Petroleum Systems and Exploration Potentials of the Northern Deepwater South China Sea

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Introduction

The Northern Margin of the South China Sea (SCS) covers an area of 3.5 million km^2 and has accumulated more than 8 km of Mesozoic to recent sediments. The deepwater area of the Northern margin include Pearl River Mouth Basin (PRM), Qiongdongnan Basin (QDN) and from east to west. Over time, operators in SCS have targeted shallow water plays and significant shallow water discoveries have been made in the northern, western, southern, and eastern margins. Many shallow water basins have produced oil and gas for decades. Only a few deepwater exploratory wells have been drilled in the northern margin and regional geological studies and the use of new technologies to acquire, process and interpret seismic data tied by drilled well data suggest the huge potentials in deepwater SCS (Wu et al., 2009). Deepwater discoveries have been made in the northern, western and southern margins. The recent deepwater discoveries e.g. LW3-1 in PRMB in 2006, LH29-1 and LH34-2 in PRMB in 2009, LS22-1 in QDN in 2010, and LS17-2 and LS25-1 in QDN in 2014 have successfully tested the deepwater prospects in the lightly explored northern deepwater margin (Figure 1).

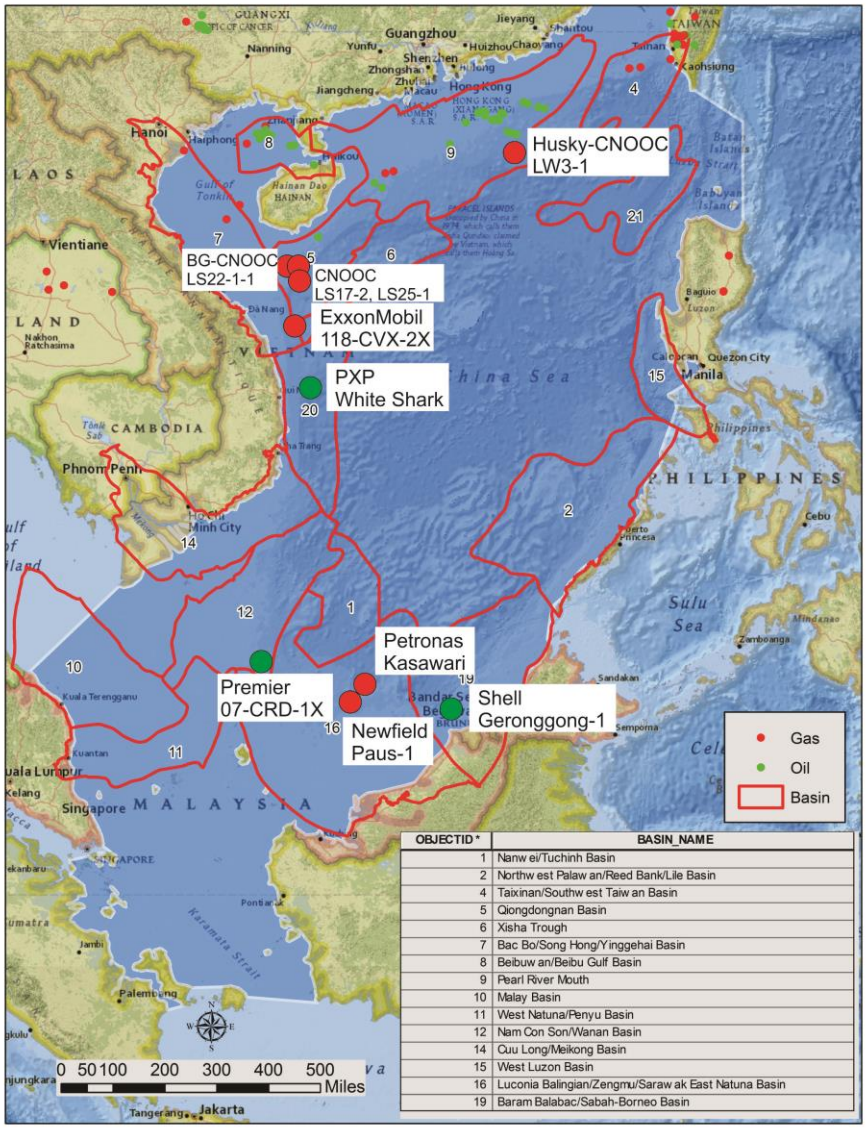

Figure 1 Basins in the South China Sea (SCS) and recent deepwater discoveries.

Regional Geology

Regional studies suggest the South China Sea (SCS) is a marginal sea located in a very unique geologic setting with the complex interaction of Indochina, Indo, Australia, Philippine, Eurasia and Pacific plates and there are no mobile salt and shale diapirs in SCS compared to the U.S. Gulf of Mexico and West Africa-Brazil Atlantic margins (Li et al., 1999; Li et al., 2012). During Mesozoic, the SCS region was part of Paleo-Tethys and the SCS developed from continental margin rifting to current SCS floored with oceanic crust in Cenozoic (Shi and Li, 2012). The Mesozoic history of the northern SCS has not been fuly understood (Wu et al., 2009). The Cenozoic SCS has been experiencing Wilson cycle from continental break-up and seafloor spreading to subduction even though its small size and short evolutional history compared to major ocean basins in conjugate margins. The origin of SCS is still debatable between tectonic extrusion of Indo-China Block as a result of India-Asia collision, back-arc and slab pull due to complex geology and sporadic data and interpretations

(Tapponnier et al., 1982; Taylor, B., and Hayes, 1983; Hall, 1996). It is commonly accepted that basins in SCS all experienced similar syn-rift lacustrine sediments to post-rift marine sediments cycles even though the tectonic origin of SCS remains controversial and the tectonostratigraphic evolutions between these basins in Northern deepwater SCS are different due to variations of tectonic settings and depositional evolution scenario. The rifting of the Northern margin of SCS is estimated to be imitated as early as Early Paleocene in response to a rifting event that led to the opening of SCS, the incipient spreading of it is dated from Late Oligocene. The basins are characterized by two layers architecture and evolved from syn-rift stage lacustrine in Paleocene and Eocene and partly Oligocene and finally the formation of post-rift. The Paleogene syn-rift lacustrine sequences are separated from the overlying post-rift Neogene marine sheet-like layers by the major break-up unconformity with a large stratigraphic gap dated from Middle Eocene to Late Oligocene and transitional deposits (Figure 2). The vast area in Northern Margin of SCS remained unexplored, especially in deepwater Pear River Mouth Basin (PRM), Yinggehai Basin (YGH), Qiongdongnan Basin (QDN), Zhongjiannan Basin, Taixinan Basin, Jianfeng Basin, Shuangfengnnan Basin and Bijia Basin. These basins in the northern margin were formed by three times of extensions since late Cretaceous to Late Oligocene and distributed over a thinned continental crust on a passive margin (Li et al, 1999). The PRM covers 17.5X10^4 km^2 with one third of area in deepwater. The QDN in SE Hainan Island covers 8.92X10^4 km^2 with more than 2 X10^4 km^2 in deepwater (Wu et al., 1999).

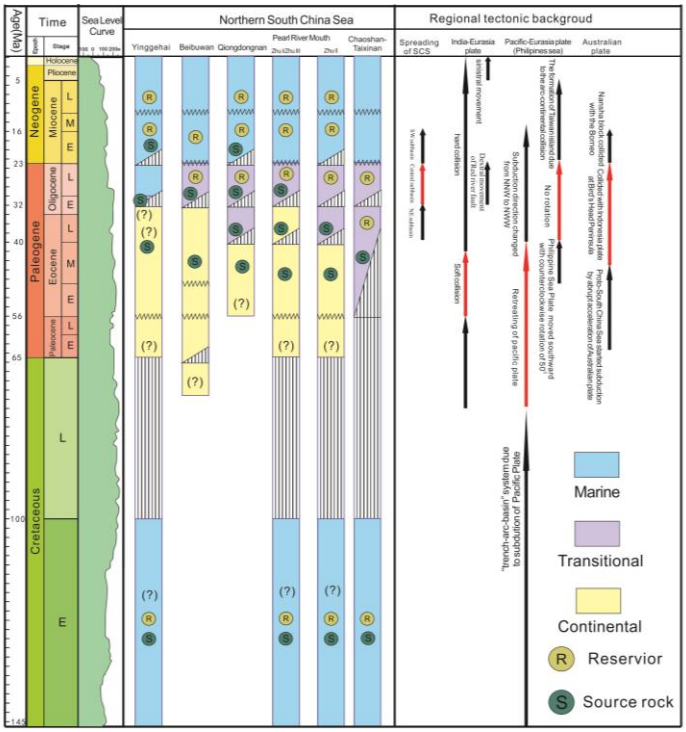

Figure 2 Tectono-stratigraphic framework of the Northern SCS. Compiled from various resources.

Petroleum Systems

A number of hydrocarbon systems are present and have been proven by historic and recent drilling. But, there has been little exploration in the deepwater regions in the northern SCS. Recent regional seismic acquision, processing and interpretation and deepwater drillings, basin filling architecture, tectonic and depositional evolutions, and burial history suggest the multiple petroleum systems associated with lacustrine, transitional and marine sequences in the deepwater area of the northern SCS. Paleocene and Eocene sequences of early syn-rift successions are favorable potential targets for lacustrine hydrocarbon systems; A transitional peneplanation phase with coastal swamp deposits followed rifting form the world-class coal measure source rock and deltaic plain reservoir systems; Neogene marine successions of drift successions are favorable for deltaic, marine carbonate and deepwater turbidite hydrocarbon systems.

1) Source Rocks

Comparing to the source rocks in Atlantic margins, the Northern deepwater SCS has the lacustrine mudstone source rock deposited in rifting stage, coal measure source rock deposited in transitional stage from rift to post-rift and marine shale source rock deposited in post-rift stage. Detailed study based on regional geology, available seismic and well data reveals the deepwater area in the northern margin has the wide distribution of three source rocks: 1) type I to II lacustrine source rock in Eocene syn-rift setting (e.g. Wenchang Fm in PRM and local equivalent Fm in YGH and QDN); 2) type II to III shale to gas prone coal measure source rock in Oligocene late-rift transitional coastal swamp setting (Enping Fm in PRM and Yacheng Fm and Lingshui Fm in YGH and QDN) and 3) Type II marine source rock in post-rift setting (Upper Oligocene Zhuhai Fm in PRM and Miocene Sanya, Meishan and Huangliu Fm in YGH and QDN) (Figure 2). These three identified source rocks sourced the oil and gas fields discovered. But the different basins with different tectonic settings have different source rocks, e.g. the source rocks in deepwater PRM have several source rocks of Eocene lacustrine shale, transitional coal measure and post-rift marine shales, while the source rocks in YGH are dominated by post-rift Miocene marine source rocks. The lacustrine shale in rift stage may be present in YGH but has not been penetrated by drilling.

2) Reservoir rocks

Multi-phase tectonic and depositional evolutions resulted in diverse reservoirs. Historical drilling and production have proved numerous reservoirs in different depositional systems. The historical proven reservoirs consist of lacustrine delta in the gentle slope, fan delta sandstone in the steep slope, and shallow marine delta sandstone. Recent studies and drilling reveal that Large-scale deepwater channelized reservoirs were developed in PRM, YGH and QDN during Neogene as they received major vast sediments from Pearl Mouth River and Red River (Figure 3). The deepwater reservoir distributions are mainly controlled by structural activities and configuration of paleogeography, sea level change, shelf break trajectory evolution, and sediments transportation from source to sink. The potential other reservoirs in the northern deepwater SCS include the undrilled Cenozoic deep lake turbidte sandstones, Cenozoic marine carbonate reef, Mesozoic marine strata and fractured basement.

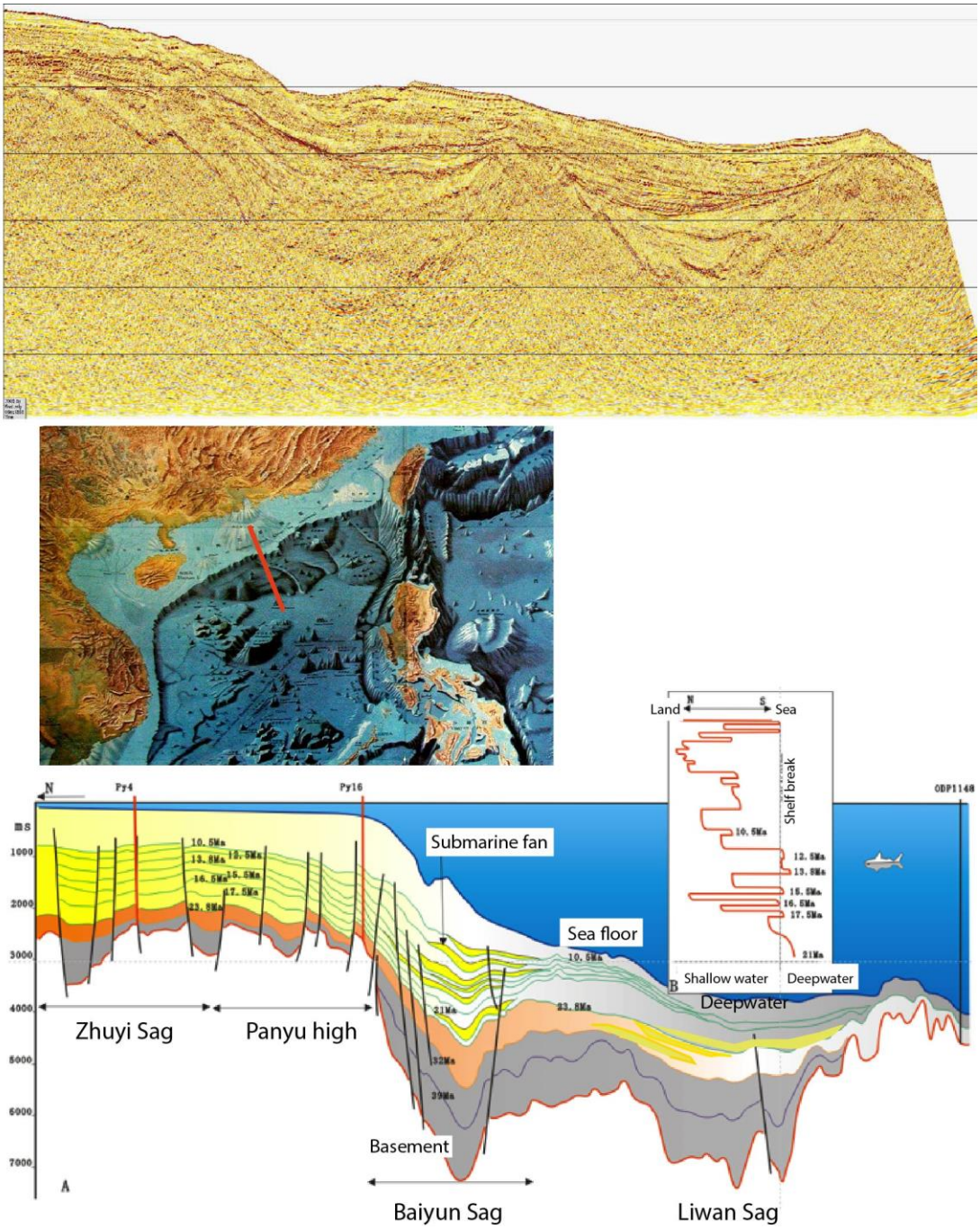

Figure 3 The regional seismic cross section and its interpretation in Pearl River Mouth Basin (PRM), showing the submarine fan in the deepwater area.

3) Traps and seals

The successful E&P in the past and studies show the traps in northern SCS include the structural traps (tilted fault blocks, structural closures associated with regional tectonic movements), combination structural-stratigraphic trap, and pure stratigraphic trap. The paleohigh and tectonic inversions created many structural traps in syn-rift and post rift successions. Many pinch-out of sandstone stratigraphic and combination

structural-stratigraphic trap traps exist in syn-rift and post-rift, e.g. combination structural-stratigraphic and stratigrahic traps of sand-rich deepwater turbidites. For the syn-rift lacustrine and transitional reservoirs in northern deepwater SCS, the lacustrine shale and post-rift marine shales act seals. For the post-rift marine reservoirs, the Miocene marine Zhujiang and Hanjiang shales in PRM and Miocene Sanya to Yinggehai shales in YGH and QDN provide regional seals.

4) Petroleum systems model

In the northern deepwater SCS, there are three sets of proven source rocks and multiple reservoir rocks deposited in lacustrine to deep marine environments. These multiple source rocks and multiple reservoirs formed multiple petroleum systems from basement, syn-rift lacustrine to post-rift marine sequences in different structure settings. These proven and potential petroleum systems include one source rock and multiple accumulations via multiple migration paths and multiple source rocks and multiple accumulations. Cenozoic Petroleum systems showing play concepts in the northern deepwater SCS is summarized based on E&P results and regional synthesis (Figure 4). Huge hydrocarbon potential are remaining for further exploration in the northen deepwater of SCS, which includes Cenozoic deepwater channels/fans, reef, syn-rift lacustrine delta and fan delta and lacustrine turbidites. The un-penetrated fractured basement and Mesozoic strata could also have potentials.

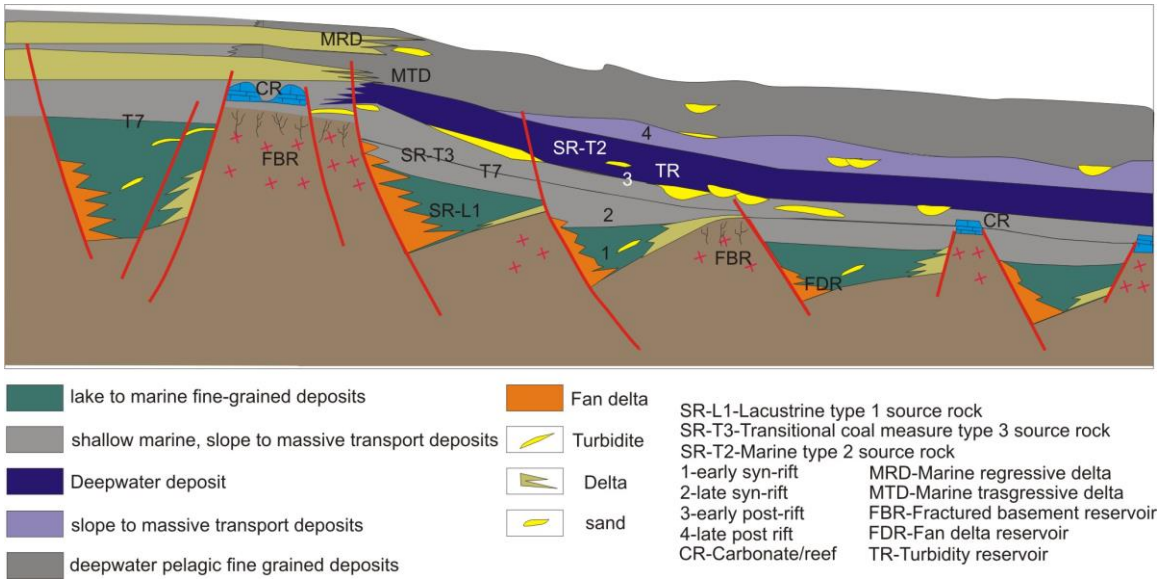

Figure 4 Petroleum systems model showing play concepts in the northern deepwater South China Sea (SCS)

Conclusions

The Cenozoic northern South China Sea (SCS) evolved from rift lacustrine, transitional coastal swamp to post-rift marine settings. The three source rocks (organic-rich lacustrine shale, coal measure and marine shale) and numerous lacustrine to deepwater marine reservoirs correspondingly developed in different depositional successions. The northern deepwater SCS (e.g. PRM, QDN and YGH

basins) have the presence of these Cenozoic source rocks and deepwater channels/fans, reef, syn-rift lacustrine delta and fan delta and lacustrine turbidite reservoirs, Mesozoic unexplored strata, and fractured basement, which has huge potentials.

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