Journal of Asian Earth Sciences 85 (2014) 26–39

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

journal homepage: www.elsevier.com/locate/jseaes

Provenance analysis of the Miocene accretionary prism of the Hengchun Peninsula, southern Taiwan, and regional geological significance

Xinchang Zhang [a,b], Yi Yan [a,*], Chi-Yue Huang [a,c,*], Duofu Chen [a], Yehua Shan [a], Qin Lan [a,b], Wenhuang Chen [a,b], Mengming Yu [a,b]

[a] Key Laboratory of Marginal Sea Geology, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Department of Earth Sciences, National Cheng Kung University, Tainan, Taiwan

ARTICLE INFO

Article history:
Received 31 July 2013
Received in revised form 11 January 2014
Accepted 20 January 2014
Available online 3 February 2014

Keywords:
Provenance
Taiwan
Hengchun accretionary prism
Turbidite sequences

ABSTRACT

Petrographic analysis, detrital zircon U–Pb geochronology and Neodymium isotope are applied to the Middle-Late Miocene turbidite sequences in the Hengchun accretionary prism, southern Taiwan, to constrain the provenance and nature of sedimentation in the Manila subduction system. Both petrographic study and detrital zircon U–Pb ages show that the Middle-Late Miocene turbidite sequences were primarily derived from Mesozoic granites and volcanic rocks of the Cathaysian Block in SE China, which were transported southeastward via rivers like Minjiang and Jiulongjiang to the Taiwan area. This conclusion is further supported by Nd isotope analyses of shales intercalated within sandstone sequences showing negative εNd values (−13.3 to −10.5) of a continental origin. During the Late Miocene when global sea-level fell significantly, the SE China coastline shifted seaward to the eastern part of the present Taiwan Strait, which would have facilitated these continent-derived sediments being transported southeastward to the shelf-upper slope of the Chinese continental margin. These turbidite sequences were then deformed and accreted into the accretionary prism of the Hengchun Peninsula when the South China Sea oceanic lithosphere subducted eastward beneath the Philippine Sea Plate in the Late Miocene. Our study suggests that sedimentary deposition of the turbidite sequences in the Hengchun Peninsula could be strongly controlled by different river system supply, submarine channeling transport and fluctuations of sea-level.

1. Introduction

The Taiwan Island is located at the boundary between the Eurasian Plate and the Philippine Sea Plate (Fig. 1A). During the Early Cenozoic, the Eurasia continent in east China had experienced normal faulting to develop a series of NE-trending rift basins (Li and Rao, 1994; Huang et al., 2001). Among them the South China Sea oceanic lithosphere spread in Oligocene-Middle Miocene (32–17 Ma, Taylor and Hayes, 1983; 32–16 Ma, Briais et al., 1993; 31–20.5 Ma, Barckhausen and Roeser, 2004; 37–15 Ma, Hsu et al., 2004). Soon after cessation of oceanic spreading, the South China Sea oceanic lithosphere subsequently subducted eastward along the Manila Trench beneath the west-moving Philippine Sea Plate to develop the Hengchun Ridge accretionary prism and the Luzon arc–forearc basin (Fig. 1; Huang et al., 1992, 1997; Reed et al., 1992). The formation of this accretionary prism marks the transition of the Asian continental margin from the passive to active margin.

Sequences in the accretionary prism of the upper plate are sediments originally deposited on the subducting lower plate. During subduction, parts of these passive margin sediments are scraped off and accreted into the accretionary prism in the overlying upper plate (Cathy and Raymond, 1995; Clift and Vannucchi, 2004). Accordingly, the Miocene sequences in the accretionary prism of the Hengchun Peninsula were originally deposited on the passive Asian continental margin before they were accreted into the accretionary prism. Nowadays the Hengchun Peninsula is about 400 km away from the SE China mainland coast (Fig. 1A). Southward or southeastward paleocurrent measurements in the Hengchun Peninsula indicate that Miocene turbidite sequences were mostly transported from China continent to the northwest (Huang, 1984). However, northwestward paleocurrents are also reported

* Corresponding author at: Key Laboratory of Marginal Sea Geology, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China (C.-Y. Huang). Tel.: +86 20 85290212.
E-mail addresses: yanyi@gig.ac.cn (Y. Yan), huangcy@mail.ncku.edu.tw (C.-Y. Huang).

http://dx.doi.org/10.1016/j.jseaes.2014.01.021
1367-9120/

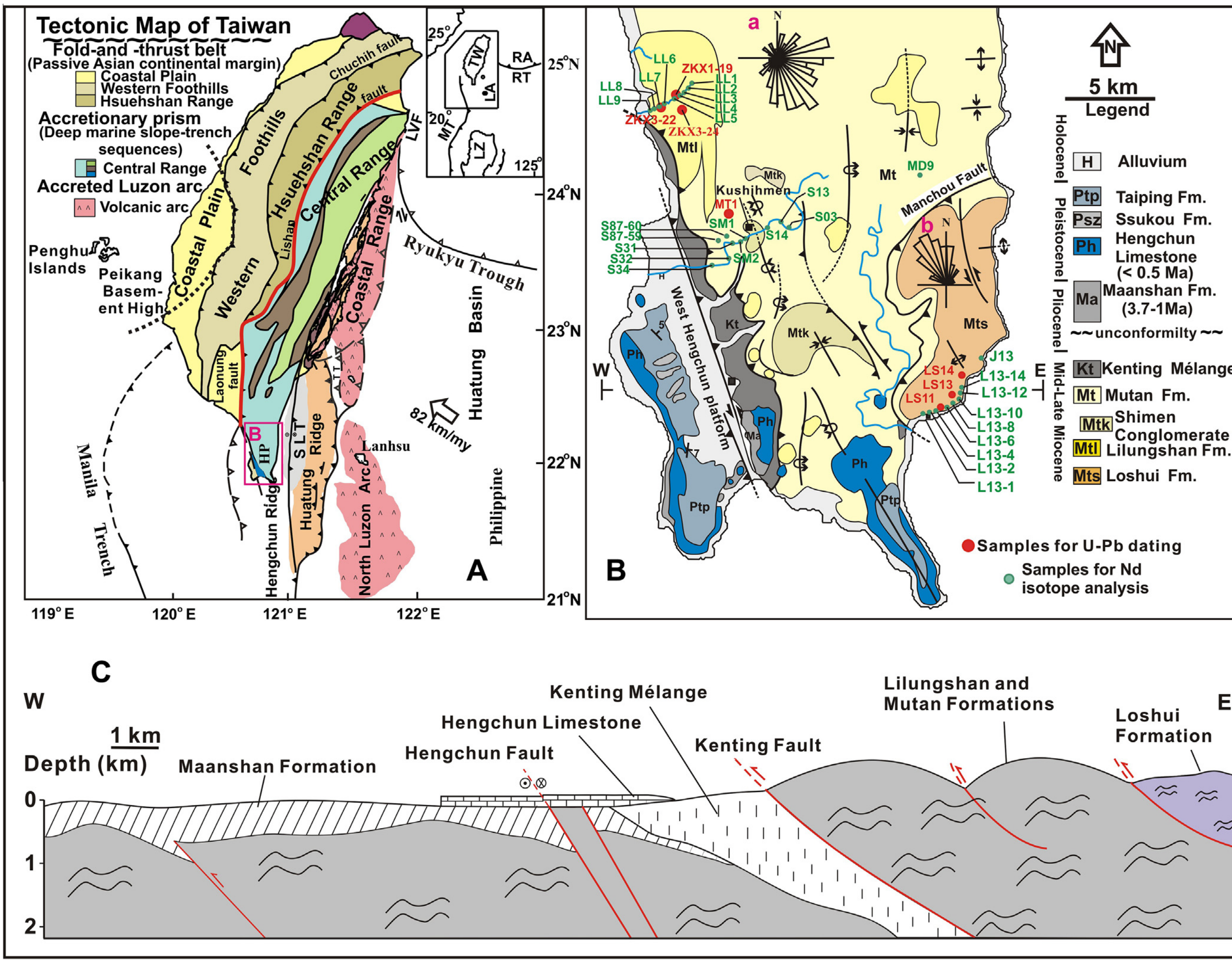

Fig. 1. (A) General tectonic and stratigraphic map of Taiwan. From west to east, the geological divisions include: the Coastal Plain (CP), Western Foothills (WF), Hsuehshan Range (HR), Central Range (CR) (Hengchun Peninsula (HP)), Longitudinal Valley (LV) and Coastal Range (CoR) and Luzon Arc (LA). The submarine topography offshore of southern Taiwan includes a number of north–south trending submarine ridges and troughs (Hengchun Ridge; Southern Longitudinal Trough (SLT); Huatung Ridge; Taitung Trough (TT); Lutao-Lanshu Ridge)(Huang et al., 2006). Inset black arrows shows the direction of plate motion from Yu et al. (1997); (TW) Taiwan; (MT) Manila Trench; (RA) Ryukyu Arc; (RT) Ryukyu Trough; (LZ) Luzon Island; (LA) Luzon Arc. B: Simplified geological map of the Hengchun Peninsula showing the major units, sampling position referred in the text and the distribution of the Miocene accretionary prism sediments. Rose diagrams a and b in (B) represent the paleocurrent direction of Lilungshan and Mutan formations (a) and Loshui Formation (b), respectively (adapted from Huang, 1984; Cheng et al., 1984; Sung and Wang, 1986). (C) simplified geological map and cross section of the Hengchun Peninsula, southern Taiwan (modified after Chang et al., 2003; Shan et al., 2013).

in the Loshui Formation (N14-N15, ~11.6 to 9.8 Ma, rare planktonic foraminifera can be found) from the eastern coast of the Hengchun Peninsula (Huang, 1984; Cheng et al., 1984; Figs. 1B and 2). Consequently there are two contrast paleocurrents in the Hengchun Peninsula and raises a question about their sediment sources. Could these Miocene turbidite sequences, including upper fan conglomerates and well-preserved oyster/leave fossils, be transported for about 400 km from the Chinese continent to the Hengchun Peninsula in southernmost Taiwan? In addition to the Chinese continent would there also have other sources to provide sediments to the Hengchun Peninsula, for examples the Luzon arc–forearc to the east (Kirstein et al., 2010) or the proto-Taiwan to the north (Page and Lan, 1983; Clift et al., 2003).

To solve the controversial debates, petrographic analysis and detrital zircon U–Pb geochronology are applied to the Miocene sequences in the Hengchun accretionary prism to constrain the provenance and nature of sedimentation in the Manila subduction system. In addition, we also determine Nd isotopic values of the Miocene shales to test if they were derived from the SE China mainland or the Luzon arc. If the sediments were derived from the Luzon arc (εNd: +9.5 to −1.1), εNd values of the Miocene shales will be much less negative than those eroded from the Asian continent source (Goldstein and Jacobsen, 1988; Chen et al., 1990a,b).

2. Tectonic setting and stratigraphy

The Hengchun Peninsula in southern Taiwan represents the accretionary prism of the Manila subduction system. It extends southward to the offshore Hengchun Ridge between Taiwan and Luzon Islands and connects northward to the Central Range (Fig. 1; Huang et al., 1997). The Hengchun Peninsula-Central Range accretionary prism contacts the arc–forearc Coastal Range along the collision suture of the Longitudinal Valley fault system (LVF), which further extends southward to the collision suture basin (Southern Longitudinal Trough; SLT in Fig. 1; Huang et al., 2000). The volcanism of the northern Luzon arc starts from Middle Miocene (Yang et al., 1995) when the South China Sea oceanic lithosphere subducted eastward beneath the Philippine Sea Plate.

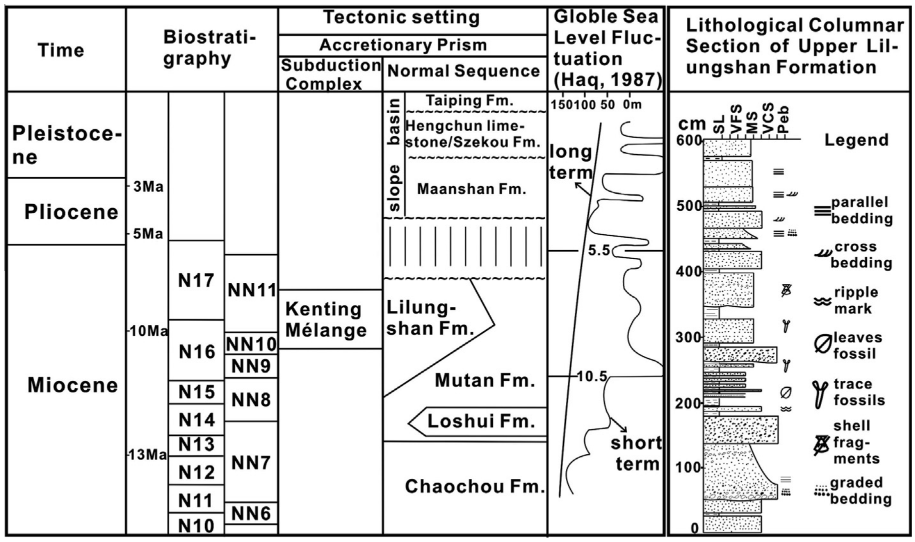

Fig. 2. Stratigraphic units and their tectonic settings of the Hengchun Peninsula (Left; Huang et al., 1997, 2000), showing also Middle-Late Miocene global sea level fluctuation curve (Haq et al., 1987) and the lithological column of the upper section of Lilungshan Formation. Biostratigraphy compiled from (Chang, 1964, 1965, 1966; Huang et al., 1997). SL-shale, VFS-very fine sand grains, MS- Medium sand grains, VCS-very coarse sand grains, Peb-pebble.

The Hengchun Peninsula in southernmost Taiwan marks the latest exposed part of the accretionary prism. It is composed primarily of Middle-Late Miocene turbidite sequences, shallow-marine Plio-Pleistocene slope basin strata and the Late Miocene Kenting Mélange (Figs. 1B and 2). The Late Miocene sequences are mainly of sandy turbidite strata with Bouma sequence (Fig. 3A). The Upper Miocene Lilungshan Formation (2000 m thick of planktonic foraminiferal Zones N15-17, ~11.2 to 6.4 Ma; Chang, 1964) exposes along the western Coast (Fig. 1). This formation is characterized by a coarsening and thickening upward sequence starting from thin sandy turbidite layers in the lower part, thick sandstones in the middle part and conglomerates in the upper part (Fig. 2). This coarsening upward sequence (~11.2 to 6.4 Ma) was substantially consistent to the long-term change of global sea level (Fig. 2; Haq et al., 1987), although in detail, there are some small "finning upward" and/or "coursing upward" cycles. Hence, they correspond to lower, middle and upper fan of regressive depositions during sea-level fall, respectively (Walker, 1978). In addition, in the upper part of this formation, submarine channel or canyon is further characterized by a fining and thinning upward succession, which possibly related to lobe switching of the submarine fan (Fig. 2). Conglomerates are mostly rounded to sub-rounded, whiles composition are highly variable, including igneous origin of gabbro, diabase and sedimentary or metamorphic origins of sandstone, quartzite, marl, schist and gneiss (Facies A). Shallow-marine mollusks of large *Ostra* fossils up to 10 cm in length (Fig. 4A) are commonly well-observed in thick conglomerate part (Bouma Ta) or sandy turbidite layers (Tb-c part) with ripple marks (Fig. 4C), whiles plant leaves are found in thin carbonaceous shale (Te part; Fig. 4B). Imbricated gravel deposition and hummocky cross-stratification can also be found (Fig. 4D and E). All these features including the assemblages of Facies A, B, C, E suggest that the upper part of the Lilungshan Formation was in shelf environments and may represent an upper fan or feeder channel deposits (Fig. 4). Measurements of paleocurrent further indicate that these clasts were transported from the NW to the SE, which was similar to the Mutan Formation. The Mutan Formation (~2000 m thick of planktic foraminiferal zones N14–N17, ~11.6 to 6.4 Ma; Chang, 1964, 1965, 1966) widely exposes in the Hengchun Peninsula (Fig. 2). It is mainly composed of turbidite (Facies D) and shale (Facies E) with subordinately thick sandstones (Facies B) and conglomerates (Facies A). Some channel deposits develop, such as the Kushihmen battlefield (Facies A). Deep-sea microfossils of *Nerites* facies are commonly found. Occurrence of benthic foraminifers, like *Bulimina, Uvigerina, Cibicides* (Chang, 1964, 1965, 1966), indicates that the Mutan Formation was deposited in a slope deep-water environment. Channel deposits and Facies D, E often developed in middle fan, representing a braided channel system (Walker, 1978).

In the eastern part of the peninsula, the Loshui Formation is contact with the Mutan Formation by the Manchou Fault (Fig. 1C). The Loshui Formation (~1000 m thick of planktic foraminiferal Zones N14) (Chang, 1964, 1966) is composed predominantly of thick fine-medium grained sandstone beds (Facies B) and subordinate sandy turbidite layers (Facies C). In addition to Bouma sequences in the sandy turbidite layers, there are also climbing ripples in the upper surface bedding and dish structures with gas-escaping structures in the sandstone beds (Fig. 3D). Slumping features (Fig. 3C) are observed in sandy turbidite layers (Facies F of Mutti and Lucchi, 1972) between the thick sandstone beds (Facies B). Deep-sea ichnofossils of *Nerites* facies are commonly found in the basal part of thick sandstone beds (Cheng et al., 1984). In addition, there are no channel deposits and tiny igneous detrital in the Loshui Formation. Lithofacies and ichnofacies indicate that the Loshui Formation was deposited in middle-lower fan of slope environment (Fig. 3). However, measurements of flute cast direction (Fig. 3B) show paleocurrents from the SE to the NW (Huang, 1984; Cheng et al., 1984; Fig. 1B), which is different from the Lilungshan and Mutan formations. All these features indicate that the source and transport path of the Loshui Formation may be different from the Lilungshan and Mutan formations.

3. Sampling and analysis methods

Thirteen sandstone samples were selected for petrographic modal analysis with approximately 300 framework grains counted per thin section using the Gazzi–Dickinson method (Dickinson and Suczek, 1979) (Table 1).

Six sandstone samples and one conglomerate were selected for the detrital zircon U–Pb geochronology analysis (Fig. 1B). Zircon U–Pb dating was analyzed at the Key Laboratory of Isotope Geochronology and Geochemistry, Guangzhou Institute of Geochemistry,

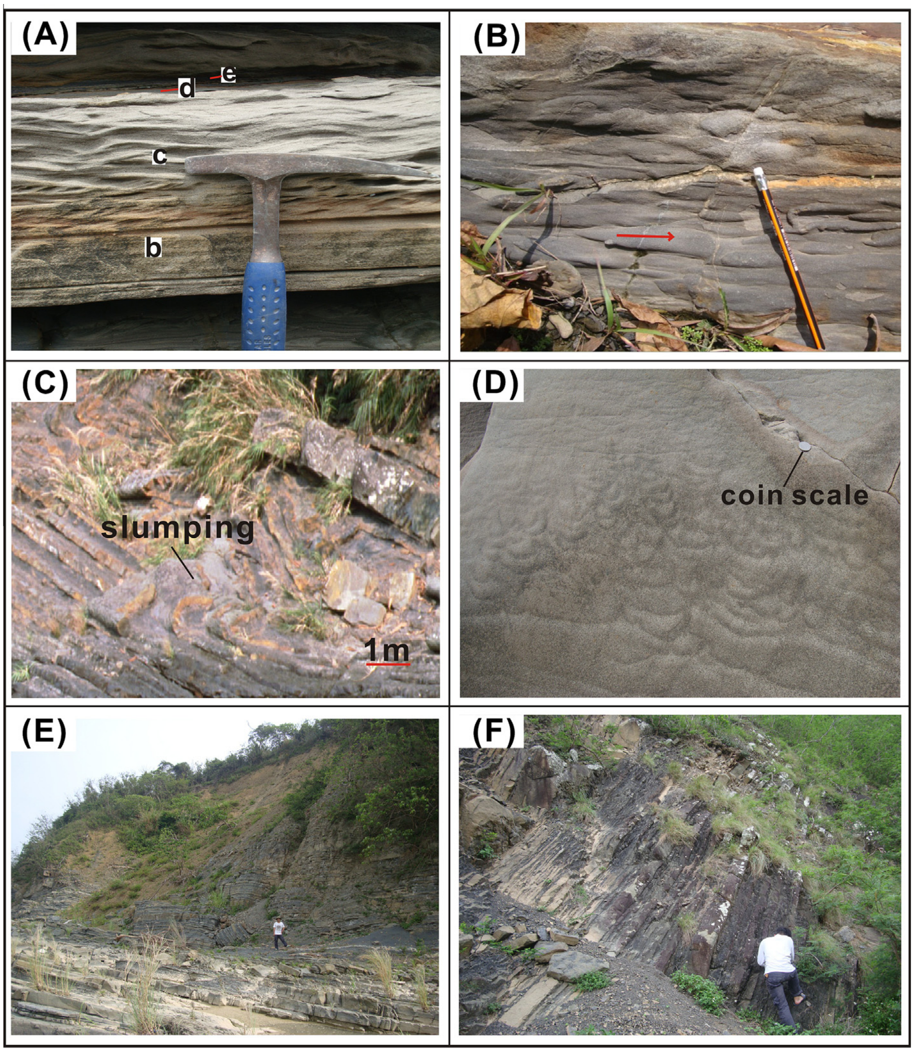

Fig. 3. Field photos at Hengchun Peninsula. (A) Turbidite strata with typical Bouma sequence, Tb-e, found in Loshui Formation, (B) flute cast can be seen easily in Mutan Formation and Loshui Formation (arrow pointing downstream), (C) slumping phenomenon in the Loshui Formation, (D) dish and plume structure are common in Loshui Formation showing a rapid deposition, (E) and (F) Flysch deposition in Mutan Formation.

Chinese Academy of Sciences. The LA-ICPMS system is composed of an Agilent 7500a ICP-MS coupled with a Resonetic RESOLution 50-M ArF-Excimer laser source ($\lambda = 193$ nm). NIST610 and TEM ($^{206}Pb/^{238}U = 415 \pm 5$ Ma) were used as external calibration standards and ^{29}Si as the internal standard. The calculation of isotope ratios was calculated using ICPMSDataCal 7.7 (Liu et al., 2010a,b). The age relative probability of detrital zircons was processed using Isoplot (Version 3.23) (Ludwig, 2000, 2003). For statistical purposes, zircon ages with discordance <10% are considered as to be valid (Hu et al., 2012a), therefore zircon ages with discordance >10% were deleted, by which more than 53 valid data were obtained for each study sample (Data Repository) for further analyses. Usually, detrital zircon U–Pb dating needs more than 100 grains to get good enough statistics (Vermeesch, 2004). Due to the analytical limitations, the number of analyzed grains in some samples is less than the prescribed minimum of 100 (Vermeesch, 2004) and certain fraction of the population comprising less than 5% of the total may be missed. This deficiency should not have significant impact on our inferences since we are concerned more with the general provenance of the sediment. Following Griffin et al. (2004) ages of $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{238}U$ were determined, respectively, for the older (>1 Ga) and younger ages (<1 Ga) of zircon grains. All results from the samples are shown in Data Repository.

In addition, twenty-seven shale samples in the Miocene strata of the Hengchun Peninsula were selected for Neodymium geochemical analysis (Table 2 and Fig. 1B). The samples were first reacted with 2 N of acetic acid (HAc) to remove biogenic carbonates. The Nd isotopic measurements were performed on a MicroMass Isoprobe multi-collector-inductively coupled plasma-mass spectrometer (MC–ICP–MS) at the State Key Laboratory of Isotope Geochemistry at Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. Mass bias during Nd isotope measurements was normalized using $^{146}Nd/^{144}Nd = 0.7219$. A standard Nd solution, BHVO-2, was measured together with the samples, yielding a mean value of 0.512972 ± 7 (2σ) for $^{143}Nd/^{144}Nd$. For details of the method, see Wei et al. (2002).

4. Results

4.1. Petrogrphic study result

Sandstones of Hengchun Peninsula are mostly poorly sorted and angular to sub-rounded in shapes. Monocrystalline quartz commonly has wavy extinction (Fig. 5a) and there is lots of polycrystalline quartz, whose internal crystals is crenulated and sutured (Fig. 5b). Sandstones of the Lilungshan Formation are lithic

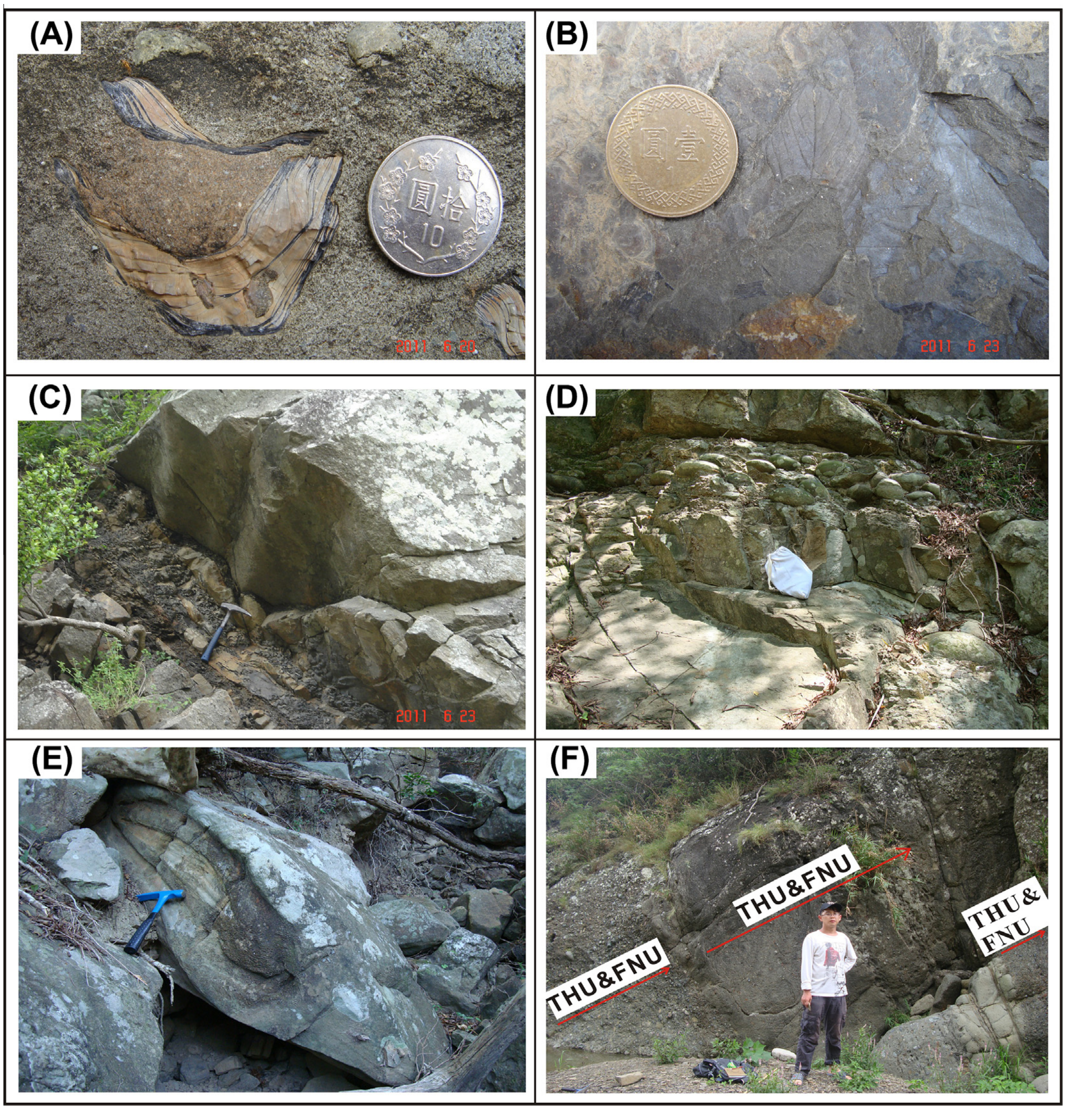

Fig. 4. Field occurrence of strata (A-E: Lilungshan Formation at Chukeng Valley). (A) Well-preserved oyster fossils in the sandstone-conglomerates beds, (B) well-preserved leaves, (C) asymmetric wave ripple marks, (D) imbricated gravels deposition, (E) Hummocky cross-stratification and (F) channel deposition in Mutan Formation (THU&FUN represent a fining and thinning upward succession).

Table 1
Petrographic description of the Miocene sandstones of the Hengchun Peninsula.

Samples	Location	Total Number	Qp	Qm	Qt	P	K	Ft	P/K	Lv	Ls	Lm	L	Lt(Qp)	Qt%	Qm (%)	L (%)	Ft (%)	Lt%
LS13	Loshui Formation	396	12	234	246	38	28	66	1.36	84	0	0	84	96	62.1	59.1	21.2	16.7	24.2
LS11	Loshui Formation	376	80	178	258	44	7	51	6.29	65	0	2	67	147	68.6	47.3	17.8	13.6	39.1
LS13-1	Loshui Formation	245	23	121	144	29	27	56	1.07	34	2	9	45	68	58.8	49.4	18.4	22.9	27.8
LS35	Loshui Formation	328	30	178	208	48	4	52	12.00	58	4	6	68	98	63.4	54.3	20.7	15.9	29.9
ZK3	Lilungshan Formation	546	10	259	269	38	26	64	1.46	196	12	5	213	223	49.3	47.4	39.0	11.7	40.8
ZK7	Lilungshan Formation	402	18	177	195	35	22	57	1.59	137	10	3	150	168	48.5	44.0	37.3	14.2	41.8
NO.9	Lilungshan Formation	465	6	240	246	34	25	59	1.36	155	4	1	160	166	52.9	51.6	34.4	12.7	35.7
ZKX3-22	Lilungshan Formation	281	49	99	148	20	16	36	1.25	85	7	5	97	146	52.7	35.2	34.5	12.8	52.0
ZKX4-20	Lilungshan Formation	324	22	100	122	36	24	60	1.50	118	0	24	142	164	37.7	30.9	43.8	18.5	50.6
ZKX10-23	Lilungshan Formation	249	32	83	115	25	13	38	1.92	83	4	9	96	128	46.2	33.3	38.6	15.3	51.4
MT1	Mutan Formation	350	84	88	172	77	25	102	3.08	35	0	42	77	161	49.1	25.1	22.0	29.1	46.0
MT2	Mutan Formation	350	77	70	147	74	21	95	3.52	49	7	53	109	186	42.0	20.0	31.1	27.1	53.1
MT3	Mutan Formation	350	91	77	168	56	35	91	1.60	56	4	49	109	200	48.0	22.0	31.1	26.0	57.1

Table 2
Whole-rock Nd isotopic compositions of the Miocene shales from the Hengchun Peninsula.

Samples	$^{143}Nd/^{144}Nd$	2σ(StdErr)	Epsilon Nd
Mutan Formation			
S03	0.511954	7	−13.3
S13	0.512002	10	−12.4
S14	0.512030	8	−11.9
SM1	0.512084	9	−10.8
SM2	0.512163	7	−9.3
S31	0.512290	7	−6.8
S32	0.511985	8	−12.7
S34	0.511979	7	−12.8
MD9	0.511971	6	−13.0
Loshui Formation			
L13-1	0.511990	6	−12.6
L13-2	0.512030	7	−11.9
L13-4	0.512029	7	−11.9
L13-6	0.512049	7	−11.5
L13-8	0.512054	7	−11.4
L13-10	0.512053	7	−11.4
L13-12	0.512070	6	−11.1
L13-14	0.512053	7	−11.4
J13	0.512032	8	−11.8
Lilungshan Formation			
LL1	0.512009	7	−12.3
LL2	0.511973	9	−13.0
LL3	0.512024	12	−12.0
LL4	0.512018	8	−12.1
LL5	0.512019	7	−12.1
LL6	0.512006	6	−12.3
LL7	0.512034	7	−11.8
LL8	0.511997	9	−12.5
LL9	0.512005	7	−12.4

arenites (Table 1) with averaged Q–F–L ratios of 48:14:38 (Fig. 6), containing some meta-sedimentary, sedimentary, igneous lithic fragments and carbonate minerals (Fig. 5a–d). In comparison, sublithic sandstones of the Loshui Formation with averaged Q–F–L rations of 64:17:19 (Fig. 6) contain more quartz but less igneous lithic fragments (Fig. 5e and f) than the Lilungshan Formation, indicating a higher maturity. However, sandstones of the Mutan Formation have averaged Q–F–L ratios of 45:27:28 (Fig. 6; Table 1), a value between the Loshui and Lilungshan Formations (Fig. 6).

4.2. Zircon U–Pb geochronology and $^{143}Nd/^{144}Nd$ ratios of shales

All U–Pb data obtained in this study are listed in Data Repository. Shapes of studied zircon grains range from sub-rounded to sub-angular and grain sizes are from ~50 to 200 μm. Many grains show oscillatory zonings, suggesting a magmatic origin with ages of 100–600 Ma, while the metamorphic zircons often show a homogeneous internal structure. Moreover, the metamorphic recrystallized zircons often have some enclaves, rounded growth lines and round-shaped kernel (Fig. 7). Studied zircon samples yield a wide range of U–Pb ages from Archean (~2500 Ma) to Late Mesozoic (~90 Ma) with main peaks of 110–180 Ma, 200–260 Ma and 1600–2000 Ma together with some minor peaks of 400–600 Ma, 700–1000 Ma and 2000–2600 Ma (Fig. 8). The characteristics of age distribution patterns of the study samples are generally similar to each other. However, the Loshui Formation is lack of the age intervals of the Hercynian and Caledonian events (400–600 Ma) which are commonly observed in the Lilungshan and Mutan formations (Fig. 8), suggesting a different source.

$^{143}Nd/^{144}Nd$ ratios of shales from the Hengchun Peninsula range from 0.511954 to 0.512097, corresponding to εNd values between −13.3 and −6.8 (Table 2 and Fig. 10).

5. Discussions

5.1. Sediment provenance mainly from the Cathaysian Block in SE China

5.1.1. Mode of sandstones

Ratios of Plagioclase/K-feldspar of sandstones in the Hengchun Peninsula are more than 1, suggesting a low maturity of sandstones (Dickinson and Suczek, 1979; Dickinson, 1985; Tucker, 2001). Considering the strong monsoon during the Late Miocene (Clift et al., 2008; Steinke et al., 2010), the low maturity of sandstones could be related to fast sediment transport. In addition, well-preserved oyster and leaves fossils (Fig. 4A and B) in the Lilungshan Formation also suggest that these autochthonous fossils were fast burial after short transport from the source area. Occurrences of wavy extinction of monocrystalline quartz and crenulated, sutured characteristics in polycrystalline quartz may suggest that source rocks have suffered a low to moderate metamorphism (Basu et al., 1975; Young, 1976). On the QFL ternary diagram, these sandstones are plotted in the 'magmatic arc' and 'recycled orogen' provenance fields (Fig. 6); Sung and Wang (1985), indicating the Cathaysian Block in SE China could be the sediment source of the Hengchun Peninsula. The Cathaysian block in SE China is characterized by wide occurrence of Mesozoic granites and volcanic rocks due to westward subduction of the Paleo-Pacific Plate in Late Mesozoic Zhou and Li, (2000); Yui et al., 2009). Detrital modes of sandstones of the Lilungshan Formation are dominated by lithic grains (mainly felsic volcanic) and monocrystalline quartz grains, which could be eroded from the 'magmatic arc' of the Cathaysian Block in SE China (Fig. 9). In addition, Paleozoic sedimentary rocks are also exposed in the eastern Cathaysian block, such as strata in the Fuding inlier in northern Fujian province (Shi and Liu, 1980; Wu and Li, 1990) and in the upper reach of Minjiang River of the Wuyishan terrain in the NW Fujian province (Fig. 9). The Wuyishan terrane is characterized by dominant Paleoproterozoic (approximately 1.86 Ga) and lesser Neoarchean basement (Hu et al., 2012a). All these sediments could be the 'recycled orogen' sediment source area.

5.1.2. U–Pb age patterns of detrital zircon grains

Studied zircon samples in the Hengchun Peninsula yield a wide range of U–Pb ages from Archean (~2500 Ma) to Late Mesozoic (~90 Ma) with main peaks of 110–180 Ma, 200–260 Ma and 1600–2000 Ma together with some minor peaks of 400–600 Ma, 700–1000 Ma and 2000–2600 Ma (Fig. 8). These age peaks are consistent with geological character of the Cathaysian Block in SE China (Fig. 8f). Several magmatic events have been identified in the Cathysian Block including Caledonian (600–400 Ma), Hercynian-Indosinian (260–200 Ma) and Yanshannian (180–100 Ma) (Li, 1997; Wang et al., 2005; Wan et al., 2007; Xu et al., 2007; Wong et al., 2009; Yu et al., 2009, 2012). The most prominent feature of zircon ages in our study samples is the occurrence of the highest peak centered in 110–180 Ma of the Yanshanian tectonic event (Fig. 8). This is consistent to the widest occurrences of the Yanshanian granites accounting for >30% area along the coast of South China (Fig. 9) (Wong et al., 2009). The other major (200–260 Ma; 1600–2000 Ma) and minor (400–600 Ma) age peaks also suggest that the zircon grains in sandstones of the Hengchun Peninsula are derived from SE China. Permian–Triassic granitic plutons (200–260 Ma) commonly occur in the Cathaysian and Yangtze blocks, whiles Early Paleozoic granitoids (400–600 Ma) occur along the suture between the Cathaysian Block and the Yangtze Block (Fig. 9). On the other hands, zircon grains with ages of 700–1000 Ma and 2000–2600 Ma could be derived from Precambrian rocks exposed in

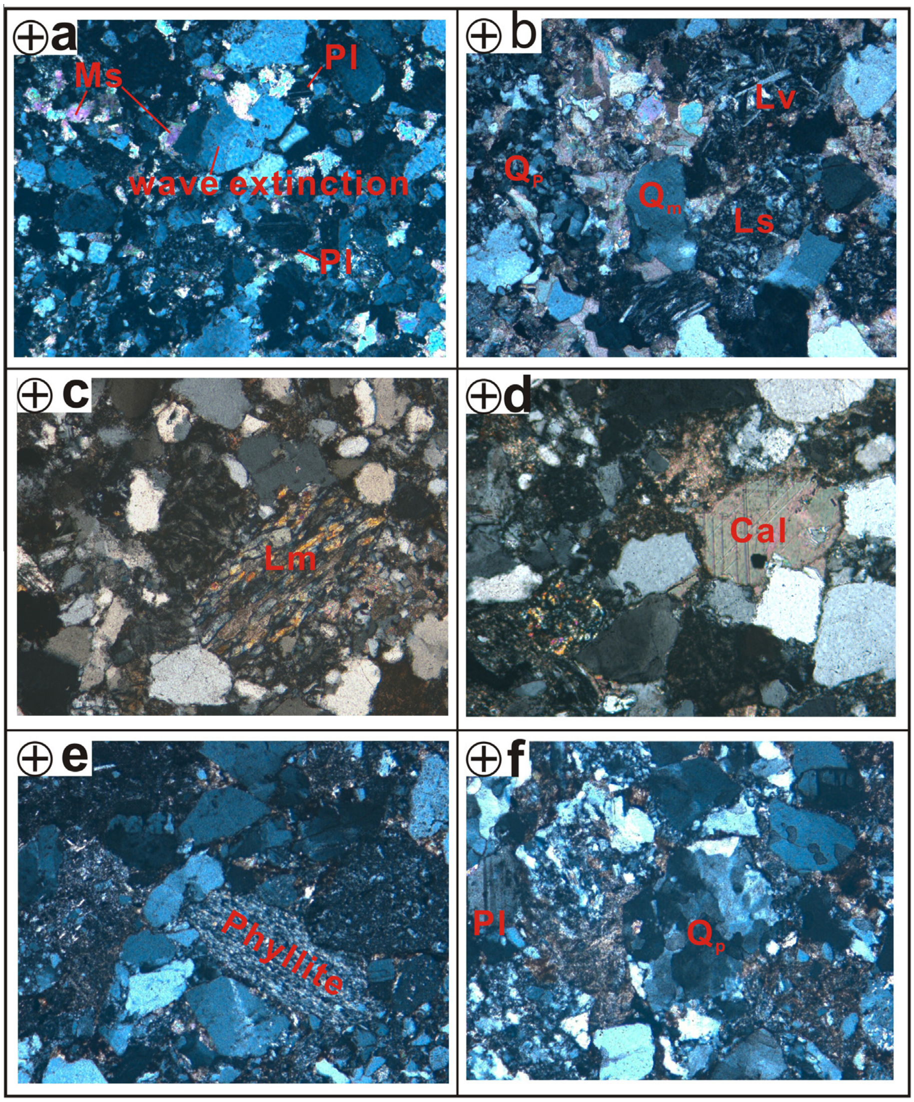

Fig. 5. Photomicrographs of the Miocene sandstones in the Hengchun Peninsula. Wave extinction (a), monocrystalline quartz (b), polycrystalline quartz (b), lithic fragments (b and c), carbonate minerals (d) and muscovite (a) in sandstones of Lilungshan Formation, (e) phyllite grain in Loshui sandstone (f) crenulated and sutured characteristic in polycrystalline quartz and polysynthetic twins of Plagioclase in sandstones of Mutan Formation. Lv-volcanic grain, Ls-sedimentary lithic fragments, Qm-monocrystalline quartz, Qp-polycrystalline quartz, Pl-plagioclase, Ms-Muscovite, Lm- Metasedimentary lithclastic.

the NW Fujian and SW Zhejiang (e.g., Mayuan Group and Badu Group) or recycled from sedimentary formations (Li, 1997; Wan et al., 2007; Yu et al., 2009, 2012; Li et al., 1996; Li, 1997; Xu et al., 2007). All these zircon age features indicate a closed geological relationship between the rocks in SE China provenance and the Miocene sandstones in the Hengchun Peninsula.

Furthermore, the similarity of age distribution between samples of Lilungshan and Mutan formations, 400–600 Ma, 700–1000 Ma and 1600–2000 Ma zircon grains are commonly observed, indicates that both of these two formations were deposited in a same deep-water fan system (Fig. 8; Sung and Wang, 1986). In comparison, 400–600 Ma zircon grains are generally absent and 700–1000 Ma and 1600–2000 Ma zircon grains are mild in the Loshui Formation (Fig. 8). These may reveal that sandstones of the Loshui Formation could be transported via a different deep-sea fan (Fig. 11). This conclusion is consistent with measurements of different paleocurrent directions between the Loshui Formation and the Mutan-Lilungshan Formations in the Hengchun Peninsula (Huang, 1984; Cheng et al., 1984; Chang et al., 2003).

5.1.3. Comparison with U–Pb ages of modern river sands in South China

U–Pb age patterns of detrital zircons in Miocene sandstones of the Hengchun accretionary prism differ significantly from that of the modern sands in the Yangtze Estuary, which contain abundant detrital zircons of $\sim$1.1 Ga and $\sim$0.86 to 0.78 Ga (Fig. 8; Wang et al., 2010; Zheng et al., 2013). Consequently, Miocene sandstones of the Hengchun Peninsula are unlikely derived from the Yangtze Block via the Yangtze River. Whereas U–Pb ages of Miocene sandstones in the Hengchun Peninsula are comparable with modern estuary sands in the Minjiang River and the Jiulongjiang River of southern China. U–Pb age distributions of zircon grains in modern estuary sands of the Minjiang and Jiulongjiang are also predominated by peaks of 110–180 Ma, consistent with what obtained in Miocene sandstones of the Hengchun Peninsula (Fig. 8; Xu and Chen, 2010). Moreover, the U–Pb age patterns of zircon grains of Minjiang estuary sands are identical to those of the Lilungshan-Mutan formations, while zircon age patterns of the Jiulongjiang estuary sands are similar to those

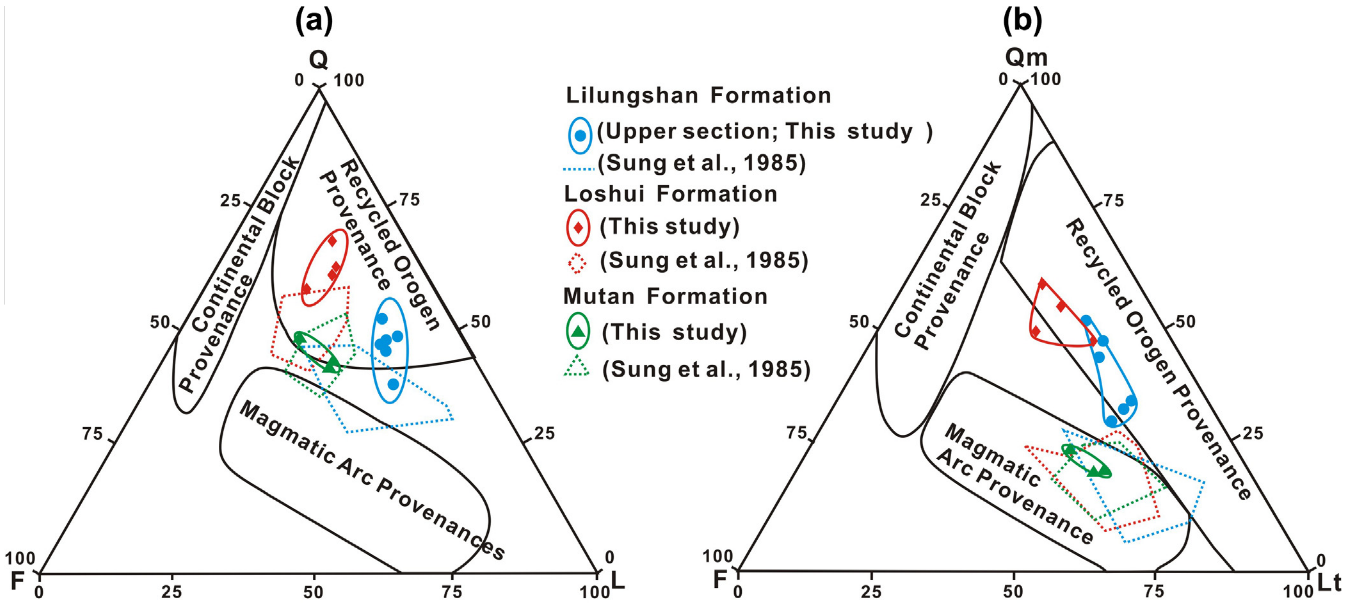

Fig. 6. Q–F–L (a) and Qm–F–Lt (b) plots for the detrital modes of the Miocene sandstones of Hengchun Peninsula. The provenance fields are from Dickinson and Suczek, 1979.

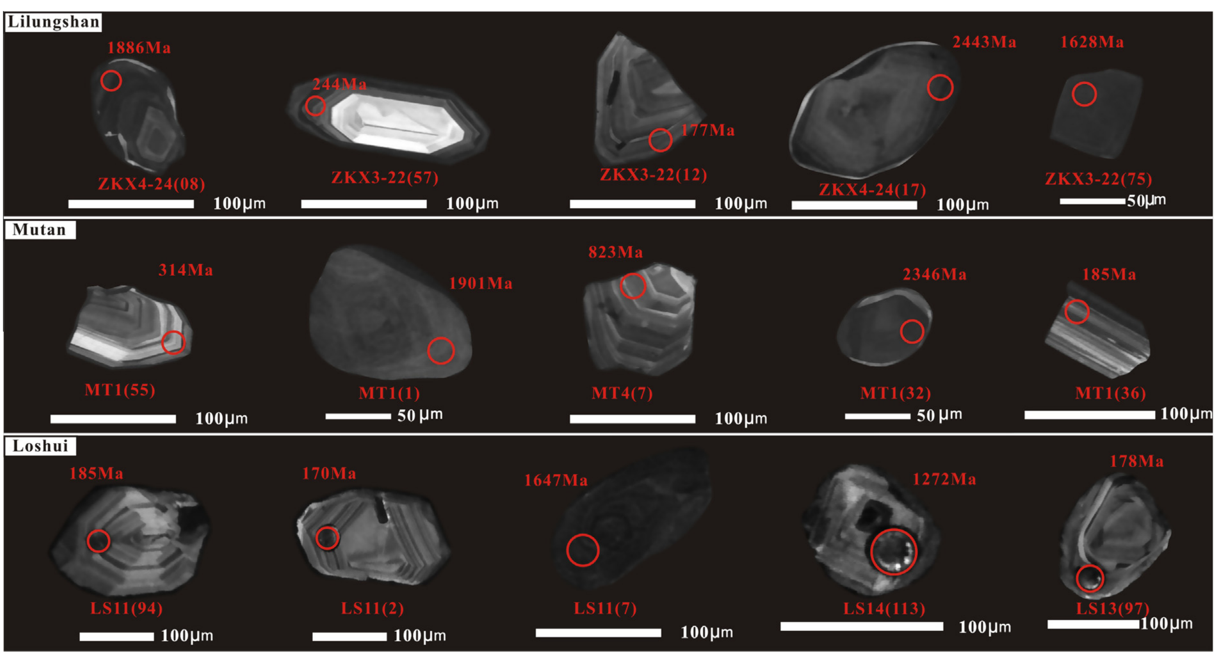

Fig. 7. Cathodoluminescent images of zircons from the Miocene sandstones in the Hengchun Peninsula.

of the Loshui Formation characterized by absence of 400–600 Ma zircon grains and less 700–1000 Ma and 1600–2000 Ma zircon grains (Fig. 8).

Analytic results and discussions above all point to that the zircon grains in Late Miocene sandstones of the Hengchun Peninsula were primarily eroded from the Cathaysian Block via Minjiang/Jiulongjiang Rivers in southern China (Fig. 11). These turbidite sequences were then deformed and accreted into the accretionary prism of the Hengchun Peninsula when the South China Sea oceanic lithosphere subducted eastward beneath the Philippine Sea Plate with counterclockwise rotation. The abnormal paleocurrent of Loshui Formation is caused by different river system and a tectonic rotation later (Chang et al., 2003).

5.1.4. εNd values

In addition, the Nd isotope analysis results also support that Upper Miocene sedimentary rocks in the Hengchun Peninsula were sourced from the mainland of southern China. Except three samples near the Kushihmen Battlefield show a little less negative εNd values (−10.8, −9.3, −6.8; Fig. 10) where igneous pebbles and muds appear in the feeder channel conglomerate beds, the other twenty-five shale samples of Miocene strata in the Hengchun Peninsula show $^{143}Nd/^{144}Nd$ ratios of 0.511954–0.512097 that correspond εNd values range from −13.3 to −10.5 (Table 2 and Fig. 10), suggesting a continental crust source. Similar εNd values can be found in the sediments in southern China, for examples, −11.1 to −12.4 from the ODP 1148 above

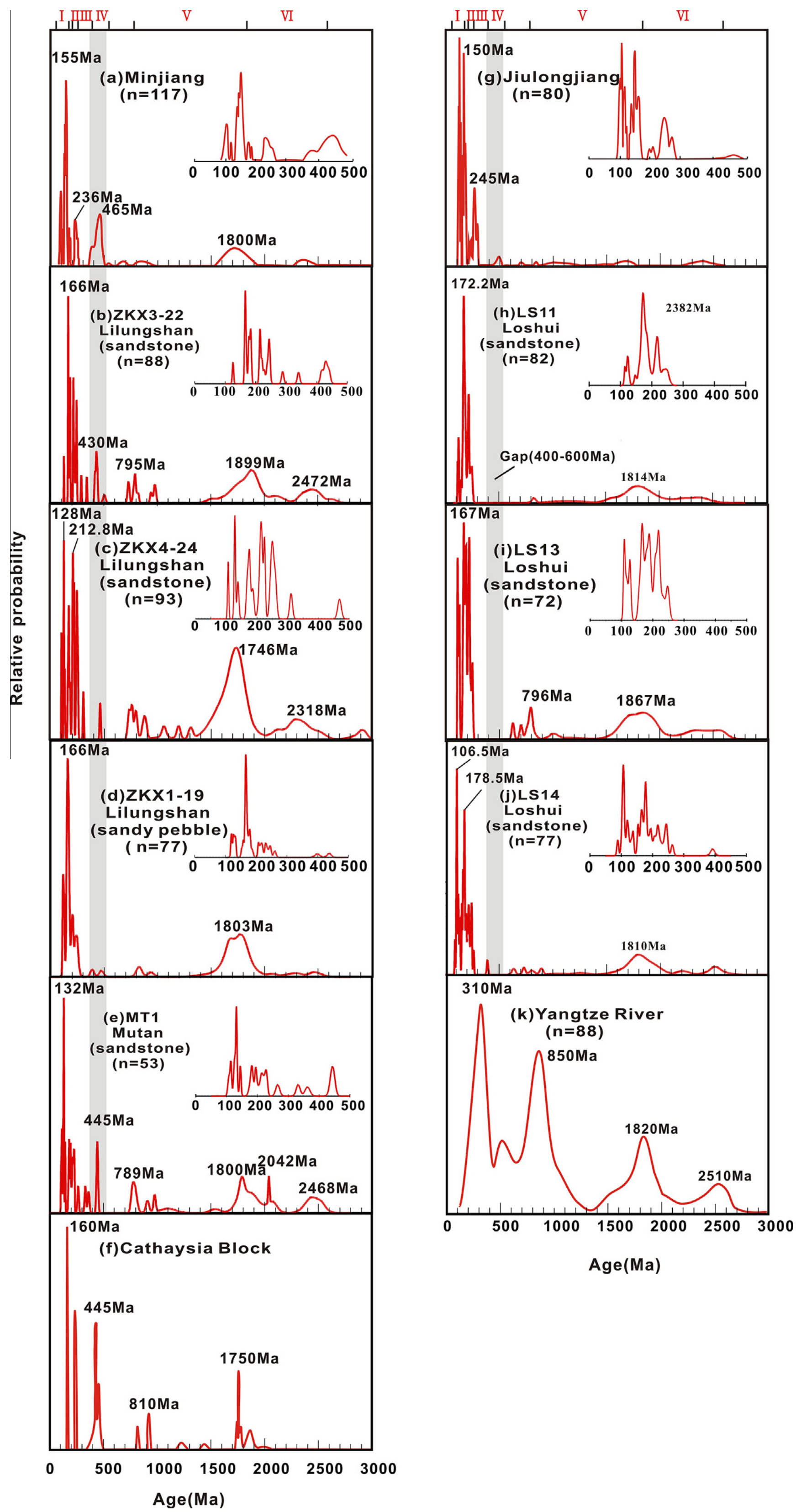

Fig. 8. Relative probability of detrital zircons from the Miocene accretionary prism of Hengchun Peninsula. Plots use ages ⩽10% discordant with $^{206}Pb/^{238}U$ used for ages <1000 Ma and $^{207}Pb/^{206}U$ age for older grains. (a) (g) samples of modern estuary sandstones of Minjiang and Jiulongjiang, respectively (Xu and Chen, 2010); (b and c) samples of Lilungshan sandstones; (d) sample of sandy pebble of Lilungshan Formation; (e)Mutan sandstone; (f) Cathaysia Block (Enkelmann et al., 2007); (h–j) samples of Loshui sandstones; (k) sample of the Yangtze River (Zheng et al., 2013). I–VI represents the key tectonic events in the SE China, including Yanshanian, Indosinian, Hercynian, Caledonian, Jinningian and Luliangian Movement.

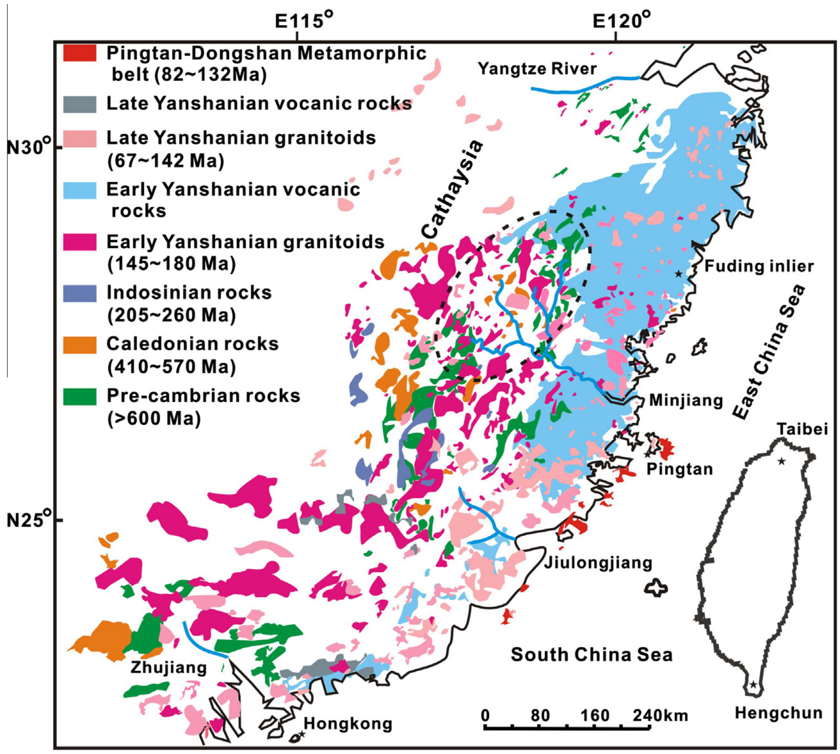

Fig. 9. Schematic map of SE China showing the distribution of Caledonian to Yanshanian granitoids and Pre-Cambrian strata after Wong et al. (2009).

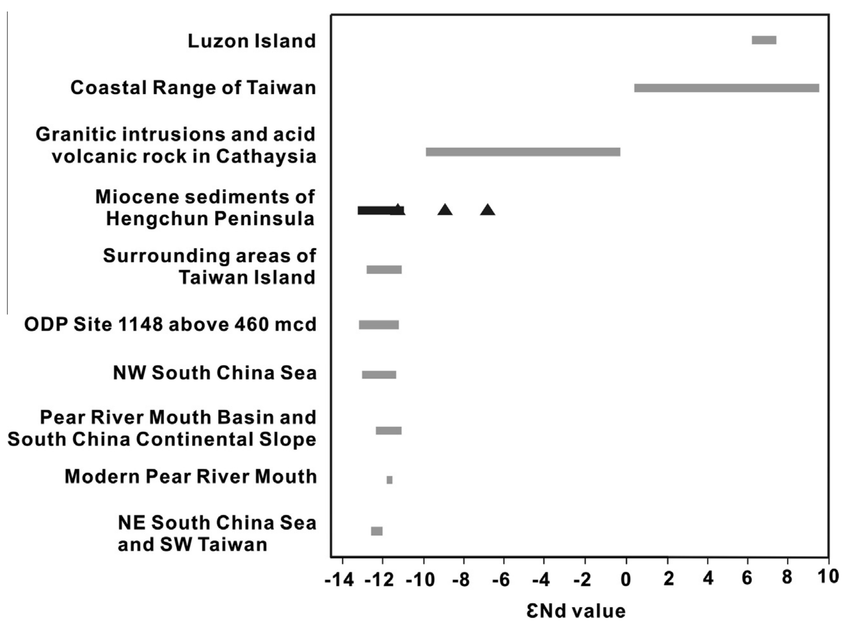

Fig. 10. Comparison of the εNd values of the Miocene sediments in Hengchun Peninsula with possible sources surrounding Taiwan Island. Data from this study, Chen et al., 1990a,b; Chen and Jahn, 1998; Goldstein and Jacobsen, 1988; Li et al., 2003; Yan et al., 2007. Three outlet samples (SM1, SM2, S31; Fig. 1B), showing less negative εNd values (−6.8; −9.3; −10.8), were collected from Kushihmen Battlefield, and they may be polluted by the igneous rocks of Kushihmen channel deposition (Table 2).

460 mcd (Li et al., 2003), −10.9 to −9.5 from the Late Miocene sediments of ODP 1148 (Clift et al., 2002), −11.5 to −9.7 from the 0–14 Ma sediments of ODP 1144 (Li et al., 2003; Hu et al., 2012b), −13.5 to −10.2 from the modern river sediments of the Pearl River, −13.0 to −11.3 in sediments offshore Hainan Island and −12.7 to −11.5 from eastern South China and Taiwan Island, respectively (Chen et al., 1990a; Liu et al., 2008; Shao et al., 2009; Wei et al., 2012; Hu et al., 2013).

In SE China, there are several stages of magmatism in Mesozoic, including Late Yanshanian (67–142 Ma), Early Yanshanian (142–180 Ma) and Indosinian (205–260 Ma) (Zhou and Li, 2000). Indosinian granitoids are mostly exposed inland, whiles Early and Late Yanshanian granitoids distribute widely along the coast (Fig. 9). The Indosinian granitoids are mostly of “S-type” with more negative εNd isotope values, whiles the Yanshanian granitoids are of I-type or more juvenile ones with less negative εNd isotope values

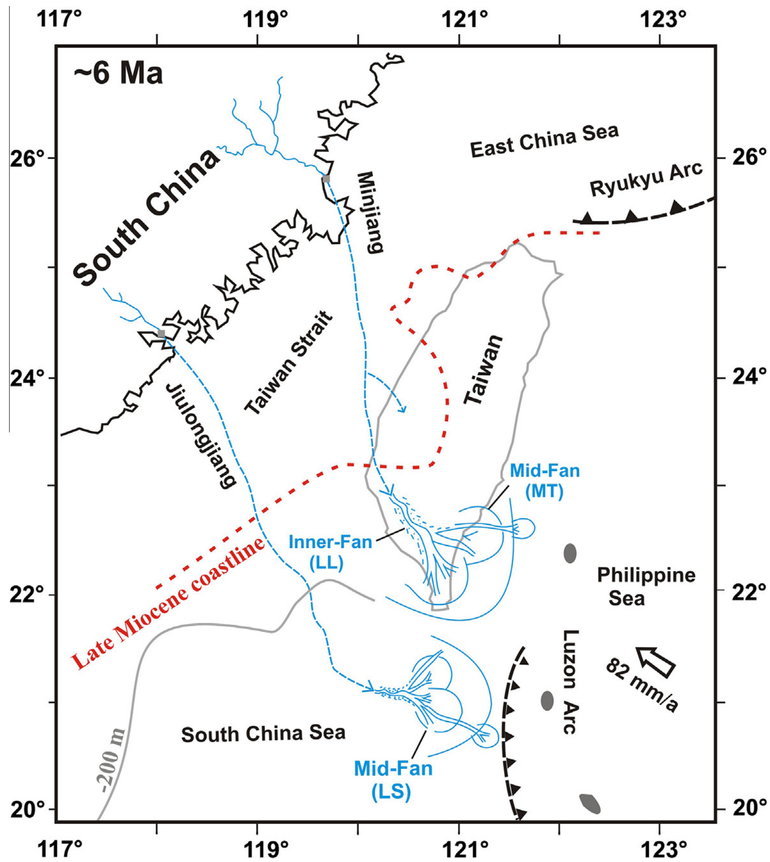

Fig. 11. Schematic map of the paleogeographic of the SE China in Late Miocene, black dashed line represent the NW Fujian province and SW Zhejiang province; red dashed line and blue line represent the paleocoastline and the paleo-transport path, respectively(LL-Lilungshan Formation; LS-Loshui Formation; MT-Mutan Formation). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(−12.6 to −1.5; Chen and Jahn, 1998; Wang and Shen, 2003). Comparing to our results from the Hengchun Peninsula, the major age peak (centered in 140–180 Ma) of zircon grains in sandstones and associated shale samples with εNd −13.3 to −10.5 indicate that they were primarily eroded from Early Yanshanian granitoids along the SE China coast.

5.2. The paleogeography of the southern section of the Taiwan Strait in Late Miocene

One of the long debates about the sediment source of the Hengchun Peninsula is: "Could subrounded pebbles and well-preserved oyster/leave fossils be transported for 400 km from SE China coast to the Hengchun Peninsula in southern Taiwan?" To argue this debate, one must consider the fluctuations of sea-level during the last 15 Ma (Fig. 2). Due to dramatic expansions of the Antarctic glaciation, the Late Miocene sea-level fell significantly at 10.5 Ma and 5.5 Ma for about 100 m lower than the present sea-level (Fig. 2; Haq et al., 1987). Consequently, positions of the China coast line in the Late Miocene time (13–6 Ma) would be very different from the present position. At Penghu volcanic islands, Miocene basalt directly overlain on the red soil layer formed by weathering on land or sedimentary rocks of littoral face, showing the lava of Penghu is a product belonging to the land or shallow water environment (Tsao et al., 1999). Similar Late Miocene paraconformity has been documented from the subsurface stratigraphy of the coastal plain in western Taiwan (Tang, 1977) and also from the Taiwan Strait (Huang, 1982; Liu and Pang, 1984; Lin et al., 2003). In these areas, seismic surveys and drilling data show that the Late Miocene strata are generally missing (Liu and Pang, 1984). Moreover, stratigraphy and sedimentology study onland Western Foothills indicates that Late Miocene strata are either missing in the Peikang Basement High area (Huang, 1986) or deposited in coastal or swamp environments (Chou, 1973, 1980, 1988). All these evidences indicate that during the Late Miocene when global sea-level fell significantly, the SE China coastline shifted seaward to the eastern part of the present Taiwan Strait (Fig. 11). Sediments eroded from the Cathaysian block can be easily transported via some rivers or submarine canyons (for example the submarine Penghu Canyon) to the slope of the NE South China Sea (Fig. 10). At the same time, strong monsoon during the Late Miocene (Clift et al., 2008; Steinke et al., 2010) would also facilitate these continent-derived sediments being transported southeastward to the shelf-slope of the Chinese continental margin near SW Taiwan.

5.3. Luzon arc–forearc source and other source(s)

Based on zircon fission-track study and U–Pb age dating of detrital zircon grains, Kirstein et al. (2010) proposed that in addition to SE China there might have other sources including Luzon arc–forearc in the east and the so-called Pro-Taiwan in the north to provide sediments to the Hengchun Peninsula. In their paper, all reliable U–Pb age data (discordance < 10%) of detrital zircon grains of Late Miocene strata in the Hengchun Peninsula are all >88 Ma with the main high peak in 100–250 Ma, consistent with our results. This indicates that Yanshanian magmatic rocks of the Cathaysian Block in SE China are the main sediment provenance to contribute sediments to the Hengchun Peninsula. But in their data there are 4 zircon grains with young Miocene ages (12.2 Ma, 18.9 Ma, and 10.9 Ma in the Lilungshan Formation and 7.2 Ma in the Loshui Formation) and also Miocene fission track age components 8.1 Ma ($n = 1$) in the Lilungshan Formation and 14.8 Ma ($n = 3$) in the Loshui Formation (Kirstein et al., 2010). Consequently, they proposed that occurrence of these younger ages would be derived from the Luzon arc–forearc now exposed in the Coastal Range, eastern Taiwan. However, our εNd study on shales collected from the Hengchun Peninsula indicates that the Luzon arc–forearc source was impossible or very tiny. The εNd values of the Luzon arc range from +9.5 to −1 (for examples, +0.3∼ +9.5 in the Coastal Range of Taiwan, +6.5 to +7.1 from the Luzon Islands and +6 ∼ −1 from the North Luzon Arc in the Taiwan segment (Goldstein and Jacobsen, 1988; Chen et al., 1990b). εNd values (−13.3 to −10.5) of shale samples in the Hengchun Peninsula (Table 2 and Fig. 10). Consequently, if these young aged zircons would be derived from the Luzon arc, in this case, these arc-soured zircon grains could be firstly deposited in the passive Asian continental margin off SE China through volcanic eruptions and then accreted into the Hengchun Peninsula accretionary prism during the subduction tectonics. Moreover, the Miocene (intraplate) volcanism and relative rocks offshore the western Taiwan could also supply these young zircon grains. Because most of the volcanic rocks are not zircon bearing, the Miocene zircons didn't appear in all of the samples of Kirstein et al. (2010) and this study.

5.4. Another proposed sediment source from the so-called "Proto-Taiwan"

In addition to the Luzon arc–forearc source model, there are also other controversial arguments about sediment source of Miocene strata in the Hengchun Peninsula. Study on exhumation history of Taiwan strongly indicates that the metamorphosed Central Range exposed in the last ∼5 Ma (Huang et al., 2006; Lee et al., 2006). Such a late exposed modern Central Range cannot be the sediment source of the Upper Miocene sequences in the Hengchun Peninsula. However, it is worth noting that the collision between Luzon Arc and mainland Asia has been propagating towards the southwest through time and the northern Taiwan Mountain is collapsing. Page and Lan (1983) claimed that subrounded feeder channel pebbles in the bedded conglomerate sequence of the Mutan Formation, which were misunderstood by them as the Kenting Mélange, were derived from a now-vanished accretionary prism. Clift et al. (2002) further proposed that the now-vanished accretionary prism has been exposed earlier in the Miocene further to the northeast of the Martin Island. Page and Lan (1983) claimed that this now-vanished accretionary prism contained igneous blocks of the South China Sea oceanic lithosphere origin. From this accretionary prism igneous blocks were either eroded and transported eastward into the North Luzon Trough as the Lichi Mélange in the Coastal Range or slumped westward into the Manila Trench as the Kenting Mélange now in the Hengchun Peninsula. However, micropaleontology study indicates that the igneous blocks in the Lichi Mélange are angular showing block-in-matrix feature without discernible stratification. They are embedded in highly sheared forearc matrix with predominant early Pliocene microfossils (Chi et al., 1981; Huang et al., 2008). In contrast, the igneous pebbles in feeder channel conglomerate beds of the Mutan Formation are Late Miocene age. These so-called "South China Sea origined igneous pebbles" are sub-rounded and well-stratified in association with sedimentary and metamorphic pebbles in a same well-stratified bed. The feeder channel conglomerate beds in the Hengchun Peninsula and the igneous blocks in the Lichi Mélange of the Coastal Range are completely different in pebble composition, ages, tectonic setting and formation mechanisms (Huang et al., 2008). The feeder channel conglomerates in the Hengchun Peninsula were deposited in Late Miocene submarine channel in upper fan environment of the passive Asian continental margin before they were accreted into the Hengchun accretionary prism in Late Miocene. Therefore they occurred with metamorphic and volcanic pebbles of Mesozoic age or older derived from the Cathaysian Block of the continent source in a same bed. In contrast, the Lichi Mélange in the Coastal Range contains Miocene andesitic agglomerate blocks of the Luzon arc origin and Middle Miocene crust and upper mantle blocks developed above subduction channel during initiation subduction of the South China Sea lithosphere beneath the Philippine Sea Plate. There are no metamorphic pebbles (such as schist and gneiss) in the Lichi Mélange. Moreover, the sheared mudstones of the Lichi Mélange are primarily of Pliocene age, similar to the remnant forearc strata to the east. Whatever the Mutan Formation or the Late Miocene Kenting Mélange in the Hengchun Peninsula is totally different from Pliocene collision forearc Lichi Mélange in the Coastal Range.

Sung and Wang (1986) regarded that in Late Miocene time the Hengchun Peninsula represented a half-graben basin on the Asian passive continental margin. The graben was filled with sediments derived from an uplifted low-grade metamorphosed terrane comprised of accretionary prism and forearc basin (Sung and Wang, 1985). However, they did not show any piece of graben basin evidence (for example seismic profile, stratigraphic break, normal faulting) to support their interpretation. In the last four decades, intensive seismic surveys conducted by industrial companies did not find any Late Miocene graben developed off SE Asia continent margin near Taiwan. Instead, grabens in the East China Sea and the South China Sea regions are exclusively developed in the Paleocene-Eocene time (Sun, 1982; Wang et al., 1989; Huang et al., 2013), but not in Late Miocene time. Within these Early Cenozoic grabens, normal faulting might continue from Paleocene-Eocene until Late Miocene post-rift deposition, but it is not necessary to mean that there was a Late Miocene graben in the Taiwan area.

6. Conclusions

Petrographic analysis, Neodymium isotope and detrital zircon U–Pb geochronology show that the Miocene turbidite sequences in the Hengchun accretionary prism were mainly derived from the Cathaysian Block via rivers like Minjiang/Jiulongjiang in SE China and then transported southeastward to the Taiwan area. In addition, the contribution from the Luzon arc through volcanic eruptions must be tiny.

Compared with the modern estuary sediments of major rivers, including Yangtze, Minjiang and Jiulongjiang rivers, in SE China, the age spectrums of Lilungshan and Mutan sandstones are similar to that of Minjiang River, but the age spectrums of Loshui sandstones are identical to that of Jiulongjiang. This suggests that sedimentary deposition of the turbidite sequences in the Hengchun Peninsula could be strongly controlled by different river system supply and submarine channeling transport. The abnormal paleocurrent of Loshui Formation is caused by different river system and a tectonic rotation later.

Based on the fluctuation of global sea level, seismic surveys and drillings in the Taiwan Strait and the stratigraphy and sedimentology study onland Western Foothills, a conclusion can be made that in the Late Miocene the global sea-level fell significantly and was lower than the present sea-level. Therefore, a large part of the present East China Sea-Taiwan Strait was exposed. Accordingly, sediments eroded from the Cathaysian block can be easily transported via some deep-sea channels (for example the Penghu submarine channel) to the NE South China Sea upper slope near the present Hengchun Peninsula.

Acknowledgments

We are grateful to two anonymous reviewers and the editor-in-chief professor Bor-ming Jahn for their critical reviews and helpful suggestions. This work was financially co-supported by the Knowledge Innovation Program of the Chinese Academy of Sciences (Grant KZCX2-EW-101), the National Natural Science Foundation of China (Grant 41176041 and 91128211) and Major State Basic Research Program of the People's Republic of China (2009CB219401). This is contribution No. IS-1816 from GIGCAS.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jseaes.2014.01.021.

References

Barckhausen, U., Roeser, H.A., 2004. Seafloor spreading anomalies in the South China Sea revisited. In: Clift, P., Wang, P., Kuhnt, W., et al. (Eds.), Continent-Ocean Interations within East Asian Marginal Seas, AGU Geophys Monogr, vol. 149. pp. 121–125.

Basu, A., Suttner, L.J., James, W.C., Mack, G.H., 1975. Re-evaluation of the use of undulatory extinction and polycrystallinity in detrital quartz for provenance interpretation. J. Sed. Petrol. 45 (4), 873–882.

Briais, A., Patriat, P., Tapponnier, P., 1993. Updated interpretation of magnetic anomalies and seafloor spreading stages in the South China Sea: Implications for the Tertiary tectonics of Southeast Asia. J. Geophys. Res. Sol. Ea. (1978–2012) 98 (B4), 6299–6328.

Cathy, J.B., Raymond, V.I., 1995. Tectonics of Sedimentary Basins. Blackwell Science, Cambridge, Massachusetts, USA.

Chang, L.S., 1964. A biostratigraphic study of the tertiary in the Hengchun Peninsula, Taiwan, based on smaller foraminifera (I: Northern Part). Proc. Geol. Soc. China 7, 48–62.

Chang, L.S., 1965. A biostratigraphic study of the tertiary in the Hengchun Peninsula, Taiwan, based on smaller foraminifera (II: Middle Part). Proc. Geol. Soc. China 8, 9–18.

Chang, L.S., 1966. A biostratigraphic study of the tertiary in the Hengchun Peninsula, Taiwan, based on smaller foraminifera (III: Southern Part). Proceedings of the Geological Society of China 9, 55–63.

Chang, C.P., Angelier, J., Lee, T.Q., Huang, C.Y., 2003. From continental margin extension to collision orogen: structural development and tectonic rotation of the Hengchun peninsula, southern Taiwan. Tectonophysics 361, 61–82. http://dx.doi.org/10.1016/S0040-1951(02)00561-9.

Chen, J.F., Jahn, B.M., 1998. Crustal evolution of southeastern China: Nd and Sr isotopic evidence. Tectonophysics 284, 101–133. http://dx.doi.org/10.1016/S0040-1951(97)00186-8.

Chen, C.H., Jahn, B.M., Lee, T.P., Chen, C.H., Jean, C., 1990a. Sm–Nd isotopic geochemistry of sediments from Taiwan and implications for the tectonic evolution of southeast China. Chem. Geol. 88, 317–332. http://dx.doi.org/10.1016/0009-2541(90)90096-P.

Chen, C.H., Shieh, Y.N., Lee, T., Chen, C.H., Mertzman, S.A., 1990b. Nd–Sr–O isotopic evidence for source contamination and an unusual mantle component under Luzon Arc. Geochim. Cosmochim. Acta 54 (9), 2473–2483. http://dx.doi.org/10.1016/0016-7037(90)90234-C.

Cheng, Y.M., Huang, C.Y., Yen, J.J., 1984. The Loshui formation: Deeper-water sandstones on the Hengchun Peninsula, Southern Taiwan. Acta Geol. Taiwanica 22, 100–117.

Chi, W.R., Namson, J., Suppe, J., 1981. Stratigraphic record of the plate interactions of the Coastal Range of eastern Taiwan. Memoir Geol. Soc. China 4, 155–194.

Chou, J.T., 1973. Sedimentology and palegeography of the upper Cenozoic system of western Taiwan. Proc. Geol. Soc. China 16, 111–143.

Chou, J.T., 1980. Stratigraphy and sedimentology of the Miocene in western Taiwan. Petrol. Geol. Taiwan 17, 33–52.

Chou, J.T., 1988. Eocene formations in Taiwan. Petrol. Geol. Taiwan 24, 51–59.

Clift, P.D., Vannucchi, P., 2004. Controls on tectonic accretion versus erosion in subduction zones: implications for the origin and recycling of the continental crust. Rev. Geophys. 42 (2). http://dx.doi.org/10.1029/2003RG000127.

Clift, P.D., Lee, J.I., Clark, M.K., Blusztajn, J., 2002. Erosional response of south China to arc rifting and monsoonal strengthening; a record from the South China Sea. Marine Geol. 184 (3–4), 207–226.

Clift, P.D., Schouten, H., Draut, A.E., 2003. A general model of arc-continent collision and subduction polarity reversal from Taiwan and the Irish Caledonides. Geological Soc., London, Special Publications 219 (1), 81–98.

Clift, P.D., Hodges, K.V., Heslop, D., Hannigan, R., Van Long, H., Calves, G., 2008. Correlation of Himalayan exhumation rates and Asian monsoon intensity. Nat. Geosci. 1 (12), 875–880.

Dickinson, W.R., 1985. Interpreting provenance relations from detrital modes of sandstones. NATO ASI Ser., Ser. C Mathe. Phys. Sci. 148, 333–361.

Dickinson, W.R., Suczek, C.A., 1979. Plate tectonics and sandstone compositions. AAPG Bull. 63, 2164–2182.

Enkelmann, E., Weislogel, A., Ratschbacher, L., Eide, E., Renno, A., Wooden, J., 2007. How was the Triassic Songpan-Ganzi basin filled? A provenance study. Tectonics 26, TC4007.

Goldstein, S.J., Jacobsen, S.B., 1988. Nd and Sr isotopic systematics of River water suspended material – implications for crustal evolution. Earth Planetary Sci. Lett. 87 (3), 249–265.

Griffin, W.L., Belousova, E.A., Shee, S.R., Pearson, N.J., O'Reilly, S.Y., 2004. Archean crustal evolution in the northern Yilgarn Craton: U–Pb and Hf isotope evidence from detrital zircons. Precambr. Res. 131, 231–282. http://dx.doi.org/10.1016/j.precamres.2003.12.011.

Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology fluctuating sea levels since the Triassic. Science 235, 1156–1167. http://dx.doi.org/10.1126/science.235.4793.1156.

Hu, X.M., Huang, Z.C., Wang, J.G., Yu, J.H., Xu, K.D., Jansa, L.B., Hu, W.X., 2012a. Geology of the Fuding inlier in southeastern China: implication for late Paleozoic Cathaysian paleogeography. Gondwana Res. 22, 507–518. http://dx.doi.org/10.1016/j.gr.2011.09.016.

Hu, D., Böning, P., Köhler, C.M., Hillier, S., Pressling, N., Wan, S., Brumsack, H.-J., Clift, P.D., 2012b. Deep sea records of the continental weathering and erosion response to East Asian monsoon intensification since 14 ka in the South China Sea. Chem. Geol. 326–327, 1–18. http://dx.doi.org/10.1016/j.chemgeo.2012.07.024.

Hu, D., Clift, P.D., Böning, P., Hannigan, R., Hillier, S., Blusztajn, J., Wang, S., Fuller, D.Q., 2013. Holocene evolution in weathering and erosion patterns in the Pearl River delta. Geochem. Geophys. Geosyst. 14, 2349–2368. http://dx.doi.org/10.1002/ggge.20166.

Huang, C.Y., 1982. Study on Smaller Foraminifera from the Oligocene and Miocene Formations of Northern Taiwan. Doctoral thesis, Institute of Geology, National Taiwan University.

Huang, C.Y., 1984. Field Trip Guide to the Hengchun Peninsula, Southern Taiwan. Sino-French Colloquium on Geodynamics of the Eurasian – Philippine Sea Plate Boundary, April 26–30, pp. 77–94.

Huang, C.Y., 1986. Oligocene and Miocene stratigraphy of the Kuohsing area, central Taiwan. Acta Geol. Taiwanica 24, 281–318.

Huang, C.Y., Shyu, C.T., Lin, S.B., Lee, T.Q., Sheu, D.D., 1992. Marine geology in the arc-continent collision zone off southeastern Taiwan: implications for late Neocene evolution of the coastal range. Mar. Geol. 107, 183–212. http://dx.doi.org/10.1016/0025-3227(92)90167-G.

Huang, C.Y., Wu, W.Y., Chang, C.P., Lin, C.W., 1997. Tectonic evolution of the accretionary prism in the arc-continent collision terrane of Taiwan. Tectonophysics 281, 31–51. http://dx.doi.org/10.1016/S0040-1951(97)00157-1.

Huang, C.Y., Yuan, P.B., Lin, C.W., Wang, T.K., 2000. Geodynamic processes of Taiwan arc-continent collision and comparison with analogs in Timor, Papua New Guinea, Urals and Corsica. Tectonophysics 325, 1–21. http://dx.doi.org/10.1016/S0040-1951(00)00128-1.

Huang, C.Y., Xia, K.Y., Yuan, P.B., Chen, P.G., 2001. Structural evolution from Paleogene extension to Latest Miocene-Recent arc-continent collision offshore Taiwan: comparison with on land geology. J. Asian Earth Sci. 19, 619–639. http://dx.doi.org/10.1016/S1367-9120(00)00065-1.

Huang, C.Y., Yuan, P.B., Tsao, S.J., 2006. Temporal and spatial records of active arc-continent collision in Taiwan: a synthesis. Geol. Soc. America Bull. 118 (3–4), 274–288. http://dx.doi.org/10.1130/B25527.1.

Huang, C.Y., Chien, C.W., Yao, B., Chang, C.P., 2008. The Lichi Mélange: A collision mélange formation along early arcward backthrusts during forearc basin closure, Taiwan arc-continent collision. In: Draut, A.E., Clift, P.D., Scholl, D.W., (Eds.), Formation and Applications of the Sedimentary Records in Arc Continent Collision Zone. Geological Society of America Special Paper 436, pp. 127–154, doi: 10.1130/2008.2436(06).

Hsu, S.K., Yeh, Y.C., Doo, W.B., Tsai, C.H., 2004. New bathymetry and magnetic lineations identifications in the northeasternmost South China Sea and their tectonic implications. Mar. Geophys. Res. 25 (1), 29–44.

Huang, C.Y., Yen, Y., Liew, P.M., He, D.J., Chi, W.R., Wu, M.S., Zhao, M.X., 2013. Significance of indigenous Eocene larger foraminifera *Discocyclina dispansa* in Western Foothills, Central Taiwan: a Paleogene marine rift basin in Chinese continental margin. J. Asian Earth Sci. 62, 425–437.

Kirstein, L.A., Carter, A., Chen, Y.G., 2010. Testing inferences from palaeocurrents: application of zircon double-dating to Miocene sediments from the Hengchun Peninsula, Taiwan. Terra Nova 22 (6), 483–493. http://dx.doi.org/10.1111/j.1365-3121.2010.00970.x.

Lee, Y.H., Chen, C.C., Liu, T.K., Ho, H.C., Lu, H.Y., Lo, W., 2006. Mountain building mechanisms in the Southern Central Range of the Taiwan Orogenic Belt – From accretionary wedge deformation to arc-continental collision. Earth Planetary Sci. Lett. 252, 413–422. http://dx.doi.org/10.1016/j.epsl.2006.09.047.

Li, X.H., 1997. Timing of the Cathaysia Block formation: constraints from SHRIMP U–Pb zircon geochronology. Episodes 20, 188–192.

Li, P., Rao, C., 1994. Tectonic characteristics and evolution history of the Pearl River Mouth Basin. Tectonophysics 235, 13–25.

Li, S.G., Chen, Y.Z., Ge, N.J., Hu, X.J., Liu, D.L., 1996. Isotopic ages of Metavolcanic Rocks and Metacryst Mylonite in the Badu Group in Southwestern Zhejiang Province and their implication for tectonics. Acta Petrol. Sin. 12 (1), 79–87.

Li, X.H., Wei, G.J., Shao, L., Liu, Y., Liang, X.R., Jian, Z.M., Sun, M., Wang, P.X., 2003. Geochemical and Nd isotopic variations in sediments of the South China Sea: a response to Cenozoic tectonism in SE Asia. Earth Planetary Sci. Lett. 211, 207–220. http://dx.doi.org/10.1016/S0012-821X(03)00229-2.

Lin, A.T., Watts, A.B., Hesselbo, S.P., 2003. Cenozoic stratigraphy and subsidence history of the South China Seamargin in the Taiwan region. Basin Res. 15, 453–478. http://dx.doi.org/10.1046/j.1365-2117.2003.00215.x.

Liu, C.H., Pang, Y.S., 1984. Seismic stratigraphic study on the tertiary sequences in the Hsinchu Basin, Taiwan. Petrol. Geol. Taiwan 20, 97–112.

Liu, Z.F., Tuo, S.T., Colin, C., Liu, J.T., Huang, C.Y., Selvaraj, K., Chen, C.T.A., Zhao, Y.L., Siringan, F.P., Boulay, S., Chen, Z., 2008. Detrital fine-grained sediment contribution from Taiwan to the northern South China Sea and its relation to regional ocean circulation. Mar. Geol. 255 (3–4), 149–155. http://dx.doi.org/10.1016/j.margeo.2008.08.003.

Liu, Y.S., Gao, S., Hu, Z.C., Gao, C.G., Zong, K.Q., Wang, D.B., 2010a. 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. J. Petrol. 51 (1–2), 537–571. http://dx.doi.org/10.1093/petrology/egp082.

Liu, Y.S., Hu, Z.C., Zong, K.Q., Gao, C.G., Gao, S., Xu, J., Chen, H.H., 2010b. Reappraisement and refinement of zircon U–Pb isotope and trace element analyses by LA-ICP-MS. Chin. Sci. Bull. 55 (15), 1535–1546. http://dx.doi.org/10.1007/s11434-010-3052-4.

Ludwig, K.R., 2000. Isoplot/Ex version 2.3. – A Geochronological Toolkit for Microsoft Excel. Berkeley Geochronology Center, Special, Publication No. 1a.

Ludwig, K.R., 2003. User's Manual for Isoplot 3.0: Geochronological Toolkit for Microsoft Excel. Berkeley Geochronology Center Special Publication 4, 1–70.

Mutti, E., Lucchi, F.R., 1972. Turbidites of the Northern Apennines: introduction to facies analysis. Int. Geol. Rev. 20, 125–166.

Page, B.M., Lan, C.Y., 1983. The Kenting Mélange and its record of tectonic events. Mem. Geol. Soc. China 5, 227–248.

Reed, D.L., Lundberg, N., Liu, C.S., Luo, B.Y., 1992. Structural relations along the margins of the offshore Taiwan accretionary wedge: implications for accretion and crustal kinematics. Acta Geol. Taiwanica Sci. Rep. Natl. Taiwan Univ. 30, 105–122.

Shan, Y.H., Nie, G.J., Yan, Y., Huang, C.Y., 2013. The transition from the passive to active continental margin: a case study of brittle fractures in the Miocene Loshui Sandstone on the Hengchun Peninsula, southern Taiwan. Tectonics 32, 65–79. http://dx.doi.org/10.1029/2012TC003178.

Shao, L., Qiao, P.J., Pang, X., Wei, G.J., Li, Q.Y., Miao, W.L., Li, A., 2009. Nd isotopic variations and its implications in the recent sediments from the northern South China Sea. Chin. Sci. Bull. 54 (2), 311–317. http://dx.doi.org/10.1007/s11434-008-0453-8.

Shi, Y.S., Liu, S.H., 1980. Discovery of flysch construction at Nanxi, Fuding: implications to the Paleozoic basement and tectonics (in Chinese with English abstract). J. Nanjing Univ. (Nat. Sci.) 4, 121–127.

Sun, C.S., 1982. The Tertiary basins of offshore Taiwan. In: Proc. 2nd ASCOPE Conference and Exhibition, Manila, Philippines, 1981, pp. 125–135.

Sung, Q.C., Wang, Y., 1985. Petrofacies of late Miocene sediments in the Hengchun Peninsula and its tectonic implication. Proc. Geol. Soc. China 28, 23–44.

Sung, Q.C., Wang, Y., 1986. Sedimentary environments of the Miocene sediments in the Hengchun Peninsula and their tectonic implications. Mem. Geol. Soc. China 7, 325–340.

Steinke, S., Groeneveld, J., Johnstone, H., Rendle-Bühring, R., 2010. East Asian summer monsoon weakening after 7.5 Ma: Evidence from combined planktonic foraminifera Mg/Ca and $\delta^{18}O$ (ODP Site 1146; northern South China Sea). Palaeogeography, Palaeoclimatology, Palaeoecology 289 (1), 33–43.

Tang, C.H., 1977. Late Miocene erosional unconformity on the subsurface Peikang high between the Chiayi-Yunlin coastal plain, Taiwan. Geol. Soc. China 2, 155–167.

Taylor, B., Hayes, D.E., 1983. Origin and history of the South China Sea basin. In: Hayes, D.E., (Ed.), The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands: Part 2. Geophys. Monogr. Ser., AGU, Washington, D.C., vol. 27, pp. 23–56 doi:10.1029/GM027p0023.

Tsao, S.J., Song, S.R., Lee, C.Y., Shea, K.S., 1999. Penghu Islands, Geologic Map of Taiwan. Central Geological Survey, Xinbei.

Tucker, M.E., 2001. Sedimentary Petrology: An Introduction to the Origin of Sedimentary Rocks, 3rd ed. Blackwell Science, London (pp. 262).

Vermeesch, P., 2004. How many grains are needed for a provenance study? Earth and Planetary Science Letters 224 (3), 441–451.

Walker, R.G., 1978. Deep-water sandstone facies and ancient submarine fans: models for exploration for stratigraphic traps. The American Assoc. Petrol. Geol. 62 (6), 932–966.

Wan, Y.S., Liu, D.Y., Xu, M.H., Zhang, J.M., Song, B., Shi, Y.R., Du, L.L., 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 Res. 12, 166–183. http://dx.doi.org/10.1016/j.gr.2006.10.016.

Wang, D.Z., Shen, W.Z., 2003. Genesis of granitoids and crustal evolution in southeast China (in Chinese with English abstract). Earth Sci. Front. (China University of Geosciences, Beijing) 10 (3), 210–219.

Wang, N., He, X., Lu, S., 1989. Cenozoic Paleobiota of the Continental Shelf of the East China Sea (Foraminifera). Geological Publishing House, Beijing (pp. 6–136).

Wang, Q., Li, J.W., Jian, P., Zhao, Z.H., Xiong, X.L., Bao, Z.W., Xu, J.F., Li, C.F., Ma, J.L., 2005. Alkaline syenites in eastern Cathaysia (South China): link to Permian-Triassic transtension. Earth Planet. Sci. Lett. 230 (3–4), 339–354. http://dx.doi.org/10.1016/j.epsl.2004.11.023.

Wang, Y., Zhang, F., Fan, W., Zhang, G., Chen, S., Cawood, P.A., Zhang, A., 2010. Tectonic setting of the South China Block in the early Paleozoic: resolving intracontinental and ocean closure models from detrital zircon U–Pb geochronology. Tectonics 29, TC6020 (doi:10.1029/2010TC002750).

Wei, G.J., Liang, X.R., Li, X.H., Liu, Y., 2002. Precise measurement of Sr isotopic composition of liquid and solid base using (LP) MC-ICPMS (in Chinese with English abstract). Geochimica 31 (3), 295–299.

Wei, G.J., Liu, Y., Ma, J.L., Xie, L.H., Chen, J.F., Deng, W.F., Tang, S., 2012. Nd, Sr isotopes and elemental geochemistry of surface sediments from the South China Sea: implications for Provenance Tracing. Mar. Geol. 319, 21–34. http://dx.doi.org/10.1016/j.margeo.2012.05.007.

Wong, J., Sun, M., Xing, G., Li, X.H., Zhao, G., Wong, K., Yuan, C., Xia, X., Li, L., Wu, F., 2009. Geochemical and zircon U–Pb and Hf isotopic study of the Baijuhuajian metaluminous A-type granite: extension at 125–100 Ma and its tectonic significance for South China. Lithos 112, 289–305. http://dx.doi.org/10.1016/j.lithos.2009.03.009.

Wu, Q., Li, X.M., 1990. Carboniferous stratigraphy and tectonic environment in Fuding, Fujian (in Chinese with English abstract). Reg. Geol. China 4, 327–333.

Xu, Y.H., Chen, J., 2010. Uranium-lead dating of detrial zircons from the Minjiang and Jiulong Estuaries in the western coast of the Taiwan Strait: implication for its provenance (in Chinese with English abstract). Acta Oceanolog. Sin. 32, 110–117.

Xu, X.S., O'Reilly, S.Y., Griffin, W.L., Wang, X.L., Pearson, N.J., He, Z.Y., 2007. The crust of Cathaysia: age, assembly and reworking of two terranes. Precambr. Res. 158, 51–78. http://dx.doi.org/10.1016/j.precamres.2007.04.010.

Yan, Y., Xia, B., Lin, G., Carter, A., Hu, X.Q., Cui, X.J., Liu, B.M., Yan, P., Song, Z.J., 2007. Geochemical and Nd isotope composition of detrital sediments on the north margin of the South China Sea: provenance and tectonic implications. Sedimentology 54, 1–17. http://dx.doi.org/10.1111/j.1365-3091.2006.00816.x.

Yang, T.Y., Tien, J.L., Chen, C.H., Lee, T., Punongbayan, R., 1995. Fission-track dating of volcanics in the northern part of the Taiwan-Luzon arc: eruption ages and evidence for crustal contamination. J. SE Asian Earth Sci. 11, 81–93.

Young, S.W., 1976. Petrographic textures of detrital polycrystalline quartz as an aid to interpreting crystalline source rocks. J. Sed. Petrol. 46, 595–603.

Yu, S.B., Chen, H.Y., Kuo, L.C., 1997. Velocity field of GPS stations in the Taiwan area. Tectonophysics 274, 41–59. http://dx.doi.org/10.1016/S0040-1951(96)00297-1.

Yu, J.H., Wang, L.J., O'Reilly, S.Y., Griffin, W.L., Zhang, M., Li, C.Z., Shu, L.S., 2009. A paleoproterozoic orogeny recorded in a long-lived cratonic remnant (Wuyishan terrane), eastern Cathaysia Block, China. Precambr. Res. 174 (3–4), 347–363. http://dx.doi.org/10.1016/j.precamres.2009.08.009.

Yu, J.H., O'Reilly, S.Y., Zhou, M.F., Griffin, W.L., Wang, L.J., 2012. U–Pb geochronology and Hf–Nd isotopic geochemistry of the Badu Complex, Southeastern China: Implications for the Precambrian crustal evolution and paleogeography of the Cathaysia Block. Precambr. Res. 222–223, 424–449. http://dx.doi.org/10.1016/j.precamres.2011.07.014.

Yui, T.F., Okamoto, K., Usuki, T., Lan, C.Y., Chu, H.T., Liou, J.G., 2009. Late Triassic–Late Cretaceous accretion/subduction in the Taiwan region along the eastern margin of South China – evidence from zircon SHRIMP dating. Int. Geol. Rev. 51 (4), 304–328. http://dx.doi.org/10.1080/00206810802636369.

Zheng, H., Clift, P.D., Wang, P., Tada, R., Jia, J., He, M., Jourdan, F., 2013. Pre-Miocene birth of the Yangtze River. Proceedings of the National Academy of Sciences 110 (19), 7556–7561.

Zhou, X.M., Li, W.X., 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. http://dx.doi.org/10.1016/S0040-1951(00)00120-7.