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# The Late Mesozoic Granodiorites from the Southwest Basin in the South China Sea and Its Tectonic Implication

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**ABSTRACT: The southwest basin is a key to study the origin and development of the South China Sea (SCS). We do not know much about its boundaries, geological history, and the formation of its sea floor because it has a complex and highly regional structural background, notable sediment activity, and yet few floor rocks. Here a granodiorite sample was collected from the southern margin of the southwest basin of the South China Sea. The results indicated that the $^{40}$Ar-$^{39}$Ar ages of biotites in the sample are 110.3±0.5 Ma, suggesting that they were products of magmatic intrusion during the Early Cretaceous period. The sample's geochemistry showed it had high $SiO_2$, $K_2O$, and $Al_2O_3$ but low $TiO_2$ levels. Tectonic discriminant diagrams suggested that the sample might represent extrusion-related magmatism, either in an arc or forearc setting in the SCS area and that the sample mainly belonged to the syncollision type, whose formation was related to orogenies. The sample may be part of the main rock that made**

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**up the boundaries of rift system. The process of tension cracking was similar to the development of the Red Sea, in which the rifting and sagging occurred in the continental crust. The southwest basin may not be an original ocean, but a rift developed through finite extension on continental crust basement. The oceanic crust came into being when the width and depth of the rift valley reached a certain scale. The granodiorite sample we collected provides a means of determining the boundary of the southwest basin and the clues that may help researchers expand relevant models. It constitutes an important datum regarding the analysis of the formation and development of the SCS.**

**KEY WORDS: Late Mesozoic, granodiorite, the southwest basin, the South China Sea, $^{40}$Ar/$^{39}$Ar age, tectonic implication.**

## INTRODUCTION

The South China Sea (SCS) is one of the largest marginal seas in the western Pacific, which comprises several sub-basins. Owing to its high potential for oil and natural gas, it attracts more and more attentions in recent years. Therefore, probing into the mechanism of formation and evolution pattern is a key subject regardless of geologists or geophysicist. Although extensive surveys have been carried out over the South China Sea by industrial drilling, ODP (Ocean Drilling Program, Leg 184) and dredging, multiple channel seismic, expanded spreading seismic and ocean bottom seismic surveys, which is considerably helpful for us to better understand the origin and evolution process of the South China Sea, available samples are quite difficult to collect so that the origin and nature of these sea basins distributed in the South China Sea have remained controversial. Tectonically, it is located on the interface between Europe and Asia, the Indian-Australian plate and Pacific plate (the Philippine Sea plate). It developed on the extensional structures formed by rifting in the Late Mesozoic–Paleogene period. It also developed on the orogenic belt, wedge deformation zone, and subduction zone formed by eastward subduction of the South Sea during the Late Miocene. There are many different points of view regarding the formation and development of the South China Sea basin and regarding the mechanism by which it continues to change, most notably in the context of co-existing tension and compression (Chen and Wen, 2010; Yao et al., 2005; Zhou et al., 2005a; Yao, 1997; Briais et al., 1993; He, 1988; Taylor and Hayes, 1980).

The southwest sea basin is one of the most important tectonic units in the South China Sea. It is a critical area of exploration with regard to the evolutionary history of the South China Sea. It is also the focus of attention of many research teams. The sea basin is located between the block of Xisha Islands and Middle Shoal and the block of Nansha Islands, appearing as an open triangular basin in the northeast. The basin is connected to the central basin in the vicinity of 115°E. The axial length is about 600 km, the opening width is about 400 km, and water depth is between 3 000 and 4 000 m. The bottom of the basin is flat, and there are seamounts, sea knolls and sea swamps of different sizes distributed on the northeast part of the bottom (Gao et al., 2009; Yao, 1999; Bao and Xue, 1993). It is one of the most active regions in the world for Cenozoic deposition. The main obstacle to understanding the constitution of the basin floor is the large number of sediments. Our current, limited understanding of the constitution is mainly based on the interpretation of geophysical data (Fang et al., 2007; Zhang et al., 2005; Liu and Yan, 2003; Liu et al., 2003; Ding et al., 2002). Because of the lack of the strong support from rock samples and ocean drilling, the time of formation, crustal properties, ridge structures, ocean basin boundaries, mechanism of formation of the southwest basin, and the relationship between the northwest basin and the central basin remain to be properly understood.

Granite is common in continental land areas around the South China Sea, such as southern China, Hainan Island, the south peninsula, and other places (Lin et al., 2009; Liu et al., 2007; Zhou et al., 2005b; Chen et al., 2003; Li et al., 2003; Li, 2000). Granite samples had been found on the Natuna Sea field in the southwestern of South China Sea and the southern Nansha Sea (Yan et al., 2010; Hutchison, 2004; Areshev et al., 1992; Kudrass et al., 1986). However, according to relevant literature, this is the first time that a granite sample has been collected this far away from the mainland, in the southwest basin, by trawling.

The samples provide a good means of addressing the problems listed above, which have important geological significance regarding the structure of the South China Sea, the process of its development, and the boundary of the southwestern basin.

## MATERIALS AND ANALYTICAL METHODS

### Sample Description

The samples are from the southern margin of the southwest basin, collected at 11°28'N, 114°05'E (bottom trawling with coordinates) at a depth of 3 100 m. They were collected by the Guangzhou Marine Geological Survey, “Ocean IV” in 2005 in during S-08 cruise, through trawling (Fig. 1). The samples are irregular blocks. In addition to the cross-section, the surface with clay-like, fine-grained sediments adhered, and the black oxide coated the section that had faced the water, and region about 1 cm or so under the alteration zone showed light red color. The cross section pictured below was fresh, shown in pink white, and mineral crystals were identified visually. The freshness of the cross section is clear in the image below and shows itself to be part of the more integral body. The sample was believed to have been found in its original place. Sampling points were far from the mainland, where water depth is over 3 000 m. Artificial samples and the possibility of movement by water from the South China Sea can be excluded. The samples were found at low latitude, so the possibility that they were carried by ice raft is small. The samples can then be said to be basic native basement rocks, but their occurrence and other related characteristics are not clear.

The rock samples were pale, and their massive structure showed the coarse-grained quality characteristic of granite. The main minerals were plagioclase, potassium feldspar, quartz, biotite, and hornblende. Particle size was about 1–5 mm. The plagioclase lath content, from euhedral to subhedral, was about 30%. Semi-shaped potassium feldspar was about 15%. Quartz in other granular forms was about 20%, and biotite and hornblende were about 10%. The rock surface and the section, which were in contact with water, showed obviously alteration phenomena.

The silicon content was about 67% and that of quartz about 20%. Biotite and hornblende were patchy. In this way, the samples were identified as granodiorite.

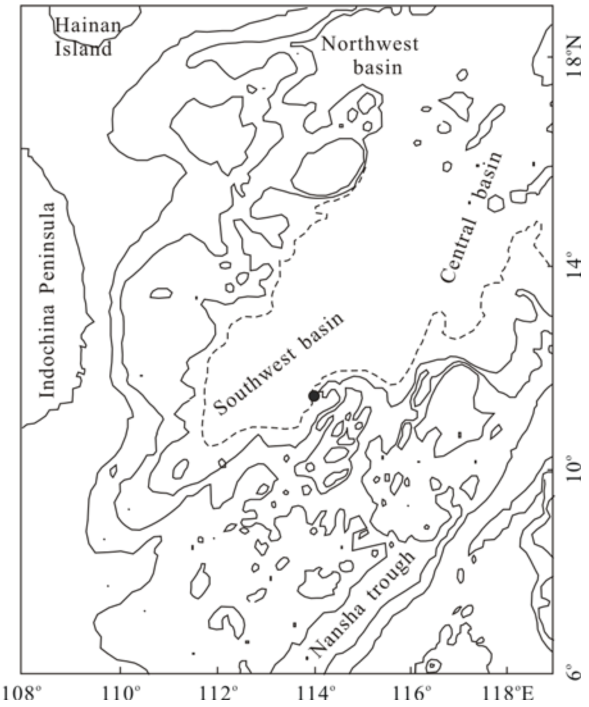

**Figure 1. Distribution of the sea basin and location of the sampling site.**

In view of their value, samples weighing about 0.5 kg or so were taken for the study. The upper boundary is straight because it is cut from the large sample. That is the cutting surface, not the broken surface by natural breakdown (shown in Fig. 2).

### Geochemical Composition

XRF, ICP-MS, and instruments from the Experimental Center of the China University of Geosciences (Beijing) were used on the rock samples for geochemical analysis. Results showed the following: $SiO_2$ content 67.75 wt.%, $Al_2O_3$ content 15.20 wt.%, $K_2O$ content 3.36 wt.%, $Na_2O$ content 3.96 wt.%, CaO content 3.15 wt.%, MgO content 0.73 wt.%, $TiO_2$ content 0.37 wt.%, $P_2O_5$ content 0.14 wt.%, MnO content 0.09 wt.%, $TFe_2O_3$ content 2.98 wt.%, and loss on ignition (LOI) was 0.56 wt.%.

By analysis and testing, the main components of the samples were found to show the following characteristics: (1) high $SiO_2$ content (67.75 wt.%); (2) high total alkali content, $Na_2O+K_2O$=7.32 wt.%, $K_2O<Na_2O$ ($K_2O/Na_2O$=0.85). The samples were relatively rich in potassium, especially in the region of K calc-alkaline rock series in the $K_2O$-$SiO_2$ diagram projection; (3) $Al_2O_3$ content of 15.20 wt. %>15 wt.%; (4) Mg# value below (Mg#=100×$Mg^{2+}/(Mg^{2+}+Fe^T)$), which is 32.7; and (5) poor $TiO_2$ content, only 0.37 wt.%. The total REE of the samples was low, ΣREE= 105.17×$10^{-6}$. The sample was rich in LREE, LREE/HREE=15.76.

The distribution curve is right-wing, and the fractionation of REE and LREE was obvious. There were clear negative Eu anomalies, *δ*Eu=0.22. The La/Ta ratio (46.43) was significantly greater than 22, the La/Nb ratios (1.72) were greater than 1.5, and the Zr/Ba ratio (0.22) was close to 0.2. The samples had high Sr content (391.36×$10^{-6}$) and Ba content (773.61×$10^{-6}$), indicating a partial melting of crustal magma.

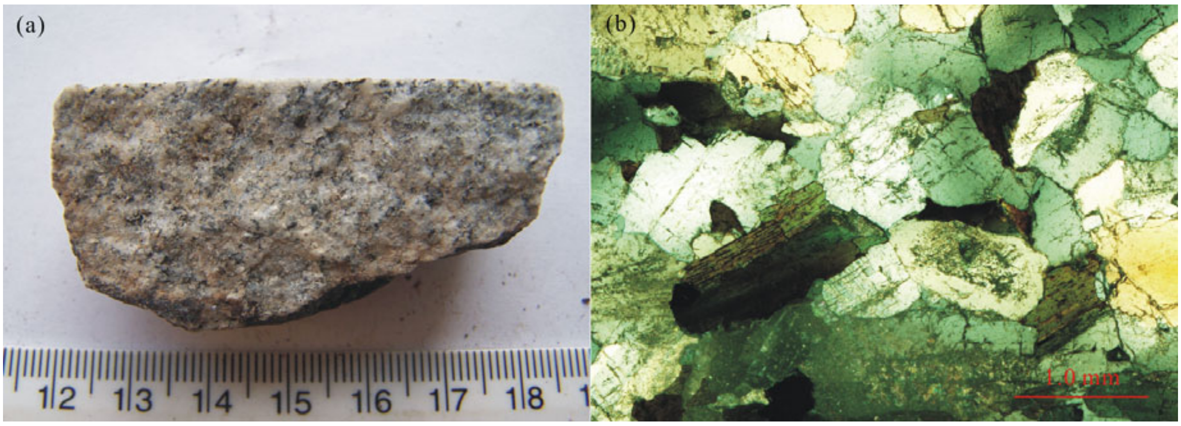

**Figure 2. Shape and microstructure of the sample.**

### $^{40}Ar/^{39}Ar$ Age

The $^{40}Ar/^{39}Ar$ laser probe dating system, developed by the Orogenic Belts and Crustal Evolution Key Laboratory of the Ministry of Education in Beijing University, was used to test the sample composition of the mineral biotite $^{40}Ar$-$^{39}Ar$ for dating purposes. The various points of test samples made up $^{40}Ar/^{36}Ar$, $^{39}Ar/^{36}Ar$ isochrons with a good linear relationship, and the isochron age was found to be 109.5±1.5 Ma (Fig. 3). $^{40}Ar/^{36}Ar$ and $^{40}Ar/^{39}Ar$ isochrons also showed a good linear relationship. The error of each testing point was small, indicating that the tested minerals were within a good closed system. Based on the test data, the $^{40}Ar/^{36}Ar$ average ratio was found to be 2 079.7±57.3 (MSWD=0.1), which shows that mineral crystallization is in a closed state, and the impact of fluid is small. Test data show the $^{40}Ar/^{36}Ar$ initial ratio to be 295.5±0.5, and the error range to be

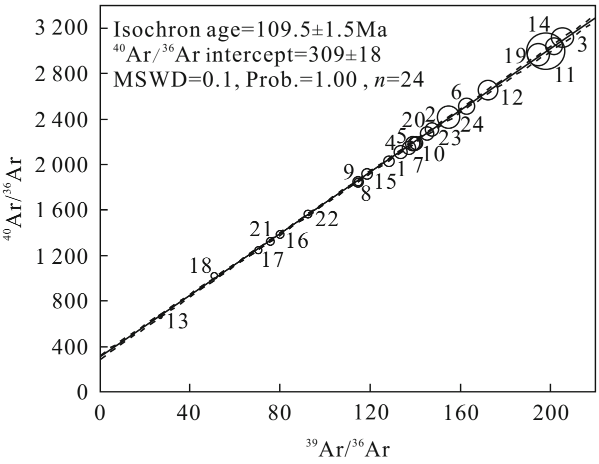

**Figure 3. Isochron age of the biotites.**

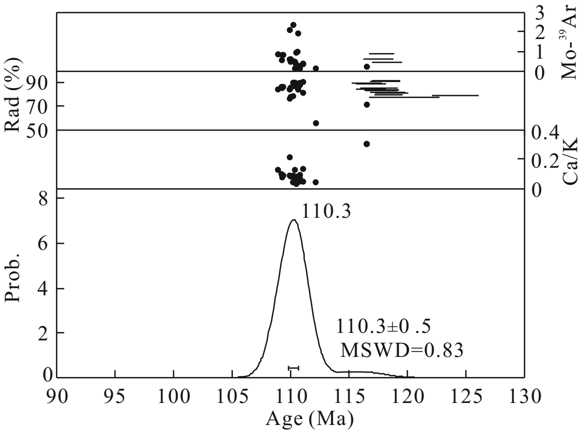

**Figure 4. Age-probability of the biotites.**

very similar to that of the modern atmospheric argon ratio, 295.5. The presence of excess argon in the biotite could be ruled out, which proves that the isochron age was reliable. The emplacement age of crystallization was represented accurately. Age probability shows 110.3 Ma to be the most concentrated peak value and that 110.3±0.5 Ma (MSWD=0.83) might be closer to the crystallization age of the rock (Fig. 4). It can be determined the sample is the product of Early Cretaceous magmatic intrusion.

## TECTONIC SETTING

Granites cluster with other geological information. This can reveal the different tectonic environments and geodynamic backgrounds of a given sample (Wang, 2000). Generally it is believed that K-rich calc-alkaline granites are developed in tensional environments (Barbarin, 1999; Pitcher 1997; Dong, 1995). Granodiorite may indicate the presence of a subduction or delamination zone (Harris et al., 1986). However, it should be noted that using the granite geochemical information to discriminate tectonic environment is highly inaccurate. Similar types of granite and similar combinations of granite can be produced in different tectonic environments. For example, I-type granites can be produced not only in island arc environments but also in post-orogenic extensional environments. A granite mix similar to that found in aggregate plate edges can also be developed in extensional volcanic passive continental margins (Zhou and Li, 2000; Xu et al., 1999). In contrast, using the characteristics of granite evolution to determine tectonic environment is more reliable. After determining the causes of type and age, the directional signs of geodynamics and tectonic dynamic evolution can be studied.

Using chemical-tectonic discrimination diagrams, the tectonic settings of the output samples were evaluated. In the sample, the Nb content was 14.29 ppm, Y content was 10.42 ppm, Ta content was 0.53 ppm, and Yb content was 0.69 ppm. Granite Nb-Y and Ta-Yb discrimination diagrams (Pearce et al., 1984) show that, for these samples, the former could be projected on volcanic arc granite (VAG) and syn-collisional granites (syn-COLG) (Fig. 5a), and the latter on volcanic arc granite (VAG) (Fig. 5b). $R_1$-$R_2$ factor discrimination diagrams, $R_1$=2 235.7 and $R_2$=671.4, showed the samples to be the products of a tectonic environment preceding plate collision (Bechelor and Bowden, 1985) (Fig. 5c). The major elements of granite can also be used to determine the tectonic environment. According to the tectonic settings of granite types, granite can be divided into granite island arc granitoids (IAG), continental arc granitoids (CAG), continental collision granitoids (CCG), post-orogenic granitoids (POG), rift-related granitoids (RRG), continental epeirogeny uplift granitoids (CEUG), and ocean plagioclase granite (OP). IAG, CAG, CCG, and POG are orogenic granite, and RRG, CEUG, and OP are the non-orogenic granites (Maniar and Piccoli, 1989). Projection onto granite major element discrimination diagrams showed the samples to be orogenic granitoids (Fig. 5d) (Hugh, 2000).

As noted above, chemical-tectonic discrimination diagrams gave similar results. The granite samples in the southern margin of the southwest basin of the South China Sea were mainly volcanic arc granite and the products of tectonic setting before the plates collided. The formation of granite has a close relationship with orogeny. The samples were found to be orogenic-type granite.

## TECTONIC SIGNIFICANCES AND CONCLUSION

As mentioned earlier, the southwest basin is a critical region of exploration of the South China Sea's formation, structure, and development. It is also the focus of some controversy. Due to a lack of chronology data, researchers differ regarding the time of formation of the southwest basin. Since the 1980s, geophysicists have identified magnetic anomaly bands in the southwestern basin and used these to speculate on the basin's expansion time. Conclusions have ranged from the Early Cretaceous 126–120 Ma (Jin and Li, 2000) and 118–125 Ma (Chen et al., 2003) to the turn of Late Cretaceous–Paleocene 70–63 Ma (Lü et al., 1987), Late Paleocene 55 Ma (Zhou et al., 1995), and Eocene–Early Oligocene 42–35 Ma (Yao et al., 1994) to the Early Eocene 21 (Taylor and Hayes, 1980) and 15 Ma (Liu et al., 1992). At present, the layered

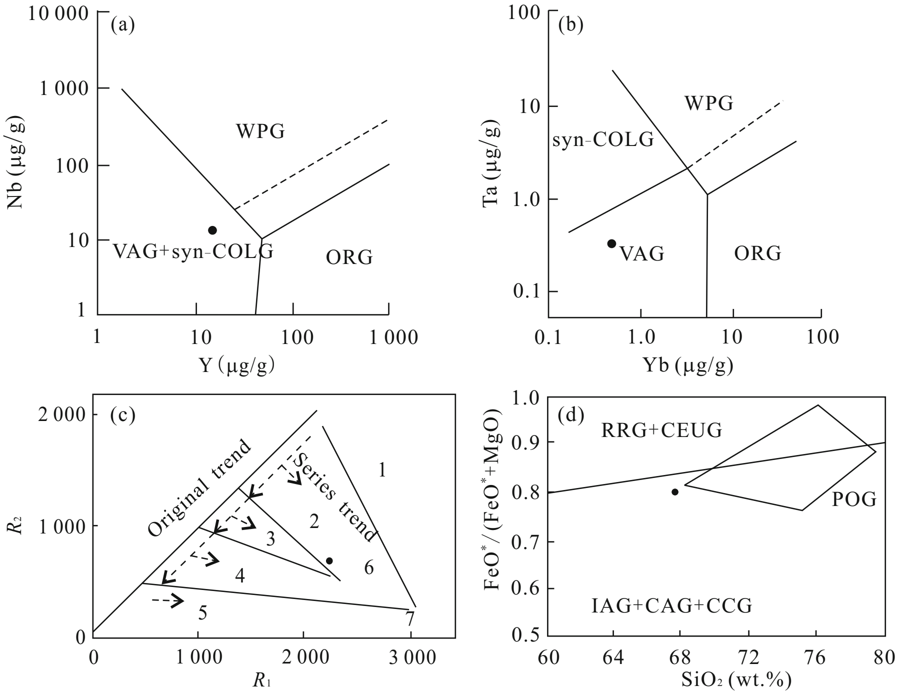

**Figure 5. Geochemistry-tectonic discriminant diagrams. FeO*. Total FeO.**

structure identified by changes in seismic wave velocity in the upper basin and the basin's general size and profile are the best sources of information on the time of origin of the southwest basin.

Although granitic samples are difficult to collect from basin, these rocks are common in the surrounding areas of the South China Sea. The temporal and spatial distributions of Mesozoic and Cenozoic magmatism were reviewed with outcrops, drilling, dredge and seismic data. Late Mesozoic granite was widely spread over the South China to Indochina, which extended over several hundred kilometers along the southeastern Asian margins (Liu et al., 2007; Yan et al., 2006; Yan and Liu, 2005; Zhou et al., 2005b; Shu and Zhou, 2002; Yan and Zhou, 2002; Zhou and Li, 2000).

In this study, samples were analyzed and dated using chemical-tectonic discrimination diagrams, giving clear results. The Pacific plate dived to the northwest during the Early Cretaceous. Many micro-blocks were pieced together in the ancient South China Sea (Yan et al., 2010). As part of this process, the subducted oceanic crust and the upper continental crust were mixed and melted, forming granodiorite by magma intrusion. In other words, the western or northwestern subduction of Pacific plate since the Early Cretaceous had played a crucial role in the post-Late Mesozoic tecto-magmatism. The sample we collected may be the same cause of formation with Southeast China, especially with NEE-trending granitic magmatism in Early Cretaceous.

The formation of the southwest basin can be said to be closely related to the northern movement of the India-Australian plate, although the process and mechanism need to be discussed further. However, it may be suggested that the southwest basin is not an original ocean, but a rift developed through finite extension on continental crust basement, perhaps formed on the basis of Mesozoic continental crust. The oceanic crust came into being when the width and depth of the rift valley reached a certain scale. Thus, expanded age of the basin may be later than the granodiorite age. The granodiorite sample we collected provides a means of determining the boundary of the southwest basin and the clues that may help researchers expand relevant models.

Therefore, the fact that the granodiorite samples found in the southern margin of the southwest basin of the South China Sea must have formed during the Early Cretaceous has significant meaning. Firstly, there is a history of lack of granite in this area, the sample we collected which is considerably helpful for us to better understand the origin and evolution process of the South China Sea. Secondly, the sample may constitute an important rock type in the south boundary, and the key position which was joined continental crust with oceanic crust. If this is true, the sample mats assist the understanding of the base structure, rock types, and igneous intrusion of the South China Sea. Thirdly, the discovery of the sample revealed the rift extensional mode in the formation of the southwest basin of the South China Sea. But the rifting and sagging occurred initially in the continental crust. The southwest basin may be not an original ocean, but a rift developed through finite extension on continental crust basement. The process is most likely similar to the evolution of the Red Sea in modern times. After the first rift extension and subsidence, when the width and depth of the rift reached a certain degree, the oceanic crust was formed. The discovery of granodiorite samples provides an important clue to the formation, development, and dynamic background of the South China Sea.

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