Earth and Planetary Science Letters 465 (2017) 112–125

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

The 1.33–1.30 Ga Yanliao large igneous province in the North China Craton: Implications for reconstruction of the Nuna (Columbia) supercontinent, and specifically with the North Australian Craton

Shuan-Hong Zhang [a,b,*], Yue Zhao [a,b], Xian-Hua Li [c], Richard E. Ernst [d,e], Zhen-Yu Yang [f]

[a] *Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing 100081, China*
[b] *Key Laboratory of Paleomagnetism and Tectonic Reconstruction, Ministry of Land and Resources, Beijing 100081, China*
[c] *State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China*
[d] *Department of Earth Sciences, Carleton University, Ottawa, Ontario K1S 5B6, Canada*
[e] *Faculty of Geology and Geography, Tomsk State University, Tomsk 634050, Russia*
[f] *College of Resources, Environment and Tourism, Capital Normal University, Beijing 100048, China*

ARTICLE INFO

Article history:
Received 14 November 2016
Received in revised form 13 January 2017
Accepted 21 February 2017
Available online xxxx
Editor: A. Yin

Keywords:
large igneous province
diabase sill swarm
pre-magmatic uplift
continental breakup
Nuna (Columbia) supercontinent
North China Craton

ABSTRACT

The Yanliao rift zone in the northern North China Craton (NCC) is the location of the standard section for late Paleoproterozoic–Mesoproterozoic stratigraphy in China and is associated with the emplacement of large volumes of diabase sills. Detailed field investigations show that the sills are distributed over a region that is >600 km long and >200 km wide, with areal extent $>1.2 \times 10^5$ km^2 and cumulative thickness of the sills in any one area ranging from 50 m to >1800 m. High-resolution secondary ion mass spectrometry (SIMS) baddeleyite dating shows that emplacement of these sills occurred between about 1330 and 1305 Ma with a peak age of 1323 Ma. Emplacement of these diabase sills was accompanied by pre-magmatic uplift that started at about 1.35–1.34 Ga as indicated by the disconformity between the Changlongshan and Xiamaling formations and absence of sedimentation after the Xiamaling Formation in some areas. All the diabase sills exhibit similar geochemical features of tholeiitic compositions with intraplate characteristics. Given a relatively short duration of emplacement at 1.33–1.30 Ga, along with the large areal extent and volume, as well as intraplate character, this magmatic province constitutes a large igneous province (LIP). This Yanliao LIP and the accompanying pre-magmatic uplift were related either to a mantle plume and/or continental rifting during breakup of the NCC from the Nuna (Columbia) supercontinent. Paleomagnetic, ash bed and LIP data and other geological constraints suggest that the NCC had a close connection with Siberia, Laurentia, Baltica, North Australia and India crustal blocks. In particular, the most direct age match between the 1.33–1.30 Ga Yanliao LIP and the 1.33–1.30 Ga Derim Derim–Galiwinku LIP of the North Australian Craton (NAC), as well as the similarities between the late Paleoproterozoic–Mesoproterozoic stratigraphic units of the Yanliao rift in the NCC with the southeastern McArthur Basin in the NAC, indicate that the Yanliao and Derim Derim–Galiwinku events are fragmented parts of the same LIP, supporting the paleomagnetically plausible idea that the NCC and NAC were connected (or at least near neighbors) during the early Mesoproterozoic period.

1. Introduction

Large igneous provinces (LIPs) consist mainly of mafic igneous rocks with areal extents $>10^5$ km^2 and igneous volumes $>10^5$ km^3, intraplate characteristics, and a short duration pulse, or in some cases, multiple short pulses spanning a maximum duration of <50 Ma (e.g., Coffin and Eldholm, 1994; Ernst, 2014 and references therein). Many LIPs are proven to be linked to continental breakup, global environmental catastrophes, regional uplift and/or a variety of ore deposit types (Sobolev et al., 2011; Pirajno and Hoatson, 2012; Ernst and Jowitt, 2013; Ernst, 2014). The LIP record, through matching of coeval LIP units and the trends of their regional dyke swarms between crustal blocks, can play a useful role in constraining paleogeographic reconstructions, especially for pre-Mesozoic paleocontinents where there is no

---

* Correspondce to: No. 11 South Minzudaxue Road, Haidian District, Beijing 100081, China. Tel.: +86 10 88815058; fax: +86 10 68422326.

E-mail addresses: tozhangshuanhong@163.com, zhangshuanhong@geomech.ac.cn (S.-H. Zhang).

http://dx.doi.org/10.1016/j.epsl.2017.02.034
0012-821X/© 2017 Elsevier B.V. All rights reserved.

preserved record of ocean-floor spreading to help guide reconstructions (e.g., Ernst, 2014; Ernst et al., 2016).

The period 1.70–0.75 Ga is Earth's middle age that was characterized by environmental, evolutionary, and lithospheric stability contrasting with the dramatic changes in preceding and succeeding eras (Cawood and Hawkesworth, 2014). Two supercontinents, namely Nuna (Columbia) and Rodinia, existed during this period (e.g., Hoffman, 1991; Dalziel, 1991; Zhao et al., 2002; Rogers and Santosh, 2002; Li et al., 2008; Evans, 2013). Current models for Nuna (Columbia) configurations exclude the North China Craton (NCC) or put it at the edge of the supercontinent with its paleoposition highly controversial (e.g., Rogers and Santosh, 2002; Evans and Mitchell, 2011; Zhang et al., 2012a; Piper, 2013; Kaur and Chaudhri, 2014; Pisarevsky et al., 2014; Wan et al., 2015), mainly due to lack of reliable Mesoproterozoic geological units such as LIPs in the NCC for paleogeographic reconstruction. In this paper, we present new field, geochronological and geochemical evidence for the existence of a 1.33–1.30 Ga mafic LIP and pre-magmatic uplift in the northern NCC, which provide an important constraint on the paleoposition of the NCC with respect to the North Australian Craton (NAC) in the Nuna (Columbia) supercontinent.

2. The Yanliao mafic sill swarm

The Yanliao rift zone in the northern NCC hosts the standard section for late Paleoproterozoic–Mesoproterozoic strata in China (Fig. 1). The late Paleoproterozoic–Mesoproterozoic strata are composed mainly of marine clastic and carbonate platformal sedimentary rocks with a total thickness of *ca.* 12 km. A striking feature of the late Paleoproterozoic–Mesoproterozoic strata in the Yanliao area was the emplacement of large volumes of diabase sills. These sills are particularly common within the Xiamaling, Wumishan, Gaoyuzhuang and Tieling formations; also locally within the Chuanlinggou and Tuanshanzi formations (Figs. 2–3; Supplementary Figs. A1–A2). The sills display typical diabasic texture with mineral proportions (Supplementary Fig. A3) of pyroxene (35–60 vol.%), plagioclase (40–55 vol.%), magnetite (3–10 vol.%) and hornblende (0–5 vol.%). The sills were previously considered as mainly late Paleozoic–Mesozoic in age (e.g., LBGMR, 1965); however, recent zircon/baddeleyite dating of several sills emplaced into the Xiamaling and Wumishan formations yields crystallization ages of 1.35–1.31 Ga, indicating their emplacement during the mid-Mesoproterozoic (Li et al., 2009; Zhang et al., 2009, 2012b; Wang et al., 2014).

Our detailed field investigations indicate that the sills are distributed over an area that is >600 km long and >200 km wide with areal extent $>1.2 \times 10^5$ km^2 (Fig. 1B). The individual sills are several tens of meters to several hundred meters thick, and can be traced for a few kilometers or even up to several tens of kilometers. Our 43 geological sections crossing the sills and their host rocks (Fig. 4; Supplementary Figs. A4–A5) show that the aggregate total thickness of the sills in different areas ranges from 50 m to >1800 m, with a decreasing trend in cumulative thickness from northeast to southwest (Fig. 2). In several locations, the sills that were emplaced into the Xiamaling or Tieling formations exhibit a disconformable contact with the overlying Cambrian strata (Fig. 2F–H; Supplementary Figs. A1–A2), not an intrusive contact as shown on previous maps (e.g., LBGMR, 1965). Our field investigations and geological sections also show that, although the uppermost part of the Xiamaling Formation was intruded by diabase sills, no sills have been identified in the overlying Changlongshan and Jingeryu formations (Fig. 2A–E; Fig. 3A–B; Supplementary Figs. A4C, K–L, U).

3. Analytical methods

3.1. Sample preparation and imaging

Baddeleyites were separated using conventional crushing and separation techniques and were then handpicked under a binocular microscope. They were mounted in epoxy resin together with baddeleyite standards and polished to expose the cores of the grains in readiness for photomicrograph, cathodoluminescence (CL), backscattered electron (BSE) and SIMS U–Pb/Pb–Pb analyses. Baddeleyites were imaged using the LEO 1450VP scanning electron microscope attached with a GATAN Mini-CL detector at the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing. CL and BSE images of representative baddeleyite grains are shown in Supplementary Fig. A6.

3.2. Baddeleyite SIMS U–Pb/Pb–Pb dating

Baddeleyite SIMS dating was performed in two independent sessions using a Cameca IMS 1280HR large-radius ion microprobe at the Institute of Geology and Geophysics, Chinese Academy of Sciences in Beijing. SIMS U–Pb analyses were conducted on baddeleyites from samples 09005-1, 09038-1, 09056-1, 09060-1, 10540-1 and 10543-1 in the first session, following the analytical procedures similar to those described by Li et al. (2010). During analysis, the primary O_2^- ion beam was accelerated at 13 kV, with an intensity of ∼8 nA and an analytical spot size of 20 × 30 μm. In the secondary ion beam optics, a 60 eV energy window was used, together with a mass resolution of ∼5400 (at 10% peak height), to separate Pb^+ peaks from isobaric interferences. An electron multiplier was used in ion-counting mode to measure secondary ion beam intensities by peak jumping mode. Each measurement consists of 7 cycles. U–Pb isotopes and abundances were determined relative to the Phalaborwa baddeleyite standard (Heaman and LeCheminant, 1993; Heaman, 2009). The oxygen flooding technique was used, as it significantly improves the analytical precision by enhancement of the secondary Pb^+ ion yield by a factor of ∼7 (Li et al., 2010), and depresses the "crystal orientation effect" that biases the SIMS baddeleyite U–Pb analyses (Wingate and Compston, 2000). It is noted, however, the "orientation effect" cannot be entirely eliminated by using oxygen flooding (Li et al., 2010), which results in an additional 2% (1σ relative standard deviation (RSD)) uncertainty for U–Pb ages of the ∼1.3 Ga baddeleyites of this study.

On the other hand, SIMS Pb–Pb analysis gives a better precision (<1%, 1σ RSD) for dating the Mesoproterozoic baddeleyites. Thus, we carried out SIMS baddeleyite Pb–Pb analysis for samples 11062-1 and 12081-1 in the second session, with each measurement consisting of 10 cycles. The Phalaborwa standard was analyzed for correction of the instrumental mass fractionation of Pb isotopes (∼0.1%). The measured Pb isotopic compositions were corrected for common Pb using non-radiogenic ^{204}Pb. An average of present-day crustal composition (Stacey and Kramers, 1975) was used for the common Pb, assuming that the common Pb is largely surface contamination introduced during sample preparation. Concordia diagrams and weighted mean ages were produced using the program ISOPLOT/Ex 3.23.

3.3. Major and trace element geochemistry

Major elements, except FeO, were analyzed on fused glass discs by X-ray fluorescence spectrometry and FeO contents by classical wet chemical analysis at the Analytical Laboratory of the Beijing Research Institute of Uranium Geology. Trace elements (including REE) were determined by ICP-MS (PerkinElmer ELAN 6000 ICP-MS