Neoarchean convergent margin tectonics associated with microblock amalgamation in the North China Craton: Evidence from the Yishui Complex

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A B S T R A C T

Archean tectonic history of the North China Craton (NCC) involved complex processes of amalgamation of microcontinents along multiple subduction zones prior to the consolidation of the major crustal blocks and their assembly into unified cratonic architecture. Here we report a suite of granitoids, diabase, metabasalts, volcanic tuff, banded iron formations and quartzite from the Yishui Complex along the southern margin of the Jiaoliao microblock within the Eastern Block of the NCC. The geochemical features of the magmatic suite are consistent with calcalkaline magmatism in a convergent margin setting. In tectonic discrimination diagrams, the mafic suite shows variable IAB, MORB and OIB affinities typical of rocks formed in an arc-related subduction environment. Zircons in most of the rocks from Yishui Complex display core–rim texture with the cores showing magmatic crystallization and the narrow structureless rims corresponding to metamorphic overgrowth. The 206Pb/207Pb ages of magmatic zircons show 2504 ± 19 Ma for the volcanic tuff, 2581 ± 21 Ma for the granitoid, 2501 ± 19 Ma for the metavolcanics, 2537 ± 38 Ma for the pyroxenite, and 2506 ± 13 Ma for the diabase. Metamorphism is constrained from the 2451 ± 18 Ma and 2466 ± 23 Ma age groups in the metavolcanics and (meta-)pyroxenites. Zircons from BIF show multiple population with the oldest showing a spot age of 2503 Ma, followed by a number of distinct groups of Paleoproterozoic zircons corresponding to later thermal events. The oldest population of magmatic zircons from the quartzite shows 206Pb/207Pb mean age of 2495 ± 24 Ma. The dominantly positive εHf(t) values of the magmatic zircons from the Yishui suite are broadly consistent with a depleted mantle source with only minor input of crustal components. Their Hf crustal residence ages (TDM) range from 2586 to 3181 Ma and Hf depleted mantle model ages (TDM) are in the range of 2548–2927 Ma. The data indicate that magma production involved Meso- to Neoarchean juvenile sources within a continental arc setting, suggesting the Jiaoliao microblock as one of the ancient continental nuclei in the NCC. We trace the continuity of a Neoarchean subduction system along the western and southern margins of the Jiaoliao microblock with convergence of the Qianhuai and Xuhuai microblocks towards the Jiaoliao microblock with subduction–accretion–collision during the Archean–Proterozoic transition.

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1. Introduction

The construction, recycling, preservation and destruction of continental crust on the globe constitute unified themes to address the crustal evolution history through time as well as to understand supercontinent cycles (e.g., Santosh et al., 2009; Stern, 2011; Roberts, 2013; Nance et al., 2014; Spencer et al., 2015). Modern orogenic belts, such as the world’s largest Phanerozoic orogen, the Central Asian Orogenic Belt (e.g., Xiao and Santosh, 2014; Xiao et al., 2014, 2015) have provided important insights into crustal growth involving prolonged subduction and accretion with both juvenile and recycled components contributing to the construction of continents. Both vertical additions by magmas and lateral growth through accretion have been traced as the principal components of continent building in both ancient and modern orogenic belts (Santosh, 2013). Accretionary orogeny as a fundamental process of continental growth includes a series of arc–arc, arc–continent and continent–continent collisions (e.g., Cawood and Buchan, 2007; Santosh et al., 2009; Xiao et al., 2015).

Archean cratonic nuclei provide important natural museums to evaluate crustal evolution processes in the early history of the Earth. The North China Craton (NCC), as one of the ancient cratonic domains in Asia, has been the focus of several investigations relating to Archean and Paleoproterozoic crustal evolution and related tectonic processes (e.g., Zhao et al., 2005; Santosh, 2010; Zhao and Zhai, 2013; Zhai, 2014; Tang et al., 2015; Yang and Santosh, 2015; Yang et al., 2015, and references therein). Recent studies have identified several old continental nuclei ranging in age from dominantly Mesoarchean to Neoarchean...
within the major crustal blocks of the NCC leading to the concept of microblocks as the fundamental elements that built the larger crustal blocks eventually constructing the composite cratonic architecture (Zhai and Santosh, 2011; Zhai, 2014; Yang et al., 2015).

In this study, we investigate a sequence of lithological units in the Yishui Complex along the southern margin of a major microblock in the NCC, the Jiaoliao Block. We present petrological, geochemical, zircon U–Pb and Lu–Hf data, and propose a model for the rock suite as accreted remnants of an active subduction system during Neoarchean. Our study contributes to the understanding of the early Precambrian evolutionary history of the NCC, and its analogues in other parts of the world.

2. Regional geological framework

Popular tectonic models on the NCC consider it to be composed of two major crustal blocks (Fig. 1), the Eastern Block and the Western Block, which were sutured during late Paleoproterozoic along the Trans-North-China Orogen (TNCO) (Zhao et al., 2005; Santosh, 2010; Zhao and Zhai, 2013). The Western Block is a composite of the Yinshan and Ordos Blocks which were amalgamated along the Inner Mongolia Suture Zone (IMSZ) (incorporating the Khondalite Belt, Zhao et al., 2005; Santosh, 2010). A third Paleoproterozoic suture, the Jiao–Liao–Ji Belt, has also been identified within the Eastern Block (Santosh, 2010; Zhao and Zhai, 2013) (Fig. 1). However, recent models propose that the core of the NCC is composed of a number of ancient microblocks (e.g., Zhai and Santosh, 2011; Zhai, 2014; Yang et al., 2015) which preserve cratonic nuclei as old as 3.8 Ga such as those reported from the Anshan region in the Eastern Block (Liu et al., 1992; Song et al., 1996; Wan et al., 2001, 2005; Wu et al., 2005; Zhai, 2014). The seven microblocks in the NCC, welded together by Neoarchean greenstone belts representing oceanic sutures, are: Jiaoliao (JL), Qianhuai (QH), Ordos (OR), Ji’ning (JN), Alashan (ALS), Xuhuai (XH) and Xuchang (XCH) blocks (Zhai and Santosh, 2011; Zhai, 2014; Yang et al., 2015). These microblocks preserve evidence for subduction and accretion accompanied by arc magmatism, followed by collision resulting in partial melting and high grade metamorphism (Zhai and Santosh, 2011; Yang et al., 2015). Zircon U–Pb data show that the major crustal growth in the NCC occurred 2.9–2.7 Ga (Geng et al., 2002; Peng et al., 2012; Wang et al., 2012), and the amalgamation of the microblocks is proposed to have occurred at 2.6–2.5 Ga (Zhai and Santosh, 2011; Yang et al., 2015). The greenstone belts occurring along the margins of the microblocks are considered to represent island arc or back-arc basin setting suggesting an oceanic realm. Representative examples include the Zunhua greenstone belt in QH Block and JN Block, the Yanlingguan greenstone belt in the boundary of JL Block and QH Block, the Wutai greenstone belt in OR Block and QH Block, the Dongwufenzi greenstone in JN and OR Blocks, the Xuchang greenstone belt in XCH and QH Blocks, among others (Zhai and Santosh, 2011).

A suite of Neoarchean charnockites, amphibolites, metagabbros and orthogneisses from the Qianxi Complex were investigated by Yang et al. (2015) from the western margin of Jiaoliao microblock. Based on geochemical and zircon U–Pb and Lu–Hf data, they identified a Neoarchean convergent margin along the western margin of the Jiaoliao microblock. Yang et al. (2015) also proposed that multiple subduction zones might have been active during late Neoarchean building the fundamental tectonic framework of the craton.

The NCC witnessed Paleoproterozoic convergent margin processes including extensive arc magmatism (Zhao and Zhai, 2013; Santosh et al., 2015a; Yang and Santosh, 2015) associated with the final assembly of the craton involving the amalgamation of the Yinshan and Ordos Blocks into the unified Western Block along the IMSZ and the collision between the Eastern and Western Blocks along the TNCO. Within the TNCO, both convergent and divergent tectonics operated among microblocks during this period (Tang et al., 2015). The prolonged Precambrian evolution of the NCC involved multiple crustal growth recycling during Mesoarchean, Neoarchean and Paleoproterozoic (Zhai and Santosh, 2011) before the craton finally became a stable platform.

Fig. 1. Generalized geological and tectonic framework of the North China Craton showing the major crustal blocks and intervening suture zones. The location of Yishui Complex is shown by the box. (after Zhao et al., 2005; Santosh, 2010; Yang et al., 2015). Abbreviations: Xuanhua Block (XH), Huai’an Block (HA), Northern Hebei Block (NH), Chengde Block (CD), Chengshan Block (HS), Wutai Block (WT), Fuping Block (FP), Lüliang Block (LL), Zanhuang Block (ZH), Zhongtiao Block (ZT), Taihua Block (TH), and Dengfeng Block (DF).
3. Geology of the study area

The Yishui Complex is located in the Eastern Block of the NCC and occurs along the southern margin of the Jiaoliao microblock (Fig. 1). Previous studies have recorded a variety of rock suites in this complex ranging in age from 2.9 to 1.8 Ga (Shen et al., 1993, Su et al., 1999; Shen et al., 2004, 2007; Zhao et al., 2008; Song et al., 2009; Zhao et al., 2009, 2011; Wu et al., 2012, 2013; Zhao et al., 2013). The lithological units in this complex have been broadly classified into the Neoarchean granitoids and Mesoarchean metamorphic series exposed over an area of 12 × 23 km² (Fig. 2). The Neoarchean complex includes the Caiyu Terrane, Xueshan Terrane, Yinglingshan Terrane, Niuxinguanzhuang Terrane, Dashan Terrane, Linjiaguanzhuang Terrane, and Mashan Terrane. The Mesoarchean metamorphic units include mafic granulites, garnet- and sillimanite-bearing metapelitic gneiss (Shen et al., 2007; Zhao et al., 2009, 2013). Cao (1995) divided the Yishui Complex into the Shishanguanzhuang and Linjiguanzhuang groups. Zhao et al. (2008, 2009, 2011, 2013) presented zircon SHRIMP U–Pb ages from the Yinglingshan granite, Niuxinguanzhuang metapelite, ultramafic rocks and mafic granulite which show a range from 2530 to 2695 Ma. The Nd and Hf isotope data trace source rocks as old as 2997 Ma in this complex (Shen et al., 1993; Song et al., 2009). The Neoarchean Mashan, Xueshan, Caiyu and Dashan groups yielded U–Pb ages of 2538 ± 6 Ma, 2532 ± 9 Ma, 2562 ± 14 Ma, and 2545 ± 10 Ma (Shen et al., 2004, 2007). Recent LA-ICP-MS zircon ages from metapelites, granitoid gneisses and charnockites show ages of 2.54–2.53 Ga, 2.57–2.55 Ga, and 2.56–2.53 Ga, respectively. The zircon Hf isotopes show depleted mantle ages in the range of 2.92 to 2.60 Ga (Wu et al., 2012, 2013).

In this study, we include eleven representative samples from the Yishui Complex for geochemistry, U–Pb dating and Lu–Hf analysis. These samples include four granitoids, two metavolcanics, and one each of volcanic tuff, banded iron formation (BIF), pyroxenite, quartzite, and diabase (Fig. 2, Table 1). A brief description of the field occurrence of the various rock types is given below, and representative field photographs of the various rock types are shown in Fig. 3.

A hillock section to the east of Changjiagou village exposes thick bedded volcanic tuff in association with trondhjemitic leuco granite and aplitic veins. The rocks have been deformed and sliced and occur as imbricated layers (Fig. 3a). The felsic volcanic tuff is fine grained and the layers range in thickness from 3 to 5 m. These rocks have been thrust upon medium grained trondhjemitic leuco granite slivers...
with an assemblage of plagioclase, quartz, minor biotite and secondary K-feldspar. The rocks have been metamorphosed and show obvious foliation (Fig. 3b).

Leucocratic granitoids are widely exposed in the Yishui Complex and most of these show weak foliation and effects of metamorphism. The granite samples YS-6C, YS-6D and YS-6E in this study collected from Changjiagou village are white to pinkish and medium grained and occurs as slivers in association with felsic volcanic tuff layers. Granite sample YS-15A was collected from Bingfangling village where leucocratic gneissic granites are exposed along a road cutting. The rocks are composed of elongate quartz and white felspar, set in a medium to coarse grained texture. Altered diabase dykes varying in width from 0.5 to 1.0 m cut across the granite (Fig. 3c).

Metavolcanic samples YS-10A and YS-10B were collected from a gold mine in the Nanxiaoyao village. The rocks are fine grained, schistose and dark greenish with abundant sulfide mineralization, either

### Table 1

Sample numbers, localities, rock types, GPS reading and mineralogy assemblage of samples from the different groups of Yishui Complex.

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Sample No.</th>
<th>Locality</th>
<th>Rock type</th>
<th>Coordinates</th>
<th>Assemblage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>YS-6B</td>
<td>Changjiagou</td>
<td>Volcanic tuff</td>
<td>N35°49.544′, E118°41.542′</td>
<td>Bt + Kfs + Qtz + Pl</td>
</tr>
<tr>
<td>2</td>
<td>YS-6C</td>
<td>Changjiagou</td>
<td>Granite</td>
<td>N35°49.544′, E118°41.542′</td>
<td>Qtz + Kfs + Mic + Pl + Bt + Hbl</td>
</tr>
<tr>
<td>3</td>
<td>YS-6D</td>
<td>Changjiagou</td>
<td>Granite</td>
<td>N35°49.544′, E118°41.542′</td>
<td>Qtz + Kfs + Mic + Pl + Bt + Hbl</td>
</tr>
<tr>
<td>4</td>
<td>YS-6E</td>
<td>Changjiagou</td>
<td>Granite</td>
<td>N35°49.544′, E118°41.542′</td>
<td>Qtz + Kfs + Mic + Pl + Bt + Hbl</td>
</tr>
<tr>
<td>5</td>
<td>YS-10A</td>
<td>Nanxiaoyao</td>
<td>Metavolcanic</td>
<td>N35°45.318′, E118°40.666′</td>
<td>Chl + Pl + Py + Cal + Qtz</td>
</tr>
<tr>
<td>6</td>
<td>YS-10B</td>
<td>Nanxiaoyao</td>
<td>Metavolcanic</td>
<td>N35°45.318′, E118°40.666′</td>
<td>Qtz + Mag + Amp + Br</td>
</tr>
<tr>
<td>7</td>
<td>YS-14A</td>
<td>Qianyianjiu</td>
<td>BIF</td>
<td>N35°46.217′, E118°39.950′</td>
<td>Qtz + Mag + Amp + Br</td>
</tr>
<tr>
<td>8</td>
<td>YS-14E</td>
<td>Qianyianjiu</td>
<td>Pyroxenite</td>
<td>N35°46.217′, E118°39.950′</td>
<td>Hbl + Opx + Pl</td>
</tr>
<tr>
<td>9</td>
<td>YS-14F</td>
<td>Qianyianjiu</td>
<td>Quartzite</td>
<td>N35°46.217′, E118°39.950′</td>
<td>Qtz</td>
</tr>
<tr>
<td>10</td>
<td>YS-15A</td>
<td>Bingtangling</td>
<td>Granite</td>
<td>N35°44.527′, E118°39.739′</td>
<td>Qtz + Kfs + Mic + Pl + Bt + Hbl</td>
</tr>
<tr>
<td>11</td>
<td>YS-15B</td>
<td>Qinglongyu</td>
<td>Diabase</td>
<td>N35°46.132′, E118°42.500′</td>
<td>Cpx + Pl + Amp + Chl + Mag</td>
</tr>
</tbody>
</table>

Mineral abbreviations: Bt—biotite; Kfs—K-feldspar; Pl—plagioclase; Opx—Orthopyroxene; Hbl—hornblende; Qtz—quartz; Mic—microcline; Chl—chlorite; Py—pyrite; Cal—calcite; Mag—magnetite; Amp—amphibole; Cpx—clinopyroxene.

**Fig. 3.** Representative field photographs: (a) Felsic volcanic tuff exposes association with trondhjemite leucogranite and aplite veins. (b) Fine grained felsic volcanic tuff layers. (c) Medium grained granite with typical granitic texture. (d) Greenish metavolcanic from gold mine carrying thin quartz veins with sulfides. (e) Banded iron formation (BIF). (f) Greenish gray pyroxenite.
scattered in the rock matrix, or occurring as coarser aggregates in close association with calcite and quartz veins traversing the host metavolcanics (Fig. 3d).

The BIF sample YS-14A was collected from a discontinuous band of iron formation in Qianyanjiapu village that shows two types of textures: (1) as cherry red colored thinly banded layers of hematite and cryptocrystalline quartz; and (2) as broad and coarse recrystallized bands of magnetite and quartz, together with other minor mafic minerals (Fig. 3e). The quartzite sample YS-14F was collected from a quartzite band occurring adjacent to the BIF band above. The rock shows recrystallization into medium to coarse pale to milky quartz.

The pyroxene sample YS-14E was collected from the same location as above where blocks and boudins of the ultramafic rock occur around 50 m across the BIF band. The rock is dark greenish and foliated, medium to coarse grained and shows cumulative texture (Fig. 3f).

The diabase sample YS-15B was collected from a dyke intruding leuco granites from the Qinglongyu village in the southwest-western part of the study area. The rock is greenish and fined grained.

4. Analytical methods

4.1. Petrography

Polished thin sections for petrographic study were prepared at the Peking University, China. Petrographic and thin section studies were carried out at the Institute of Earths Sciences, China University of Geosciences Beijing.

4.2. Geochemistry

The least altered and homogeneous portions of seven representative rock samples were crushed and powered to 200 mill for geochemical analyses after petrographic observation. Major and trace (including rare earth elements) elements analyses were conducted in the National Research Center for Geoanalysis, Beijing. The major elements were determined by X-ray fluorescence (XRF model PW 4400), with an analytical uncertainty 1–3%. Loss on ignition was obtained using about 1 g of sample powder heated at 980 °C for 30 min. Trace elements were determined as solute by Agilent 7500ce inductively coupled plasma mass spectrometry (ICP-MS). About 50 mg of powder was dissolved in 7 N HNO3 and taken to incipient dryness again, and then was dissolved in 7 N HNO3 and taken to incipient dryness again, and then was re-dissolved in 2% HNO3 to a sample/solution weight ratio of 1:1000. The analytical errors range from 5 to 10% depending on the concentration of any given element. During analysis an internal standard was used for monitoring drift and more details are given by Gao et al. (2008).

4.3. U–Pb dating and Lu–Hf analysis

Zircon separation for U–Pb dating and Hf analysis was performed at the Yu'Eneng Geological and Mineral Separation Centre, Langfang City, Hebei Province, China and after gravimetric and magnetic separation zircon grains were selected by hand picking under the binocular microscope from the crushed rock powder. The grains were mounted onto an epoxy resin discs and then polished to expose the internal texture. Cathodoluminescence (CL), transmitted and reflected light images were used for checking the internal textures to choose the most suitable sites for U–Pb analyses.

Zircon U–Pb dating and element analyses were carried out on a laser ablation inductively coupled plasma spectrometry (LA-ICP-MS) housed at National Key Laboratory of Continental Dynamics of Northwest University, Xi’an following the analytical procedures described by Yuan et al. (2004). In the LA-ICP-MS method, the laser spot diameter and frequency were 30 μm and 10 Hz, respectively. Standard zircon 91500 is for the data correcting and silicate glass NIST was used to optimize the instrument. The raw data were processed using ISOPLOT 4.15 software Yuan et al. (2004) and common Pb correction were used the method of Anderson (2002).

In situ zircon Hf isotopic analyses were performed at Tianjin Institute of Geology and Mineral Resources using a Neptune MC-ICP-MS equipped with a 193 nm laser at the IGGAS, with a spot size of 50 μm and a laser repetition rate of 10 Hz at 100 mJ. More detailed analytical procedure and correction are described by Wu et al. (2006). The zircon (GJ-1) and (Mud Tank) were analyzed as a standard with 176Hf/177Hf ratio of 0.282000 ± 0.000030 (2σ, n = 200) and 0.282500 ± 0.000030 (2σ, n = 200), respectively. The 176Hf/177Hf ratio of GJ-1 is similar to Ehlou et al. (2006) reported and Mud Tank is based on the long-term extensive LA–MC-ICP-MS analyses (Woodhead and Hergt, 2005; Griffin et al., 2006).

5. Results

5.1. Petrography

5.1.1. Volcanic tuff

The representative sample YS-6B from the volcanic tuff is biotite-rich (25–30 vol.%), together with K-feldspar (25–30 vol.%), quartz (15–20 vol.%), and plagioclase (15–20 vol.%). Fine grained magnetite and zircon occur as accessories (<5 vol.%) (Fig. 4a). The brownish biotite laths defining the foliation of the rock are highly altered. K-feldspar is the dominant mineral, which is medium to fine grained (0.6–1.6 mm), and subhedral. The quartz is equigranular, fine grained (0.4–1.1 mm) and shows rounds to prismatic morphology. Most of plagioclase is medium to fine grained (0.3–0.8 mm), and subhedral to anhedral.

5.1.2. Granite

The granite shows white to pink color with medium grained granitic texture. Three granite sample YS-6C, YS-6D and YS-6E show similar composition and typical granoblastic texture. The rock is composed of K-feldspar (mostly microcline 30–40 vol.%), quartz (20–35 vol.%), plagioclase (10–15 vol.%), biotite (5–10 vol.%), and minor hornblende (<5 vol.%), with zircon and magnetite as accessory (Fig. 4b). Quartz is rounded to prismatic, medium to fine grained (0.4–1.1 mm), euhedral to anhedral and shows wavy extinction. The K-feldspar is coarse to medium grained (0.5–1.2 mm). Plagioclase is coarse medium grained (0.3–1.0 mm) and altered. Hornblende also shows partial alteration.

Granite sample YS-15A collected from Bingfangling village shows similar composition with the previous sample and is composed of K-feldspar (30–40 vol.%), quartz (20–30 vol.%), plagioclase (10–15 vol.%), and hornblende (10–15 vol.%).

5.1.3. Metavolcanics

Metavolcanics in the Nanxiangyao village have been mined for gold. The greenish basalts here carry quartz veins with sulfide mineralization which is the principal ore for gold mining.

The sample YS-10A and YS-10B for this study are fine grained and schistose metavolcanic rocks composed of chlorite (15–20 vol.%), plagioclase (20–25 vol.%), pyrite (20–25 vol.%), calcite (10–15 vol.%), quartz (5–10 vol.%), and accessory epidote and zircon (<5 vol.%). The greenish chlorite-rich matrix is cut across by calcite veins. Fine grained plagioclase and quartz are also found in the matrix. Pyrite is medium to coarse grained (0.5–2.3 mm), cubic to anhedral morphology and shows pale yellow color. Epidote is also fine grained (Fig. 4c).

5.1.4. Banded iron formation (BIF)

The BIF was sampled in this study from a band in the Qianyanjiapu village which shows typical alternating layers of iron oxide and...
cryptocrystalline silica. The rock has been metamorphosed iron oxide shows recrystallization to magnetite.

The sample YS-14A of BIF is composed of quartz (40–50 vol.%), magnetite (20–25 vol.%), amphibole (10–15 vol.%), plagioclase (5–10 vol.%) and biotite (5–10 vol.%) with few zircon grains as accessory. Quartz is recrystallized and cryptocrystalline, fine to medium grained (0.6–1.5 mm), and shows rounded to anhedral elongated morphology. Magnetite is medium to coarse grained (0.5–5.5 mm) and occurs as bands or as inclusions in quartz and biotite. Brownish biotite is medium to coarse grained (0.3–1.3 mm) and altered (Fig. 4d).

5.1.5. Pyroxenite

The sample YS-14E was collected from the same location as above, and is composed of hornblende (45–55 vol.%), orthopyroxene (35–45 vol.%), and plagioclase (3–5 vol.%), with magnetite and zircon as accessory (Fig. 4e,f). The hornblende and orthopyroxene are medium to coarse grained (0.2–3.0 mm). A part of orthopyroxene is replaced by hornblende. Plagioclase is fine to medium grained (up to 0.8 mm), and sometimes occurs as inclusions in hornblende or within the matrix showing polysynthetic twin. Biotite is coarse grained (0.9–1.5 mm) and brownish in color.

5.1.6. Quartzite

The quartzite band occurs in association with the BIF described above and is medium to coarse grained. The dominant mineral is quartz with accessory zircon.

5.1.7. Diabase

The sample YS-15B of diabase was collected from a dyke intruding leuco granites southwest of Qinglongyu village. The rock is fine grained and composed of clinopyroxene (30–35 vol.%), plagioclase (25–30 vol.%), and amphibole (10–15 vol.%), together with magnetite and chlorite (10–15 vol.%) and accessory zircon, similar to Zhao et al. (2013) reported.

5.2. Geochemistry

The whole rock geochemical data are given in Table 2 (Supplementary data), including major, minor, trace and rare earth elements in seven representative sample from Yishui Complex. These include four granites, two metavolcanics and one pyroxenite, and the data are plotted in Figs. 5–8. The total alkali (Na₂O + K₂O) and SiO₂ content are utilized to classify the protolith, and the trace elements are employed for tectonic discrimination.
The granites show high SiO$_2$ concentration and narrow variations within the range of 74.01–75.63 wt.%, and moderate variation in Al$_2$O$_3$ (13.33–13.76 wt.%), Fe$_2$O$_3$ (0.28–1.26 wt.%), and CaO (0.34–1.44 wt.%). Their total alkalis (Na$_2$O + K$_2$O) range from 7.94 to 9.86 wt.%. The two metavolcanic samples display moderate variation in their major element contents (SiO$_2$ between 49.01 and 50.11 wt.%, Al$_2$O$_3$ 11.97 and 13.15 wt.%, Fe$_2$O$_3$ 15.79 and 14.28 wt.%, CaO 2.94 and 3.34 wt.%). The Mg # varies from 35.61 and 40.90 and the (Na$_2$O + K$_2$O) concentration shows minor variation from 4.06 and 4.31. The pyroxenite shows high Fe$_2$O$_3$ (10.85 wt.%), MgO (20.27 wt.%) and CaO (6.59 wt.%). Their Mg # is up to 78.72 (Table 2, Supplementary data). In TAS plot (Wilson, 1989), the four granite samples fall in the granite field whereas the pyroxenite displays gabbro to gabbroic diorite features. The metavolcanics are located in the basalt field. These classifications broadly correlate with those inferred from the mineral assemblages (Fig. 5a, b).

Two metavolcanic samples display high ΣREE concentration compared to the other samples (Table 2, Supplementary data). The mafic rocks show considerable variation of Sc 23.6–38.2 ppm, V 168–364 ppm, Cr 39.9–86.6 ppm, Ni 67.1–807 ppm, Zn 74.1–182 ppm. The large iron lithophile element (LILE) concentration of the granite samples shows considerable variation (Rb 84.5–170 ppm, Ba 779–1688 ppm). The high field strength elements (HFSE) including Zr, Hf, Nb, Ta contents are higher for the metavolcanics. In the chondrite-normalized REE patterns, the granite sample shows LREE enriched nature, with a large range of (La/Yb)$_N$ from 8.8 to 94.7 (Fig. 6a) (McDonough and Sun, 1995). The pyroxenite and metavolcanics show narrow LREE/HREE fractionation. They show moderate variation of (Gd/Yb)$_N$ (1.0–3.3), (La/Sm)$_N$ (1.2–4.8), and Dy/Yb (0.6–1.8). The pyroxenite displays a broadly tholeiitic affinity. The metavolcanics show minor negative Eu anomalies, whereas the granite and pyroxenite samples do not display any obvious Eu anomalies.

![Fig. 5. Plots of SiO$_2$ vs. Na$_2$O + K$_2$O diagram, (a) for plutonic rocks, and (b) for volcanic rocks from the Yishui Complex. Fields after Wilson (1989).](image-url)
In primitive-mantle normalized (Sun and McDonough, 1989) trace elements diagram (Fig. 6b), the rocks show obvious Rb, Pb, Nd enrichment, and Sr, Th, U, Nb depletion (except metavolcanics), together with marked variation of Nb/Yb (0.69–10.83) and Th/Yb (0.26–13.33) ratio, suggesting crustal input. The granite sample also shows continental feature with positive (La, Pb, Zr, Hf) anomalies and negative (Th, Ta, La) anomalies.

In Th–Hf–Ta diagram (Wood, 1980), the granite and pyroxenite samples fall within the island arc basalt field and the metabasalts are located in the MORB and OIB fields (Fig. 7a). In the Y–La–Nb diagram, the granite samples fall in the volcanic-arc field, whereas the pyroxenite is located in the tholeiitic field (Fig. 7b). From (Fig. 8), Th/Yb versus Nb/Yb (Pearce, 2008) relations of the metabasalt and one granite display oceanic island basalt affinity whereas the pyroxenite shows E-MORB feature and slightly depleted source. The other three granite samples fall in the active continental margin field suggesting crustal input. The Nb/Yb ratio of the alkali basalts is markedly higher than that of typical tholeiitic basalt.

5.3. Zircon U–Pb geochronology

Representative cathodoluminescence (CL) images of zircons from the different rocks are shown in Figs. 9–11, together with the analytical spots. The U–Pb age data are presented in Table 3 (Supplementary data), which are plotted in concordia diagrams together with age data histograms and bar charts. The zircon characteristics and age results in individual samples are discussed below.

5.3.1. Zircon morphology

5.3.1.1. Volcanic tuff. In CL images, the zircon grains from volcanic tuff (sample YS-6B) display well-defined prismatic to stumpy morphology. Most of the grains are colorless and some show light brownish color. The zircons show grain size of 80–120 μm × 100–200 μm and aspect ratios of 2:1 to 1.2:1 (Fig. 9a). The grains are transparent to translucent and show clear oscillatory zoning at the core, with overgrowth metamorphic rim. Some zircon grains show subhedral to anhedral morphology and thin unzoned overgrowth with light luminescence and a typical core–rim boundary. The cores show bright domains.

5.3.1.2. Granite. The zircons from granite sample YS-6C show prismatic shape and few zircons are anhedral. Most grains are dark brown in color with size range of 120–200 μm × 120–300 μm and aspect ratios of 3:1 to 1:1. (Fig. 9b). Under CL, some zircons display a clear core–rim boundary with oscillatory zoned core surrounded by a very thin luminescent rim.

5.3.1.3. Metavolcanics. Zircons from sample YS-10A of the metavolcanic rock are very small and show prismatic or elliptical morphology. Most grains are light brownish and transparent. They show euahedral to anhedral shape with length varying from 50–80 μm × 50–150 μm and aspect ratio of 2:1 to 1:1. In CL images, the grains show a typical core–rim structure with a very thin luminescent boundary. Some grains show patchy zoning and sector zoning, suggesting a metamorphic recrystallization (Fig. 10a).

Fig. 6. (a) Chondrite-normalized REE patterns for granite (YS-6C), metavolcanic (YS-10A, YS-10B), pyroxenite (YS-14E) are from McDonough and Sun, 1995. (b) Primitive mantle-normalized multi-element variation diagrams from Sun and McDonough, 1989.

Fig. 7. Discrimination diagram for the rocks from Yishui Complex. (a) Hf/3–Th–Ta diagram. (b) Y/15-La/10-Nb/8 diagram. Fields after Wood, 1980.
5.3.1.4. BIF. Zircon grains from the BIF sample display irregular structure and a weak core–rim boundary. Most zircons show dark brownish color with no oscillatory zoning. They range in size from 50–100 μm × 150–350 μm with aspect ratio of 2.5:1 to 1.5:1 (Fig. 10b).

5.3.1.5. Pyroxenite. Zircons from the pyroxenite are light brownish and some grains show recrystallization with thin luminescent rim (Fig. 10c). They are stumpy to rounded in shape and are small in size from 40–60 μm to 60–70 μm with aspect ratio of 1.5:1 to 1:1. They show patchy or banded zoning under CL.

5.3.1.6. Quartzite. The zircons from quartzite sample display light to dark brownish color with weak oscillatory zoning in some grains. Some grains show clear core–rim boundary consistent with bright core domains and overgrowth rim. They show prismatic to stubby structure and anhedral morphology. The grains range in size from 30–80 μm to 60–200 μm with aspect ratio of 3:1 to 1.5:1 (Fig. 11a).

5.3.1.7. Diabase. The zircon grains in this rock display irregular stubby to rounded shape with light brownish color. They show a large size range of 120–200 μm × 150–300 μm with aspect ratio of 3:1 to 1:1 (Fig. 11b). Most grains show typical core–rim boundary with overgrowth. Some of the grains show weak oscillatory, patchy or sector zoning.

5.3.2. U–Pb data

5.3.2.1. Volcanic tuff. Totally thirty spots were analyzed on both magmatic cores and overgrowth rims of thirty zircons of the felsic volcanic tuff sample YS-6B. Their Th contents range from 52 to 644 ppm and U contents show a range of 138–770 ppm. The Th/U ratios are in the range of 0.21–0.83 and these high values are typical of magmatic zircons. The age data can be divided into two groups as follows. The first group includes sixteen concordant spots yielding 207Pb/206Pb weighted mean age of 2476 ± 17 Ma (MSWD = 0.084, N = 16) with high concordance (100%). The second group contains fourteen spots that define a discordia (except spot 30) with upper intercept age of 2503.9 ± 8.6 Ma (MSWD = 0.23, N = 13) which is comparable with the 207Pb/206Pb mean age of 2504 ± 19 Ma (MSWD = 0.048, N = 13) and show high concordance (>99%) (Fig. 12).

5.3.2.2. Granite. Thirty zircon grains were dated from sample granite YS-6C, the results from which can be divided into two groups. The first group includes eighteen spots which show Th contents ranging from 60 to 834 ppm and U contents from 208 to 1967 ppm and Th/U values of 0.39–0.42, suggesting magmatic crystallization. The data yield 207Pb/206Pb mean age of 2526 ± 16 Ma (MSWD = 0.25, N = 18) with high concordance (>95%). The second group defined by ten spots show Th contents of 104 to 414 ppm and U contents of 305 to 802 ppm with high Th/U ratio 0.25–0.39. The age data fall along a discordia defining upper intercept age of 2590 ± 20 Ma (MSWD = 1.06, N = 10) and 207Pb/206Pb mean age of 2581 ± 21 Ma (MSWD = 0.25, N = 10) with high concordance (95%). Some grains show Pb loss (Fig. 13).

5.3.2.3. Metavolcanic. Twenty-eight spots were dated from twenty zircon grains from the metavolcanic sample YS-10A and the results can be divided into two groups. The first group is represented by fifteen zircon spots showing Th contents ranging from 153 to 425 ppm and U from 210 to 487 ppm with high Th/U values of 0.51 to 0.87 consistent with magmatic crystallization. The data define a discordia upper intercept age of 2457 ± 13 Ma (MSWD = 0.23, N = 15) and a 207Pb/206Pb mean age of 2451 ± 18 Ma (MSWD = 0.43, N = 15) with high concordance (except spot 19 with discordance more than 22%). The second group comprises thirteen zircon spots showing Th contents ranging from 121 to 583 ppm and U contents of 173 to 540 ppm, with high Th/U ratios of 0.36–1.25 consistent with igneous crystallization. These spots fall along a discordia with upper intercept age of 2504 ± 12 Ma (MSWD = 0.89, N = 13). The 207Pb/206Pb mean age is 2501 ± 19 Ma (MSWD = 0.21, N = 13) with high concordance (except spot 5). Some grains show Pb loss (Fig. 14).

5.3.2.4. Banded iron formation. Twenty five spots were analyzed from twenty five zircon of the BIF sample YS-14A and the data can be divided into five groups. The oldest data age comes from one grain with spot age of 2503 Ma, which shows Th content 56 ppm and U content 421 ppm with low Th/U ratio 0.13. Four younger spots (spot 1, 2, 14, 30) can be divided into two groups with a high concordance (>95%). The youngest group includes two spots with age 1781 Ma and 1785 Ma and show low Th/U ratio 0.05. The other group shows spot ages of 1999 Ma and 2025 Ma and also with low Th/U ratio 0.05. Eight spots fall along a discordia with an upper intercept age of 2179 ± 54 Ma (MSWD = 1.13, N = 8) and a 207Pb/206Pb mean age of 2093 ± 36 Ma (MSWD = 1.5, N = 8). Their Th contents show a range of 70–1454 ppm and U contents show a range of 1574–2471 ppm, with low Th/U ratios of 0.04–0.06 (excluding spot 7 with the Th/U ratio of 0.59). The last group includes twelve zircon spots spread along a discordia with an upper intercept age of 2381 ± 15 Ma (MSWD = 0.57, N = 12) and a 207Pb/206Pb mean age of 2372 ± 24 Ma (MSWD = 0.14, N = 8) with high concordance (excluding spots 4, 23, 27, 28). Their Th content ranges from 114 to 461 ppm and U contents from 2259 to 3817 ppm with low Th/U ratio 0.04–0.17. The variable ages and low Th/U ratios in most cases suggest a mixture of detrital and metamorphic zircons (Fig. 15).

5.3.2.5. Pyroxenite. Nine spots were analyzed in nine zircon grains from pyroxenite sample YS-14E. These spots can be divided into two groups. The first one includes four spots that fall along discordia with an upper intercept age of 2466 ± 23 Ma (MSWD = 1.19, N = 4) and show high concordance (except spot 17 with discordance more than 25%, considered as statistical outlier). Their Th contents range from 143 to 429 ppm and U from 436 to 1299 ppm with high Th/U ratio of 0.32 to 0.53. The second group includes five spots that fall along a discordia with an upper intercept age of 2537 ± 38 Ma (MSWD = 0.73, N = 5). These spots show Th contents ranging from 110 to 425 ppm and U...
from 283 to 882 ppm with Th/U ratios of 0.18–0.61. Some grains show Pb loss (Fig. 16).

5.3.2.6. Quartzite. Twenty four spots were analyzed from twenty four zircon grains in sample YS-14F, which can be divided into two groups. The first one includes sixteen spots spread on a well-defined discordia with upper intercept age of 2417.6 ± 6.9 Ma (MSWD = 0.76, N = 16) and a 207Pb/206Pb mean age of 2421 ± 19 Ma (MSWD = 0.18, N = 13) with a high concordance (95%). They show Th contents ranging from 75 to 513 ppm and U contents of 489 to 1832 ppm with a range of Th/U ratios from 0.09 to 0.38. The second group includes eight spots falling along a discordia with upper intercept age of 2478 ± 25 Ma (MSWD = 1.5, N = 8) and 207Pb/206Pb mean age of 2495 ± 24 Ma (MSWD = 0.38, N = 8). They show high concordance (>95%) and some grains show Pb loss. Their Th contents range from 91 to 386 ppm and U from 311 to 1007 ppm with Th/U ratios in the range of 0.15 to 0.42 (Fig. 17).

5.3.2.7. Diabase. Thirty spots were analyzed from sample YS-15B. Excluding two spots (spot 12, 28) which show younger age of 2440 Ma and 2467 Ma, the other twenty eight spots fall along a well-defined discordia with upper intercept age of 2507.4 ± 7.6 Ma (MSWD = 0.17, N = 28) and 207Pb/206Pb mean age of 2506 ± 13 Ma (MSWD = 0.04, N = 27) with high concordance >99% (except spot 1). The grains show Th contents ranging from 70 to 853 ppm and U contents from 155 to 808 ppm and high Th/U ratios of 0.32–1.06, suggesting magmatic crystallization (Fig. 18).

5.4. Lu–Hf isotopes

Lu–Hf isotopes were analyzed in the same domains in the zircon grains from where U–Pb age data were gathered. The results are presented in Table 4, plotted in Fig. 19a, b, and briefly discussed below.

5.4.1. Volcanic tuff

Eight zircons from volcanic tuff (sample YS-6B) display initial \(^{176}\text{Hf}/^{177}\text{Hf}\) values between 0.281178 and 0.281436. Among these, four zircons show both positive and negative \(\varepsilon\)Hf(t) values in the range of −3.1 to 6.6 with an average of 2.5, when calculated by the \(207\text{Pb}/206\text{Pb}\) mean age of 2476 ± 17 Ma from high concordance grains (>95%). Their Hf crustal residence ages (\(T_{DM}\)) range from 2586 to

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**Fig. 9.** Representative Cathodoluminescence (CL) images of zircon grains from volcanic tuff (sample YS-6B), granite (sample YS-6C) of Yishui Complex. Zircon U–Pb ages (Ma) and \(\varepsilon\)Hf(t) values are also shown. The smaller yellow circles indicate spots of LA-ICP-MS U–Pb dating, whereas the larger red circles represent locations of Hf isotopic analyses.
3181 Ma and Hf depleted mantle model ages (TDM) are 2548–2927 Ma. The other four zircons display positive εHf(t) values of 1.4 to 4.7 with an average of 2.2, when calculated by the upper intercept age of 2503.9 ± 8.6 Ma. Their crustal residence ages (TDMc) range from 2723 to 2919 Ma and depleted mantle Hf model (TDM) age is 2642–2764 Ma (Table 4). The data suggest that the magma was sourced from Meso- and Neoarchean juvenile mantle components with limited reworked crustal materials.

5.4.2. Granite

Eight zircons spots were analyzed from granite sample (YS-6C), which shows initial 176Hf/177Hf values between 0.281292 and 0.281376. These zircons can be divided into two groups. The first group includes three grains with positive εHf(t) values between 5.2 and 6.6 and an average of 5.7, when calculated by the 207Pb/206Pb mean age of 2590 ± 20 Ma. Their crustal residence ages (TDMc) range from 2684 to 2739 Ma and depleted mantle Hf model (TDM) age is 2659–2680 Ma. The other group displays positive εHf(t) values between 2.8 to 5.7 with an average of 4.0, when calculated by the upper intercept age of 2526 ± 13 Ma. Their crustal residence ages (TDMc) range from 2854–3017 Ma and depleted mantle Hf model (TDM) age is 2690–2777 Ma (Table 4). The data indicate that the zircons crystallized in magmas sourced from Meso- and Neoarchean juvenile mantle components with limited reworked crustal materials.

5.4.3. Metavolcanics

Six zircon grains from the metavolcanic sample can be divided into two groups. The first group includes two zircons, which display initial 176Hf/177Hf values 0.281213 and 0.281277 with εHf(t) values of 0.1 and 1.3 and an average of 0.7, when calculated by the upper intercept age of 2504 ± 12 Ma. Their crustal residence ages (TDMc) are 2925 and 3006 Ma and depleted mantle Hf model (TDM) age is 2768 Ma, 2819 Ma, respectively. The other group includes four zircons show initial 176Hf/177Hf values 0.281260 and 0.281324 with εHf(t) values in the range of −1.8 to 2.0 and an average of 0.6, when calculated by the upper intercept age of 2457 ± 13 Ma. Their crustal residence ages (TDMc) range from 2854–3017 Ma and depleted mantle Hf model (TDM) age is 2690–2777 Ma (Table 4). The data indicate that the zircons crystallized in magmas sourced from Meso- and Neoarchean juvenile mantle components with limited reworked crustal materials.

5.4.4. Quartzite

One zircon grain from quartzite sample (YS-14F) shows initial 176Hf/177Hf value of 0.281373 with a positive εHf(t) values of 4.5, when calculated by 207Pb/206Pb age 2481 Ma. Its crustal residence age (TDMc) is 2711 Ma and depleted mantle Hf model (TDM) age is 2625 Ma. The other four zircon spots show initial 176Hf/177Hf values between 0.281286 and 0.281351 with positive εHf(t) values of 1.4 to 2.3 and an average of 1.7, when calculated by the upper intercept age of 2417.6 ± 6.9 Ma from high concordance grains (>95%). They yield crustal residence...
Fig. 11. Representative Cathodoluminescence (CL) images of zircon grains from quartzite (YS-14F), diabase (YS-15B). $^{207}\text{Pb}/^{206}\text{Pb}$ ages and $\varepsilon_{\text{Hf}}(t)$ values are also shown. The smaller yellow circles indicate spots of LA-ICP-MS U–Pb dating, whereas the larger red circles represent locations of Hf isotopic analyses.

Fig. 12. U–Pb concordia plots (a) and age data histograms with probability curves (b) for volcanic tuff (YS-6B). All the ages in histograms are $^{207}\text{Pb}/^{206}\text{Pb}$ ages.
ages (\(T_{DM}\)) range from 2808 to 2884 Ma and depleted mantle Hf model (\(T_{DM}\)) age is 2668–2722 Ma, suggesting that the magmatic source which supplied the detritus crystallized from magma source Meso- and Neoarchean juvenile sources (Table 4).

5.4.5. Diabase

Eight zircons from diabase sample (YS-15B) show initial \(^{176}\text{Hf}/^{177}\text{Hf}\) values between 0.281261 and 0.281425 and positive \(\varepsilon_Hf(t)\) values of 1.7 to 5.4 with an average of 4.2, when calculated by \(^{207}\text{Pb}/^{206}\text{Pb}\) mean age of 2506 ± 13 Ma on high concordance grains (>95%). The data yield crustal residence ages (\(T_{DM}\)) ranging from 2677 to 2909 Ma and depleted mantle Hf model (\(T_{DM}\)) age is 2612–2759 Ma (Table 4). The data indicate that the magma was derived from Meso- and Neoarchean juvenile mantle with limited reworked crustal material.

6. Discussion

6.1. Summary of lithological and geochemical features

The lithological assemblages reported in this study from the southern margin of the Jiaoliao microblock including granitoids, diabase, volcanic tuff, banded iron formation, quartzite and basalt (metavolcanics) (Fig. 20) suggest a typical continent–trench–ocean section (Santosh et al, 2015a). The sliced and tectonically imbricated nature of the volcanic tuff and leucogranite suggest accretionary processes along a convergent margin boundary. The gold-bearing metavolcanics form part of metamorphosed basaltic ocean crust, with the BIF sequence deposited on top, and accreted onto the continent together with the continental detritus in the trench represented by quartzite and the arc-derived detritus represented by the felsic volcanics.

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Fig. 13. U–Pb concordia plots (a) and age data histograms with probability curves (b) for granite (YS-6C). All the ages in histograms are \(^{207}\text{Pb}/^{206}\text{Pb}\) ages.

Fig. 14. U–Pb concordia plots (a) and age data histograms with probability curves (b) for metavolcanic (YS-10A). All the ages in histograms are \(^{207}\text{Pb}/^{206}\text{Pb}\) ages.
The high SiO₂ concentration and enrichment in LREE in the granitoids are typical of calc-alkaline felsic magmas generated in convergent settings. The metavolcanics show minor negative Eu anomalies, whereas the granite and pyroxenite samples show a flat REE pattern with no obvious Eu anomalies. All the rocks except the pyroxenite display LILE enrichment. The granite shows positive La, Pb, Zr, Hf anomalies, and negative Th, Ta, La anomalies. The tectonic discrimination diagrams show that the mafic rocks have variable IAB, MORB and OIB affinities typical of rocks formed in an island arc related subduction environment.

6.2. Summary of zircon U–Pb age data

Zircon grains in most of the rocks from Yishui Complex display core-rim texture with the cores representing magmatic crystallization and the narrow structureless rims corresponding to metamorphic overgrowth. The zircons from volcanic tuff show two groups, one with upper intercept age of 2503.9 ± 8.6 Ma and 207Pb/206Pb mean age of 2504 ± 19 Ma representing magmatic crystallization and the second group showing 207Pb/206Pb weighted mean age of 2476 ± 17 Ma corresponding to metamorphism (Fig. 12). Zircons from granite sample YS-6C also show two populations, the first falling along a discordia line with upper intercept age of 2590 ± 20 Ma and 207Pb/206Pb mean age of 2581 ± 21 Ma, and the second group of concordant zircons showing 207Pb/206Pb mean age of 2526 ± 16 Ma, both corresponding to magmatic events (Fig. 13). Among the two groups of zircons from the metavolcanics, the first one shows upper intercept age of 2504 ± 12 Ma and 207Pb/206Pb mean age 2501 ± 19 Ma whereas the second group falls along a discordia with upper intercept age of 2457 ± 13 Ma and 207Pb/206Pb mean age of 2451 ± 18 Ma (Fig. 14). Zircons from BIF show multiple population with the oldest showing a spot age of 2503 Ma (Fig. 15), followed by a number of distinct groups with the first two showing upper intercept ages of 2381 ± 15 Ma and 2179 ± 54 Ma the remaining two showing spot ages of 2025 Ma, 1999 Ma, 1781 Ma and 1785 Ma. The Paleoproterozoic ages can be broadly correlated with the multiple thermal events in the NCC during this period (Zhai and Santosh, 2011; Yang and Santosh, 2015). Nine zircon spots from pyroxenite fall into two age groups, the first defining upper intercept age of 2537 ± 38 Ma and the second yielding upper intercept age of 2466 ± 23 Ma (Fig. 16). Age data from twenty four zircon grains in the quartzite sample show two populations with 207Pb/206Pb mean ages of 2495 ± 24 Ma (Fig. 17) and 2421 ± 19 Ma. Zircons from the diabase show a well-defined discordia with upper intercept age of 2507.4 ±
7.6 Ma and $^{207}\text{Pb}/^{206}\text{Pb}$ mean age of 2506 ± 13 Ma (Fig. 18). A second group of zircons yield slightly younger ages of 2440 Ma and 2467 Ma. In summary, the dominant population of magmatic zircons defines ca. 2.5 to 2.6 Ga age, corresponding to major magmatism during late Neoarchean. This was closely followed by metamorphism at ca. 2.44–2.46 Ga. The rare Paleoproterozoic metamorphic zircons in the BIFs suggest that the thermal events during Paleoproterozoic associated with the assembly of major crustal blocks within the NCC also affected the margins of the Jiaoliao microblock.

### 6.3. Summary of Lu–Hf data

The Lu–Hf data plotted in Fig. 19a,b indicate that the melts from which the magmatic zircons in the Yishui Complex rocks crystallized are broadly consistent with a depleted mantle and juvenile source with only minor input of crustal components. Zircons from the volcanic tuff show positive εHf(t) values of 1.4 to 4.5 with crustal residence ages (TDMC) of 2677 to 2909 Ma and depleted mantle Hf model (TDM) ages in the range of 2612–2759 Ma. The data suggest that the magma sources also involved Meso- and Neoarchean components, consistent with a continental arc setting where juvenile magmas mixed with trench material derived from older sources, or partial contamination of juvenile magmas with older basement rocks occurred.

### 6.4. Previous studies on the Yishui Complex

Previous studies on the Yishui Complex have identified the existence of ~2.5 Ga Neoarchean basement that underwent amphibolite to granulite facies metamorphism (Shen et al., 2004; Zhao et al., 2008, 2009;
Zhai and Santosh, 2011; Zhao et al., 2011; Wu et al., 2013). Shen et al. (1993) reported Sm–Nd isochron age of 2997 Ma from metabasites in the Yishui Complex with protoliths showing tholeiitic composition. These rocks show flat REE patterns and εNd(t) value of 3.8 ± 0.3, suggesting depleted mantle source (Shen et al., 1993). These results are broadly similar to those from our present study. Zhao et al. (2013) reported magma emplacement at 2657–2702 Ma and metamorphism at 2552–2585 Ma for ultramafic rocks in Yishui, and correlated these high Mg mafic to magma emplacement during Neoarchean. Their SHRIMP U–Pb age data from mafic granulites constrain crystallization at 2551 ± 24 Ma, followed by multiple thermal events at 2231–2235 Ma and 1850 ± 19 Ma. The multiple populations of zircons from quartzite in our study also record similar ages. Su et al. (1999) reported magmatic crystallization ages of 2537–2582 Ma from charnockites in the Yishui Complex.

Metapelites belonging to the Niuxinguanzhuang group in Yishui carry detrital zircons with upper intercept age of 2695 ± 32 Ma and a metamorphic age of 2537 ± 5 Ma (Zhao et al., 2009). Zhao et al. (2008) reported zircon SHRIMP U–Pb ages of 2530 ± 7 Ma and 2531 ± 8 Ma from the Yinglingshan alkali granites which are characterized by high SiO2 (73.36–74.44%), low total REE, slightly positive Eu anomaly and distinct LREE/HREE fractionation. In another study, Zhao et al. (2011) reported 2719 Ma magmatic zircons from ultramafic rock that also carries metamorphic zircons with ages in the range of 2560 – 2605 Ma. The positive εHf(t) value of 8.2 from the magmatic zircons indicate source from depleted mantle of 2680 Ma. Shen et al. (2007) obtained 207Pb/206Pb weight mean ages of 2538 ± 6 Ma and 2532 ± 9 Ma from granitoids in the Mashan and Xueshan areas, which are similar to the age of 2491 ± 5 Ma reported by Li et al. (2011) from the granodiorite of Xueshan. Their zircon SHRIMP data show 207Pb/206Pb mean ages of 2562 ± 14 Ma and 2545 ± 10 Ma for the crystallization of the Caiju and Dashan granitoids which were subsequently metamorphosed at 2518 ± 13 Ma and 2508 ± 5 Ma, respectively. They also reported inherited zircon grains of 2.93 Ga and 3.07 Ga from these rocks.

Song et al. (2009) investigated the granitoid gneiss in Yishui Complex and correlated the magma source with partial melting of depleted mantle. Zhao et al. (2008) inferred that continental growth in this region occurred at 2530 – 2740 Ma. Wu et al. (2013) reported zircon LA-ICP-MS data from metapelites and granitoid gneisses with magmatic zircons showing age ranges of 2.54–2.53 Ga and 2.57–2.55 Ga. The εHf(t) values of these zircons range from 1.4 to 7.8 and yield depleted mantle model ages of 2.92–2.60 Ga. Petrological studies by Wu et al. (2012) on the mafic granulite enclaves and boudins from Yishui Complex suggest an anticlockwise P–T path consistent with near-isobaric cooling. They suggested that the metamorphism of Yishui Complex was related to the underplating of mantle-derived magma, which is also consistent with a subduction-related setting.

The zircon age data presented in our study are broadly consistent with those from previous studies and indicate the presence of Mesoproterozoic basement in the region and major continent growth during 2.7–2.5 Ga. The subsequent Paleoproterozoic thermal events as shown by younger zircon population in our study are consistent with some of the previous observations (e.g., Zhao et al., 2008, 2011) which interpret two metamorphic events ranging in grade from amphibolite facies to granulite facies at 2.2 Ga and 1.8 Ga (e.g., Zhao et al., 2008, 2011, 2013).

6.5. Implications for regional tectonics of NCC

Although the North China Craton has long been considered to be composed of the coherent Eastern and Western Blocks in several previous studies (see Zhai and Zhai, 2013, and references therein), recent investigations have launched the concept that the craton is indeed a collage of several Archean microblocks (Zhai and Santosh, 2011, Zhai, 2014).
which were amalgamated along multiple subduction zones during the Archean–Proterozoic transition (Yang et al., 2015). These models lead to the concept that a series of active convergent margins involving subduction–accretion–collision might have operated during late Archean in the NCC. In a recent study, Yang et al. (2015) reported a suite of magmatic rocks from the Qianxi Complex along the western periphery of the Jiaoliao microblock. These rocks include charnockites, amphibolites, metagabbros and orthogneisses with calc-alkaline affinity and subduction-related arc magmatic geochemical features. Zircon U–Pb data on magmatic population show upper intercept ages of 2587 ± 10 Ma to 2543 ± 17 Ma for the charnockite suite, and the overgrowth rims as well as discrete neformed grains show possess spot ages in the range of 2533 Ma to 2490 Ma correlated to metamorphism. Zircons in the metagabbro suggest protolith emplacement age of 2556 ± 20 Ma followed by metamorphism at 2449 ± 58 Ma. Zircons in the amphibolite yield 207Pb/206Pb mean age of 2539 ± 9 Ma, representing the crystallization age of this rock. Zircons from the garnet-bearing biotite gneiss show 207Pb/206Pb mean age of 2561 ± 9 Ma. This rock also contains inherited zircons with 207Pb/206Pb ages of 2664 ± 26 Ma and 2628 ± 26 Ma. Zircon Lu–Hf data show dominantly positive εHf(t) values and the Hf model ages suggest Mesoarchean to Neoarchean juvenile crust formation in the NCC. The rocks from Yishui Complex that we investigated in the present study occur along the southern margin of the Jiaoliao microblock. Our age data are closely comparable with those reported in Yang et al. (2015). The lithological assemblages and their geochemical features suggest their formation in an active convergent margin regime as schematically shown in Fig. 20. Thus, we trace the continuity of the subduction system along the western margin of the Jiaoia microblock identified by Yang et al. (2015) to further south. Convergence of the Qianhuai and Xuhuai microblocks towards the Jiaoliao Block is envisaged to have generated the subduction- and accretion-related lithological units along the western and southern periphery of the Jiaoliao Block, which underwent subsequent metamorphic during collision.

In a recent study, Santosh et al. (2015b) reported the discovery of a dismembered ophiolite suite from the Yishui complex. The suite is composed of lherzolite, pyroxenite, noritic and hornblende gabbro, and hornblendite intruded by veins and sheets of leucogranite. Zircon U–Pb geochronology of the rocks constrain the timing of emplacement as ca. 2.5 Ga. Together with transposed layers and bands of metavolcanics and amphibolites, banded iron formation (BIF), and diabase dykes in the adjacent locations, Santosh et al. (2015b) interpreted the Yishui suite to represent a dismembered suprasubduction zone ophiolite suite. These Neoarchean ophiolites are far separated from the margins of the major crustal blocks and suture zones in the NCC and strengthen the concept.
that the NCC is a mosaic of several microblocks with intervening oceans that closed along multiple subduction zones, complementing the inferences in the present study.

7. Conclusions

➢ The suite of granitoids, diabase, metabasalts, volcanic tuff, banded iron formations and quartzite reported in this study from the Yishui Complex along the southern margin of the Jiaoliao microblock within the Eastern Block of the NCC is correlated to subduction- and accretion-related origin.

➢ The granitoids show high SiO₂ content and enrichment in LREE and other features typical of calc-alkaline felsic magmas. All the rocks except the pyroxenite display LILE enrichment. The granite shows positive La, Pb, Zr, Hf anomalies, and negative Th, Ta, La anomalies. In tectonic discrimination diagrams, the mafic rocks have variable IAB, MORB and OIB affinities broadly similar to rocks developed in an island arc related subduction environment.

➢ The weighted mean 207Pb/206Pb mean age of magmatic zircons show 2504 ± 19 Ma for the volcanic tuff, 2581 ± 21 Ma for the granitoid, 2501 ± 19 Ma for the metavolcanics, 2537 ± 38 Ma for the pyroxenite, and 2506 ± 13 Ma for the diabase. These results show prominent Neoarchean magmatism in the region during 2.5 to 2.6 Ga. Metamorphism is constrained from the subordinate groups as 2.44 to 2.46 Ga.

➢ The zircon εHf(t) values of the magmatic zircons from the Yishui suite are dominantly positive, suggesting depleted mantle source with only minor input of crustal components. Their crustal residence ages (TDM) of 2586 to 3181 Ma suggest that the magma sources involved Mesozoic Neoarchean juvenile sources within a continental arc setting.

➢ A Neoarchean subduction system is traced along the western and southern margins of the Jiaoliao microblock.

➢ Our study lends support to the concept that the Archean tectonic history of the North China Craton involved multiple crustal growth/recycling and the accretion of ancient microcontinents along several subduction systems prior to the construction of the cratonic framework.

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