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Linking source and sink: Detrital zircon provenance record of drainage systems in Vietnam and the Yinggehai–Song Hong Basin, South China Sea

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ABSTRACT

Cenozoic sedimentary strata of the continental margin are well preserved in ocean basins and offer an important geological window for studying source-to-sink relationships between potential source areas and sedimentary basins over time. We conducted coupled U-Pb dating and Lu-Hf isotope analysis of detrital zircon in fluvial sediments along northern and central Vietnam and sediment core in the western Yinggehai–Song Hong Basin in order to characterize the potential sources, investigate the sedimentary provenance, and decipher the crustal evolution processes of the source areas. The detrital zircons from the fluvial sediments reveal marked spatial changes in their age signatures that correlate with changing basement characteristics. The Red River system generally has multiple zircon age populations with peaks at ca. 30–25 Ma, 247–239 Ma, 441–414 Ma, 751–743 Ma, 1876–1742 Ma, and 2700–2200 Ma, in contrast to the sediments from central Vietnam, which commonly exhibit markedly different age patterns with well-defined Silurian and Triassic peaks (ca. 244–234 Ma and 438–419 Ma). The source-to-sink study demonstrates that both the Red River and central Vietnam materials have made important provenance contributions to the western Yinggehai–Song Hong Basin since the middle Miocene. The western basin has had constantly changing provenance since the middle Miocene because the contributions from these two source areas vary temporally. This integrated study also indicates that the southern Yangtze block and eastern Indochina block had a significantly different tectonic evolution history, as manifested by the age populations of major tectonic-magmatic events. Juvenile crustal growth occurred in the southern Yangtze block during the Neoproterozoic and late Paleozoic to Mesozoic, while the eastern Indochina block is characterized by prominent crustal additions in the Paleoproterozoic.

INTRODUCTION

A long-standing goal of the geological community is to offer quantitative analyses of the ways in which perturbations on Earth's surface are preserved within continental margin sedimentary sequences (Kuehl et al., 2016). Marginal seas connect the continents to open oceans and thus contain a key component of the source-to-sink system (Thomas et al., 2004; Z. Liu et al., 2016). Understanding the source-to-sink relationship through time between the source and the depositional site is central to our ability to unravel surface transport processes and paleogeography. In particular, it is important to know where sediment is formed through the drainage systems and how the provenance of sediment is distinguished in the depositional area. During the last two decades, many studies have investigated marine sediment source-to-sink processes using different methods (Cawood et al., 1999, 2003; Clift, 2006; Marsaglia et al., 2010; Warrick, 2014). However, there are few studies that have taken a systematic approach to understanding a complete process from the continental mountain source to the ocean sink.

Generally, fluvial sediments eroded from drainage catchments are precipitated mostly on the continental shelf and marginal slope (Z. Liu et al., 2016). They contain the total source characteristics of the river basin, and they are crucial to providing detritus to the depositional site. By contrast, marine sediments represent the longest and most complete archives of continental geological evolution (Clift and Giosan, 2014). The provenance of clastic sediments offers important constraints on drainage scales and sediment pathways in ancient depositional systems (Cawood et al., 2004; Hallsworth and Chisholm, 2008; Z. Liu et al., 2010; Clift et al., 2012), which are fundamental to reconstructions of tectonic, paleogeographic, and paleodrainage histories (Cawood et al., 2003; Z. Liu et al., 2007; Thomas, 2011; Shao et al., 2016; Jonell et al., 2017a), and which help in the prediction of sandstone distribution and reservoir quality in petroliferous basins (Fontanelli et al., 2009). Consequently, the provenance study of the marine stratigraphic record in the Yinggehai–Song Hong Basin of the South China Sea (Fig. 1) provides an excellent case for understanding the source-to-sink transport processes of fluvial sediments in the marginal sea.

Most studies on the provenance of clastic sediments in the western Yinggehai–Song Hong Basin have traditionally relied upon seismic methods and petrographic data sets and have suggested that the sediments in this region were mostly derived from central Vietnam (Fig. 1; Gong et al., 1997; Xie, 2009). Based on the multichannel seismic reflection data, Clift and Sun (2006) indicated that central Vietnam is not an important source terrane for the Yinggehai–Song Hong Basin, especially the central and eastern parts of the basin. However, these study methods have some inherent and critical shortcomings; they are limited in their ability to identify, characterize, and effectively distinguish potential sources. Recent U-Pb dating of detrital zircon by Jiang et al. (2015) indicated that the sediments in the western basin primarily originated from central Vietnam, although there is relatively little awareness of the source terrane. Wang et al. (2016b) proposed that during the middle Miocene, in addition to the Red River system, detrital materials were also derived from central Vietnam. In many cases, it is hard to evaluate the relative influence of these source areas due to the lack of signature features and systematic studies.

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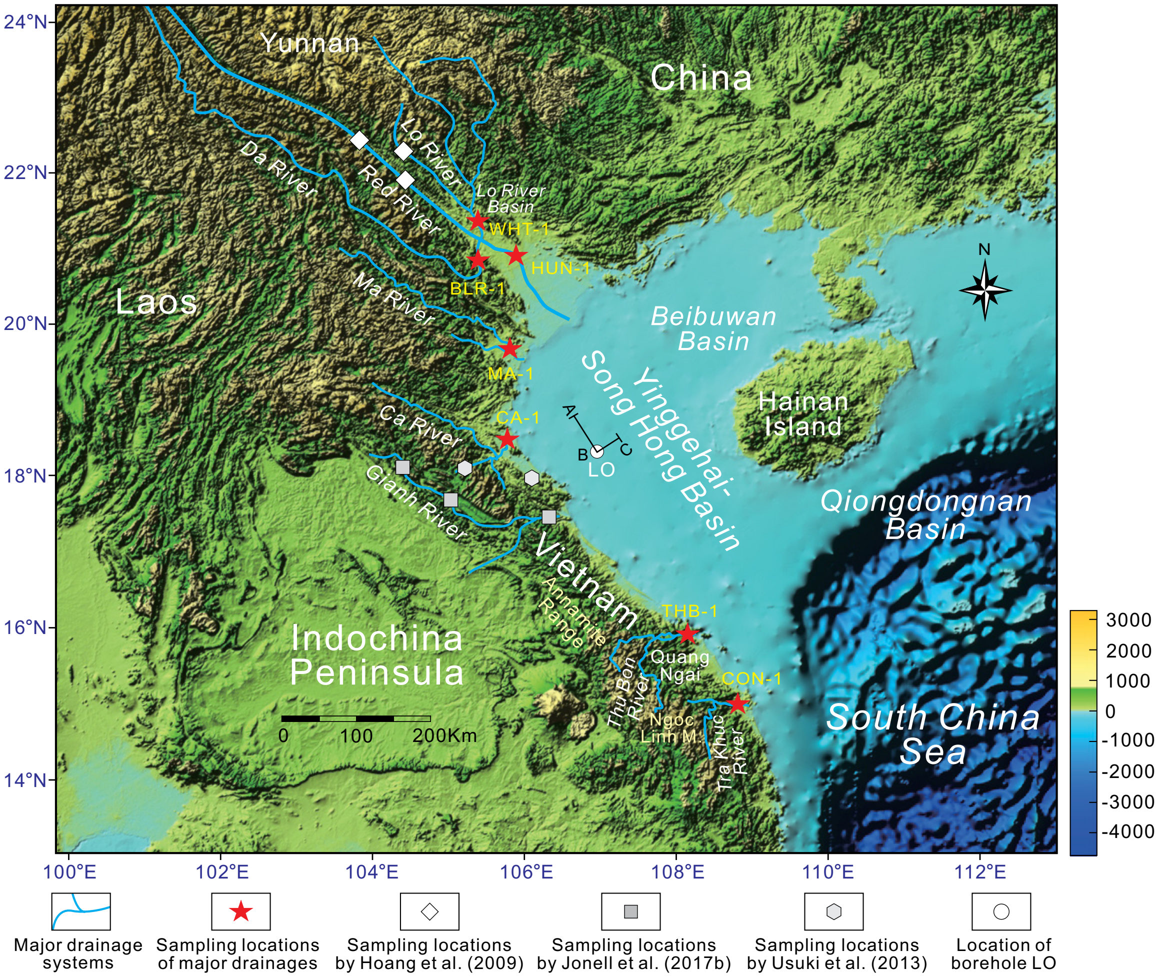

Figure 1. Regional setting and sampling locations on modern drainage systems along central and northern Vietnam and borehole LO in the Yinggehai–Song Hong Basin (elevation in m).

Geochronological and isotopic measurements on single grains of minerals preserved in both modern river and sedimentary rocks can potentially help to decipher the time-integrated provenance evolution and constrain the tectonic history of the source area (Cawood et al., 2012; Gehrels and Pecha, 2014). Recent studies that used the integrated methods of U-Pb dating and Lu-Hf isotopic analysis of detrital zircon were successfully applied to determine the provenance, characterize the source from which the zircon grains were shed, and understand the geological evolution of the host sediments (e.g., Griffin et al., 2004; Belousova et al., 2009; Hoang et al., 2009; Yao et al., 2011). In this study, we systematically examined the U-Pb ages and Lu-Hf isotopes of detrital zircon from drainage systems in central and northern Vietnam, as well as borehole samples in the western Yinggehai–Song Hong Basin. The principal research objectives were to characterize the source of the different drainage systems in northern and central Vietnam, to investigate the source-to-sink relationships and the sedimentary provenance of the western Yinggehai–Song Hong Basin, and further to understand the crustal evolution of the source terranes.

GEOLOGICAL SETTING

Drainage Systems

All the rivers of interest in this study flow into the Gulf of Tonkin in the South China Sea after flowing from sources in South China and the Indochina Peninsula (Fig. 1). The Red River system and the rivers in central Vietnam represent two different kinds of river basins because they have significantly distinct sources of sediments that drain from the South China (Yangtze and Cathaysia blocks) and eastern Indochina blocks, respectively (Fig. 2).

The modern Red River is one of the largest modern drainage systems in SE Asia; it originates from the Yunnan Province of SW China and flows ~1200 km to the South China Sea. In addition to its main stream, the Red River also receives two major tributaries in NW Vietnam, the Lo River and the Da River (Fig. 1). The paleo–Red River has been assumed to have been much larger in the past than it is today and to have progressively lost its headwaters as a result of drainage capture in East Asia (Brookfield, 1998; Clark et al., 2004; Clift et al., 2008; Hoang et al., 2010). Most of the sediments of the Red River system deposited in the Yinggehai–Song Hong Basin are eroded from SW China (Yangtze block), as well as the southern margin along the Red River fault zone (Clift et al., 2006, 2008; Hoang et al., 2009). The catchment of the river systems consists of varying rock types formed in different geological times. Igneous rocks are abundant in the drainage systems and range from Proterozoic to Cenozoic in age (Fig. 2).

Two rivers (i.e., Ma River and Ca River) are located in the Truong Son belt of the eastern Indochina block (Fig. 2). The Ma River is one of the major drainage systems in Vietnam

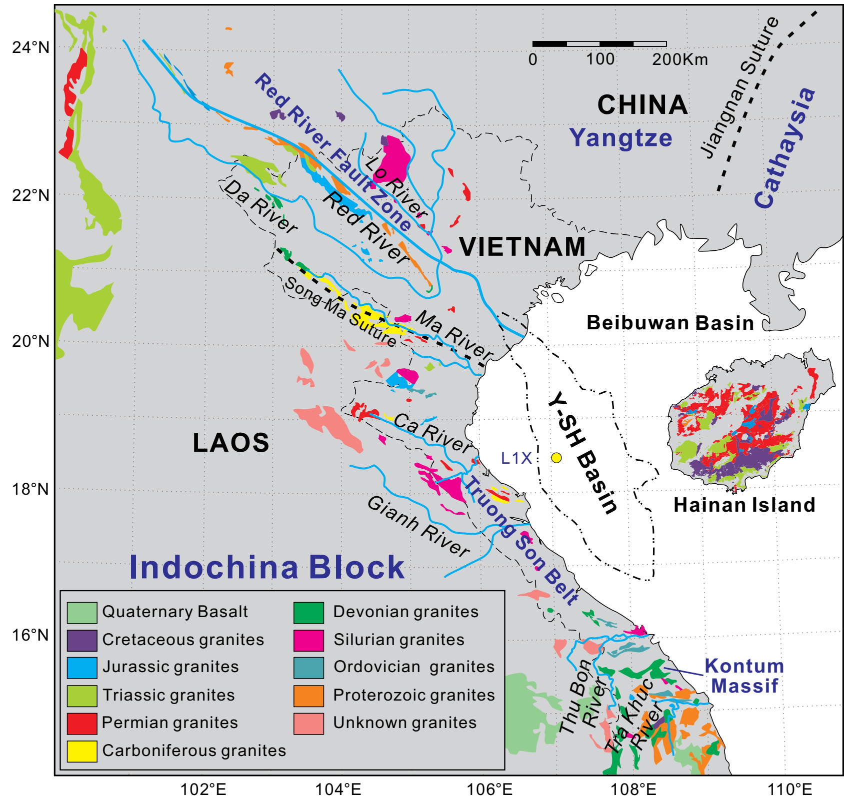

Figure 2. Igneous rocks distribution and drainage systems for the major source areas of the Yinggehai–Song Hong Basin. The geological map of Southeast Asia was modified from Wen et al. (2013) and Xiang et al. (2015).

along the Song Ma suture. The river originates in northwestern Vietnam, runs for ~400 km, and flows into the Gulf of Tonkin in the South China Sea. The Ca River originates from the eastern margin of Laos (Fig. 1) and has a total length of 300 km. The drainage basins of the rivers consist mainly of sandstones, limestone, mudstone, and conglomerate and are intruded by different types of intrusive rocks (Fig. 2).

Both the Thu Bon River and the Tra Khuc River in central Vietnam drain from the Kontum Massif of the eastern Indochina block (Fig. 2). The Thu Bon River begins at Ngoc Linh Mountain (Fig. 1), which is a high mountain of the Annamite Range in Vietnam, and flows almost 200 km to the South China Sea. The Tra Khuc River is the largest river in the Quang Ngai Province of Vietnam, and it drains the eastern slopes of the Ngoc Linh mountain range; the river's main stream is 135 km in length. High-grade metamorphic rocks (granulite facies) prevail in most parts of the catchments and are covered by Mesozoic continental red beds (Rangin et al., 1995). Early Paleozoic to Mesozoic magmatism is intensively manifested in almost all structural zones of the river basins, with complicated variations from source to sink (Hoa et al., 2008).

Yinggehai–Song Hong Basin

The Yinggehai–Song Hong Basin is geographically located on the northern margin of the South China Sea continental shelf between Hainan Island of China and the eastern coast of Vietnam (Fig. 1). It covers an area of ~500 × 60 km, with the long axis oriented from the north-northwest to the south-southeast, and it is bordered by the Beibuwan and Qiongdongnan Basins on the north and east, respectively. The formation and development of the Yinggehai–Song Hong Basin have been linked to the southeastward strike-slip motion of the Red River fault zone and the clockwise rotation of the Indochina block, caused by the collision and indentation of India into Asia (Tapponnier et al., 2001; Sun et al., 2003). The basin is the principal repository of detritus eroded from the Red River and its tributaries and is filled with a large thickness of Paleogene to Quaternary sedimentary rocks (Gong et al., 1997; Clift and Sun, 2006; Yan et al., 2011). Most of the sediments deposited in the Yinggehai–Song Hong Basin have been eroded from SW China and the Indochina Peninsula (Wang et al., 2014; Cao et al., 2015) and were delivered by the Red River system and the drainage system running along the coast of Vietnam (Fig. 1).

The Cenozoic tectonic evolution of the Yinggehai–Song Hong Basin can be divided into three periods, including the synrift stage during the Eocene to Oligocene, the postrift stage during the middle–late Miocene and a stage of renewed thermal subsidence from the Pliocene to Holocene (Rangin et al., 1995; Gong et al., 1997; Lei et al., 2011). Three successive deformation phases have been identified in high-resolution seismic reflection and borehole data, including left-lateral movement from 30 to 15.5 Ma, reverse slip between 15.5 and 5.5 Ma, and slow right-lateral movement after 5.5 Ma (Zhu et al., 2009). The primary sequence boundaries can be effectively identified by well-seismic correlation and detailed seismic sequence analysis and can be dated based on nannofossil biostratigraphy. These stratigraphic units range from the Eocene Lingtou Formation to the Quaternary Ledong Formation and are covered by modern sediments and underlain by a pre-Paleogene basement.

SAMPLING AND ANALYTICAL METHODS

Sampling

In total, 11 samples were collected from both drainage systems and a borehole in the western Yinggehai–Song Hong Basin (Fig. 1). Seven samples of fluvial sand were collected from different drainage systems in central and northern Vietnam, including the Lo River (WHT-1), Red River (HUN-1), Da River (BLR-1), Ma River (MA-1), Ca River (CA-1), Thu Bon River (THB-1), and Tra Khuc River (CON-1; Table 1). The fine to medium sand fraction was chosen to avoid possible influence of the grain-size fraction (Yang et al., 2012) and because it

TABLE 1. LOCATIONS OF SAMPLING POINTS AND RIVERS CONSIDERED IN THIS STUDY.

Sample	Location	Place name	Latitude (°N)	Longitude (°E)	Material
WHT-1	Lo River	Viet Tri	21.3024	105.4458	Fine sand
HUN-1	Red River	Long Bien	21.0080	105.9060	Fine sand
BLR-1	Da River	Hoa Binh	20.8425	105.3576	Medium sand
MA-1	Ma River	Thanh Hoa	19.8395	105.7930	Fine sand
CA-1	Ca River	Vinh	18.6459	105.7109	Fine sand
THB-1	Thu Bon River	Dien Ban	15.8590	108.2737	Fine sand
CON-1	Tra Khuc River	Quang Ngai	15.1386	108.8060	Medium sand

is ideal for a single-grain mineral provenance study (Jonell et al., 2017b). Four sedimentary rocks (i.e., LO-9, LO-10, LO-11, and LO-12) were collected from borehole LO in the western Yinggehai–Song Hong Basin (Fig. 1), for which borehole drilling was conducted with cooperation between China and Vietnam. Samples of 1–2 kg were collected from fine- to coarse-grained sandstone and siltstone. The stratigraphic units of these samples range from the Miocene Huangliu Formation to the Quaternary Ledong Formation. Detailed locations and information about the samples are shown in Figures 1 and 3. The samples, together with those from previous studies, are well distributed over central and northern Vietnam (Fig. 1) and represent a continuous marine stratigraphic record in the western Yinggehai–Song Hong Basin since the middle Miocene (Fig. 3).

Zircon U-Pb Isotopic Analysis

The zircons were separated from more than 1 kg samples using conventional heavy liquids and magnetic separation techniques. After hand sorting under a binocular stereoscope, the zircon grains were mounted in transparent epoxy and polished down to approximately half sections to expose the internal structures. To identify the origins and internal structures and to choose potential target sites, cathodoluminescence (CL) images were taken using a Mono CL3 detector attached to an electron microprobe. Zircon grains without potential defects or zonal overlap under CL were randomly picked for laser-ablation analyses.

The zircons were dated using laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at the State Key Laboratory of Isotopic Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIGCAS). Sample mounts were placed in the two-volume sample cell flushed with Ar and He. Laser ablation was performed at a constant energy of 80 mJ and at 8 Hz, with a spot diameter of 33 μm. The ablated ions were carried by He gas to the Agilent 7500a ICP-MS. The TEMORA standard was used as the age standard, with $^{206}Pb/^{238}U$ = 416.8 Ma (Black et al., 2003). Detailed analytical operating and data processing procedures used in this study are similar to those given by Jackson et al. (2004). Isotopic ratios of U-Th-Pb were calculated by ICPMSDataCal (version 7.2; Y. Liu et al., 2010). Common Pb was corrected by ComPbCorr#3_151 using the method of Andersen (2002).

Zircon Lu-Hf Isotopic Analysis by LA-MC-ICP-MS

In situ zircon Lu-Hf isotopic analyses were carried out on a Neptune Plus multicollector (MC) ICP-MS equipped with a RESOlution M-50 laser-ablation system at the same laboratory. The Lu-Hf isotopic measurements were made on the same spots previously analyzed for U-Pb isotopes. The laser parameters were as follows: spot size, 45 μm; repetition rate, 8 Hz; energy, 80 mJ. Helium was used as carrier gas, and a small flow of nitrogen was added to the gas line to enhance the sample signal. A normal single-spot analysis consisted of 30 s gas blank collection and 30 s laser ablation. The integration time was 0.131 s, and ~200 cycles of data were collected. The ^{173}Yb and ^{175}Lu values were

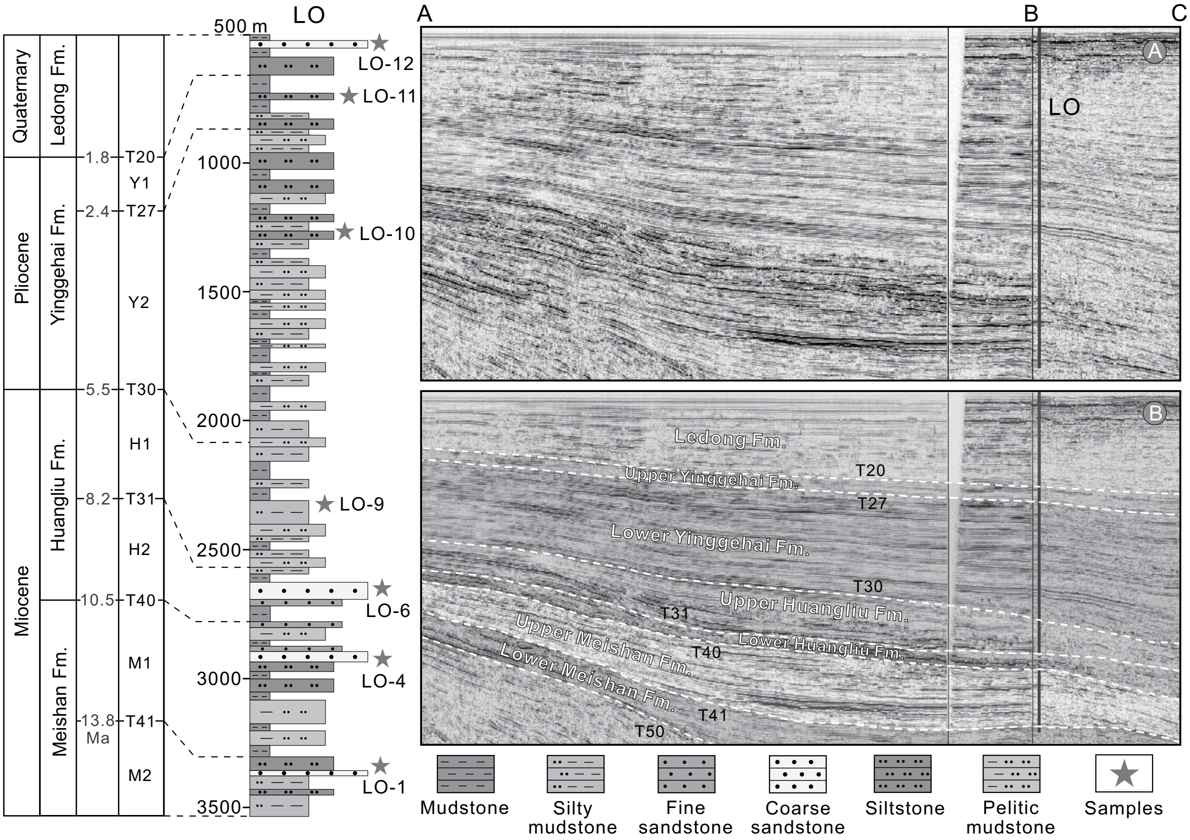

Figure 3. (Left) Measured Miocene to Quaternary sequences of borehole LO in the western Yinggehai–Song Hong Basin and the positions of the investigated sandstone samples. (Right) Uninterpreted (A) and interpreted (B) seismic profiles show the stratigraphic sequence of the study region. Location of the borehole LO is shown in Figure 1. Sample positions of LO-1 and LO-4 are from Wang et al. (2016b), and position of LO-6 is from Xie et al. (2016).

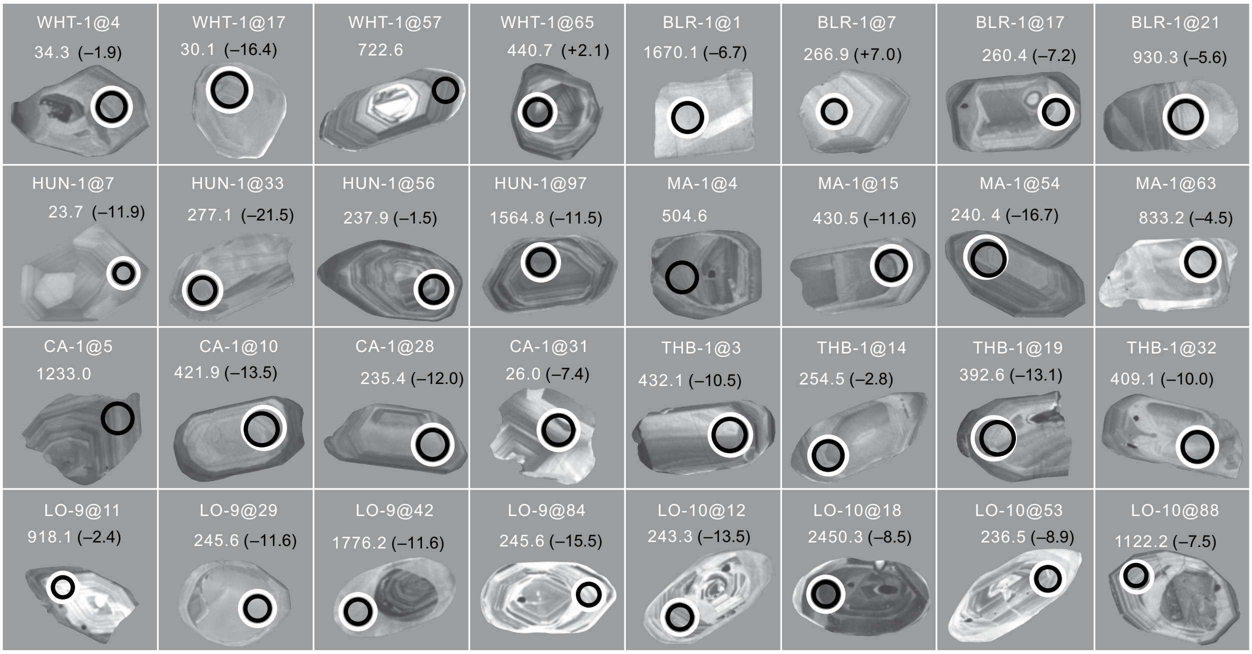

Figure 4. Cathodoluminescence (CL) images of representative detrital zircons analyzed for U-Pb ages and Lu-Hf isotopes. White and black circles denote the LA-(MC)-ICP-MS analytical spots for U-Pb age dating and Lu-Hf isotope analysis, respectively. Numbers near the circles are the U-Pb ages (white) and $\varepsilon_{Hf}(t)$ values (black). The white and black circles are 33 μm and 45 μm in diameter, respectively.

used to correct the isobaric interference of ^{176}Yb and ^{176}Lu on ^{176}Hf. The ^{176}Hf/^{177}Hf was normalized to ^{179}Hf/^{177}Hf = 0.7325 using an exponential law for mass bias correction. The Penglai sample was used as the reference standard (Li et al., 2010). The initial Hf isotope ratios are denoted as $\varepsilon_{Hf}(t)$ values, which were calculated using the chondritic uniform reservoir (CHUR) at the time of zircon crystallization and the present-day ^{176}Hf/^{177}Hf and ^{176}Lu/^{177}Hf ratios of chondrite and depleted mantle of 0.28277 and 0.0332, respectively (Blichert-Toft and Albarède, 1997). Initial ^{176}Hf/^{177}Hf values were calculated based on a ^{176}Lu decay constant of 1.865×10^{-11} yr^{-1} (Scherer et al., 2001). Single-stage model Hf ages (T_{DM1}) were computed with reference to the depleted mantle with a present-day ^{176}Lu/^{177}Hf ratio of 0.28325 and ^{176}Lu/^{177}Hf ratio of 0.0384 (Griffin et al., 2000). Two-stage model Hf ages (T_{DM2}) were computed using a ^{176}Lu/^{177}Hf value of 0.015 for the average continental crust (Griffin et al., 2002).

RESULTS

In total, 1020 zircon analyses were performed using LA-ICP-MS, including the cores and rims of the grains extracted from the different drainage systems in Vietnam and the stratigraphic units in the western Yinggehai–Song Hong Basin. The morphologies of the zircon grains were colorless to light pink and transparent and showed a wide range of prismatic to oval-shaped crystals. The CL images of the representative zircons and the spots ages are shown in Figure 4. These zircon grains were mostly concentrated in the 70–160 μm range, and a proportion had subrounded or rounded corners. The euhedral grains revealed a relatively close transportation distance, whereas the rounded grains may imply prolonged or multicycle transport. Most of the Precambrian grains were characterized by inner cores and outer rings or light zones on the surface, indicating the influence of tectonic-magmatic hydrothermal events in their source areas (Cheng et al., 2016). Some zircon grains displayed a typical metamorphic origin with a low Th/U ratio (<0.1; Table DR1[1]). Most zircon grains showed oscillatory growth zoning under CL (Fig. 4), with overwhelmingly high Th/U values (>0.4), pointing to a dominant magmatic origin (Wu and Zheng, 2004). The major age groups and their corresponding peak ages were evaluated with kernel density estimations (KDEs; Fig. 5) using the DensityPlotter program (Vermeesch, 2012) and are presented in detail in Table DR1 (see footnote 1). The Lu-Hf isotopic results are given in Table DR2 (see footnote 1) and are illustrated in Figure 6.

The samples WHT-1, HUN-1, and BLR-1 were collected from the Red River system located in northern Vietnam (Fig. 1). The zircon crystals were euhedral with partially round corners (Fig. 4). In total, 70, 100, and 100 zircon grains were analyzed, and 66, 82, and 99 concordant ages were obtained for these samples, respectively. Measured ^{206}Pb/^{238}U (younger than 1000 Ma) and ^{207}Pb/^{206}Pb (older than 1000 Ma) ages ranged from 2680 to 24 Ma (Table DR1 [see footnote 1]). The concordant zircons showed five major age peaks at ca. 30–25 Ma, 247–239 Ma, 441–414 Ma, 751–743 Ma, and 1876–1742 Ma (Figs. 5A–5C). The Th/U ratios of the zircons ranged from 0.02 to 1.73 and were concentrated in the range of 0.4–0.6 (Table DR1 [see footnote 1]). In total, 102 dated zircon grains from the three samples were selected for in situ Lu-Hf isotope analysis. The result showed a broad range of initial ^{176}Hf/^{177}Hf ratios from 0.280889 to 0.282820, with the $\varepsilon_{Hf}(t)$ values of –21.9 to +8.6 (Fig. 6A). The two-stage Hf isotopic model ages (T_{DM2}) for these zircons ranged from 3501 to 711 Ma (Fig. 6C).

Samples MA-1, CA-1, THB-1, and CON-1 were collected from the drainage systems in central Vietnam (Fig. 1). The morphology of these zircon grains showed a wide range, from prismatic to irregular-shaped with some rounded corners (Fig. 4). In total, 100 grains for each sample were analyzed, and 92, 86, 98, and 90 concordant ages were obtained for these samples,

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[1] GSA Data Repository item 2018213, Table DR1 and Table DR2, is available at http://www.geosociety.org/datarepository/2018 or by request to editing@geosociety.org.

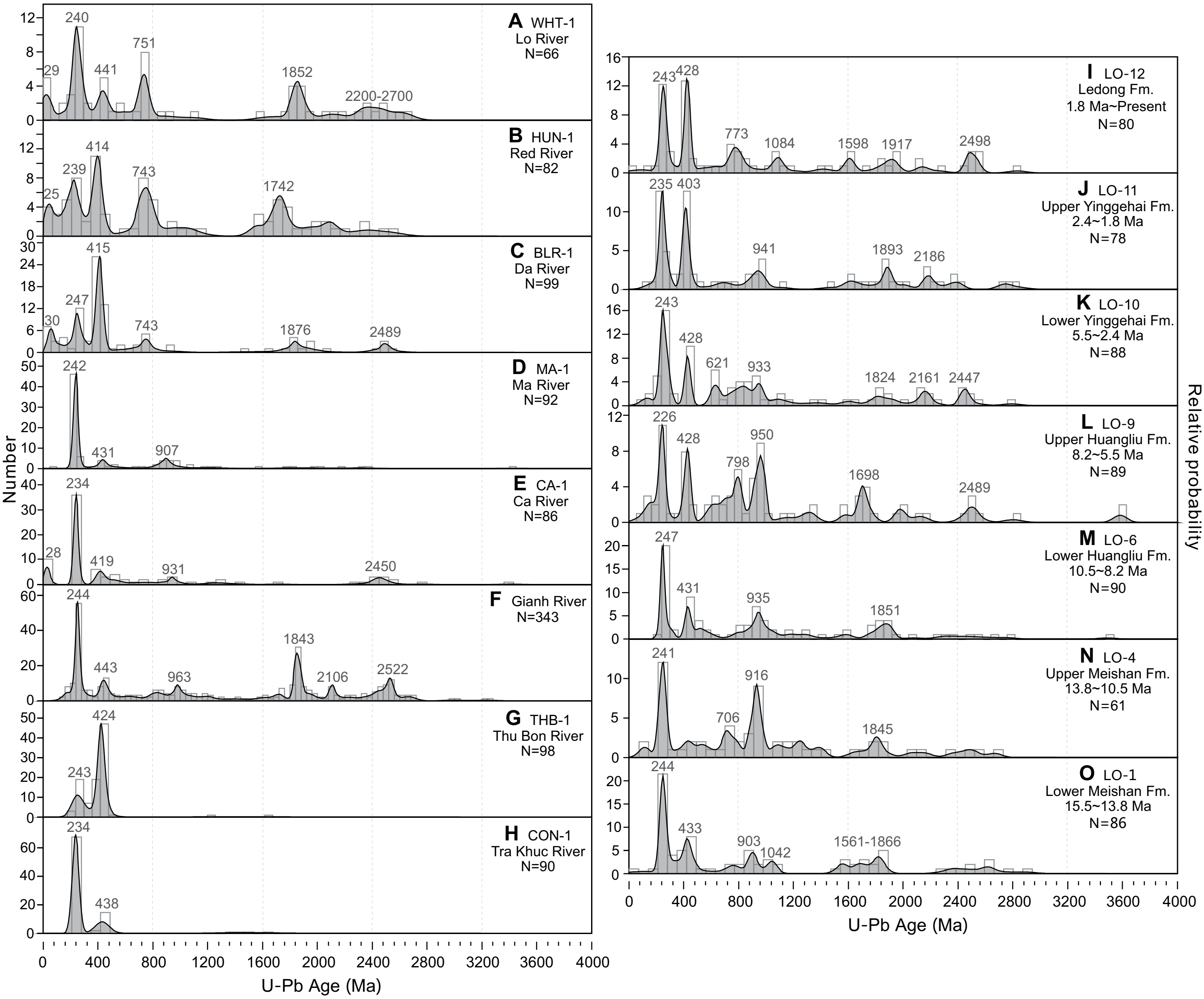

Figure 5. Kernel density estimations (KDEs) of detrital zircon from the drainage systems in (A–H) Vietnam and (I–O) borehole LO in the Yinggehai–Song Hong Basin. Data from the Gianh River are from Jonell et al. (2017b), data for samples LO-1 and LO-4 are from Wang et al. (2016b), and data for sample LO-6 are from Xie et al. (2016).

respectively. The rivers yielded concordant U-Pb ages ranging from 3418 to 22 Ma and exhibited two prominent age peaks at ca. 244–234 Ma and 438–419 Ma (Figs. 5D, 5E, 5G, and 5H). The 108 dated zircon grains from samples MA-1, CA-1, and THB-1 displayed a range of initial $^{176}Hf/^{177}Hf$ ratios from 0.280889 to 0.282675, with corresponding $\varepsilon_{Hf}(t)$ values between –25.2 and +6.6 (Fig. 6A). The T_{DM2} ages for these zircons varied between 3454 and 902 Ma (Fig. 6C).

Samples LO-12, LO-11, LO-10, and LO-9 were collected from the borehole LO in the western Yinggehai–Song Hong Basin (Fig. 1). These zircons were prismatic to oval-shaped with mostly rounded corners (Fig. 4). In total, 90, 80, 90, and 90 zircon grains were analyzed, and 80, 78, 88, and 89 concordant ages were obtained for the samples, respectively. Measured $^{206}Pb/^{238}U$ (younger than 1000 Ma) and $^{207}Pb/^{206}Pb$ (older than 1000 Ma) ages ranged from 3418 to 22 Ma (Table DR1 [see footnote 1]). The KDEs plots contain two major age peaks at ca. 226–243 Ma and 403–428 Ma, along with several subordinate peaks (Figs. 5I–5L). The Th/U ratios ranged from 0.01 to 2.07 and were concentrated in the range of 0.4–0.6 (Table DR1 [see footnote 1]). In total, 144 dated zircon grains from samples LO-4, LO-6, LO-9, LO-10, and LO-12 displayed a range of initial $^{176}Hf/^{177}Hf$ ratios from 0.280768 to 0.282768, with $\varepsilon_{Hf}(t)$ values of –28 to +7.0 (Fig. 6B; Table DR2 [see footnote 1]). Among them, samples LO-4 and LO-6 are from Wang et al. (2016b) and Xie et al. (2016), respectively. The T_{DM2} for these zircons ranged from 3703 to 792 Ma (Fig. 6D).

DISCUSSION

Source Characteristics of the Drainage Systems

The U-Pb ages and Lu-Hf isotopes described here provide a relatively robust characterization of the zircon grains that accumulated along eastern Vietnam. As manifested by the detrital

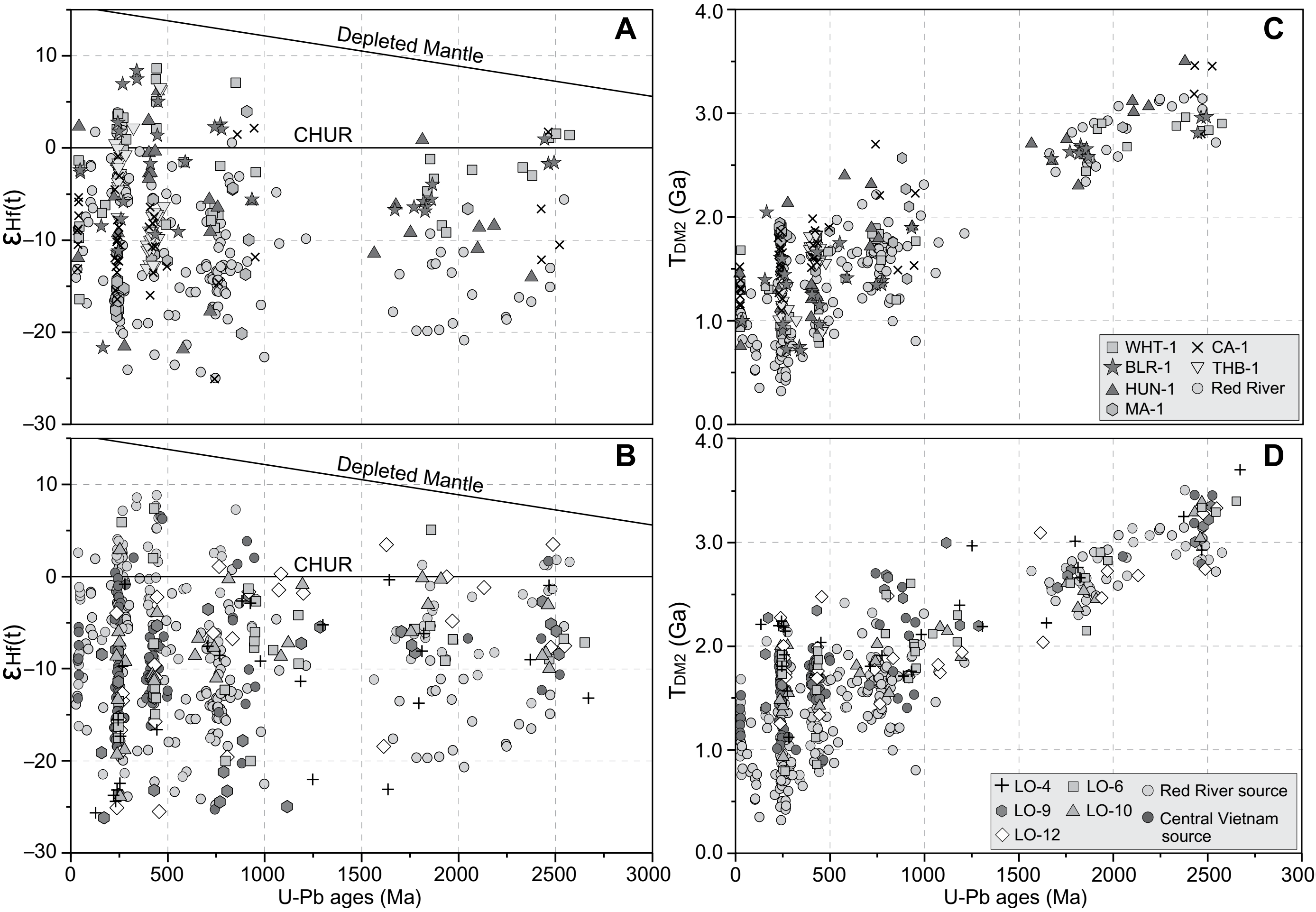

Figure 6. Diagrams showing the relationships between (A–B) $\varepsilon_{Hf}(t)$ values and U-Pb age and (C–D) two-stage Hf model ages and U-Pb age for detrital zircons. Data from Red River with gray circle are from Hoang et al. (2009). CHUR—chondritic uniform reservoir.

zircon age patterns, the sediments from these drainage systems record a considerably long geological history from the Archean to the Cenozoic (Fig. 5). Clearly, the Red River system and rivers in central Vietnam display different age characteristics, indicating that they were derived from heterogeneous sources.

The Red River system is often regarded as one of the most important pathways for transporting sediments to the South China Sea (Clift et al., 2006, 2008; Hoang et al., 2009). These samples (i.e., Lo River, Red River, and Da River) generally have multiple zircon age populations (Figs. 5A–5C) and yield strong similarities in the sets of ages, with the age groups of ca. 30–25 Ma, 247–239 Ma, 441–414 Ma, 751–743 Ma, 1876–1742 Ma, and 2700–2200 Ma. These zircon ages show a strong affinity to the polyphase evolution of the Yangtze block (Sun et al., 2009) and probably suggest that the detritus carried by this drainage system was mainly eroded from the southern Yangtze block (Clift et al., 2006; Hoang et al., 2009).

The Cenozoic zircon grains with age peaks between 30 and 25 Ma do not account for a significant portion of the total (Figs. 5A–5C) but directly represent the input eroded from the Red River fault zone (Fig. 1). These youngest ages are considered to be the result of melting and exhumation triggered by motion on the Red River fault zone (Zhang and Schärer, 1999; Gilley et al., 2003; Clift et al., 2006). The zircon grains with age peaks at ca. 247–239 Ma and 441–414 Ma dominate the spectra of the Red River system, which suggests that both the Indosinian and Caledonian (or Kwangsian) orogenies existed and were eroded widely in the drainage basins. However, these age groups are ubiquitous in different source terranes and therefore have limited potential as decisive source indicators. The Neoproterozoic peaks ranging from 751 to 743 Ma are the distinctive age signature of the Yangtze block (Hoang et al., 2009; Wang et al., 2014), which is consistent with the coeval tectonic-magmatic event in the block. The associated Neoproterozoic granitic and volcanic rocks that occur sporadically around the Yangtze block were probably related to the pre-breakup history of Rodinia and the subsequent migration of South China between 1000 and 700 Ma (Li et al., 2003). Clearly, the Lo River and the main stream of the Red River are close to SW China, which has well-developed Neoproterozoic populations, in contrast to the Da River (Figs. 5A–5C). The Archean to Proterozoic age peaks of ca. 1876–1742 Ma and 2700–2200 Ma are probably derived from the basement of the Yangtze and/or Indochina blocks (Zheng et al., 2006; Usuki et al., 2013) and also appear to have been reworked via sedimentary basins from the Songpan-Garze block (Hoang et al., 2009).

Clift et al. (2008) proposed that the Lo River joined the Red River after the middle Miocene (ca. 9 Ma) and contributed ~40% of the sediments to the main stream. Based on the restricted range of the observed U-Pb ages with a dominant peak at ca. 401 Ma in the Lo River, Hoang et al. (2009) suggested that there was less input from the Lo River to the main stream. However, our sample from the Lo River showed diverse age populations (Fig. 5A) similar to the main stream of the Red River and Da River (Figs. 5B–5C), which means we cannot minimize the important role of the Lo River, although our study is likely unable to make an accurate contribution. In fact, the samples in these two studies were collected from different locations of the Lo River (Fig. 1). The sand sample by Hoang et al. (2009) was taken from quite far upstream in the Lo River, whereas our sample was collected from the downstream Lo River, which has mixed sediments from different tributaries and can represent the source characteristics of the whole river. In addition, the diverse age populations in this study might be related to the local erosion and recycling of the Miocene sedimentary rocks in the Lo River Basin (Fig. 1), because these rocks contain a wide range of zircon ages similar to the main stream of the Red River (Hoang et al., 2009). Compared with the sediments upstream of the Red River (Fig. 1), more Neoproterozoic and early Paleozoic zircons occur in sample location HUN-1, downstream of the junction of the Lo River and Da River (Fig. 5B), which indicate the provenance contributions of these two rivers.

By contrast, apart from the Gianh River, sediments from central Vietnam commonly exhibit markedly different age patterns compared to the Red River system, with relatively well-defined populations dominated by Silurian and Triassic age peaks (Figs. 5D–5H). Both the Truong Son Belt and Kontum Massif of the Indochina block are characterized by widely distributed Ordovician–Silurian and Permian–Triassic granitic and metamorphic rocks (Carter et al., 2001; Roger et al., 2007; J. Liu et al., 2012; Shi et al., 2015), which correspond to the widespread Caledonian and Indosinian orogenic events in SE Asia, respectively. The Gianh River, however, displays the multiple peaks of the total samples (Fig. 5F), but it also shows a particularly large peak at ca. 250 Ma at the river mouth (Jonell et al., 2017b). More abundant Precambrian U-Pb ages are found in the Gianh River compared with other rivers in central Vietnam. These zircon grains were probably eroded from the Paleozoic sedimentary rock in the drainage basin, because Precambrian strata with the relevant ages are distributed widely in the upstream catchment (Usuki et al., 2013; Wang et al., 2016a). It is noteworthy that Cenozoic zircon grains were first detected in the Ca River of central Vietnam in this study. The coeval ages corresponding to Cenozoic tectonic activity are mainly located along the Red River fault zone (Fig. 2). These zircons show the characteristics of a magmatic origin, with high Th/U ratios >0.1, indicating that central Vietnam experienced the Cenozoic tectonic-magmatic event resulting from the convergence between India and Asia (Tapponnier et al., 1986; Rowley, 1996).

The Lu-Hf isotopic compositions of the detrital zircons add another dimension for tracing the source of the modern drainage systems. Figure 6 shows that the zircons from the Red River system and central Vietnam have distinct Hf isotopic characteristics, although there are limited overlaps among different age populations. The Red River system generally shows wide ranges of $\varepsilon_{Hf}(t)$ values for each age group, whereas central Vietnam exhibits a relatively narrow distribution. The broad $\varepsilon_{Hf}(t)$ values of the Indosinian and Caledonian zircons from the Red River system (Fig. 6A) suggest that the host rocks were formed by the remelting of ancient crust, as well as juvenile components. In contrast, the Ca River and Thu Bon River in central Vietnam are characterized by the closely spaced negative $\varepsilon_{Hf}(t)$ values (Fig. 6A); combined with the fact that the T_{DM2} values are concentrated in the range from 2000 to 1000 Ma (Fig. 6C), this indicates that the protolith was potentially formed by the reworking of Proterozoic crust.

In summary, the spatial heterogeneity in the detrital zircon U-Pb ages and the Lu-Hf isotopic compositions of these drainage systems, which correlate with the regional geological background and basement characteristics, reflect the petrographic composition distributions and formation ages in their drainage basins.

Source-to-Sink Relationships between the Sources and Sedimentary Basin

Three potential source terranes for the Yinggehai–Song Hong Basin have been defined in earlier studies (Xie, 2009; Yan et al., 2007; Wang et al., 2014; Jiang et al., 2015); they include the Red River, central Vietnam, and Hainan Island (Fig. 2). The detrital zircons from the LO borehole in the western Yinggehai–Song Hong Basin exhibit widely distributed U-Pb ages ranging from 3594 to 22 Ma; together with the wide range of the $\varepsilon_{Hf}(t)$ values, this indicates input from multicomponent sources. Recent studies have shown that the source from Hainan played an important role in contributing detritus to the central and eastern parts of the Yinggehai–Song Hong Basin (Yan et al., 2011; Wang et al., 2016b). However, the distinguishable age populations for the Hainan source (ca. 90–110 Ma) are not found in the borehole samples here, suggesting that Hainan Island has not been the source terrane for the western basin since the middle Miocene.

The Paleozoic- to Mesozoic-aged zircon populations dominate the provenance record of borehole LO (Figs. 5I–5O), indicating significant provenance from Caledonian and Indosinian orogenic sources. However, although those zircon grains are widely distributed in each sample, they are not unequivocal indicators for provenance analysis. A comparison of the drainage systems (Fig. 5) indicates that abundant Neoproterozoic zircons with peaks of ca. 760–730 Ma in these core samples should be interpreted as having originated from the southern Yangtze block through the Red River system, while the 970–940 Ma zircon grains could be derived from the eastern Indochina block via drainage systems in central Vietnam. The older ages have been considered as the basement of the southern Yangtze block but are also possibly recycled from the Paleozoic sedimentary rocks in the eastern Indochina block (Clift et al., 2006; Usuki et al., 2013). Although the Lu-Hf isotopic composition of the detrital zircon shows that the Red River system is overlapped by counterparts from central Vietnam, the core sediments display some features closely related to both source areas, especially in zircons younger than 1000 Ma (Fig. 6B). The broad $\varepsilon_{Hf}(t)$ values of the samples in the western basin are consistent with the Hf isotopic compositions of the Red River system, suggesting that the source of the Red River probably dominated the provenance. The significantly negative $\varepsilon_{Hf}(t)$ values and T_{DM2} ages for the Indosinian and Caledonian zircons also imply an important influence of central Vietnam (Fig. 6).

We used the newly developed multidimensional scaling (MDS) method (Vermeesch, 2013) to quantitatively assess the relative dissimilarities of the multiple sources and illustrate the source-to-sink relationships between the source areas and sediments of the Yinggehai–Song Hong Basin. The MDS plot, based on the Kolmogorov-Smirnov (K-S) statistical method, is an effective method for distinguishing the zircon ages from different sources. In the metric MDS plot (Fig. 7), the different sediment samples in the western Yinggehai–Song Hong Basin show distinct affinities with the drainage systems around the basin. Not surprisingly, the rivers in Hainan plot far away from the core samples (Fig. 7), further confirming that Hainan was not the source terrane for the western Yinggehai–Song Hong Basin. The Thu Bon River and Tra Khuc River, in the southern part of central Vietnam, are also far from these core samples, indicating that the Kontum Massif of the Indochina block was not a major source contributor. Significantly, these sediments fall adjacent to the Red River, Lo River, and Gianh River on the MDS plot, which suggests major contributions from these source areas. In addition, the Ma River, Ca River, and Da River show a weak affinity to the samples from the LO borehole, which probably indicates that they have a minor influence on the depositional site.

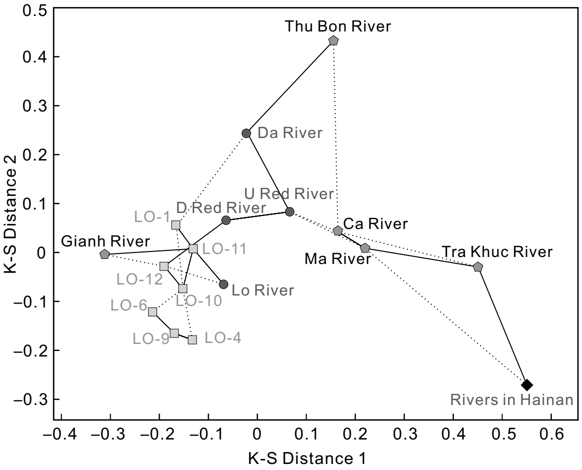

Figure 7. Multidimensional scaling (MDS) plot showing the Kolmogorov-Smirnov (K-S) distances between the zircon U-Pb ages of the modern drainage systems and core sediments in the Yinggehai–Song Hong Basin. Solid and dashed lines connect the samples with their closest and second-closest neighbors, respectively. Data for the rivers in Hainan are from Wang et al. (2015). Data for upstream Red River is from Hoang et al. (2009). Data symbols are the same as in Figure 5. U Red River—upstream Red River; D Red River—downstream Red River (HUN-1, this study).

Previous studies have proposed that central Vietnam was not a major source area for the Yinggehai–Song Hong Basin (Yan et al., 2007, 2011; Sun et al., 2014; Wang et al., 2014). However, Jonell et al. (2017b) believed that the rivers along the margins of central Vietnam played an important role with regard to the total sediment volumes of the basin (17%–21% of the total). We agree with the important contribution of the Gianh River; however, other drainage systems also suggest that central Vietnam was not the principal source terrane for the western basin. The source of the Red River has a great influence in the central and eastern parts of the Yinggehai–Song Hong Basin (Wang et al., 2014; Cao et al., 2015; Jiang et al., 2015); combined with the results of our study in the western basin, it is probable that the Red River played a fundamental role in the provenance contribution to the entire Yinggehai–Song Hong Basin (Clift and Sun, 2006; Yan et al., 2011).

Accordingly, the detrital zircon record implies a causal relationship between the two source areas of the Red River and central Vietnam and the western Yinggehai–Song Hong Basin. Based on the comparison of the detrital zircon U-Pb ages and the Lu-Hf isotopes of borehole LO with the source drainage systems, we can deduce that the Red River system dominates the provenance of the western Yinggehai–Song Hong Basin, with an additional source shed westwards from central Vietnam mainly through the Gianh River.

Reconstruction of the Provenance Evolution of the Western Yinggehai–Song Hong Basin

To date, few studies have been conducted on the evolution of provenance of sediments in the western part of the Yinggehai–Song Hong Basin due to a lack of samples and accurate data. A systematical analysis of the detrital zircons preserved in the stratigraphic units from this study allows us to discriminate the source areas and understand the provenance evolution since the middle Miocene. The MDS plots for the stratigraphic units of the western Yinggehai–Song Hong Basin are shown in Figure 8. In Figure 9, the source-to-sink characteristics of the drainage systems and the western Yinggehai–Song Hong Basin have been schematically sketched based on the basin evolution, regional stratigraphy, and detrital zircon provenance analysis.

Middle Miocene (15.5–10.5 Ma)

In the early middle Miocene (ca. 15.5–13.8 Ma), the provenance of the western Yinggehai–Song Hong Basin was principally sourced from the Red River system, because the statistical data of the zircon ages primarily match the downstream Red River and the Lo River, and secondarily match the Da River and Gianh River (Fig. 8A). However, the Lo River probably joined the Red River after ca. 9 Ma (Clift et al., 2008), which means that the drainage system might not have provided detritus to the basin or at least not through the Red River system during the middle Miocene. In the case of the Da River, where the catchment contains fewer young Neoproterozoic granitic rocks (Fig. 2), this should result in a considerably lower proportion of coeval populations (Fig. 5O). The Red River and its tributaries drain part of the Yangtze block, and erosion in these reaches would provide the detritus for transport to the depositional site. In addition, central Vietnam should be another source terrane for the western basin of detrital material transported through the Gianh River (Fig. 9A). The late middle Miocene section (ca. 13.8–10.5 Ma) yields dominantly Neoproterozoic and Mesozoic ages compared with the early stage (Fig. 5N). The age peaks at ca. 916 Ma and 706 Ma represent inputs from central Vietnam and the Red River, respectively. Sample LO-4 lies close to the Lo River, Red River, and Gianh River in the MDS plot (Fig. 8B), which indicates dominant contributions from these three river basins or rivers next to the Gianh River with similar basements. Similar to the early stage, the provenance contribution of the Lo River is hard to evaluate due to the evolution of this drainage system. In addition, the wide ranges of $\varepsilon_{Hf}(t)$ and T_{DM2} values (especially the Indosinian zircons) demonstrate similarities to the source of the Red River (Fig. 6B). During the middle Miocene, the western basin received sediments from mixed sources of both the Red River system and central Vietnam (Figs. 9A–9B).

Late Miocene (10.5–5.5 Ma)

The late Miocene samples are close to the Lo River, Gianh River, and downstream Red River samples on the MDS plots (Figs. 8C–8D), which means the western basin was largely influenced by the sources of the Red River system and central Vietnam during the time of deposition. However, there are some differences between these two stages (Figs. 5L and 5M). Compared to the early stage, the late stage contains more Neoproterozoic zircons with a peak at ca. 798 Ma, similar to the Lo River and Red River, and this suggests that more sediments were derived from the Red River system. The relatively concentrated $\varepsilon_{Hf}(t)$ values of LO-6 are accordant with the source from central Vietnam, whereas the LO-9 sample is characterized by widely scattered $\varepsilon_{Hf}(t)$ values similar to the Red River system (Fig. 6B), indicating derivation from a mixture of these two source areas. In a study of the U-Pb ages of detrital zircons and heavy minerals, Jiang et al. (2015) proposed that both central Vietnam and the Red River played important roles in deposition of sediments in the western and central Yinggehai–Song Hong Basin during the late Miocene, which is supported by our results. The sediments of the western basin were mainly derived from central Vietnam during the early late Miocene (Fig. 9C), and the sediment source changed to a mixed source from both the Red River and central Vietnam during the late stage (Fig. 9D).

Pliocene (5.5–1.8 Ma)

The sediment provenance in the western basin generally exhibits no significant change during the Pliocene, which is supported by the analogous KDEs (Figs. 5J–5K) and MDS maps (Figs. 8E–8F) for the lower and upper Yinggehai Formation. A rise in young Neoproterozoic

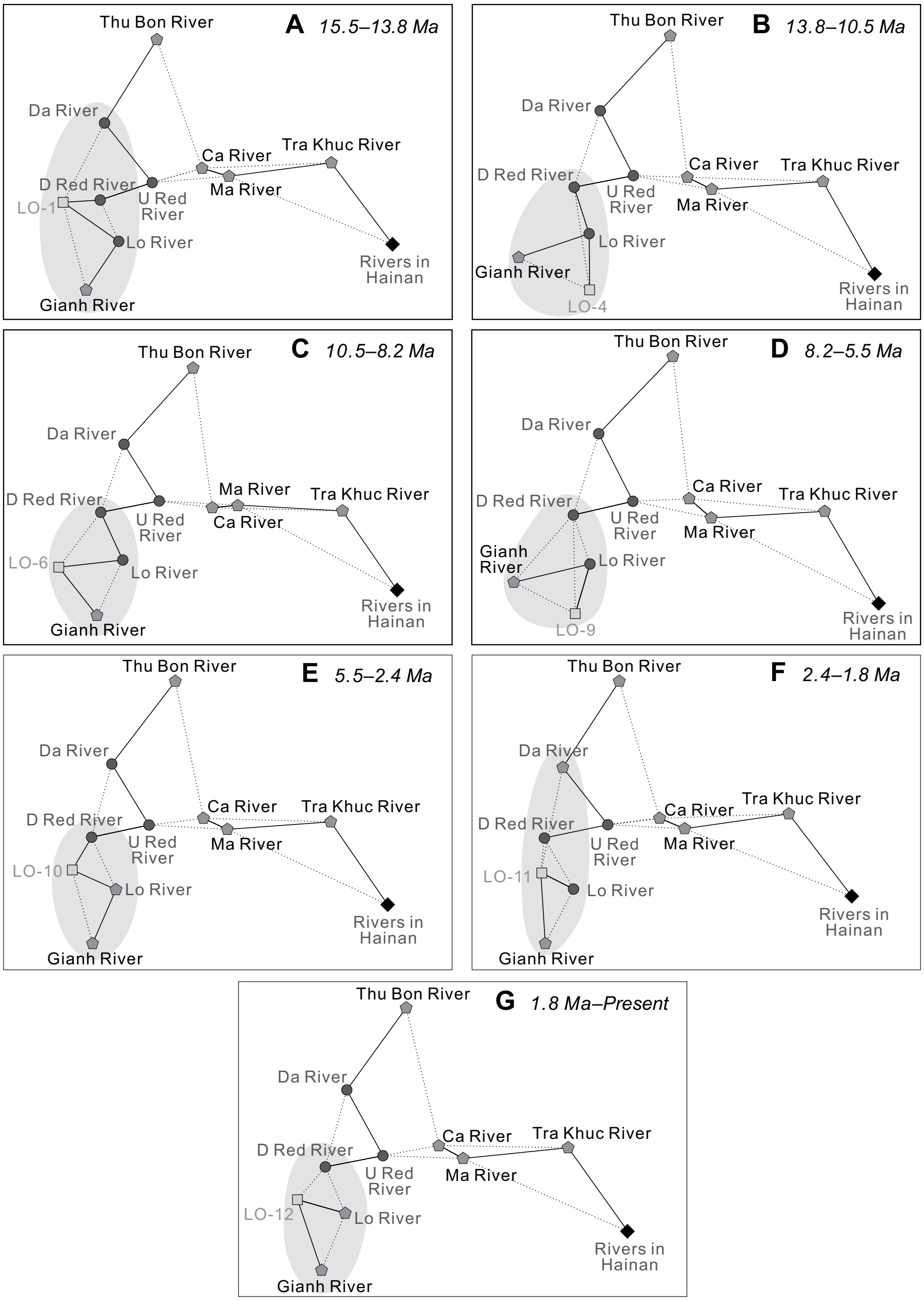

Figure 8. Multidimensional scaling plots for the stratigraphic units in the western Yinggehai–Song Hong Basin. The data are the same as in Figure 7.

grains for sample LO-10 was interpreted as reflecting a large amount of detritus originating from the Lo River. The widely distributed $\varepsilon_{Hf}(t)$ values also suggest an affinity to the Red River system (Fig. 6B). The evidence demonstrates that the Red River system was still the major source during the early Pliocene (Fig. 9E). By comparison, the sediments are relatively complex during the late Pliocene, because the LO-11 sample shows a remarkable proximity to the Red River, Lo River, Da River, and Gianh River, which means that the detrital sediments were derived from both the Red River and central Vietnam at the same time (Fig. 9F).

Quaternary (1.8 Ma–Present)

The MDS plot shows that sample LO-12 is close to the Red River, Lo River, and Gianh River (Fig. 8G). The zircon age structure and Hf composition are similar to the Red River system (Figs. 5 and 6) but different from the drainage systems in central Vietnam, except for the Gianh River. This evidence supports the conclusion that the sediments at this time originated principally from the Red River system. Like the other sedimentary periods, the Quaternary was also partly affected by the central Vietnam source via the Gianh River (Fig. 9G).

This provenance study emphasizes that in the marginal basin, where the link between the source and the depositional site can be preserved, it is feasible to use the detrital zircon method to identify the source areas and constrain the provenance evolution. This study shows that the provenance of the western Yinggehai–Song Hong Basin has not changed significantly since the middle Miocene (15.5 Ma), although there are still subtle variations in different depositional periods. Comparison of the zircon U-Pb ages of the core samples from different source areas consistently demonstrates the continuous contributions from the Red River system and central Vietnam sources since the middle Miocene.

Implications for Crustal Evolution of the Southern Yangtze and Eastern Indochina Blocks

Detrital zircon U-Pb ages from fluvial sediments should be representative of the range of tectonic-magmatic events within the drainage basin (Cawood et al., 2003; Clift, 2006; Hoang et al., 2010; He et al., 2013) and therefore can potentially help to decipher the time-integrated evolution of continents (Bodet and Schärer, 2000). However, use of a zircon age alone cannot provide conclusive information on the nature of such magmatic events (X. Liu et al., 2008; Wang et al., 2012; Yao et al., 2012). Combining the Hf composition with the U-Pb ages allows investigation of the possible relationships between sediments and evolution of the crust for the source areas (Yao et al., 2011; Li et al., 2012).

As discussed herein, the sediments in the Red River system were preferentially eroded from the Yangtze block and its deformed margins (Clift et al., 2006), which provides a new view of the crustal evolution of the southern Yangtze block. Figure 10 displays the data for the Red River system in relation to the ages of the major tectonic-magmatic events distinguished by the comprehensive analyses of the detrital zircons. The major tectonic-magmatic events that occurred in the southern Yangtze block have age peaks at ca. 2465 Ma, 1842 Ma, 752 Ma, 412 Ma, 245 Ma, and 31 Ma. The wide range of negative to positive $\varepsilon_{Hf}(t)$ values for almost all of the age groups (Fig. 10) suggests that both juvenile materials and reworking of ancient crust took place in the formation of the block. Moreover, the Neoproterozoic to Mesozoic could represent the periods with prominent juvenile crust

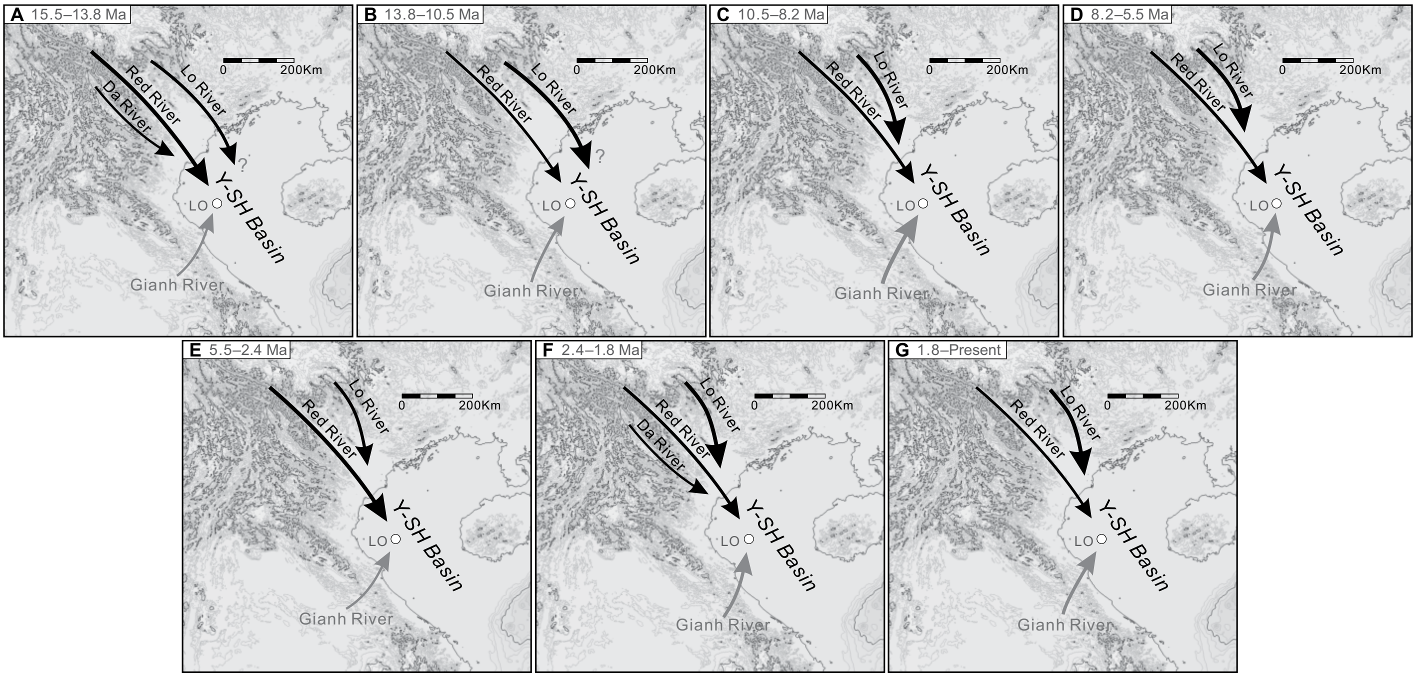

Figure 9. Schematic reconstruction of the provenance evolution of the western Yinggehai–Song Hong Basin since the middle Miocene. Arrows indicate the possible routes of sediment transport. Black arrows represent a source from the Red River system, whereas gray arrows indicate a source from central Vietnam. The thickness of the line shows the relative contribution of the sources.

due to the large number of positive $\varepsilon_{Hf}(t)$ values for those zircon grains.

The crust-building process involves two stages: (1) the extraction of primitive basaltic juvenile crustal materials from the mantle, and (2) remelting of the juvenile crustal materials to form felsic crust (Campbell and Hill, 1988; Wang et al., 2009; Li et al., 2012). The zircon Hf model age (T_{NC}^{C}) could be considered to indicate the timing of the separation of juvenile crust from the mantle, whereas the zircon U-Pb age represents crustal melting and cratonization. The difference between them is called the crustal incubation time (Griffin et al., 2006). In order to quantitatively assess the history of crustal growth, the crustal incubation time is presented here to show the difference between the initial formation of continental crust and later cratonization (Belousova et al., 2009). Generally, the generation of new crust is signified by a low crustal incubation time (less than 300 m.y.), whereas high crustal incubation time (more than 300 m.y.) represents the reworking of preexisting ancient crust (Li et al., 2012). The detrital zircons in the age groups of ca. 2600–2450 Ma, 870–740 Ma, and 270–230 Ma fall into the range of the crustal incubation time less than 300 m.y. (Fig. 11), implying the involvement of juvenile crustal materials for the southern Yangtze block during the three magmatic stages. On the contrary, the detrital zircons in the age groups of ca. 2200–1600 Ma, 1500–1100 Ma, 490–

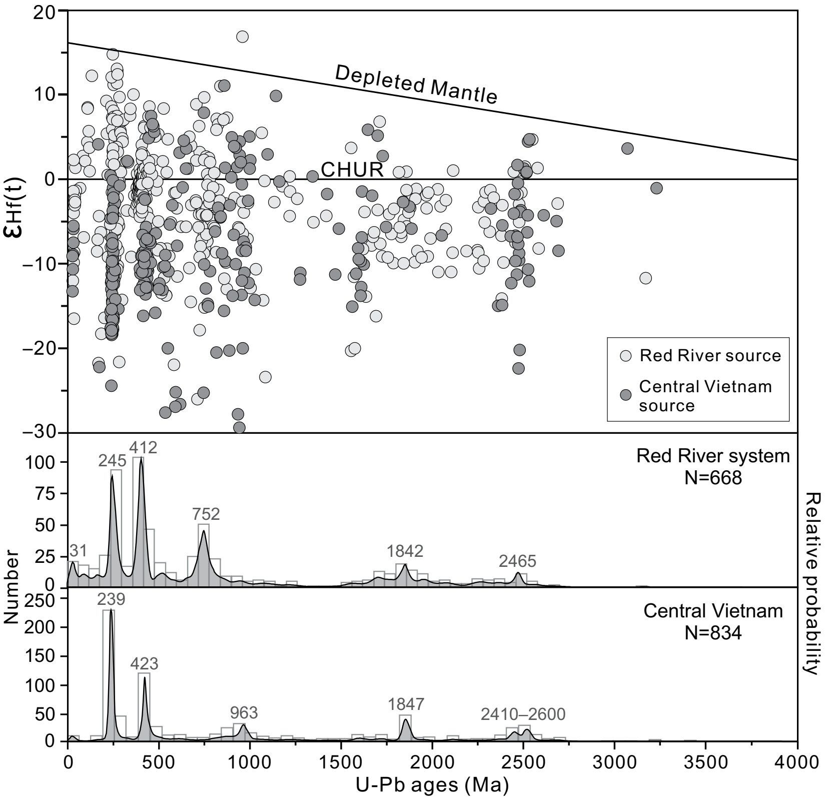

Figure 10. Composite plots of $\varepsilon_{Hf}(t)$ values vs. U-Pb ages for the Red River system and central Vietnam. Part of the data for the Red River system is from Clift et al. (2006) and Hoang et al. (2009). Part of the data for central Vietnam is from Usuki et al. (2013) and Jonell et al. (2017b). CHUR—chondritic uniform reservoir.

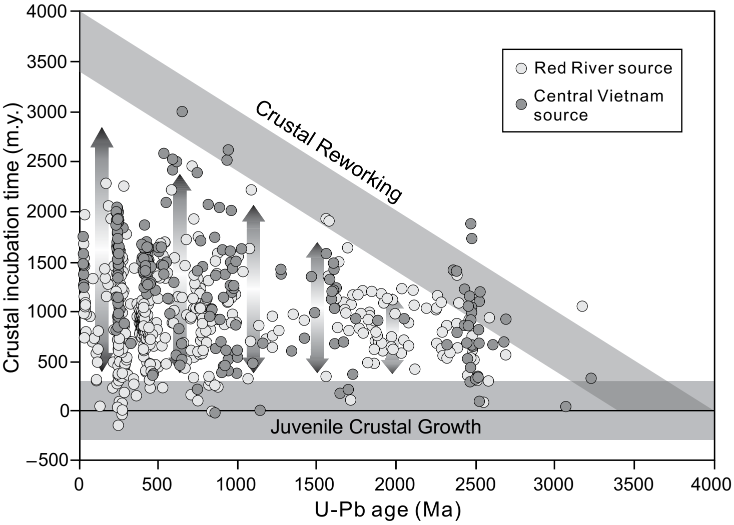

Figure 11. Plot of crustal incubation time vs. zircon U-Pb ages of detrital zircons from the Red River system and drainage systems in central Vietnam. The T_{NC}^{C} Hf model age is used here to represent the timing of initial formation of the juvenile continental crust (Dhuime et al., 2011). Some data for the Red River system and central Vietnam data are from Hoang et al. (2009) and Usuki et al. (2013), respectively.

420 Ma, and 40–20 Ma mainly are outside of the crustal incubation time range of 0 ± 300 m.y., suggesting that ancient crustal reworking processes occurred during these time intervals. The crustal growth of the southern Yangtze block shows alternating periods of juvenile continental crust and reworking of the continental crust; this is different from the adjacent Cathaysia block, which is dominated by juvenile crustal growth occurring at ca. 1870 Ma, 1400 Ma, 1140–940 Ma, 445 Ma, and 280 Ma (Li et al., 2012).

The eastern margin of the Indochina block is made up of the Truong Son belt and the Kontum Massif (Fig. 1). The five drainage systems for these two tectonic units in the main drainage area of central Vietnam provide the best record of crustal evolution in the eastern Indochina block. The detrital zircons reveal five major tectonic-magmatic events, with age peaks or age groups at ca. 2600–2410 Ma, 1847 Ma, 963 Ma, 423 Ma, and 239 Ma (Fig. 10). However, the ages around 1847 Ma and 963 Ma from the basement are rarely reported in this region (Usuki et al., 2013; Wang et al., 2016a), which probably indicates that the host rocks were eroded completely on the surface, or they were being eroded out of sedimentary rocks, which were in turn transported long distances from sources located far from the present outcrop. The Hf isotopic compositions for eastern Indochina have mainly negative $\varepsilon_{\mathrm{Hf}}(t)$ values and few positive values (Fig. 10), suggesting they were dominated by reworked existing crustal materials. A diagram of the crustal incubation time versus zircon U-Pb ages shows a rough trend of increasing maximum crustal incubation time with decreasing zircon crystallization age (Fig. 11). The zircons in the age groups of ca. 2530–2460 Ma, 1700–1640 Ma, 860–740 Ma, and older than 3000 Ma fall into the range of the crustal incubation time less than 300 m.y., indicating that juvenile crustal growth occurred during these magmatic stages. It is noteworthy that the primary magmatic stages of ca. 423 Ma and 239 Ma are dominated by reworking and recycling of the ancient continent crust, which is obviously different from the neighboring Yangtze and Cathaysia blocks (Yao et al., 2011; Li et al., 2012; Yao et al., 2012). Although the southern Yangtze and eastern Indochina blocks show some apparently similar zircon groups, they have distinct histories of formation and evolution. The former is dominated by Neoproterozoic and Mesozoic crustal growth, whereas the latter is characterized by prominent crustal additions in the Paleoproterozoic.

CONCLUSIONS

The new data set of detrital zircon ages and Lu-Hf isotopes presented herein shows that the Red River system and the rivers in central Vietnam had significantly different sources. The Red River system (i.e., Lo River, Red River, and Da River) has a similar age structure that is characterized by multipeak distributions ca. 30–25 Ma, 247–239 Ma, 441–414 Ma, 751–743 Ma, 1876–1742 Ma, and 2700–2200 Ma, which indicate that the materials were mainly derived from the southern Yangtze block. In contrast, apart from the Gianh River, the fluvial sediments in central Vietnam commonly exhibit markedly different age components with relatively well-defined populations at ca. 243–234 and 438–419 Ma. We interpret this to indicate that the detritus was eroded from local sources in the Truong Son belt and the Kontum Massif in the eastern Indochina block. The detrital zircon record implies a causal relationship between the source areas and the marine sedimentary basin. Comparison of the age populations in the western Yinggehai–Song Hong Basin and the source drainage systems indicates that the provenance of the Red River system dominates the western Yinggehai–Song Hong Basin, along with an additional source shed from central Vietnam through the Gianh River. Obviously, Hainan has not been the source terrane for the western basin since the middle Miocene. The measured age distributions also suggest a relatively stable provenance during deposition, although the provenance of the western Yinggehai–Song Hong Basin changed during different depositional periods with varying contributions from these two source areas, reflecting evolving sediment dispersal patterns since the middle Miocene.

Our study also reveals that the southern Yangtze block and eastern Indochina block have significantly different histories of crustal evolution. The detrital zircon U-Pb and Lu-Hf isotopic results suggest multiple stages of crustal growth and reworking processes in the southern Yangtze block and eastern Indochina block. The major tectonic-magmatic events occurred in the southern Yangtze block with age peaks at ca. 2465 Ma, 1842 Ma, 752 Ma, 412 Ma, 245 Ma, and 31 Ma. In contrast, the eastern Indochina block had five tectonic-magmatic events with age peaks or groups at ca. 2600–2410 Ma, 1847 Ma, 963 Ma, 423 Ma, and 239 Ma. Juvenile crustal growth occurred in the southern Yangtze block during the Neoproterozoic and late Paleozoic to Mesozoic, whereas the eastern Indochina block is characterized by prominent crustal additions in the Paleoproterozoic.

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