# Geodynamic characteristics of tectonic extension in the northern margin of South China Sea

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**Abstract** Based on the geothermal and gravitation methods, this paper investigated the rheological and thermal structure of the lithosphere under the northern margin of South China Sea. The result shows that the temperature of the upper crust is 150—300℃ lower than that of the lower crust, and the viscous coefficient of the upper crust is 2—3 orders of magnitude larger than that of the lower crust. It reveals that the upper crust is characterized by brittle deformation while the lower crust by ductile deformation. A channel of lower-viscosity should be formed between the upper and lower crust when the lithosphere is scattered and spreads out toward ocean from northwest to southeast along the northern margin of South China Sea. And, a brittle deformation takes place in the upper part of the lithosphere while a ductile deformation takes place in the lower part of the lithosphere due to different viscous coefficients and temperature. The layered deformation leads the faulted blocks to rotate along the faulting and the marginal grabens to appear in the northern margin of South China Sea in Cenozoic tectonic expansion.

**Keywords: the northern margin of South China Sea, the zone of continental margin, thermal and rheological structure, layered deformation of lithosphere.**

The northern margin of South China Sea is located in the circum-Pacific tectonic zone, an active tectonic zone of global scale. This zone is possessed of the following common features[1]: wide magma intruding, strong deformation, frequent earthquake and clear geophysical anomaly. However, they are distributed in different areas and occur alternatively in time. There is not only various material replacement between deeper crust and mantle, but also different tectonic framework and dynamic environment in this zone. On the northern margin of South China Sea, there are a series of normal faults[2] in the northeast direction. These faults formed extensional or spread structure which generates lithospheric stretch and crustal thinning from the northern margin to the deep basin of the South China Sea since the Late Cretaceous to Cenozoic. With the background of active continental margin, this region is mainly characterized by the continental crust disintegration, the massif splitting and the formation of a series of tensile grabens. The layered deformation of lithosphere is the important geotectonic characteristic of the continental margin.

Different models have been put forward aiming at the deformation of continental lithosphere. Mc Kenzie[3] studied the continental margin, and proposed the model of uniform lithospheric extension under the effect of extensional stress field, which has been known as the pure-shear model.

White et al.[4] believed that the partial melt of mantle and magma intruding can cause split of lithosphere and expansion of sea floor. Wernicke[5,6] studied the field geology and some low-angle normal faults of the Basin-Range Province, and suggested that the extensional stress field operated there, producing lithospheric faults and fault block motions, thereby creating lithospheric extension and thinning. He mentioned a simple-shear model. These models have been used to conduct quantitative calculations of the history of heat flow and subsidence on the continental margin and rifting sedimentary basins predicted. According to the observation of a typical crustal section across the passive continental margin in the northern part of the South China Sea, Yao[7] put forward a deformation model of layered shear.

Based on the observation of heat flow and the model of gravitational field, the authors calculated the distribution of temperature and the structure of rheology under the northern margin. And, based on the computed result and the tectonic feature, the authors also discussed the dynamic characteristic of lithosphere in tectonic extension and layered deformation. This work provides a foundation for further analysis and study on thermal evolution and deep tectonic deformation of the South China Sea Margin.

## 1 The tectonic characteristics

The South China Sea is one of the most important marginal seas to the west of the Pacific. Previous study declares that [1] the main tectonic framework between the East Asia and the Pacific Ocean has formed in continent disintegration and margin outspreading since the late Cretaceous. During the early Cenozoic the continental margin in the northern part of the South China Sea experienced several steps of extensions, which plausibly caused the crustal thickness there to be reduced and thus produced the present-day South China Sea. The basic feature of this tectonic framework is that there are a series of fallen-basins, island arcs and marginal seas in continental margin (fig. 1).

The joint scientific investigation has been carried out in the South China Sea since the 1970s. The data of these investigations indicate[2] that the crustal structure is complex. Here, the oceanic crust and continental crust as well as transitional crust are concomitant.

The crustal thickness does not change smoothly and continuously from the continental shelf to the slope and to the deep basin of the South China Sea. The central deep basin has the structure of oceanic crust with the crustal thickness of 10—12 km and the lithospheric thickness of 35—40 km[1]. The northern margin has the structure of continental crust and the crustal thickness thins seaward. Beneath the continental shelf near the upper continental slope, the average crustal thickness is 26—30 km. Beneath the central part of the continental slope, the crustal thickness is 22—24 km. Near the lower continental slope or the continental-ocean boundary, the crustal thickness is about 14 km. The lithospheric thickness of the northern margin is about 60—96 km[1]. The crustal structure of the northern margin is exhibited in fig. 2.

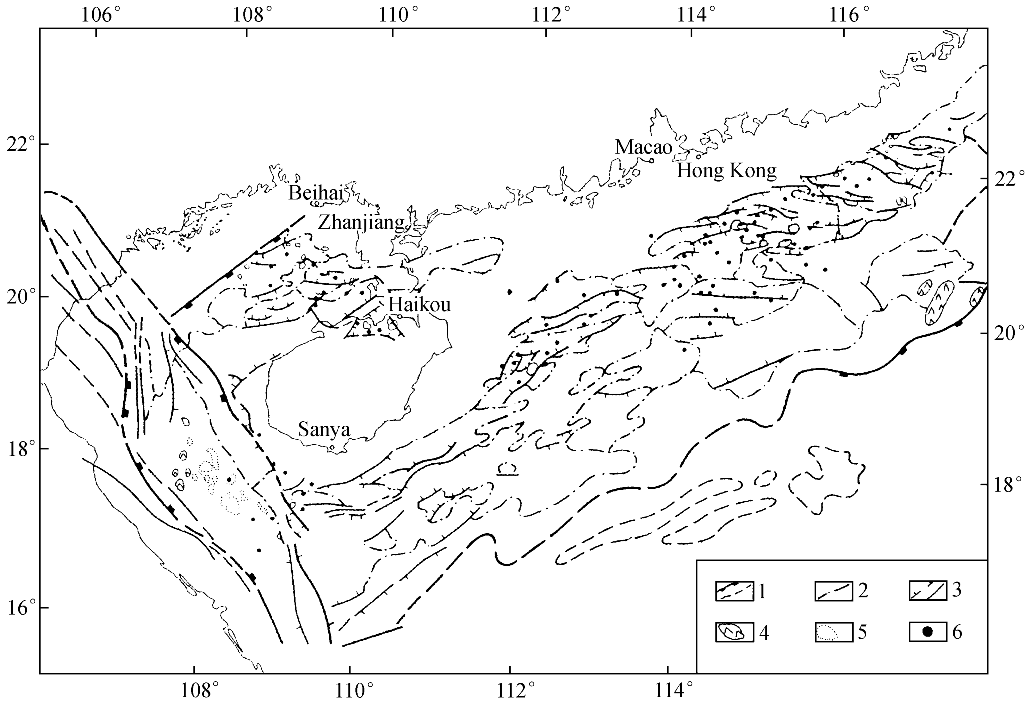


Fig. 1. The tectonic sketch of the northern margin of South Chine Sea (modified from ref. [2]). 1, Fault of basin boundary; 2, tectonic limits; 3, fault in basin; 4, volcanic; 5, anomalous body of seismic reflection; 6, borehole.

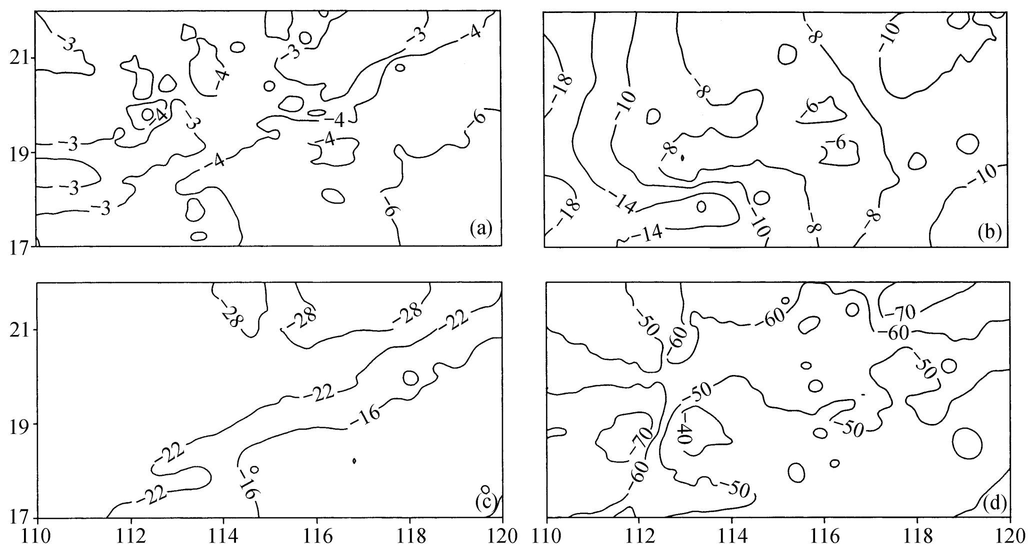


Fig. 2. The crustal structure of the northern margin of South China Sea. (a) Depth of sedimentary base; (b) depth of interface between upper and lower crust; (c) depth of the Moho; (d) depth of lithospheric bottom (unit: km).

The crustal structure in the north part is different from that in the south part of the fault that lies in the boundary of the northern margin and deep basin of the South China Sea. The north crust apart from the fault is a thinning continental crust. The south crust apart from the fault is a weak belt. Along the weak belt, the crust was drawn away and continental margin was formed when actual sea-floor spread and produced the present-day South China Sea. In this process, the magma intruded and generated the violent tectonic activity in the Cenozoic. This region is situated on oceanic and continental crust. The different mode of mantle convection between continent and ocean may cause sub-convection and local current and convergence in upper mantle. As a result, unstable states of energy appear and cause violent tectonic activity. Under the effect of heat and gravitational potential energy, the continental crust was disintegrated and the massif was split piecemeal. Being the background of active continental edge, the northern margin of South China Sea has intense tectonic activity.

The extension of lithosphere brings the crustal thinning from the northern margin to the ocean. This phenomenon arouses our attention to the deformation mechanism and the deeper dynamic characteristic of lithosphere. Consequently, our investigation was aimed at using the methods of geothermal and rheology and gravity to study the relationship between plate movement and mantle convection and to deduce the likely mechanism of the formation and evolution of the extensional sedimentary basins in the northern margin of South China Sea.

## 2 The deep dynamic characteristics

### 2.1 Geothermal characteristic

Terrestrial heat flow is an important parameter mirroring lithosphere thermal state. So far, there are 584[8] observation data of heat flow in the South China Sea. 39.4% of the data come from the northern margin. The average value of heat flow in the northern margin is about 74.9 mW/m$^2$. Statistic result shows that terrestrial heat flow gradually increases from the northern continental margin to the deep basin of the South China Sea with the crust thinning in the same direction. The average value of heat flow is about 60 mW/m$^2$ in the middle of the continental shelf, about 80 mW/m$^2$ in the turning point of the continental shelf to the slope, about 100 mW/m$^2$ near the lower continental slope. In sedimentary basins of the northern margin, the highest value of heat flow appears in Yinggehai Basin where the average value of heat flow is 84.1 mW/m$^2$. The average value of heat flow is about 78.7 mW/m$^2$ in Ying-Qiong Basin, about 71.9 mW/m$^2$ in Pearl River Mouth Basin and about 61.2 mW/m$^2$ in Beibu Gulf Basin.

With the help of observed heat flow and the equation of heat transfer, we can get the distribution of the temperature in the deeper part. The calculated distribution of temperature is given in fig. 3.

The computed results show (fig. 3(a)) that the temperature on sedimentary base is about 140—190℃, and the value gradually rises from the northwest margin to the southeast central sea-basin of South China Sea. There is slight increase in temperature from upper crust to sedimentary layer (fig. 3(a), (b)). It suggests that the temperature of upper crust is not high. The temperature of the Moho is about 750—900℃ (fig. 3(c)). It can be seen that there is a temperature step between the upper crust and lower crust. In lithospheric bottom, the temperature is about 1200—1240℃ (fig. 3(d)). The value is lower than the melting point of peridotite. From the above discussion, we can see that the temperature distribution in fig. 3 exhibits a "sandwich" structure, that is, the temperature of upper crust and lithospheric mantle is relatively low whereas the temperature of lower crust is relatively high in the northern margin of South China Sea.

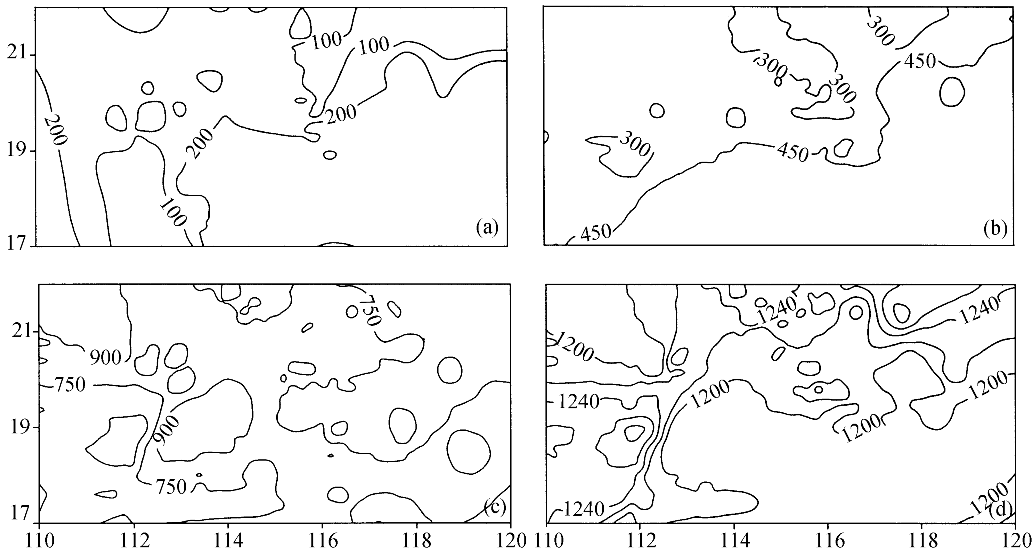


Fig. 3. The distribution of temperature of the northern margin of South China Sea. (a) Temperature of sedimentary base; (b) temperature of interface between upper and lower crust; (c) temperature of the Moho; (d) temperature of lithospheric bottom (unit: ℃).

## 2.2 Rheological characteristic

Different material has different rheomorphism under definite temperature and pressure. Using some representative rocks and single strain rate, we can get the approximate distribution of lithospheric rheomorphism. In our study, the material construction of the northern margin was roughly expressed as the sedimentary layer with quartz-rich rock, the upper crust with intermediate rock, the lower crust with basic rock and the lithospheric mantle with ultrabasic rock.

The lithospheric rheomorphism is expressed by effective viscous coefficient in this paper. The parameter of rheology is selected as in table 1[9], and the strain rate $\dot{\varepsilon}$ is taken in $10^{-15}$ $s^{-1}$.

Table 1 The material rheological parameter[9]

| Material | Log $A$/MPa$^{-n}$ • s$^{-1}$ | $N$ | $E$/kJ • mol$^{-1}$ |
|---|---|---|---|
| Quartz-rich rock | –6.0 | 2.8 | 150 |
| Intermediate rock | –3.0 | 3.0 | 230 |
| Basic rock | –2.5 | 3.2 | 270 |
| Ultrabasic rock | 4.5 | 3.5 | 535 |

Fig. 4 is the $\text{Log}_{10}\eta$ distribution of the northern marginal lithosphere. The $\text{Log}_{10}\eta$ is the logarithmic expression of effective viscous coefficient $\eta$ (unit: Pa • s). The volume of effective viscous coefficient $\eta$ can reflect the hardness of the lithosphere. It is an index of lithospheric tectonic activity. Fig. 4(a) and 4(b) show that there is a high $\eta$ background in the sedimentary layer and the upper crust. Their effective viscous coefficient $\eta$ is about $10^{22}$—$10^{25}$ Pa • s. It mirrors that there is the higher brittleness in sedimentary layer and upper crust. However, the $\eta$ value in the upper crust gradually decreases from $10^{24}$ Pa • s to $10^{22}$ Pa • s in the direction of northwest to southeast in the northern margin. It hints that crust may gradually soften from northern margin to central deep basin of the South China Sea. The $\eta$ value is about $10^{21}$—$10^{22}$ Pa • s in the lower crust (fig. 4(c)). The $\eta$ value of the lower crust is 3 orders of magnitude lower than that of the upper crust. This characteristic shows that the lower crust is softer than the upper crust. The $\eta$ value of lithospheric upper mantle is about $10^{20}$—$10^{21}$ Pa • s which coincides with the mantle viscosity from the data of ice age[10]. It proves that the mantle under the northern margin has the physical condition of convection in geological time scale.

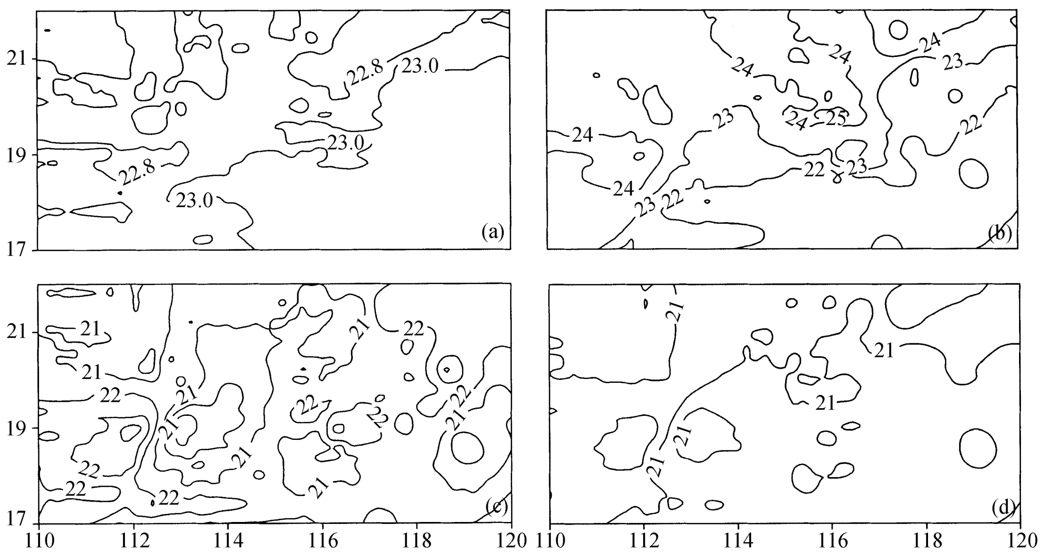


Fig. 4. The $\text{Log}_{10}\eta$ distribution of the northern margin of South China Sea. (a) $\text{Log}_{10}\eta$ of Cenozoic sediment; (b) $\text{Log}_{10}\eta$ of upper crust; (c) $\text{Log}_{10}\eta$ of lower crust; (d) $\text{Log}_{10}\eta$ of lithospheric upper mantle.

The feature of rheology under the northern margin in fig. 4 shows that the upper part of lithosphere including the sedimentary layer and upper crust is brittle. Therefore, the main deformation form of the upper part of the lithosphere is breaching or gliding along the fault. In contrast, the deeper part of lithosphere including the lower crust and lithospheric upper mantle is ductile. Hence, the main deformation of the deeper part of the lithosphere can be considered as rheomorphism.

## 3 The deformation characteristic of the continental lithosphere

The South China Sea lies in the converging belt of the Eurasian, the Pacific and the Indo-Australian plates. Tectonically, this area belongs to the junction zone of the continental crust and the oceanic crust tectonic domains. Because of the collision between the Indo-Australian plate and the Eurasian plate, and the change of the moving direction from NNW to NW of the Pacific plate, a special tectonic framework has been formed in this area. The feature of this framework is that there is extension in the northern margin and compression in the southern margin and shear on both the east and west sides of the South China Sea.

The continental margin in the northern part of the South China Sea was a passive continental margin in the Cenozoic. Under the effect of an early Cenozoic extensional stress field, the continental margin was stretched and thinned. In this process, a series of extensional faults was developed into the northern marginal basins and formed extensional or spread marginal structure. They constitute the outspread background of the northern margin of the South China Sea. From Late Cretaceous to Cenozoic, this region was mainly characterized by the lithosphere thinning, cracking and subsidence. Under the outspread background, the northern marginal crust was drawn away and disintegrated seaward.

The seismic reflection profile collected through the joint Sino-US geological investigation project in the northern margin of South China Sea shows[7] that there are some slope faults in the upper crust but not in the lower crust at the continental-ocean boundary. On the slope of the upper crust there is a continuous reflection, which indicates that it is a smooth and strong wave impedance surface. In the lower crust, there are some non-continuous and sub-horizontal reflected waves, indicating some non-continuous interfaces. This fact suggests that under the extensional stress, there is different deformation mechanism between the upper and lower crust in the spreading continental lithosphere. A brittle deformation takes place in the upper part of lithosphere while a ductile deformation takes place in the lower part of lithosphere.

The lithospheric rheological and thermal structure calculated in our work also shows that the dynamic characteristic of the upper and lower crust is different in the outspread process of lithosphere under the northern margin. The upper crust exhibits low temperature and brittle nature, while the lower crust exhibits high temperature and ductile nature. The continental lithosphere material can deform by brittle deformation if it is cool and at low confining pressure, while increase in temperature ductile deformation occurs. As a consequence brittle faults take place in the upper crust and the flexible stretching takes place in the lower crust. The brittle upper crust experienced fracturing and slit along the faults, while with the increase in depth and temperature of the lower crust, ductile deformation becomes dominant in the extensional stress field of the lithosphere. The calculated result of lithospheric rheological and thermal structure lead us to believe that the continental lithospheric deformation was layered in physical property and deformation style under the effect of an extensional stress field. In the northern margin of the South China Sea, the mode of layered deformation can be considered as that the upper crust expresses brittle nature and normal faults happened in it. The lower crust has ductile character and undergoes ductile deformation.

## 4 Discussion

We conjecture that there was a tensile stress in the bottom of the lithospheric plate when the lithosphere was drawn away and disintegrated at the northern margin. The tensile stress field of lithosphere primarily generates breach and fault blocks in the brittle upper crust. Then, these fault blocks slide on the ductile lower crust following the mantle convection. In the process of the lithosphere's scattering toward the ocean, the brittle upper crust changes into lumpish movement and graben system. Some faulted blocks rotated along the faulting and formed an almost vertical fault-interface between continental lower crust and oceanic crust at the continental-ocean boundary. This vertical fault-interface of the boundary between continent and ocean may be caused by the pulling fashion of "bottleneck" in the layered deformation of the lithosphere. This fashion can be actuated in the ductile lower crust when the lithosphere was split by the local convection motion.

The characteristics of geotherm and rheology show that there is a bigger gap of the viscous coefficients between the upper and lower crust in the northern margin of South China Sea. The upper crust has high viscous coefficient and exhibits brittle nature, and the lower crust has small viscous coefficient and exhibits ductile nature. Thus, under the effect of an extensional stress field, the upper crust should express brittle deformation and produce a series of extensional faults and fault blocks. They stretched and thinned the crust and created a series of grabens and half-grabens in the surface. The lower crust should undergo ductile extension and associated crustal thinning. Following the deformation model of layered shear brought forward by Yao[7], we agree with the view that the upper crust with brittle character was deformed by simple-shear mode, and the lower crust with ductile character was deformed by pure-shear mode. We believe that the layered deformation is a correct model for the passive continental lithosphere in the process of tectonic extension and scattered along the South China Sea margin.

The earthquake near here can also confirm the characteristic of lithospheric layered deformation. Earthquake is the consequence of rock rupture and displacement. Many destructive earthquakes have happened in South China coastland and its adjacent sea area. The tectonic zone from Taiwan of China to Luzon arc and Manila Trench is the well-known active region of earthquakes. Some earthquakes of shallow source have continually raided the continental marginal arc, Taiwan, since September 21, 1999. Here, most earthquakes take place in the upper crust and only a few in the lower crust. It indicates that the upper crust is a brittle layer and may rupture or be displaced, while the lower crust is a ductile layer and cannot accumulate enough strain energy to cause earthquakes.

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