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Crustal structure and development of Sulu UHPM Terrane in east-central China

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This article provides a brief view of development of the Sulu ultrahigh pressure metamorphic (UHPM) terrane involved in a conceivable intracontinental collision between the Sino-Korean Plate and the Yangtze Plate during the Mesozoic Era. Integrated study of geological and geophysical data reveals crustal structures in the Sulu terrane, and provides evidence for an evolution model of the UHPM terrane called "the dual intracontinental subduction model".

Introduction

Since the discovery of coesite and micro-diamond inclusions in the Dabie-Sulu area, the ultrahigh pressure metamorphic (UHPM) belt has been attracting worldwide attention of geoscientists (Xu et al., 1996). Studying this outstanding geological terrane may greatly enhance our understanding of metamorphism, deep effects of continental collision and geodynamics in convergent plate boundaries. The study may also be very helpful to provide some evidence to reveal the interaction between continental crust and mantle, and the formation of new types of diamond deposits as well. However, many questions about the ultra-high pressure metamorphism puzzle the geoscientists, such as how and why could a continental terrane be sunk into a depth of more than 100 km and then uplifted to the surface quickly? To answer these questions we must at least understand the lithospheric structures of a typical UHPM terrane, such as the Sulu terrane in the east-central part of China.

Encouraged by the International Continental Drilling Program (ICDP), both intensified geological and geophysical investigations have been carried out since 1996. The geophysical surveys include reflection seismic lines in both Dabie and Sulu areas, seismic tomographic profile in Dabieshan, MT lines, and the compilation of 1:200,000 aeromagnetic and gravity maps. The project has been very successful, obtaining new high-quality data and valuable geophysical profiles, proving some significant constraints on continental collision. Integrated study of these results, especially the seismic reflection patterns has enabled us to understand more about present-day lithospheric structures of the Sulu terrane, which show clearly the geometry of the UHPM slice and the collision between the Sulu terrane and the Yangtze Plate. Integrated interpretation of the geophysical profiles leads to a model of evolution of the Sulu UHPM terrane. The model is called "the dual intra-continental subduction model" and will be discussed later. In the ICDP Workshop on "Pre-Site Selection of Continental Scientific Drilling in Dabie-Sulu UHPM Belt" held in Qingdao, China on August 18-20, 1997, the author have presented all geophysical profiles in detail to participants coming from Germany, United States, France, Canada, Japan, and China. This paper will be a brief summary of the presentation in the workshop, specifying the Sulu area.

Geological settings

Dabie-Sulu area is located in the eastern part of the Central Orogenic Belt running across China from the Kunlun Mountain Range in the west to the Sulu area in the east, between the Yangtze Plate in the south and the Sino-Korean Plate in the north (see Figure 1, upper-left). The area has been recognized as an outstanding geological place for studying ultrahigh pressure metamorphism since the discovery of coesite and micro-diamond inclusions in the eclogite outcrops spread out all over the area. The area consists mainly of old metamorphic strata of lower Proterozoic Subera, bounded by faults or subduction zones. The Dabie-Sulu UHPM belts are characterized by the following facts: (a) coesite-bearing eclogite, together with HP rocks, found in gneiss, marble or ultra-mafic rocks, striking as long as 900 km; (b) so far ophiolite has not been found in this belt; (c) there is no syn-subduction granite belt of the Gangdise analog, and (d) there were strong granodiorite intrusions of about 120 Ma, 100 m.y. later than the collision (about 220 Ma). Therefore continent-to-continent collision between the Yangtze and the Sino-Korean Plates and intra-continental subduction are suggested and have attracted attention of many scientists, as Dabie and Sulu terranes should preserve good geological records for understanding these events.

The UHPM belt can be divided into two parts: the Dabieshan in the southwest and the Sulu in the northeast, but they were originally joined in one before cutting and slipping by the Tan-Lu Fault. In fact, during the early Triassic Period these two terranes were linked together and located in the northern margin of the Yangtze Plate (Liu Guangding, 1994). According to palaeomagnetic data (Seguin and Zai, 1995), the Yangtze and Sino-Korean plates collided right at the location of the Dabie-Sulu belt in the Triassic Period (220 Ma). The collision provided enormous energy for metamorphism, uplifting and exhumation of the UHPM belt (Wang Q. and Cong B., 1996; Xu Shutong, 1994; Ames et al., 1993). In the middle Jurassic Period, the Dabieshan and the Yangtze Block rotated clockwise and attached to the Sino-Korean Plate in the west of the Tan-Lu Fault, while the Sulu area was sliding northward and rotating about 20 degrees counterclockwise, and finally collided with the Sino-Korean Plate.

After coesite and micro-diamond were found in eclogite rocks in both the Dabie and Sulu terranes, P-T-t curves have been measured by several institutions with some minor controversy (Shandong Bureau, 1996; Li S. et al., 1993). When the coesite-bearing eclogite was formed, the pressure measured was greater than 30 kbar in Sulu and 40 kbar in Dabie. The highest temperature was about 700 degree in Dabie and 800–900 degree in Sulu. All the data suggest that the eclogite was formed at a depth of 80–120 km and uplifted during the Indosinian movement (Jahn, et al., 1996; Li, et al., 1997).

The Sulu terrane is bounded in the north by the Wulian-Qingdao fault zone striking northeast, and by the Tan-Lu fault in the west, and the Jiashan-Xiangshui fault in the south (Figure 1). The geology of the area is characterized by some collision-orogenic features as follows: metamorphic mixture, HP and UHP metamorphic

Figure 1 The east part of the Qinling-Dabie Orogen (upperleft) and the Sulu area (main). I: Sino-Korean Plate; II: Qinling-Dabie Orogen; III: Yangtze Plate. 1: Jiaobei uplift; 2: Jiaolai Basin; 3: Cretaceous System; 4: Precambrian gneiss mixture; 5: eclogite; 6: coesite; 7: Upper Proterozoic granite; 8: Mesozoic granite; 9: fault; 10: collisional suture line; 11: regional geophysical line.

rocks, large-scale ductile deformation, as well as post-collisional granite bodies. The metamorphic mixture distributed in the area is called the Jiaonan Group in the north or the Donghai Group in the south, mainly consists of Proterozoic gneiss, amphibolite, felsic schist, and marble. Most of the gneiss was changed by later anatexis and became granitic gneiss.

The Sulu terrane is different from the Dabie in the following facts: (a) topographically it is almost a flat lowland with small hills of about 100 m in height, (b) the surface is covered by soils usually 1–3 m deep, making geological mapping difficult, (c) the depth of Moho is about 35 km, less than that in the Dabie Mts (about 43 km), and (d) it moved northward after the collision, the movement might consume some collisional energy and prolong the collision period.

The eclogite shown in this area can be divided into three zones. The north zone runs from south of Zhucheng to Jiaonan, normal to the seismic profile I. The middle zone is along profile II where MT observations were carried out. The south eclogite zone near Donghai is cut by the seismic profile III.

Crustal structures

Reflection data were acquired by using 30 kg dynamite source for each shot which is put into a hole of 20 meters. We employed an 120-channel DSF-V system with a sampling rate of 2 ms for recording seismic signals. The record length is 20 s, receiver spacing 50 m and folds of 15–20, minimum offset 300 m. In the seismic experiment 93% records are excellent in quality. Data processing employs the DISCO software system, usually containing following stages: statics and residual statics, velocity analysis and CMP stack, amplitude recovery and migration. High-quality seismic profiles were obtained by employing the above procedures (Figure 2).

Two seismic reflection lines, Line I and Line III, have been completed in Sulu area, among them Line I is a regional long profile

crossing the northern boundary as marked in Figure 1. After reflection data processing the crust in northern Sulu can be divided into three parts. The upper crust (0–4 s) shows many dipping events, indicating the UHPM belt is dipping northward here. There are few reflections existing in the section from 5 s to 9.5 s, indicating that the lower crust is a more or less uniform ductile layer. However, strong reflectors again appear in the section from 9.5 s to 14 s, showing remarkable interaction between the crust and the mantle (Yang, 1997a,b). Line II is a non-seismic line.

Line III is located in southern Sulu starting from the Tan-Lu fault in the north, UHPM belt in the midway and the southern boundary in the south end. The central part of the profile (about 25 km in length) is shown in Figure 2. There are many merged wedges of different scales as well as dipping events in the crust and uppermost mantle, similar to worldwide collisional reflection patterns (Meissner and Tanner, 1993). In the upper crust, Some strong south-dipping reflectors coincide with surface mylonite zones, and the eclogite outcrops of UHPM are also dipping south. The reflection characters in the upper part of the seismic profile represent the deformed brittle upper crust. An important fact is that most events and wedges below the upper crust are dipping or pointing to the north, different from the events in the upper crust, showing that the Yangtze Plate subducted under the Sulu terrane.

After inversion from both seismic and MT data (see Yang, 1987 for the inversion method employed), P-wave velocity and resistivity columns are obtained and shown in Figure 3. It is clear that the UHPM belt are characterized by a slice of high-velocity (6.4–6.8 km/s) and high-resistivity (>6000 ohm.m) with thickness of 8–10 km from the surface. The UHPM slice in upper crust has undergone subduction under the Sino-Korean Plate and then exhumation quickly, as well as strong deformation during and after the collision. Beneath this slice rocks have lower velocity and resistivity, they might be slabs of either Yangtze or Sino-Korean, or even the “missing oceanic crust” as some geologists predicted. We can reveal them by the only means of deep scientific drilling which now China is planing. The

Figure 3 Velocity and resistivity structure in south and north Sulu. The unit of P-wave velocity is km/s, that of resistivity is ohm.m.

Figure 2 Migrated seismic section in Donghai County, South Sulu (central part of Line III).

Figure 4 Schematic illustration of the dual intra-continental subduction

velocity and resistivity of the middle and lower crust are normal, but the resistivity in the uppermost mantle is very low ($<50 \text{ ohm.m}$), implying that heat flow might play remarkable role at least in the last episode of the evolution of the Sulu terrane.

Dual intra-continental subduction and development of Sulu UHPM Terrane

Based on the present-day crustal structures in the Sulu we know that there was a collision in southern Sulu, marking the subduction of the Yangtze Plate under the Sulu terrane. On the other hand, we also know that the Sulu UHPM slice, dipping north in northern Sulu, represents an earlier subduction and exhumation of the Sulu terrane under the Sino-Korean Plate. Therefore, there were two subductions occurred at different places: the earlier subduction at the northern boundary of Sulu and the later at the southern boundary. The author uses the term of "dual subduction" to delineate this type of collisional pattern and suggests the following model to explain the development of the Sulu UHPM terrane (Figure 4).

(a) Before the collision (Figure 4a), the Sulu terrane might be a part of the Yangtze Plate cut by Jiashan-Xiangshui fault in the south, which had not fully developed in early Triassic Era. The northern boundary of the Sulu with the Sino-Korean Plate was the Wulian-Qingdao fault, fully developed and dipping north.

(b) In early Triassic, the Yangtze Plate collided to the Sino-Korean Plates (Figure 4b), the Sulu terrane was subducted under the Sino-Korean Plate due to inertial force, with part of its crust sinking into the mantle and causing UHPM (Figure 4c). It is the first subduction that could deepen the Jiashan-Xiangshui fault and make the Sulu terrane separate from the Yangtze. The lithospheric thickness of the Sino-Korean Plate might be less than Sulu's, and partial melting might occur in the uppermost mantle of the collision zone, making the subduction easier.

(c) After Sulu terrane sank to a depth of about 100 km where down-going and up-going forces equiponderated, the Yangtze Plate in the south started to subduct northward under the Sulu by the inertial force, then exhumation of the Sulu terrane developed due to the reaction force of Yangtze's subduction and buoyancy generated by part of Sulu sinking into the asthenosphere (Figure 4d). This second subduction might play an important role to the exhumation and deformation of the Sulu terrane.

(d) In the final phase, the subduction and exhumation ended and post-subduction processes started with partial melting in the uppermost mantle, magma intrusions and volcanicity through the deformed pathway. Then the top part of Sulu was eroded, resulting in exposed UHPM belt and adjacent sedimentary basins on both sides of the terrane, i.e. what we see today (Figure 4e).

References

- Ames, L., Tilton, G.R., and Zhou G., 1993. Timing of collision of the Sino-Korean and Yangtze Cratons: U-Pb zircon dating of coesite-bearing eclogites: *Geology*, 21, 239.
- Jahn, B.M., Cornichet, J., Cong, B.L., and Yui, T.F., 1996. Ultrahigh-P eclogites from an ultrahigh pressure metamorphic terrane of China: *Chem. Geol.*, 127, 61-79.
- Kern, H., Shan Cao, Qing-Shen Liu, 1996. Seismic properties and densities of middle and lower crustal rocks exposed along the North Geoscience transect: *Earth Planet. Science Letters*, 139, 439-455.
- Li, S., Xiao, Y., Liu, D. et al., 1993. Collision of the North China and Yangtze Blocks and formation of coesite bearing eclogites: *Chemical Geology*, 109, 89.
- Liu Guangding, 1993. *Atlas of Geology and Geophysics of China Seas and Adjacent Regions*, Science Press, Beijing, New York, 1994.
- Liu Zhenbo, You Zhendong and Zhong Zengqiu, 1996. Eclogites from the middle and north Dabie Mountains in southern Henan and northern Hubei, China: *Science in China (series D)*, 39, 293-300.
- Meissner, R., and Tanner, B., 1993. From collision to collapse: Phases of lithospheric evolution as monitored by seismic records: *Physics of Earth & Planetary Interior*, 79, 75-86.
- Okay, A.I., 1993. Petrology of a diamond and coesite-bearing metamorphic terrane: Dabieshan, China: *Eur. J. Mineral.*, 5, 659.
- Seguin, M.K. and Zai Y., 1995. Palaeomagnetic evidences for collision of the Sino-Korean and the Yangtze Blocks: *Acta Geophysica Sinica*, 38, 34-45.
- Shandong Bureau of Geology and Mineral Resources, 1996. *Proceedings of Researches on the Geology and Mineral Resources in Shandong Province*. Jinan (in Chinese): Presentation to 30th IGC, Beijing.
- Wang Qingchen and Cong Bolin, 1996. Tectonic implication of UHP rocks from the Dabie Mountains: *Science in China (Series D)*, 39, 311-318.
- Xu Zhiqin, Xiao Xuchang and Yang Wencai, 1996. A proposal to conduct the first scientific continental drilling project in Dabie region, east-central China, submitted to ICDP, June 1996.
- Yang Wencai, 1987. Velocity imaging from reflection seismic data by joint inversion technique: *Acta Geophysica Sinica*, 30, 617-627, (in Chinese).
- Yang Wencai, 1997a, Geophysical investigations for pre-site selection of Dabie-Sulu scientific drilling, abstract in "International Workshop on the pre-site selection of scientific drilling in the Dabie-Sulu UHPM Region, hold at Qingdao, China, 18-20 August, 1997.
- Yang Wencai, 1997b, Unconformity-like reflection pattern under the Moho in Sulu area: *Continental Dynamics*, vol.2, No.3 (in press).

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