The subducted slab of Yangtze continental block beneath the Tethyan orogen in western Yunnan

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Abstract The western Yunnan area is a natural laboratory with fully developed and best preserved Tethyan orogen in the world. Seismic tomography reveals a slab-like high velocity anomaly down to 250 km beneath the western Yunnan Tethyan orogen, to its west there is a low-velocity column about 300 km wide. In the region from Lancangjiang to Mojiang an obvious low velocity in the lower crust and uppermost mantle overlies on the slab. Synthesizing the available geological and geochemical results, the present paper demonstrates that this slab-like high velocity anomaly is a part of the subducted plate of Yangtze continental segment after the closure of Paleotethys. The collision of India and Eurasia continent starting from 50—60 MaBP might trigger thermal disturbance in the upper mantle and cause the uprising of asthenosphere, in that case the subducted Yangtze plate could be broken off, causing Cenozoic magmatic activities and underplating in the

Lancangjiang-Mojiang region.

Keywords: **seismic tomography, Tethyan orogen in western Yunnan, subduction remains of Yangtze Block.**

Plate tectonics theory is a revolution of earth sciences in the 20th century, it established the mobilism in earth sciences[1]. Oceanic lithosphere can be viewed as formed by the rifting of ocean ridge, it then returns to the mantle through subduction to be recycled, its life time is generally less than 200 Ma. Based on this the oceanic lithosphere evolution gives a useful conceptual analogy for the continents. On the other hand the continents were formed by collision and amalgamation of various continental blocks and oceanic basin remains in about 4 500 Ma, plate tectonics is not satisfactory in explaining the complicated formation process of continents. The tectonic cycle of growth and extinction of oceanic crust has long been established on geophysical, geological, and geochemical evidence[2—7]. In contrast very important basic questions remain open in regard to the growth and evolution of continents. The theory of continental crust growth and the lithosphere break-off model of collisional orogen demonstrate that the mafic rocks of lower crust need to break off or plunge into the upper mantle in the tectonic process[8—10]. However these models need to be further tested by observational facts, especially the geophysical evidence similar to the subduction of oceanic plates.

The lithosphere detachment model of Davies et al.[8,9] suggests that, following the subduction of oceanic lithosphere, the continental lithosphere subducted during continent-continent collision, accompanied by the detachment of continental lithosphere from the oceanic lithosphere, i.e. the so-called break-off of subducting slab. They also suggested that the Alpine collisional orogen formed by the closure of Tethys is the best place for testing this model. Obviously, to reveal deep geophysical evidence in the mantle has become the key problem for such kind of studies.

The western Yunnan region is a natural laboratory with the fully developed and best preserved Tethyan orogen in the world. Systematic comprehensive geological and geochemical studies have been carried out since the 1980s, important results have been achieved which show the evidence of the extinction of Paleotethys and the continent-continent collision and subduction in that area.

Based on the seismic tomographic images of the Tethyan orogen in western Yunnan, this note tries to find the relics of the subducted Yangtze continental block.

1 Tectonic setting of the study area

The tectonic framework of the study area is shown in fig. 1, which shows the present distribution and structural relation of various stable blocks and active belts during Paleotethys evolution stages. According to Zhong et al.[11], in the study area there occur several important Tethyan suture zones sandwiched in between blocks of different sizes. As seen in the insert of fig.1, they are listed from west to east as follows: a and b are the Bitu-Changning-Menglian suture zone; c and d the Jinshajiang-Mojiang suture zone; e the Luxi suture zone; f the Ganzi-Litang suture zone; Yangtze Block (YZ); Simao Block (SM); Baoshan Block (BS); Tengchong Block (TC). The study shows that the Simao and Yangtze blocks together constitute the Yangtze-affinity block group, while the Baoshan Block and Tengchong Block belong to the Gondwana-affinity group. Between the Yangtze-affinity Simao Block and the Gondwana-affinity Baoshan Block there developed the main Paleotethyan basin, and between the Simao and Yangtze blocks there was a branch Paleotethyan basin. Their remains are respectively the Menglian and Mojiang suture zone.

A collisional tectonic belt is spatially a complex deformational belt of considerable width, which cannot be represented solely by a suture zone of oceanic basin remains. In fig.1 it is denoted by the collisional orogen such as the Changning-Menglian collisional orogen (A) and Jinshajiang-Mojiang collisional orogen (B), their tectonic framework was mainly formed in Late Triassic to Early Jurassic.

The present right-lateral strike-slip Ailaoshan-Honghe fault[12] cuts obliquely belt B. In Late Oligocene to Early Miocene it underwent large-scale left-lateral shear with an offset about 200—300 km[11], even reaching 400—500 km[12,13], and served as a boundary to accommodate intracontinental deformation during the Cenozoic collision of India and Eurasia plates. It obliquely displaces the Jinshajiang-Mojiang Tethyan orogen into two segments: the north segment is the Jinshajiang collisional orogen and the south segment is the Mojiang collisional orogen.

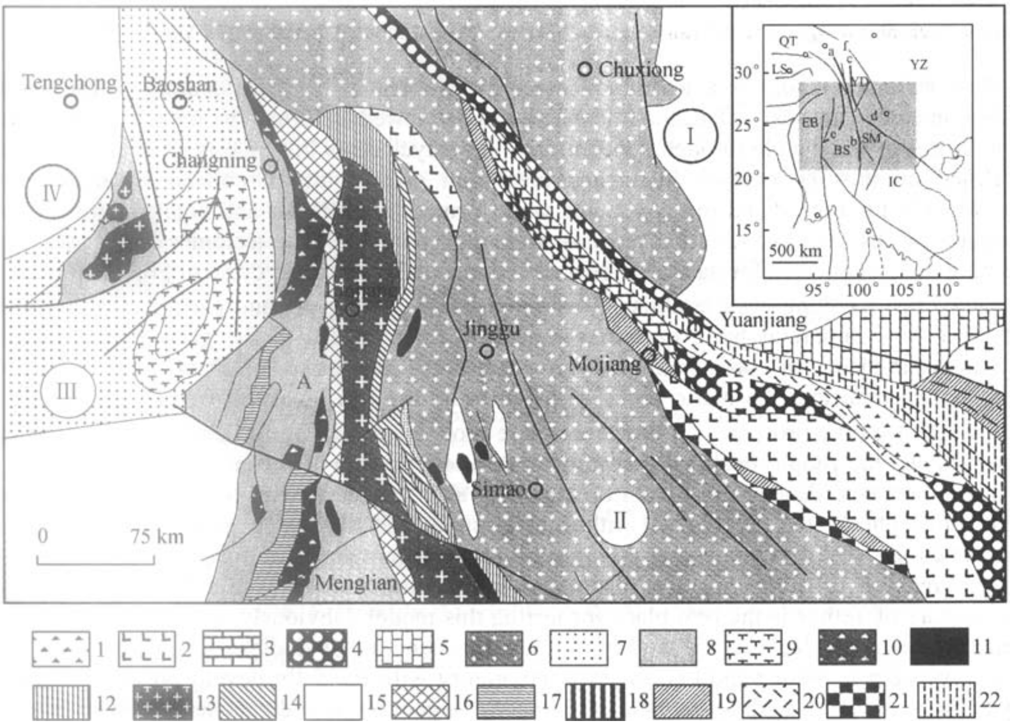

Fig. 1. Geological map of the study area. I, Yangtze Block; II, Simao Block; III, Baoshan Block; IV, Tengchong Block. a, Bitu suture zone; b, Changning-Menglian suture zone; c, Jinshajiang suture zone; d, Mojiang suture zone; e, Luxi suture zone; f, Ganzi-Litang suture zone. 1, Platform slope sediments (Palaeozoic); 2, continental margin sediments (Late Precambrian to Early Palaeozoic); 3, continental margin sediments (Late Palaeozoic); 4, rift-valley or turbidite sedimentary basin (Triassic); 5, platform carbonatite sediments (Triassic); 6, red sediments basin (Mesozoic-Cenozoic); 7, sedimentary cover continental margin sediments (Late Precambrian to Triassic); 8, continental margin sediments; 9, twin-peak type volcano - sedimentary rocks (Late Triassic). A. Changning-Menglian collisional orogen: 10, ophiolite complex belt (Devonian to Middle Triassic); 11, island-arc volcanic rocks (Triassic); 12, continental margin volcano-sedimentary rocks (Middle to Late Triassic); 13, collision-type granite; 14, fore-arc sediments (Late Carboniferous to Permian); 15, back-arc sediments (Middle to Late Triassic), 16, reactivated basement; 17, foreland sedimentary basin (Late Triassic). B. Jinshajiang-Mojiang collisional orogen: 18, ophiolite complex belt; 19, island-arc volcanic rocks; 20, continental margin volcanic rocks (Middle to Late Triassic); 21, fore- and back-arc sediments (Permian, Jinshajiang-Mojiang belt); 22, reactivated basement.

2 The seismic tomographic profile crossing the Mojiang Paleotethyan orogen

Seismic tomography is getting mature since its origin in the early 1980s from a similar medical technique. In the past ten odd years, the global horizontal grid spacing has been reduced from 10° in the past to 2° — 0.6° at present[14,15], the depth range of imaging increased from 1 000 km[3–6] down to 2 700 km[16], the time limit for tracing subducted slabs from about 100 Ma[4,5] back to 200 Ma in searching fossil slabs[16]. In seismic tomographic studies in China on the continental and regional scale the horizontal resolution has been much improved from 2°—5° to 1°—0.5° or even better[17–19], seismic data used in the inversion increased from a single phase to multiple modes and phases, thus ensuring more rays crossing the target grid cell in different directions.

Plate Ⅰ shows the seismic tomographic profile crossing the Mojiang Paleotethyan orogen along 23.5°N latitude. The color in the figure represents the value of seismic velocity: green stands for the average reference velocity at that depth, blue indicates high velocity anomaly, while red color indicates low velocity anomaly. The black arrow above the horizontal scale near 102°E indicates the Ailaoshan-Honghe strike-slip fault. Here in the figure exists a slab-like high velocity anomaly dipping west, the velocity anomaly values range from +1% to +3% or even higher, as indicated by the white line in the figure, its maximum depth reaches 250 km. We infer that it is a subducted slab. The evidence in the following section shows that it is the relics of subduction of the Yangtze continental block. On the west of this high velocity anomaly between 97.5° and 100.5°E there is a low velocity column rising from 450 km depth. Between depths 200—250 km it is narrowed by the high velocities on its east and west side. The low velocity anomalies range from −1% to −5%. The low velocity zone extends upward to 70—80 km depth where a high velocity layer appears, indicating the top boundary of asthenosphere as shown by a white broken line in the figure. The lithosphere here is obviously thin. Another white broken line about 40 km deep indicates the Moho discontinuity.

The dense seismological stations and frequent earthquakes in the study region, as well as the seismic data accumulated in more than 10 years enable us to pick out several hundred thousand travel time data from rays traversing at different depths and with good azimuth coverage. The best horizontal resolution of this profile is 20—30 km, the best vertical resolution is 10—15 km in the crust and about 30 km in the upper mantle.

3 The slab-like high velocity anomaly is the subduction remains of Yangtze Block

Abundant research results of seismic tomography have demonstrated that the high velocity slabs observed globally in the upper and lower mantle are subducted oceanic lithosphere. The high velocity slab revealed in this note is located in the Tethyan orogen in western Yunnan, which underwent a series of complex tectonic movements such as the Wilson cycle. If this high velocity anomaly is viewed as a subducted slab, what tectonic element does it belong to?

(i) The subduction of Mojiang Tethys oceanic basin and Yangtze continental block. Previous studies have shown that the oceanic crust of the Mojiang Paleotethyan Basin appeared in Early Carboniferous, the lower U-Pb intersection age of zircon of gabbro in the ophiolite tectonic melange zone is 362 Ma, that of plagioclase granite is 328 Ma[20]; the $^{40}Ar/^{39}Ar$ age of clino-augite of gabbro is (339.2±3.9) Ma[11].

To the west of the ophiolite tectonic melange zone (suture zone) (see fig.1, referring to present position, the same hereafter), there is a set of Late Permian-Early Triassic island-arc-type volcanic rocks and granodiorite, to the east are the Late Palaeozoic passive continental margin sediments of the western margin of the Yangtze Block. These indicate that the oceanic basin started westward subduction before Late Permian. Based on the facts that overlying Middle and Late Triassic collisional and post-collisional volcanic rocks outcrop along the Luchun-Yuanyang area, as well as Late Triassic foreland and backland molasse or turbidite basin sediments unconformably overlie on the ophiolite tectonic melange zone, the Simao Block and Yangtze Block collided in Late Triassic.

As seen in fig. 1, the early Late Triassic deep trough turbidite deposits were developed on the western margin of the Yangtze continental block, then changed into the Late Triassic-Jurassic-Cretaceous foreland basin, with the sedimentary center gradually shifting from west to east towards the interior of the Yangtze Block, which indicates that the Yangtze continental block was dragged by subducting oceanic slab and subducted under the Simao block.

(ii) Thoughts suggested by the shape and depth of the slab-like high velocity anomaly. In the 1980s seismic tomography revealed that the subducted northwestern Pacific plate appeared as high velocity anomaly[2,4,5]. Since then Grand[21] found the subducted Farallon plate in North and South America using S wave tomography, which was considered a breakthrough in this research field, Van der Hilst[7] further demonstrated that slab-like high velocities are common under past and present subduction zones, hence Van der Voo et al.[16] used the term "seismoslabology". Therefore, it is straightforward to interpret the slab-like high velocity anomaly dipping downward from the Ailaoshan-Honghe strike-slip fault as a subducted slab.

Continents of vast area are composed of smaller continental blocks, the oceanic plates previously in between the blocks have been consumed[22]. The Paleotethyan branch ocean basin between the Simao and Yangtze Blocks was closed before the Late Triassic, causing the collision of the two continental blocks. The evidence in section (i) demonstrates that the Yangtze Block subducted westward under the traction of oceanic subducted plate. The reasons for interpreting the high velocity anomaly as the remains of Yangtze Block are as follows.

According to the prevailing model, continental lithosphere follows the leading oceanic slab to be subducted because of the downward traction of the latter. Because the continental lithosphere weakens and the temperature increases with increasing depth, the strength of subducted slab decreases with the continuing subduction of continental lithosphere, eventually the upward buoyancy of continental slab and the downward traction of oceanic slab will cause the break-off of the latter from the former, the oceanic slab will sink into deep mantle. Considering that the subduction of Mojiang Tethys started before Late Permian, slab break-off should have taken place. This will rule out the possibility that the subducted slab presently at 250 km depth belongs to Tethyan subduction.

Van der Voo et al.[16] calibrated the time scale of subducted slabs entering the mantle in their study on the Jurassic subduction slabs under Siberia. According to their result the time for a slab to reach 2 000 km depth into the lower mantle needs at least 200 Ma, while to enter the upper mantle down to 200 km depth needs 50 Ma. This discovery is important because it provides a new information source for studying the global plate tectonics and the process of continent growth. Considering that the subduction of Yangtze Block took place in the Mesozoic, according to their calibrated time scale, if the leading part of the subducted slab still exists, it should reach at least 2 000 km depth. Therefore, the slab existing at 250 km depth should be the remains of Yangtze Block subducted 50 Ma ago.

(iii) Thoughts arisen from Cenozoic magmatic activities. In the subducted Yangtze Block dipping westward from the Ailaoshan-Honghe strike-slip fault, the high velocity anomaly is not homogeneous. At the depths of 120 and 250 km the high velocity anomaly values are +3%, the corresponding velocities are respectively 8.32 and 8.64 km/s, which are close to the velocity of upper mantle of eclogite facies. On its west there is a low velocity column about 300 km wide which extends upward from 450 to 70—80 km depth, indicating the uprising of asthenosphere. Between depths 200—250 km the low velocity column is narrowed by the high velocity slab on its two sides, its width there is reduced to 200 km. In between the Lancangjiang and Mojiang (see Plate I and cover) the lower crust and upper most mantle overlying the slab are obviously of low velocity, the anomaly values are about −4% to −5%, the corresponding velocities are respectively 6.7 and 7.5 km/s, indicating a typical crust-mantle transition zone.

Along one side of the Yangtze Block subduction remains (roughly along the present Ailaoshan-Honghe strike-slip fault), mantle-origin lamprophyre rocks are widely distributed, their average age is about 50 Ma[23]. The initial He, Ar isotope values of fluid inclusion of minerals (0.0—51.42 Ra for $^{3}He/^{4}He$, 328.8—9 114.4 for $^{40}Ar/^{39}Ar$) in Ailaoshan gold veins closely related to lamprophyre indicate that part of the fluid is originated from deep mantle. Of extraordinary significance is that the gold metallogenetic period is also about 50 Ma as indicated by the quartz ESR age on average[24]. This shows that the mantle-origin lamprophyre and the gold-bearing metallogenetic fluid were formed in the same period. In addition, on the west side of the subducted Yangtze slab, there also occurs Neogene effusion of mantle-origin basalt in Tongguan, Puer, and other places. All the above-mentioned magmatic activities indicate that mantle thermal disturbance and asthenosphere uprising took place about 50 Ma ago.

If the above inference concerning the subducted slab and its history is correct, based on the evidence of low velocity column and magmatic activities we can infer that when the India and Eurasia plates collided (50—60 Ma), the western Yunnan-Sichuan region was at the leading edge of oblique subduction. Besides compression and shortening, large-scale strike slip and right-lateral block rotation occurred. At that time the subducted Yangtze Block might be broken off, followed by mantle thermal disturbance and asthenosphere uprising which led to the Cenozoic magmatic activities and underplating in the Lancangjiang-Mojiang region.

4 Conclusion and discussion

The result of seismic tomography revealed a high-velocity subducted slab under the Tethyan orogen of western Yunnan, which extends from the Ailaoshan-Honghe strike-slip fault westward to a depth of 250 km. Based on the results of global seismoslabology studies and the evidence from geological and geochemical studies in the area, it is inferred to be a part of the subducted slab of the Yangtze continental block after the closure of Paleotethys.

On the west side of the subducted slab, there is a conspicuous low-velocity column of uprising mantle, which significantly thinned the overlying lithosphere to 70—80 km thick, and made the velocity of lower crust and uppermost mantle in between 100.5° and 102.5°E obviously low. The widespread Cenozoic mantle-origin lamprophyre along Ailaoshan-Honghe and the mantle-origin effusive basalt in Puer and Tongguan resulted from magmatic activities are related to above-mentioned mantle uprising. The India-Eurasia collision started in Early Cenozoic triggered mantle thermal disturbance and asthenosphere uprising, resulting in the Cenozoic magmatic activities and underplating in the Lancangjiang-Mojiang region.

The western Yunnan area has undergone complicated tectonic movements including the Paleotethys, Neotethys, and Cenozoic collision between India and Eurasia. What revealed by seismic tomography are the existing remains of these tectonic events. Many problems, e.g. the effects of Neotethyan subduction and the compression and shortening caused by India-Eurasian collision on the subduction mechanism of the Yangtze continental block are to be further studied.

About the break-off of subducted slabs there is a variety of models and discussions at the present time. Because the controlling factors are multiple, the published observational results are very different and theoretical studies have not reached a unified conclusion. Therefore, it still takes much time to settle the problem.

The present study is limited to the depth of 450 km, the resolving power with the available observations is not sufficient to answer the above questions. It is obviously necessary to carry out observations with dense digital seismological stations and make further studies down to the lower mantle. Nevertheless, the scientific implication of the recognition of subducted slabs of Yangtze Block remained after the closure of Paleotethys and continental subduction is useful and important for connecting the continental dynamics with superficial tectonic processes.

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