Acta Oceanol. Sin., 2021, Vol. 40, No. 2, P. 114–122
https://doi.org/10.1007/s13131-021-1756-8
http://www.hyxb.org.cn
E-mail: hyxbe@263.net

Sediment source and environment evolution in Taiwan Island during the Eocene–Miocene

Yuanli Hou[1], Weilin Zhu[1]*, Peijun Qiao[1], Chi-Yue Huang[1], Yuchi Cui[1], Xianbo Meng[1]
[1] State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, China

Received 29 September 2019; accepted 16 June 2020

Abstract

Taiwan Island's outcropping strata can provide important insights into the sedimentary environment and source development of the southeast China margin. This research is based on the Eocene–Miocene strata of the Tsukeng area in the central Western Foothills, northeast shoreline of Taiwan Island and two sites of the East China Sea Shelf Basin (ECSSB), using petrology and detrital zircon U-Pb age for the analysis. Results show that central and northeast Taiwan Island experienced a transformation from continental to marine facies during the Eocene–Miocene, and the sandstone maturity changed with time. Source analysis shows that sediments from the Eocene–early Oligocene strata mainly originated from near-source Mesozoic rocks, whose zircon age is consistent with the igneous rock in the surrounding area and coastal Cathaysia, showing 120 Ma and 230 Ma peaks in the age spectrum diagram. Since the late Oligocene, peaks of 900 Ma and 1 800 Ma are seen, indicating that deposition of matter from the old block began. The sediments could be a mixture of the surrounding Mesozoic volcanic and fewer pre-Cambrian rocks sourced from the coastal river and sporadic old basement in the ECSSB instead of long-distance transportation.

Key words: Taiwan Island, sedimentary source, sandstone, zircon, sedimentary environment

Citation: Hou Yuanli, Zhu Weilin, Qiao Peijun, Huang Chi-Yue, Cui Yuchi, Meng Xianbo. 2021. Sediment source and environment evolution in Taiwan Island during the Eocene–Miocene. Acta Oceanologica Sinica, 40(2): 114–122, doi: 10.1007/s13131-021-1756-8

1 Introduction

East Asia has experienced a series of tectonic movements since the Cenozoic, including the turnover and subduction of the Pacific Plate (Sharp and Clague, 2006), collision of the Philippine Plate and Eurasia (Hall, 1996), and collision of the India Plate and Eurasia, which resulted in the uplift of the Tibetan Plateau (Wang et al., 2002; Hu et al., 2015). These events greatly influenced the tectonics, geological evolution and climate of East Asia. Specifically, the reversal of the west-tilting topography in East Asia, resulting from the uplift of the Tibetan Plateau (Wang, 2004; Cao et al., 2018), led to a dramatic shift in the sediment transportation and deposition in East China (Clark et al., 2004; Shao et al., 2007; Zheng et al., 2013). Thus, studying the sedimentary materials in East China is a useful method to understand the tectonic and geological development of East Asia during the Cenozoic.

Taiwan Island is an important area in East Asia, whose sediments formed from the erosion and deposition of terrigenous material from the East Asian continental margins (Huang et al., 2012). When the Philippine Plate drifted northwestward and collided with Eurasia during the middle Miocene, the Cenozoic sedimentary sequence of the East Asian continental margins underwent distortion and uplift, eventually formed the Taiwan Island (Suppe, 1984; Huang et al., 2000). Hence, the exposed strata of Taiwan Island sediments can be viewed as the Cenozoic sedimentary record of the East Asian continental margins.

There have been numerous studies regarding the Cenozoic sedimentary environment of Taiwan (Huang et al., 1997, 2000); however, there is controversy regarding the sediment sources. One of these controversies concerned the shifting of the Eocene-Miocene sediment source recorded in the Taiwan Island sediments (Deng et al., 2017a, 2017b; Lan et al., 2016; Zhang et al., 2014, 2017; Wang et al., 2018; Chen et al., 2019). Recently, a strengthened theory claimed that the Changjiang River could have influenced the Eocene-Miocene source shifting by transporting its sediments after entering the East China Sea, southward through the East China Sea Shelf Basin (ECSSB) (Deng et al., 2017b; Zhang et al., 2014, 2017; Wang et al., 2018). However, integrated and comprehensive studies on the mechanism of southward transportation are scarce. Meanwhile, as the present studies mainly focused on zircon U-Pb age regarding the sediment source development (Deng et al., 2017b; Zhang et al., 2017; Wang et al., 2018; Chen et al., 2019), multiple solutions cannot be ignored. Hence, more information regarding the detrital zircon U-Pb age and petrological features from widely distributed locations is required to understand the sediment source development.

In this study, the petrology and sediment source features of Eocene-Miocene samples from middle and north Taiwan Island were investigated. This was combined with sedimentary data from two sites of the ECSSB (Xihu Sag and Changjiang Depression) and some published data of East Asian areas. This investigation aimed to reveal the sedimentary environment and source development of Taiwan Island, and the connection of the source development between Taiwan Island and the ECSSB. Furthermore, the feasibility of the present source development model and new understanding are discussed (Fig. 1).

Foundation item: The National Natural Science Foundation of China under contract Nos 42076066, 41874076 and 92055203; the National Key Research and Development Program of China under contract No. 2018YFE0202400; the National Science and Technology Major Project under contract No. 2016ZX05026004-002.

*Corresponding author, E-mail: zhuwl@tongji.edu.cn

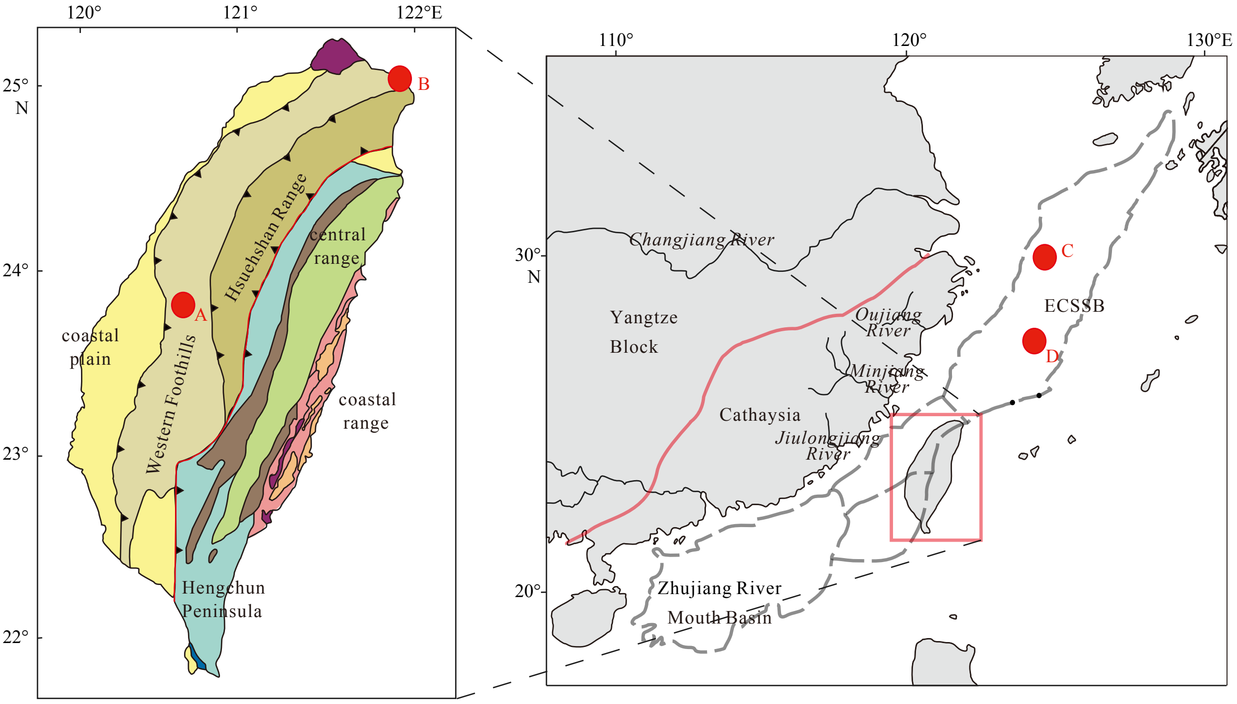

Fig. 1. Tectonic map of the study area and surrounding geological units. ECSSB is the East China Sea Shelf Basin. Points A, B, C and D represent sampling locations: A is the Tsukeng area in the Western Foothills, B is the northeast shoreline, C is the Changjiang Sag and D is the Xihu Sag. The red line represents the boundry between Yangtze Block and Cathaysia Block. The age of the strata at each location as well as the corresponding section can be found in Fig. 2 (modified from Huang et al. (2012)).

2 Geological setting

From the late Mesozoic to early Cenozoic, large-scale rifting events at the margins of Eurasia formed a series of fault basins (Huang et al., 2012). In this process, extremely thick sediments were deposited in the basins, which provide insights into the development of the sedimentary environment and water system.

The ECSSB is located to southeastern China, near the convergence zone between Eurasia and the Philippine Plate (Zhou et al., 2001; Cukur et al., 2011). It is a Mesozoic–Cenozoic rift basin divided into the Western Depression Belt (WDB) and Eastern Depression Belt (EDB) (Yang et al., 2006). The WDB is made up of the Haipijiao Uplift, Changjiang Depression, Haijiao Uplift and Taibei Depression (from north to south), while the EDB is made up of the Fujiang, Xihu and Diaobei depressions (from north to south). The tectonic evolution of the ECSSB can be divided into three major stages: (1) early extension and rifting during the Paleocene–Eocene, (2) compression and tectonic inversion during the Oligocene–Miocene and (3) thermal subsidence during the Pliocene–Quaternary (Suo et al., 2015; Zhang et al., 2016; Wang et al., 2018). The Cenozoic strata include the Paleocene Mingyuefeng Formation; the Eocene Oujiang, Wenzhou, and Pinghu formations, the Oligocene Huagang Formation, the Miocene Longjing, Yuquan, and Liulang formations, and the overlying Pliocene-Quaternary strata (Ye et al., 2007; Suo et al., 2015) (Fig. 2). The Fujian-Zhejiang Uplift, to the west of the ECSSB, contains volcanic and Proterozoic metamorphic rock outcrops (Yang et al., 2006). The Diaoyudao Uplift, to the east of the ECSSB, is a volcanic arc covered by Miocene–Quaternary sediments, whose basement is composed of Cenozoic volcanic rocks (Li and Li, 1995; Jin et al., 2005; Zhang et al., 2020) and Proterozoic, upper Paleozoic, and Mesozoic rocks (Li et al., 1995).

The tectonic evolution of Taiwan Island, a product of plate subduction and accretion (Huang et al., 1997; Li et al., 2003), can be separated into several stages (Fig. 2). (1) Epicontinental fault basin stage (45–34 Ma): sediments were mainly fluvial-lacustrine, and Mesozoic–Paleozoic continental-neritic clastic sedimentary and metamorphic rocks formed the basement. Graben-half graben rift basins were formed in these fault zones. (2) Oceanic expansion stage (34–16 Ma): Taiwan Island was a part of the northern South China Sea (SCS) and experienced the oceanic rifting of the SCS (Cui et al., 2019). (3) Oceanic crust subduction stage (16–6.5 Ma): the SCS crust subducted eastward beneath the Philippine Plate along the Manila Trench. Simultaneously, sediments from the continental shelf and slope, along with turbidites, were scraped to form an accretionary prism. (4) Continental-arc collision stage (6.5 Ma): the North Luzon Arc collided with the margins of Eurasia, forcing the strata in the passive continental margins westward and over the surface (Huang et al., 1997, 2000).

The sediments in the Western Foothills of Taiwan Island are typical passive continental margin sediments. The exposed strata are generally divided into syn-rift and post-rift strata (Huang et al., 1997, 2000) (Fig. 2). The syn-rift strata are mainly Eocene strata, while the post-rift strata are from the late Oligocene and Miocene. They are separated by the breakup unconformity known as the "Puli Movement" in Taiwan Island. This breakup unconformity corresponded to the opening of the SCS (33–39 Ma), i.e., rifting of the Asian continental margin that formed the SCS oceanic crust (Huang et al., 2017).

3 Samples and analytical methods

In this study, Eocene–Miocene sandstone samples were collected, including 44 samples from Tsukeng, Nantou, and middle Taiwan Island, 17 samples from the northeast shorelines of Taiwan Island, 6 samples from the Xihu Sag, and 8 samples from the Changjiang Depression, ECSSB. The sample collecting loca-

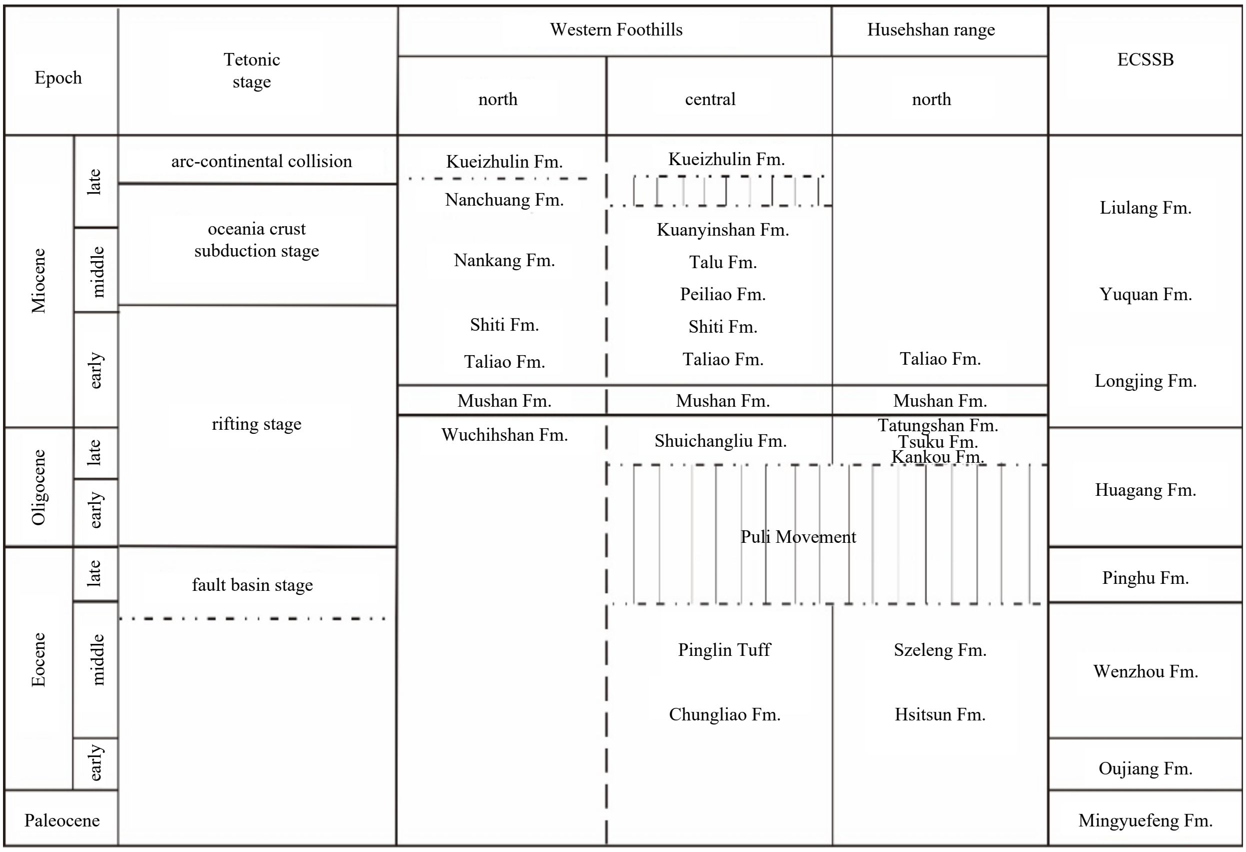

Fig. 2. Early Cenozoic strata of the studied area of Taiwan Island and the East China Sea Shelf Basin (ECSSB) (modified from Huang et al. (2012) and Zhu et al. (2019)).

tions are showed in Fig. 1. Experiments were conducted in the State Key Laboratory of Marine Geology, Tongji University, China. Rock slices were made from 34 samples to conduct petrological identification. The mineral identification and composition counting were based on the methods of Dickinson and Suczek (1979).

The zircon U-Pb age analysis was conducted on 26 Tsukeng samples, 8 northeast shoreline samples, together with 5 Xihu Sag and 2 Changjiang Depression samples. Zircons were pulverized and extracted with conventional magnetic and heavy liquid separation techniques in the laboratory of the Institute of Regional Geology and Mineral Resources, Hebei Province, China. After targeting and polishing, cathodoluminescence (CL) images of the samples were taken with analytical spots (30 μm) in oscillatory zoning. U-Pb isotopic dating was then conducted using laser ablation–inductively coupled plasma–mass spectroscopy (LA-ICP-MS) at the State Key Laboratory of Marine Geology, Tongji University, Shanghai, China, with a Thermo Elemental X-Series ICP-MS coupled to a New Wave 213 nm laser ablation system (Thermo Fisher Scientific, USA). Zircon ages were calculated by the ICPMSDataCal software combined with the common Pb correction (Liu et al., 2010) using a standard subset of both $\leqslant$10% discordance and $\leqslant$10% uncertainty (1σ). Finally, the age distribution patterns were presented by histograms and kernel density estimation plots (Vermeesch, 2012).

4 Results

4.1 *Petrological results*

Petrological identification of the Eocene–Miocene sandstones from Tsukeng and northeast shoreline of Taiwan Island is presented below.

Samples of the Eocene are mostly medium to fine grained, sub-angular to sub-rounded and medium sorted. Samples contain 80% grains and 15% matrix. Grains are composed of 70% quartz, 25% rock fragments and 5% feldspar, with calcsparite cement. Edge dissolution of grains is commonly seen. Among the rock fragments, the magma flint fragments dominate, while mud and metamorphic fragments are also found. Feldspars are mainly plagioclase, with distinct kaolinization. Furthermore, in the late Eocene samples, foraminifera fossils and glauconite were found (Fig. 3a).

Samples of the early Oligocene are mostly 100 μm grains, medium to well sorted, sub-angular to sub-rounded. They contain 67% grains, 30% matrix, with clay sparite cement. Grains are composed of 70% quartz, 28% rock fragments, and 2% feldspar. Edge dissolution of grains and secondary outgrowth of quartz are observed. Rock fragments are mainly magma flint, with some volcanic fragments and a spot of metamorphic fragments. The mud matrix accounts for about 30% (Fig. 3b).

Samples of the late Oligocene are mostly fine sand with 100 μm grains, well sorted, sub-angular to sub-rounded. Grains account for 80%–90% of the samples, dominated by quartz (70%). Rock fragments constitute 28% of the sandstones, mostly magma flint with some mud and metamorphic fragments. Samples are kaolinite-cemented. Autogenetic glauconite is commonly seen. Samples of this era experienced elevation of maturity (Fig. 3c).

Samples of the Miocene are mostly medium to fine grained, well sorted, sub-angular to sub-rounded, cemented with sericite and calcsparite. Samples contain 80%–90% grains, mainly quartz

(60%), with prevalent edge dissolution. Rock fragments account for about 35%, and mainly consist of magma flint, with rare mud and metamorphic fragments. Feldspar accounts for 5%, and comprises mostly orthoclase and plagioclase. Samples have abundant foraminifera and bivalve bioclasts, indicating a marine sedimentation environment (Fig. 3d).

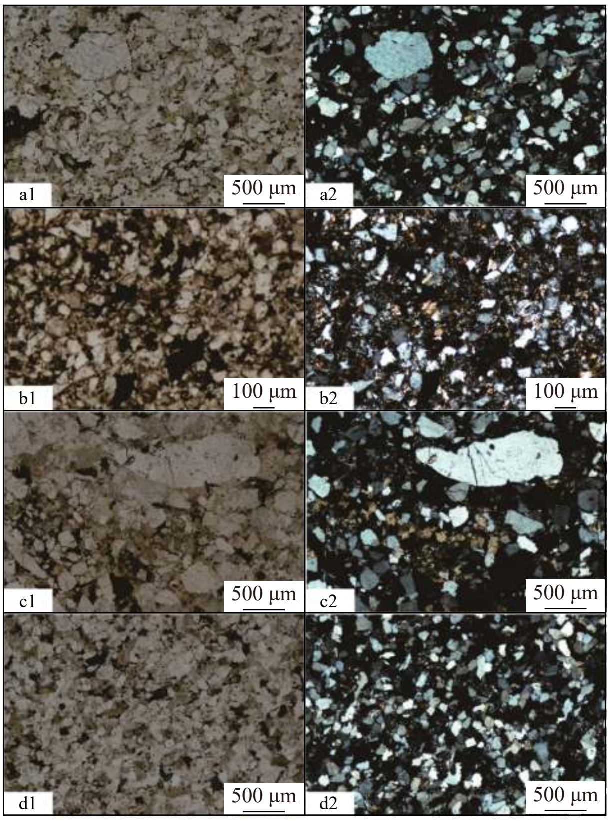

Fig. 3. Typical sediment slice of central and north Taiwan Island. a. Typical Eocene sediment sample (sample number CK09A); b. typical early Oligocene sediment sample (sample number DB15); c. typical late Oligocene sediment sample (sample number CK2); d. typical Miocene sediment sample (sample number DK05). 1 and 2 represent samples under plane-polarized light and crossed-polarized light separately.

Samples are generally defined as lithic sandstone or lithic quartz sandstone, with relatively medium to low maturity. There are no distinct differences between the sandstone compositions in both areas. In both areas, samples of the Miocene are lithic sandstone, showing the lowest maturity. Samples show dominant volcanic flint fragments and some mud fragments. Both areas show increasing proportions of volcanic flint fragments over time (Fig. 4).

4.2 *Zircon U-Pb age results*

Through the zircon U-Pb age analysis, the age of Tsukeng samples can be separated into two groups: Eocene and late Oligocene to Miocene (Fig. 5). The strata of the early Oligocene are missing due to the development of the breakup unconformity (Huang et al., 1997). All the zircon U-Pb age data show a concordance of 80% or more, and is further discussed in the provenance study.

In total, 6 samples (500 data points) were analyzed from the Eocene Tsukeng area. The age of zircons is concentrated at 0–500 Ma, while the peak at 122 Ma (Mesozoic Yanshanian) is particularly prominent, accounting for over 50%. Another distinct peak appears at 433 Ma (Caledonian). In general, the Eocene zircon age of this area is centralized and distributed, indicating a relatively unitary source of sediment input.

In the second group of Tsukeng samples, there are 9 samples (473 data points) from the late Oligocene, and 10 samples (870 data points) from the Miocene. The age spectrum features show great resemblance in these two epochs, and a distinct divergence from that of the Eocene. Zircons aged 0–500 Ma still dominated, with a peak at about 120 Ma. Peaks at 230 Ma (Indosinian) and about 420 Ma are easily seen. Apart from the Eocene, older zircons from the Jingningian and Luliang are augmented, with peaks at about 760 Ma and 1 870 Ma. Broadly speaking, the zircon age distribution changed relatively with the increase in content of older zircon, indicating the alteration of the sediment source area.

In the northeast shoreline, 2 samples (89 data points) from the Eocene and 2 samples (159 data points) from the early Oligocene were analyzed. The age spectra of those epochs share similar features, with a preponderance of 0–500 Ma zircons. In the Yanshanian, about 120 Ma zircons account for over 50% in the Eocene, with the prominence of the Caledonian 423 Ma zircons. In the early Oligocene, the Yanshanian 111 Ma zircons even

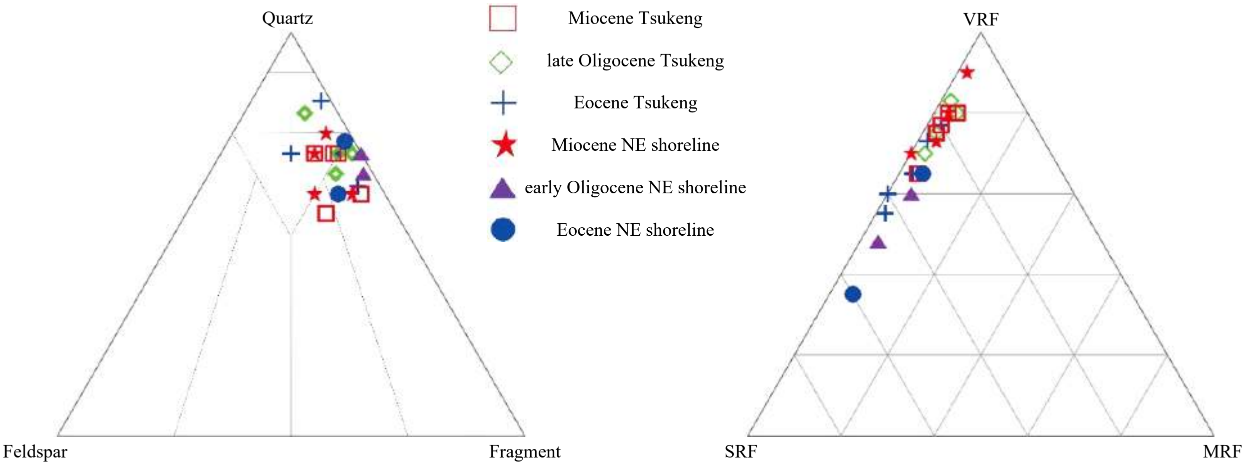

Fig. 4. Petrographic data of sandstone and rock fragments of Taiwan Island. VRF represents volcanic rock fragments; SRF represents sedimentary rock fragments; MRF represents metamorphic rock fragments.

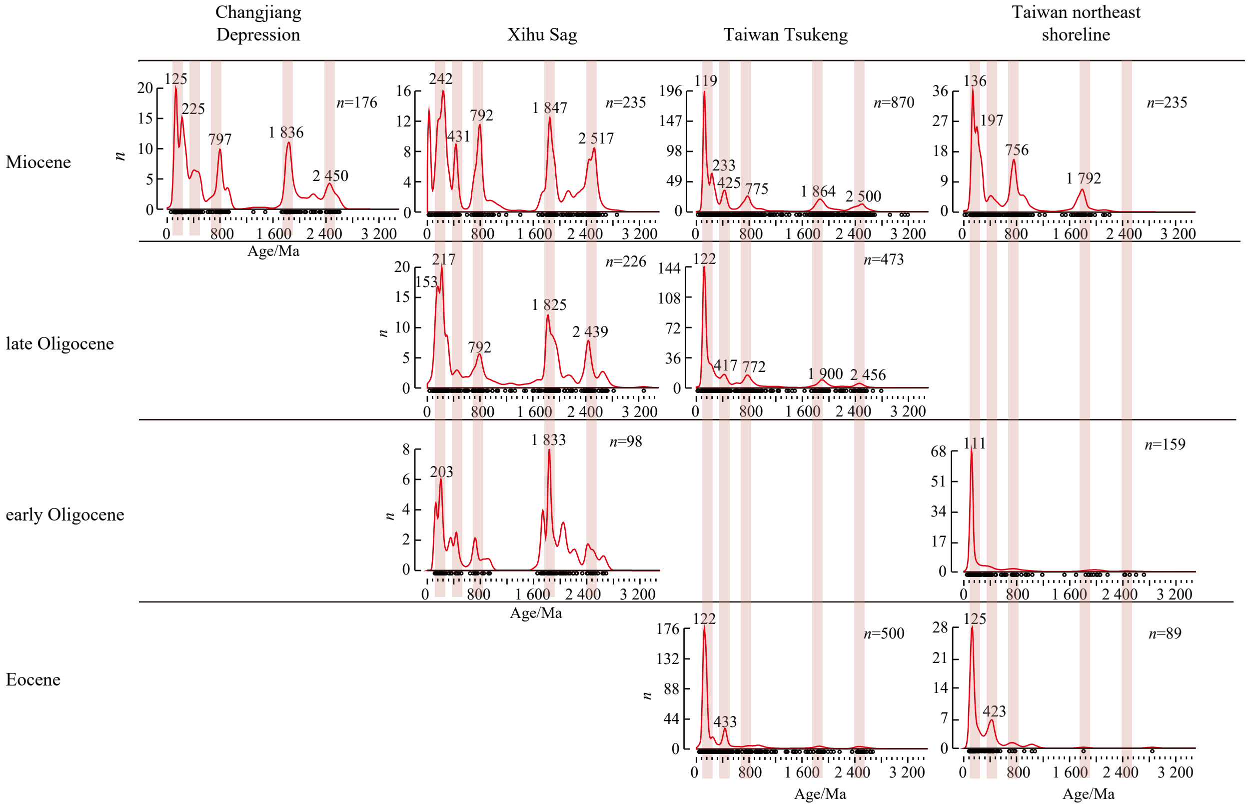

Fig. 5. Detrital zircon U-Pb age and its concord diagram of East China Sea Shelf Basin and Taiwan Island. *n* presents number of zircon grains.

reach over 80%.

The 4 samples (235 data points) from the Miocene northeast shoreline show a distinct divergence from that of the Eocene and early Oligocene. The Jingningian 756 Ma and Luliang 1 792 Ma peaks can be observed. Meanwhile, the Mesozoic zircons still outnumber the older zircons, with peaks of 136 Ma and 197 Ma. These features are consistent with the Tsukeng late Oligocene to Miocene zircon age spectrum. Older zircon input indicates the enlargement of the age distribution extent (Fig. 5).

The 5 samples of the Xihu Sag, 2 samples of the Changjiang Depression and 735 data points in total from the early Oligocene to Miocene showed relatively similar zircon age spectrum features. The most prominent peaks were at about 200 Ma (Indosinian) and 1 830 Ma (Luliang), with sub-protruding peaks at 800 Ma and 2 500 Ma. Samples from the Miocene showed a relatively broader distribution of zircon ages. Additionally, disparate from the Xihu Sag, 125 Ma Yanshanian zircons were dominant in the Changjiang Depression. Zircons from both areas showed remarkable differences from Taiwan Island, as far more pre-Cambrian zircons were recorded (Fig. 5).

5 Discussion

5.1 *Sediementary environment study*

The sedimentary environment of Eocene Taiwan Island consisted of a braided river-swamp, with shallow and relatively dynamic water, indicating the continental facies. The late Oligocene strata contained glauconite grains and marine fossils, indicating a transformation from continental to marine facies. The sea level rose further after the early Miocene, resulting in neritic-half pelagic sediments and carbonate deposition in some areas (Fig. 6).

The numerous volcanic siliceous fragments in the sandstones indicate the near source transportation from volcanic rocks in the Eocene. Subsequently in the late Oligocene, the roundness and sorting show a distinct amelioration, yet the maturity somehow worsened in the Miocene as the content of feldspar and volcanic fragments increased. At the same time, the proportion of volcanic fragments gradually increased, indicating that a certain degree of drainage basin area expansion could have occurred. However, despite the overall amelioration of sediment maturity, a considerable number of volcanic fragments were present. Therefore, near-source sediment transport from adjacent volcanic rocks was dominant instead of long-distance transportation.

The zircon U-Pb age spectrum diagrams show that in Eocene and Oligocene Taiwan Island, the Phanerozoic zircons, especially the Yanshanian zircons, predominated, while the pre-Cambrian zircons were relatively rare. The volcanic rocks formed from the Permian to Cretaceous and were widely distributed in coastal South China (Sun, 2006), showing a gradual aging trend in the inland direction (Li, 2000; Zhou and Li, 2000; Zhou et al., 2006; Li and Li, 2007). The U-Pb age of coastal river zircons in South China shows that the modern river in Cathaysia mainly deposited Yanshanian, Indosinian and Caledonian sediments, with the absence of Neoproterozoic or older material (Xu et al., 2007; Lan et al., 2016). This greatly corresponded with the zircon age in Eocene and early Oligocene Taiwan Island (Fig. 7). Due to the presence of volcanic fragments in sandstones and the low maturity of sedimentation, it could be inferred that the Mesozoic Taiwan Island sediments were sourced from the volcanic rocks of

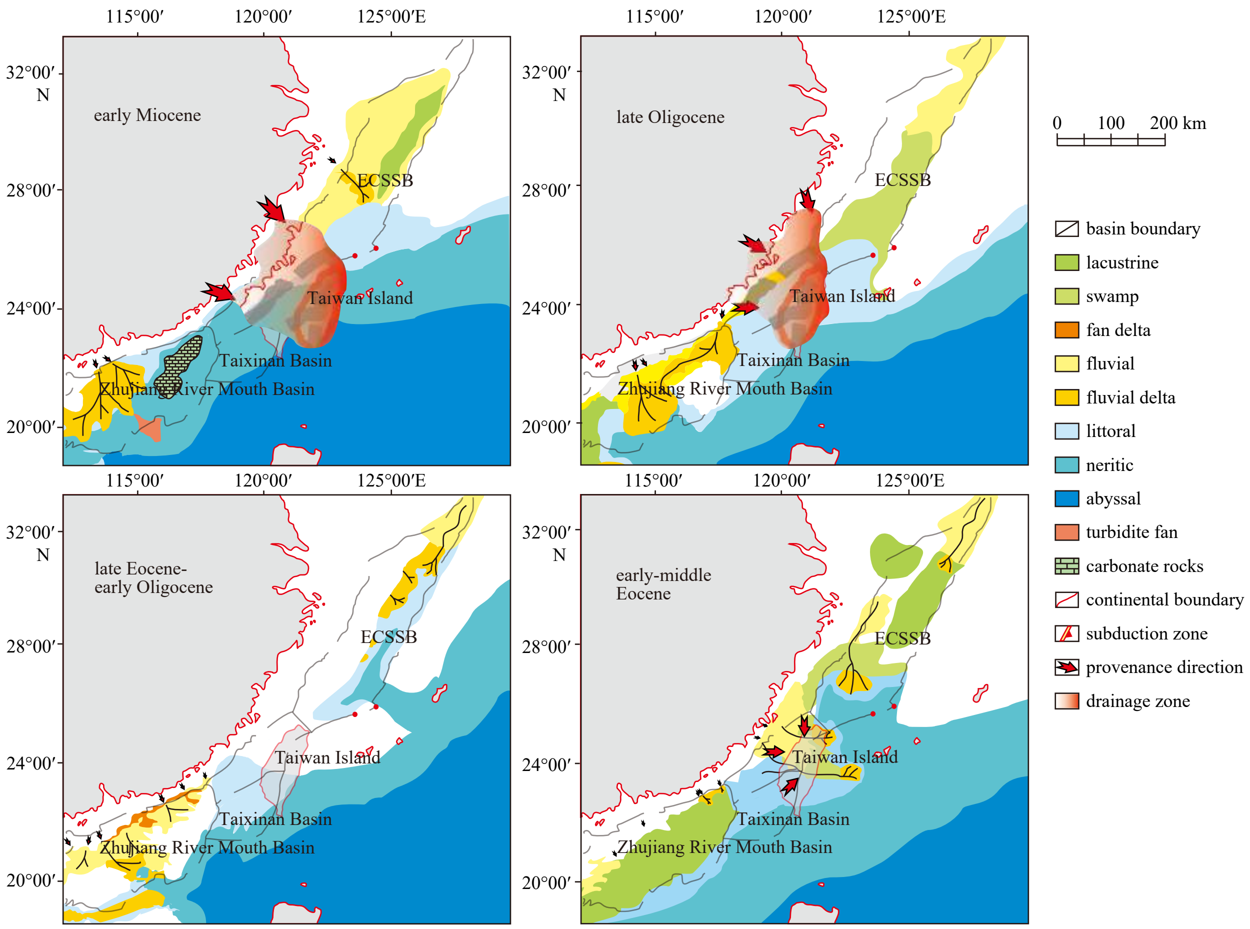

Fig. 6. Brief development pattern of the early Cenozoic sedimentary facies and source transportation of Taiwan Island, East China Sea Shelf Basin (ECSSB) and north the South China Sea (SCS) showing (1) transformation of ECSSB's sedimentary environment from separated lacustrine facies to wide-spread fluvial facies; (2) transformation of Taiwan Island's sedimentary environment from continental to marine facies; (3) transformation of Taiwan Island's provenance from *in situ* deposition to short-distance transportation. The data source from Wang and Zhu (1992) and Zhu et al. (2019). The wells of Taixinan Basin includ CFC-10, CFC-16, CFD-1, CFM-1, CFS-2, DP-21, CIT-1, CJA-1, PK-1, and seismic data are from CNOOC Ltd., Shenzhen.

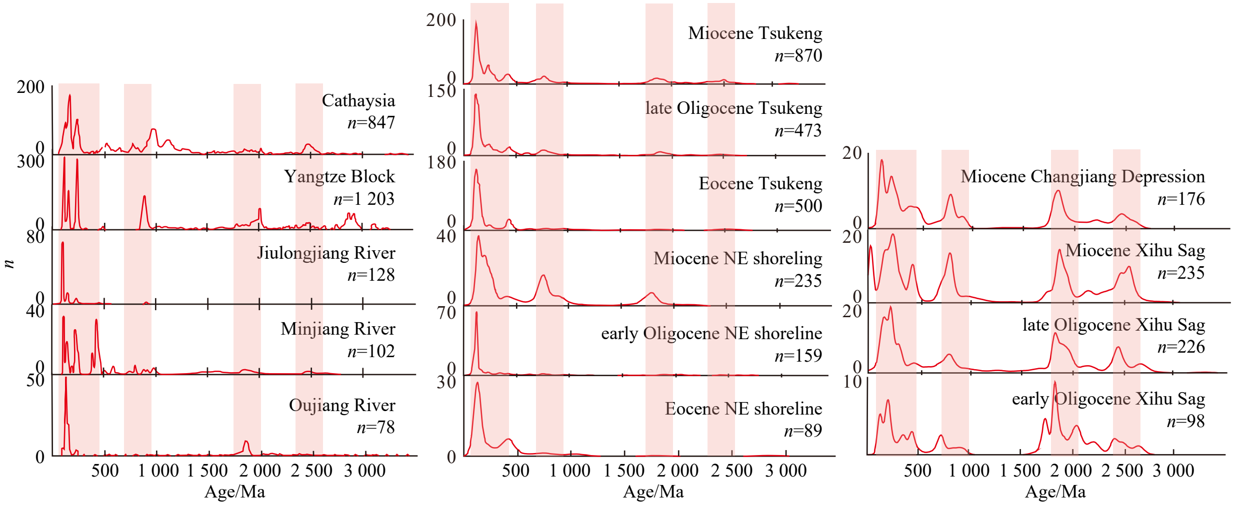

Fig. 7. Detrital zircon U-Pb age comparison among Taiwan Island, East China Sea Shelf Basin and the potential source area. Data of Cathaysia are from Yao et al. (2011) and Xu et al. (2014); data of Yangtze Block are from Wang and Fan (2013); data of Jiulongjiang, Minjiang and Oujiang rivers are from Zhang et al. (2017). n presents number of zircon grains.

that era in South China. The transportation is nearly *in situ*, as evidenced by the poor maturity and Mesozoic granites distributed along the shoreline (Sun, 2006). Coastal rivers like the Jiulongjiang and Minjiang rivers could also provide limited sediments (Fig. 7).

It is worth noting that in Tsukeng, the pre-Cambrian zircons multiplied after the late Oligocene, marking the shift in the sediment source. Some hypotheses stated that the sediments may be derived from inland China or the Yangtze Block, or from the Changjiang River source (Deng et al., 2017b; Zhang et al., 2014). The prominent 760 Ma Jingningian peak could correspond to the breakup of Rodinia (Li et al., 2005) or the joining of the paleo-Yangtze Block and Cathaysia (Wang et al., 2010). However, in this study, several zircon age inconsistencies have been recorded between the Taiwan Island sediments and Cathaysia interior. The peak of Jingningian at about 760 Ma was posterior to the prominent 950 Ma peak in Cathaysia, 958 Ma peak in the east Indochina Block (Annamite Mountain) (Usuki et al., 2009), and 800–840 Ma peak in the Yangtze Block (Yang et al., 2018). The 750 Ma peak appeared as a secondary peak in the Cathaysia and Yangtze Block zircon age diagram, while the 950 Ma or 840 Ma peak was not found in the Taiwan Island sediments. Meanwhile, 2 500 Ma zircon was not recorded in the northeast shoreline. Moreover, despite the record of Proterozoic and Archean zircon in the interior of Cathaysia (Wan et al., 2007; Yao et al., 2011), the modern coastal rivers in the Fujian and Zhejiang provinces generally recorded fewer such zircons. Together with the low maturity and absence of evidence supporting the existence of a large river originating from the Cathaysia or Yangtze Block interior, it does not seem reasonable to assert that the Taiwan Island sediments were influenced by inland material since the late Oligocene.

5.2 *Source-to-sink system*

The Changjiang River has a vast drainage basin and wide distribution of zircon age, which is consistent with that of the late Oligocene–Miocene Taiwan Island (Zheng et al., 2013; Wang and Fan, 2013). Hence, some hypotheses assume that the Changjiang River acted as an important sediment source at that time (Deng et al., 2017b; Zhang et al., 2014, 2017; Wang et al., 2018), with sediments being transported through ocean currents to reach Taiwan Island or northeast SCS. However, the low maturity of sand from this study contradicted this long-distance transportation. Besides, recent assumptions consider that the Changjiang River's east-west passing trough had not completed until the late Pliocene to early Pleistocene (Fan et al., 2005; Jia et al., 2010; Yuan et al., 2012), while the Proterozoic volcanic rocks mainly emerged at the southwest Yangtze block and joined Cathaysia (Yuan, 1996). As for the ECSSB, samples from two sites show great distinction from the data of Taiwan Island as pre-Cambrian zircons are significantly numerous (Fig. 7). Faint disparity from the early Oligocene to Miocene in the Xihu Sag could not record the potential influence of the Changjiang River material input. These old zircons could be derived from the ECSSB basement (Yang et al., 2006) as Proterozoic or older rocks have been recorded in the Diaoyudao Island, Fujian-Zhejiang and Hupijiao Uplifts in WDB (Yang et al., 2006; Li et al., 1995; Zhang et al., 2018). Moreover, the Xihu Sag was an important depocenter in the Eocene–Oligocene (Zhang et al., 2018; Wu et al., 2017), with sediments coming in from the west and north. There is no evidence indicating the sediment transport across the Xihu Sag and Diaobei Sag or re-erosion from sediments in the Xihu Sag (Wang et al., 2018). Hence, more information and data are required to affirm the Changjiang River-transported hypothesis.

Meanwhile, studies showed the existence of a similar Proterozoic peak of zircon U-Pb age in Zhujiang River Mouth Basin samples (Shao et al., 2016), whereas the inland sediments containing older zircons were not deposited inside the basin until Miocene (Shao et al., 2008, 2019). Hence, the Zhujiang River could not influence the source transition of late Oligocene–Miocene Taiwan Island.

With the expanding zircon age distribution and increasing volcanic flint fragments in the sandstone, we can assume that from the late Oligocene, the drainage basin of source transportation extended to a larger area of the surrounding Mesozoic volcanic rocks (Fig. 6). The fewer pre-Cambrian zircons recorded in the Minjiang River zircon age spectrum and sporadic distribution of the pre-Cambrian rocks in the Lishui Sag and Diaoyudao Uplift (Li et al., 1995; Li et al., 2000; Wang et al., 2014) could have contributed to the old zircon in late Oligocene to Miocene Taiwan Island samples. Dominant Mesozoic zircons and fewer pre-Cambrian zircons greatly corresponded with the age spectrum of late Oligocene to Miocene Taiwan Island samples. Admittedly, more work for this particular model of source development is required.

6 Conclusion

This study analyzes the Eocene–Miocene sediments from Tsukeng, Nantou, middle Taiwan Island, northeast shoreline area of Taiwan Island, the Changjiang Depression, and the Xihu Sag by conducting petrological and detrital zircon U-Pb age analysis. New findings about the sediment composition and source development are as follows:

(1) Taiwan Island experienced a transition from continental facies in the Eocene to marine facies since the late Oligocene.

(2) Sediments of Eocene–Miocene Taiwan Island contain abundant volcanic fragments in sandstones, showing relatively low maturity. Detrital zircon U-Pb age spectrums of Taiwan Island show that both areas had a similar source development pattern. In the Eocene–early Oligocene, the sediment source was relatively singular, as the zircon age was concentrated in Yanshanian while pre-Cambrian zircons were extremely rare. After the late Oligocene, older zircons from Jingningian and Luliang were recorded, indicating a more complex sediment source. Age spectrums of the ECSSB were distinct from that of Taiwan Island as the proportion of older zircon was higher. However, little variation was observed between different eras in ECSSB samples.

(3) Taiwan Island sediments might have experienced a shift of provenance from nearly *in situ* deposition in the Eocene to limited transportation from the surrounding volcanic rocks in the late Oligocene to Miocene. Coastal river sediments and sporadic pre-Cambrian rocks in the ECSSB basement might have contributed to the expansion of the zircon age distribution.

References

Cao Licheng, Shao Lei, Qiao Peijun, et al. 2018. Early Miocene birth of modern Pearl River recorded low-relief, high-elevation surface formation of SE Tibetan Plateau. Earth and Planetary Science Letters, 496: 120–131, doi: 10.1016/j.epsl.2018.05.039

Chen Chenghong, Lee C, Lin Jianwei, et al. 2019. Provenance of sediments in western Foothills and Hsuehshan Range (Taiwan): A new view based on the EMP monazite versus LA-ICPMS zircon geochronology of detrital grains. Earth-Science Reviews, 190: 224–246, doi: 10.1016/j.earscirev.2018.12.015

Clark M K, Schoenbohm L M, Royden L H, et al. 2004. Surface uplift, tectonics, and erosion of eastern Tibet from large-scale drainage patterns. Tectonics, 23(1): TC1006

Cui Yuchi, Shao Lei, Qiao Peijun, et al. 2019. Upper Miocene-Pliocene provenance evolution of the central canyon in northwestern South China Sea. Marine Geophysical Research, 40(2): 223–235, doi: 10.1007/s11001-018-9359-2

Cukur D, Horozal S, Lee G H, et al. 2011. Structural evolution of the northern East China Sea Shelf Basin interpreted from cross-section restoration. Marine Geophysical Research, 32(3): 363–381, doi: 10.1007/s11001-011-9114-4

Deng Kai, Yang Shouye, Bi Lei. 2017a. Reply to comment by Yonghang Xu on “Detrital zircon geochronology of river sands from Taiwan: Implications for sedimentary provenance of Taiwan and its source link with the east China mainland”. Earth-Science Reviews, 168: 235–239, doi: 10.1016/j.earscirev.2017.03.009

Deng Kai, Yang Shouye, Li Chao, et al. 2017b. Detrital zircon geochronology of river sands from Taiwan: Implications for sedimentary provenance of Taiwan and its source link with the east China mainland. Earth-Science Reviews, 164: 31–47, doi: 10.1016/j.earscirev.2016.10.015

Dickinson W R, Suczek C A. 1979. Plate tectonics and sandstone compositions. AAPG Bulletin, 63(12): 2164–2182

Fan Daidu, Li Congxian, Yokoyama K, et al. 2005. Monazite age spectra in the Late Cenozoic of the Changjiang Delta and its implication on the Changjiang run-through time. Science in China Ser. D Earth Sciences, 48(10): 1718–1727, doi: 10.1360/01YD0447

Hall R. 1996. Reconstructing Cenozoic SE Asia. In: Hall R, Blundell D, eds. Tectonic Evolution of Southeast Asia. London: The Geological Society of London, 106(1): 153–184

Hu Xiumian, Garzanti E, Moore T, et al. 2015. Direct stratigraphic dating of India-Asia collision onset at the Selandian (middle Paleocene, 59±1 Ma). Geology, 43(10): 859–862, doi: 10.1130/G36872.1

Huang Chi-Yue, Shea K H, Li Qianyu. 2017. A foraminiferal study on Middle Eocene-Oligocene break-up unconformity in northern Taiwan and its correlation with IODP Site U1435 to constrain the onset event of South China Sea opening. Journal of Asian Earth Sciences, 138: 439–465, doi: 10.1016/j.jseaes.2016.09.014

Huang Chi-Yue, Wu Weiyu, Chang Chungpai, et al. 1997. Tectonic evolution of accretionary prism in the arc-continent collision terrane of Taiwan. Tectonophysics, 281(1–2): 31–51, doi: 10.1016/S0040-1951(97)00157-1

Huang Chi-Yue, Yen Yi, Zhao Quanhong, et al. 2012. Cenozoic stratigraphy of Taiwan: Window into rifting, stratigraphy and paleoceanography of South China Sea. Chinese Science Bulletin, 57(24): 3130–3149, doi: 10.1007/s11434-012-5349-y

Huang Chi-Yue, Yuan P B, Lin C W, et al. 2000. Geodynamic processes of Taiwan arc-continent collision and comparison with analogs in Timor, Papua New Guinea, Urals and Corsica. Tectonophysics, 325(1-2): 1–21, doi: 10.1016/S0040-1951(00)00128-1

Jia Juntao, Zheng Hongbo, Huang Xiangtong, et al. 2010. Detrital zircon U-Pb ages of late Cenozoic sediments from the Yangtze delta: Implication for the evolution of the Yangtze River. Chinese Science Bulletin, 55(15): 1520–1528, doi: 10.1007/s11434-010-3091-x

Jin Bingfu, Lin Xiaotong, Ji Fuwu. 2005. Sediments of upper Pleistocene in core Q43 north of Diaoyu Island in the East China Sea. Marine Geology & Quaternary Geology (in Chinese), 25(1): 25–31

Lan Qing, Yan Yi, Huang Chi-Yue, et al. 2016. Topographic architecture and drainage reorganization in Southeast China: Zircon U-Pb chronology and Hf isotope evidence from Taiwan. Gondwana Research, 36: 376–389, doi: 10.1016/j.gr.2015.07.008

Li Bingfu, Jiao Xiangheng, Liu Baohua. 1995. Discuss on seismic reflection features of volcanic rocks, Diaoyudao uplift, East China Sea. Oil Geophysical Prospecting (in Chinese), 30(S2): 150–154

Li Guiqun, Li Xuelun. 1995. Geological tectonic characteristics of the outer margin upwarped zone of the East China Sea shelf. Journal of Ocean University of Qingdao (in Chinese), 5(2): 199–205

Li Peilian, Hou Hongbin, Ma Huifu. 2000. Tectonics and Petroleum potential of the East China Sea Shelf Rift Basin. Acta Geologica Sinica, 74(3): 651–660

Li Wuxian, Li Xianhua, Li Zhengxiang. 2005. Neoproterozoic bimodal magmatism in the Cathaysia Block of South China and its tectonic significance. Precambrian Research, 136(1): 51–66, doi: 10.1016/j.precamres.2004.09.008

Li Xianhua. 2000. Cretaceous magmatism and lithospheric extension in Southeast China. Journal of Asian Earth Sciences, 18(3): 293–305, doi: 10.1016/S1367-9120(99)00060-7

Li Xianhua, Wei Gangjian, Shao Lei, et al. 2003. Geochemical and Nd isotopic variations in sediments of the South China Sea: a response to Cenozoic tectonism in SE Asia. Earth and Planetary Science Letters, 211(3–4): 207–220, doi: 10.1016/S0012-821X(03)00229-2

Li Zhengxiang, Li Xianhua. 2007. Formation of the 1300-km-wide intracontinental orogen and postorogenic magmatic province in Mesozoic South China: A flat-slab subduction mode. Geology, 35(2): 179–182, doi: 10.1130/G23193A.1

Liu Yongsheng, Gao Shan, Hu Zhaochu, et al. 2010. Continental and oceanic crust recycling-induced melt-Peridotite interactions in the Trans-North China Orogen: U-Pb dating, Hf isotopes and trace elements in zircons from mantle xenoliths. Journal of Petrology, 51(1–2): 537–571, doi: 10.1093/petrology/egp082

Shao Lei, Cao Licheng, Pang Xiong, et al. 2016. Detrital zircon provenance of the Paleogene syn-rift sediments in the northern South China Sea. Geochemistry, Geophysics, Geosystems, 17(2): 255–269, doi: 10.1002/2015GC006113

Shao Lei, Cui Yuchi, Stattegger K, et al. 2019. Drainage control of Eocene to Miocene sedimentary records in the southeastern margin of Eurasian Plate. GSA Bulletin, 131(3–4): 461–478, doi: 10.1130/B32053.1

Shao Lei, Pang Xiong, Qiao Peijun, et al. 2008. Sedimentary Filling of the Pearl River Mouth Basin and its response to the evolution of the Pearl River. Acta Sedimentologica Sinica (in Chinese), 26(2): 179–185

Shao Lei, You Hongqing, Hao Hujun, et al. 2007. Petrology and depositional environments of Mesozoic strata in the Northeastern South China Sea. Geological Review (in Chinese), 53(2): 164–169

Sharp W D, Clague D A. 2006. 50-Ma initiation of Hawaiian-emperor bend records major change in Pacific plate motion. Science, 313(5791): 1281–1284, doi: 10.1126/science.1128489

Sun Tao. 2006. A new map showing the distribution of granites in South China and its explanatory notes. Geological Bulletin of China (in Chinese), 25(3): 332–335

Suo Yanhui, Li Su, Zhao Shujuan, et al. 2015. Continental margin basins in East Asia: tectonic implications of the Meso-Cenozoic East China Sea pull-apart basins. Geological Journal, 50(2): 139–156, doi: 10.1002/gj.2535

Suppe J. 1984. Kinematics of arc-continent collision, flipping of subduction, and back-arc spreading near Taiwan. Memoir of the Geological Society of China, 6: 21–33

Usuki T, Lan C Y, Yui T F, et al. 2009. Early Paleozoic medium-pressure metamorphism in central Vietnam: evidence from SHRIMP U-Pb zircon ages. Geosciences Journal, 13(3): 245–256, doi: 10.1007/s12303-009-0024-2

Vermeesch P. 2012. On the Visualisation of detrital age distributions. Chemical Geology, 312–313: 190–194, doi: 10.1016/j.chemgeo.2012.04.021

Wan Yusheng, Liu Dunyi, Xu Meihui, et al. 2007. SHRIMP U-Pb zircon geochronology and geochemistry of metavolcanic and metasedimentary rocks in Northwestern Fujian, Cathaysia block, China: Tectonic implications and the need to redefine lithostratigraphic units. Gondwana Research, 12(1–2): 166–183, doi: 10.1016/j.gr.2006.10.016

Wang Chengshan, Li Xianghui, Hu Xiumian, et al. 2002. Latest marine horizon north of Qomolangma (Mt Everest): implications for closure of Tethys seaway and collision tectonics. Terra Nova, 14(2): 114–120, doi: 10.1046/j.1365-3121.2002.00399.x

Wang Guochun, Zhu Weilin. 1992. Cenozoic sedimentary environment in East China Sea Basin. Acta Sedimentologica Sinica (in Chinese), 10(2): 100–108

Wang Pinxian. 2004. Cenozoic deformation and the history of sea-land interactions in Asia. In: Clift P, Kuhnt W, Wang Pinxian, et al, eds. Continent-Ocean Interactions within East Asian Marginal Seas. Washington: American Geophysical Union, 1–22

Wang Qiang, Wyman D A, Li Zhengxiang, et al. 2010. Petrology, geochronology and geochemistry of ca. 780 Ma A-type granites in South China: Petrogenesis and implications for crustal growth during the breakup of the supercontinent Rodinia. Precambrian Research, 178(1–4): 185–208

Wang Wei, Bidgoli T, Yang Xianghua, et al. 2018. Source-to-sink links between East Asia and Taiwan from detrital zircon geochronology of the oligocene Huagang formation in the East China Sea Shelf Basin. Geochemistry, Geophysics, Geosystems, 19(10): 3673–3688, doi: 10.1029/2018GC007576

Wang Yangyang, Fan Daidu. 2013. U-Pb ages and Hf Isotopic composition of crystalline zircons from igneous rocks of the Changjiang drainage basin and their implications for provenance. Marine Geology & Quaternary Geology, 33(5): 97–118

Wang Zhangshi, Zhu Weilin, Chen Chunfeng, et al. 2014. Basement lithology and distribution of Lishui-Jiaojiang Cenozoic Sag in East China Sea. Journal of Tongji University (Natural Science) (in Chinese), 42(4): 636–644

Wu Jiapeng, Zhang Lan, Wan Lifen, et al. 2017. Provenance analysis of Pinghu Formation in Xihu sag. China Petroleum Exploration (in Chinese), 22(2): 50–57

Xu Xisheng, O’Reilly S Y, Griffin W L, et al. 2007. The crust of Cathaysia: Age, assembly and reworking of two terranes. Precambrian Research, 158(1–2): 51–78, doi: 10.1016/j.precamres.2007.04.010

Xu Yonghang, Sun Qinqin, Yi Liang, et al. 2014. Detrital zircons U-Pb age and Hf isotope from the western side of the Taiwan Strait: Implications for sediment provenance and crustal evolution of the northeast Cathaysia block. Terrestrial, Atmospheric and Oceanic Sciences, 25(4): 505–535, doi: 10.3319/TAO.2014.02.18.01(TT)

Yang Xianghua, Li Anchun, Qin Yunshan, et al. 2006. U-P dating of zircons from Cenozoic sandstone: constrain on the geodynamic setting of East China Sea Shelf Basin. Marine Geology & Quaternary Geology (in Chinese), 26(3): 75–86

Yang Zhenning, Yang Kunguang, Polat A, et al. 2018. Early crustal evolution of the eastern Yangtze Block: Evidence from detrital zircon U-Pb ages and Hf isotopic composition of the Neoproterozoic Huashan Group in the Dahongshan area. Precambrian Research, 309: 248–270, doi: 10.1016/j.precamres.2017.05.011

Yao Jinlong, Shu Liangshu, Santosh M. 2011. Detrital zircon U-Pb geochronology, Hf-isotopes and geochemistry—New clues for the Precambrian crustal evolution of Cathaysia Block, South China. Gondwana Research, 20(2–3): 553–567, doi: 10.1016/j.gr.2011.01.005

Ye Jiaren, Qing Hairuo, Bend S L, et al. 2007. Petroleum systems in the offshore Xihu Basin on the continental shelf of the East China Sea. AAPG Bulletin, 91(8): 1167–1188, doi: 10.1306/02220705158

Yuan Shengyuan, Li Chang’an, Zhang Yufeng, et al. 2012. Trace element characteristics of sediments in Jianghan Basin: Implications for expansion of the upper reaches of the Yangtze River. Geology in China (in Chinese), 39(4): 1042–1048

Yuan Xuecheng. 1996. Atlas of Geophysics in China (in Chinese). Beijing: Geological Publishing House

Zhang Guohua, Li Sanzhong, Suo Yanhui, et al. 2016. Cenozoic positive inversion tectonics and its migration in the East China Sea Shelf Basin. Geological Journal, 51(S1): 176–187, doi: 10.1002/gj.2809

Zhang Hao, Shao Lei, Zhang Gongcheng, et al. 2020. The response of Cenozoic sedimentary evolution coupled with the formation of the South China Sea. Geological Journal, 55(10): 6989–7010, doi: 10.1002/gj.3856

Zhang Jingyu, Lu Yongchao, Krijgsman W, et al. 2018. Source to sink transport in the Oligocene Huagang Formation of the Xihu Depression, East China Sea Shelf Basin. Marine and Petroleum Geology, 98: 733–745, doi: 10.1016/j.marpetgeo.2018.09.014

Zhang Xinchang, Huang Chi-Yue, Wang Yuejun, et al. 2017. Evolving Yangtze River reconstructed by detrital zircon U-Pb dating and petrographic analysis of Miocene marginal Sea sedimentary rocks of the Western Foothills and Hengchun Peninsula, Taiwan. Tectonics, 36(4): 634–651, doi: 10.1002/2016TC004357

Zhang Xinchang, Yan Yi, Huang Chi-Yue, et al. 2014. Provenance analysis of the Miocene accretionary prism of the Hengchun Peninsula, southern Taiwan, and regional geological significance. Journal of Asian Earth Sciences, 85: 26–39, doi: 10.1016/j.jseaes.2014.01.021

Zheng Hongbo, Clift P D, Wang Ping, et al. 2013. Pre-Miocene birth of the Yangtze River. Proceedings of the National Academy of Sciences of the United States of America, 110(19): 7556–7561, doi: 10.1073/pnas.1216241110

Zhou Xinmin, Li Wuxian. 2000. Origin of Late Mesozoic igneous rocks in Southeastern China: implications for lithosphere subduction and underplating of mafic magmas. Tectonophysics, 326(3-4): 269–287, doi: 10.1016/S0040-1951(00)00120-7

Zhou Xinmin, Sun Tao, Shen Weizhou, et al. 2006. Petrogenesis of Mesozoic granitoids and volcanic rocks in South China: A response to tectonic evolution. Episodes, 29(1): 26–33, doi: 10.18814/epiiugs/2006/v29i1/004

Zhou Zuyi, Jiang Jianyi, Liao Zongting, et al. 2001. Basin inversion in Xihu depression, East China Sea. Gondwana Research, 4(4): 844–845, doi: 10.1016/S1342-937X(05)70627-4

Zhu Weilin, Zhong Kai, Fu Xiaowei, et al. 2019. The formation and evolution of the East China Sea Shelf Basin: a new view. Earth-Science Reviews, 190: 89–111, doi: 10.1016/j.earscirev.2018.12.009