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북중국판내 산둥-요동-길림 충돌대에서 일어난 고원생대 화성 및 변성작용과 이들의 지구조적 의미에 대한 기존 연구 종합검토

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요 약

산둥-요동-길림 충돌대는 북중국판의 용강 블록과 한반도의 낭림육괴가 충돌하여 형성된 고원생대 충돌대이다. 산둥-요동-길림 충돌대에서는 고원생대 화성 및 변성작용이 광범위하게 일어났다. 이 논문에서는 산둥-요동-길림 충돌대에서 일어난 퇴적작용, 화성작용, 변성작용을 종합검토하고 이를 바탕으로 산둥-요동-길림 충돌대의 지구조진화 과정에 대해 종합 정리 및 해석을 수행하였다. 산둥-요동-길림 충돌대에서는 약 2.21-1.92 Ga 시기에 주로 퇴적작용이 일어났다고 보고되고 있으나 퇴적환경이 열곡대인지 아니면 후배호분지인지는 논쟁 중에 있다. 본 연구에서는 후배호분지 환경에서 일어난 약 2.19-2.08 Ga 화성작용을 근거로 산둥-요동-길림 충돌대내 퇴적작용이 후배호분지 환경에서 일어난 것으로 판단하였다, 그리고 산둥-요동-길림 지역 남부경계 지역에서는 약1.87-1.84 Ga 시기에 많은 화성작용과 변성작용이 보고되었고 이러한 지질작용의 원인으로 열곡환경 혹은 충돌 후 지구조환경이 제시되고 있다. 산둥-요동-길림 충돌대에서 약1.95-1.90 Ga 시기에 대륙충돌에 의해 일어난 중압형 변성작용이 그리고 1.89-1.84 Ga 시기에는 저압형 변성작용이 보고되었다. 본연구에서는 이들 자료를 바탕으로 약1.87-1.84 Ga의 화성작용은 충돌 후 환경에서 형성되었다고 판단하였다. 이러한 지질정보는 약 2.2-2.1 Ga 시기에 산둥-요동-길림 충돌대를 따라 화산호 관련 화성작용을 수반한 남쪽으로 섭입하는 섭입대가 존재하였고 약 1.95-1.90 Ga 시기에 대륙충돌이 일어났음을 지시한다. 또한 대륙충돌은 먼저 길림 지역에서 먼저 일어났으며 점차적으로 산둥반도 지역으로 진행되었으며 충돌 후에는 1.89-1.84 Ga 시기에 대륙충돌 후 환경에서 화성 및 변성작용이 일어났음을 지시한다.

주요어: 산둥-요동-길림 충돌대, 퇴적작용, 화성작용, 변성작용, 지구조진화

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ABSTRACT: The Jiao-Liao-Ji Belt (JLJB) is a Paleoproterozoic collisional belt between the Longgang Block in the eastern North China Craton and the Nangrim Massif in the Korean Peninsula. Paleoproterozoic igneous and metamorphic activities are widely distributed in the JLJB. In this paper, we reviewed previous studies on sedimentation, igneous activity, and metamorphism in the JLJB and discussed the tectonic evolution of the JLJB. Previous studies reported that there was a sedimentary deposition in the JLJB during 2.21-1.92 Ga. However, it is still uncertain whether the sedimentation occurred in a Rifting or a back-arc basin tectonic environment. In this paper, the sedimentation in the JLJB was considered to occur in the back-arc basin tectonic setting based on 2.19-2.08 Ga igneous activities occurred in the back-arc basin tectonic setting in the JLJB. Along the southern margin of the JLJB, 1.87-1.84 Ga igneous activities were reported. It is also under argument whether the igneous activities occurred in the rifting or post-collision tectonic setting. In the JLJB, the intermediate-P/T type metamorphism occurred due to collision along the JLJB during ~1.95-1.90 Ga and then low-P/T type metamorphism occurred during 1.89-1.84 Ga. Based on the metamorphic information, we considered that 1.87-1.84 Ga igneous activity occurred in the post collisional tectonic setting. Based on these and other information, we suggested that the JLJB experienced (southward) arc-related subduction during 2.2-2.1 Ga and continent-continent collision during ~1.95

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-1.90 Ga. The collision may have first occurred in the Jinan area and then propagated to the Jiaobei area. After continental collision, postcollisional extension occurred with related igneous and metamorphic activities during 1.89-1.84 Ga.

Key words: the JLJB, sedimentation, igneous activity, metamorphism, tectonic evolution

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1. Introduction

The Jiao-Liao-Ji Belt (JLJB) is one of the most important Paleoproterozoic orogenic belts in the eastern part of the North China Craton (NCC) (Zhao *et al.*, 2005) (Fig. 1). In the belt, Paleoproterozoic sedimentation, igneous and metamorphic activities occurred during 2.2-1.8 Ga. The Paleoproterozoic

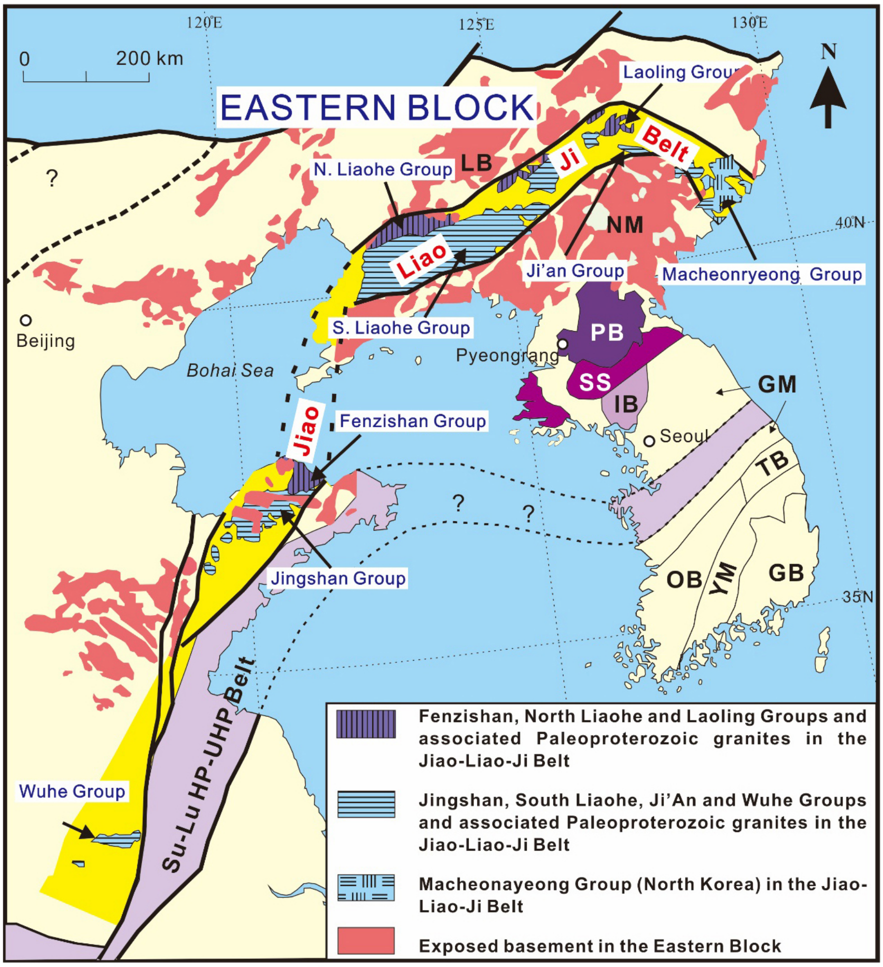

Fig. 1. Tectonic map of the North China Craton and Koran Peninsula (modified after Zhao *et al.*, 2012). The squares indicate the study areas. NM, Nangrim Massif; PB, Pyeongnam Basin; SS, Sangwon System; IB, Imjingang Belt; GM, Gyeonggi Massif; TB, Tabaeksan Basin; OB, Ogcheon Metamorphic Belt; YM, Yeongnam Massif; GB, Gyeongsang Basin.

sedimentary rocks in the JLJB are divided into eight groups, from northeast to southwest: the Macheonryeong, Laoling, Ji'an, North and South Liaohe, Fenzishan, Jingshan, and Wuhe Groups (Fig. 1). Felsic and mafic igneous rocks with an age of 2.2-2.1 Ga widely intruded the JLJB, and 1.87-1.84 Ga porphyritic granitoids mainly intruded the southern part of the JLJB (Hao *et al*., 2004; Lu *et al*., 2004a; Li and Zhao, 2007; Lan *et al*., 2015; Yang *et al*., 2015; Song *et al*., 2016; Liu *et al*., 2017a; Wang *et al*., 2017c; Xu *et al*., 2018a; Wang *et al*., 2020b, 2020c, 2020d). Previous studies suggested a clockwise P-T path in the northern part of the JLJB and a counterclockwise P-T path in the southern part of the JLJB (He and Ye, 1998; Li *et al*., 2001b). However, recent metamorphic studies reported a clockwise P-T path in the southern part of the JLJB (Lu *et al*., 1996; Wang *et al*., 2010, 2020b; Tam *et al*., 2012a, 2012b, 2012c; Liu *et al*., 2013a, 2017c, 2019; Cai *et al*., 2017, 2019; Zou *et al*., 2017, 2019, 2020). Although studies on the JLJB have increased, the tectonic model of the belt is still not clear, and several different tectonic models have been proposed (Zhang and Yang, 1988; Bai, 1993; Faure *et al*., 2004; Li *et al*., 2011, 2017a; Zhao *et al*., 2012; Li and Chen, 2014; Peng *et al*., 2014; Yuan *et al*., 2015; Xu and Liu, 2019). The tectonic model in which rifting followed by collision due to closure of the rift basin model has been suggested based on metamorphism with a counterclockwise P-T path in the southern part of the JLJB and the similarities of the Precambrian basement (the Longgang and Nangrim Blocks) on both sides of the JLJB (Zhang and Yang, 1988). Continental collision after the subduction model has also been suggested based on the discovery of subduction-related igneous activities, metamorphism with a clockwise P-T path and the existence of granulites along the southern margin of the JLJB (Bai, 1993; Faure *et al*., 2004). It is necessary to ascertain which tectonic model is correct.

In this study, the deposition age of sedimentary rocks in the JLJB was figured out by combining the detrital zircon ages in the metasedimentary rocks and intrusion and extrusion ages of igneous rocks in the JLJB in the previous studies. The review on the petrogenesis and ages of the igneous rocks and the metamorphic evolution in the JLJB were also carried out for a comprehensively interpretation on the igneous and metamorphic evolution of the JLJB. By combining these review results on the sedimentary, igneous and metamorphic rocks, we tried to ascertain which tectonic model is correct for the tectonic evolution of the JLJB.

2. Sedimentary events in the JLJB

The whole JLJB experienced a series of sedimentary events during the Paleoproterozoic. From northeast to southwest, eight groups were identified, namely, the Macheonryeong, Laoling, Ji'an, North Liaohe, South Liaohe, Fenzishan, Jingshan, and Wuhe Groups (Fig. 1: Zhao *et al*., 2005, 2012; Lu *et al*., 2006; Liu *et al*., 2018a). Previous studies divided these groups into two parts based on the rock type and metamorphic degree. The northern part consists of the Laoling, North Liaohe, and Fenzishan Groups, and the southern part is composed of the Ji'an, South Liaohe, and Jingshan Groups (Fig. 1).

2.1 The Macheonryeong Group

The Macheonryeong Group is located between the Nangrim and Kwanmo Massifs in the northeastern Korean Peninsula and has a northwest-southeast direction (Liao et al., 2016) (Fig. 1). The Macheonryeong Group consists of the Songjin Formation (marble, schist, and amphibolite), the Puktaechon Formation (carbonate), and the Namdaechon Formation (terrigenous clastic rocks), from bottom to top (Paek *et al*., 1996). Based on the remarkable differences in rock type and metamorphism between the Songjin Formation and the Puktaechon and Namdaechon Formations, Liao *et al*. (2016)

suggested that the Songjin Formation should be part of the Neoarchean supracrustal rocks rather than the Macheonayeong Group. The SIMS U-Pb age data show that the Puktaechon Formation was deposited after 2178 Ma and metamorphosed 1846 Ma, and the Namdaechon Formation was deposited after 2018 Ma and metamorphosed 1961 Ma (Liao *et al*., 2016) (Table 1).

2.2 The Laoling and Ji'an Groups

The Laoling Group is located in the northern part of the Jinan area in the JLJB (Fig. 1). It mainly consists of quartzite, metasandstone, marble, staurolite- or garnet-bearing schist, quartz schist, and phyllite. The Laoling Group consists of the Dataishan (quartzite, granulite, and marble), Zhenzhumen (Mg-rich marble), Huashan (staurolite- or garnet-bearing schist or quartz phyllite and marble), Linjiang (quartzite), and Dalizi (schist, phyllite, and marble) Formations, from bottom to top (Zhang *et al*., 2018). Zhang *et al*. (2018) studied the maximum deposit ages and concluded that the Dataishan, Zhenzhumen, Huashan, Linjiang, and Dalizi Formations formed after 2178 Ma, 2190 Ma, 1990 Ma, 1957 Ma, and 1940 Ma, respectively. On the other hand, Meng *et al*. (2017a) studied the Laoling Group and reported a maximum deposit age of 2037 Ma and a metamorphic age of 1899 Ma.

The Ji'an Group is mainly exposed in the Tonghua area in the southern part of the Jinan area in the JLJB (Fig. 1). It mainly consists of amphibolite-facies metamorphosed volcanic-sedimentary rocks, including two-mica schists, marble, quartzofeldspathic gneisses, and granulite-facies pelitic metamorphic rocks (Zhang *et al*., 2018). The Ji'an Group can be divided into the Mayihe, Huangchagou, and Dadongcha Formations, from bottom to top. The Mayihe Formation is a boron-bearing sequence, and its main rock types include tourmaline-bearing leptites-leptynites, with minor marbles and amphibolites (Meng *et al*., 2018). The Huangchagou Formation is a graphite- bearing sequence, and the main rock types are graphite-bearing biotite schists to gneisses, graphite- and diopside-bearing felsic granite rocks, graphite-bearing calc-silicate rocks and graphite-bearing marbles, and amphibolites (Zhang *et al*., 2018). The Dadongcha Formation is an aluminum-rich sequence, and the main rock types include biotite plagioclase gneisses, garnet-sillimanite plagioclase gneisses, cordierite-sillimanite plagioclase gneisses and biotite felsic rocks (Meng *et al*., 2018; Zhang *et al*., 2018). The maximum deposit times of the Mayihe, Huangchagou, and Dadongcha Formations are 2126, 2100, and 1950 Ma, respectively (Zhang *et al*., 2018). On the other hand, Meng *et al*. (2018) reported an age of ~2038 Ma as the maximum deposit time of the Huangchagou Formation. The Mayihe Formation underwent metamorphism 1915 Ma, and the Huangchagou and Dadongcha Formations underwent two metamorphisms ~1.90 and ~1.85 Ga (Lu *et al*., 2006; Liu *et al*., 2015b; Meng *et al*., 2017b, 2018) (Table 1).

2.3 The North and South Liaohe groups

The Liaohe Group is located in the Liaodong area of the JLJB and is divided into the North and South Liaohe Groups (Fig. 1). The Liaohe Group mainly consists of sedimentary and volcanic sequences that experienced greenschist- to granulite-facies metamorphism. Both the North and South Liaohe Groups consist of the Li'eryu, Gaojiayu, Dashiqiao, and Gaixian Formations, from bottom to top, and the Langzishan Formation lies under the Li'eryu Formation in the North Liaohe Group (Wang *et al*., 2017b, 2020a; Xu *et al*., 2019). The Langzishan Formation mainly consists of basal conglomerate-bearing quartzites at its bottom, chlorite-sericite quartz schists, phyllites, garnet-bearing mica schists, minor graphite-bearing garnet-staurolite mica schists, and kyanite-bearing mica schist (Xu *et al*., 2019). The conformably overlying Li'eryu Formation mainly consists of greenschist, amphibolite, and felsic gneiss (Li *et al*., 2015; Liu *et al*., 2015a; Wang *et al*., 2017b). The Gaojiayu

Table 1. Representative geochronological data of sedimentary rocks in the JLJB.

Group	Formation	Sample No.	Rock type	Detrital zircons (Ma)	Metamorphic age (Ma)	References
Ji'an	Mayihe	17th-42-02	biotite leptynite	2206-2124		Zhang *et al*. (2018)
		17th-44-01	garnet bearing biotite plagioclase paragneiss	2466-1992	1915	Zhang *et al*. (2018)
	Huangchagou	17th-48-01	amphibolite-bearing plagioclase paragneiss	2473-2134		Zhang *et al*. (2018)
		TH30-2	garnet-bearing biotite-felsic gneiss	3446-2044	1854	Meng *et al*. (2018)
		TH42-3	amphibole-bearing biotite-plagioclase gneiss	2053-2021	1906	Meng *et al*. (2018)
	Dadongcha	17th-34-01	biotite K-feldspar-plagioclase paragneiss	3350-1920		Zhang *et al*. (2018)
		17th-35-01	garnet-sillimanite plagioclase paragneiss		1900-1806	Zhang *et al*. (2018)
		TH49-1	biotite-plagioclase gneiss	2935-2033	1901	Meng *et al*. (2018)
		TH49-5	quartz-bearing mica schist	3234-2020	1919	Meng *et al*. (2018)
Laoling	Dataishan	17th-46-01	quartz sandstone	2725-2131		Zhang *et al*. (2018)
	Zhenzhum	17th-31-02	marble	2623-1888		Zhang *et al*. (2018)
	Huashan	17th-49-01	mica schist	2492-1931		Zhang *et al*. (2018)
		17th-49-02	quartz sandstone	2348-1969		Zhang *et al*. (2018)
	Linjiang	17th-23-01	mica schist	2813-1822		Zhang *et al*. (2018)
		17th-23-02	arkose-quartzite	3412-1857		Zhang *et al*. (2018)
	Dalizi	17th-30-01	phyllite	2480-1932		Zhang *et al*. (2018)
North Liaohe	Langzishan	D9008-3	muscovite quartzite	3783-2447		Xu *et al*. (2019)
		D9006-9	muscovite quartzite	3176-2469	2432	Xu *et al*. (2019)
		D3001-5	biotite quartzite	3603-2226		Xu *et al*. (2019)
		17XW009-2	muscovite-quartz schist	2705-2159		Xu *et al*. (2019)
		D9001-4	garnet-staurolite-mica schist	3432-2107	1869; 1847	Xu *et al*. (2019)
		D9002-9	garnet-mica schist	3218-2173	1926; 1861	Xu *et al*. (2019)
		D9007-2	garnet-muscovite schist	2724-2177		Xu *et al*. (2019)
		D1002-6	phyllitic slate	2757-2250		Xu *et al*. (2019)
	Li'eryu	LEY1	marble	2546-2079		Wang *et al*. (2020a)
		LEY2	Ms-bearing monzogneiss	2229-2020		Wang *et al*. (2020a)
		LEY3	Mag-bearing felsic rock	2256-2010		Wang *et al*. (2020a)

Table 1. continued.

Group	Formation	Sample No.	Rock type	Detrital zircons (Ma)	Metamorphic age (Ma)	References
		LEY4	Ms-bearing monzogneiss	2521-2106		Wang *et al*. (2020a)
		LEY5	Mag-bearing felsic rock	2314-2103		Wang *et al*. (2020a)
		LEY6	Ms-bearing monzogneiss	2465-2098		Wang *et al*. (2020a)
	Gaojiayu	GJY1	marble	2627-2102		Wang *et al*. (2020a)
		GJY2	marble	2584-2113		Wang *et al*. (2020a)
		GJY3	slate	2657-2096		Wang *et al*. (2020a)
	Dashiqiao	DSQ1-4	marble	2709-2028		Wang *et al*. (2020a)
South Liaohe	Li'eryu	SJZ09-1	felsic paragneiss	2262-1993	1828	Wang *et al*. (2017b)
		SJZ10-4	Bt-Pl paragneiss	2203-1925		Wang *et al*. (2017b)
		SJZ14-1	felsic paragneiss	~2160		Wang *et al*. (2017b)
		SJZ17-1	Bt-Pl paragneiss	3506-2006		Wang *et al*. (2017b)
		SJZ18-2	Bt-Pl paragneiss	2195-1924	1844	Wang *et al*. (2017b)
		SJZ19-1	Bt-Pl paragneiss	2389-1936	1933-1810	Wang *et al*. (2017b)
	Gaojiayu	18GJY01	Ms-bearing felsic rock	2928-2039		Wang *et al*. (2020a)
		18GJY03	Grt-bearing Ms-Bt quartz schist	3592-1994		Wang *et al*. (2020a)
		SJZ22-2	Sil-Grt paragneiss		1813	Wang *et al*. (2017b)
		SJZ22-3	quartzite	3276-1988	1836	Wang *et al*. (2017b)
	Dashiqiao	SJZ21-1	Sil-Grt paragneiss		1842	Wang *et al*. (2017b)
		SJZ25-1	marble	~2495		Wang *et al*. (2017b)
		SJZ28-1	Sil-Grt paragneiss	2202-1957	1860	Wang *et al*. (2017b)
		SJZ46-1	marble	~2165	1883-1839	Wang *et al*. (2017b)
	Gaixian	SJZ39-1	Grt-Bt schist	2575-1903	1880-1811	Wang *et al*. (2017b)
		SJZ41-1	Grt-Bt schist	2702-1879	1853	Wang *et al*. (2017b)
Wuhe	Zhuangzili	14BB07-3	calcite quartzite	3155-2167		Liu *et al*. (2018a)
		14BB29-3	diopside marble	2877-2368		Liu *et al*. (2018a)
		14BB29-4	marble	2561-2177		Liu *et al*. (2018a)
		14BB30-1	dolomite-bearing marble	2531-2102		Liu *et al*. (2018a)
		14BB38-2	calcite quartzite	3540-2155		Liu *et al*. (2018a)
		14BB39-1	phlogopite marble	3660-2129		Liu *et al*. (2018a)
		14BB39-2	phlogopite marble	3516-2154		Liu *et al*. (2018a)
	Yinjian	14BB46-1	biotite-bearing muscovite-quartz schist	3572-2162		Liu *et al*. (2018a)
Macheonayeong	Namdaechon	13NK-127	Sil-bearing two mica schist	3299-2018	1961	Liao *et al*. (2016)
	Puktaechon	13NK-140	two mica schist	2585-2178	1846	Liao *et al*. (2016)

Formation mainly consists of mica schist and the Dashiqiao Formation consists of marble and mica schist (Li *et al*., 2015; Liu *et al*., 2015a; Wang *et al*., 2017b). The top layer Gaixian Formation consists of phyllites, mica schist, and granulites (Li *et al*., 2015; Liu *et al*., 2015a; Wang *et al*., 2017b). The cumulative probability diagrams show that the Langzishan Formation was deposited on a passive continental margin, whereas the Li'eryu Formation was formed in an active continental margin setting (Xu *et al*., 2019). Xu *et al*. (2019) studied detrital zircons of the Langzishan Formation and reported that the Langzishan Formation was deposited after 2205 Ma (Table 1). Wang *et al*. (2017b) concluded that the Li'eryu, Gaojiayu, Dashiqiao, and Gaixian Formations in the South Liaohe Group were deposited after ~2.05 Ga, ~2.07 Ga, ~2.04 Ga, and ~1.92 Ga, respectively. The Li'eryu, Gaojiayu, and Dashiqiao Formations in the North Liaohe Group were considered to have been deposited after ~2.08 Ga, ~2.10 Ga, and ~2.03 Ga, respectively (Wang *et al*., 2020a). 1.93 Ga to 1.95 Ga metamorphic ages were reported by Luo *et al*. (2008) from the Li'eryu and Dashiqiao Formations in the North and South Liaohe Groups.

2.4 The Fenzishan and Jingshan Groups

The Fenzishan Group is exposed in the northern and western parts of the Jiaobei area, and the Jingshan Group is located in the southern and eastern parts of the Jiaobei area (Fig. 1). Both Groups were probably deposited on the Archean TTG gniesses within the period of 2.2-2.1 Ga and metamorphosed during 1.95-1.80 Ga (Wan *et al*., 2006; Tam *et al*., 2011).

2.5 The Wuhe Group

The Wuhe Group is located in the Bengbu area, Anhui Province (Fig. 1). It mainly consists of greenschist- to granulite-facies metamorphosed flysch-type metasedimentary rocks and metavolcanic rocks and can be further subdivided into five formations, from bottom to top: the Xigudui, Zhuangzili, Fengshanli, Xiaozhangzhuang, and Yinjian Formations (Liu *et al*., 2018a). The Xigudui Formation consists of biotite-amphibole gneiss, plagioclase amphibolite, amphibolite, leptite, biotite leptynite, serpentinized marble, and minor metamorphosed pyroxene peridotite, diabase, and pyroxenite. The Zhuangzili Formation consists of amphibole leptynite and minor leptynite with interbedded marble, quartzite, and biotite schist in the lower part and thick-layered marble, interlayered leptynite and plagioclase amphibolite in the upper part. The Fengshanli Formation is composed of banded amphibole gneiss and interbedded leptite, marble and plagioclase amphibolite. The Xiaozhangzhuang Formation consists of feldspar gneiss, tourmaline leptynite and leptite with dolomitic marble. The Yinjian Formation is composed of muscovite-quartz schist with interbedded meta-rhyolite in the lower part and epidote-amphibole schist with a locally preserved andesitic texture, pores and amygdaloid structures in the upper part (Liu *et al*., 2018a). The detrital zircon data suggest that the Wuhe Group was deposited after 2.16-2.10 Ga and metamorphosed 1.88 Ga and 1.84 Ga (Liu *et al*., 2018a) (Table 1).

3. Magmatic events

3.1 Igneous activities during 2.2-2.1 Ga

3.1.1 Igneous activities in the Liaoji area

Igneous rocks with an age range of 2.2-2.1 Ga were widely distributed in the Liaoji area (Fig. 2; Table). In this part, we will introduce serval well studied plutons in the Liaoji area. Two felsic plutons (the Mafeng and Muniuhe plutons) are present in the northwest part of the Liaoji area. The Mafeng hornblende monzogranites, within an area of 35 km × 3 km, are located northwest of the North Liaohe Group in the Liaodong area (Wang *et al*., 2017c). Two studies were performed in this area, and they reported that the Mafeng pluton formed during 2.17-2.18 Ga (Li and Zhao, 2007;

Wang *et al*., 2017c). Wang *et al*. (2017c) classified the Mafeng monzogranites into A-type granites, and Wang *et al*. (2020d) further divided them into A_2-type granites. The Muniuhe granitic plutons are located in the northwestern Liaoji area and mainly consist of granodiorite and syenogranite with no distinct boundary between them (Wang *et al*., 2020d). The Muniuhe plutons formed ~2.18 Ga and were metamorphosed ~1.88 Ga (Wang *et al*., 2020d). Based on geochemical data, Yang *et al*. (2015) and Wang *et al*. (2020d) confirmed that the Muniuhe granite could be classified as I-type granite.

Four felsic plutons are located in the central part of the Liaoji area: the Hupiyu-Hadabei, Simenzi-Gujiabao, Qianzhuogou, and Dafangshan plutons. The Hupiyu-Hadabei pluton intruded during 2.15-2.16 Ga (Fig. 2; Table 2) (Lu *et al*., 2004a; Li and Zhao, 2007; Yang *et al*., 2015). Lu *et al*. (2004a) classified the Hupiyu-Hadabei plutons as A-type granite intrusions, whereas Yang *et al*. (2015) classified the Hupiyu-Hadabei pluton as I-type granite intrusions. The Simenzi-Gujiabao pluton intruded during 2.15-2.2 Ga (Yang *et al*., 2015; Song *et al*., 2016). Both Yang *et al*. (2015) and Song *et al*. (2016) considered the Simenzi-Gujiabao pluton an I-type granite; however, Wang *et al*. (2020d) suggested that they consist of both I- and A_2-type granites based on geochemical variations. The Qianzhuogou pluton is located in the northeastern part of the Liaoji area and intruded ~2.16 Ga (Lu *et al*., 2004b). The Dafangshan pluton is located south of the Muniuhe pluton and formed 2.14 Ga (Li and Zhao, 2007). Both the Qianzhuogou

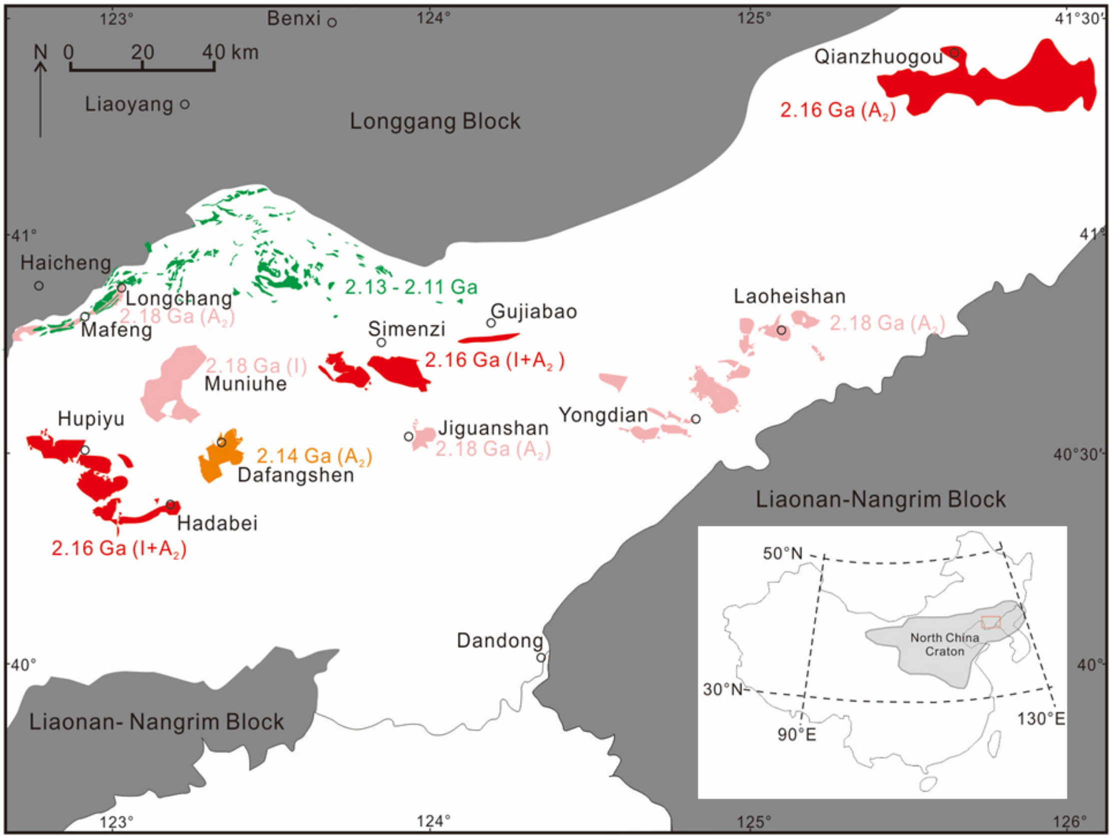

Fig. 2. Schematic diagram showing the locations of the 2.2-2.1 Ga felsic intrusions in the Liaoji area (modified after Wang *et al*., 2020d).

Table 2. Representative geochronological data of igneous rocks in the JLJB.

Intrusions/ Locations	Sample No.	Lithologies	Intrusion Ages (Ma)	Methods	References
2.2-2.13 Ga Liaoji granite					
Mafeng Pluton	LJ035	Magnetite monzogranitic gneiss	2176±11 (n=7)	SHRIMP	Li and Zhao (2007)
	601SDG1	Hornblende monzogranite	2181±6 (n=20)	CAMECA	Wang *et al*. (2017a)
	LD9822	biotite granite	2173±3 (n=10)	SHRIMP	Wan *et al*. (2006)
Muniuhe Pluton	187401	syenogranite	2180±6 (n=14)	SHRIMP	Wang *et al*. (2020d)
	187404	granodiorite	2177±6 (n=13)	SHRIMP	Wang *et al*. (2020d)
Hupiyu-Hadabei Pluton	FW10-327	syenogranite	2161±12 (n=30)	LA-ICP-MS	Lu *et al*. (2004a)
	LJ044	Biotite monzogranitic gneiss	2150±17 (n=13)	SHRIMP	Li and Zhao (2007)
	HP-1	Biotite monzogranitic gneiss	2159±19 (n=18)	LA-ICP-MS	Yang *et al*. (2015)
	HPX 1	Biotite monzogranitic gneiss	2215±3 (n=19)	LA-ICP-MS	Chen *et al*. (2016)
	HD-2	Biotite monzogranitic gneiss	2173±20 (n=30)	LA-ICP-MS	Yang *et al*. (2015)
Simenzi-Gujiabao Pluton	SM-1	Hornblende monzogranitic gneiss	2203±20 (n=18)	LA-ICP-MS	Yang *et al*. (2015)
	TW12	monzogranite	2157±14 (n=5)	SHRIMP	Song *et al*. (2016)
	T02-1	syenogranite	2169±11 (n=6)	SHRIMP	Song *et al*. (2016)
Qianzhuogou Pluton	Lu1065	syenogranite	2173±20 (n=11)	LA-ICP-MS	Lu *et al*. (2004a)
	Lu0007	syenogranite	2164±8 (n=11)	SHRIMP	Lu *et al*. (2004b)
Dafangshen Pluton	LJ040	Hornblende monzogranitic gneiss	2143±17 (n=12)	SHRIMP	Li and Zhao (2007)
Jiguanshan Pluton	LJ035	Magnetite monzogranitic gneiss	2175±13 (n=14)	SHRIMP	Li and Zhao (2007)
Laoheishan-Yongdian Pluton	LJ010	Magnetite monzogranitic gneiss	2166±14 (n=14)	SHRIMP	Li and Zhao (2007)
2.14-2.10 Ga Mafic intrusion in the Liaoji area					
Dike or lens	A1102	Meta-gabbro	2110±31 (n=2)	SHRIMP	Dong *et al*. (2012)
	DZ91-1	Meta-diabase	2161±12 (n=22)	LA-ICP-MS	Meng *et al*. (2014)
	DZ73-1	Meta-gabbro	2159±12 (n=14)	LA-ICP-MS	Meng *et al*. (2014)
	DZ85-1	Meta-gabbro	2157±17 (n=6)	LA-ICP-MS	Meng *et al*. (2014)
	DZ74-1	Meta-gabbro	2144±16 (n=24)	LA-ICP-MS	Meng *et al*. (2014)
	YK12-1-4	Meta-gabbro	2127±6 (n=16)	CAMECA	Yuan *et al*. (2015)
	16KD68-1	Meta-gabbro	2188±9 (n=38)	LA-ICP-MS	Xu *et al*. (2019)
	D9001-1	Meta-gabbro	2118±6 (n=26)	LA-ICP-MS	Xu *et al*. (2019)
	D2066-1	Amphibolite	2083±13 (n=10)	LA-ICP-MS	Xu *et al*. (2019)
	SJZ07-5	Amphibolite	2054-2061 (n=2)	LA-ICP-MS	Xu *et al*. (2019)
	SJZ11-1	Amphibolite	2119±19 (n=20)	LA-ICP-MS	Xu *et al*. (2019)
	16KD55-1-1	Amphibolite	2063±23 (n=8)	LA-ICP-MS	Xu *et al*. (2019)
2.2-2.1 Ga Igneous rocks in the Jiaobei area					
Changyi iron deposit	CY2-92	alkali-feldspar granite	2193±11 (n=22)	LA-ICP-MS	Lan *et al*. (2015)
	CY2-43	albite granite	2171±10 (n=13)	LA-ICP-MS	Lan *et al*. (2015)
Dongbaishishan	188001	granite	2105±10 (n=16)	SHRIMP	Wang *et al*. (2020c)

Table 2. continued.

Intrusions/ Locations	Sample No.	Lithologies	Intrusion Ages (Ma)	Methods	References
Gujiacun	188101	granite	2084±12 (n=21)	SHRIMP	Wang *et al*. (2020c)
	QX16-1	Hornblende granitic gneiss	2095±12 (n=22)	LA-ICP-MS	Liu *et al*. (2011)
Xiliu	QX2	Meta-gabbro	2102±3 (n=75)	LA-ICP-MS	Liu *et al*. (2013b)
1.87-1.84 Ga Igneous rocks					
Wolongquan Pluton	FW02-62	Porphyritic granite	1848±10 (n=22)	LA-ICP-MS	Lu *et al*. (2004a)
Kuandonggou Pluton	FW01-31	Hornblende pyroxene syenite	1843±23 (n=20)	LA-ICP-MS	Lu *et al*. (2004a)
	03JH079	Coarse-grained syenite	1879±17 (n=19)	LA-ICP-MS	Yang *et al*. (2007)
	03JH080	Fine-grained syenite	1874±18 (n=17)	LA-ICP-MS	Yang *et al*. (2007)
	03JH082	Fine-grained diorite	1870±18 (n=12)	LA-ICP-MS	Yang *et al*. (2007)
Honghuagoumen Dike	10JL13	Granite pegmatite	1870±8 (n=13)	LA-ICP-MS	Wang *et al*. (2011)
Haiguan	28-4	Porphyritic granite	1842±5 (n=5)	SHRIMP	Wang *et al*. (2020)
Shisandaogou	JN1	Grt-bearing porphyritic granite	1868±9 (n=20); 1848±13 (n=11)	LA-ICP-MS	Liu *et al*. (2017a)
Shierdaogou	JN2	Bt-bearing porphyritic granite	1868±6 (n=34); 1849±13 (n=8)	LA-ICP-MS	Liu *et al*. (2017a)
	JN3	Grt-bearing porphyritic granite	1872±6 (n=42); 1851±14 (n=9)	LA-ICP-MS	Liu *et al*. (2017a)
Shiyidaogou	JN4	Bt-bearing porphyritic granite	1872±7 (n=34); 1849±9 (n=14)	LA-ICP-MS	Liu *et al*. (2017a)
	JN5	Flesh-red porphyritic feldspar granite	1868±7 (n=30); 1849±8 (n=24)	LA-ICP-MS	Liu *et al*. (2017a)
Qinghe	JN6	Bt-bearing porphyritic granite	1865±7 (n=24); 1849±9 (n=19)	LA-ICP-MS	Liu *et al*. (2017a)
Huairen	JN7	Grt-bearing porphyritic granite	1871±7 (n=26); 1850±12 (n=13)	LA-ICP-MS	Liu *et al*. (2017a)
Huairen	JN8	Bt-bearing porphyritic granite	1872±7 (n=28); 1850±13 (n=10)	LA-ICP-MS	Liu *et al*. (2017a)
Yilin	LN1	Bt-bearing porphyritic granite	1867±10 (n=17); 1842±12 (n=11)	LA-ICP-MS	Liu *et al*. (2017a)
Taipingshao	LN2	Flesh-red porphyritic feldspar granite	1866±6 (n=39); 1846±13 (n=8)	LA-ICP-MS	Liu *et al*. (2017a)
Yongdian	LN3	Grt-bearing porphyritic granite	1872±8 (n=25); 1851±12 (n=11)	LA-ICP-MS	Liu *et al*. (2017a)
Lianhuapeng	LN4	Bt-bearing porphyritic granite	1865±6 (n=33); 1849±8 (n=16)	LA-ICP-MS	Liu *et al*. (2017a)
Kuandian	LN5	Bt-bearing porphyritic granite	1864±8 (n=18); 1844±9 (n=14)	LA-ICP-MS	Liu *et al*. (2017a)
Fengcheng	LN6	Grt-bearing porphyritic granite	1870±7 (n=31); 1850±11 (n=13)	LA-ICP-MS	Liu *et al*. (2017a)
Yaitai	JB1	Flesh-red porphyritic feldspar granite	1868±6 (n=34); 1848±14 (n=7)	LA-ICP-MS	Liu *et al*. (2017a)
Taochun	JB2	Grt-bearing porphyritic granite	1866±7 (n=24); 1840±10 (n=16)	LA-ICP-MS	Liu *et al*. (2017a)
Qixia	JB3	Bt-bearing porphyritic granite	1872±8 (n=23); 1848±7 (n=25)	LA-ICP-MS	Liu *et al*. (2017a)
Laiyang	JB4	Grt-bearing porphyritic granite	1871±7 (n=23); 1851±11 (n=12)	LA-ICP-MS	Liu *et al*. (2017a)

and Dafangshan plutons have been classified as A_2-type granite (Yang *et al*., 2015; Wang *et al*., 2017a, 2020d; Liu *et al*., 2018b).

Two felsic plutons are located in the southeastern part of the Liaoji area, including the Jiguanshan and Laoheishan-Yongdian plutons (Fig. 2; Table 2). Li and Zhao (2007) reported that they formed at ~2.18 Ga and can be classified as A_2-type granite (Li *et al*., 2017a, 2017b; Teng *et al*., 2017).

Mafic intrusions have mostly been discovered in the middle to northern Liaoji area in the JLJB, and they intruded the Liaohe Groups during 2.08-2.15 Ga and were metamorphosed during 1.92-1.84 Ga (Meng *et al*., 2014; Yuan *et al*., 2015; Xu *et al*., 2018a; Wang *et al*., 2020b). Xu *et al*. (2018a) concluded that these mafic rocks formed in a subduction-related back-arc extensional environment.

3.1.2 Igneous activities in the Jiaobei area

The 2.2-2.1 Ga granitic igneous rocks intruded in two stages (~2.19-2.17 Ga and ~2.10 Ga) (Liu *et al*., 2011, 2014; Lan *et al*., 2015; Wang *et al*., 2020c). Mafic rocks with an age range of 2.2-2.1 Ga mainly occurred as enclaves or deformed dikes in TTG gneisses or granitic gneisses (Liu *et al*., 2013b). Lan *et al*. (2015) reported alkali feldspar granite (2193 Ma) and albite granite (2171 Ma) from the Changyi iron deposit, and they can be classified as A-type granite (Table 2). Wang *et al*. (2020c) reported 2.1 Ga mafic and granitic rocks in the southern part of the Jiaobei area, and these rocks are considered to have formed in a subduction-related back-arc extensional environment.

3.2 Igneous activities during 1.87-1.84 Ga

Magmatism in the age range of 1.87-1.84 Ga also occurred regionally, forming porphyritic granite and alkaline syenite, and 1.87-1.84 Ga igneous rocks are mostly distributed along the southern part of the JLJB (Fig. 3; Table 2) (Hao *et al*., 2004; Li and Zhao, 2007; Liu *et al*., 2017a; Wang *et al*., 2020b). The zircons in the felsic rocks give intrusion ages of 1.87-1.84 Ga without a metamorphic signature (Li and Zhao, 2007; Liu *et al*., 2017a; Wang *et al*., 2020b). Liu *et al*. (2017a) proposed that these rocks formed in an anorogenic environment based on their A-type character; however, Wang *et al*. (2020d) suggested that they were further classified into A_2-type granite and formed in a post-collisional tectonic setting by melting of the crust, which was highly enriched during subduction before the continent-continent collision.

4. Metamorphic events

The metamorphic aspect of the JLJB has been studied for more than 20 years (Lu *et al*., 1996; He and Ye, 1998; Li *et al*., 2001b; Wang *et al*., 2010, 2020b; Tam *et al*., 2012a, 2012b, 2012c; Liu *et al*., 2013a, 2017c, 2019; Cai *et al*., 2017, 2019; Zou *et al*., 2017, 2019, 2020). Early studies have suggested that the northern and southern parts experienced different P-T paths (Lu *et al*., 1996; He and Ye, 1998; Zhao and Cawood, 2012). He and Ye (1998) reported clockwise P-T paths for the North Liaohe and Laoling Groups based on staurolite inclusions in garnet. Zhao *et al*. (2012) also confirmed a clockwise P-T path for the Fenzishan Group. These studies indicate a clockwise P-T path metamorphism of the northern JLJB. A counterclockwise P-T path metamorphism of the southern part of the JLJB was suggested based on P-T estimation using a conventional geothermobarometer (Lu *et al*., 1996; He and Ye, 1998). However, recent studies did not support different P-T paths in the northern and southern parts of the JLJB (Wang *et al*., 2010, 2020b; Tam *et al*., 2012a, 2012b, 2012c; Liu *et al*., 2013a, 2017c, 2019; Cai *et al*., 2017, 2019; Zou *et al*., 2017, 2019, 2020).

4.1 Metamorphism in the Jiaobei area

In the Jiaobei area, clockwise P-T paths with granulite facies metamorphic events have been widely discovered in the Jingshan Group (Tam *et al*., 2012a, 2012b, 2012c; Liu *et al*., 2013a, 2017c; Zou *et al*., 2017, 2019, 2020). High-pressure (>12 kbar) metamorphic events have been reported in the Taipingzhuang-Pingdu region, including Laiyang and Laixi areas (Tam *et al*., 2012a, 2012b, 2012c; Liu *et al*., 2013a, 2017c; Zou *et al*., 2017, 2019, 2020). Tam *et al*. (2012b) studied mafic samples from the Malianzhuang and Hetoudian areas, west of Laiyang city, and reported 13.1-15.1 kbar and 780-890℃ for the P-T conditions of the peak (M2) metamorphic stage and 7.8 and 8.4 kbar and 820-880℃ for the P-T conditions of the post-peak (M3) metamorphic stage. Tam *et al*. (2012c) studied pelitic granulites from the Taipingzhuang area and reported 14.8-16.2 kbar and 860-890℃ and 6.3-8.5 kbar and 710-740℃ for the M2 and M3 metamorphic stages, respectively. Similarly, Liu *et al*. (2013a) reported 14.5-16.5 kbar and 850-880℃ for the P-T conditions of the peak metamorphic stage from mafic granulites in the Taipin-gzhuang and Laixi areas, and (Liu *et al*., 2017c) reported 12.8-14.4 kbar and 757-805℃ for the peak metamorphic P-T conditions of mafic granulites in the Pingdu-Anqiu area. In addition, Zou *et al*. (2017), Zou *et al*. (2019) and Zou *et al*. (2020) also reported 14-17 kbar and 850-890℃ for the peak metamorphic conditions and 4-7 kbar and >840℃ for the P-T conditions of the retrograde stages ~1.85 Ga in Jiaobei area. Therefore, we can conclude that the Jingshan Group experienced pressures >14 kbar and temperatures in

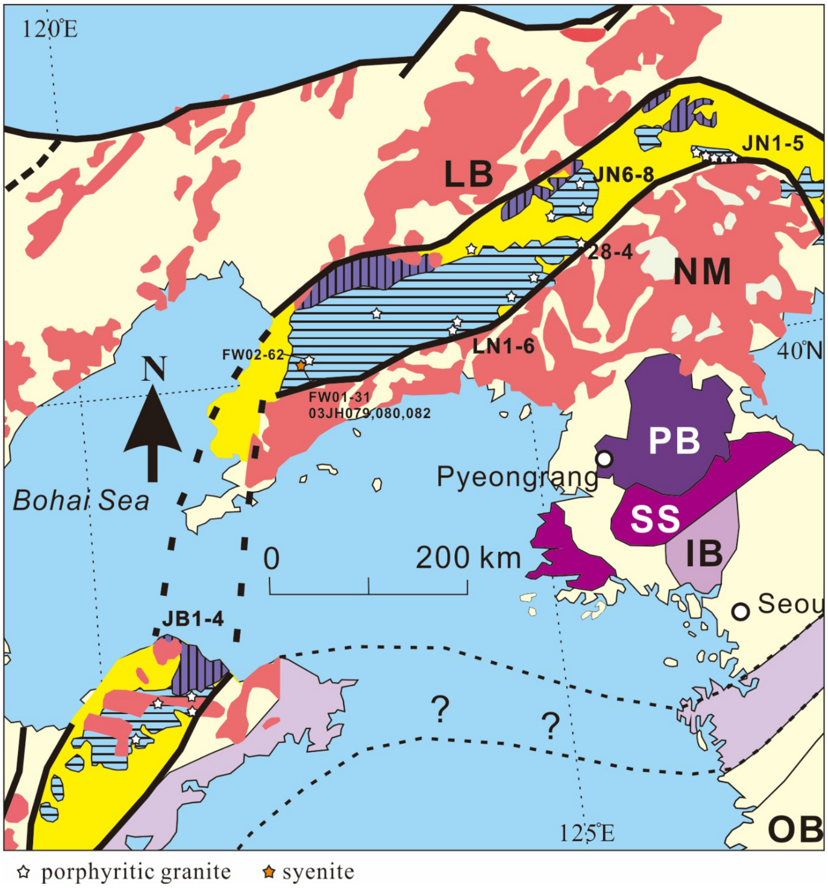

Fig. 3. Schematic diagram of the JLJB showing the locations of the 1.87-1.84 Ga igneous rocks including porphyritic granite and syenite. Data are from multiple sources (Lu *et al*., 2004a; Yang *et al*., 2007; Liu *et al*., 2017a; Wang *et al*., 2020b).

the range of 800-890℃ during peak metamorphism, which was followed by isothermal decompression.

Zou *et al*. (2019, 2020) and Liu *et al*. (2017c) reported zircon and monazite age data and concluded that the peak metamorphic stages occurred during 1.94-1.93 Ga, and the post-peak metamorphic stages occurred during 1.87-1.84 Ga. Moreover, some low- to medium-pressure granulites have been reported in the Jiaobei area (Tam *et al*., 2012a; Zou *et al*., 2020). Zou *et al*. (2020) concluded that at least some of these low- to medium-pressure granulites were related to post-peak metamorphism of the High-pressure (HP) granulites based on kyanite relics in the low to medium pressure (LMP) granulite samples.

4.2 Metamorphism in the Liaodong area

In the Liaodong area, Liu *et al*. (2017b) and Liu *et al*. (2019) reported clockwise P-T paths in the northern part of the South Liaohe Group (Fig. 4b). Liu *et al*. (2017b) reported a garnet-bearing amphibolite that intruded the Li'eryu Formation, South Liaohe Group, and then underwent three stages of metamorphism: the M1 (7.2-6.8 kbar and 600-570℃), M2 (9.8-10.1 kbar and 710-690℃), and M3 (6.1-5.2 kbar and 700-670℃) stages. The sample experienced peak metamorphism at the M2 stage and then experienced an increase in the geothermal gradient, resulting in a transition from intermediate- (M2) to low- (M3) P/T type metamorphism. Liu *et al*. (2017b) obtained ages of 1.96-1.94 Ga and 1.92-1.83 Ga for the peak M2 and post-peak M3 metamorphic stages, respectively, from the amphibolite sample. Liu *et al*. (2019) reported the M1 (7.1-6.6 kbar and 650-620℃), M2 (11-9.6 kbar and 840-790℃), M3 (6.5-6.2 kbar and 785-725℃), and M4 (5.5-4.3 kbar and 625-595℃) metamorphic stages from pelitic granulite collected from the Dashiqiao Formation in the South Liaohe Group. The sample experienced peak metamor-

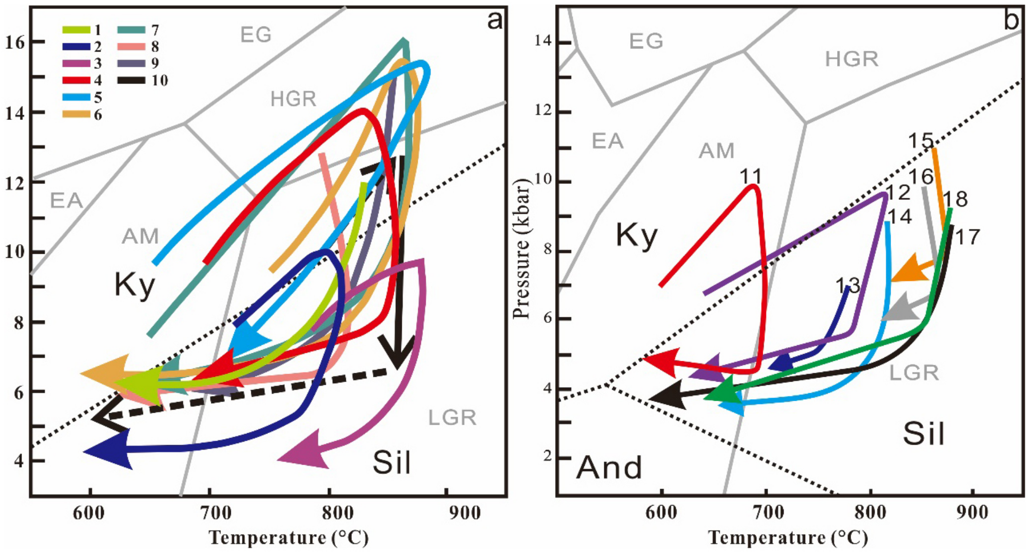

Fig. 4. Metamorphic P-T path diagram of the JLJB. The arrows represent the P-T paths of Paleoproterozoic metamorphic rocks in the Jiaobei area (a) and the Liaodong and Jinan areas (b) in the JLJB from the previous studies. 1. Zhou *et al*. (2004); 2. Wang *et al*. (2010); 3. Tam *et al*. (2012a); 4. Tam *et al*. (2012b); 5. Tam *et al*. (2012c); 6. Liu *et al*. (2013a); 7. Zou *et al*. (2017); 8. Liu *et al*. (2017c); 9. Zou *et al*. (2019); 10. Zou *et al*. (2020); 11. Liu *et al*. (2017b); 12. Liu *et al*. (2019); 13 and 14. Wang *et al*. (2020b); 15. Cai *et al*. (2019); 16. Cai *et al*. (2017); 17 and 18. Wang *et al*. (2021). Metamorphic facies diagram after Oh and Liou (1998). BS, blueschist facies; EG, eclogite facies; EA, epidote-amphibolite facies; GS, greenschist facies; AM, amphibolite facies; HGR, high-pressure granulite facies; LGR, low-pressure granulite facies; And, andalusite; Ky, kyanite; Sil, sillimanite.

phism at the M2 stage and post-peak metamorphism at the M3 stage. According to the P-T conditions of M2 and M3, the sample experienced an increasing geothermal gradient indicated by the transition from intermediate- (M2) to low- (M3) P/T type metamorphism. Liu *et al*. (2019) obtained ages of ca. 1.95 Ga and 1.85-1.84 Ga for the peak M2 (intermediate-P/T type) and post-peak M3 (low-P/T type) metamorphic stages in the granulite, respectively. Wang *et al*. (2021) studied two granulite facies metamorphic rocks on the southern margin of the South Liaohe Group and reported that these rocks experienced peak metamorphic conditions of 890-860℃ and 6.9- 9.2 kbar and then underwent retrograde metamorphism at 570-670℃ and 3.3-4 kbar (Fig. 4b). The SHRIMP zircons in the two granulite facies metamorphic rocks give a peak metamorphic age of ~1.87 Ga.

4.3 Metamorphism in the Ji'an area

In the Ji'an Group, Cai *et al*. (2019) reported peak stage (9-11 kbar and 830-880℃) and post-peak stage (4.5-7.5 kbar and 810-900℃) metamorphism from pelitic granulite samples (Fig. 4b). During the transition from peak to post-peak, the granulites experienced isothermal decompression and a clockwise P-T path. The metamorphic zircons yield 1.87-1.89 Ga and metamorphic monazites yield 1.88-1.84 Ga. Wang *et al*. (2020b) also reported granulite-facies metamorphism and obtained peak metamorphic conditions of 770-840℃ and 8.5-6.9 kbar (Fig. 4b). Metamorphic monazites in the study yield an age of ~1.84 Ga, which coincides with the metamorphic ages obtained in previous studies.

5. Discussion

5.1 Age of sedimentation

The ages of sedimentation in the Liaodong and Jinan areas in the JLJB are similar according to detrital zircon studies. Zhang *et al*. (2018) reported that the Laoling and Ji'an Groups in the Jinan area were deposited between 2.18-1.94 Ga, Whereas, The Liaohe Groups in the Liaodong area except Gaixian Formation were considered to be deposited between 2.21-1.92 Ga (Wang *et al*., 2017b, 2020a; Xu *et al*., 2019). The interlayered volcanic successions were dated to ~2.17 Ga in the Dashiqiao and Gaojiayu Formations, 2.2~2.03 Ga in the Li'eryu Formation and 2.18 Ga in the Ji'an Group and the ~2.2-2.1 Ga Liaoji granite were also found to intrude the Liaohe Groups (Chen *et al*., 2017; Meng *et al*., 2017b; Bi *et al*., 2018). These igneous ages represent that some sedimentary rocks in the JLJB may be deposited before 2.2 Ga. These data indicate may that the sedimentary rocks in the JLJB had been deposited during a long period from 2.21 Ga to ~1.95 Ga. The Gaixian Formation, the top formation of the South Liaohe Group, was deposited after continental collision ~1.92 Ga and metamorphosed ~1.85 Ga (Wang *et al*., 2017b, 2018). Together with the metamorphic ages, alkali syenite with an ~1.86 Ga intrusion age within the Gaixian Formation confirms that this stratum was deposited between ~1.92 Ga and ~1.86 Ga (Cai *et al*., 2002; Yang *et al*., 2007). These data indicate that the sedimentary rocks in the Liaodong and Jinan areas mainly deposited during 2.21-1.92 Ga with local deposition between 1.92-1.86 Ga. Based on limited information of the Macheonryeong and Wuhe Groups, they were reported experienced similar depositional periods during ~2.18-~1.84 Ga according to the age data form detrital zircons (Liao *et al*., 2016; Liu *et al*., 2018a).

5.2 Igneous and metamorphic evolution of the JLJB

The JLJB experienced widespread igneous activities. Depending on time differences, these activities can be divided into two stages: 2.2-2.1 Ga magmatism and 1.87-1.84 magmatism (Liu *et al*., 2017a; Wang *et al*., 2020b, 2020d). Rocks resulting from 2.2-2.1 Ga igneous activities are widely distributed in the JLJB, especially in the Liaoji area, and consist of granite and mafic igneous rocks (Li *et al*., 2004; Lu *et al*., 2004a, 2004b; Yang *et al*., 2015; Song *et al*., 2016; Teng *et al*., 2017; Wang *et al*., 2017a, 2017b, 2017c, 2020d; Liu *et al*., 2018b). In the Jiaobei area, only a few 2.2-2.1 Ga igneous rocks have been identified, and most mafic intrusions occurred as dikes or enclaves (Wang *et al*., 2020c). The 2.2-2.1 Ga granite from the Liaoji area shows the geochemical characteristics of A2-type or I-type granite, and metabasite shows the geochemical characteristics of an arc tectonic setting, representing their origin in a back-arc tectonic setting (Wang *et al*., 2020d). Whereas, most of the 1.87-1.84 Ga igneous rocks have also been classified as A2-type granite, which indicates that they were formed in a postcollisional tectonic setting (Oh and Lee, 2018; Wang *et al*., 2020b).

Metamorphic conditions and the time of metamorphism are also useful for understanding tectonic evolution. In the JLJB, as we reviewed above, 2.2-2.1 Ga and 1.87-1.84 Ga magmatic activities have been widely discovered, whereas metamorphism has only been reported to have occurred during 1.95-1.84 Ga. Therefore, understanding the metamorphism is important to interpret the tectonic evolution after 1.95 Ga in the JLJB along with the 1.87-1.84 Ga igneous activities.

In the Jiaobei area, ~1.95 Ga and ~1.85 Ga metamorphisms have been reported, and the former and latter represent intermediate- and low-P/T type metamorphisms, respectively (Liu *et al*., 2017c; Zou *et al*., 2017, 2019, 2020). Although some studies have considered that intermediate-P/T type metamorphism occurred from 1.90-1.86 Ga, most studies on intermediate-P/T type metamorphism have suggested that it occurred during 1.95-1.90 Ga due to continent-continent collision and was followed by ~1.85 Ga metamorphisms (Tam *et al*., 2012a, 2012b; Liu *et al*., 2013a, 2017c; Zou *et al*., 2017, 2019, 2020). Zou *et al*. (2020) suggested that at least some of the ~1.85 Ga metamorphisms represent the post-peak stage after the ~1.95 Ga intermediate-P/T type metamorphism. Wang *et al*. (2021) considered that ~1.85 Ga metamorphism occurred in the postcollisional tectonic setting.

In the Liaodong area, ~1.95 Ga and ~1.85 Ga metamorphisms have both been reported (Liu *et al*., 2017b, 2019; Wang *et al*., 2021). However, the ~1.95 Ga metamorphism has only been found in the middle part of the Liaodong area (Liu *et al*., 2017b, 2019). The ~1.85 Ga metamorphism has been identified as a post-peak stage after the 1.95 Ga intermediate-P/T type metamorphism in the middle part and as the peak stage of the low-P/T type metamorphism in the southern part of the Liaodong area (Wang *et al*., 2020b). This metamorphic pattern is similar to that in the Jiaobei area and could indicate an increase in the geothermal gradient from 1.95 Ga to 1.85 Ga in the JLJB.

The metamorphic studies of the Jinan area suggested that low-P/T type metamorphism occurred during 1.89-1.84 Ga (Cai *et al*., 2019; Wang *et al*., 2020b). Although no studies have confirmed metamorphic conditions of the ~1.95 Ga intermediate P/T type metamorphism, staurolite-bearing schist found in the middle to northern part of the Jinan area, indicates that intermediate-P/T type metamorphism may have occurred in the Jinan area similar to the Liaodong area. In addition, Zhang *et al*. (2018) reported that the maximum deposit age of the Huashan, Linjiang and Dalizi Formations are 1990, 1957, and 1940 Ma, respectively, whereas no ~1.99-1.94 Ga igneous activity has been identified. Therefore, considering the existence of ~1.95 Ga intermediate-P/T type metamorphism in the Liaodong area and the occurrence of staurolite in the northern Jinan area, it is possible to deduce that the 1.99-1.94 Ga age may indicate the time of intermediate-P/T type metamorphism.

These data indicate that the whole JLJB experienced a clockwise P-T path in which intermediate-P/T type metamorphism occurred at ~1.95-1.90 Ga and then followed by low-P/T metamorphism at ~1.89-1.84 Ga, suggesting an increase of geothermal gradient. The subduction related 2.2-2.1 Ga igneous rocks and the post collisional ~ 1.87-1.84 Ga igneous rocks support the collision event at ~1.95-1.90 Ga together with the intermediate-P/T type metamorphism at ~1.95-1.90 Ga. The post collisional ~ 1.87-1.84 Ga igneous rocks indicate that low-P/T metamorphism at ~1.89-1.84 Ga also occurred in the postcollision tectonic setting. The two type metamorphisms represent an increase in geothermal gradient from ~1.95-1.90 Ga to ~1.89-1.84 Ga, which was caused by heat supply from upwelling mantle through opening formed by slab break-off after collision as will be explained in the next discussion part.

5.3 Tectonic implications of the JLJB

The JLJB is one of the Paleoproterozoic collision belts in the NCC and is essential for understanding the evolution of the NCC and the Korean Peninsula. Several different tectonic models have been proposed in the JLJB, but the tectonic evolution is still under debate (Zhang and Yang, 1988; Bai, 1993; Faure *et al*., 2004; Li *et al*., 2011, 2017a; Zhao *et al*., 2012; Li and Chen, 2014; Peng *et al*., 2014; Yuan *et al*., 2015; Xu and Liu, 2019).

Zhang and Yang (1988) first suggested a rifting-collision model, which was improved by other studies (Liu *et al*., 1997; Li *et al*., 2001a, 2003, 2004, 2005, 2006, 2011). In this model, the Archean Longgang and Nangrim Blocks were considered one block, which was then separated by early Paleoproterozoic rifting. Rifting thus provided an environment for successive sedimentation and associated igneous activities. The model was proposed due to the discovery of counterclockwise P-T path metamorphism in the southern Groups (Jinshan, South Liaohe, and Ji'an Groups) in the JLJB and the widespread 2.20-2.13 Ga A-type granitoids (Lu *et al*., 1996; He and Ye, 1998; Li *et al*., 2001b). However, there are some geologic features that contradict this rifting-collision model. The clockwise P-T path in the northern Groups of the JLJB (Fenzishan, North Liaohe, and Laoling Groups) is difficult to explain by the rifting-collision model. Recently, instead of the counterclockwise P-T path, a clockwise P-T path has been confirmed in the southern part of the JLJB (Cai *et al*., 2017, 2019; Liu *et al*., 2017b, 2019; Wang *et al*., 2020b). Mafic igneous rocks in the JLJB have been suggested to have formed in a back-arc basin environment with enriched mid-oceanic ridge basalt (E-MORB) characteristics instead of ocean island basalt (OIB) characteristics (Cawood *et al*., 2012; Xu *et al*., 2018a, 2018b). Furthermore, Wang *et al*. (2020d) studied 2.2-2.13 Ga felsic igneous rocks and proposed that these igneous rocks are mainly A_2-type granites with some I-type granites, confirming a back-arc basin environment instead of a continental rift tectonic setting. Moreover, it is also difficult to explain the high-pressure (>13 kbar) pelitic granulite found in the Jiaobei area by this model (Tam *et al*., 2012b, 2012c; Liu *et al*., 2013a, 2017c; Zou *et al*., 2017, 2019, 2020).

Bai (1993) first introduced a continental collision and subduction model, and then the model was modified to a continent-arc-continent collision model by Faure *et al*. (2004). Similar models have been proposed within recent decades (He and Ye, 1998; Lu *et al*., 2006; Yuan *et al*., 2015; Chen *et al*., 2016; Tian *et al*., 2017). Zhao *et al*. (2012) suggested that a rift basin first developed into an ocean basin, and then the continuous extension resulted in subduction of the oceanic lithosphere, which was followed by the final continent-continent collision, forming high-pressure granulites in the Jingshan Group, JLJB. However, within the JLJB, evidence of subduction, such as suture zones or ophiolites, has not been discovered. Recently, Wang *et al*. (2020b) proposed a back-arc rifting tectonic setting in the Liaoji Belt during 2.18-2.11 Ga based on the coexistence of 2.18-2.14 Ga A_2- and I-type granitoids and the 2.13-2.11 Ga mafic igneous rocks formed in a back-arc basin environment. Postcollisional metamorphic and igneous activities during 1.87-1.84 Ga after the continent-continent collision along the southern margin of the JLJB also support the subduction-collision model together with the clockwise P-T path and high-pressure granulite-facies metamorphism in the JLJB (Wang *et al*., 2020b, 2021).

Combining the above discussion and previous studies, we suggest a subduction-collision-post-collision model. As explained in discussion 5.1 and 5.2 in the JLJB, 2.2-2.1 Ga felsic and mafic igneous activities were active under back-arc basin environments, and the deposition of the sedimentary rocks occurred ~2.20-1.86 Ga. Therefore, we propose that there was an arc-related subduction zone with a back-arc basin during 2.2- 2.1 Ga along the Liaoji Belt. Wang *et al*. (2020d) suggested that back-arc extension started >2.18 Ga and continuously expanded until 2.11 Ga when mafic rocks intruded the area (Fig. 5a and b). Continent-continent collision is suggested by the identification of intermediate-P/T type metamorphism during 1.97-1.90 Ga (Fig. 5c). After the collision between

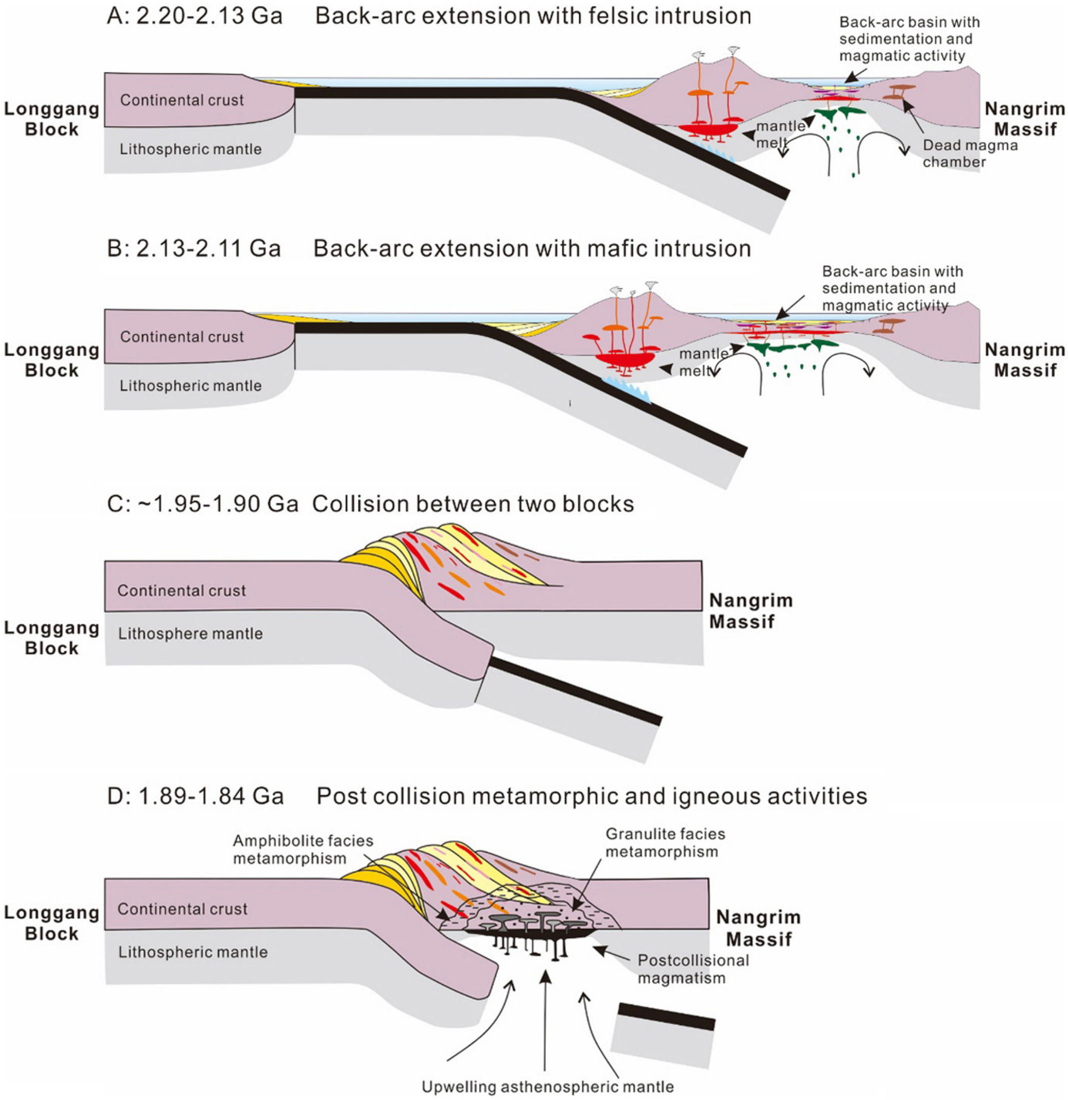

Fig. 5. Simplified model of the tectonic evolution of the JLJB from 2.2 Ga to ~1.84 Ga.

the two blocks, postcollisional metamorphic and igneous activities occurred during 1.87-1.84 Ga (Fig. 5d). The postcollisional metamorphism is a low-P/T type metamorphism and mainly occurred along the southern part of the JLJB with postcollisional granites. Wang *et al.* (2021) explained that postcollisional igneous and metamorphic activities were caused by high heat supplied from the upwelling asthenospheric mantle. The upwelling of asthenospheric mantle occurred due to slab break-off between the continental and oceanic slabs at depths where the buoyancy of the subducted continental slab became stronger than the pulling force exerted by the previously subducted oceanic slab. Near isothermal decompression of the P-T path could be additional evidence for postcollisional extension, as it reflects rapid uplift after collision. These data indicate that the southern part of the JLJB experienced a postcollisional extension (Fig. 5d).

The subduction location and direction in the JLJB are difficult to evaluate because no suture zone or ophiolite was reported in the JLJB. Previous studies have reported widely distributed postcollisional porphyritic granites not only along the southern part of the JLJB but also in the Nangrim Massif and northern Gyeonggi Massif in the Korean Peninsula (Lee *et al.*, 2014; Yengkhom *et al.*, 2014). Besides, compared to the Nangrim and northern Gyeonggi Massifs, almost no 1.90-1.80 Ga postcollisional igneous and metamorphic events have been reported from the Longgang Block, indicating no slab beak-off event under the Longgang Block. These data indicate southward subduction, in which the Longgang Block subducted under the Nangrim Massif before the collision between them.

The amalgamation process along the JLJB can be figured out based on the change of metamorphic

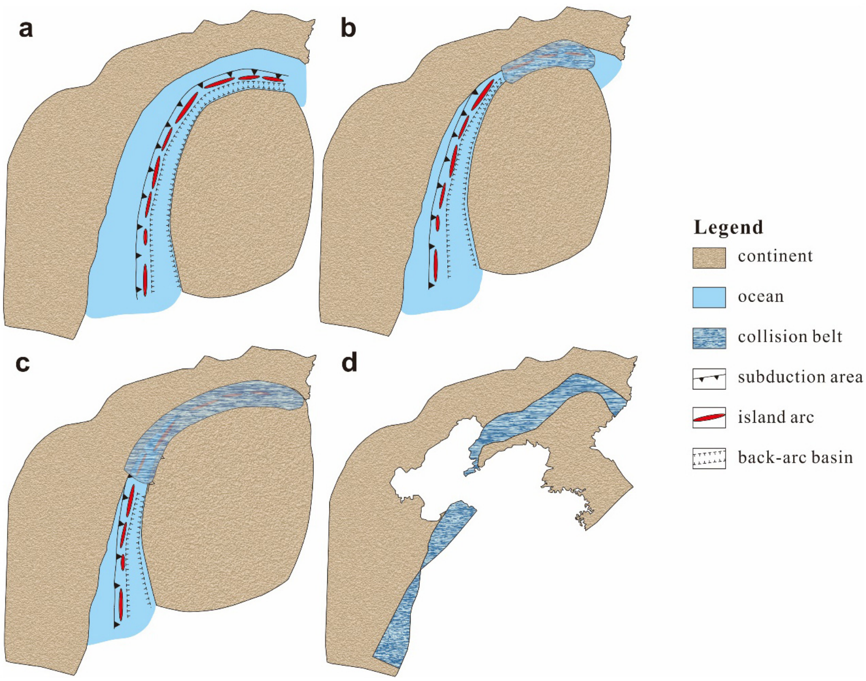

Fig. 6. Cartoon diagram showing the Paleoproterozoic amalgamation of the eastern North China Craton. (a) Before 1.95 Ga, the Longgang Block subducted under the Nangrim Massif and forming an arc and back-arc basin. (b) Subduction continued, and the collision between the Longgang Block and Nangrim Massif occurred first in the northern part. (c) The collision between the Longgang Block and Nangrim Massif propagated southwards, (d) Finally the collision along the JLJB was completed.

pattern and age along the JLJB as did for the Himalayan collision belt and Qinling-Dabie-Hongseong collision belt (Oh, 2010; Oh and Lee, 2018). As introduced above, the Liaodong area experienced intermediate-P/T type metamorphism during 1.95-1.96 Ga, whereas the Jiaobei area experienced intermediate-P/T metamorphism during 1.93-1.94 Ga. Based on the time difference, we proposed that the collision first occurred in the northeastern part of the JLJB and propagated towards the southwest (Fig. 6).

During the collision, the continental slab subducts until the buoyancy of the continental slab became stronger than the pulling force exerted by the oceanic slab that subducted before the collision; then, slab break-off between the continental slab and oceanic slab occurs at that depth (Ernst, 2006; Oh and Lee, 2018; Wortel and Spakman, 2000). The slab break-off depth increased with an increased in the pulling force exerted by the oceanic slab, which subducted before the collision. The pulling force increases as the amount of subducted oceanic slab increases, and the amount of subducted oceanic slab can be increased as the width of the ocean between two continents increases (Oh, 2010, 2016; Oh and Lee, 2018). The peak pressures of intermediate-P/T type metamorphism in the Liaodong area were at least 3 kbar lower than those in the Jiaobei area (Liu *et al*., 2013a, 2017b, 2017c, 2019; Zou *et al*., 2017, 2019, 2020). These data indicate that the ocean between the two continental blocks was wider in the Jiaobei area than in the Liaodong area which caused slab break-off at shallower depths (~10 kbar = ~30-33 km) in the Liaodong area and deeper depths (>13 kbar = >39-43 km) in the Jiaobei area. In the Jiaobei area, the continental slab subducted to a deeper depth (>13 kbar, >39-43 km) as (1) the subduction period was 10-30 million longer and (2) there was a larger pulling force caused by the more subducted oceanic slab due to the wider ocean compared to that in the Liaoji area.

The low-P/T type metamorphism in the southern margin of the Liaoji area was the result of the high heat supplied by upwelling of the asthenospheric mantle through the opening formed by slab break-off during the postcollisional stage. The ages of low-P/T type metamorphism generally became younger from 1.89-1.87 Ga in the Jinan area through 1.87-1.85 Ga in the Liaodong area to 1.87-1.83 Ga in the Jiaobei area (Liu *et al*., 2017b, 2017c, 2019; Cai *et al*., 2019; Zou *et al*., 2019, 2020). These data indicate that slab break-off occurred in the Liaoji area (1.89-1.85 Ga) and then propagated to the Jiaobei area (1.87-1.83 Ga) with an increasing slab break-off depth.

Therefore, we suggest the following collision process along the JLJB. The width of the ocean between the Longgang Block and Nangrim Massif was narrower in the Liaoji area than in the Jiaobei area before the collision. Subduction occurred southeastwards along the back-arc basin during 2.2-2.11 Ga. The collision and subduction of the continental slab first occurred in the Liaoji area at ~1.95 Ga and propagated towards the Jiaobei area until ~1.93 Ga. The metamorphism related to the postcollisional event occurred ~10-30 Ma earlier in the Liaoji area with a shallower slab break-off depth (30-33 km) and propagated to the Jiaobei area, where the slab break-off occurred at deeper depths (39-43 km).

6. Conclusions

According to reviewed data and related discussion, we conclude the followings:

Igneous rocks with an age range of 2.2-2.1 Ga intruded in an arc tectonic setting with a back-arc basin in the JLJB.

Igneous intrusions with an age range of 1.87-1.84 Ga have been widely discovered along the southern part of the JLJB, and they have been suggested to have occurred under a postcollisional tectonic environment.

Clockwise P-T paths with isothermal decompression during uplift were identified in both the northern and southern JLJB. The ~1.95-1.90 Ga peak and ~1.89-1.84 Ga post-peak metamorphisms have been identified. The ~1.95-1.90 Ga metamorphism shows intermediate-P/T type metamorphic characteristics indicating a continent-continent collision tectonic environment. The ~1.89-1.84 Ga metamorphism shows low-P/T type metamorphic characteristics and occurred together with 1.87-1.84 Ga postcollisional igneous activities under a postcollisional extension environment.

Along the JLJB, the Longgang Block in the NCC subducted under the Nangrim Massif on the Korean Peninsula during 2.2-2.1 Ga. Then, the JLJB started to close and finally collided during ~1.95-1.90 Ga. After collision, the belt experienced postcollisional extension during ~1.89-1.84 Ga.

The collision between the Longgang Block and the Nangrim Massif began in the Jinan area and then propagated towards the Jiaobei area.

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