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ORIGINAL ARTICLE

The U–Pb ages and Hf isotopes of detrital zircons from Hainan Island, South China: implications for sediment provenance and the crustal evolution

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Abstract In situ U–Pb dating and Hf isotopic of detrital zircons from beach sediments of Yalong Bay were analyzed to trace sedimentary provenance and reveal the crustal evolution of Hainan Island in South China. The grain size distribution of the sediments displays a clear single-peak feature, indicating the sediments were formed under the same condition of hydrodynamic force. The detrital zircons had Th/U ratios of greater than 0.1, and REE pattern displayed a positive Ce anomaly and a negative Eu anomaly, indicating that these zircons are predominantly of magmatic origin. The U–Pb spectrum of detrital zircons mainly peaked at the Yanshanian (96–185 Ma), Hercynian–Indosinian (222–345 Ma) and Caledonian (421–477 Ma). A portion of the detrital zircons were of Neoproterozoic origin (728–1,003 Ma), which revealed that the basement in the eastern region of Hainan Island was mainly of Neoproterozoic, with rare Archean materials. The positive $\varepsilon_{\mathrm{Hf}}(t)$ values (0 to +10.1) of the Neoproterozoic detrital zircons indicated that the juvenile crust grew in the southeastern Hainan Island mainly during the Neoproterozoic period. The Neoproterozoic orogeny in the southeastern part of the island (0.7–1.0 Ga) occurred later than in the northwestern region of the island (1.0–1.4 Ga). Importantly, the Grenvillian orogeny in the southeastern area of Hainan Island shared the same timing with that of the western Cathaysia Block; i.e., both areas concurrently underwent this orogenic event, thereby forming a part of the Rodinia supercontinent. Afterwards, the crust experienced remelting and reworking during the Caledonian Hercynian–Indosinianand Yanshanian accompanied by the growth of a small amount of juvenile crust.

Keywords U–Pb age · Hf isotope · Provenance · Crustal evolution · Hainan Island

Introduction

Hainan Island is located at the junction of the Pacific Plate, Indo-Australian Plate and Eurasian Plate, and is separated from the Cathaysia Block (CB) by the Qiongzhou Channel (Fig. 1). The island is characterized by a remarkable tectonic location and a complicated history of crustal evolution. To date, considerable effort has been devoted to investigating the Precambrian metamorphic basement, metabasite, Hercynian–Indosinian granite and alkaline rocks on the island, which facilitates the reconstruction of the crucial tectonic events of the island (Metcalfe et al. 1993; Zhang et al. 1998; Li et al. 2002, 2006; Xu et al. 2007a, 2008a). However, studies of the sedimentary rocks of the island remain inadequate (Xu et al. 2007b, c), which inevitably hinders an understanding of the tectonic

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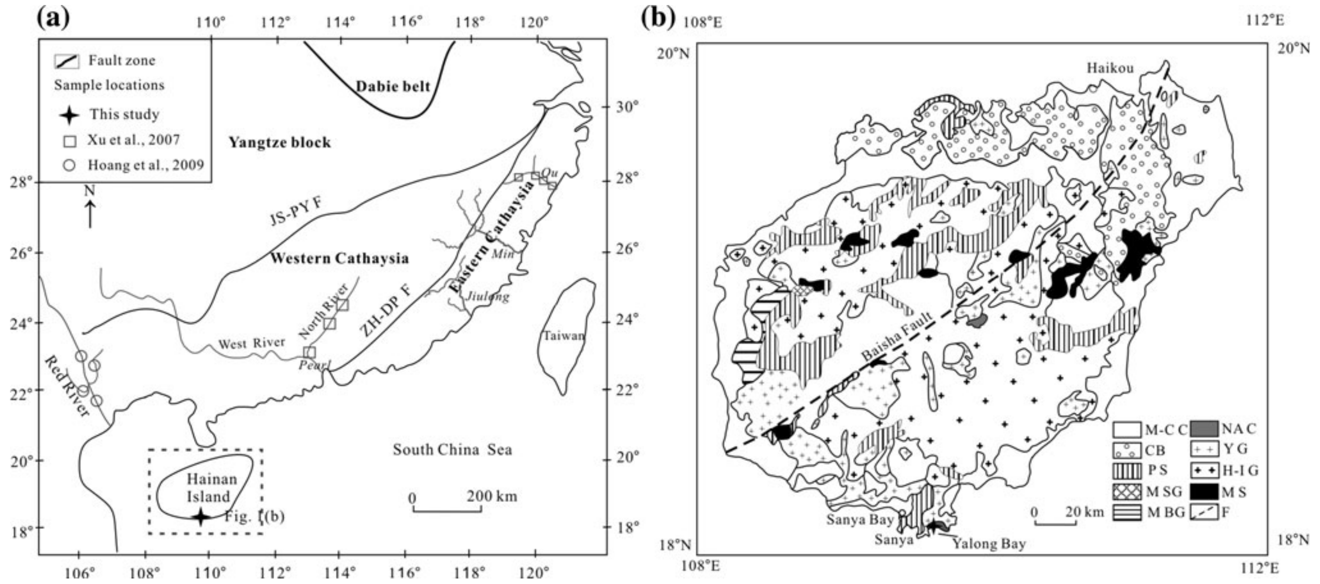

Fig. 1 River systems and sample locations in Cathaysia region (**a**) and simplified geological map of Hainan Island shows the main stratigraphic and magmatic units (**b**) (revised after Xu et al. 2007b). Division of Hainan Island into the southeast and northwest Islands is from Metcalfe et al. (1993). *JS-PY F* Jiangshao-Pingyu fault, *ZH-DP F* Zhenghe-Dapu fault, *M-C C* Mesozoic-Cenozoic covers, *C B* Cenozoic basalts, *PS* Paleozoic volcanic-clastic sediments, *M SG* Mesoproterozoic Shilu Group, *M B G* Mesoproterozoic Baoban Group and Mesoproterozoic granitoid rocks, *NA C* Neo-archean complex, *Y G* Yanshanian granites, *H–I G* Hercynian–Indosinian granites, *M S* metabasites and associated sedimentary rocks, *F* proposed faults

evolution. The detrital components of sediments are the products of the uplift, weathering, erosion, transport and deposition of a source area and have captured pivotal information, including the history of the orogeny, uplift and denudation (Singh and Rajamani 2001). The combination of U–Pb and Hf isotopes of detrital zircons not only offers the most effective tool of tracing the sedimentary provenance, but also provides an effective method to elucidate the paleogeographic history, regional tectonic evolution and crustal evolution (Bodet and Schärer 2000; Griffin et al. 2004; Richards et al. 2005; Wang et al. 2009, 2011a).

Zircon is an accessory mineral commonly found in various types of rocks and is also an important heavy mineral of sediments. Due to its excellent resistance against weathering, abrasion and thermal alteration, zircon resists damage in mechanical transport process and thus is able to preserve the petrologic composition of its origins. Hence, U–Pb dating and Hf isotope analyses are powerful tools for effectively constraining source areas and exploring crustal evolutions (Cawood et al. 2003; Iizuka et al. 2005; Wang et al. 2009). The coastline of Hainan Island is approximately 1,682 km in length, 80 % of which is of the sandy category. The objective of this study was to examine the detrital zircons in the beach sediments using U–Pb dating and Hf isotopic analyses, thereby investigating the sedimentary provenance and revealing the crustal evolution and tectonic features of Hainan Island in South China.

Geological background

Hainan Island is situated at the junction of the Pacific Plate, Indo-Australian Plate and Eurasian Plate. The island is bisected by the NE–SW oriented Baisha fault to form two entities (Fig. 1b), the northwestern and southeastern regions of the island (Metcalfe et al. 1993). Hainan Island consists predominantly of Permian to Mesozoic granitoids, with minor Precambrian and Paleozoic metamorphic rocks. Precambrian rocks on the island were divided into the Baoban Group, Shilu Group, and Shihuiding Formation (Zhang et al. 1990; Ma et al. 1998). Neoarchean rocks may outcrop in the Wuzhi Mountain and Sanya region of the southeastern area; these structures are mainly composed of a set of plagioclase-amphibole gneiss and charnockite that exhibit granulite-facies metamorphic traits (Zeng et al. 1992; Zhang et al. 1997).

The Baoban Group is mainly located in the northwestern area (Fig. 1) and consists of a set of volcanic-clastic sedimentary rock-series (Ma et al. 1997; Xu et al. 2006). Displaying intense metamorphism, these rocks have an overall high greenschist-facies and amphibolite-facies, with some eclogite-facies (Wang et al. 1991). Li et al. (2008) obtained a weighted mean $^{207}Pb/^{206}Pb$ age of 1,433 ± 6 Ma for a meta-volcaniclastic sample, confirming the Mesoproterozoic age of the Baoban Group.

The Shilu Group has outcrops in the Changjiang area and has been subjected by an EW-trending multiple syncline and a NE-trending shear control. The well-known

Shilu iron mine is established in these strata (Fig. 1). The Shilu Group is a set of marine-abyssal-facies complexes that contain volcanic-clastic components as well as carbonate rocks and display characteristics of turbidite-flow deposition (Xu et al. 2007b). The Shilu Group was traditionally considered to represent the Neoproterozoic strata unconformably overlying the Baoban Group. However, Li et al. (2008) obtained a SHRIMP Pb–Pb zircon age of 1,439 ± 9 Ma for a meta-tuff from the Shilu Group, remarkably similar to the age of meta-volcaniclastics of the Baoban Group. Li et al. (2008) concluded that the Shilu Group was approximately coevally with the Baoban Group, despite their differing metamorphic grades. The Shihuiding Formation comprises quartzite and quartzoschists, which were considered to unconformably overlie the Shilu Group, and defining its maximum deposition age at ca. 1,200 Ma (Li et al. 2008).

The most commonly outcropped strata on the island are the Paleozoic followed by the Proterozoic and Meso-Cenozoic (Fig. 1b). The Paleozoic strata distributed in the northwestern area are composed of a set of marine-facies metamorphic siltstone, fine sandstone and carbonate, which harbors interbedded series of metabasic and acidic volcanic rocks, manifesting as lenticular structures (Fig. 1) (Xia et al. 1991; Zhang et al. 1997, 1998). However, the Paleozoic strata in the southeastern area comprise a set of deep-sea facies volcanic-clastic sedimentary rocks.

Granitic magmatic rocks are widely distributed on Hainan Island and multi-periodic magmatism. Among these rocks, the Mesoproterozoic granite has only been discovered in the northwestern region of the island and is emplaced in the Paleo-Mesoproterozoic Baoban Group (Xu et al. 2001a). The Caledonian granite was firstly found in the Baomei Ridge of the Changjiang area of the northwestern region (Fu and Zhao 1997). In the early Mesozoic, the oceanic basin closed and subsequent collision between two separated massifs resulted in the formation of the Shilu mélange, intruded by voluminous Indosinian to early Yanshanian granites (240–190 Ma; Wang et al. 1991). Cretaceous granites and mafic dikes (130–80 Ma) and coeval volcanic on Hainan Island further reveal that this extensional event had commenced by the early Cretaceous (Wang et al. 1991; Wang et al. 2011b). Outcrops of intrusive rocks, including the Hercynian–Indosinian porphyritic granite, Yanshanian granite porphyry and granodiorite, account for approximately 60 % of the total island area (Fig. 1b; Xu et al. 2003).

Samples and analytical methods

Forty-eight surface sediment samples were collected from the beaches of Sanya Bay (30 samples) and Yalong Bay (18 samples). All samples were analyzed for grain size at the Third Institute of Oceanography, State Oceanic Administration. The grain size was analyzed using a Mastersizer 2000 particle size analyzer, which has a detection range of 0.02–2,000 μm, a grain-size resolution of 0.01 ϕ and a relative error of less than 3 % for repeated measurements. One sample from Yalong Bay was analyzed for U–Pb dating and Hf isotope of detrital zircons.

Zircon U–Pb geochronology

After washing, magnetic sorting and heavy liquid separation, detrital zircons were glued to one side of double-sided tape and filled with epoxy resin to form targets. Experiments were carried out at the MC-ICPMS laboratory of the Institute of Geology and Geophysics, Chinese Academy of Sciences. An Agilent 7500a quadruple (Q)-ICPMS was used for simultaneous determination of zircon U–Pb age and trace elements with a 193 nm excimer ArF laser-ablation system attached. The analytic methods and equipment parameters were similar to those of a previous study (Xie et al. 2008).

The spot size was 44 μm in diameter. The $^{208}Pb/^{232}Th$ ratios were corrected using zircon 91500 as external standard. The fractionation correction and results were calculated using GLITTER 4.0. Subsequently, the method of Andersen (2002) was used to perform common Pd correction. The weighted mean U–Pb ages and concordia plots were processed using ISOPLOT 3.0 (Ludwig 2003). The trace element analysis was performed simultaneously with the U–Pb analysis.

Zircon Lu–Hf isotopic measurements

The in situ determination of zircon Lu–Hf isotopes was performed using a Neptune multi-collector ICPMS, which used a Geolas-193 ArF laser ablation system, at the Institute of Geology and Geophysics, Chinese Academy of Sciences. A stationary spot was used for the present analyses, with a beam diameter of about 63 μm.

In this study, the mean $^{173}Yb/^{171}Yb$ ratio of the individual spot is used to calculate the fractionation coefficient (β_{Yb}), and then derive the contribution of ^{176}Yb to ^{176}Hf (Iizuka et al. 2005). Detailed test procedures and equipment operating conditions were previously described (Wu et al. 2006). Interference corrections were facilitated using $^{175}Lu/^{176}Lu = 0.02655$ and $^{176}Yb/^{172}Yb = 0.5887$. The ^{176}Lu decay constant required for the calculation of $\varepsilon_{Hf}(t)$ was 1.867×10^{-11} a^{-1} (Söderlund et al. 2004). The present-day chondrites had a $^{176}Hf/^{177}Hf$ ratio of 0.282772 and $^{176}Lu/^{177}Lu$ ratio of 0.0332 (Blichert-Toft and Albarède 1997). To calculate model ages based on a depleted mantle source, a model was adopted with

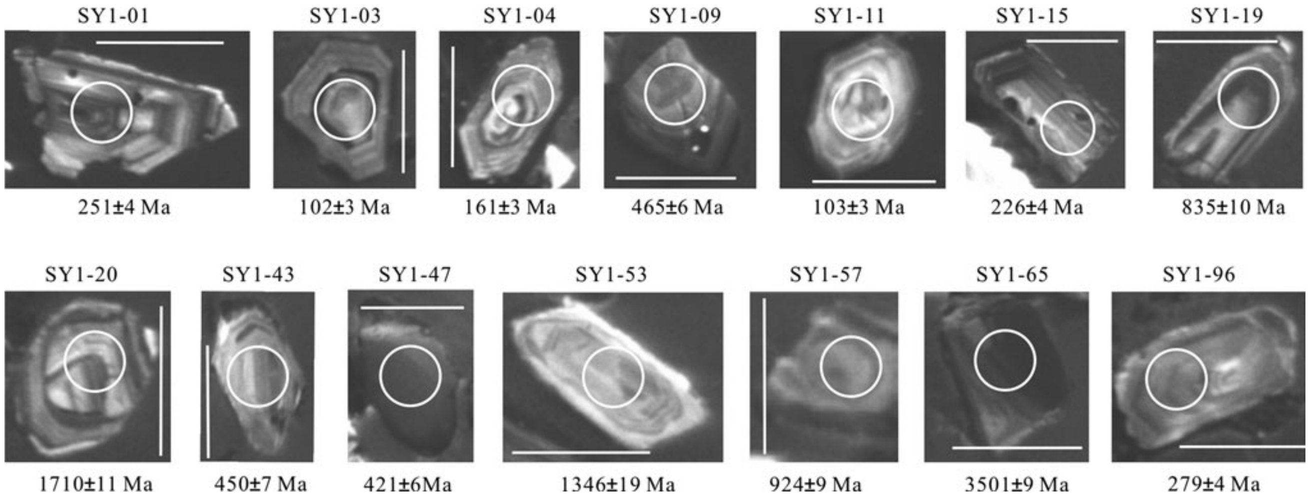

Fig. 2 Cathodoluminescence images of representative zircons (*scale bar* 100 μm)

^{176}Hf/^{177}Hf = 0.28325 and ^{176}Lu/^{177}Hf ratio of 0.0384 (Vervoort and Blichert-Toft 1999).

CL imaging of zircons

The cathodoluminescence (CL) emission images have been widely used to distinguish igneous zircons from metamorphic zircons. In order to investigate the internal structures of the zircon particles, zircon CL imaging (Fig. 2) was taken using a scanning electron microprobe at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences.

Results

The grain size of the beach sediments

The surficial beach sediments of Yalong Bay were dominated by medium–fine and fine sand, although two specimens presented with a low abundances of coarse sand (Fig. 3). The overall grain size distribution exhibited a single-peak pattern with dominant particle diameters in the range of 63–500 μm and sorting coefficients of 0.44–0.98 ϕ; the latter value is indicative of a good sorting property. In comparison, the sediments of Sanya Bay had slightly greater sizes and were mainly medium–fine and coarse–medium sand, although a few specimens had fine particles (Fig. 3). The grain size distribution also showed single-peak characteristics with dominant particle diameters in the range of 125–1,000 μm and sorting coefficients of 0.41–1.01 ϕ, indicating an intermediate sorting property.

Rare earth element geochemistry of zircons

Most of the zircons exhibit REE patterns compatible with an igneous origin, namely enriched heavy rare earth (HREE) and depleted light rare earth (LREE), and exhibited a positive cerium anomaly and a negative europium anomaly (Fig. 4). Five zircons showed no positive Ce anomaly but obvious negative Eu anomaly (Fig. 4), suggesting they are likely to be of granitoid origin (Peck et al. 2001). All these zircons are enriched in HREE except in two cases (SY01-92 and SY01-93) with U–Pb age of 296 Ma and 246 Ma, zircons probably generated by granulite facies metamorphism (Whitehouse and Platt 2003). The differences in REE patterns may represent the differences in source material.

The U–Pb ages of the detrital zircons

The analytical results are summarized in ESM Table 1. The U–Pb age analysis of the detrital zircons from Yalong Bay employed 96 points, among which 83 had concordant ages (concordance of 90–110 %). The following discussion is confined to the concordant zircons. In the U–Pb concordia diagram (Fig. 5), the majority of the analytical points lie along the concordia line, and very few points were discordant. The age distribution of the detrital zircons exhibited four major groups (Fig. 5), i.e., the Late Yanshanian (96–140 Ma, accounting for 16.9 % of the total points), the Early Yanshanian (156–185 Ma, 7.2 %), the Hercynian–Indosinian (222–345 Ma, 43.4 %) and the Caledonian (421–513 Ma, 18.1 %). Furthermore, certain detrital zircons belonged to the Precambrian (Fig. 5), most of which were of Neoproterozoic (728–984 Ma). One particle was an Archean zircon and had a U–Pb age of 3,501 ± 9 Ma.

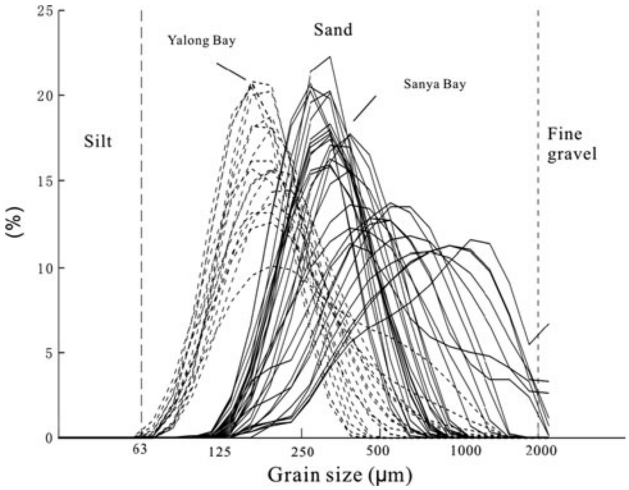

Fig. 3 Grain size distributions of sediments from Yalong Bay and Sanya Bay

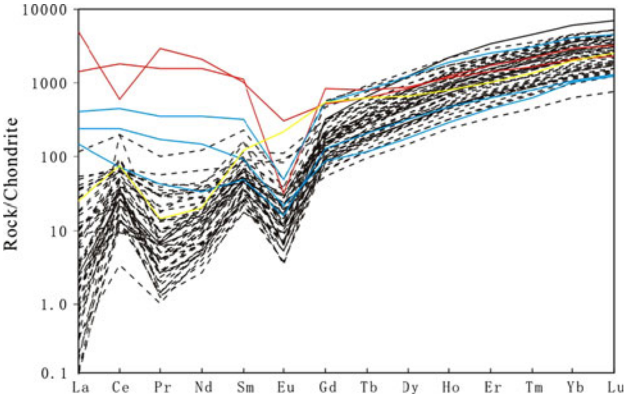

Fig. 4 Chondrite-normalized REE pattern of detrital zircons

The Hf isotope of the detrital zircons

The analytical results are summarized in ESM Table 2. The majority of the zircons had ^{176}Lu/^{177}Hf ratios of less than 0.002, indicating that low levels of radiogenic Hf had accumulated after their formation. It has been established that the current ^{176}Hf/^{177}Hf ratio of a zircon can represent the ^{176}Hf/^{177}Hf ratio when the particle formed (Amelin et al. 1999). The ^{176}Hf/^{177}Hf ratios of the detrital zircons were predominantly distributed in the range of 0.281293–0.282877, except that one point had a ^{176}Hf/^{177}Hf ratio of 0.280509, a U–Pb age of 3,501 Ma and $\varepsilon_{\mathrm{Hf}}(t)$ of -3.6 (Fig. 6a). Moreover, the majority of the ^{176}Hf/^{177}Hf ratios were greater than 0.282083, corresponding to an age of 96–1,346 Ma, and zircon $\varepsilon_{\mathrm{Hf}}(t)$ values of between -12.4 and $+10.1$. The Hf model age (T_{DM2}) had a range of 0.7–4.0 Ga and peak values of 1.3–1.6 Ga (Fig. 6b).

Discussion

The detrital zircons of the Yalong Bay are characterized by euhedral, short prismatic shape, with display oscillatory bands in CL images (Fig. 2), as commonly observed in magmatic zircons. The euhedral zircons suggested a near-source region. Most zircons had Th/U ratios of greater than 0.10 (only two particles Th/U ratios less than 0.10), which are characteristic of magmatic (rather than metamorphic) zircon (Rubatto 2002).

Sedimentary provenance

The beach sediments of Sanya Bay are mainly composed of fine–medium and medium–coarse sand, and are slightly larger than the medium–fine and fine sand of Yalong Bay (Fig. 3). The larger particles in Sanya Bay are probably attributed to its stronger hydrodynamics associated with its more open waters. The grain size distribution of the sediments exhibits a conspicuous unimodal feature, reflecting the sediments were formed under the same condition of hydrodynamic force.

The U–Pb age spectrum of the detrital zircons is dominantly Mesozoic Hercynian–Indosinian and Yanshanian, as well as the Paleozoic Caledonian, with only a few zircons corresponding to the Precambrian (Figs. 5, 7a). Hainan Island has few outcroppings of Neoarchean and Paleoproterozoic rocks, which are probably in Wuzhi Mountain and the Sanya region (Zeng et al. 1992; Zhang et al. 1997). In terms of the U–Pb ages of the Precambrian detrital zircons in Yalong Bay, the majority of the zircons were of Neoproterozoic, although two spots corresponded to the Paleoproterozoic (1,710 ± 11 and 2,408 ± 9 Ma) and one was from the Archeozoic (3,501 ± 9 Ma), indicating that they may have originated from the Neoarchean–Paleoproterozoic rocks in the Sanya region. The Precambrian strata of Hainan Island, represented by the Mesoproterozoic Baoban Group (1,433 ± 6 Ma) and Shilu Group (1,439 ± 9 Ma), are mainly outcropped in the northwestern part of the island. Hence, the beach of Yalong Bay contains few Precambrian materials.

The Caledonian movement is an important orogenic event in the geological evolution history of Hainan Island. This event not only caused the strata of the Early Paleozoic and earlier ages to experience intense folding but also prompted the island to undergo uniform uplifting that was accompanied by regional metamorphism and granitic magmatism (Fu and Zhao 1997; Zhang et al. 1999; Ding et al. 2002). Therefore, abundant Caledonian materials have been observed on the beach of Yalong Bay. Hainan Island is dominated by intrusive rocks such as Hercynian–Indosinian granite, Yanshanian granite porphyry and granodiorite. Correspondingly, Hercynian–Indosinian

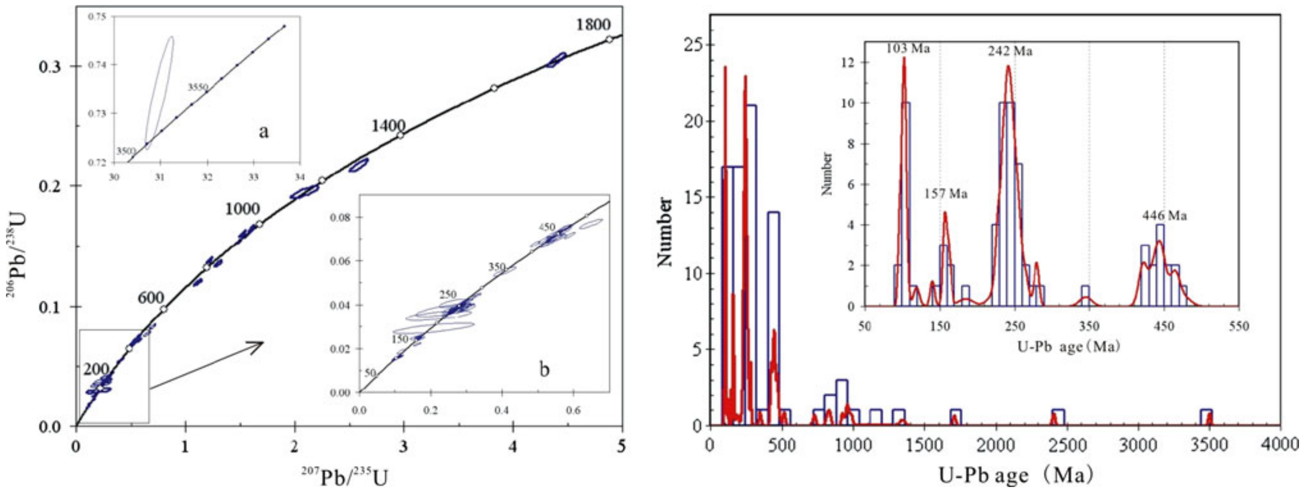

Fig. 5 *Left panels* show U–Pb concordia plots of the detrital zircons. Insets show expanded plots for older zircon (*a*) and younger zircons (*b*). *Right panels* show corresponding relative probability plots of U–Pb ages for concordant detrital zircons

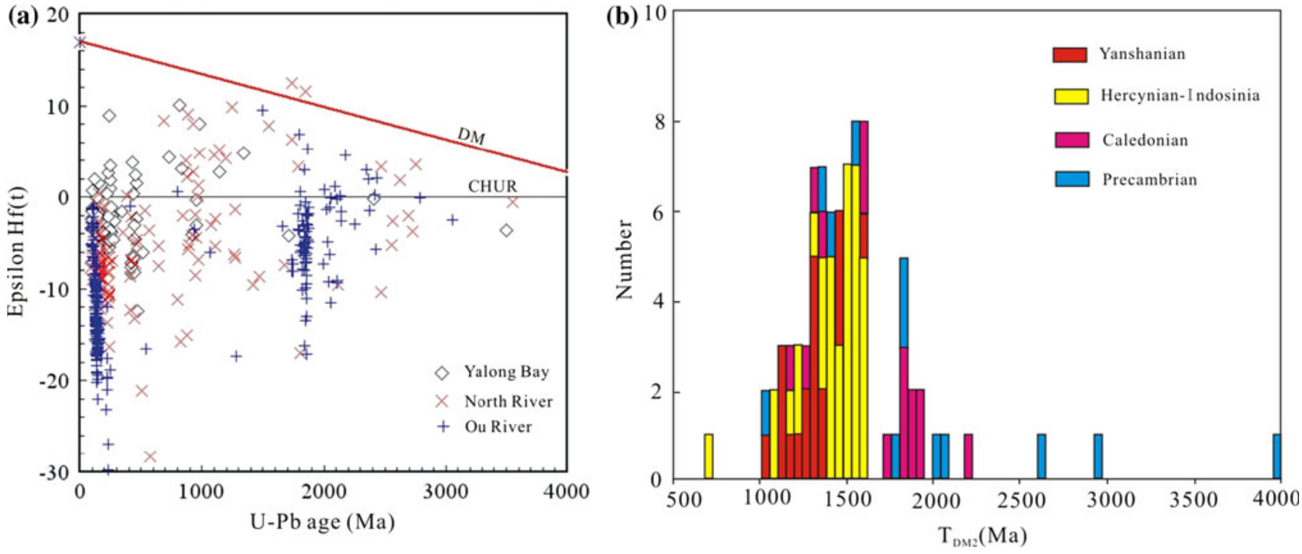

Fig. 6 *Left panels* show correlation between the U–Pb ages and $\varepsilon_{Hf}(t)$ values for the concordant zircons. North River in western Cathaysia and Ou River in eastern Cathaysia (Xu et al. 2007d). The intersection of these lines with the DM curve represents the crustal model age of grains lying along the *line*. *DM* depleted mantle, *CHUR* chondritic uniform reservoir. *Right panels* show histograms of T_{DM2} for concordant detrital zircons

granite has the largest proportion of 43 % in Yalong Bay. In addition, Hercynian–Indosinian syenite was discovered in Sanya and shown to have a sensitive high-resolution ion microprobe (SHRIMP) U–Pb age of 237–251 Ma (Xie et al. 2005). The widespread invasion of Yanshanian granite possibly provided the source materials for the Yanshanian sediments of Yalong Bay.

Further constraints on provenance can be gained by the Fig. 7, which shows the U–Pb age spectra derived from various potential source rocks. The highest age probability of the Ou River in the eastern Cathaysia Block is centered at 100–155 Ma, and is followed by peaks at 1,850–1,870 Ma (Xu et al. 2007d). Not surprisingly, there are very few Paleoproterozoic (1,850 Ma) zircons in Sanya beach because this block now lied outside the Hainan Island. The age spectrum of North River shows Late Jurassic (160 Ma) grains with a minor Cretaceous (100 Ma), and an Indosinian (240 Ma) age peak, which is distinct from that of the Sanya sample. Although the Red River could have entered the South China Sea via southern Hainan Island during the Miocene (Van Hoang et al. 2009), the U–Pb ages of the detrital zircons from the river mainly display features of the Indosinian (250 Ma), Caledonian (450 Ma), Neoproterozoic (700–900 Ma) and Paleoproterozoic (1,800–2,000 and 2,200–2,500 Ma) periods (Fig. 7a). Importantly, the U–Pb ages of the detrital zircons

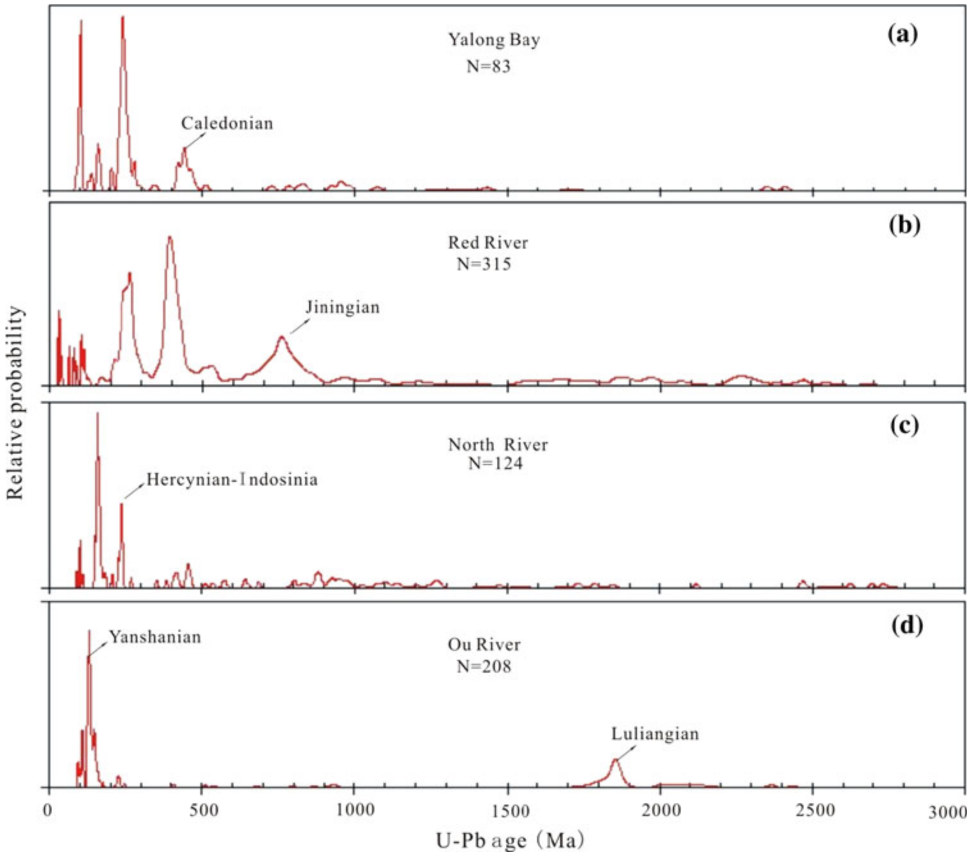

Fig. 7 U–Pb zircon age spectrum of the modern sediments from Yalong Bay, North River in western Cathaysia and Ou River in eastern Cathaysia (Xu et al. 2007d), Red River (Van Hoang et al. 2009)

from the Red River have Paleoproterozoic peaks, which is a significantly distinct result from that of the Sanya beach. Therefore, the Red River is not a primary contributor to the detrital zircons in the Sanya beach.

Implications for the crustal evolution of Hainan Island

Zircons U–Pb ages alone cannot provide compelling constraints on the timing of crustal generation, as many tectonothermal events may only involve the reworking of older crust. However, integration of U–Pb age and Hf isotope data on zircons has become a powerful tool for unravelling crustal evolutionary history (Bodet and Schärer 2000; Griffin et al. 2004; Iizuka et al. 2005).

To date, it has not been clearly determined whether Hainan Island has any ancient Archean basement. From the beach sand sample of Yalong Bay, two Paleoproterozoic detrital zircons were obtained and had U–Pb ages of 1,710 ± 11 and 2,408 ± 9 Ma as well as $\varepsilon_{Hf}(t)$ values of −4.1 and −0.24, respectively. These data indicate that the source rocks have experienced the reworking of older crustal evolution. Zhang et al. (1997) examined the detrital zircons in the Shang’an region, which is in the central island and is east of the Baisha fault, and observed that the upper intercept age of the U–Pb concordia of the zircons was 2,562 Ma. The Nd model ages of the metasediments in the Mesoproterozoic Baoban Group also imply that Hainan Island harbors information indicative of an ancient crystalline basement of the early Paleoproterozoic or Archean era (Xu et al. 2001b). Moreover, an Archean zircon was also found with a U–Pb age of 3,501 ± 9 Ma, a low $^{176}Hf/^{177}Hf$ value of 0.280509 and a negative $\varepsilon_{Hf}(t)$ value of −3.6 (Fig. 6a). Therefore, the available data generally supported the existence of an ancient crystalline basement on Hainan Island.

Hainan Island is bisected by the NE–SW Baisha fault to form two entities, the northwestern and southeastern regions of the island (Metcalfe et al. 1993). Among the detrital zircons obtained from Yalong Bay in the southeastern region, 12 were of Precambrian origin, and 7 were of Neoproterozoic origin (728–984 Ma), indicating that the Neoproterozoic activities constituted a significant geological event in the southeastern area. Furthermore, the positive $\varepsilon_{Hf}(t)$ values (0 to +10.1) of the Neoproterozoic detrital zircons from the southeastern region of the island (Fig. 6a) were consistent with the low but positive $\varepsilon_{Hf}(t)$ values (+0.29 to +0.93) of the Neoproterozoic granitoids of the Shang’an region in the central island (Xu et al. 2008b). These results demonstrate that the Neoproterozoic was a critical period of juvenile crustal growth for the southeastern area of Hainan Island.

Phanerozoic zircons comprise approximately 85 % of the zircons in Sanya beach. The zircon U–Pb age spectrum of Phanerozoic zircons defines at least four age groups (Fig. 5): Caledonian (~446 Ma), Indosinian (~242 Ma), Early Yanshanian (~157 Ma) and Later Yanshanian (~103 Ma), suggesting that Hainan Island was experiencing four major magmatic events in the Phanerozoic period. The detrital zircons with Caledonian (421–513 Ma) show very large ranges of Hf isotopes, i.e., $\varepsilon_{Hf}(t)$ values between −12.4 and +3.7, and T_{DM2} values mainly between 1.4 and 2.0 Ga (Fig. 6b), suggesting mixing between an old crustal component and little input of juvenile material. The geochemical characteristics of Caledonian metavolcanic rocks in Tunchang display the incorporation of mantle-derived substances (Ding et al. 2002).

The Hercynian–Indosinian zircons had $\varepsilon_{Hf}(t)$ values between −5.5 and +8.9 and T_{DM2} values mainly of 1.2–1.6 Ga (Fig. 6). The Hercynian–Indosinian granite is mainly exemplified by the Danxian rock and the Qiongzhong rock; the zircons had T_{DM} (Nd model age) values of 1,130–1,327 Ma and ε_{Nd} (290 Ma) ranging from −3.3 to −0.1, which revealed an infiltration of mantle materials. Compared with the concurrent granites in southeast China, the Indosinian granites of the Hainan Island block have higher ε_{Nd} (t) values and lower Nd model ages. The granites of Hainan Island mainly originated from juvenile crust recycling that involved mantle-derived materials or contained a high level of mantle materials, suggesting a low degree of crustal maturity of the island (Xu et al. 2001b). In addition, the Sr–Nd–Pb isotopic compositions of Sanya peralkaline syenite (244 ± 7 Ma) were similar to that of enriched lithospheric mantle (EM II) (Xie et al. 2005). This process is in agreement with the finding that some of the zircons showed positive ε_{Hf} (t) values. The Yanshanian zircons exhibited $\varepsilon_{Hf}(t)$ values between −7.0 and +1.9 and T_{DM2} values mainly of 1.0–1.5 Ga (Fig. 6). The incorporation of mantle-derived substances is supported by the findings that late Yanshanian mafic dyke swarms that originated from mantle source regions are widely distributed in Sanya (Tang et al. 2010) and that the late Yanshanian granites have ε_{Nd} (134 Ma) values ranging from −0.8 to −6.3 (Xu et al. 2001b).

Tectonic significance

A Neoproterozoic (1.0–0.7 Ga) peak could be clearly recognized, indicating that the Neoproterozoic activities constituted a significant geological event in the southeastern area. However, according to the SHRIMP zircon U–Pb ages of metasediments in the northwest area (Xu et al. 2007b) and the SHRIMP zircon U–Pb ages of the granitic rocks that were emplaced in the Baoban Group, the western part of the island had undergone a structural-thermal metamorphic event during 1.4–1.0 Ga, earlier than the southeastern area. This result indicates that the Precambrian basements of southeastern and northwestern regions of the island are different. In addition, the Grenvillian orogeny of South China shared the same timing with the orogenic events (1.0–0.7 Ga) in the southeastern regions of Hainan Island (Li 1999), suggesting that the southeastern region is tectonically similar to the CB. A report from Xu et al. (2007d) indicated that the eastern part of the CB basement was mainly of Paleoproterozoic origin and underwent large-scale crustal remelting and reforming during the Yanshanian (100–155 Ma) (Fig. 7d). In contrast, the western part of the CB basement was mainly of Neoproterozoic origin and contained a small amount of Archean and Mesoproterozoic material and experienced intense crustal remelting and reforming during the Caledonian (450 Ma), Indosinian (240 Ma) and early Yanshanian (160 Ma) (Fig. 7c). Because the eastern CB and western CB have apparent differences in the history of their crustal evolution, they may represent separate microcontinents (Xu et al. 2007d). In comparison, southeastern Hainan Island is more similar to the western CB (Fig. 6, 7).

Prior to the convergence of the Rodinia supercontinent, northwestern Hainan Island was very likely a part of the southern Laurentia continental, whereas the southeastern region (which may also include the CB) probably belonged to the eastern margin of Australia (Xu et al. 2007b). Southeastern Hainan Island and the western CB experienced the Neoproterozoic orogeny together, thereby forming a part of the Rodinia supercontinent. Subsequently, during the Paleozoic and Mesozoic periods, Hainan Island and the western CB underwent Caledonian, Hercynian–Indosinian and Yanshanian crustal reworking along with the growth of a small amount of juvenile crust (Fig. 6a). Nevertheless, due to the differences in the crustal sources, the compositions of the Hf isotopes are different between the region of southeastern Hainan Island and the western CB in Proterozoic. The current block pattern of Hainan Island may be related to the 90° rotation of the Rodinia supercontinent that was caused by the super mantle plume 800 Ma ago (Li et al. 2004).

Conclusions

1. The beach sediments of Sanya Bay are mainly composed of fine–medium and medium–coarse sand; these particles are slightly larger than their counterparts in Yalong Bay. The larger particle size of the sediments in Sanya Bay is probably attributed to its stronger hydrodynamics associated with more open waters. The grain size distribution of the sediments displays a clear single-peak feature, indicating the sediments were formed under the same condition of hydrodynamic force.

2. The detrital zircons had Th/U ratios of greater than 0.1 and REE pattern displayed a positive Ce anomaly and a negative Eu anomaly. These findings, in conjunction with the CL imagery, indicated that these zircons are predominantly of magmatic origin. The U–Pb spectrum of detrital zircons mainly peaked at the Yanshanian (96–185 Ma), Hercynian–Indosinian (222–345 Ma) and Caledonian (421–477 Ma). A portion of the detrital zircons were of Precambrian origin, although the majority were of Neoproterozoic origin (728–1,003 Ma). In comparison with the Red River, Yalong Bay shows an apparent lack of Paleoproterozoic detrital zircons (1,800–2,000 and 2,200–2,500 Ma), and its sediments mainly originate from Hainan Island.
3. The U–Pb age spectrum of detrital zircons revealed that the basement of eastern Hainan Island was mainly of Neoproterozoic but contained low levels of Archean substances. The Hf isotopic data indicated that the Neoproterozoic was a major period for juvenile crustal growth in southeastern Hainan Island. Subsequently, the crust experienced remelting and reforming during the Caledonian (421–477 Ma), Hercynian–Indosinian (222–345 Ma) and Yanshanian (96–185 Ma), which was accompanied by the minor growth of juvenile crust.
4. The Neoproterozoic orogeny in the southeastern region of the island (0.7–1.0 Ga) occurred later than in the northwestern region (1.0–1.4 Ga), suggesting that the two areas had distinct Precambrian basements. The orogeny in the southeastern Hainan Island shared the same timing as the western CB, indicating that both areas simultaneously underwent this orogenic event, thereby producing a part of the Rodinia supercontinent.

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