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Miocene Provenance Changes in Taiwan Caused by Southward Input of Sediments From East China Sea Basin

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The Cenozoic sediments in marginal basins of East Asia ultimately reflected coupling between the tectonics, landscape evolution, and drainage reorganization. Recently, the provenance of Miocene sediments in the East China Sea Basin (ECSB) and Taiwan has been in hot debate, and several models were proposed to interpret the provenance changes. Most of them are related to river reorganization in East Asia and highly relied on detrital zircon U-Pb dating. In this study, a large number of detrital zircon U-Pb ages of Miocene sediments from the ECSB, Taiwan region, and the potential source areas have been compiled for quantitative provenance analysis. The results suggested that all the early–middle Miocene sediments in Taiwan and the ECSB were closely linked to North China and the Korean Peninsula. Over 80% sediments in Taiwan were delivered from the ECSB whose sediments were predominantly contributed by North China and the Korean Peninsula (70%). However, for the late Miocene to Quaternary sediments in the ECSB, the contribution of the Yangtze River system was 72%, which indicates distinct reorganization of river networks and initial formation of the Yangtze River in the late Miocene. The quantitative provenance analysis together with southward environmental changes from dominantly fluvial sediments in the northern and middle ECSB to shallow marine sediments in Taiwan region suggested that the early–middle Miocene sediments of Taiwan were mainly sourced from the North China and the Korean Peninsula by passing the ECSB. Thus, these sediments in Taiwan region would experience the river–delta–shallow marine route from the ECSB to Taiwan region.

Keywords: Taiwan region, East China Sea Basin, detrital zircon age, Yangtze River (Changjiang River), Miocene provenance changes

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INTRODUCTION

The Cenozoic East Asia has experienced great tectonic movement, especially the uplift of Tibetan Plateau by India–Asia collision and the subsidence of East Asia margin associated with evolving of numerous rift basins, followed by contrasting topography and climatic changes and reorganization of continental river networks (Wang, 2004; Zheng, 2015) (**Figure 1**). The sedimentary record in marginal basins was believed to ultimately reflect the coupling between these deep earth and surface processes (Clift, 2006; Richardson et al., 2010).

As one of the ultimate destination of sediments derived from the Tibetan Plateau, the East China margin might preserve crucial evidence associated with the links between Tibetan Plateau and the sea. Recently, the provenance of Miocene sediments of the East China Sea Basin (ECSB) and Taiwan has attracted great interest and been in hot debate. A sharp provenance change was recognized at the

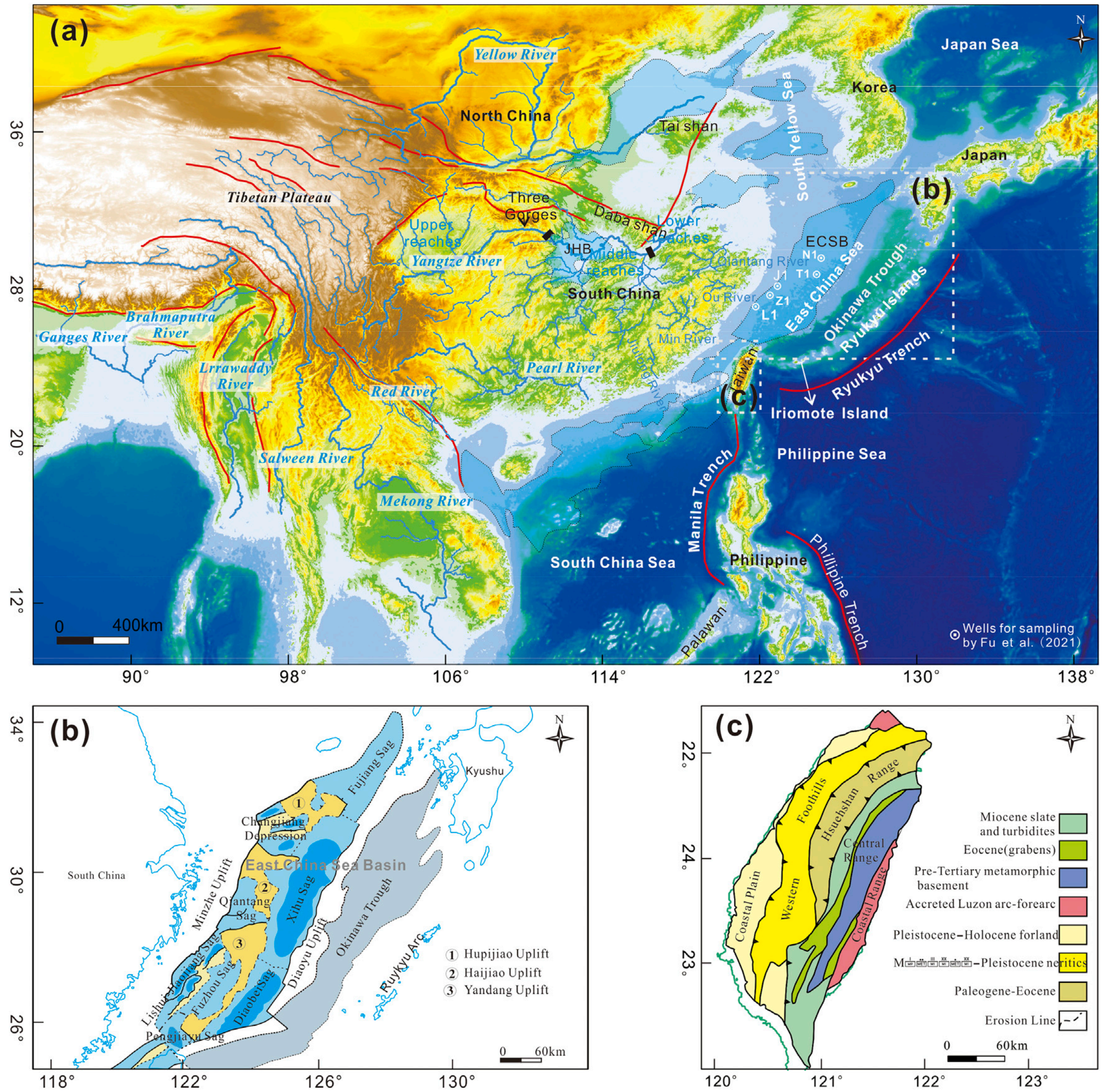

FIGURE 1 | (A) Topographic map of East Asia showing major basins and rivers. **(B)** Tectonic sketch of the East China Sea Basin (modified from Zhu et al., 2019). **(C)** Tectonic framework of Taiwan (modified from Huang et al., 2012). The basins are modified from Ren et al. (2002). ECSB, East China Sea Basin; JHB, Jianghan Basin.

beginning of the Miocene in the Taiwan region that the provenance of western foothills of Taiwan changed from the adjacent South China to new source areas characterized by an obvious increase in old zircon ages (Lan et al., 2014; Deng et al., 2017; Zhang et al., 2017; Chen et al., 2019). Lan et al. (2016) claimed that an enlarged paleo-Min River that extended to the Yangtze Block contributed to this change. Zhang et al. (2017) proposed that this provenance change was caused by the establishment of the Yangtze River, and Deng et al. (2017) suggested the North China Craton (NCC) also supplied detritus. In contrast to these large-scale drainage reorganization models, most recently, Chen et al. (2019) suggested that an unknown macroblock that collided with the Asian margin and now covered by thick sediments resulted in this change. Wang et al. (2018) noticed the similarities between Miocene sediments in western Taiwan and Oligocene sediments in Xihu Sag, one of the subordinate subsiding centers in the ECSB, and suggested that erosion and reworking of these Oligocene sediments were responsible for the Miocene provenance changes in western Taiwan.

Although some authors agreed with the view that Miocene sediments in Taiwan were closely linked with the contemporaneous sediments of the ECSB, the routes for sediment derived from the ECSB to paleo-Taiwan region are also under debate. Deng et al. (2017) suggested that longshore current played an important role in sediment transport from shallow marine environments of the east of the present Yangtze Delta to the Taiwan region. Xu et al. (2007) argued that the transport ability of a longshore current is limited. Zhang et al. (2017) and Zhang et al. (2021a) preferred river transport along the ECSB.

Although several different methods have been applied to trace the Miocene provenance change in Taiwan region (Lan et al., 2014; Lan et al., 2016; Chen et al., 2019), the most powerful and widely used one is the detrital zircon U-Pb dating that clearly shows obvious increase in the proportion of zircon grains with ages peaking at 220, 1800, and 2,500 Ma (Lan et al., 2016; Zhang et al., 2017). Advances in quantitative and statistical provenance analysis of detrital zircon U-Pb dating (Vermeesch et al., 2016; Sundell and Saylor, 2017), especially inverse Monte Carlo modeling, can be used to calculate mixing proportions of every source area (Sundell and Saylor, 2017). These quantitative methods together with rapid increase in detrital zircon U-Pb dating of potential areas and Cenozoic sediments in the ECSB and Taiwan region make it possible to re-examine the Miocene provenance change that occurred in Taiwan region.

In this study, we have compiled a large number of literature detrital zircon ages from Cenozoic sedimentary rocks of Taiwan region, the ECSB, and the potential areas including the adjacent rivers in South China and far inland areas of Yangtze block, North China, and Korean Peninsula to determine the proportions of different sources that fed the Miocene sediments in Taiwan region and the ECSB by inverse Monte Carlo modeling. Considering tectonics and changes of sedimentary environment in east China margin, we provide a more comprehensive understanding on drainage reorganization from the sediments in marginal basins and further constraints on sediments transported along the marginal basins.

Geological Background

The Taiwan island is located in the south of the East China Sea and is subducting by South China Sea plate and Luzon arc (Huang et al., 2012). The arc–continent collision between the Luzon arc and Eurasia since 6.5 Ma resulted in the basic tectonic pattern of Taiwan region (Huang, 2017). Consequently, narrow N-S tectonic belts and the high mountain ranges were formed (Chen et al., 2019). The Taiwan island can be divided into five zones: coastal plain, western foothills, the Hsuehshan Range, the Central Range, and the Coastal Range (**Figure 1C**). The coastal plain, western foothills, and Hsuehshan Range are located in the fold-thrust belt resulted from the deformed and uplifted passive continental margin sediments (Huang et al., 2012). The Central Range and Coastal Range are composed of accretionary prism and forearc basin–volcanic island arc, respectively. Before this collision, Taiwan region received Paleogene sediments of the rift basin and Oligocene to Miocene sediments in the passive margin setting after the opening of South China Sea (Lin et al., 2003).

The ECSB is located in the east of the present Yangtze Estuary (**Figure 1**). This basin is the largest Cenozoic rift basin in the east Asia margin and deposited relatively complete Cenozoic sediments and thus was believed to be one of the crucial places to trace reorganization of river networks in East Asia (Richardson et al., 2010; Fu et al., 2021). The ECSB roughly consists of two subsequently rifted zones (**Figure 1B**), the west zone mainly rifted from the late Mesozoic to the Paleocene and the east zone rifted during Eocene to Oligocene (Zhu et al., 2019). Both of them are composed of several sub-basins that are controlled by boundary faults. Since the Miocene, the uplifts in the ECSB were covered by sedimentary strata due to post-rift subsidence, and the ECSB became a broad continental shelf (Lee et al., 2006).

The rift and its associated sediments of the southern ECSB connected with basins around the Taiwan region (**Figure 1**), and the evolution of these basins have been profoundly affected by the opening of the South China Sea (Huang et al., 2012; Zhu et al., 2019).

Samples and Methods

We compiled most of the detrital zircon U-Pb ages reported by Lan et al. (2016), which covered Eocene to middle Miocene sedimentary rocks of western foothills in Taiwan. Two sand samples from the Zhuoshui River, two samples from the beach sand in northwestern and southwestern Taiwan Island, respectively (**Table 1**). In the ECSB, thirteen detrital zircon samples with a total of 1,161 grain ages from the Miocene to Quaternary sediments were compiled from Fu et al. (2021).

Previous studies suggested that the adjacent South China, Yangtze Block, North China Block, and Korean Peninsula could be the potential areas for the Miocene sediments in Taiwan region and the ECSB (Deng et al., 2017; Fu et al., 2021; Zhang J. et al., 2021). We used the fluvial samples that were collected from the rivers covering most part of these potential areas (**Table 1**; **Figure 2**) to represent the provenance features of the source areas, rather than the bedrock U-Pb ages, as the previous studies did (e.g., Deng et al., 2017; Fu et al., 2021). The fluvial samples are concise to represent general distribution of U-Pb ages of source areas and efficiently used to provenance analysis in East Asia (Cao et al., 2018; He et al., 2020; Zheng et al., 2020). Despite that, hydraulic sorting, mechanical abrasion, and weathering might bias the detrital zircon ages of source regions (Malusà et al., 2013). For geological time, it is hard to determine the erosion patterns of the paleo rivers, which also have a great influence on the age distributions yielded by source rocks (Wissink and Hoke, 2016).

The qualitative and quantitative statistical provenance analyses were both applied to compare the large detrital data set (**Table 1**). The R package (Vermeesch et al., 2016) and DZmix (Sundell and Saylor, 2017) were utilized for qualitative and quantitative analyses, respectively. Kernel density estimates (KDE) showed the probability distributions of samples (Vermeesch, 2013). Multidimensional scaling (MDS), which was applied to detrital zircon U-Pb age data sets to measure dissimilarities between samples, was used to highlight differences (Vermeesch, 2013; Vermeesch et al., 2016) and identify source areas which appear to be the most similar to Miocene sedimentary rocks in Taiwan and the ECSB. The DZmix can calculate the contributions of different source areas by Monte Carlo mixture modeling (Sundell and Saylor, 2017) and further assist to determine if the sediments in the ECSB and Taiwan were fed by the same sources.

RESULTS

The kernel density estimates (KDE) using a 20 Ma bandwidth show that a sharp provenance change occurred in Miocene in

TABLE 1 | Compilation of detrital zircon ages for provenance analysis.

Sample location	Region	No. of ages (n)	Samples	Depositional age	References
Potential areas					
YR Mainstream LD	—	567	Fluvial sands	Present	He et al. (2014)
YR Mainstream LD		426	Fluvial sands	Present	Yang et al. (2012)
YR Mainstream LD		155	Fluvial sands	Present	Iizuka et al. (2010)
YR branches in midstream		548	Fluvial sands	Present	He et al. (2014)
Yongding River	North China Craton	86	Fluvial sands	Present	Yang et al. (2009)
Luan River		108	Fluvial sands	Present	Yang et al. (2009)
Yellow River		729	Fluvial sands	Present	Nie et al. (2016); Yang et al. (2009)
Chongchon River	North Korea	66	Fluvial sands	Present	Wu et al. (2007)
Taedong River		54	Fluvial sands	Present	Wu et al. (2007)
Hantan River	South Korea	83	Fluvial sands	Present	Choi et al. (2016)
Han River		82	Fluvial sands	Present	Choi et al. (2016)
Geum River		60	Fluvial sands	Present	Choi et al. (2016)
Seomjin River		80	Fluvial sands	Present	Choi et al. (2016)
Nam River		80	Fluvial sands	Present	Choi et al. (2016)
Nakdong River		71	Fluvial sands	Present	Choi et al. (2016)
Qiantang River	Cathaysia	322	Fluvial sands	Present	Zhang et al. (2015)
Ou River		126	Fluvial sands	Present	Xu et al. (2007)
Min River		395	Fluvial sands	Present	Xu et al. (2016); Zhang et al. (2017)
Jiulong River		205	Fluvial sands	Present	
Marginal basins					
Western foothills	Taiwan	1,034	Outcrop	Eocene–Miocene	Lan et al. (2016)
Boreholes of offshore basins	East China Sea Basin	1,161	Cuttings	Miocene–Quaternary	Fu et al. (2021)
Fluvial sediments	Taiwan and Penghu Island	426	Fluvial sands	present	Deng et al. (2017), Chen et al. (2019)

Taiwan region characterized by obvious increase in zircon age populations with peaks at ~220 Ma, ~800 Ma, ~1800 Ma, and ~2,500 Ma (**Figure 2**). This change in the age distribution after Oligocene was first reported by Lan et al. (2016). The similar age distribution also can be observed from the early–middle Miocene sedimentary rocks in the ECSB and present sediments from Coast Plain in Taiwan Island (**Figure 2**).

The MDS plot with a stress value of 0.056 suggests good quality of the fit (**Figure 3**). In the MDS plot (**Figure 3**), three clusters are clearly exhibited. The early–middle Miocene samples from Taiwan, the synchronous deposits in the ECSB, and present sands from Taiwan fall in the same cluster with Korea and North China affinity. The late Miocene–Quaternary samples from the ECSB links best with mainstream of the middle–lower Yangtze River, which is consistent with the view that the present-day Yangtze River initially was formed in the late Miocene (Fu et al., 2021). The Eocene samples from Taiwan are closely linked to the Min River, while the Oligocene samples links with the Qiantang River and the Late Miocene–Quaternary of the ECSB, despite of obviously different age distribution in KDE plots (**Figure 2**).

Three contradictory views that enlarged Min River (Lan et al., 2016), concealed microcontinent (Chen et al., 2019), and far inland sources by passing the ECSB (Deng et al., 2017; Zhang et al., 2017; Zhang J. et al., 2021) have been suggested to interpret the provenance change in Miocene. The age features of enlarged Min River and concealed microcontinent cannot be conclusively drawn though associated hypotheses were proposed. If the Miocene provenance change resulted from the sediments that were delivered by passing the ECSB, the contemporaneous deposits in the ECSB and the adjacent rivers in South China would represent the potential sources. According to this, Monte Carlo mixture modeling was constructed by DZmix using the cross-correlation coefficient for finite mixture distributions of probability density plots (Sundell and Saylor, 2017). The mixing model shows source contributions of 88% for the ECSB and 10% for the Min River (**Figure 4A**). Both contributions of the Jiulong River and Ou River are 1%, suggesting very limited contribution. For the present sediments in the coastal plain of Taiwan, which were believed to be mainly derived from the Miocene sedimentary rocks (Deng et al., 2017), and the mixing model with a mean cross-correlation coefficient of 0.89 and very low standard deviation demonstrates reliable evaluation (**Figure 4B**). Similarly, source contributions of 81% are from the ECSB, 8% from the Min River, 3% from the Jiulong River, and 7% from the Ou River. All these indicate that the early–middle Miocene sediments in Taiwan mainly were supplied by detrital materials from the ECSB and mixed with a small amount of sediments from the Min River, Jiulong River, and Ou River, and did not require an enlarged Min River or the microcontinent.

To determine if the early–middle Miocene sediments in Taiwan region were associated with the Yangtze River, samples were taken from middle–lower mainstream of the Yangtze River, branches of the middle Yangtze River, North China, Korea, and other local rivers near Taiwan region to represent the features of the potential source (**Figure 5A**). Since ~90% of sediments in mainstream of present middle and lower reaches of the Yangtze River were eroded from the eastern margin of the Tibetan Plateau (Wissink and Hoke, 2016), we compiled samples from the mainstream and branches to represent the Yangtze River and local contributions from

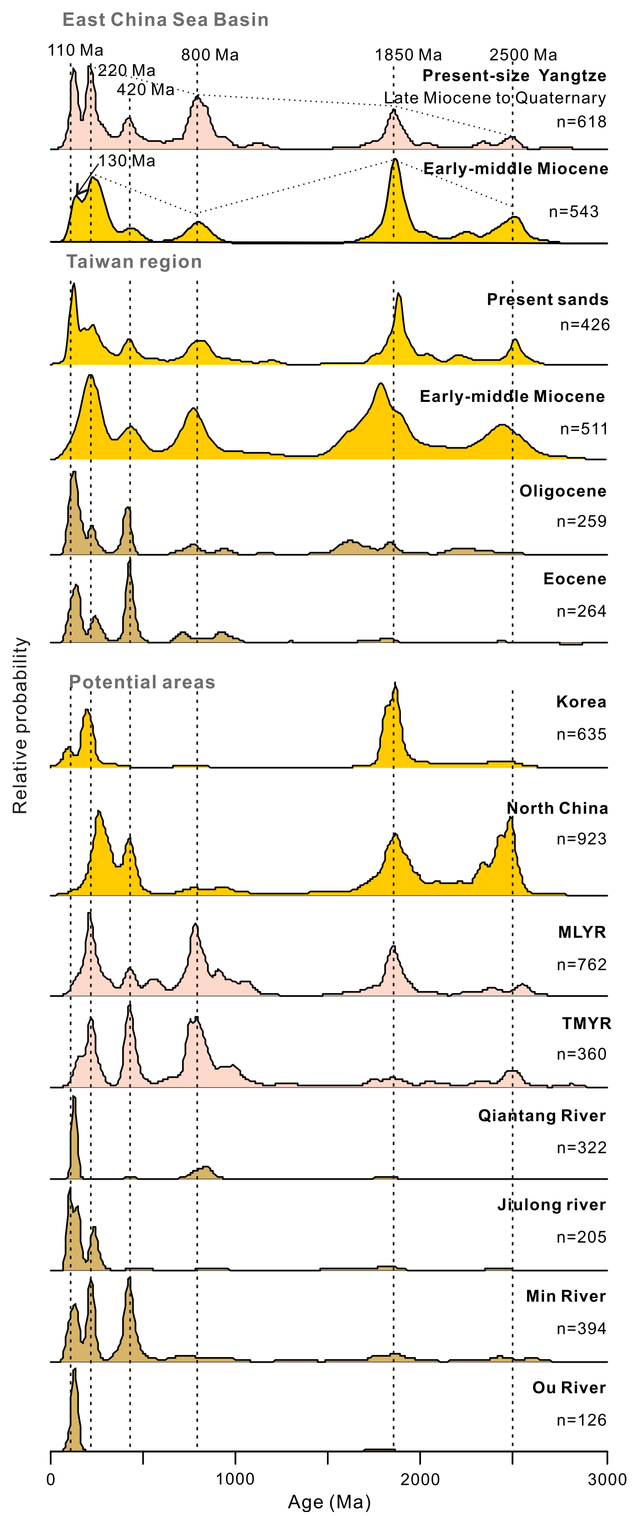

FIGURE 2 | Spectra of detrital zircon ages from the ECSB, Taiwan, and potential areas. The provenance package in R (Vermeesch et al., 2016) was used to make the KDE plots (bin = 20). See **Table 1** for source of literature data. MLYR, middle and lower reaches of the Yangtze River trunk stream; TMYR, tributaries in the middle reaches of the Yangtze River.

middle reaches of the Yangtze River, respectively, to distinguish the contribution of the middle Yangtze River system before the establishment of the present-size Yangtze River. Monte Carlo mixing models of early–middle Miocene sedimentary rocks in Taiwan suggest that the source contributions of 33% were from the Yangtze River and 28% from North China (**Figure 5A**). Korea and branches of the lower Yangtze River contributed roughly the same sediments (14%). In contrary, present sediments in Taiwan were mainly contributed by North China (22%) and Korea (25%), minor by the Yangtze River (16%), and branches of the middle Yangtze River (12%) (**Figure 5B**).

For the early–middle Miocene sediments in the ECSB, they were predominantly derived from the North China (40%) and Korea (30%) and the contributions of the Yangtze River system were limited: mainstream (15%) and branches in middle reaches (7%) (**Figure 5C**). However, for the late Miocene–Quaternary sediments in the ECSB, the Yangtze River contributed the most sediments that the contributions of mainstream were 52% and the branches in middle reaches were 20%, while Korea and North China only contributed a total of 13% sediments (**Figure 5D**). The cross-correlation coefficient (R^2) of modeling for the ECSB sediments was over 0.9, indicating a high level of confidence.

DISCUSSION

Implications for the Evolving of the Yangtze River

Previous studies suggested that the Miocene provenance changes are closely linked with the Yangtze River system (Zhang et al., 2017; Zhang J. et al., 2021). However, most recent studies suggested that the Yangtze River might not have been established until the late Miocene (12 Ma -10 Ma) (Fu et al., 2021; Sun et al., 2021; Zhang Z. et al., 2021). The ECSB would be one of the most possible places to preserve the crucial evidence for evolution of the Yangtze River (Richardson et al., 2010; Fu et al., 2021). Our MDS plot (**Figure 3**) clearly shows that the late Miocene–Quaternary sediments in the ECSB were closely linked with the present Yangtze River systems, but the early–middle Miocene sediments in the ECSB and Taiwan region fall into the same cluster with North China and Korea, which was consistent with the most recent view that the Yangtze River was initially formed in the late Miocene (Zhang Z. et al., 2021; Fu et al., 2021; Guo et al., 2021). The modeling also suggested the change in provenance from 70% sediments derived from North China and Korea in the early–middle Miocene to 72% sediments sourced from the Yangtze River system since the late Miocene. Contrasting to our results, Zhang et al. (2021) proposed that about 50% sediments fed by the Yangtze River system in the early Miocene for ECSB sediments. As we have compiled much larger data (**Table 1**; **Figure 5**) and obtained mixing models with higher mean cross-correlation coefficient of 0.92 for the early–middle Miocene samples and 0.94 for late Miocene–Quaternary samples than those (0.843) models (**Figure 5**), our results are more reliable. The

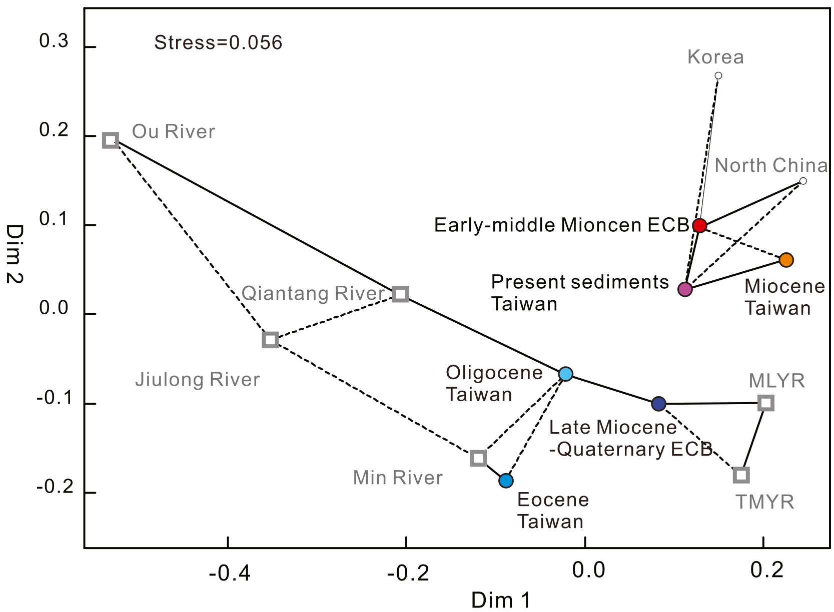

FIGURE 3 | Non-metric multidimensional scaling (MDS, Vermeesch et al., 2016) plot of detrital zircon data. See **Table 1** for source of literature data.

contrasting contributions of sediments for the Yangtze River system before and after the late Miocene support the view that the Yangtze River with present-day erosion patterns and similar size of catchment established in the late Miocene, as proposed by Fu et al. (2021).

Provenance of the Taiwan Region in the Miocene

The provenance of the Miocene sediments in the western foothills of the Taiwan region has been a hot topic of debate, despite a large amount of data obtained (Deng et al., 2017; Lan et al., 2016; Zhang et al., 2017; Chen et al., 2019). The provenance transition from ~31 to 25 Ma has been inferred from elaborate interpretations of major elements, trace elements, rare elements, and Nd isotopes (Lan et al., 2014). The Miocene sediments show a much higher proportion of old zircons and monazite (~1850 Ma) (**Figure 2**) and lower Nd isotope values (Lan et al., 2014; Lan et al., 2016; Chen et al., 2019). It is widely accepted that these sediments were not largely supplied by adjacent small local rivers that derived from the Cathaysia Block (Lan et al., 2016; Deng et al., 2017; Zhang et al., 2017; Chen et al., 2019). However, Chen et al. (2019) claimed that the sediments forming the Miocene strata were from a microcontinent that has been concealed under western Taiwan by overlying strata. Another competitive view is that these sediments were supplied by a large distal river derived from Eurasia, despite the transport routes being a hot debate. Lan et al. (2016) proposed that an enlarged paleo-Min River reached the lower Yangtze craton, resulting in provenance changes. Zhang et al. (2017) suggested that the Yangtze River supplied most of the sediments. Additionally, North China might also have contributed terrigenous clastics (Deng et al., 2017). Wang et al. (2018) noticed similarities in zircon age distribution between Oligocene sediments from the Xihu Sag and Miocene sediments from the Taiwan region. They proposed a mixed model of the Yangtze River and reworked sediment of pre-Miocene sediments of the ECSB.

Several pieces of evidence make the microcontinent model seem impossible. First, in their research, the Yangtze River and rivers derived from the Cathaysia Block were regarded as potential source areas without considering the possibility of North China and Korea, which contributed the most zircons according to our quantitative mixing models (**Figures 4**, **5**); second, seismic sections across the region containing the proposed microcontinental block have revealed that the pre-rift basement is covered by Eocene and Miocene marine strata (Lin et al., 2003). This scenario indicates that even if this "concealed block" existed, it could not have provided a large amount of detritus. Furthermore, it cannot explain why the Eocene sediments in Taiwan are predominantly from nearby South China (Lan et al., 2014; Lan et al., 2016) in the rifting stage (Lin et al., 2003) and why the Miocene sediments sourced from local uplifts concealed the microcontinent as they suggested especially during passive margin subsidence (Huang et al., 2012).

The samples from the Miocene sequences in the western foothills of Taiwan exhibit detrital zircon features similar to the contemporaneous sediments in the ECSB in the KDE plots (**Figure 2**). The MDS plot also suggests that the Taiwan sediment has a close affinity with that in the ECSB (**Figure 3**). The mixing modeling clearly shows that approximate 80–90% of zircons were contributed by ECSB sediments (**Figure 4**). And the 70% of zircons in ECSB sediments were derived from North China and Korea (**Figure 5C**). Thus, we suggest that the Miocene sediments of western foothills in Taiwan have nearly the same sources with the ECSB and were mainly derived from North China and Korea.

The cross-correlation coefficient is 0.6 for early–middle Miocene sedimentary rocks and 0.89 for present sediments which are mainly derived from these rocks. All the model

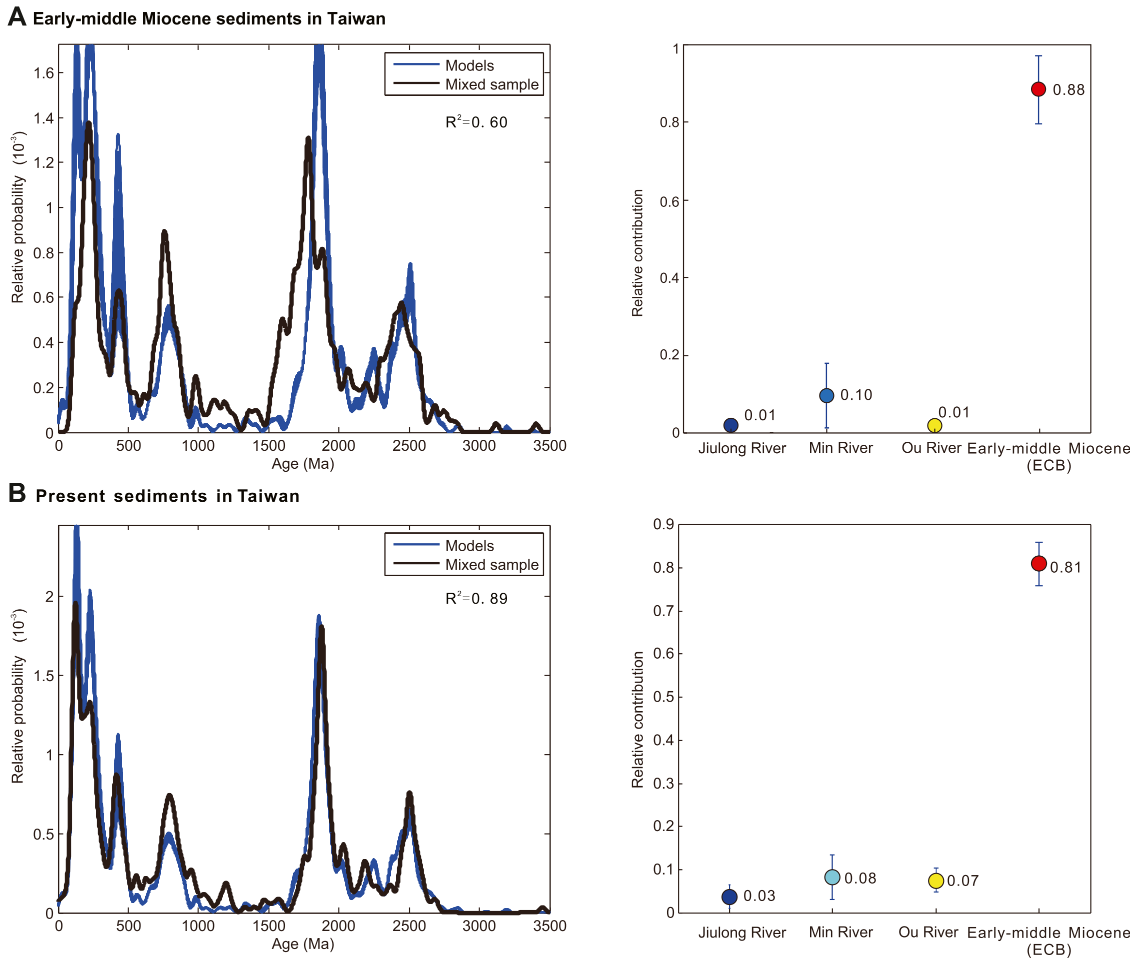

FIGURE 4 | The mixing modelling showing contribution of source areas for early-middle Miocene sandstones and present sediments from Taiwan. The modelling was generated by the Monte Carlo model (Sundell and Saylor, 2017). The Jiulong River, Min River, Ou River and the early-middle Miocene sediments in ECSB were considered as the potential sources to observe the links between sediments in ECSB and the Taiwan. MLYR, middle and lower reaches of the Yangtze River trunk stream; TMYR, tributaries in the middle reaches of the Yangtze River.

trails of finite mixture distributions yield a high peak at ~1.8 Ga with much narrower age range than the counterpart of mixed samples from Miocene sediments in Taiwan but show identical age range with the present sediments from Taiwan and Miocene sedimentary rocks from the ECSB (**Figures 4**, **5**). We noticed that the zircon ages of early–middle Miocene sediments reported by Lan et al. (2016) show obvious variations between samples and the grains for dating per sample between 75 and 91 are also significantly less than the suggested number (120 grains per sample) for provenance analysis proposed by Vermeesch (2004). Therefore, it would produce much better fits for MDS and mixing modelling if high quality of detrital zircon age data can be obtained from the Miocene sedimentary rocks in Taiwan.

Routes of Sediments From East China Sea Basin to Paleo-Taiwan Region

Notably, the routes for sediments delivered from the ECSB to paleo-Taiwan region are under debate. Deng et al. (2017) suggested that a longshore current played an important role in sediment transport from shallow marine environments to the east of the present Yangtze Delta to the Taiwan region. Xu et al. (2007) argued that the transport ability of a longshore current is limited. Zhang et al. (2017) preferred river transport along the ECSB.

The depositional environment from northern ECSB to Paleao-Taiwan region suggests southward tilting, which was consistent with southward delivering of the detrital material. The ECSB formed a wide continental shelf (Lee et al., 2006). In the northern ECSB, the strata of early–middle Miocene dominantly consists of sandstone and mudstone conglomerate interbedded by coal, conglomerate, and freshwater limestone, indicating fluvial to lacustrine environments (Kwon and Boggs, 2002). For the middle ECSB, the lithology predominantly composed of fluvial coarse sandstone and red glutenite mudstone with interbred of coal (Fu et al., 2021).

In the southern ECSB, the Miocene strata consist of alternating lacustrine–flood plain and shallow marine sediments, showing frequent fluctuation of the sea level (Yu and Chow, 1997). The sea

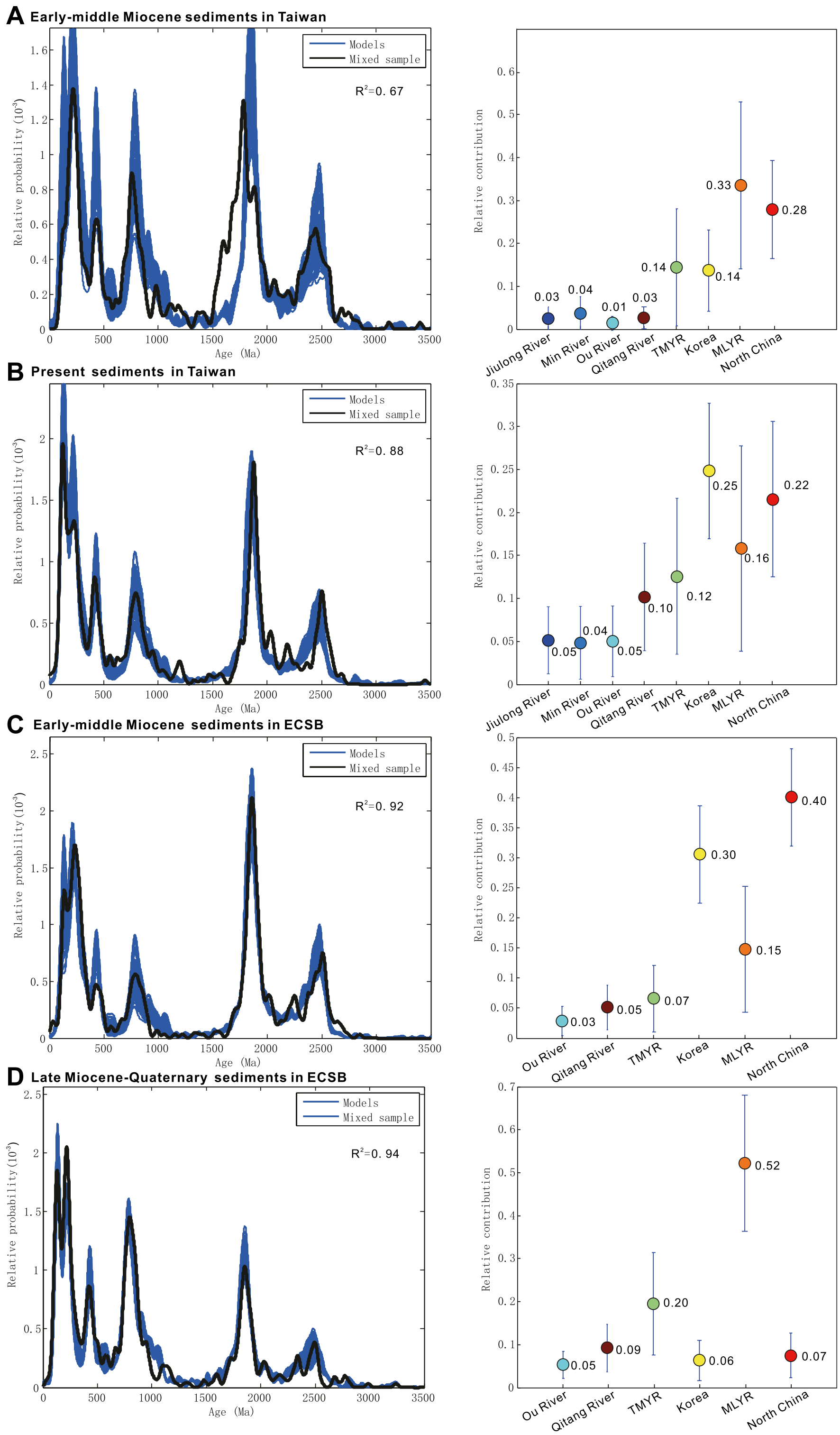

FIGURE 5 | The mixing modelling showing contribution of source areas for early-middle Miocene sandstones and present sediments from Taiwan, Miocene-Quaternary sandstone from ECSB. The modelling was generated by the Monte Carlo model (Sundell and Saylor, 2017). The fluvial samples in the source areas were compiled to quantitatively determine the ultimate contributions from different sources. Note that the Min River and Jiulong River are not used in the modelling for ECSB. MLYR, middle and lower reaches of the Yangtze River trunk stream; TMYR, tributaries in the middle reaches of the Yangtze River.

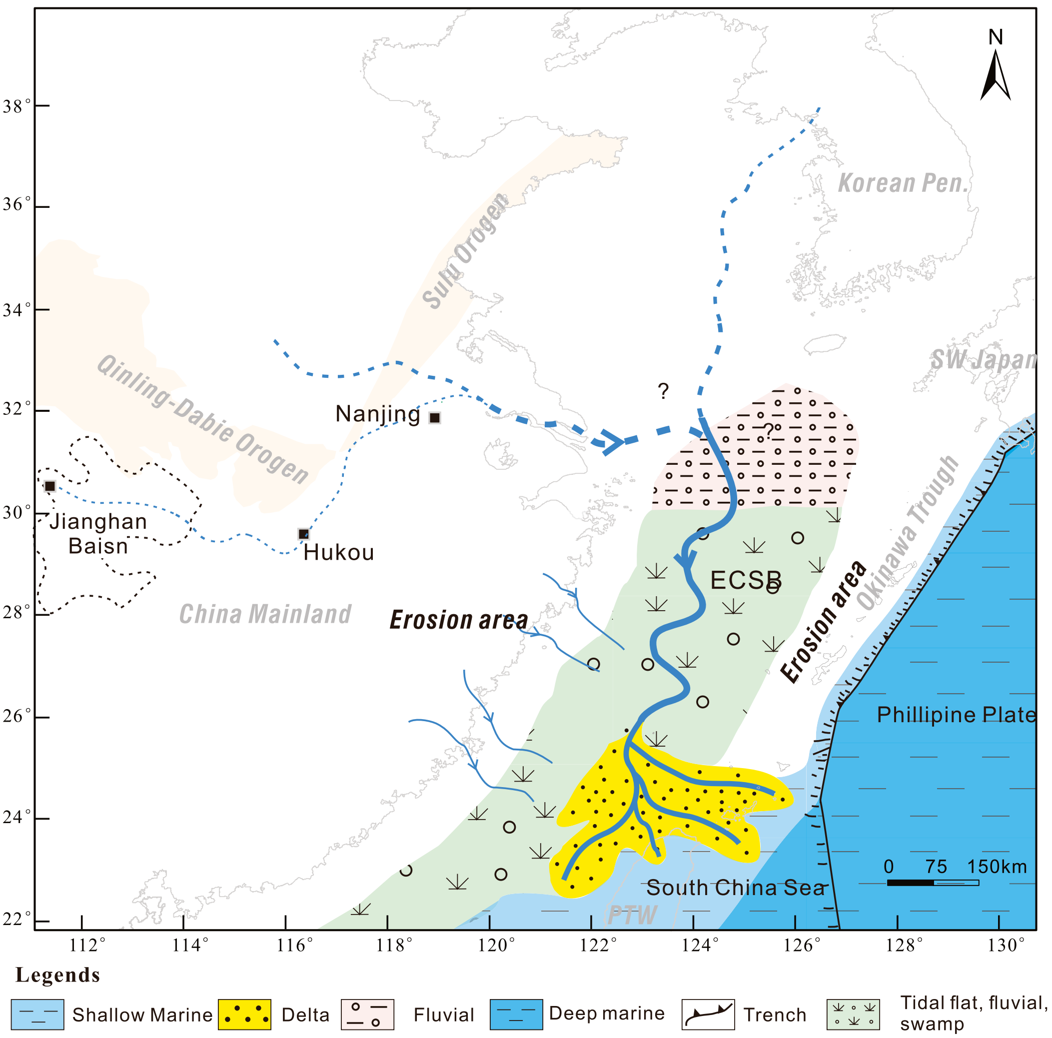

FIGURE 6 | Schematic map showing the sediments delivered from the source areas to the paleo-Taiwan region. PTW, paleo-Taiwan.

water deepened to the east of the southern ECSB. In the southern Ryukyu Islands, the Iriomote Island (**Figure 1A**) is mostly covered by the lower Miocene Iriomote Formation, which was subdivided into A-G member from lower to upper (Saitoh and Masuda, 2004). Iriomote Formation was mainly deposited in a shallow marine setting, but member F containing fossilized roots and coal indicate the terrestrial environment. The well-sorted and roundness sandstone grains combining with framework modes of sandstones that enriched in quartz demonstrate that the siliciclastics were derived from Eurasian continent (Saitoh and Masuda, 2004). In the Taiwan region, the passive continental sediments of early–middle Miocene with well-developed marine microfossils were mainly formed in shallow marine setting (Huang et al., 2012).

Furthermore, back-arc rifting in the northern Okinawa Trough initiated in the middle Miocene and has developed widely since the late Miocene (Letouzey and Kimura, 1985; Letouzey and Kimura, 1986), which was based on observations of the acoustic basement in seismic sections (Gungor et al., 2012). Before that, this region was possibly a zone of uplift, as inferred from the absence of pre-Miocene sediments (Shang et al., 2017), which blocked the sediments of the ECSB to be delivered eastward (**Figure 6**). Although previous studies did not report the existence of a large Miocene delta, we infer there might be a delta somewhere in the southern ECSB between the river system and the shallow marine sea (**Figure 6**). The widespread coal and high frequency sea level fluctuations in the southern ECSB (Yu and Chow, 1997; Saitoh and Masuda, 2004) might imply a Miocene delta system. Therefore, from the northern ECSB to the paleo-Taiwan region, a complete sediment delivering system from the river and delta to shallow marine can be suggested (**Figure 6**). If that was the case, southward delivery by fluvial processes played a major role in the ECSB. The longshore current, wave, and tidal current cannot be neglected, since the Miocene Taiwan region was largely controlled by marine setting (Huang et al., 2012), and the sediments need to be delivered from the delta to the shallow marine.

Moreover, the early–middle Miocene Paleogeographic characteristics in East Asia might be different from the present, which can be inferred from the predominantly terrestrial deposits in region of the South Yellow Sea (Song et al., 2020). Thus, the river systems which are entirely different from the present might play an important role in the sedimentary transporting system from the North China and Korean Peninsula to the ECSB, but further research is required to trace the detailed routes.

CONCLUSION

In this study, quantitative and qualitative analyses were applied to determine the provenance of early–middle Miocene sediments in the ECSB and Taiwan region based on a large number of detrital zircon age data, together with regional trend in the sedimentary environment. We have drawn the following conclusions:

1) Early–middle Miocene sediments in the ECSB and Taiwan show close affinity with North China and Korea, and the contribution of 70% was from the two source areas for the ECSB.
2) Over 80% sediments in Taiwan were supplied from the ECSB, possibly by the river in the middle and northern ECSB, and by longshore current, wave, and tidal current from the southern ECSB to paleo-Taiwan region.
3) The contribution of the Yangtze River system was 72% for late Miocene–Quaternary sediments in the ECSB, which was consistent with the late Miocene establishment of the Yangtze River.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

XF processed the data processing, wrote the manuscript, and provided funding and helped with conception of idea. LH compiled the data, drew plots and edited the manuscript. WZ contributed to the conception, reviewed and edited the manuscript. XH contributed to data processing and participated in discussion. KF and ZZ reviewed and edited the manuscript.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.