The gravity and isostatic Moho in North China Craton and their implications to seismicity

Yangfan Deng · Weiming Fan · Zhongjie Zhang · Kai Liang

Received: 2 August 2013 / Accepted: 13 September 2013 / Published online: 20 November 2013

© The Seismological Society of China, Institute of Geophysics, China Earthquake Administration, and Springer-Verlag Berlin Heidelberg 2013

Abstract The Bouguer gravity is the combination of field sources in different depths. Based on the multi-scale analysis of the Bouguer gravity, we can get the gravity anomaly caused by the Moho undulation. This study presents the various orders of approximation of gravity anomaly in North China Craton (NCC), the possible source depths with radial logarithmic power spectrum, and the relationship between the deep structure and gravity anomaly. Furthermore, we discuss the isostatic compensation about the Moho depth from gravity and deep seismic sounding profiles (DSS). The results show that: (1) the fourth approximation could have resulted from the Moho undulation, (2) in contrast to the isostatic Moho, the inverted gravity Moho and the DSS Moho show that most of NCC has been isostatically compensated, and (3) the isostatic compensation rate has some close relation to the seismicity.

Keywords Multi-scale analysis · North China Craton · Gravity Moho · Compensation rate · Seismicity

Zhongjie Zhang (1964–2013)

Y. Deng · W. Fan
Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China

Y. Deng (✉) · Z. Zhang
State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
e-mail: dengyangfan@mail.iggcas.ac.cn

K. Liang
China University of Petroleum (Hua Dong),
Qingdao 266580, China

1 Introduction

The North China Craton (NCC) is characterized by a thick, diamond-bearing lithospheric keel, and behaved as a stable lithospheric block throughout the Proterozoic and Palaeozoic (Albee and Cullins 1975; Kusky et al. 2003; Rogers and Santosh 2004). It is located on the eastern margin of Asia, and is composed of east block, west block, and middle belt, whose elevation corresponds to plain, plateau, and orogen, respectively (Fig. 1). Resultantly, they collided to form a unified whole at early Proterozoic (Zhao et al. 2001, 2003, 2005). During the Mesozoic, the eastern part of the NCC experienced the effects of tectonic activity, as evidenced by voluminous magmatism and widespread deformation (Liu et al. 1992; Fan et al. 2000, 2007; Deng et al. 2012; Wu et al. 2003, 2005; Zhang et al. 2003, 2012; Zhao et al. 2003; Huang and Zhao 2004; Zhai et al. 2007; Xu et al. 2008; Kusky 2011; Meng et al. 2011; Zheng et al. 2001, 2006). At present, the NCC is affected by the removal of a layer of lithospheric material 80–100-km thick (Menzies et al. 2007; Fan et al. 2000; Chen et al. 2008; Zhu and Zheng 2009), and the lithosphere of the eastern part of the NCC can now be classified as transitional (Zhang et al. 2003; Menzies et al. 2007; Wang et al. 2009a, b).

It is supposed that the Archean NCC experienced tectonothermal reactivation during the Mesozoic, resulting in widespread calc-alkaline magmatism (Menzies and Xu 1998; Xu et al. 2004). At the end of this event, numerous basins have surged up, and the faults widely developed (mainly in NNE direction; Fang et al. 2002), which resulted that the seismicity is strong in NCC; such as the Tangshan earthquake (M_s 7.8) occurred at 1976, at least 240,000 people died and 85 % of the buildings fell collapsed (La et al. 2006; Zhong and Shi 2012), as well as Xingtai earthquake (M_s 6.8) occurred at 1966 (Teng et al. 1975; Zhu et al. 1995), the Haicheng earthquake (M_s 7.3)

Fig. 1 The simplified tectonic map of NCC. The brown line is the boundary of the NCC, which is further subdivided into three parts: western block (WCNN), central orogenic belt (CNCC), and eastern block (ENCC) by two black lines (Zhao et al. 2001, 2003). Inset map shows geographic position of the NCC in China mainland (Zhang et al. 2011b). The fault belts are outlined in white and the boundaries of political provinces are shown by continuous black lines, QDOB Qinling-Dabie orogenic belt, YSOB the Yanshan orogenic belt

occurred at 1975 (Jin and Aki 1986), and the Pinggu earthquake (M_s 8.0) occurred at 1679 (Liu et al. 2007).

Most studies on NCC are from geochemistry, tectonics, and seismology. However, both the seismic P- and S-wave velocities do not provide sufficient information about the density structure of the lithosphere (Mooney and Kaban 2010). The cratonic roots, which show positive S-wave velocities, offer a clear example of the ambiguity of the seismic models for determining lithospheric density. In this paper, to improve the analysis of the multi-scale decomposition of Bouguer gravity, we get the gravity anomaly caused by the Moho undulation; then, a gravity Moho map is displayed in contrast to the isostatic Moho. The compensate rate of the gravity Moho and the Moho from deep seismic sounding (DSS) profiles, as well as the relationship with the seismicity are also discussed.

2 Methods

The variation of the gravity field is the comprehensive reflection of inhomogeneous density at different depths. Therefore, one of the most common problems encountered in gravity data studies is how to separate them. There are four major methods to tackle this problem as smoothing, high level derivative, analytic continuation, and frequency

filter (Zeng 2005), which mean the filters in time domain or space domain to the gravity anomaly. But either in time domain or in space domain, they cannot express the detailed properties. The wavelet analysis, a kind of time-frequency analysis, widely used in signal processing, has recently been introduced in the realm of potential fields both as a filtering and a source-analysis tool. Because of overcoming the defect in frequency domain or in time domain only, wavelet method also has a wide application in potential field separation (Cheng and Zhang 2006; Hou and Yang 1997, 2011; Hou et al. 1998; Gao et al. 2000; Jiang et al. 2010; Yang et al. 2001).

2.1 Derivation of wavelet transform

Let $g(x)$ as a square integral function in L^2 space, filling the condition as follows (Li and Liu 1994):

$$\begin{cases} g(x) \in L^2 & \text{and} & G(w)|_{w=0} = 0, \\ \int_{-\infty}^{+\infty} \frac{|G(w)|^2}{|w|} dw < \infty, \end{cases} \quad (1)$$

($G(w)$ is the Fourier transform of $g(x)$).

So $g(x)$ is known as a basic wavelet or mother wavelet. We can get the wavelet basic function by extending and translating the $g(x)$, as $g_{a,b} = \frac{1}{\sqrt{|a|}} g\left(\frac{x-b}{a}\right)$, $a, b \in R$, $a \neq 0$, a is the scale function and b is location function.

The wavelet transform is

$$W_f(a, b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{+\infty} f(x) \overline{g\left(\frac{x-b}{a}\right)} dx. \quad (2)$$

The corresponding inverse transform is

$$f(x) = \frac{1}{c} \int_{-\infty}^{+\infty} db \int_{-\infty}^{+\infty} W_f(a, b) \overline{g\left(\frac{x-b}{a}\right)} \frac{da}{a^2}, \quad (3)$$

where

$$c = \int_{-\infty}^{+\infty} \frac{|G(w)|^2}{|w|} dw. \quad (4)$$

For (2), we regard $a = a_0^m$, $b = nb_0 a_0^m$, $a_0 > 1$, $b_0 > 1$, then the discrete form of wavelet transform is as follows:

$$W_f(m, n) = a_0^{-\frac{m}{2}} \int_{-\infty}^{+\infty} f(x) \overline{g(a_0^{-m}x - nb_0)} dx, \quad (5)$$

and

$$g_{mn}(x) = a_0^{-\frac{m}{2}} g(a_0^{-m}x - nb_0), \quad m, n \in Z. \quad (6)$$

Assume $a_0 = 2$, $b_0 = 1$ for special research.

Then

$$\begin{cases} g_{mn}(x) = 2^{-\frac{m}{2}} g(2^{-m}x - n), \\ W_f(m, n) = 2^{-\frac{m}{2}} \int_{-\infty}^{+\infty} f(x) \overline{g(2^{-m}x - n)} dx. \end{cases} \quad (7)$$

Assuming the scale function ϕ satisfies the condition:

$$\begin{cases} \int_{-\infty}^{+\infty} \phi(x) dx = 1, \\ \phi_{mn}(x) = 2^{-\frac{m}{2}} \phi(2^{-m}x - n) \perp g_{m'n'}, \text{ when } n \neq n', m \neq m'. \end{cases} \quad (8)$$

and $f(x)$ can be deduced as

$$\begin{aligned} f(x) = & \sum_{n=-\infty}^{\infty} W_f(0, n) \phi_{0n}(x - n) \\ & + \sum_{m=0}^{\infty} \sum_{n=-\infty}^{\infty} W_f(m, n) g_{mn}(x). \end{aligned} \quad (9)$$

The first part is the approximation of $f(x)$, and the second part stands for the detail; refer to the Mallat algorithm (1989).

The most popular wavelets in the data process are Haar, Daubechies, coif, bior, and sym2. Not all the wavelets are fit for the potential data processing. Compared with the property of orthogonal, symmetry, regularity, and vanishing moment, Li et al. (2001) found that the boir3.5 has remarkable advantages over Haar, bd, and binl wavelet. Thus, in this paper we use the boir3.5 wavelet.

2.2 The theory of radial logarithm spectrum power

One of important issues in researching the gravity data is the estimation of the average depth of anomaly constructions, which was originally proposed in the 1970s with the power spectrum (Naidu 1970). Cianciara and Marcak (1976) gave the connection between the radial logarithm and source depth. Later, the theory about this made great progress. Likewise, the statistical relationship between the radial logarithm spectrum and source depth was obtained (Lou and Wang 2005; Yang et al. 2001; Qiu et al. 2007). Now we reorganize and list the theory process.

First, the anomaly structure fills the two-dimensional (2D) Laplace equation. $g(x_j, z)$ is the gravity anomaly of grid point x_j ($j = 1, 2, \dots, n$) in elevation z . The solution of 2D Laplace equation is as follows:

$$g(x_j, z) = \sum_{j=0}^{n-1} A_k e^{i2\pi k x_j} e^{2\pi k z}, \quad (10)$$

the wave number $k = 1/\lambda$, A_k is the amplitude of spectral coefficients, so the inverse Fourier transform is:

$$A_k = \sum_{j=0}^{n-1} g(x_j, z) e^{-i2\pi k x_j} e^{\pm 2\pi k z}. \quad (11)$$

When $z = 0$, then

$$(A_k)_0 = \sum_{j=0}^{n-1} g(x_j, 0) e^{-i2\pi k x_j}. \quad (12)$$

Taking the (12) into (11), and

$$A_k = (A_k)_0 e^{\pm 2\pi k z}. \quad (13)$$

and the logarithm P_k

$$P_k = A_k^2 = (P_k)_0 e^{\pm 4\pi k z}. \quad (14)$$

Taking logarithmic we can get

$$\ln(P_k) = \ln(A_k^2) = \ln((P_k)_0) \pm 4\pi k z. \quad (15)$$

So $h = \frac{\Delta P}{4\pi \Delta k}$, if consider $w = 2 \times \pi$ and then

$$h = \frac{\Delta P}{2\Delta w}. \quad (16)$$

Let P as the power spectrum, and u and v is the length and width, respectively, $s = \sqrt{u^2 + v^2}$, and $u = s \cos \theta$, $v = s \sin \theta$, then radial spectrum is

$$R(s) = \frac{1}{2\pi} \int_0^{2\pi} P(s \cos \theta + s \sin \theta) d\theta, \quad (17)$$

which stands for the average of the power spectrum along arbitrary direction.

From the discussion above, as long as we know the relationship of power spectrum and wave number, the source depth can be known.

Fig. 2 Bouguer gravity anomaly in NCC

Fig. 3 The relationship between the radial logarithm power of the details and the wave number. **a** The second detail, **b** the fourth detail, **c** the sixth detail, and **d** the eighth detail

3 Data processing

3.1 The original Bouguer gravity anomaly

The starting data of Bouguer gravity with reference to the study region were taken from the Earth Gravitational Model 2008 proposed by Pavlis et al. (2008, 2012), which provides information on a $2.5' \times 2.5'$ sized grid displayed both inland and on the ocean, including synthetic gravity generated by GRACE and terrestrial gravity anomaly. The standard deviation of the field data is less than 5 mGal in the study region (Pavlis et al. 2008).

The Bouguer gravity sums all density changes due to the non-homogeneous structure of the crust caused by different geological formations, shallow deposits of materials, and

the undulation or dipping of the layers (Wang et al. 2003; Zeng 2005). In NCC, small positive gravity anomalies (<40 mGal) are confined to regions near the coastal areas (Fig. 2). On a larger scale, negative gravity anomalies (around -240 to -80 mGal) are distributed widely in the central and western NCC. In the west of Qinling-Dabie orogenic belt (QDOB), the Bouguer gravity increases progressively westward to more negative values reaching up to -260 mGal. In the Yanshan orogenic belt (YSOB), the Bouguer gravity has the larger negative value compared with the surrounding area. Thus, it can be summarized that the region with lower gravity data is characterized with the higher elevation. Another important feature is that the threads of the gravity isograms are always in NE–SW direction. While, other direct information related to the

Fig. 4 The approximations of Bouguer gravity. **a** The second approximation, **b** the fourth approximation, **c** the sixth approximation, and **d** the eighth approximation

faults and boundaries separating the tectonic units cannot be observed clearly in the study area.

3.2 The relation between logarithm power spectrum and source depth

As the multi-scale analysis method described above, the logarithm power spectrum and the asymptotes are shown in Fig. 3. According to the formula (16) we can calculate that the field source caused the second order detail in the depth of 10–15, 30–40 km caused the fourth order,

60–70 km caused the sixth order, and 120–140 km caused the 8th detail. As a supplementary specification, the depths are the average control effect of the whole NCC, and if we divided the NCC into three parts as west, center, and east, we can get different field source depths, respectively.

3.3 The multi-scales of Bouguer gravity

Decomposing the measured gravity, we can get different scales of approximation and detail (Hou et al. 1998; Lou

and Wang 2005). Figure 4a–d correspond to the two, four, six, and eight order approximation, respectively. Through the analysis and comparison, the second order approximation has the biggest similarity with the measured gravity anomaly. Though the fourth order approximation is different with the measured gravity, the trend of the NE–SW direction of the isograms is retained. As the asymptotes are shown in Fig. 3, we know that this approximation gravity is caused by the Moho undulation, so the Moho depth could be inverted, which will be discussed in the next part. The sixth and eighth order approximation have the same trend, but with some discrepancy in value, perhaps these features are the reflection of the anomaly generated by deeper interface.

4 Discussion

4.1 The inverted gravity Moho

The Parker–Oldenburg (Oldenburg 1974) iterative method has been widely used in potential field. According to the description about this method, we can inverse the gravity Moho with the fourth gravity approximation (Yao et al. 2003, 2007), reference depth 37 km (average Moho depth from DSSs) and density contrast 0.35 g/cm^3 , as shown in Fig. 5a. The Moho relief in NCC gradually uplifts from west to east. Bohai Bay Basin has the lowest Moho depth with 30 km, while west of Ordos Basin has the depth of about 45 km. Along the NE direction there is an obvious Moho gradient belt. The feature presented from the gravity Moho is similar with the fourth approximation of Bouguer gravity.

4.2 Isostatic compensation in NCC

The compensation required by isostasy can be accomplished in several ways, and the most popular accepted one is the Airy isostasy theory, in which the sinking of the Moho is considered to be resulted by the excessive topographical mass loading (Watts 2001; Wang et al. 2003). From the Airy isostatic theory, the topography has close connection with Moho depth, and the compensation percentage plays great role in the geologic background (Wang et al. 2009a, b).

By comparing the topography (t) (from Gtopo30 with grid $0.25^\circ \times 0.25^\circ$) and gravity Moho (m), we get the relationship $m = 31.3 + 0.0078 \times t$ by the least-squares linear regression (Braitenberg et al. 2000), shown in Fig. 5b. It is seen that the gravity Moho depth of 31.3 km corresponds to the zero-topography, which is consistent with the results derived from DSS profile in Qinghuangdao (Zhang et al. 2002), so according to the Airy isostatic model

$$\rho_c(H + t) = \rho_m t,$$

$$t = \left(\frac{\rho_c}{\rho_m} - \rho_c \right) H.$$

If we consider $\rho_c = 2.7 \text{ g/cm}^3$, $\rho_m = 3.3 \text{ g/cm}^3$, then we can get $t = 4.5H$.

The isostatic Moho $D = T + t$ (T is the standard isostatic Moho (in km), t is root (in km), H is topography (in km); Wang et al. 2003; Zhang et al. 2010); and 31.3 km could be the standard isostatic Moho. Herein the isostatic Moho can be obtained by $D = 31.3 + 4.5 \times H$, as shown in Fig. 6a.

In contrast to the error from the gravity inversion, we also take consideration of the DSS Moho. According to the

Fig. 5 **a** The gravity Moho and **b** scatterplot of gravity Moho and topography with regression red line

Fig. 6 **a** The isostatic Moho, **b** the Moho from deep seismic sounding profiles (DSS; Zhang et al. 2011a; Teng et al. 2013), **c** compensation rate of the gravity Moho, and **d** compensation rate of the DSS Moho

DSSs since 1970s, Zhao and Xu (2009) received the Moho depth in east China and Zhang et al. (2011b) got the whole China Moho depth including this area. Now we collect 25 DSS profiles and interpolate the Moho depth with kriging method (Zhang et al. 2011c). Figure 6b shows the Moho depth and the Bouguer gravity. The Moho depth from DSS profiles is similar to the gravity Moho and has a better resolution than gravity Moho depth where the profiles cross, so we can provide a contrast between the gravity Moho and DSS Moho.

The isostatic compensation percentage is defined as the percentage of the gravity Moho or DSS Moho–isostatic Moho with respect to the gravity Moho. The positive value is equivalent to the gravity Moho and is deeper than the

isostatic Moho depth, just as overcompensation, while the negative value has the opposite means. As shown in Fig. 6c, d, most of the NCC is isostatically compensated, the value being -10% to 10% . The overcompensation area is located in the west of NCC, and the under-compensation is in the east of NCC, the largest un-compensation amplitude is about 20% .

The un-isostatic area will cause material to vertically move in the lithosphere and the relatively geodynamics phenomenon come into being (Wang et al. 2009a, b). Where the gravity Moho is deeper than the isostatic Moho, the elevation in this region should rise, leading the topography higher and isostatic Moho deeper in order to keep isostatic. This process could cause the strong tectonic

Fig. 7 The relationship between the seismicity and compensation rate. **a** Compensation rate of the gravity Moho and **b** compensation rate of the DSS Moho. The circles stand for the earthquake $M_L > 4$ (from 1980 to 2010, edited by China Earthquake Network Center)

Fig. 8 The relationship between the compensation rate and the earthquakes ($M_L > 4$) along latitude 37°N . The green shaded area stands for the region where earthquakes occur relatively frequently

movement, such as earthquakes. So in the next part we will talk about the relationship between seismicity and compensation rate.

4.3 The relationship between compensation rate and seismicity

The continental crust has experienced the horizontal and vertical directions migration and adjustment in the long process of development, and gradually tends to a steady state. As the isostatic Moho is close to the observed Moho, there is little material and energy exchange, migration and adjustment below this region; while, if there is a large discrepancy between the isostatic Moho and the observed Moho, it indicates that the crust is in the non-isostatic status, and the larger discrepancy would lead the stronger movement of the material and energy (Zhang

et al. 2010, 2013a, b). In previous studies, the non-isostatic area is suggested to the main zone where strong earthquakes occur frequently, and the steep compensation rate gradient belt is the place that is worth more attention concerning earthquake prediction (Wang et al. 2008; Zhang et al. 2010). Now, we project the earthquakes ($M_L > 4$) from 1980 to 2010 on the compensation rate map, as shown in Fig. 7.

The earthquakes occurred always in the area which is between the non-compensation and compensation status. While, though the non-compensation is up to 20 % in the northwest and southwest region, the earthquakes are little.

These results could be confirmed with the presentation of the compensation rate and the earthquakes along latitude 37°N (Fig. 8). The earthquakes occurred at the position where the edges are between the non-compensation and compensation status (the green shaded area), while in the

non-compensation interior (106–111°N) or compensation region (115–117°N), the earthquakes are relatively little.

5 Conclusions

The Bouguer gravity sums all density changes due to the non-homogeneous structure of the crust caused by different geological formations, shallow deposits of materials, and the undulation or dipping of the layers. The wavelet transform operator has recently been introduced in the domain of potential fields both as a filtering and a source-analysis tool. Here we study the multi-scale decomposition on the Bouguer gravity based on wavelet analysis and power spectrum; analyze the gravity Moho, isostatic Moho, and compensation; discuss the relationship between compensation rate and seismicity. The result shows:

- (1) The fourth approximation of the gravity reflects the Moho relief. An inverted gravity Moho map presented similar to the DSS Moho.
- (2) By comparison with the isostatic Moho, most of NCC has been isostatically compensated.
- (3) Based on the study in this and previous paper, we suggest that the isostatic compensation has close relation to the seismicity.

Acknowledgments The study was supported financially by the National Nature Science Foundation of China (41021063, 41004017). We appreciate the fruitful discussions with Professor Wang Qianshen and Doctor Zhang Yongqian.

References

- Albee HF, Cullins HL (1975) Geologic map of the Alpine Quadrangle, Bonneville County, Idaho, and Lincoln County Wyoming. United States Geological Survey Geologic Quadrangle Map GQ-1259, scale 1:24,000
- Braitenberg C, Zadro M, Fang J, Wang Y, Hsu H (2000) The gravity and isostatic Moho undulations in Qinghai-Tibet plateau. *J Geodyn* 30(5):489–505
- Chen CH, Lee CY, Shinjo R (2008) Was there Jurassic Paleo-Pacific subduction in South China? Constraints from 40Ar/39Ar dating, elemental and Sr–Nd–Pb isotopic geochemistry of the Mesozoic basalts. *Lithos* 106(1):83–92
- Cheng S, Zhang J (2006) The view of the spectral analysis method of gravity potential field. *Prog Geophys* 21(4):1113–1119 (in Chinese with English abstract)
- Cianciara B, Marcak H (1976) Interpretation of gravity anomalies by means of local power SPECTRA*. *Geophys Prospect* 24(2):273–286
- Deng Y, Fan W, Zhang Z, Badal J (2012) Geophysical evidence on segmentation of the Tancheng–Lujiang fault and its implications on the lithosphere evolution in East China. *J Asian Earth Sci*. doi:10.1016/j.jseas.2012.11.006
- Fan WM, Zhang HF, Baker J, Davis KE, Mason PRD, Menzies MA (2000) On and off the North China Craton: where is the Archean keel? *J Petrol* 41:933–950
- Fan WM, Guo F, Wang YJ, Zhang HF (2007) Late Mesozoic mafic magmatism from the North China Block: constraints on chemical and isotopic heterogeneity of the subcontinental lithospheric mantle. In: Zhai MG, Windley BF, Kusky TM, Meng QR (eds) Mesozoic sub-continental lithospheric thinning under eastern Asia. Geological Society, London, Special Publications, vol 280, pp 77–100. doi:10.1144/SP280.40305-8719/07
- Fang SM, Zhang XK, Jia SX, Duan YH, Yang ZX, Qiu SY (2002) Multi-scale decomposition of Bouguer gravity anomaly and seismic activity in north China. *J Geodesy Geodyn* 22(1):34–39 (in Chinese with English abstract)
- Gao DZ, Hou ZZ, Tang J (2000) Multiscale analysis of gravity anomalies on East China Sea and adjacent regions. *Chin J Geophys* 43(6):842–849 (in Chinese with English abstract)
- Hou ZZ, Yang WC (1997) Wavelet transform and multi-scale analysis on gravity anomalies of China. *Chin J Geophys* 40(1):85–95 (in Chinese with English abstract)
- Hou ZZ, Yang WC (2011) Multi-scale inversion of density structure from gravity anomalies in Tarim Basin. *Sci China Earth Sci* 41(1):29–39 (in Chinese with English abstract)
- Hou ZZ, Yang WC, Liu JY (1998) Wavelet inversion of the density contrast within the crust of China. *Chin J Geophys* 41(5):651–656 (in Chinese with English abstract)
- Huang J, Zhao D (2004) Crustal heterogeneity and seismotectonics of the region around Beijing, China. *Tectonophysics* 385(1–4):159–180
- Jiang WL, Zhang JF, Jiao MM, Lu J (2010) Structure characteristics in the capital area using wavelet multi-scale method of Bouguer gravity anomaly. *Acta Geol Sin* 84(4):457–465 (in Chinese with English abstract)
- Jin A, Aki K (1986) Temporal change in coda Q before the Tangshan earthquake of 1976 and the Haicheng earthquake of 1975. *J Geophys Res* 91(B1):665–673
- Kusky TM (2011) Geophysical and geological tests of tectonic models of the North China Craton. *Gondwana Res* 20(1):26–35
- Kusky TM, Stern RJ, Tucker RD (2003) Evolution of East African and related orogens and the assembly of Gondwana. *Precamb Res* 123:81–85
- La XL, Sun Y, Liu Z (2006) Study of deep seismic sounding in strongly seismic regions of North China. *J Geodesy Geodyn* 26(1):55–62 (in Chinese with English abstract)
- Li SX, Liu JQ (1994) Wavelet transform and mathematics of inversion (in Chinese). Geological Publishing House, Beijing
- Li J, Zhou YX, Xu HP (2001) The selection of wavelet generating functions in data processing of gravity field. *Geophys Geochem Explor* 25(6):410–417 (in Chinese with English abstract)
- Liu DY, Nutman AP, Compston W, Wu JS, Shen QH (1992) Remnants of 3800 Ma crust in the Chinese part of the Sino-Korean Craton. *Geology* 20:339–342
- Liu BY, Shi BP, Zhang J (2007) Strong motion simulation by the composite source modeling: a case study of 1679 M 8.0 Sanhe-Pinggu earthquake. *Acta Seismol Sin* 20:319–331 (in Chinese with English abstract)
- Lou H, Wang CY (2005) Wavelet analysis and interpretation of gravity data in Sichuan–Yunnan region, China. *Acta Seismol Sin* 27(5):515–523 (in Chinese with English abstract)
- Mallat SG (1989) Multifrequency channel decompositions of images and wavelet models. *IEEE Trans Acoust Speech Signal Process* 37(12):2091–2110
- Meng Q, Wei H, Qu Y, Ma S (2011) Stratigraphic and sedimentary records of the rift to drift evolution of the northern North China Craton at the Paleo-to-Mesoproterozoic transition. *Gondwana Res* 20(1):205–218
- Menzies MA, Xu Y (1998) Geodynamics of the North China Craton. In: Flower MFJ, Chung SL, Lo CH, Lee TY (eds) Mantle dynamics and plate interactions in East Asia, vol 100. American

- Geophysical Union, Geodynamics Series, Washington, DC, pp 155–165
- Menzies MA, Xu YG, Zhang HF, Fan WM (2007) Integration of geology, geophysics and geochemistry: a key to understanding the North China Craton. *Lithos* 96:1–21
- Mooney WD, Kaban MK (2010) The North American upper mantle: density, composition, and evolution. *J Geophys Res* 115(12):B12424
- Naidu PS (1970) Statistical structure of aeromagnetic field. *Geophysics* 35:279
- Oldenburg DW (1974) The inversion and interpretation of gravity anomalies. *Geophysics* 39(4):526–536
- Pavlis NK, Holmes SA, Kenyon SC, Factor JK (2008) An earth gravitational model to degree 2160: EGM2008. Paper presented at General Assembly, European Geosciences Union, Vienna, pp 13–18
- Pavlis NK, Holmes SA, Kenyon SC, Factor JK (2012) The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). *J Geophys Res* 117(B4):B04406
- Qiu N, He ZX, Chang YJ (2007) Ability of improving gravity anomaly resolution based on multiresolution wavelet analysis and power spectrum analysis. *Prog Geophys* 22(1):112–120 (in Chinese with English abstract)
- Rogers JJW, Santosh M (2004) Continents and supercontinents. Oxford University Press, New York
- Teng JW, Wang GC, Liu DH, Hsing JR, Liang WD, Xu SL (1975) Crustal structure of the part of the north china plain and the Hsingtai earthquake (II). *Chin J Geophys (Acta Geophys Sin)* 18(3):196–207 (in Chinese with English abstract)
- Teng JW, Zhang Z, Zhang X, Wang C, Gao R, Yang B, Qiao Y, Deng Y (2013) Investigation of the Moho discontinuity beneath the Chinese mainland using deep seismic sounding profiles. *Tectonophysics*. doi:10.1016/j.tecto.2012.11.024
- Wang QS, An YL, Zhang CJ, Jiang FZ (2003) *Gravimetry*. Seismological Press, Beijing, pp 17–33
- Wang QS, Teng JW, Zhang YQ, Yang H (2008) The effect of crustal gravity isostasy and Wenchuan earthquake in Longmenshan faults and adjacent area. *Prog Geophys* 23(6):1664–1670 (in Chinese with English abstract)
- Wang QS, Teng JW, Zhang YQ, Zhang XM, Yang H (2009a) The crustal structure and gravity isostasy in the middle western Sichuan area. *Chin J Geophys* 52(2):579–583 (in Chinese with English abstract)
- Wang YJ, Zhang YZ, Zhao GC, Fan WM, Xiao XP, Zhang FF, Zhang AM (2009b) Zircon U–Pb geochronological and geochemical constraints on the petrogenesis of the Taishan sanukitoids (Shandong): implications for Neoproterozoic subduction in the Eastern Block, North China Craton. *Precamb Res* 174(3–4):273–286
- Watts AB (2001) *Isostasy and flexure of the lithosphere*. Cambridge University Press, Cambridge
- Wu FY, Walker RJ, Ren XW, Sun DY, Zhou XH (2003) Osmium isotopic constraints on the age of lithospheric mantle beneath northeastern China. *Chem Geol* 196:107–129
- Wu FY, Yang JH, Wilde SA, Zhang XO (2005) Geochronology, petrogenesis and tectonic implications of Jurassic granites in the Liaodong Peninsula, NE China. *Chem Geol* 221(1):127–156
- Xu YG, Ma JL, Huang XL, Iizuka Y, Chung SL, Wang YB, Wu XY (2004) Early Cretaceous gabbroic complex from Yanan, Shandong Province: petrogenesis and mantle domains beneath the North China Craton. *Int J Earth Sci* 93:1025–1041
- Xu YG, Blusztajn J, Ma JL, Suzuki K, Liu JF, Hart SR (2008) Late Archean to Early Proterozoic lithospheric mantle beneath the western North China Craton: Sr–Nd–Os isotopes of peridotite xenoliths from Yangyuan and Fansi. *Lithos* 102:25–42
- Yang WC, Shi ZQ, Hou ZZ, Cheng ZY (2001) Discrete wavelet transform for multiple decomposition of gravity anomalies. *Chin J Geophys* 44(4):534–541 (in Chinese with English abstract)
- Yao CL, Hao TY, Guan ZN, Zhang YW (2003) High speed computational and effective storage in 3-D gravity and magnetic inversion based on genetic algorithms. *Chin J Geophys* 46(2):252–258 (in Chinese with English abstract)
- Yao CL, Zheng YM, Zhang YW (2007) 3-D gravity and magnetic inversion for physical properties using stochastic subspaces. *Chin J Geophys* 50(5):1576–1583 (in Chinese with English abstract)
- Zeng HL (2005) *Gravity field and gravity exploration*. Geological Publishing House, Beijing
- Zhai MG, Windley BF, Kusky TM, Meng QR (eds) (2007) *Mesozoic subcontinental lithospheric thinning under eastern Asia*. Geological Society, London (Special Publications)
- Zhang CK, Zhang XK, Zhao JR, Ren QF, Zhang JS, Hai Y (2002) Study and review on crust-mantle velocity structure in Bohai Bay and its adjacent areas. *Acta Seismol Sin* 24(4):428–435 (in Chinese with English abstract)
- Zhang HF, Sun M, Zhou X, Zhou M, Fan W, Zheng J (2003) Secular evolution of the lithosphere beneath the eastern North China Craton: evidence from Mesozoic basalts and high-Mg andesites. *Geochim Cosmochim Acta* 67:4373–4387
- Zhang YQ, Teng JW, Wang QS (2010) The crustal isostatic anomaly beneath eastern Tibet and western Sichuan and its relationship with the distribution of earthquakes. *Chin J Geophys* 53(11):2631–2638 (in Chinese with English abstract)
- Zhang ZJ, Chen Q, Bai Z, Chen Y, Badal J (2011a) Crustal structure and extensional deformation of thinned lithosphere in Northern China. *Tectonophysics* 508(1–4):62–72
- Zhang ZJ, Yang LQ, Teng JW, Badal J (2011b) An overview of the earth crust under China. *Earth Sci Rev* 104(1–3):143–166
- Zhang ZJ, Deng YF, Teng JW, Wang CY, Gao R, Chen Y, Fan WM (2011c) An overview of the crustal structure of the Tibetan Plateau after 35 years of deep seismic soundings. *J Asian Earth Sci* 40(4):977–998
- Zhang ZJ, Wu J, Deng Y, Teng J, Zhang X, Chen Y, Panza G (2012) Lateral variation of the strength of lithosphere across the eastern North China Craton: new constraints on lithospheric disruption. *Gondwana Res* 22(3–4):1047–1059
- Zhang YQ, Teng J, Wang Q, Hu G (2013a) Density structure and isostatic state of the crust in the Longmenshan and adjacent areas. *Tectonophysics*. <http://dx.doi.org/10.1016/j.tecto.2013.08.018>
- Zhang ZJ, Wang Y, Deng Y, Chen L, Wu J, Teng J, Chen Y, Fan W, Panza G (2013b) Geophysical constraints on Mesozoic disruption of North China Craton by underplating-triggered lower-crust flow of the Archean lithosphere. *Terra Nova* 25(3):245–251
- Zhao ZX, Xu JR (2009) Three-dimensional crustal velocity structure of P-wave in East China from wide-angle reflection and refraction surveys. *Chin Sci Bull* 54(8):1389–1397
- Zhao G, Wilde SA, Cawood PA, Sun M (2001) Archean blocks and their boundaries in the North China Craton: lithological, geochemical, structural and P–T path constraints and tectonic evolution. *Precamb Res* 107:45–73
- Zhao GC, Sun M, Wilde SA, Li SZ (2003) Assembly, accretion and breakup of the Paleo–Mesoproterozoic Columbia supercontinent: records in the North China Craton. *Gondwana Res* 6(3):417–434
- Zhao G, Sun M, Wilde SA, Sanzhong L (2005) Late Archean to Paleoproterozoic evolution of the North China Craton: key issues revisited. *Precamb Res* 136(2):177–202
- Zheng JP, O'Reilly SY, Griffin WL, Lu FX, Zhang M, Pearson NJ (2001) Relict refractory mantle beneath the eastern North China block: significance for lithosphere evolution. *Lithos* 57:43–66
- Zheng JP, Griffin WL, O'Reilly SY (2006) Mineral chemistry of garnet peridotites from Paleozoic, Mesozoic and Cenozoic lithosphere: constraints on mantle evolution beneath Eastern China. *J Petrol* 47:2233–2256

- Zhong Q, Shi BP (2012) Aftershock duration of the 1976 Ms 7.8 Tangshan earthquake and implication for seismic hazard estimation. *Acta Seismol Sin* 34(4):494–508 (in Chinese with English abstract)
- Zhu RX, Zheng TY (2009) Destruction geodynamics and Paleoproterozoic plate tectonics of the North China Craton. *Chin Sci Bull* 54(14):1950–1961
- Zhu ZP, Zhang XK, Gai YJ, Zhang JS, Nie WY, Shi JH, Zhang CK, Ruan H (1995) Velocity structure of the crust and upper mantle in Xingtai earthquake region and its adjacent area. *Acta Seismol Sin* 17(3):328–334 (in Chinese with English abstract)