Cenozoic Basins of the South China Sea

by Wu Jinmin

The South China Sea is a region of greatly varying crustal structures, extensive tectonic activity and complex geophysical and geomorphological features. Cenozoic sediments are well developed, and the area has been the recent target of intense exploration for oil and gas. This article, presented at a recent IUGS seminar in Guangzhou, reviews current ideas on the evolution and hydrocarbon resources of the South China Sea. (Ed.)

Cenozoic Basins of the South China Sea

The Cenozoic deposits of the South China Sea are dominated by unmetamorphosed clastic sediments, with volcanoclastic rocks well developed in the east, and carbonate rocks in central portions in the regions of Dongsha, Xisha, Zhongsha, Nansha and the offshore of Palawan (Figs. 1 and 2). Based on geological and geophysical data, some 37 Cenozoic sedimentary basins or groups of basins have been recognized in the South China Sea (Fig. 2), in about 18 of which oil and gas have been found. The maximum thickness of Cenozoic sediments here is over 10,000 m, and studies of their depositional characteristics are of obvious importance to the development of exploration for oil and gas in the region.

In broad order of stratigraphic sequence, six major depositional areas can be recognized (Fig. 1). In the Beibuwan - Zhu-3 Depression Tertiary strata, especially lower Tertiary, are developed completely and exhibit characteristic rhythms and cycles. These rocks are primarily terrestrial facies with greatly varying thickness, whereas the upper Tertiary strata are dominated by clastic sediments of neritic facies.

In the Western Area, upper Tertiary strata are better developed than those of the lower Tertiary. Lower Palaeocene deposits are thin or absent but terrestrial-transitional sediments accumulated during early Tertiary time, changing to marine facies during the late Tertiary. This marine transition is more obvious from west to the east where clastic rocks predominate. Carbonate rocks are distributed locally, and Upper Miocene strata are missing in places.

The Southern Area is situated south of the Nansha Islands and the Nansha (Palawan) trough, but it excludes the North Palawan Basin. Lower Tertiary strata here (the Ranjang Group in Sarawak and the Crocker Formation in Sabah) are composed of flysch and ophiolite formations, slightly metamorphosed to phyllite and slate and severely folded into steeply dipping and imbricated structures. Upper Tertiary strata (including Upper Oligocene in parts) are fully developed here and are composed of shallow clastics with carbonate intercalations. Upper Miocene regressive deltaic sediments are broadly developed.

The Eastern Area comprises the Philippines and offshore areas, where lower Tertiary strata have been folded and metamorphosed. Upper Tertiary (including Upper Oligocene) deposits contain abundant volcanic rubble and other volcanics, with a maximum thickness over 15,000 m.

The Xisha-Nansha areas include Zhongsha, North Palawan and adjacent areas. Lower Tertiary deposits here are not so well developed, though a relatively complete clastic section

of early Tertiary age has been found in Liyue (Reed) Bank. Carbonate rocks of late Tertiary age are more fully developed.

The Deep-Sea Basin is underlain by the oceanic crust. Sedimentary strata here are dominated by upper Tertiary (including Upper Oligocene) and Quaternary unconsolidated abyssal ooze and volcanic deposits.

As mentioned above the depositional environments in the marginal areas of the South China Sea changed greatly from Palaeocene-Eocene to Late Oligocene. Four major stages in the Cenozoic development of the region can be distinguished as follows.

Eocene Depositional Environments

During Eocene time (Fig. 3) there were three uplifts, on the northern margin of the South China Sea: Wanshan-Hainan, Shenhui-Xisha, and Penghu-Dongsha. These NE-SW uplifts were separated by depressions consisting of a series of small sags. Some of these also occur within the uplifts and contain well-developed fluvial-lacustrine deposits. The sediments thin from west to east in these depressions. The present Taixinan Basin appears to have then been part of the Penghu uplift, for it did not receive deposits at this time. Southwest of Hainan, the Yinggehai Basin consisted of NW-SE lacustrine basins, into which the Red River flowed.

The continental margin of the southern South China Sea during Eocene time was divided by the Natuna uplift (Fig. 2) into western and eastern parts, each with quite different sedimentary environments (Fig. 3). To the west, the Gulf of

Figure 1: Distribution of Cenozoic sedimentary areas (underlined) of the South China Sea. Some important wells are shown: 1- CF-1; 2- Zhu 5; 3- Wan 2; 4- Ying 2; 5- Ying 9; 6- Xiyong 1; 7- Sampaguita; 8- AQ-4; 9- 16-B-1; 10- 16-C-1; 11- 4-B-1.

Figure 2: Cenozoic sedimentary basins of the South China Sea showing oil and gas fields. After Wu (1987).

Thailand was then a landmass, though fluvial-lacustrine deposits may have formed then in the separated Pattani, Malay and West Natuna basins (Fig. 2). The Wananxi Basin might have been a deltaic deposit related to the Mekong River. Abyssal flysch deposits formed at this time in Sarawak, Brunei, Sabah and south Palawan (Haile, 1974), and sand, mud and carbonates, ranging from littoral to abyssal facies, were deposited on the Nansha massif, including the Liyue Bank and the west edge of North Palawan Island (Fig. 1).

Late Oligocene to Early Miocene Environments

The continental margin of the northern South China Sea underwent widespread marine transgression following Late Oligocene time, resulting in a substantial decrease in the area of the Wanshan-Hainan, Shenhu-Xisha, and Penghu-Dongsha uplifts (Figs. 1 and 4). Sediments deposited during this transgression become younger to the northwest, with the earliest marine sedimentary record in the Taixinan Basin dating from about the NP 22 zone (Huang, 1982). In the Zhujiangkou Basin sediments are equivalent to the calcareous nannofossil zones NP 24-NN3. The northern edge of this marine transgression is situated near the Zhu 5 well (Fig. 1), and the separate depressions and sags that existed here in the Eocene (Fig. 3) were unified into a single basin during Oligocene time.

Evidence of a subsidiary transgression has been found in the Qiongdongnan Basin coming from the Xisha Trough (Fig. 2), where nannofossil zone NP 25 was discovered. The waters

of the Qiongdongnan and Yinggehai basins were then joined, but the transgression stopped short of the northwest end of the latter basin. Transitional and littoral deltaic sediments occur in the Hanoi Depression of Vietnam (Skorduli et al., 1983).

The marine transgression in the Beibuwan Basin occurred slightly later. The Upper Oligocene rocks here consist of nonmarine assemblages characterized by spore-pollen and freshwater ostracoda, whereas the marine Xiyang Formation is only equivalent in age to the late Early Miocene (top of nannofossil zone NN3-NN4, according to Duan et al., 1987). Littoral-neritic sandstones and mud stones predominate in the wide continental margin of the northern South China Sea, but in uplifts such as Dongsha, Shenhu, Xisha, and along the south edge of the Hainan uplift, carbonate rock and reefs are extensively developed. West of Natuna the area was dominated by transitional deposits of fluvial-lacustrine and littoral-swamp facies (Woolands and Haw, 1976). Higher in the sequence marine facies occur in western Natuna, with fine dark mudstone containing

coal and plant debris dominating the center of each basin. There may also be marine intercalations with planktonic foraminifera in the southeastern Malay Basin (Armitage and Viotti, 1977). Littoral marine carbonates predominate east of Natuna and over the Nansha area and Liyue massif, whereas bathyal clastics occur between the carbonate

Figure 3: Eocene depositional facies of the South China Sea. Solid squares - wells as in Figure 1.

platforms. The southern boundary of Zengmu and Brunei-Sabah basins shifted northward, as Kalimantan Island rose, and coastal littoral-neritic and bathyal facies clastic sediments were deposited from south to north in these basins. The Zengmu Basin sloped eastward and accumulated littoral-neritic sediments.

Middle to Late Miocene Deposition

As the marine transgression spread farther inland over the continental margin of the northern South China Sea during Middle to Late Miocene time, the uplifts were further submerged (Fig. 5). The northern boundary of the coastline was submerged to almost the present 30 m water depth line, and the whole area was dominated by neritic clastics, except for some uplifts containing carbonates.

A broad area of the continental margin rose during the early Late Miocene time, and most of the uplifts (e.g. Dongsha and Shenhu) again emerged above sea level and were eroded. A sedimentary hiatus occurred in each basin, and nannofossil zones NN9-NN10 and lower NN11 are absent.

In the Nansha area, including the Nankong and Beikong platforms (Central Luconia) of the Zengmu Basin (Figs. 1 and 2), a littoral-neritic depositional environment still prevailed, with carbonates and reefs developed mainly on platforms surrounded by deeper water clastics. Deltaic deposits formed at the mouth of the Baram River of the Brunei-Sabah Basin during late Middle to Late Miocene time, while a turbidite fan deposit dominated offshore Sabah (ASCOPE, 1981). In the Gulf of Thailand the ancient coastline moved westwards to the center of the Malay Basin, and marine sediments were widely deposited in the Mekong and Malay basins.

Pliocene-Quaternary Environments

The transgression reached its maximum extent along the continental margin of the northern South China Sea during Early to Middle Pliocene time (Wu, 1985), when the ancient coastline was at almost the same location as at present, and when all of the uplifts had been submerged again, except for Hainan Island. Neritic and shelf clastics dominated during this interval, but south of Hainan and Taiwan rapid subsidence took place, with from 3000 to 5000 m of bathyal clay-shale deposited (Chou, 1971, 1973).

Figure 4: Late Oligocene depositional facies of the South China Sea. Solid squares - wells as in Figure 1.

In the south, the depositional center of the Zengmu and Brunei-Sabah basins moved farther seaward due to the rising of Kalimantan, and littoral-neritic clastic deposits predominated, with neritic carbonates developed in Liyue and North Palawan basins. West of the Natuna uplift, the Pattani, Malay, and West Natuna basins were by this time submerged, though not to great depths, and littoral-neritic clastics were again being deposited. The eastern part of the Natuna-Khorat (NE Thailand) uplift has subsided rapidly, since the Early Quaternary, and deposits up to 1500-2300 m thick accumulated.

Figure 5: Middle Miocene depositional facies of the South China Sea. Solid squares - wells as in Figure 1.

Cenozoic Sedimentary Cycles

In the northern part of the region, the Cenozoic sediments of the South China Sea can be divided into two sedimentary cycles, with the unconformity between Lower and Upper Oligocene deposits as the boundary. According to the data available, the basinal sediments changed progressively from terrestrial facies to marine facies from bottom to top along the continental margin of northern South China Sea. The typical sedimentary sequence is: red clastics (Palaeocene-Lower Eocene), dark argillaceous lacustrine shales (Middle Eocene-Lower Oligocene), littoral plain and swamp coal-bearing and biogenic bank formations (Upper Oligocene), littoral clastic formations and shallow bank carbonates (Lower-Middle Miocene), neritic and bathyal clastic formations (Upper Miocene-Quaternary). Figure 6 illustrates the mainly transgressive cycles, which began in Late Oligocene time. Of the three peaks - late Early Miocene, late Middle Miocene and Early Pliocene - the latter is the greatest one, characterized by abundant fossils and thick widespread and well-developed mudstones overlying older strata.

In the southern South China Sea the marginal basins formed later than those of the northern South China Sea. Data from the northern part of Kalimantan and its offshore area indicate that the Palaeocene-Eocene sequence here has been subject to regional metamorphism and folding (CCOP-IOC, SEATAR, 1980) and forms the present basement to the basins here. The following sedimentary sequence of regressive cycles from bottom to top is developed in these basins: abyssal flysch (Upper Eocene-Lower Miocene), neritic clastics and carbonates (Lower-Middle Miocene), deltaic and reef carbonate formations (Middle-Upper Miocene), and neritic and littoral clastics and carbonates (Pliocene-

Quaternary). The Baram Delta has eight regressive cycles (ASCOPE, 1981) within the upper sedimentary cycle (Fig. 7). During the major regression of late Middle Miocene-Late Miocene time, deltaic deposits were most extensive. The sedimentary characteristics in the southwest South China Sea are similar to those in the north, though the transgressions began later here.

Figure 6: The upper sedimentary cycle (Cenozoic) of the northern South China Sea (Wu, 1987).

Figure 7: The upper sedimentary cycle in the Baram Delta of Kalimantan. After Ramli (1985).

Plate Tectonics and Cenozoic Basins

Cenozoic plate movements characteristic of the South China Sea region are such that microplates, which earlier had been sutured together (e.g. South China, Indochina and Burma-Malay), have undergone a realignment process, involving extension-thinning, rifting-disintegration, strike-slip, and convergence and collision as a result of the collisions of the Indo-Australian and Pacific plates. The history of plate movement during the Cenozoic Era here is marked by the Nanhai (South China Sea) movement, which occurred between Early and Late Oligocene time. During this period subduction of oceanic crust in the ancient South China Sea, continuing from the Late Cretaceous Period, was followed by spreading and formation of the modern South China Sea after Late Oligocene time (Wu, 1987).

Development of the Cenozoic basins of the South China Sea was inevitably controlled by the structural evolution of the area bordering the Deep-sea Oceanic Basin between Xisha-Zhongsha and Luzon (Fig. 2). Based on the mechanisms of plate tectonics, these basins can be divided into four main categories as follows:

Extensional Structures: From late Mesozoic to early Tertiary times, the northern South China Sea was part of the continental margin of Andean-type that formed the eastern edge of Asia (Guo et al., 1983), but after the Late Oligocene it became an Atlantic-type margin. As shown above, the continental margin in the northern South China Sea was successively controlled by tensional stresses from different directions throughout the Mesozoic-Cenozoic. The overlap here of early NE to NNE extension fractures with later ones trending ENE-WSW (Fig. 8) led to a structural framework represented by zonal structures from north to south and blocky structures from west to east (Wu, 1985) that resulted in a series of extensional basins, such as Beibuwan, Qiongdongnan, Zhujiangkou, and Taixinan (Fig. 2).

These Marginal Tension and Fracture Basins represent intra-plate fractures and depressions (Table 1). Their extension was controlled by the spreading direction of the South China Sea, and their long axes are parallel to the shoreline.

Beneath the basins the crust has generally thinned to about 24 km. In the early stages, separate depocenters existed, which coalesced subsequently to form the distinct basins (Figs. 9, 10). These have, therefore, a two-layered structure reflecting these two stages of development. The lower one (Late Cretaceous-Early Oligocene) is dominated by NE-SW structures and is a product of rift-faulting, whereas the better developed upper one mainly consists of NNE-SSW structures produced during subsidence. Normal faults also developed, and horst-graben structures predominate in the basins. Basement uplifts are well developed as are "covering" structures, "buried hills" structures, and tilted fault block structures (Fig. 11).

Convergence Structures: Palaeomagnetic data show that in the early Palaeogene counterclockwise rotation took place in the western part of Kalimantan Island (Borneo microplate - (50° according to Haile et al., 1977) and in Luzon (70° - Hsu and Scharon, 1970). These formed respectively a convergent margin in the southern and an underthrusting-compressive margin in the eastern South China Sea.

The extension direction of the basins in these regions is similar to that of the regional tectonic grain. In the southern South China Sea the basins lie on thinned continental crust, where the Moho is at depths of 20-22 km. In the east

Figure 8: Tectonic framework of the continental margin of the northern South China Sea.

the basins formed on transitional oceanic crust, where the Moho is 26 km deep. The lower structural layer here is generally folded and metamorphosed and forms the basement to the basins. The fold structures are young, well developed, and associated with thrust faulting. The compressive basins located on the edge of the subduction zone have low geothermal gradients, except for the Zengmu Basin, which has a 3.7-9.4°C/100m geothermal gradient. In the West Palawan, Cagayan and Central Valley basins, the gradient is less than 2.5°C/100m.

The Zengmu Basin, which lies on the mild collision zone between the Nansha and Borneo microplates, is regarded as a Foreland Basin. It is obviously asymmetric, with the intensity and age of folding decreasing northward (ASCOPE, 1981). Between the Pacific plate subduction zone and the orogenic belt-volcanic arc of the Philippines lie the Forearc Basins such as Central Valley (Bachman et al., 1983) and Cagayan, in which volcanic sediments are well developed. The Cagayan structure is an interarc basin formed by extension and rifting between two volcanic arcs. Forearc basins are not developed in the Brunei-Sabah region.

Transformational Structures: Shear faults are well developed in western South China Sea. Tapponnier and others (1982) have pointed out that the development of the Red River and Gulf of Thailand faults are related to the subduction of the Indian

Figure 9: Interpreted seismic reflection profile across the Beibuwan Basin. After Zhai Guangmin and Qiu Zhongjian (1984). 1- Middle Miocene to Quaternary; 2- Lower to Middle Miocene; 3- Upper Oligocene to Lower Miocene; 4- Eocene to Lower Oligocene; 5- Palaeocene.

under the Eurasian plate (Fig. 12). According to them when the Indian plate underthrust northwards the Eurasian plate at 40 Ma, major sinistral strike-slip faults developed, radiating eastwards from the subduction zone north of India. These faults made up several triangular continental blocks that widen from west to east, and which moved eastward or southeastward along the faults. The general tendency of these lateral movements was an eastward squeezing out of Southeast Asia, in a so-called "propagating extrusion tectonics" pattern.

The Cenozoic depressions that formed against this background are termed "Shearing Extensional Basins," such as Yinggehai, Malay and West Natuna. The extension in these basins is controlled by regional structural lineations, and the

Table 1: Thickness of Cenozoic structural layers on the continental margin of the northern South China Sea.

Basins Thickness of Structural Layer (m)	Intra-plate fracture and depression basins		Marginal tension and fracture basin			
	Beibuwan	Zhujiangkou			Qiongdongnan	Taixinan
		Zhu 3	Zhu 1	Zhu 2		
Upper Oligocene to Quaternary	3000	3500	5000	6000	8000	9000
Palaeocene to Lower Oligocene	6000	6000	2000	3000	3000	0

basins are elongated with no obvious separation features. Within them the upper structural layer is dominant, and the lower one is incompletely developed. The basins become younger to the north. Reversed faults occur in addition to normal faults, but commonly the latter are older. Folds formed rather late, and mud diapirs are common. In general, the geothermal gradient is relatively high in these basins.

Gravity-Settling Structures: These basins constitute two types. The Deep Sea Accumulational basins (e.g. the Shuanfengnan) formed on oceanic crust that gradually subsided in the rifting and tension setting because of the

increase in cooling and density of the oceanic crust, and on which younger deposits accumulated. The other type - the Rifted Block basins - formed on continental fragments that were separated by rifting and drifting. The Liyue Basin is an example of these structures that are underlain by oceanic or thinned continental crust and that are almost inactive and monotonous, dominated by normal faults.

Oil and Gas Resources

At present, seven countries bordering the South China Sea are carrying out exploration for hydrocarbons, and oil and gas have been discovered in most of the marginal basins. In the southern margin of the South China Sea hydrocarbon development has continued for a long time, and extensive drilling has led to good results. During the period 1970 to 1986, about 1000 wells were drilled. In Pattani, Malay, West Natuna, Zengmu, Brunei-Sabah and North Palawan basins, 108 oil and gas fields have been discovered.

In the Sabah area of the Brunei-Sabah Basin, 60 structures have been tested, and 16 have yielded oil and gas. For the Zengmu Basin the comparable figures are 126 and 52, for the Nankong and Beikong shoals 43 and 20, for the Esso blocks of the Malay Basin 40 and 23 (ASCOPE, 1981). In the Thai portion of the Gulf of Thailand 110 wells have been drilled, of which 62 have produced natural gas with condensate and crude oil (Polahan, 1985). Overall, the success rates for the southern and western margins have averaged 45%, with the range 27% (Sabah) to 58% (Malay Basin).

In the northern South China Sea encouraging results from oil and gas exploration have been achieved, although the work here started rather late. In the Beibuwan, Yinggenai, Qiongdongnan, Zhujiangkou and Taixinan basins, 162 wells have been drilled, including 14 by the U.S.S.R. in the Hanoi Depression of Vietnam (Skorduli et al., 1983). From these 32 oil and gas fields or hydrocarbon-bearing structures have been discovered. In the Zhujiangkou Basin, 10 out of 30 structures drilled have yielded oil and gas, and the comparable figures for Beibuwan are 6 and 16, for a success rate of 38%. The Wei 10-3 oil-field in the Beibuwan Basin was the first one put into production (on August 9, 1986), and to November 15, 1987, the accumulated oil output was 453 thousand tons, with 1140 million m³ of gas. The discoveries of the giant gas field Ya 13-1 in the Qiongdongnan Basin and the sizeable oil field Lihua 11-1 in the Zhujiangkou Basin are encouraging.

Experience so far indicates that basins with oil and gas in the South China Sea have higher geothermal gradients, except for the deep sea accumulational and forearc basins.

Figure 10: Interpreted seismic reflection across Zhujiangkou Basin. After Zhai Guangmin and Qiu Zhongjian (1984). 1- Upper Miocene to Quaternary; 2- Middle Miocene; 3- Lower Miocene; 4- Upper Oligocene; 5- Palaeocene; 6- Upper Cretaceous.

Figure 11: Schematic sketch of traps in the Zhujiangkou Basin. 1- fault nose, 2- fault block, 3- compressive anticline, 4- drape anticline, 5- growth anticline, 6- roll-over anticline, 7- semi-anticline, 8- rollover semi-anticline, 9- overtrap, 10- buried hill, 11- unconformity, 12- reef. After Zhai Guangmin and Qiu Zhongjian (1984).

Three source rock suites have been identified: Eocene, Upper Oligocene-Lower Miocene, and Middle-Upper Miocene. Reservoirs, which are dominated by clastics, are found in similar suites: Eocene, Upper Oligocene-Lower Miocene and Middle Miocene-Pliocene, with deltaic and turbidite sandstones and reef carbonates constituting important reservoir rocks.

Traps are related to fault blocks in the basement especially along the northern margin of the South China Sea. In the south, the traps are related to folding, growth faults and piercement structures. Oil and gas are spatially distributed in the margins of depressions or in slowly rising parts of the basins and the major gas-generating areas may be closely controlled by organic source and geothermal gradient.

In terms of their future prospects, the Zengmu, Zhujiangkou, Brunei-Sabah, Malay, Qiongdongnan and Yinggehai basins are regarded as having the best potential. The prospects are somewhat less for Taixinan, Pattani, West Natuna, Mekong, Beibuwan and North Palawan, and poor for Liyue and west

Palawan. More discoveries will undoubtedly be found as exploration efforts continuously go deeper and the number of wells increases.

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Figure 12: Major strike-slip faults of East and Southeast Asia. After Tapponnier and others (1982).