Three-dimensional density structure of the lithosphere beneath the North China Craton and the mechanisms of its destruction

Xinsheng Wang [a,b], Jian Fang [b,*], Houtse Hsu [b]

[a] National Earthquake Infrastructure Service, Beijing, 100045, China
[b] State Key Laboratory of Geodesy and Earth's Dynamics, Institute of Geodesy and Geophysics, CAS, Wuhan 430077, China

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ABSTRACT

The lithosphere beneath the North China Craton (NCC) has been thinning since the Phanerozoic. Previous geophysical studies on NCC structures have mainly focused on the results of seismic wave propagation. In this study, we obtained 3D density structures of the NCC lithosphere by using the sequential inversion of observed gravity data and P-wave travel times. Analyses of the resulting density model and discussions of the destruction of the NCC are provided. Our density model shows that distinct horizontal and vertical density heterogeneities exist throughout the lithosphere beneath the NCC; in the west of the craton, the Ordos block is characterised by a relatively uniform high-density lithospheric mantle, while laterally heterogeneous densities are observed at shallower than 100 km depth. Distinct low-density anomalies are imaged in the Cenozoic Yinchuan–Hetao and Shaanxi–Shanxi rifts surrounding the Ordos block. Comparing with the thinned lithosphere and high Poisson's ratio, the low density in the rifts may indicate partial melting induced by thermo-mechanical erosion. Predominantly low-density anomalies, which represent an upwelling of the asthenosphere, are revealed in the south of the Taihang orogen, as well as at the junction of the Yinshan–Yanshan orogen (near Datong volcano) and the Taihangshan orogen, from 100 to 200 km depth. This supports the hypothesis of thermo-mechanical erosion in these regions. High-density anomalies are visible at the base of the lithosphere or in the upper mantle beneath the central North China Basin. Combined with high velocities at 300 km depth indicated by seismic tomography, these high densities suggest that the lithospheric destruction of this region may not be explained by thermo-mechanical erosion, as there is no evidence of deep, hot upwelling that could support thermo-mechanical erosion.

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1. Introduction

A craton is generally considered to be a stable tectonic unit with a thick lithospheric root. However, part of the North China Craton (NCC) has lost its lithospheric keel (Menzies et al., 1993). Receiver function studies (Chen et al., 2008, 2009) have revealed thinned lithosphere in the eastern NCC (60–100 km depth) and the Yinchuan–Hetao and Fenwei rifts (up to 80 km depth) around the Ordos block. Additionally, the physical–chemical properties of the lithospheric mantle have been fundamentally transformed (Rudnick et al., 2004; Zheng et al., 2001; Zhu et al., 2011). Although consensus exists that the NCC lithosphere is being destroyed in recent time, questions regarding the destruction mechanism and dynamic factors remain controversial. At present, two mainstream destruction mechanisms are used to account for the destruction of the NCC: delamination of the lower crust and lithospheric mantle resulting from gravity instability (Deng et al., 2007) and thermo-mechanical erosion, in which the lowermost lithospheric mantle is gradually transformed into asthenosphere (Menzies et al., 1993; Zheng et al., 1998). Zhang (2005) suggested that the melting of peridotite is responsible for the lithospheric mantle through a study of the zoned structure of olivine xenocrysts/xenoliths entrained in the basalts. Cenozoic–Mesozoic mantle-derived magmas and their mantle xenoliths can provide direct information about lithospheric compositions and physical properties, as well as provide evidence of NCC lithospheric thinning. However, the limited spatial distribution of the samples has hindered further understanding of the destruction of the NCC (Zhu and Zheng, 2009). Geophysical observations provide high-resolution data that can be used to obtain refined images of the lithospheric structure. There have been many studies on the lithospheric structures of the NCC based on seismic velocities (Huang et al., 2009; Zhao et., 2009; Huang and Zhao, 2006; Sun and Toksöz, 2006; Sun et al., 2008; Tian et al., 2009; Zhang et al., 2011; Zheng et al., 2006, 2007), which have been used to identify velocity anomalies, interface depths, and crustal and mantle anisotropy. These results show clear lithospheric structure, but there are usually different results for the same region due to differing inversion methods and datasets. In contrast, there has been little research on the 3D lithospheric density structures beneath the NCC (Yan and Hou, 1996), which are fundamental to understanding

* Corresponding author at: 340 XuDong Rd. Wuhan 430077, Hubei, China.

lithospheric deformation. Refined 3D lithospheric density structures are important to the study of delamination, crust–mantle interaction and deep dynamic processes. In this paper, we obtain the 3D density structure of the NCC lithosphere.

Bouguer gravity is sensitive to lateral and vertical density variations, which allows the inversion of subsurface density structure using gravity data recorded at the surface. However, Bouguer gravity anomalies decrease rapidly with increasing source depth, and gravity inversion is highly non-unique. Seismic tomography can be used to obtain three-dimensional velocity models, but its resolution and accuracy depend on the distribution of seismic raypaths, especially in a near-surface region sampled by sub-vertical rays. The joint inversion of seismic and gravity data can provide an effective constraint for density inversion while preserving detailed lateral resolution. The following two types of methods are often used for datasets containing gravity and seismic data. The first method is a generalised joint inversion in which all data are inverted simultaneously, and the relative weights of the two types of data can be problematic (Lines et al., 1988). The second method is a sequential inversion in which each data type is inverted successively (Vernant et al., 2002). Joint inversions of gravity and seismic data have been used to study crustal and mantle velocity and density structures (Kuhn et al., 2002; Maceira and Ammon, 2009; Onizawa et al., 2002; Tiberi et al., 2003; Tondi et al., 2000, 2009; Vernant et al., 2002), and they provide better results than individual seismic or gravity inversions. As determining the proper relative weights of seismic and gravity data due to their differing accuracies and resolutions, we applied sequential inversion to obtain the density structure beneath the NCC lithosphere.

2. Data preparation

In this study, we inverted gravity data and seismic arrival times from local, regional and teleseismic earthquakes. Fig. 1 shows the topography and major geological features of our study region (modified from Chen et al., 2009). The dashed lines show the major fault zones and/or block boundaries.

2.1. Seismic data

The seismic data used are the same as those used in Tian et al. (2009): 149,054 P-wave travel times from 7940 local and regional events recorded by 585 seismic stations with picking accuracies of 0.1–0.2 s for most data and 193,085 teleseismic P-wave travel time residuals from 12,657 teleseismic events recorded by 285 stations (Fig. 2).

2.2. Gravity data

The original gravity dataset consists of 5′ × 5′ free-air gravity anomalies (Fig. 3). Bouguer gravity anomalies were obtained by applying terrain corrections to free-air gravity anomalies using GTOPO30 grid terrain data.

Gravity anomalies measured at the surface are the integrated response to interface undulations and subsurface density heterogeneities. Bouguer gravity anomalies mainly arise from a combination of the following sources: (1) density changes across the Moho; (2) density changes in deposits; (3) lateral density variations arising from
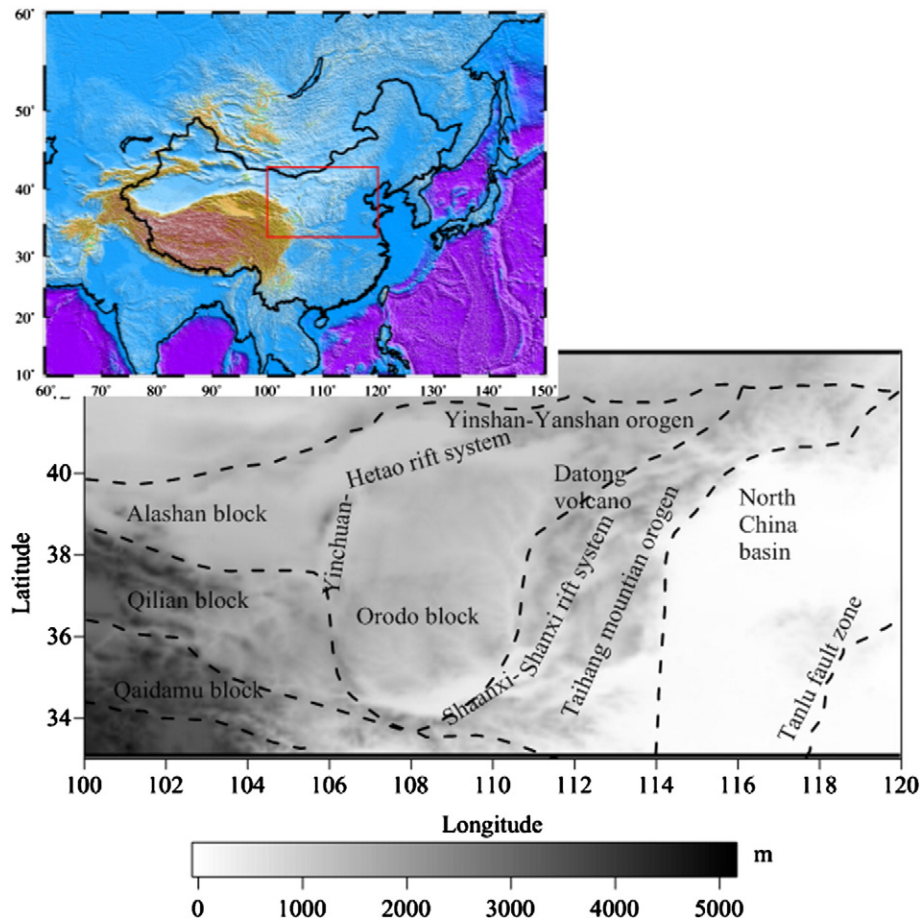

Fig. 1. Topography and major geological features of the study region. The dashed lines show the major fault zones and/or block boundaries. Modified from Chen et al. (2009).