The crustal structure under Sanjiang and its dynamic implications: Revealed by seismic reflection/refraction profile between Zhefang and Binchuan, Yunnan

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Abstract The fault belts in Sanjiang mainly include Jinshajiang-Honghe fault, Lancangjiang fault and Nujiang fault (called Sanjiang faults) in western Yunnan Province, China. By interpreting the wide-angle seismic reflection/refraction profile between Zhefang and Binchuan, which crosses Tengchong and Baoshan blocks in Dianxi (western Yunnan) tectonic zone, we reconstruct the crustal structure with seismic traveltime tomography for crustal P-wave velocity and the seismic scattering image for crustal seismic reflection structure. In this paper, we firstly present the crustal structure images of P-wave velocity and seismic reflection under the wide-angle seismic profile. These results demonstrate that, the crustal velocity structure and seismic reflection structure along the profile can be divided into 3 segments, and there is an obvious difference of crustal structure among the eastern, the western and the middle segment. Generally, crustal P-wave velocities in the Baoshan segment are 0.1—0.2 km/s slower and seismic reflection amplitudes from Moho discontinuity are stronger than the other 2 segments. In the studied area, crustal thickness is about 40 km, and shows the thickening tendency from west to east along the profile. Additionally, it can be seen that there is one strong-amplitude seismic reflection event as bright points at the depths of 8—10 km, along the segment of 80—115 km of the profile (southward of Tengchong); and seismic reflection wave-field from Moho discontinuity varies obviously along the lateral direction. Finally, we make some discussions on the crustal thickening pattern in the Sanjiang fault belt, structural environment of earthquake development and the contact relationship between the Tengchong block, Banshan block and Luxi trough.

Keywords: Sanjiang area, wide-angle seismic profile, crustal structure.

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The Sanjiang area in southwest China is considered as a tectonic intersection belt between the Tethys-Alps and the western Pacific, and has endured three-phase evolution processes: Proto-Tethys，Paleo-Tethys and Meso-Tethys[1−4]. In this area, its tectonics and structure are extremely complicated, and intensively extrusive deformation and faults are widely developed[1−3]. For that, the area is considered as the ideal nature-laboratory to study the evolution of Paleo-Tethys and also one key place to discuss the cingulum history of Eurasian continent and Gondwanaland[4−8]. Jinshajiang-Honghe fault, Lancangjiang fault and Nujiang fault (shortly as Sanjiang fault belt) extend with strike of NNW, SSE, and nearly NS, respectively (Fig. 1).The Jinshajiang-Honghe fault belt starts northward from Jiangda, then southward to Deqinjiaruo to Yuanjiang, and then extends along the Honghe River with numerous Permian eruption activities of benthal volcanoes in the Jingsha valley. Triassic benthal lava often accretes with mix-rock clay mafic and ultra-mafic from benthal slump. All these rocks form the called ophiolite block clay, which has not complete layer succession of oceanic crust. The Lantcang fault starts from the Dingqing region at its northwest; southward to Leiwuqi, Weixi, Wuliangshan and ends at Jinghong, where the Paleozoic and Triassic metamorphic belt and the lava belt are well developed[2,3].

Yunnan is one of the most active earthquake areas in western China. Not only many middle and above-middle magnitude earthquakes often happen, but also the activities of volcanoes and hot springs are active. Large-scale fault belts usually control the intensive earthquake belts. The epicenters of earthquakes during 1950 and 2000 were mainly distributed along Luxi Geosyncline, Jinshajiang and Mojiang. The focal depths are approximately 20—40 km, and the depths in the west of Yunnan are about 10—20 km shallower than that in the east. These earthquakes are considered as the shallow source earthquakes. Obviously, the studies on crustal structure and tectonics have important meanings to understand the earthquake development and occurring mechanism of the studied area.

In the project named ‘Dianshen 82’, Chinese Seismological Bureau (CSB) and other cooperation units carried out the deep sounding seismic exploration (3 profiles in total), which include the wide-angle seismic profile between Zhefang and Binchuan, and applied seismic geometrical features to reconstructing crustal structure and velocity distribution[9−11], and provide

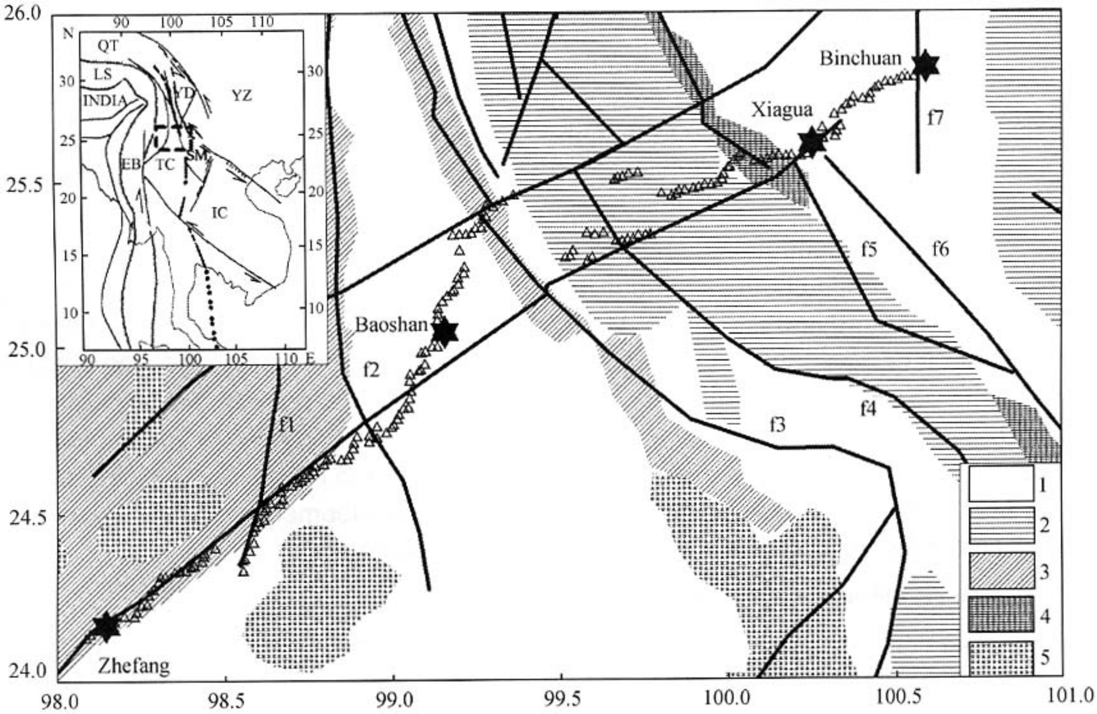

Fig. 1. Sketch map showing geologic structure in Sanjiang area. 1, Deposit in Trias; 2, deposit in Jurassic-Eocene; 3, super metamorphic rock; 4, metamorphic rock belt in Aliaoshan Honghe (high press deteroprate or low press deteroprate); 5, infracrustal rock; f1, Tengchong fault; f2, Nujiang fault; f3, Lancangjiang fault; f4, Wuliangshan fault; f5, Weixi-Qiaohou-Weishan fault; f6, Honghe fault; f7, Chenghai fault; EB, East Burma block; IC, Indo-China block; YE, Yangtze block; INDIA, India block; LS, Lhasa block; QT, Qiangtang block; YD, Yidun block; TC, Tengchong block.

the good basement to further deepen our understanding of the fine crustal structure. The previous processing and interpreting scheme are based on the horizontal layered model, and focused on the geometrical characteristics of seismic waves. It is very important to deepen our recognition of crustal structure, tectonics and dynamic attributives by integrating multi-shot observations, and using new imaging methods[13] that adapt to study heterogeneity structure and pick up new properties of crustal structure. In our study, we adopt a new method of travel-time tomography[12] and scatter imaging algorithm[13] for reconstructing crustal velocity and seismic reflection structure under the wide-angle seismic profile between Zhefang and Binchuan, and obtain the fine structure of the crust revealed by the wide-angle seismic observation, and make some discussions on its geodynamics implications.

1 Tectonic setting in the studied area

The wide-angle reflection profile studied here starts from Zhefang and ends at Binchuan in Yunnan. It crosses Tengchong and Baoshan blocks of Dianxi tectonic domain (Gandwana continent). Between these two blocks is the Luxi belt. Additionally, this profile crosses the Bitu-Changning-Menglian suture, Lanping block, Jinshajiang-Mojiang suture and the southwest of Yangtze block. So, the re-interpretation of the wide-angle seismic data between Zhefang and Binchuan is helpful to understanding the crustal structure and evolvement of Gondwana continent. This profile extends nearly in the east-west direction, and it almost vertically cuts 7 fault named Tengchong fault, Nujiang fault, Lancangjiang fault, Wuliangshan fault, Weixi-Qiaohou-Weishan fault, Honghe fault and Chenghai fault.

2 Wide-angle seismic data and crustal velocity structure

The wide-angle seismic profile between Zhefang and Binchuan is about 310 km long. 4 shots are triggered in Zhefang, Bapshan, Xiaguan and Binchuan, respectively. The explosive charge of each shot is about 3000 kg explosive. The average shot interval is about 100 km with uneven shot interval. Single component (vertical-component) analogical seismographers with trace gap of about 4 km are used to record the wide-angle seismic data as the in-line observation system. After Analog/Digital (A/D) conversion, we obtain the digitized seismic records along the profile with reduction velocity of 6.0 km/s. To enhance the signal-to-noise ratio (S/N), seismic sections are filtered with the band-pass filter of with a band range of 1—10 Hz. Fig. 2(a) and (b) illustrate the reduced seismic gathers for the shots located at Zhefang and Baoshan.

From traveltime tomography of Pg, P-wave velocity structure from the surface to the crystallized basement is obtained. Then, we use seismic reflecting traveltime inversion of seismic reflection events from the interfaces of Moho and other discontinuities between Moho and the crystalline basement, and obtain P-wave velocity and its geometry of the whole crust (Fig. 3). The results of crustal velocity imaging indicate that:

(1) The geometry of crystallized basement varies abruptly. The depth of crystalline basement thickens from 8 km on both sides of this profile to 15 km in the middle segment of this profile. The thickest one is under the segment between Baoshan and Xiaguan. The seismic P-wave velocity range above the crystalline basement is 5.5—5.8 km/s.

(2) In addition to the crystallized basemen, there is another layer in the upper crust with P-wave velocity from 6.2 km/s to 6.5 km/s and thickness range of 5—10 km. For the segment of 0—100 km along the profile, the variation of P-wave velocity is small. The lateral variation of P-wave velocity in other parts of the profile is obvious. Especially, the highest value of P-wave velocity is in the middle segment of the profile, and hits 6.5 km/s.

(3) Seismic velocity in the third layer varies abruptly, and the range of velocity variation is 6.4—6.8 km/s. P-wave seismic velocity under Baoshan is highest; the thickness of the layer is about 7 km.

(4) The range of seismic wave velocity variation is 6.7—7.5 km/s in the fourth layer. The slowest one is under Baoshan. As the boundary at Baoshan, P-wave velocity variation becomes more obvious both east-

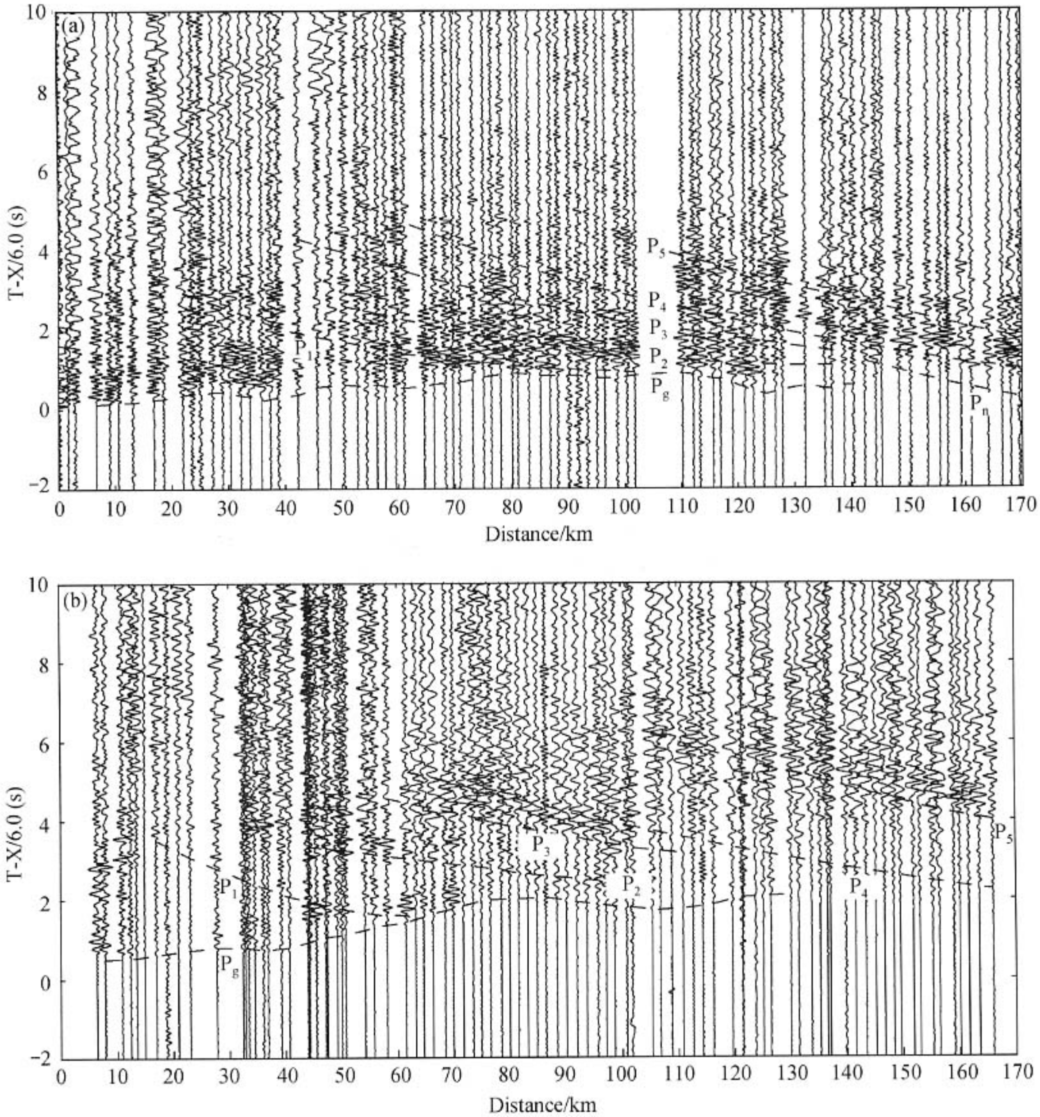

Fig. 2. Sketch map showing the reduced seismic profile of P-wave from Zhefang to Binchuan for the shot of Zhefang and Baoshan. (a) Vertical component record of Zhefang shot; (b) vertical component record of Binchuan shot. Reduction velocity of P-wave is 6.0 km/s. The event of Pg is inverse wave from crystallized basement, P5 is the reflecting wave from the upper mantle, P4 is reflecting wave from Moho, P1-P3 is reflecting from some other interfaces within the crust.

ward and westward. The thickness of the layer is about 10 km.

(5) The range of seismic wave variation in the fifth layer is 7.6—8.1 km/s. The fastest velocity is under the segment 170—230 km along the profile, and hits 8.0—8.1 km/s. The thickness of the layer is about 20—30 km.

The discontinuity between the fourth and the fifth layer is interpreted as the boundary between crust and upper mantle, namely Moho interface. From the above results, we can see that the crustal thickness trends to thicken from the western to the eastern segment along the profile.

3 The crustal seismic-reflection structure

With the above-mentioned crustal P-wave velocity model, and using the scattering imaging (migration) technique[13], we reconstruct the crustal seismic reflection structure from wide-angle seismic reflection data along the profile between Zhefang and Binchuan. In

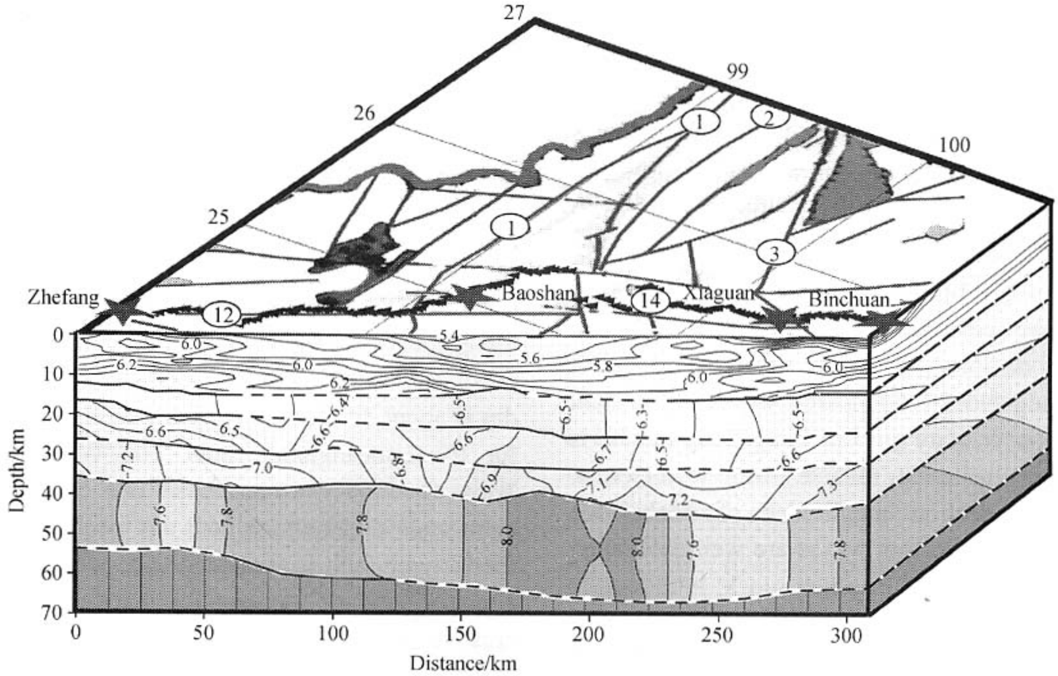

Fig. 3. Crustal velocity structure under the profile from Zhefang to Binchuan. Reflection interface obtained by inversion is graphed with a solid line, conferring interface position is graphed by dashed line, corresponding P-wave velocity is numbered between the solid lines, except depth and location coordinate along the profile, the rest data show longitude and latitude in two other directions. Faults: ① Nujiang fault; ② Lancangjiang fault; ③ Weixi-Qiaohou-Weishan fault; ⑫ Longlin fault; ⑭ Wuliangshan fault.

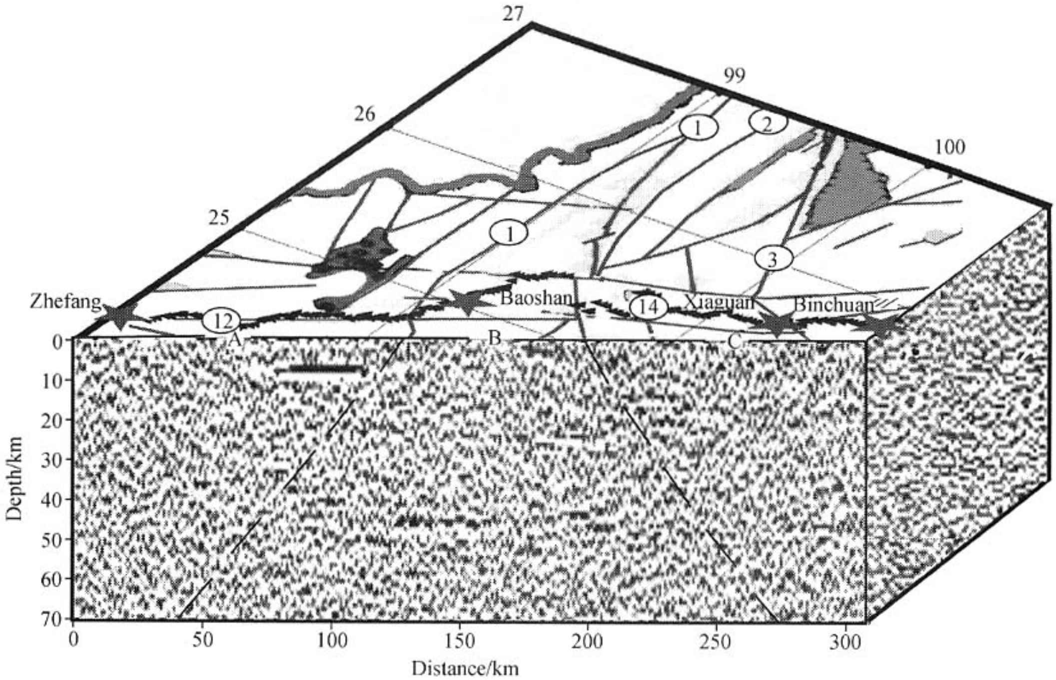

Fig. 4. Reflection structure of the crust from Zhefang to Binchuan. The names of the faults are the same as in Fig. 3.

the calculation, we make an extension of model's depth to 70 km, crustal velocity structure is discrete by 1 km × 1 km grid. Suppose P-wave velocity under Moho is homogeneous. The result of reconstructing crustal reflection structure along the profile is shown in Fig. 4. The major features of crustal seismic reflection structures can be summarized as follows:

(1) Taking the boundary at Baoshan (150 km), crustal P-wave velocity and the seismic reflection structures are obviously different between the Baoshan and Tengchong blocks. Compared with the Baoshan block, P-wave velocity of the Tengchong block is higher in the upper crust, reverse in the lower crust, and seismic reflection amplitudes of Moho are stronger. Seismic reflection waves are well developed in the upper crust of the Baoshan block; additionally there are seismic reflection events with lateral continuity within the depth range of 15—25 km.

(2) There is a set of strong reflection seismic events at a depth range of 8—10 km, in the 80—115 km segment along the profile.

(3) There is a set of strong reflection events at the depth of 38—44 km along the whole profile, but the seismic reflection magnitudes of this set of events obviously vary along the profile. This set of seismic reflection event is considered as seismic reflection from Moho. The segment (100—200 km) along the profile presents the strongest Moho seismic reflections, and shows seismic reflection characteristics from abrupt Moho discontinuity. For the segments of 0—100 km and 200—300 km, seismic reflections are well developed in the lower crust and present a similar reflection pattern, which indicates the crust's blocking feature in these 2 blocks.

(4) There is a set of strong reflection events along the 80—140 km segment of the profile, at the depth of about 60 km, and there is 'bright point' reflection characteristic in the segment of 120—140 km.

In general, crustal seismic reflections are well developed in the Tengchong and Baoshan blocks, while seismic reflections in the upper crust are well developed in the Luxi belt.

4 Discussion

4.1 Crustal structure, tectonics and crustal thickening pattern

By integrating the seismic P-wave velocity model and the seismic reflection structure, we can see that there are strong heterogeneities in the lateral or vertical direction, and there are different responses in the deep for 7 faults (cut by the profile at surface). The Tengchong, Nujiang and Lancangjiang faults are all crust-scale faults with the westward dip. Where, the dip is about 30° for the Nuijiang fault, and about 25° for the Lancangjiang fault. The Wuliangshan and Weixi-Qiaohou-Weishan faults are crystalline basement-scale faults which both dip toward the east, and the Honghe fault is crust-scale one whose obliquity is about 25°. The Chuxiong-Tonghai fault is the upper crust-scale one whose obliquity is about 25° with the east slip.

The P-wave velocities of the lower crust under the Sanjiang area range from 6.7 to 7.5 km/s. From the interpretation results of wide-angle seismic profiles for the global orogen belts, the average thickness of the lower crust is about 14 km and P-wave velocity ranges from 6.5 to 6.9 km/s, and we can know that P-wave velocity in the lower crust is about 0.2—0.4 km/s higher than the average of global orogen, and maybe similar to P-wave velocity structure in the lower crust in the south of the Bangonghu-Nujiang suture. It is attributive to crust-mantle mixture in the lower crust. We can see from the velocity structure of P-wave and reflection image in the crust that: crustal thickening of the Tengchong and Baoshan blocks present mainly in the lower crust. The thickness of the middle and upper crust of the profile is about 18 km, while it hits about 22 km in the lower crust. So we know that thickening of the lower crust is obvious compared with average thickness of the upper and lower crust of global different structure zones. This is interpreted as showing that it is related to subduction of Tethys oceanic crust, consume, collision orogenesis and interaction between the crust and mantle.

From the velocity structure of P-wave and reflection image in the crust, we can see that crusts of

Gondwana-typed Baoshan, Simao blocks and Yangtze block thicken mainly in lower crust. Thickness of middle and lower crust is about 18 km, while in lower crust it is about 22 km. Compared with thickness in upper crust and lower crust to globally different structure zones, we can get such a conclusion that the thickness of lower crust remarkably thickens in the studied area. The thickening of lower crustal thickness is inferred to be related to subduction of Tethys oceanic crust, consumation, collision orogenesis and the crust/mantle interaction.

4.2 Earthquake development environment

There is a set of obviously strong reflection zones in 0—115 km along the profile, corresponding to the variation belt of seismic P-wave velocity from 6.1—6.3 km/s to 5.7—6.1 km/s. The belt is located at the south of Tengchong at the surface. Combining with lower P-wave velocity characteristics in the upper crust from “Tengshen 99 Project”, we make such an inference that the belt with the alternativeness of high and low P-wave velocity and the occurrence of bright points, as strong seismic reflection, is the response of magma batch in volcanic field of Tengchong. In addition, 2 earthquakes with magnitude of 7.3 and 7.4 and epicenter depth of about 12 km consecutively occurred in Longling on 29 May, 1976. These earthquakes are just located in the transitional zone between high and low P-wave velocity. From the above-mentioned evidence, we deduce that the belts with strong reflections and the alternative low and high velocity are main regions where there are stress accumulation, energy congregation, strong earthquake development and occurrence.

In Tongchong and its neighboring area, there are some exposures of lava group. In Jianchuan, there is exposing porphyry with rich alkali, which is equivalent to basalt or the magma series transiting to andesite viz. intermediate magma in composition. This indicates that porphyritic magma is the basaltine magma residual from basic plagioclase differentiation of mantle-source materials. Experimental petrology demonstrates that the source of basalt is about 50—80 km deep where is consistent with the depth of 50—60 km (obtained in this study) of the layer between the lower crust (with P-wave velocity of 6.8—7.2 km/s) and upper mantle (with P-wave velocity of 7.8—8.0 km). It might be the slap of mantle residual in the crust-mantle transition zone. Volcanoes in the crust of Tengchong are thought to be derived from the fraction of partial-melting of oceanic upwelling body of asthenosphere, and the present situation of tectonics at the surface had undergone multistage tectonic overprints and reconstructions, or had been completely changed by the old rocks for the tectonic geothermal events induced by the melting body of upwelling body from asthenosphere or the vertical diaper and lateral detachments.

4.3 Contact relationship between blocks

Seismic wave velocity distribution and seismic reflection pattern in the crust can be used to study the contact relationship between the Tengchong and Baoshan and Baoshan and Luxi blocks along the wide-angle seismic profile. From the crustal P-wave distribution and seismic reflection structure, the studied profile crust can be divided into three segments A,B,C respectively, which correspond to the Tengchong, Luxi and Baoshan blocks. Where, seismic P-wave velocity of sedimentary deposit at the top crystalline basement in segment for segment A is relatively faster than that in segment C. P-wave velocity of the middle and lower crust in segment A is a little lower than that in segment B. For segment B, P-wave velocity is slowest above the crystalline basement and fastest in the middle crust, and slowest in the lower crust. The seismic reflection from Moho in segment B is clear. The Moho depth from the seismic reflection section in segment A is shallower than that in B. Even not strong, we still can see the seismic reflection in the depth range of 8—10 km. The seismic reflection energy from Moho in segment C is relatively weak, but seismic reflection events as bright points could be seen at the depths of 18—22 km, 40 km and 50 km.

Combining with the plate evolution process of the studied area[14,15], we can see that it is very possible that the west-inclined fault between the Luxi and Baoshan blocks is the residual of the Proto ocean eastward subduction, and the east-inclined fracture between Tengchong and Luxi ocean-trough denotes the westward subduction residual of Nujiang suture, and consequently presents the subduction image with converse direction Jurassic-Cretaceous period. The above-mentioned features and inference support the result about crust by the multilayered structure model in the studied area[8].

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