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Geochronology and geochemistry of late Paleozoic volcanic rocks on the western margin of the Songnen–Zhangguangcai Range Massif, NE China: Implications for the amalgamation history of the Xing'an and Songnen–Zhangguangcai Range massifs

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ABSTRACT

We here elucidate the tectonic evolution of the Xing'an and Songnen–Zhangguangcai Range massifs during the early Carboniferous–early Permian, based on zircon U–Pb dating and whole-rock geochemical analyses of volcanic rocks of the Songnen–Zhangguangcai Range Massif in the Sunwu area, Heilongjiang Province, NE China. Euhedral–subeuhedral zircons from three rhyolites and one dacite from the study area display fine-scale oscillatory growth zoning, indicating a magmatic origin. Zircon U–Pb dating by LA–ICP–MS indicates that these acidic volcanic rocks formed in the early Carboniferous–early Permian; i.e., early Carboniferous (~351 Ma), early late Carboniferous (~319 Ma), and early Permian (295–293 Ma). The early Carboniferous rhyolites exhibit chemical affinities to A-type rhyolites, implying an extensional environment. Their positive εHf(t) values (+8.67 to +13.4 except for one spot of +1.63) and Hf two-stage model ages (T_{DM2} = 562–988 Ma) indicate that the primary magma was possibly derived from partial melting of newly accreted continental crust. The early late Carboniferous rhyolites and dacites (~319 Ma) exhibit calc-alkaline peraluminous signature [molar $Al_2O_3/(CaO + K_2O + Na_2O)$ ratio, or A/CNK = 1.04–1.22]. The εHf(t) values and T_{DM2} ages of zircons from the 319 Ma dacites are in the range of +5.33 to +9.32 and 907–1268 Ma, respectively, suggesting that the primary magma was derived from partial melting of newly accreted crust. The early Permian rhyolites (295–293 Ma) show chemical affinities to A-type rhyolites, implying an extensional tectonic environment; their positive εHf(t) values (+8.82 to +13.8) and Hf two-stage model ages (484–743 Ma) indicate that the primary magma was derived from partial melting of newly accreted crust. Combined with the geochemical features of coeval igneous rocks from the eastern margin of the Xing'an Massif, these data reveal the late Paleozoic tectonic history and relationships of the Xing'an and Songnen–Zhangguangcai Range massifs, i.e., early Carboniferous westward subduction of the Paleo-Asian oceanic plate beneath the Xing'an Massif, followed by early late Carboniferous collision and amalgamation of microcontinental blocks, and early Permian post-collisional extension.

1. Introduction

Tectonically, northeast (NE) China has traditionally been considered as the eastern segment of the Central Asian Orogenic Belt (CAOB), located between the Siberian and the North China cratons (Jahn et al., 2000; Li, 2006; Sengör et al., 1993; Windley et al., 2007; Xiao et al., 2004). The Paleozoic tectonic evolution of NE China was dominated by the amalgamation of multiple microcontinental massifs (including, from west to east, the Erguna, Xing'an, Songnen–Zhangguangcai Range, Jiamusi, and Khanka massifs) (Sengör et al., 1993) and the closure of the Paleo-Asian ocean, whereas the Mesozoic tectonic evolution of the area was characterized by overprinting of the circum-Pacific system in the east and the Mongol–Okhotsk system in the northwest (Meng et al., 2010, 2011; Tang et al., 2014; Wang et al., 2012; Wu et al., 2007; Xu et al., 2009, 2013). However, the timing of the amalgamation of the massifs during the Paleozoic remains controversial (Cui et al., 2013; Li, 2006; Meng et al., 2010; Miao et al., 2007; Sorokin et al., 2004; Wang et al., 2012; Wilde et al., 2003; Windley et al., 2007; Xiao et al., 2004). For example, the amalgamation between the Xing'an and Songnen–Zhangguangcai Range massifs has been assigned to the Late Devonian (Su, 1996), the Late Devonian–early Carboniferous (Hong et al., 1994; Tang et al., 2011), the late early Carboniferous (Cui et al., 2013; Liu et al., 2012; Zhao et al., 2010a), the pre-Permian (Shi et al., 2004; Sun et al., 2000; Tong et al., 2010), and the Triassic (Chen et al., 2000;

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Miao et al., 2003). Controversies have arisen because of a lack of precise dating and detailed geochemical data for the Paleozoic igneous rocks in both the Xing'an and Songnen–Zhangguangcai Range massifs.

In recent years, a large amount of geochronological and geochemical data has been obtained for intrusive rocks from NE China, especially for granites (Jahn et al., 2000; Wang et al., 2012; Wu et al., 2002, 2011; Xu et al., 1999). In contrast, few studies have examined Paleozoic volcanic rocks in the region. In the present study, therefore, we undertook zircon U–Pb dating and geochemical analyses of early Carboniferous–early Permian volcanic rocks that outcrop on the western margin of the Songnen–Zhangguangcai Range Massif, which is adjacent to the Heihe–Nenjiang suture zone. Our data, combined with data from late Paleozoic igneous rocks in the Xing'an Massif, reveal the tectonic evolution and relationships of the Xing'an and Songnen–Zhangguangcai Range massifs during the early Carboniferous–early Permian.

2. Geological background and sample descriptions

NE China, located in the eastern section of the CAOB, includes the Erguna and Xing'an massifs in the northeast, the Songnen–Zhangguangcai Range Massif in the center, and the Jiamusi and Khanka massifs in the east, with the various massifs separated by major faults. The present study area is situated on the western edge of the Songnen–Zhangguangcai Range Massif; geographically, the region is in the Sunwu area, Heilongjiang Province, NE China, which is adjacent to the Heihe–Nenjiang suture zone, which represents the final amalgamation between the Xing'an and Songnen–Zhangguangcai Range massifs. The Songnen–Zhangguangcai Range Massif is made up mainly of the Songliao Basin and the Lesser Xing'an–Zhangguangcai Ranges. The Songliao Basin formed during the late Mesozoic, based on the geochronology of basement rocks in the basin, which consist of weakly deformed and metamorphosed Phanerozoic granites and Paleozoic strata (Meng et al., 2011; Wang et al., 2014; Wu et al., 2011). The strata outcropping on the western margin of the Songnen–Zhangguangcai Range Massif include the Middle Devonian Fuxingtun Formation (D_2f), lower Carboniferous Kunaerhe Formation (C_1k), upper Carboniferous Hetaoshan Formation (C_3h), middle Permian Wudaoling Formation (P_2w), upper Jurassic Tamulangou (J_3t) and Shangkuli (J_3sh) formations, and lower Cretaceous Jiufengshan (K_1j) and Ganhe (K_1g) formations. In addition, voluminous Paleozoic and Mesozoic granitoids, known as the “granite ocean”, occur in the study area and adjacent areas (HBGMR, 1987, 1991, 1993; Wu et al., 2011). The volcanic rocks in this study were collected from the Kunaerhe, Hetaoshan, and Wudaoling formations (Fig. 1b–d). The Kunaerhe Formation (C_1k), previously thought to be early Carboniferous in age, is composed mainly of intermediate–acidic volcanic rocks, silty slate, and fine sandstone. The Hetaoshan Formation (C_3h), previously thought to be late Carboniferous in age, consists mainly of rhyolites and dacites. The Wudaoling Formation (P_2w), previously thought to be middle Permian in age, is composed mainly of rhyolites, dacites, and silty slate (HBGMR, 1987, 1991).

In the present study, samples HSW10 (13HSW3), HSW4, HSW5, 12HSW4 (13HSW5), and HSW8 (13HSW1) are from volcanic rocks previously mapped as Carboniferous–Permian in age. Note that sample numbers (e.g., HSW5) represent locations; if more than one sample was collected from a given location, the samples are labeled with a sequence of numbers (e.g., HSW5-1); some samples in parentheses were collected in the same location in different years [e.g., HSW10 (13HSW3)]. The summary of the early Carbiniferous–early Permian volcanic rocks is shown in Table 1.

Sample HSW10 (13HSW3) was collected from rocks previously mapped as the early Carboniferous Kunaerhe Formation in a 1:200,000 regional geological survey (HBGMR, 1991). The sample was collected from near Qilingang (49°58′41.3″N, 127°06′59.8″E). The rhyolites have porphyritic textures and rhyolitic structures (Fig. 2a, b). The phenocrysts (25% by volume, vol) consist of quartz (~6%), sanidine (~12%), and plagioclase (~7%); the groundmass (75% by vol) is composed of aphanitic felsic minerals with minor opaque minerals.

Rhyolite sample HSW4 and dacite sample HSW5 were collected from the Wudaoling Formation, which was previously mapped as middle Permian in age during a 1:200,000 regional geological survey (HBGMR, 1987). The samples were collected from near Chenqing (49°02′24.7″N, 127°02′14.0″E and 49°02′51.9″N, 127°02′14.0″E, respectively). Sample HSW4 is dark gray in color and exhibits porphyritic textures and rhyolitic structures. The phenocrysts (35% by vol) consist of quartz (~8%), sanidine (13%–15%), and plagioclase (12%–14%); the groundmass (65% by vol) is composed of aphanitic felsic material. Sample HSW5 is also dark gray in color and exhibits porphyritic textures and rhyolitic structures. The phenocrysts (30% by vol) consist of quartz (~8%), sanidine (8%), and plagioclase (~14%); the groundmass (70% by vol) is composed of aphanitic felsic minerals (Fig. 2c, d).

Sample 12HSW4 (13HSW5) was collected from the Wudaoling Formation, which was previously mapped as middle Permian in age during a 1:200,000 regional geological survey (HBGMR, 1987). The sample was collected from the south of Qingxi (49°19′32.0″N, 127°08′32.6″E). The rhyolite is dark gray in color with spherulitic textures and rhyolitic structures (Fig. 2e, f). The phenocrysts (20% by vol) are quartz (~5%), sanidine (~9%), and plagioclase (~6%); the groundmass (80% by vol) is composed of aphanitic felsic minerals with opaque minerals.

Sample HSW8 (13HSW1) was collected from the Hetaoshan Formation, which was mapped previously as late Carboniferous in age (HBGMR, 1991). The sample was collected from a site ~12 km along the highway from Songshugou to Qilingang (49°58′32.8″N, 127°10′58.0″E). The sample is gray in color and with porphyritic texture and massive structure. The phenocrysts (20% by vol) are quartz (~5%), sanidine (~9%), and plagioclase (~6%); the groundmass (80% by vol) is composed of aphanitic felsic minerals with minor opaque minerals.

3. Analytical methods

3.1. Zircon U–Pb dating

Zircons were separated from whole-rock samples using the conventional heavy liquid and magnetic techniques, and then by handpicking under a binocular microscope, at the Langfang Regional Geological Survey, Hebei Province, China. The handpicked zircons were examined under transmitted and reflected light with an optical microscope. To reveal their internal structures, cathodoluminescence (CL) images were obtained using a JEOL scanning electron microscope housed at the State Key Laboratory of Continental Dynamics, Northwest University, Xi'an, China. Distinct domains within the zircons were selected for analysis, based on the CL images. LA-ICP-MS zircon U–Pb analyses were performed using an Agilent 7500a ICP-MS equipped with a 193 nm laser, housed at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, China. The zircon 91500 was used as an external standard for age calibration, and the NIST SRM 610 silicate glass was applied for instrument optimization. The crater diameter was 32 μm during the analyses. The instrument parameter and detail procedures were described by Yuan et al. (2004). The ICPMSDataCal (Ver. 6.7; Liu et al., 2008, 2010) and Isoplot (Ver. 3.0; Ludwig, 2003) programs were used for data reduction. Correction for common Pb was made following Anderson (2002). Errors on individual analyses by LA-ICP-MS are quoted at the 1σ level, while errors on pooled ages are quoted at the 95% (2σ) confidence level. The dating results are presented in Supplementary Table 1.

3.2. Major and trace element determinations

For geochemical analysis, whole-rock samples, after the removal of altered surfaces, were crushed in an agate mill to ~200 mesh. X-ray