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Geochronology and geochemistry of the Yilan greenschists and amphibolites in the Heilongjiang complex, northeastern China and tectonic implications

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Abstract

The Heilongjiang complex, extending along a suture zone between the Jiamusi and Songliao blocks in Northeast China, is composed mainly of blueschists, greenschists, meta-ultramafic rocks, quartzites, muscovite–albite schists and two-mica schists. Controversy has long surrounded the ages and tectonic settings of major rocks in the complex, which are crucial part of the complex. The lithological associations and their major and trace element compositions indicate that the mafic protoliths of the Yilan greenschists can be subdivided into alkali and tholeiitic basalts, which were derived from partial melting of a garnet-bearing and spinel-bearing mixed source, whereas the protoliths of the amphibolites are tholeiitic and were generated from the partial melting of spinel peridotite. Magmatic zircons from a tholeiitic amphibolite sample yielded a 206Pb/238U age of 256 ± 2 Ma, interpreted as its protolithic age. The sample also contains small amounts of older inherited zircons up to 344 Ma, which, together with its origin from shallow lithospheric mantle, indicate that the tholeiitic rocks were generated in a continental rift. The geochemical data suggest that further rifting led to the formation of an ocean between the Jiamusi and Songliao blocks, in which some oceanic islands developed, represented by the alkali basaltic protoliths of the Yilan greenschists. Magmatic zircons from an alkaline greenschist sample yielded a 206Pb/238U age of 162 ± 3.9 Ma, which, together with protolithic age of 141.9 ± 1 Ma previously obtained for the Yilan blueschist, support the model that the ocean between the Jiamusi and Songliao blocks closed at some time after ~141 Ma, not earlier at 210–180 Ma as previously considered.

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1. Introduction

Five micro-continental blocks have been recognized in northeast China, named the Jiamusi, Songliao, Xing’an, Khanka and Erguna blocks (Fig. 1; Natal’In, 1991, 1993; Cao et al., 1992; HBGMR, 1993; Sengör et al., 1993; Sengör and Natal’In, 1996; Wilde et al., 1997, 1999, 2000, 2003; Wu et al., 2007). The tectonic relationships between these blocks and how they were assembled to form a coherent landmass in present-day northeast China still remain controversial (Wu et al., 2011). This is particularly the case with the Jiamusi and Songliao blocks, which are separated by a high-pressure metamorphic belt, named the Heilongjiang complex (Fig. 2; Cao et al., 1992; Zhang, 1992; Wu et al., 2007; Zhou et al., 2009, 2010a, 2010b; Meng et al., 2010; Xu et al., 2013; Zhu et al., 2015). However, there is an ongoing debate on when and how the Jiamusi and Songliao blocks collided to form the Heilongjiang complex (Wu et al., 2007; Zhou et al., 2009, 2010a, 2010b; Zhu et al., 2015). One school of thought argues that the Jiamusi and Songliao blocks sutured along a N–S trending belt, defined as the Heilongjiang complex, during Early Paleozoic time (Cao et al., 1992; Zhang, 1992; Meng et al., 2010; Xu et al., 2013). In contrast, others suggest that the amalgamation of the two blocks happened along the Heilongjiang complex belt in the Early Mesozoic (Wu et al., 2007, 2011; Zhou et al., 2009, 2010a, 2010b). At the center of the above controversy are the tectonic nature and age of the Heilongjiang complex (Cao et al., 1992; Zhang, 1992; Zhou et al., 2009, 2010a, 2010b; Meng et al., 2010; Xu et al., 2013; Zhu et al., 2015).

Lying along the Mudanjiang Fault between the Jiamusi and Songliao blocks, the Heilongjiang complex is a high metamorphic belt (Fig. 2; Zhou et al., 2009, 2010a, 2010b). It is characterized by serpentinites, blueschists and greenschists, whose protoliths are considered to be ultramafic–mafic rocks; some of which may represent an oceanic lithosphere but whose ages are still on debate. Previous studies suggested that these ultramafic–mafic rocks were emplaced around ~640 Ma (Cao et al., 1992; Zhang, 1992), but recent investigations argue that the Heilongjiang complex formed during Late Permian and Early Triassic time (Wu et al., 2011; Zhou et al., 2009, 2010a, 2010b). More recently, Zhu et al. (2015) obtained 206Pb/238U zircon age of 141.8 ± 1 Ma for the Yilan blueschist, and thus proposed that the mafic rocks in the Heilongjiang complex were related to the development of an ocean between the Jiamusi and Songliao blocks during Permian to Jurassic time. It can be seen that the above tectonic

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scenarios regarding the tectonic setting and ages of the Heilongjiang complex are mutually exclusive, and these models were established only on the geochemical and geochronological data for the blueschists of the complex (Cao et al., 1992; Li et al., 1999; Zhou et al., 2009, 2010a, 2010b). In contrast, little work has been done on the greenschists and amphibolites, another two significant components of the Heilongjiang complex, which has hindered the further understanding of the nature of the ocean separating the Jiamusi Block from the Songliao Block.

In this study, we carried out an extensive geochronological and geochemical investigations on the greenschists and amphibolites from the Heilongjiang complex. The results will not only provide important constraints on the tectonic setting and ages of the mafic rocks from the Heilongjiang complex, but will also shed light on issues of when and how the Jiamusi and Songliao blocks amalgamated along the Heilongjiang complex.

2. Regional geology

Northeast China evolved from the amalgamation of several microcontinental blocks, including the Erguna Block in the northwest, the Xing'an and Songliao blocks in the middle, and the Jiamusi and Khanka blocks in the east (Fig. 1; HBGMR, 1993). The Erguna block is located in the northernmost part of Northeast China and separated from the Xing'an and Songliao blocks to its south by the Tanyuan–Xiguitu Fault (Fig. 1). The Xing'an and Songliao blocks are separated from each other by the Hegenshan–Heihe Fault, and both are separated from the Jiamusi and Khanka blocks by the Mudanjiang Fault (Figs. 1 and 2).

Conventionally, the Jiamusi Block is considered to represent the easternmost segment of the Central Asian Orogenic Belt, which extends from Xinjiang in northwest China, through Inner Mongolia, to northeast China (Natal'In, 1991, 1993; Natal'In and Borukayev, 1991; Sengör et al., 1993; Sengör and Natal'In, 1996; Jahn et al., 2000; Jahn, 2004; Xiao et al., 2003, 2004a, 2004b; Li, 2006). The lithology of the Jiamusi Block can be divisible into three rock assemblages: the Mashan supracrustals, deformed and undeformed granitoids and the Heilongjiang complex (Fig. 2). The Mashan supracrustals are also known as the Khondalite series in the Chinese literature, which are composed dominantly of sedimentary rocks and minor volcanic rocks that were metamorphosed from upper amphibolite- to granulite-facies, and crop out as pelitic granulites/gneisses, marbles, calc-silicate rocks, minor amphibolites and mafic granulites (Wilde et al., 2000; Wu et al., 2007). These rocks were previously considered to be Neoarchean in age (HBGMR, 1993).
but recent SHRIMP U–Pb zircon dating results indicate that their protoliths were formed during Meso-Neoproterozoic time and underwent granulite-facies metamorphism at ca. 500 Ma (Wilde et al., 1997, 2000). The deformed granitoids, which form tectonic sheets dismembering the Mashan supracrustals, were initially considered to be Archean–Paleoproterozoic in age, but recent geochronological data suggest that they were emplaced at 530 to 515 Ma (Wilde et al., 2000, 2003), consistent with coeval magmatism in South Australia. These granitoids contain zircons that show a recrystallization event at ~500 Ma, representing a later phase of the Pan-African event. Thus, Wilde et al. (1997, 1999, 2003) proposed that the Jiamusi Block was located at the edge of Gondwana during Early Paleozoic time and then drifted northward to form part of Northeast China. Other than these deformed granitoids, undeformed granulites are also widespread in the Jiamusi Block, and are thought to have emplaced during Permain time, but their tectonic implication still remains unclear.

Lying west of the Jiamusi Block is the Songliao Block that is covered by the Mesozoic Songliao Sedimentary Basin. Recent drill data have revealed that the basin has a basement that is composed of Paleozoic granitoids and sedimentary strata (Wu et al., 2001, 2007; Gao et al., 2007; Pei et al., 2007). The eastern and northern parts of the Songliao Block are known as the Zhangguangcai and Lesser Xing’an Ranges, respectively, which are characterized by a large volume of Mesozoic granitoids (Wu et al., 2011; Wang et al., 2012, 2015). The Great Xing’an Range, located south of the Songliao Basin, is represented by voluminous Mesozoic volcanic rocks and granitoids (Wu et al., 2011; Zhang et al., 2012). Although numerous geological, petrological and geochronological investigations have been carried out on these granitoids, their tectonic settings still remain controversial (Wu et al., 2011).

Intervening between the Jiamusi and Songliao blocks, the Heilongjiang complex is exposed along the Jiayin–Mudanjiang Fault, extending from Luobei in the north, through Yilan in the middle, to Mudanjiang in the south (Fig. 2). The complex is composed mainly of serpentinite, blueschist, greenschist, marble, amphibolite, muscovite–albite schist and quartzite (Zhang, 1992; Li et al., 1999; Wu et al., 2007). The serpentinites are only locally exposed and occur usually within their unaltered ultramafic equivalents, which include dunites, lherzolites, and harzburgites. The quartzites are commonly associated with the greenschists and characterized by the appearance of Fe–Mn nodules (pyrolusite and psilomelane), a mineral assemblage of serpentine, stilpnomelane, sodium-amphibole and piemontite, which suggest a deposition of cherts in an abyssal setting (Li et al., 1999).

![Simplified geological map of the Yilan area showing the main tectonic units, and spatial and temporal distributions of greenschists and amphibolites including sampling locations (modified from Zhou et al., 2009).](image)

Fig. 3. Simplified geological map of the Yilan area showing the main tectonic units, and spatial and temporal distributions of greenschists and amphibolites including sampling locations (modified from Zhou et al., 2009).
The muscovite–albite schists are generally fine-grained and metamorphosed from shales or mudstones (Cao et al., 1992; Li et al., 1999). All of these rocks in the Heilongjiang complex are tectonically juxtaposed, indicating their possible association in a mélangé (Wu et al., 2007). Several geochronological methods have been applied in an attempt to constrain the age of the Heilongjiang complex, but no conclusive agreement has been reached. Zhou et al. (2009; 2010) identified numerous magmatic zircons from blueschists, and obtained U–Pb ages of 213–224 Ma from the Mudanjiang blueschists and ~260 Ma from the Yilan blueschists. These blueschists have an affinity with E-MORB or OIB and these mafic magmas are interpreted to have originated in a continental-rifting environment (Zhou et al., 2009, 2010a, 2010b). The mica Rb–Sr and 40Ar/39Ar methods were previously used to constrain the timing of metamorphism, and the results suggested that the metamorphism of the Heilongjiang complex took place at 166 Ma–185 Ma, indicating that the suturing time between the Jiamusi and Songliao along the Mudanjiang Fault (Wu et al., 2007, 2011; Zhou et al., 2009, 2010a, 2010b). However, a recent study reports that the protolith ages of blueschists from the Yilan area have two populations, with one at ~275 Ma and the other at ~141 Ma (Zhu et al., 2015). The ~275 Ma blueschists are interpreted as having generated in a continental rifting basin between the Jiamusi and Songliao blocks based on their geochemical features (Zhu et al., 2015).

Like blueschists, the greenschists and amphibolites are also crucial components in understanding the formation of the mafic rocks in the Heilongjiang complex. In the Heilongjiang complex exposed in the Yilan area (Fig. 3), the greenschists are either massive or schistose, of which the former type appears as small blocks or thick sheets, whereas the latter occurs in thin sheets or lenses that surround the blueschists. They are often tectonically juxtaposed with felsic gneisses/schists, pelitic gneisses and serpentinites (Fig. 4b, d, e, g). The greenschists display a porphyroblastic texture, in which epidote occurs as a dominant matrix mineral commonly with elongated crystals up to 2–4 mm, while plagioclase (albite) occurs as porphyroblasts (Fig. 5a, b). The typical mineral
The assemblage of the greenschists is epidote + chlorite + plagioclase (albite) + biotite + quartz ± stilpnomelane (Fig. 5a, b). These greenschists can be regarded as the medium-pressure metamorphosed equivalents to the high-pressure blueschists of the Heilongjiang complex.

The amphibolites in the Heilongjiang complex are foliated and commonly occur as thick sheets (Fig. 4a, c, f). They are often found in tectonic contact with pelitic gneisses, marbles, greenschists, and serpentinites (Fig. 4a). The amphibolites also display a porphyroblastic texture, in which amphibole minerals occur in the matrix with generally elongated crystals of up to 2–4 mm length, while plagioclases and/or quartz define the porphyroblasts (Fig. 5c, d). The typical mineral assemblage of the amphibolites is amphibolite + plagioclase + quartz + epidote + chlorite + biotite ± magnetite.

3. Analytical methods

The fresh greenschist and amphibolite samples of the Heilongjiang complex were collected on outcrops in the Yilan, Mudanjiang and Luobei areas along the Mudanjiang Fault (Figs. 2 and 3).

3.1. Major and trace elements

Whole-rock major element contents were analyzed using an X-ray fluorescence spectrometer (XRF) at the Hebei Geology and Resource Bureau, Langfang, China following standard sample processing procedures. Uncertainties for major elements are generally less than 2%. Whole-rock trace element contents were analyzed using a Quadrupole ICP-MS at the State Key Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang using international standards AGV-2 (andesite), BCR-1 (basalt), G-2 (granite), OU-6 (slate), AMH-1 (andesite), and GBPG-1 (plagiogneiss) for analytical quality control (Thompson et al., 2000; Potts et al., 2000a, 2000b, Potts and Zdravkovic, 2001). Analytical precision of most trace elements is generally better than 5%. Detailed analytical procedures are described in Qi et al. (2000).

3.2. Zircon U–Pb dating

Zircon grains were separated by using standard density and magnetic separation techniques before hand picking under a binocular microscope. Representative grains were handpicked, mounted in epoxy resin and then polished to expose grain interiors. Cathodoluminescence (CL) images were obtained from a scanning electron microscope (SEM. Leo 1450VP, Germany) in the Department of Earth Sciences, The University of Hong Kong, prior to in-situ U–Pb isotopic analyses.

Zircon U–Pb analyses were performed using an LA-ICP-MS at Northwest University in Xi’an and another identical one at Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. Laser ablation was performed using a 193 nm excimer laser ablation system (GeoLas 2005), while ion intensities were measured through an ICP-MS (Agilent 7500a). Spot diameters were ~32 μm. Zircon 91,500 was used as an external standard (Wiedenbeck et al., 1995), which was analyzed twice after analysis of five samples grains. Each analysis included a
background acquisition of 20–30 s (gas blank) and a 50 s data acquisition on the sample. Trace element abundances were calibrated against multiple USGS-recommended reference materials (BCR-2G and BIR-1G) using 29Si as an internal standard (Liu et al., 2010). Off-line selection and integration of background and sample signals, time dependent drifts for U–Th–Pb isotopic ratios correction, U–Pb dating and quantitative calibration for zircon trace element analyses were all performed by ICPMDataCal_ver8.0 (Liu et al., 2010). Detailed LA-ICP-MS operating conditions and data reduction procedures were outlined in Liu et al. (2008). Common lead correction, if required, followed Andersen et al. (1993). Concordia diagrams and U–Pb ages including their mean square of weighted deviates (MSWD) were calculated using Isoplot/Ex_ver3 (Ludwig et al., 2003).

4. Analytical results

4.1. Major and trace elements

Whole-rock major element compositions of the greenschist and amphibolite samples from the Heilongjiang complex in the Yilan area are listed in Tables 1 and 2. The samples have undergone blueschist metamorphism with the P–T conditions at 9–11 kbar and 350–450 °C (Zhou et al., 2009; Wu et al., 2007). In most cases, the regional metamorphism is in a closed system for most elements of rocks. At the scale of several centimeters or more, the effects of solid-state diffusion and melt generation on element mobility are ignorable with only loss

Table 1

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of volatile phase (Rollinson, 1993; Roser and Nathan, 1997). The whole-rock major element analytical results show an overall basaltic composition when plotted on the total alkalis vs. SiO$_2$ diagram of Le Maitre et al. (1989), with SiO$_2$ contents ranging from 45.97 wt.% to 49.09 wt.%, high contents of total FeO from 11.06 wt.% to 15.61 wt.%, large variations in TiO$_2$ and P$_2$O$_5$ (2.17–4.01 wt.%, 0.13–0.46 wt.%) and low contents of Na$_2$O (2.17–4.01 wt.%). The basalts can be generally divided into alkaline and subalkaline groups (Fig. 7). In order to further distinguish between calc-alkaline and tholeiitic compositions, the samples were plotted onto a FeO$_{total}$/MgO vs. SiO$_2$ diagram (Fig. 7) exposing a predominantly tholeiitic composition. All samples can be geochemically divided into three groups: alkaline greenschists (G1), tholeiitic greenschists (G2) and tholeiitic amphibolites (A) with respect to their protolithic source compositions. There are distinct differences among the three groups. The alkaline greenschists are comparatively rich in MgO (MgO = 6.37–11.07, Mg# = 51.40–61.48), low in FeO$_{total}$ (10.40–12.49 wt.%). In contrast, the tholeiitic amphibolites have highest contents in FeO$_{total}$ (11.95–15.61 wt.%) but lowest contents in Mg# (35.34–48.82). In comparison, the tholeiitic greenschists occupy an intermediate position among the three groups (FeO$_{t}$, 11.06–14.04 wt.%; Mg#, 43.58–51.63).

### 4.1.2. Trace elements

Whole-rock trace element data are listed in Tables 1 and 2. Low field-strength elements are mostly mobile and susceptible to changes during alteration, while high-field-strength elements (HFSE) and trace elements are essentially immobile during all but the most severe seafloor-hydrothermal alterations (Pearce and Norry, 1979; Wood et al., 1979). Thus, immobile elements such as REEs and high-field-
strength Selements (Ti, Zr, Y, Nb, Ta, Hf, Th) can be used to identify the magmatic affinity and petrogenesis of mafic rocks.

The mafic rocks of the Heilongjiang complex tend to a generally pronounced enrichment in U and Ti, low REEs contents and Th/Hf, but high values of Hf/Sm and Ti/Zr. (Fig. 8). Despite their overall similarity, differences can still be observed between the three rock groups as defined above. The greenschists (G1 and G2) have high concentrations in high-field-strength elements (HFSE, Th, U, Nb, and Ta), REEs and FPTM (Ti, Cr, Ni) compared to the two tholeiitic rock groups. In particular, the alkaline greenschists exhibit higher contents of Ce/Nb, Hf/Sm, but to a lesser degree depletion of Zr and Hf compared to two tholeiitic groups (G2 and A). Primitive mantle-normalized trace-element patterns of the samples reveal that the greenschists (G1 and G2) resemble those of OIB, whereas the amphibolites (A) have affinities with E-MORB, although with higher element concentrations (Fig. 9a, b).

Fig. 6. Mg# vs. major elements.
Differences among the mafic rocks from the Heilongjiang complex can also be observed utilizing rare earth elements (REEs) features. The greenschists (G1 and G2) display a light REE (LREE) enrichment (Fig. 9b) relative to the heavy REE’s (HREE), and show chondrite-normalized REE patterns that are similar to those of ocean island basalts (OIB) or enriched oceanic mid-ridge basalts (E-MORB) with positive Eu anomalies (Eu/Eu∗ = 1.09–1.22), a large (La/Yb)n variation (5.44–7.61), and moderate LREE fractionation ([La/Sm]n = 1.30–2.56). In comparison, the REE patterns of the amphibolites (A) are flat without Eu anomalies (1.17–1.30), with small (La/Yb)n (1.17–1.30) and LREE fractionation ([La/Sm]n = 0.93–1.05).

4.2. Zircon U–Pb dating

A greenschist sample (13JM19C) from the alkaline group was selected for LA-ICP-MS U–Pb zircon analysis. Zircons from this sample are generally equant to short prismatic, colorless and transparent. Crystal lengths range from 40 to 100 μm, with length/width ratios between 1:5:1 and 2:1. In CL images (Fig. 10a), most zircons display weak oscillatory or patchy zoning with low luminescence. Some grains display bright luminescent rims and unzoned cores. There are no metamorphic overgrowth rims or erosional features on the zircons (Fig. 10a). Eighteen zircon grains were analyzed, yielding 206Pb/238U ages ranging from 194 Ma to 156 Ma (Fig. 10d), of which the youngest seven zircons gave a weighted mean U–Pb age of 162 ± 3.9 Ma (Fig. 10d; MSWD = 0.68, n = 8), with Th/U ratios ranging from 0.45 to 1.33 (Table 3), indicating their magmatic origin (Hoskin and Schaltegger, 2003), consistent with their oscillatory or inherited zircons.

Three groups of basalts were recognized based on their geochemical signatures, which not only provide an insight into their origins but also into the tectonic settings. Understanding the causes of volcanic activity in the region, given a precise geochronology, is essential to the reconstruction of the tectonic evolution of the study area. The characterization of their whole-rock trace and major element signatures opens a window into the nature of the source magmas and the tectonic setting in which they were produced, thus enabling us to better understand the formation and evolution of the Heilongjiang complex.

5.1. Crustal contamination

Crustal assimilation may play an important role during magmatic differentiation. Low degrees of crustal contaminations/assimilations occur generally during ascent of tholeiitic magmas. Incompatible elements that are sensitive to continental contamination, such as Nb/U, can be used to infer crustal assimilation. Hofmann et al. (1986) observed that Nb/U ratios are uniform in both MORB and OIB, and they interpreted this feature as a characteristic for mantle sources of oceanic basalts. These ratios (Nb/U > 40) are higher than those of the primitive mantle (Nb/U = 30) and the average continental crust (Nb/U = 10) (Hofmann et al., 1986; Niu et al., 1999). Most of the tholeiitic samples have generally moderate Nb/U ratios (14–29) corresponding to average continental crust or primitive mantle (Fig. 11a). In addition, most tholeiitic samples display weak negative Nb anomalies in primitive mantle normalized trace element patterns (Fig. 9a), suggesting that they have experienced some crustal contamination. The existence of xenocrystic or inherited zircons in the tholeiitic magmas, however, indicates crustal contamination to some degrees. In contrast, the greenschist protoliths seem to have not experienced crustal contamination since their Nb/U ratios (17.1–51) are relatively high and no negative Nb anomaly can be observed.

5.2. Parental magma

In this study, at least three distinct geochemical groups of mafic rocks, with respect to their protolithic compositions, were recognized in the Heilongjiang Complex: alkaline greenschists (G1), tholeiitic greenschists (G2) and tholeiitic amphibolites (A). Their geochemical features suggest that they evolved from different parental magma reservoirs. The greenschists (G1 and G2) have higher concentrations of incompatible elements and lower values of Mg# compared to the
amphibolite group (A), the latter of which shows different trends in the incompatible elements versus Mg# diagrams. Moreover, the trace element signature of the amphibolites (Fig. 8) also indicates that they were derived from a different magma source. The greenschists contain larger concentrations of immobile elements than the amphibolites, indicating that they evolved independently and did not originate from the same mantle source, or a variation of it in terms of degrees of melting or fractional crystallization.

Though it is impossible to explore the possible magma source compositions, we can explore the possible mantle source characteristics by the utility of trace element compositions that are generally immune to effects of the fractional crystallization and crustal assimilation, and thus can be utilized to characterize possible mantle sources and their chemical compositions. A positive correlation between \((\text{La/Yb})_n\) and \((\text{Dy/Yb})_n\) in the greenschist samples (groups G1 and G2) indicates the presence of garnet as a residual phase in the source (Fig. 10a; cf. Miller et al., 1999; Zhao et al., 2009). Several scenarios can explain the presence of garnet in the residual phase. Recent studies suggest that garnet pyroxenites and thickened lower crust can produce alkali magmas (Hirschmann and Stolper,

![Fig. 8. Mg# vs. incompatible elements. Plots of (a) total REE vs. MgO; (b) total REE vs. P2O5; (c) Eu/Eu* vs. Mg#; (d) \((\text{La/Yb})_n\) vs. MgO; (e) La/Yb vs. Sm/Nd; and (f) \((\text{Sm/Yb})_n\) vs. Mg#.](image-url)
melts with low Ni/MgO and moderate SiO₂ contents (Sobolev et al., 2005), may be a possible magma source. Furthermore, no covariations were observed between La/Yb and Yb or Dy/Yb and La/Yb, consistent with the melts from spinel-bearing sources (Fig. 12a, c). The lower ratios of both La/Yb and Zr/Y compared to the greenschists provide another line of evidence that the protoliths were derived from spinel-peridotite melts (Fig. 12d). This interpretation is also supported in the La/Sr vs. Sm/Yb plots. The tholeiitic protoliths of amphibolites (A) have low La/Sr and Sm/Yb ratios, suggesting high degree of partial melting from a relatively shallow lithospheric mantle (spinel peridotite) (Fig. 12e).

Different sources of magmas alone cannot account for Variations in incompatible elements and REE concentrations between the three groups of mafic protoliths, therefore variable degrees of partial melting may also have a profound effect. Since the greenschists (G1 and G2) and amphibolites (A) were derived from different sources of magma, the effects of partial melting will be discussed based on individual geochemical groups. The greenschist protoliths are alkaline and tholeiitic, and were generated from similar magma sources at different degrees of partial melting, which can be reflected in the concentrations of the highly incompatible trace elements. Variations in La/Yb ratios between the alkaline (G1: 5.44–7.61) and tholeiitic (G2: 1.3–3.0) protoliths suggest a general increase in the degrees of partial melting from alkaline (G1) to tholeiitic (G2). This is also verified by the La/Yb ratios, which increases from the alkaline to tholeiitic compositions, since Sm has a greater incompatibility than La with decreasing degree of partial melting (Fig. 12e). Thus, both the alkaline and tholeiitic protoliths were generated from the partial melting of a mixed garnet- and spinel-bearing mantle source, while the alkaline greenschist protoliths experienced a smaller degree of partial melting than the tholeiitic ones.

In comparison to the greenschist protoliths, the tholeiitic amphibolite protoliths differ also in their degree of partial melting during their formation. Trace element ratios with the same degree of incompatibility like Zr/Y exhibit a rather constant trend within the amphibolites, whereas the ratios of La/Yb are almost the same within the amphibolites (Fig. 12d). It suggests that the protoliths of the amphibolites (A) were produced at different degrees of partial melting of spinel peridotite. Furthermore, all amphibolites plot along the melting curves of spinel lherzolite in the Yb vs. La/Yb diagram, indicating different degrees of partial melting of the same magma source (Fig. 12c). Thus, the tholeiitic samples formed by different degrees of partial melting of spinel peridotite.

5.3. Tectonic environments

The Heilongjiang complex, extending N–S along the Mudanjiang Fault, is an important tectonic belt that recorded the suturing between the Jiamusi and Songliao blocks. As discussed above, the greenschists with alkaline protoliths (G1) yielded a protolithic age of 162 ± 3.9 Ma, whereas the amphibolites (A) formed at 256 ± 2.1 Ma. The greenschists (G1 and G2) appear to be generated at depths ranging from garnet- to spinel-bearing mantle, whereas the amphibolites formed at variable degrees of partial melting of spinel peridotites. Although the greenschists with tholeiitic protolith and amphibolites were generated from independent magma sources, their geochemical features suggest that the amphibolites (A) were generated in different tectonic setting from that in which the greenschists were formed (G1 and G2). The REE patterns of the amphibolites are generally flat with a slight enrichment in LREE relative to HREE and more similar to
E-MORB patterns (Fig. 9a, b, 11b), precluding their genesis from a mid oceanic ridge setting. The tholeiitic magmas experienced some crustal contamination during their magmatic ascent, implying that they may have erupted in a continental setting. Continental rifting took place between the Jiamusi and Songliao blocks during Permian to Triassic time, resulting in eruptions of mafic–ultramafic magmas, some of which have

![Figure 10](image)

**Fig. 10.** Representative cathodoluminescence (CL) images of zircons from (a) sample 13JM19C and (b) sample 13JM21A; Plots of lead isotopic ratios: (c) $^{206}\text{Pb}/^{238}\text{U}$ vs. $^{206}\text{Pb}/^{207}\text{U}$ of sample 13JM21A and (d) $^{206}\text{Pb}/^{238}\text{U}$ vs. $^{206}\text{Pb}/^{235}\text{U}$ of sample 13JM19C. Isotopic compositions of three geochemistry end-members are given in Table 2.

**Table 3** LA-ICP-MS U–Pb dating data of the greenschist in the Yilan area from the Heilongjiang Complex.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Isotopic ratios</th>
<th>Isotopic ages (Ma)</th>
<th>Th</th>
<th>U</th>
<th>Th/U</th>
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<td>$^{206}\text{Pb}/^{238}\text{U}$</td>
<td>1 s</td>
<td>$^{206}\text{Pb}/^{207}\text{U}$</td>
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been metamorphosed subsequently to blueschists (Zhou et al., 2010a, 2010b; Zhu et al., 2015). These blueschists have similar E-MORB affinities and slightly younger ages (220–230 Ma) compared to the tholeiitic amphibolites in this study, implying that the tholeiitic amphibolites may also be part of the magmatic eruptions during the continental rifting.

In addition to the geochemical and age features, the petrogenesis of the tholeiitic amphibolites also provides a high potential link to this continental rifting. The amphibolites were derived from a shallow, depleted, lithospheric spinel-bearing mantle source. The tholeiitic blueschists in the Yilan area, however, were generated from high degree...
of partial melting of a garnet peridotite source (Zhu et al., 2015). These characteristics are consistent with a model of progressive lithospheric rifting and thinning with time, which produced melts from an extended depth ranging from garnet-facies to spinel-facies. Taken together, we conclude that the eruption of the ~256 Ma tholeiitic groups (G2 and A) was associated with a continental rifting event that happened between the Jiamusi and Songliao blocks.

Unlike the tholeiitic amphibolites (A), the greenschists (G1 and G2) have OIB-like REE patterns that are characterized by the enrichment in LREEs compared to HREEs (Fig. 9b), precluding the possibility that they have OIB-like REE patterns that are characterized by the enrichment in Nb/Th (Fig. 9a); (2) incompatible trace element ratios (e.g. La/Th < 12; Nb/Th < 15) illustrate a similarity to OIB compositions; (3) tectonic discrimination diagrams also indicate an intra oceanic alkaline basalt origin (Fig. 11b). Considering a genesis from mixed garnet- to spinel-bearing magma sources, our study suggests that the alkaline group (G1) was most likely generated in the lower part of the lithospheric mantle or in the asthenospheric mantle below an oceanic plate. Our geochronological data further corroborate an oceanic crust origin. The greenschists with alkaline protoliths contain no inherited/xenocrystic zircons older than 270 Ma and have a protolithic age of 163 Ma, which is slightly older than the ~141 Ma alkaline basaltic protolith of the Yilan blueschists (Zhu et al., 2015), suggesting that some greenschists in this study were generated from the same oceanic crust as those of the Yilan blueschists. Thus, the alkaline greenschists (G1) are representative of the oceanic crust between the Jiamusi and Songliao blocks. In summary, an intracontinental rift, in which the E-MORB tholeiitic groups were generated, may have developed from the Permian to Triassic. It then evolved to an open ocean between the Jiamusi and Songliao blocks in which several oceanic islands formed. This ocean was previously considered to have closed at 210–185 Ma, mainly based on Ar/Ar ages of phengites and glaucophanes from the blueschists of the Heilongjiang Complex (Wu et al., 2007; Zhou et al., 2009, 2010a, 2010b). However, the alkali mafic protolith of the OIB-type blueschists from Zhu et al. (2015) formed at ~140 Ma, demonstrating that the closure of this ocean must have occurred at some time after ~140 Ma. The protolithic age of 163 Ma obtained in this study for the alkaline greenschists further supports this scenario.

Several studies in the region reported Jurassic granitoids with an age range of 210–155 Ma in the eastern part of Northeast China (e.g., the Zhangguangcai Range; Zhang et al., 2010; Wu et al., 2011), which are believed to be related to the subduction of the ocean between the Jiamusi and Songliao blocks (Wu et al., 2011). Therefore, our study provides strong evidence that the ocean between the Jiamusi and Songliao blocks closed in the Late Jurassic (~140 Ma), not in the Late Triassic or Early Jurassic (210–185 Ma) as previously considered. We argue that the continental rifting between the joint Jiamusi and Songliao blocks took place during Permian to Triassic time and continued its evolution into an open ocean that subsequently closed after ~140 Ma.

6. Conclusions

Geochemical and geochronological data presented in this study on the Yilan greenschists and amphibolites from the Heilongjiang Complex in Northeast China lead to the following conclusions:

(1) The mafic protoliths of the Yilan metamorphic rocks can be subdivided into three groups: greenschists with alkali protolith (G1), greenschists with tholeiitic protolith (G2) and amphibolites with
the ophiolitic protolith (A), of which the protolith of the G1 greenschists formed at 162 ± 3.9 Ma, whereas the protolith of the amphibolites formed at 256 ± 2.1 Ma.

(2) Geochemical data suggest that the G1 and G2 protoliths were generated from the partial melting of a mixed granit- and spinel-bearing mantle source, but the G1 protolith may have formed at lower degrees of partial melting than the G2 ones. Moreover, the the ophiolitic protolith of the amphibolite (A) was formed at different degrees of partial melting of spinel-peridotite.

(3) The existence of some – 300 Ma inherited/xenocrytic zircons in the ophiolitic amphibolites (A) and their geochemical features indicate that their mafic protoliths may have originated from a continental rifting setting, whereas the greenschists (G1 and G2) were most likely formed in an oceanic island setting within an open ocean between the Jiamusi and Songliao blocks.

(4) Continental rifting between the joint Jiamusi and Songliao blocks occurred during Permian to Jurassic time, and the continued extension ultimately led to the opening of an ocean, which subsequently closed at some time after – 140 Ma.

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