Characteristic of crustal structure beneath the rifts in southern Tibetan plateau*

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Abstract The method of 2-D travel time inversion, which can be applied to determining 2-D velocity structure and interfaces simultaneously, is used in this paper to reprocess the data of Paiku Co-Pumoyingcuo seismic profile across the Nyima-Tingri rift and Shenzha-Dinggye rift. P-wave velocity structure and interfaces beneath the profile are obtained. The interfaces in the crust near Tingri and Dinggye which are located on rifts have a tendency to uplift, and velocities of middle and lower crusts are high. Low velocity layer in upper crust has an offset. Compared with the distribution of the earthquakes in this region, it is speculated that normal faults near Tingri and Dinggye extend to the upper mantle. Apparently it is affected by deep material: the uplift of mantle causes partial melting in the crust, thus the thickness of crust in this area becomes thin, and tension failures occur in this region easily. On the basis of the characteristics of the earthquakes' distribution and the structures of the crustal velocity and interfaces, materials from the mantle still uplifts and the failures are still active.

Key words: rifts; Southern Tibet; travel time inversion; velocity structure; crustal interface

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1 Introduction

Tibetan Plateau is a special tectonic unit on the Earth surface, and the Himalaya mountain is the youngest one since the Cenozoic (Teng, 1985). Since late 1970s, for the purpose of detecting the collision and subduction between the Indian and Eurasia plates, geoscientists have done a lot of geological surveys on southern Tibetan plateau and given characteristics of the crustal velocity models (Teng et al, 1983), discontinuity (Xiong et al, 1985) and high heat flow (Shen, 1985; Wei et al, 1985). Except for west-east large faults, there exist a series of rifts which strike nearly north-south (Yin et al, 1999; Armijo et al, 1986, 1989). They are related to the uplift of the Tibetan plateau (Molnar and Tapponnier, 1978; Burchfiel and Royden, 1985; England and Houseman, 1986). Whether they are a sign of Tibetan plateau collapse (Coleman et al, 1995; Searle, 1995) caused by tensions in the crust due to material's eastward extrusion which attribute to N-S compression after Tibetan plateau reaches its highest, or they are just caused by compres-

sion in NS direction. The whole process of the development of these rifts also relates to the uplift and subsidence of materials in upper mantle. The structures of velocity and interfaces beneath the region near the rifts are affected by the rifts' own development. We know that most of the rifts in the southern Tibet cut through the upper crust and make crustal structures in west-east direction much different, but little are known about their deep reasons.

Two-dimensional travel time inversion (Zelt and Smith, 1992) is widely used to processing the seismic reflection/refraction data, in which both velocity and depth are estimated and structures of velocity and interfaces are given. And it is more effective to assess the non-uniqueness compared with the other programs such as SEIS88. In this paper we will use the method to reprocess the data of Paiku Co-Puma Yumco seismic profile obtained in 1981 during Sino-Frence cooperation. About the profile people have done some work. Teng et al (1983) gave 1-D velocity models beneath the Paiku Co, Dinggye, Gangba, and Puma Yumco, and Zhang et al (2004) reprocessed the data using SEIS88. However, both of them have not considered effect of depth of interfaces, and their results are subjective. Besides, with

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attentions to N-S rifts increasing and new methods appearing, it is necessary to reprocess the data. Two-dimensional structures of velocity and interfaces beneath the profile are derived in this paper. According to the results, some explanations on the rifts nearby the region are presented.

2 Method

Two-dimensional travel time inversion developed by Zelt (Zelt and Ellis, 1988; Zelt and Smith, 1992) for processing wide angle seismic data is based on model parameterization in which the model is supposed to be composed of several layers, and each layer contains both velocity points and depth points by which the layer is divided into trapezoids. Velocity in each trapezoid can be analytically represented by the velocities at the four corners of a trapezoid. Ray tracing and travel time inversion are based on the model. Inversion is convenient and rapid because parameters can be set whether to be inverted or not according to the needs.

Linearized equation (Zelt and Smith, 1992) is as follows:

$$\mathbf{A}\Delta\mathbf{m} = \Delta\mathbf{t} \quad (1)$$

where $\mathbf{A}$ is $M \times N$ matrix, M is the number of data points used in the inversion, N is the number of model parameters, and $\Delta\mathbf{m}$ is a model adjustment vector and $\Delta\mathbf{t}$ is a travel time residual vector. Ordinarily the inversion problems are overdetermined, so this equation is solved by damped least-square method and the solution (Zelt and Smith, 1992) is

$$\Delta\mathbf{m} = (\mathbf{A}^T \mathbf{C}_t^{-1} \mathbf{A} + D \mathbf{C}_m^{-1})^{-1} \mathbf{A}^T \mathbf{C}_t^{-1} \Delta\mathbf{t} \quad (2)$$

where D is the overall damping factor and usually equals one (Zelt and Ellis, 1988; Zelt and Smith, 1992;

Zelt et al, 1994, 2003), $\mathbf{C}_t$ and $\mathbf{C}_m$ are covariance matrices estimated from data and model, they are represented below:

$$\mathbf{C}_t = \text{diag}\{\sigma_i^2\}, \quad \mathbf{C}_m = \text{diag}\{\sigma_j^2\}, \quad (3)$$

where the standard deviation σ_i is the estimated uncertainty of the i -th travel time measurement, and the σ_j is the priori estimate of the uncertainty of the j -th model parameter. The solution given by the equation (3) is added to the current model, and then ray tracing is applied through the updated model. Repeat these operations until most of the observations have a ray path and the misfits between observed travel times and theoretic travel times are small.

3 Data processing

3.1 Reflection/refraction seismic records in the southern part of the Tibetan plateau

The reflection/refraction seismic profile oriented west-east in southern part of the Tibetan plateau, which starts from Paiku Co lake and goes towards east, is across the Nyima-Tingri rift and Shenzha-Dinggye rift with length of about 490 km. three shotpoints are fired at Pukucuo, Dinggye and Puma Yumco, respectively (Figure 1), the wave signal from the shotpoints is picked up by about fifty seismic recorders along the profile. Based on the data, four seismic time sections are plotted with reduce velocity of 6 km/s (Teng et al, 1983). Six seismic phases can be traced in the sections, there are corresponding to six groups of travel times denoted by t_1 to t_6 . t_1 is the travel time of direct wave Pg, and t_6 is the travel time reflected from Moho, this phase has more stronger energy, and its first arrival appears at the distance of 230 km and can be traced clearly to 300 km. Travel times t_2 to t_5 correspond to different reflection waves from the

Figure 1 Location of the Paiku Co-Puma Yumco seismic profile and local faults. Black lines represent tectonic lines.

interfaces in the crust. They all have weaker energies but can be continually traced, especially the seismic phase denoted by t_2 reflected from the first interface in the upper crust and the seismic phase denoted by t_4 reflected from the middle crust. Part seismic time sections with the reduced travel time curves are shown in Figures 2 and 3.

Figure 2 Western seismic time section of shotpoint of Puma Yumco. Travel time t_1 corresponds to direct waves, travel times t_2 to t_5 correspond to waves reflected from interfaces in the crust, and travel time t_6 corresponds to waves reflected from Moho.

Figure 3 Western seismic time section of shotpoint of Dinggye. Travel time t_1 corresponds to direct waves, travel times t_2 to t_5 correspond to waves reflected from interfaces in the crust, and travel time t_6 corresponds to waves reflected from Moho.

3.2 Results

Based on 1-D velocity models beneath Paiku Co, Dinggye, Gangba, and Puma Yumco (Teng et al, 1983), an initial 1-D model is constructed to be used in later ray tracing and travel time inversion, which contains 137 parameters (Figure 4), forming five layers and 76 blocks. All interfaces in the initial model are flat, and each layer has a constant velocity. Smoothing layer boundary simulation is used each time in the processing. During the inversion process, layer-stripping method is used. From the top layer to the bottom layer, each time only parameters in the same layer are set to be inverted, others

Figure 4 Parameters to be inverted. Black squares denote boundary points, black cycles denote velocity point.

being fixed. Iterations continue till rays are traced to most of observation points and the misfits between the observed travel times and the theoretic travel times are small, and this operation is repeated for each layer. Usually it is enough that RMS travel time residual is less than 15 and parameter resolution is larger than 0.5. The parameter resolution is related to the coverage of the rays, the more the ray cover a parameter, the higher the resolution of the parameter is. The final ray paths and travel times are shown in Figure 5 and the structures of velocity and interfaces are shown in Figure 6. According to ray path (Figure 5), the ray is very sparse in such part of the model as two sides and lower central part, which are shown by the dashed line (Figure 6). Because of lower level of ray coverage, the results of inversion are unbelievable in those parts.

The 119 seismic events from January 1, 1970 to December 31, 2008 released by the China Earthquake Networks Center, which are located in the region from 28°N to 32°N and from 85°E to 91°E , are added to the Figure 6 by the focal depth and its longitude (converted to the distance to Paiku Co).

As is shown in Figure 6, the origin of the coordinates is set at Paiku Co, the horizontal axis indicates the distance to Paiku Co. The horizontal axis is positive towards east, and the vertical axis denotes the depth and is positive downward. The profile illustrates the following characters:

1) The first and second layers belong to upper crust. Velocities in these layers vary little, but the interfaces' change is apparent. The segments of the interfaces from 170 km to 300 km have a tendency to uplift. The thickness of the layer ranges from 12 km to 15 km.

2) The thickness of the third layer is thin and about

6 km. The bottom interface of this layer varies at the segment from 70 km to 250 km. In the middle of the profile at about 300 km, the velocity is about 6.2 km/s.

On both sides of the object, the velocity is low, and about 5.5 km/s.

Figure 5 Illustration of ray paths. Black cycles denote theoretic travel time. Crosses denote observed points.

Figure 6 Structure of velocity and interfaces and distribution of earthquake sources. The solid lines denote interfaces, and the colors denote velocities showed by the right bar. The sizes of open circles correspond to magnitude of sources.

3) The fourth layer subjects to middle crust. Its mean thickness is about 12 km, and on the two sides of the distance of about 180 km, there exists low velocity objects. But the bottom interface at this distance is downward a little. Low velocity also exists under the distance 420 km.

4) The fifth layer belongs to lower crust, and its thickness is about 25 km. The velocity in this layer is high. Moho uplifts a little at the range from 100 km to 200 km.

4 Discussion and conclusions

According to geological structure in this region (Zhang et al, 1999; 2002; Wang and Zhang, 2006), there exist two rifts at Tingri and Dinggye, located at 130 km and 230 km, separately. Abnormal geothermal objects

exist in the crust of southern Tibetan plateau (Shen et al, 1985). The seismic profile is located in the northern part of the Himalya Mountain, there are many earthquakes happened in this area, most of them are shallow earthquakes, a few is deep earthquakes (Teng et al, 1999). According to Figure 6, epicenters mainly concentrate on Tingri and Dinggye. The number of the earthquakes near Tingri is less but their amplitudes are larger while the number of earthquakes near Dinggye is larger but their amplitudes are smaller, and both of their distribution is centralized, almost vertically extending to upper mantle. The focuses are mainly located in the high velocity area and beneath the segments that uplifts.

The model derived from the Paiku Co-Dinggye-Puma Yumco seismic profile illustrates that the velocity varies strongly and the low velocity layer (LVL) in up-

per and middle crust disappears where the rifts exist in the crust. With high velocity uplifting, Moho boundary has a tendency to uplift. On two sides of rifts in middle crust there are low velocity zones, which suggest that the activities of rifts cut LVL off and made high velocity material intrude. The abnormal variation is more apparent beneath Tingri by contrast to the wide distribution of high velocity materials in the east of Dinggye. The epicentral distribution is also corresponding to such rift structure. So it is speculated that rifts near Tingri and Dinggye extend to the upper mantle. Apparently it is affected by deep material: the uplift of mantle's material cause partial melting in the crust, thus the thickness of crust in this area becomes thin, and under tension a series of extension structures arise.

The structures of velocity and interfaces illustrate that the development of the rifts in southern Tibet may be related to the uplift of material with high velocity, which causes the velocity structure taking on three blocks horizontal with Nyima-Tingri rift and Shenzha-Dinggye rift being their boundaries which is consistent with the activity of the earthquakes.

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