Halaqin volcano-sedimentary succession in the central-northern margin of the North China Craton: Products of Late Paleoproterozoic ridge subduction

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\textbf{Abstract}

The Halaqin volcano-sedimentary succession (HVSS) is tectonically situated on top of the largely Late Archean to Early Paleoproterozoic Yinshan terrane in the central-northern margin of the North China Craton. It comprises green schist- to amphibolite-facies schists, quartzites, marbles and amphibolites, which were originally pelites, pebbly sandstones, sandstones, limestones and volcanic rocks. The presence of tight to isoclinal folds and thrusts of the HVSS indicates tectonic transport from southeast to northwest (present coordinates). U–Pb ages of detrital zircon grains in the clastic rocks suggest provenance from both the Fengzhen belt in the south and the Yinshan terrane in the north. Zircon U–Pb ages of the HVSS volcanic rocks, e.g., 1909 ± 10 Ma, 1894 ± 6 Ma, 1887 ± 6 Ma, and 1884 ± 8 Ma indicate volcanism in the period ~1910–1880 Ma. Detrital zircon age study of the neighbouring Majiadian Group reveals significant ~2700 Ma crust growth and ~2500 Ma metamorphism events in the Yinshan terrane. The HVSS volcanic rocks have a trimodal geochemical distribution demonstrated by SiO\textsubscript{2}-contents of 45–50 wt.% (basalts), 53–60 wt.% (andesites), and 70–76 wt.% (dacites–rhyolites). The basalts and andesites are tholeiitic in chemistry, and show distinct depletion in high-field strength elements (HFSE, e.g., Nb, Zr, Ti), compared to neighbouring elements in spider-diagrams. Specifically, low-Mg basalts and andesites (MgO < 5 wt.\%) have enriched light REE patterns (La/Yb\textsubscript{N} = 2.79–7.89), and enriched large ion lithophile elements (LILE). However, high-Mg rocks (MgO > 5 wt.\%) have more or less flat REE patterns (La/Yb\textsubscript{N} = 0.45–1.76) and LILE.

\textbf{Keywords:}

North China Craton
Late Paleoproterozoic
Halaqin volcano-sedimentary succession
Ridge subduction
Ultra-high temperature metamorphism

\section{Introduction}

Subduction of an oceanic ridge can be expected to be a common consequence of ridge-trench interaction and ocean closure in the plate tectonic paradigm (e.g., Sisson et al., 2003 and reference therein). Modern examples are Taiwan–Luzon (Yang et al., 1996), Central Japan (Soh and Tokuyama, 2002), Taitao (Guivel et al., 2007), Patagonia (Espinoza et al., 2008), and Alaska–California (Cole and Stewart, 2008). More interpretative examples occur in Proterozoic (e.g., Santosh and Kusky, 2010) and Neoarchean terranes (e.g., Manya et al., 2007). In Alaska, a ridge subduction model is well established with evidences from magmatism, metamorphism, and structural geology (e.g., Sisson et al., 1989; Bradley et al., 1993, 2003; Kusky and Young, 1999). Ridge subduction may cause arc-type to OIB-type volcanism (e.g., Thorkelson and Taylor, 1989; Hole et al., 1991; Hole and Larter, 1993; Kinoshita, 1995; Guivel et al., 1999; Bourdon et al., 2007; Manya et al., 2007; Espinoza et al., 2008; Cole and Stewart, 2008), and high-temperature (HT) to ultrahigh-temperature (UHT) metamorphism or paired metamorphic belts.
Late Archean blocks, the final amalgamation of which took place at 2.5 Ga (Fig. 1b; see Peng et al., 2010 and references therein). The sediments in this belt experienced two episodes of high-grade metamorphism: medium- to high-pressure granulite-facies at 1.95 Ga, and UHT metamorphism at 1.93–1.92 Ga (Li et al., 1993, 2000, 2010; Santosh et al., 2006, 2007a,b, 2010; Guo et al., 2006; Wan et al., 2008; Yin et al., 2009, 2011). The Xuwujia gabbro-norites, which have extremely high MgO contents (up to 20 wt.%), are considered to be responsible for the UHT metamorphism (Peng et al., 2010). The Liangcheng crustal melt granites probably originated from the metasediments in the Fengzhen belt, together with minor contributions from the parental magma of the Xuwujia gabbro-norites (Peng et al., 2010). The sediments in the Fengzhen Belt could be stable platform sediments in the front of an ancient block (e.g., the Erdos terrane as suggested by Zhao et al., 2005; Zhao, 2009) or wedge sediments before an arc (Peng et al., 2010).

The Archean Yishan terrane is overlain by Paleoproterozoic low-grade (up to amphibolite-facies) volcanic and sedimentary rocks. In the study area, these include the Erdos and Majidian Groups (Figs. 1b and 2; Wang and Xiu, 1996; Wang and Sun, 1996; Wang et al., 1999; Li et al., 2007). The Erdoa group consists of metamorphosed (amphibolite-facies) pebbly sandstones, sandstones, pebbles, limestones and volcanic rocks (Wang and Xiu, 1996; GBIM, 1973a,b; Wang and Xiu, 1996; GBIM, 1973a,b; Wang and Xiu, 1996; GBIM, 1973a,b; Wang and Xiu, 1996) and Wang et al. (1999) suggested that the Group was deposited at 2450–2200 Ma and metamorphosed at 2200–2100 Ma during formation of the Yinshan basement. Here, we define the Halaqin volcano-sedimentary succession (HVSS) to comprise the Erdoa group, because we have structural evidence that this is a tectonic rather than a stratigraphic unit (see Section 3). The >1000 m-thick, Majidian Group, which rests unconformably on the Yishan high-grade rocks, is composed of greenschist-facies meta-clastic rocks and marbles. It has been considered to be comparable with the neighbouring Baiyun’erbo (Bayan Obo) and Zhaertai Groups, in a so-called Meso/Neoproterozoic Baiyun’erbo-Langshan-Zha’ertai (Langshan) rift that has poor age constraints (GBIM, 1973a,b; Tao et al., 1998; Nie et al., 1993, 1995; Zhao et al., 2003; Li et al., 2007).

3. Occurrences and stratigraphic relationships

Traditionally, the HVSS (Erdoa group) is subdivided into the Hongshangou Formation and the Halaqin Formations (GBIM, 1973a,b; RGSIM, 1991; Wang and Xiu, 1996; Wang et al., 1999) (Fig. 1b). The Hongshangou Formation is composed of meta-pebbly sandstones, schists and marbles with a total apparent thickness of over 1000 m (without considering tectonic shortening or thickening) (Fig. 3C–F), whereas the Halaqin Formation comprises a 150 m-thick volcanic-dominated lower section and a 150 m-thick limestone-dominated upper section (also without consideration of tectonic shortening or thickening) (Fig. 3D–F). The Hongshangou Formation contains meta-tuff beds up to tens of centimetres thick (Fig. 3E). The Halaqin volcanic rocks contain well-preserved beds with sharp contacts and variable thickness (Fig. 3F): melanocratic rocks are basalts and andesites, and leucocratic rocks are dacites and rhyolites. Also hypabyssal granitic rocks have intruded the lower parts of the HVSS (GBIM, 1973a,b; RGSIM, 1991) with numerous feeder dykes cutting the limestones and lower volcanic and clastic rocks (Figs. 1c and 3G–I). The HVSS has been very highly deformed, as shown by extremely attenuated
Fig. 1. Maps showing (a) the study area in the North China Craton (revised after Peng et al., 2010), and (b) the distribution of the Halaqin volcano-sedimentary succession (HVSS).

isoclines associated with ductile thrusts and sheath folds in marbles, indicating major transport from southeast to northwest (Fig. 3K–P). It has long been considered that the HVSS rests unconformably on the Late Archean-Early Paleoproterozoic Weijiaoyazi and Wulashan Groups of the Yinshan terrane, and in turn is unconformably covered by the Majiadian Group (GBIM, 1973a,b; Wang and Xiu, 1996). However, our recent field investigations demonstrate that these contacts are mostly tectonic (Fig. 3Q–R).

We emphasis that the Halaqin volcanic rocks occur as layers within a sedimentary succession dominated by marbles, and it is for this reason that we use the non-genetic term ‘Halaqin volcano-sedimentary succession’. Our recent field study indicates that this ‘succession’ is in fact a huge tectonic pile of very attenuated isoclinal folds, thrusts, and sheath folds. No modern structural studies have been made to unravel this tectonic succession.

The Majiadian Group was traditionally divided into two lithological units (GBIM, 1973a,b). The upper formation mainly comprises of marbles (150 m-thick volcanic-dominated lower section and a 150 m-thick limestone-dominated upper section with a few mica schist layers about 500 m thick without considering tectonic shortening or thickening) (GBIM, 1973a,b). The lower formation consists of meta-sedimentary schists derived from conglomerates, pebbly sandstones, sandstones and slates with well-preserved sedimentary structures and bedding (Fig. 3B), rhythmically changing lithology from pebbly sandstones to slates, and the total thickness is about 600 m without consideration of tectonic shortening or thickening (GBIM, 1973a,b). The pebbles are rounded and up to tens of centimetres in diameter (Fig. 3B). In contrast to the HVSS, the Majiadian Group underwent greenschist-facies metamorphism and less deformation.

4. Samples and analytical methods

Seven samples were selected for zircon U–Pb age dating and Lu–Hf analyses (Fig. 2 and Supplementary data Tables 1 and 2): two from the Majiadian Group (08MJD02 and 08PYS02, meta-pebbly sandstone) and five from the HVSS, i.e., 08EDW01 (schist-pebbly sandstone) and 08HS18 (two-mica tuffaceous schist) (Hongshangou Formation), 08HLQ17 (biotite schist-basaltic andesite) and 08HLQ07 (amphibolite schist-basalt) (the Halaqin Formation), and 08HLQ04 (a hypabyssal rock from the Laoyemiao body). Samples
were selected for analyses of their bulk whole-rock compositions and Sr–Nd isotopes (Supplementary data Tables 3 and 4).

All analyses were performed in the State Key Laboratory of Lithospheric Evolution, Chinese Academy of Sciences, Beijing. Zircon grains were separated using standard heavy liquid and magnetic techniques, and were selected and mounted in an epoxy resin together with standard Temora zircons (417 Ma). The mount was polished to expose the centers of the grains, and then gold coated. Optical microscope images were taken to obtain information on the shapes of the grains and their positions in the mount. Cathodoluminescence and backscattered electronic images were made in order to examine their internal structures.

Zircon U–Pb isotope analyses (Supplementary data Table 1) were undertaken with a Cameca IMS 1280 or a Neptune MC-ICPMS. The diameter of the ion spot was ~20 µm on the Cameca. Common Pb was corrected using the determined 204Pb. All data were processed using the Squid 1.02 and Isoplot 3.0 programs (Ludwig, 2002, 2003). The data in Supplementary data Table 1 are given with 1-sigma errors with a weighted mean at a 95% confidence level.

Zircon U–Pb isotopes (Supplementary data Table 1) and in situ Hf (Supplementary data Table 2) analyses of selected samples were determined using a Neptune MC-ICPMS and zircon 91500 as a reference standard. A 63 nm spot size was applied during ablation with a laser repetition rate of 10 Hz in most cases. During the analyses, isotopic interference corrections of 176Lu on 176Hf were not processed due to the extremely low 176Lu/177Hf in zircon (normally <0.002), although 175Lu/176Lu = 0.02655 was used for elemental fractionation correction. Procedures and data processing were after Wu et al. (2006).

Major element determinations were performed by X-ray fluorescence (Shimadzu XRF-1700/1500) after fusion with lithium tetraborate using Chinese national standard GBW07101-07114. The precision was better than 0.2 wt.% in the analysis range. Loss on ignition was measured as the weight loss of the samples after 1 hour baking under a constant temperature at 1000 °C. Trace element analyses were determined using an ELEMENT ICP-MS after HNO3 + HF digestion of about 40 mg of sample powder in a Teflon vessel, with accuracy and reproducibility monitored using Chinese national standard samples GSR1 (granite), GSR2 (rhyolite) and GSR3 (basalt). The relative standard deviation was better than 5% above the detection limits. Data are shown in Supplementary data Table 3.

Sr–Nd isotope determinations (Supplementary data Table 4) were made on a Finnigan MAT 262 spectrometer. NBS987 (Sr standard) and Ames (Nd standard) reference materials were used to quantify analytical bias; however, no adjustment was applied to the unknowns as the measurements for the standard agreed with the standard value, within error, during this analytical session. Procedure backgrounds for Rb–Sr and Sm–Nd isotope analyses were better than 100 and 50 pg, respectively. The external precisions (2σ) of 87Rb/86Sr and 147Sm/144Nd ratios were both better than 0.5%.

5. Age results

5.1. Pebbly sandstones (samples 08PYS02, 08MJD01 and 08EDW01)

5.1.1. 08PYS02: Majiadian Group

Sample 08PYS02 was collected from an outcrop near Panyangshan village (Figs. 1b and 3A, GPS: N41°14’ E112°11’). It is a metamorphosed pebbly sandstone with quartz-feldspar-dominated pebbles about 1–2 cm across. The rocks in this area were previously mapped as the Erdaowa Group (e.g., GBIM, 1973b) or the Seertengshan (Seerteng) Group (Late Archean e.g., GBIM, 2000). We correlate these rocks with the Majiadian Group, because they have a much lower metamorphic grade than the amphibolite-facies Yinshan terrane basement (GBIM, 1973a,b, 2000), and it has a lithological units and detrital zircon age peaks comparable to those of the Majiadian Group (see below). The zircon grains are mostly over 100 µm in diameter and some are up to 400 µm. Some have distinct rhythmically zoned dark cores and homogeneous light rims, but others are homogeneous light rims, but others are homogeneous (Fig. 4a).

Forty six determinations (mostly on different grains; those from the same grain are distinguished by decimal spot numbers in Supplementary data Table 1, as below) were made with the Neptune LA-ICP MS. They show three 206Pb–207Pb age populations at ~2700 Ma (14 analyses: 206Pb/207Pb mean = 2716 ± 14 [2σ] Ma, Th/U = 0.32–2.10), at ~2500 Ma (17 analyses: 206Pb/207Pb mean = 2522 ± 10 [2σ] Ma, Th/U = 0.19–1.53) and at ~2400 Ma (15 analyses: 206Pb/207Pb mean = 2376 ± 9 [2σ] Ma, Th/U = 0.10–0.90.

Fig. 2. Simplified stratigraphic profile of the Halaqin volcano-sedimentary succession (HVSS) (the Erdaowa Group) and the Majiadian Group.
Fig. 3. Selected photographs showing field aspects of the Halaqin volcano-sedimentary succession (HVSS) and related associations: (A) meta-pebbly sandstone (Majiadian Group, locality of sample 08PYS02); (B) meta-pebbly sandstone (Majiadian Group, locality of sample 08MJD01); (C) meta-pebbly sandstone (Hongshangou Formation, locality of sample 08EDW01); (D) typical meta-volcanic beds; (E) bedded meta-tuffs (Hongshangou Formation, locality of sample 08HSG18); (F) close-up of well-bedded meta-volcanic rocks; (G) a 30 cm-wide meta-volcanic feeder dyke in marbles; (H) a ~20 m-wide meta-volcanic feeder dyke in volcanic rocks; (I) a ~1 m-wide meta-volcanic feeder dyke in the Laoyemia hypabyssal granite; (J) close-up of the Laoyemia hypabyssal granite (locality of sample 08HLQ04); (K) tight isoclinal fold hinges of meta-volcanic amphibolites in marbles; (L) late open folds in meta-volcanic rocks; (M) metre-size sheath folds in marbles, showing up-north (left) thrust, see the arrows for directions; (N) inter-bedded and inter-thrust marbles and meta-volcanic amphibolites (locality of sample 08HLQ17); (O) dyke boudinage in marbles; (P) close-up of meta-volcanic amphibolites inter-thrust with marbles; (Q) and (R) a questionable “unconformable” contact between the HVSS and the Majiadian Group; we consider that this is a tectonic contact; above-right: marbles of the HVSS, below-left: schists (pebbly sandstone) of the Majiadian Group. The scale in A, B, G, I, J, M, L, O, Q and R is a same 30 cm-long hammer; in C, E and F a coin is about 1.5 cm in diameter; in D, H, K, N and P persons are about 165–190 cm tall.
Fig. 4. Selected CL imagines of analyzed zircon grains: (a) sample 08PYS02 (meta-pebbly sandstone, Majiadian Group); (b) sample 08MJD01 (meta-pebbly sandstone, Majiadian Group); (c) sample 08EDW01 (meta-pebbly sandstone, Hongshangou Formation); (d) sample 08HSG07 (meta-basalt, Halaqin Formation); (e) sample 08HLQ17 (meta-basaltic andesite, Halaqin Formation); (f) sample 08HLQ04 (hypabyssal rock, Laoyemiao body); (g) sample 08HSG18 (meta-tuff, Hongshangou Formation).
with two analyses >1.0) (Supplementary data Table 1 and Figs. 5 and 6a). Because most ~2700 Ma ages are from well-zoned zircon cores, they are most likely of magmatic origin. The ~2500 Ma ages are from homogeneous rims that are likely of metamorphic origin. The ~2400 Ma ages are from both cores and rims; we interpret them as magmatic overgrowths. These zircon ages suggest that the time of deposition was after ~2300 Ma.

5.1.2. 08MJ01: Majiadian Group

This metamorphosed pebbly sandstone from the Majiadian Group near Majiadian village contains quartz–feldspar–felsic rock gravel and pebbles up to ~10 cm diameter (Figs. 1b and 3B, GPS: N40°56' E111°31'). The zircon grains are prismatic, but more or less eroded with clear rhythmic zones, and most are over 200 μm long (Fig. 4b). There are two types: elongate prismatic, and short round. Th/U ratios range from 0.1 to 1.2, mostly about 0.4 (Supplementary data Table 1 and Fig. 5). Only one rim was successfully analyzed; it has a Th/U ratio of 0.2 (Supplementary data Table 1).

Thirty nine analyses, obtained with a Neptune LA-ICP MS, show a very clear ~2500 Ma. 206Pb–207Pb age peak (38 analyses: 206Pb–207Pb mean = 2474 ± 10 [2σ] Ma) (Fig. 6b). The fact that all the zircons show a clear magmatic morphology (Fig. 4b) suggests that the sediments were derived from a ~2500 Ma magmatic provenance. One analysis of a grain rim gives a much younger age of 2001 ± 31 [1σ] Ma; this could be of metamorphic origin (Supplementary data Table 1 and Fig. 5). This Group has only undergone low degrees of metamorphism (greenschist-facies), this 2001 Ma age likely represents zircon overgrowth prior to deposition rather than during metamorphism of the rock. Thus the deposition age is likely younger than ~2200 Ma.

5.1.3. 08EDW01: Hongshangou Formation, HVSS (Erdaowa Group)

Sample 08EDW01 is from the lower part of the Hongshangou Formation near Erdaowa village (Figs. 1b and 3C, GPS: N 40°58' E111°33'). It is a metamorphosed pebbly sandstone with volcanic-granitic clasts up to >10 cm across. Most zircon grains from this sample are large (~100 μm), eroded to different degrees, and a few have overgrowth rims (Fig. 4c). The Th/U ratios range from 0.2 to 2.7 in cores and from 0.4 to 0.8 in rims (Fig. 5 and Supplementary data Table 1).

Forty 206Pb–207Pb ages show populations in the range 1800–2000 Ma (34 analyses), and 2400–2500 Ma (6 analyses) (Supplementary data Table 1 and Fig. 6c). Twenty two of the 40 have a morphology that suggests a metamorphic origin: two have ages of ~2000 Ma (with Th/U = 0.4 and 0.8), and the other 20 grains have a weighted mean 206Pb–207Pb age of 1819 ± 14 [2σ] Ma (MSWD = 2.1). The morphology of the remaining 18 zircons (of the 40 grains) suggests an igneous origin; they have two weighted mean 206Pb–207Pb ages of 1905 ± 25 [2σ] Ma (MSWD = 2.9) and 2463 ± 12 [2σ] Ma (MSWD = 1.7). We suggest that 1905 ± 25 Ma was the minimum time of deposition of this pebbly sandstone.

5.2. Volcanic rocks (samples 08HSG07, 08HLQ17, 08HLQ04 and 08HSG18)

5.2.1. 08HSG07: amphibolitic schist (meta-basalt)

Sample 08HSG07 is a metamorphosed basalt (tholeiitic, see Section 6) from the Halaqin Formation near Hongshangou village (Fig. 1b, GPS: N40°55' E111°38'). Its zircon grains are mostly broken fragments about 200 μm long and have broad internal zones (Fig. 4d). Th/U ratios are around 0.2 (Supplementary data Table 1 and Fig. 5). Two grains have clear rhythmic zones (Fig. 4d) with Th/U ratios of 0.5 and 0.7 (Supplementary data Table 1). Some grains have narrow rims, which could be metamorphic overgrowths, but unfortunately they are too narrow to be analyzed (Fig. 4d).

Eighteen zircons were analyzed with the CAMECA IMS 1280: two grains with clear rhythmic zones have ages of about 2500 Ma, whereas the other 16 grains give ages around 1890 Ma (Supplementary data Table 1 and Fig. 6). Except for one spot (spot 2), which has a distinct younger age: 206Pb–207Pb age = 1853 Ma, the other 15 grains yield a 206Pb–207Pb average age of 1887 ± 6 [2σ] Ma (MSWD = 0.86) (Fig. 6d), which probably represents the time of crystallization of this basalt.

5.2.2. 08HLQ17: biotite schist (meta-basaltic andesite)

This schist from the Halaqin Formation near Halaqin village was originally a basaltic andesite (calc-alkaline, see Section 6) (Figs. 1b and 3N, GPS: N 40°55' E 111°42'). Its zircons mostly have cores and rims, but they are not well zoned. Some cores have a patchy texture (Fig. 4e) and variable U-contents from 12 to 1159 ppm and Th/U ratios from 0.2 to 1.7 (three >2.5), whereas the rims have U-contents of 13 to 24 ppm and Th/U ratios of 0.6 to 0.8 (one at 2.5) (Supplementary data Table 1).

Thirty four analyses were obtained using the Neptune LAICP-MS. Thirty one analyses from cores give two age populations: 7 analyses (8 without one, i.e., spot 22 which is a little younger) give a 206Pb–207Pb mean age at 2330 ± 10 [2σ] Ma (MSWD = 1.4), whereas the other 18 analyses (23 without five, i.e., spots 3, 5, 9, 10 and 19, that give mixed ages of ~2000 Ma) yield a 206Pb–207Pb mean age of 1909 ± 10 [2σ] Ma (MSWD = 0.73) (Fig. 6e). Three spots from rims yield 206Pb–207Pb ages within the range 1887–1963 Ma with large errors (Fig. 6e). We suggest that the 2330 Ma age reflects an inherited magmatic event, whereas the 1909 Ma age represents the time of volcanism. We suggest that the rims, which have ages close to the magmatic age of the volcanic rocks, are magmatic overgrowths, although there is a small possibility they are metamorphic.

5.2.3. 08HLQ04: Laoyemiao body (hypabyssal rocks)

Sample 08HLQ04 is from a massive (about 10 km²) hypabyssal body at Laoyemiao village (Figs. 1b and 3J, GPS: N 40°57' E111°41'). Constituent zircons are mostly about 100–200 μm long, prismatic, and have very clear rhythmic zones (Fig. 4f). U contents are 335–1765 ppm; and Th/U ratios range from 0.1 to 0.8 (Supplementary data Table 1 and Fig. 5).

Thirty age determinations, made with the Neptune LAICP-MS, yield different age populations: 7 grains give 206Pb–207Pb ages of about 2450 Ma, 20 grains yield a 206Pb–207Pb average age of 1886 ± 8 [2σ] Ma (MSWD = 1.7), and the remaining 3 grains (grains 24, 26 and 27) give much younger ages (1812–1847 Ma), which may be a result of metamorphic recrystallization (Fig. 6f). We interpret the 1886 Ma age as the time of magmatic crystallization, and the ~2450 Ma age as inherited from partly re-crystallized precursors.
Fig. 6. U–Pb concordia diagrams indicating the age of the Halaqin volcano-sedimentary succession (HVSS): (a) sample 08PYS02 (meta-pebbly sandstone, Majiadian Group); (b) sample 08MJD01 (meta-pebbly sandstone, Majiadian Group); (c) sample 08EDW01 (meta-pebbly sandstone, Hongshangou Formation); (d) sample 08HSG07 (meta-basalt, Halaqin Formation); (e) sample 08HLQ17 (meta-basaltic andesite, Halaqin Formation); (f) sample 08HLQ04 (hypabyssal rock, Laoyemiao body); (g) sample 08HSQ18 (meta-tuff, Hongshangou Formation). All the mean ages are weighted average $^{206}\text{Pb}^{\text{207}}\text{Pb}$ ages.

5.2.4. 08HSG18: two-mica schist (tuff)

This is a meta-tuff from the Hongshangou Formation near Hongshangou village (Figs. 1b and 3E, GPS: N40°54′E111°38′). Most zircons are about 100 µm in size, dark and homogeneous, and lack growth zones. Some grains have narrow leucocratic rims (Fig. 4g), and a few have relict cores (Fig. 4g). The leucocratic rims have extremely low Th-contents (~0.3 ppm) and Th/U ratios (close to 0); others have similar Th/U ratios (about 0.3) and U- and Th-contents (Supplementary data Table 1 and Fig. 5).

Thirty age determinations were obtained with the Cameca IMS 1280: two from leucocratic rims with extremely low Th/U ratios give ages of 1803–1822 Ma, one from a relict core has a much
We suggest that the 1894 Ma age represents the time of volcanism, whereas the 1803–1821 Ma ages represent times of metamorphic overgrowth.

6. Chemistry

6.1. Alteration and significance of whole-rock compositions

Metamorphism and/or fluid-assisted alteration processes have the potential to selectively modify whole-rock chemistry, which most obviously may be indicated by high loss-on-ignition (LOI) values, by some scatter (due to variable mobility) of major elements, or by addition or subtraction of large ion lithophile elements (LILE) (e.g., Rb, Sr, Ba) (Fig. 7, e.g., Pandarinath et al., 2008). In contrast, high field-strength elements (HFSE) and rare earth elements (REE) are relatively immobile during metamorphism, and in general tend to reflect igneous processes (Wood et al., 1979; Middelburg et al., 1988). Therefore, we have used the relatively immobile major elements, REEs and HFSEs, to determine the characteristics and origins of the rocks.

6.2. Basalts and andesites

The basalts and (basaltic-) andesites are mostly tholeiitic in composition, and some are calc-alkaline (Fig. 8). They are divisible into two groups according to their MgO contents: a

![Fig. 7. Nine diagrams showing major elements versus MgO of volcanic rocks from the Halaqin volcano-sedimentary succession (HVSS).](image1)

![Fig. 8. Chemical discrimination diagrams of the Halaqin volcanics: (a) SiO₂ vs. Zr/TiO₂ × 0.0001 diagram (after Winchester and Floyd, 1977), and (b) Al vs. Mg vs. Fe + Ti diagram (after Jesen, 1976).](image2)
high-Mg group (MgO >5 wt.%) and a low-Mg group (MgO<5 wt.%) (Fig. 7). The high-Mg group has SiO₂ of 45.7–50.3 wt.%, TiO₂ of 0.88–2.12 wt.%, Al₂O₃ of 10.2–18.1 wt.%, MgO of 5.75–9.27 wt.%, FeO (total iron) of 10.2–18.1 wt.%, CaO of 7.58–11.03 wt.%, Na₂O of 1.07–2.12 wt.%, K₂O of 1.40–4.83 wt.%, and P₂O₅ of 0.04–1.00 wt.% (Fig. 7 and Supplementary data Table 3). Except for sample 08HLQ25 that has trace element and isotopic affinities with the low-Mg Group (see below), the trace elements show light rare earth element (REE) enrichments (La/YbN = 0.45–1.76; Supplementary data Table 3) (Fig. 9a) and slightly negative Eu anomalies (Eu/Eu*= 0.63–0.89; Eu/Eu* = EuN/[(SmN)*(GdN)]−1/2, normalized to the chondrite values of Sun and McDonough (1989). These rocks show slightly negative anomalies in high field strength elements (HFSEs, e.g., Nb, Zr, Ti), compared with the neighbouring elements in spidergrams (Fig. 9b). Their ⁸⁷Sr/⁸⁶Sr (t = 1.89 Ga) ratios vary from 0.698 to 0.709; and εNd (t = 1.89 Ga) values range from −6.3 to −4.4 (Supplementary data Table 4).

6.3. Dacites and rhyolites

These volcanic rocks have SiO₂ contents of 70.5–75.9 wt.%, Al₂O₃ of 12.83–15.98 wt.%, FeO of 0.66–3.4 wt.%, MgO of 0.25–0.92 wt.%, CaO of 0.93–2.15 wt.%, low TiO₂ of 0.07–0.46 wt.%, P₂O₅ of 0.24–0.82 wt.% and K₂O of 0.80–4.05 wt.% (Fig. 7 and Supplementary data Table 3). They show strong light rare earth element (REE) enrichments (La/YbN = 7.29–47.8; Supplementary data Table 3) (Fig. 9a) and negative anomalies in HFSEs (e.g., Nb, Zr, Ti) (Fig. 9b). Their ⁸⁷Sr/⁸⁶Sr (t = 1.89 Ga) ratios vary from 0.711 to 0.729 and εNd (t = 1.89 Ga) values range from −7.5 to −3.9 (Fig. 10 and Supplementary data Table 4). The samples can be subdivided into two sub-groups according to their Eu anomalies: one has negative Eu anomalies (Eu* = 0.32–0.70), whereas the other has...
positive anomalies (Eu* = 1.08–13.17) (Fig. 9a). Those with negative Eu anomalies have higher trace element concentrations.

7. Discussion

7.1. Ages of the HVSS

We have produced 5 new age determinations of the HVSS volcanics, i.e. 1909 ± 10 Ma (sample 08HLQ17), 1887 ± 6 Ma (sample 08HSG07), 1886 ± 8 Ma (sample 08HLQ04), 1894 ± 6 Ma (sample 08HSIG18, from the cores of the zircons) and ~1820 Ma (sample 08HSIG18, from the rim of one grain). We suggest that the age of the volcanism was confined to the period ~1910–1880 Ma with the peak at ~1890 Ma, and that the peak of metamorphism age was at about ~1820 Ma. Sample 08EDW01 (pebbly sandstone) from the lower HVSS has ages of 1905 ± 25 Ma (mean of an age population interpreted as igneous in origin) and 1819 ± 14 Ma (mean age interpreted as metamorphic in origin). The average 1905 ± 25 Ma age could include some young metamorphic overgrowths. We have arbitrarily taken 1930 Ma as the maximum age, and 1880 Ma as the youngest age of the volcanism in the HVSS.

7.2. Provenance of the sediments and regional tectono-thermal events

Fig. 11 includes all the age data of the detrital zircons from the three sedimentary samples (08EDW01, 08PS02 and 08MD01), which have 3 age peaks at ~1800–2000 Ma, ~2300–2550 Ma and ~2650–2750 Ma. We can identify 3–4 metamorphic events (~2550 Ma, ~2450 Ma, ~1850 Ma) and possibly ~1950–2000 Ma, and 4 magmatic events (~2700 Ma, ~2500 Ma, ~2400 Ma, and ~1900 Ma). The magmatic peaks at ~2500 Ma and ~2400 Ma were identified by Wan et al. (2009), but we had little information of the ~2700 Ma event. The relevant zircons have εHf values close to those of the depleted mantle at that time (Fig. 12b). Thus, this event could correspond to ~2700 Ma juvenile crust in the Yinshan terrane. Noticeable 2550–2450 Ma peak(s) indicates significant metamorphic events have happened at late Archean, which could be records of early tectonic events. Fig. 11 also shows that the provenance of the Majiadian Group (represented by samples 08MD01 and 08PS02) was probably the basement of the Yinshan terrane, which has similar age peaks (~2500 Ma and ~2400 Ma; cf. Wan et al., 2009). However, the HVSS has detrital zircon age populations that are comparable to those in the Fengzhen belt (Fig. 11; cf. Wan et al., 2006; Xia et al., 2006, 2008). Hf isotopes also suggest that the HVSS sediments were derived from juvenile crust, similar to the kandholites of the Fengzhen belt (Fig. 12). The Majiadian Group has previously been considered to be unconformable on the HVSS (GBIM, 1973a,b). However, their mutual contacts are clearly tectonic, and their provenance was from the Yinshan terrane.

7.3. Petrogenesis of the HVSS volcanics

The volcanic samples of the HVSS show a trimodal compositional distribution (Figs. 8c and 13). For example, three SiO2-content populations cluster at 45–50 wt.%, 53–57 wt.%, and 72–76 wt.%, three differentiation index (DI, calculated as a Qtz + Or + Ab + Ne + Lc + Kp CIPW mineral norm) populations at
Fig. 13. SiO₂ and DI (differentiation index, DI = quartz + orthoclase + albite + nepheline + leucite + kaliophilite CIPW norms) density plots of the Halaqin volcanics.

95–85, 65–55, and 45–20 (Fig. 12), and three MgO-content populations grouped at 9–6 wt.%, 4–2 wt.% and <1 wt.% (Fig. 7). Because these three groupings lack concentration correlations, it is hard to interpret their element variations as a result of fractional crystallization. Alternatively, on a εNd against SiO₂ and Nb/Zr diagram (Fig. 14a and b), the samples are distributed approximately in an area that can be modeled by three different components: component 1 has depleted Nd isotopes and a trace element pattern similar to that of MORB, either N(normal)-MORB or E(enriched)-MORB (represented by sample 08HSG07 in the high-Mg group); component 2 shows enriched Nd isotopes and distinct depletion in HFSEs (represented by sample 08HLQ25 in the high-Mg group and other low-Mg group samples); and component 3 is acidic and has enriched Nd isotopes and depleted HFSEs (dacite and rhyolite samples) (Figs. 9a and b and 14a and b). Components 1 and 2 could represent two types of magma sources, whereas component 3 could be a melt from the crust.

The basaltic-basaltic andesites and the dacites–rhyolites share similar chemical characteristics with the Xuwujia gabbronite intrusions and the Liangcheng garnet-rich crustal melt granites in the khondalites of the Fengzhen belt, respectively (Figs. 9a and b and 14a and b). In Fig. 15 Sm/Yb is plotted against Sm. Because Yb is compatible with garnet but incompatible with clinopyroxene, the Sm/Yb ratio can be used to constrain the source mineralogy of the volcanics (e.g., Aldanmaz et al., 2000). This demonstrates that both the garnet-bearing and spinel-bearing herzolite regions of the mantle have probably contributed to the source material of the volcanic rocks.

7.4. Tectonic implications: a succession related to ridge subduction?

The Th-Hf/3-Ta discrimination diagram is based upon immobile HFSEs in order to distinguish volcanic basalts from MORB (Fig. 16a; Wood, 1980). In this diagram, the HVSS volcanics plot mostly in two fields: N-MORB (to E-MORB) (component 1 in Fig. 14) and volcanic arc basalts (component 2 in Fig. 14). This is consistent with the trace element patterns in the spidergram (Fig. 9). Fig. 16b and c was compiled by Cole and Stewart (2008) to show different fields of arc basalts and andesites. The HVSS basalt and basaltic-andesite samples, especially those from the high-Mg Group, fit the fields of, or are consistent with, slab window basalts and basaltic andesite (c.f. Cole and Stewart, 2008 and reference therein; Fig. 16b and c). Thus
we suggest that the volcanic rocks had undergone similar genetic processes as slab window basalts and basaltic andesites, i.e., they had magma sources generated from an asthenospheric mantle that had risen from a slab window and possibly altered by melts from a mantle wedge and the crust. The volcanic rocks in the HVSS basically have similar ages as the Liangcheng granites (1930–1890 Ma), and they are only slightly younger than the early generation of the Xuwujia gabbro-norites (~1930 Ma) (Peng et al., 2010). In addition, the basalts and basaltic andesites have a strong chemical affinity with the Xuwujia gabbro-norites, and the dacites and rhyolites are chemically akin to or comparable with the Liangcheng granites (Figs. 9 and 14). Accordingly we propose that these mafic and felsic associations are basically cogenetic and were emplaced in different crustal levels.

The Halaqin volcano-sedimentary succession is situated tectonically on a basement of the Yinshan terrane. It has undergone very high deformation that gave rise to highly attenuated isoclinal folds and associated thrusts, which indicate thrust transport from the south-east to the north-west (present coordinates) probably at ~1820 Ma (the age of peak metamorphism). We suggest that this thrust deformation might eventually correspond to a ~1850 Ma collisional orogeny in the central NCC as those suggested by Zhao et al. (2005) and references therein or Trap et al. (2007, 2009), or alternatively, in the northern margin of the NCC as those suggested by Kusky and Li (2003) and Kusky et al. (2007). The Majidian Group contains sediments that were deposited on the Late Archean to Early Paleoproterozoic Yinshan terrane and thus their provenances were from that basement. They were deposited before the amalgamation of the Fengzhen Belt with the Yinshan terrane, or after this amalgamation but contemporary with the ridge subduction, or after the ~1.82 Ga orogenic event. We prefer the former two possibilities because these rocks contain no isotopic record of the
1.8–1.9 Ga events, which they would have if they were deposited after this time.

It has been postulated that the 1.93–1.92 Ga UHT metamorphism in the khondalites of the Fengzhen belt was caused by a post-collision process (e.g., Zhao, 2009), a mantle-derived plume (e.g., Santosh and Kusky, 2010), or alternatively by ridge-subduction (e.g., Peng et al., 2010). In this paper we demonstrate that the volcanic rocks of the HVSS are petrologically similar to those produced by ridge subduction after the collision of the Fengzhen Belt with the Yinshan terrane. The fact that the sediments of the HVSS were derived from juvenile crust, as in the Fengzhen belt rather than from an ancient crust (Yinshan terrane), is more compatible with a foreland setting (c.f. DeCelles and Giles, 1996; Sissingham, 2001) than an intra-continental rift. It is also likely that the HVSS formed on continental margin with carbonate-platform (c.f. Sami and James, 1994; Saylor, 2003), because the presence of thick carbonates in this succession suggests deposition on a platform in warm water against an open ocean. However, there is also a possibility that the marbles were tectonically thrust onto the volcanics, and thus the marbles did not originate in the same environment as the Halaqin volcanics. The Majiadian Group consists largely of pebbly sandstones, which could have been deposited in a molasse basin (c.f., Bachmann et al., 1987; Jin et al., 1995), their provenance being the hinterland, i.e., the Yinshan terrane. However, there are also massive marbles in the Majiadian Group, indicating a possible affinity with those from passive margins. The existence of a passive margin is consistent with the fact that passive margins were abundant in the period 1900–1890 Ma (Bradley, 2008), the time of formation of the HVSS. With regard to a passive margin, there are two possible tectonic relationships worth considering. The carbonates in the Majiadian Group, possibly as well as those in the HVSS, were deposited: (1) on the northern margin of the Huanian terrane and were tectonically thrust onto the Yinshan basin at ~1.85 Ga, or (2) on the southern margin of the Yinshan terrane and were inter-thrust at ~1.95 Ga. Further discussion would be beyond the scope of this paper. In Fig. 17, we interpret the HVSS as a product of ~1900 Ma ridge subduction that developed under an active margin, which had previously formed by the accretion of the Fengzhen belt with the Yinshan terrane, and which had become a continental arc of the Yinshan terrane at ~1900 Ma. The Majiadian Group could have been deposited on a passive margin formed before the juxtaposition of the Yinshan terrane with the Fengzhen belt, or in a molasse basin after this juxtaposition but prior to the proposed ridge subduction in the North China craton.

8. Conclusions

Our field observations, new U–Pb zircon age determinations and geochemical data from the HVSS in the central–northern margin of the NCC lead to the following conclusions:

(1) The HVSS has a depositional age in the period ~1930–1880 Ma, and a volcanic peak age at ~1890 Ma. It was probably tectonically transported onto the Late Archean–Early Paleoproterozoic Yinshan basin, and juvenile crust (~1.9–2.0 Ga) in the Fengzhen belt was the major source of the sediments. The whole Halaqin succession underwent strong thrust-controlled deformation and greenschist- to lower amphibolite-facies metamorphism at ~1820 Ma.

(2) Detrital zircon ages of the Majiadian Group reveal significant magmatic events at ~2700 Ma, ~2500 Ma, ~2400 Ma, and metamorphic events at ~2550 to ~2450 Ma in the Yinshan terrane. Specifically, the ~2700 Ma magmatic ages probably represent an episode of crust growth; whereas the ~2550–2450 Ma metamorphic ages are of early tectonic events.

(3) The volcanic rocks of the HVSS are characterized by a trimodal compositional distribution, i.e., with SiO₂-contents concentrated at 45–50 wt.% (basalt), 53–57 wt.% (andesite), and 72–76 wt.% (rhyolite and dacite). These most likely resulted from mixing of three end-members, i.e., one similar to N-MORB, a second comparable to arc basalt, and the third to continental crustal melt.

(4) We conclude that a ridge subduction model is most appropriate for the environment of the HVSS: the N-MORB affinities represent melt that rose through a slab window from the asthenosphere, whereas the arc-affinities are attributed to melts from a mantle wedge. This model also provides a viable means of generating the Xuwuji gabbronorites and Liangcheng granitoids, as well as the UHT metamorphism in the khondalite belt in the central–northern margin of the NCC. The ridge subduction was terminated by the amalgamation of the NCC in the Late Paleoproterozoic.

Acknowledgements

This study was supported by projects no. 40730315 and 41072146. Xudong Ma, Jingzhi Chen, Liang Chen, and Fu Liu are thanked for their help in the field. We are grateful to Drs. Ming-guo Zhai, Guochun Zhao, Yusheng Wan, Chunming Xiao, Xuping Li, and Wouter Bleeker for their constructive advice and suggestions.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.precamres.2011.03.006.

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