Geochronological Framework of Paleoproterozoic Intrusive Rocks and Its Constraints on Tectonic Evolution of the Liao-Ji Belt, Sino-Korean Craton

Jingsheng Chen, Zhongzhu Yang, Dexin Tian, Dehe Xing, Lidong Zhang, Fan Yang, Bin Li, Miao Liu, Yi Shi, Chao Zhang

1. Shenyang Geological Survey Center of China Geological Survey, Shenyang 110034, China
2. Non-Ferrous Metals Geological Exploration Bureau of Zhejiang Province, Shaoxing 312000, China

ABSTRACT: The Liao-Ji belt (LJB) is one of the Paleoproterozoic tectonic belts located in the North China Craton. A large number of Paleoproterozoic meta-volcanic-sedimentary rock and intrusive rocks are preserved in the LJB, which provide reliable carriers for the study of the Paleoproterozoic tectonic evolution of the North China Craton. The Paleoproterozoic intrusive rock in the LJB can be divided into the following seven types: syenogranite, quartz diorite, porphyry granite, migmatitic granite, syenite, metamorphic plutonic rock, and granitic pegmatite and metagabbro (metamorphic diabase). Zircon U-Pb dating of 15 samples from intrusive rocks was carried out in this study. The chronological framework of the Paleoproterozoic intrusive rock in the LJB was established, and the magmatism of intrusive rocks can be divided into three stages: 2 200 to 2 110, 2 010 to 1 937, 1 900 to 1 820 Ma. The chronological framework supported the evolution model of subduction accretionary arc-continent collision in the LJB effectively. Combined with previous geochemical work, it was a passive continental margin environment at approximately 2 200 Ma, and then transformed into and active continental margin. The bimodal intrusive rocks between 2 180 and 2 150 Ma indicated a back-arc tension environment which lasted until approximately 2 110 Ma with a large number of basic intrusive rocks. And then the back-arc basin began to contract and the magmatic activities were reduced, with only a small number of intrusive rock activities occurring at approximately 2 040, 2 010 and 1 937 Ma. After the orogenic activities, there was a post-orogenic extension stage from 1 900 to 1 820 Ma. Magmatic activities caused by the environmental extension started to occur more frequently and subsequently resulted in the large-scale intrusive rocks in eastern Liao-Ning.

KEY WORDS: Liao-Ji belt, Paleoproterozoic intrusive rocks, geochronological framework, tectonic evolution.

0 INTRODUCTION

The Paleoproterozoic tectonic belts are the most active tectonic-magmatic belts in the Precambrian of the North China Craton and records the evolution of the Precambrian crust (Zhao et al., 2012, 2005). They can be divided into three distinctive tectonic belts from west to east as follows: The khondalite belt (KB) in the west; the Central Orogenic Belt (COB) in the middle area; and the Jiao-Liao-Ji belt (JLB) in the east (Zhao et al., 2005) (Fig. 1a). Among those, the JLB is known to have been formed by the collision of the Longgang and Langlin blocks at 1.9 Ga, which subsequently formed the eastern block of the North China Craton (Meng et al., 2017; Liu F L et al., 2015; Liu J H et al., 2011; Wu et al., 2014a, b; Zhao and Zhai, 2013; Zhao et al., 2012; Li et al., 2011, 2005; Tam et al., 2011; Li and Zhao, 2007) (Fig. 1b). In recent research studies, a great deal of progress has been made in the study of the geochronology and geochemistry of the granitoids, metasedimentary rock, and meta-volcanic rock in the JLB (Meng et al., 2017, 2014; Liu J H et al., 2014, 2011; Zhao et al., 2012, 2005; Li et al., 2011, 2006; Tam et al., 2011; Li and Zhao, 2007; Faure et al., 2004). However, the previous research results have presented many different views regarding the formation and evolution models of the LJB. The main theories were as follows: (1) Continental rift opening- closing model: The researchers holding this view believed that the JLB began to experience deposits following the tensioning of the continental rift, and then was recombined through subduction and collision activities (Zhao and Zhai, 2013; Zhao et al., 2012, 2011, 2005; Li et al., 2006; Zhang and Yang, 1988). (2) Subduction accretion model: This model combined the modern theory of plate tectonics and evidence based in aspects of the rock, tectonic, and paleo-geothermal characte-
The LJB has experienced a long and complex history of tectonic evolution, especially in the Paleoproterozoic, which recorded many important magmatic events. In addition to the bimodal volcanic rock, Paleoproterozoic intrusions have been developed, which directly reflect the tectonic evolution of the LJB. Most of the previous studies are focused on a single area or a single rock mass, and without an overall understanding (Liu et al., 2018; Xu et al., 2018b; Wang P S et al., 2017; Wang X J et al., 2017; Wang X P et al., 2017; Song et al., 2016; Yuan et al., 2015; Meng et al., 2014; Qin, 2013; Han et al., 2010; Li and Zhao, 2007; Lu et al., 2005, 2004a, b). The Paleoproterozoic intrusive rock is considered to be formed ~2.2 Ga ago at the sedimentary basin of the Liaohe Group (Lu et al., 2005, 2004a, b), or it was the product of magmatic activity in the same period with the Liaohe Group formed 2.0–1.9 Ga, or regarded as the sign of the end of the LJB (~1.85 Ga) in accordance with the observed intrusions into the Liaohe Group (Chen et al., 2001; Qu et al., 2000; Li, 1997). The confusion in understanding these intrusive rocks has seriously restricted the study of Paleoproterozoic tectonic evolution. Therefore, it is urgent to establish the geochronological framework of Paleoproterozoic intrusive rocks. With this goal in mind, this study summarized the types of rock which made up the Paleoproterozoic intrusive rock in the LJB. Then, detailed petrological and zircon U-Pb dating of 15 samples of intrusions were conducted, and a chronological framework was established combining with previous data. The framework provided new
constraints for the in-depth understanding of the Paleoproterozoic tectonic evolution of the North China Craton.

1 GEOLOGICAL SETTING

The Precambrian basement of the North China Craton is composed of Archean crystalline basement along three Paleo-proterozoic orogenic belts and records a long-term and complicated tectonic history (Zhao and Zhai, 2013; Zhao et al., 2012, 2005; Li and Zhao, 2007; Lu et al., 2006; Li et al., 2005; Wan et al., 2005; Song et al., 1996). The eastern block was formed by the collision of Longgang Block in northern Liaoning and Langrim blocks in southern Liaoning along the Jiao-Liao-Ji belt (Fig. 1a), recording a complicated history of volcano-magmatism, metamorphism, and deformation (Wu M L et al., 2016; Wu K K et al., 2013; Zhao and Zhai, 2013; Zhao et al., 2012, 2005; Li and Zhao, 2007; Lu et al., 2006; Li et al., 2005). The the ca. 3.8 Ga Longgang Block in northern Liaoning is characterized by widespread distribution of tonalite-trondhjemite-granodiorite rocks (TTGs) (Li et al., 2020, 2019b; Li and Chen, 2019; Peng et al., 2015) and basic volcanic rock (Li and Wei, 2017). Additionally, several magmatic, xenocrystal, and detrital zircons with ages ≥3.0 Ga have been reported in the Anshan area (Wan et al., 2005; Song et al., 1996). Moreover, Neoproterozoic TTGs are also widely exposed in the Langrim Block in southern Liaoning (Meng et al., 2013; Lu et al., 2004a). But in recent years, with the development of regional geological survey in eastern Liaoning Province, large area of Archean crystalline basement has been proved to be less and less by the zircon U-Pb dating methods in the southern Liaoning.

The Paleoproterozoic NE-trending LJB between these two blocks mainly contains metavolcano-sedimentary successions and granitic to mafic intrusions that were metamorphosed to greenschist-amphibolite facies. These paleoproterozoic metavolcano-sedimentary successions are termed the Liaohou Group, which is divided into the North and South Liaohou groups by the Gaixian-Ximucheng-Taziling-Caohekou-Aiyang shear zone (Bureau of Geology and Mineral Resource of Liaoning Province, 2014). Meanwhile these Paleoproterozoic stratigraphic equivalents were termed the Laoling and Ji’an groups in the southern Jilin, and Fenzishan and Jingshan groups in the eastern Shandong (Zhao et al., 2012, 2005). The sequence of Liaohou Group has been subdivided into the Langzishan, Lieryu, Gaojiayu, Dashiqiao and Gaixian formations from bottom to top, distributed in the whole LJB. The five formations are well developed in the north area, and having low degree of metamorphism and deformation. In the south area, the Langzishan and the bottom of Lieryu formations are missing, the Gaixian Formation distributes widely, the Lieryu and Gaojiayu formations generally have stronger metamorphism and deformation, and were intruded by granitic complex at the bottom (Tang et al., 2009; Liu et al., 1997; Zhang and Yang, 1988).

2 CLASSIFICATION OF THE PALEOPROTEROZOIC INTRUSION ROCK

The present study was carried out in the Paleoproterozoic Liao-Ji belt in Liaodong Peninsula (Fig. 1). The Paleoproterozoic intrusions in the LJB were first referred to as the “Liao-Ji granite”, a term which was put forward by Zhang (1988). They are formerly denoted as migmatite or migmatitic granite and are mainly distributed in the eastern Liaoning and southern Jilin. The intrusions are generally output in the form of stocks or batholith (granitic complexes), and spatially display intrusive contact relationships with the Liaohou Group, Ji’an Group, and Laoling Group, or are covered by Paleoproterozoic metasedimentary rock. The majoritly present the development of “striated or gneissic” and “megaporotic or porphyritic” tectonics (Yang et al., 2007; Lu et al., 2005, 2004a, b). During the full coverage of the 1 : 250 000 regional geological survey in eastern Liaoning from 2010, as well as the development of the 1 : 50 000 regional geological survey in the LJB since 2016, a series of metamorphic plutonites (mainly gneissic rock), pegmatites (dikes) and metagabbros (metadiabase dikes) have also been classified from the Paleoproterozoic metasedimentary strata (Li et al., 2016), in addition to the disintegration of the Paleoproterozoic Liao-Ji granite classified in previous surveys. The Paleoproterozoic intrusions can be divided into seven types according to the characteristics of the rock assemblages.

2.1 Syenogranite

The syenogranite represented by the Qianzhuogou and Hupiyu (Tongjiangyu) rock bodies are mainly distributed in the belt from Huinan and Hupiyu to Qinghe, which also contains the Bahechuan rock body and they intrude into the Lieryu Formation and Gaojiayu Formation. In the southern Jilin area, the south side is adjacent to the Dadongcha and Shuanghe rock bodies without contact relationships. The north side is mainly in contact with the Huangchagou Formation, and the gneiss occurrences of the rock bodies are the same with the Huangchagou Formation, forming a type of integrated relationship, which was considered to a metamorphic core complex by some researchers (Lu et al., 2004a, b). The main rock type has been determined to be medium to fine grained syenogranite, characterized with uneven distributions of hornblende (Fig. 2a). In addition, many amphibolite xenoliths and metamorphic basic dykes can be observed in the rock bodies (Lu et al., 2004a, b).

2.2 Quartz Diorite Gneiss

The quartz diorite gneiss represented by the Qinghe and Liujiapuzi rock bodies are mainly distributed near Qinghe Town and Maodianzi Town in Kuandian County, which intrude into the Huangchagou Formation of the Ji’an Group, Gaojiayu Formation of the Liaohou Group, Gaixian Formation, and the Hupiyu rock body. These rock bodies are deformed intensely and have the same gneiss that also occurances with the Huangchagou Formation (Lu et al., 2004a, b). The rock type is mainly medium grained quartz diorite gneiss with fine-grained diorite inclusions. The quartz diorite has gneissic structures due to transformations caused by metamorphism and deformation, which were considered to be Paleoproterozoic metamorphic sedimentary rock previously. Since the rock are composed of typical twin crystal and semi automorphic granular structures, which are typical igneous structures, the protolith has been determined to be intrusive rock (Lu et al., 2004a, b).

2.3 Porphyry Granite

The large porphyry granite outcrop indicates a strong
magmatic activity during this period. The porphyry granite represented by the Shuangcha (Tandianzi) and Lujiapuzi rock bodies are distributed from the area east of Huanren to Shuangcha Town and also in the Bajecheuan-Lujiapuzi region, presenting a nearly east-west distribution and formed a deep diagenetic series at the inner margin of the craton (Zhang, 1988). According to the field output state, these rock bodies intrude into the syenogranite of the Qianzhuogou rock body and are covered by the quartz sandstone of Diaoyutai Formation in Niuxinshan (Lu et al., 2004a, b). There are a large number of gneiss and granulite xenolith from the Dadongcha Formation and Huangchagou Formation distributing unevenly. The rock bodies are typically characterized by large and abundant megaphenocryst or ring phenocryst and they are rich in muscovite and garnet with other aluminum-rich minerals (cordierite and sillimanite) displaying an output of lumpy aggregate. However, the mineral compositions of the Shuangcha (Tandianzi) and Lujiapuzi rock bodies are quite different from that of typical ring phenocryst, and are “S” type granite. According to the phenocryst morphology, these rock bodies can be further divided into three rock types: megaporphyry granite, globular porphyry granite, and ring phenocryst granite (rapakivi), which have been found to be in a gradual transition relationship (Fig. 2b). The mineral content distribute unevenly in different sections of the rock bodies, caused the rock type to be quartz monzonite.

2.4 Migmatitic Granite

The migmatitic granite represented by the Hushan and Wolongquan rock bodies are mainly distributed in the Dandong-Kuandian and Wolongquan areas along a NE-SW direction, with output in the form of stocks or batholith (Lu et al., 2004a, b). These rock bodies spatially intrude into the Huipiu rock body, Liaohe Group, and Ji’an Group. Xenoliths have often been observed in both rock bodies. In addition, the long axis is consistent with the foliation of the surrounding rock.

The lithology is composed of gneissic or weakly gneissic (porphyry like) monzogranite (Fig. 2c) and biotite monzogranite which turned into mylonitized granite or granitic mylonite in the strong deformation area (Lu et al., 2004a, b).

2.5 Syenite

The syenite represented by Kuangdonggou rock body is distributed in the area of Kuangdonggou, Liangtun Town, Gaixian County, Liaoning Province. It can be observed in the field that the rock body intruded into the Liaohe Group and has a weak gneissic texture. The rock types include biotite pyroxene syenite, hornblende pyroxene syenite, and biotite hornblende syenite with the xenolith of gabbro forming early, which have the characteristics of multi-stage intrusion (Yang et al., 2007; Cai et al., 2002). The rock body is light gray and gray white, with yellowish brown weathered surfaces, medium and fine-grained structures, and massive tectonics.

2.6 Metamorphic Pluton Rock

This type of rock is composed of a series of different types of gneiss rock including granodioritic gneiss (red pillar) and sillimanite garnet biotite (anorthosite) gneiss which have been redetermined from the Paleoproterozoic metasedimentary strata. They may have been separated from the Huaziyu sections of the Dashiqiao Formation or from the lower part of the Gaixian Formation and the Gaojiayu Formation, and distribute in the eastern sections of Kuandian and Longchang-Jidongyu of Liaoyang. The metamorphic pluton rock type was found to be displayed in interbedded occurrences with granulite and schist in the stratum, and was characterized by obvious blastogranitic textures and gneissic structures. This rock type contains garnet and shows the characteristics of “S” type granite, which is also called as deep melting granite (Figs. 2d, 2e) (Liu et al., 2015). The Granitic (primary) mylonite, which occurred in the Gaojiayu Section of the Gaojiayu Formation, was mainly interbedded with felsic mylonite and mylonitized lamellar fine-grained
plagioclase amphibolite. The brecciated granite were mainly found in the Jidongyu area of Liaoyang, and also occurred in the Lieryu Formation. These were interbedded with hornblende gabbro and magnetite bearing biotite plagioclase granulite.

2.7 Granitic Pegmatite Rock (Dykes) and Metabasite Rock (Dykes)
Granitic pegmatite rock (dyke) can be found throughout the LJB. The widths of the dyke body vary from the centimeter level, up to several meters and tens of meters, indicating irregular dyke output. In the region, these dykes are common to penetrate or cut through the gneissic textures and schistosity. The granite pegmatite (dykes) display a gray-white colour, pegmatite structures, graphic textures, and massive tectonics (Yang et al., 2017).

The metabasite rock (dykes) was mainly distributed in Shisi County of Haicheng City, as well as the Chaoyang Valley of Kuandian, Mantoushan of Shenyang, and they were also found to be scattered in Shenhezi of Xiuyan and Xioachengzi of Kuandian. They intruded into the Archean metamorphic complex and lower section of the Paleoproterozoic Liaohe Group in dyke form, along the NE, EW, and NW directions. The extension directions were generally parallel to the contact interfaces between the Archean metamorphic complex and the Liaohe Group. They intruded old terranes along the strata or by cutting phenomena locally. The output of the metabasite were in the form of irregular stocks or dykes (Fig. 2f), and parts of the basic rock were distributed along the rock wall with internal and external facies locally. Metabasic rock (dykes) bodies include metagabbro, metadiabase, and amphibolite that are weakly carbonated.

3 ZIRCON U-PB GEOCHRONOLOGY
In this study, 15 samples from different types of Paleoproterozoic intrusive rocks were collected from eastern Liaoning Province for Zircon U-Pb dating. The sample locations are shown in Fig. 1.

3.1 Analytical Methods of Zircon U-Pb Dating
Zircon analysed in this study was extracted from whole-rock samples by using combined magnetic and heavy liquid separation at the Langfang Yuneng Mineral Separation Limited Company, Hebei Province, China. The handpicked grains were polished to exposed the inner structures of zircons and then examined under transmitted and reflected-light with an optical microscope. Cathodoluminescence (CL) images were also obtained with a CAMECA SX51 microprobe operated at conditions of 50 kV and 15 nA, at the Beijing Zirconium Year Navigation Technology Limited Company, China.

The LA-ICP-MS U-Pb isotope analyses were conducted on a quadrupole ICP-MS (Agilent 7500a) equipped with a UP-193 Solid-State Laser (193 nm, New Wave Research Inc.). For the present work, laser spot size was set to 32 μm for most analyses, laser energy density at 10 J/cm² and repetition rate at 8 Hz. The procedure of laser sampling is 30-s blank, 30-second sampling ablation, and 2 min-sample-chamber flushing after the ablation. The ablated material is carried into the ICP-MS by the high-purity helium gas stream with flux of 1.15 L/min. The whole laser path was flushed with Ar (600 mL/min) in order to increase energy stability. The counting time is 20 ms for ²⁰⁴Pb, ²⁰⁶Pb, ²⁰⁷Pb and ²⁰⁸Pb, 15 ms for ²³²Th and ²³⁸U, 20 ms for ⁴⁰K, and 6 ms for other elements. Calibrations for the zircon analyses were carried out using NIST 610 glass as an external standard and Si as internal standard. U-Pb isotope fractionation effects were corrected using zircon 91500 (Wiedenbeck et al., 1995) as external standard. Zircon standard Plesovice (337 Ma) is also used as a secondary standard to supervise the deviation of age measurement/calculation (Jiří Sláma et al., 2008). Isotopic ratios and element concentrations of zircons were calculated using Glitter. Concordia ages and diagrams were obtained using Isoplot/Ex (3.0) (Ludwig, 2003). The common lead was corrected using LA-ICP-MS Common Lead Correction (ver. 3.15), followed the method of Andersen (2002). The analytical data are presented on U-Pb concordia diagrams with 2σ errors. The mean ages are weighted means at 95% confidence levels (Ludwig, 2003). Analyses of five samples (D15003, D15008, D15016, D15018-2 and D15023) were conducted at the Key Laboratory of Mineral Resources Evaluation in Northeast Asia, Ministry of Land and Resources of China, the others at the Geologic Lab Center, China University of Geosciences (Beijing). The data were listed in Table S1.

3.2 Analytical Results
3.2.1 Syenogranite
A total of four samples were collected for this rock type (HXY-5, D058-4, TWD15023 and D1475-2, respectively). Sample HXY-5 is a monzonitic granite with stripe marks collected from Houxianyu area of Dashiqiao City. Zircons within this sample are generally colorless, transparent, and mostly subhedral to euhedral in shape. They have a size range of 100–150 μm and have a Th/U ratios of 0.41–0.70, with higher Zr, Hf content and higher Nb, Ta content (mean 6.77 ppm and 2.81 ppm, respectively). In the CL images (Fig. 3), most grains display fine-scale oscillatory growth zoning and clearly internal structure, the smooth edge may be the later metamorphic hyperplasia part. These characteristics indicate magmatic zircon (Li, 2009; Liu D Y et al., 2009; Belousova et al., 2002; Hoskin and Ireland, 2000). A total of 24 U-Pb isotopic analyses were conducted on 24 zircon grains from this sample, the analyses plot on or below the concordia curve, indicating varying degrees of radiogenic Pb loss. These analyses yield an upper intercept age of 2 160±21 Ma (n=24, MSWD=3.5), which is consistent with their ²⁰⁶Pb/²³⁸Pb weighted mean age (2 166.4±8.4 Ma, n=24, MSWD=7.0) (Fig. 4a). Thus, the age of 2 160 Ma represents the magmatic crystallization age.

Sample D058-4 is a tourmaline-bearing mica granite collected from Xiuyan Hanjia Village. Zircon grains from sample are euhedral rhombohedral with diameters of 100–140 μm and have length to width ratios of 1:1 to 3:1, display fine-scale oscillatory growth zoning (Fig. 3). The zoning, combined with Th/U ratios of 0.31–1.01, indicates a magmatic origin (Li, 2009; Liu D Y et al., 2009; Belousova et al., 2002; Hoskin and Ireland, 2000). It is worth noting that most zircon crystals have dark edges with different widths, which may be the proliferative edges formed by recrystallization during metamorphism. Twenty-five isotopic analyses were conducted on 25 zircons
grains from this sample, yielding apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages of $2.112\pm 0.56\text{ Ma}$. The analyses plot on or below the concordia curve and the ages can be divided into two distinct groups. The first group consists of 20 analyses that yield a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of $2.150\pm 0.12\text{ Ma (MSWD=6.1)}$, interpreted as the crystallization age of granite. The second group, comprising five analyses, yields a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of $2.527\pm 0.21\text{ Ma (MSWD=2.9)}$ with Th/U ratios of $0.36\sim 0.95$ (Fig. 4b). The five analyses are considered to be inherited zircon.

Sample TWD15023 is a granite with stripe marks collected from the Hongqiyangzi area of Xiuyan. The zircon grains are mostly self-shaped rhombohedral, generally black, visible uneven absorption stripes and irregular growth ring (Fig. 3), combining with its higher Th/U ratios ($0.23\sim 0.56$), higher Zr, Hf content, and very high Nb, Ta content (mean content of $50.48\text{ ppm}$ and $18.09\text{ ppm}$, respectively), indicate that it is magmatic-derived zircon (Li, 2009; Liu D Y et al., 2009; Belousova et al., 2002; Hoskin and Ireland, 2000). A total of 21 analyses on 21 zircon grains were conducted. All the analyses are concordant, with the exceptions exhibiting a younger zircon age. The $^{207}\text{Pb}/^{206}\text{Pb}$ ages of concordant zircons range from $1.995\sim 2.084\text{ Ma}$, and give a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of $2.041\pm 0.9.1\text{ Ma (n=21, MSWD=4.4)}$, which is consistent with the upper intercept age of $2.035\pm 0.35\text{ Ma (n=21, MSWD=1.13)}$ (Fig. 4c). Therefore, the age of $2.035\pm 0.35\text{ Ma}$ is interpreted as the crystallization age of magmatic.

Sample D1475-2 is gneissic monzogranite collected from Xialugouli area of Kuandian City, which intruded into the plagioclase amphibolite of the Lieryu Formation. The zircons have a size range from 100–200 μm and have Th/U ratios of $0.26\sim 0.69$, with higher Zr, Hf content and higher Nb, Ta content (mean $5.67\text{ ppm}$ and $2.07\text{ ppm}$, respectively). Most of the zircon grains is euhedral rhombohedral, the internal absorption degree is different, the light and shade are uneven, most crystals can see the growth oscillation ring zone development (Fig. 3), showing magmatic origin zircon (Li, 2009; Liu D Y et al., 2009; Belousova et al., 2002; Hoskin and Ireland, 2000). In addition, most of the zircon around the visible width of the white transparent edge, which may be magmatic zircon imaging of different parts of magmatic zircons, or may be the proliferative edges formed during metamorphism (Fig. 3). Twenty-one analyses on 21 zircon grains define two age groups (Fig. 4d). The first group consists of three analyses and yield a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of $2.090\pm 0.22\text{ Ma (n=3, MSWD=0.45)}$, which is considered to be inherited or xenocrystic zircon. The second age group yields a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of $1.915\pm 0.21\text{ Ma (n=18, MSWD=13)}$, which is consistent with their upper intercept age of $1.927\pm 0.27\text{ Ma (n=18, MSWD=19)}$ (Fig. 4d). Thus, the age of $1.927\pm 0.27\text{ Ma}$ represents the crystallization age of the magmatic protolith of sample D1475-2.

3.2.2 Porphyry granite

This type selected two samples for chronology study, named for HK-2 and D017-2.

Sample HK-2 is gigantic phenocryst granite collected from Hekou area of Dandong City. The zircon grains from this sample are transparent to translucent and generally euhedral-subhedral. The zircons have a size range of 200–310 μm. In the CL images, zircon grains display fine-scale and weak oscillatory growth zoning (Fig. 3). The zoning, combined with Th/U

Figure 3. Cathodoluminescence (CL) images for representative zircons. The circles on zircons represent analyzed spots.
Figure 4. Zircon U-Pb ages for the Paleoproterozoic granitic intrusions from the Liao-Ji belt.
with the weighted mean 207Pb/206Pb age of 1839.9±8.3 Ma. Twenty-five U-Pb isotopic analyses were conducted on 25 zircon grains and were plotted on a concordia curve, yielding a weighted mean 207Pb/206Pb age of 1876.1±7.2 Ma (n=25, MSWD=4.5). These analyses yield an upper intercept age of 1878±11 Ma (n=25, MSWD=15), which is within error of the weighted mean age (Fig. 4e). Thus, the age of 1876 Ma is interpreted as the age of magmatic emplacement of the granite sample.

Sample D017-2 was collected from 2 km east of Penghai Town, Kuandian County. The lithology of the sample is giant porphyry biotite-monzonogranite, which invades the Lieryu Formation of Liaohe Group. Zircons within the granite are transparent to translucent, and euhedral to subhedral in shape. They range in length from 180–305 μm and have a higher Th/U ratios (0.30–0.56) (Fig. 3), with high Zr, Hf content and high Nb, Ta content (mean 3.78 ppm and 1.47 ppm, respectively). In CL images, most of them display fine-scale oscillatory zoning, indicating a magmatic origin (Fig. 3) (Li, 2009; Liu D Y et al., 2009; Belousova et al., 2002; Hoskin and Ireland, 2000). A total of 24 U-Pb isotopic analyses were conducted on 24 zircon grains from this sample, yielding an upper intercept 207Pb/206Pb age of 1839±38 Ma (n=25, MSWD=0.25) and a weighted mean 207Pb/206Pb age of 1839.9±8.3 Ma (n=25, MSWD=0.25) (Fig. 4f). Therefore, the age of 1839 Ma represents the crystallization age of the giant porphyry biotite-monzonogranite.

### 3.2.3 Magmatic granite

Sample HK-1 was collected from HS pluton in Dandong Hekou area for Geochronological analyses. The lithology of the sample is a weak gneissic monzogranite. Zircon grains used for analysis were of typical magmatic origin (Li, 2009; Liu D Y et al., 2009; Belousova et al., 2002; Hoskin and Ireland, 2000); they were euhedral to subhedral in shape, were within the size range of 180–305 μm, had a length/width ratios of 2 : 1 to 3 : 1, subhedral to euhedral and prismatic with length/width ratios of 2 : 1 to 7 : 1. The whole crystal is slightly blackened, and display banded structures or oscillatory zoning in CL images (Fig. 3) as well as the high Th/U ratios (2 : 1 to 7 : 1) (Li, 2009; Liu D Y et al., 2009; Belousova et al., 2002; Hoskin and Ireland, 2000). A weighted mean 207Pb/206Pb age of 1867.4±4.8 Ma (n=23, MSWD=4.5) are obtained from twenty-three analyses, which is consistent with the upper intercept age of 1864±11 Ma (n=23, MSWD=0.43), representing the crystallization age of monzogranite (Fig. 4g).

### 3.2.4 Syenite

Sample TWD15016 is a middle-fine grained granite collected from the Xiuyan Sanjiazi area. Zircons from this sample are subhedral to euhedral with well developed oscillatory zoning and high Th/U ratios (0.31–0.59). They also have a size range from 100–130 μm, a length/width ratios of 4 : 1 to 1 : 1 (Fig. 3), indicating they are magmatic origin (Li, 2009; Liu D Y et al., 2009; Belousova et al., 2002; Hoskin and Ireland, 2000). In addition, a very narrow, round, slipping, white, metamorphic margin can be seen from the outside of many zircon grains. Twenty-four analyses made on 24 zircon grains give 207Pb/206Pb ages ranging from 1825 to 2153 Ma, and yield a weighted mean 207Pb/206Pb age of 1964±8.7 Ma (n=24, MSWD=47). This age is consistent with the upper intercept age of 1964±8.7 Ma (n=24, MSWD=1.07) and represents the magmatic crystallization age (Fig. 4h).

### 3.2.5 Metamorphic plutonic rocks

The rock samples collected by the age test of metamorphic deep diagenesis include granitic mylonite, granodiorite gneiss, and bearing biotite plagioclase gneiss.

Sample D1455-1 is a medium-coarse granodiorite gneiss collected from eastern area of Kuandian Taipingshao. It is "symbiotic" with biotite leptynite (containing a small amount of graphite) and sillimanite garnet biotite schist. Zircons from sample D1455-1 are colorless, transparent, and subhedral to euhedral in shape. CL imaging revealing that most grains have fine oscillatory zones (Fig. 3). A total of 22 analyses were made on 22 zircons, and they have Th/U ratios ranging from 0.35 to 0.61. The average content of Nb and Ta was 4.94 and 1.83, respectively. These analyses yield an upper intercept age of 1672±33 Ma (n=22, MSWD=0.20) and yield a weighted mean 207Pb/206Pb age of 1673.9±5.0 Ma (n=22, MSWD=0.65) (Fig. 5a). The weighted mean age is within error of the upper intercept age, representing the magmatic crystallization age of this granodiorite gneiss.

Sample TWD15018-2 is granitic mylonite collected from Xiuyan Sanjiazi area. The zircon grains selected form this sample are generally enuhedral and prismatic with length to width ratios of 2 : 1 to 4 : 1. The whole crystal is slightly blackened, and the growth oscillation ring is developed (Fig. 3). The zircons contain relatively high Th (mean content 2917 ppm), U (mean content 4344 ppm), Zr, Hf, Nb (mean content 8.41 ppm) and Ta (mean content 3.32 ppm) concentrations and high Th/U ratios (0.30–3.59), showing that they were magmatic zircon. The 207Pb/206Pb ages given by 25 analytical zircons range from 1724 to 1875 Ma, and yield a weighted mean 207Pb/206Pb age of 1810±14 Ma (n=24, MSWD=10) (Fig. 5b). This age is consistent with the upper intercept age of 1820±16 Ma (n=25, MSWD=1.9). Thus, the age of 1810 Ma represents the crystallization age of the magmatic protolith.

Sample D1420-1 is an andalusite sillimanite garnet biotite plagioclase gneiss collected from Liaoang Jixiangyu area, and the original stratum is Huaziyu rock section of Dashiqiao rock formation. Zircons from sample D1420-1 are mostly clear, subhedral to euhedral with length/width ratios of 1 : 1 to 3 : 1. CL imaging reveals that most grains have fine oscillatory zones (Fig. 3), and they have Th/U ratios of 0.20–0.68. In addition, they have high contents of Zr, Nb and Ta, showing that it is magmatic zircon (Li, 2009; Liu D Y et al., 2009; Belousova et al., 2002; Hoskin and Ireland, 2000). A total of 25 spots were analyzed on 25 zircons from this sample. All of the 25 analyses are concordant and yield an weighted mean 207Pb/206Pb age of 1954±19 Ma (n=24, MSWD=1.8), which is consistent with the upper intercept age of 1946±24 Ma (n=24, MSWD=0.99), representing the crystallization age of the magmatic protolith of sample D1420-1 (Fig. 5c). In addition, one analyzed plot on the concordia curve and has an apparent 207Pb/206Pb age of 2070±30 Ma, which is much older than the other ages and can be regarded as the age of xenocrystic zircon in the sample D1420-1 (Fig. 5c).
Figure 5. Zircon U-Pb ages for the Paleoproterozoic metamorphic plutonic rock and metagabbro (metamorphic diabase) in the Liao-Ji belt.
Sample D14121-1 is also andalusite sillimanite garnet biotite plagioclase gneiss collected from Liaoyang Jidongyu area. Zircons from sample are generally euhedral in shape and exhibit well-developed oscillatory zoning in CL images (Fig. 3). A total of 19 analyses were made on 19 zircons, and all yielded high Th/U ratios (0.37–1.03). In the Concordia diagram, all ratios plotted on or near the concordia curve, yielding a weighted mean age of 1 961±32 Ma (n=17, MSWD=19). These analyses yield an upper intercept age of 1 954±56 Ma (n=19, MSWD=8.3), which is within error of the weighted mean age (Fig. 5d). Thus, the age of 1 961 Ma represents the crystallization age of the magmatic protolith.

Sample D14123-1 is similar to sample D14121-1 collected from the Liaoyang Jidongyu area. Zircon grains selected from sample D14123-1 can be divided into two groups. The first group are typical magmatic origin, including the euhedral to subhedral in shape, relatively high Th/U ratios (0.42–0.61), high average contents of Na and Ta (8.01 ppm and 3.49 ppm, respectively), and display banded structures or oscillatory zoning in CL images (Fig. 3). The other group of zircon internal structure is relatively uniform with unclear of the growth zone, and some of them have relatively old cores (Fig. 3). The ratio of Th/U is 0.01–0.09, and the content of Nb and Ta is relatively low (the average content is 0.68 ppm and 0.63 ppm respectively), indicating that they are metamorphic zircons (Li, 2009; Liu D Y et al., 2009; Belousova et al., 2002; Hoskin and Ireland, 2000). A total of 21 U-Pb isotopic analyses were conducted on 21 zircon grains from this sample. The result of these zircon analyses can be divided into two distinct groups. The older group consists of three analyses and define a weighted mean \(^{207} \text{Pb}/^{206} \text{Pb}\) age of 1 874±16 Ma (n=3, MSWD=0.54), we interpret this value as the crystallization age of the magmatic gneiss. The younger age group yields a weighted mean age of 1 868±21 Ma (n=18, MSWD=11.9), which is consistent with their upper intercept age of 1 891±41 Ma (n=18, MSWD=3.2) (Fig. 5e), interpreted as the time of late metamorphism.

3.2.6 Metagabbro (metamorphic diabase)
Sample TW15D003 is a metamorphic diabase collected from the Benxi Wufengguan area. The zircons selected from this sample have a smaller and irregular shape (50–80 μm in size), are fuzzy and white on the surface, have no visible growth oscillation ring band and have many cracks in the crystal (Fig. 3). The ratio of Th/U is 0.22–0.75, and the content of Nb and Ta is relatively high (the average content is 8.22 ppm and 3.27 ppm, respectively), showing the typical characteristics of zircons in basic magma (Li, 2009; Liu D Y et al., 2009; Belousova et al., 2002; Hoskin and Ireland, 2000). A weighted mean \(^{207} \text{Pb}/^{206} \text{Pb}\) age of 1 830±66 Ma (n=17, MSWD=0.54), we interpret this value as the crystallization age of the magmatic gneiss. The young age group yields a weighted mean age of 1 821±78 Ma (n=15, MSWD=20) (Fig. 5f), which is within error of the weighted mean age.

Sample TW15D008 is a metagabbro collected from the Liaoyang Helanyu area. The zircons selected from this sample are generally smaller and have an irregular shape (40–85 μm in size), and the surface was gray and fuzzy with uneven streaks (Fig. 3). Combined with its higher Th/U ratio (0.46–2.30) and higher Nb and Ta content (average of 21.41 ppm and 6.41 ppm, respectively) suggests that the zircon is most likely magmatic in origin (Li, 2009; Liu D Y et al., 2009; Belousova et al., 2002; Hoskin and Ireland, 2000). Twenty-five analyses made on 25 zircon grains yield an upper intercept age of 2 006±71 Ma (n=23, MSWD=13) (Fig. 5g). If seven data with a \(^{207} \text{Pb}/^{206} \text{Pb}\) age above 2.0 Ga are selected for calculation, the upper intercept age is 2 014±27 Ma (n=7, MSWD=1.6), and the weighted mean age of \(^{207} \text{Pb}/^{206} \text{Pb}\) is 2 010±27 Ma (n=7, MSWD=5.3) (Fig. 5h). The above data show that the crystallization age of gabbro should be ~2 010 Ma.

4 DISCUSSION
4.1 Chronological Framework of the Paleoproterozoic Intrusive Rock in the Liao-Ji Belt
The systematic study of the Liao-Ji granite began during the previous century (Zhang, 1988). However, the obtained ages were not found to be accurate due to the constraints of the test conditions at that time. However, by the year 2000, due to the emergence and general applications of zircon U-Pb dating technology, many researchers were able to obtain reliable chronological data for the Paleoproterozoic intrusive rock in the LJB (Liu F L et al., 2017; Yang et al., 2017; Meng et al., 2014). A chronological framework of Paleoproterozoic magmatic activities in the study area was established based on the statistical data of previous chronology results and results of the regional geological survey for the last 10 years, combined with the new data obtained in this study. The zircon U-Pb ages of more than 150 samples (Table S2) have been obtained, which could be utilized to roughly delineate the Paleoproterozoic intrusive chronology framework of the LJB. According to these data, the Paleoproterozoic magmatism in the study area could be divided into three periods: 2 200 to 2 110, 2 110 to 1 937, and 1 900 to 1 820 Ma, displayed the shape of “two peaks and one valley”, as illustrated in Fig. 6.

4.1.1 2 200 to 2 110 Ma intrusive rock
The intrusive rock of the period ranging between 2 200 and 2 110 Ma showed strong magmatic activities, with the acid intrusive rock and basic intrusive rock developing together including syenogranite and metagabbro (Fig. 6). The magmatic activities of the acid intrusive rock lasted for a long time and could be divided into the following three periods: Approximately 2 200, 2 180 to 2 150 Ma, and approximately 2 110 Ma, respectively. The corresponding basic magmatic activities were mainly concentrated in the latter two periods (for example, 2 170 to 2 150 Ma and approximately 2 110 Ma). The acid intrusive rocks of approximately 2 200 Ma were distributed in Houxianyu-Hupiyu-Simenzi. The rock type was mainly adamellite, and the chronological results revealed a range from 2 214 to 2 191 Ma (Li C et al., 2017; Chen et al., 2016; Yang et al., 2015a; Han et al., 2010). The acid intrusive rock ranging from 2 150 to 2 180 Ma were found to have the largest distribution, and also contained the most age data. They distributed throughout the LJB, but were mainly concentrated in the Hupiyu-Houxianyu area, as illustrated in Fig. 1b. The lithology included monzonogranite (Liu et al., 2018; Li C et al., 2017; Wang P S et al., 2017; Wang X J et al., 2017; Wang X P et al.,
intrusive rock from the Liao-Ji belt. (a) Ages of Paleoproterozoic granitic intrusions; (b) AGES of Paleoproterozoic metamorphic plutonic rock and metagabbro (metamorphic diabase).

4.1.2 2 010 to 1 937 Ma intrusive rock

There were few magmatic activities from 2 010 to 1 937 Ma, which can be seen as a “valley” in the map shown in Fig. 6. The intrusive rock was composed of gneissic monzogranite, medium-fine-grained granite, and metamorphic pluton (Table 1). In previous studies the granodiorite of 1 995 Ma had been only found in the town of Huanghuadian (Wang P S et al., 2017). The geochronology of the two acid intrusions was carried out in this study. The fine-grained granite from the Sanjiazhi Hushan rock body in Xiuyan was determined to be 1 971 Ma, and the monzonitic granite in the Xialuhe scenic area of Kuantian was 1 937 Ma. Meanwhile, the metamorphic pluton identified also revealed the magmatic activities which had occurred during that period. The ages of andalusite-sillimanite-garnet-biotite plagioclase-gneiss in Jixiangyu and Jidongyu were confirmed to be 1 954 and 1 961 Ma, respectively. However, the basic magmatic activities of the period have not yet been reported. Only a magmatic record of 2 010 Ma was obtained from the Helanyu metagabbro in this study.

4.1.3 1 900 to 1 820 Ma intrusive rock

The intrusive rock during the period ranging from 1 900 to 1 820 Ma were collected to have the most data, and both the acid and basic intrusive rock were developing (Fig. 6). The lithology included quartz diorite-gneiss, porphyry granite, migmattic granite, syenite, metagabbro, meta-diabase and granitic pegmatite dykes. The magmatic activities of the acid intrusive rock were divided into three peaks as follows: ~1 890, ~1 870, and 1 840 Ma. The basic magmatic activities were observed to be mainly concentrated in the latter two periods during ~1 875 and ~1 825 Ma, respectively.

The acid intrusive rock ~1 890 Ma have been found to be mainly distributed in the Shuangcha, Wolongquan, and Dandong areas including monzogranite, syenite, and plagiogranite, with the age ranging from 1 900 to 1 882 Ma (Ren et al., 2017; Yang et al., 2015b). The intrusive rock having the most age data during the 1 870 Ma period included medium acid intrusive bodies, which distributing throughout the LJB (Fig. 1b). It indicated the most intense magmatic activity in the study area. The lithology included monzogranite (Song et al., 2016; Qin, 2013; Li and Zhao, 2007), porphyry granite (Liu F L et al., 2017; Lu et al., 2005), syenite (Yang et al., 2007), diorite (Yang et al., 2007; Lu et al., 2005), pegmatitic veins (Yang et al., 2017; Wang et al., 2011), and metamorphic deep pluton (Liu et al., 2014), with an age from 1 879 to 1 857 Ma. We obtained the ages of the porphyritic granite and gneissic adamellite from the Hupiyu rock body of Hekou in Dandong City and the results were 1 876 and 1 867 Ma, respectively. The magmatic activities of the basic intrusive rock during the same time were mainly distributed in Helanyu, and the lithology was dominated by pillow lava (Wang et al., 2011). Meanwhile, it was observed that gabbro was exposed in the Erpendianzi area with a confirmed age of 1 880 Ma. The intermediate-acid intrusive rock in the peak period of ~1 840 Ma were distributed relatively widely and composed of complex rock types. The lithology included monzogranite (Lu et al., 2005, 2004a), syenite (Lu et al., 2004a), pegmatite (Yang et al., 2017), porphyry granite (Song et al., 2016), and metamorphic deep pluton (Liu et al., 2014).
<table>
<thead>
<tr>
<th>No.</th>
<th>Name of intrusion</th>
<th>Lithology</th>
<th>Mineral assemblage</th>
<th>Location</th>
<th>Chronology sample in this study</th>
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<tbody>
<tr>
<td>1</td>
<td>QZG pluton and HPY pluton</td>
<td>Syenogranite</td>
<td>K-f+Qtz+Pl+Amp+Bt</td>
<td>Huanren, Hupiyu and Qinghe</td>
<td>HK-2, D017-2, D058-4</td>
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<tr>
<td>2</td>
<td>QH pluton and LJPZ pluton</td>
<td>Quartz diorite</td>
<td>Pl+Amp+Qtz+Bt</td>
<td>Qinghe, Kuandian and Maodian</td>
<td>D42061-1, D4121-1, D4123-1</td>
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<tr>
<td>3</td>
<td>SC pluton and LJBZ pluton</td>
<td>Large-porphyritic granite</td>
<td>Pl+Kfs+Qtz+Bt</td>
<td>East of Huanren reservoir, Shuangcha, Bahechuan and Lujiabaozi</td>
<td>TWD5016, TWD5018-2</td>
</tr>
<tr>
<td>4</td>
<td>HS pluton and WLQ pluton</td>
<td>Monzogranite</td>
<td>Qtz+Pl+Mic+Per+Bt+Mus</td>
<td>Dandong, Kuandian and Wolongquan</td>
<td>HK-1</td>
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<tr>
<td>5</td>
<td>KDG pluton</td>
<td>Syenite</td>
<td>K-f+Amp+Qtz+Pl+Cpx+Bt</td>
<td>Kuangdonggou area in Gaixian County</td>
<td>TWD15016</td>
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<tr>
<td>6</td>
<td>Metamorphic plutonic rocks</td>
<td>Granodioritic gneiss</td>
<td>Pl+Qtz+Bt+Kfs</td>
<td>East of Kuandian</td>
<td>TWD15018, TWD15018-2</td>
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<td>7</td>
<td>Granitic pegmatite and Metagabbro</td>
<td>Granite pegmatite</td>
<td>Pl+Kfs+Qtz+Sil+Amph+Per+Bi</td>
<td>Ji'an Group, Penghai Town</td>
<td>TWD5908</td>
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Kfs. K-feldspar; Qtz. quartz; Pl. Plagioclase; Amph. amphibole; Bi. biotite; Mic. microcline; Per. perthite; Cpx. clinopyroxene; Mus. muscovite; And. andalusite; Gar. garnet; Sil. sillimanite.
well as the opposite $P-T-t$ evolutionary trajectory. It was believed that the formations were joined together through continent-continent collisions during the Paleooproterozoic Period (Li et al., 2001; He and Ye, 1998; Lu, 1996).

With the deepened understanding gained in the aforementioned studies, an increasing number of researchers have come to support the subduction accretionary model (Dong et al., 2019; Xu and Liu, 2019; Bi et al., 2018; Liu et al., 2018). In this study, by establishing a chronology framework of the Paleooproterozoic intrusive rock in the LJB, it was believed that the chronological characteristics of the magmatic activities and rock assemblages also supported the subduction accretionary model. At approximately 2 200 Ma, the lower crust was partially melted by plate actions, resulting in acid granites. At that time, the area was a passive continental margin, which was then transformed into an active continental margin (Xu and Liu, 2019). The first peak of the magmatic activity occurred in the intrusive rock between 2 180 and 2 150 Ma. The rock assemblages were composed of acid granite and basic intrusive rock, which indicated that a back-arc extensional environment had existed at that time, and the back-arc basin had begun to receive sedimentation (Dong et al., 2019; Bi et al., 2018). This extensional environment lasted until approximately 2 110 Ma. The extensional degree reached the maximum at that time, forming a large number of basic intrusive rock. Afterward, the back-arc basin began to contract. Minimal magmatic activity resulted from the contraction processes of the back-arc basin to the orogenic stage, and there were only a small number of intrusive activities observed during the periods of 2 040 and 2 010 to 1 937 Ma. Then, at the end of the sedimentary activities of the first peak metamorphism in 1 950 Ma, the deposition in the LJB lasted approximately 230 Ma. In addition, after 1 900 Ma, the area entered a post orogenic extension stage following the orogeny, and large-scale intrusive rock were formed in the area. The magmatism reached its peak between 1 870 and 1 840 Ma, and acidic granite, syenite, and basic gabbro (green) rock were exposed.

4.3 Constraints on the Paleooproterozoic Metamorphism

The Paleooproterozoic metamorphic age in the LJB has been studied by analyzing the metamorphic volcanic-sedimentary and metamorphic intrusive rock in the area (Liu et al., 2015; Meng et al., 2013; Lu et al., 2006). Some of the previous research studies have obtained the metamorphic ages of between 1 90 and 1 95 and 1 85 Ga for the different types of metamorphic rock in the Langzishan Formation and Lieryu Formation, Laoling Group, and Ji’an Group (Liu P H et al., 2019, 2017; Bi et al., 2018; Wang et al., 2017; Liu F L et al., 2015; Liu Y C et al., 2009). Other research studies obtained a large number of metamorphic ages between 1 90 and 1 85 Ga in the Paleooproterozoic intrusive rock in the study area (Xu C et al., 2018, Xu W et al., 2018a; Gao et al., 2017; Wang F et al., 2017; Meng et al., 2014). Liu et al. (2015) systematically studied the metamorphic zircons in the Al rich schist-gneiss in the Ji’an Group and Laoling Group, South and North Liaohou Group, Jingshan Group, and the Fanzhishan Group of the Jiao-Liao-Ji Paleooproterozoic belt. It is believed that there were two peak metamorphic periods, 1 90 to 1 95 Ga and approximately 1 85 Ga.

Based on the U-Pb dating of zircon and monazite and the study of the $P-T-t$ trajectory of the granulite (Liu et al., 2015), Liu et al. (2019) believed that the orogeny which caused the Paleooproterozoic metamorphic event lasted for a long period of time. For example, from 1 950 to 1 800 Ma (Liu et al., 2019).

Large regional metamorphism usually occurs during the orogenic stages. Meanwhile, magmatism is considered to be rare during orogenic stages due to the compressional environmental conditions. The appearance of the 1.95 Ga metamorphic zircon marked the beginning of Paleooproterozoic orogeny, and the first metamorphic peak was determined to be at 1.90 Ga (Liu et al., 2015). During that period, there were minimal activities of the Paleooproterozoic intrusive rocks, and only the Hupu monzogranite (1 937 Ma) and Helanyu hornblende gabbro (1 914 Ma) were exposed. This also confirmed the compressional orogenic environmental conditions in the study area. Then, between 1 870 and 1 840 Ma, extremely strong magmatic activities were evident, as illustrated in Fig. 6. In addition, both acid and basic intrusive rock were present, which indicated that a tension environment had existed at that time, and magmatic hydrothermal fluid was very active (Xu and Liu, 2019).

During the Early Cretaceous Period, the magmatic rocks which are distributed in a large area of eastern China were formed under extensional environmental conditions. This theory has been widely recognized by researchers. However, during the Early Cretaceous Period, only ductile shear zones and metamorphic core complexes had existed, and large-scale regional metamorphism had not occurred (Liu et al., 2011). There remains some uncertainty regarding whether or not a large-scale metamorphism occurred between 1 900 and 1 820 Ma under extensional environmental conditions. Also, there is some controversy regarding whether or not the 1.85 Ga metamorphic zircon age obtained by many previous researchers accurately represents a metamorphism, or if the zircon was actually transformed by magmatic hydrothermal solutions. Therefore, further investigations will be required.

5 CONCLUSIONS

Our zircon U-Pb dating and established chronological framework for the Paleooproterozoic intrusive rocks of the LJB, allow us to draw the following conclusions.

(1) Based on the characteristics of rock association, the Paleooproterozoic intrusive rocks can be divided into seven types: syenogranite, quartz diorite gneiss, porphyry granite, migmatic granite, syenite, metamorphic plutonic rock, granitic pegmatite and metagabro (metamorphic diabase). 15 zircon U-Pb ages of Paleooproterozoic intrusive rocks have been obtained.

(2) The Paleooproterozoic intrusive rock can be divided into three periods. The first active peak period occurred between 2 200 and 2 110 Ma, which was further divided into the following three periods: acidic magmatic activity (2 200 Ma), bimodal magmatic activity (2 180–2 150 Ma), and basic magmatic activity (2 110 Ma). There are rare acidic magmatic activity during the period ranging from 2 010 to 1 937 Ma. The intrusive rock had recorded the most magmatic activities from 1 900 to 1 820 Ma, which were further divided into three peaks: acidic magmatic activity (1 890 Ma), and two peaks of bimodal magmatic activities (1 875–1 870 and 1 840–1 825 Ma, respectively).
(3) The chronological framework effectively supported the evolution model of subduction accretionary arc-continent collision in the LJB. It was characterized by a passive continental margin environment at the time approximately 2.200 Ma. Then it was transformed into an active continental margin. Between 2.180 and 2.150 Ma, the bimodal intrusive rock indicated a back-arc tension environment which lasted until approximately 2.110 Ma. The occurrence of a large number of basic intrusive rock indicated the maximum degree of tension had been reached. Following that period, the back-arc basin began to contract and the magmatic activities were reduced, with only a small number of intrusive rock activities occurring from 2.040 to 1.937 Ma. Following the orogenic activities, this area entered into a post-orogenic extension stage from 1.900 to 1.820 Ma. These extensional environmental conditions caused the magmatic activities to occur more frequently, subsequently resulting in the large-scale intrusive rock formations in the study area.

(4) The 1.900 to 1.820 Ma magmatic activity peak period indicates an extensional environment. Comparing with the Early Cretaceous, whether or not a large-scale regional metamorphism had occurred during 1.85 Ga in this extensional environment? Does the metamorphic zircon of this period represent metamorphism or magmatic hydrothermal transformation? Further research investigations are required for those aspects.

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