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Water contents and electrical conductivity of peridotite xenoliths from the North China Craton: Implications for water distribution in the upper mantle

Qin Wang [a,*], Nikolai Bagdassarov [b], Qun-Ke Xia [c], Beibei Zhu [a,d]

[a] State Key Laboratory for Mineral Deposits Research, Department of Earth Sciences, Nanjing University, Nanjing 210046, China
[b] Institute for Geosciences, University of Frankfurt, Frankfurt am Main 60438, Germany
[c] School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China
[d] SINOPEC Geophysical Research Institute, Nanjing 211103, China

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ABSTRACT

The eastern North China Craton (NCC) experienced significant lithospheric thinning and widespread magmatism in the Mesozoic, and is characterized by high surface heat flow and high conductivity layers (HCL) in the upper mantle. An integrated study of petrology and petrophysics will improve our understanding of the relationships between the electrical structure, thermal structure and chemical compositions (iron content and water content) of the upper mantle. Nine spinel peridotite xenoliths were collected from four Cenozoic basalts (Yangyuan, Hannuoba, Hebi and Nushan) in the Eastern Block and the Taihang Mountains of the NCC. These samples show compositional variations from depleted harzburgites to fertile lherzolites, representing the relic Archean lithosphere, modified Proterozoic lithosphere and newly accreted lithosphere after the lithospheric thinning event. The water contents of the peridotite samples were analyzed using Fourier transform infrared spectrometry. The water contents in olivine are very low (2–13 ppm H_2O), hence the whole-rock water concentration is controlled by orthopyroxene (Opx) and clinopyroxene (Cpx). Different hydration states of peridotites are distinguished according to the water contents in Opx: saturated (350 ppm), water-rich (>120 ppm), water-poor (40–90 ppm) and dry (~1 ppm). Using a piston cylinder press and Solartron 1260 phase-gain analyzer, the electrical conductivity of sintered peridotites was measured at pressures of 1–2 GPa and temperatures of 350–1150 °C. The electrical conductivity (σ) follows an Arrhenius equation: $\sigma = \sigma_0 \cdot \exp(-\Delta H / kT)$, where T is in Kelvin and k is the Boltzmann constant. The pre-exponential factor (σ_0) and activation enthalpy of electric conductivity (ΔH) of spinel peridotites vary in the range of $10^{0.65}$–$10^{2.38}$ S/m and 1.03–1.45 eV, respectively. Based on electrical conductivity of mantle minerals, we proposed a new equation to model the effect of iron content and water content on the conductivity of olivine, Opx and Cpx. The calculated conductivity using the Hashin–Shtrikman average can match the measured values of the peridotite samples by assuming a mixture of dry olivine and hydrogen-bearing Opx and Cpx. This demonstrates the contribution of both small polaron conduction and proton conduction mechanisms to the bulk conductivity of peridotites, and the dominant contribution of olivine to the bulk conductivity. Based on the thermal state of the lithosphere in different tectonic units, we obtained in situ conductivity of peridotites and pyroxenites with different hydration states. A comparison between in situ conductivity of mantle rocks and the magnetotelluric (MT) data in the eastern NCC suggests that in most regions, the shallow lithospheric mantle consists of both water-rich and water-poor peridotites, while the underlying lithospheric mantle is dry. The HCL in the upper mantle could be caused by partial melting in the lithospheric mantle (e.g., beneath the northern Taihang Mountains), or by water-rich peridotites near the lithosphere–asthenosphere boundary (e.g., beneath the Jizhong depression and the Luxi uplift) and in the asthenosphere (e.g., beneath the southern Taihang Mountains). Combined with water contents in peridotite xenoliths, we propose that the lithospheric mantle of the Eastern Block has been further dehydrated by the early Cretaceous giant igneous event and the Cenozoic volcanism. The dehydration process was accompanied with the lithospheric thinning and gradually increased the strength of the lithosphere, which finally resulted in the lithospheric thickening in the late Tertiary and Quaternary beneath the Eastern Block. In contrast, the Taihang Mountains are subjected to progressive lithospheric thinning since late Miocene and the lithospheric mantle has been significantly dehydrated. Our study not only provides an example to trace the heterogeneous water concentration in the continental upper mantle, but also highlights the contribution of magmatism-induced dehydration to the evolution of cratons.

* Corresponding author. Tel.: +86 25 83596887.
E-mail address: qwang@nju.edu.cn (Q. Wang).

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1. Introduction

Cratons, the ancient and stable cores of continents (>2.5 Gyr old), are characterized by the thick (>180 km), cold (40 mW/m^2), refractory and rheologically strong lithospheric keel (Eaton et al., 2009; Griffin et al., 2003; Wang, 2010). Although the Archean crust accounts for only 7% of the total area of the continents, studies of the global crustal growth history suggest that >60% of the present continental crust was formed in Archean, implying that destruction of cratons plays an important role in the continental evolution (Belousova et al., 2010). As one of the oldest cratons in the world, the North China Craton (NCC) contains crustal remnants as old as 3.8 Ga (Liu et al., 1992), and showed all characteristics of a typical craton until the Ordovician (e.g., Dobbs et al., 1994; Griffin et al., 1998; Menzies et al., 1993). In the Mesozoic and Cenozoic, the Western Block of the NCC still preserves the lithospheric keel, while its Eastern Block is characterized by a thin (<80 km), hot (>64 mW/m^2) and fertile "oceanic" lithosphere with widespread magmatism, extensional structures and seismic activity (e.g., Chen, 2009; Liu and Yang, 2005; Menzies et al., 2007; Xu and Zhao, 2009). Clearly, the NCC is an ideal place to study processes and mechanisms of craton destruction.

Nominally anhydrous minerals, such as olivine (Ol), orthopyroxene (Opx), clinopyroxene (Cpx) and garnet, can incorporate small amounts of hydrogen in lattice defects (e.g., Bell and Rossman, 1992; Ingrin and Skogby, 2000; Miller et al., 1987). Because water can significantly decrease the melting point and viscosity of the upper mantle (e.g., Hirschmann, 2006; Hirth and Kohlstedt, 1996, 2003; Karato, 2010; Wang, 2010), subduction-related hydration and weakening has been proposed as a possible mechanism for craton destruction. For example, the lithospheric thinning beneath eastern China (Huang and Zhao, 2006; Niu, 2005) and western US (Dixon et al., 2004; Li et al., 2008) was attributed to the long subduction history of the Pacific plate and the Farallon plate, respectively. In contrast to the high water contents of peridotite xenoliths from the Colorado plateau and vicinity (Li et al., 2008), peridotite xenoliths from Cenozoic basalts in the eastern NCC contain very low water contents, which are even lower than the average values of the cratonic and off-cratonic peridotites (Xia et al., 2010). Hence Xia et al. (2010) argued that the present-day lithospheric mantle beneath the eastern NCC is the relict ancient lithospheric mantle after the thinning event, rather than the newly accreted asthenospheric mantle hydrated by subduction of the Pacific slab. However, Xia et al. (2013) found very high water contents in clinopyroxene phenocrysts from the early Cretaceous (~120 Ma) Feixian basalt in the eastern NCC. The estimated water content in the lithospheric mantle source of the Feixian basalt is >1000 ppm H_2O, which is much higher than 50–200 ppm H_2O in the source of MORB and ~120 ppm H_2O in the Kaapvaal cratonic mantle in South Africa, implying that subduction-related hydration of the lithospheric keel did occur during the peak time of the NCC destruction. If so, the transition from the hydrated lithosphere in the Mesozoic to the dry lithosphere in the Cenozoic is critical to the destruction process of the NCC.

Given the possible biased sampling by mantle xenoliths, it is very important to explore in situ water distribution in the upper mantle in a large scale. Long-period magnetotelluric (MT) data reveal that the electrical conductivity at a depth of 100–250 km is on the order of 10^{-2}–10^{-4} S/m beneath a stable craton (e.g., Evans et al., 2011; Jones, 1999; Jones et al., 2003; Schultz et al., 1993), about one order of magnitude more resistive than the oceanic and tectonically activated upper mantle (e.g., Evans et al., 2005; Ichiki et al., 2009; Lizarralde et al., 1995; Neal et al., 2000). Based on diffusion and solubility of hydrogen in olivine, Karato (1990) proposed that hydrogen could considerably increase the electrical conductivity of olivine, which provides a link between the electrical structure and in situ water concentration of the upper mantle. Recent electrical conductivity experiments confirm that water can significantly enhance the electrical conductivity of olivine (Poe et al., 2010; Wang et al., 2006; Yoshino et al., 2006, 2009), orthopyroxene (Dai and Karato, 2009a; Yang et al., 2012), clinopyroxene (Yang and McCammon, 2012; Yang et al., 2011), and garnet (Dai and Karato, 2009b). Following Karato's hypothesis, the contrasting electrical conductivity between the continental and oceanic upper mantle has been attributed to the difference in olivine hydration, i.e., the dry Archean lithosphere and the wet oceanic asthenosphere (e.g., Evans et al., 2005; Hirth et al., 2000; Lizarralde et al., 1995). The MT profiles in the eastern and central NCC show several high conductivity layers (HCL) (>0.01–0.1 S/m) in the upper mantle (Wei et al., 2008). However, it is still not clear if these HCL can be regarded as evidence of high water contents in a thinned cratonic lithosphere.

In fact, besides hydrogen in olivine, the electrical conductivity of peridotites is also sensitive to temperature, iron content and oxidation state in major minerals and the oxygen fugacity of fluids, as well as the connectivity of minor conductive phases. The regional HCL in the upper mantle may be caused by the presence of interconnected silicate, carbonatite or basaltic melts (Evans et al., 2005; Gaillard et al., 2008; Yoshino et al., 2006, 2010), phlogopite (Boerner et al., 1999), graphite, sulfides or iron metals (Evans et al., 2011; Jones et al., 2003), and Fe^{3+}-rich augite (Yang and McCammon, 2012). Despite extensive studies on the electrical conductivity of mantle minerals, so far conductivity measurements of peridotites under upper mantle conductions are very limited (Bagdassarov et al., 2007, 2011; Dai et al., 2008; Duba and Constable, 1993; Wang et al., 2008), which hampers our interpretation of the mantle electrical structure.

This paper presents an integrated study of petrology, water contents and electrical conductivity of nine peridotite xenoliths from four localities (Yangyuan, Hannuoba, Hebi and Nushan) in the NCC. Based on the experimental results of the electrical conductivity of mantle minerals and our experimental results, we determined the combined effects of chemical composition (iron content and water) and temperature on the electrical conductivity of peridotites. The present-day in situ water concentration in the upper mantle of the Taihang Mountains and the eastern NCC was inferred by a comparison between calculated electrical conductivity of peridotites/pyroxenites and the MT data. Combining the water distribution of the lithospheric mantle derived from the electrical conductivity and from mantle xenoliths allows us to trace the evolution of water concentration in the upper mantle.

2. Geological setting

The NCC is bounded by the Central Asian orogenic belt in the north and the Qinling–Dabie–Sulu orogen in the south (Fig. 1). The assemblage of the Eastern and Western Blocks at ~1850 Ma formed the Trans-North China orogen and established the framework of the NCC (Zhao et al., 2001, 2005). The kimberlite-hosted garnet-diamond-facies peridotite xenoliths in the Ordovician demonstrate the existence of a cold, thick (180–200 km) and refractory lithospheric keel beneath the NCC in the early Paleozoic (e.g., Chi et al., 1992; Dobbs et al., 1994; Menzies et al., 1993). In contrast, the Cenozoic basalt-hosted xenoliths are predominantly composed of spinel peridotites (75–80 km), suggesting a removal of ~120-km-thick lithosphere beneath the eastern NCC (e.g., Fan et al., 2000; Griffin et al., 1998; Zheng, 2009 and references therein). The Trans-North China orogen is parallel to the North-South Gravity Lineament (NSGL) and behaves as a boundary of crustal elevation, crustal and lithospheric thickness, magmatism and deformation between the Eastern and Western Blocks (e.g., Chen et al., 2008; Xu, 2007; Xu and Zhao, 2009).

The NCC has experienced several important tectonic and magmatic events since the Ordovician. In the Carboniferous, the southward subduction of the Paleo-Asian plate beneath the NCC produced a suite of calc-alkaline, I-type granites of 324–300 Ma in the northern margin of the NCC (Zhang et al., 2007). The closure of the Paleo-Asian ocean between the Siberian Craton and the NCC in the late Permian was followed by southward subduction of the Siberian Craton, together with a collage of blocks and oceanic crust, beneath the NCC (Li, 2006). Therefore the