Lithos 192–195 (2014) 116–131

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Petrogenesis of late Paleozoic volcanic rocks from the Daheshen Formation in central Jilin Province, NE China, and its tectonic implications: Constraints from geochronology, geochemistry and Sr–Nd–Hf isotopes

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ARTICLE INFO

Article history:
Received 18 September 2013
Accepted 29 January 2014
Available online 7 February 2014

Keywords:
Late Paleozoic
Volcanic rocks
Zircon U–Pb geochronology
Geochemistry
Daheshen Formation
NE China

ABSTRACT

We present geochronological, geochemical, whole-rock Sr–Nd and zircon Hf–isotopic data for late Paleozoic volcanic rocks from the Daheshen Formation in central Jilin Province, northeastern China, and constrain the petrogenesis of the volcanic rocks and late Paleozoic tectonic evolution of the northern margin of the Northern China Craton, which is regarded as the eastern segment of the Central Asian Orogenic Belt (CAOB). Lithologically, the Daheshen Formation is composed mainly of rhyolite, rhyolitic tuff, dacite and andesite, with minor basalt. The zircons from three rhyolites, two dacites, one rhyolitic tuff and one basalt are euhedral–subhedral, display oscillatory zoning and have high Th/U ratios (0.50–2.28), implying a magmatic origin. LA–ICP-MS zircon U–Pb age data indicate that the volcanic rocks from the Daheshen Formation formed during Late Carboniferous–Early Permian time (302–299 Ma). Geochemically, late Paleozoic volcanic rocks have $SiO_2 = 52.13–81.77$ wt.% and $K_2O = 0.86–6.88$ wt.%, belonging to mid-K to high-K calc-alkaline series. These rocks are characterized by enrichment in large ion lithophile elements (LILEs) and light rare earth elements (LREEs), and depletion in high field strength elements (HFSEs, such as Nb, Ta, and Ti) and heavy rare earth elements (HREEs), with affinities to igneous rocks forming in an active continental margin setting. All volcanic rocks have depleted Nd isotopic compositions ($\varepsilon_{Nd}(t) = +2.4$ to $+2.5$ for the basalts and $+5.8$ to $+7.1$ for the andesites and dacites, respectively). In situ Hf isotopic results of zircon from the rhyolites show that they have $\varepsilon_{Hf}(t) = -1.1$ to $+10.6$. All these geochemical features indicate that the andesites, dacites, and rhyolites likely originated from the partial melting of Meso-Neoproterozoic accreted lower crust (Hf and Nd model ages (T_{DM2}) of 1384–662 Ma and 1061–800 Ma, respectively). In contrast, the basalts were derived from the partial fusion of a depleted lithospheric mantle that had subsequently been metasomatized by subducted slab-derived fluids. These data, along with the regional geological investigations, suggest that the generation of late Paleozoic volcanic rocks from the Daheshen Formation was related to southward subduction of the Paleo-Asian oceanic plate beneath the northern margin of the North China Craton. This also indicates that the Paleo-Asian Ocean may have not closed before the Early Permian.

1. Introduction

The Central Asian Orogenic Belt (CAOB) is the largest Phanerozoic orogenic belt in the world which extends from Urals in the west to the Pacific Ocean in the east, separating the Siberian Craton in the north from the Tarim and North China cratons in the south (Badarch et al., 2002; Jahn et al., 2000; Mossakovsky et al., 1994; Sengör et al., 1993). It is generally considered to have formed by the subduction of the Paleo-Asian Ocean and the amalgamation of terranes (Badarch et al., 2002; Buslov et al., 2001; Dobretsov et al., 1995; Xiao et al., 2003). Numerous recent regional studies have reconstructed the tectonic setting of this orogenic belt and proposed a suture that extended from Solonker via Xra Moron to Changchun in north China (Huang, 1983; Li and Wang, 1983; Wang and Liu, 1986; Wang et al., 1991; Wu et al., 2011). As the suture marks the final closure of the Paleo-Asian Ocean, the timing of collision and formation of the Solonker–Xra Moron–Changchun suture plays a significant role for us to understand the evolution of the Paleo-Asian Ocean. In terms of the western segment of the suture, the results of extensive investigations in western Inner Mongolia show a late Permian to middle Triassic collision along the suture, implying that a wide ocean still existed between the Siberia and North China prior to this time (Chen et al., 2000; Jian et al., 2010; Xiao et al., 2003, 2009). However, there is still a debate about the tectonic evolution of the eastern segment of the suture during late Paleozoic time. In

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0024-4937/$ – see front matter
http://dx.doi.org/10.1016/j.lithos.2014.01.016

particular, it still remains controversial about the timing of final closure of the eastern segment of the Paleo-Asian Ocean and the nature of the north margin of the NCC in the late Paleozoic.

Northeast China is located between the Siberia Craton (SC) and the North China Craton (NCC), and tectonically considered to be the eastern segment of the Central Asian Orogenic Belt (Jahn et al., 2000, 2004; Li, 2006; Sengör and Naial'in, 1996; Sengör et al., 1993; Windley et al., 2007; Xiao et al., 2004). It was previously suggested that NE China was an area that underwent two stages of evolution under different tectonic regimes, of which the first one occurred in the Paleozoic, with the closure of the Paleo-Asian ocean and the amalgamation of micro-continental massifs (including the Erguna, Xing'an, Songnen, and Jiamusi massifs) (Li, 2006; Wilde et al., 2001, 2003; Wu et al., 2000, 2011; Xiao et al., 2004; Ye and Zhang, 1994; Zhao et al., 1996), whereas the second one occurred in the Mesozoic–Cenozoic, with geological events related to the development of the circum-Pacific tectonic system (Jia et al., 2004; Wu et al., 2004, 2007a; Xu et al., 2009; Yu et al., 2012; Zhang et al., 2004b). As mentioned above, most researchers consider that the Solonker–Xra Moron–Changchun suture represents the final suture zone between the North China and Siberia cratons (Huang, 1983; Li and Wang, 1983; Wang and Liu, 1986; Wang et al., 1991; Wu et al., 2011). However, the time of the final closure of the Paleo-Asian Ocean, together with the tectonic nature of the northern margin of the NCC during late Paleozoic, still remain controversial. Based on Sm–Nd isotope data for the mafic and ultramafic rocks from the Toudaogou Formation, as well as metamorphic data for the Hulan Group, some geologists suggested that the closure occurred during early Paleozoic time, and a subsequent change of the regional tectonic setting from subduction to extension developed along the northern margin of the NCC during late Paleozoic (Peng and Zhao, 2001; Peng et al., 1999; Su, 1996; Tang, 1989; Wang and Su,1996; Wang et al., 1997; Zhang et al., 1998; Zhao et al., 1996). In contrast, the zircon U–Pb data for the syn-collisional Dayushan granitic pluton (248 Ma) from the Xra Moron–Changchun suture, together with the relationship between this pluton and the metamorphism of the Hulan Group, have led some other geologists to believe that the northern margin of the NCC existed as an active continental margin until the end of the Permian (Jia et al., 2004; Li, 2006; Li et al., 2007; Lin et al., 2008; Meng et al., 2008, 2010; Sun et al., 2004; Wen et al., 1996; Wu et al., 2007b; Zhang et al., 2004b). These conflicting opinions are, to a large extent, the direct consequence of a lack of research on the volcanic rocks exposed along the northern margin of the NCC.

In this contribution, we focus on the Daheshen Formation in central Jilin Province in NE China, since this stratum was located in the accretionary zone of the northern margin of the NCC and tectonically experienced the evolution of the Paleo-Asian Ocean during Paleozoic time. Here, we present geochemical and Sr–Nd isotopic data, together with zircon U–Pb ages and Hf isotopic compositions for late Paleozoic volcanics from the Daheshen Formation in order to provide constraints on the late Paleozoic tectonic evolution of the northern margin of the NCC and the timing of the final closure of the eastern segment of the Paleo-Asian Ocean.

2. Geological background and sample descriptions

The Daheshen Formation was initially established in central Jilin Province near the Daheshen village in the Changshan district of Huadian city (BGMRJ, 1997), and traditionally considered to be part of the eastern segment of the Solonker–Xra Moron–Changchun suture zone (Fig. 1a). Tectonically, the study area is bounded by the Dunhua–Mishan Fault to the northeast, the Chifeng–Bayan Fault to the south, and the Songliao basin to the west (Fig. 1a). The Daheshen Formation consists mainly of rhyolites, rhyolitic tuffs, dacites and andesites, with minor basalts and sedimentary rocks. The measured stratigraphic section is shown in Fig. 2. Meanwhile, field observations show that the Daheshen Formation is conformably overlain by the Fanjiatun Formation (Figs. 1b and 2; BGMRJ, 1997), with rock assemblages consisting mainly of limestone and mudstone (Fig. 2; BGMRJ, 1997).

The analyzed samples from the Daheshen Formation (Fig. 1b) are composed of rhyolite, rhyolitic tuff, dacite, andesite, and basalt. The basalt (DH012) is dark gray and displays a porphyritic texture and massive structure (Fig. 3a and b), with phenocrysts (~10% of the rock mass) of plagioclase and pyroxene, as well as groundmass of intergranular–intersertal texture (Fig. 3a and b). The andesite is also dark gray and shows porphyritic texture and massive structure, the phenocrysts of which mainly suffered alteration with carbonate mineral appearing on

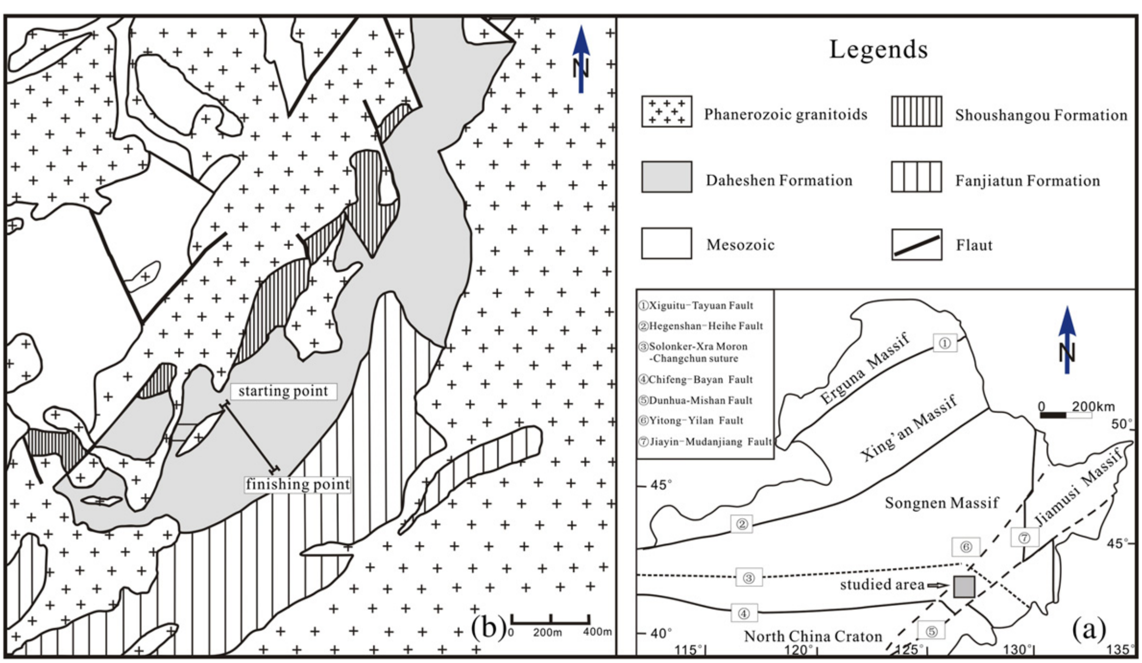

Fig. 1. (a) Geological sketch map of the studied area (after BGMRJ, 1997); (b) Tectonic sketch map of northeastern (NE) China (after Wu et al., 2011). Abbreviations: F1 = Xiguitu–Tayuan Fault; F2 = Hegenshan–Heihe Fault; F3 = Solonker–Xar Moron–Changchun zone; F4 = Chifeng–Bayan Fault; F5 = Dunhua–Mishan Fault; F6 = Yitong–Yilan Fault; F7 = Jiayin–Mudanjiang Fault.