UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Tectonics of the Yellow Sea and the East China Sea

By

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Translated by K. Y. Lee[2]

This report was published in "The Geology of the Yellow Sea and the East China Sea": Section 1, Tectonics and Earthquake Zone, p. 1-22.

Open File Report 84-421

This report is a translation from the Chinese, thus has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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1984

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ILLUSTRATIONS

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ABSTRACT

Detailed geophysical investigation of geophysical features in the Yellow Sea and the East China sea provides information which aids in deciphering tectonic patterns and in constructing structural models; it also provides a means of comparing their genetic relation with geophysical features in the Asian epicontinental seas (marginal seas) of the western Pacific Ocean.

Seven magnetic fields are determined: 1) magnetic anomaly field with large gradient variation along the northern margin of the South Yellow Sea, 2) negative anomaly field consisting of broad anomalies with low intensity in a large area of the South Yellow Sea, 3) magnetic anomaly field with large variation trending northeastward from the southeastern China coastal region to the Korean Peninsula, 4) negative anomaly field with small variation in shallow areas of the East China Sea, 5) high gradient magnetic anomaly field west of the Okinawa trough, 6) negative anomaly field with small variation in the Okinawa trough, and 7) field of positive magnetic anomalies in alternate positions with negative anomalies in the area of the Ryukyu Islands. Generally, positive anomaly zones reflect positive structural belts, and negative anomaly zones are mostly associated with negative structural belts.

Positive Bouguer anomalies are dominant in the Yellow and East China Seas. They are relatively low, about 10 milligals, in the Yellow Sea and relatively high, about 20 milligals, in the East China Sea. Most readings in the Okinawa trough are over 100 milligals. Generally, the gravity fields of the Yellow and East China Seas are not isostatic, and the isostasy of the gravity fields of the transitional continental slope belt is highly unstable.

Areas of highest heat flow in the Okinawa trough form a pattern that follows the trend of the trough axis and average 3.62 HFU, reaching a maximum of as much as 8.95 HFU. On the rough sea floor of areas adjacent to the trough, values range from 1.05 to 8.95 HFU. This relation indicates that the Okinawa trough is in a youthful development stage and is in the process of expanding.

Three linear seismic zones are defined: 1) the Subei-South Yellow Sea seismic zone in the South Yellow Sea zone of subsidence, 2) the Central East China Sea seismic zone in the East China Sea zone of subsidence, and 3) the Taiwan-Ryukyu seismic zone, which is part of the well known Circum-Pacific seismic zone where seismic activity is more intense than in other areas. The Okinawa trough has a transitional earth's crust (15 to 21 km), which borders the continental crust (30 to 33 km) on the west and the oceanic crust (6 to 9 km) on the east. Thick sedimentary cover overlying the acoustic basement has been determined by correlation of seismic records. It includes

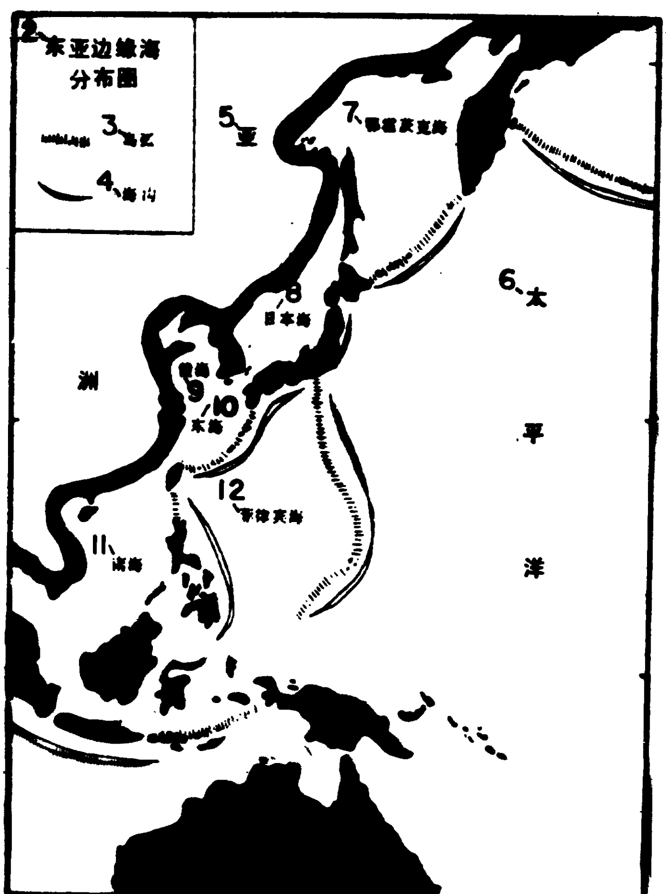
rocks of Lower Tertiary, Miocene, and Pliocene to the Plio-Pleistocene ages. Locally, the Miocene is missing.

It is believed that the earth's rotation and thermal dynamics are the primary moving forces producing the plate collision, secondary expansion, and cognate torsional expansion. In detail, seven structural units are identified in the Yellow Sea and the East China Sea: 1) the North Yellow Sea-Jiaoliao rise zone, which extends from the Jiaodong Peninsula via the North Yellow Sea to the Liaodong Peninsula; 2) the South Yellow-Subei subsidence zone, which extends from the South Yellow Sea northeasterly to south-central Korea; 3) the Fujian-Lingnan rise zone, which extends from the mountain terrain of Guangdong, Fujian, and Southern Zhejiang provinces via the seafloors of the Yellow Sea and the East China Sea, and Jizhou Island and northeastward beyond the Korean Peninsula; 4) the East China Sea subsidence zone, which includes almost the entire East China continental shelf. Miocene strata in this zone possibly contain source beds for hydrocarbons. 5) the marginal rise zone of the East China Sea continental shelf, which occurs along the margin of the East China Sea continental shelf; 6) the Okinawa trough rift zone, a linear expanded tectonic belt with a north-northeastern trend; and 7) the Ryukyu Island arc-trench system, which is a typical model of an island arc-trench structure of the western Pacific Ocean.

Plate collisions have lead to the formation of secondary expansion and cognate torsional expansion, which are responsible not only for the structural patterns of the Yellow Sea and the East China Sea but also for the origin of epicontinental seas and the growth of continental crust. The sea-floor topography is described in detail.

INTRODUCTION

A chain of marginal seas, including the Sea of Okhofsk, Sea of Japan, Bohai, Yellow Sea, East China Sea, and South China Sea (fig. 1), borders the western Pacific island arc on the east and the Asian continent on the west. Li, Siguang (1948) mentioned that the "problem on the origin of these Neocathaysian seas: Bohai, Yellow Sea, East China Sea, and Sea of Japan has not yet been solved; and in addition to its own merits, this problem has similar significance in view of the importance of Pacific Ocean basin development and the structural history of Asian continent."



1. Figure 1
2. Distribution of the East Asian epicontinental seas.
3. Island arc.
4. Sea trench.
5. Asia.
6. Pacific Ocean.
7. Sea of Okhofsk.
8. Sea of Japan .
9. Yellow Sea.
10. East China Sea.
11. South China Sea.
12. Philippine Sea.

During the 1930's, J. S. Lee (1939, p. 211-241) proposed the "Neocathaysian Structural System" to represent three north-northeasterly trending uplift belts which alternate with three subsidence belts along the East Asian continental shelf. Otsuka (1939, p. 481-519) pointed out that three folded belts extend from the Sakhalin Island, Japan, Ryukyu Islands to Taiwan. Jin, Xianglong and others (1962, p. 110-111), based on field investigations, concluded that the South China Sea is a subsiding belt, which consists of two depressions and one swell and thus should not be included in the secondary Neocathaysian uplift belt. Since the 1960's, numerous countries have expanded geophysical investigation in the South Yellow Sea and the East China Sea (Emery and Niino, 1967; Wageman and others, 1970; Leyden and others, 1973; Ludwing and others, 1973; and Mu Cun Zheng Zhao and others, 1975). Five structural belts, such as Fujian-Lingnan fold belt, Okinawa trough, and Ryukyu island arc, are recognized beneath the sea floor of the Yellow and East China Seas. The basic structural patterns of the Yellow Sea and the East China Sea are common knowledge; but in detail, proposed structural models and relation to Asian epicontinental seas (marginal seas) differ. This paper attempts to resolve problems on the basis of fundamental characteristics of the geology and geophysics of the Yellow Sea and the East China Sea.

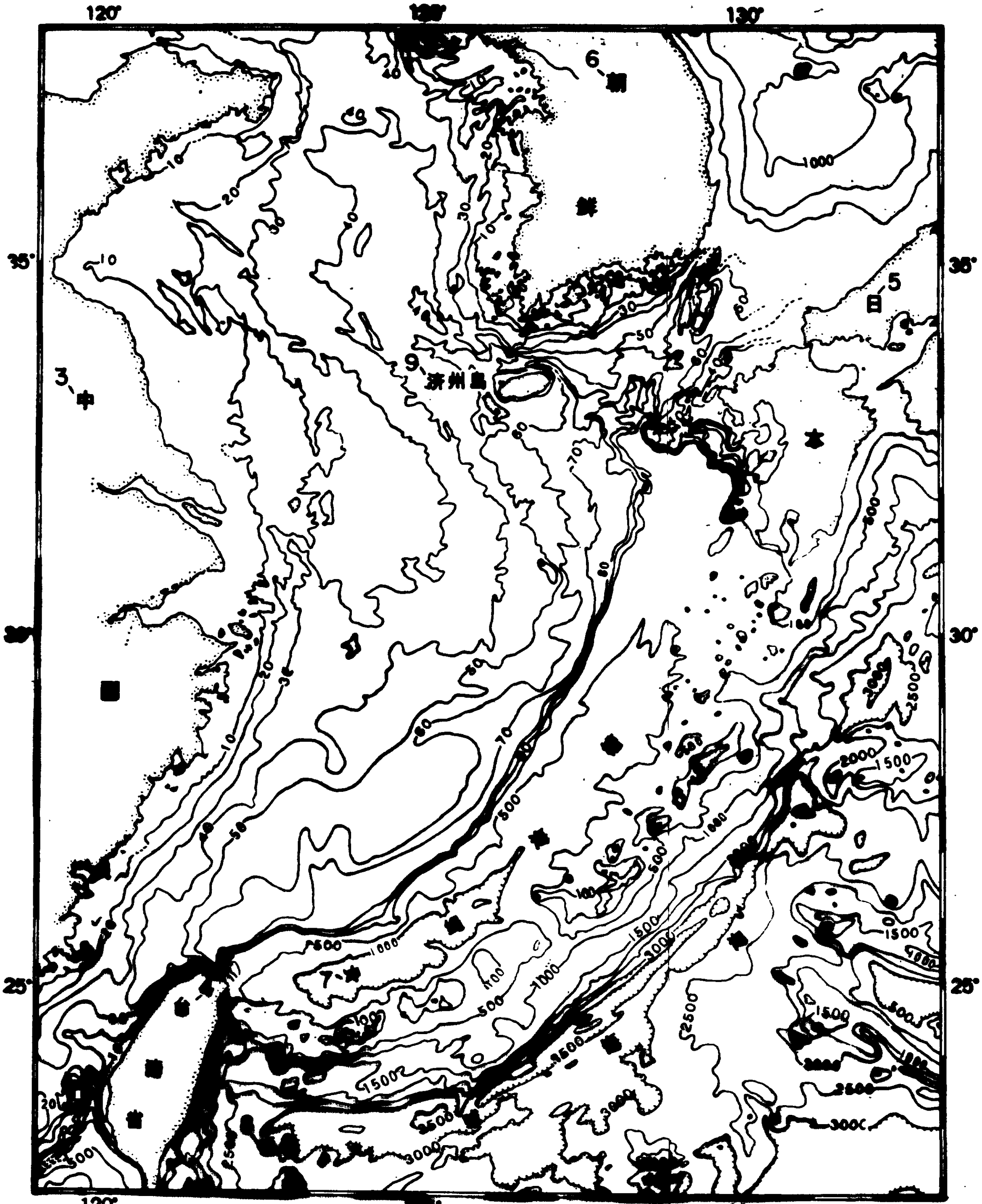
BASIC CHARACTERISTICS OF GEOLOGY AND GEOPHYSICS OF THE YELLOW SEA AND THE EAST CHINA SEA

The Yellow Sea and the East China Sea are marginal seas between the Asian continent and the Pacific Ocean island arcs. They are situated in the eastern part of China and are bounded by the continental shelf on the west and by Korea, the Kyushu and Ryukyu Islands of Japan, and Taiwan of China on the east.

Topography of the Sea Floor

The floors of the Yellow Sea and the East China Sea slope gently downward to the southeast. They are adjacent to the continental shelf on the west and connect with Bohai on the north to form a large-scale epicontinental sea, which is one of the largest continental-shelf seas in the world. The topography of the East China Sea floor, which is part of the continental slope, is varied. Generally, this slope represents a transitional zone between the Asian continent and the western Pacific Ocean (fig. 2).

The topography of the Yellow Sea floor has an average slope angle of 1' 21". It is covered with an average water depth of from 60 to 80 m, and is as much as 103 m deep north of Jizhou Island in the Korean strait. The East China Sea is widely open and has an average water depth of 349 m. The western two-thirds of the East China Sea is underlain by the continental shelf, and the eastern third is underlain by the transitional zone. The continental shelf of the East China Sea is wide to the north and narrow to the south. The sea floor is inclined 1' 17" toward the southeast. This floor is covered with an average water depth of 72 m, but most of the sea floor is covered with a water depth ranging from 60 to 140 m. Depths range from 120 to 200 m outside the margin of the continental shelf. The continental shelf is divided approximately into the eastern and western parts by the 50 to 60 water depth line. The topography of the floor of the western part of the East China Sea is complex and contains numerous islands and islets; whereas the topography of the floor beneath the eastern part has little relief. Between the Yellow Sea and the East China Sea are several small submarine rock reefs (socotra rock), such as the Suyan reef and the Hupi (tiger skin) reef, etc. These rock reefs and interspersed islands follow an irregular line that trends northeastward from the Zhoushan Islands on the south to Jizhou Island on the north. This line of islands and reefs is the natural division between the Yellow Sea and the East China Sea and reflects some of the characteristics of the regional structure. Of special interest among these reefs and islands are: a) an area 2 km (32°07'N, 125°11'E) east of Hupi reef where water depth ranges from 31 to 55 m and where a submarine volcano was discovered beneath a cover of coral reef (S. M. Lee, 1973); b) the Jizhou Island, northeast of the Hupi reef, which contains volcanoes; and c) numerous lava flows which are extensive near the Zhejiang shoreline, southwest of the Hupi reef. The presence of volcanoes indicates that these reefs and islands are with the same structural belt.



1、 2
圖 2 東海海底地形圖
(根據美國海軍海洋局資料*)

* U. S. Naval Oceanographic office, 1969. Bathymetric Atlas of the Northwestern Pacific Ocean.

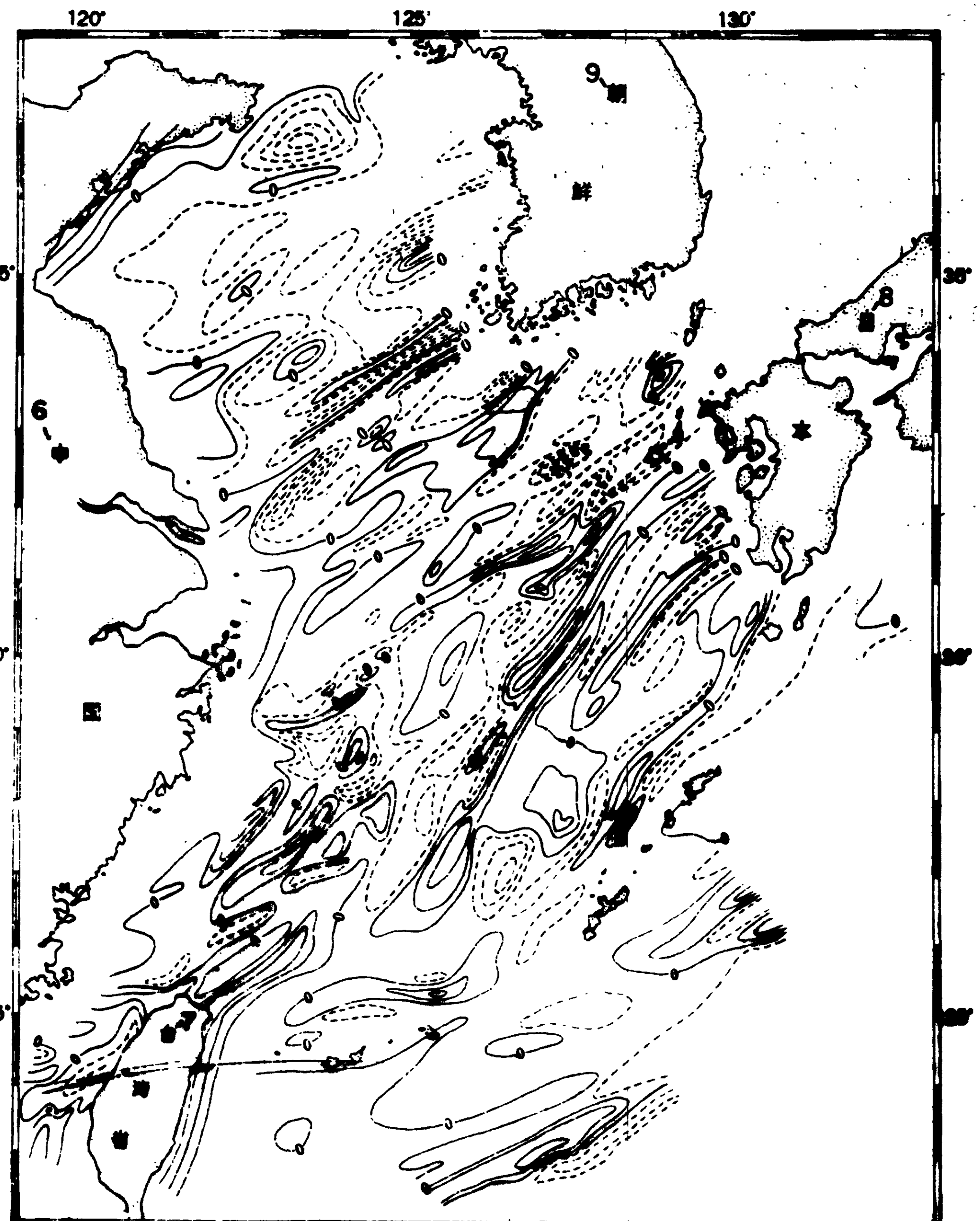
1. Figure 2. 2. Sea-floor topography of East China Sea (based on U.S. Naval Oceanographic Office, 1969, Bathymetric Atlas of the Northwestern Pacific Ocean). 3. China. 4. Taiwan. 5. Japan. 6. Korea. 7. Okinawa trough. 8. Ryukyu trench. 9. Jizhou Island.

The continental slope of the East China Sea is arc-shaped and is inclined about 3°, which is more than 300 times steeper than the inclination of the continental shelf.

The Okinawa trough is the principal topographic feature of the continental slope of the East China Sea. It is a north-northeasterly trending arc-shaped trough. The northern part of this trough is about 600 to 800 m deep and has a small angle of slope, whereas the southern part is about 2,500 m deep and has a large angle of slope. The maximum water depth is 2,717 m to the north-east of Taiwan. The angle of slope of both flanks of this trough is about 10°. The angle of slope of the trough floor is very small. The Ryukyu Islands, Kyushu Island, and the submarine island chains of these islands and islets are east of the Okinawa trough. The width of the submarine island chain at Kyushu Island is 30 to 50 nautical miles, and at the Ryukyu Islands, it is 2 to 20 nautical miles. Numerous sand banks, rock bars, and volcanoes along the island chain give rise to a complex topography. The Ryukyu Islands are part of the marginal island arcs of the western Pacific Ocean and form the natural division between the Pacific Ocean and the East China Sea. These islands are in the outer arc of two parallel island arcs. This outer arc or fore arc (ocean flank) is nonvolcanic, and where it projects above sea level forms the Ryukyu Islands. The back arc (East China Sea flank) is a submarine volcanic ridge. Outside the Ryukyu Islands in all directions the water depth generally rapidly increases, and the bottom slopes at angles of as much as 10 to 13°. The sea floor descends to a depth of about 6,000 m in the Ryukyu trench, which marks the lower limit of the continental slope. The western Pacific Ocean floor (Philippine Sea) is to the east of this sea trench.

Magnetic Field

The magnetic fields of the Yellow Sea and the East China Sea fully reflect the characteristics of sea-floor geologic structures and are the source of the principal data for explaining sea-floor structural patterns (Jin and Yu, 1978; Emery and Niino, 1967; Wageman and others, 1970; and Burton and others, 1970). The entire area of regional magnetic anomalies trends northeasterly. Total intensity values of the magnetic field of the Yellow Sea and the East China Sea range from 45,000 gammas north of Taiwan to 48,000 gammas in the sea area adjacent to Jizhou Island. The isogams in the sea area north of Taiwan generally trend north-northeasterly, but locally they are somewhat disordered because of interference caused by faulting and magmatic activity in the magnetic basement. The isogams are also somewhat disordered north of the Gonǧgu Island. On the basis of the isogams seven anomaly fields are delineated in the Yellow Sea and the East China Sea (fig. 3).



1. Figure 3. 2. Map of magnetic anomaly contours in ΔTa of East China Sea. 3. Dash contour, negative ΔTa. 4. Solid contour, positive ΔTa. 5. Based on data of Jin, Xianglong and Yu, Puzhi, 1978; and data modified after Emery and Niino, 1967; Wagemen, Hilde, and Emery, 1970; and Bosum, Burton, Hsieh, Kind, Schreiber, and Tang, 1970. 6. China. 7. Taiwan. 8. Japan. 9. Korea.

Magnetic Anomaly Field with Large Gradient Variation

A magnetic anomaly field with large gradient variation is located in the northern margin of the South Yellow Sea. Magnetic anomalies form a zonal or linear pattern and trend chiefly northeasterly to easterly. The magnetic intensity of anomalies generally ranges from -300 to +500 gammas but locally is as much as 800 gammas. A relatively complex sea-floor structure is indicated by a large gradient and closely interspersed positive and negative anomalies with frequency of variation in amptitude and magnetic field disorders as reflected by local trend variation. The depth of the magnetic bodies ranges from 0.2 to 2 km.

Negative Anomaly Field Consisting of Broad Anomalies with Low Intensity

A dominantly negative anomaly field consisting of broad anomalies with low intensity occupies a large area in the South Yellow Sea. Negative anomalies trend northeasterly. Generally, magnetic intensity of negative anomalies ranges from -150 to -200 gammas. The magnetic gradient is small. The buried depth of the magnetic basement is about 4 to 7 km, but beneath the field along the northern margin it is only 0.2 km. Intensity of positive anomalies in the central part of this field ranges from 50 to 150 gammas. The depth of magnetic basement is 2 to 4 km below the sea floor.

Magnetic Anomaly Field with Large Variation in Intensity

A magnetic anomaly field with large variations in intensity trends northeasterly from the southeastern China coastal region to the Korean peninsula. The field is characterized by closely spaced intense variation of large gradient positive and negative anomalies. The anomalies with an intensity variation average of about -100 gammas. The interspersed positive and negative anomalies reflect sea-floor faulting, magmatic intrusion, and volcanic eruptions. The positive anomalies are dominant in the southeastern China coastal region on the southwest and near the Korean peninsula on the northeast. In both of the foregoing areas the positive and negative anomalies generally alternate. Positive anomalies have intensities of as much as 400 gammas, and intensites of negative anomalies are as low as -500 gammas. In the central part of the field the negative anomalies are dominant, such as in the area where the Yellow Sea joins the East China Sea beyond the mouth of the Yangzi River (Chang Jiang), and intensity in variation of the negative anomalies ranges from slightly less than zero to -200 gammas. The depth of the magnetic basement in the central part of the field is about 4 km but is only 0.5 km in the southeastern China coastal region and near the Korean peninsula.

Negative Anomaly Field with Small Variations in Intensity

A negative anomaly field with small variations in intensity dominates in the shallow areas of the East China Sea. The small variation gives rise to broad open anomalies. The average negative anomaly has a value of about

-200 gammas. The undulate magnetic variation values are about $\pm$ 100 gammas. The sedimentary cover in these areas is very thick. The magnetic basement is generally at a depth of 4 to 6 km with a maximum depth of 10 km. In this field there are some positive anomalies having values of as much as 200 gammas. These positive anomalies separate small areas of the East China Sea, which are dominated by negative anomalies. Generally, these small areas of dominant negative anomalies coincide with basins of the subsidence zone in the East China Sea. Some positive anomalies appear in the Taiwan Strait. Probably these anomalies are due to relatively recent volcanic flows.

High-Gradient Magnetic Anomaly Field

A high-gradient magnetic anomaly field is located west of the Okinawa trough. The anomaly field has a width of about 20 to 40 km and consists of northeasterly or north-northeasterly trending positive anomalies, which show distinct linear alignment and little variation along the strike. The gradients normal to the strike are relatively large. Generally, the average magnetic anomaly level is about 200 gammas. The anomaly linear alignment indicates faulting northeast of Taiwan (west of Gonggu Island). The magnetic basement is at shallow depth, about 1 to 2 km.

Negative Anomaly Field with Small Variation in Intensity

A negative anomaly field with small variation is located in the Okinawa trough. It consists of alternating rectangular-shaped positive anomalies and negative anomalies, of which negative anomalies are dominant. The anomalies form belts that trend north-northeasterly. The average value of the anomalies is about -100 gammas; however the maximum value of the negative anomalies is as much as -300 gammas, and the maximum value of the positive anomalies is constant at about +200 gammas. Depth to magnetic basement is about 3 km.

Field of Positive Magnetic Anomalies in Alternate Position with Negative Anomalies

A field of positive magnetic anomalies in alternate position with negative anomalies is located in the Ryukyu Islands. The alternating positive and negative anomalies form lineaments that trend north-northeasterly. Variation in gradient is relatively large. Negative anomalies with values of 0 to -100 gammas are dominant. The negative anomalies are coincident with and reflect the fore-arc island chain where sedimentary rocks are dominant, whereas the positive anomalies are coincident with the back arc where volcanic rocks are dominant.

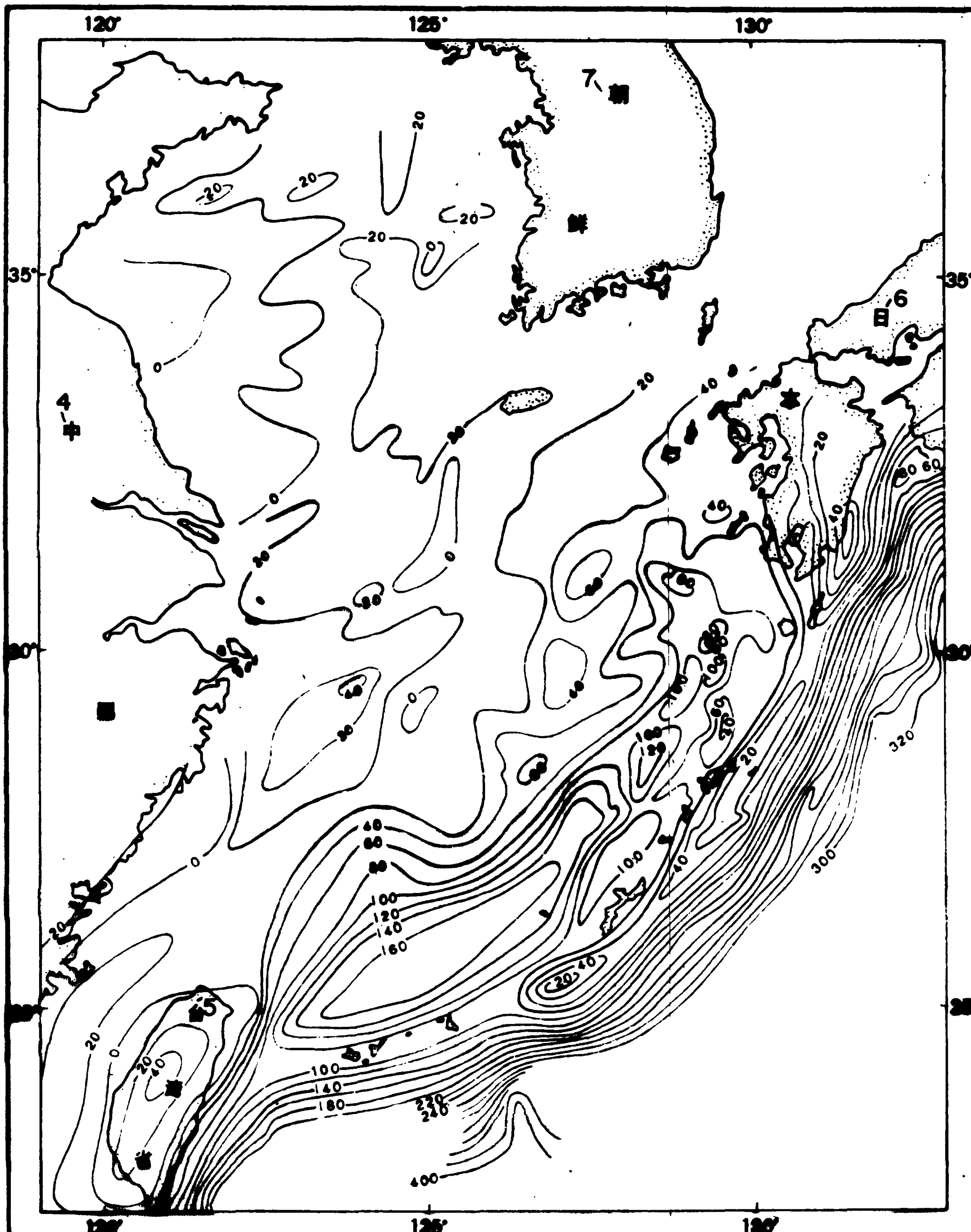
Gravity Field

Gravity fields of the Yellow and East China Seas are characterized by dominant positive Bouguer anomalies (Tomoda and others, 1968; Segava, 1968; Vajk, 1964; and Frazier and others, 1972). Negative Bouguer anomalies are locally present only along the Fujian coastal region and on Taiwan Island of China (fig. 4).

Bouguer anomalies of the continental shelf of the Yellow and East China Seas have average amplitudes of about 20 milligals. Amplitudes in the Yellow Sea are relatively low, about 10 milligals, and in the East China Sea they are relatively high, about 20 milligals. Two characteristics of the distribution of Bouguer gravity values in the continental shelf are noteworthy: 1) Bouguer values gradually increase with increasing water depth and, as the edge of the continental shelf is approached, increase as much as 40 milligals; and 2) Bouguer values are relatively large in areas of uplift and are relatively small in areas of subsidence. For example, the Fujiàn-Lǐngnan upwarped belt (Fukien-Reinan massif between southeastern Korea and the Yangtze River, as stated by Wageman and others, 1970) is outlined by the 20-milligals-Bouguer anomaly-contour, and in the central part of this belt is an area of low Bouguer values, which define anomalies with a distribution pattern similar to that of magnetic anomalies (fig. 8 and unit 3). The subsidence zones of the southern Yellow Sea and the East China Sea appear to have Bouguer values near zero.

The gravity fields from the Asian continent to the transitional continental slope of the western Pacific Ocean vary considerably in intensity. In the Okinawa trough the Bouguer gravity values are generally greater than 80 milligals (most are greater than 100 milligals). In the southern part of the trough, the values are greater than 160 milligals and range from 80 to 100 milligals in the northern part. These values indicate the earth's crust of this trough is not in isostatic equilibrium. In the Ryukyu Islands arc, the Bouguer values decrease rapidly and drop down to their lowest, about 20 milligals along the eastern flank of this arc (between the Ryukyu Islands arc and the Kyukyu trench). To the east of this low Bouguer gravity belt, the gravity gradient is very precipitous, and the Bouguer values increase rapidly; along both flanks of the Ryukyu trench, Bouguer values are more than 300 milligals.

In short, the earth's crust of gravity fields of the Yellow Sea and East China Sea are unisostatic, and isostasy of the crust of transitional continental slope belt is almost completely destroyed. The magnitude of the isostatic disequilibrium of the Ryukyu trench is comparable to that of other trenches of the western Pacific Ocean, such as the Aleutian trench, Sakhalin-Kamchatka trench, and Japan trench, etc. The magnitude of isostatic disequilibrium of the crust in the Okinawa trough, however, is more or less similar to that of the marginal ocean basins in the western Pacific Ocean, but it, nevertheless, greatly exceeds that of the marginal sea areas. The authors believe that the isostatic disequilibrium of the earth's crust in these trenches is closely related to the dynamic processes associated with the rising and spreading of mantle materials, which cause thinning of the earth's crust.



1、图 4 2、东海重力布格异常等值线图
2a、等值线间距 20 毫伽
3、(根据文献 [12, 13, 14, 15] 资料编)

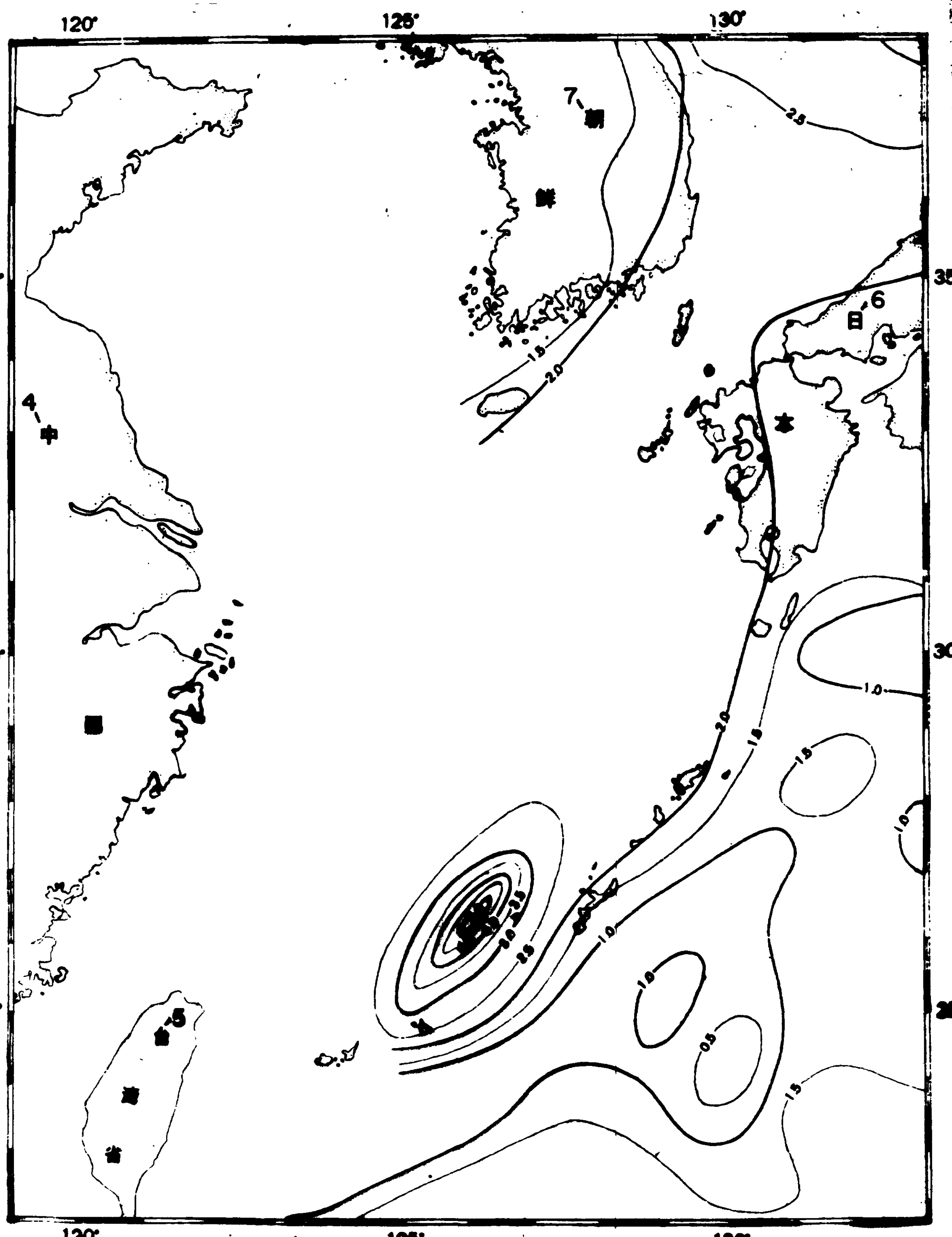
1. Figure 4. 2. Map of Bouguer gravity anomaly contours of the East China Sea.
2a. Contour interval 20 milligals. 3. Based on data of Tomoda and others, 1968; Segava, 1968; Jajk, 1964; and Frazier and others, 1972. 4. China. 5. Taiwan. 6. Japan. 7. Korea.

Sea-Floor Heat Flow

As we know, sea-floor heat flow is the principal basis for current research on geodynamics. Reliable heat-flow data, however, are very difficult to obtain from the continental shelf of the Yellow and East China Seas, because depth of sea water is relatively shallow in the western Yellow Sea and East China Sea and water temperature variation greatly affects the heat-flow measurements. Reliable measurements of sea-floor heat flow, however, can be obtained in the Okinawa trough where the water is relatively deep (fig. 5).

Although reliable data of heat flow are lacking in the sea-floor of the Yellow Sea and East China Sea continental shelf, the geothermal data of the southern part of Korea are herein presented for reference, because the structure of the area, which is in a tectonic belt, is similar to that of the Yellow and East China Seas. The heat flow in the southern part of Korea averages 1.70 HFU (Heat Flow Unit - microcalorie/centimeter^2 . sec), but heat flows are more than 2 HFU and as much as 2.53 HFU along the coastal region in the southeastern part of Korea. The average value of heat flows in the southern part of Korea is greater than the total average value (1.64 HFU) in the ocean area, and they also exceed the total average geothermal value (1.65 HFU) in the continent. These data show that the southern part of Korea is tectonically active. The high values of heat flows along the southeastern coastal region of Korea is probably genetically related to the development of subsidence zones in the East China Sea.

The heat-flow value is very high in the Okinawa trough (Watanabe, 1970 and 1972); it averages 3.62 HFU. The maximum measured value is 8.95 HFU. The greatest heat-flow range is 1.05 to 8.95 HFU on the trough floor. In the trough, the heat flow value is, however, patterned along the axial trend, and on the flanks of the trough the heat-flow value is more or less parallel with the 2 HFU-contour. Two areas of high heat flow occur along the axial portion of this trough. Heat flow in the northern area is small with a maximum value of 3 HFU and in the southern area is large with a maximum value greater than 5 HFU. The general distribution trend of heat flow in this trough shows a gradual decrease in value toward the north and a rapid decrease toward the south, as in the area to the northeast of Taiwan where the heat-flow value rapidly drops below the 1 HFU. It is worthwhile, however, to point out that the average heat-flow value of the Okinawa trough greatly exceeds the average value, about 2 HFU, from the heat-source area in the mid-ocean ridge. Based on a study by Horai and Simmons (1969), the average value of heat flow is 2.26 HFU from the eastern Pacific rise, 1.50 HFU from the mid-ridge of the Atlantic Ocean, and 1.46 HFU from the mid-ridge of the Indian Ocean. The heat-flow distribution in the Okinawa trough is qualitatively similar to that of numerous epicontinental seas of the western Pacific, but numerical values are commonly relatively higher than those of the western Pacific epicontinental Seas; for example, the average value of heat flow is 1.54 HFU for the Bering Sea, 2.05 HFU for the Sea of Okhotsk, 2.23 HFU for the Sea of Japan, and 1.42 HFU for the Philippine Sea. As to the numerical comparison of heat flow, the Okinawa trough can be compared with those "new-born oceans," which are in the process of expansion. Examples are: the Red Sea, average heat-flow



1 图 5 2 东海及其邻近区地壳热流图

3、([illegible] [10, 16, 17] [illegible])

1. Figure 5.
2. Map of earth's crust heat flows in the East China Sea and its vicinity.
3. Based on data from Lee, Sang Man, 1973; Dubuyunyan, 1970 and 1972.
4. China. 5. Taiwan. 6. Japan. 7. Korea.

value, 3.66 HFU; the Gulf of Aden, 3.95 HFU, etc. The phenomenon of high heat flow of the Okinawa trough is identical to the imbalance of gravity isostasy of the trough. The authors consider that these high heat-flow values are genetically related to local rising temperature, melting, and secondary heat convection within the shallow part of the mantle. This phenomenom is interpreted as indicating that the Okinawa trough is a new-born marginal sea and a secondary unbroken linear expansion zone.

Earthquake and Volcano

The earthquake distribution in the Yellow and the East China Seas has a distinct regularity. Based on frequency of earthquake occurrence and location of epicenters, Barazangi and Dorman (1969), the Institute of Geophysics, Academia Sinica (1976), Katsumata and others (1969), Yujindezhi* (1974), and Murphy (1973) delineate three linear seismic zones. The zones trend northeasterly to north-northeasterly and comprise: 1) the Subei-South Yellow Sea seismic zone, 2) the central East China Sea seismic zones, and 3) the Taiwan-Ryukyu seismic zones (fig. 6).

The Subei-South Yellow Sea seismic zone is in the South Yellow Sea subsidence zone, which extends southwesterly from the southern part of the Korean to the northern part of Jiangsu province. The central East China Sea seismic zone is in the East China Sea subsidence zone and extends from the Taiwan strait via central East China Sea to Kyushu and Tsushima strait of Japan. The seismically active coastal regions of western Taiwan and eastern Fujian are entirely within this seismic zone. Earthquakes within these two seismic zones have shallow foci; the focal mechanism is as yet not understood. The distribution of foci, however, is identical to that of the negative structural areas. This phenomenon helps to explain seismic activity in these two seismic zones, which are probably genetically related to the development of the structural framework of two subsidence zones of the Southern Yellow Sea-Subei and the East China Sea.

The Taiwan-Ryukyu seismic zone is part of the well known Circum-Pacific seismic zone. The seismic activities of this zone are more intense than the activities of the Subei-South Yellow Sea seismic zone and the central East China Sea seismic zone; generally this seismic zone is accompanied by numerous volcanic activities. This seismic zone is relatively complicated and is generally delimited by the Ryukyu seismic zone on the north and the Taiwan-East China Seashore seismic zone on the south. The Ryukyu seismic zone trends north-northeasterly. Most of the shallow earthquakes occur in the Ryukyu Islands. Intermediate-depth earthquakes are mostly located along the inner flank of the Ryukyu arc; most are in the Okinawa trough. According to statistics (Katsumata and Sykes, 1969), from 1934 to 1967 the occurrence of 90 percent of the intermediate-depth earthquakes was concentrated in the Okinawa trough. A distinct Benioff zone dips 35° to 45° northwesterly beneath the Ryukyu Islands arc-trench system. The maximum depth of the hypocenter is 280 km. The focal mechanism is due to ocean crustal subduction. This mechanism

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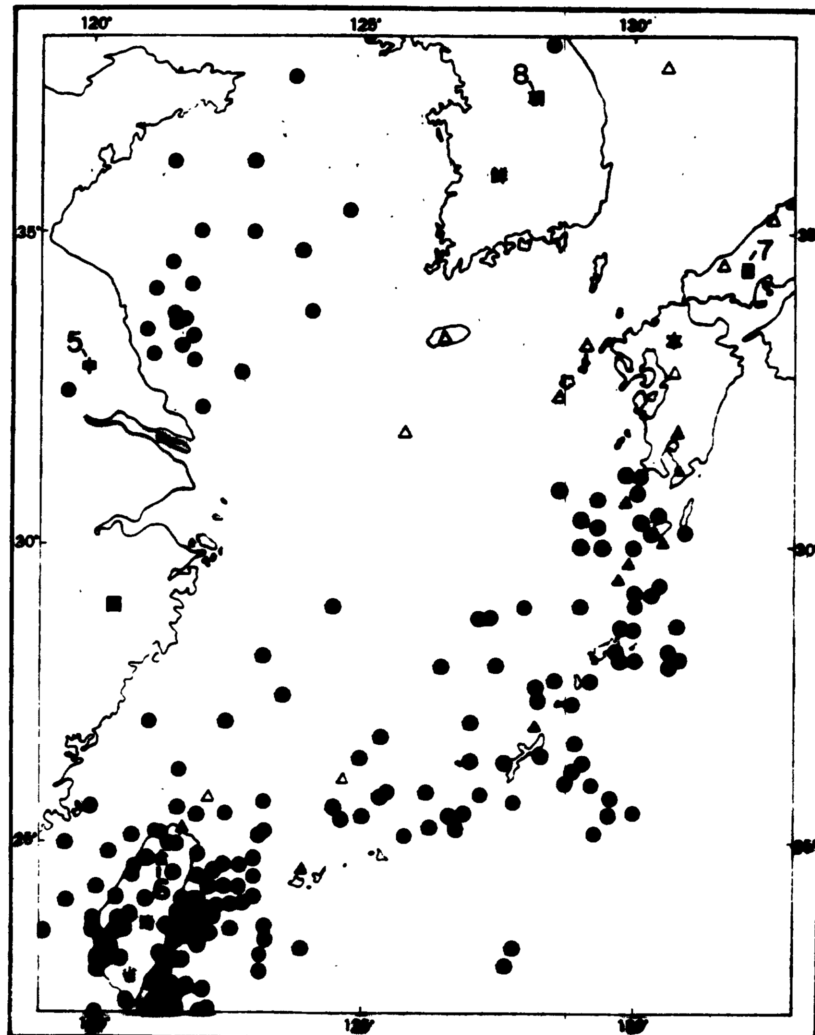
* Chinese pinyin transliteration



1 图6　2 东海及邻区地震震中与火山分布图

3 黑圆点为震中；黑三角是活火山；白三角是死火山

4（根据文献[19, 20, 21, 22, 23]资料编）

1. Figure 6.
2. Map showing the distribution of earthquake epicenters and volcanoes in the East China Sea and its vicinity.
3. Epicenter, solid black circle; active volcano, black triangle; and extinct volcano, white triangle.
4. Compiled after Barazangi and Dorman (1969), Institute of Geophysics of the Academia Sinica (1976), Katsumata and Sykes (1969), and Yujindezhi (1974).
5. China. 6. Taiwain. 7. Japan. 8. Korea.

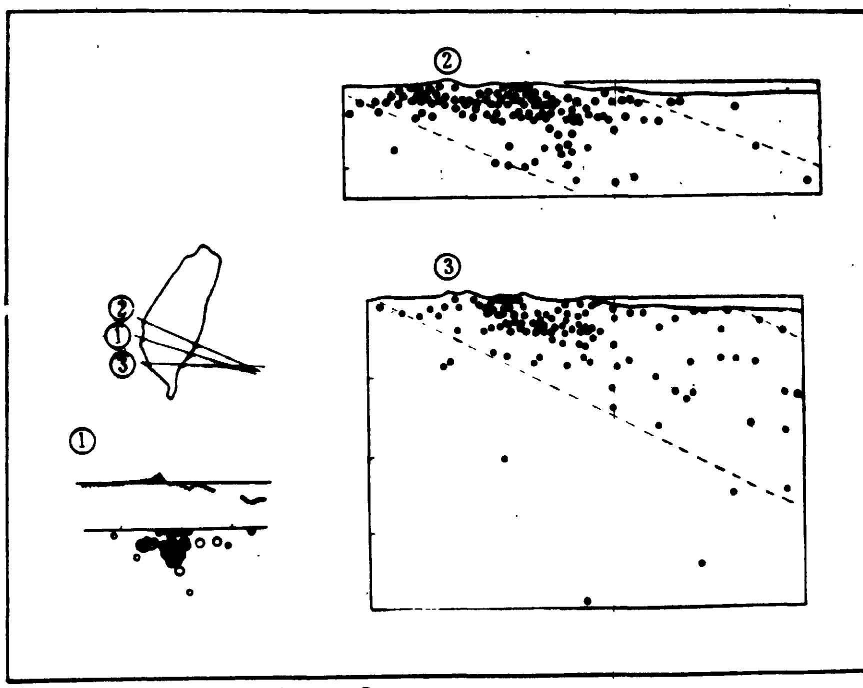
is sufficient to adequately explain the regular distribution of the shallow-foci and the intermediate-depth earthquakes of the Ryukyu Islands arc. The Taiwan-East China Seashore seismic zone trends slightly east of due north. The hypocenter distribution is rather chaotic, but there is a slight easterly dipping Benioff seismic surface. Generally, intermediate depth earthquakes are confined to an area east of the area of shallow earthquakes. The maximum depth of hypocenters is less than 100 km. The trend of this seismic zone is in alignment with the Philippine seismic zone, but unlike the Philippine zone, the focal mechanism is rather complicated and further research is needed. Initially it is believed that the focal mechanism is a shear-strain type. Several left-lateral rotary faults in eastern Taiwan are definitely related to the seismic activity; however, they are not the only and probably not the principal factor that causes the irregular distribution of hypocenters (fig. 7).

There are two distinct volcanic chains in the East China Sea. The first volcanic chain extends from the island of Kyuchu in southwestern Japan to the Taibei of Taiwan via the inner zone of the Ryukyu Islands. This volcanic chain contains some Miocene to Recent active volcanic zones in which the volcanic rocks are principally tholeiites. In the Okinawa trough, this chain splits, and elements of it occupy both flanks of the trough. The eastern element, which is located between the Okinawa trough and the Ryukyu Islands, had its inception during the Late Tertiary. Extrusive andesite was the dominant lava flow during the Miocene and Pliocene. It is referred to by some as the ancient Ryukyu volcanic zone. The western volcanic element is in the marginal rise of the continental shelf west of the Okinawa trough. Volcanic activity began in Late Miocene. The second volcanic chain of the East China Sea consists chiefly of andesite and basalt; volcanoes are extinct. This chain trends north-northeasterly and extends from the Ullung Island in the Sea of Japan via the Korean and Tsushima volcanic zone, Jizhou Island, and the submarine volcanic group (32°07' N, 125°11' E) in the vicinity of the Hupi reef to the coastal region of Zhejiang and Fujian provinces. The origin of both these volcanic chains has been influenced by tectonic activities in the East China Sea.

Earth's Crust Thickness and Rift System

All known refractive seismic measurements in the East China Sea are not adequate to estimate accurately the thickness of the earth's crust, because none of the measurements reached the Mohorovicic discontinuity. A rough estimate of the earth's crust thickness, however, can be made on the basis of data on gravity and natural seismic waves and on the basis of some refractive seismic measurements.

The thickness of the earth's crust of the continental shelf beneath the Yellow and East China Seas generally ranges from 30 to 33 km, and is more than 25 km in the Taiwan strait. The Okinawa trough crust, however, is about 21 km thick with maximum thickness of no more than 24 km, although it is considered by Gaynanov (1974) to be only 15 km thick. In short, the crust of the Okinawa trough crust appears to be transitional; it is relatively thinner than the



1、图7 2、台湾震中分布剖面

3、①是根据 Katsumata 和 Sykes, 1969; ②和③是根据 Lee, 1962

1. Figure 7.

2. Profile of epicenter distribution in Taiwan.

3. Profiles: (1) After Katsumata and Sykes (1969).

   (2) and (3) After Lee (1962).

continental crust but thicker than the oceanic crust. Thickness of the earth's crust ranges from about 27 to 30 km in the Ryukyu Islands and in areas adjacent to the east. However, further to the east of the Ryukyu trench (and including the Ryukyu trench), crustal thickness is only 6 to 9 km, which indicates an oceanic crust. In the East China Sea, the seismic velocities of the deepest strata range from 5.3 to 6.2 km/sec, which can be compared to the Wageman's second facies of mappable lithologic units, and are interpreted as "acoustic basement" consisting of Mesozoic and pre-Mesozoic complexly metamorphosed sedimentary rocks (Wagaman and others, 1970; p. 1622). Generally, this acoustic basement is herein included with the magnetic basement. Four sedimentary sequences overlie the acoustic basement. They are: Lower Tertiary (4.6 to 5.3 km/sec), Miocene (3.7 to 4.4 km/sec), Pliocene (2.6 to 3.5 km/sec), and Pliocene-Pleistocene (1.8 to 2.5 km/sec) ages. The Miocene sequence varies considerably in thickness and is locally missing.

The rift system of the Yellow and East China Seas consists of north-northeastern and northwestern sets of faults. The north-northeastern set is the product of torsional stress and is made up of extensive individual faults which dip southeasterly. Commonly, this set forms large-scale fault zones of regional extent. They were probably formed during the Mesozoic as suggested by wide distribution of the Mesozoic and Tertiary volcanic rocks throughout the zone. The northwestern set was probably formed by torsional tension stress and at many places cut off north-northeasterly trending rises or faults to form faulted basins, such as the Gongu faulted depression (probably formed during Miocene-Pleistocene), the Tokara rift, the Ishigaki Islands rift zones, etc. (fig. 8).

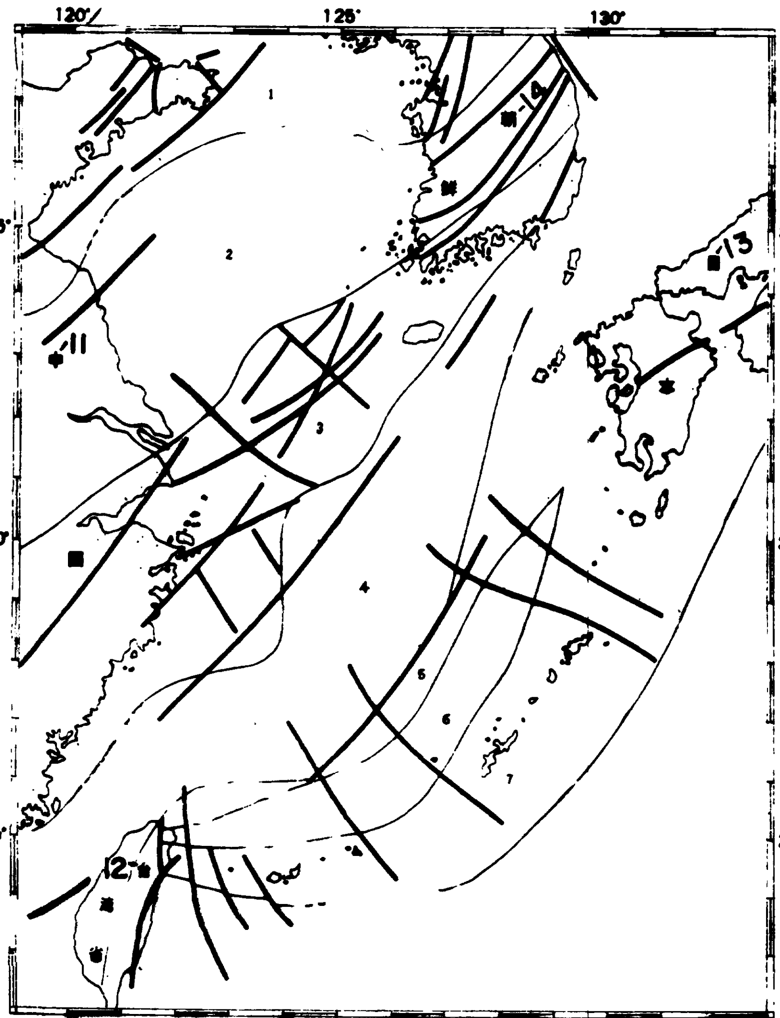


图 8 东海构造图

1. 北黄海-胶辽隆起带； 2. 南黄海-苏北沉降带； 3. [illegible]； 4. [illegible]；
5. [illegible]； 6. [illegible]； 7. [illegible]海沟-[illegible]； [illegible]

1. Figure 8.
2. Structural map of the East China Sea.
3. 1) North Yellow Sea - Jiaoliao rise zone.
4. 2) South Yellow Sea - Subei subsidence zone.
5. 3) Fujian-Lingnan rise zone.
6. 4) East China Sea subsidence zone.
7. 5) Marginal rise zone of East China Sea continental shelf.
8. 6) Okinawa trough tensional rift zone.
9. 7) Ryukyu trench-Island arc system.
10. Thick black line is the principal rift.
11. China. 12. Taiwan. 13. Japan. 14. Korea.

STRUCTURAL DEVELOPMENT MODEL AND ITS RELATION TO THE ASIAN EPICONTINENTAL SEA

Geotectonics or geodynamics is the principal research method of studying movement within the lithosphere and the dynamic mechanisms that played a role in the history of the earth's development. The present status of geodynamic research is more or less similar to that of nuclear physics during its early years of development. That is, although the fundamental principle has been thoroughly considered, for some time in the future the understanding of many earth's science phenomena will remain obscure due to the magnitude of their complexity and technologic limitations. At present, many ideas related to geology and geophysics have been derived by inference and generalization. Ideas concerning origins and causes of geologic phenomena are numerous and some are hotly contested, even some that are based on so-called irrefutable proof. Regardless of controversies, an open-minded approach should pave the way to resolving problems of earth science to the benefit of mankind.

Li Siguang (1926) proposed that change in velocity of the earth's rotation has been the principal factor that has caused the movement of seawater and rock alteration. Later, the concept of geotectonics was established as the result of experimentation and analyses of tectonic elements (Li, 1945, 1953, and 1973). In his concept of geodynamics, Li introduced three principal geotectonic systems: the latitudinal tectonic system, the longitudinal tectonic system, and the torsional tectonic system that included different types of structures. He provided a detailed description of the geological structure of China and the region bordering the Pacific Ocean. He then proposed the megalo torsional tectonic system (vortex structure system) and the so-called "Neocathaysian tectonic system," which consists of a series of north-northeasterly trending rise zones and alternating subsidence zones. It is believed that these positive and negative structural elements are rebound features that were formed by horizontal torsion movement during encounter of the southward moving Asian continent with the obstructing Pacific Ocean floor. Within the general area considered in this report, the extreme eastern rise zones of the Neocathaysian tectonic system are marked by a series of islands: Kuril, Japan, Ryukyu, and Luzon. The western part of these islands are marked by subsidence zones, which are characterized by a series of structural depressions: Sea of Okhofsk, Sea of Japan, East China Sea, and Yellow Sea. An uplifted belt to the northwest of offshore subsidence zones is made up of folded mountain ranges, such as the Changbaishan, Jiaoliao, and Wuyishan ranges. As to the discussion of the linear structural belts of the Yellow and East China Seas, these units would be represented by the rise zones and alternating subsidence zones.

During the last several decades, improvement of geophysical investigation and a great amount of new data accumulation have given rise to some new concepts and ideas concerning the pattern of movement of the lithosphere and the dynamic mechanism within it. Dietz (1961) and Hess (1962) proposed the sea-floor spreading concept. Later Morgan and others (1968) further developed that concept into the Plate-tectonic theory. Isacks and others (1968) again expanded the plate-tectonic concept into the new global tectonics. To a certain extent these concepts are a rejuvenation of A. Wegener's continental drift theory which was developed in the 1920's. LePichon (1968) attempted to further extend Morgan's (1968) investigation on the geometry of the displacement of the ocean floor and continents and to test whether the more uniformly distributed data on sea-floor spreading now available are compatible with a non-expanding earth. Using the distribution of active tectonic belts of mid-ocean ridges, trenches, and transform faults for the study of ocean evolution and vectors of differential motion between blocks along all the boundaries, LePichon proposed an earth model consisting of rigid blocks. He observed that both sea-floor spreading and plate tectonics point to the heat convection in the mantle as the driving force of the movement in the lithosphere. In the lower lithosphere, heat accumulation generally causes melting of mantle rocks. In the mid-ocean ridges, where these melted rocks are ejected, new ocean crusts are continuously being formed and the sea floors spread laterally. As the process progresses, new-born oceans are evolved, and the moving ocean crusts reach the sea trenches where they collide with the earth's crust and subduct into the mantle to complete the heat convection circulation. This theory still has shortcomings, but it has merit in that heat convection in the mantle is a possible explanation of the mechanism whereby movement takes place in the lithosphere. Based on information available in the 1940's, Holmes (1945) proposed a mantle heat convection concept that adequately explained the origin of the Atlantic Ocean basin and is consistent with current data. Morgan (1971 and 1972), using the idea of heat convection, proposed the concept of "hot spots" or "convection plumes," which succesfully explained plate tectonic movements of the earth's lithospere and the origins of the ocean basins, as well as the more than 20 "hot spots" revealed by orbital satellite imagery.

In short, earth rotation and thermal dynamics are the primary moving forces of movement within the lithosphere. In the following discussion on the structural patterns and developing models of the Yellow and East China Seas, these two types of moving forces are given careful consideration.

Structural Pattern

The earth's crust of the continental shelf of the Yellow and East China Seas is of the continental type, and the continental slope of the East China Sea is the transitional type between continental and oceanic. Since the Paleozoic, frequent movements of the earth's crust have had a profound effect on the regional structure of the Yellow and East China Seas and established the present structural patterns. As to the structural patterns, there are several linear alternating arrangements in which rise belts are alternately spaced with subsidence belts. Principal tectonic trends are north to northeast (particularly northeast). These structural belts that form structural patterns of the Yellow and East China Seas consist of, from west to east, the North Yellow Sea-Jiáoliao rise zone, the South Yellow Sea-Subei subsidence zone, the Fujiàn-Lingnan rise zone, the East China Sea subsidence zone, the marginal rise zone of the East China Sea continental shelf, the Okinawa trough rift zone, and the Ryukyu Islands arc-trench system (fig. 8).

1. North Yellow Sea-Jiaoliao rise zone.

The North Yellow Sea-Jiaoliao rise zone extends from Jiaodong peninsula through the northern marginal sea areas of South Yellow Sea and the North Yellow Sea to the Liaodong peninsula and northern Korea. The structural basement consists chiefly of metamorphosed rocks of the pre-Sinian and Sinian series. During the Mesozoic Yanshanian orogeny, the basement was intensely rifted. Rifting was accompanied by plutonic acidic intrusions and intermediate to basic volcanic flow eruptions. Locally, since the Jurassic, some structural basins have formed that trend north-northeasterly with an en echelon arrangement. The North Yellow Sea occupies a small structural basin of this rise zone. The long axis of the basin trends northeasterly. In the basin, two small depositional centers form an epsilon-shaped pattern along the northeastern part of this trend. The basement of the basin consists of metamorphosed rocks of pre-Mesozoic age. The depth to the top basement ranges from less than a meter to 2,700 m. The depth to basement beneath the depositional centers is in excess of 2,000 m. The sedimentary cover of the basement is made up of Mesozoic and Tertiary strata of which the Mesozoic beds (Jurassic-Cretaceous system) range in thickness from about 1,000 to 1,500 m. The Quaternary and Holocene, which are unconsolidated sediments, are about 300 m thick. Tertiary beds (especially those of the Lower Tertiary) are probably missing. This structural zone, except the marginal part such as the west flank of Jiaodong peninsula, was locally invaded by the sea during the earliest stage of the Early Paleozoic. Since Sinian time, especially post-Early Paleozoic, this zone was raised above sea level and had a long period of structural stability. The Holocene North Yellow Sea, however, was possibly formed during post-Tertiary time when the sea transgressed into an area of structural weakness.

2. South Yellow Sea-Subei subsidence zone.

The South Yellow Sea-Subei subsidence zone extends from the South Yellow Sea northeasterly to south-central Korea. This zone connects with the Subei basin along its southwestern border. Southward it extends inland into southern Anhui, western Zhejiang, Jiangxi, Hunan, the Guangxi provinces of China, and into northern Vietnam. The basal sequence of strata consists of a very thick sequence of rocks of Paleozoic and Mesozoic ages. The Cambrian-Silurian and Carboniferous-Triassic beds are well represented. The Early Paleozoic strata were intensely folded. During the Mesozoic, a few small-graben faulted basins were formed. In the areas of the South Yellow Sea and the northern Jiangsu province (Subei), sedimentary strata of Early Tertiary age cover the Paleozoic and Early Mesozoic sequence. The Early Tertiary strata are tectonically deformed and subaereally eroded. Late Tertiary and Quaternary beds, which unconformably overlie the older rocks, are slightly deformed. The thickness of Late Tertiary and Quaternary strata is in excess of 1,000 m; maximum thickness is as much as 1,500 m. The subsidence zone in the South Yellow Sea can be subdivided, from the north to the south, into three secondary structural zones: a northern depression, a central rise, and a southern depression. The northern depression is relatively shallow, and the stratified sequence has a maximum reflected time of 2.5 sec. The southern depression is relatively deep, and the maximum reflection time of the stratified sequence is 2.9 sec. The central rise shows disordered reflected waves, which indicate shallow depth to basement and relatively abundant tectonic fractures. The Lower Tertiary strata in both the southern and northern depressions have promising potential as a source for oil. During the entire Paleozoic and Mesozoic, the subsidence zone was covered by a sea that invaded the area from the southwest. Since Jurassic time until Tertiary the area was above sea level, but tectonically the zone has been rather unstable.

3. Fujian-Lingnan rise zone.

The Fujian-Lingnan rise zone forms a linear belt that extends from the mountain terrain of Guangdong, Fujian, and the southern Zhejiang provinces, via the sea floors of the Yellow and East China Seas and Jizhou Island to a point southeast of the Korean peninsula (Lingnan area). Generally, the rise zone is located along the junction of the Yellow Sea and the East China Sea. It has a north-northeastern structural trend. The topography of this rise zone is represented by a series of linear submarine island reefs, which consist of the Suyan reef, Hupi reef, Huadǎoshan, and Zhoushan Islands. The basement rocks of the rise zone are made up of a sequence of lower pre-Cambrian metamorphosed rocks and partly of metamorphosed Paleozoic geosynclinal marine deposits and upper Mesozoic volcanic detrital rocks. These basement rocks were folded, metamorphosed, uplifted, and intruded by igneous rocks. In the sea areas, the basement is overlain by about 800 m to 1,200 m of Cenozoic sedimentary cover, which is generally Upper Tertiary and Quaternary in age. Lower Tertiary sediments possibly occur locally. These Cenozoic sedimentary rocks unconformably overlie older strata. Since Sinian time, this rise zone was extensively uplifted above sea level; only along the northwestern margin did a sea transgression occur during the Early Paleozoic. However, during the Late Paleozoic the sea transgressed over both flanks of the rise zone. During the Jurassic-Cretaceous periods, tectonic activities were associated with large-scale volcanic flow eruptions, which formed the coastal mountain ranges in East China. The flows prevented Pacific Ocean water from invading areas to the west. During the Indosinian and Yanshanian movements, a series of north-northeasterly trending rifts and north-northeasterly Mesozoic to Cenozoic en echelon faulted depressions were formed. Generally, both rift and depression are characterized by lower gravity and magnetic readings. Since the Tertiary, the rise zone has undergone rifting and gradual fore-shortening, and the sea has slowly invaded the broken rise zone and extended into the Yellow Sea. Volcanic activity along the rise zone was frequent during the Tertiary and Quaternary.

4. East China Sea subsidence zone.

The East China Sea subsidence zone includes almost the entire continental shelf of East China Sea and possibly extends southward via the Taiwan strait to the South China Sea. The trend of the subsidence zone is north-northeast. The characteristics of the basement rocks are generally obscure. Most of the rocks are Mesozoic and Paleozoic sequence consisting of complexly metamorphosed sedimentary and volcanic rocks (velocity of longitudinal seismic waves ranges from 5.3 to 6.2 km/sec). Based on inference from the geology of Taiwan and Japan, the Mesozoic strata consists possibly of a series of deep and semi-deep marine flysch geosynclinal detritus, which is intercalated with volcanic rocks. The sedimentary cover of the basement is composed of a very thick sequence of Tertiary and Quaternary sedimentary rocks, which, in general, have a total thickness in excess of 4,000 m and a maximum of as much as 9,000 m. The Lower Member of the Cenozoic strata consists of tectonically deformed Early Tertiary beds (velocity of longitudinal seismic waves is 4.6 to 5.3 km/sec); and the Upper Member comprises Late Tertiary and Quaternary beds (velocity of longitudinal seismic waves, 1.8 to 4.4 km/sec). An unconformity separates the Lower from the Upper Members. The Upper Member consists chiefly of rocks of Late Tertiary age. Locally there is an unconformity between rocks of Miocene age and rocks of Pliocene to Pleistocene ages. Total thickness of the Upper Member is about 2,000 m. It becomes thinner northward and is only 200 m thick in the Tsushima strait. It is much thicker to the south, generally in excess of 4,000 m and is more than 5,000 m thick in the western part of Taiwan. Based on comparison of depths to the magnetic basement, the authors, during a preliminary investigation of the continental shelf magnetic fields and geological structure of the East China Sea in 1978, discovered three depositional centers in the East China Sea. They are the northern, central, and southern depressions. The northern depression is south of Jizhou Island. Depth to basement in this depression ranges from about 3,000 to 4,000 m. The thickness of Late Tertiary and Quaternary strata ia about 1,500 m. The central depression is east of the mouth of the Yangzi River (Chang Jiang). Depth to basement is about 7,000 m. The thickness of Late Tertiary and Quaternary sediments exceeds 4,000 m. The southern depression includes the west coastal plain of Taiwan and an offshore area to the northwest. Depth to basement generally is more than 7,000 m and locally exceeds 9,000 m. The thickness of Late Tertiary and Quaternary sedimentary beds exceeds 5,000 m. The present shape of this subsidence zone is due to initial rifting and expansion, probably during Early or very Early Tertiary ???. Because the very thick Miocene strata of western Taiwan are excellent source-beds, this basin is believed to hold promising potential for production of hydrocarbons.

5. Marginal rise zone of the East China Sea continental shelf.

This marginal rise zone is along the margin of the continental shelf of the East China Sea in the vicinity of north latitude 26°30' (fig. 8); it protrudes slightly toward the seaward margin of the continental shelf. This zone is the only structural element along the East China Sea continental shelf margin. The structural trend is north-northeast. The characteristics of basement rocks are obscure, but they are probably metamorphic generally and are similar in age and lithology to those of the East China Sea subsidence zone. These metamorphic events can be proved by the Danaxiu glaucophane schist complexes of Taiwan. During Mesozoic time, locally metamorphosed zones of Mesozoic Lingjia-Sanbachuan* strata in Kyushu Island of Japan possibly extended over the basement fold belt of this marginal rise zone and connected with the locally metamorphosed zones of the Mesozoic Yuli-Tailuge beds of Taiwan (Sugimura and Uyeda, 1973; Miyashiro, 1972; Miyashro, 1961; Yan*, 1972; and

* Chinese pinyin transliteration

Yen, 1966). The sedimentary cover of this rise zone consists chiefly of folded and very thick Upper Tertiary and Quaternary sedimentary rocks, which are intercalated with submarine volcanic flows. In the northern part of the rise zone covering islands to the west of the Kyushu, there are folded Tertiary beds, intruded by granodiorite and quartz-andesite, and in the southern part, the cover consists of folded Pliocene to Pleistocene strata, intruded by quartz-andesite in the Central Mountain Ranges, Diaoyu Island, and other islands of Taiwan. These rocks are generally overlain unconformably by Pleistocene limestone, the so-called "high-rise coral reef." In the East China Sea, a sequence of unconsolidated sediments, about 800 m thick, subjacently underlie the sea floor (velocity of longitudinal seismic waves is about 2 km/sec); beds beneath have a longitudinal seismic wave velocity range of from 3 to 5 km/sec, which indicates that they are probably tectonically deformed Tertiary strata and acidic volcanic rocks. Since Late Miocene, a linear zone of andesite-basaltic volcanic rocks has accumulated along the outer margin of the East China Sea continental shelf. This rise zone was initially formed as a marginal island arc during Early Tertiary. During Late Tertiary it again was tectonically compressed to form a type of remnant island arc.

6. Okinawa trough rift zone

The Okinawa trough is topographically a deep-water trough and structurally a linear expanded tectonic belt with a north-northeastern trend. To the north, this sea trough possibly connects with the Lower Tertiary intensely rifted and folded belt of Japan. A great number of basic volcanic rock eruptions occurred during the Late Tertiary and Quaternary. To the south, this sea trough penetrates into eastern Taiwan and forms a peculiar Quaternary deltaic plain, the Yilan plain, along the coast of eastern Taiwan. Seismic activities of the central part of the Yilan plain occur along a narrow belt that trends N. 63° E. (hypocenter depth is within 2 km). The seismic zone extends from the northeast of Taiwan near the seashore via Guishan Island to the junction of the Okinawa trough. The basement of the sea trough probably consists of complexly metamorphosed Lower Tertiary beds and volcanic intrusive rocks (velocity of longitudinal seismic waves, 3.5 to 5.5 km/sec). The basement rocks are overlain by Quaternary and a small amount of Recent sediments consisting of sandy turbidites and volcanic detrital rocks (velocity of longitudinal seismic waves, 1.8 to 3.1 km/sec). Generally, the thickness of sediments exceeds 1,200 m (reflected time, 0.8-2.2 sec). Thickness increases near Taiwan Island. The Quaternary strata are folded and rifted and are intricately cut by volcanic rocks of Pleistocene age. The volcanic rocks consist chiefly of alkaline basalt and tholeiite (exposed at Guishan Island), which are the typical rock types that accompany sea-trough expansion. They are different from the andesite area of the Datun volcanic district, Taibei of Taiwan (Bowin and others, 1978). The amount of heat flow of the earth's crust in the Okinawa trough is relatively high (average 3.62 HFU). The recent graben-faulting is very well developed in the trough. The amounts of heat flow and recent graben-faulting in the Okinawa trough indicate that the Okinawa trough is a rift valley in the initial stage of expansion, which possibly began at the end of the Miocene or at the beginning of the Pliocene (according to the dating by Bowin and others, 1978, it began development within the past 12 m.y.). The expansion of the Okinawa trough caused the Ryukyu Islands arc to break along the marginal rise zone of the continental shelf; for example, coalbearing sandstone of Middle Miocene age, which occurs on Diaoyu Island in the southern part of the rise zone and on Yunagu* Island and Xibiao* Island of the southeastern flank of the Okinawa trough, was at one time a continuous sequence but has since been broken into segments by expansion of the Okinawa trough. All these islands belong to the Ryukyu Islands arc.

7. Ryukyu Islands arc-trench system.

The Ryukyu Island arc-trench system is the typical model of island arc-trench structures of the western Pacific Ocean. This system extends along the Ryukyu Islands chain and forms a natural dividing line between the East China Sea and the Pacific Ocean. Topographically, the Ryukyu Islands arc connects with the northern part of Taiwan Island and the Kyushu Island of Japan. The Ryukyu Islands arc consists of a back arc and a fore arc which are parallel. The back arc is between the Ryukyu Islands and the Okinawa trough in the East China Sea and is made up chiefly of Miocene-Pliocene andesite, the so-called Ancient Ryukyu volcanic belt. Topographically, this arc consists of submerged ridges or islands (such as, Tokara Islands, etc.), and its origin is contemporaneous with the formation of the volcanic belt of the continental shelf marginal rise zone in the East China Sea and rifting of the Okinawa trough. The fore arc is the Ryukyu Islands chain and consists of the Paleozoic and Mesozoic metamorphic rocks and Tertiary folded sedimentary strata, which are intruded by granite and gabbro. The area has been volcanically active during the Holocane. According to palaeontological data, the oldest metamorphosed rocks are of Permian age, but the radiometric datings give ages of 195 m.y. (Rb-Sr method) and 174 m.y. (K-Ar method), which indicates a Jurassic age. The Ryukyu trench is east of the Ryukyu Islands arc. The maximum depth of this trench is 7,881 m. It is adjacent to the eastern and southern parts of the islands arc. The trench is a colliding attenuated zone, the so-called Benioff zone, between the Philippine plate of the Pacific Ocean and the Eurasian Plate. The transitional slope surface between the island arc and the trench is a bench where the negative gravity anomaly readings are higher than those of the trench. Generally, this relation indicates the approximate position of contact between these two colliding plates. The crust east of the trench is the typical oceanic crust. The entire island arc-trench system extends westward to the steep margin of northeastern Taiwan, where it is truncated by a nearly northerly trending rift.

Structural Pattern and Development Model

Three basic structural patterns can be deduced from tectonic activities of the Yellow and the East China Seas. They are patterns produced by plate collision, secondary expansion, and cognate torsional expansion.

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* Chinese pinyin transliteration

The principal structural pattern is caused by plate collision. The magnitude of tectonic activity is similar to that of mid-ocean ridge expansion. In accordance with the concept of plate tectonics, the structure of the earth has three principal types: mid-ocean ridge (or rift valley), collision zone (or attenuated zone), and transform fault. They form the plate boundaries. Each type is formed by a different mechanism of geomechanics. The mid-ocean ridge is a tensional structure; the collision zone is a compressed structure; the transform fault is a torsional structure (shearing structure).

A secondary expansion is a result of plate collision as the secondary structural pattern. Generally, plate collision, oceanic plate subduction, and heat-yielding friction produce the secondary heat convection, which in turn thermodynamically promotes the formation of a secondary thermal expansion. This secondary expansion is the principal factor leading to the formation of a marginal sea.

A cognate torsional expansion is similar in magnitude to that of the secondary expansion, and also both of them mechanically form a complete set of structure. Under stress of plate collision, the geologic bodies generally yield the strain, which is then geodynamically indicated by the appearance of a cognate torsional expansion.

Since Latest Paleozoic time, these three basic structural patterns have appeared in the Yellow and East China Seas. Two linear collision zones, representing different periods, two linear secondary expansion zones, and several cognate torsional expansion zones are recognized. The development of these three structural patterns has been repeated in many cycles. The collision zone between the western Pacific Ocean plate and the Eurasian plate migrated continuously eastward, thereby producing the complicated structural patterns of the Yellow and East China Seas. Numerous secondary expansions apparently influenced the formation of the East China Sea and the Okinawa trough.

Because of different types of tectonic activity, the tectonic history of the Yellow and East China Seas is rather complicated. Due to the cover of sea water and very thick young sediments, little is known about the basement rocks, particularly about the Early Paleozoic basement rocks (fig. 9). Therefore, the structural development models of the Yellow and East China Seas can only be deduced as follows.

During the Early Paleozoic, the North Yellow Sea (North Yellow Sea-Jiaoliao rise zone) and the southeastern coast (Fujian-Lingnan rise zone) were all land. The northern part of this land area was part of the "North China Platform," and the southern part was part of the "Cathysian Massif." A deep sea along the junction of the present day Yellow Sea and the East China Sea separated the two areas. This deep sea is here referred to as the "Ancient Cathysian Sea." The "Ancient Cathysian Sea" extended from the northern part of Vietnam via the Guangxi, Hunan, Jiangxi, southern Anhui, and western Zhejiang provinces, and then cut through the present South Yellow Sea-northern Jiangsu subsidence zone and continued northeasterly to the Wochuan depression in South Korea. Locally, the "Ancient Cathysian Sea" transgression covered the margins

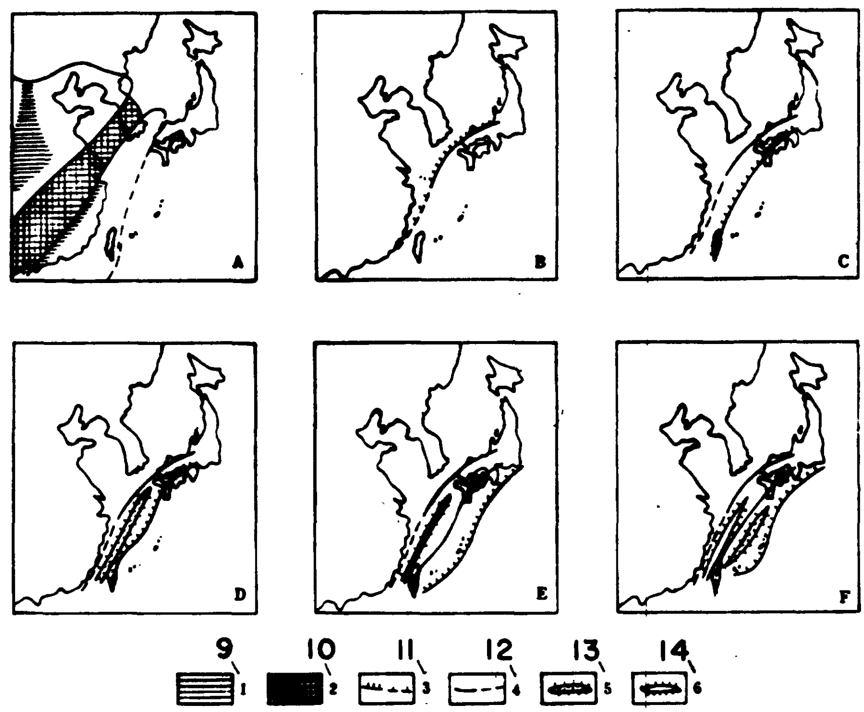

图 9 东海构造发展图

A. 下古生代; B. 海西—印支运动初期（志留—三叠纪）; C. 燕山运动初期（侏罗—白垩纪）; D. 早第三纪; E. 中新世末; F. 晚第三纪—第四纪; 1. 局部海侵; 2. 古华夏海; 3. 正在活动的碰撞消亡带（贝尼奥夫带）（虚线为推测的）; 4. 已衰亡的碰撞-消亡带（贝尼奥夫带）; 5. 正在扩张的次生扩张带; 6. 扩张已终止的次生扩张带。

1. Figure 9.
2. Structural development of the East China Sea.
3. A) Lower Paleozoic.
4. B) Initial stage of Hercynian-Indosinian movement (Silurian-Triassic).
5. C) Initial stage of Yanshanian movement (Jurassic-Cretaceous).
6. D) Early Tertiary.
7. E) End of Miocene.
8. F) Late Tertiary-Quaternary.
9. 1) Local sea transgression.
10. 2) Ancient Cathysian Sea.
11. 3) In process of actively colliding attenuated zone (Benioff zone) (dashed line, inferred).
12. 4) Withered away collision- attenuated zone (Benioff zone)
13. 5) Secondary expansion zone in process of expansion.
14. 6) Secondary expansion zone of already terminated expansion.

of the north and south land masses. The relation between the eastern margin of "Cathysian Massif" and the Pacific Ocean is obscure. During the latest Early Paleozoic Caledonian movements, the "Ancient Cathysian Sea" withdrew and the Early Paleozoic strata were folded to form the so-called "Caledonian fold belt." Tectonically, the North China platform and the Cathysian Massif joined, thus enlarging the continental plate. In Devonian time, the sea withdrew from the South Yellow Sea-northern Jiangsu subsidence zone and became a shallow sea in the area of North Vietnam-Guangxi province, China.

During the period from Early Paleozoic to Mesozoic (Silurian-Triassic), there were frequent invasions by the sea which transgressed northeastward across the area occupied by the "Ancient Cathysian Sea" and into the present-day Yellow and East China Seas. The sea, which was shallow, has been called the "Cathysian Sea." During this time, the eastern part of the East China Sea (including the coastal region of the Zhejiang and Fujian provinces) was probably a semi-deep to deep sea and was connected to the Pacific Ocean. The Dananao complex of Taiwan is a complex of metamorphosed marine deposits of sandstone, shale, limestone, and basic volcanic detrital rocks. The limestone contains fusulinid fossils, which identifies them as Permian in age. Marine sediments of Devonian and Carboniferous age have been discovered at the towns of Xiangshan and Shipu along the coast of Zhejiang province, and marine strata of Carboniferous age have been discovered at the town of Fuding along the coast of Fujian province. These sedimentary strata consist chiefly of marine detrital rocks, which are intercalated with siliceous rock, crystalline limestone and volcanic detrital rock. These lithofacies show that a sequence of Late Paleozoic geosynclinal deposits was deposited along the coastal region of Fujian and Zhejiang provinces. They were subsequently regionally metamorphosed. In the Hokkaido, Honshu, Shikoku, Kyushu, and Ryukyu Islands of Japan, a sequence of marine flysch sediments deposited in a Late Paleozoic deep or semi-deep sea environment has been found. In summary, during the Late Paleozoic, the vast area of the eastern flank of the "Cathysian Massif" was a deep or semi-deep sea, which connected with the Pacific Ocean. Marine sedimentary rocks that accumulated in this area were complexly metamorphosed by pressure and heat generated by plate collision. In the southwestern interior of Japan, the Feidan-Sanjun*, a locally metamorphosed zone, consists, in part, of high-temperature and low-pressure metamorphic rocks (radiometric dating 180-250 m.y.) and, in part, of low-temperature and high-pressure metamorphic rocks (205-330 m.y.) (Sugimura and Uyeda, 1973; Otsuka, 1939; and Konishi, 1965). The high-temperature and low-pressure metamorphic zone occurs on the peninsula where it is associated with extensive exposures of Triassic granite (190-225 m.y.) (Lee, 1973). The Late Paleozoic and part of Mesozoic (Triassic) strata of Taiwan and the coastal area of Zhejiang and Fujian provinces were intensively folded and metamorphosed. An attenuated linear collision zone between the Pacific Oceanic plate and the Asian plate extended from Japan to the sea neighboring the Zhejiang and Fujian provinces during Permian-Triassic time. That is to say, the Hercynian-Indosinian movements united individual small Asian plates together to form a unified Asian plate, and caused drastic changes in the distribution of land and sea areas. These events not only caused the end of the "Cathysian Sea" but

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* Chinese pinyin transliteration

also united the south and north landmasses in East China, and also contributed to the southeastward growth and expansion of the Asian continental crust, thereby forcing the so-called plate-colliding "Benioff zone" to migrate eastward.

During the Jurassic and Cretaceous periods, a collision zone between the Asian and the Pacific Ocean plates extended from the Kyushu Island of Japan to the Central Mountain Ranges of Taiwan. This attenuated collision zone is indicated by locally metamorphosed zones of the Jurassic and Cretaceous Lingjia (low pressure) - Sanbochuan (high pressure) beds and the Zeng* Island (equivalent to the Lingjia zone) - Siyuan* Island (equivalent to the Sanbochuan zone of the Ryukyu Islands) of Japan; and by locally metamorphosed zones of the Mesozoic (Cretaceous) Tailuge (low pressure and high temperature) - Yuli (high pressure and low temperature) (radiometric ages, 86 m.y.) (Yen, 1972) in the Dananao structural belt of Taiwan. The intensity of the plate collision is apparently indicated by the occurrence of the glaucophane mineral suite, which is commonly present in high-pressure zones (such as the Yuli zone). Along the inner flank of this attenuated collision zone, the Jurassic-Cretaceous granite (68-120 m.y. and 135-183 m.y.) is extensive in the southern part of the Korean peninsula. A Late Jurassic-Early Cretaceous low-pressure and high-temperature metamorphosed zone occurs in a belt that extends from the areas of Zhangpu and Duxun of Fujian province, via the Dongshan Island, to the Nanao Island of Guangdong province. In this metamorphosed zone, minerals of the andalusite suite are common. The metamorphosed zone and the occurrence of andalusite are evidence indicating the collision zone. The Mesozoic tectonic movements gradually united several Asian and European plates to form one huge Euroasian plate. During the Yanshanian movement at the end of the Mesozoic, the sea withdrew from the areas of the Yellow and East China Seas, and a wide open coastal mountain system emerged that occupied the southeastern part of the Korean peninsula and the northwestern part of the East China Sea and extended across the coastal region of Fujian and Zhejiang provinces to the south of the Yellow Sea. Three coastal mountain ranges, similar to the coastal mountain ranges of western North America and the Andes mountain system of western South America, bordered the Asian continent on the west and the Pacific Ocean on the East. This rising mountain system along the margin of Asia was the product of collision along an attenuated collision zone of the Pacific Ocean plate and the Eurosian plate, located along the eastern flank of this coastal mountain system.

During Early Tertiary (from the end of the Cretaceous to Eocene), expansion activities in the East China Sea occurred due to subduction of the Pacific Ocean plate beneath the Asian plate. This resulted in the development of secondary heat convection in the lithosphere, the gradual break-down of the coastal mountain system, the breakage between the Fujian-Lingnan rise zone and the area to the east, the gradual sea invasion of the rift zones, and the formation of a marginal sea due to continued expansion, which also was a factor contributing to gradual development of the East China Sea subsidence zone. Secondary expansion activities continued into the Miocene. At present, although the secondary expansion zone has ceased to expand, the remnants of this waning zone are the sea floor of the East China Sea, which contains two

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* Chinese pinyin transliteration

trends of large-scale strike faults, spotted seismic activities, and by the occurrence of glaucophane in metamorphic rocks found in southern Zhoushan Islands in the sea-floor areas beyond the mouth of the Yangzi River (Chang Jiang) and in the central part of the East China Sea. Both flanks of this expansion zone are occupied by the Hupi reef volcanic belt on one side and the volcanic belt of the marginal rise zone of the continental shelf on the other. As a result of the development of the East China Sea expansion zone, the "Benioff zone" between the Pacific Ocean plate and the Asian plate was shoved easterly. During this time, the marginal rise zone of the East China Sea continental shelf was a linear marginal island arc.

During the Miocene-Pliocene time, the intensity and direction of tectonic movements in the western Pacific Ocean varied greatly. The movement of the Philippine plate in the western Pacific Ocean changed from its western direction to a northwestern direction. The Ryukyu Islands arc prior to direction change was more tightly arcuate and to the south changed to an almost easterly direction. The plate collision zone was situated along an alignment in much the same position as are the Japan trench, Ryukyu trench, and Philippine trench at present. Since the Pliocene, a series of intense tectonic movements has occurred in the western Pacific Ocean, and the subduction of the Philippine plate has caused intense folding and uplifing accompanied by intrusions of great amounts of ultra-basic magnesian rocks, volcanic activities, and accumulation of turbidites and hard heterogeneous sandstones. Because of the great compression of the Philippine plate and the resistance of the Euroasian plate, intense folding and thrust faulting occurred on Taiwan Island and on other islands between the plates. The inclination of the "Benioff zone" of Taiwan shifted from west to east (the cause is yet to be investigated). As a consequence of the compression, Taiwan was rapidly uplifted. It is most important to mention that during the end of the Miocene or the beginning of the Pliocene, rifting began to appear in the eastern part of the East China Sea due to the subduction of the Philippine plate. Near the close of the Pliocene, continued rifting gradually produced a new expansion zone, the Okinawa trough rift zone. The marginal volcanic zone of the East China Sea continental shelf and the Ryukyu ancient volcanic zone occupied the flanks of the Okinawa trough. The presence of secondary expansion in the trough is further indicated by the high heat flow within the trough, the abundance of earthquakes, and a relatively thin crust (less than 24 km). As a result of compression forces exerted by the new expansion zone against the flanks of the Okinawa trough, the western flank of the trough was uplifted to form the remnant island arc-marginal rise zone of the East China Sea continental shelf, and the Ryukyu Islands arc along the eastern flank. At the same time the "Benioff zone" was forced to shift eastward. The Okinawa trough might be considered as the embryonic form of the marginal sea.

During Early Tertiary to Quaternary time, an orderly and continuous appearance of numerous activities of the secondary expansion, which progressively shifted eastward, gradually expanded the area of the East China Sea and lay the foundation for the present structural patterns of the Yellow and East China Seas. During this time, some secondary expansion activities appeared sequentially in the Sea of Japan, the South China Sea, and the Philippine Sea. These activities produced a complicated distribution of structural patterns in the areas of the western Pacific Ocean island arc-trench systems. A sea of Early Tertiary and Quaternary age covered the areas of the East China Sea, partially covered the Fujian-Lingnan rise zone, and invaded areas of the South Yellow Sea and northern Jiangsu province. At the end of the Quaternary (Late Pleistocene), the Tali glaciation began; the sea level dropped, the sea partially withdrew, and the continental shelf of the Yellow and East China Seas became a large coastal plain, which was inhabited by fauna accustomed to a frigid environment. At the close of the Pleistocene, the climate became warm, the sea level gradually rose, and the sea began to cover the eastern margin of this large coastal plain. During the Quaternary, the sea continuously rose and moved further and further inland. The continental shelf of the East China Sea and the South Yellow Sea once again became sea. Later, the sea invaded further into the area of the North Yellow Sea and then passed over the Bohai strait and entered the Bohai.

Secondary Expansion and Marginal Sea

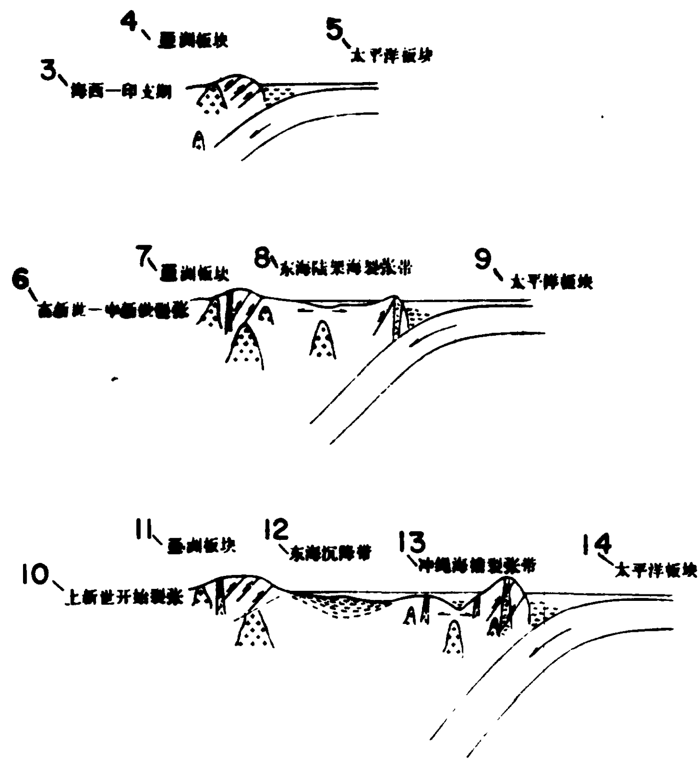
Numerous episodes of secondary expansion controlled the development of the complex structural patterns of the Yellow and East China Seas. Many collisions of the Pacific Ocean plate with the Asian plate, in turn, led to episodes of secondary expansion as well as to simultaneous torsional expansion. Since the Paleozoic, the attenuated collision zone of both plates migrated several times eastward. The position of the collision zone during the Early Paleozoic is obscure, but it was probably east of the Fujian-Lingnan rise zone. From Late Paleozoic to Early Mesozoic time, when the Hercynian-Indosinian movements occurred, the collision zone extended from the Feidan-Sanjun metamorphosed zones on the southwestern inland of Japan to the sea areas near the Fujian-Zhejiang coastal region (the actual location of the zone is uncertain). During Jurassic-Cretaceous time, the collision zone, however, extended from the Lingjia-Sanbochuan metamorphosed zones on the Kyushu Island of Japan, via the Zeng Island-Shiyuan Island metamorphosed zones of the Ryukyu Islands (then west of their present position) to the Tailuge-Yuli metamorphosed zones in the Dananao structural belt of Taiwan. From the end of the Miocene to the Holocene, the collision zone of the western Pacific Ocean plate and the Asian plate was aligned along the Japan trench, Ryukyu trench, and Philippine trench. The cause of the southeastern migration of the collision zone is yet to be determined, but the movement is possibly due to the earth's rotation. The development of the secondary expansion in the Paleozoic still needs further study, but since the Mesozoic, the secondary expansion development can be traced elsewhere. The Jurassic-Cretaceous attenuated collision zone facilitated development of secondary expansion on the continental shelf of the East China Sea during Paleocene to Miocene time and produced the East China Sea subsidence zone. The appearance of the attenuated collision zone of the Pacific Ocean plate, which is presently active, first appeared at the close of the Miocene. Since the Pliocene, the formation of a new secondary expansion zone has occurred in the East China Sea. This is the rift zone of the Okinawa trough. The marginal rise zone of the East China Sea continental shelf is a remnant of an island arc. The Tokara rift, the Gongu faulted depression, and the Ishigaki Islands rift zone are evidence indicating torsional expansion of synkinematic development and secondary expansion. In addition to the subduction and compression of the Pacific Ocean plate, the formation of torsional expansion is probably closely related to the earth's rotation, which caused the Asian continent to shift southeastward.

Numerous secondary expansions have not only controlled the structural patterns of the Yellow and East China Seas, but they also have been the principal factors contributing to development of marginal seas. At present, the definition of "marginal sea" has yet to be defined (Karig, 1971; Watts and others, 1977). The authors herein consider the seas behind the arcs as "marginal seas." Two marginal seas of different ages were developed by numerous secondary expansions in the East China Sea. One is the waxing marginal sea that occupies the Okinawa trough and the other is the East China Sea (fig. 10), a waning marginal sea on the continental shelf. Because of sequential occurrence of many secondary expansions, the marginal seas have followed a regular pattern in the process of aging. Typical marginal seas in the western Pacific Ocean and their ages are:

Youthful marginal sea, represented by the Okinawa trough.

Mature marginal sea, represented by the Sea of Japan and the South China Sea.

Old Marginal Sea, represented by the continental shelf sea of the East China Sea.



1、图 10 2、

1. Figure 10.
2. Shows structural evolution of the East China Sea.
3. Hercynian-Indosinian stage.
4. Asian plate.
5. Pacific Ocean Plate.
6. Paleocene-Miocene rift.
7. Asian plate.
8. Rift zone of continental shelf sea of the East China Sea.
9. Pacific Ocean plate.
10. Beginning of rift of the Pliocene.
11. Asian plate.
12. Subsidence zone of the East China Sea.
13. Rift zone of the Okinawa trough.
14. Pacific Ocean plate.

Macrostructural processes that have affected the earth's surface during geologic history are of two types: 1) those that have contributed to the origin of oceans and their expansion, and 2) those that have contributed to the origin of continents and their enlargement. Those that have contributed to the origin and enlargement of continents are of two types: 1) those resulting from junction of continents, such as, structural processes resulting from the collision and junction of the Indian plate with the Euroasian plate; and 2) those resulting from the formation of marginal seas. The secondary expansions generally originated in the margins of continental plates (near the collision zone) and caused separation of a small part of the continent to form the marginal sea and the marginal island arc. Under the process of continuous expansion, the plate beneath the marginal sea forced the island arc against the attenuated collision zone and thereby caused the collision zone to migrate toward the oceanic plate. Although the development of young and mature stages of marginal seas in the continental crust showed the appearance of oceanic mantle materials, the processes of sedimentation on the marginal sea floors were, nevertheless, active. As the crust continued to be worn down, accompanied by the aging of the marginal seas, the oceanic mantle materials changed into new crustal materials deposited on the original continent segments. Henceforth, the deposition of new crustal materials facilitated the enlargement of the continents. Research on the tectonics of the Yellow and the East China Seas has contributed to the knowledge of the development of marginal seas and to the knowledge of the origin and development of continents.

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