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The neotectonic movement and geological hazards in the Nansha Islands

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Abstract: The paper analyses the types of neotectonic movement and geological hazards in the Nansha Islands and its vicinity. The distribution and values of modern tectonic stress field in the studied region are discussed based on the method of finite element analysis.

INTRODUCTION

In 1987, 1989 and 1990, "She Yan 2" vessel of the South China Sea Institute of Oceanology carried out three sea-bottom seismic researches (about 1,700 km) in the Zengmu Basin, Liyuetan and other regions of the Nansha Islands (Fig. 1). The information on the Quaternary, landforms and neotectonic movement in the studied area were obtained. Combining with other geophysical information of the surrounding region, the neotectonic movement, hazard geology, and regional stability in the Nansha Islands are analysed in this paper.

NEOTECTONIC MOVEMENT TYPES IN THE NANSHA ISLANDS AND ITS VICINITY

Because of different controlled conditions (that is, tension in the north, compression in the south, shear and tension in the west, and consumption in the northeast), and rotation in the Philippines and Kalimantan, the neotectonic movement can be classified into 4 types namely, tension, compression, strike-slip, and rotation (Liu Yixuan, 1981).

Tension type

This type includes those of crustal movements, that is, fault-extension, fault-branch, fault-step, fault-block, and so on.

Fault extension movement

This is distributed in the marine basin of the northern margin of the Nansha Islands, and is the extension movement resulting from the fracture of the continental margin crust, uplift of mantle, thinning of the crust, upwelling of mantle material and the formation of oceanic crust. In late Oligocene, the first extension movement took place at about 18°N. In Early Miocene, the spreading ridge moved southwards to about 15°N. The movement had undergone the course of uplift of the mantle, extension, rift, and formation of oceanic crust.

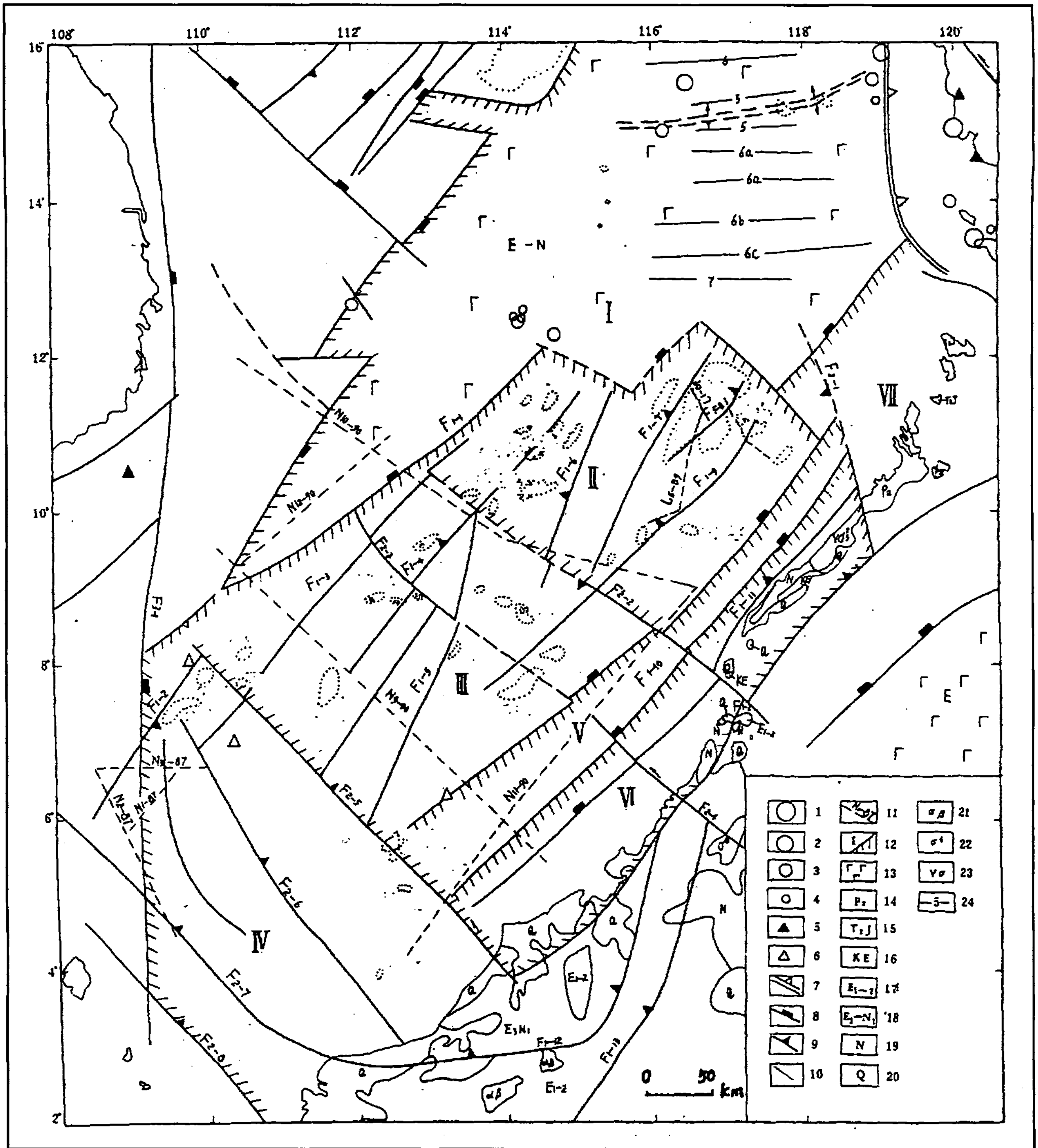
Fault-branch

The fault-branch is obvious in the Zengmu Basin, southwest of the Nansha Islands. The basin is mainly on the shelf and slope of Malaysia, and some on land. It strikes in the NW direction. It is a fault-branch sedimentary basin controlled by the NW striking Beikang Fault. Before late Pliocene, there were several depressions and sedimentation centers in the Zengmu Basin. After late Pliocene, the sedimentary centers moved to the north. Till Quaternary, there is only one sedimentary center filled by 2 km in thickness of mud and sand.

In addition, there are fault branches controlled by NE striking faults east of the Beikang Fault. In late Oligocene-Miocene, the Liyue Crust-Block, accompanied by the S-N spreading of the South China Sea drifted to its present day position. Later, one faultbranch basin was formed between its southeastern part and Haimatan. Here, there was a thickness of 100–150 m of marine sediments deposited in Pliocene-Quaternary. It is a fault-ranch which had been formed since Pliocene.

Fault-blocks

These are distributed in the Nansha Crust Block. They are blocks cut by NE and NW striking faults. There are four step surfaces as shown by shallow reefs, with depths of 30 m, 50 m, 60 m and 70 m. The erosion relics on these surfaces mean that these reefs have been exposed above sea level. In the sedimentary strata of the fault-branch in



1.	epicenter of M_s = 7–7.9	2.	epicenter of M_s = 6–6.9	3.	epicenter of M_s = 4–5.9
4.	epicenter of M_s < 4	5.	active volcano	6.	died volcano
7.	extremely-active fault	8.	medium-active fault	9.	weakly-active fault
10.	micro-active fault	11.	seismic section	12.	distribution region of Neotectonism
13.	oceanic crust	14.	Paleozoic stratum	15.	Mid-Triassic-Jurassic stratum
16.	Cretaceous-Early Tertiary stratum	17.	Paleocene-Eocene stratum	18.	Oligocene-Early Miocene stratum
19.	Late Tertiary stratum	20.	Quaternary stratum	21.	Cenozoic eruption rock of intermediate-basalt
22.	Cenozoic ultrabasic rock	23.	basic-ultrabasic rock		
24.	magnetic anomaly lineation				

I.	Southwest fault-block depression zone of south China Sea Basin	II.	Zhenhe-Liyue fault — block uplift zone
		III.	Yunqing-Nanhua fault — block uplift zone
IV.	Zengmu depression zone	V.	Nansha trough fault — block depression zone
VI.	Palawan-Sabah shelf margin thrust fault uplift zone		

F_1 : The fault system striking NE (F_{1-1}—F_{1-13}) F_2 : The fault system striking NW (F_{2-1}—F_{2-8})
F_3 : The fault system striking SN (F_{3-1})

Figure 1. Neotectonism of the Nansha Islands.

southeast Liyuetan, there are erosional surfaces or buried reefs between Q_2 and Q_1, and Q_1 and N (Fig. 2). It is shown that the fault-block movement in Liyuetan and its vicinity is obvious.

Fault-block inclined

This is distributed in Zengmu Basin, which is a northwards inclining fault-branch basin. In some parts of its south, the upper strata of Miocene and Oligocene are missing. In its northern parts, strata are almost continuous. The thickness of the Quaternary in the north is about 2 km, while in the south is about 500 m. These all show that the basin is northwards inclined.

Fault-step and gravitational slide

This can mostly be seen at the margin of the Southwest Oceanic Basin of South China Sea and the northwest margin of Liyuetan (northwest of Section L_1). Between the depths of 2,000 m and 0 m, there are four fault-steps (at depths of 1,740 m, 1,350 m, 765 m and 300 m), which are all controlled by faults (Fig. 3) on the eastern margin of Liyuetan, and in addition there are also two steps which are controlled by faults and covered by 100–200 m thickness of later sediments.

Compression types

These are distributed in the system of island arc-trench on the eastern and southern margin of the Nansha Islands. They are compression structures resulting from continental margin spreading of the South China Sea, southwards and eastwards oceanic crust subduction, terrane collision, and so on.

Fold structure

The strata of E_3-N_1 in northwest Kalimantan were strongly folded by Mily Movement in late Middle Miocene. The Mily Geosynclinal Fold Zone was formed by the outer Early Himalaya Geosynclinal Fold Zone. During the late Pliocene and early Pleistocene, the N_2 stratum of the Mily Geosynclinal Fold Zone was gently folded by the Taiwan Movement and magmatism. The strata of N_2 and its lower horizons in the Zengmu Basin were lightly deformed, resulting in an angular unconformity with the upper Quaternary stratum.

Thrust and nappe structure

Northeast Kalimantan was strongly compressed and folded by the Early Himalaya Movement at the end of Eocene, which was accompanied by thrust faults. The resulting ocean, geosynclinal flysch, basic-ultrabasic volcanic rocks and so on, were thrusted again during Pliocene.

Analyses of seismic information, show that the limestone of Oligocene-Early Miocene in the northwest continental margin of Sabah was napped by a mélange that came from another place formed after Early Miocene (Fig. 4).

Subduction and consumption

Because of a new S-N spreading of the South China Sea in Oligocene-Middle Miocene, there was new oceanic crust formed in the Central Basin. For the counter-clockwise rotation of Luzon Island and its obduction on the oceanic crust of the South China Sea, and the counter-clockwise rotation of about 45° of Kalimantan till Miocene, the Paleo-South China Sea was subducted under the Sulu Sea Basin and Northeast Kalimantan.

Strike-slip and rotation

They are mainly shown on crustal block float, strike-slip fault, and the relatively vertical and rotation movement of two crust blocks.

After the Indo-China Movement, the Paleo-Tethys Sea was closed. The Liyuetan-North Palawan Crust Block was distributed on the active north continental margin of the South China Sea. With the development of the new S-N spreading, the block floated extensively southwards. In Late Cretaceous-Miocene, Kalimantan had rotated about 45° anti-clockwise, resulting in the consumption of M8-M11 oceanic crust under the Sulu Sea Basin and Northeast Kalimantan, and the formation of three accreting belts. When spreading of the South China Sea ceased in late Miocene, the Nansha Crust Block converged with Kalimantan, North Palawan collided with South Palawan, resulting in the present day structure system.

The NW striking faults, such as Beikang fault, are strike-slip faults which are related mainly to the continuous rotation northwards of the Philippine Island-Arc tectonic zone.

THE TYPES AND CHARACTERISTICS OF THE ACTIVE FAULTS

The directions of the active faults are NE, NW, and SN in the Nansha Islands and its vicinity.

NE fault system

The southern marginal fault zone of the sea basin

The fault zone reaching down to the basement of the lithosphere is situated along the margin of the southern South China Sea basin. It is a boundary between the transitional crust and the oceanic crust, consisting of four faults, striking

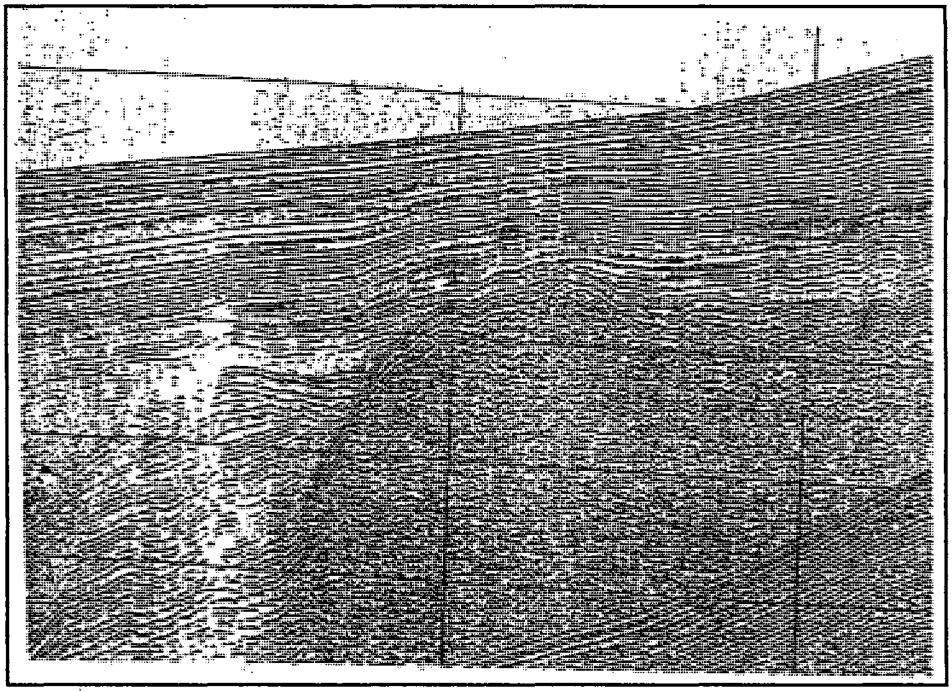


Figure 2. Buried reef in the southeast margin of Liyuetan shown in Section L_2.

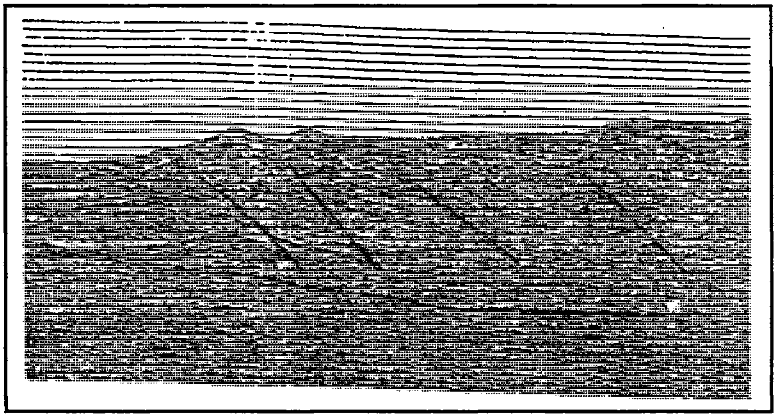


Figure 4. Nappe structure shown in the southeast margin of the southwest part of the Nansha Trough.

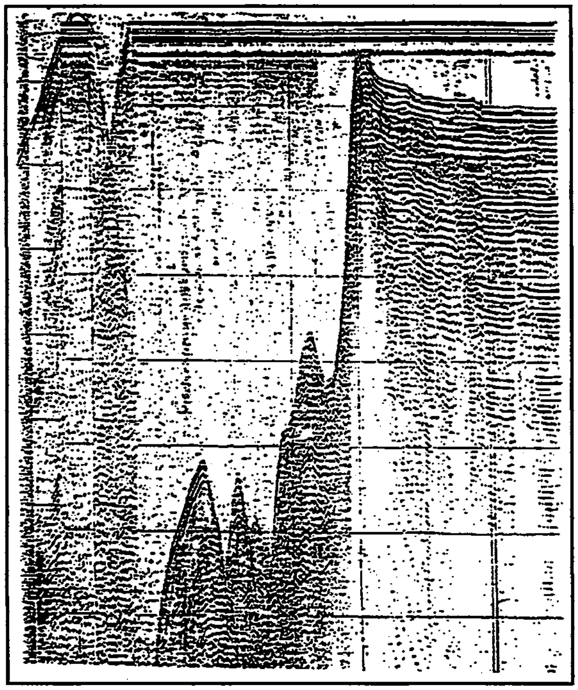


Figure 3. Step-fault zone in the northwest of Liyuetan shown in Section L_1.

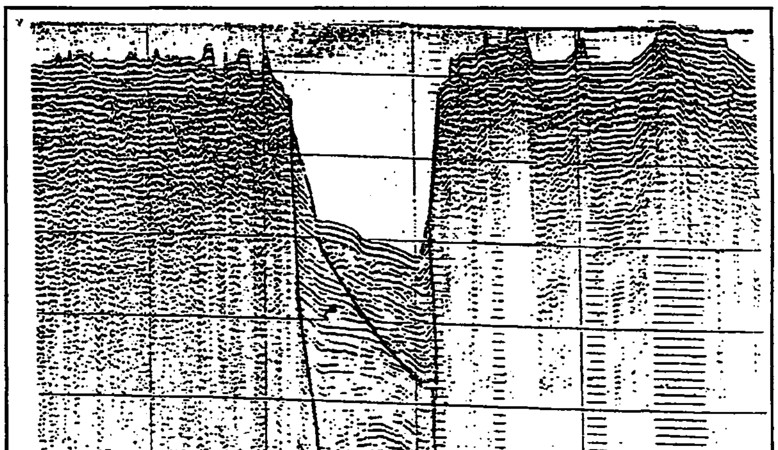


Figure 5. Fault graben structure of Liyuedong fault zone shown in Section L_1.

N65°E, with a length of about 1,000 km. The landform contrast along the fault is very remarkable. South of it is an uplifted continental slope zone; while north of it is a deep basin with depths of 3,500–4,000 m. North of this sea basin is a stripe changing area of positive and negative anomalous magnetic field, striking ENE to EW. The southern continental slope is a wide and flat high positive anomalous magnetic area. Along the fault zone the Bouguer anomalies show a grading belt. The fault zone was formed by the first spreading of South China in Late Cretaceous-Neogene. It has been active since Neogene, being a medium active fault (Liu Yixuan, 1985).

Dayuantan fault zone

This zone lies in the vicinity of latitude 11.5°N, longitude 110.4°E in Section L_1, striking N28°E, dipping to the NW, with a length of 350 km. It is an active Quaternary fault, consisting of four small faults, with fault separations of 525 m, 510 m, 198 m and 287 m. The marine landform along the fault zone varies very strongly. The depth of sea water changes from 30 m to 1,200 m, forming the deep trough between Dayuantan and Liyuetan (Fig. 3). There is no record of earthquake along the fault zone. It belongs to a weak active fault.

Liyuedong fault zone

This zone is shown in Section L_1 and Section L_2 in the vicinity of latitude 11°N, longitude 116.5°E of Section L_1. The marine landform along the fault zone varies very remarkably. The water depth changes from 30 m to 100 m. Because of the influence of ocean current erosion, a submarine trough has formed with a width of about 5 km (Fig. 5). At latitude 11.3°N, longitude 117°E of the Section L_2, the landform contrast is very remarkable. The surface deposits in the north are different from those in the south of this fault zone. The water depth changes from 90 m to 170 m. The fault separation is 280 m (Fig. 6). It belongs to the weak active fault.

Zhongxiaotan fault zone

The fault zone extends from northern Zhongxiaotan to Andutan, a length of 600 km. It is shown in Section L_2 and Section L_5. In Section L_2, the fault zone cuts through the layer of submarine deposit and forms small submarine valley (Fig. 7). In Section L_5, there is a volcano along the fault (Fig. 8). It belongs to the weak active fault.

Nansha trough fault zone

This zone lies in the marine trough of the Nansha Islands, striking N35°E, with a length of 1,000 km. The submarine landform contrast is very remarkable. The vertical displacement is 1,500–2,000 m. It consists of a series of small faults (Hinz, 1987). The fault separation reaches 730 m in the upper part of the Cretaceous Period. The Bouguer anomalies in the Nansha Trough show a positive anomalous-zone. The gravity field shows a gravity grading belt. The fault zone was mainly active in Tertiary and was still active in Quaternary. An earthquake of $M_s = 6$ took place in July 21, 1930. It belongs to a medium active fault.

NW fault system

Haimatandong fault zone

This zone is a left-rotated shear fault, striking N25°W, with a length of 500 km. The landform contrast is remarkable. The seismic section shows that the fault cuts the Miocene strata, with a fault-separation of 200 m. Because of the first spreading of the South China Sea in L. Cretaceous-Neogene, the Liyuetan-Palawan block drifted to the southeast. The fault zone is the tectonic line of the collision between the drifting block and southern Palawan (Mitchell, 1985). Strong activities occurred in the Eogene period. The earthquake activity is relatively weak. It belongs to the weak active fault.

Cheguajiao fault zone

This zone strikes N45°W, dips to the SW, with a length of 600 km. It is a left-rotated shear glading fault, cutting the L. Miocene through to the Cretaceous layer, with a fault separation of 100 m. No volcanoes and earthquakes occurred along the fault zone. It belongs to the weak active fault.

Beikang fault zone

This zone extends from Guangyatan to Beikang Ansha and extends to Kalimantan, with a length of 700 km. It is an obvious tectonic boundary between the NE and NW striking faults. The fault zone consists of a series of the normal slip faults shown in seismic profiles, striking NW, dipping to the SW with dip angles of 30°–48°, cutting the Cretaceous-Miocene strata, and some cutting the Pliocene or Quaternary strata, with a fault separation of 0.5–1 km. It belongs to the weak active fault.

SN fault system

This system lies in vicinity of longitude 109°E, with a length of 1,000 km. The submarine landform contrast is very remarkable. The vertical separation is about 2,000 m. There is volcano activity along the fault system at Polu Island. The fault cuts the Q_4 sequence shown in Section N_2 (Fig. 9). It belongs to a medium active fault.

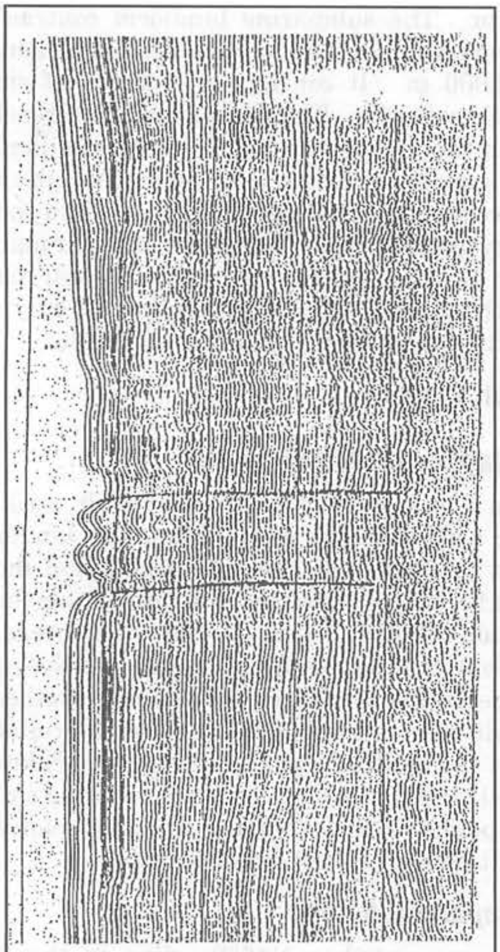


Figure 7. Zhongxiaotan fault zone shown in Section L_2

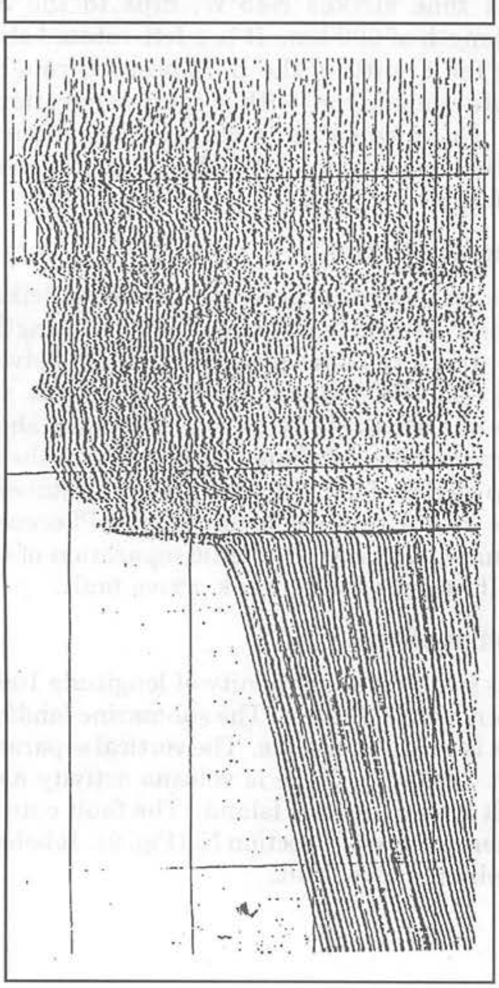


Figure 6. Liyuedong fault zone shown in Section L_2

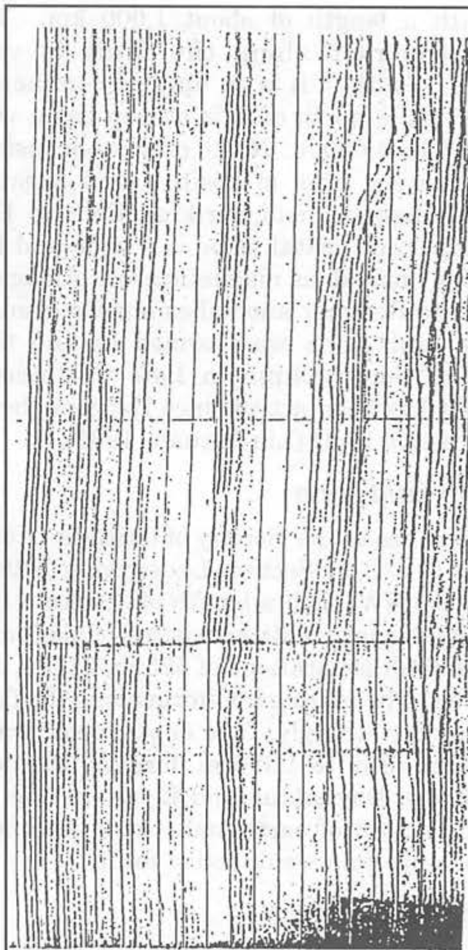


Figure 9. Binghai fault of the west South China Sea shown in Section N_2.

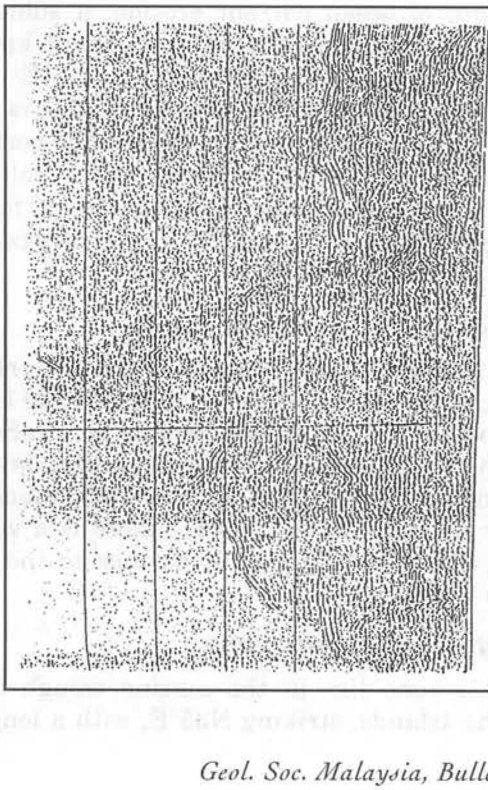


Figure 8. Eruption of basalt along Zhongxiaotan fault zone.

THE TYPES OF THE GEOLOGICAL HAZARDS

Slides, collapse, active faults and graben, modern tide, erosional landforms, buried negative landforms, reef pinnacles and buried reefs, mud cones, volcanoes, mud interlayers and gas eruptions are the types of geological hazards which are harmful to sea-floor engineering.

Earthquakes and volcanoes

Earthquake activities are relatively weak in the Nansha Islands. Only a earthquake of M = 6 took place in the Huangroad reef (7.10°W, 114°E) on July 21, 1930. In the northern waters of the Nansha Islands, there are two earthquakes of M_s = 4.5–6, four earthquakes of M_s = 3–4.4, and three earthquakes of M_s < 3. The volcanic activities are relatively quiet in the Nansha Islands and its vicinity. There are three died Quaternary volcanoes, located 5 km from Xiweitan, 80 km from southern Wanantan and very close to Nantongtan. A modern volcano activity occurred in Polu Island in 1923, belongs to a active volcano.

Active faults and grabens

The locations where faults cut Q or N_2-Q sequences reflected by the seismic profiles, or fault cliffs and fault steps, are especially hazardous districts. There is a graben in Section L_1 (Fig. 4), controlled by the two Quaternary faults.

Sea-floor slide

The sea-floor slides in the Nansha Islands are shown in the Section N_3 and Section N_{12} (Figs. 10–11).

Reef pinnacle and buried reefs.

A reef pinnacle is shown in Section L_1 in Liyuetan, at water depths of 50–80 m together with a series of small valleys (Fig. 12). There are about 110 reefs around the Liyuetan area at water depths of 30–40 m. This is a dangerous region for navigation because there are ancient reefs covered by the modern sediments as shown in Section L_2.

Marine valley and mud cone (Fig. 13)

There are a lot of small valleys in the Nansha Islands resulting from the development of a series of active faults. The largest valley is the Nansha trough, with a length of 675 km and a width of 15–65 km and a depth of 1,600–2,900 m. There is a mud cone in Section N_3.

Buried negative landform (Figs. 14–15)

The sea-floor landforms were formed by river, tide, wave and current in a low sea-level condition during the Quaternary glacial stages. These negative topographic units were covered by post-sedimentation after the postglacial period, creating the buried ancient delta, river bed, sea valley, low area and lagoon. They may cause unbalanced sinking of constructions because of the large

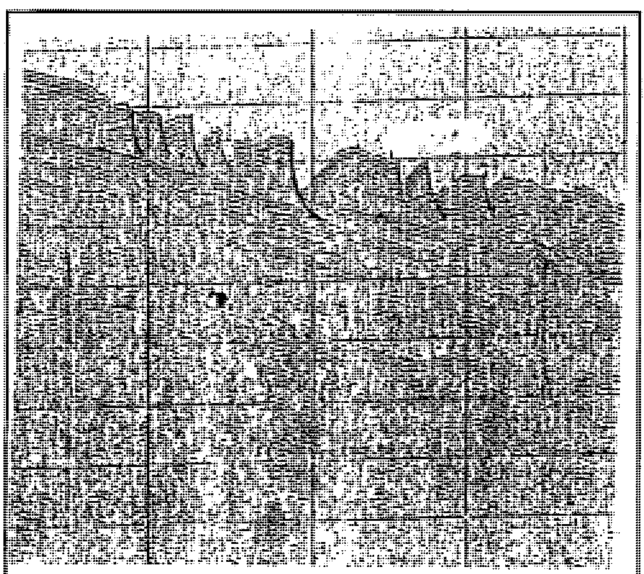


Figure 10. Battery slides shown in Section N_{12}.

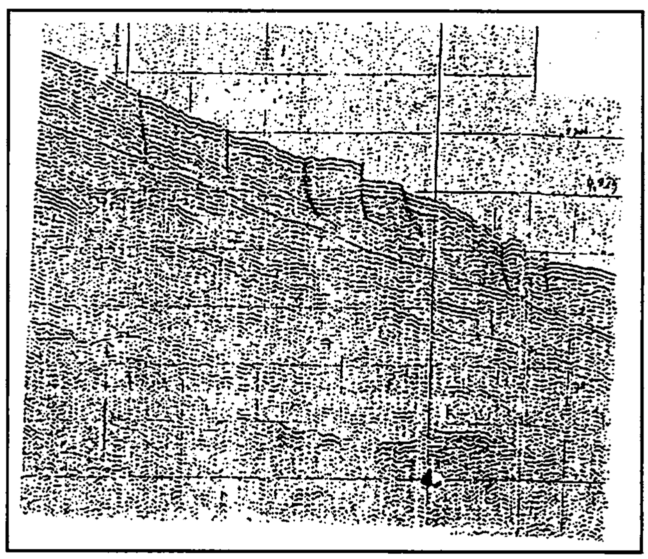


Figure 11. Sea-floor slides shown in Section N_{12}.

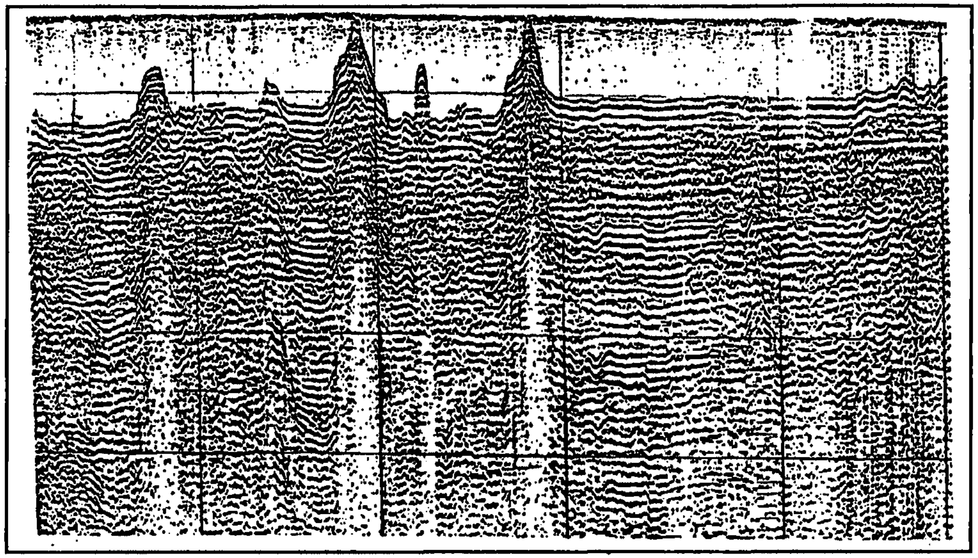


Figure 12. Reefs developing in Liyuetan.

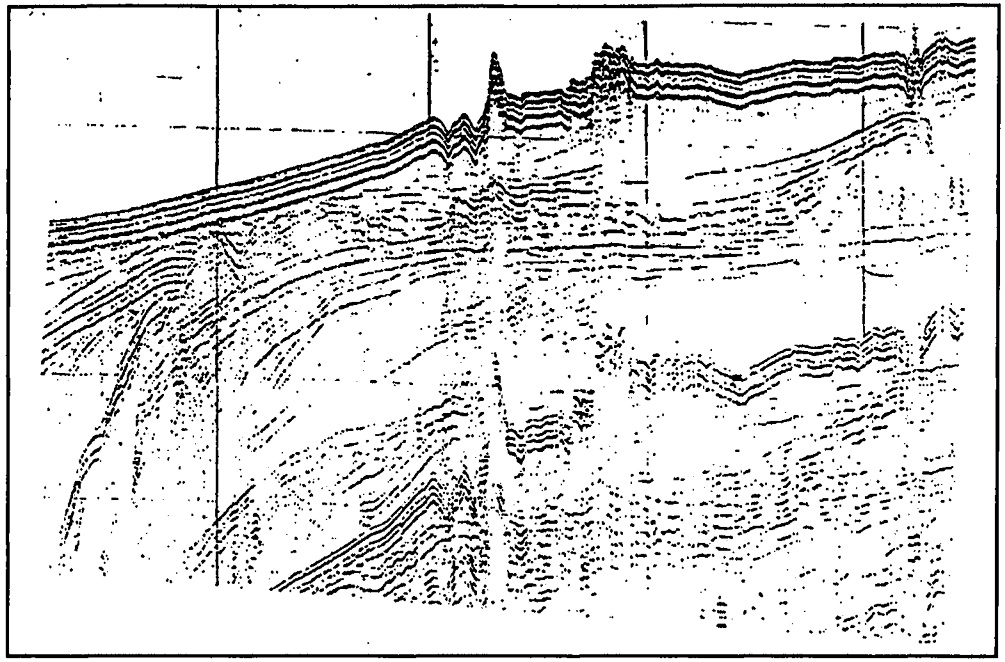


Figure 13. Mud shown in Section N_3.

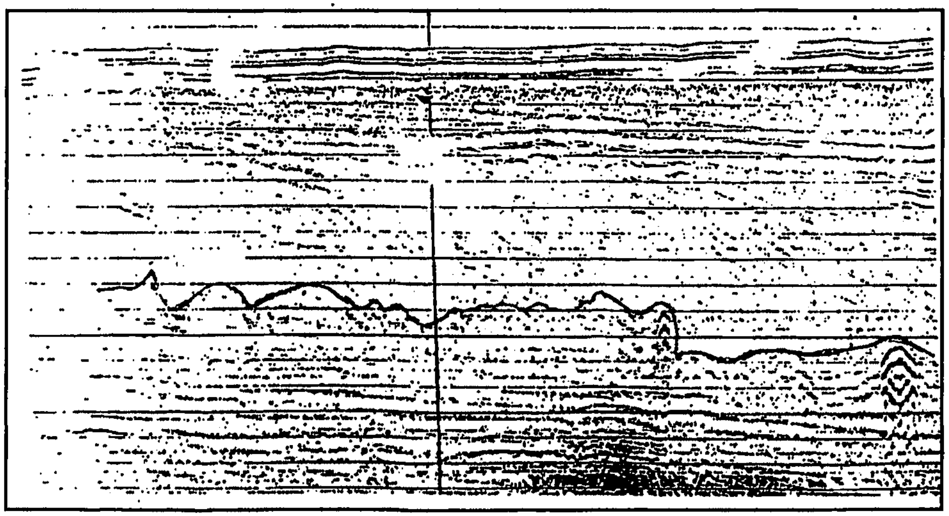


Figure 14. Ancient erosion shown in Section N_2.

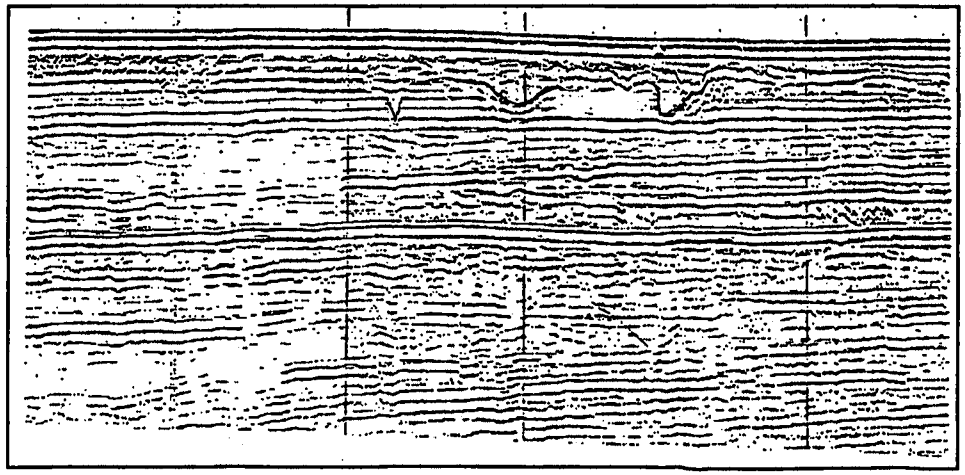


Figure 15. Buried ancient river valley shown in Section N_3.

gradient, coarse sediments and fine overlying strata. Drilling sites near these paleo-landforms should pay attention to these hazardous geological factors.

THE DISTRIBUTION OF THE MODERN TECTONIC STRESS FIELD AND EVOLUTION OF THE NANSHA ISLANDS

The distribution framework of the modern tectonic field in the Nansha Islands and its vicinity

The modern tectonic stress field of the Nansha Islands and its vicinity as a stress problem of elastic plate has been computed by means of the finite element method. Taking trench-subduction zones as major boundaries the studied region comprises 5 parts divided into 1,130 triangular elements with 612 points with different crustal thicknesses, velocity of P-Wave, density or Poisson's ratio. Four models of boundary forces, which represent the forces exerted to the Nansha and its vicinity by Indian Ocean-Australia Plate and Philippine Sea plate respectively, have been tested (Zhan Wenhuan *et al.*, 1990). The directions of maximum compressive principal stress obtained from the calculation have been compared with those of focal mechanism solutions. The model which agreed most satisfactorily with focal mechanism solutions was selected as the available model (Fig. 16).

Modern tectonic stress field and evolution of the Nansha Islands

The tectonic stress field in the Nansha Islands has experienced a complicated dynamic evolutionary process in the geological history. Four evolutionary periods, namely, compression, tension, gravity adjustment, and present compression and convergence periods, have been experienced under the influence of the periphery lithospheric plates.

Subduction and compression period

The Pacific Plate accreted, and Kula Plate drifted to the northeast, leading to the profuse subduction beneath the continent of South China and Indochina during M. and L. Jurassic to E. Cretaceous time. The subduction zone is approximately located from the East Taiwan Longitudinal Valley to south of Dongsha and then to the Natuna arc. The continent of South China uplifted, and tectonics and magma activated, forming a series of NNE compression faults, continental fault-subsided basins, and calc-alkaline magma belt. The L. Mesozoic eugeosyncline sediments developed in the continental margin. The central and northern area of the South China Sea and the coast of South China belong to the Cathaysoid (Andes) active continental margin in this period. South China in Mesozoic is called Circle-Pacific activation (ocean-continent subduction) in the view of geotectonics.

Period of continental margin spreading

The feature of tectonic stress field in the Nansha Islands and its vicinity changed from compression to tension during E. Cretaceous to Miocene. The India and Eurasia Plates were brought to mutual collision, and convergence, and the mantle flowed to the east and southeast, the mantle uplifted, high heat flowed upwards to the surface, crust thinned and separated leading to the two or three times of spreading. This might be ascribed to the blocking of mantle flow by the subduction of the Kula-Pacific oceanic ridge to the southeast Asian continent. The first spreading occurred at the end of Cretaceous to M. Eocene (126–63 Ma), was a tensional spreading in the direction of NW-SE and created the Paleo-South China Sea. The second spreading occurred during L. Oligocene to M. Miocene (32–17 Ma), with the spreading axis located in the vicinity of 15°N forming the Central Basin. The third spreading occurred during Miocene time (15.1 Ma), characterized by the small spreading in the direction of NW-SE in South west of the basin. The spreading of the South China Sea created the present topographic framework of the marginal sea. The northern area became a spreading continental margin; the eastern area an obducted compressive margin; the southern area a convergent margin; the western area a tensional-shear margin; and the Central Basin a small spreading basin. The spreading of Cenozoic continental margin of the South China Sea might be called an activation of marginal sea in the view of geotectonics.

Gravity adjustment period

The Luzon island-arc has been rotated counter-clockwise 14° since M. Miocene. This was caused by the compression of the Philippine Sea Plate to the west and the India-Australia Plate to the NNE during Pliocene to Pleistocene time (Taylor and Hayes, 1983). Because of the collision between the East Taiwan volcanic arc and the West Taiwan block, the spreading of the South China Sea was blocked, causing the cooling of the oceanic crust and the subsidence of the Central Sea Basin. The gravity subsidence terraces were formed from the perimeter to the center of the basin. The adjustment occurred during the transition of the horizontal spreading to compression and the vertical gravity subsidence. The gravity subsidence of step fault is called gravity gliding tectonics.

Figure 16. Distribution of maximum compressive principal stress in the Nansha Islands and its vicinity.

Compression and convergence period

The modern tectonic stress field in the Nansha Island is considered to be overall compressive and convergent according to the result of the calculation and analysis mentioned above. A strong compressive stress came from the east, because the Philippine Sea Plate moved to the northwest, while the India-Australia Plate moved to the northeast. This resulted in a biaxial compression in the Nansha Islands. The compressive transcurrent activities are dominant among the active faults in the plate margin. A M = 5.75 earthquake occurred on October 7, 1965 in the southwest subbasin of South China Sea with the focal depth of 5 km. The horizontal compressive direction is 355° and it is a thrust fault indicated by the focal function. This indicates that the modern tectonic stress field in the Nansha Islands might be in the compressive and convergent period.

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