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Zircon U-Pb chronology, geochemistry and geological significance of the Tongjiang-Fuyuan Mesozoic magmatic rocks, NE China

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Abstract

Typical ophiolitic rock assemblages such as siliciclastic rocks, basalts and gabbros, together with the subduction-related intermediate-acidic intrusive rocks, are newly discovered in the Tongjiang-Fuyuan area of the Heilongjiang Provence, NE China. To determine the formation age and genesis of the mafic rocks (basalts and gabbros) and intermediate-acidic intrusive rocks (granodiorites) in the area, as well as their geodynamic settings, the whole-rock geochemical analysis and zircon LA-ICP-MS U-Pb dating were carried out. Zircon U-Pb results suggest that the granodiorites are 93–95 Ma and gabbro is 95 Ma, respectively. Geochemical results show that the gabbros and basalts exhibit characteristics of ocean island basalt (OIB) affinity and are typically related to having originated from mantle plumes. While the granodiorites show the nature of the island-arc magmatic rocks and may originate from the lower crust. Based on the coeval igneous rock associations and regional tectonic evolution, we conclude that the late Cretaceous magmatic rocks in the Tongjiang-Fuyuan area are the product of continuous subduction of the Palaeo-Pacific plate and reflect the subduction rollback process of the Palaeo-Pacific plate.

1. Introduction

Ophiolites, as fragments of ancient oceanic lithosphere (e.g. Dewey & Bird, 1971; Coleman, 1977), play irreplaceable roles in the recognition and reconstruction of the evolution history of an ancient ocean, including the opening, closure, development of subduction systems and the consequent orogeny (Dilek, 2003; Dilek *et al.*, 2007; Dilek & Furnes, 2011). Investigation of the formation and emplacement age of an ophiolite can unravel the process of accretionary orogenesis (Xiao *et al.*, 2009a, 2013). Furthermore, the ophiolite or ophiolitic mélange is the most basic tectonic member in the subducted wedge of an orogenic belt, which is not only an important marker of the Palaeo-plate boundary but also important for understanding the evolution process of the orogenic belt (Jian *et al.*, 2003; Zhang *et al.*, 2003; Shi, 2005; Dilek & Furnes, 2011; Furnes & Dilek, 2017).

Northeast China (NE China) is located in the eastern part of the Central Asian Orogenic Belt (CAOB), which underwent the complicated subduction-accretionary orogenic processes (Xiao *et al.*, 2009b; Zhang *et al.*, 2013, 2015; Chen *et al.*, 2015; Ge *et al.*, 2015; Wang *et al.*, 2015). As we all know, the NE China is tectonically composed of four micro-blocks and an accretionary terrane, i.e. Erguna Block (EB), Xing'an Block (XB), Songliao-Xilinhot Block (SXB), Jiamusi Block (JB) and the Nadanhada Terrane (NT). A large number of ophiolites or ophiolitic complexes are widely distributed in NE China, significantly marking the suture zones among the above-mentioned blocks and terrane. From west to east, they are the Xinlin-Xiguitu, Heihe-Nenjiang-Hegenshan, Mudanjiang-Yilan and Yuejinshan belts (Fig. 1), involving the closure of the ancient oceans of Neoproterozoic-Late Cambrian Xinlin-Xiguitu branch ocean, the Early Cambrian-Late Carboniferous Nenjiang branch ocean, Neoproterozoic Heilongjiang branch ocean, the Late Permian-Middle Jurassic Mudanjiang branch ocean and the subduction of the Mesozoic Palaeo-Pacific ocean, respectively (Zhang *et al.*, 2008; Feng *et al.*, 2019; Liu *et al.*, 2019).

During the Mesozoic, NE China was affected by the closure of the Mongolian-Okhotsk Sea and the subduction of the Palaeo-Pacific plate, resulting in large-scale tectonic-magmatic activities (e.g. Wu *et al.*, 2000; Meng *et al.*, 2014; Feng *et al.*, 2019; Liu *et al.*, 2019; Li *et al.*, 2020). Previous studies on Mesozoic volcanic rocks in NE China show that the Mesozoic accretive complexes, the arc magmatic belts of JB and the eastern margin of SXB in NE China are

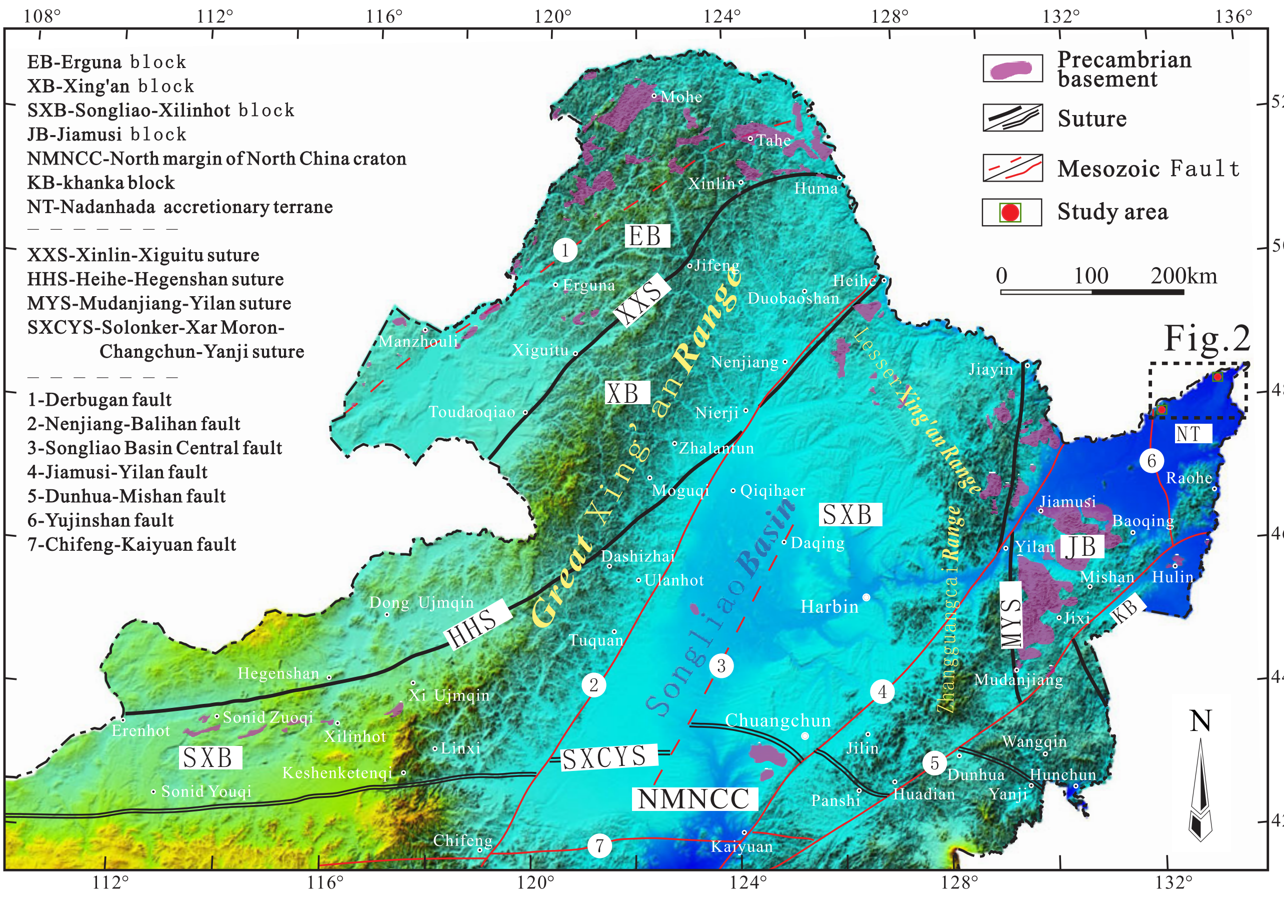

Figure 1. (Colour online) Tectonic divisions of the NE China (after Liu *et al.*, 2017b).

distributed in the south-north direction (e.g. Xu *et al.*, 2013; Wilde, 2015; Liu *et al.*, 2017b, 2019, 2021; Han *et al.*, 2022). These accretive complexes formed in the Late Triassic to Early Cretaceous and showed a trend of becoming younger from west to east (Sun, 2013; Sun *et al.*, 2014; Li *et al.*, 2020). The above facts indicate that the Mesozoic accretive complex in NE China is closely related to the western subduction of the Palaeo-Pacific plate (Li *et al.*, 2020; Han *et al.*, 2022).

To the eastmost of NE China, the typical ophiolites (ophiolitic complexes) are discovered in the Raohe and Yuejinshan areas from the NT. Zhang *et al.* (1997) found that the Yuejinshan Complex is a tectonic mélange with the block-in-matrix texture and proposed that the original rocks are N-MORB-type basalts, which are typical ophiolites. Meanwhile, the concept of the Raohe ophiolite was first proposed by Li (1980) and further has been accepted by many scholars (Kojima & Mizutani., 1987; Kojima, 1989; Zhang *et al.*,1989; Kang, *et al.*, 1990; Mizutani & Kojima, 1992). However, typical mantle peridotites do not develop in ophiolites in the Raohe area (Zhang *et al.*, 2000), and the geochemical characteristics of mafic-ultramafic complexes are quite different from typical ophiolites, so some scholars regard it as the OIB-type Complex (Zhang *et al.*, 1998, 2003; Zhang and Zhou, 2001).

In recent years, the studies on the NT have pointed out that the Yuejinshan Complex and the Raohe Complex are the direct products of the long-term subduction and accretion of the Palaeo-Pacific plate beneath the Eurasian continent (Zeng *et al.*, 2018). However, the research on the evolution process of the NT is still controversial; especially, there is a lack of evidence for the age of the Late Cretaceous. Yu *et al.* (2013) discovered the Late Cretaceous granites in the Tongjiang-Fuyuan area in the northern part of the NT, which is different from the previous research that the granites developed in the late Indosinian belt in Raohe (HBGMR, 1993). According to field surveys and whole-rock geochemical analysis, it is found that the Late Cretaceous granites in the Tongjiang-Fuyuan area were formed in the active continental margin tectonic environment generated by the subduction of the Palaeo-Pacific plate to the East Asian continent (Yu *et al.*, 2013). Significantly, the typical ophiolites such as siliceous rocks, basalts and gabbros are also developed in the Tongjiang-Fuyuan area; however, they have not been systematically studied.

This study therefore focuses on the ophiolitic rock assemblages such as siliciclastic rocks, basaltic rocks and gabbros together with the granodiorite exposed in the Tongjiang-Fuyuan area in the northern part of the NT, NE China and carried out the systematic studies on field investigations, geochronology and geochemistry, to further reveal the subduction-accretionary process of the Palaeo-Pacific plate.

2. Geological setting and sampling

2.a Regional geology

The NE China comprises multiple micro-continental blocks or terranes, namely the EB, XB, SXB and JB, as well as the easternmost Nadanhada (Tang *et al.*, 1995; Li, 2006; Zhou & Wilde, 2013), and it is tectonically located in the triangular zone of the Palaeo-Asian

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Ocean, Mongolia-Okhotsk Ocean and the Palaeo-Pacific plate tectonic domains (Tang *et al.*, 1995; Li, 2006; Zhou *et al.*, 2009, 2014) (Fig. 1). The EB is distributed in a northeastward direction and is connected with the XB on the southeast side, and the magmatic rock age of EB is mainly Neoproterozoic, Early Palaeozoic, Late Palaeozoic and Mesozoic. (Liu *et al.*, 2008; Wu *et al.*, 2011; Zhang *et al.*, 2011; Zhou *et al.*, 2014; Dong *et al.*, 2019; Li *et al.*, 2020; Han *et al.*, 2022). The XB is adjacent to the EB and SXB and is mainly composed of Palaeozoic-Mesozoic magmatic rocks and related volcanic - sedimentary layers (Zhang *et al.*, 2011; Zhou *et al.*, 2014; Dong *et al.*, 2019; Li *et al.*, 2020; Han *et al.*, 2022). The SXB is located between the XB and JB, the magmatic rocks are mainly formed in Neoproterozoic, Early Palaeozoic, Late Palaeozoic and Mesozoic (Zhang *et al.*, 2011; Zhou *et al.*, 2014; Dong *et al.*, 2019; Li *et al.*, 2020; Han *et al.*, 2022). The JB is adjacent to the SXB and NT, the magmatic rocks are dominated by granitic rocks, and the ages are mainly early Palaeozoic Cambrian, Late Palaeozoic Permian, Mesozoic Triassic and Cretaceous (Zhang *et al.*, 2011; Zhou *et al.*, 2014; Dong *et al.*, 2019; Li *et al.*, 2020; Han *et al.*, 2022). The NT is located in the easternmost part of the NE China and is mainly composed of Yuejinshan complex, Raohe complex and Early Cretaceous magmatic rocks (Zhou *et al.*, 2014; Tang *et al.*, 2018; Li *et al.*, 2020; Han *et al.*, 2022).

In recent years, the key and difficulty to the study on the tectonics of NE China, as well as the dynamic mechanism of the major tectonic domains, lies in the superposition and transformation of the subduction-accretion of the Palaeo-Pacific plate, and the NT in the easternmost part of NE China happens to be the subduction-accretionary process of Palaeo-Pacific plate tectonic domain (e.g. Kojima & Mizutani, 1987; Mizutani & Kojima, 1992; Zhou *et al.*, 2014; Tang *et al.*, 2018; Han *et al.*, 2022).

The NT preserves relatively intact marine sedimentary strata. A stratigraphic palaeontological comparison suggests that the NT in the NE China, the Sikhote-Alin terrane in the Russian Far East and the Menon-Tamba terrane in Japan formed a super Jurassic accretionary terrane on the eastern edge of Eurasia continent before the opening of the Sea of Japan (Mizutani *et al.* 1989; Kojima, 1989). In the past half-century, many previous researchers provided different understandings of the tectonic properties of the NT. Wang (1959) regarded the area as a Mesozoic trough folded zone. Li *et al.* (1979) considered the area to be a Late Palaeozoic trough fold zone based on fossils from the Carboniferous to Permian in the tuffs. Ren *et al.* (1980) suggested that the area is a Mesozoic geosyncline on a Variscan folded basement. In addition, since the Carboniferous gill fossils in the limestone of the NT have typical Tethys tectonic domain fossil assemblages (Zhang *et al.*, 1989), Palaeomagnetic evidence and radiolarian fossil comparisons also show that the NT has experienced a long period of migration history at the Mesozoic (Mizutani *et al.*, 1989; Ren *et al.*, 2015). Therefore, some scholars believe that the NT is an extraneous terrane from low latitudes (Mizutani *et al.*, 1989; Wu *et al.*, 2011; Li *et al.*, 1979; Zhang & Ma, 2010). More recently, with the gradual maturation of plate tectonic theory and the identification and study of sedimentary rocks, some scholars have also suggested that the NT is an accretionary terrane formed by the subduction of the Palaeo-Pacific plate beneath the JB (Zhou *et al.*, 2014; Sun *et al.*, 2015b; Liu *et al.*, 2017b, 2021; Li *et al.*, 2020).

According to previous studies, the NT is divided into two main tectonic units, e.g. Yuejinshan Complex and Raohe Complex (e.g. Zhou *et al.*, 2014, 2018; Bi *et al.*, 2015, 2016, 2017a, 2017b; Wilde, 2015; Sun *et al.*, 2015a; Zeng *et al.*, 2019; Xu *et al.*, 2020; Zhang *et al.*, 2020; Han *et al.*, 2022). The Yuejinshan Complex is mainly composed of siliceous rocks, metamorphic clastic rocks and mafic-ultramafic rocks. Metamorphic clastic rocks include quartz schist, marble and mica schist, suffering the greenschist-facies metamorphism (Zhang *et al.*, 1997; Yang *et al.*, 1998; Bi *et al.*, 2016, 2017a, 2017b; Ge *et al.*, 2016; Zhou *et al.*, 2018; Han *et al.*, 2022). The mafic-ultramafic rocks show a typical ophiolite sequence, which is composed of metabasalt, gabbro and clinopyxroxenite (Zhou *et al.*, 2014; Bi *et al.*, 2016, 2017a, 2017b; Ge *et al.*, 2016; Zhou *et al.*, 2018; Han *et al.*,2022). Due to the destruction of tectonic deformation, the Yuejinshan Complex shows a tectonic mélange with metamorphic clastic rocks as the matrix and mafic-ultramafic rocks as blocks; thus, the Yuejinshan Complex is considered as a set of ophiolitic mélanges (Zhang *et al.*, 1997; Zhou *et al.*, 2014; Dong *et al.*, 2019; Han *et al.*, 2022). The formation of Yuejinshan Complex has been the subject of debate, with some studies suggesting that it was formed in the middle of the Palaeozoic, while others suggest that it may have formed from the Late Triassic to the Early Jurassic (HBGMR, 1993; Zhang *et al.*, 1997; Yang *et al.*, 1998). Recent studies have shown that the Yuejinshan Complex formed at around 210–180 Ma and that it represents the first stage of an accretion complex created by subduction-accretion of the Palaeo-Pacific plate (Zhou *et al.*, 2014; Yang *et al.*, 2015; Bi *et al.*, 2016, 2017a, 2017b; Cao *et al.*, 2019; Han *et al.*, 2022).

The Raohe Complex is mainly composed of tuffs, siliceous rocks, mafic-ultramafic rocks and clastic rocks and the clastic rocks mainly contain sandstone and mudstone, which form the matrix of the Raohe Complex (Zhou *et al.*, 2014; Bi *et al.*, 2016, 2017a, 2017b; Ge *et al.*, 2016; Zhou *et al.*, 2017; Han *et al.*, 2022). The Raohe Complex is similar to typical ophiolitic suites in that they are stratified by oceanic plate sediments, pillow basalt, stacked crystal gabbro and ultramafic rocks, which led to the conclusion that the Raohe Complexes are a set of tectonic mélanges associated with the subduction of the oceanic plate (Zhu *et al.*, 2015; Zeng *et al.*, 2019; Zhang *et al.*, 2020). The formation ages of basalt and gabbro in the Raohe-Dadai area are 166 ± 2 Ma and 214 ± 5 Ma, respectively (Zhou *et al.*, 2014; Han *et al.*, 2022), and the sedimentary lower limit ages of silty mudstone and sandstone samples are 167 ± 3 Ma and 133 ± 4 Ma (Zhou *et al.*, 2014; Sun *et al.*, 2015a; Zeng *et al.*, 2019; Han *et al.*, 2022). Additionally, the stapled granite intruded into the Raohe Complex was mainly formed at 126–110 Ma, limiting the final emplacement age of the Raohe Complex to 133–126 Ma (Cheng *et al.*, 2006; Zhou *et al.*, 2014; Zeng *et al.*, 2019; Han *et al.*, 2022).

Previous studies on magmatic rocks in NE China showed that the formation age of magmatic rocks was distributed from the Early-Middle Jurassic to the Late Cretaceous (Wu *et al.*, 2011; Zhang and Mizutani, 2004, Cheng *et al.*, 2006; 2008; Wang *et al.*, 2009; Wilde *et al.*, 2010; Yu *et al.*, 2013; Ge *et al.*, 2015; Zeng *et al.*, 2018, 2019; Li *et al.*, 2020). Late Cretaceous granites were firstly discovered in the Tongjiang-Fuyuan area in the north of NT (Yu *et al.*, 2013), and these granites were considered to be formed in the tectonic setting related to the subduction of the Palaeo-Pacific plate beneath the East Asian continent.

2.b Sample locations and simple description

The investigated Tongjiang-Fuyuan area is located at the junction of the JB and the NT (HBGMR, 1993; Yu *et al.*, 2013; Wang *et al.*, 2017), which is heavily covered and has few exposed rock masses. Through field investigation, it is found that the rocks exposed

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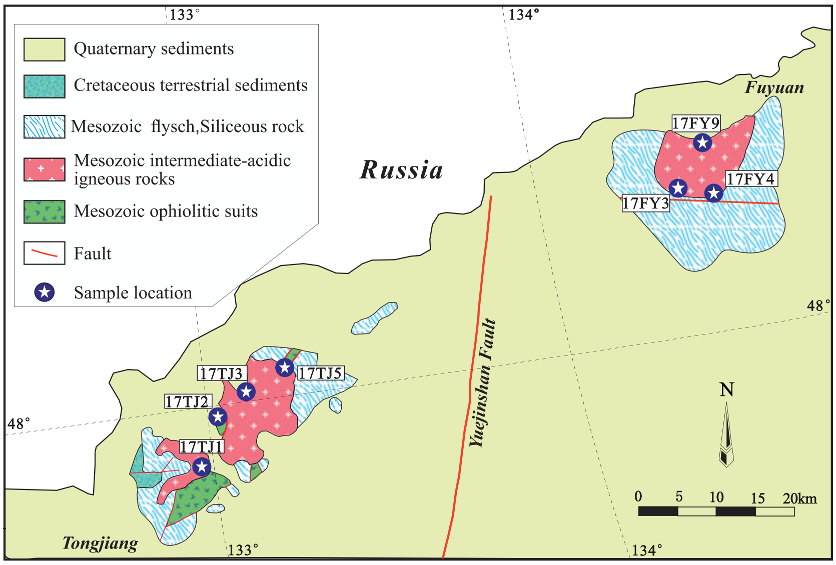

Figure 2. (Colour online) Geological map of the study area of Tongjiang-Fuyuan (modified after HBGMR, 1993; Yu *et al.*, 2013).

in the area are mainly composed of siliceous rock, basalt, gabbro and granodiorite, looking like the dismembered ophiolitic suites (Fig. 2).

Our petrological investigations suggest that the gabbro, basalt and siliceous rocks developed in the Tongjiang-Fuyuan area are contacted by the top-to-west thrusting faults, indicating a near EW-trending compression (Fig. 3a). The gabbros are greyish green or greyish black with various weathering degree and have the massive or lensed structure (Fig. 3b). The basalts occasionally show the pillow-like structure (Fig. 3c). The siliceous rocks (cherts) are strongly deformed, generally forming the tight folds (Fig. 3d). The granodiorites are grey or white in colour with coarse-grained phanerocrystalline texture and massive structure (Fig. 3e, f).

In the study, we collected a total of 9 samples, including 3 mafic rocks and 6 intermediate-acidic intrusive rocks. The detailed sampling locations and petrographic features are available in Figs. 3 and 4 and Table 1. The detailed descriptions for the representative samples are as follows.

Basalts (17TJ2) exhibit porphyritic textures with phenocrysts of clinopyroxene (70%) and minor plagioclase (25%). Clinopyroxene phenocrysts are 100–150 μm in size and display irregularity and obvious fractures. Minor plagioclase phenocrysts are 90–120 μm in size and display polysynthetic twinning (Fig. 4a). The matrix is composed of plagioclase microlites, granular clinopyroxene, chlorite and opaque minerals (Fe-Ti oxide). Many clinopyroxenes are partially to completely replaced by chlorite and opaque minerals (Fig. 4a).

Gabbros (17TJ5-1) display a diabase structure and consist of orthopyroxene (50%), plagioclase (45%), chlorite and Fe-Ti oxides (opaque minerals). Plagioclases are relatively subhedral and vary from 200 to 400 μm in size. The clinopyroxenes are subhedral and partly replaced by chlorite (Fig. 4b).

Granodiorites (17FY3) display fine-grained granitic textures, and have the mineral assemblage of plagioclase (~50%) and quartz (~35%), with a minor amount of hornblende and biotite. Plagioclases are subhedral and vary from 150 to 300 μm. Quartz is subhedral to anhedral and 70–110 μm in size (Fig. 4c).

Granodiorites (17FY9) display coarse-grained granitic textures and are composed mainly of plagioclase (~40%), quartz (~35%), hornblende (20%) and biotite (15%). Plagioclases are euhedral and vary from 150 to 200 μm. Quartz is subhedral to anhedral and 200–400 μm in size (Fig. 4d).

3. Analytical methods

3.a Zircon U-Pb dating

Zircons were separated from crushed investigated samples using conventional heavy liquid and magnetic techniques and purified by handpicking under a binocular microscope at the Yuneng Mineral Separation Company in Hebei Province, China. The selected zircons were adhered to the surface of the epoxy resin and polished, and exposed to the surface of the zircon nuclear portion to make a target. The laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) zircon U-Pb analyses were completed using an Agilent 7500a ICP-MS system equipped with a 193-nm laser at the Key Laboratory of Mineral Resources Evaluation in Northeast Asia, Ministry of Land and Resources, Jilin University.

To achieve the most accurate experimental results, the NIST SRM610, a reference material for synthetic silicate glass developed by the National Institute of Standards and Technology, was used to optimize the instrument. Harvard International Standard zircon 91500 zircon was selected as the experimental external standard to calibrate for elemental and isotopic fractionation. Isotope ratio data processing was performed by GLITTER (Ver. 4.0 Macquarie University). To reduce the effect of ordinary Pb on the test results, the experimental data were calibrated by Andersen (2002) to correct the isotope ratios. The age calculation was performed using ISOPLOT 4.0.

3.b Bulk rock major and trace elements analyses

After trimming off weathered surfaces, the selected samples were crushed in an agate mill and sifted into fine powders (<200 mesh). Geochemical analyses were conducted at the Key Laboratory of Mineral Resources Evaluation in Northeast Asia, Ministry of Land and Resources, Jilin University. Major element compositions of bulk rock samples were determined using XRF, with analytical uncertainties ranging from 2% to 3%. Trace element concentrations were determined using ICP-MS (Agilent 7500a) after acid digestion of samples in Teflon bombs and dilution in 2% HNO3 in

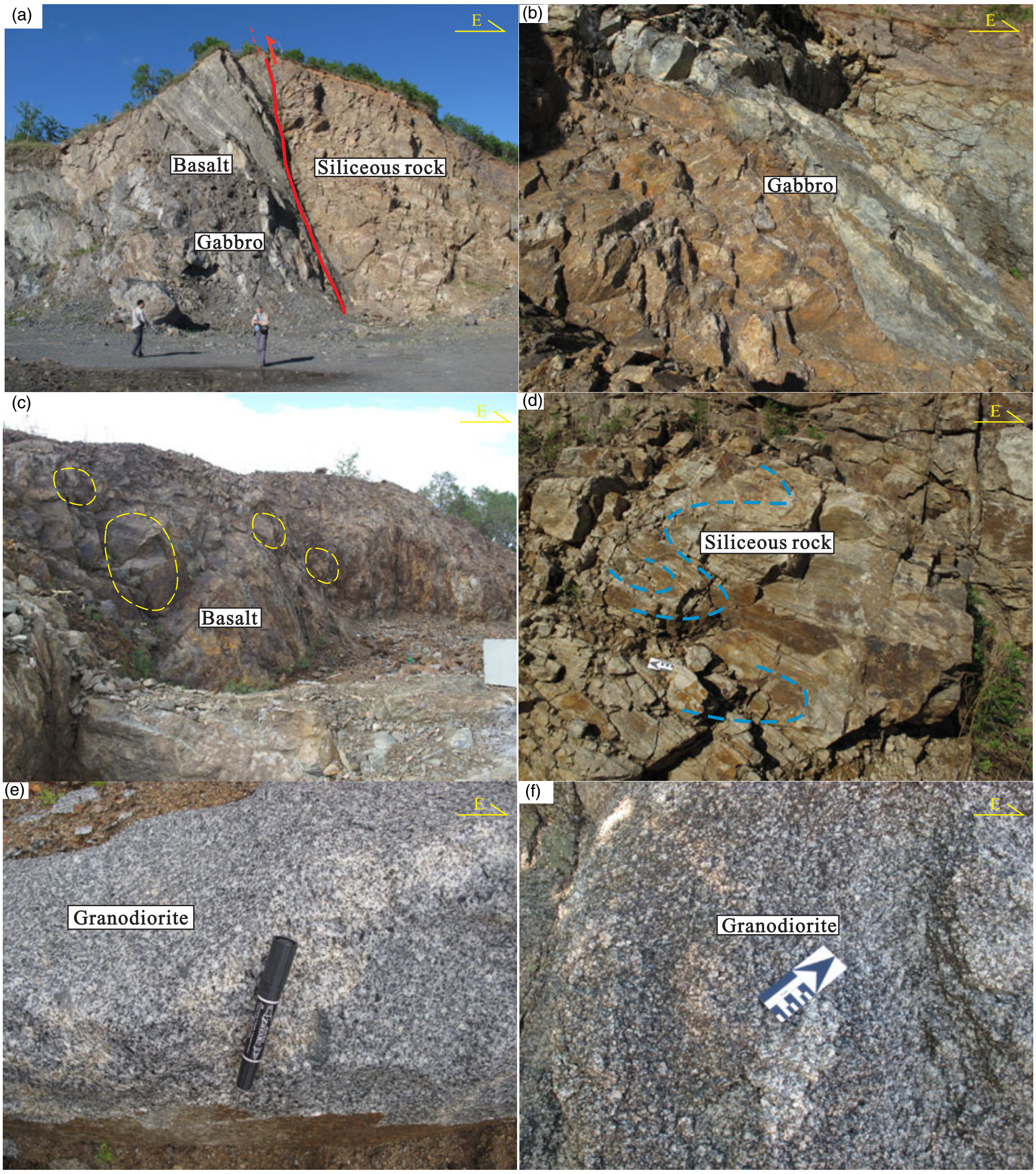

Figure 3. (Colour online) Field photographs of the basalt, gabbro and granodiorite collected from the Tongjiang-Fuyuan area, NE China. (a) A thrust fault developed between the basalts, gabbro and siliceous rock. (b) Partially weathered gabbro. (c) Basalts with the pillow-like structure. (d) A strongly deformed siliceous rock (cherts) forming the tight folds. € (f) coarse-grained granodiorite.

the same laboratory. The accuracy is generally better than 5% for trace and rare earth elements (REE).

4. Analytical results

4.a Zircon LA-ICP-MS U-Pb age

4.a.1 Sample 17TJ3 (Granodiorite)

Zircon grains separated from the granodiorite are colourless, euhedral, or broken grains with varying long axial lengths (70–120 μm) and an axial ratio of ca. 1:1 to 2:1 (Fig. 5a). CL imaging reveals that most grains have fine oscillatory zones. Zircons have high U (118–884 ppm) and Th (80–570 ppm) with Th/U ratios of 0.37–0.97 (Table S1), together with the oscillatory zoning shown in the CL images, significantly indicating that they were magmatic zircon. 17 zircons yield apparent $^{206}Pb/^{238}U$ ages of 90–96 Ma, giving a weighted mean of 93 ± 2 Ma (MSWD = 0.05) (Fig. 5a).

4.a.2 Sample 17TJ5-1(Gabbro)

Zircons selected from the gabbro are colourless, euhedral to subhedral grains and 50–100 μm in length, with an aspect ratio of 1:1 to 3:1 (Fig. 5b). CL imaging reveals that most grains are fairly dark with weak, banded zones, representing characteristic of mafic igneous origin (Baines *et al.*, 2009; Grimes *et al.*, 2009; Koglin *et al.*, 2009). Zircons have high U (266–1182 ppm) and Th (87–757 ppm) with Th/U ratios of 0.37–0.59, indicating that they are magmatic

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Table 1. Mineral association and petrographic characteristics of the investigated Tongjiang-Fuyuan magmatic rocks

NO.	Rock types	GPS position	Mineral assemblage
17TJ2	Basalt	N 47°53′01″ E 132°59′10″	clinopyroxene (70%) + feldspar (25%) + amphibole and biotite (<5%)
17TJ5-2	Basalt	N 48°0′53″ E 133°15′38″	clinopyroxene (65%) + feldspar (30%) + amphibole and biotite (<5%)
17TJ5-1	Gabbro	N 48°6′30″ E 133°13′40″	Orthopyroxene (50%) + plagioclase (45%) + quartz and hornblende (<5%)
17TJ1-1	Granodiorite	N 47°51′45″ E 132°55′29″	Plagioclase (40%) + quartz (35%) + hornblende (15%) + biotite (<10%)
17TJ1-2	Granodiorite	N 47°51′45″ E 132°55′29″	Plagioclase (45%) + quartz (30%) + hornblende (15%) + biotite (<5%)
17TJ3	Granodiorite	N 47°55′13″ E 133°3′35″	Plagioclase (40%) + quartz (35%) + hornblende (20%) + biotite (<5%)
17FY3	Granodiorite	N 48°16′4″ E 134°19′27″	Plagioclase (50%) + quartz (35%) + biotite (10%) + hornblende and apatite (<5%)
17FY4	Granodiorite	N 48°15′20″ E134°23′40″	Quartz (30%) + plagioclase (35%) + hornblende (20%) + biotite (15%)
17FY9	Granodiorite	N 48°21′28″ E 134°22′56″	Plagioclase (40%) + quartz (35%) + hornblende (20%) + biotite (15%)

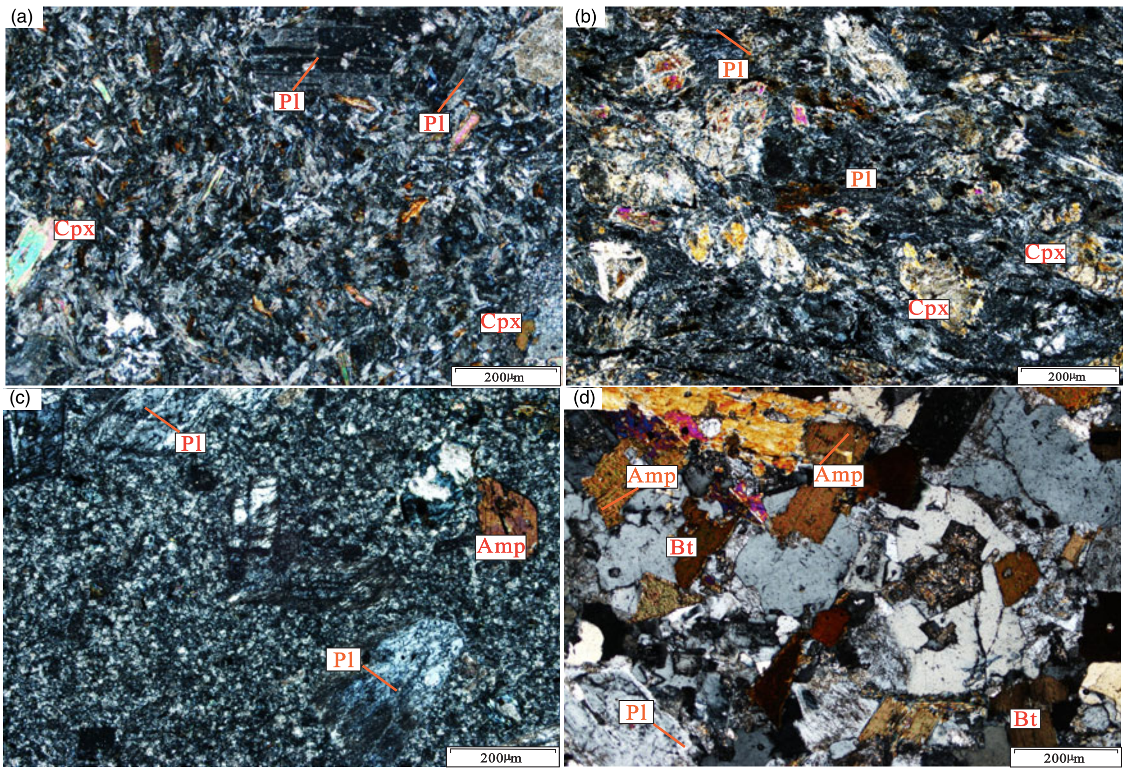

Figure 4. (Colour online) Photomicrographs of the basalt, gabbro and granodiorite rock samples collected from the Tongjiang-Fuyuan area, NE China. (a), Basalt (17TJ2). (b), Gabbro (17TJ5-1). (c), Fine-grained granodiorites (17FY3). (d), Coarse-grained granodiorites (17FY9). Pl = plagioclase; Cpx = clinopyroxene; Bt = biotite; Amp = amphibolite.

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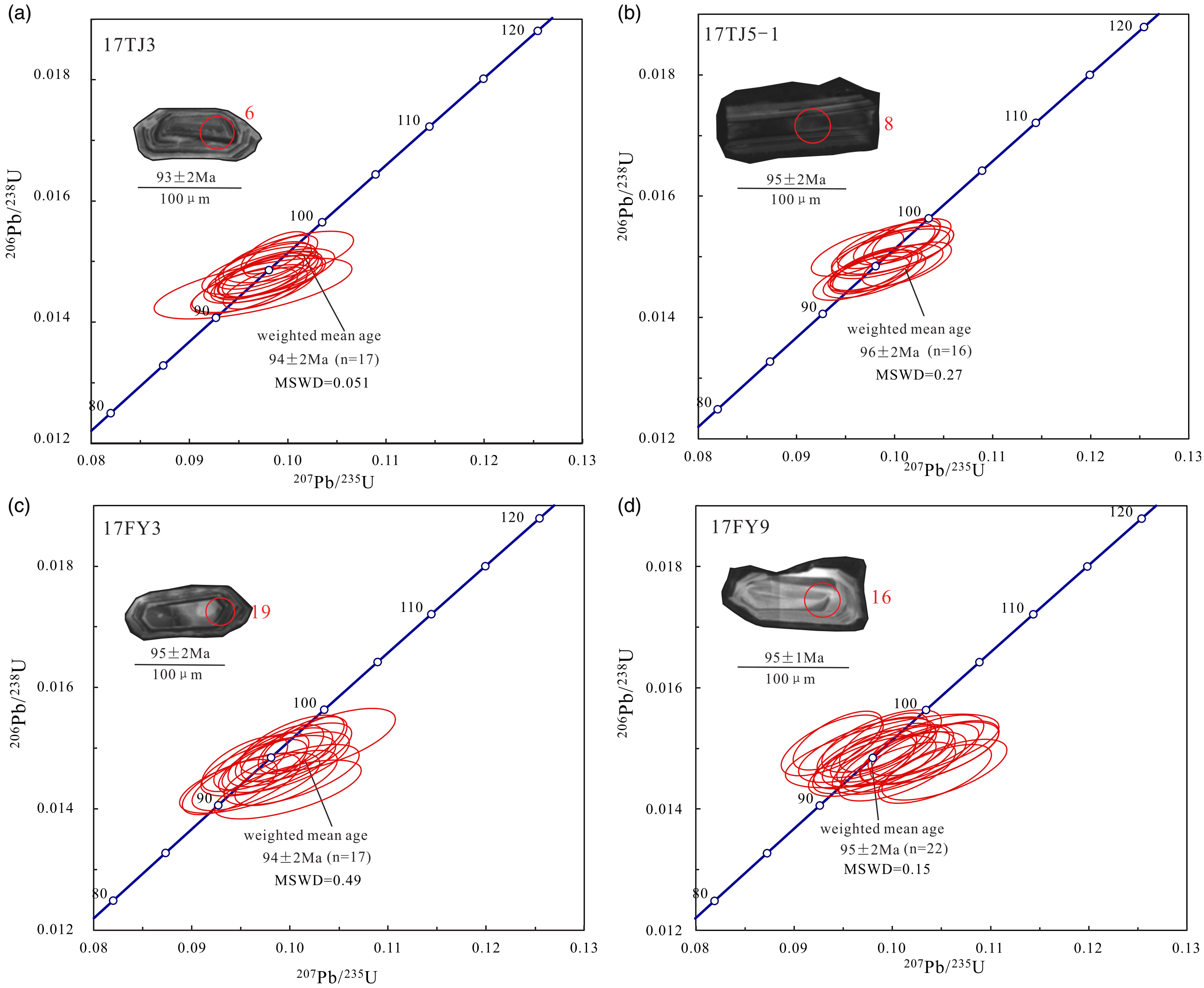

Figure 5. (Colour online) Zircon U-Pb age concordia diagram and representative cathodoluminescence (CL) images of zircons from the Mesozoic magmatic rocks in the Tongjiang-Fuyuan area, NE China.

origin (Table S1). 16 zircons yield apparent $^{206}Pb/^{238}U$ ages of 93–97 Ma, giving a weighted mean of 95 ± 2 Ma (MSWD = 0.27) (Fig. 5b).

4.a.3 Sample 17FY3 (Granodiorite)

Zircons from granodiorite are colourless, transparent and subhedral to euhedral in shape. Their sizes range from 50 to 180 μm in length, with aspect ratios of 1.5:1 to 2:1 (Fig. 5c). CL images commonly show the oscillatory zonings for the investigated zircon grains. A total of 17 analyses were made on 17 zircons, they have U and Th contents and Th/U ratios ranging from 279 to 799 ppm, 124 to 270 ppm, and 0.25 to 0.78, respectively (Table S1). 17 zircons yield apparent $^{206}Pb/^{238}U$ ages of 90–98 Ma, giving a weighted mean of 95 ± 2 Ma (MSWD = 0.49) (Fig. 5c).

4.a.4 Sample 17FY9 (Granodiorite)

Zircons picked out from granodiorite are colourless, subhedral or broken grains. Their grain sizes range from 70 to 180 μm in length, with aspect ratios of 2:1 to 3:1 (Fig. 5d). CL image reveals that most grains have well-developed oscillatory zones, which is suggestive of a magmatic origin. A total of 22 analyses were made on 22 zircons, the zircons have U and Th contents and Th/U ratios in the range of 235–853 ppm, 66–357 ppm and 0.29–0.79 ppm, respectively (Table S1). 22 zircons show the apparent $^{206}Pb/^{238}U$ ages ranging from 90 Ma to 98 Ma and a weighted mean of 95 ± 1 Ma (MSWD = 0.85) (Fig. 5d).

4.b Bulk rock major and trace elements

4.b.1 Major and trace elements in mafic rocks (basalts and gabbros)

Total 2 basaltic and 2 gabbroic samples were selected from the Tongjiang-Fuyuan area for whole-rock major and trace element analysis (Table S2).

The basalts have SiO_2 contents ranging from 42.79 to 49.33 *wt*%, total FeO from 10.50 to 11.19 *wt*%, MgO from 3.68 to 19.72 *wt*% and TiO_2 from 1.35 to 1.67 *wt*%, while the gabbros are characterized by SiO_2 (46.49–47.77 *wt*%), FeO (12.17–12.29 *wt*%), MgO (12.59–13.07 *wt*%) and TiO_2 (2.06–2.26 *wt*%) (Table S1). In the MgO-SiO_2 diagram (Fig. 6a), the basalts and gabbros plot in the basalt and the peridotite fields, respectively. In the Zr/TiO_2-Nb/Y diagram (Fig. 6b), all the Tongjiang-Fuyuan basalts and gabbros and previously documented Raohe pillow basalts plot into the alkali basalt field. By contrast, the Tongjiang-Fuyuan gabbros have lower

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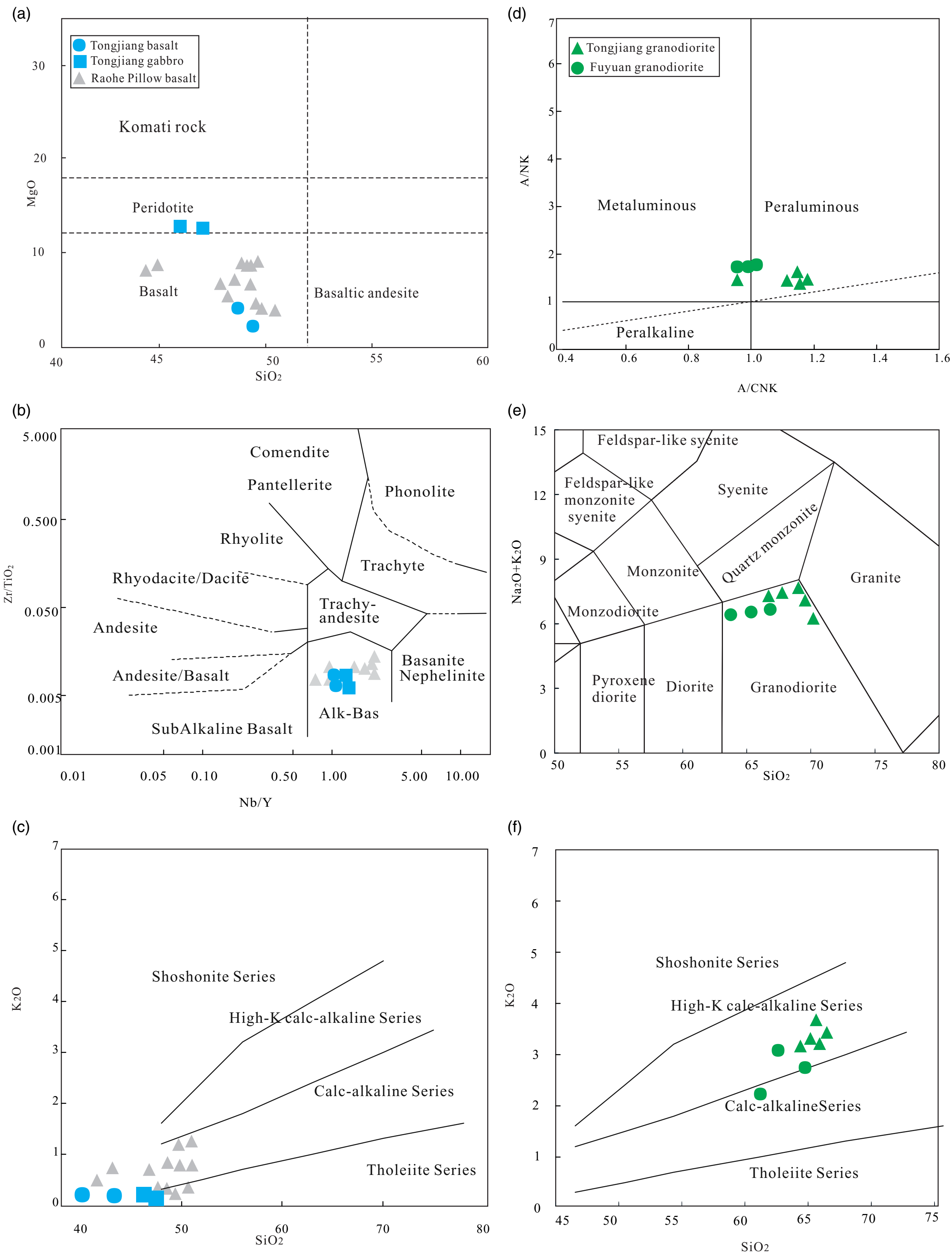

Figure 6. (Colour online) Classification diagrams of the intermediate-acidic intrusive rocks in the Tongjiang-Fuyuan area, NE China, MgO-SiO_2 (a; after Le Bas M J, 2000), Zr/TiO_2-Nb/Y (b; after Winchester and Floyd, 1976), K_2O-SiO_2 (c; after Maniar and Piccoli, 1989), A/NK-A/CNK (d; after Peccerillo & Taylor, 1976), Na_2O+K_2O-SiO_2 (e; after Irvine and Barragar, 1971), K_2O-SiO_2 (f; after Maniar & Piccoli, 1989). Data for the Raohe pillow basalts are cited from Zhou *et al.*, 2014 and Zeng *et al.*, 2018.

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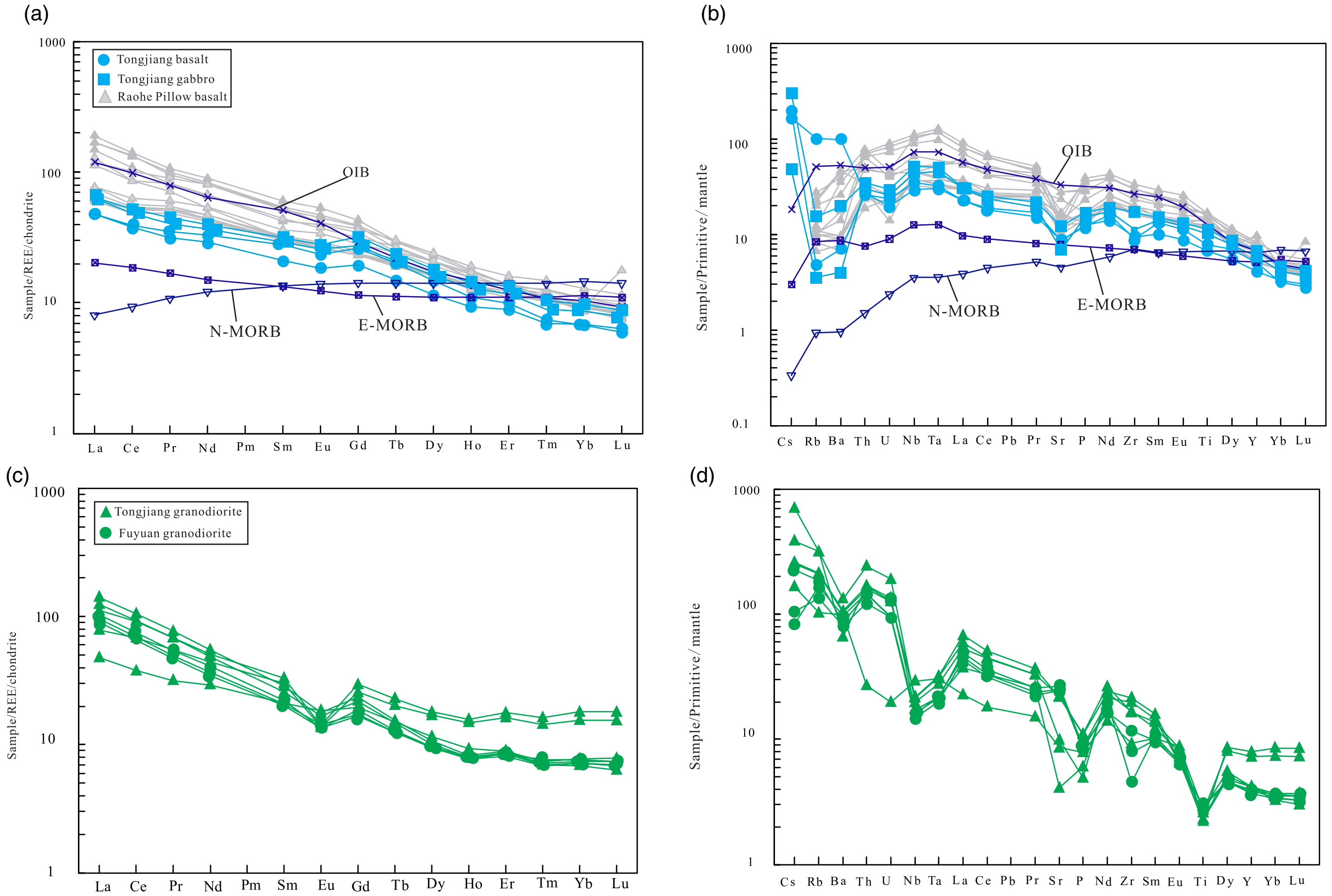

Figure 7. (Colour online) Chondrite normalized REE patterns (a and c, normalization values after Boynton, 1984) and primitive mantle normalized trace elements spider diagram (b and d, normalization values after Sun and McDonough, 1989) of Tongjiang-Fuyuan area, NE China. (a, b) basalts and gabbros. (c, d) granodiorites. Data for Raohe pillow basalts are cited from Zhou *et al.*, 2014 and Zeng *et al.*, 2018. OIB = ocean island basalt. E-MORB = Enriched mid-ocean ridge basalt. N-MORB = Normal mid-ocean ridge basalt.

Al_2O_3 (11.25–11.45 *wt* %), higher $Fe_2O_3^T$ (13.55–13.56 *wt*%) and lower Mg# [100Mg/ (Mg + Fe^{2+}) = 64–65] than those of the Tongjiang-Fuyuan basalts (Al_2O_3 = 11.25–11.45 *wt*%, $Fe_2O_3^T$ = 11.67–12.44 *wt*% and Mg# = 70–75). In the K_2O-SiO_2 diagram (Fig. 6c), the Tongjiang-Fuyuan gabbros and basalts fall into the tholeiite series and are similar to the Raohe pillow basalts in the geochemical characteristics.

Considering the chondrite-normalized REE patterns, the Tongjiang-Fuyuan basalts have relatively higher ΣREE (86.27–95.27 ppm) and LREE/HREE (4.55–5.21 ppm), and show strong LREE enrichment, with $(La/Yb)_N$ ratios ranging from 6.95 to 7.15. All the facts suggest the basalts have the geochemical characteristics of ocean island basalt (OIB) affinity (Fig. 7a). Similarly, the Tongjiang-Fuyuan gabbros (17TJ5-1A, B) also show the characteristics of the OIB-affinity (Fig. 7a).

In the primitive mantle (PM) normalized multi-element diagram (Fig. 7b), both the Tongjiang-Fuyuan gabbros and basalts show similar patterns to the present-day OIB-affinity, which are geochemically enriched in high field strength elements (HFSE; such as Nb, Ta, Hf and Zr) and relatively enriched in large-ion lithophile elements (LILE; e.g. Rb, Sr and Ba), together with the slightly negative Eu (Eu/Eu* = 0.87–0.91) anomalies (Fig. 7b).

4.b.2 Major and Trace elements in intermediate-acidic rocks (granodiorites)

Total 8 granodiorites were selected from Tongjiang-Fuyuan for whole-rock major and trace element analysis (Table S1).

The granodiorites have SiO_2 contents ranging from 65.18 to 71.06 *wt*%, Na_2O from 2.31 to 4.39 *wt*%, and K_2O from 2.26 to 3.98 *wt*%. Additionally, all the granodiorites are characterized by relatively low TiO_2 (0.45–0.60 *wt*%), Al_2O_3(14.26–15.87 *wt*%), $Fe_2O_3^T$ (3.19–4.28 *wt*%), MgO (1.02–2.31 *wt*%) in their geochemical compositions. In the A/NK vs. A/CNK diagram (Fig. 6d), they show quasi-aluminous to weakly peraluminous characteristics. In the Na_2O+K_2O-SiO_2 diagram (Fig. 6e), all the granodiorites fall in the granodiorite category. In the K_2O-SiO_2 diagram (Fig. 6f), the granodiorites show a transitional character of high K-medium K-Ca alkaline series.

Granodiorites have relatively high ΣREE (124.29–193.57 ppm) and show strongly enriched in LREE and extremely depleted in HREE (LREE/HREE = 5.51–12.03), with $(La/Yb)_N$ ratios ranging from 5.04 to18.38 (Fig. 7c). In the primitive mantle (PM) normalized multi-element diagram (Fig. 7d), all granodiorites show enrichment of LILEs (e.g. Rb, Ba and Sr) and depletion of HFSEs (such as Nb, Ta, Zr and Hf) and P, with negative Eu (Eu/Eu*=0.45–0.71) anomaly (Fig. 7d).

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5 Discussion

5.a Origin of the Tongjiang-Fuyuan Mesozoic magmatic rocks

5.a.1 Mafic rocks

The active elements of Rb, K, Ba and Sr are greatly affected by weathering in the process of metamorphism and alteration. On the contrary, the trace elements, e.g. Nb, Ta, Zr, Hf and Y, are inactive elements, and their contents will not change due to weathering, alteration and certain metasomatism. Moreover, its content does not vary with the degree of partial melting of mantle rocks and the degree of separation and crystallization of basaltic magma (Li, 1992; Janney and Castillo, 1996).

According to the analysis, the mafic rocks (basalts and gabbros) have high TiO_2, MgO and low Al_2O_3, CaO, P_2O_5 and K_2O. Furthermore, these samples exhibit an enrichment in LILEs (Rb, Sr and Ba), and they display right-inclined trend curves on both the trace element spider and rare earth element distribution diagrams, with ΣLREE/ΣHREE ratios ranging from 4.55 to 5.21. Additionally, there is no or slightly negative δEu anomalies (0.87–0.91). All of the analysed mafic rocks have relatively high Nb and Ta contents (Nb > 1.73 ppm, Ta > 0.14 ppm), distinguishing them from arc-related basalts. In the Ti/100-Zr-3*Y (Fig. 8a), Nb*2-Zr/4-Y (Fig. 8b) and Zr/Yb-Zr (Fig. 8c) diagrams, the Tongjiang-Fuyuan basalts and gabbros plot in the within-plate field, consistent with that of the previous reported Raohe pillow basalts. In addition, in the Th/Yb-Nb/Yb diagram (Fig. 8d), the Tongjiang-Fuyuan mafic rocks plot in the MORB-OIB array. Similarly, in the Nb/La-La/Yb (Fig. 8e) and Th/Nb-La/Yb (Fig. 8f) diagrams, they also plot in oceanic islands. In general, Tongjiang-Fuyuan mafic rocks (gabbros and basalts) are mainly formed in intraplate environments and the oceanic island-related tectonic setting. Therefore, it can be concluded that the Tongjiang-Fuyuan mafic rocks are fragments of oceanic island seamount (Fan *et al.*, 2021).

Compared with the Raohe Complex, the previous studies suggested that they were a set of mafic-ultramafic rocks composed of peridotite, pyroxene peridotite, hornblendite, cumulate gabbro, diabase and pillow basalt (Tian *et al.*, 2006; Bi *et al.*, 2016, 2017a; He *et al.*, 2016, 2017b; Cao *et al.*, 2019; Han *et al.*, 2022). Regarding the tectonic setting of these mafic-ultramafic rocks, Zhang and Zhou (2001) suggested that the basalts or pillow lavas developed in the Raohe area were formed in an oceanic environment and have the characteristics of OIB-affinity. Further, Zhou *et al.* (2014) regarded that the geochemical characteristics of pillow basalts exposed in the Raohe-Guanmen area are similar to those of OIB. As discussed before, the gabbros and basalts in the Tongjiang-Fuyuan area are also originated in intraplate environments and oceanic island-related tectonic settings, exhibiting the characteristics of OIB, which is consistent with characteristics of the Raohe ophiolitic basalts.

As is well known, the OIB-related magma is formed through contributions from different endmember components such as mantle plume, asthenosphere, lithospheric mantle (e.g. Xu, 2002; Zeng *et al.*, 2018). Besides, the OIB samples show much higher ratios of Ta/Hf, Th/Yb and Ta/Yb, and such strong enrichment in highly incompatible elements may indicate partial melting of a mantle source (Aldanmaz, 2002). Further, Mg# values (64–75, avg. = 67) of the mafic rocks in this study are lower than the primary magma range (68–75), indicating that the magma undergoes crystallization fractionation. The Tongjiang gabbros and basalts are high in MgO contents (3.68–19.72 *wt*%, 8.95 *wt*% on average), enriched in LREEs, and have 'Th' peaks on the normalized spider diagram of trace elements (Fig. 7b), implying that the source area may have the characteristics of a mantle plume (Hou *et al.*, 1996). A similar conclusion has been drawn for the OIB magmatic rocks in the Raohe area (e.g. Wang *et al.*, 2013).

In summary, the Tongjiang-Fuyuan gabbros and basalts in this study show obvious characteristics of OIB and generally relate to the mantle plume within the Palaeo-Pacific plate, consistent with the origin of the Raohe ophiolites (Zhou *et al.*, 2014).

5.a.2 Intermediate-acidic intrusive rocks

The granodiorites, collected from the Tongjiang-Fuyuan area, have relatively high SiO_2, Al_2O_3 and Na_2O+K_2O contents, and low MgO, Fe_2O_3 and CaO, indicating that the magma originated from partial melting of crustal materials (Barbarin, 1999). In addition, these samples are enriched in LREEs and LILEs, and deficient in HREEs and HFSEs, indicating that the magma was formed in the lower crust (Taylor & McLennan, 1985; Hofmann, 1988; Wu *et al.*, 2007; Zhang *et al.*, 2008).

The I-type granites were derived from the lower part of the continental crust at the margin of convergent plates, and the source rocks were probably mantle-derived underplating (Pitcher, 1993). In the FeO^T/MgO-(Zr+Nb+Y+Ce) diagram (Fig. 9a) and Ce-SiO_2 diagram (Fig. 9b), the granodiorites plot in the I-type granite field. In the Sr/Y-Y diagram (Fig. 9c) and $(La/Yb)_N$-Yb_N diagram (Fig. 9d), the granodiorites plot in the island-arc field. Further, in the Rb-Y+Nb diagram (Fig. 9e) and Nb-Y diagram (Fig. 9f), the granodiorites fall within the volcanic island-arc area. Therefore, we propose that the granodiorites from the Tongjiang-Fuyuan area are I-type granites, which may be formed in the lower crust and polluted by mantle-derived materials, and generally formed in a volcanic arc environment.

Besides, the REE distribution mode of the granodiorites in this area has a right-inclined trend, and are enriched in LILEs, and deficient in HFSEs, especially Ti, Nb and Ta. Trace element characteristics suggest that the granodiorite in the Tongjiang-Fuyuan area might originate from partial melting of the lower crust (Yu *et al.*, 2017). In conclusion, all the facts suggest that the granodiorites from Tongjiang-Fuyuan are island-arc magmatic rocks, and the magma may originate from the partial melting of the lower crust.

5.b Formation age of the Tongjiang-Fuyuan Mesozoic magmatic rocks

Field investigation and rock associations show that the predominant rock types in the Tongjiang-Fuyuan region are siliceous rocks, gabbro, metamorphic sandstone, basalt and so on, which are typical ophiolite mélange types and are present with granodiorite intrusion. The zircon LA-ICP-MS U-Pb data from a gabbroic sample (17TJ5-1) and three granodiorite samples (17TJ3, 17FY3 and 17FY9) yield the weighted mean age of 95 ± 2 Ma (Fig. 5b) and 93–95 Ma (Fig. 5a, c and d).

According to the previous studies, the Raohe Complex is considered as the subduction-accretionary product of the Palaeo-Pacific plate (Zhou *et al.*, 2014; Bi *et al.*, 2016, 2017a, 2017b; Ge *et al.*, 2016; Zhou *et al.*, 2017; Han *et al.*, 2022), and their formation ages of magmatic rocks (pillow basalt and gabbro) and intermediate acid intrusive rocks (granite) in the Raohe area are 167–168 Ma and 128–129 Ma, respectively (Cheng *et al.*, 2006; Zhou *et al.*, 2014; Zeng *et al.*, 2019; Han *et al.*, 2022). In this study, zircon age analysis shows that gabbro and granodiorite in the

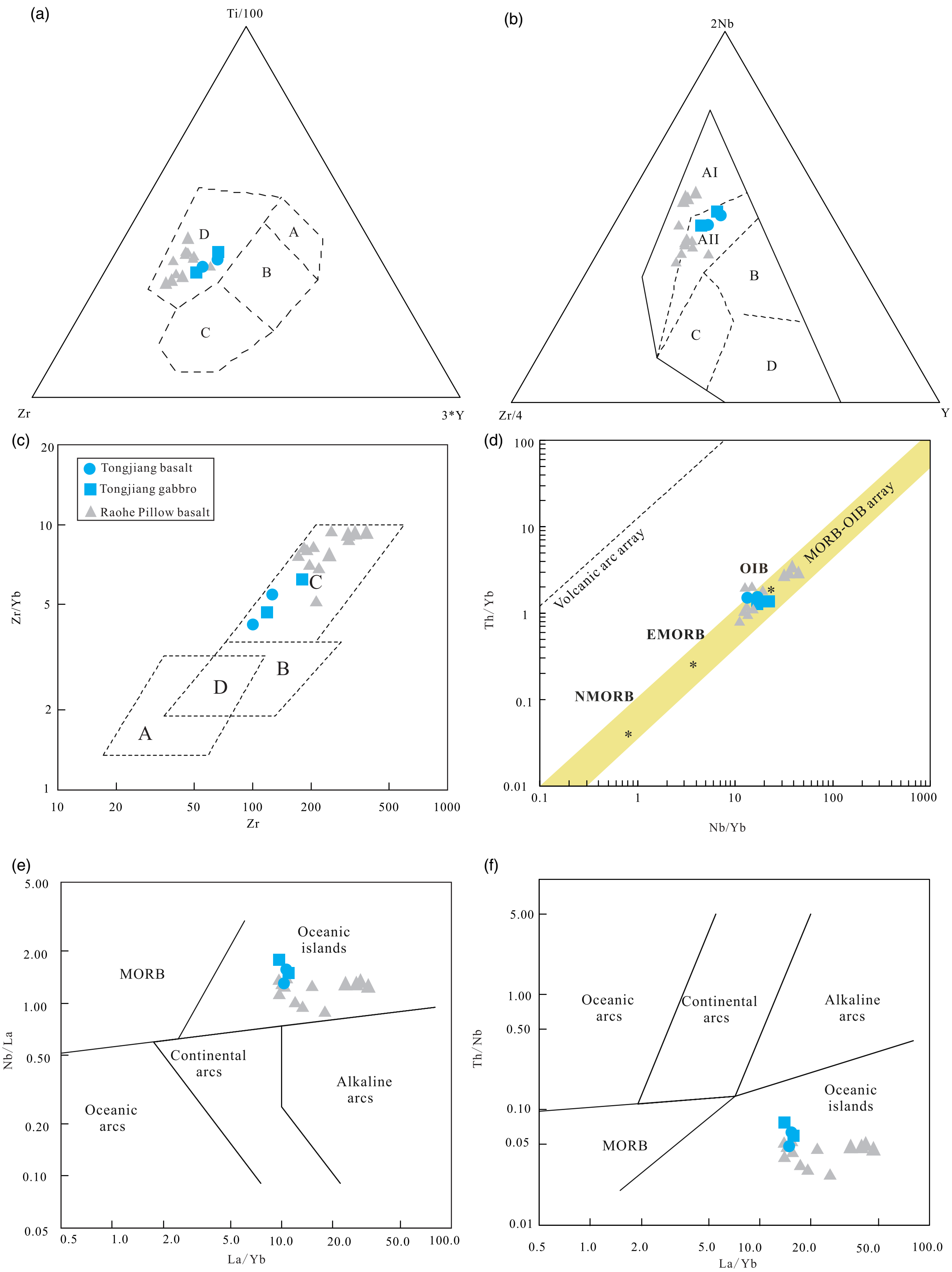

Figure 8. (Colour online) Discriminant diagrams of the Tongjiang gabbros and basalts, Ti/100-Zr-3*Y, 2Nb-Zr/4-Y(a,b; after Pearce & Cann, 1973), Zr/Yb-Zr, Th/Yb-Nb/Yb(c,d; after Pearce & Norry, 1979), Nb/La-La/Yb and Th/Nb-La/Yb(e,f; after Hollocher *et al.*, 2012). Data for Raohe pillow basalts are cited from Zhou *et al.*, 2014 and Zeng *et al.*, 2018. In the Ti/100-Zr-3*Y diagram, A-Island-arc tholeiite; B-Mid-Ocean ridge basalt/ Calc-alkali basalt/Island-arc tholeiite; C-Calc-alkali basalt; D-Within-plate basalt. In the 2Nb-Zr/4-Y diagram, AI-Within-plate alkali basalt; AII-Within-plate tholeiite; B-Plume-influenced mid-ocean ridge basalt; C-Within-plate tholeiite/ volcanic arc basalt; D-Volcanic arc basalt/ Normal mid-ocean ridge basalt. In the Zr/Yb-Zr diagram, A-Island-Arc Basalts; B-Mid-Ocean Ridge Basalt; C-Within-Plate Basalts; D-Mid-Ocean Ridge Basalt/ Island-Arc Basalt. OIB = Ocean Island basalt. E-MORB = Enriched mid-ocean ridge basalt. N-MORB = Normal mid-ocean ridge basalt.

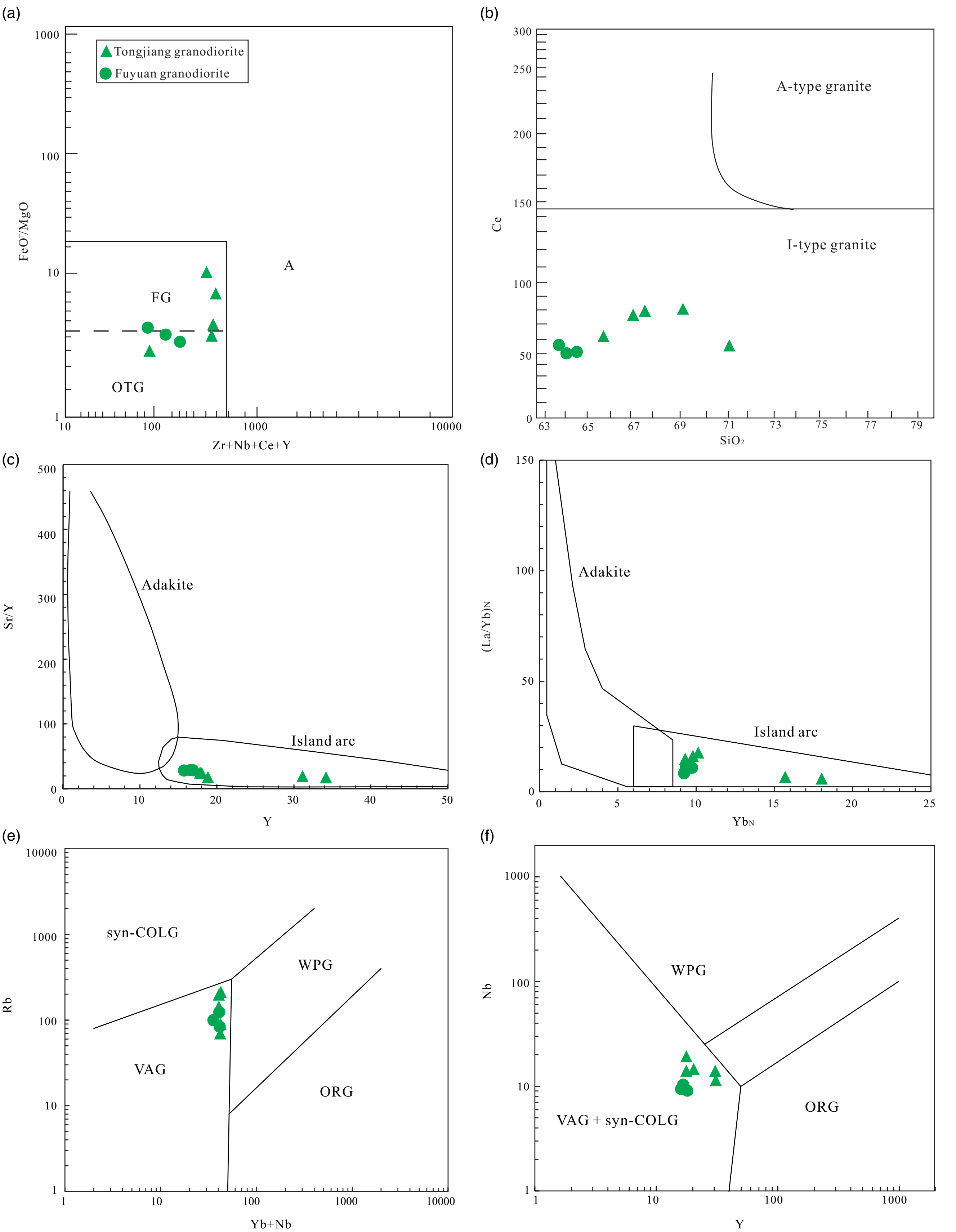

Figure 9. (Colour online) Discrimination diagrams of Tongjiang-Fuyuan granodiorites, FeO^T/MgO-(Zr+Nb+Y+Ce) (a; after Whalen *et al.*, 1987), Ce-SiO_2 (b; after Whalen *et al.*, 1987), Sr/Y-Y (c), $(La/Yb)_N$-Yb_N (d; after Hansen *et al*, 2002), Rb-Yb+Nb (e), Nb-Y (f; after Pearce *et al*, 1984). Syn-COLG = syn-collisional-granites; VAG = volcanic arc granites; ORG = oceanic ridge granites; WPG = within-plate granites.

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Tongjiang-Fuyuan area are 93–95 Ma. Therefore, the Tongjiang-Fuyuan mafic rocks and intermediate acid intrusive rocks resemble the Raohe Complex in nature but are younger in age, proving that they are the results of continuous subduction-accretion of the Palaeo-Pacific plate.

In addition, in the northeastern NE China, synchronous magmatism was also discovered by predecessors, for instance, the gabbros (96–101 Ma) in the eastern Jixi Basin (Zhu *et al.*, 2009), the diorites (97.5 Ma) in the Shuangyashan Basin (Zhang *et al.*, 2009), the olive trachyandesites (88 Ma) in the Songliao Basin (Wang *et al.*, 2009), the dacites (93.2 Ma) in the Suifenhe region (Ji *et al.*, 2007), the alkaline basalts (81.6 Ma) in Qujiatun of Liaodong (Wang *et al.*, 2006) and so on. All of the Late Cretaceous magmatic rocks were interpreted as the subduction-related magmatism, significantly suggesting the continuous subduction of the Palaeo-Pacific plate beneath the eastern margin of the JB till to Late Cretaceous (~80 Ma).

5.c Tectonic implications

5.c.1 Subduction and rollback of the Palaeo-Pacific plate

During the Mesozoic, the tectonic evolution of the Northeast Asian continental margin was mainly influenced by the subduction of the Palaeo-Pacific plate, which has been recognized by many geologists. A large number of magmatic belts were formed along the Northeast Asian continental margin along with the subduction of the Palaeo-Pacific plate (e.g. Wu *et al.*, 2007, 2011; Sun *et al.*, 2013, Xu *et al.*, 2013; 2015a; Wilde, 2015). Notably, a Mesozoic subduction-related magmatic belt with NNE-trending distribution is widely developed in the eastern continental margin of the Northeast Asia, extending from the Russian Far East, via NE China to the SW Japan (e.g. Isozaki, 1997; Lin *et al.*, 1998; Shao & Tang, 2015; Li *et al.*, 2020). In the NE China, these magmatic rocks are mainly distributed in the SXB (Such as Yichun area, Nenjiang area, and Tuanshanzi area; Zhang *et al*,.2007; Ji *et al.*, 2019; Pei *et al.*, 2008), in the JB (such as Boli area, Jixi area and Jiamusi area; Sun *et al.*, 2013, 2014) and in the NT (such as Raohe area, Yuejinshan area, Tongjiang-Fuyuan area; Yu *et al.*, 2013; Zhou *et al.*, 2014, 2015). A large number of geochronological and geochemical studies have been carried out on the magmatic rocks from the SXB, JB and NT and proposed that the formation age of various magmatic rocks is mainly Mesozoic, and their tectonic environment is closely related to the westward subduction of the Palaeo-Pacific plate (e.g. Cheng *et al.*, 2006; Liu *et al.*, 2008; Li *et al.*, 2011; Wu *et al.*, 2011; Zhang *et al.*, 2011; Yu *et al.*, 2013; Sun *et al*, 2013, 2015; Zhou *et al.*, 2014, 2015; Bi et al, 2015; Wang *et al.*, 2015, 2016; Yang *et al*, 2015; Zhu *et al*, 2015; Ge *et al*, 2016, 2017, 2019; Liu *et al*, 2017a, 2017b; Zeng *et al.*, 2017, 2018; Dong *et al*, 2019; Ji *et al*, 2019; Li *et al.*, 2020).

Meanwhile, previous studies show that in the late Early Cretaceous, the magmatic rocks in northeast China are mainly distributed in EB, XB, SXB, JB and NT. (e.g. Zhou *et al.*, 2014, 2015; Bi *et al*, 2015; Wang *et al.*, 2015, 2016; Yang *et al*, 2015; Zhu *et al*, 2015; Zeng *et al*, 2017, 2018; Liu *et al.*, 2019; Li *et al.*, 2020). The distribution characteristics of magmatic rocks during the Late Early Cretaceous period suggest that the Palaeo-Pacific plate began a wide range of low-angle subduction to Eurasia, and the magmatic range in NE China contracted to the east, suggesting the eastward drift of the Eurasia continent and the rollback of the Palaeo-Pacific subduction plate (e.g. Engebretson *et al.*, 1985; Maruyama *et al.*, 1997; Yu *et al.*, 2013; Sun *et al.*, 2013, 2014; Li *et al.*, 2020).

This research gathers various ages from the SXB to the NT based on other investigations on the chronology of magmatic activity in NE China (Fig. 10). The ages of the Mesozoic magmatic rocks in the SXB, JB, and NT areas reveal a west-to-east and old-to-young trend of magmatic activity in NE China, especially during the Cretaceous (145–190 Ma) (Fig. 10). Such a pattern, which indicates the tectonic rollback process of the Palaeo-Pacific plate, is perfectly consistent with the subduction rollback pattern revealed by previous researchers (Sun *et al.*, 2013, 2014; Li *et al.*, 2020).

5.c.2 Mesozoic tectonic evolution of the eastern NE China

The formation and evolution of the East Asian continental margin have involved complicated tectonomagmatic processes, including subduction, accretion and magmatism. Furthermore, the tectonic processes are characterized by the 'transform' nature or strike-slip displacement of individual terranes or blocks of different tectonic history (e.g. Kojima, 1989; Khanchuk, 2001, 2006; Kirilova, 2003; Kemkin, 2008; Isozaki *et al.*, 2010; Abrajevitch *et al.*, 2012; Maruyama *et al.*, 1997; Zonenshain *et al.*, 1990a; 2004b; Tazawa, 2004). The tectonic evolution and crustal formation in NE China are intimately linked to the interaction between the Palaeo-Pacific (so-called Izanagi) and Eurasian plates. Besides, the quasi-continuous magmatism in Late Cretaceous of the NE China (Fig. 10) indicates that the Palaeo-Pacific plate subduction was long-term active. An important implication from the present geochronological work is that during Late Cretaceous the Palaeo-Pacific plate motion probably changed from a parallel or sub-parallel (magmatic quiescence) to oblique (active arc magmatism) relative to the continental margin of Sikhote-Alin (Zhou *et al.*, 2014; Tang *et al.*, 2018; Han *et al.*, 2022). Late Cretaceous rapid sea-floor spreading at about 100 Ma (Larson & Pitman, 1972; Larson, 1991) induced highly active subduction and led to voluminous magmatism in the entire circum-Pacific areas (Jahn, 1974).

A large part of the Russian Far East is built up of accretionary complexes that formed along the convergent margin during the Cretaceous. A complex distribution of coeval complexes as well as juxtaposition of different age units indicates a considerable margin-parallel translation of terranes, which was represented by the sinistral strike-slip fault systems in the region, of which the Central Sikhote-Alin Fault is the most celebrated (e.g. Khanchuk, 2001, 2006; Otsuki, 1992; Sengor & Natal'in, 1996; Tazawa, 2004). A palaeomagnetic study led Abrajevitch *et al.* (2012) to hypothesize that the West Sakhalin Basin has moved from sub-equatorial latitude during the early Cretaceous to about 40°N by the late Cretaceous. Similarly, the NT of NE China was probably accreted to the Asian continental margin from low latitude during the late Mesozoic (Mizutani & Kojima, 1992).

As described earlier, the NT is mainly divided into Yuejinshan Complex and Raohe Complex (Bi *et al.*, 2015, 2016, 2017a, 2017b; Sun *et al.*, 2015a; Wilde, 2015; Zeng *et al.*, 2019; Li *et al.*, 2020; Xu *et al.*, 2020; Han *et al.*, 2022). Zircon chronology and geochemistry indicated that the Yuejinshan Complex mainly consisted of siliceous rocks, MORB and broken seamount fragments (Zhou *et al.*, 2014, 2018; Zhang *et al.*, 2020). The formation age of the complex is 210–180 Ma (Zhou *et al.*, 2014; Zeng *et al.*, 2018), while their protolith has a formation age of 310–270 Ma (Zhou & Li, 2017; Li *et al.*, 2020). Besides, the Yuejinshan Complex may have formed because of the westward subduction of the Palaeo-Pacific plate (Zhou *et al.*, 2014; Li *et al.*, 2020; Han *et al.*, 2022). The Raohe complex consists primarily of OIB, limestone, siliceous rock and

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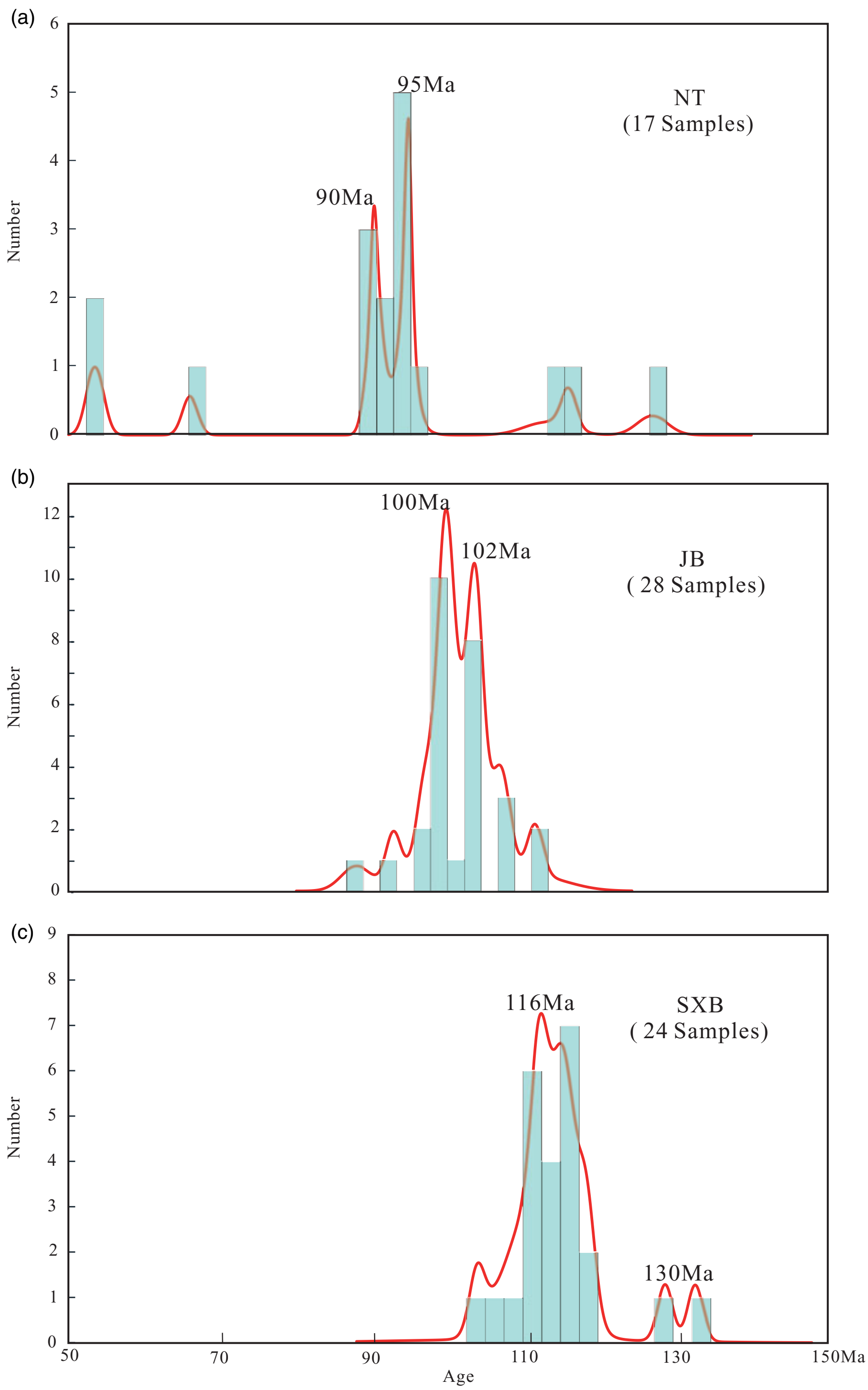

Figure 10. (Colour online) Age distributions of the Mesozoic subduction-related magmatic rocks in the NT (a), JB (b) and SXB (c).
Data source: Bi *et al.*, 2015; Ji *et al.*, 2019; Pei *et al.*, 2008; Sun *et al.*, 2013, Wu *et al.*, 2011; Yu *et al.*, 2013; 2014; Zhang *et al.*, 2007, 2011; Zhou *et al.*, 2014, 2015.

seamount fragments (Zeng *et al.*, 2019; Li *et al.*, 2020). It is emplaced between 133 Ma and 126 Ma (Zeng *et al.*, 2017, 2019), and its protoliths range in age is from 228 Ma to 116 Ma (Cheng *et al.*, 2006; Wang *et al.*, 2016; Li *et al.*, 2020). It is believed that the Raohe Complex is the product of the subduction of the Palaeo-Pacific plate (Zhou *et al.*, 2014; Zeng *et al.*, 2019; Li *et al.*, 2020; Han *et al.*, 2022). However, the Late Cretaceous rocks in NT have been scarcely studied, and their link with the Palaeo-Pacific plate subduction is poorly understood.

In this paper, we collect mafic rocks (gabbro, basalt) and intermediate-acidic intrusive rocks (granodiorite) through field investigation in the northern of the NT (Tongjiang-Fuyuan area). Zircon LA-ICP-MS U-Pb results show that the formation age of the Tongjiang-Fuyuan mafic rocks (gabbros) and intermediate-

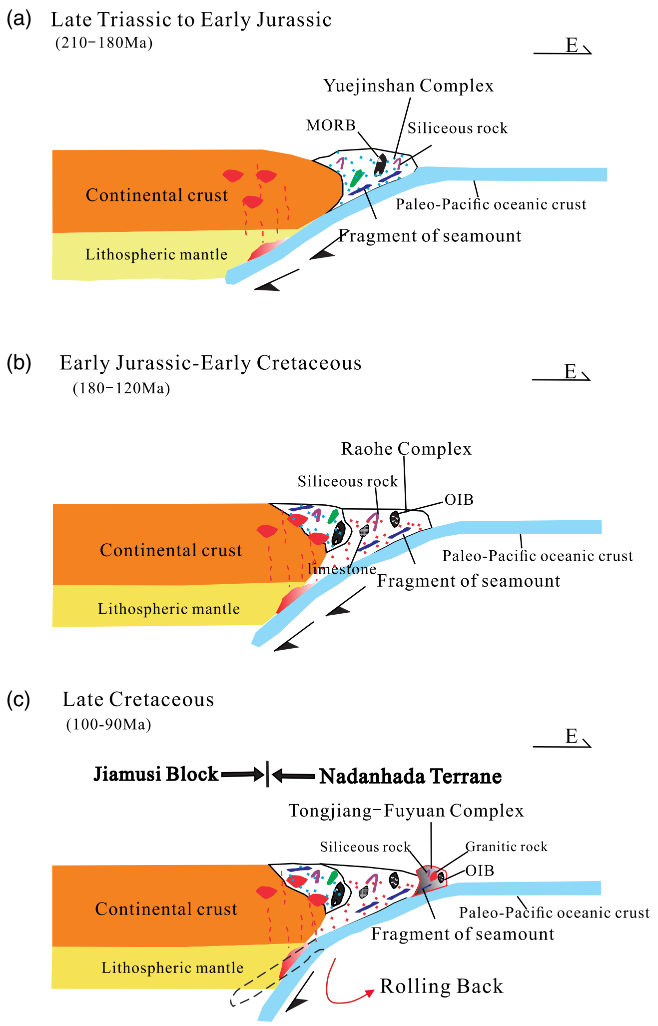

Figure 11. (Colour online) Map of the subduction-accretionary pattern of the Late Triassic-Late Cretaceous Palaeo-Pacific plate (NT as an example).

acidic intrusive rocks (granodiorites) is 93–95 Ma. Besides, the results of geochemistry show that mafic rocks (gabbros) and intermediate-acidic intrusive rocks (granodiorites) in the Tongjiang-Fuyuan area are similar to Raohe Complex in nature and younger in age; therefore, it is newly named Tongjiang-Fuyuan Complex in this paper. More significantly, all the Late Cretaceous magmatic rocks show the characteristics of the subduction-related magmatism, we thus interpreted that the Tongjiang-Fuyuan Complex is also the product of the continuous subduction of the Palaeo-Pacific plate.

Based on the above evidence and the combination of the previous studies, a tectonic model of subduction accretionary of the Late Triassic to Late Cretaceous Palaeo-Pacific plate in the NT is proposed, which can be divided into three stages. (1) Late Triassic to Early Jurassic (210–180 Ma) is the time when the onset of westward-directed accretion related to Pacific-Plate plate subduction. The Palaeo-Pacific plate subducted westward and formed the emplacement of the Yuejinshan Complex on the eastern margin of the JB (e.g. Zhou *et al.*, 2014, 2015; Zeng *et al.*, 2018; Li *et al.*, 2020) (Fig. 11a). (2) During the Early Jurassic to the Early Cretaceous (180–130 Ma), the Palaeo-Pacific plate with Early Jurassic seamounts collided with the East Asian continental margin and brought associated limestone, bedded chert and siliceous shale, and a large number of terrigenous debris and seamount fragments were tectonically mixed and accumulated in the trench to form the Raohe Complex (e.g. Zhou *et al.*, 2014; Li *et al.*, 2020; Han *et al.*, 2022) (Fig. 11b). (3) During the Late Cretaceous (90–100 Ma), the Palaeo-Pacific plate continued to subduct, and with the change of subduction angle, the Palaeo-Pacific plate began to roll back (Yu *et al.*, 2013; Sun *et al.*, 2014; Li *et al.*, 2020; Han *et al.*, 2022). Along with the accumulation of seamount fragments, siliceous rocks and OIB as well as the invasion of the granitic rocks, the Tongjiang-Fuyuan Complex was formed (Fig. 11c).

In short, these successive accretionary complexes, gradually younger to the east in the NE China, significantly indicate the subduction and rollback process of the Palaeo-Pacific plate (Zhang *et al.*, 2011; Sun *et al.*, 2013).

6. Conclusion

Based on the zircon LA-ICP-MS U-Pb ages and geochemical data presented above, we draw the following conclusions.

1. Field observation shows that the rock association in the Tongjiang-Fuyuan area resembled the ophiolite suite and was newly defined as the Tongjiang-Fuyuan Complex. Zircon U-Pb ages show the formation age of the Tongjiang-Fuyuan mafic rocks (gabbros), and intermediate-acidic intrusive rocks (granodiorites) are 93–95 Ma, that are slightly younger than the similar rock associations developed in the Raohe Complex.
2. As Mesozoic magmatic rocks in the Tongjiang-Fuyuan complex, mafic rocks (gabbros and basalts) show geochemical features similar to those of OIB, and their primitive magmas are generated from the mantle thermal plume. Meanwhile, intermediate-acidic intrusive rocks (granodiorites) are I-type granites, forming in a magmatic arc setting, and probably originated from the partial melting of the lower crust.
3. Combined with the coeval igneous rock associations and regional tectonic evolution, we conclude that the Late Cretaceous magmatic rocks in the Tongjiang-Fuyuan area are the result of continuous subduction of the Palaeo-Pacific plate beneath the eastern margin of the JB. Furthermore, the distribution of magmatic rocks, which are gradually younger to the east, significantly reflects the rollback of the subducted Palaeo-Pacific plate.

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References

Abrajevitch A, Zyabrev S, Didenko AN and Kodama K (2012) Paleomagnetsim of the West Sakhalin Basin: evidence for northward displacement during the Cretaceous. *Geophysical Journal International* **190**, 1439–54.

Aldanmaz E (2002) Mantle source characteristics of alkali basalts and basanites in an extensional intracontinental plate setting, western Anatolia, Turkey: implications for multi-stage melting. *International Geology Review* **44**, 440–57.

Andersen T (2002) Correction of common lead in U–Pb analyses that do not report ^{204}Pb. *Chemical Geology* **192**, 59–79.

Baines AG, Cheadle MJ, John BE, Grimes CB, Schwartz JJ and Wooden JL (2009) SHRIMP Pb/U zircon ages constrain gabbroic crustal accretion at Atlantis bank on the ultraslow-spreading Southwest Indian Ridge. *Earth and Planetary Science Letters* **287**, 540–50.

Barbarin B (1999) A review of the relationships between granitoid types, their origins and their geodynamic environments. *Lithos* **46**, 605–26.

Bi JH, Ge WC, Yang H, Wang ZH, Dong Y, Liu XW and Ji Z (2017a) Age, petrogenesis, and tectonic setting of the Permian bimodal volcanic rocks in the eastern Jiamusi Massif, NE China. *Journal of Asian Earth Sciences* **134**, 160–75.

Bi JH, Ge WC, Yang H, Wang ZH, Tian DX, Liu XW, Xu WL and Xing DH (2017b) Geochemistry of MORB and OIB in the Yuejinshan Complex, NE China: implications for petrogenesis and tectonic setting. *Journal of Asian Earth Sciences* **145**, 475–93.

Bi JH, Ge WC, Yang H, Wang ZH, Xu WL, Yang JH, Xing DH and Chen HJ (2016) Geochronology and geochemistry of late Carboniferous–middle Permian I- and A-type granites and gabbro–diorites in the eastern Jiamusi Massif, NE China: implications for petrogenesis and tectonic setting. *Lithos* **266–267**, 213–32.

Bi JH, Ge WC, Yang H, Zhao GC, Xu WL and Wang ZH (2015) Geochronology, geochemistry, and zircon Hf isotopes of the Dongfanghong gabbroic complex at the eastern margin of the Jiamusi massif, NE China: Petrogenesis and tectonic implications. *Lithos* **234–235**, 27–46.

Boynton WV (1984) Cosmochemistry of the rare earth elements: meteorite studies. *Rare Earth Element Geochemistry* **2**, 63–114.

Cao JL, Zhou JB and Li L (2019) The tectonic evolution of the ChangChun-Yanji suture zone: constraints of zircon U-Pb ages of the Yantongshan accretionary complex (NE China). *Journal of Asian Earth Sciences* **194**, 104110.

Chen D, Zhang F, Chen H, Dilek Y, Yang S, Meng Q and Yang C (2015) Structural architecture and tectonic evolution of the Fang Zheng sedimentary basin (NE China), and implications for the kinematics of the Tan-Lu fault zone. *Journal of Asian Earth Sciences* **106**, 34–48.

Cheng RY, Wu, FY, Ge WC, Sun DY, Liu XB and Yang JH (2006) Emplacement age of the Raohe complex in eastern Heilongjiang Province and the tectonic evolution of the eastern part of northeastern China. *Acta Petrologica Sinica* **22**, 353–76. (in Chinese with English abstract)

Coleman RG (1977) *Ophiolites*. New York: Springer, pp. 1–110.

Dewey JF and Bird JM (1971) The origin and emplacement of the ophiolite suite: Appalachian ophiolites in Newfoundland. *Journal of Geophysical Research* **76**, 3179–206.

Dilek Y (2003) Ophiolite concept and its evolution. *Geological Society of America* **373**, 1–16.

Dilek Y and Furnes H (2011) Ophiolite genesis and global tectonics: geochemical and tectonic fingerprinting of ancient oceanic lithosphere. *GSA Bulletin* **123**, 387–411.

Dilek Y, Furnes H and Shallo M (2007) Suprasubduction zone ophiolite formation along the periphery of Mesozoic Gondwana. *Gondwana Research* **11**, 453–75.

Dong Y, Ge WC, Yang H, Liu XW, Bi JH, Ji Z and Xu WL (2019) Geochemical and SIMS U-Pb rutile and LA–ICP–MS U-Pb zircon geochronological evidence of the tectonic evolution of the Mudanjiang Ocean from amphibolites of the Heilongjiang Complex, NE China. *Gondwana Research* **69**, 25–44.

Engebretson DC, Cox A and Gordon RG (1985) Relative motions between oceanic and continental plates in the Pacific basins. *Geological Society of America*, Special Paper **206**, 1–59.

Fan JJ, Li C, Niu YL, Xie CM and Wang M (2021) Identification method and geological significance of intraplate Ocean Island-Seamount fragments in the Orogenic Belt. *Earth Science* **46**, 381–404. (in Chinese with English abstract)

Feng ZQ, Liu YJ, Li L, Jin W, Jiang LW, Li WM, Wen QB and Zhao YL (2019) Geochemical and geochronological constraints on the tectonic setting of the Xinlin ophiolite, northern Great Xing'an Range, NE China. *Lithos* **326–327**, 213–239.

Furnes H and Dilek Y (2017) Geochemical characterization and petrogenesis of intermediate to silicic rocks in ophiolites: a global synthesis. *Earth-Science Reviews* **166**, 1–37.

Ge MH, Zhang JJ, Li L and Liu K (2019) Ages and geochemistry of early Jurassic granitoids in the Lesser Xing'an–Zhangguangcai Ranges, NE China: Petrogenesis and tectonic implications. *Lithosphere* **11**, 804–20.

Ge MH, Zhang JJ, Liu K, Ling, YY, Wang M and Wang JM (2016) Geochemistry and geochronology of the blueschist in the Heilongjiang Complex and its implications in the late Paleozoic tectonics of eastern NE China. *Lithos* **261**, 232–49.

Ge MH, Zhang JJ, Liu K, Ling, YY, Wang M and Wang JM (2017) Geochronology and geochemistry of the Heilongjiang Complex and the granitoid from the Lesser Xing'an-Zhangguangcai Range: implications for the late Paleozoic-Mesozoic tectonics of eastern NE China. *Tectonophysics* **717**, 565–84.

Geological and Mineral Bureau of Heilongjiang Province (1993) *The Regional Geological Record of Heilongjiang Province*. Beijing: Geological Press, pp. 1–734.

Ge WC, Chen JS, Yang H, Zhao GC, Zhang YL and Tian DX (2015) Tectonic implications of new zircon U–Pb ages for the Xinghuadukou Complex, Erguna Massif, northern Great Xing'an Range, NE China. *Journal of Asian Earth Sciences*, **106**, 169–85.

Grimes CB, John BE, Cheadle MJ, Mazdab FK, Wooden JL, Swapp S and Schwartz JJ (2009) On the occurrence, trace element geochemistry, and crystallization history of zircon from in situ ocean lithosphere. *Contributions to Mineralogy and Petrology* **158**, 757–83.

Han WZF, Liu Y, Zhou JXL, Zhang T and Fan X (2022) Geochronological and geochemical constraints from the Yuejinshan Complex and its implications for the tectonic evolution of Northeast China. *Acta Petrologica Sinica* **38**, 2489–509. (in Chinese with English abstract)

Hansen J, Skjerlie KP, Pedersen RB and De La Rosa J (2002) Crustal melting in the lower parts of island arcs: an example from the Bremanger Granitoid Complex, west Norwegian Caledonides. *Contributions Mineralogy Petrology* **143**, 316–35.

He S, Sun XM, Zhang XQ, Wan K, Zheng H and Li DZ (2016) Geological and geochemical characteristics of Raohe pillow basalts of Heilongjiang Province and its tectonic implication. *World Geology* **35**, 942–54. (in Chinese with English abstract)

Hofmann AW (1988) Chemical differentiation of the Earth: the Relationship between mantle, continental crust, and oceanic crust. *Earth and Planetary Science Letters* **90**, 297–314.

Hollocher K, Robinson P, Walsh E and Roberts D (2012) Geochemistry of amphibolite-facies volcanics and gabbros of the Støren Nappe in extensions west and southwest of Trondheim, Western Gneiss Region, Norway: a key to correlations and paleotectonic settings. *American Journal of Science* **312**, 357–416.

Hou ZQ, Mo XX, Zhu QW and Sheng SY (1996) Mantle plume in the Sanjiang Paleo-Tethyan lithosphere: evidence from mid-ocean ridge basalts. *Acta Geoscientica Sinica* **17**, 343–61. (in Chinese with English abstract)

Irvine TN and Baragar WRA (1971) A guide to the chemical classification of the common volcanic rocks. *Canadian Journal of Earth Sciences*, **8**, 523–48.

Isozaki Y (1997) Jurassic accretion tectonics of Japan. *Island Arc* **6**, 25–51.

Isozaki Y, Aoki K, Nakama T and Yanai S (2010) New insight into a subduction related orogeny: a reappraisal of the geotectonic framework and evolution of the Japanese Islands. *Gondwana Research* **18**, 82–105.

Jahn BM (1974) Mesozoic thermal events in southeast China. *Nature* **248**, 480–83.

Janney PE and Castillo PR (1996) Basalts from the central pacific Basin: evidence for the origin of Cretaceous igneous complexes in the Jurassic Western Pacific. *Journal of Geophysical Research: Solid Earth* **101**, 2875–93.

Ji WQ, Xu WL, Yang DB, Pei PF, Jin K and Liu XM (2007) Chronology and geochemistry of volcanic rocks in the cretaceous Suifenhe formation in Eastern Heilongjiang, China. *Acta Geologica Sinica* **81**, 266–77.

Ji Z, Meng QA, Wan CB, Ge WC, Yang H, Zhang YL, Dong Y and Jin X (2019) Early Cretaceous adakitic lavas and a-type rhyolites in the Songliao Basin, NE China: implications for the mechanism of lithospheric extension. *Gondwana Research* **71**, 28–48.

Jian P, Liu DY, Zhang Q, Zhang FQ, Shi YR, Shi GH, Zhang LQ and Tao H (2003) SHRIMP dating of ophiolite and leucocratic rocks within ophiolite. *Earth Science Frontiers* **10**, 439–56. (in Chinese with English abstract)

Kang BX, Zhang HR, Liu CS, Cui XS and Zhang SF (1990) Raohe ophiolite and its geological significance in Nadanhadaling. *Geology of Heilongjiang* **1**, 3–18. (in Chinese with English abstract)

Kemkin IV (2008) Structure of terranes in a Jurassic accretionary prism in the Sikhote-Alin-Amur area: implications for the Jurassic geodynamic history of the Asian eastern margin. *Russian Geology and Geophysics* **49**, 759–70.

Khanchuk AI (2001) Pre-neogene tectonics of the sea-of-Japan region: a view from the Russian side. *Earth Science (Chikyu Kagaku)* **55**, 275–91.

Khanchuk AI (2006) Geodynamics, magmatism, and metallogeny of Eastern Russia. Book 1. Dal'nauka, Vladivostok, 572 pp, (in Russian).

Kirilova GL (2003) Cretaceous tectonics and geological environments in East Russia. *Asian Earth Sciences* **21**, 967–77.

Koglin N, Kostopoulos D and Reischmann T (2009) The Lesvos mafic–ultramafic complex, Greece: ophiolite or incipient rift? *Lithos* **108**, 243–61.

Kojima S (1989) Mesozoic terrane accretion in Northeast China, Sikhote-Alin, and Japan Regions. *Paleogeography, Palaeoclimatology, Palaeoecology*, **69**, 213–32.

Kojima S and Mizutani S (1987) Triassic and Jurassic Radiolaria from the Nadanhada range, Northeast China. *Transactions and Proceedings of the Paleontological Society of Japan* **148**, 256–75.

Larson RL (1991) Latest pulse of Earth: evidence for a mid-Cretaceous superplume. *Geology* **19**, 547–50.

Larson RL and Pitman WC (1972) World-wide correlation of Mesozoic magnetic anomalies, and its implications. *Geological Society of America Bulletin* **83**, 3645–62.

Le Bas MJ (2000) IUGS reclassification of the high-Mg and picritic volcanic rocks. *Journal of Petrology* **41**, 1467–70.

Li CN (1992) *Microelement Petrology of Igneous Rocks*. Wuhan: Geological Press, pp. 1–75.

Li CY (1980) A preliminary study of plate tectonics of China. *Acta Geoscientica Sinica* **2**, 19–22. (in Chinese with English abstract)

Li JY (2006) Permian geodynamic setting of Northeast China and adjacent regions: closure of the Paleo-Asian Ocean and subduction of the Paleo-Pacific Plate. *Journal of Asian Earth Sciences* **26**, 207–24.

Li WK, Han JX, Zhang SX and Meng FY (1979) The main characteristics of the upper paleozoic stratigraphy at the north Nadanhada Range, Heilongjiang Province, China. *Acta Geoscientica Sinica* **1**, 104–120+141–142. (in Chinese with English abstract)

Li WM, Liu YJ, Zhao YL, Feng ZQ, Zhou JP, Wen QB, Liang CY and Zhang D (2020) Tectonic evolution of the Jiamusi Block, NE China. *Acta Petrologica Sinica* **36**, 665–84. (in Chinese with English abstract)

Li WM, Takasu A, Liu YJ, Genser J, Zhao YL, Han G and Guo XZ (2011) U-Pb and 40Ar/39Ar age constrains on protolish and high-P/T type metamorphism of the Heilongjiang Complex in the Jiamusi Massif, NE China. *Journal of Mineralogical and Petrological Sciences* **106**, 326–31.

Lin Q, Ge WC, Sun DY, Wu FY, Yuan ZK, Min GD, Chen MZ, Li, MY, Quan ZC and Yi CX (1998) Tectonic significance of Mesozoic volcanic rocks in northeastern China. *Chinese Journal of Geology (Scientia Geologica Sinica)* **33**, 129–39. (in Chinese with English abstract)

Liu JF, Chi XG, Dong CY, Zhao Z, Li GR and Zhao YD (2008) Discovery of early paleozoic granites in the eastern Xiao Hinggan Mountains, Northeastern China, and their tectonic significance. *Geological Bulletin of China* **27**, 534–44. (in Chinese with English abstract)

Liu K, Zhang JJ, Wilde SA, Zhou JB, Wang M, Ge MH, Wang JM and Ling YY (2017a) Initial subduction of the Paleo-Pacific Oceanic plate in NE China: constraints from whole-rock geochemistry and zircon U-Pb and Lu-Hf isotopes of the Khanka Lake granitoid. *Lithos* **274–275**, 254–70.

Liu YJ, Feng ZQ, Jiang LW, Jin W, Li WM, Guan QB, Wen QB and Liang CY (2019) Ophiolite in the eastern Central Asian Orogenic Belt, NE China. *Acta Petrologica Sinica*, **35**, 3017–47. (in Chinese with English abstract).

Liu YJ, Li WM, Feng ZQ, Wen QB, Neubauer F and Liang CY (2017b) A review of the Paleozoic tectonics in the eastern part of the Central Asian Orogenic Belt. *Gondwana Research* **43**, 123–48.

Liu YJ, Li WM, Ma YF, Feng ZQ, Guan QB, Li SZ, Chen ZX, Liang CY and Wen QB (2021) An orocline in the eastern Central Asian Orogenic Belt. *Earth-science Reviews* **221**, 103808.

Maniar PD and Piccoli PM (1989) Tectonic discrimination of granitoids. *Geological Society of American Bulletin* **101**, 635–43.

Maruyama S, Isozaki Y, Kimura G and Terabayashi M (1997) Paleogeographic maps of the Japanese Islands: Plate tectonic synthesis from 750Ma to the present. *The Island Arc*, **6**, 121–42.

Meng FC, Liu JQ, Cui Y, Gao JL, Liu X and Tong Y (2014) Mesozoic tectonic regimes transition in the Northeast China: Constriants from temporal-spatial distribution and associations of volcanic rocks. *Acta Petrologica Sinica* **30**, 3569–86 (in Chinese with English abstract)

Mizutani S and Kojima S (1992) Mesozoic radiolarian biostratigraphy of Japan and collage tectonics along the eastern continental margin of Asia. *Palaeogeography, Palaeoclimatology, Palaeoecology* **96**, 3–22.

Mizutani SJ, Shao JA and Zhang QL (1989) The Nadanhada terrane in Relation to Mesozoic Tectonics on Continental Margins of East Asia. *Acta Geologica Sinica (English Edition)* **3**, 204–16. (in Chinese with English abstract)

Otsuki K (1992) Oblique subduction, collision of microcontinents and subduction of oceanic ridge: their implications on the Cretaceous tectonics of Japan. *Island Arc* **1**, 51–63.

Pearce JA and Cann JR (1973) Tectonic setting of basic volcanic rocks determined using trace element analyses. *Earth and Planetary Science Letters* **19**, 290–300.

Pearce JA, Harris NBW and Tindle AG (1984) Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology* **25**, 956–83.

Pearce JA and Norry MJ (1979) Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks. *Contributions to Mineralogy Petrology* **69**, 33–47.

Peccerillo A and Taylor AR (1976) Geochemistry of Eocene Calc-alkaline volcanic rocks from the Kastamonu area, Northern Turkey. *Contributions to Mineralogy and Petrology* **58**, 63–81.

Pei FP, Xu WL, Yang DB, Ji WQ, Yu Y and Zhang XZ (2008) Mesozoic volcanic rocks in the Southern Songliao Basin: Zircon U-Pb ages and their constraints on the nature of Basin Basement. *Earth Science* **5**, 603–17 (in Chinese with English abstract).

Pitcher WS (1993) *The Nature and Origin of Granite*. Glasgow: Blackie Academy, 1–387.

Ren JS, Jiang CF, Zhang ZK and Qin DY (1980) *Geotectonic Evolution of China*. Beijing: Geological Press, pp. 1–218.

Ren SM, Zhu RX, Qiu, HJ, Zhou JB and Deng CL (2015) Paleomagnetic study on middle Jurassic lavas of Heilongjiang Province, NE China and its tectonic implications. *Chinese Journal of Geophysics-Chinese Edition* **58**, 1269–83. (in Chinese with English abstract)

Sengor AMC and Natal'in BA (1996) Turkic-type orogeny and its role in the making of the continental crust. *Annual Review of Earth and Planetary Sciences* **24**, 263–337.

Shao JA and Tang KD (2015) Research on the Mesozoic Ocean-continent transitional zone in Northeast Asia and its implications. *Acta Petrologica Sinica* **31**, 3147–54. (in Chinese with English abstract)

Shi RD (2005) Comment on the progress in problems on the ophiolite study. *Geological Review* **51**, 681–93. (in Chinese with English abstract)

Sun MD (2013) Late Mesozoic magmatism and its tectonic implication for the Jiamusi Block and adjacent areas of NE China. Ph. D. Dissertation. *Hangzhou: Zhejiang University*. (in Chinese with English summary)

Sun MD, Chen HL, Zhang FQ, Wilde SA, Minna A, Lin XB and Yang SF (2014) Cretaceous provenance change in the Hegang Basin and its connection with the Songliao Basin, NE China: evidence for lithospheric extension driven by Paleo-Pacific roll-back. *Geological Society, London, Special Publications* **413**, 91–117.

Sun MD, Xu YG, Wilde SA, Chen HL and Yang SF (2015a) The Permian Dongfanghong Island-arc gabbro of the Wandashan Orogen, NE China: implications for Paleo-Pacific Subduction. *Tectonophysics*, **659**, 122–36.

Sun MD, Xu YG, Wilde SA and Chen HL (2015b) The provenance of Cretaceous trench slope sediments from the Mesozoic Wandashan orogen, NE China: implications for determining ancient drainage systems and tectonics of the Paleo-Pacific. *Tectonics* **34**, 1269–89.

Sun SS and McDonough WF (1989) Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. Magmatism in the Ocean Basins. *Geological Society London Special Publications* **42**, 313–45.

Tang J, Xu W L, Wang F and Ge W C. (2018) Subduction history of the Paleo-Pacific slab beneath Eurasian continent: Mesozoic-Paleogene magmatic records in Northeast Asia. *Science China Earth Sciences*, **61**, 527–59. (in Chinese with English abstract)

Tang KD, Wang Y, He GQ and Shan, JA (1995) Continental-margin structure of Northeast China and its adjacent areas. *Acta Geologica Sinica(English Edition)* **69**, 16–30. (in Chinese with English abstract)

Taylor SR and McLennan SM (1985) *The Continental Crust: Its Composition and Evolution*. Oxford: Blackwell Scientific Publication, pp. 1–132.

Tazawa J (2004) The strike-slip model: a synthesis on the origin and tectonic evolution of the Japanese Islands. *The Journal of the Geological Society of Japan* **110**, 503–17.

Tian DJ, Zhou JB, Zheng CQ and Liu JH (2006) Geochemical characteristics and tectonics mechanism of the meta-basic rocks for ophiolite Complex in Wandashan Orogenic Belt. *Mineralogy And Petrology* **26**, 64–70. (in Chinese with English abstract)

Wang JY, Yang YC, Huang YW, Hou YS, Tang Y and Zhang GB (2016) Formation ages and tectonic significance of ophiolites in Wandashan terrane of eastern Heilongjiang. *Journal of Earth Sciences and Environment* **38**, 182–95. (in Chinese with English abstract)

Wang PJ, Gao YE, Ren YG, Liu WZ and Zhang JG (2009) 40Ar/39Ar age and geochemical features of mugearite from the Oingshankou Formation; Significances for basin formation, hydrocarbon generation and petroleum accumulation of the Songliao Basin in Cretaceous. *Acta Petrologica Sinica* **25**(5), 1178–1190.

Wang W, Xu WL, Ji WQ, Yang DB and Pei FP (2006) Late Mesozoic and Paleogene basalts and deep-derived xenocrysts in eastern Liaodong province China: constraints on nature of lithospheric mantle. *Geological Journal of China Universities* **12**, 30–40. (in Chinese with English abstract)

Wang XZ (1959) Marine Mesozoic strata in the Mesozoic fold belt of Raohe area, NE China. *Chinese Journal of Geology (Scientia Geologica Sinica)* **2**, 50–51. (in Chinese with English abstract)

Wang ZH, Ge WC, Yang H, Zhang YL, Bi JH, Tian DX and Xu WL (2015) Middle Jurassic oceanic island igneous rocks of the Raohe accretionary Complex, northeastern China: petrogenesis and tectonic implications. *Journal of Asian Earth Sciences* **111**, 120–37.

Whalen JB, Currie KL and Chappell BW (1987) A-type granites: geochemical characteristics and discrimination and petrogenesis. *Contributions to Mineralogy and Petrology*, **95**, 420–36.

Wilde SA (2015) Final amalgamation of the central Asian Orogenic Belt in NE China: Paleo-Asian Ocean closure versus Paleo-Pacific plate subduction: a review of the evidence. *Tectonophysics* **662**, 345–62.

Wilde SA, Wu FY and Zhao GC (2010) The Khanka Block, NE China, and its significance for the evolution of the Central Asian Orogenic Belt and continental accretion. *Geological Society, London, Special Publications*, **338**, 117–37.

Winchester JA and Floyd PA (1976) Geochemical magma type discrimination: application to altered and metamorphosed basic igneous rocks. *Earth and Planetary Science Letters* **28**, 459–69.

Wu FY, Jahn BM, Wilde SA and Sun DY (2000) Phanerozoic crustal growth: U-Pb and Sr-Nd isotopic evidence from the granites in northeastern China. *Tectonophysics* **328**, 89–113.

Wu FY, Li XH, Yang JH and Zheng YF (2007) Discussions on the petrogenesis of granites. *Acta Petrologica Sinica* **23**, 1217–38. (in Chinese with English abstract)

Wu FY, Sun DY, Ge WC, Zhang, YB, Grant ML, Wilde SA and Jahn BM (2011) Geochronology of the phanerozoic granitoid in Northeastern China. *Journal of Asian Earth Sciences* **41**, 1–30.

Xiao WJ, Windley BF, Allen MB and Han C (2013) Paleozoic multiple accretionary and collisional tectonics of the Chinese Tianshan orogenic collage, *Gondwana Research* **23**, 1316–41.

Xiao WJ, Windley BF, Huang BC, Han CM, Yuan C, Chen HL, Sun M, Sun S and Li, LJ (2009b) End-Permian to mid-Triassic termination of the accretionary processes of the southern Altaids: implications for the geodynamic evolution, Phanerozoic continental growth, and metallogeny of Central Asia. *International Journal of Earth Sciences* **98**, 1219–20.

Xiao WJ, Windley BF, Yuan C, Sun M, Han CM, Lin SF, Chen HL, Yan QR, Liu DY, Qin KZ, Li J L and Sun S (2009a) Paleozoic multiple subduction-accretion processes of the southern Altaids. *American Journal of Science* **309**, 221–70.

Xu WL, Pei FP, Wang F, Meng E, Ji WQ, Yang DB and Wang W (2013) Spatial-temporal relationships of Mesozoic volcanic rocks in NE China: constraints on tectonic overprinting and transformations between multiple tectonic systems. *Journal of Asian Earth Sciences* **74**, 167–93.

Xu YG (2002) Mantle plumes, large igneous provinces, and their geological consequences. Earth Science Frontiers 9, 341–53. (in Chinese with English abstract)

Xu ZJ, Kong JT, Cheng RY and Zhou JB (2020) The subduction of the Paleo-Pacific Plate to the Jiamusi Block: evidence from the Early Mesozoic sedimentary rocks of the eastern Jiamusi Block. *Island Arc* **29**, e12364.

Yang H, Ge WC, Zhao GC, Yu JJ and Zhang YL (2015) Early Permian-Late Triassic granitic magmatism in the Jiamusi-Khanka Massif, eastern segment of the central Asian Orogenic Belt and its implications. *Gondwana Research* **27**, 1509–33.

Yang JZ, Qiu HJ, Sun JP and Zhang XZ (1998) Yuejinshan complex and its tectonic significance. *Journal Of Jilin University (Earth Science Edition)* **28**, 380–5. (in Chinese with English abstract)

Yu JJ, Hou XG, Ge WC, Zhang YL and Liu JC (2013) Magma mixing genesis of the Early Permian Liulian Pluton at the northeastern margin of the Jiamusi Massif in NE China: Evidence from Petrography, Geochronology, and Geochemistry. *Acta Petrologica Sinica* **29**, 2971–86. (in Chinese with English abstract)

Yu M, Wang YX, Wang XW, Ren WX, You ZH and Gao ZJ (2017) The origin and geochemical characteristics of island arc volcanic rocks. *Gansu Geology* **26**, 17–21.

Zeng Z, Sun L, Zhang XZ, Cui WL and Jiang L (2019) Zircon U-Pb chronology and geochemistry of the pillow basalts from Raohe Complex: geological implications. *Geology and Resources* **28**, 119–27. (in Chinese with English abstract)

Zeng Z, Zhang XZ, Zhou JB, Zhang HT, Liu Y and Cui WL (2018) Geochemistry and zircon U-Pb age of Permian metabasalts in the Yuejinshan Complexes and its tectonic implications. *Geotectonic et Metallogenia* **42**, 365–78. (in Chinese with English abstract)

Zhang D, Liu YJ, Li WM, Li SZ, Iqbal MZ and Chen ZX (2020) Marginal accretion processes of Jiamusi Block in NE China: evidence from detrital zircon U-Pb age and deformation of the Wandashan Terrane. *Gondwana Research* **78**, 92–109.

Zhang FQ, Chen HL, Yu X, Dong CW, Yang SF, Pang YM and Batt GE (2011) Early Cretaceous volcanism in the northern Songliao Basin, NE China, and its geodynamic implication. *Gondwana Research* **19**, 163–176.

Zhang KW, Shao J, Tang KD, Zhang Q and Li XY (1997) The geochemical characteristics and the geological significance of green-schists in Yuejinshan Group, East Heilongjiang Province, China. *Acta Petrologica Sinica* **13**, 168–172. (in Chinese with English abstract)

Zhang L, Han BF, Zhu YF, Xu Z, Chen JF and Song B (2009) Geochronology, mineralogy, crystallization process and tectonic implications of the Shuangyashan monzogabbro in eastern Heilongjiang Province. *Acta Petrologica Sinica* **25**, 577–87. (in Chinese with English abstract)

Zhang L, Hao T, Xiao Q, Wang J, Zhou L, Qi M, Cui X and Cai N (2015) Magnetotelluric investigation of the geothermal anomaly in Hailin, Mudanjiang, northeastern China. *Journal of Applied Geophysics* **118**, 47–65.

Zhang Q, Qian Q and Chen Y (1998) Ophiolite overlying rock series of ophiolite and their comparison to the oceanic crust. *Earth Science Frontiers* **5**, 193–99. (in Chinese with English abstract)

Zhang Q, Qian Q and Wang Y (2000) Rock assemblages of ophiolites and magmatism beneath oceanic ridges. *Acta Petrologica Et Mineralogica* **19**, 1–7. (in Chinese with English abstract)

https://doi.org/10.1017/S0016756823000675 Published online by Cambridge University Press

Zhang Q, Wang Y, Pan GQ, Li CD and Jin WJ (2008) Sources of granites: some crucial questions on granite study(4). *Acta Petrologica Sinica* **24**, 1193–204. (in Chinese with English abstract)

Zhang Q and Zhou GQ (2001) *Ophiolites in China*. Beijing: Science Press, 1–182.

Zhang Q, Zhou GQ and Wang Y (2003) The distribution of time and space of Chinese ophiolites, and their tectonic settings. *Acta Petrologica Sinica* **19**, 1–8. (in Chinese with English abstract)

Zhang QL and Mizutani S (2004) From plate tectonics to the Terrane concept. *Jiangsu Geology* 28, 1–6. (in Chinese with English abstract)

Zhang QL, Mizutani SJ, Kojima S and Shan J (1989) The Nadanhada terrane in Heilongjiang Province. *Geological Review* **35**, 67–71. (in Chinese with English abstract)

Zhang S, Gao R, Li H, Hou H, Wu H, Li Q, Yang K, Li C, Li W, Zhang J, Yang T, Keller GR and Liu M (2013) Crustal structures revealed from a deep seismic reflection profile across the Solonker suture zone of the Central Asian Orogenic Belt, Northern China: an integrated interpretation. *Tectonophysics* **612–613**, 26–39.

Zhang XZ and Ma ZH (2010) Evolution of Mesozoic-Cenozoic basins in the Eastern Heilongjiang Province, Northeast China. *Geology and Resources* **19**, 191–6. (in Chinese with English abstract)

Zhang XZ, Zhou JB, Chi XG, Wang CW and Hu DQ (2008) Late Paleozoic tectonic-sedimentation and petroleum resources in Northeastern China. *Journal of Jilin University (Earth Science Edition)* **38**, 719–25. (in Chinese with English abstract)

Zhou JB, Cao JL, Wilde SA, Zhao GC, Zhang JJ and Wang B (2014) Paleo-Pacific subduction-accretion: evidence from Geochemical and U-Pb zircon dating of the Nadanhada accretionary Complex, NE China. *Tectonics* **33**, 2444–66.

Zhou JB and Li L (2017) The Mesozoic Accretionary Complex in Northeast China: Evidence for the accretion history of Paleo-Pacific Subduction. *Journal of Asian Earth Sciences* **145**, 91–100.

Zhou JB and Wilde SA (2013) The crustal accretion history and tectonic evolution of the NE China segment of the Central Asian Orogenic Belt. *Gondwana Research*, **23**, 1365–1377.

Zhou JB, Wilde SA, Zhang XZ, Zhao GC, Zheng CQ, Wang YJ and Zhang XH (2009) The onset of Pacific margin accretion in NE China: evidence from the Heilongjiang High-Pressure Metamorphic Belt. *Tectonophysics* **478**, 230–46.

Zhou JB, Wilde SA, Zhao GC and Han J (2018) Nature and assembly of microcontinental blocks within the Paleo-Asian Ocean. *Earth-Science Reviews* **186**, 76–93.

Zhou LY, Wang Y and Wang N (2015) Syn-tectonic magmatic emplacement in Wanda Mountain, Northeast China: a response to the Late Mesozoic sinistral strike-slip motion. *Geological Bulletin of China* **34**(Suppl. 1), 400–18. (in Chinese with English abstract)

Zhu CY, Zhao G, Sun M, Liu Q, Han Y, Hou W, Zhang X and Eizenhofer PR (2015) Geochronology and geochemistry of the Yilan blueschists in the Heilongjiang Complex, northeastern China and tectonic implications. *Lithos* **216–217**, 241–53.

Zhu ZP, Liu L, Ma R, Qiu ZK and Ma SH (2009) ^{40}Ar/^{39}Ar isotopic dating and geological significance of mafic rocks from the Jixi Basin Heilongjiang Province. *Journal of Jilin University (Earth Science Edition)* **39**, 238–43. (in Chinese with English abstract)

Zonenshain LP, Kuzmin MI and Natapov LM (1990a) Plate tectonics of the USSR territory. *Nedra, Moscow* **2**, 334.

Zonenshain LP, Kuzmin MI and Natapov LM (1990b) Geology of the USSR. A plate tectonic synthesis. *AGU Publications* **21**, 242.