2.8–1.7 Ga history of the Jiao-Liao-Ji Belt of the North China Craton from the geochronology and geochemistry of mafic Liaohe meta-igneous rocks

Kaj Hoernle a,b,⁎, Bruce Schaefer c, Sanzhang Li d, Folkmar Hauff a, Xiyaol Li d, Dieter Garbe-Schönberg b, Ruixin Zhang d, Yiming Liu d

⁎ Corresponding author at: GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstr. 1-3, 24148 Kiel, Germany.
E-mail address: khoernle@geomar.de (K. Hoernle).

1. Introduction

Archean to Paleoproterozoic terranes record protracted periods of crustal formation, lithospheric stabilization, subsequent orogenesis and early history of plate tectonics. The inevitably poly-deformed nature of the oldest cratonic regions on Earth requires multiple geochronological and geochemical tools in order to unravel the complete and complex history of lithospheric formation, stabilization, crustal differentiation and subsequent reworking through subduction and orogenesis. Zircon geochronology employing U–Pb and Lu–Hf isotope systems has emerged as the most widely used tool for tracing parts of these processes; however, information derived from such studies is through necessity limited to stages of the orogenic cycle in which zircon grows or is recrystallized. This leaves significant portions of the geologic record, particularly those involving mafic rocks, underrepresented and effectively unsampled. Hence integration of complementary isotopic techniques to constrain the timing, onset and duration of processes acting upon Precambrian lithosphere is required. Critically, mafic and ultra-mafic rocks represent significant portions of the Precambrian record and offer links between the early crust, the mantle (both lithospheric and asthenospheric) from which it is derived, and its subsequent amalgamation into cratons (e.g. Manikyamba and Khanna, 2007; Hawkesworth et al., 2010; Naeraa et al., 2012; Zhao and Zhai, 2013).

The North China Craton is one of the oldest cratons on Earth, containing rocks ≥3.8 Ga (e.g. Liu et al., 1992; Song et al., 1996). It is subdivided into micro-continental blocks (Li et al., 2018) by three Paleoproterozoic mobile/orogenic belts: 1) the Khondalite Belt within the Western Block, 2) the Trans-North China Orogen separating the Eastern and Western Blocks and 3) the Jiao-Liao-Ji Belt (JLJB) within the Eastern Block (Fig. 1A).
The Khondalite Belt separates the Western Block into the Yinshan (NW) and Ordos (SE) blocks and presumably formed through the collision of the two smaller blocks at ~1.85 Ga (e.g. Zhao et al., 2002a, 2002b, 2005; Xia et al., 2006; Santosh et al., 2007). The Trans-North China Orogen separates the Western and Eastern blocks and resulted from their collision and amalgamation at ~1.85 Ga (e.g. Zhao et al., 1998, 1999, 2000, 2001a, b, 2002a, b, 2003, 2004, 2005, 2006a, b, 2010, 2012, 2013; Zhai et al., 1993, 2000, 2005; Zhai and Liu, 2003; Kröner et al., 1998, 2005, 2006; Guan et al., 2002; Guo et al., 2002, 2005; Xing et al., 2006, 2007; Zhao, 2009; Santosh, 2010; Zhai, 2011; Zhai and Santosh, 2011; Li et al., 2010, 2012; Wang et al., 2013; Santosh et al., 2013, 2015; Li and Santosh, 2018). The JLJB divides the Eastern Block into the Longgang (NW) and Liaonan-Nangrim (SE) blocks, but its origin and tectonic evolution remain controversial despite a large number of recent studies on the belt (Shen and Hu, 1986; Jiang, 1987; Zhang and Yang, 1988; Yang et al., 1988; Jahn et al., 2008; LBGMR, 1989; Wang and Yan, 1992; Liu et al., 1992; Hu, 1992; Sun et al., 1993, 1996; Cao, 1996; Yu, 1996; Liu and Li, 1996; Lu, 1996; Li et al., 1996; Paek and Jon, 1996; Kim and Jon, 1996; Wang et al., 1997; Li and Yang, 1997; Chen et al., 2001; Li et al., 2001a, 2001b, 2005a, 2005b, Li et al., 1997a, 1997b; Li et al., 2011a, 2011b; Li and Zhao, 2007; Lin et al., 1998; Xu et al., 1998; Liu et al., 1998; Xu et al., 1998; Xie et al., 2011; Zhou et al., 2003, 2005, 2006; Zhou et al., 2008a, b; Cai et al., 2002; Kim and Cho, 2003; Hao et al., 2004; Wu et al., 2013, 2014; Tan et al., 2005, 2012; SDICMR, 2005; Tan et al., 2005, 2006, 2011, 2012; Li and Zhao, 2007; Tam et al., 2011, 2012a, b, c; Zhao and Zhai, 2013; Liu et al., 2013a, b; Zhao et al., 2010, 2011, 2012; Lu et al., 2004a, b, 2005, 2006; Lu et al., 2008; Wu et al., 2013, 2014; Meng et al., 2014; Liu et al., 2017a, 2017b, 2018a, 2018b, 2019a, 2019b; Zhou et al., 2001, 2003, 2005, 2006; Zhou et al., 2008a; Zhang et al., 2018; Oh et al., 2019; Xu et al., 2018a, 2018b, 2020; Xu and Liu, 2019; Lee et al., 2019). Models for explaining the origin of the JLJB include: 1) opening (at ~2.2 Ga) and closing (at ~1.9 Ga) of an intracontinental rift (Zhang and Yang, 1988; Li et al., 2004, 2005a, 2005b, 2006, 2012; Luo et al., 2004, 2006 and Li and Zhao, 2007; Li et al., 2012), 2) arc-continent collision (Bai, 1993; Fauré et al., 2004; Lu et al., 2006), and 3) a combination of the two previous scenarios with intracontinental rifting progressing to formation of a new ocean basin or back-arc basin, which was subsequently closed by subduction (Zhao et al., 2011; Zhao and Zhai, 2013; Zhang et al., 2018; Xu and Liu, 2019). Integrated studies considering geochronology, metamorphic and igneous petrology, geochemistry, structural geology and crustal structure are necessary to distinguish between these models.

Here we present new whole rock geochemical and isotopic data from the mafic/ultramafic metamorphic rocks (amphibolites, hornblendites, anthophyllite-rich rock and metagabbro) in the North Liaohe Group (and one sample from the South Liaohe Group) of the JLJB on the Liaodong Peninsula (Figs. 1B and 2). Whole rock analysis potentially allow access to portions of the geologic record that are not accessible through zircons alone, since they effectively sample a larger chemical equilibration volume and are potentially robust on the centimeter to meter scale despite high grade metamorphism and metasomatism. Further, integrated whole rock analysis of mafic rocks across a terrane potentially allows insights into mantle (lithospheric and asthenospheric) processes operating on the regional scale. Application of whole rock data in the context of existing zircon geochronology therefore offers a powerful tool for resolving the time-integrated thermal evolution of the terrane and construction of geodynamic models.

Hence, through integration of previously published results from the entire JLJB with our new whole rock geochronological and geochemical data from mafic/ultramafic meta-igneous rocks, we present a new model for the geodynamic evolution of the JLJB from ~2.8–1.7 Ga.

2. Regional geology

The JLJB is located in the northeastern part of the Eastern Block of the North China Craton (Fig. 1A). The northeast-southwest-trending belt is ~50–300 km wide and extends for ~1200 km from the eastern Liaoning, via the eastern Liaoning, to the eastern Shandong province. Its central segment is situated between the Archaean Northern Liaoning-Northern Jilin Complex (Longgang Block) and the Archaean Southern Liaonian-Nangrim Complex (Nangrim Block). Its southern segment stretches across the Bohai Strait into the Archaean Eastern Shandong Complex on the Jiaodong Peninsula. The geology of the JLJB is summarized by Li et al., 1996, 2006, Li et al., 2011a, 2012; Li et al., 1997a; Li et al., 1997b, Li and Zhao (2007), Liu and Li (1996), Tan et al. (2011, 2012a, b, c) and Xu and Liu (2019). The JLJB consists of deformed and metamorphosed (up to high pressure granulite facies; Zhou et al., 2004, 2008a) volcanic and sedimentary sequences, granitoid and gabbroic intrusives, and mafic dikes (Fig. 1B). The volcanic and sedimentary sequences are
referred to (going from north to south) as the Laoling and Ji’an groups in southern Jilin (Lu et al., 2004a, b, 2005) and possibly the Macheonayeong Group in North Korea, the South and North Liaoh group in eastern Liaoning, the Fenzishan and Jingshan groups, part of the Jiaobai Terrane in eastern Shandong on the Jiaodong Peninsula (Zhou et al., 2004, 2008a). The stratigraphic succession is transitional from a clastic-rich and bimodal volcanic sequence at the base through a middle carbonate-rich sequence to an upper pelitic sequence (Luo et al., 2004; Li et al., 2005a). The JLJB can be subdivided into a northern sub-belt, including the Laoling, North Liaoh and Fenzishan groups, and a southern sub-belt, including the Ji’an, South Liaoh and Jingshan groups. Faults and ductile shear zones separate these two sub-belts (Li et al., 2005a).

The Liaohe Group, in the central portion of the belt, has been subdivided (going from bottom to top) into the Langzishan, Li’eryu, Gaogiaoyu, Dashiqiao and Gaixian formations, with the lowermost Langzishan Formation only being found in the North Liaoh Group (e.g., Li et al., 2005a; Dong et al., 2019). The Ji’an Group from bottom to top is subdivided into the Maiyihe, Huangchagou and Dadongcha formations. The Liaohe Group can be divided from bottom to top into the Dataishan (Linjiagou), Zhenzhumen, Huashan, Linjiang and Dasuzi formations. The Laoling Group can be divided from bottom to top into the Mayihe, Huangchagou and Dadongcha formations. Faults and ductile shear zones separate these two sub-belts (Li et al., 2005a, 2005b, 2012; Luo et al., 2004, 2008).

3. Description of rock types

Ten mafic (amphibolites, hornblende and a metagabbro) and one ultramafic (anthophyllite-rich rock) meta-igneous rocks from the Liaoh Group were selected for geochemical analyses in this study (see Table 1 and Figs. 1, 2). They form layers, blocks or lenses in the Liaoh Group, which have intrusive or tectonic contacts with the Liaoji Granitoids (Li et al., 2005a). All but one sample are from the North Liaoh Group (Fig. 2) and the remaining sample (LH05–26–1) from the South Liaoh Group (Fig. 1B).

The amphibolites, consisting of 50–60% hornblende and 40–50% plagioclase, have undergone low- to medium-grade metamorphism (lower-amphibolite facies; 0.3–0.8 GPa; 500–700 °C; Li et al., 2001b) but extensive deformation (Li et al., 2005a). The metagabbro sample consists of ~45% pyroxene, 10% hornblende converted from pyroxene, and ~45% plagioclase and shows evidence of lower-grade metamorphism (lower-greenschist facies; 0.3–0.5 GPa; 350–450 °C; Li et al., 2001b). The hornblende, consisting of ~90% hornblende and ~10% plagioclase, show signs of medium-grade metamorphism (lower-amphibolite facies; 0.4–1.0 GPa; 500–650 °C; Li et al., 2001b). The anthophyllite-rich rock consists of 90% anthophyllite amphibole (lower-amphibolite facies; 0.3–0.8 GPa; 550–650 °C; Li et al., 2001b). Protoliths of hornblende and amphibolites were mafic (basaltic) volcanic rocks, whereas the anthophyllite-rich rock was most likely derived from an ultramafic protolith (possibly pyroxenite).

4. Analytical methods (major and trace element and isotope ratios)

Major and trace element data are shown in Table 1, Sr-Nd-Hf isotope data in Table 2, and Pb isotope data in Table 3. Major elements and selected trace elements (V, Zn, Ba, Sr and Zr) were determined on a Phillips X’Unique PW1480 X-ray fluorescence spectrometer.
TiO2, MgO and CaO in JB-1, V, Zn, Ba, Sr and general generally deviate by infrared photometry on a Rosemount CSA 5003. Values determined on reference samples JB-2, JB-3, JA-2 and JR-1, measured along with the samples, lie within 5% of Jochum et al. (2016) for JB-2 and JA-2 and Govindaraju (1994) for JB-3 and JR-1 for the major elements, except MnO in JB-2, and at several tenth weight percent of MgO and CaO in JB-2. Refer to Table 1 for XRF standard materials see Appendix A2.

| Sample | Rock Type | 011–1 | 012–1 | 013–2 | 014–7 | 016–1 | 026–1 | 034–1 | 034–1* | 035–4 | 035–7 | 038–1 | 040–1 |
|--------|-----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|        | amph.     | amph. | anphy. | amph. | m-gab. | bbl.  | bbl.  | bbl.  | bbl.  | bbl.  | bbl.  | bbl.  | bbl.  |
| XRF    |           |       |        |       |       |       |       |       |       |       |       |       |       |
| SiO2   | 50.69     | 54.86 | 40.51  | 57.58 | 49.71 | 49.49 | 49.29 | 49.22 | 49.26 | 49.59 | 49.39 | 42.92 | 49.26 |
| TiO2   | 0.95      | 0.51  | 0.23   | 0.68  | 1.22  | 1.25  | 2.96  | 2.14  | 1.52  | 1.38  | 1.02  | 0.95  |
| Al2O3  | 13.88     | 9.51  | 4.25   | 17.16 | 13.26 | 13.49 | 12.72 | 13.2  | 12.72 | 14.22 | 12.12 | 14.22 | 12.12 |
| Fe2O3  | 12.31     | 9.4   | 13.18  | 10.69 | 14.57 | 14.76 | 21.43 | 17.6  | 17.22 | 13.96 | 13.09 | 13.96 | 13.09 |
| MnO    | 0.2       | 0.18  | 0.16   | 0.05  | 0.18  | 0.23  | 0.26  | 0.19  | 0.18  | 0.18  | 0.21  | 0.18  | 0.21  |
| MgO    | 7.85      | 11.92 | 28.47  | 3.51  | 7.09  | 7.41  | 3.98  | 5.97  | 6.02  | 7.24  | 10.59 | 6.02  | 7.24  |
| CaO    | 10.81     | 9.79  | 2.41   | 2.28  | 9.64  | 8.36  | 8.99  | 6.58  | 7.43  | 10.39 | 10.29 | 7.43  | 10.39 |
| Na2O   | 2.36      | 1.52  | <0.01  | 1.45  | 2.53  | 2.46  | 2.24  | 1.73  | 2.09  | 1.55  | 2.4   | 1.73  | 2.09  |
| K2O    | 0.55      | 0.11  | 0.01   | 0.53  | 0.78  | 1.51  | 1.18  | 2.14  | 0.75  | 0.95  | 0.12  | 0.95  | 0.12  |
| P2O5   | 0.07      | 0.07  | 0.12   | 0.07  | 0.12  | 0.12  | 0.15  | 0.23  | 0.35  | 0.15  | 0.07  | 0.35  | 0.15  |
| V      | ppm       | 355   | 391    | 95     | 105   | 90    | 120   | 137   | 137   | 137   | 137   | 137   | 137   |
| Zn     | ppm       | 83    | 69     | 96     | 87    | 64    | 116   | 97    | 78    | 108   | 91    | 108   | 91    |
| Ba     | ppm       | 118   | 226    | 42     | 624   | 129   | 438   | 651   | 130   | 139   | 8     | 139   | 8     |
| Sr     | ppm       | 199   | 126    | 25     | 449   | 158   | 314   | 110   | 130   | 204   | 94    | 204   | 94    |
| Zr     | ppm       | 52    | 64     | 28     | 135   | 86    | 79    | 167   | 133   | 116   | 67    | 116   | 67    |
| H2O    | ppm       | 1.53  | 1.93   | 9.34   | 1.89  | 1.97  | 2.17  | 1.58  | 3.04  | 1.77  | 1.45  | 1.77  | 1.45  |
| CO2    | ppm       | 0.03  | 0.04   | 0.75   | 0.07  | 0.05  | 0.13  | 0.47  | 0.2   | 0.33  | 0.21  | 0.04  |
| TOTAL  | ppm       | 101.33| 100.92 | 99.60  | 101.07| 101.24| 101.55| 101.54| 101.14| 101.70| 101.44| 101.00| 101.00|

Solution ICPMS analyses for trace elements were carried out on an Agilent 7500cs instrument at the Institute of Geosciences at Kiel University following the methods of Garbe-Schönberg (1993). Initial sample digestion was done in Parr® pressure digestion vessels in an oven at 120 °C for 4 days. Reference material BHVO-2, BIR-1 and JGb-2 (two dissolution) were prepared and measured along with the samples. See Appendix 3a for ICP-MS standard analyses. JGb-2 replicates at 1.7 ± 1.5% (1SD) except Zn (7.8%), Zr (21.9%) and Mo (35.2%). Sample 34–1 was replicated at 2.1 ± 1.6% (1SD) except Sc (12.7%), V (9.4%).
and 146Nd/144Nd = 0.7219 for each integration, while Pb was externally

U-Th-Pb isotopic data for the Liaohe ma

Table 3

Circa 100 mg of unleached sample powders were used for the isotope

Mo (28.3%), Cs (20.2%), Ta (94.7%), Tl (38.9%) and Pb (48.2%).

errors of NBS981 (n = 195) are ~200 ppm / amu and translate to 2SD errors of 0.0445%, 0.0607% and 0.0797% for 206Pb/204Pb, 207Pb/204Pb and 208Pb/204Pb respectively. 143Sm/144Nd and 180Hf/177Hf sample ratios are reported relative to 143Sm/144Nd = 0.710250 ± 0.000006 (n = 5; 2SD) for NBS987 and 143Sm/144Nd = 0.511850 ± 0.000006 (n = 10; 2SD) for La Jolla. Hf chemistry followed the methods of Blichert-Toft et al., 1997, and 176Hf/177Hf was determined on a Nu-Plasma MC-ICPMS at GEOMAR. The long-term (2011–2018) standard bracketing normalized value of the in-house Hf SPEX CertiPrep ™ solution is 176Hf/177Hf = 0.282170 ± 0.000006 (2SD, n = 553) corresponding to 176Hf/177Hf = 0.282163 for JMC475. Sr-Nd-Hf-Pb replicate analysis of LH05-040-1 lie within 2SD of the standards (Tables 2 and 3). Age calculations were conducted using a root sum of squares approach to propagate the external 2SD of the isotopic standards and a conservative 5% 2 sigma error from parent/daughter ratios. For regressions that returned MSWD values which were less than the appropriate value for the number of samples in the regression (typically MSWD = 1.89 for n = 10) no further error magnification was applied. For those above the target

Table 2

Sr-Nd-Hf isotopic data for the Liaobe mafic/ultramafic rocks. Abbreviations: anthoph. = anthophyllite, amph. = amphibolite, m-gab. = metagabbro, hbl. = hornblende.

Table 3

U-Th-Pb isotopic data for the Liaobe mafic/ultramafic rocks. Abbreviations: anthoph. = anthophyllite, amph. = amphibolite, m-gab. = metagabbro, hbl. = hornblende.

and Cr (11.1%). See Appendix 3b for details of sample replicates. The accuracy of BIR-1 lies within 4.0 ± 2.6% (1SD) of the preferred GeoReM values of Jochum et al. (2016) except Ti (67.1%) and U (29.1%). For BHVO-2 deviations of 1.5 ± 1.1% (1SD) from compiled GeoReM values are observed (http://georem.mpch-mainz.gwdg.de/). Larger deviations exist for Nb (47.6%), Sr (6.0%), Mo (10.1%), Hf (6.9%), Ta (9.2%) and Th (5.9%). For the less well characterized JGb-2 material, deviations of 8.7 ± 5.6% (1SD) are observed from compiled GeoReM values (http://georem.mpch-mainz.gwdg.de/). See Appendix 3b for details of sample replicates. The accuracy of the 207Pb/204Pb isotope ratios is 1.5 ± 1.1% (1SD) from GeoReM values.

The precision of the Sr-Nd-Hf isotope data for the Liaobe ma

vet/144Nd = 0.512417 ± 0.000006 for each integration, while Pb was externally

and 146Nd/144Nd = 0.7219 for each integration, while Pb was externally

U-Th-Pb isotopic data for the Liaohe mafic/ultramafic rocks. Abbreviations: anthoph. = anthophyllite, amph. = amphibolite, m-gab. = metagabbro, hbl. = hornblende.

and 146Nd/144Nd = 0.7219 for each integration, while Pb was externally

and 146Nd/144Nd = 0.7219 for each integration, while Pb was externally

176Hf/177Hf = 0.282170 ± 0.000006 (2SD, n = 5; 2SD) for NBS987 and 143Sm/144Nd = 0.511850 ± 0.000006 (n = 10; 2SD) for La Jolla. Hf chemistry followed the methods of Blichert-Toft et al., 1997, and 176Hf/177Hf was determined on a Nu-Plasma MC-ICPMS at GEOMAR. The long-term (2011–2018) standard bracketing normalized value of the in-house Hf SPEX CertiPrep ™ solution is 176Hf/177Hf = 0.282170 ± 0.000006 (2SD, n = 553) corresponding to 176Hf/177Hf = 0.282163 for JMC475. Sr-Nd-Hf-Pb replicate analysis of LH05-040-1 lie within 2SD of the standards (Tables 2 and 3). Age calculations were conducted using a root sum of squares approach to propagate the external 2SD of the isotopic standards and a conservative 5% 2 sigma error from parent/daughter ratios. For regressions that returned MSWD values which were less than the appropriate value for the number of samples in the regression (typically MSWD = 1.89 for n = 10) no further error magnification was applied. For those above the target

Table 2

Sr-Nd-Hf isotopic data for the Liaobe mafic/ultramafic rocks. Abbreviations: anthoph. = anthophyllite, amph. = amphibolite, m-gab. = metagabbro, hbl. = hornblende.

Table 3

U-Th-Pb isotopic data for the Liaobe mafic/ultramafic rocks. Abbreviations: anthoph. = anthophyllite, amph. = amphibolite, m-gab. = metagabbro, hbl. = hornblende.
MSWD, the error has been multiplied by the square root of the MSWD, highlighting additional sources of error beyond analytical uncertainty. See Table 4 for further discussion regarding the MSWD.

5. Results

5.1. Major and trace element compositions for the Liaohe mafic-metamorphic rocks

The amphibolites, excluding sample LH05–14–7, generally have higher SiO₂ (49.3–54.9 wt%), MgO (7.2–11.9 wt%) and CaO (7.2–10.8 wt%) but lower FeO (8.5–13.3 wt%) and TiO₂ (0.5–1.4 wt%) than the higher-grade metamorphic hornblendites (SiO₂ = 45.5–49.4 wt%; MgO = 4.0–6.9 wt%; CaO = 6.6–9.0 wt%; FeO = 15.5–19.3 wt%; TiO₂ = 1.5–3.0 wt%). The composition of the metagabbro is similar to that of the amphibolites (SiO₂ = 49.7 wt%; MgO = 7.1 wt%; FeO = 13.1 wt%; CaO = 9.6 wt%; TiO₂ = 1.2 wt%). No systematic differences exist between the aforementioned rock types in Al₂O₃ (9.5–14.2 wt%), Na₂O (1.5–2.5 wt%) and K₂O (0.1–2.1 wt%). All of the samples have basaltic whole rock compositions. Amphibolite sample LH05–14–7 has a distinct composition from the other amphibolites, metagabbro and hornblendites, displaying the highest SiO₂ (57.6 wt%), Al₂O₃ (17.2 wt%) and K₂O (5.4 wt%), lowest MgO (3.5 wt%) and CaO (2.3 wt%), and second lowest FeO (9.6 wt%) and TiO₂ (0.7 wt%). It has an andesitic type chemical composition. Compared to all other samples, the anthophyllite-rich rock has the lowest SiO₂ (40.5 wt%), Al₂O₃ (4.2 wt%), TiO₂ (0.2 wt%) and nearly the lowest CaO (2.4 wt%) but highest MgO (28.5 wt%) and intermediate FeO (13.2 wt%).

The Liaohe mafic rocks generally show relative enrichments in fluid-mobile elements, such as C₆, Ba, K and Pb (Fig. 3). The only exception is the anthophyllite-rich rock, which has relative depletions in Rb, Ba, K and Sr. These elements are likely to have been removed during metamorphism. All samples show distinct relative depletion in Nb and Ba, K and Sr. These elements are likely to have been removed during metamorphism. All samples show distinct relative depletion in Nb and Sr (n = 10). Tremolite LH-05-012-2 not included in regressions. Isochron plots in Fig. 4–6. Abbreviations: conv = conventional; inv. = inverse.

### Table 4

Summary of whole rock isochron data for the Liaohe mafic-ultramafic units. All regressions based on bomb dissolution including at least one duplicate (n = 1) with the exception of Sr (n = 10). Tremolite LH-05-012-2 not included in regressions. Isochron plots in Figs. 4–6. Abbreviations: conv = conventional; inv. = inverse.

| System          | Age ±2 SE initial ±2SE | MSWD | ±2SE no MSWD* |
|----------------|------------------------|------|--------------|
| 147Sm–144Nd     |                        |      |              |
| Ga              | 2.833 ±0.180           | 0.50935 | 0.00399 | 1.2 | 0.180 |
| 176Lu–177Hf     | 2.251 ±0.310           | 0.28141 | 0.00029 | 1.3 | 0.310 |
| 207Pb–206Pb conv| 1.865 ±0.599           | 0.434 | 0.090 |
| 207Pb–206Pb inv| 1.824 ±0.019           | 0.1115 | 0.0068 | 1.2 | 0.019 |
| 232Th–238U Pb   | 1.699 ±1.711           | 0.367 | 1.2 | 0.178 |
| 235U–238U Pb    | 1.671 ±0.058           | 0.70404 | 0.00120 | 2.3 | 0.039 |
| 235U–238U Pb    | 1.636 ±2.911           | 15.6 | 0.2 | 0.179 |
| 235U–238U Pb    | 1.534 ±5.044           | 17.4 | 1.7 | 0.262 |

* for regressions of 11 samples, the target MSWD = 1.89, as based upon the ratio of the minimization parameter (S) and the degrees of freedom in the system (2). Standard practice has been to multiply the error of the regression by the square root of the MSWD when the regressions return a MSWD target, hence reflecting the greater uncertainty within the regression than implied by the assigned analytical uncertainties. We include here for reference the associated errors which have not had the a priori MSWD multiplication, since there may be non-geological sources of error and hence the non-corrected errors allow some sense of “errorchron” age ranges beyond the conventional statistical evaluation.

5.2. Sm–Nd, Lu–Hf, U-Th-Pb and Rb–Sr age data for the Liaohe mafic meta-igneous rocks

Whole rock regressions have been conducted for 147Sm–144Nd (Fig. 4A), 176Lu–177Hf (Fig. 4B), 207Rb–206Sr (Fig. 5), 207Pb–206Pb (Fig. 6), 235U–238U (Appendix 4A), 235U–207Pb (Appendix 4B), and 232Th–208Pb (Appendix 4C), excluding the sample LH05 012–2 (anthophyllite-rich rock). The results are summarized in Table 4.

In summary, 147Sm–144Nd preserves a whole rock isochron age (Fig. 4A), which predates the age of the surrounding sedimentary package in which the mafic igneous rocks are hosted. The 10 mafic metamorphic Liaohe samples yield a bulk-rock Sm–Nd isochron age of 2.83 ± 0.18 Ga, an initial 143Nd/144Nd ratio of 0.50935 ± 0.00039 (MSWD of 1.2). cNd(2.83 Ga) ranges from +1.52 to +5.89 with one sample having a value of +6.38.

The 176Lu–177Hf bulk rock isochron of 2.25 ± 0.31 Ga (Fig. 4) lies just outside of the 2 sigma error of the Sm–Nd age but covers the age range of the related granites (2.2–2.0 Ga) based on zircon age dating (e.g. Zhou et al., 2008a, b). The initial 176Hf/177Hf = 0.28141 ± 0.00029 and εHf(2.25 Ga) range from +0.85 — +8.48 with the majority around +3.5—4.5.

The 207Rb–206Sr system preserves a near isochronous relationship (MSWD = 2.3) at 1671 ± 58 Ma with an initial ratio of 0.70404 (Fig. 5). This initial ratio is relatively radiogenic and is consistent with derivation from a metamorphic or reset isochron.

An inverse 207Pb–206Pb isochron diagram yields a precise age of 1824 ± 19 Ma (MSWD = 1; Fig. 6), whereas a conventional Pb–Pb isochron yields a far less precise, but overlapping age of 1.87 ± 0.60 Ga (MSWD = 44). Given the radiogenic nature of the measured ancient Pb isotopes and the correspondingly highly correlated errors and relatively low 206Pb abundances, the inverse isochron approach is generally the favored for samples of this antiquity, and in the following discussion we consider this isochron as the preferred Pb–Pb isotope age in this sample suite.

Not surprisingly, U-Th-Pb isochron diagrams display varying degrees of open system behavior. Both U and Th are geochemically very different to Pb, and hence metamorphism and metasomatism will readily fractionate the parent element from the daughter. Nevertheless, all systems preserve broadly linear arrays with slopes corresponding to ~1.70, 1.64 and 1.53 Ga for 235U–238U Pb versus 207Pb–208Pb, 235U–207Pb versus 207Pb–208Pb, and 232Th–208Pb versus 238U–208Pb respectively. The very high MSWD’s for these regressions render propagation of errors on the ages of these regressions as geologically meaningless, however the simple errors generated by the spread of the data in the arrays (of the order of ~0.20 Ga) allow for these ages to reflect either cooling of the terrane or a subsequent, very young event, which only partially reset the U-Th-Pb system.

6. Discussion

6.1. Constraints on the age of formation and metamorphism of the Liaohe mafic meta-igneous rocks

The Liaohe mafic meta-igneous rocks form good positive linear correlations on the Sm–Nd, Lu–Hf, Rb–Sr and inverse 207Pb–206Pb isochron diagrams. Linear correlations on these isotope diagrams can either represent: 1) isochrons (or pseudo-isochrons) formed through radioactive decay of parent to daughter isotopes over extended time periods, or 2) two-component mixing in young samples or age-corrected older samples. Positive linear correlations of the measured isotopic composition on all isotope correlation diagrams in these presumed Paleoproterozoic rocks point to radiogenic ingrowth having formed these arrays, in particular since the linear arrays on all isotope correlation diagrams have positive slopes. Two-component mixing could also generate linear negative correlations. In addition, the Pb isotope ratios are more extreme than any
Phanerozoic rocks that we are aware of and thus are likely to reflect radiogenic ingrowth of U and Th rather than two-component mixing. As discussed below, zircons dated from other rocks in the Jiao-Liao-Ji

Fig. 3. Incompatible multi-element diagram showing the ten mafic meta-igneous (amphibolites, hornblendites and meta-gabbro) and one meta-ultramafic (anthophyllite-rich) rocks. Note the distinct negative Nb-Ta anomalies (troughs) and positive anomalies (peaks) for most fluid-mobile elements, such as Rb, Ba, K and Pb, in the incompatible-element patterns for the Liaohe rocks, in contrast to the positive anomalies (peaks) for Nb-Ta and lower concentrations of fluid-mobile elements in the incompatible-element patterns for normal mid-ocean-ridge basalt (N-MORB), enriched mid-ocean ridge basalt (E-MORB) and ocean island basalt (OIB) patterns. These geochemical features point to generation of the Liaohe mafic melts in a subduction-zone setting rather than at an ocean spreading center (MOR) or in an intraplate tectonic setting. Abundances are normalized to primitive mantle after Hofmann, 1988. Reference patterns for ocean island basalt (OIB), normal mid ocean ridge basalt (N-MORB) and enriched (E-) MORB after Sun & McDonough, 1989.

Fig. 4. a) Whole-rock Sm–Nd and b) whole-rock Lu–Hf isochrons for the Liaohe mafic rocks. For symbols see Fig. 3.

Fig. 5. Whole-rock Rb–Sr isochron diagram for the Liaohe mafic rocks. For symbols see Fig. 3.

Fig. 6. Inverse whole-rock Pb–Pb isochron diagram for the Liaohe mafic igneous rocks. For symbols see Fig. 3.
Beit have similar ages to those we report here for whole rocks. Alter-
ation can affect parent–daughter ratios after emplacement, espe-
cially of Rb, Sr, U and Pb; however, Sm, Nd, Lu and Hf are generally
fairly resistant to alteration and to metamorphism, through at least
amphibolite metamorphic grade. Therefore, we interpret these lin-
ear arrays to form isochrons that provide age information about the
origin and metamorphic history of the Liaohe mafic meta-igneous
rocks.

Nine of the ten samples plotting on the Sm—Nd, Rb—Sr and
207Pb/206Pb isochrons come from the North Liaohe Group and therefore
the age information strictly only applies to the North Liaohe Group. One
sample from the South Liaohe Group, however, plots on all of the posi-
tive linear arrays formed by the North Liaohe samples, suggesting that
the South Liaohe Group rocks, or at least some of them, were formed
at a similar time and experienced a similar history to the North Liaohe
Group rocks. Hence the bulk rock approach employed here explores
processes that took place on lithospheric scales.

6.1.1. Sm—Nd and Lu—Hf isochrons: formation age of the mafic meta-
igneous Liaohe rocks and their mantle source

Of the studied isotope systems, the Sm—Nd system is considered the
most robust, due to the relative immobility of Sm and Nd (e.g., Schaefer,
2016). The excellent correlation of Zr with Sm (r2 = 0.98) and Nd (r2 =
94) and between Sm and Nd (r2 = 0.96), excluding anomalous sample
LH05-14-7, suggests that late-stage processes have not mobilized these
elements. If post-emplacement mobilization due to alteration had taken
place, it is unlikely that such a good correlation would have been pre-
erved on the Sm—Nd isochron diagram. Therefore, we interpret the
2.83 ± 0.18 Ga Sm—Nd isochron age to reflect the age when Sm and
Nd were last significantly fractionated from one another.

There are two possible interpretations for the Sm—Nd isochron: 1) The age is that of eruption/emplacement of the subsequently meta-
morphosed mafic rocks, or 2) the age reflects the stabilization/isolation
of the mantle source from which these rocks were subsequently de-
uced. On a whole rock scale, the latter scenario is plausible for large de-
gres of partial melting from sources that themselves contain uniform
143Nd/144Nd and Sm/Nd ratios. In the case of Precambrian rocks, these
include previously depleted reservoirs, which have maintained closed-
system behavior from the rest of the convecting mantle for extended
periods of time. Examples of whole rock Sm—Nd isochrons preserving
ages that are hundreds of million years older than their emplacement
have been reported in the literature for quite some time - signifi-
cantly these include Archean komatites (Chauvel et al., 1985), Proterozoic
mafic dikes (Schaefer, 1998) and metamorphosed mafic and felsic in-
trusive rocks (e.g., Theriault and Ross, 1991; Zhao and McCulloch,
1995). Indeed, such occurrences are possibly relatively common; how-
ever, they are overlooked in preference to calculated model ages from
the data, or the isochrons are simply ignored as other geological con-
straints clearly rule out older isochron ages representing the time of
emplacement.

In the Liaohe mafic meta-igneous rocks, field relationships show
some intrusive contacts with the Liaoji Granitoids (dated between 2.2
and 2.0 Ga with a peak at ~2.15 Ga; Zhou et al., 2008a, b; Meng et al.,
2014; Wang et al., 2017; Zhang et al., 2018; Liu et al., 2019b) for some
of the mafic outcrops, although others may be simply tectonically inter-
leaved (Li et al., 2005a, 2005b). In any case, it is unlikely that the mafic protoliths were emplaced at ~2.83 Ga, therefore a younger emplace-
ment age of ~2.2–2.1 Ga, similar to the major age range of the Liaoji
Granitoids (e.g. Zhou et al., 2008a, b), seems to be the best age estimate
for these rocks based on stratigraphic considerations. U—Pb dating of
magnetic zircons from mafic meta-igneous rocks from the central Liao-
dong Peninsula (North Liaohe Group), similar to those studied here,
yield two age groups: 1) 2547–2493 Ma, peak at 2503 Ma and 2)
2246–2135 Ma, peak at 2154 Ma with peak in T1Sr model ages at
2.19 Ga (Meng et al., 2014). The older ages are interpreted to be
inherited zircons derived from melting of underlying 2.5 Ga crust,
providing direct evidence for Archean crust beneath this part of the
JLJB. Therefore, it is likely that the Sm—Nd isochron reflects the time
of formation of the mantle source from which these rocks were derived.
Below we summarize literature studies providing evidence that parts of
the crust beneath the JLJB separated from the mantle as much as 3.9 Ga
ago with major crustal growth stages at 3.0–2.9 Ga, 2.8–2.7 Ga and
– 2.5 Ga, consistent with the 2.83 ± 0.18 Ga Sm—Nd whole rock
isochron age reflecting lithospheric mantle stabilization between
3.0–2.6 Ga. The younger zircon age group is interpreted to reflect the
emplacement age of the meta-igneous protoliths, derived by partial
melting of depleted lithospheric mantle metasomatized by
subduction-zone fluids/melts. Lu—Hf age of 2.25 Ga is within error of
the peak of the younger zircon group (2.15 Ga). Thus, it is reasonable
to suggest that whole-rock Lu—Hf ages record the emplacement of
the Liaohe mafic rocks appears to have been contemporaneous with the
more voluminous felsic magmatism and most likely reflects the mafic
endmember of this event. Hence the period ~2.2–2.0 Ga represents sig-
nificant addition of both mafic and felsic material to the crust (Lu et al.,
2008; Li et al., 2006).

6.1.2. 204Pb/206Pb–207Pb/206Pb (inverse Pb) and Rb—Sr isochrons provide
constraints on the age of retrograde metamorphism

The inverse Pb isochron provides a robust age of 1824 ± 19 Ma
(MSWD = 1), and this represents the last time that the peak metamor-
phic mineral assemblage was open to Pb exchange. Since this age is
wholly derived from Pb, it implies that Pb has been immobile over the
subsequent ~1.8 Ga. This becomes significant when considering the
U—Pb and Th—Pb pseudo-isochrons, which show excess scatter due to
open-system behavior between the parent elements (U and Th) and the
daughter (Pb). Even though U—Pb and Th—Pb preserve ages which
apparently coincide with the Rb—Sr age, significant ancient addi-
tion of U or Th to the Liaohe mafic rocks would have resulted in signifi-
cant ingrowth in radiogenic Pb and hence disturbed the Pb—Pb
isochron. Preservation of the Pb—Pb isochron indicates that this was
not the case, and hence it is likely that any U or Th addition to the system
had to occur relatively recently and the “ages” preserved by U-Th-Pb re-
fect closed system behavior between 1824 ± 19 Ma and a very young
geologic event, very likely exposure and alteration of the rock units,
which opened the isotopic systems.

Interestingly, metamorphic zircons or rims of older (2.5 or 2.2 Ga)
zircons (n = 18) from the Liaohe mafic meta-igneous rocks yield a
weighted average 207Pb/206Pb metamorphic age of 1896 ± 22 Ma
(MSWD = 0.08; Meng et al., 2014) distinct from the whole-rock inverse
Pb isochron age of 1824 ± 19 Ma from the same type of protoliths.
Below we will show that the zircons and whole rocks most likely record
distinct metamorphic events, peak prograde and post-peak retrograde
amphibolite metamorphism respectively.

In contrast, the Rb—Sr system preserves a whole rock age of 1671 ±
58 Ma, which is significantly younger than the Pb—Pb age. Depending
on the mineralogy present, whole rock Rb—Sr has long been recognized
to have a significantly lower closure temperature than Pb—Pb (of the
order of ~500 °C versus ~600 °C; Schaefer, 2016 and references therein)
and hence it is reasonable to suggest that the Rb—Sr may simply reflect
a cooling age. Whether these whole rock ages reflect uniform cooling
from peak metamorphism, corresponding to ~1 °C per million years,
or a subsequent, distinct thermal event which completely reset the
Rb—Sr (but not the Pb—Pb system) at 1671 Ma cannot be resolved by
this dataset alone. 40Ar/39Ar ages of 1830–1803 Ma were obtained from
amphiboles in meta-volcanic rocks (amphibolite and mafic gru-
nite) from J’An, South Liaohe and Jingshan Groups in the JLJB (Faure
et al., 2004; Liu et al., 2015). Such high temperature amphiboles tend
to have Tc of ~540 ± 40 °C (Braun et al., 2006), slightly above that of
Rb—Sr whole rock, and hence these data suggest the terrane cooled
rapidly to ~540 °C by ~1.8 Ga, but remained open to Sr at ~500 °C for
the next ~130 Ma. This would suggest that the terrane remained at mid-crustal levels (25–35 km) until after ~1671 Ma.

In conclusion, we interpret the younger Rb—Sr and 204Pb/206Pb–207Pb/206Pb ages compared to the Sm—Nd and Lu—Hf ages to reflect retrograde metamorphism of the Liaohoe mafic meta-igneous rocks. This interpretation implies that the isotopic composition of Sr and Pb was rehomogenized during metamorphism, but that the rocks remained largely closed systems until recently.

6.2. Geochemical Implications for the Tectonic Setting in which the Liaohoe Meta-igneous Rocks Originated

Based on the metamorphic mineral assemblages and the major element chemistry, the protoliths of the amphibolites and hornblendites were most likely mafic (basaltic to andesitic) rocks (lavas or dikes) and the protolith of the metagabbro was a gabbroic rock, representing the intrusive equivalent of the basaltic protoliths. The Liaohoe amphibolites and metagabbro samples have compositions similar to modern-day mafic calc-alkaline volcanic rocks from active continental margins, for example Central America (e.g. Sadowsky et al., 2009; Heydolph et al., 2012), Kamchatka (Duggen et al., 2007; Portnyagin et al., 2007) and Chile (e.g. Jacques et al., 2013), although they extend to more mafic compositions. The more mafic compositions are likely to reflect greater degrees of melting in a hotter Neoarchaean to Paleoproterozoic mantle.

The distinct composition of amphibolite sample LH05–14–7 compared to the other amphibolites (having the highest SiO₂, Al₂O₃, and K₂O and lowest MgO and CaO and second lowest FeO and TiO₂) suggests that the protolith for this sample was more evolved and had a more K-rich (high-K) calc-alkaline type composition compared to the protoliths of the other samples (Table 1; Fig. 7).

The high-grade hornblendite samples have distinct major element contents compared to the medium-grade amphibolite and metagabbro samples. The positive correlation between MgO and SiO₂ is not consistent with a link between the amphibolites and hornblendites through differentiation. The lower SiO₂ and CaO but higher FeO and TiO₂ in the hornblendites compared to the amphibolites are consistent with a greater abundance of hornblende (90% versus 50–60%) compared to plagioclase (10% versus 40–50%) (Table 1). The lower MgO in the higher-grade metamorphosed hornblendites with greater hornblende to plagioclase ratio, however, is unexpected and either reflects less magnesium-rich hornblende in the hornblendites or may reflect a greater abundance of hornblende (90% versus 50–60%) compared to plagioclase (10% versus 40–50%) (Table 1). The lower MgO in the higher-grade metamorphosed hornblendites with greater hornblende to plagioclase ratio, however, is unexpected and either reflects less magnesium-rich hornblende in the hornblendites or may reflect a greater abundance of hornblende (90% versus 50–60%) compared to plagioclase (10% versus 40–50%) (Table 1)

The patterns on the incompatible multi-element diagram (Fig. 3) for the Liaohoe mafic meta-igneous rocks point to a subduction zone origin for all of the samples, as reflected by pronounced negative troughs in Nb and Ta relative to neighboring elements and general enrichment in fluid-mobile elements (Cs, Rb, Ba, U, K, P, and Sr) and Th (Fig. 3). Elements that are fluid mobile in subduction systems can also be mobilized by fluids in the crust, so we must be cautious in using these elements for petrogenetic interpretations. Nevertheless, the incompatible element patterns in general are very similar for the different samples. Only the absolute concentrations vary, reflecting concentration or dilution of the incompatible elements as a group as a result of differentiation or accumulation processes.

To minimize problems with post-emplacement mobilization of elements, we now look at fluid-immobile-element discrimination diagrams to distinguish the tectonic setting in which the protoliths formed. Elements that are highly resistant to alteration processes include lightly compatible transition trace elements, such as Co, and incompatible elements, in particular the middle (M) and heavy (H) rare earth elements (REE), e.g., Nd, Sm, Tb, Yb, and high field strength elements (HFSE), e.g., Nb, Ta, Zr, and Ti, and Y, and Th. Since SiO₂ and the alkalis (Na₂O and K₂O) are very mobile during alteration and metamorphism, we use the Nb/Y versus Zr/Ti diagram (Fig. 7A; e.g., Pearce, 1996) as an immobile proxy for the TAS (total SiO₂ vs. alkali) diagram, to assess the nature of the protoliths for the Liaohoe mafic meta-igneous rocks. All the samples plot within the basalt to basaltic andesite field, consistent with their major element compositions. In order to distinguish between a mid-ocean ridge and subduction-zone origin, we use the Nb/Yb versus Th/Yb diagram after Pearce (2008), which is capable of distinguishing MORB, intraplate or ocean island basalt (OIB) and volcanic arc basalts (Fig. 7B). All samples have elevated Th/Yb for their Nb/Yb ratios and plot within the range of volcanic arc samples. On an earlier version of this diagram, Ta/Yb versus Th/Yb, Pearce (1982) distinguishes between oceanic and active continental margin basalts and through leucite, calc-alkaline, medium- and high-K calc-alkaline and shoshonitic arc rocks (Fig. 7C). Most of the Liaohoe samples plot within the active continental margin calc-alkaline field, except sample LH05–14–7 with Th/Yb ratio of 7.1. This sample plots in the high-K calc-alkaline field, consistent with its high K₂O content and enriched incompatible trace element composition (see Fig. 3). In order to further test the nature of the Liaohoe mafic meta-igneous rocks, we use the Co versus Th diagram after Hastie et al. (2007), considered to be an immobile proxy for the SiO₂ vs K₂O diagram (Fig. 7D), also used to discriminate between the leucite, calc-alkaline and high-K calc-alkaline/shoshonite series. Co is considered to be an even better proxy for SiO₂ than Zr/Ti (Hastie et al., 2007). The Liaohoe samples plot within the calc-alkaline field except LH05–14–7, which again plots in the high-K calc-alkaline/shoshonite field, which agrees well with the Ta/Yb versus Th/Yb diagram and major element chemistry.

As noted by Pearce (2008), the classification diagrams need to be applied with caution to Archaean rocks and to rocks that have been metamorphosed above low-grade amphibolite facies. Nevertheless, we believe that the general consistency between the incompatible element patterns and immobile incompatible element discrimination diagrams provide us with an accurate picture of the origin of their protoliths, despite amphibolite facies metamorphism of the studied rocks. In summary, the Liaohoe mafic/ultramafic rocks have chemical characteristics consistent with being derived from primarily calc-alkaline basaltic protoliths formed in an active continental margin setting.

Alternative hypotheses for explaining the incompatible trace element abundances in the basalts include large amounts of crustal assimilation by upper mantle E-MORB type basalts, for example during continental rifting, or by flood basalt (Large Igneous Province = LIP) melts with relatively flat incompatible element abundances. Trondjemite-tonalite-granodiorite (TTG) crustal rocks with ages of 2.9–2.7 Ga were present in the Jiaobei Terrane of the JLJB in eastern Shandong when the Liaohoe mafic and ultramafic rocks formed (An, 1990; Wang and Yan, 1992; Tang et al., 2007; Zhou et al., 2008a, b; Liu et al., 2013a, b), providing further evidence for the presence of continental lithosphere. These TTG crustal rocks formed during stabilization of the lithospheric mantle as recorded by the Sm/Nd isochron of 2.83 ± 0.18 Ga. The TTG gneisses have very high SiO₂ but low MgO, FeO, CaO and TiO₂ contents. As noted above, the Liaohoe amphibolites and metagabbro samples have compositions similar to modern-day mafic calc-alkaline volcanic rocks from active continental margins, for example Central America (e.g. Sadowsky et al., 2009; Heydolph et al., 2012), Kamchatka (Duggen et al., 2007; Portnyagin et al., 2007) and Chile (e.g. Jacques et al., 2013). In the aforementioned studies, the authors conclude that the data allow only very minor crustal contamination. Large amounts of assimilation of crust, which would be required to generate the incompatible-element abundances, would have shifted the composition of the Liaohoe mafic meta-igneous rocks towards andesitic to rhyolitic compositions and also have resulted in dramatically lower cNd, values than observed. Therefore, large amounts of crustal assimilation are not consistent with the mafic and ultramafic compositions of the studied samples.
The positive initial εNd values (1.5–6.4) calculated for all samples at 2.83 Ga indicate that the Liaohe samples were derived from a long-term depleted source, relative to the Chondritic Uniform Reservoir (CHUR). There is no correlation between initial εNd(2.83 Ga) or Sm/Nd and indicators of crystal fractionation (e.g. MgO, SiO2, Ni, Zr, Nb/Yb), which usually occurs in conjunction with assimilation (DePaolo, 1981). We also note a similar range in initial εNd for ~2.7 Ga rocks from Abitibi, Canada (Blichert-Toft and Puchtel, 2010) and the Gadwal, India (Khanna et al., 2014), where assimilation of continental crust is believed to have played no more than a minor role. In summary, we do not find any evidence in support of significant crustal assimilation in the Liaohe mafic and ultramafic metamorphic rocks, implying that at least the immobile incompatible element ratios reflect the composition of the mantle melts and not major interaction between crust and mantle. The presence of older TTG rocks, together with the SmNd lithospheric mantle stabilization age, provides further evidence that the Liaohe mafic meta-igneous rocks were formed in an active continental margin setting. In conclusion, we note that Faure et al. (2004) came to a similar conclusion based on the trace element geochemistry of what they describe as gabbro and pyroxenite samples from the North Liaohe Group.

6.3. Temporal and geochemical evolution of the Jiao-Liao-Ji Belt

The lithospheric stabilization, emplacement and metamorphic ages that we have determined on the Liaohe mafic meta-igneous rocks are consistent with other geological and age data from the JLJB. Below we review the Neoarchean through Paleoproterozoic history of the JLJB (~2.8–1.7 Ga) using literature data combined with our new data.

As mentioned above, the JLJB can be subdivided into a northern belt, including the Fenzishan, North Liaohe and Laoling groups, and a southern belt, consisting of the Wuhe, Jingshan, South Liaohe and Ji’an groups (going from southwest to northeast). Detrital zircons in metasediments from the Jiaobei Terrane (southwestern JLJB), the South Liaohe Group (central JLJB), and the Ji’an and Laoling groups...
(northeastern JLJB) record nearly continuous magmatism (on a scale of ~100 Ma) from 3.6 to 2.0 Ga (Luo et al., 2004; Wan et al., 2006; Zhou et al., 2008a, b; Liu et al., 2013a, b; Wang et al., 2017; Zhang et al., 2018; Liu et al., 2015, 2019b). Such detrital zircon records are heavily weighted towards intermediate to felsic magmatism as mafic and ultramafic lithologies produce a paucity of zircons available to be eroded. Considerable age and geochemical data are available from the Jiaobei (Jiaodong) Terrane from magmatic and metamorphic zircons. Mafic magmatic zircons are characterized by low luminescence, often show zoning, and high Th/U ratios, whereas metamorphic zircons and zircon rims show nebulosity zoning or are structureless, have high luminescence and relatively low Th/U ratios. SHRIMP and LA-ICP-MS zircon U–Pb analyses from supracrustal rocks and granitoid gneisses in the Jiaobei Terrane record three magmatic events between 2.9 and 2.5 Ga, taking place at ~2.9, ~2.8–2.7 and ~2.55 Ga (Tang et al., 2007; Jahn et al., 2008; Zhou et al., 2008b; Liu et al., 2013a, b; Wu et al., 2014).

Mafic meta-igneous lenses, enclaves and blocks, probably representing parts of stretched and thinned dikes, in the Archean TTG gneisses of the Jiaobei Massif produce similar and younger ages than the TTG gneisses. A mafic granulite sample yielded SHRIMP \(^{207}\text{Pb}/^{206}\text{Pb}\) zircon weighted mean ages of 2638 ± 22 Ma, interpreted as the crystallization age of the mafic igneous protolith of the granulate sample, and 2703 ± 12 Ma, interpreted as the crystallization age of xenocrystic zircons in the protolith derived from the underlying basement (Tam et al., 2011). Mafic magmatic zircons from the supracrustal amphibolites in the Jiaobei Terrane yielded weighted mean concordant U–Pb zircon ages of 2.59–2.50 Ga, interpreted as the crystallization ages of the mafic magmatic protoliths (Zhang et al., 2003; Tang et al., 2007; Wu et al., 2014). Xenocrystic U–Pb zircon ages in mafic meta-igneous rocks from the Liaohe Group range from 2.55 to 2.46 Ma and show largely overlap ages of the younger amphibolites in the Jiaobei Massif (Meng et al., 2014; Xu et al., 2020). Finally, a mafic granulite from the Jiaobei Terrane yielded a LA-ICP-MS weighted mean \(^{207}\text{Pb}/^{206}\text{Pb}\) zircon crystallization age of 2379 ± 54 Ma (Tang et al., 2007). In conclusion, the mafic zircon age data provide evidence that mafic magmatism took place at least from ~2.7–2.5 Ga (Tang et al., 2007; Meng et al., 2014), overlapping with the younger end of TTG formation in the JLJB (Lu et al., 2008).

Geochemical data is sparse from these mafic meta-igneous rocks. An amphibolite (03SD06) in the Jiaobei TTG gneisses, which produced a weighted mean \(^{207}\text{Pb}/^{206}\text{Pb}\) zircon age of 2506 ± 18 Ma interpreted to be the crystallization age of a mantle-derived mafic dike, however, has subduction-type geochemical characteristics, e.g. Nb depletion relative to Th and La (Tang et al., 2007). HF model ages from the magmatic zircons in the Jiaobei Terrane range from 3.9 to 2.6 Ga with a major peak at 3.4–3.1 Ga and a subordinate peak at 2.8–2.7 Ga (Wu et al., 2014). The HF isotopes point to major juvenile crustal growth with substantial additions of older crust between 3.4 and 3.1 Ga and 2.8–2.7 Ga and crustal reworking with minor juvenile addition at ~2.55 Ga (Wu et al., 2014). The younger ~2.55 Ga episode of granitoid formation presumably resulted primarily from remelting of the ~2.8–2.7 Ga juvenile crust. The sparse geochemical data available for these older mafic meta-igneous rocks are consistent with formation in a subduction zone.

Our 2.83 ± 0.18 Ga lithospheric stabilization (Sm–Nd whole rock) isochron for Liaobe mafic meta-igneous rocks provides evidence of the complementary mantle contribution to the 2.8–2.7 Ga crustal evolution in the Jiaodong Terrane (e.g. Liu et al., 2013a, b), and reflects the timing of final melt extraction and possibly ultimate crystallization of the SCLM beneath this terrane. Rocks with ages >3 Ga are rare in the Eastern Block of the North China Craton but are found in the Anshan Domain north of the Liaobe Group (~3.8–2.5 Ga; Song et al., 1996; Wan et al., 2005; Lu et al., 2006; Wu et al., 2014), suggesting that the studied igneous rocks were formed on basement of the former Longgang Block (northeastern part of the present Eastern Block).

Abundant evidence exists that mafic and granitic magmatism took place between ~2.25–2.00 Ga in the central JLJB. In one of the earliest studies, zircons from a granite in the South Liaobe Group (also called the Kuandian Complex) in eastern Liaoning Province produced a minimum upper intercept U–Pb age of 2.14 ± 0.05 Ga, whereas whole rock Nd isotope data point to an age between 2.4 and 2.3 Ga for granite and amphibolite rocks (Sun et al., 1993). The authors interpreted the granites to be derived from the amphibolite protoliths (basalts) through fractional crystallization with little to no crustal assimilation based on the Nd isotope ratios and REE abundances. In the absence of crustal assimilation, the MORB normalized (Th, Ce)/(Nb, Ta) ratios >1 in the amphibolites (estimated from Fig. 4 in Sun et al., 1993) point to a subduction zone origin rather than through intraplate (continental flood basalt) volcanism as proposed by the authors. A subduction-zone origin is also consistent with the high fluid-mobile-element (Sr, K, Rb, Ba) and Th contents.

A compilation of U–Pb zircon ages (267) from 17 Liaobe mafic samples from the Liaodong Peninsula give an age range of ~2.25–2.02 Ga with a peak of activity at 2.12–5 Ga (Xu et al., 2020). SHRIMP and LA-ICP-MS U–Pb zircon ages for the Liaoji Granitoids (North and South Liaobe Groups), monzogranitic gneisses from the Jiaobei Terrane, and syenogranites from the Jilin Province yield a very similar range in crystallization ages of ~2.25–2.00 Ga (Li et al., 2003, 2006; Lu et al., 2004a, b, 2006; Luo et al. 2004, 2008; Wan et al., 2006; Li and Zhao, 2007; Liu et al., 2013a, b; Meng et al., 2014; Xu et al., 2018a, b). U–Pb zircon ages (88) from four felsic tuffs from the Liaodong Peninsula primarily fall within the range of 2.3–2.1 Ga with a peak at 2.17 Ga (Xu et al., 2020). It is therefore reasonable that the mafic meta-igneous rocks investigated here were part of this magmatic event, and indeed represent the mafic end member of subduction-zone magmatism active during this time. In conclusion, we interpret the mafic rocks to have been derived from a lithospheric mantle source, which was isolated at 2.83 ± 0.18 Ga (Sm–Nd isochron), which was part of a convergent margin when the mafic magmas formed at 2.25 ± 0.31 Ga (Lu–Hf isochron).

Now we will review the geochemical data for the Jiaobei Terrane and Liaobe Group mafic meta-igneous rocks. Liu et al. (2013a, b) suggest that the crustal reworking at ~2.5 Ga resulted from magma underplating by upwelling plumes. Granitoid formation as a result of plume-related underplating applies well to the Taishan area in western Shandong Province, where ~2.7 Ga greenschist to amphibolite facies komatitic and tholeiitic basalts are associated with a ~2.5–2.7 Ga TTG and supracrustal sequence (Wang et al., 2013). When comparing the Jiaobei (Tang et al., 2007) and Liaobe mafic meta-igneous rocks with similar-aged komatitic and tholeiitic basalts from the Taishan area in western Shandong Province (Wang et al., 2013), the difference in origin can be demonstrated in highly immobile incompatible element ratios, such as Nb/La (0.71–1.61 in the Taishan mafic volcanics versus 0.04–0.98 in the Jiaobei and Liaobe mafic meta-igneous rocks), Nb/Th (7.25–23.75 versus 0.22–4.56, respectively) and Th/Yb (0.05–0.60 versus 0.40–7.12, respectively). Low Nb/La, Nb/Th, and high Th/Yb are source characteristics transferred into the resulting subduction zone mafic magmatism. The compositions of the mafic Liaobe rocks in the JLJB overlap with modern-day mafic arc igneous rocks, providing strong support that they formed in a subduction-zone environment. Excluding one sample, the initial cNd(i) of the Jiaobei amphibolites show depleted (+3.4 – +5.7) mantle source compositions (Tang et al., 2007), similar to the Liaobe mafic/ultramafic meta-igneous rocks (cNd = +1.5 – +6.4). The zircons also yield normal mantle O isotope compositions for these samples (Tang et al., 2007). In conclusion, there is no evidence for plume-related magmatism between ~2.6–2.0 Ga in the JLJB, but rather for subduction-related magmatism.

Thousands of metamorphic zircons or zircon rims have been dated from the JLJB. An older metamorphic episode has been recorded in mafic meta-igneous rocks from the Jiaobei Terrane following the 2.55 Ga magmatic event. Wu et al. (2014), for example, report weighted \(^{207}\text{Pb}/^{206}\text{Pb}\) metamorphic ages of 2.52–2.46 Ga in amphibolites and granitoids and an apparent \(^{207}\text{Pb}/^{206}\text{Pb}\) age of 2.4 Ga in a biotite-plagioclase gneiss. Most U–Pb ages from
The granulite-facies metamorphic evolution of the northern (including Fenzishan, North Liaohe and Laoling groups) and southern (including Jingshan, South Liaohe and Ji’an groups) zones of the JLJB were believed to be distinct with the northern zone undergoing a clockwise P-T-t path and the southern zone an anti-clockwise path (Lu, 1996; Lu et al., 1996; He and Ye, 1998; Li et al., 2001; Zhao et al., 2012), but recently it has been demonstrated that the southern, like the northern, zone also underwent a clockwise P-T-t path (see Liu et al., 2019a, b and references therein). Mineral inclusions in dated zircons indicate that peak granulite-facies metamorphism took place at ~1.94–1.89 Ga along the entire JLJB (including the North and South Liaohe Group rocks and the Liaoji Granitoids in the central JLJB, the Jingshan Group in the southern JLJB, and the Ji’an and Laoling Groups in the northeastern JLJB), which is interpreted to reflect collision of the Nangrim with the Longgang Block (Luo et al., 2004, 2008; Li et al., 2005a, 2005b; Lu et al., 2006; Wan et al., 2006; Li and Zhao, 2007; Tam et al., 2011, 2012a, b; Wu et al., 2014; Wang et al., 2017; Zhang et al., 2018; Liu et al., 2019a, b). Specifically, the metamorphic zircons and rims from the Liaohe mafic meta-igneous rocks (with an age range of 1.92–1.87 Ga and a peak at 1.90 Ma; Meng et al., 2014) demonstrate that these rocks underwent this metamorphic event, recorded along the entire JLJB.

Inclusions in dated metamorphic zircons from meta-sedimentary and meta-mafic/ultramafic rocks throughout the JLJB indicate that retrograde metamorphism took place from ~1.88 to ~1.73 Ga (Lu et al., 2006; Zhao et al., 2006b; Zhou et al., 2008a; Tam et al., 2011; Wu et al., 2014; Liu et al., 2019a, b). Felsic magmatism, including intrusion of porphyritic monzogranites, granites and syenogranites, also took place throughout the JLJB between 1.88 and 1.80 Ga in an anorogenic or post-tectonic extensional setting (Cai et al., 2002; Li et al., 2004; Lu et al., 2004a,b, 2006; Zhao et al., 2008a; Tam et al., 2011; Wu et al., 2014; Liu et al., 2019a, b). In summary, dating of detrital zircons shows that crustal formation in the JLJB extends back to ≥3.6 Ga, whereas direct dating of meta-igneous rocks shows that the lithospheric mantle became isolated and presumably stabilized between ~3.0–2.6 Ga based on our whole-rock mafic Liaohe meta-igneous Sm–Nd age (2.83 ± 0.18 Ga). Felsic magmatism at ~2.55 Ga, was predominantly generated by remelting of ~2.8–2.7 Ga TTG (Jahn et al., 2008) and supracrustal rocks, but some juvenile mafic magmas with calc-alkaline (subduction-related) compositions were also produced during this event (Tang et al., 2007). Subsequent mafic volcanism at ~2.25–2.02 Ga in the Liaohe Group also shows subduction-related geochemical characteristics (Lu et al., 2006; Li and Zhao, 2007). This complete package, including supracrustal sedimentary sequences, experienced prograde collision-related metamorphism between ~1.96–1.88 Ga, whereas retrograde post-tectonic metamorphism (extension, cooling and exhumation) and anorogenic magmatism commenced between ~1.88–1.80 Ga, passing through Pb–Pb whole-rock, Ar–Ar hornblende and Rb–Sr whole-rock closure temperatures at 1824 ± 19, 1800 ± 10 and 1671 ± 58 Ma respectively.

6.4. Model for the evolution of the Jiao-Liao-Ji Belt from ~2.8 to 1.7 Ga

Results of this study, in conjunction with those from previously published lithological, structural, geochemical and geochronological studies, enable us to place constraints on the evolution of the JLJB. We will begin by reviewing existing models and then will propose a new model integrating our new whole rock data with published whole rock and zircon data. The existing models for the origin and evolution of the JLJB can be divided into two endmember groups (e.g. see summary by Zhao and Zhai, 2013): 1) opening and closing of an intra-continental rift (e.g. Zhang and Yang, 1988; Peng and Palmer, 1995; Li et al., 2004, 2005a, 2005b, 2006; Luo et al., 2004, 2008; Li and Zhao, 2007) and 2) arc (island arc or active continental margin) - continent collision (e.g., Bai, 1993; Bai and Dai, 1998; He and Ye, 1998; Faure et al., 2004; Lu et al., 2006; Li et al., 2018; Xu et al., 2018a, b).

Rift-related models propose that the Longgang and Nangrim (= Langrim = Langling) Blocks originally formed a single continental block that was rifted apart in the early Paleoproterozoic (2.2–1.9 Ga), accompanied by deposition of sedimentary and volcanic rocks into the rift basin and intrusion of mafic and granitoid rocks along rift-related faults. Closure of the rift in the late Paleoproterozoic resulted in the formation of the Jiao-Liao-Ji Belt (Yang et al., 1988; Zhang and Yang, 1988; Zhang et al., 1988; Li et al., 2001a, 2001b, 2004, 2005a, 2006, 2012). Zhao and Zhai (2013) argue that the following lines of evidence support this model: (1) bimodal volcanic suites in the JLJB, including meta-mafic volcanic rocks (greenschists and amphibolites) and meta-rhyolites (Zhang and Yang, 1988; Sun et al., 1993; Peng and Palmer, 1995); (2) large volumes of A-type granites in the JLJB (e.g. Li and Zhao, 2007); (3) low-pressure, anticlockwise, P-T paths of the Ji’an, South Liaohe and Jingshan Groups (Lu, 1996; Lu et al., 1996; He and Ye, 1998b; Li et al., 2001b), which are not consistent with arc- or continent-continent collision, and (4) non-marine borate deposits in the JLJB with similarities to borate-bearing successions in other Proterozoic rifting environments (Jiang, 1987; Peng et al., 1998). Problems with the rift model are explaining 1) what triggered its closing and the deformation event at ~1.96–1.88 Ga, 2) the high-pressure, clockwise P-T-t paths found in both the northern (Fenzishan, North Liaohe and Laoling) and more recently also in the southern zone of the JLJB (e.g. Jingshan, South Liaohe and Ji’an groups; Liu et al., 2019a, b), showing that the anti-clockwise paths were incorrect, and 3) the origin of high-pressure pelitic rocks that require subduction or continental collision to get them to sufficient depths to undergo high pressure metamorphism (e.g. Zhao and Zhai, 2013; Liu et al., 2019a), and 4) the presence of mafic meta-igneous rocks with subduction-related geochemistry (Faure et al., 2004; Meng et al., 2014; Xu et al., 2018a,b, 2020; Xu et al., 2020; this study).
The second group of models argue for arc (island arc or active continental margin) - continent collision (e.g. Bai, 1993; Bai and Dai, 1998; He and Ye, 1998; Faure et al., 2004; Li et al., 2006; Li et al., 2018). Bai (1993), the first to argue that arc-continent collision formed the JLJB, proposed that the Liaonian-Nangrim Block was an island arc and the Liaohu Group a back-arc basin. Collision of this arc system with the Archean Longgang Block caused the closure of the back-arc basin and formation of the JLJB in the Palaeoproterozoic. Faure et al. (2004) showed that the mafic/ultramafic meta-igneous rocks have incompatible-element characteristics similar to continental arcs and proposed that subduction was beneath the southern Palaeoproterozoic (Nangrim) continental block and that it was thrust upon the Anshan Block when the two blocks collided. Other variations of the arc-continent collisional model have also been proposed (e.g. Bai and Dai, 1998; He and Ye, 1998; Li et al., 2006) with the most recent models favoring subduction of the Nangrim Block northwards beneath the Longgang active continental margin block (e.g. Wang et al., 2017; Xu et al., 2018b; Zhang et al., 2018). Meta-sediments in the JLJB have been interpreted as having formed in the forearc and passive margin of the Nangrim Block (e.g. South Liaohu Group; Wang et al., 2017) or in a backarc basin (e.g. North Liaohu group; Wang et al., 2017; J’ian and Laoling groups; Zhang et al., 2018). The mafic Liaohu meta-igneous rocks have been interpreted by some to have EMORB type compositions and thus it has been argued that they formed in a backarc basin flooded by oceanic crust (Tang et al., 2007; Meng et al., 2014). The absence of an ophiolite associated with the JLJB, however, is not consistent with a backarc basin flooded by ocean crust, since closure of back-arc basins flooded by ocean crust generally result in subduction (rather than subduction) of the seafloor. We note that non-marine borate deposits could have formed in a backarc rift setting that had not progressed to becoming a marine backarc basin. Finally, the geochemical data from mafic meta-igneous rocks in the JLJB point to them having been formed as part of a magmatic arc (active continental margin; e.g. Faure et al., 2004 and this study) rather than in a back-arc basin setting.

We now review our whole rock data combined with published results from whole rocks and zircons to present an integrated model for the evolution of the JLJB from ~2.8–1.7 Ga. As summarized above, U–Pb zircon age data from detrital zircons in supracrustal rocks (3.6–2.0 Ga), TTT gneisses (2.9–2.5 Ga) and mafic meta-igneous rocks from the Liaohu and the jiaobei Terranes (2.7–2.5 Ga) provide direct evidence that Neoarchaeon crust exists beneath the Liaohu Group and Liaohne granitic rocks and/or that the JLJB crust was located adjacent to crust with these ages (Tang et al., 2007; Jahn et al., 2008; Zhou et al., 2008b; Liu et al., 2013a, b; Wu et al., 2014; Zhang et al., 2018; Liu et al., 2015, 2019b). The HF model ages from the zircons in the Jiaobei Terrane extend as far back as 3.9 Ga and show major juvenile crustal growth between 3.4 and 3.1 Ga and 2.8–2.7 Ga and crustal reworking with minor juvenile addition at ~2.5 Ga (Wu et al., 2014). Our Sm–Nd lithospheric mantle age of 2.8 ± 0.2 Ga from the mafic meta-igneous rocks from the Liaohu Group points to lithospheric mantle stabilization (cratonization) between ~3.0–2.6 Ga (Fig. 8A). Unfortunately, there is little geochemical data available from the mafic samples with ages >2.3 Ga, which provides information about the petrogenesis of these rocks. An amphibolite sample dated at 2.50 Ga, however, shows a subduction-type geochemical signature, suggesting that subduction took place at this time (Tang et al., 2007) and may have caused the crustal reworking. Lithospheric stabilization taking place at 2.8 ± 0.2 Ga argues against a significant role for mantle plumes and lithospheric drips (Nebel et al., 2018) in causing crustal growth between 2.9 and 2.7 Ga, because plumes and lithospheric drips would cause lithospheric mantle thinning rather than stabilization. Therefore, although speculative, we favor formation of the ~3.0–2.5 Ga crust and lithospheric mantle forming the JLJB basement through subduction.

The major phase of magmatism in the JLJB took place between 2.3 and 2.0 Ga and was subduction-related (Fig. 8B). The Liaohu mafic meta-igneous rocks were emplaced at 2.25 ± 0.31 Ga (whole rock isochron) and ~2.25–2.02 Ga with peak age at 2.15–2.1 Ga (U–Pb zircon ages; Xu et al., 2020), overlapping with the Liaoe granite rocks emplaced between ~2.2–2.0 Ga (e.g. Li and Zhao, 2007; Zhou et al., 2008a, b). The geochemistry of the Liaohu mafic/ultramafic meta-igneous rocks is consistent with mafic arc magmatism having formed along an active continental margin (e.g. Bai and Dai, 1998; Faure et al., 2004). An active continental margin setting is further supported by the presence of Neoarchaeon supracrustal rocks and TTT gneisses in the JLJB covering the age range of 2.9–2.5 Ga (Tang et al., 2007; Jahn et al., 2008; Zhou et al., 2008a, b; Liu et al., 2013a, b; Wu et al., 2014). In addition, U–Pb ages of detrital zircons from meta-sediments along the entire JLJB record nearly continuous (on a scale of ~100 Ma) intermediate to felsic magmatism and/or metamorphic events from 3.6 to 2.0 Ga (Luo et al., 2004; Wu et al., 2006; Zhou et al., 2008a, b; Liu et al., 2013a, b; Wang et al., 2017; Zhang et al., 2018; Liu et al., 2019b), and Hf model ages indicate crustal growth between 3.9 and 2.5 Ga (Wu et al., 2014). Crustal rocks with such ages have been identified in the Archaean Anshan Sequence in the Liaohe Province on the Longgang Block (3.8–2.5 Ga), which consists primarily of granitic rocks that experienced greenschist- to granulite-facies metamorphism, but not on the Nangrim Block (2.55–2.45 Ga), which consists primarily of quartz diorites and amphibolites that were exposed to amphibolite-facies metamorphism (Lu et al., 2006; Dong et al., 2017; Liu et al., 2017c; Wang et al., 2017; Liu et al., 2019a). Considering the overlap in magmatic evolution of the crust beneath the JLJB and on the Longgang Block, we place the active Palaeoproterozoic (~2.3–2.0 Ga) continental margin on the southeast side of the Longgang Block rather than on northwest side of the Nangrim Block (Fig. 8B). Although it is likely that the protoliths of some of the meta-sedimentary rocks were deposited in a back-arc (as well as forearc) basin (e.g., Wang et al., 2017; Zhang et al., 2018), there is no direct evidence in the form of an ophiolite for this basin having been flooded by oceanic crust formed by back-arc spreading.

The clockwise P-T-t path for the northern and southern zones of the JLJB (e.g. Liu et al., 2019a) is consistent with a collisional event having taken place between ~1.96–1.88 Ga, as seen in metamorphic zircons and zircon rims from both felsic and mafic meta-igneous rocks throughout the JLJB. Mineral assemblages in the zircons indicate that peak granulite-facies metamorphism occurred at ~1.94–1.89 Ga. This prograde metamorphic event no doubt represents collision and orogenesis between the Longgang Block and the Nangrim (micro-continental) Block to form the Eastern Block of the North China Craton (Fig. 8C). Inclusions in U–Pb dated zircons indicate that retrograde metamorphism took place between ~1.88–1.73 Ga throughout the JLJB (e.g. Liu et al., 2019a, b). Felsic magmatism and migmatites with granitic leucosomes, representing partial melting of felsic minerals (quartz and feldspars), record post-peak MP-LP granulite facies retrograde metamorphism with near isothermal decompression between 18.7 and 18.4 Ga along the JLJB, followed by an amphibolite facies retrogression between 1.83 and 1.80 Ga (e.g. Liu et al., 2015, 2019b). Our whole rock inverse Pb–Pb isochron age of 1.82 ± 0.2 Ga for the Liaohu mafic (amphibole-bearing) meta-igneous rocks records this event. This post-orogenic period is associated with regional cooling, but temperatures remained above 500°C (at mid-crustal levels of ~25–35 km) until ~1.67 ± 0.6 Ga (Liaohu mafic meta-igneous whole-rock Rb–Sr isochron). We propose that overthickening of the lithosphere during the collisional event is likely to have resulted in lithospheric destabilization, resulting in lithospheric mantle detachment/delamination (Li and Zhao, 2007). Lithospheric mantle removal triggered orogenic collapse, causing extension and thinning, coupled with exhumation and anatexis (Fig. 8D).

Assembly of the North China Craton appears to have taken place through amalgamation of at least four micro-continental blocks via three collisional events. The Nangrim-Longgang collision described here formed the Eastern Block (Fig. 8), whereas amalgamation of the Yinshan and Ordos micro-continental blocks formed the Western Block. Assembly of these four blocks occurred contemporaneously but
Fig. 8. Tectonic evolution of the Jiao-Liao-Ji Belt of the East China Block between ~2.8–1.7 Ga. (A) ~2.8 Ga. Major phase of crustal growth and lithospheric stabilization (cratonization) beneath the Jiao-Liao-Ji Belt, North China Craton. We favor formation of crust and lithosphere through subduction processes, since mantle plumes and lithospheric dripping are likely to cause thinning of the lithospheric mantle rather than its stabilization. We show subduction but the direction of subduction is assumed. Subduction is likely to have occurred intermittently until ~2.3 Ga. (B) ~2.3–2.0 Ga. Subduction of oceanic crust attached to the Nangrim Block northwestwards beneath the active southeast continental margin on the Longgang Block. Mafic melts in the subduction zone are derived from the ~2.8 Ga lithospheric mantle. Melting results from addition of hydrous fluids/melts from the subducting oceanic crust to the lithospheric mantle beneath the southeast edge of the Longgang Block (Li et al., 2010). Granites are formed coevally and primarily by differentiation of mafic melts due to mafic magma underplating (Li et al., 2001, 2005; Li and Zhao, 2007). (C) ~1.95–1.88 Ga. Collision of the active Longgang continental margin with the passive Nangrim continental margin caused closure of the ocean basin, crustal thickening, orogenesis, and peak metamorphism up to granulite grade. (D) ~1.88–1.67 Ga. Destabilization of the thickened lithosphere resulted in delamination/detachment of the lithospheric mantle and possibly lower crust, causing extension and thinning of the lithosphere in the JLJB and orogenic collapse. Exhumation resulted in retrograde metamorphism and crustal anatexis that generated post-tectonic anorogenic granites and migmatites. MP-LP retrograde metamorphism was isothermal between ~1.87–1.84 Ga and went through the amphibolite facies between ~1.83–1.80 Ga (Liu et al., 2019a, b), which is recorded in the whole-rock inverse Pb–Pb isochron of the Liaohe mafic meta-igneous rocks. Rocks cooled from ~600 to ~500 °C between ~1.82 Ga (Pb–Pb inverse isochron) and ~1.67 Ga (Rb–Sr isochron).
4) Collision of the active Longgang continental margin with the passive
A.1. Description of sample locations

5) Crustal thickening related to the collisional event triggered lithospheric destabilization and detachment/delamination, resulting in exhumation and retrograde metamorphism, crustal anatexis and generation of a post-tectonic anorogenic granites at ~1.88–1.80 Ga, recorded in the mafic meta-igneous rocks (whole-rock Pb–Pb age of 1.82 ± 0.02 Ga) and metamorphic zircons (U–Pb) throughout the Jiao-Liao-Ji Belt. Cooling due to exhumation reached a temperature of 500 °C at ~1.67 ± 0.06 Ga, based on the Pb–Sr whole rock isochron.

In conclusion, whole-rock isotopic analysis of mafic lithologies enables extension of the zircon geochronological record to include the age of lithospheric mantle stabilization (Sm–Nd), the timing of mafic magmatism (Lu–Hf), consistent with zircon age data from similar mafic meta-igneous Liaohe rocks, exhumation and retrograde amphibolite metamorphism (Pb–Pb), and constraints on post-orogenic cooling (Rb–Sr, U–Pb and Th–Pb).

Credit author statement

K.H wrote the manuscript with significant input from BS and SL. SL carried out field work to collect samples. FH carried out the isotope analyses and contributed to the manuscript text. XL contributed to the interpretations in the manuscript. DG-S carried out the ICP-MS analyses. RZ contributed to the interpretations in the manuscript. YL contributed to development of the model and drafted the model figure.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded by the NSFC project (China) to SL (Grants 91958214, 41325009, 41072152 and 41190072) and by the Leibniz and Helmholtz Societies (Germany). The research was initiated by a visit of Prof. Dr. Sanzhong Li to GEOMAR in 2007 and concluded during a sabbatical by Prof. Dr. Bruce Schaefer to GEOMAR in 2019, which was funded by Macquarie University (Australia).

Appendix A. Appendix

A.1. Description of sample locations

Appendix 1

Descriptions of samples from the Liaohe Group, which consists of five formations (from lower to upper): Langzishan Fm., Lieryu Fm., Gaojiayu Fm., Dashiqiao Fm. and Gaixian Fm

| Sample number | Rock types | Location | Stratigraphic unit |
|---------------|------------|----------|--------------------|
| LH05-011-1    | deformed amphibolite | river bank south of Sankiel, Xiaonzhuai Town | Lieryu Fm., North Liaohe Group |
| LH05-012-1    | foliated muscovite amphibolite | 1km west of northwest bridge of Mafeng Town | Lieryu Fm., North Liaohe Group |
| LH05-012-2    | amphibolite | 2km west of southeastern bridge of Mafeng Town | Lieryu Fm., North Liaohe Group |
| LH05-014-7    | amphibolite | quarry of Huazhu deposit | third member of Dashiqiao Fm., North Liaohe Group |
| LH05-016-1    | metagabbro | Wangjiakan Reservoir | Gaojiayu Fm., North Liaohe Group |
| LH05-026-1    | amphibolite | Erdaogangzi of Maojiadian Town, Kuangdian County | Lieryu Fm., South Liaohe Group |
| LH05-034-1    | coarse-grained hornblende | roadside 2km east of Lianshanguan | upper Langzishan Fm., North Liaohe Group |
| LH05-035-4    | fine-grained hornblende | 5km south of Shuijuan Town, Liaoyang City | first member of Dashiqiao Fm., North Liaohe Group |
| LH05-037-5    | medium-grained hornblende | roadside between Helan Town and Puzi River, Liaoyang | first member of Dashiqiao Fm., North Liaohe Group |
| LH05-038-1    | fine-grained amphibolite | bridge south of Zhanggou Village, Helan Town | first member of Dashiqiao Fm., North Liaohe Group |
| LH05-040-1    | fine-grained deformed amphibolite | river channel of Puzi River | first member of Dashiqiao Fm., North Liaohe Group |

Individually at ~1.95 Ga. Collision between the Western and Eastern Blocks took place at ~1.85 Ga during the time that the JLB rocks were undergoing isothermal retrograde metamorphism. As continental blocks became larger, thicker and more abundant in the Palaeoproterozoic, collisional tectonics may have resulted in the amalgamation of many smaller blocks into cratons (Li et al., 2018), such as the North China Craton, that later were fused together through further collisions to form supercontinents such as the Meso-Palaeoproterozoic Supercontinent Columbia (Zhao et al., 2002a, b; Li et al., 2019), which at some stage became unstable and broke apart only to reassemble again at a later stage (Zhao et al., 2004).

7. Conclusions

Our study of whole rock geochronology and geochemistry of mafic/ultramafic meta-igneous rocks from the Liaohe Group of the Eastern Block of the North China Craton, when interpreted in conjunction with the U–Pb and Lu–Hf zircon record, allows us to add key constraints to the evolution of Neoproterozoic-Palaeoproterozoic tectonics of the North China Craton. These include:

1) Mantle lithospheric stabilization took place at ~2.8 Ga beneath the Jiao-Liao-Ji Belt. This lithospheric mantle was subsequently sampled by the Liaohe mafic and ultramafic subduction-related magmas. Due to high degrees of melting, the mafic magmas preserved the Sm–Nd age of their lithospheric mantle source.

2) The geochemistry of the Liaohe mafic magmatism points to an origin along an active continental margin. Available published data from other parts of the Jiao-Liao-Ji Belt also point to a subduction origin and display similar emplacement and metamorphic ages as the Liaohe mafic meta-igneous rocks.

3) Emplacement of the Liaohe mafic and ultramafic rocks, as preserved in a whole-rock Lu–Hf isochron (2.25 ± 0.31 Ga), was likely synchronous with the formation of the Liaohe granitoids intruded between 2.2 and 2.0 Ga in an active continental margin subduction-zone setting. We place the active continental margin on the southeastern side of the Longgang Block, since Archaean supracrustal rocks and TTG gneisses from the JLB have zircon U–Pb ages and Hf model ages (3.9–2.5 Ga) in the northern Liaoning Province on the eastern side of the Longgang Block, since Archaean supracrustal rocks and TTG gneisses from the JLB have zircon U–Pb ages and Hf model ages (3.9–2.5 Ga) in the northern Liaoning Province on the eastern side of the Longgang Block, since Archaean supracrustal rocks and TTG gneisses from the JLB have zircon U–Pb ages and Hf model ages (3.9–2.5 Ga) in the northern Liaoning Province.

4) Collision of the active Longgang continental margin with the passive Nangrim continental margin at ~1.96–1.88 Ga, as recorded in metamorphic zircons (by U–Pb age dating) from the Liaohe mafic meta-igneous rocks and felsic rocks along the entire Jiao-Liao-Ji Belt, caused orogenesis and granulite-grade metamorphism.
### A.2. XRF reference materials

| Standard | JB-2 | 2SD | JB-2 | JB-2 | AVG | RSD% | Diff% | JB-3 | 2SD | JB-3 | JB-3 | AVG | RSD% | Diff% |
|----------|------|-----|------|------|-----|------|-------|------|-----|------|------|-----|------|-------|
| SiO₂ wt% | 53.14 | 0.18 | 53.61 | 53.23 | 53.42 | 0.42 | 0.5 | 51.04 | 51.31 | 51.3 | 51.31 | 0.0 | 0.5 | 51.31 |
| TiO₂ wt% | 1.167 | 0.009 | 1.18 | 1.18 | 1.18 | 0.0 | 1.1 | 1.45 | 1.42 | 1.41 | 1.42 | 0.4 | 2.4 | |
| Al₂O₃ wt% | 14.62 | 0.1 | 15.02 | 15 | 15.01 | 0.1 | 2.7 | 16.89 | 17.6 | 17.53 | 17.57 | 0.2 | 4.0 | |
| Fe₂O₃ wt% | 14.28 | 0.12 | 14.4 | 14.41 | 14.41 | 0.0 | 0.9 | 11.88 | 12.08 | 12.04 | 12.06 | 0.2 | 1.5 | |
| MnO wt% | 0.213 | 0.00028 | 0.21 | 0.21 | 0.21 | 0.0 | 1.4 | 0.16 | 0.18 | 0.18 | 0.18 | 0.0 | 12.5 | |
| MgO wt% | 4.43 | 0.35 | 4.78 | 4.72 | 4.75 | 0.6 | 7.2 | 5.2 | 5.25 | 5.25 | 5.25 | 0.0 | 1.0 | |
| CaO wt% | 9.852 | 0.082 | 9.92 | 9.91 | 9.92 | 0.1 | 0.6 | 9.86 | 9.83 | 9.79 | 9.81 | 0.2 | 0.5 | |
| Na₂O wt% | 2.054 | 0.03 | 1.98 | 1.91 | 1.95 | 1.8 | 5.3 | 2.82 | 2.83 | 2.71 | 2.70 | 0.4 | 4.3 | |
| K₂O wt% | 0.4224 | 0.0059 | 0.42 | 0.42 | 0.42 | 0.0 | 0.6 | 0.78 | 0.77 | 0.77 | 0.77 | 0.0 | 1.3 | |
| Rb ppm | 0.309 | 0.00029 | 0.31 | 0.31 | 0.31 | 0.0 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.0 | 1.0 | |
| Sr ppm | 15.6 | 108.6 | | | | | | | | | | | | |
| Y ppm | | | | | | | | | | | | | | |
| Zr ppm | 48.25 | 0.88 | 52 | 54 | 53 | 1.9 | 9.8 | 98.3 | 92 | 92 | 92 | 0.0 | 6.4 | |
| TOTAL | 96.40 | | 101.73 | 101.21 | 101.47 | | | 100.51 | 101.57 | 101.42 | 101.49 | | | |

### A.3. ICP-MS reference materials (a) and sample replicates (b)

| Appendix 3a | BIR-1 | 2SD | BIR-1 | BHYO-2 | 2SD | BHYO-2 | JGc-2 | 2SD | JGc-2 | JGc-2 | JGc-2 | 2SD | 2SD |
|-------------|------|-----|------|------|-----|------|------|-----|------|------|------|-----|-----|
| Li ppm | 3.033 | 0.069 | 3.45 | 4.500 | 0.085 | 4.43 | 13.7 | 3.3 | 16.6 | 16.2 | 16.4 | 0.5 | 3.1 |
| Sc ppm | 320.6 | 0.59 | 47.1 | 31.83 | 0.34 | 31.8 | 24.0 | 21.0 | 23.0 | 23.3 | 23.8 | 0.0 | 1.7 |
| V ppm | 392.9 | 3.9 | 401 | 287.2 | 3.1 | 290 | 126 | 6 | 120 | 122 | 121 | 3 | 2.5 |
| Cr ppm | 52.2 | 0.57 | 53.5 | 44.89 | 0.32 | 44.8 | 29.3 | 4.9 | 24.5 | 25.1 | 24.8 | 0.7 | 2.9 |
| Co ppm | 168.9 | 1.9 | 171 | 119.8 | 1.2 | 118 | 13.4 | 0.9 | 13.4 | 13.5 | 13.5 | 0.1 | 0.6 |
| Ni ppm | 120.7 | 0.6 | 124 | 129.3 | 1.4 | 129 | 11.2 | 0.6 | 10.4 | 10.6 | 10.5 | 0.3 | 3.2 |
| Cu ppm | 70.4 | 1.1 | 71.8 | 104 | 1.0 | 104 | 48.3 | 0.7 | 49.6 | 46.9 | 48.3 | 0.0 | 7.8 |
| Zn ppm | 15.46 | 0.23 | 16.5 | 21.4 | 0.2 | 21.6 | 15.9 | 0.0 | 16.0 | 16.2 | 16.1 | 0.2 | 1.2 |
| Ga ppm | 0.21 | 0.0081 | 0.222 | 9.261 | 0.096 | 9.24 | 2.10 | 0.78 | 2.28 | 2.30 | 2.29 | 0.021 | 0.9 |
| Rb ppm | 108.6 | 0.7 | 108 | 394.1 | 1.7 | 370 | 400 | 10 | 410 | 412 | 410 | 5 | 1.3 |
| Sr ppm | 15.6 | 0.17 | 16.2 | 25.91 | 0.24 | 25.5 | 4.05 | 1.20 | 3.53 | 3.53 | 3.53 | 0.001 | 0.1 |
| Zr ppm | 14.8 | 0.22 | 15.9 | 171.2 | 1.3 | 174 | 9.91 | 3.48 | 9.26 | 7.93 | 8.60 | 1.88 | 21.9 |
| Nb ppm | 0.553 | 0.014 | 0.573 | 18.10 | 0.2 | 18.3 | 1.31 | 0.92 | 0.678 | 0.692 | 0.685 | 0.019 | 2.7 |
| Mo ppm | 0.068 | 0.021 | 0.072 | 4.07 | 0.16 | 4.48 | 0.558 | 0.234 | 0.450 | 0.350 | 0.400 | 0.141 | 35.2 |
| Cs ppm | 0.00646 | 0.00072 | 0.006 | 0.0996 | 0.0022 | 0.099 | 0.482 | 0.137 | 0.580 | 0.579 | 0.580 | 0.002 | 0.3 |
| Ba ppm | 6.75 | 0.13 | 7.23 | 131 | 1 | 131 | 35.5 | 2.50 | 35.8 | 35.8 | 35.8 | 0.0 | 0.0 |
| Appendix 3a | BIR-1 2SD | BIR-1 | BHVO-2 2SD | BHVO-2 | JGb-2 2SD | JGb-2 | JGb-2 | JGb-2 2SD | JGb-2 2SD |
|------------|------------|--------|-----------|--------|------------|--------|--------|------------|------------|
| La ppm     | 0.627      | 0.012  | 0.629     | 15.20  | 0.08       | 15.0   | 1.43   | 0.25       | 1.52       |
| Ce ppm     | 1.92       | 0.023  | 1.96      | 37.53  | 0.19       | 36.8   | 2.87   | 0.72       | 3.14       |
| Pr ppm     | 0.3723     | 0.0047 | 0.386     | 5.339  | 0.028      | 5.26   | 0.390  | 0.069      | 0.414      |
| Nd ppm     | 2.397      | 0.043  | 2.52      | 24.27  | 0.25       | 24.5   | 1.80   | 0.82       | 1.93       |
| Sm ppm     | 1.113      | 0.018  | 1.17      | 6.023  | 0.057      | 6.11   | 0.478  | 0.085      | 0.535      |
| Eu ppm     | 0.5201     | 0.0047 | 0.553     | 2.843  | 0.012      | 2.08   | 0.546  | 0.107      | 0.627      |
| Gd ppm     | 1.309      | 0.021  | 1.90      | 6.207  | 0.036      | 6.13   | 0.512  | 0.178      | 0.604      |
| Tb ppm     | 0.3623     | 0.005  | 0.375     | 0.939  | 0.006      | 0.931  | 0.098  | 0.041      | 0.102      |
| Dy ppm     | 2.544      | 0.028  | 2.73      | 5.280  | 0.028      | 5.34   | 0.605  | 0.078      | 0.675      |
| Ho ppm     | 0.5718     | 0.0047 | 0.599     | 0.987  | 0.0053     | 0.972  | 0.128  | 0.019      | 0.140      |
| Er ppm     | 1.68       | 0.015  | 1.72      | 2.511  | 0.014      | 2.44   | 0.357  | 0.048      | 0.389      |
| Tm ppm     | 0.2558     | 0.004  | 0.258     | 0.349  | 0.0031     | 0.234  | 0.055  | 0.013      | 0.061      |
| Yb ppm     | 1.631      | 0.015  | 1.72      | 1.994  | 0.027      | 1.96   | 0.355  | 0.073      | 0.405      |
| Lu ppm     | 0.2484     | 0.0032 | 0.267     | 0.2754 | 0.0024     | 0.283  | 0.055  | 0.011      | 0.065      |
| Hf ppm     | 0.5822     | 0.0088 | 0.581     | 4.470  | 0.025      | 4.16   | 0.261  | 0.078      | 0.246      |
| Ta ppm     | 0.0414     | 0.002  | 0.040     | 1.154  | 0.019      | 1.05   | 0.956  | 1.538      | 0.052      |
| Ti ppm     | 0.0021     | 0.0007 | 0.004     | 0.0224 | 0.0015     | 0.023  | 0.030  | 0.000      | 0.018      |
| Pb ppm     | 3.037      | 0.049  | 3.21      | 1.653  | 0.038      | 1.57   | 1.78   | 1.79       | 0.933      |
| Th ppm     | 0.0328     | 0.0015 | 0.033     | 1.224  | 0.016      | 1.15   | 0.151  | 0.095      | 0.150      |
| U ppm      | 0.01051    | 0.00041| 0.014     | 0.412  | 0.035      | 0.403  | 0.035  | 0.022      | 0.030      |

GeoRm* Jochum KP, Weis U, Schwager B, Stoll B, Wilson SA, Haug GH, Andreae MO, Enzweiler J (2016) Reference Values Following ISO Guidelines for Frequently Requested Rock Reference Materials. Geostandards and Geoanalytical Research 40(3):333–350. GeoRm* average of published data 090619.
A.4. A) $^{238}\text{U}-^{206}\text{Pb}$, B) $^{232}\text{U}-^{207}\text{Pb}$ and C) $^{232}\text{Th}-^{208}\text{Pb}$ errorchrons
Wang, M.J., Liu, S.W., Fu, J.H., Wang, K., Guo, R.R., Guo, B.R., 2017. Neoarchean TTG granites in southern Liaoning Province and their constraints on crustal growth and closure of the nature of the Liaojiao-Ji Belt in the Eastern Block. Precambrian Res. 303, 163–207.
Wang, W., Yang, E.X., Zhai, M.G., Li, S.Z., Sun, M., Zhao, G.C., 2013. Zircon U-Pb geochronology and Hf isotopes of major lithologies from the Yishui Terrane: Implications for the crustal evolution of the Early Neoproterozoic. Lithos 160–161, 22–32.
Wu, M.L., Zhao, G.C., Sun, M., Li, S.Z., He, Y.H., Bao, Z.A., 2013. Zircon U-Pb geochronology and Hf isotopes of major lithologies from the Jiaodong Terrane: Implications for the crustal evolution of the Early Neoproterozoic. Lithos 190–191, 71–84.
Xia, Y., Sun, M., Zhou, G.C., Luo, Y., 2006. LA-ICP-MS U-Pb geochronology of detrital zircons from the Jining Complex, North China Craton and its tectonic significance. Precambrian Res. 144, 199–212.
Xie, L.W., Yang, J.H., Wu, F.Y., Yang, Y.H., Wilde, S.A., 2011. PbSL dating of garnet and staurolite: Constraints on the Paleoproterozoic crustal evolution of the Eastern Block, North China Craton. J. Asian Earth Sci. 42, 142–154.
Xu, B.L., Yan, G.H., Mo, B.L., 1998. Rb-Sr age and its implication of Alkaline from Liangtun area in the west of Jiaobei region. Shandong Geology 12 (1), 24–34.
Zhai, M.G., Ni, Z.Y., Oh, C.W., Guo, J.H., Cho, S.G., 2005. SHRIMP zircon age of a Proterozoic garnet-pyroxene granulite from the Jingshan Group in the Jiaobei massif. Chin. Sci. Bull. 50, 1009–1021.
Zhai, M.G., Liu, W.J., 2003. Palaeoproterozoic tectonic history of the North China Craton: a new perspective. Earth Sci. Front. 10 (4), 257–263.
Zhang, W., Liu, F.L., Cai, J., Liu, C.H., Liu, J.H., Liu, P.H., Liu, L.S., Wang, F., Yang, H., 2018. Geochemical and Sr-Nd isotope systematics of the Jingshan Group in the Jiaobei massif. Chin. Sci. Bull. 53, 1628–1637.
Zhao, J.X., McCulloch, M.T., 1995. Geochemical and Nd isotopic systematics of granites from the Arunta Inlier, central Australia: Implications for Proterozoic crustal evolution. Precambrian Res. 71, 265–284.
Zhao, G.C., Simon, A.W., Wilde, S.A., 2003. Correlations between the Eastern Block of the North China Craton and its tectonic significance. Precambrian Res. 118, 31–39.
Zhao, G.C., Zhai, M.G., 2013. Lithotectonic elements of Precambrian basement in the North China Craton: review and tectonic implications. Gondwana Res. 23, 1207–1240.
Zhao, G.C., Simon, A.W., Cawood, P.A., 2005. Thermal evolution of Archean basement rocks from the eastern part of the North China Craton and its bearing on tectonic setting. International Geophysical Review 40, 706–721.
Zhao, G.C., Simon, A.W., Cawood, P.A., Lu, L.Z., 1999. Tectonostratigraphic history of the basement rocks in the western zone of the North China Craton and its tectonic implications. Tectonophysics 310, 37–53.
Zhao, G.C., Cawood, P.A., Simon, A.W., Sun, M., Lu, L.Z., 2000. Metamorphism of basement rocks in the central zone of the North China Craton: implication for Palaeoproterozoic tectonic evolution. Precambrian Res. 103, 55–88.
Zhao, G.C., Cawood, P.A., Simon, A.W., Lu, L.Z., 2001a. High-pressure granulite (retrograded eclogites) from the Hengshan Complex, North China Craton: petrology and tectonic implications. J. Petrology 42, 1141–1170.
Zhao, G.C., Simon, A.W., Cawood, P.A., Sun, M., 2002a. SHRIMP U-Pb zircon ages of the Fuying Complex: implications for late Achaean to Palaeoproterozoic accretion and assembly of the North China Craton. Am. J. Sci. 302, 191–226.
Zhao, C.C., Cawood, P.A., Wilde, S.A., Sun, M., 2002b. SHRIMP U-Pb zircon ages of the Fuying Complex: implications for a pre-Rodinia supercontinent. Earth Sci. Rev. 59, 125–162.
Zhai, M.G., Sun, M., Simon, A.W., 2001. Correlations between the Eastern Block of the North China Craton and the South Indian Block of the Indian Shield: a pre-Rodinia North China–India link. Precambrian Res. 122, 201–233.
Zhao, G.C., Sun, M., Wilde, S.A., Li, S.Z., 2004. A Paleoproterozoic–mesoproterozoic supercontinent: assembly, growth and breakup. Earth Sci. Rev. 67, 51–123.
Zhao, G.C., Sun, M., Simon, Wilde, L.Z., 2005. Late Archean to Palaeoproterozoic evolution of the North China Craton: key issues revisited. Precambrian Res. 136, 177–202.
Zhao, G.C., Sun, M., Wilde, L.Z., Li, S.Z., Liu, S.W., Zhang, J., 2006a. Composite nature of the North China–Grande–Facies Belt: Tectonostratigraphic and geochemical constraints. Gondwana Res. 9, 337–348.
Zhao, G.C., Cao, L., Wilde, S.A., Sun, M., Cao, W.J., Li, S.Z., 2006b. Implications based on the first SHRIMP U-Pb zircon dating on Palaeoproterozoic granitoid rocks in North Korea. Earth Planet. Sci. Lett. 251, 365–379.
Zhao, G.C., Yin, C.Q., Guo, J.H., Sun, M., Li, S.Z., Li, X.P., Wu, C.M., Liu, C.H., 2010. Metamorphism of the Liaoning amphibolite: implications for the tectonic evolution of the North China Craton. Am. J. Sci. 310, 1480–1502.
Zhao, G.C., Li, S.Z., Sun, M., Wilde, S.A., 2011. Assembly, accretion, and break-up of the Palaeo–Mesoproterozoic Columbia supercontinent: records in the North China Craton revisited. Int. Geol. Rev. 53, 1331–1356.
Zhao, G.C., Cawood, P.A., Li, S.Z., Wilde, S.A., Sun, M., Zhang, J., He, Y.H., Yin, C.Q., 2012. Amalgamation of the North China Craton: Key issues and discussion. Precambrian Res. 222–223, 55–76.
Zhou, J.X., McCulloch, M.T., 1995. Geochemical and Nd isotopic systematics of granites from the Arunta Inlier, central Australia: implications for Proterozoic crustal evolution. Precambrian Res. 71, 265–299.
Zhou, J.B., Wilde, S.A., Zhao, G.C., Zheng, C.Q., Jin, W., Zhang, X.Z., Cheng, H., 2006b. SHRIMP U-Pb zircon dating of the Neoproterozoic Fergal Complex and Archean granites from the Jiaobei Terrane, North China Craton, and their tectonic implications. Precambrian Res. 160, 323–340.
Zhou, X.W., Dong, Y.S., Wei, C.D., 2001. The genesis and evolution of the metamorphic minerals of Khondalite series in Nanxian district of Shandong Province. Journal of Changchun University of Science and Technology 11, 116–121 (in Chinese with English abstract).
Zhou, X.W., Wei, C.J., Dong, Y.S., Lu, L.Z., 2003. Characteristics of diffusion zoning in garnet and implications for genesis from Al-rich rock series of the Jingshan group in northern Jiaobei. Acta Petrol. Sin. 19, 752–760 (in Chinese with English abstract).
Zhou, X.W., Wei, C.J., Geng, Y.S., Zheng, L.F., 2004. Discovery and implications of high-pressure pelitic granulites from the Jiaobei massif. Chin. Sci. Bull. 49, 1942–1948 (in Chinese with English abstract).
Zhou, X.W., Wei, C.J., Geng, Y.S., Zhang, L.F., 2005. Electron microprobe monazite Th-Pb dating and its constraints on multi-stage metamorphism of low-pressure pelitic granulite from the Jingshan Group in the Jiaobei massif. Chinese Sci. Bull. 50, 1009–1015 (in Chinese with English abstract).
Zhou, X.W., Wei, C.J., Zhang, S.K., 2006. Implications of micro-compositions of garnet and biotite from high-grade meta-metapelites. Prog. Nat. Sci. 16, 209–214.
Zhou, X.W., Wei, C.J., Geng, Y.S., 2007. Phase equilibrium P-T path of the high- and low-pressure pelitic granulites from the Jiaobei massif. Earth Science Frontiers 14 (1), 135–143 (in Chinese with English abstract).
Zhou, X.W., Zhao, G.C., Wei, C.J., Geng, Y.S., Sun, M., 2008a. EMPA U-Pb monazite and SHRIMP U-Pb zircon geochronology of high-pressure pelitic granulite in the Jiaobei massif of the North China Craton. J. Asian Earth Sci. 30, 328–350.