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First Discovery of Paleoproterozoic (*ca.* 2.25 Ga) Meta-Mafic Dyke on the Northeastern Margin of the Longgang Block, North China Craton

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INTRODUCTION

Cratonization of the North China Craton (NCC) is widely accepted as having been completed by the end of the Neoarchean (*ca*.. 2.5 Ga), with the NCC subsequently undergoing intensive rifting during the Paleoproterozoic (Zhai, 2014). Traditionally, magmatism associated with the Paleoproterozoic rifting was recorded in three tectonic belts, i.e., the Khondalite (or Fengzhen), Trans-North China Orogenic (or Jinyu), and Jiao-Liao-Ji (JLJB) belts (Zhai and Liu, 2003; Zhao and Zhai, 2013). In the JLJB, 2.2–2.1 Ga felsic and mafic magmatism is widespread throughout eastern Liaoning to southern Jilin province (Liu et al., 2018c; Xu and Liu, 2019). In contrast, little contemporaneous magmatism has been confirmed in the adjacent Longgang Block (LGB), an important component of the eastern NCC. Therefore, whether the LGB also experienced the Paleoproterozoic rifting needs to be further examined. Duan et al. (2019) recently reported a meta-mafic dyke in the Qingyuan area, in the interior of the LGB, with complicated zircon ages with groupings of *ca.* 1.84, *ca.* 2.12 and *ca.* 2.49 Ga. Of these, the *ca.* 2.12 Ga group was interpreted as representing the emplacement age of the dyke. Based on detailed field investigations, we have discovered a new Paleoproterozoic (*ca.* 2.25 Ga) meta-mafic dyke on the northeastern margin of the LGB (**Figure 1A**), which is much older than other Paleoproterozoic mafic dykes of the JLJB and LGB. The newly discovered *ca.* 2.25 Ga mafic dyke reported here may provide valuable insights into the influence of Paleoproterozoic rifting on the northeast margin of the NCC.

SAMPLES AND METHODS

Samples

Samples for geochronological and geochemical analyses were collected from the meta-mafic dyke in Luanjiajie Village (42°25′31.1″N; 124°48′50.4″E), on the northeastern margin of the NCC (**Figure 1A**). This region is divided into two distinct domains by the Qinghe Fault. The region to the south of the Qinghe Fault is dominated by Neoarchean basement of the NCC, which comprises mainly tonalite-trondhjemite-granodiorite (TTG) gneisses (**Figure 1B**); the region to the north is characterized by voluminous Jurassic-Cretaceous granitoids with minor Neoarchean xenoliths (**Figure 1B**). Several Permian-Trassic granitoids and associated volcanic-sedimentary rocks are distributed along the Qinghe Fault (**Figure 1B**). Pre-Jurassic rocks on both sides of the Qinghe Fault are intensively deformed. The newly identified meta-mafic dyke is ~3 m wide and intrudes the Neoarchean TTG gneisses roughly along foliations (**Supplementary Figures S1A,B**). The dyke comprises meta-gabbro containing mineral assemblages of plagioclase (45%), orthopyroxene (25%),

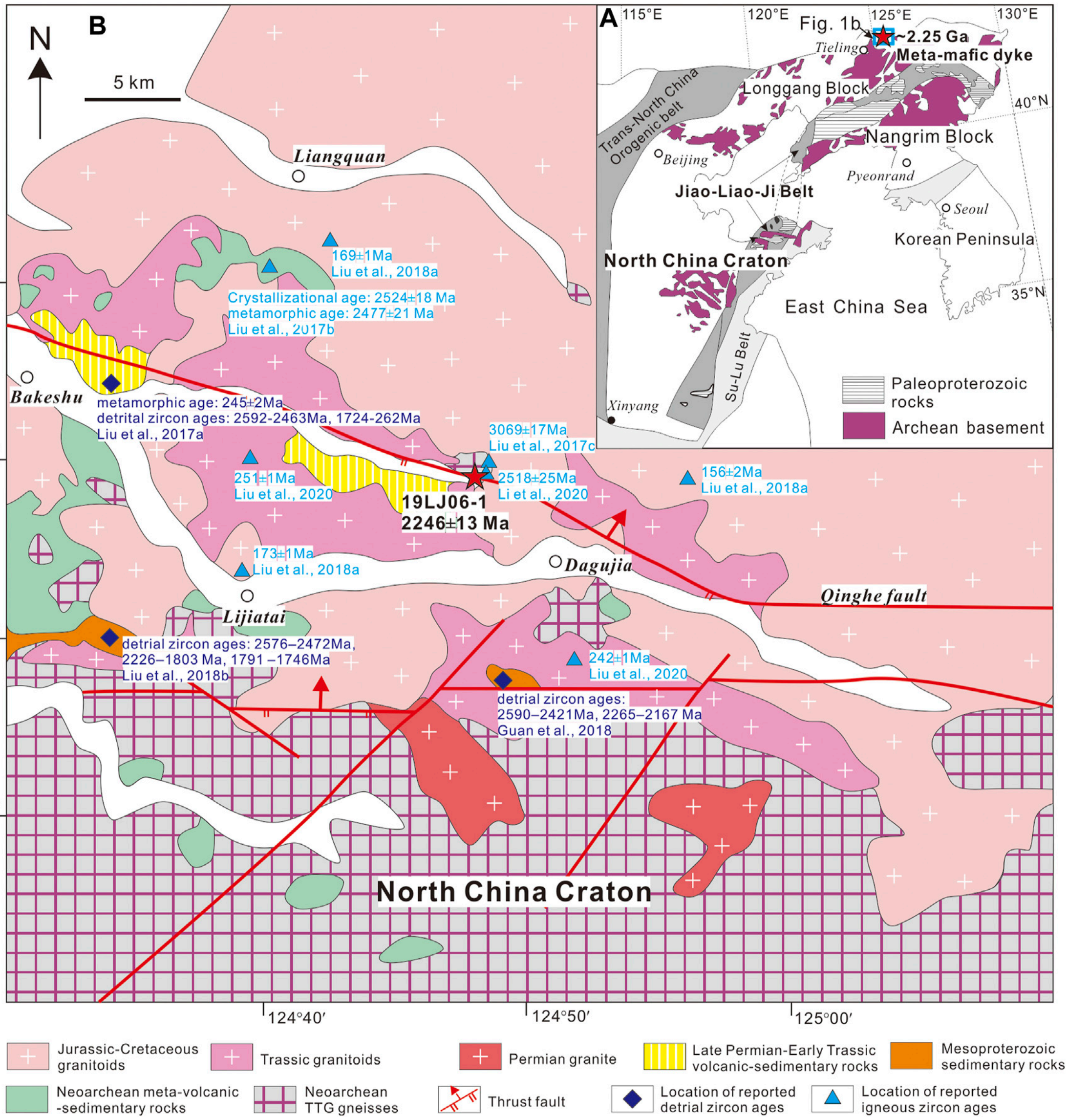

FIGURE 1 | (A) Sketch map showing tectonic unites of the eastern North China Craton (after Zhao and Zhai, 2013); **(B)** Geological map of the study area (reported ages are from Liu et al., 2017a; Liu et al., 2017b; Liu et al., 2017c; Liu et al., 2018a; Liu et al., 2018b; Guan et al., 2019; Li et al., 2020; Liu et al., 2020).

clinopyxene (15%), hornblende (10%), minor quartz (2%), and other accessory minerals (3%, e.g., magnetite and zircon) (**Supplementary Figures S1C,D**). The major minerals are subhedral with grain sizes of 0.2–1 mm.

Methods

Major- and trace-element analyses were undertaken at Tuoyan Testing Technology Co., Ltd, Guangzhou, China. Fresh samples were crushed to centimetre-sized pieces, and fresh pieces were selected and powdered to <200 mesh in an agate mill. The powder was fluxed with $Li_2B_4O_7$ (1:8) at 1,250°C to make homogeneous glass disk using a V8C automatic fusion machine. The glass disk was then analyzed for major elements by X-ray fluorescence spectrometry using an XRF-1800. The sample powder for trace-element analysis was dissolved in distilled HF + HNO_3 in a screw-top Teflon beaker for 4 days at 100°C before analysis of the solution by inductively coupled plasma–mass spectrometry (ICP–MS; Agilent 7500A). Analytical precision and accuracy based on multiple analyses of standard materials GSR-3, GSD-4, GSD-6, OU-6, GSR-12, and GSR-13 were better than 5% and 10% for major and trace elements, respectively.

Zircon separation was carried out at Chengxin Geological Service Co., Ltd., Langfang, China. The fresh sample was firstly ground to 40 mesh, and the powders were separated into the light and heavy fractions. After magnetic selection and electromagnetic filter, the heavy fraction was dominated by non-magnetic minerals, from which zircons were obtained by heavy-liquid separation. Zircons were hand-picked under a

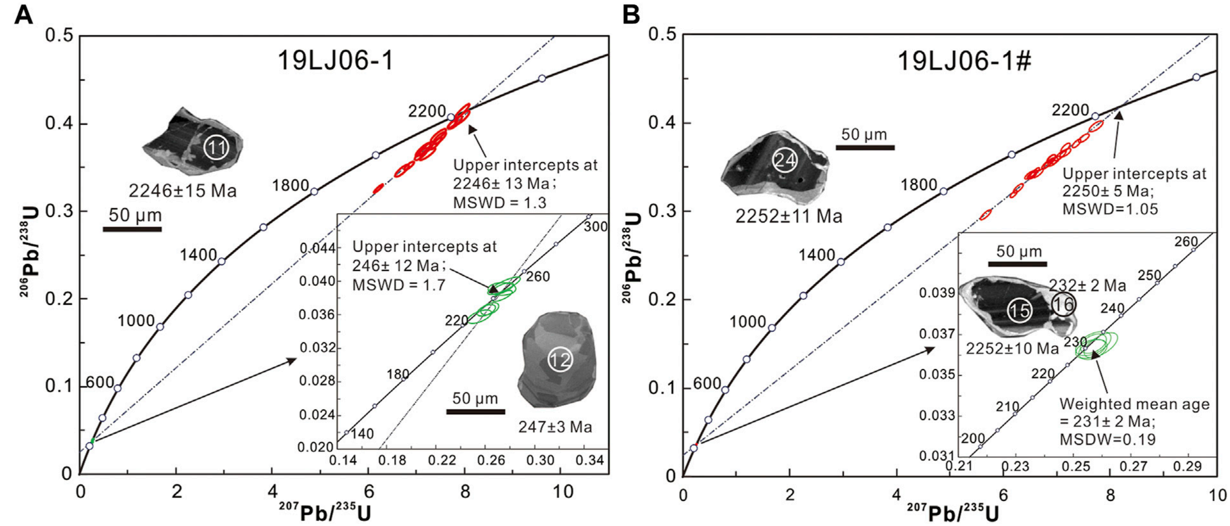

FIGURE 2 | Zircon U–Pb Concordia diagrams and typical CL images for the *ca.* 2.25 Ga meta-mafic dyke.

binocular microscope, mounted in epoxy resin and polished to approximately half thickness for cathodoluminescence (CL) imaging to reveal internal structures. CL images were obtained using a Quanta 200 field-emission environmental scanning electron microscope (FE-SEM) at Nanjing Hongchuang GeoAnalysis, Nanjing, China. U-Pb dating of samples 19LJ06-1 and 19LJ06-1# were conducted by laser-ablation (LA)–ICP–MS at Yandu Zhongshi Geological Analysis Laboratories, Beijing, China, using a GeoLas 2005 laser (beam diameter 24 μm) attached to an Agilent 7500 ICP–MS instrument. Each analysis involved background acquisition of 20–30 s (gas blank) followed by 50 s of sample data acquisition. Standard zircons 91,500 and Plesovice were used for external standardization of U/Pb ratios and calibration of instrumental mass deviation, being analyzed once for every four and eight zircon analyses respectively. Weighted mean $^{206}Pb/^{238}U$ ages for the 91,500 and Plesovice zircons were consistent with recommended values of 1,065.4 ± 0.6 Ma (Wiedenbeck et al., 1995) and 336.86 ± 0.76 Ma (Solari et al., 2010), respectively. Calibrations involved ICPMSDataCal software (Liu et al., 2008), and Concordia diagrams and weighted mean ages were processed using Isoplot 4.15 (Ludwig, 2012).

DISCUSSION AND CONCLUSION

Results of geochemical analysis and zircon U-Pb dating are listed in **Supplementary Table S1** and **Supplementary Table S2**. The amphibolite sample has low SiO_2 (50.2 wt%), high MgO (8.44 wt %), and ΣFe_2O_3 (7.34 wt%) contents. The sample displays enrichment in compatible elements (e.g., Cr, Co, Ni, V) and large-ion lithophile elements (e.g., Rb, Ba, K, and Sr), but depletion in high-field-strength elements (e.g., Nb, Ta, Ti, and P), with a low La_N/Yb_N ratio (5.29) and slightly negative Eu anomaly (Eu/Eu* = 0.97). These features indicate that the magma of the amphibolite had a mantle origin, possibly undergoing crustal contamination during ascent.

Zircons of sample 19LJ06-1 can be divided into two groups based on CL images. Group#1 has obvious core-rim structures, with the cores being relatively dark and most displaying wide oscillatory zoning with high Th/U ratios (0.37–1.80, barring two of 0.13 and 0.22), indicating a magmatic origin. Fourteen core analyses yielded $^{207}Pb/^{206}Pb$ ages of 2,265–2,199 Ma (**Supplementary Table S2**) with an upper intercept age of 2,246 ± 13 Ma (**Figure 2A**). Zircon rims of group#1 are structureless and luminous, with most being too narrow for analysis. Group#2 zircons display sector zoning or lack of internal textures, indicating a metamorphic origin. These metamorphic zircons have $^{206}Pb/^{238}U$ ages of 250–227 Ma with an upper intercept age of 246 ± 12 Ma (**Figure 2A**). Zircons of sample 19LJ06-1# are similar to those of sample 19LJ06-1. Zircons with core-rim structures were selected for analysis. Despite of the pronounced Pb loss, 19 zircon core analyses yielded clustered $^{207}Pb/^{206}Pb$ ages of 2,252–2,211 Ma with an upper intercept age of 2,250 ± 5 Ma (**Figure 2B**). Five analyses of the rims yield a weighted mean age of 231 ± 2 Ma (**Figure 2B**), consistent with the metamorphic ages of sample 19LJ06-1. Zircon cores of the meta-mafic dyke may have been captured from country rock during magma ascent, although other geological evidence discounts that possibility. As shown in **Supplementary Figure S1**, the meta-mafic dyke intruded the surrounding *ca.* 2.5 Ga TTG gneiss. If the zircons of the dyke were captured from the country rock, they would have ages of *ca.* 2.5 Ga rather than *ca.* 2.25 Ga. In addition, only a small amount of *ca.* 2.2 Ga zircons have been reported from Mesoproterozoic sedimentary rocks (Liu et al., 2018b; Guan et al., 2019; **Figure 1B**). Nonetheless, these Mesoproterozoic sedimentary rocks were dominated by the *ca.* 2.5 Ga detrial zircons rather than *ca.* 2.2 Ga zircons. The relatively clustered zircon ages of *ca.* 2.2 Ga and the lack of any *ca.* 2.5 Ga zircons preclude the possibility that the zircons of the meta-mafic dyke were captured from sedimentary rocks. Furthermore, the meta-mafic dyke itself could be a potential source for the *ca.* 2.2 Ga zircons of Mesoproterozoic strata. To sum up, we propose that the *ca.* 2.25 Ga zircon-core age represents the crystallization age of the meta-mafic dyke. The metamorphic age (*ca.* 240 Ma) is consistent with the timing of regional metamorphism related to closure of the Paleo-Asian Ocean (Liu et al., 2017a). The *ca.* 2.25 Ga meta-mafic dyke is obviously older than the ca. 2.20–2.16 Ga A-type granitoids and *ca.* 2.15–2.10 Ga mafic dykes from the JLJB (Xu and Liu, 2019), which are regarded as indicators of the Paleoproterozoic rifting in the eastern NCC. Thus, we suggest that the *ca.* 2.25 Ga mafic dyke might represent a magmatic event independent of the successive event in the JLJB. The *ca.* 2.25 Ga mafic dyke suggests that the northeastern margin of the NCC was also influenced by Paleoproterozoic rifting, and the timing of initial extension or rifting on the northeastern margin is earlier than that in the JLJB.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

ZL, XS, JL, and ZL contributed to conception and design of the study. ZL and HY organized the database. ZL and JL wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2021.796618/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.