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Paleo - position of the South China Craton in the Rodinia Supercontinent: Evidence from the U - Pb age and Hf isotope of detrital zircon from the Nam Co Complex

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ABSTRACT

To constrain the paleo - positions of the South China Cratons in the Rodinia Supercontinent during the Neoproterozoic, the in - situ U - Pb dating, and Hf isotope analysis of the detrital zircon from the Nam Co Complex, Song Ma Suture zone, northwestern Vietnam was performed. The U - Pb isotopic dating on detrital zircons shows that the Nam Co Complex demonstrates the major population (>50%) of around ~850 Ma while the minor population is scattered between ~1.2÷3.0 Ga. The Neoproterozoic age spectrum exhibits a large range of the $\varepsilon Hf_{(t)}$ *from strongly negative to positive values (- 17.418022÷ 14.600527), indicating that the source of the magma for this age range has been not only derived from reworking of the Archean basement rocks, but also generated from the juvenile material. The U - Pb age distribution patterns and Hf isotopic data of the detrital zircon in the Nam Co Complex are compatible with those of the South China Craton rather than those of the Indochina Craton. The data also indicate that sedimentary protoliths of the Nam Co Complex were deposited in a convergent - related basin along the southwestern margin of the South China Craton during the Neoproterozoic. Combined with the similarities of the detrital zircon age between western Cathaysia, Indochina, East Antarctica and East India, it is proved that the South China Craton was situated at the margin of the Rodinia Supercontinent and in close proximity to the Indochina, East Antarctica and East India.*

1. Introduction

The South China Plate is composed of the Yangtze Craton to the northwest and the Cathaysia Block to the southeast (Figure 1). The Yangtze

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block consists of the oldest core of the granitic gneiss (ca. 2.90÷2.95 Ga) in its northern part (Zhang et al., 2006; Zhao et al., 2012), and the Archaeanbasement is widespread beneath the Proterozoic upper - crustal rocks (Zheng et al., 2006; Zhang et al., 2006; Zhao et al., 2012). The Neoproterozoic magmatism was extensive in the Yangtze Craton (Zhao and Zhou, 2007; Sun et al., 2008; Dong et al., 2011, 2012; Qi et al., 2012; Cai et al., 2014; Figure 1). On the other hand, the Cathaysia block is composed of metamorphic rocks, most of which are the Neoproterozoic to the early Paleozoic in age, and mainly found in the northeastern part (southern Zhejiang - northern and western Fujian - eastern Jiangxi, i.e. Wuyishan area) and the southwestern part (Figure 1). The oldest rocks in the Cathaysia block are about 1.9÷1.8 Ga and are limited to southern Zhejiang and northwestern Fujian areas (Li and Li, 2007; Liu et al., 2009; Yu et al., 2009; Xia et al., 2012). Therefore, the two blocks may have been constructed of different Precambrian crustal components and might be juxtaposed only after ~1.0 Ga (Li, 1999; Zhang et al., 2015).

The Yangtze and Cathaysia blocks were considered to amalgamate along with the Jiangnan collision orogenic belt (Figure 1) during the Neoproterozoic (Li, 1999; Li et al., 2007; Yu et al., 2008; Zhao et al., 2011; Wang et al., 2012; 2013; Cawood et al., 2013). On a global scale, this tectonic event was linked to the assembly of the Rodinia Supercontinent. In particular, the position of the South China Craton in the Rodinia reconstruction is controversial (Li, 1999, 2006; Zheng, 2004; Li et al., 2007b; Yu et al., 2008; Wang et al., 2012; Cawood et al., 2013). Based on the stratigraphic correlation and tectonic analyses, Li et al. (1999) proposed that the South China Craton is considered to be a link between Laurentia and Australia - East Antarctica. In contrast, other researchers believe that the South China Craton was on the periphery of the Rodinia, close to Western Australia and India (Zheng, 2004; Yu et al., 2008; Wang et al., 2012a; Cawood et al., 2013). Therefore, the Neoproterozoic tectonic evolution of the Yangtze block plays an important role in the reconstruction of the Rodinia Supercontinent.

The Nam Co Complex located in northwestern Vietnam (see the detailed regional geological background in Hau et al., 2018) is interpreted to record Neoproterozoic northward subduction of a Proto - Tethys branch under the southwestern South China Craton. Detrital zircon U - Pb ages from metasandstones are unimodal and yield a major

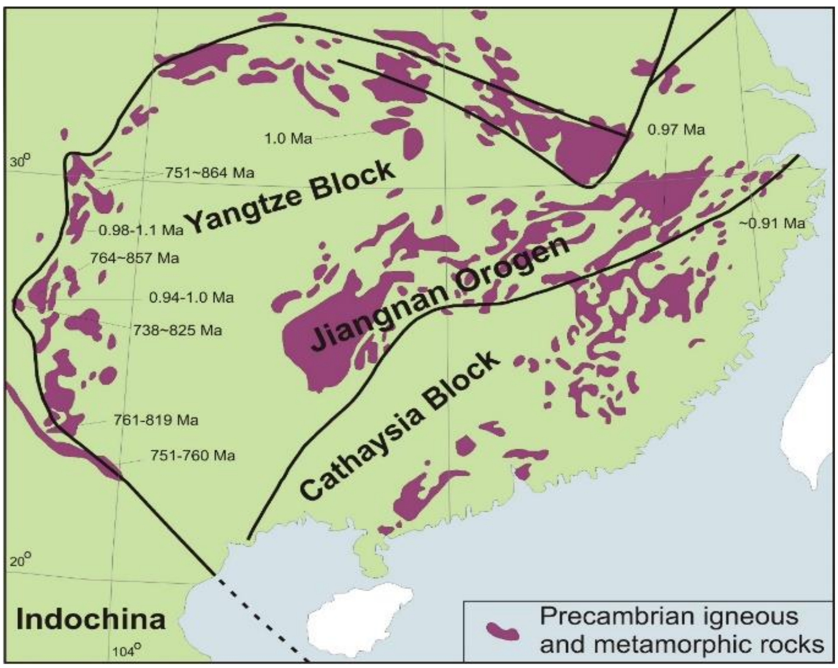

Figure 1. Map of outcropping Precambrian igneous and volcanic rocks in the South China Craton showing the abundance of Neoproterozoic subduction - related magmatic rocks along the western Yangtze block (modified after Yu et al., 2008).

peak centered around ~850 Ma, with characteristics of a magmatic arc setting (Hau et al., 2018). The detrital zircon U - Pb age distribution is comparable to that of the southern Yangtze Block, but differs from Indochina and Cathaysia, suggesting a primary detrital input derived from the southern Yangtze Block (Hau et al., 2018). Based on this interpretation, in this study, U - Pb age and Hf isotope of detrital zircon separated from Nam Co Complex were used in order to consider the paleo - position of the South China Craton in the Rodinia Supercontinent

2. Materials and methods

In the Son La area, the Nam Co Complex mostly consists of pelitic and semi - pelitic schist, with interbedded thin layers of fine - grained sandstones. Three samples from the Nam Co Complex have been collected for zircon separation (Figure 2). Samples SM14 and SM20 are semi - pelitic rocks, consisting of quartz, muscovite, chlorite, and minute granite; sample SM09 is fine - grained sandstone (Hau et al., 2018). The U - Th - Pb isotopic dating on the detrital zircon was carried out from two semi - pelitic samples (SM14 and SM20, Figure 2b), whereas Hf isotopic analysis was carried out from SM14, SM20 and SM09. Zircon grains in the samples are 40÷200 μm in the longest dimension, and their morphology is variable (Figure 3). Euhedral zircon grains show the oscillatory zonation, whereas subhedral to anhedral ones are variable from the homogeneous through the sector to oscillatory zoning patterns in their cathodoluminescence (CL) images.

The U - Th - Pb isotopic compositions of zircon from sample SM14 and SM20 were measured using Nu plasma II multicollection inductively coupled plasma mass spectrometer equipped with a New Wave Research 193 nm ArF excimer Laser Ablation system (LA - MC - ICP - MS) housed at the

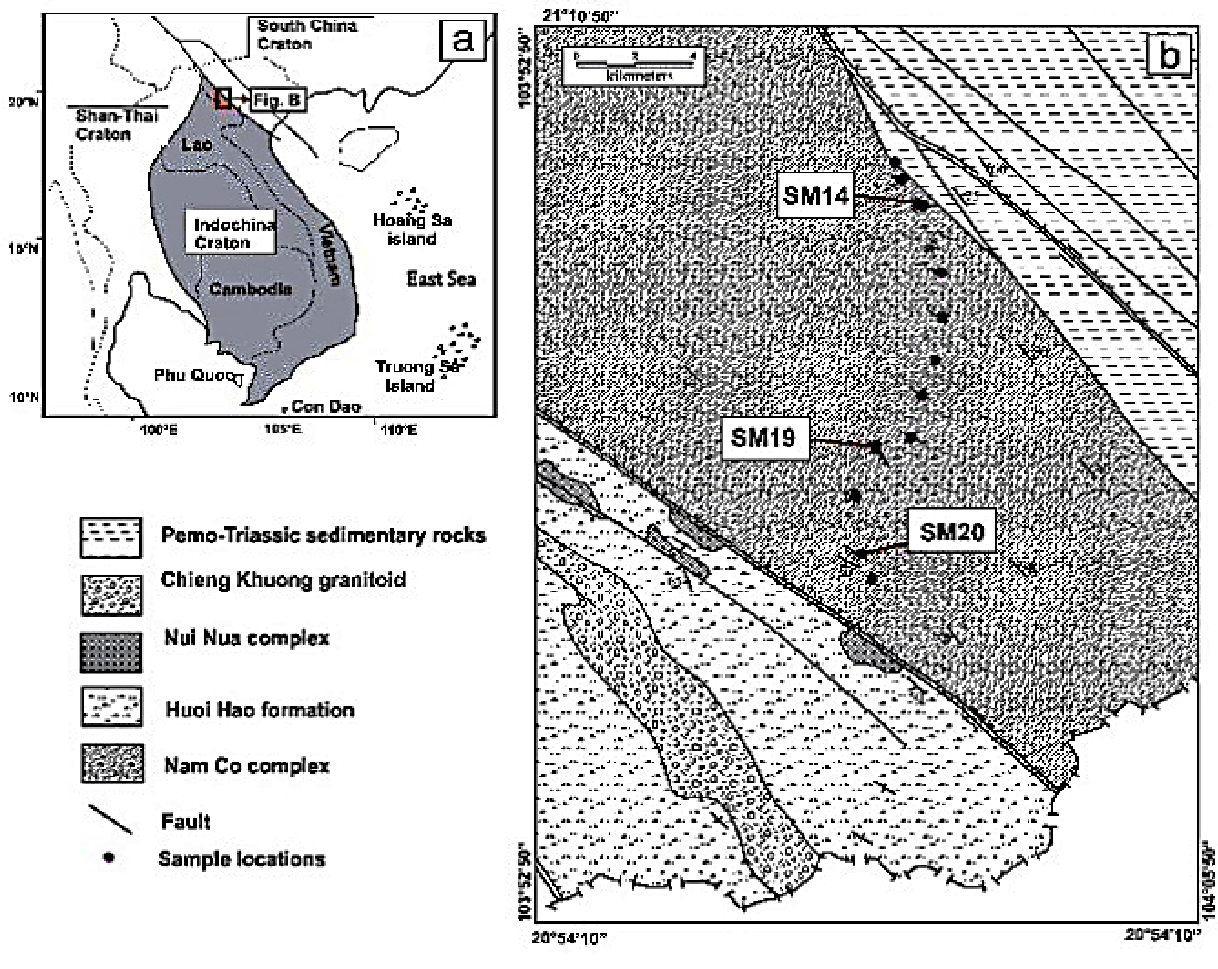

Figure 2. Geological map and sample locations of study area.

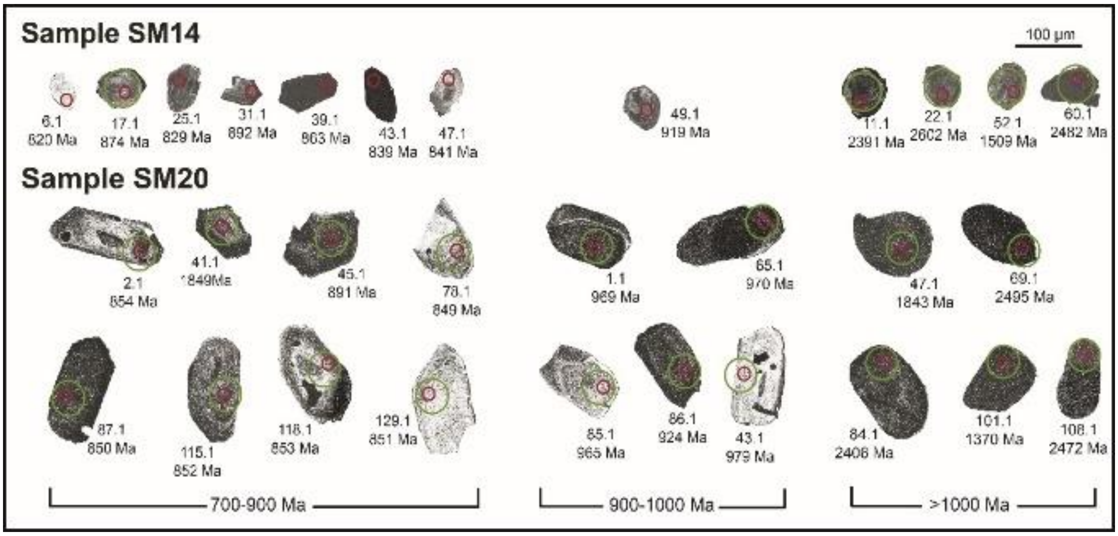

Figure 3. Cathodoluminescence images of the representative detrital zircon grains from samples SM14 and SM20. Open red and blue circles in the sample SM14 and SM20 represent the analytical spots of U - Pb ages (20 μm) and Hf isotopes (50 μm), respectively.

coupled plasma mass spectrometer equipped with a New Wave Research 193 nm ArF excimer Laser Ablation system (LA - MC - ICP - MS) housed at the Ochang campus in Korea Basic Science Institute (KBSI) and presented in the appendix 2. The Nu Plasma II mass spectrometer contains fixed collectors of sixteen Faraday detectors and five ion - counting electron multipliers. The collectors were set to simultaneously detect for U - Pb age determination in the following array: ^{202}Hg (IC 4), ^{204}(Hg+Pb) (IC 3), ^{206}Pb (IC 2), ^{207}Pb (IC 1), ^{208}Pb (IC 0), ^{232}Th (high 7) and ^{238}U (high 9), respectively. ^{235}U was calculated from the signal at mass ^{238}U using a natural ^{238}U/^{235}U=137.88. Mass number 204 was used as a monitor for common 2^{04}Pb after the ^{204}Hg background had been discarded. All analyses were carried out with a spot size of 20 μm in diameter, 5 Hz repetition rate, and energy density of 3 J/cm^2. He (940 ml/ Min.) was used as carrier gas. Background intensities, dwell time, and wash - out time was measured as 30 s, 30 s and 20 s, respectively. A Time - Resolved Analytical (TRA) procedure was employed to monitor the measured isotope ratio. Signal intensities for each collector were collected every 0.2 s (integration time). Raw data were corrected for the background, laser - induced elemental fractionation, mass discrimination and drift in ion counter gains. U - Pb isotope ratios were calibrated by concordant reference zircons 91500 (1065 Ma; Wiedenbeck et al., 1995) and Plešovice zircon (337.13±0.37 Ma; Sláma et al., 2008) that was used at the beginning and end of each analytical session, and at regular intervals during each session, using protocols adapted from Andersen (2002). A correlation of signal vs time was also assumed for the reference zircons. The Iolite software (Paton et al., 2010) running in IgorPro (WaveMetrics, Inc;www.wavemetrics.com) was used for the data reduction of LA - MC - ICP - MS analyses. Once processed with Iolite, the data were exported in EXCEL, and Isoplot (Ludwig, 2008) was used to calculate weighted average ages and make Tera - Wasserburg plots. Age probability distribution diagrams of detrital zircon were constructed primarily using the ^{207}Pb/^{206}Pb and ^{206}Pb/^{238}U ages of detrital zircon older and younger than 1.2 Ga, respectively, in case of less than 10% discordance.

In situ zircon, Lu - Hf isotopes were also analyzed using laser ablation - multicollection - inductively coupled plasma - mass spectrometer (LA - MC - ICP - MS) employing 193 nm ArF excimer Laser Ablation attached to a Nu Plasma II MC - ICP - MS instrument at the KBSI. Masses 172, 173, 174 175, 176, 177, 178, 179, 180, and 182 were analyzed simultaneously in Faraday collectors using static - collection mode, with the resulting data normalized to ^{176}Hf/^{177}Hf = 0.7325. The interference of ^{176}Yb and ^{176}Lu on ^{176}Hf was corrected by measuring the intensity of the interference - free ^{173}Yb and ^{175}Lu isotopes, with the resulting data corrected using Iolite and

$^{176}Yb/^{173}Yb$ = 0.79631 (Vervoort et al., 2004) and $^{176}Lu/^{175}Lu$ = 0.026549 (Chu et al., 2002) ratios. This analysis used laser energy of approximately 6÷7 J/cm^2 with a laser - ablation spot size of 50 μm and a repetition rate of 10 Hz. Details of the instrumental conditions and the data handling processes are given in Lee et al. (2015). $^{176}Hf/^{177}Hf$ results of 91500 and FC1 zircon standards during analyses of this study are 0.2822982±0.0000064 (2σ, n=42) and 0.282166±0.000012 (2σ, n=20), respectively. Epsilon Hf values and model ages used in the figures were calculated using the decay constant (1.865×10-11 per year) proposed by Scherer et al. (2001). Single - stage model ages (TDM) were calculated relative to the depleted mantle with a present - day $(^{176}Lu/^{177}Hf)_{DM}$ = 0.0384 and $(^{176}Hf/^{177}Hf)_{DM}$ = 0.28325 (Griffin et al., 2000); two - stage model ages (T_{DM}^{C}) were calculated by forcing a growth - curve through the initial zircon ratio with an assumed $(^{176}Lu/^{177}Hf)_{C}$ value of 0.0015 correspondings to the upper continental crust (Griffin et al., 2004).

3. Analytical results

3.1. U - Pb ages

The U - Th - Pb isotopic compositions of hundred and sixty - six spots on one hundred and sixty - two grains from samples SM14 and SM20 were measured by LA - MC - ICP - MS (Appendix 1).

The U - Pb isotopic compositions of zircon were plotted in the Tera - Wasserburg concordia and probability distribution diagrams (Figure. 3). Similar to the three metasandstone samples in Nam Co Complex reported by Hau et al., 2018, LA - MC - ICP - MS zircon age data from samples SM14 and SM20 show the major zircon age peak at ~800÷980 Ma and less important peaks at ~1600 Ma, ~1850 Ma and ~2500 Ma (Figure 4). The median $^{206}Pb/^{238}U$ ages of Neoproterozoic zircon population in two samples SM14 and SM20 were calculated as 855±20 Ma (2σ) and 940±16 Ma (2σ), respectively (Figures 4a, c). The bi - modal age distribution patterns of the Neoproterozoic. Zircon population in the samples are also presented in age probability distribution diagrams (Figures 4b, d). The strongest Neoproterozoic peaks in samples SM14 and SM20 are located at ~835 Ma and ~850, respectively, and the secondary Neoproterozoic peaks at~870 Ma and ~975 Ma, respectively (Figures 4b, d).

3.2. Zircon Hf isotopes

The Hf isotopic compositions of one hundred and eighty - five zircon grains from three samples SM09, SM14, and SM20 were analyzed and shown

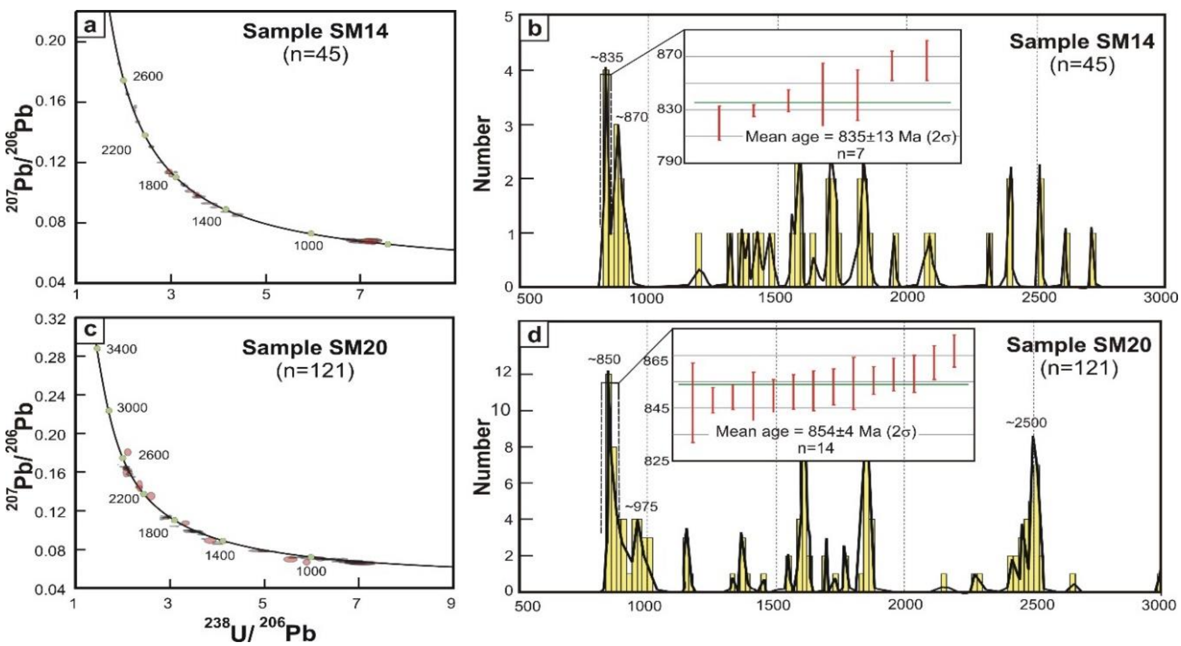

Figure 4. Tera - Wasserburg concordia diagrams (a: SM14, c: SM20) and age histograms with the probability diagrams (b: SM14, d: SM20) of LA - MC - ICP - MS detrital zircons. Error ellipses of each data point in the concordia diagrams are 2σ.

in appendix 2. The U - Pb age vs epsilon Hf diagram is shown in Figure 5 together with data from adjacent Cratons such as Indochina and South China (western Cathayisa and the southwestern Yangtze). The Neoproterozoic age groups from the three samples exhibit large ranges of $\varepsilon Hf_{(t)}$ from - 17.418022 to 14.600527 and Hf crustal model ages ($T_{DM}{}^{C}$) ranging from 908 to 2690 Ma (Appendix 2 and Figure 5), suggesting that the host magma of zircons from this groups have diverse sources. The minor group ages of 1500÷1650 Ma, 1800÷1900 Ma, and 2450÷2550 Ma also have large ranges of $\varepsilon Hf_{(t)}$ (- 15.824900÷8.671319; - 8.357700÷ 15.623150; and - 10.590000÷10.752430, respectively), whereas the Hf crustal model ages ($T_{DM}{}^{C}$) of these group ages yield 1829÷3122 Ma; 1645÷2847 and 2506÷3558 Ma, respectively (Appendix 2 and Figure 5).

4. Discussions

4.1. Crustal evolution of the southwestern Yangtze during Neoproterozoic

According to Hau et al. (2018), sedimentary rocks of the Nam Co Complex were deposited in subduction - related basins along the southwestern margin of the Yangtze block during the Neoproterozoic. The Hf isotopic compositions of the detrital zircons also support this interpretation. Figure 5a compares *εHf(t)* of detrital zircons from the Nam Co Complex with those from the Southwestern Yangtze, western Cathaysia and Indochina. The Neoproterozoic age group of the Nam Co Complexhasa large range of *εHf(t)* and overlaps with that of the southwestern Yangtze block; whereas, the Neoproterozoic age group of the Indochina and the western Cathaysia yield the *εHf(t)* values from strong negative values to positive, (from ~ - 30÷~+10) that differ from those of the Nam Co Complex. Moreover, the large ranges of *εHf(t)* of the Neoproterozoic age group prove that the source of the magma from this age group has been not only derived from reworking of the Archean basement rocks, but also generated from the juvenile material.

Additionally, the relative change in *εHf(t)* of the zircon through time in the magmatic arc manisfests the interplay between tectonic activity and magma source in an evolving accretionary orogen (Kemp et al., 2009; Nelson and Cottle, 2018). Kemp et al. (2009) pointed out that the increase of the zircon εHf(t) is an indicator/ a

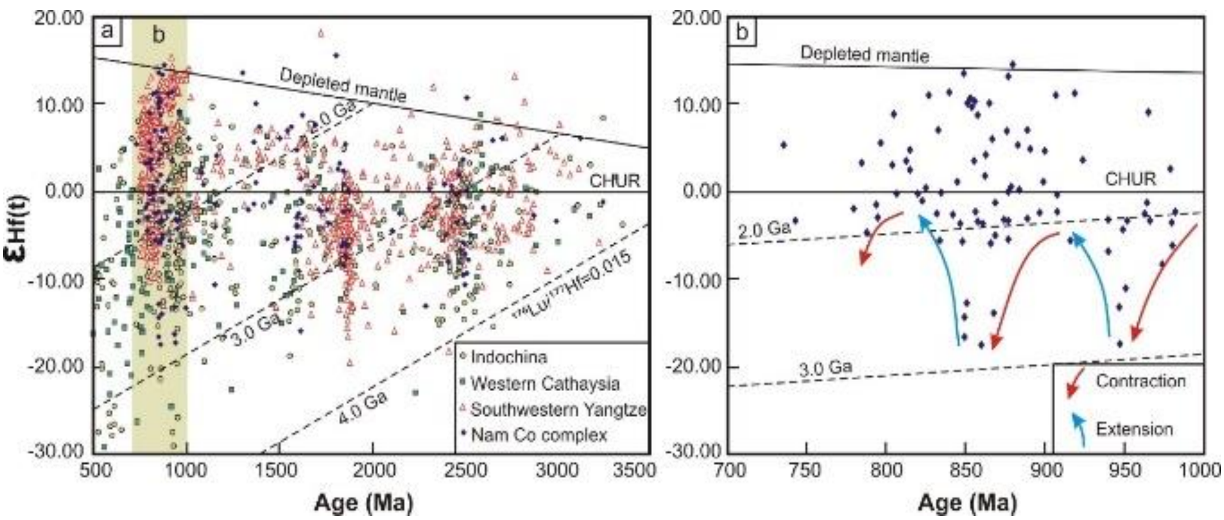

Figure 5. Age vs. epsilon Hf plot of zircons from samples SM09, SM14 and SM20. For comparison (a), detrital zircons data from Indochina, western Cathaysia, and southwestern Yangtze are also plotted. Data sources: Indochina: Usuki et al., 2013, Western Cathaysia: western Cathaysia: Yu et al. (2008, 2010), southwestern Yangtze: Sun et al., 2009; Wang et al., 2012. Colored arrows in the (b) correspondence to geodynamic interpretations of extension or contraction based on the ralative change in zircon epsilon Hf values through time (Kemp et al., 2009). CHUR: Chondritic uniform Reservoir. The declining parallel lines indicate Hf crustal model ages ($T_{DM}{}^{C}$) based on the assumption that $^{176}Lu/^{177}Hf$ of average continental crust is 0.015 (Griffin et al., 2004).

typical character of an extensional arc system, whereas the contractional arc system is characterised by the decrease of zircon *εHf(t)*. The zircon εHf(t) change of the Nam Co Complex during Neoprotezoic has been observed and probably represents the "tectonic switching" between two contrasting tectonic states in an accretionary orogen: retreating orogens undergoing extension and advancing orogens undergoing contraction (Nelson and Cottle, 2018). The contractional period is observed during ~980÷~950 Ma, ~900÷~850 Ma, and 800÷750 Ma based on the decrease of *εHf(t)* values (Figure 5), which may result from increasing crustal assimilation during crustal thickening, and/or melting of ancient enriched mantle (Kemp et al., 2009; Nelson and Cottle, 2018). In contrast, the increase of εHf(t) values from ~950÷~900 Ma and ~850÷~800 Ma (Figure 4) is interpreted by reducing crustal assimilation during the thickening of juvenile crust and/or melting of upwelling depleted mantle, which indicates extensional arc systems during the periods (Kemp et al., 2009; Nelson and Cottle, 2018). These results indicate that there were two arc - forming periods at ~950 Ma and ~850 Ma recorded in the southwestern Yangtze, which is consistent with the Neoproterozoic bi - modal age distribution of detrital zircon described in Hau et al. (2018).

4.2. The paleo - position of South China and Indochina in the Rodinia Supercontinent

Various Neoproterozoic plutons and felsic volcanic rocks in the western to the southwestern Yangtze have been reported to have subduction - related geochemical affinity: e.g. TIMS U - Pb zircon ages from dacite and rhyolite of Xixiang arc volcanic yielded 950±4 and 895±3 Ma, respectively (Ling et al., 2003); ICP - MS U - Pb zircon age from mafic - intermediate plutons, Bikou Terrane have ages from 884±5.5÷877±13 Ma (Xiao et al., 2007); 840÷750 Ma from the mafic intrusion of the Hannan massif (Dong et al., 2011), 987 - 761 Ma granitoid in Daping pluton (Qi et al., 2012); 846÷776 Ma volcanic rocks in the Bikou area (Yan et al., 2004); 870÷820 Ma mafic intrusion and granitoid of the Hannan and Micangshan massifs (Dong et al., 2012). Moreover, the typical characteristic of Neoproterozoic zircon from the Nam Co Complex, as described in Hau et al. (2018) provides a window into a subduction - related magmatic system (which supplied detritus for the Nam Co Complex) in the southwestern margin of the Yangtze Block. The detrital zircon ages also show that there is no obvious age gap in the Neoproterozoic from ~1000÷~750 Ma, indicating that the magmatism had been continuous during this time. This suggestion is in agreement with Sun et al. (2009), who proposed continuous eastward subduction of oceanic lithosphere (~1000÷~740 Ma) along the western Yangtze block based on *in situ* U - Pb geochronological and Lu - Hf isotopic studies of detrital zircon from a variety of the Precambrian strata along the western margin of the Yangtze Block. It is impossible for such a long - live Neoproterozoic (~1000÷~750 Ma) subduction system (arc - back/arc system) to develop within the Rodinia Supercontinent as proposed by Li et al. (1999), and thus it has to occur at a peripheral position.

South China has been placed near the Laurentia in several reconstruction models (Li et al., 1995, 2002). However, the zircon age spectra from South China (Yangtze and Cathaysia blocks) record a significantly different Precambrian tectonic thermal history from that of Laurentia (Figure 6). Zircon age patterns from Laurentia (North Ameria) are characterized by a major population of ~1.2÷1.3 Ma; ~1.4 Ma; ~1.7÷1.8 Ma; and ~2.0÷2.8 Ma; whereas, the Neoproterozoic populations are absent (Figure 6). Moreover, the western Cathaysia block is dominated by the peak of ~950 Ma, similar to the Eastern Ghats (~960 Ma) in East India and Northern Prince Charles Mountains (~990÷950 Ma) in East Antarctica (Figure 6; Yu et al., 2008; Wang et al., 2012a; 2013). The continuous subduction tectonic setting of the west to southwestern Yangtze block (~1000÷~750 Ma), in combination with the similarities of the detrital zircon ages between western Cathaysia, East Antarctica, and East India proved that the South China Craton including Yangtze Block was situated at the margin of Rodinia Supercontinent and in close proximity to East Antarctica and East India (Figure 7) rather than between Laurentia and eastern Australia. The Indochina Craton has the peak ages at ~950 and 1135 Ma (Usuki et al., 2013), consistent with those of western Cathaysiawhich also has the peak at ~950, ~1110 Ma (Usuki et al., 2013).

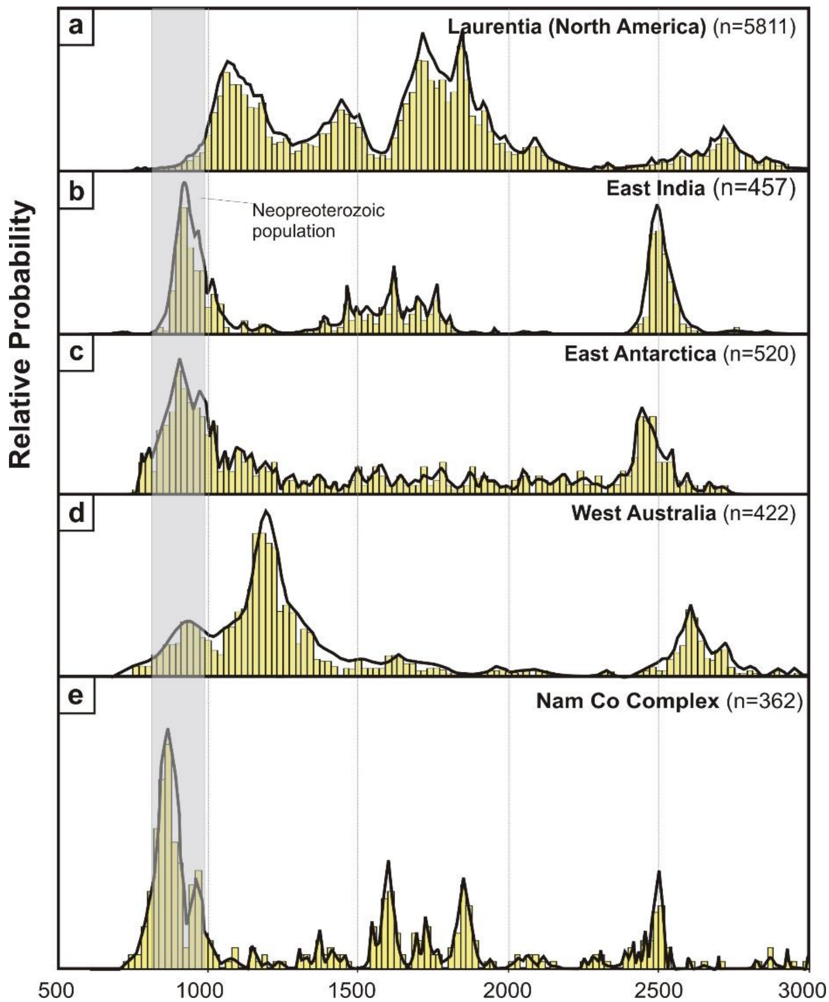

Figure 6. Density probability diagrams of detrital zircon with age histograms representative for (a) the Laurentia, (b) the East India, (c) the East Antarctica, (d) the West Australia, and (e) the Nam Co Complex. Age data were compiled from Laskowski et al. (2013) for the Laurentia; from Bose et al. (2011) and Saha et al. (2016) for the East India; from Boger et al. (2000), Kelley et al. (2002) and Carson et al. (2002) for the East Antarctica; from Sircombe and Freeman (1999), Cawood and Nemchin (2000) and Veevers et al. (2005) for the West Australia; from Hau et al. (2018) and this study for the Nam Co Complex.

This indicates that the detrital zircons from the Indochina and western Cathaysia shared a common source provenance at this time. Recently, some younger Grenvillian ages have been reported in Cathaysia block: e.g., 984÷969 Ma U - Pb zircon age from matabasic rocks (Wang et al., 2013); furthermore, the younger Grenvillian ages of inherited zircons (~1000÷950 Ma) have also been found in granitoid along the Truong Son belt, Indochina Craton (Shi et al., 2015). However, neither Indochina nor Cathaysia has been reported to have igneous rocks with precise Grenvillian ages (1300÷1000 Ma); hence, the Grenvillian age in Indochina and Cathaysia probably sourced/originated from adjacent Cratons. The ~990÷950 Ma and ~1300÷1050 Ma orogenic belts have been documented in East Antarctica and East India (Hoffman, 1991; Yu et al., 2008) and these Cratons were considered to be close to the Cathaysia block in Rodinia Supercontinent (Hoffman, 1991; Yu et al., 2008; Wang et al., 2013). Therefore, it is reasonable to place Indochina Craton near the Cathaysia, East Antarctica, and East India in the Rodinia Supercontinent (Figure 7).

5. Conclusions

The U - Pb age and Hf data of detrital zircon from Nam Co Complex indicate that South China

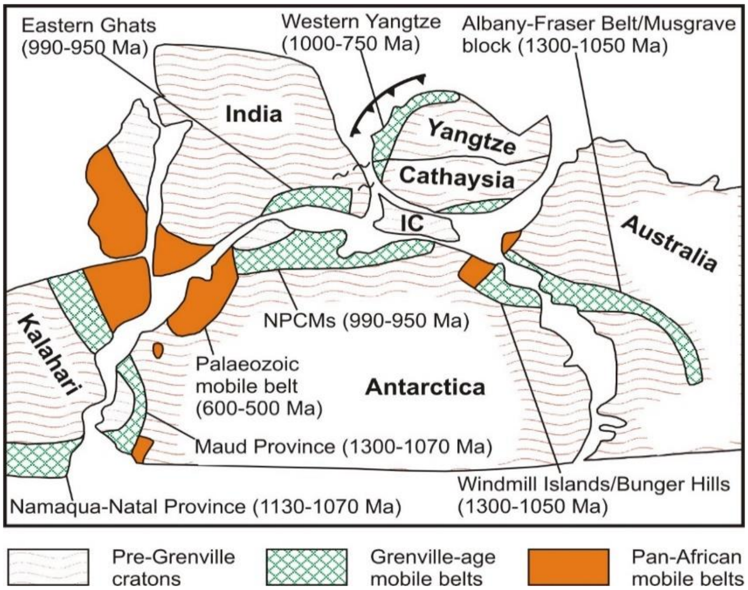

Figure 7. Positions of South China and Indochina in Rodinia Supercontinent (edited after Yu et al., 2008).

Craton was situated at the margin of Rodinia Supercontinent and in close proximity to Indochina, East Antarctica, and East India.

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Author contributions

The author Hau Vinh Bui proposes ideas and contributes to the manuscript. The author Yoonsup Kim constructs the manuscript and contributes to the material analyses. The authors both declare no conflict of interest.

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