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Electrical resistivity structure of the upper mantle beneath Northeastern China: Implications for rheology and the mechanism of craton destruction

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A B S T R A C T

The North China Craton (NCC) and Central Asian Orogen Belt (CAOB) in Northeastern China experienced a range of tectonic events during the Phanerozoic, dominated by lithospheric thinning of the eastern NCC in the late Mesozoic and Cenozoic. In order to better understand the tectonic evolution of the NCC and the CAOB, new broadband and long period magnetotelluric data were collected along a north-west to south-east trending profile that extended from the CAOB across the Yanshan Belt, the Tanlu Fault Zone to the Liaodong Peninsula. A two-dimensional (2-D) resistivity model was derived from inversion of the transverse electric mode, transverse magnetic mode and vertical magnetic field data.

In the crust of the CAOB, the resistivity model shows a northwest dipping low resistivity zone beneath the Solonker suture that is identified as the suture zone formed by the collision between the Siberian and North China cratons.

The upper mantle of the CAOB is characterized by moderate resistivity values (300–1000 Ω m) that are best explained by the presence of hydrogen dissolved in olivine. The water concentration of the CAOB mantle is comparable to values reported for the asthenosphere and cratons that have been significantly hydrated. The NCC upper mantle is generally lower in resistivity than the CAOB upper mantle, and a zone of lower resistivity is observed in the upper mantle at the southeast end of the profile beneath the NCC (<100 Ω m) which requires around 1% partial melt to account for the observed resistivity.

Superimposed on this southeast decrease in upper mantle resistivity, three low resistivity zones were imaged: (1) below the Xilamulun fault, (2) close to the North–South Gravity Lineament, and (3) between the northern Yanshan Belt and Tanlu Fault Zone. The low resistivities can be explained as regions of partial melts or fluids, perhaps caused by asthenospheric upwelling.

Together with seismic imaging results and geochemical data, the resistivity model shows that the modification of the lithosphere associated with craton destruction has occurred in a spatially non-uniform manner in the region of the NCC investigated in this study.

1. Introduction

Cratons are lithospheric blocks that have remained stable for billions of years, and their longevity has often been attributed to their buoyancy and rigidity. Recent research suggests that these factors may not be sufficient to prevent cratons being destroyed by mantle convection (O'Neill et al., 2008). It has been suggested that it is the low water content of cratonic lithosphere which causes the high strength and allows cratons to survive for billions of years (Peslier et al., 2010). Under certain circumstances, the cratonic lithosphere can be weakened and the craton destroyed. A key part of this process may be the hydration of the cratonic lithospheric upper mantle, which will lower the strength. This type of hydration is occurring today in the Southwest United States, where water was transported into the upper mantle by the subducted Farallon Plate (Li et al., 2008).

Another location where this process may be at work is beneath the eastern North China Craton (NCC). The westward subduction of the Pacific Plate resulted in the NCC being located within the back arc region of the subduction zone. Elevated back arc temperatures led to extensive magmatism and deformation (Niu, 2005; Wu et al., 2003, 2005; Xu et al., 2009; Zhang, 2009). Since the water content controls the strength of the lithospheric upper mantle, a study of

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craton destruction should use geophysical methods that can determine the water content of the mantle. Magnetotellurics is one such method and is used in this paper.

The lithosphere of the Northeastern NCC had a complex history prior to the onset of craton destruction. During the Late Permian to Early Triassic, the NCC was sutured to the Central Asian Orogenic Belt (CAOB) in the north along the Solonker suture zone (Xiao et al., 2003) (Fig. 1). After the collision, a phase of post-collisional extension took place and formed the Xilamulun tectonic–metallogenic belt (Zhang et al., 2009). Subduction of the Pacific Plate beneath Northeast China began in the Late Mesozoic and continues to the present (Kusky et al., 2007). Craton destruction began in the Mesozoic and continued into the Cenozoic, as the eastern NCC experienced significant thermo-tectonic reactivation which led to widespread lithospheric extension and magmatic activity (Windley et al., 2007). This reactivation process resulted in the lower part of the 200 km thick lithosphere being heated, removed and partially replaced by hot material to give a lithosphere that is only 60–80 km thick. It also changed the physical–chemical properties of the lithospheric mantle, as indicated by geochemical and petrological studies (Menzies et al., 1993; Griffin et al., 1998; Xu, 2001; Wu et al., 2006; Zheng et al., 2007a; Zhang et al., 2008). Deformation continues today, as evidenced by frequent intraplate earthquakes (China Earthquake Networks Center, 2013).

In recent years, seismic studies have been used to image the lithosphere of the NCC and investigate the present day structure (Chen et al., 2006, 2008, 2009, 2010; Chen, 2009, 2010; Zhang et al., 2007; Zheng et al., 2008, 2012; Tang and Chen, 2008; Huang et al., 2009; Li and Niu, 2010; Zhao et al., 2010; Xu et al., 2011; Wei et al., 2011; Li and He, 2011). Magnetotelluric (MT) data provide constraints on lithospheric composition that can complement those obtained from seismic studies, especially with regard to the presence of volatile phases (Hirth et al., 2000). This is important because even small amounts of water and partial melt can have profound impacts on the rheology of the crust and upper mantle. This paper describes a 1200 km NW–SE MT profile in NE China (Fig. 1) which includes the first long period magnetotelluric measurements made on the Northeastern NCC. The profile was collected to address some of the outstanding tectonic questions regarding the lithospheric structure and history of Northeast China including:

(1) What is the present day fluid distribution and rheology of the lithosphere beneath the CAOB and NCC? Resistivity models derived from MT data provide valuable constraints on the water content of the upper mantle (Selway, 2014) which in turn have a major influence on lithospheric strength.
(2) What does the present day structure imply about the mechanism by which lithospheric removal occurred during craton destruction?

2. Geological and geophysical background

2.1. Geological setting

Northeastern China consists of two major tectonic elements, the Central Asian Orogenic Belt (CAOB) in the north, and the North China Craton (NCC) in the south (Fig. 1).

The CAOB is approximately 300 km wide and located between the NCC and the Siberian Craton (Fig. 1). It is comprised of a number of Neoproterozoic–Phanerozoic accretionary complexes, and extends from the Altai Mountains in the west to eastern Siberia (Xiao et al., 2003). It was formed by north–south-directed subduction of the Paleo-Asian Ocean during the Paleozoic, which ultimately led to the suturing of the NCC to the southern edge of the CAOB. Most researchers favor a date in the late Permian to early Triassic for the terminal collision along the Solonker suture zone (Xiao et al., 2003; Miao et al., 2007; Windley et al., 2007). The Xilamulun Fault and Chifeng-Kaiyuan Fault are major litho-tectonic boundaries also formed during the closure of the Paleo-Asian Ocean (Zeng et al., 2011).

The North China Craton (NCC) is the oldest continental fragment in China. The Archean to Paleoproterozoic basement rocks are overlain by Mesoproterozoic to Cenozoic sedimentary cover (Liu et al., 1992; Zhao et al., 2003). The NCC is composed of two Archean continental blocks: the Eastern and Western blocks which have experienced very different geological histories, and are separated by the Paleoproterozoic Trans-North China Orogen (Zhao et al., 2001, 2005) (Fig. 1b). The Western Block has been stable since the early Proterozoic (1.85 Ga) with minor deformation since the end of the Paleozoic. In contrast, the Eastern Block has undergone significant tectonic changes during the Phanerozoic as described below. Since the Triassic, tectonic events have been focused in the Eastern Block of the NCC and have been dominated by the Mesozoic–Cenozoic craton destruction. This has resulted in a thinned lithospheric mantle, an increase in heat flow, widespread volcanism and formation of large-scale sedimentary basins (Griffin et al., 1998; Fan et al., 2000; Zhou et al., 2002). It has generated two major geological and geophysical lineaments:

(1) The NNE striking North–South Gravity Lineament (NSGL) is a remarkable feature, that is 100 km wide and extends over 3500 km in a N–S direction across most of eastern China and traverses the NCC (Fig. 1). Within the NCC, the NSGL separates areas to the west that have negative Bouguer anomalies, low heat flow, high mantle seismic velocities, thicker lithosphere and mountainous topography, from low-lying areas to the east that have zero to slightly positive gravity anomalies, high heat flow, lower mantle seismic velocities, thinner lithosphere (Xu, 2007; Windley et al., 2007).
(2) The Tanlu Fault Zone (TLFZ) is a major strike-slip fault zone that bisects the eastern NCC. It is up to 500 km wide and extends from the Yangtze River to the Russian Far East. The TLFZ has accumulated over 700 km of left-lateral offset, mostly during the Cretaceous (Xu et al., 1987; Xu and Zhu, 1994). Motion on the TLFZ may be related to asthenospheric upwelling and lithospheric reactivation of the eastern NCC since the Mesozoic (Zheng et al., 1998; Xu et al., 2004; Chen et al., 2006). Over 1000 earthquakes with magnitude Ms > 2.0 have occurred on the northern TLFZ since the 1950s (Fig. 2). The largest recent earthquake was the left lateral Ms = 7.3 1975 Haicheng earthquake (China Earthquake Networks, 2013; Cipar, 1979).

2.2. Previous geophysical studies

The North China Interior Structure Project (NCISP) collected a number of broadband seismic profiles in the NCC and adjacent areas (Chen et al., 2010). Zheng et al. (2007b) used teleseismic receiver functions to develop a crustal S-wave velocity model for the northern margin of the NCC (NCISP III in Fig. 3a) which showed that the crust beneath the Yanshan Belt was 30–40 km thick, with significant lateral variations and a sharply defined Moho. Shear wave splitting gave evidence for a complex pattern of upper mantle deformation beneath the YSB and CAOB (Zhao and Zheng, 2007) and suggested that lithospheric thinning had occurred primarily by delamination along the northern edge of the NCC. Chen et al. (2008) studied the northeastern NCC with S-wave receiver function migration and detected strong lateral variations in lithospheric thickness. They reported that the lithosphere beneath the