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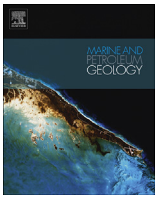

Research paper

Zircon U-Pb geochronology and heavy mineral composition constraints on the provenance of the middle Miocene deep-water reservoir sedimentary rocks in the Yinggehai-Song Hong Basin, South China Sea

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ABSTRACT

The provenance of the middle Miocene deep-water sedimentary rocks was studied by detrital zircon U-Pb ages and heavy mineral assemblages in the Yinggehai-Song Hong Basin. U-Pb age data for 936 detrital zircons from eleven sedimentary rock samples from the Meishan Formation (Langhian-Serravallian) range in age from 3252 Ma to 28 Ma and suggests input from multiple sources. The provenance of the sediments changes from one part of the basin to another. The sedimentary rocks located on northern and western Yinggehai-Song Hong Basin generally have multiple detrital zircon age populations and a wide range ages, suggesting consistent with derivation from the Red River. By contrast, the zircon ages from eastern side of the basin generally show bimodal detrital zircon age populations consisting of ca. 98 Ma and 241 Ma components, which suggest that these sandstones were derived locally from Hainan. Comparison of the age populations and heavy mineral assemblages with the potential sources terrains indicates that both southern Yangtze Block and Hainan Uplift contributed the clastic material to the basin during middle Miocene. The majority of clastic material was supplied from the northwest and east through the "Red River delta" and other deltas near to the western Hainan, respectively. Heavy mineral assemblages and zircon ages also reveal that small amounts of sediment were shed westwards from the Indochina Block. Moreover, no significant change is indicated between the Upper and Lower Meishan Formation by zircon U-Pb ages and heavy mineral data suggesting that the Yinggehai-Song Hong Basin sources were similar throughout the middle Miocene.

1. Introduction

Provenance studies are proved especially useful for the understanding of the evolution of sedimentary basins because the define source terranes, constrain paleogeographic reconstructions, identify sediment transport routes, and clarify stratigraphic and tectonic reconstructions (Fontana et al., 1989; Haughton et al., 1991; Morton et al., 2001, 2011; Fontanelli et al., 2009). Generally, studies of the sediment provenance and its transport routes are critical factors in establishing reservoir presence in a sedimentary basin (Morton et al., 2001; Tsikouras et al., 2011). Clastic sedimentary rocks may also contain important information relating to their provenance and the sedimentary processes that took place during deposition (Oliveira et al., 2015). In last decades, U-Pb dating of detrital zircon extracted from clastic sedimentary rocks has been widely used in provenance studies, because of the stability of zircon in both weathering and diagenetic regimes (Fedo et al., 2003; Morton et al., 2008). Ages of detrital zircon populations can provide a direct fingerprint for the identification and location of source terranes as long as those terranes contain zircon bearing rocks (Cawood and Nemchin, 2000).

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A large number of factors can control the distribution of reservoirs, such as deposition environment, diagenesis, and the provenance and distribution of sediments (Morton et al., 2008). The middle Miocene Meishan Formation (Langhian-Serravallian) is an important potential hydrocarbons exploration target in the Yinggehai-Song Hong (Y-SH) Basin. The search for hydrocarbons in the strata has been hampered by a poor understanding of the sediment sources. Recently, the studies of river sediments and rocks in the potential source regions around the basin suggest that detrital zircon populations derived from the Red River are fundamentally different to those derived from central Vietnam and Hainan Island (Bodet and Schärer, 2000; Clift et al., 2006; Hoang et al., 2009; Wang et al., 2014b, 2015a, 2015b; Jiang et al., 2015). Therefore, detrital zircon U-Pb studies could constrain the provenance of the Meishan Formation in this basin.

Although there have been detrital zircon studies of the Cenozoic sedimentary rocks of the Y-SH Basin (Yan et al., 2011; Wang et al., 2014b; Cao et al., 2015; Jiang et al., 2015; Wang et al., 2015a, 2016b), no attempt has been made to apply the zircon geochronology and heavy minerals to the middle Miocene strata systematically. This study, we set out to document U-Pb ages of detrital zircons and heavy mineral assemblages from marine core samples to constrain the possible sediment provenance and transport pathway of the middle Miocene Meishan Formation and discuss the contribution of the source terrains.

2. Geological setting

The NNW-SSE trending Y-SH Basin is located in the northern margin of the South China Sea continental shelf (Fig. 1). The basin formed in Cenozoic time due to the southeastward strike-slip deformation and clockwise rotation of the Indochina Block as a result of the collision and indentation of India into Asia and seafloor spreading of the South China Sea (Fig. 1) (Molnar and Tapponnier, 1975, 1978; Tapponnier et al., 1986; Rangin et al., 1995; Guo et al., 2001; Morley, 2002; Sun et al., 2003). The Y-SH Basin is bordered on the north and east by the Beibuwan and Qiongdongnan basins, respectively (Fig. 1).

Over the past decades, a number of hydrocarbon reservoirs have been discovered in the deepwater area of the Y-SH Basin. One of last discoveries in the basin is the Dongfang 13-2, located in the Dongfang gas field within the central Yinggehai Depression (Xie et al., 2014). The stratigraphic units that form the sources and reservoirs for hydrocarbons range from the Eocene Lingtou Formation to the Pliocene Yinggehai Formation, which are covered by Quaternary sediments and underlain by pre-Paleogene strata (Fig. 2) (Gong et al., 1997; Geng et al., 1998; Gong and Li, 2004). Relatively high temperature and overpressure, rapid subsidence rate, large volumes and diapir structures typify this Cenozoic basin (Zhang et al., 1996; Hao et al., 1998; Huang et al., 2003, 2004; Luo et al., 2003, 2009; Clift and Sun, 2006; Hoang et al., 2010; Xie et al., 2014). These parameters are also significant for hydrocarbon production in the basin.

Cenozoic tectonic evolution of the basin could be divided into two periods: the syn-rift stage and the post-rift stage thermal subsidence stage (Fig. 3) (Gong et al., 1997). The NE-SW trending faults divided the basin into four secondary tectonic units, including two depressions (Hanoi Depression and Yinggehai

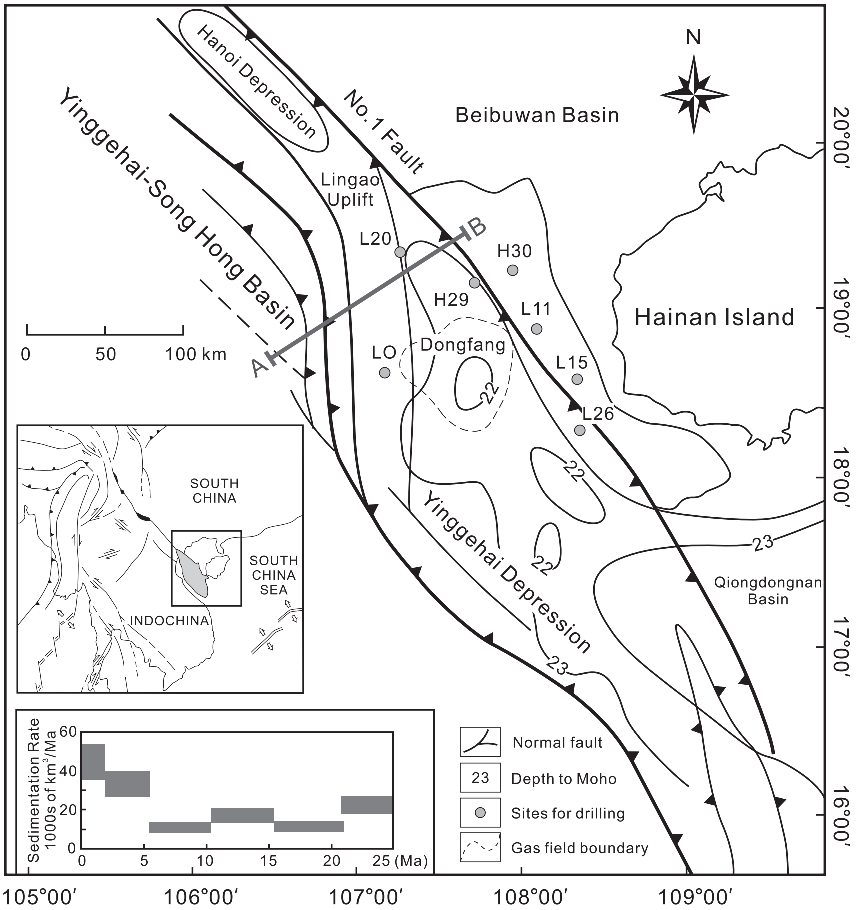

Fig. 1. Geologic sketch map and drilling locations in the Yinggehai-Song Hong Basin, modified after He et al. (2002). Sedimentation rate of the basin are from Hoang et al. (2010).

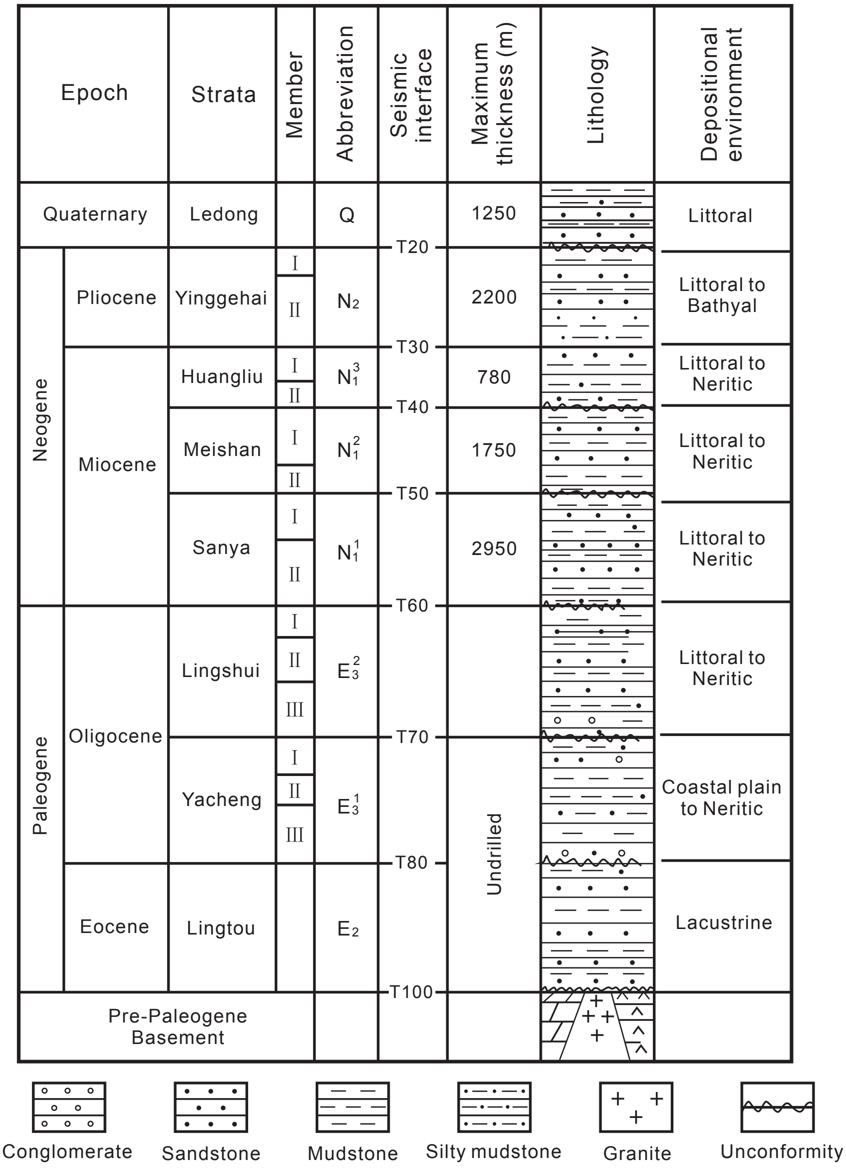

Fig. 2. Region stratigraphic column of the Y-SH Basin, modified after Gong et al. (1997), Huang et al. (2003) and Gong and Li (2004).

Depression) and two slope areas (Western Slope and Eastern Slope). Between the two depressions there is a structural uplift, known as Lingao Uplift (Fig. 1).

The Y-SH Basin contains up to 17 km of Paleogene to Quaternary sedimentary rocks (Gong et al., 1997; Yan et al., 2011). The clastic sediments that filled the central Yinggehai depression during the Neogene to Quaternary include lacustrine, coastal plain and neritic (before 30 Ma), littoral to neritic (30–10 Ma) and littoral to bathyal environments (after 10 Ma) (Fig. 2). The depositional environment of the Meishan Formation was interpreted to from littoral to neritic delta facies (Gong et al., 1997). Sedimentation rates in the Y-SH Basin were modest from 50 to 29.5 Ma, fell again between 21 and

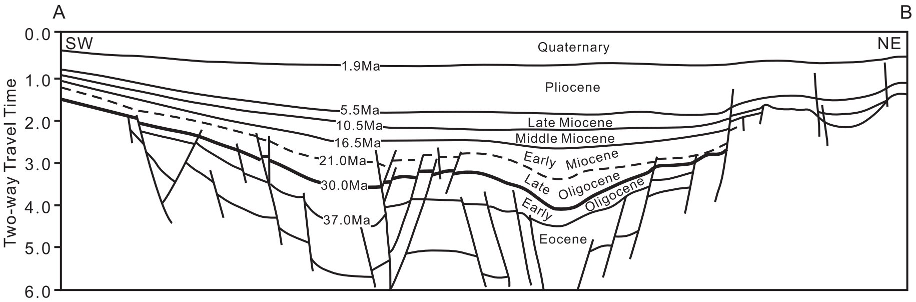

Fig. 3. Interpreted seismic profiles of the Y-SH Basin, whose position is shown in Fig. 1, modified after Sun et al. (2003) and Xie (2009).

15.5 Ma, and increased between 15.5 and 10.5 Ma (Clift and Sun, 2006; Hoang et al., 2010). The pressure coefficient and geothermal gradient can reach 2.0–2.3 and 4.25–4.56 °C/100 m, respectively (Zhang et al., 1996; Huang et al., 2002, 2003). The depocenters are mainly controlled by NW- and roughly N-S-trending faults (Sun et al., 2003), which show a migration to the southeastern basin between 21 and 16 Ma, which led to basin inversion and formation of an angular unconformity (Rangin et al., 1995; Clift and Sun, 2006). During 16–5.5 Ma, depocenters gradually migrated back to the northwest, and paused in the northwestern basin (Zhu et al., 2009). Slowdown of dextral movement and high rates of sediment supply led to overflow of the Y-SH Basin to the east into the Qiongdongnan Basin (Yan et al., 2011).

3. Sampling and analytical methods

Eleven sedimentary rocks (including sandstone and siltstone) were collected from 7 drilling holes in the Y-SH Basin. Samples H29-4, H30-2, L20-1, LO-4, L11-13 and L26-2 were from the Upper Meishan Formation and H29-6, L20-3, LO-1, L15-2 and L26-1 were from the Lower Meishan Formation. Positions of the drilling holes and information of samples are shown in Fig. 4 and Table 1.

Separation and preparation of heavy minerals followed standard procedures (Morton, 1985; Mange and Maurer, 1992). Minerals such as zircon, garnet, rutile and tourmaline were hand-picked and chosen for statistical purpose. Almost 600 grains were observed for each sample. The percentage contents of the samples were

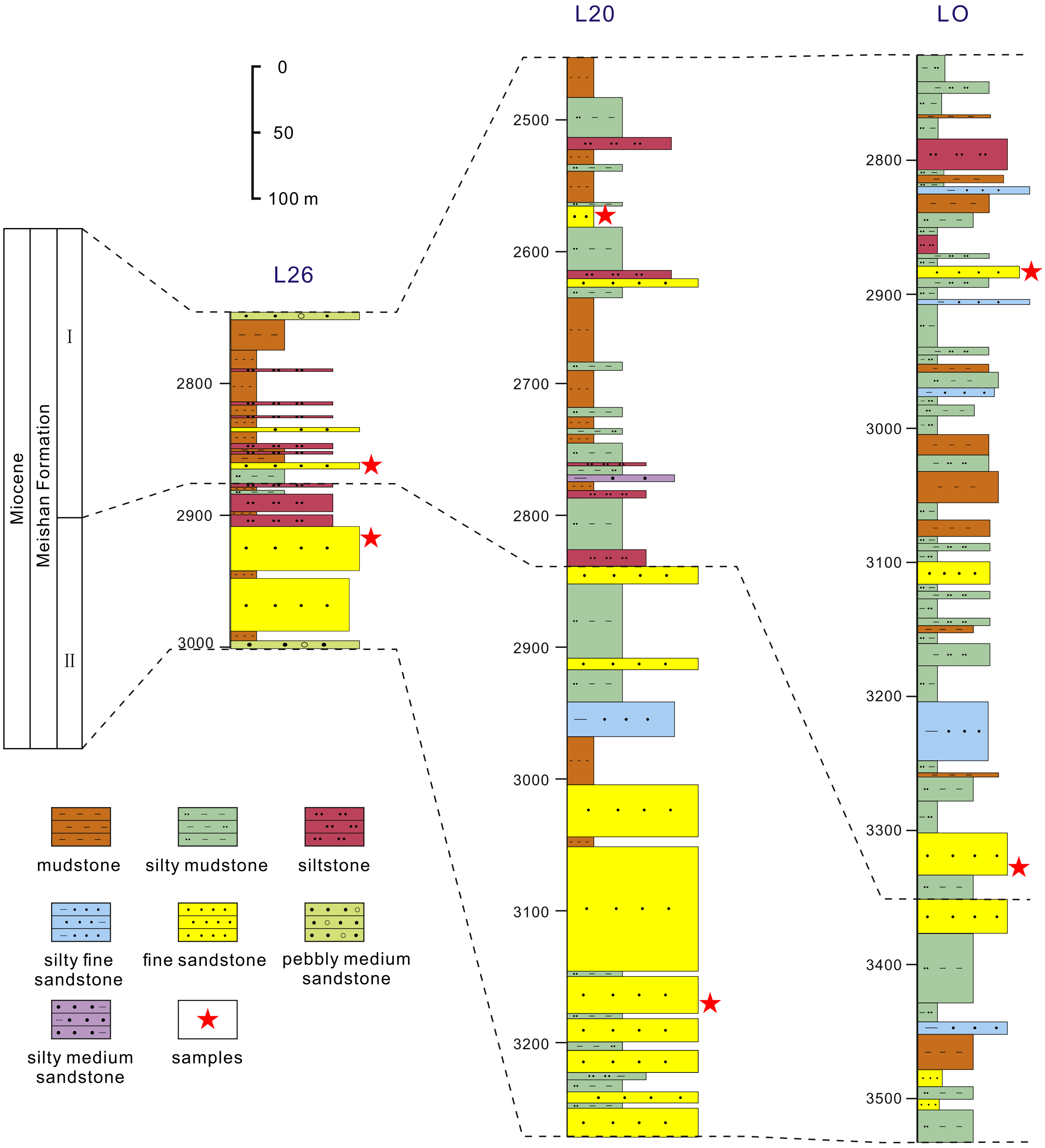

Fig. 4. Representatives of stratigraphic column and samples position of L26, L20 and LO with positions of samples marked. The locations of the core drill are shown in Fig. 1.

Table 1
Location and stratigraphic information of samples analyzed during this study. The well positions are shown in Fig. 1.

Sample no	Lithology	Material	Drilling	Depth
The Lower Meishan Formation				
H29-6	Siltstone	Core chip	H29	3265–3267 m
L20-3	Sandstone	Core chip	L20	3164–3166 m
LO-1	Sandstone	Core	LO	3328–3329 m
L15-2	Sandstone	Core chip	L15	750–753 m
L26-1	Sandstone	Core	L26	2919–2921 m
The Upper Meishan Formation				
H29-4	Siltstone	Core chip	H29	2880–2885 m
H30-2	Sandstone	Core	H30	1648–1650 m
L20-1	Sandstone	Core chip	L20	2575–2576 m
LO-4	Sandstone	Core	LO	2884–2887 m
L11-13	Siltstone	Core chip	L11	2280–2282 m
L26-2	Sandstone	Core	L26	2860–2861 m

calculated according to the number of the heavy mineral grains.

Zircons were picked from heavy liquids and Frantz magnetic separator fractions. Following purified by hand sorting zircon grains were mounted in epoxy and polished down to near half sections to expose internal structures. Cathodoluminescence (CL) image of those zircon grains was carried out using a Mono CL3 detector attached to an Electron Microprobe (JXA-8100, JEOL, Japan), to identify the internal structures and to select target sites for laser ablation analyses. Zircons were dated using LA-ICP-MS housed at the State Key Laboratory of Isotopic Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. Sample mounts were placed in the two-volume sample cell flushed with Ar and He. Laser ablation was operated at a constant energy 80 mJ and at 8 Hz, with a spot diameter of 33 μm. The ablated material was carried by the He gas to the Aglient 7500a ICP-MS. Element corrections were made for mass bias drift, which was evaluated by reference to standard glass NIST SRM 610. The Temora was used as the age standard ($^{206}Pb/^{238}U = 416.8$ Ma) (Black et al., 2003). The details of analytical procedure, precision and accuracy are described by Jackson et al. (2004), Yuan et al. (2004), Liu et al. (2010).

Isotopic ratios of U-Th-Pb were calculated using ICPMSDataCal (Version 7.2) (Liu et al., 2008). Common Pb was corrected by ComPbCorr#3_151 using the method of Andersen (2002). Ages which have more than ±10% discordance were rejected for statistical purposes in this study. The $^{206}Pb/^{238}U$ ages are used for grains less than 1000 Ma, whereas $^{207}Pb/^{206}Pb$ ages are selected if the $^{206}Pb/^{238}U$ ages are older than 1000 Ma. The age calculation and concordia plots were made using ISOPLOT (Version 3.0) (Ludwig, 2003). To show accuracy and analytical precision, data points are displayed on concordia plots as filled error ellipses, with all errors reported at the 1 Sigma confidence level.

4. Results

4.1. Heavy minerals

Heavy mineral abundances of the 11 samples from Meishan Formation are given in Table 2. The analyzed samples contain various heavy minerals assemblages (Fig. 5). Hematite, magnetite, leucoxene and zircon account for the majority of the proportion in the sedimentary rocks. These samples could be divided into three groups based on the location of the drill holes (Fig. 1). The sediments located in the western Y-SH Basin (LO-1 and LO-4) show the high concentration of hematite and leucoxene, with the assemblage of zircon and tourmaline. The samples (L20-1, L20-3, H29-4, H29-6, H30-2) in north and northeast parts of the basin generally have high magnetite, garnet and anatase comparing with other samples. Among these samples, L20-3 and L20-4 are characterized by relatively low hematite and leucoxene, and more abundant magnetite, anatase, apatite, leucoxene, hematite, tourmaline, garnet and zircon. Samples from the Eastern Slope of the basin, L11-3, L15-2,

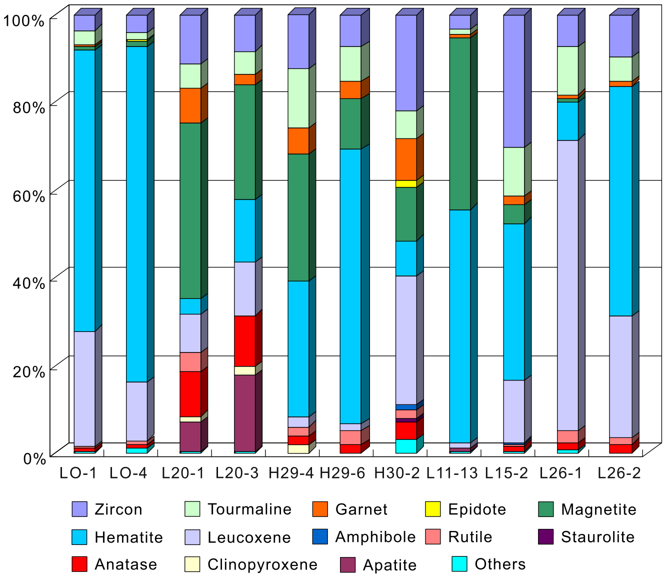

Fig. 5. Heavy mineral abundances of the middle Miocene sediments from the Y-SH Basin.

Table 2
The abundances of heavy minerals of the Meishan Formation sediments in the Y-SH Basin, expressed as frequency %.

Heavy minerals	LO-1	LO-4	L20-1	L20-3	H29-4	H29-6	H30-2	L11-13	L15-2	L26-2	L26-1
Zircon	3.6	4.3	11.2	8.3	12.6	7.3	22.4	3.4	30.5	9.7	7.6
Tourmaline	3.3	1.4	5.7	5.4	13.5	7.8	6.3	1.2	11.0	5.5	10.9
Rutile	0.4	0.7	4.4	0.0	2.1	3.3	2.1	0.0	0.4	1.4	2.8
Garnet	0.3	0.2	7.9	2.5	5.9	3.9	9.6	0.9	2.0	1.1	0.8
Apatite	0.0	0.0	6.8	17.4	0.0	0.0	0.0	0.8	0.0	0.0	0.0
Clinopyroxene	0.1	0.2	1.3	2.1	1.8	0.0	0.0	0.0	0.0	0.0	0.0
Anatase	0.8	0.7	10.1	11.6	2.1	1.7	4.0	0.0	1.2	2.0	1.5
Staurolite	0.0	0.1	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0
Amphibole	0.0	0.2	0.0	0.0	0.0	0.0	1.2	0.0	0.4	0.0	0.0
Leucoxene	26.4	13.5	8.6	12.2	2.1	1.7	29.8	1.1	14.2	27.8	67.6
Hematite	64.1	77.9	3.8	14.1	30.9	62.5	8.1	53.4	35.8	52.4	8.7
Magnetite	0.9	1.5	40.1	26.1	29.0	11.6	12.4	39.0	4.1	0.3	0.9
Epidote	0.0	0.1	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0
Others	0.1	1.0	0.3	0.2	0.0	0.0	2.9	0.1	0.4	0.0	0.6

Fig. 6. CL images of representative detrital zircons analyzed for U-Pb ages. The Red circles denote the LA-ICP-MS analytical spots for U-Pb ages. Numbers near the circles are the U-Pb ages. The red circles are 33 μm in diameter. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

L26-1 and L26-2 have high of leucoxene and zircon and low garnet contents, with the assemblage of tourmaline and leucoxene. The different assemblages of these sediments may suggest that they were derived from multiple source regions or reworked from older sedimentary rocks.

4.2. Zircon U-Pb ages

The CL images of representative zircons together with spots ages are shown on Fig. 6. A total of 936 detrital zircon analyses were undertaken by LA-ICP-MS, including the cores and rims of the grains extracted from the Meishan Formation. U-Pb data for the Upper and Lower Meishan Formation are shown on concordia plots and relative age probability diagrams (Figs. 7 and 8), and presented in detail in Appendix A.

The morphologies of these zircon grains are colorless to light pink and transparent, and showed a wide range from prismatic crystals to oval-shaped. The grains reach up to 300 μm in length, but were mainly in the range of 90–110 μm. Some grains are incomplete and may have been damaged during transport. A proportion of grains are sub-rounded or rounded corners (Fig. 6). The rounded grains reveal prolonged or multi-cycle transport whereas the euhedral grains usually suggest the short transportation. Most grains are oscillatory growth zoning under CL (Fig. 6) and have high Th/U values (>0.4) (Appendix A), indicates that the majority of the analyzed zircons are of magmatic origin (Wu and Zheng, 2004). Some grains also show typical metamorphic Th/U values (<0.1).

5. Discussion

5.1. Possible sediment sources

The previous provenance studies have illustrated that the Cenozoic sediments of the Y-SH Basin were from three major source terrains, the southern Yangtze Block (Red River), Indochina Block (central Vietnam) and Hainan Uplift (Gong et al., 1997; Brookfield, 1998; Clift and Sun, 2006; Xie, 2009; Yan et al., 2011; Wang et al., 2014b, 2015a; Cao et al., 2015; Jiang et al., 2015) (Fig. 9). These sources comprise potential sediment sources of sedimentary, metamorphic and igneous rocks from the northwest, west and east, respectively. Clastic material was presumably transported by paleo-fluvial and subsequently reworked during the transgressions in the Y-SH Basin (Xie, 2009).

Potential sediment sources to the east of the basin on Hainan Island are well characterized from numerous petrologic and tectonic studies. Hainan forms the southern end of the Cathaysia Block, which was accreted to the Yangtze Craton during the late Mesoproterozoic to earliest Neoproterozoic Sibao Orogeny (Li et al., 2008). Permian to Triassic granitoids dominate the island along with isolated exposures of Paleozoic and Mesoproterozoic rocks. Ca. 1430 Ma Precambrian volcaniclastic rocks have been discovered in western Hainan (Fig. 9), which may associated to the Grenvillian Orogenic event in this region (Xu et al., 2007b; Li et al., 2008). Representatives of the Indosinian intrusions in Hainan ranging from 280 to 220 Ma (Li et al., 2006; Xie et al., 2006a, 2006b; Wen, 2013; Wen et al., 2013). Cretaceous granitoids and volcanic rocks with ages ranging from 160 to 80 Ma occur in the southern part of the island (Wang et al., 1991, 2011, 2015b; Jia et al., 2009) (Fig. 9).

South China, including the Yangtze and Cathaysia blocks, was presumably part of the Precambrian supercontinent-Rodinia (Li et al., 1995; Zhou et al., 2002). The Yangtze Block is separated from the North China Craton by the Qinling-Dabie orogenic belt to the north and is bounded on the west and south by the Tibetan Plateau and Indochina Block, respectively. Archean and Proterozoic basement rocks have been recognized in southern Yangtze Block with zircon U-Pb ages at 2800–2300 Ma and 1700–2100 Ma (Qiu et al., 2000; Metcalfe, 2006; Zheng et al., 2006). Neoproterozoic magmatism (1000–700 Ma), including granites, volcanic rocks and

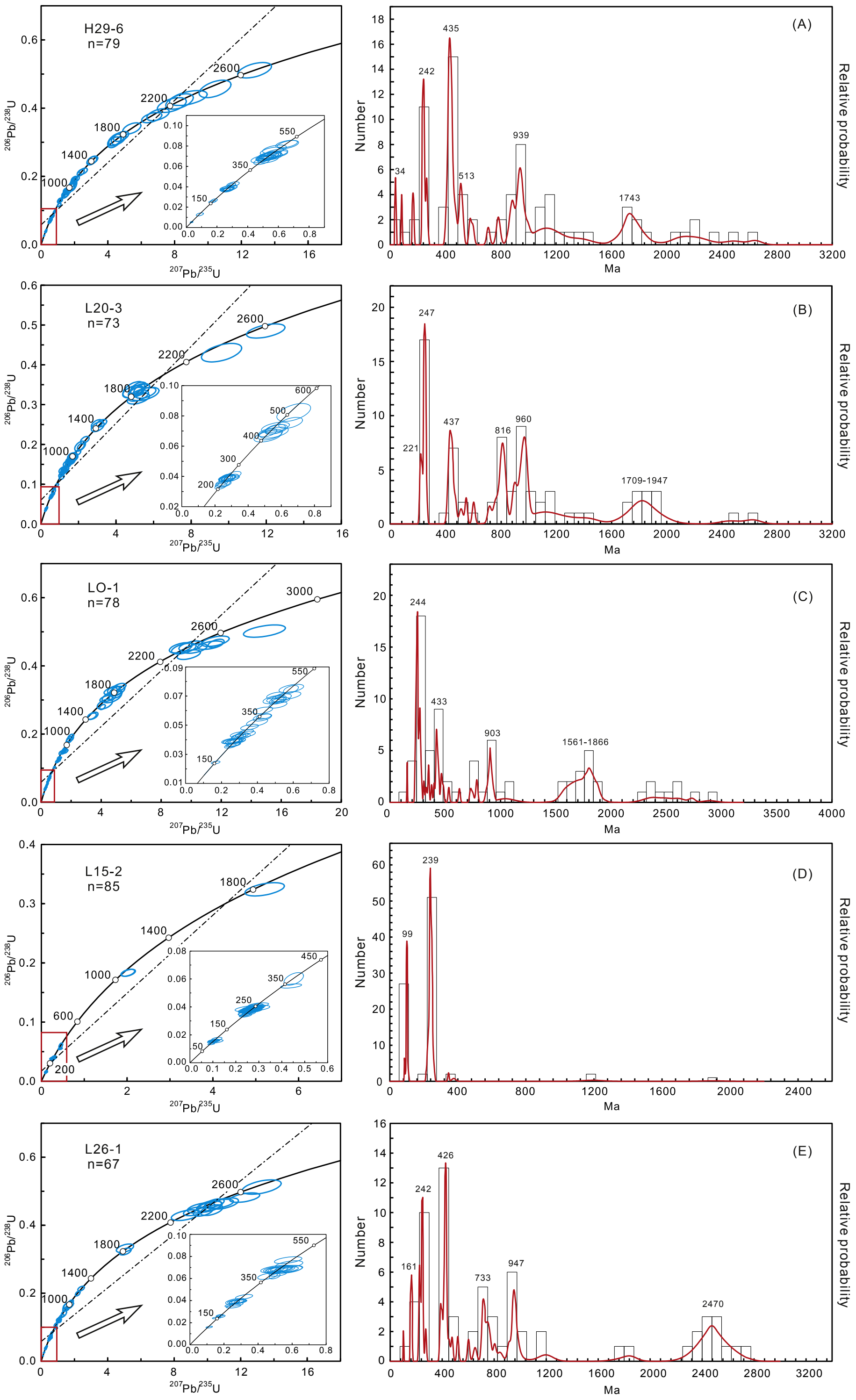

Fig. 7. U-Pb Concordia and histogram diagram of detrital zircons for the Lower Meishan Formation in the Y-SH Basin. Data-point error ellipses are 1 sigma. N-number of concordant analyses. The numbers above the relative probability curve are the peaks of zircon U-Pb ages.

ophiolites, occurred sporadically around the Yangtze Block (Li, 1999; Zhou et al., 2002, 2006; Xiao et al., 2007; Ye et al., 2007), which probably produced by the pre-breakup of Rodinia and subsequent migration of South China (Zhou et al., 2002; Li et al., 2003). U-Pb ages of Late Paleozoic igneous rocks in the Youjiang Basin and Song Chay Massif (Fig. 9) from 480 to 400 Ma (Roger et al., 2000; Carter et al., 2001; Yan et al., 2006; Yang et al., 2012). Mesozoic igneous rocks associated with the collision between several micro-continents and the Yangtze Block yield U-Pb ages between 280 and 220 Ma (Hoa et al., 2008; Zhong et al., 2009; Zhong and Xu, 2009; Roger et al., 2012; Chen et al., 2014). Middle Jurassic to Cretaceous basaltic lavas and related mafic dikes ranging from 180 to 80 Ma are located in western and eastern Yangtze Block (Chen and Jahn, 1998; Wang et al., 2003; Li et al., 2004; Cheng and Mao, 2010).

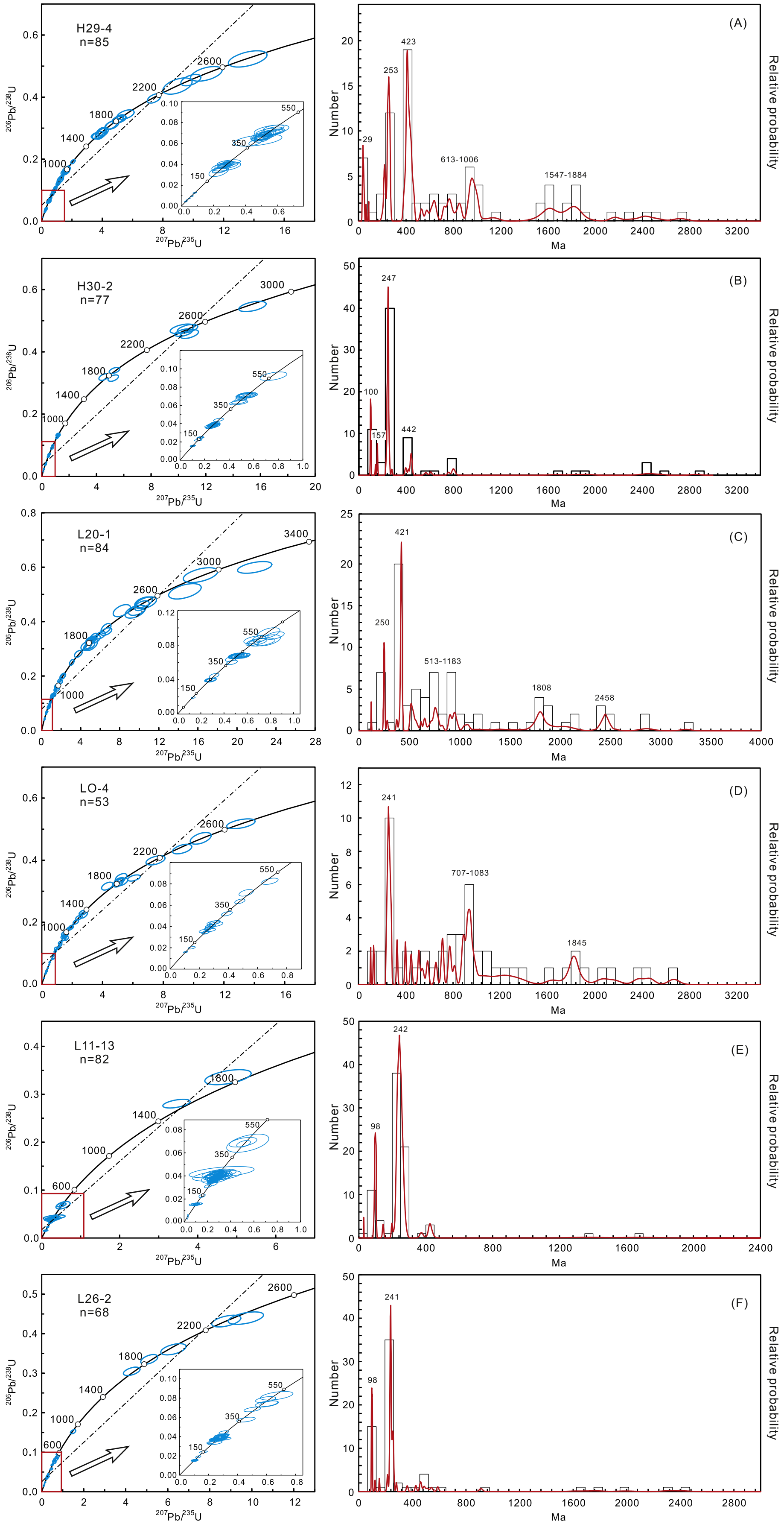

Fig. 8. U-Pb Concordia and histogram diagram of detrital zircons for the Upper Meishan Formation in the Y-SH Basin. Data-point error ellipses are 1 sigma. N-number of concordant analyses. The numbers above the relative probability curve are the peaks of zircon U-Pb ages.

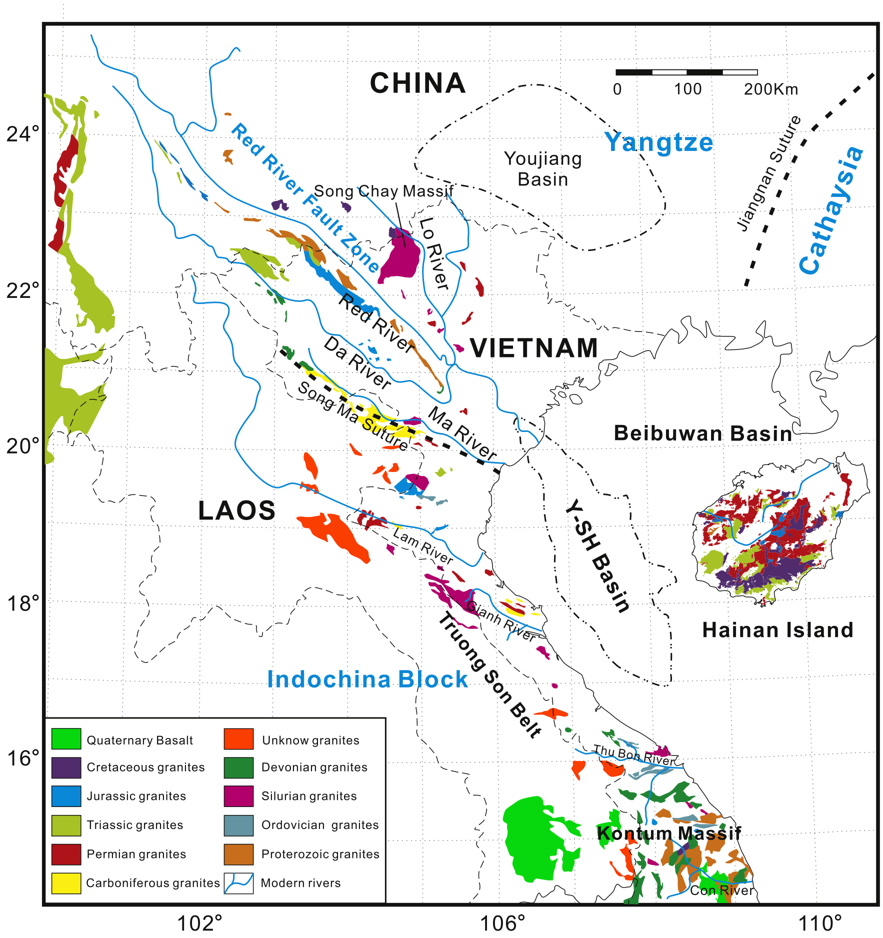

Fig. 9. Map showing the igneous rocks distribution and courses of rivers of major source areas of Y-SH Basin.

The Truong Son Belt of the Indochina Block is characterized by Silurian, Permian-Triassic granites and high-grade metamorphic rocks formed during the Caledonian and Indosinian Orogeny events, respectively. The early Permian-Triassic arc magmatism (280–270 Ma and 250–240 Ma) is widely distributed in the belt (Fig. 9) (Hoa et al., 2008; Liu et al., 2012). The Early Paleozoic granitoids within the Truong Son Belt occur mainly in the southwest of the orogenic belt, and gives aged of 460–430 Ma (Carter et al., 2001; Lan et al., 2003; Usuki et al., 2009, 2013; Wang et al., 2016a). Metamorphism occurred during the Indosinian Orogeny dated between 250 and 245 Ma (Lepvrier et al., 1997; Carter et al., 2001; Nagy et al., 2001; Roger et al., 2007).

Zircon U-Pb age distribution probability density plots based on available age data published in these regions for the rocks and modern rivers of the major potential source regions are outlined in Fig. 10.

5.2. Source of the Meishan Formation

5.2.1. The Lower Meishan Formation (16.5–13.8 Ma)

The detrital zircon age spectra from four samples (H29-6, L20-3, LO-1 and L26-1) collected from the Lower Meishan Formation are exhibit a series of similar age populations ranging from Archean to Cenozoic (Fig. 7). They have age peaks at 247–242 Ma, 437–426 Ma, 1000–700 Ma and 2000–1500 Ma, which are consistent with the source of the southern Yangtze Block and modern Red River (Fig. 10). Mesozoic igneous rocks ranging in age from 280 to 220 Ma occur in Hainan Island, Yangtze and Indochina blocks (Fig. 10) and are therefore not unique to the source regions. The early Paleozoic zircons with age peaks at 437–426 Ma corresponding to the global "Caledonian Orogeny" are manifested by a number of early Paleozoic magmatic activity and metamorphism in East Asia (Lu et al., 1999). The wide range of the Precambrian ages in these samples is consistent with the polyphase evolution of the Yangtze Block (Fig. 10A). Neoproterozoic ages ranging of 1000–700 Ma are rare or absent in other source terrains and are interpreted as a signature of the Yangtze Block (Xu et al., 2010; Wang et al., 2014b). Overall, it is reasonable to infer that the four samples have similar source that mainly derived from southern Yangtze delivered by Red River during the middle Miocene. The detritus could also have been transported from more distant sources, including Songpan-Garze, Qiangtang and Sibumasu blocks, by the Red River (Hoang et al., 2009).

Detrital zircon ages and heavy mineral assemblages suggest some changes in the dominant source terrains among these samples. Cenozoic zircon grains with age peak at ca. 35 Ma could be derived from the Red River Fault Zone where several large and small plutonic bodies of this age exist (Schärer et al., 1990; Leloup et al., 1995, 2001; Chung et al., 1997). Sample H29-6 contains numerous grains about 34 Ma suggesting more detritus from the Red River Fault Zone. Samples H29-6 and L26-1 presents major clusters of zircon at 435–426 Ma, denoting preferential erosion might from the Yangtze or Indochina blocks. The heavy mineral assemblages of L26-1 with high proportion of leucoxene and tourmaline that distinct from others (Fig. 5), combined with extra age peak at ca. 161 Ma, suggests a part of clastic material was derived from Hainan (Wang et al., 2015b).

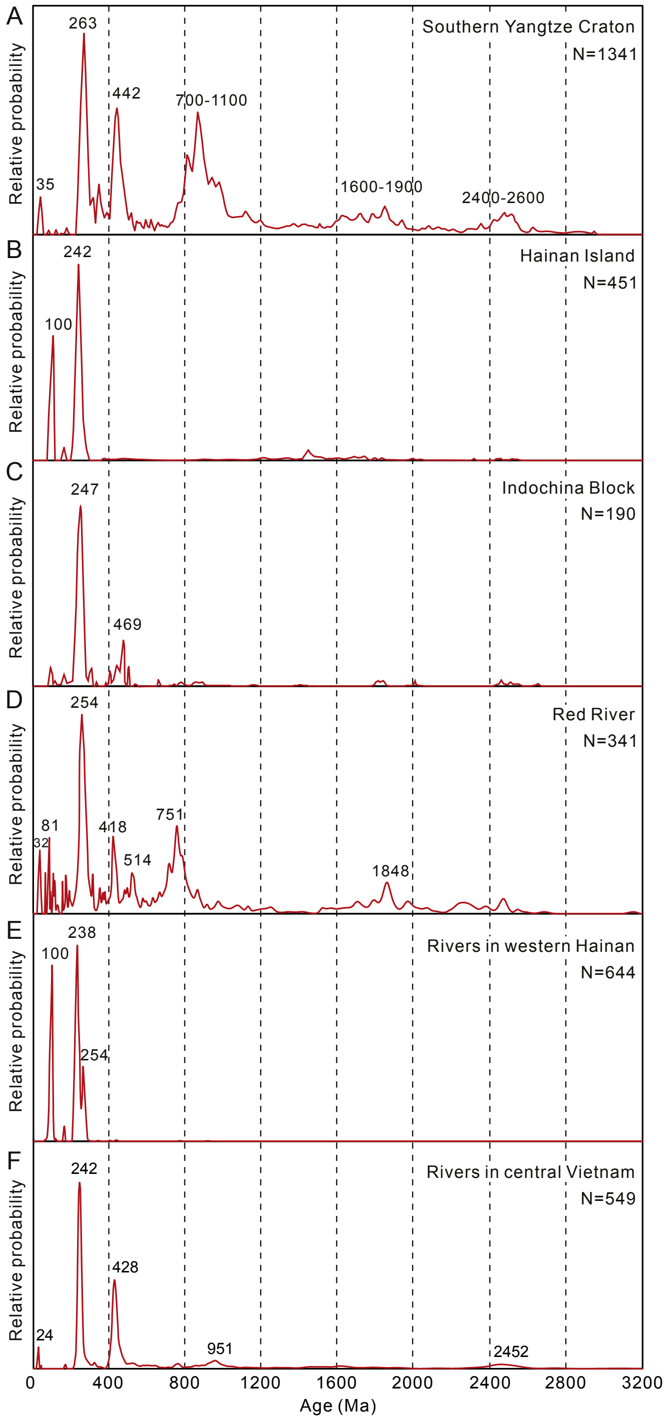

Fig. 10. Zircon U-Pb age probability density plots of the major potential source areas and modern rivers surrounding the Y-SH Basin. Data for southern Yangtze Craton are from Li (1999), Zhang and Schärer (1999), Ling et al. (2003), Nam et al. (2003), Zhou et al. (2006), Wang et al. (2007), Xiao et al. (2007), Zhou et al. (2007), Cao et al. (2011), Yang et al. (2012) and Żelaźniewicz et al. (2013). Data for Hainan Island is from Wang et al. (1991), Xie et al. (2005), Li et al. (2006), Xie et al. (2006a), Xu et al. (2007a, 2007b), Li et al. (2008), Jia et al. (2009), Zhang et al. (2009), Tang et al. (2010), Wang et al. (2011), Wen (2013) and Wen et al. (2013). Data for Indochina Block are from Carter and Moss (1999), Carter et al. (2001), Carter and Bristow (2003), Roger et al. (2007), Liu et al. (2012) and Kamvong et al. (2014). Data for Red River are from Clift et al. (2006) and Hoang et al. (2009). Data for rivers in central Vietnam are from Usuki et al. (2013) and Wang (2016). Data for rivers in western Hainan are from Wang et al. (2015b). N-number of concordant analyses. The numbers above the relative probability curve are the peaks of zircon U-Pb ages.

The age spectrum of L15-2 display prominent age peaks at ca. 99 Ma and 239 Ma (Fig. 7D). There are also some Mesoproterozoic zircons (1187 Ma and 1196 Ma), which may correspond to the "Jinning Movement" in South China (Wang et al., 1991). The Mesoproterozoic felsic volcanic rocks have been discovered in western Hainan Island, which would be considered relating to Grenvillian in Asia (Xu et al., 2007b; Li et al., 2008). Ages older than 450 Ma are scarce in this sample, whereas such grains are abundant in the source of Yangtze and Indochina blocks. The bimodal age pattern of the sample matches closely with the zircon ages in the western Hainan (Fig. 10B). Previous studies show that the provenance from Hainan has main age ranging from 110–90 Ma to 280–220 Ma on the eastern margin of the Y-SH Basin (Yan et al., 2011; Wang et al., 2015a). The sediments from modern rivers in the western Hainan also give the same results with age peaks at ca. 100 Ma, 238 Ma and 254 Ma (Fig. 10E) (Wang et al., 2015b). Cretaceous ages around 99 Ma can also be interpreted as a signature of the Hainan because they are rare or absent in other surrounding tectonic units. The range of ages has been recognized in the southeast of the Baisha Fault, southern Hainan, and yield ages around 100 Ma (Wang et al., 1991, 2011; Jia et al., 2009). The Yangtze and Indochina blocks played apparently no role on the provenance of L15-2, as indicated by the absence or scarcity of Neoproterozoic and Paleoproterozoic ages (>600 Ma). In addition, the heavy minerals of the sample show the highest zircon content (30.5%), which might correspond to the widely spread of Permian and Triassic igneous rocks in southwestern Hainan. The zircon content can reach to 44% in the Ganen River, western Hainan (Wang et al., 2014a). All of these indicate that the sample was derived solely from Hainan.

The multi-dimensional scaling (MDS) method (Vermeesch, 2013) based on Kolmogorov-Smirnov (K-S) statistics has been used to assess the relative dissimilarities between the samples and source areas (Fig. 11). The samples from Lower Meishan Formation show two distinct groups (Fig. 11A and B). LO-1, L26-1, H29-6 and L20-3 are close to southern Yangtze Block and Red River, while L15-2 is closer to Hainan and the modern rivers in western Hainan. The eastern Indochina and rivers in central Vietnam plot away from these samples, may suggest a minor contribution of this source area during the early stage of middle Miocene. This is consistent with the result discussed above.

5.2.2. *The Upper Meishan Formation (13.8–10.5 Ma)*

Age spectra from two samples (H29-4 and L20-1) collected from the Upper Meishan Formation in northern Y-SH Basin are broadly similar (Fig. 8A and C), suggesting that they were part of the same depositional system (Rainbird et al., 2001). Both samples have two major age peaks at ca. 253–250 Ma and 423–421 Ma, with subordinate Neoproterozoic and Paleoproterozoic ages (1100–500 Ma and 1900–1500 Ma, respectively). U-Pb detrital zircon ages of these two samples compare favorably with published geochronological data from the modern Red River (Bodet and Schärer, 2000; Clift et al., 2006; Hoang et al., 2009) (Fig. 9), and could be mainly from the southern Yangtze Block, or recycled via Triassic sedimentary basins (Hoang et al., 2009). The heavy mineral assemblages are magnetite, hematite, tourmaline, zircon and garnet (Fig. 5), suggests the metamorphic rocks played an important role for the provenance. It is noteworthy that the Caledonian zircons in samples H29-4 and L20-1 account for 14.1% and 28.6% of the total, respectively. Compared with the modern Red River (about 7%), the relatively high proportion of early Paleozoic grains may suggests that the erosion degree of the Caledonian granites during the late stage of middle Miocene were higher than today or influence of the evolution of Red River during this time.

The age populations of L11-13, L26-2 and H30-2 are relatively simple and show similar age characteristics (Fig. 8), with two major

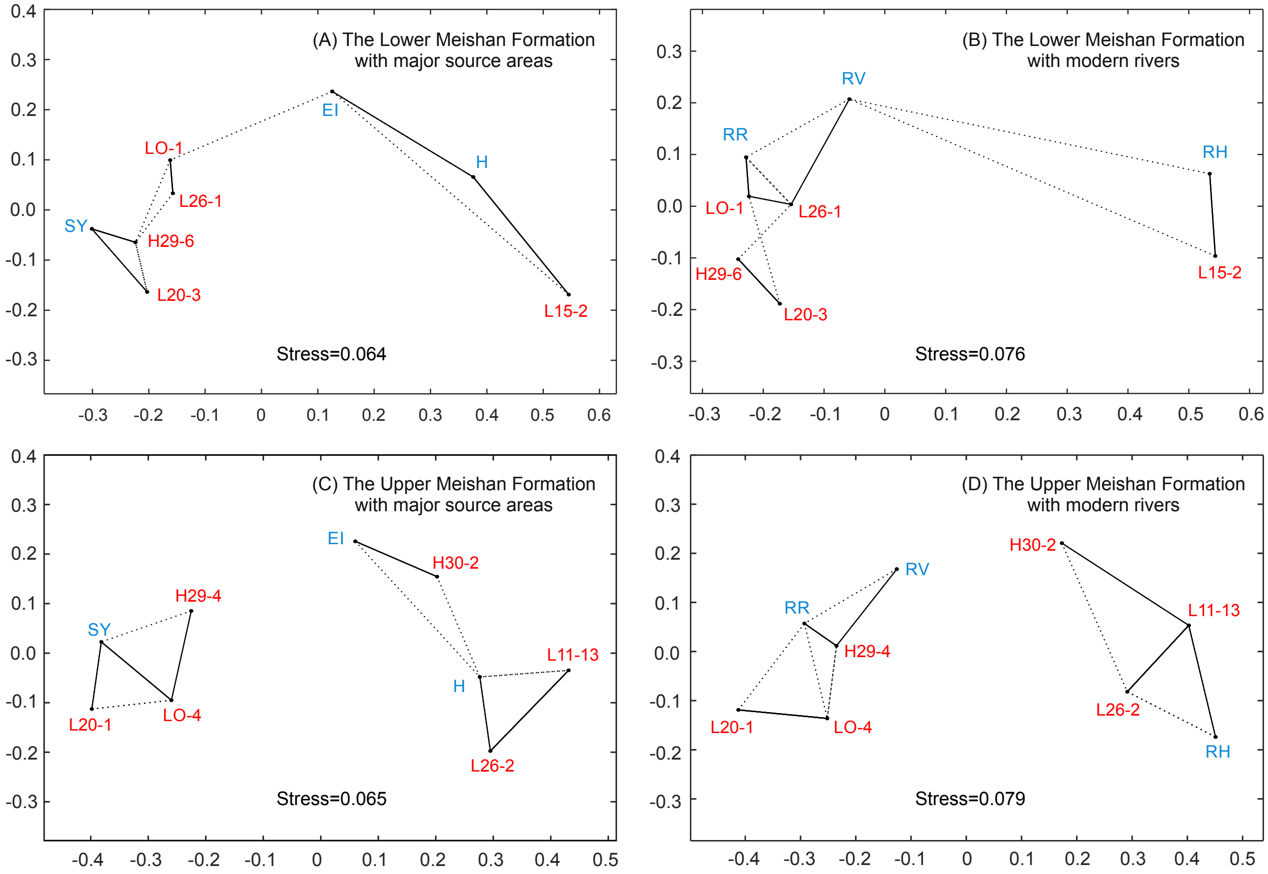

Fig. 11. Metric multi-dimensional scaling plots (Vermeesch, 2013) using Kolmogorov-Smirnov statistic for study of detrital zircon from the Yinggehai-Song Hong Basin and its source areas. SY: Southern Yangtze; EI: Eastern Indochina; H: Hainan; RR: Red River; RV: Rivers in central Vietnam; RH: Rivers in western Hainan. Solid lines and dashed lines connect samples with their closest and second closest neighbors respectively. The data is the same as Fig. 10.

age peaks at ca. 98 Ma and 241 Ma, which are significantly distinct from the two samples discussed above. Compared with the age spectrum of the potential source terrains, therefore, we suggest that the detritus could be considered as a local source likely derived from the Hainan. The three drill holes are in or near to delta depositional environments, which is consistent with local sources (Fig. 12). In addition, minor Neoproterozoic and older zircons occur in the H30-2, combined with the variety of heavy minerals, suggestive of a small part of detritus was derived from Red River. However, the Yangtze Block played apparently no role on the provenance of samples L11-13 and L26-2, as indicated by the absence or scarcity of ages older than 600 Ma.

A comparison of the LO-4 zircon age spectra with those of H29-4 and L20-1, it is noteworthy that there is no obvious age peak around 420 Ma but there are clusters of Neoproterozoic ages between ca. 707 and 1083 Ma (Fig. 8D). The absence of early Paleozoic age peak suggests that Red River was not the only source terrain. A possible interpretation is that the sediments might be influenced by the local source from central Vietnam and mixed with the detritus from Red River. The Neoproterozoic zircon grains in the sample were probably eroded from the Paleozoic sedimentary rocks near to the coast of central Vietnam (Wang et al., 2016a).

The MDS map shows that samples from Upper Meishan Formation can be divided into two parts (Fig. 11C and D). The H29-4, L20-1 and LO-4 exhibit least dissimilar to southern Yangtze Block and Red River, whereas H30-2, L26-2 and L11-13 are closer to the Hainan and Rivers in western Hainan. Indochina is far from these two other source areas but close to H29-4 and H30-2, which is discrepancy with our discussion, may be due to the influence of the mixed sources by Red River and Hainan (Fig. 11B). It is noteworthy that the statistical method does not always interpret the full richness of entire age distributions correctly (Shao et al., 2016), and the MDS result can be used as a reference in this study.

In summary, detrital zircon and heavy mineral assemblages for the Meishan Formation from the Y-SH Basin reveal that the detritus derived from multiple sources. The zircon age spectra derived from the Hainan are essentially bimodal, whereas the Red River are much more diverse, showing multiple peaks and a wider range of ages. Comparison of the age populations and heavy mineral assemblages with the potential sources terrains indicates that the Red River and Hainan played key roles contributed the clastic material to the basin during middle Miocene. The possible provenance directions and routes of the middle Miocene Meishan Formation are shown in Fig. 12.

5.3. Spatial and temporal changes

Detrital zircon ages and heavy mineral assemblages suggest some changes in the dominant source terrains through time and space (Fig. 12). The age pattern indicates diversity of age populations in the source areas and changes in sediment supply to the sample locations. In the middle Miocene, the sediments from northern and western Y-SH Basin are different from these in the east (Fig. 12). The drill holes located on eastern Y-SH Basin,

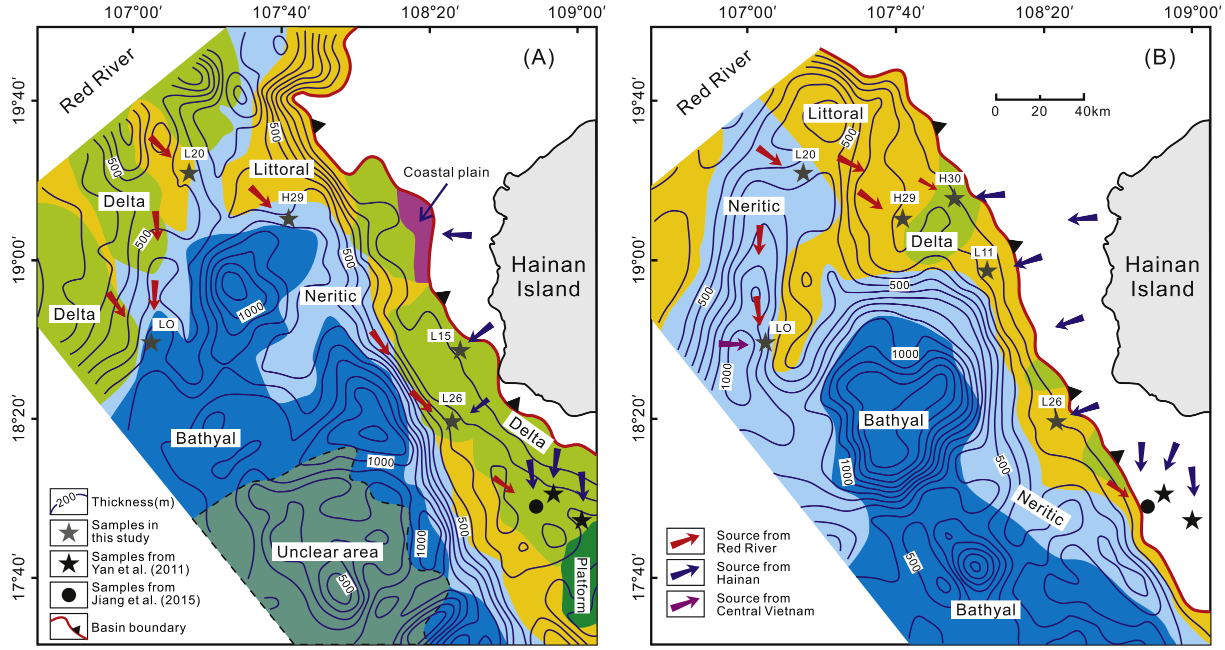

Fig. 12. Possible provenance directions of the middle Miocene Meishan Formation in the Y-SH Basin: (a) the early stage of middle Miocene and (b) the late stage of middle Miocene. The sediment isopach modified after Gong et al. (1997) and Xie (2009).

including L11, L15 and L26, are considered to have been deposited by delta fans emanating from Hainan. By contrast, the sites (L20, H29 and H30) from northern and western Y-SH Basin are much more complex. The zircon source histograms clearly show that the southern Yangtze Block could be the source terrain (Fig. 10A).

The distribution of provenance between the Upper and Lower Meishan Formation are basically similar (Fig. 12). However, samples from the drilling L26 show significant change between the upper and lower (Fig. 13A and B). The upper shows bimodal pattern with age peaks at ca. 98 Ma and 241 Ma, suggestive of sediments detritus eroded from the Mesozoic granites in the Hainan Island. The lower have a wide range ages from Archean to Cenozoic (2727–103 Ma) indicates that the detritus was mainly derived from the southern Yangtze Block delivered by Red River. The provenance change on

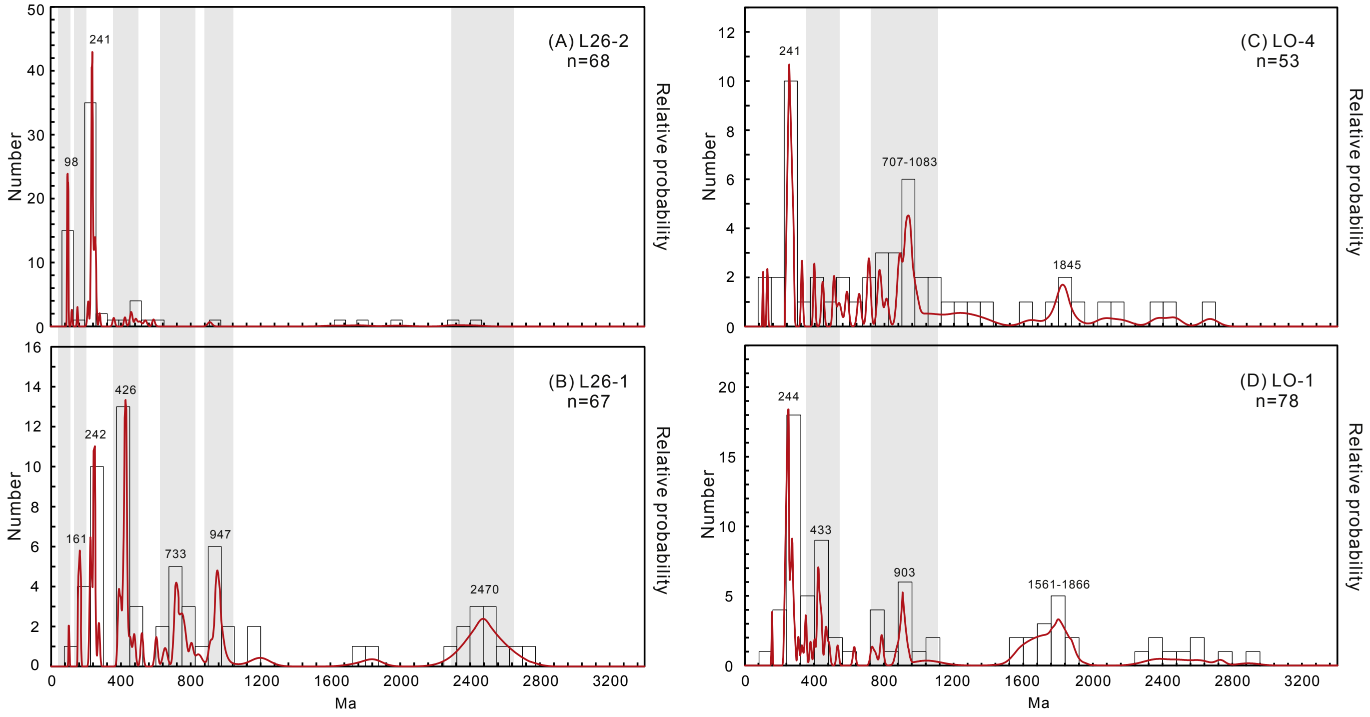

Fig. 13. Histogram diagrams of detrital zircons for the drilling LO and L26. The shadow shows the different between the Upper and Lower Meishan Formation in those of two drillings. N-number of concordant analyses. The numbers above the relative probability curve are the peaks of zircon U-Pb ages.

eastern margin of the basin reveals that Red River could transport longer distance at early stage of middle Miocene than later stage. A subtle change in source is also detected in site LO (Fig. 13C and D). The upper sample shows less early Paleozoic ages but more Neoproterozoic zircon and relatively high percentage of hematite (Fig. 5) compared with the lower which is similar to the probability density plots of the southern Yangtze Block. This suggests the influence of the source from Indochina Block.

Overall, the detrital zircon U-Pb ages and heavy mineral assemblages indicate no significant changes were recognized between the Upper and Lower Meishan Formation, which means that the Y-SH Basin was in a relatively stable source supply environment during the middle Miocene.

5.4. *Sediment contributions and transport pathways*

Due to these samples mainly located on central and eastern side of the basin and limited coverage of the whole basin, accurate calculation of the contribution of the different source terrains appears to be impossible at this time. The modern Red River, which originates in the mountains of Yunnan Province, China, and flows about 1200 km from southeast Tibet to the South China Sea, is one of the major continental discontinuities in Southeast Asia (Milliman et al., 1995). The total sediment and water discharge of the Red River is 100–130 million t/yr and 120 km^3/yr (Milliman et al., 1995; Pruszak et al., 2002), respectively, and drains an area of 160×10^3 km^2 (Tanabe et al., 2006). Detrital zircon ages from Red River suggest that the southern Yangtze Block, which prior to these tectonic regions, is an important source of detritus (Clift et al., 2006; Hoang et al., 2009). Hence, huge amounts of detrital material accumulated in the Y-SH Basin should be considered erosion from the Yunnan and northern Vietnam, which makes southern Yangtze Block become the most important source terrain for the basin via Red River. It is clear that the sediments in the eastern Y-SH Basin are linked to the drainage systems in western Hainan, thus, the model of supply by Hainan could be supplied by rivers to form deltas (Xie, 2009), then reworked and transported by gravity flow currents to the central parts of the basin, which is similar to the sedimentary model of the Qiongdongnan Basin in the east of the Y-SH Basin (Wang et al., 2015c). Wang et al. (2014b) suggests that the Hainan was not the major source terrain since late Miocene (ca. 10 Ma) based on the detrital zircon in the Dongfang gas field. This study reveals that Hainan was an important source of the Y-SH Basin during middle Miocene, which also supported by Yan et al. (2011) and Jiang et al. (2015).

Southern Yangtze Block and Hainan were the major source terrains provided massive terrigenous clastic material to Y-SH Basin from northwest and east, respectively. Previous studies suggest that Indochina Block played an important role in contributing sediments to the basin since late Miocene (ca. 10 Ma) (Xie, 2009; Cao et al., 2015), the main input rivers including Ma River, Lam River, Gianh River and other rivers in the central Vietnam. However, this study shows that the Indochina Block was not the main source area during the middle Miocene (16.5 Ma–10.5 Ma), although it may have an impact on the local sediments near to the Vietnam, such as drilling LO (Fig. 12).

6. Conclusions

U-Pb dating of detrital zircon from the middle Miocene Meishan Formation (Langhian-Serravallian) deep-water reservoir sedimentary rock samples from the Yinggehai-Song Hong Basin indicates derivation from source terranes ranging in age from Archean to Cenozoic or recycled from sediments with zircons of these ages. The broad spectrum of age ranges collected from north of the basin suggests that the detritus was derived from Red River. By contrast, the samples from the east are relatively simple with two major age peaks, the proportion of early Paleozoic and older zircons are less than that in the north, their bimodal detrital zircon population suggests that these sandstones on the eastern margin of the basin are of local origin derived from Hainan. Moreover, input possibly from the western side of the basin (Indochina Block) is also detected. The detrital zircon U-Pb ages and heavy mineral assemblages indicate no significant change was recognized between the Upper and Lower Meishan Formation, which means that the Y-SH Basin was in a relatively stable source supply environment during the middle Miocene. Compared with the three potential tectonic units, the provenance of the Meishan Formation was largely derived from Yangtze Block and Hainan Uplift at the same time.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.marpetgeo.2016.05.009.

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