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Age constraints on late Mesozoic lithospheric extension and origin of bimodal volcanic rocks from the Hailar basin, NE China

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ABSTRACT

Following the amalgamation of the late Mesoproterozoic–Carboniferous Central Asian Orogenic Belt with the Siberian and North China cratons, NE China underwent late Mesozoic lithospheric extension and widespread formation of volcano-sedimentary basins. We report U–Pb zircon ages and geochemical data for mafic and felsic volcanic rocks from the Hailar basin, located about 1000 km north of Beijing. Zircon populations of six felsic rock samples analyzed by laser ablation ICP-MS yielded similar U–Pb age spectra ranging from 158 to 125 Ma. The youngest zircon ages are interpreted as time of magma eruption and the xenocrystic zircon-age spectra as evidence for a protracted melting of lower crust due to the underplating of mantle-derived magmas during lithospheric extension. The volcanic assemblage has a bimodal composition comprising geochemically evolved trachybasalts and felsic volcanic rocks of I- and subordinate A-type compositions. The mafic volcanic rocks have negative Nb-anomalies, high Th/Nb and Ce/Pb ratios, low initial ε_{Nd} values of +0.4 to +3.4, and radiogenic Pb and Sr isotopes all interpreted as evidence for the melting of passively upwelling asthenosphere and lithospheric mantle previously modified by plate subduction. The xenocrystic zircon ages and chemical/isotopic data of the felsic rocks support an origin from juvenile crustal protoliths: the data of I-type felsic rocks are consistent with the melting of underplated mafic protoliths and those of the A-type rhyolites support the melting of a crustal source with a composition similar to the I-type felsites with apatite controlling their Nb anomaly. The evidence for the persistent melting of a subduction-modified mantle in NE China is in agreement with a model of an extending coupled upper mantle–crust system due to a retreating Paleo-Pacific trench.

1. Introduction

After the accretion of the late Mesoproterozoic to Carboniferous Central Asian Orogenic Belt (CAOB) with the Siberian and North China cratons (NCC), late Mesozoic extension of the lithosphere in NE China produced a large basin-and-range setting (Graham et al., 2012; Ren et al., 2002) in the CAOB and NCC. Crustal extension was accompanied by exhumation of metamorphic core complexes (Daoudene et al., 2009; Wang et al., 2011), formation of volcano-sedimentary basins (Li et al., 2012; Ren et al., 2002), and emplacement of granitoids and voluminous mafic and felsic volcanic rocks (Wang et al., 2006; Wu et al., 2011; Zhang et al., 2008a). Geochronological data indicate onset of late Mesozoic magmatism in the northern CAOB near the Hailar basin at ca. 160 Ma that lasted until ca. 110 Ma. The age-record of magmatism with volcanic rocks as young as 90 Ma near the Pacific coast have been interpreted as evidence for a SE migration of magmatism (Wang et al., 2006; Zhang et al., 2010). Geochemical data and field observations of the extension-related igneous rocks have documented a predominantly bimodal composition (Ge et al., 2001; Lin et al., 2003) with subduction-related characteristics in the mafic volcanic rocks (Fan et al., 2003; Meng et al., 2011; Xu et al., 2013; Zhang et al., 2008b). Wang et al. (2002) and Zhang et al. (2008b) emphasized the importance of the melting of a subduction-overprinted lithospheric mantle and compared the geological situation in NE China with that of the basin-and-range province of the western United States.

Interpretations of the geodynamic context of late Mesozoic magmatism include a variety of models such as an upwelling mantle plume (Dobretsov and Vernikovsky, 2001; Ge et al., 1999; Lin et al., 2000), post-orogenic collapse of an over-thickened lithosphere after closure of the Mongol–Okhotsk Ocean (Fan et al., 2003; Meng, 2003; Wang et al., 2006), back-arc lithospheric extension due to roll back of the subducting Paleo-Pacific plate (Faure and Natalin, 1992; Li and Shu, 2002; Sun et al., 2013; Zhang et al., 2011; Zhao et al., 1989), and lithospheric delamination (Tomurtogoo et al., 2005; Wang et al., 2006; Wu et al., 2005; Zhang et al., 2010). Recent interpretations of geodynamic models have noted the important role of lithospheric mantle sources that support a passively rifting lithosphere without plume-interaction. Plume involvement appears unlikely as there is no

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evidence for active rifting and lithospheric updoming, plume-related high-degree magmas such as picrites, olivine tholeiites, and tholeiitic basaltic magmas, as well as plume-related Fe–Ti–V and Ni–Cr–Platinum Group Element (PGE) deposits such as, for example, related to the ca. 260 Ma old Emeishan flood basalt province in China (e.g., He et al., 2007; Luo et al., 2013, 2014; Wang et al., 1989; Zhang et al., 2006; Zhou et al., 2013). In addition, the typically very short time-scales of massive volcanic eruptions over mantle plumes is contrasted by a protracted period of magmatism of 60 to 80 Ma in NE China.

In this study of mafic and felsic volcanic rocks from the region of the late Mesozoic Hailar basin in NE China, we constrain the duration of lower crustal reworking during lithospheric extension and interpret the geochemical data as evidence for the composition and temporal variation of magma sources with ongoing lithospheric thinning.

2. Geology of study area and description of samples

The late Mesozoic Hailar basin is located about 1000 km north of Beijing in the northern part of the late Mesoproterozoic to Carboniferous CAOB (e.g., Dobretsov et al., 1995; Sengör et al., 1993; Windley et al., 2007; Xiao et al., 2003). It is situated to the south of the Mongol–Okhotsk suture that closed around 160–140 Ma in this part of the CAOB (e.g., Zorin, 1999) and on the western flank of the Great Xing'an range, an uplifted section in the extending CAOB (Fig. 1a). The basin has a NE-trending axis and comprises an assemblage of predominantly mafic volcanic rocks at the bottom (Tamulangou Formation; abbreviated below as Fm.) and felsic volcanic rocks at the top (Shangkuli Fm.). The igneous rock section is overlain by non-marine sedimentary rocks ranging in age from ca. 140 Ma to Recent (A et al., 2013; IMBGMR, 1991; Zhang and Long, 1995). A drill core profile from the Hailar basin shows a highly weathered CAOB basement overlain by a 1 km thick volcanic sequence with mainly mafic volcanic rocks at the base and felsic volcanic rocks and minor intercalated basalts and sedimentary rocks at the top. The overlying 3 km thick sediment package consists of mud- and siltstones deposited from ca. 100 Ma to Recent (Gao et al., 2009; Wan, 2006).

In the study area, late Mesozoic volcanic rocks were deposited over large areas in an evolving basin-and-range setting (Graham et al., 2012). Geochronological studies of late Mesozoic volcanic rocks from the Hailar region (Chen et al., 2006; Gou et al., 2013; Meng et al., 2011; Wang et al., 2006; Wu et al., 2011; Zhang et al., 2008a) indicate contemporaneous eruption of mafic and felsic rocks (albeit more mafic rocks at the beginning of volcanism), and intrusion of granitoids from ca. 160 to 110 Ma. Geochemical and Sr and Nd isotopic data for mafic and felsic volcanic rocks have been interpreted as evidence for calc-alkaline compositions and the melting of subduction-modified mantle sources with low ε_{Nd} values of -1 to $+4$ (Fan et al., 2003; Guo et al., 2010; Zhang et al., 2008b).

The basement in the region of the Hailar basin comprises late Paleozoic ca. 360 to 295 Ma metavolcano-sedimentary assemblages of the CAOB (Budate Group; Wan, 2006) and intrusive granitoids of ca. 282 to 295 Ma (Meng et al., 2013). Initial ε_{Nd} values of -2 to $+6$ for similar CAOB assemblages to the SW of the Hailar basin (Chen et al., 2009) were interpreted as overall juvenile continental magmatic arcs with a significant proportion of late Neoproterozoic material (Zhao et al., 2010). This type of basement had evolved isotopically to ε_{Nd} values of 0 to -6 at the time of late Mesozoic volcanism in the Hailar basin.

Thirteen basaltic-trachyandesite samples were collected from areas mapped as the lower Tamulangou Fm. at the western and northern margins of the Hailar basin (Fig. 1b, Table 1). The map shows outcrops of mafic volcanic rocks mapped as the lower Tamulangou Fm. We have not determined ages on these samples and it is therefore not clear if they indeed belong to the lower Tamulangou Fm., or represent some of the subordinate mafic lavas intercalated with the felsic rocks of the upper Shangkuli Fm. For other areas also mapped as Tamulangou Fm., U–Pb zircon ages (Chen et al., 2006; Ying et al., 2010) and Ar–Ar whole-rock ages (Wang et al., 2006; Zhang et al., 2008a) yielded an age spectrum ranging from ca. 180 to 140 Ma. U–Pb zircon ages for subordinate felsic lavas associated with the mafic volcanic rocks may be taken as firm evidence for the deposition of the lower mafic volcanic rocks from ca. 160 Ma to 140 Ma (Ying et al., 2010; Zhang et al., 2008a). The mafic rock samples are mostly subaphyric to weakly porphyritic and show phenocrysts of pyroxene and plagioclase, and subordinate amounts of amphibole. The matrix is aphanitic or composed of fine-grained clinopyroxene, plagioclase, biotite, and a few opaque oxide minerals. Common are vesicles filled with agate or calcite.

The felsic volcanic rocks of the upper Shangkuli Fm. are widespread in the Hailar area and were sampled at the western and northern margins of the basin (Fig. 1b). U–Pb dating of zircons yielded crystallization ages of 140 to 110 Ma (Ying et al., 2010; Zhang et al., 2008a). The Shangkuli Fm. comprises trachytes and rhyodacites, interlayered with pyroclastic tuffs, volcanic sandstone, rhyodacitic lavas, and subordinate basaltic lava flows. The rhyolites and dacites have a porphyritic texture, with phenocrysts set in a glassy matrix. Flow banding, spherulitic and perlitic structures are common. The phenocrysts are sanidine, quartz, plagioclase, and biotite. The matrix of the trachytes shows fine-grained plagioclase and hornblende and a few opaque oxide minerals. The rhyolitic tuffs contain broken phenocrysts of quartz and feldspar set in a devitrified, microcrystalline groundmass. From this unit we analyzed seventeen felsic rock samples and dated zircons of one trachyte and five rhyolite samples by laser ablation ICP-MS.

3. Analytical methods

The zircon concentrates were prepared by hand-panning of the <500 μm grain-size fraction of the samples and magnetic- and heavy-liquid mineral separation techniques (Hou et al., 2010). Three basaltic trachyandesites that were also processed provided no zircons and we consider this finding as good evidence for the absence of magma contamination by felsic material in these mafic volcanic rocks. More than 100 zircon crystals of each sample were handpicked under a binocular microscope for analysis. The samples show similar populations of apparently magmatic zircons, only differing in size. The grains selected for analysis were transparent, colorless, and mostly subangular with some crystals showing well-defined prisms and euhedral to subhedral habitus. Under the binocular and also in cathode luminescence (CL) images there is no evidence for zircon cores, and typical xenocrystic or detrital grains, although as shown in Section 4.1 most of them are inherited xenocrysts. The zircons were placed on adhesive tape, embedded in epoxy resin, and polished to about half of their thickness. CL images of the internal structures were taken with a Cameca SX-50 microprobe at the Institute of Geology and Geophysics, Chinese Academy of Sciences (CAS), Beijing. The zircon grains show a diffuse oscillatory magmatic zoning and the analyzed grains yielded typical magmatic Th/U ratios >0.5 (Table S1; Hoskin and Schaltegger, 2003). U–Pb isotopic analyses were carried out at the Key Laboratory of Crust–Mantle Materials and Environments of CAS at the University of Science and Technology of China (USTC), Hefei. We used an inductively-coupled plasma mass spectrometer (LA–ICP-MS; Perkin Elmer Elan DRC II) equipped with a Microlas system (GeoLas 200 M, 193 nm ArF-excimer laser). The diameter of the laser-ablation pits was approximately 40 μm and the average power output about 4 W. Signal and background measuring times were 70 and 40 s, respectively. U, Th, and Pb concentrations were calibrated against the NIST610 reference material which was measured twice every 10 sample spots. The age calculations were calibrated against Zircon 91500 reference material analyzed after every fifth sample spot. In order to avoid an age bias due to selective analysis of a certain type of zircon and specific zircon domains, cores and rims of more than fifty grains of different sizes were randomly analyzed. More details on the laser-ablation U–Pb dating technique are given in Liu et al. (2007). The conventional correction procedure