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Large explosive shot gathers along the SinoProbe deep seismic reflection profile and Moho depth beneath the Qiangtang terrane in central Tibet

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Owing to extreme topography, rapid velocity and thickness variation of near-surface layer and strong seismic attenuation through the thickest crust of the Earth, it is not easy to acquire reflective Moho in central Tibet. However, with help from the SinoProbe deep seismic reflection experiment, large explosive of 1000 kg seismic sources have been tentatively detonated in the Qiangtang terrane and good quality data were acquired. Compared with multifold data, the single-fold record from single shot gather can also show clear Moho image in the Qiangtang terrane. Moho reflection appears at ~ 24 s TWT (~ 75.1 km) in the northernmost Lhasa terrane and at about 21 ~ 20 s TWT (65.7 - 62.6 km) beneath the Qiangtang terrane. We speculate that Moho gets 9.4 km-12.5 km shallower from the Lhasa to the Qiangtang terrane rather than a 20 km offset. There is no obvious change of Moho depth across the Shung Hu suture.

Introduction

Over the last 30 years, deep seismic reflection profiling had been demonstrated to be an effective method in resolving structural details in the crustal and upper mantle (Oliver, 1982). A large number of deep seismic profiling projects have provided a great number of seismic lines to image the structure the continental crust and the crust-mantle boundary. Such images are very important for explaining the process of the crust forming and other tectonic processes (Brown et al., 1987; Behr and Heinrichs, 1987; Clowes et al., 1987; Bois and ECORS Scientific Party, 1990; Klemperer et al., 1990; Balling, 2000; Cook et al., 2010).

This approach has been proven particularly successful in the studies of the tectonic development of southern Tibet in early 1990s (Zhao et al., 1993; Brown et al., 1996; Nelson et al., 1996; Gao et al.,

2005). However, compared to the southern Tibetan Plateau, seismic data acquisition in central Tibet was not successful due to insufficient dynamite, short spread and missing geophones arrays, as well as insensitive recording instruments and deteriorating weather (Ross et al., 2004).

In order to test the acquisition technique for detecting Moho structure in central Tibet, SinoProbe Project carried out a deep seismic reflection experiment, which starts west of the Silin Co in the northern Lhasa terrane, crossing the Banggong Nujiang Suture (BNS) to the west of the Lunpola and skirting the eastern extension of the central Qiangtang anticline, and ends at the Dogai Coring just to the south of the Jinsha Suture (JS). In this paper, we particularly report the single shot records of 7 large shots with 1000 kg explosive fired in every 50 km space along the deep seismic reflection profiling (Fig.1).

Geologic setting

The Qiangtang terrane lies between the Jinsha Suture (JS) to the north and the Bangong Nujiang Suture (BNS) to the south in central Tibet (Dewey et al 1988; Yin and Harrison, 2000). As the northern boundary of the Qiangtang terrane, the JS marks the Late Triassic closure of the Paleotethys ocean between the Songpan-Garze and Qiangtang terranes (Yin and Harrison, 2000; Weislogel, 2008). To the south, the BNS originally formed during a late Jurassic-Early Cretaceous collision between the Lhasa terrane and Qiangtang terrane and defined by a broad and discontinuous belt of ophiolite fragments and mélangé (Yin and Harrison, 2000; Kapp et al., 2003, 2007; Guynn et al., 2006; Wu et al., 2013). It represents remnants of a major oceanic basin that opened before the Triassic and closed by northward subduction beneath the Qiangtang terrane in the Middle to Late Jurassic (Girardeau et al., 1984; Pearce and Deng, 1988; Wang et al., 2008). During mid-Cretaceous time, the BNS was characterized by volcanism and non-marine basin development. Tertiary deformation in this zone is characterized by mainly north-dipping thrust systems with Eocene-Oligocene red beds and volcanic rocks in the footwall. Tertiary shortening and basin development in central Tibet may record continued under-thrusting of the Lhasa terrane along the BNS, which may have both accommodated and been driven by insertion of Indian

Figure 1 Topographic map of central Tibet within 87° E to 91° E and longitude 31° N to 35° N latitude. JS-Jinsha Suture, BNS-Bangong Nujiang suture. The solid red line shows the locations of SinoProbe seismic reflection profile. The black stars mark the locations of large shots using 1000 kg explosive. The images of these shot records are shown in Fig.4-Fig.10. SN is shot number.

basement into a previously thickened Tibetan crust (Kapp et al., 2005, 2007).

Structurally, Qiangtang terrane can be divided into two subterrane (the south Qiangtang terrane and north Qiangtang terrane) by a prominent blue schist-bearing metamorphic belt in its central part. The central part was occupied by an anticline of pre-Jurassic strata or metamorphic rocks and the northern and southern limbs by synclines of mainly Jurassic sedimentary rocks (Pullen et al., 2008; Zhai et al., 2011, 2013; Zhu et al., 2011).

Geophysical probing progress in Qiangtang terrane

As a good place to understand the collision process of the Indian and Asian plates, structures of the crust and upper mantle the Qiangtang terrane are of decisive importance. However, due to the hard environment condition, geophysical probing in Qiangtang terrane is not enough. Some geophysical studies showed the deep structure of the lithosphere beneath the Qiangtang terrane and surrounding zones. Meissner et al., (2004) imaged a north dipping Asian slab

rooted beneath the BNS, which could correspond to a northward subduction of the South Tibet. The slab could be around 100 km long. Shi et al., (2004) suggested that a south-dipping crustal converter is seen from the upper crust near the metamorphic core complex exposures in the Qiangtang terrane to the lower crust near the BNS. At deeper depths, a southeast-dipping mantle converter is seen extending from ~50 km to the north of the BNS at the depth of the Moho to ~100 km to the south of the BNS at a depth of ~180 km. The Indian lithosphere has been imaged as far north to central Tibet near the BNS zone (Huang et al., 2000; Kind et al., 2002; Tilmann et al., 2003). P-wave velocity structure shows that the Indian lithospheric mantle has subducted beneath central Tibet and its frontier has passed through the BNS and extended northward beneath the Qiangtang Terrane at latitude 34°N (He et al., 2010). Recent results indicated that the sub-horizontally under-thrusting Indian mantle lithosphere reached as far as ~100 km to the north of the BNS (~33°N) (Hung et al., 2010; Xu et al., 2011; Chen et al., 2012) and the under-thrusting Indian lower crust slid to latitude ~31°N (Nááílek et al., 2009).

Most of the above geophysical researches have concentrated on the structure of the upper mantle. However, clear Moho structure beneath the Qiangtang terrane is not acquired.

Table 1. Data acquisition parameters for big shots in the Qiangtang terrane. SP is shot point.

S. No.	SP Location	SP Station	Spread Location	Offset (m)	Maximum source-receiver distance (m)	Drilling depth (m)	Explosive (kg)
1	SP146	100639.5	100644-101603	225	48175	50	1000
2	SP 422	101682.5	101687-102646	225	48175	50	1000
3	SP 544	102667.5	102672-103631	225	48175	50	1000
4	SP 626	103650	103655-104614	250	48200	50	1000
5	SP 685	104650	104645-103686	250	48200	50	1000
6	SP 1002	105558	105563-106522	250	48200	50	1000
7	SP 1116	106408	106413-107372	250	48200	50	1000

Data acquisition and processing of large explosive shots

Data acquisition of large explosive shots

From October 2009 to May 2010, total seven shots with 1000 kg explosive were fired in every 50 km space along a 310 km long profile. The data were acquired by the Sercel 408 XL using 960 channels with a group interval of 50 m. Each shot point is recorded on a 47950 m (~ 48 km) single spread with a 250-225 m offset. Ten 50 m-depth holes were drilled as a circle for one large shot. 100 kg dynamite was placed in each hole (Fig. 2). These holes were drilled by powerful machines (235 kw each) to ensure the drilling depth. In the field, especially in Tibet, strong wind will greatly degrade the data quality. In order to avoid the interference of the wind, we put geophones in a pit and monitored everyday to choose the best firing time.

Figure 2. Schematic diagram of the source-receiver spread and the Drilling design of the large explosive shots. (a) Schematic diagram of the source-receiver spread. Maximum source-receiver distance is 48175 m or 48200 m, respectively with 225 m or 250 m offset. (b) Drilling design for large explosive shots. Ten 50 m-depth holes were drilled as a circle for one large shot. 100 kg dynamite was placed in each hole. The distance between farthest holes is 20 m.

Data processing of large explosive shots

All the large explosive shots data were processed with the Omega, CGG, Promax seismic processing packages. The data processing flow and main parameters are shown in Table 2.

Table 2. Processing steps for large explosive single shot record

SEG-Y Data input
Apply geometry, CMP = 25 m
Trace editing, Trace Killing
Tomography static datum level 5000 m; replacement velocity 5000 m/s; 50 Hz suppress interference
Anomalous amplitude noise attenuation (AAA); Frequency (0-6, 6-12, 12-18, 18-24, 24-30, 30-36 Hz)
Surface consistent amplitude compensation; Predicted distance 48 ms, operator length 180 ms, white noise coefficient 0.1
Energy enhancement in FK zone
Median filter: 0-6s, 6-8-28-30 Hz, 6.5-30s 4-6-20-25 Hz
Automatic gain control (AGC); AGC operator length = 1000 ms
Top mute
Data displace
Data output

Some major methods including Anomalous amplitude noise attenuation (AAA), Energy enhancement in FK zone, Median Filter, Auto Gain Control (AGC) are well effective in data processing.

Automatic Gain Control (AGC). Gain is a time-variant scaling in which the scaling function is based on a desired criterion. Often, gain is applied to seismic data for display (Yilmaz 2001). The AGC operator length defines the length of the AGC window used for gain computations. After testing, we used 1000 ms as the AGC operator length, which is a better gate width for these single shots. The AGC program moves the window down the trace sample-by-sample and calculates a scale factor at each location. The scale factor is equal to the inverse of the mean or root mean square (RMS) amplitude in the window. The scalar is applied to the sample at the beginning center or end of AGC window. This step was achieved using Promax software.

Anomalous Amplitude Noise Attenuation (AAA). In the Qiangtang terrane, noise characterized by anomalous amplitudes is removed from prestack seismic data by transforming the seismic data into frequency domain and then apply a spatial median filter. Frequency bands with amplitude that deviate from the median amplitude by a specified threshold are either scaled (multiplied by a specified scale factor) or replaced with an interpolated band using neighboring traces, this module may be used to identify amplitudes that are anomalously high or anomalously low. The AAA module scales noise based on amplitude discrimination within specified frequency bands. A frequency band is considered anomalous when its mean energy, herein called amplitude, exceeds a computed threshold. The threshold is computed by multiplying the median mean energy of frequency bands from a specified number of surrounding traces by a specified factor. Anomalous amplitudes are thus scaled or replaced with interpolated

data using neighboring traces. This step was achieved by OMEGA software.

Energy enhancement in FK zone. Owing to the energy attenuation related to overlaying the high-velocity layer in local station, some channels in raw data become weak in energy. In this paper, we used FK power module to the signal in a window of seismic data. The program performs a multichannel and time variant operation. In the process, a window of data is transformed into the FK domain. The amplitude of each FK sample is modified by raising it to a user-specified power, and the phase of the FK-domain sample is not changed. An inverse transform back to the time-space domain is performed on the data. The window is advances by 50% of the time length, and the process repeats for the new window. The output is linearly tapered between window centers. When FK samples are raised to a power greater than one, energy that is strong and localized in FK space becomes even stronger, which allows the seismic data to be displayed at a lower gain. Therefore, the random noise will appear at much lower amplitude. This process thereby enhances continuous and linear seismic data energy that maps a localized region in FK spaces. FK power module of FOCUS software was used in processing large shot gathers.

Median Filter. The median filter is a simple and effective method in signal processing that can suppress noise (especially spikes), especially in non-stationary signal processing. The method has been applied in seismic prospecting (Bednar 1983; Duncan and Beresford 1995). Based on the recent research, this filter can effectively separate the signal from noise, preserve detailed structure, and then reduce the random noise (Liu et al.,2006; Huo et al.,2012). In processing

large shots data, we respectively use 6-8-25-30Hz in 0-6 s TWT and 4-6-20-25Hz in 6.5-30 s TWT as filter parameters.

Figure 3 shows how seismic data were improved after each step of AGC, AAA, FK Power and Median filter.

Discussion

How to acquire effective data in high ambient noise levels or poor signal penetration area is still a problem encountered periodically during the data acquisition in the Tibetan plateau. The attempt of acquisition with large explosions in US is successful (Jarchow et al.,1990). It is a good example for exploring deep continental crustal structure. In SinoProbe seismic project, the 1000-kg shot gather recorded in central Tibet with phenomenal signal-to-noise ratios illustrated the energy of the reflective wave. The quality of the large explosive single shot was generally excellent with signal returns above ambient noise. Shot records of the 1000-kg explosive showed highly reflective lower crust and characterized Moho by a sharp increase band in reflectivity at the base of the crust (Fig. 4- Fig. 10).

The shot gathered showed in Figure 4 is fired at the northernmost Lhasa terrane, to the south of BNS. Figures 5 and 6 show shots gathers fired in the south Qiangtang terrane, to the south of the Shuanghu suture. Figure 7 shows shot gather fired in the central Qiangtang anticline zone. Figures 8, 9 and 10 show shots gathers fired in the north Qiangtang terrane, to the north of the Shuanghu suture. The clear reflectors with high reflectivity interpreted as being the Moho are well imaged in these larger explosive single shot records. On the shot gather fired to the south of BNS, Moho appears at ~ 24 s TWT (Fig. 4).

Figure 3. Images of the processed seismic data after main steps including AGC, AAA, FK Power and Median filter. (a) Raw data; (b) After AGC; (c) After AAA; (d) After FK Power and Median Filter; (e) Final data.

Figure 4. Single shot gather of 1000 kg explosive fired in the northern-most Lhasa terrane, to the south of BNS. Shot number is 146 . Continuous Moho reflection appears around ~ 24 s TWT.

On the 1000 kg shot record fired to the north of BNS, the Moho is marked with continuous reflection at 20 s TWT (Fig. 5). The images of Figures 4 and 5 show an apparent offset of the reflection Moho across the BNS. The Moho is present at a depth of 24 s TWT, whereas it appears at a depth of 20 s TWT to the north of BNS. In the south Qiangtang terrane and central anticline, the Moho, appearing with continuous reflections, are found at 20 - 21 s TWT (Figs. 5 to 8). Shot 626 and 685 are recorded by opposite direction spreads. For

Figure 5. Single shot gather of 1000 kg explosive fired in the south Qiangtang Terrane, to the north of BNS and to the south of the Shuanghu suture. Shot number is 422. Moho marked with continuous reflection appears at 20 s TWT.

Figure 6 Single shot gather of 1000 kg explosive fired in the south Qiangtang Terrane, to the north of BNS and to the south of the Shuanghu suture. Shot number is 544. Moho continuous reflections are found at 20 - 21 s TWT.

shot 626, the shot site is in the south and the spread is in the north. For shot 685, the shot site is in the north and the spread is in the south. They have a crossing at the middle part of the spread, which is situated 18 km to the source of SN 626 (Fig.7) and 30 km to the source of SN 685 (Fig.8). In the further north of the Qiangtang terrane, Moho reflections are evident at almost 21.5 s TWT (Figs 9 and 10).

Figure 7. Single shot gathers of 1000 kg explosive fired in central Qiangtang anticline. Shot number is 626. Moho continuous reflections are found at 20.5 s TWT in the short source-receivers spread and at 21.5 s TWT in the long source-receivers spread.

Figure 8 Single shot gathers of 1000 kg explosive fired in the north Qiangtang Terrane, to the north of the Shuanghu suture. Shot number is 685. Moho continuous reflections appear at 20 s TWT near source and at 21.5 s TWT far away the source.

Figure 10 Single shot gathers of 1000 kg explosive fired in the north Qiangtang Terrane, to the north of the Shuanghu suture. Shot number is 1116. Moho reflections are likely to be at almost 21.5 s TWT.

Figure 9 Single shot gathers of 1000 kg explosive fired in the north Qiangtang Terrane, to the north of the Shuanghu suture. Shot number is 1002. Moho reflections are imaged to be at almost 21.5 s TWT.

A single-fold dataset was built by the 7 large explosive single shot gathers. Compared with 72-folds migration data, the Moho depth from the south to north beneath the BNS and the Qiangtang terrane are almost identical (Fig.11), i.e., if the source depth and the explosive is enough, we can get the basic framework of the Moho with

sufficiently effective energy. The single-fold record can also show similar features as that of the multifold data.

Some existing examples show that the deepest continuous reflection combined with higher amplitude were easily picked as the reflection Moho (Klemperer et al., 1986; Hauser et al., 1987; Hammer and Clowes 1997). We draw the distribution of amplitude with time of these large shot gathers (Fig. 12). The amplitude analysis after AGC shows high-amplitude strong reflections that are associated with significant energy enhancement of Moho beneath the BNS and the Qiangtang terrane. For the shot number of 146, which fired in the northernmost Lhasa terrane to the south of BNS, the higher amplitude appears at about 24 s TWT. From the north of BNS to the central anticline, the higher amplitudes appear at about 20 s TWT at shot number 422, 544 and 626. In the north Qiangtang terrane, the higher amplitudes in the seismic record become deeper than in the south Qiangtang terrane. It appears at 21 s TWT beneath the southern part of north Qiangtang terrane (shot number 685) and almost 21.5 s TWT (shot number 1002 and 1116) beneath the further north Qiangtang terrane.

The Moho depth that was varied at different levels under the main suture zones of the Tibetan Plateau were detected by series of seismic investigations (Zhu and Helmberger 1998; Vergne et al., 2002; Haines et al., 2003; Wittlinger et al., 2004; Shi et al., 2009; Karplus et al., 2011; Zhang et al., 2011). In fact, there are often arguments on Moho depth beneath the BNS and Qiangtang terrane. Depending on different methods, the Moho offset beneath was suggested with different results. The Table 3 shows the Moho offset reported over the past 30 years beneath the BNS.

Few common viewpoints on the Moho depth beneath the BNS and Qiangtang terrane were evident due to poor coverage of previous surveys and lack of consistency between various seismic techniques.

Figure 11. Comparison of the multiple-fold dataset and the single fold dataset. (a) The 72-folds migration data (after Gao et al., 2013). (b) The single-fold data from the single shot gathers.

Table 3. Moho offset beneath BNS reported over the past 30 years

No.	Moho Offset beneath BNS	References
1	~ 20 km	(Hirn et al., 1984)
2	more than 10 km	(Zeng et al., 1995)
3	No	(Kind et al., 2002)
4	~ 5 km	(Zhao et al., 2001; Haines et al., 2003)
5	5 ± 3 km	(Shi et al., 2004)
6	~ 8 km	(Li et al., 2006)
7	~ 10 km	(Nábílek et al., 2009; Tseng et al., 2009; Nowack et al., 2010)
8	Somewhat smaller change	(Griffin et al., 2011)

In this paper, Moho depth imaged by seismic single shot records with 1000 kg explosive was evaluated with an average crustal P-wave velocity of 6.26 km/s (after Mechie et al., 2011) according to TWT. Based on the single shots, we conclude that Moho depth is 75.1 km (~ 24 s TWT) in the northernmost Lhasa terrane and increases to 65.7 km ~ 62.6 km (about 21 s ~ 20 s TWT) beneath the Qiangtang terrane. Moho depth revealed by large shot gathers is identical with migrated section data (Gao et al., 2013). The Moho depth gets 9.4 km-12.5 km shallower from the Lhasa terrane to the Qiangtang terrane. It is not consistent with the previously proposed offset of 20 km (Hirn et al., 1984).

Conclusions

Large explosive shots with 1000 kg can be used to discover the structure of the lower crust and Moho. Based on single shot records, we conclude that the data from single 1000-kg explosive detonated with adequate signal-to-noise ratios for delineating the features of the lower crust and Moho enough. It is applicable and maybe is a potential way for exploring the areas where the standard seismic sources fail to produce adequate data.

In central Tibet, compared with the 72-folds dataset, a single-fold record can also show similar Moho features as that of multifold data under the condition that the effective data acquisition and processing methods were carried out.

With shot records of the 1000-kg explosive, the Moho layer was characterized by a sharp increase band in reflectivity at the base of the crust. We speculate that Moho gets 9.4 km-12.5 km shallower from the Lhasa terrane to the Qiangtang terrane rather than a 20 km offset.

Moreover, Moho depth changes little across the Shuanghu suture, indicating a younger age of the suture zone instead of a Triassic age as previously proposed.

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Figure 12 Amplitude analysis of the large shot gathers. *M* = Moho. For the shot to the south of BNS, the shot number is 126, the higher amplitude appear at about 24 s TWT. Other shots to the north of BNS, the higher amplitudes appear at about 20 s TWT at shot number 422, 544 and 626. In the northern Qiangtang terrane, the higher amplitudes appear at 21 s TWT beneath the southern part of northern Qiangtang terrane (shot number 685) and almost 21.5 s TWT (shot number 1002 and 1116) beneath the further north Qiangtang terrane.

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