Article ID: 1000-9116(2006)03-0264-09

Inversion of gravity and topography data for the crust thickness of China and its adjacent region*

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Abstract

The data of Bouguer gravity and topography are inverted to obtain the crust thickness of China. In order to reduce the effect of regional non-isostasy we corrected the reference Moho depth in the inversion with regional topography relief, and performed multiple iterations to make the result more reliable. The obtained crust thickness of China is plotted on a map in cells of 1°×1°. Then we analyzed the correlation between the Bouguer gravity anomaly and fluctuation of the Moho depth. A good linear correlation is found, with a correlation coefficient of −0.993. Different correlation coefficients, 0.96 and 0.91, are found for the data in land and ocean region, respectively. The correlation result also shows that the boundary between land and ocean is generally along the bathymetric line of −800 m. In order to examine the influence of the Earth′s curvature on the calculated result, we tried two inversion models: the inversion for the whole region and the inversion for 4 sub-regions. The difference in the crust thickness deduced from the two models is less than 5 km. Possible explanation for the difference is discussed. After comparing our result with that of other studies, we suggest that with our method the Bouguer gravity and the topography data can be independently inverted to obtain the crust thickness of China and its adjacency.

Key words: **Bouguer gravity anomaly**; **crust thickness**; **gravitational isostasy**
CLC number: P313.2 **Document code**: A

Introduction

Since the middle of the century, gravitational isostasy has been a fundamental hypothesis for inverting the gravity data to find the crust thickness. Geophysicists have done a lot of researches on using gravity data to investigate the depth of Moho discontinuity. Since 1980, the International Lithosphere Program emphasized the importance of investigating the Moho depth variation. Thereafter a lot of results have been published in the world (Braitenberg *et al*, 2000; Kaban *et al*, 1999; Banjeree and Satyaprakash, 2003; Chuej, 1979; King *et al*, 2002). Many Chinese geophysicists also did important works. ZENG *et al* (1995) compiled a map of crust thickness of China based on the DSS data. LIU *et al* (1987) proposed a method of utilizing gravity data to calculate the crust thickness. Some studies gave the crustal velocity structure for different areas of China (YAO *et al*, 1994; FANG, 1999). FU (1984, 1988) developed a method to calculate the crust

* **Received** 2005-07-11; **accepted in revised form** 2006-03-11.
Foundation item: KZCX3-SW-131
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thickness. ZHANG *et al* (2004) deduced the crust thickness of the southern Qinghai-Xizang Plateau based on seismic body wave data. Using the gravity and geomagnetic data JIANG *et al* (2003) obtained the crust thickness for the Okinawa Trough and its adjacent region. At the same time WANG *et al* (2001) derived the crust velocity structure of the Tianshan mountain region based on the data of seismic reflection profile. However, due to the limitation of station coverage, from the modern seismic data one can usually obtain only a 2D crust structure, and then extrapolate it to the 3D space. It is usually difficult to obtain a 3D crust structure directly. On the contrary, the gravity data can always be used to deduce the 3D variation of crust thickness.

In the traditional approach of deducing crust thickness from gravity data one often chooses a uniform crust depth as the reference for the whole studied region. However, in the region with large variation of topography use of a single reference depth would introduce significant systematic errors in the calculated crust thickness. Moreover, the selection of a single reference depth depends largely on the seismic information and personal experience of the researcher, and this would enhance the uncertainty in the inversion result. Based on the existing gravity inversion methods and the gravitational isostasy hypothesis, in inverting the gravity observations this study adds a topography correction term to the expression of the crust reference depth. In this paper we used the Bouguer gravity anomaly data in the region of (70°E~140°E, 15°N~50°N) and calculated the crust thickness, and studied the correlation between the crust thickness variation and the topography fluctuation.

Since this method directly uses the gravity and topography data and gives the crust thickness determination independent of seismic observations, we can compare the results obtained from different analysis method and different data source. When various methods have been used for a single study region, we can obtain a more realistic result of the crust thickness and crust velocity structure for this region.

1 Iterative inversion and analysis procedure

The procedure of the traditional FFT analysis is as follows: At first we transfer the Bouguer gravity data in the time domain to that in frequency domain, and extend them down to the next reference depth D. Then the data in the frequency domain is transferred back to the time domain with inverse FFT (IFFT). Further we use the formula

$$\Delta g(x, y, D) = 2\pi G\sigma(x, y, D) \tag{1}$$

to calculate the surface density σ at the reference depth D. Then we use the relation between the volumetric density ρ and surface density σ

$$\sigma(x, y, D) = \rho H(x, y) \tag{2}$$

to deduce the fluctuation $H(x, y)$ of the Moho discontinuity. Cubic formula is used to calculate the surface gravity anomaly generated by the variation of Moho discontinuity. Then the residuals between the observed gravity anomaly and the calculated anomaly are found and inverted again to find the Moho fluctuation correction. Doing so iteratively until the residual is smaller than the error threshold, we can find the final Moho fluctuation. The coordinate system used is a rectangular system $o\text{–}x_1x_2x_3$, with the ground surface being taken as the coordinate plane $o\text{–}x_1x_2$, and the gravitational downward direction being the vertical axis $o\text{–}x_3$. To facilitate the calculation the horizontal axis $o\text{–}x_1$ and $o\text{–}x_2$ are set to be parallel to the two horizontal edges of the density anomaly cube (Figure 1).

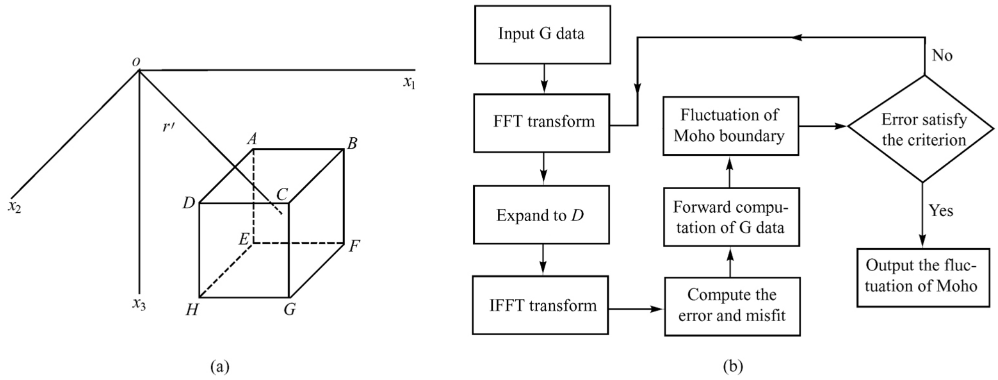

Figure 1 A density anomaly cube for calculating gravity anomaly at the coordinate origin (a); Flowchart of inverting gravity and topography data to obtain crust thickness (b)

The gravity anomaly at the coordinate origin generated by a homogeneous cube of density ρ at (x_1, x_2, x_3) is

$$\Delta g(o) = -G\rho \left\{ x_1' \ln(r' + x_2') + x_2' \ln(r' + x_1') - x_3' \arctan \frac{x_1' x_2'}{r'' x_3'} \right\} \Bigg|_A^B \Bigg|_A^D \Bigg|_A^E \tag{3}$$

where $r'^2 = x_1'^2 + x_2'^2 + x_3'^2$. Figure 1b gives the flowchart of processing the gravity and topography data to obtain the crust thickness. Finally the crust thickness can be expressed as

crust thickness = Moho depth fluctuation + corrected reference depth + topography variation.

2 Gravity isostasy and correction to the reference depth *D*

2.1 Data and its processing

This study used the 2′×2′ Bouguer gravity anomaly data provided by the CAS Geodesy and Geodynamics Laboratory (in Wuhan, China) for the region of (70°E~140°E, 15°N~50°N). In order to smooth the gravity image and suppress high frequency noise in the process of downward gravity extending, we did some preprocessing of the gravity data. We tried to use the gravity data averaged over every 31×31 grids (1°×1°), with the center of the grid array as the representative data point.

2.2 Curvature influence

Since the study region is large, Earth surface curvature may have influence on the inversion result. The topography with a variety of features, such as land, sea, mountains and basins, may also bring about the uncertainty in the result. To examine these effects we tested two models. One is inverting the data over the entire region (70°E~140°E, 15°N~50°N), and the other is dividing the whole region into four partly overlapped sub-regions and finding the solution for each sub-region, and then combining the four part solutions into one. The four sub-regions are UL (70°E~110°E, 30°N~50°N), DL (70°E~110°E, 15°N~35°N), UR (100°E~140°E, 30°N~50°N) and DR (100°E~140°E, 15°N~35°N), respectively.

2.3 Reference depth influence

In order to evaluate the influence of the reference depth on the Moho depth solution we tried four inversions by taking the reference depth as 23, 33, 43 and 53 km, respectively. The results are

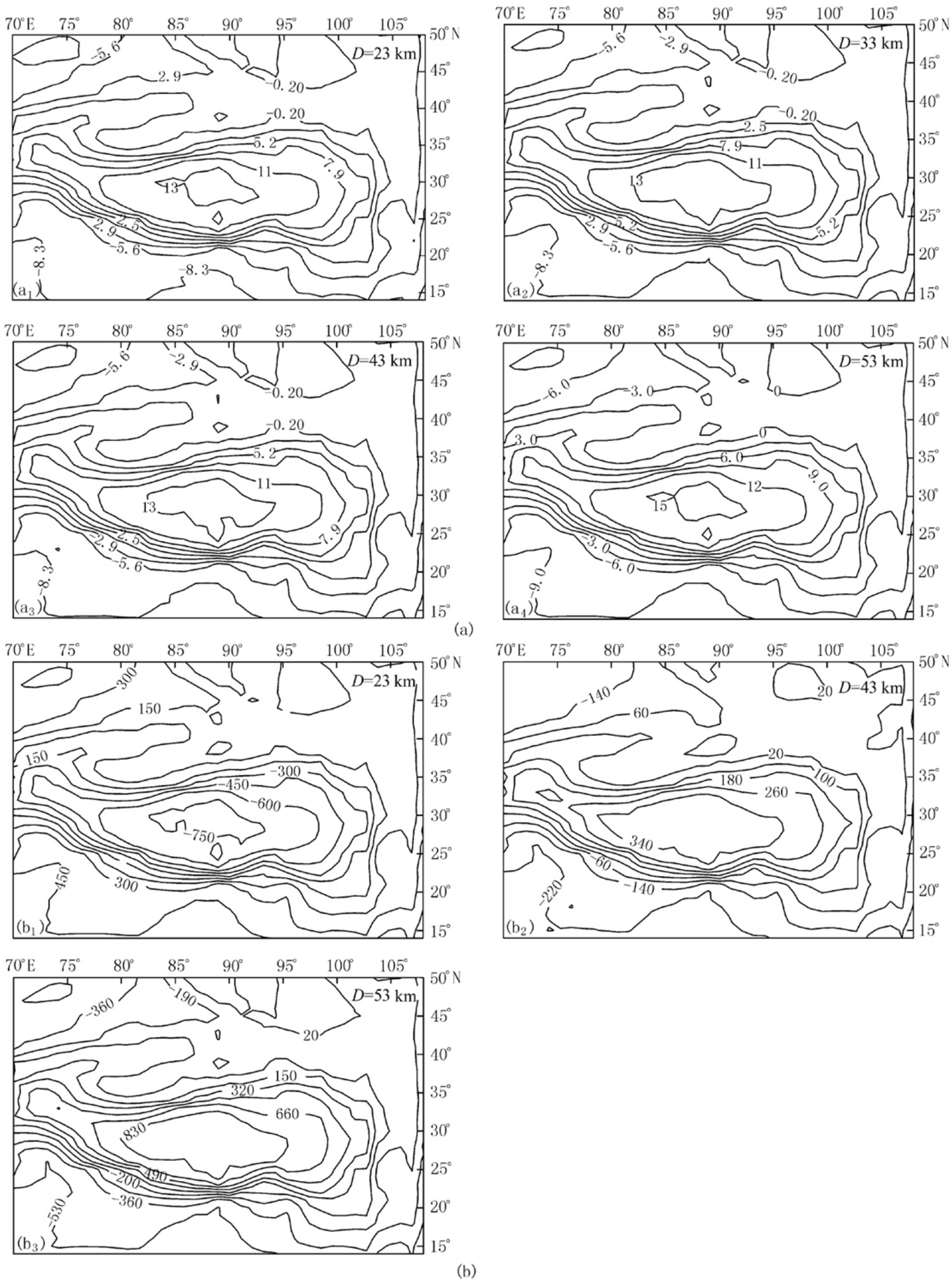

Figure 2 Moho depth fluctuation obtained for different reference depth model (the unit of isolines are km) (a); Moho depth difference deviating from the 33 km reference depth model (the unit of isolines are m) (b)

shown in Figure 2a. At the same time, the Moho depth differences deviating from the Moho depth obtained for the 33 km reference depth model were also calculated, and are illustrated in Figure 2b.

From the above result we can see that the Moho depth fluctuations for different reference depth models are less than 1 km. Such a small difference is entirely accepted. Therefore, we can choose a range of reference depth in the crust thickness calculation, rather than using only a single value. This is the basis for us to add the topography data to correct the reference depth in the inversion.

2.4 Gravity isostasy and reference depth correction.

The correlation between the Moho depth fluctuation and topography data in China is shown in Figure 3a, from which we can see that the relationship obviously consists of two linear sections: the upper land section and the lower ocean section. The link point between the two sections is at 800 m below the water level. Therefore, in this paper we divided the topography data into two parts and did the same correlation analysis as above. The results are shown in Figure 3b and 3c. An isostasy coefficient of k=4.36, with a correlation coefficient of 0.96, was found for the land region, while the k=2.00 and correlation coefficient of 0.91 were obtained for the ocean region. As can be seen, the gravity isostasy coefficient of the continental crust has a value close to the normal value of 4.45, while that of the oceanic crust is somehow deviated from the usual value of 2.73. The latter difference may be associated with the selected density contrast between the oceanic crust and the underneath mantle.

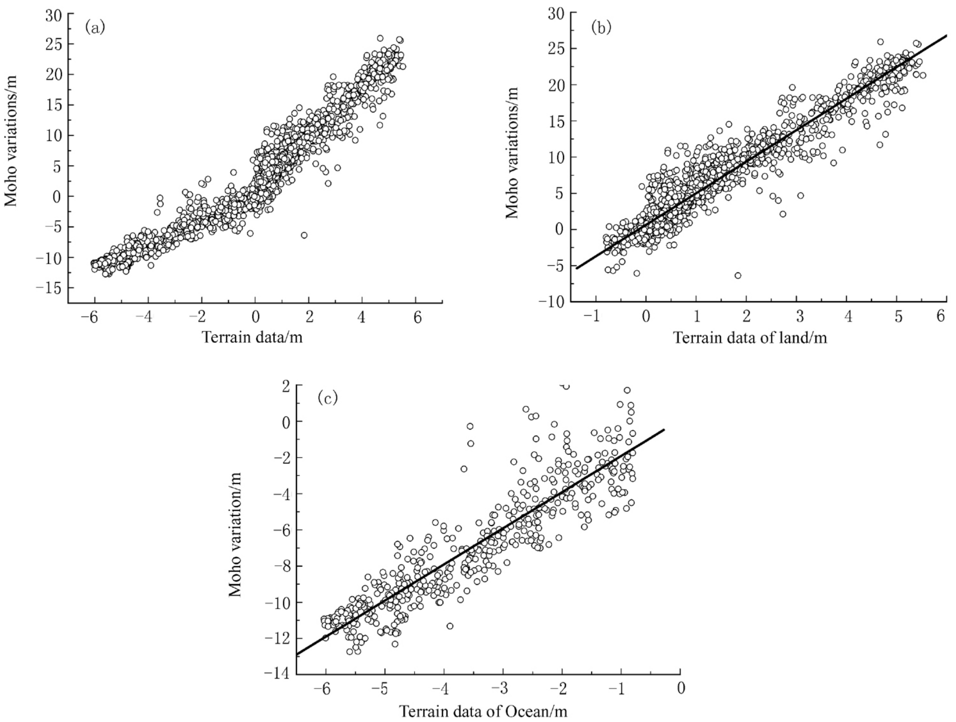

Figure 3 Correlation between topography fluctuation and Moho depth variation
(a) Correlation of the data for the whole studied region; (b) Correlation of the data for the continental region; (c) Correlation of the data for the oceanic region

From this result we can infer that the reference depth selected for the regions with different topography should be different. Following the Airy isostasy model we give the formula of calculating the reference depth D (in km) with the topography elevation (h) correction term as follows:

For whole studied region $D=(k-1)h+30$

For continental region $D=3.4h+30$
For oceanic region $D=1.0h+30$.

3 Crust thickness of China

Using the above analysis we have obtained the crust thickness of China and its adjacent region, as shown in Figure 4. The crust thickness deduced for the whole region is given in Figure 4a, while that deduced for 4 sub-regions, and then integrated into one, is presented in Figure 4b. In the sub-region map integration, for the sub-region DL (70°E~110°E, 15°N~35°N) the effective region is taken as (70°E~105°E, 15°N~33°N), for DR (100°E~140°E, 15°N~35°N) it is (105°E~140°E, 15°N~33°N), for UL (70°E~110°E, 30°N~50°N) it is (70°E~105°E, 33°N~50°N), and for UR (100°E~140°E, 30°N~50°N) the effective region is (105°E~140°E, 33°N~50°N).

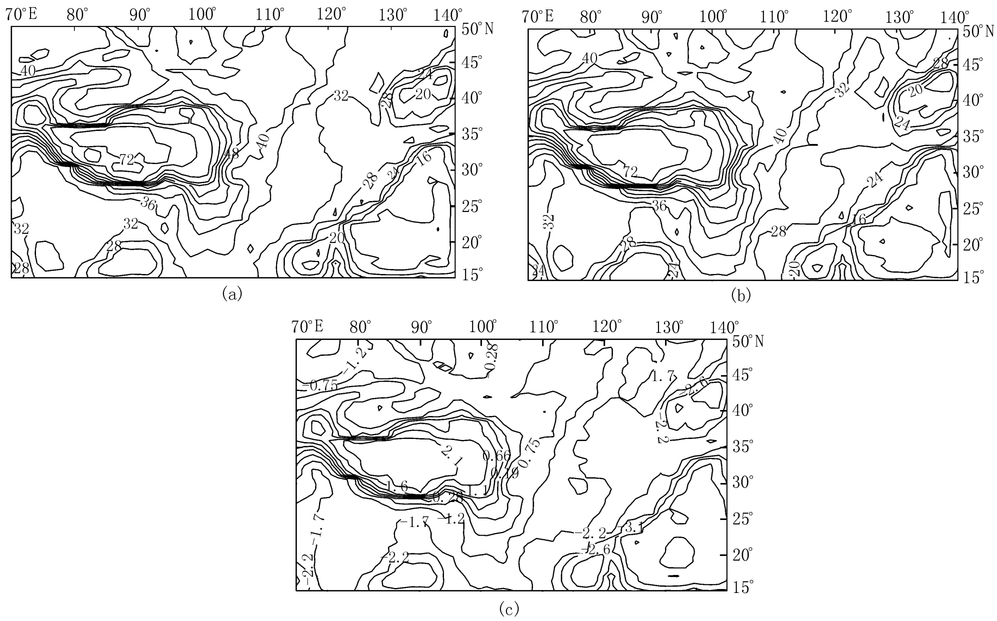

Figure 4 Crust thickness found for the whole region (a); Crust thickness obtained by integrating 4 sub-region results (b); Difference between the thickness for whole region and that for sub-regions (c)
The unit of isolines are km

To estimate the deviation between the two region approaches, we calculated the crust thickness difference between the results obtained for whole region and for sub-regions. The calculated difference is shown in Figure 4c, from which we can see that the thickness bias for most area of this study is within ±3 km and such bias should be acceptable. However, for the mountain and sea trench region, like the Qinghai-Xizang Plateau region, where complete gravity isostasy has not been reached, the bias can be up to ±5 km. This regional bias difference may be explained as that for the whole region we have analyzed the long wavelength data, which reflect a global gravity isostasy in a large region, while for sub-regions we used relatively short wavelength data, which may involve the information of local non-isostasy. For stable crustal blocks with less vertical movement, *e.g.*, the southeastern China block and Tarim basin, the difference between the two thickness results is insignificant. While for the orogenic belt and the boundary zone between land and sea, where vertical movement is remarkable, the difference is notable.

From Figure 4a and 4b we can see that the overall map feature is that the crust is thin in the east, even thinner in the eastern sea region, while it gets thicker as going from east to west. For most Qinghai-Xizang Plateau region the crust is significantly thick, in some region reaching to 78 km. At the same time, in Da Hinggan Ling mountain belt and the region surrounding the Qinghai-Xizang Plateau we see dense isolines, indicating strong variation of crust thickness there. The crust thickness only shows gentle variation in the region of Inner Mongolia, Northeast China plain and Central China, where crust deformation is relatively weak.

It is particularly noteworthy that on the southern margin of the Qinghai-Xizang Plateau, where the Indian plate meets the Eurasia, the crust thickness varies sharply, with a depth change up to 15 km. In the narrow boundary zone between the Qinghai-Xizang Plateau and the Tarim basin the crust thickness also changes dramatically. The crust thickness and the gravity data show a clear linear correlation, as illustrated in Figure 5, with a correlation coefficient of −0.993 and a standard deviation of 0.90 km. Totally 2 856 data are used in the correlation analysis.

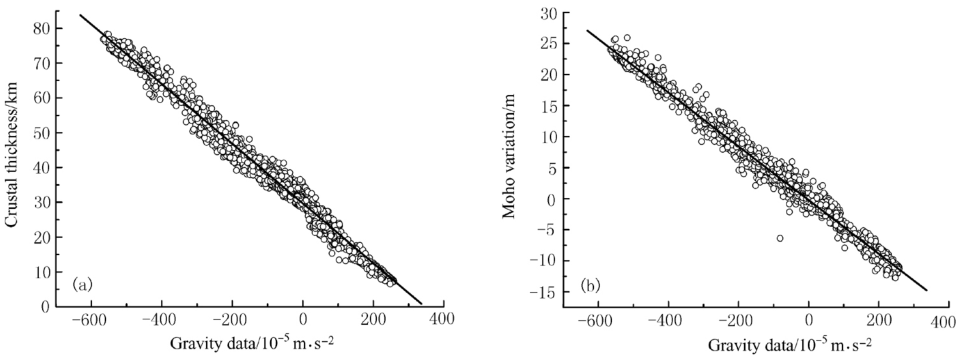

Figure 5 Correlation between crust thickness and gravity data (a), and between Moho depth and gravity data (b)

The crust thickness of China and its adjacent region found in this study generally agrees with the result deduced from the Yadong-Golmud DSS profile (ZENG *et al*, 1998), the Maqin-Lanzhou-Jinbian DSS profile (LI *et al*, 2002), the Zhubalong-Zizhong DSS profile (WANG *et al*, 2003), and the Beijing-Huailai-Fengzhen DSS profile (ZHU *et al*, 1997). The comparison of our result with that from the above 4 profiles is shown in Figure 6. The thickness difference between our result and that from seismic profiles is mostly less than 3 km. Only at a few individual data points appears large difference, which is probably due to the uncertain seismic observations.

4 Discussion and conclusions

In this article we have inverted the gravity and topography data to find the crust thickness of China and its adjacent region. Based on the topography data we corrected the reference crust depth for various regions, and hence reduced the uncertainty in derived crust thickness. We have acquired the following results:

1) Based on the gravity isostasy hypothesis and gravity observations we have obtained the crust thickness of China and its adjacent region. The uncertainty of the result is reduced by using

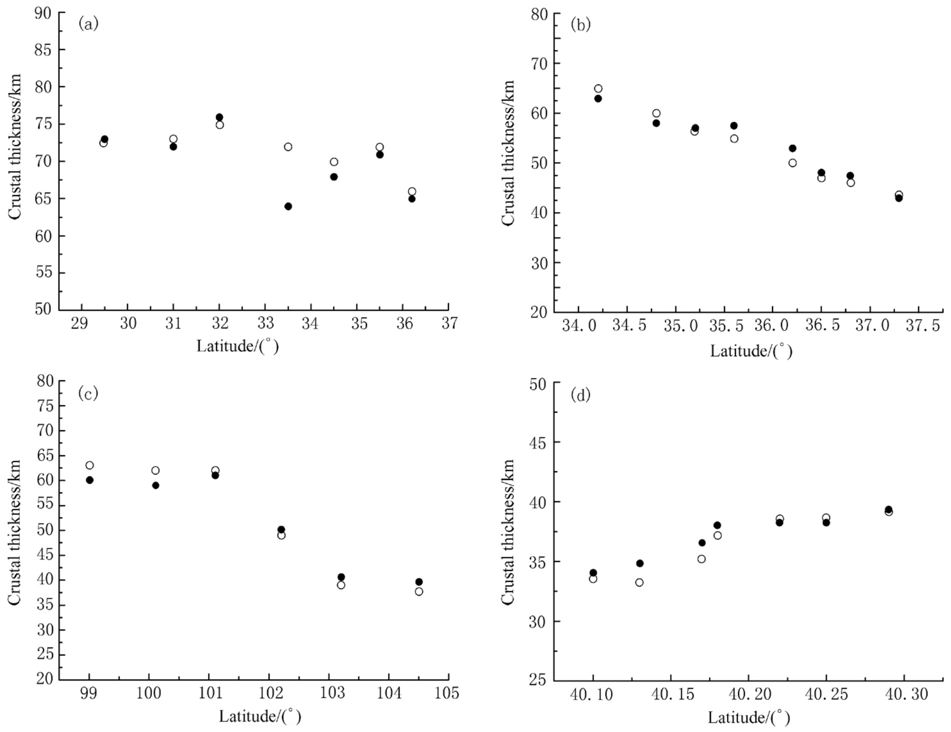

Figure 6 Comparison between the crust thickness obtained in this study (o) and that deduced from DSS profiles (•)

(a) Comparison with Yadong-Golmud DSS profile result; (b) Comparison with Maqin- Lanzhou-Jinbian DSS profile result; (c) Comparison with Zhubalong-Zizhong DSS profile result; (d) Comparison with Beijing-Huailai-Fengzhen DSS profile result

additional topography data.

2) To examine the influence of Earth′s surface curvature on the deduced crust thickness we have tested two models: inversion of the data for whole studied region and inversion for 4 sub-regions. The depth differences between the two model results are less than 3 km.

3) From Figures 3a, 3b and 3c we can easily find the isostasy coefficient k=4.36 for the continental region, with a correlation coefficient of 0.96, and the isostasy coefficient k=2.00 for the oceanic region, with a correlation coefficient of 0.91. The boundary between the continental and oceanic region is generally along the −800 m isoline below the water level.

We recognize that our inversion is based on the gravity isostasy hypothesis. Some regions, such as the plate boundary zone and the volcano activity region, may not be in a state of gravity isostasy. For such regions the inversion result may show some deviation from the real crust thickness. For these regions we need additional information from seismic data. This is the limitation in using our method and further improvement should be made in the future.

It should be pointed out that the correlation between the gravity data and the deduced crust thickness is obtained only for the region we studied, and this result may not be valid for other regions in the world. The isostasy coefficient and the correlation coefficient may be region dependent. Although the uncertainty and non-uniqueness in the inversion result have been reduced in this study, we need to make a comprehensive and multidiscipline analysis of different data, especially the seismic data, to deduce the crust thickness.

Acknowledgments We would like to thank the CAS geodesy and geodynamics laboratory (Wuhan) for providing us the Bouguer gravity anomaly data. We also thank Professor WANG Yong, XIONG Xiong and XU Jian-qiao for their thoughtful reviews on this article. The authors are grateful to the editor and the anonymous reviewers for their valuable comments.

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