fan, and lowstand prograding complex. Detailed description as followed:

- Seismic line 87EC2435 (NEE direction seismic line, perpendicular to paleo-Pearl River delta system, parallel to paleo-shelf). No incised valley was identified.
- Seismic line 86EC2485A (NEE direction seismic line, parallel to and 3.6km south of above line). A few incised valleys and their filling were discovered.
- 2.5km further south, seismic line 95EC2442 (Fig 1, NEE direction seismic line, parallel to above line) More incised valleys were identified:
- 2.5km further south, seismic line 86EC2444 (Fig 1, NEE direction seismic line, parallel to above line), Great amount of incised valleys induced by rejuvenation have been discovered.
- According to the statistics from seismic line 86EC2444, there are 3 incised valleys with width of 1500~6500 m and depth of 150m~300 m. There are 12 incised valleys with valley depth of 75~150m, average width of 2500m. Under the current standard, considerable scale of incised valleys, rejuvenation and its transportable ability are astonishing.
- Further south from seismic line 86EC2444, across the growth fault belts and enter into the slope zone, great canyons connected with incised valleys were identified.

2.3 The formation of deep-water fan system

Discovery of incised valleys promoted comprehensive studies on lowstand systems tract in Zhu 2 Depression. Until now, the project, a key one supported by National Natural Science Foundation of P. R. China, is still in progress.

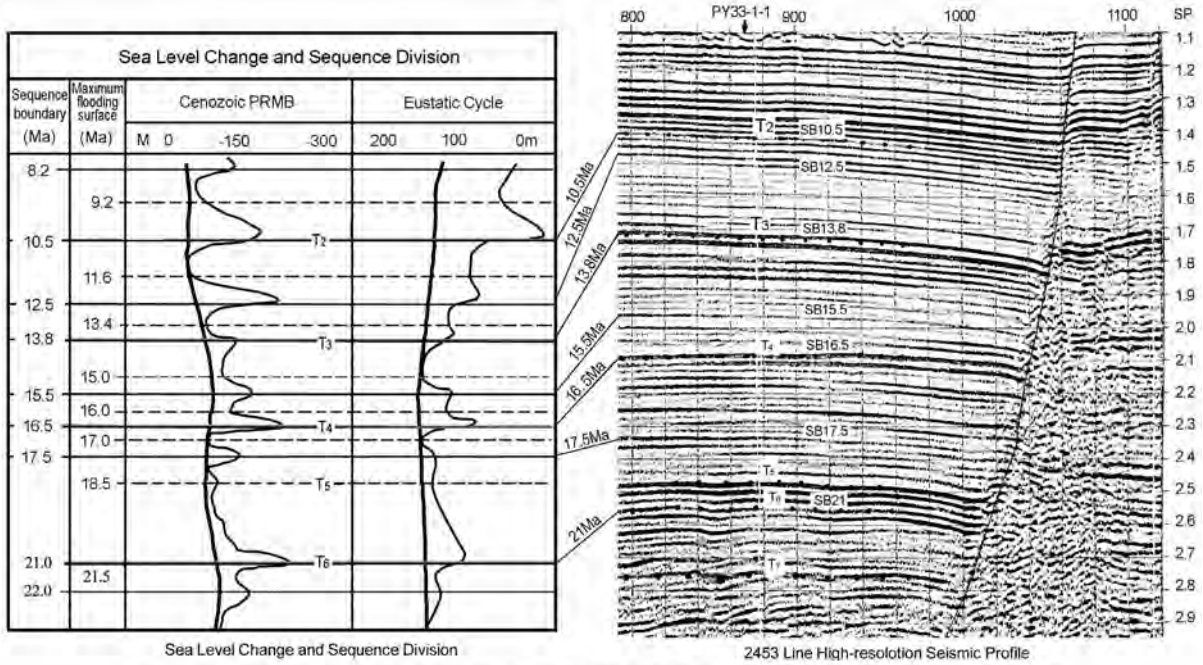

Figure 1 Eustatic Change of Cenozoic Zhu 1 and Global Cycle, Comparision between Eustatic Cycle and high-resolution Seismic Profile in Zhu 2, PRMB (after Yang, 1998)

During periods of relative sea level falling, paleo-Pearl River, carrying huge amount of clastic sediments, crossed Zhu 1 Depression and Panyu Low Uplift, flowed into Baiyun Sag. It formed a great scale of lowstand systems tract there. The location of paleo-continental shelf break is considered to be at the same place as today's continental shelf, roughly at the northern margin of Baiyun Sag. The thickness of total sedimentary stratums of Baiyun Sag between 21 Ma to 10.5 Ma reaches 4000m, much thicker than the northern continental shelf areas' (1800m) at corresponding periods. Persistent subsidence of the sag not only developed massive lowstand depositions, but also created accommodation spaces, maintained deep-water environment and promoted growth faulting belts at the same time. And it further brought up lowstand systems tract of different sequences stack vertically at some particular areas of Baiyun Sag, thus formed the deep-water fan system. Therefore, cyclic fall of sea level, huge sediment inputs from paleo-Pearl River in lowstand stages and persistent subsidence of the sag are the principle contributors to the development of great scale lowstand fans, and are also the factors that lowstand fans of different sequences are vertically stacked.

3. Seismic face configurations and deep-water depositional environment

Study of seismic face complex of high-resolution seismic profiles gradually expands the research on typical seismic face complex, started after the discovery of incised valley and its fillings, to systematic research ranging over the whole basin. Elementary outcome reveals distribution characteristics of paleo-continental shelf, shelf break, slope and deep-sea basin over different sequence development, especially characteristics of deep-water fan system at different lowstand tracts. Further studies are going to be related to more seismic exploration researches and combined with gravity and magnetic. Systematic and miscellaneous research works are still underway with more results will be achieved later. However, some key points could be introduced beforehand.

3.1 Type of seismic face complex (SFC)

According to initial study results, there are six types of seismic face complex (Fig.1):

· *Shelf environment, accretionary SFC:* It has distinguishing characteristics with overall feature of multiple parallel strata stacking vertically with each other. Several sets of seismic events formed an accretionary

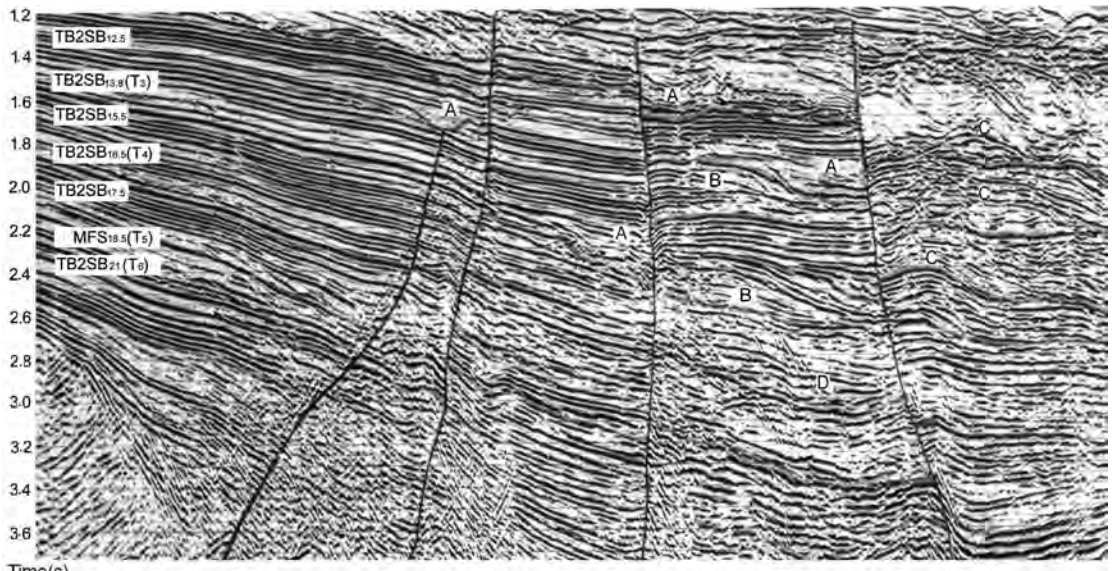

Figure 2 High-resolution Seismic Profile of 1558 Line (Zhu 2 Depression, PRMB) showing (A) incised valley and its filling, (B) prograding complex, (C) basin-floor fan, (D) Slope fan, also showing sequence boundaries of SB12.5Ma, 13.8Ma, 15.5Ma, 16.5Ma, 17.5Ma, 21Ma and maximum flooding surface of MFS 18.5Ma.

complex parallel to each other. Strong amplitudes alternating with weak ones, lateral continuity ranges from good to excellent. Generally, it displays as conformity contact or parallel unconformity contact of seismic face complex, reflects a relative stable depositional environment existing over paleo-continental shelf, mainly consists of deposits of transgression and highstand systems tract.

· *Shelf margin, progradation SFC:* It usually exists underlying accretionary SFC with progradation characteristics towards basin direction and downlap on the sequence boundary. The closer the progradation SFC is to the boundary, the stronger the amplitudes of seismic reflection events are. This type of SFC emphasize transitional zone between shelf and slope environments. Toward land direction, the paleo-shelf is stable and flat, and seismic reflection events changed into accretionary SFC; Toward ocean direction, there is depositional slope environment with topographic gradient change; magnificent progradation SFC can be observed at some sequence boundaries.

· *Shelf margin, incised valley, connecting to canyon SFC:* It displays unique characteristics at some seismic profiles perpendicular to paleo-continental shelf of paleo-Pearl River. To the south of specified boundary, various scales of incised valleys and their fillings at each sequence boundary can be identified. Usually, incised valley eroded into previous highstand systems tract; continuity and strong amplitude were interrupted on both sides of incised valley.

· *Upper-slope, mound reflection SFC:* The growth fault belts control the local shelf break zone; but the slope becomes flat within a short distance, revealing distinguishing mound reflection SFC characteristics. Both sides of mound downlap separately on the relative flat sequence boundary; one of the wings towards the basin extends very far, gradually becoming parallel to sequence boundary, while the other wind ends at fault belt.

· *Down-slope, slope fan SFC:* Wave-like reflection SFC is visible at lower part of slope while overlies gradually converged from divergent progradation SFC into parallel reflection SFC. These reflect an unstable down-slope environment both on lateral and vertical sedimentation.

· *Deep-water basin-floor fan SFC:* parallel reflection SFC feature can be easily observed because it has the characteristics of sedimental process under a relative stable environment. Thus, it is mainly consists of parallel reflection SFC, but supplemented by wave-like reflection SFC.

3.2 From SFC to deep-water fan system

If we discovered a 14 km-long incised valley on the sequence boundary 12.5Ma in 95EC1558 seismic profile (Fig.2), and also identified, after crossing the growth fault belts, connected canyon, basin-floor fan and slope system (mound-

like, progradation, downlap, onlap, wild goose flying configuration), then we will have no doubt about the massive scale of such fan system. At the nearby seismic line (95EC1561, 3 km away), the same characteristics on the SB12.5Ma are also observed with even more expansive distances on lateral sides. This deep-water fan system reaches total volume of $1.8\sim3.0\times10^{10}M^3$.

From macroscopic point of view, the deep-water fan system must include a massive scale of incised valley, connected canyon, basin-floor fan (mound), slope fan and lowstand progradation complex. From the analysis of the architecture characteristics, geological implication, reflective complex, amplitude characteristics, phase, formation velocity, absorption coefficient, relative impedance and frequency chart of SFC, as well as studying of their lateral and vertical changes, a basic understanding can be reached. That is, if there existed characteristics, of which high velocity alternate paralleling with low one, high impedance alternate with low one in parallel, strong amplitude alternate with weak one in parallel, high frequency alternate with low one in parallel and strong phase alternate with weak one in parallel, not only exhibiting excellent stratified effect, good continuity, parallel conformable stratum, and relative stable continental shelf environment, but also displaying detrital deposition of alternation sand and mud controlled by the regularity of sea level rise and fall during transgression and high-stand systems tract; then, any changes, especially paleo-environment and sea level change impacted geological processes such as progradation differential, exposed abandoned channel, newly formed channel, channel filling, collapse, regressive erosion, faulting slump and disorderly mixed accumulation, as well as formation of geological products such as incised valley, canyon, basin-floor fan and slope fan, must have lead to rapid changes in stratified appearances. This is exactly the same as discovered in incised valley filled SFC and other types of SFC. All of these are expressed as non-stratified characteristics both on configuration and sedimentary meanings, and could be easily identified in specially processed seismic profiles of high-resolution, relative impedance section, and formation velocity. And all these above build the foundation for accurate geological interpretation. As a result, various interpretations of seismic data could be unified.

4. The Perspective of Petroleum Exploration in Baiyun Deep-water Sag

Evidences of abundant hydrocarbon, active spots and AVO anomalies are encountered in the wells or reflected on the seismic data of northern margin of Baiyun Sag. These evidences reveal that the hydrocarbon, generated from the sag, had vertically passed through the overlying deep-water fan system and migrated to surrounding regions. Recently, commercial gas wells have been discovered in this area.

The successes of exploration of deep-water fan systems around the world, in the last decade, encourage exploration geologists to conduct more researches aiming at finding deep-water fan system in this particular region. The delta/strand arenaceous reservoirs, formed by paleo-Pearl River in Zhu 1 Depression, have excellent porosity, high permeability and high rate of productivity. The same story is believed to be true for Baiyun Sag because its lowstand fans are originated from the same paleo-Pearl River. The vertically stacked pattern of lowstand deep-water fan systems, overlying on the Lower Tertiary source rocks, and the growth fault belts cutting through the source rocks, as well as the reservoirs, construct good hydrocarbon migration conditions. All factors mentioned above, in addition to possible large scale of stratigraphic traps on the northern margin and combined traps on the southern margin, plot a promising future for petroleum exploration in this area.

5. Summary

The sequence stratigraphic study in the deep-water region, Baiyun Sag of PRMB, reveals a huge scale of deep-water fan systems. The cyclic falling of sea level, abundant detrital matters supplied by paleo-Pearl River and persistent geothermal subsidence are considered the three prerequisites for the development of deep-water fan system. Stacked, stratified and overlying above the Lower Tertiary source rocks, the deep-water fan systems are expected to be excellent reservoirs and hot exploration spot in PRMB.

The discovery of deep-water fan system is based on the processing of 2D high-resolution seismic data while the study of sequence stratigraphy is based on typical seismic profiles with high-accuracy and high-fidelity data. Typical sedimental face units formed in the lowstand stage since 30 Ma, and vertical stacked pattern of incised valley and basin-floor fans, which developed nearby the growth fault belts controlled paleo continental shelf break, have been discovered.

The discovery of large-scale deep-water fan systems in the South China Sea has significant economic potentials and academic values. However, due to the complexity of deep-water sedimentary systems and lacking of experiences on deep-water petroleum exploration, more scientific research and exploration activities, especially in cooperation with foreign companies and academic institutions, will be conducted in the future.

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