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Zircon LA-ICPMS U–Pb ages and Hf isotopes of Huayu (Penghu Islands) volcanics in the Taiwan Strait and tectonic implication

Cheng-Hong Chen [a,*], Pei-Shan Hsieh [a,d], Kuo-Lung Wang [b], Huai-Jen Yang [c], Wayne Lin [d], Yu-Hsuan Liang [a], Chi-Yu Lee [a], Hsiao-Chin Yang [a]

[a] *Department of Geosciences, National Taiwan University, No. 1, Roosevelt Road, Section 4, Taipei 106, Taiwan*
[b] *Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan*
[c] *Department of Earth Sciences, National Cheng Kung University, Tainan, Taiwan*
[d] *Energy and Environment Research Laboratories, ITRI, Hsinchu, Taiwan*

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A B S T R A C T

Huayu, the only non-basalt islet in the Penghu Islands, consists mainly of andesite lavas intruded by some intermediate (dacite/granodiorite) and felsic (rhyolite/granite) dikes. The LA-ICPMS U–Pb zircon age determination yields 437 ± 13 Ma (n = 16, MSWD = 6.9) for the andesite lava and 63.3 ± 1.5 Ma (n = 7; MSWD = 2.9) for its potassic altered zone, and 58.7 ± 0.8 Ma (n = 14; MSWD = 2.5) for one rhyolite dike. The old and young groups of zircon show distinctive Hf isotope compositions: $\varepsilon Hf_{(T)} = -9$ for ~437 Ma zircons vs. $\varepsilon Hf_{(T)}$ = +9 to +6 and +9 to −1 for ~63 Ma and ~59 Ma zircons. On the other hand, Sr and Nd isotopic compositions of the andesite lava (ISr = 0.7034 and $\varepsilon Nd_{(T)}$ = +3.9 if T = 437 Ma) are more depleted than the alteration zone and rhyolite dike (ISr = 0.7051 and $\varepsilon Nd_{(T)}$ = −1.3 to −1.9). Decoupling of zircon $\varepsilon Hf_{(T)}$ and whole-rock $\varepsilon Nd_{(T)}$ values of the andesite lava rules out the possibility of 437 ± 13 Ma to be the eruption time. Alternatively, based on the similarity between the published zircon fission track ages (65 ± 3 Ma for the andesite lava and 61 ± 2 Ma for the rhyolite dike; [Yang, H.C., Chen, W.S., Huang, J.C., Wang Lee, C.M., 2008. Volcanic lithofacies of the Huayu Island. Bulletin of Central Geological Survey 21, 143–164 (in Chinese with English Abstract)]) and our U–Pb zircon ages of the altered andesite zone and rhyolite dike, the span of 65–63 Ma is suggested to be the formation time of Huayu andesites. Since Huayu is situated in a NE–SW trending high-magnetic anomaly belt which has been generally interpreted as a remnant magmatic terrain, these data, along with the geochemical results, provide insights of this belt as a split part of the Southeast Coast Magmatic Belt in which Huayu volcanics represent the younger arc volcanism comparable with those appeared in southern Fujian.

1. Introduction

Southeast China coastal area is a terrain known for prevailed Yanshanian magmatic activities. Major products mainly involve Jurassic and Cretaceous intrusive and extrusive rocks, in which the Cretaceous igneous rocks define the Southeast Coast Magmatic Belt. Recent geochronological and geochemical studies reveal a general regularity of the Cretaceous magmatic evolution over this Belt: shallow intrusions of I-type granitoids occurred at 110–99 Ma, near surface intrusion of A-type granite at 110–91 Ma (peaked at 94–91 Ma), and rhyolite-dominating basalt/rhyolite bi-modal volcanism at 101–81 Ma (Martin et al., 1994; Chen et al., 2004, 2008a; Hsieh et al., 2009). Although appeared to be in small volumes, some younger andesite–rhyolite associations are also present in the Southeast Coast Magmatic Belt. For example, the age reported for the Lingtongshan rhyolite of southern Fujian is 72 Ma (Chen et al., 2008a). Further extending to eastern Guangdong, Zhu et al. (2004) reported the occurrence of the Late Cretaceous/Early Cenozoic basalt–andesite–dacite associations. All these information seem to reflect a southwestward migration of volcanism along the Southeast Coast Magmatic Belt during the Late Cretaceous/Early Cenozoic time.

The existence of andesitic rocks in Penghu Islands has only been little envisaged. Yen (1963, 1988) explained that it is an indication of the influence of the island arc tectonic setting, but the eruption time of these andesites is still unknown. Based on the fission track (FT) zircon ages for the andesitic lava and dike rocks, they have been postulated as representatives of Jurassic to Cretaceous arc volcanism pertaining to those commonly appeared in the south-east China (Yang, 1989). Due to the lower closure temperature of the FT system (240 °C for zircon; Yamada et al., 1995), these ages

* Corresponding author. Address: Department of Geosciences, National Taiwan University, No.1, Roosevelt Road Section 4, Taipei 106, Taiwan. Tel.: +886 2 3366 5872; fax: +886 2 2363 6095.
E-mail address: chench@ntu.edu.tw (C.-H. Chen).

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most likely recorded the time that zircon has lastly reached the annealing temperature since the time of volcanic eruption. In this study, we use the laser-ablation-induced coupled plasma mass spectrometry (LA-ICPMS) technique to reveal the U–Pb zircon age of the andesite lava. In situ hafnium isotopic compositions of some dated zircon are also measured for the verification of their sources. To unravel the geochemical and isotopic characteristics of the Huayu volcanics, we also conduct major and trace element analysis and Sr and Nd isotope ratio measurements for some representative samples. With the geochronological, geochemical and Sr and Nd isotope information, the nature of the andesite lava in Huayu islet can be better constrained.

2. Geological background

South China Block is a Paleoproterozoic continent accreted with Neoproterozoic terrains (Li, 2000). Major contributions came from Caledonian, Indosinian and Early Yanshanian orogenesis, as well as the final overprints of the Late Yanshanian thermal activities at the Cretaceous (Xu et al., 2005; Hsieh et al., 2008). The coastal areas of the southeast China are now exposed with large volume of Late Cretaceous shallow intrusive and volcanic rocks, representing a prevalence of post-Late Yanshanian orogenic magmatism under the lithosphere extension (Chen et al., 2004). In the Cenozoic, these areas were developed with further continental extension, magmatism were dominated by basaltic eruptions mainly occurred at Eocene and Miocene (Chen et al., 1997; Chung et al., 1994).

Penghu Islands, composed of Late Miocene basaltic rocks (Juang, 1988; Lee, 1994) in more than 60 islets in the Taiwan Strait (Fig. 1a), are typical of the products of intraplate volcanism related to this continental extension. The Huayu islet (1.8 km^2) is the only exception that is non-basaltic. Earlier investigators described that the lithology of Huayu is various kinds of porphyrite, especially the dike rocks were categorized as quartz porphyrite (Yen, 1963). Based on the geochemical studies, Yang (1989) was able to distinguish the andesite lava from dacite and rhyolite dikes for these so-called porphyrites. In addition, a basalt dike cutting through andesite lava was also reported. Sedimentary xenoliths, mainly including sandstones and shales, are common in the lava, and the host rocks have subjected to low-grade metamorphism islet-wide (Yen, 1963, 1988).

During June 2007, a new survey on the Huayu islet was conducted. Samples collected include andesite lavas and breccias as well as dacite and rhyolite dikes (Fig. 1b) that had been described by Yang (1989). In addition, a tuff-like rock was found to have closely associated with the andesite lava in the northern part of this islet (No. 7 in Fig. 1b). It is a light colored, fine-grained, compact rock showing a weak shear structure coinciding with the andesite lavas. This sample is included particularly for geochronological study, because U–Pb zircon ages of all kinds of volcanics are substantial to reveal the history of magmatic activity of this islet. For andesites, we use more fresh boulders rather than outcrop samples that are mostly altered. It is noted that, due to lack of clear usage of terminology for dike rocks in Huayu by far, e.g., dacite vs. granodiorite (our new observation) and rhyolite vs. granite (Yang, 1989; Yang et al., 2008) based on large variations of grain size, here we adopt dacite and rhyolite for intermediate and felsic dikes, respectively, because they are closer to the analyzed samples.

3. Methods of study

Six samples, including three andesites, and one dacite, rhyolite and tuff-like rock each, have been crushed for mineral separation of zircons and pulverized for measuring major and trace element contents. Unfortunately, only three samples provide enough zircon grains for U–Pb age dating. These three particular samples are further determined for Sr and Nd isotope ratios. Procedures for elemental and Sr and Nd isotopic analysis follow those described by Chen et al. (2004). Mineral compositions of primary phase in the studied samples have been carried out using an electron microprobe (Shimadzu-ARL model EMX-SM) at National Taiwan University. Furthermore, the tuff-like sample (HY-L-07) has been examined for identifying the secondary minerals and the presence or absence of quartz through an X-ray diffractometer (Rigaku model MACsci), using the dacite (HY-L-06) and the rhyolite (HY-L-05) dikes as references.

Zircon separates of one andesite (HY-G-41), the tuff-like rock (HY-L-07), and the rhyolitic dike (HY-L-05) have been subjected to the U–Pb dating following analytical procedures described by Yuan et al. (2004) and Chiu et al. (in press). Their internal growth textures were documented by cathodoluminance (CL) images using a JEOL JSM-6360LV scanning electron microscope attached with a panchromatic CL imaging system (Gatan Mini-CL) at Academia Sinica (Taipei). U–Pb isotopic ratios and concentrations of sample HY-G-41 zircons were determined on 40 μm diameter spots of single zircons by an excimer LA-ICPMS at the Northwest University (Xi'an, China) and those of samples HY-L-07 and HY-L-05 zircons, at National Taiwan University (NTU). The ICPMS used was an Elan 6100 Dynamic Reaction Cell (Perkin Elmer/SCIEX) coupled to the GeoLas 200M laser-ablation system (MicroLas) equipped with a 193 nm ArF-excimer laser and a homogenizing, imaging optical system at Xi'an and an Agilent 7500s coupled to the UP213 laser-ablation system (New Wave Research/Merchantek) at NTU. $^{207}Pb/^{206}Pb$, $^{207}Pb/^{235}U$, $^{206}Pb/^{238}U$ and $^{208}Pb/^{232}Th$ ratios were calculated using the GLITTER 4.0 software (Macquarie University), which were then corrected from the external standard—Harvard zircon 91500 (Wiedenbeck et al., 1995) at the Northwest University and GJ-1 zircon (Jackson et al., 2004) at NTU. Common lead corrections were made following the procedure of Andersen (2002). Using the ISOPLOT (rev. 3) program (Ludwig, 2003), ages were calculated (Table 1). A good agreement between same zircon grains using these two U–Pb dating systems has been reported (Hsieh, 2008).

Hafnium isotope analyses were carried out in situ using a New Wave UP 213 laser-ablation microprobe, attached to a Nu Plasma multi-collector ICPMS at Academia Sinica (Taipei). Instrumental conditions and data acquisition were that reported by Griffin et al. (2000). The Nu Plasma MC-ICPMS features a unique geometry with a fixed detector array of 12 Faraday cups and three ion counters. For this work masses 172, 175, 176, 177, 178, 179 and 180 were simultaneously analyzed in Faraday cups; all analyses were carried out in static-collection mode. Data were normalized to $^{179}Hf/^{177}Hf = 0.7325$, using an exponential correction for mass bias. Initial setup of the instrument was done using a 50 ppb solution of AMES Hf metal, which typically yielded a total Hf beam of 10–14×10^{-11} A. Isobaric interferences of ^{176}Lu and ^{176}Yb on ^{176}Hf were corrected by measuring the intensities of the interference-free ^{175}Lu and ^{172}Yb isotopes and calculations of $^{176}Lu/^{177}Hf$ and $^{176}Yb/^{177}Hf$ ratios were based on appropriate $^{176}Lu/^{175}Lu$ and $^{176}Yb/^{172}Yb$ values (0.02669 and 0.5865; Griffin et al., 2000). Reproducibility of the Hf isotope analyses is demonstrated by 28 Hf analyses on the 50 ppb solution of the AMES Hf metal. Our mean value for $^{176}Hf/^{177}Hf$ is 0.282152 ± 18 (2σ), identical to the recommended value of 0.282151 ± 13 by Münker et al. (2001). The typical 2 S.E. uncertainty on a single analysis of $^{176}Hf/^{177}Hf$ is 6–8×10^{-6}.

The New Wave UP 213 laser system delivers a beam of 213 nm UV light from a frequency-quintupled (5th harmonic) Nd:YAG laser. Most analyses were carried out with a beam diameter of ca 50 μm, a 5 Hz repetition rate, and energies of ~0.4 mJ/pulse. This resulted in total Hf signals of $1–2.5 \times 10^{-11}$ A, depending on

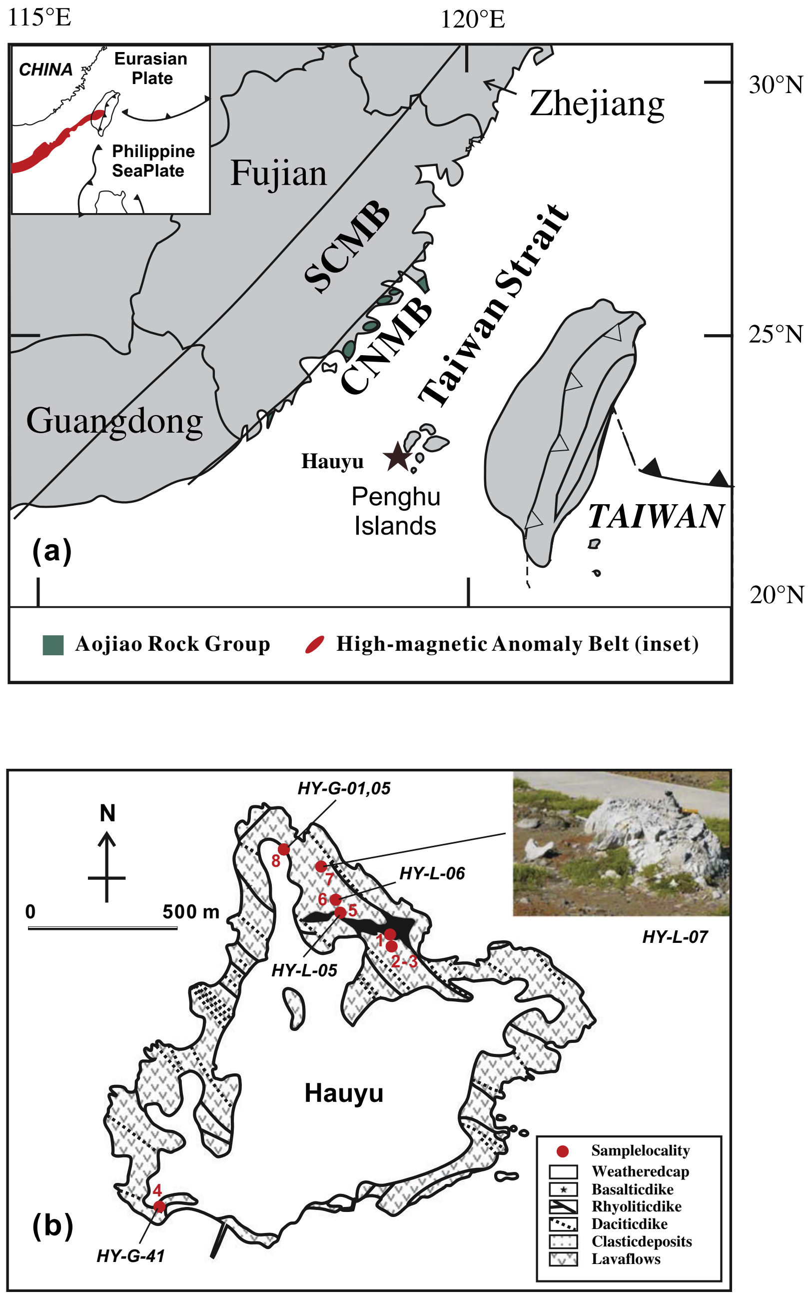

Fig. 1. (a) Position of Huayu islet (the star) in the Penghu Islands and its relation to the Southeast Coast Magmatic Belt (SCMB) and Changle-Nanao Metamorphic Belt (CNMB) in the coastal area of SE China continent. The inset shows that Huayu islet situates on a high-magnetic anomaly belt (Cheng, 2004). (b) Geological map of Huayu islet (Yang 1989) with sample localities of this study. 1: rhyolite dike; 2–3: andesite xenoliths; 4: andesite lava; 5: rhyolite dike; 6: dacite dike; 7: tuff-like rock; 8: andesite breccia.

conditions and the Hf contents. Typical ablation times were 80–120 s. He carrier gas transported the ablated sample from the laser-ablation cell to the ICPMS torch via a mixing chamber where Ar is mixed. Flux rate for He and Ar is about 1 L/min and 0.7 L/min, respectively. The laser-ablation analyses were carried out using the time-resolved analytical software, by which the signal for each mass and each ratio is displayed as a function of time. This allows the more stable portions of the ablation to be selected for analysis. Background was collected on peak for 30 s before ablation. Typical within-run precision (2S.E.) on the analysis of $^{176}Hf/^{177}Hf$ is ±0.000030, nearly equivalent to an uncertainty of one epsilon unit.

To evaluate the accuracy and precision of the laser-ablation results, we have repeatedly analyzed two zircon standards, Mud Tank and 91500 (Wiedenbeck et al., 1995; Woodhead and Hergt, 2005; Griffin et al., 2006). Our long-term result of Mud Tank zircon, yielding 0.282518 ± 48 (2σ; $n = 65$), is consistent with the reported value of 0.282522 ± 42 (2σ; $n = 2335$) by Griffin et al. (2006) and also similar to the values given by Woodhead and Hergt (2005) for solution analysis (0.282507 ± 6; $n = 5$) and LAM-MC-ICPMS analysis (0.282504 ± 44; $n = 158$). Griffin et al. (2006) pointed out that the zircon 91500 show isotopic heterogeneity, limiting its role to be used to evaluate the precision and accuracy for in situ analysis. Nevertheless, our result for the zircon 91500 is 0.282319 ± 94 (2σ; $n = 28$), comparable to many reported values from literatures. All these results demonstrate that the method in this work can produce precise and accurate data on the Hf isotope composition of zircons. To calculate $\varepsilon Hf_{(T)}$ values, we adopted the chondritic ratios of $^{176}Hf/^{177}Hf$ (0.282772) and $^{176}Lu/^{177}Hf$

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Table 1
LA-ICPMS U–Pb zircon dating results of Huayu volcanics.

Grain no.	Corrected isotope ratios				Corrected ages (Ma)			
	$^{207}Pb/^{235}U \pm 1\sigma$		$^{206}Pb/^{238}U \pm 1\sigma$		$^{207}Pb/^{235}U \pm 1\sigma$		$^{206}Pb/^{238}U \pm 1\sigma$	
HY-G-41								
01	0.997	0.137	0.0646	0.0019	702	70	403	12
02	0.228	0.012	0.0270	0.0005	208	10	171	3
03	1.753	0.062	0.0828	0.0017	1028	23	513	10
04	0.511	0.035	0.0661	0.0013	419	24	412	8
05	0.557	0.025	0.0693	0.0014	450	16	432	8
06	0.657	0.052	0.0711	0.0015	513	32	443	9
08	0.575	0.056	0.0633	0.0015	461	36	396	9
09	3.403	0.124	0.1820	0.0036	1505	29	1078	20
10	0.595	0.041	0.0666	0.0014	474	26	416	8
11	0.618	0.083	0.0695	0.0018	488	52	433	11
12	0.817	0.093	0.0703	0.0019	606	52	438	11
13	0.564	0.015	0.0395	0.0007	454	10	250	5
14	0.762	0.088	0.0707	0.0020	575	51	441	12
15	0.773	0.022	0.0752	0.0014	581	12	467	8
16	0.588	0.049	0.0685	0.0015	470	31	427	9
17	0.946	0.027	0.0749	0.0014	676	14	466	8
18	0.701	0.066	0.0737	0.0017	539	39	458	10
19	0.597	0.064	0.0678	0.0017	476	41	423	10
20	0.393	0.019	0.0388	0.0008	289	15	245	5
21	0.615	0.068	0.0742	0.0018	487	43	461	10
22	1.122	0.045	0.0767	0.0016	764	21	477	10
HY-L-07								
01	0.0640	0.0070	0.01019	0.00023	63	7	65.0	1.0
02	0.0700	0.0035	0.01017	0.00015	69	3	65.2	1.0
03	0.0600	0.0041	0.00945	0.00018	59	4	61.0	1.0
04	0.0635	0.0050	0.00999	0.00016	63	5	64.0	1.0
05	0.0610	0.0019	0.00961	0.00013	60	2	61.6	0.8
06	0.3109	0.0034	0.04350	0.00043	275	3	274	3
07	0.0910	0.0033	0.01357	0.00017	88	3	87.0	1.0
08	0.1317	0.0076	0.01811	0.00033	126	7	116	2
09	0.0779	0.0099	0.01190	0.00029	76	9	76.0	2.0
10	0.0629	0.0044	0.00990	0.00017	62	4	63.0	1.0
11	0.0673	0.0059	0.00997	0.00019	66	6	64.0	1.0
12	0.4675	0.0070	0.06130	0.00064	389	5	384	4
HY-L-05								
01	0.0602	0.0025	0.00912	0.00013	59	2	58.5	0.8
03	0.0601	0.0019	0.00945	0.00011	59	2	60.6	0.7
04	0.0574	0.0025	0.00903	0.00014	57	2	57.9	0.9
05	0.0570	0.0022	0.00896	0.00011	56	2	57.5	0.7
06	0.0637	0.0035	0.00900	0.00016	63	3	58.0	1.0
07	0.0633	0.0023	0.00942	0.00012	62	2	60.4	0.8
08	0.0596	0.0023	0.00936	0.00013	59	2	60.1	0.8
09	0.0579	0.0024	0.00911	0.00015	57	2	58.5	1.0
11	0.0573	0.0017	0.00901	0.00009	57	2	57.8	0.6
12	0.0638	0.0031	0.00910	0.00015	63	3	58.4	1.0
15	0.0612	0.0050	0.00891	0.00018	60	5	57.0	1.0
17	0.0567	0.0017	0.00892	0.00012	56	2	57.3	0.8
18	0.0594	0.0048	0.00896	0.00017	59	5	58.0	1.0
21	0.0623	0.0024	0.00944	0.00014	61	2	60.6	0.9

Note: U–Pb isotopic ratios and concentrations of sample HY-G-41 zircons were determined at Northwest University (Xi'an, China) and those of samples HY-L-07 and HY-L-05 zircons at National Taiwan University (Taipei).

(0.0332) as derived by Blichert-Toft and Albarede (1997). These values were reported relative to $^{176}Hf/^{177}Hf = 0.282163$ for the JMC475 standard. The $^{176}Hf/^{177}Hf$ value of 0.282152 ± 18 was obtained for our AMES Hf metal, which is isotopically indistinguishable to JMC475 standard. The Hf isotopic results are listed in Table 2.

4. Results

4.1. Mineral chemistry and alteration of studied samples

Although andesites are altered in various degrees, phenocrysts of predominant plagioclase and occasional clinopyroxene and amphibole can be recognized. Electron microprobe analysis on the relatively unaltered portion of phenocrysts indicates that plagioclases are largely andesine (An_{44} to An_{27}); clinopyroxenes have augite compositions within the range of $Wo_{45}En_{42}Fs_{13}$-$Wo_{38}En_{47}Fs_{15}$; and amphiboles belong to the calcic subgroup having an edenitic composition with Mg value = 37.8–42.4. Accessory minerals are mainly magnetite (TiO_2 < 1 wt%) and seldom zircon. Secondary minerals like hydrous mica, chlorite, epidote, sphene, and albite (An_9 to An_3) are common, and pyrite is rare. However, ilmenite, probably an alteration product after magnetite, is commonly present in the tuff-like rock. Detailed mineral chemistry of chlorite in Huayu volcanics has been reported by Yang (1989). It is noted that embayment of quartz, instead of euhedral grains, is observed in sample HY-G-41, an indication of xenocrystic origin of quartz.

The X-ray diffraction pattern of the tuff-like rock, as revealed by the quartz-free character relative to dacite and rhyolite dike

Table 2
Hf isotopic data for zircons of Huayu volcanics.

Grain	$^{176}Yb/^{177}Hf$	±2 S.E.	$^{176}Lu/^{177}Hf$	±2 S.E.	$^{176}Hf/^{177}Hf$	±2 S.E.	Age (Ma)	$\varepsilon Hf_{(T)}$
HY-G-41								
4-1	0.0363	0.0005	0.000751	0.000008	0.282258	0.000019	412	−9.3
4-2	0.0384	0.0008	0.000767	0.000009	0.282271	0.000016	412	−8.9
6-1	0.0306	0.0004	0.000589	0.000007	0.282255	0.000016	443	−8.7
6-2	0.0311	0.0004	0.000611	0.000014	0.282241	0.000014	443	−9.2
HY-L-07								
2	0.0677	0.0013	0.001424	0.000017	0.282976	0.000030	65.2	8.6
3	0.0441	0.0015	0.000887	0.000036	0.282889	0.000026	61	5.5
4	0.0844	0.0040	0.001663	0.000130	0.282929	0.000030	64	6.9
5	0.0712	0.0019	0.001357	0.000036	0.282966	0.000038	61.6	8.2
6	0.0297	0.0004	0.000577	0.000006	0.282514	0.000036	274	−3.0
7	0.0825	0.0019	0.001708	0.000027	0.282794	0.000030	87	2.7
9	0.0355	0.0009	0.000853	0.000078	0.282935	0.000048	76	7.4
11	0.0560	0.0022	0.000924	0.000017	0.282918	0.000052	64	6.6
HY-L-05								
1	0.0545	0.0049	0.000956	0.000061	0.282893	0.000026	58.5	5.6
3	0.0947	0.0020	0.002468	0.000025	0.282777	0.000016	(58.7)	(0.2)
4	0.1057	0.0014	0.003356	0.000110	0.282710	0.000050	57.9	−1.0
5	0.0851	0.0023	0.002007	0.000016	0.282787	0.000040	57.5	1.8
7	0.0827	0.0019	0.001708	0.000027	0.282791	0.000032	(58.7)	(0.7)
8	0.0623	0.0024	0.001591	0.000066	0.282795	0.000036	60.1	2.1
9	0.0530	0.0058	0.001332	0.000140	0.282881	0.000028	58.5	5.1
10	0.0678	0.0027	0.001532	0.000062	0.282827	0.000018	60.2	3.2
11	0.0914	0.0037	0.002142	0.000140	0.282742	0.000038	57.8	0.2
12	0.0755	0.0033	0.001620	0.000054	0.282865	0.000024	58.4	4.5
14	0.0568	0.0029	0.001491	0.000120	0.282980	0.000034	(58.7)	(7.4)
15	0.1177	0.0019	0.002740	0.000110	0.282986	0.000046	57	8.8
16	0.0996	0.0007	0.001797	0.000014	0.282989	0.000040	(58.7)	(7.7)
17	0.0930	0.0012	0.001984	0.000077	0.282867	0.000036	57.3	4.6

Note: Hf isotope analyses were carried out at Academia Sinica (Taipei).
For those which the single grain U–Pb zircon age is undetermined in the sample HY-L-05, the age used (parenthesized) for obtaining $\varepsilon Hf_{(T)}$ values is the weight mean age of this sample (Fig. 3c).

samples that are obviously rich in quartz (Fig. 2), favors a lithology linking to intermediate or basic magmas. Moreover, the dominance of hydrous mica (sericite) further indicates that it is an altered rock rich in potassium. We therefore suggest that this rock most probably represents the severe potassic alteration (sericitization) zone that is commonly found in close association with propylitization of andesitic rocks, as all andesite lavas of Huayu had been subjected to such kind of hydrothermal alteration (Yang et al., 2008). In this regard, its U–Pb zircon age can be used to stand for the eruption time of andesite lavas.

4.2. The U–Pb zircon ages

Age concordia diagrams based on $^{206}Pb/^{238}U$ vs. $^{207}Pb/^{235}U$ plots for three rock samples are depicted in Fig. 3a–c. Because the common problem of crystal inheritance can result in scattering of zircon U–Pb ages, CL images of zircon grain are examined for the existence of inherited cores (Fig. 4a–c). The CL images reveal that there are no inheritance cores in zircons from the tuff-like rock (HY-L-07) and rhyolite dike (HY-L-05), and their age ellipsoids concentrate nicely along the concordia, indicating the high reliability of these ages. On the other hand, the factor of the Pb loss must be taken into consideration as reflected by the widened $^{207}Pb/^{235}U$ apparent ages of the andesite sample (HY-G-41). One technique to filter the widened $^{207}Pb/^{235}U$ ages, as compared with $^{206}Pb/^{235}U$ ages, has been proposed by Bryan et al. (2004). Error-weighted $^{206}Pb/^{235}U$ ages filtering procedure set by these authors are used for obtaining the age group, although all measured data are listed (Table 1).

A total number of 21 zircon grains from sample HY-G-41 (andesite) provide a spectrum of $^{206}Pb/^{238}U$ apparent age ranging from ~1078 to ~171 Ma (Table 1). Among them, 16 analyses can define a significant U–Pb zircon age of 437 ± 13 Ma with MSWD = 6.9 (Fig. 3a). The grain yielding the oldest age of 1078 Ma clearly exhibits a rounded core in the CL image (G9 in Fig. 4a), and is possibly of the inheritance origin. On the other hand, there are some grains with ages (250–171 Ma) apparently younger than the cluster age of 437 Ma. On this basis, the meaning of this cluster age, and hence the source of ~437 Ma zircons needs to be considered more thoroughly (see later section).

A total number of 12 zircon grains from sample HY-L-07 (tuff-like rock) provide a spectrum of $^{206}Pb/^{238}U$ apparent age ranging from ~384 to ~61 Ma (Table 1). Among them, seven analyses can define a significant U–Pb zircon age of 63.3 ± 1.5 Ma with MSWD = 2.9 (Fig. 3b). Others, with ages older than 63 Ma and randomly distributed in a range of 384–76 Ma, are regarded as accidental. It is noted that the two oldest zircons are particularly characterized by no fluorescence, hence no zoning, in their CL images (e.g., G6 and G12 in Fig. 4b). This is in contrast to our previous works on dating few early Cretaceous rhyolites in southeast China, which reveals that only younger zircons with ages close to the eruption time behave this way (Chen et al., 2008a).

A total number of 14 zircon grains from sample HY-L-05 (rhyolite dike) provide a spectrum of $^{206}Pb/^{238}U$ apparent age ranging from ~61 to ~57 Ma (Table 1). All these analyses can define a significant U–Pb zircon age of 58.7 ± 0.8 Ma with MSWD = 2.5 (Fig. 3c). The narrow spread of zircon age spectrum indicates that this dike rock is basically uncontaminated by the crustal materials.

4.3. Zircon Hf isotope compositions

Spot analysis of Hf isotope ratios in terms of $\varepsilon Hf_{(T)}$ values (Table 2) reveal that the ~437 Ma zircons in sample HY-G-41 have $\varepsilon Hf_{(T)}$ values as low as −9. This is based on two repeated analyses on the same grain yielding $\varepsilon Hf_{(T)} = -9.3$ to −8.9 from G4 and $\varepsilon Hf_{(T)} = -9.2$ to −8.7 from G6, indicatives of good reproducibility on the same

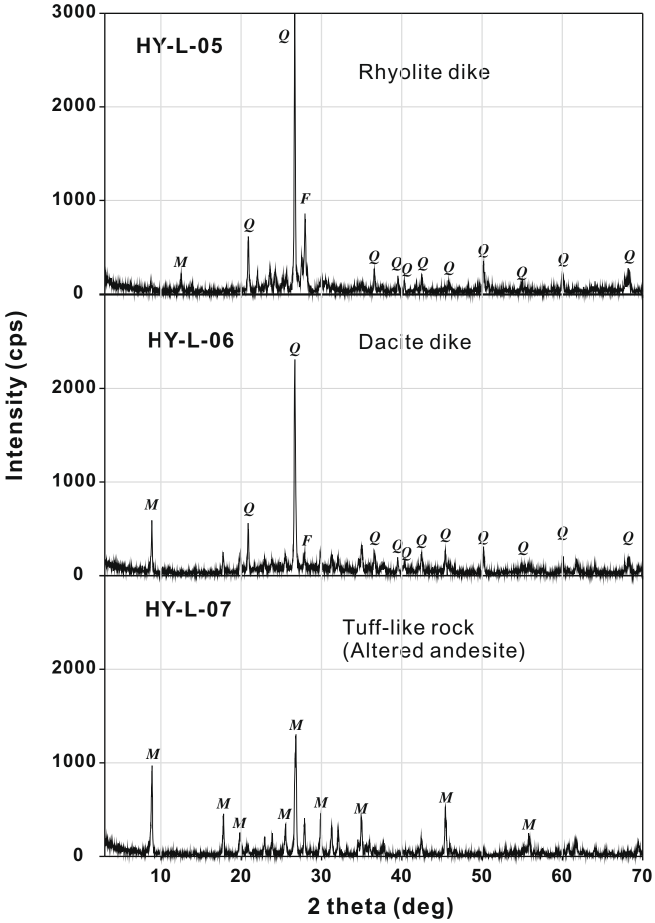

Fig. 2. X-ray diffraction spectra of Huayu volcanics. A copper target with monochromator is used (Cu Kα = 1.54050 Å) under the condition of 35 kV (voltage) and 15 mA (current). Diffraction peaks of the mineral are identified by the build-in software of the manufacture (Rigaku), in which Q = quartz, F = feldspar, M = mica. The quartz-free pattern of the tuff-like rock (HY-L-07) most likely indicates an altered andesite replaced by sericites (hydrous mica) as compared with quartz-bearing dacite (HY-L-06) and rhyolite (HY-L-05).

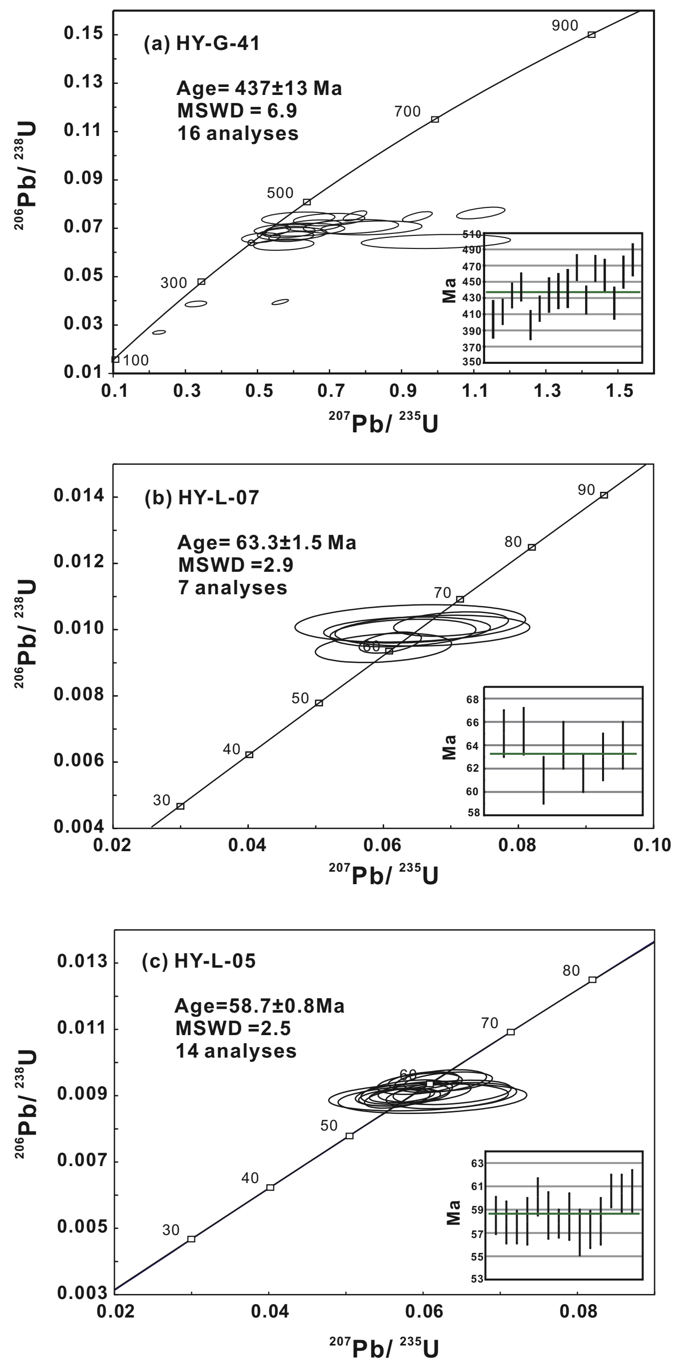

Fig. 3. Isochrons, age probabilities and U–Pb zircon age results for (a) andesite lava; (b) tuff-like rock; and (c) rhyolite dike from Huayu. MSWD: mean square of weighted deviates. Noted that some ages in andesite lava are relatively discordant.

zircon grain. On the other hand, those in samples HY-L-07 and HY-L-05 generally show positive $\varepsilon Hf_{(T)}$ values, with the highest value up to 8.8. In sample HY-L-07, except one zircon dated to be 274 Ma possesses a negative $\varepsilon Hf_{(T)}$ value, others especially those are used to define the age of 63 Ma for this rock (Fig. 3b) have rather concentrated values varying between 8.6 and 5.5. On the other hand, there is an uncommon feature reflected by zircons from sample HY-L-05: the wide range of $\varepsilon Hf_{(T)}$ values (8.8 to −1.0 for 14 analyses) in spite of the superb homogeneity of age results for this rhyolite dike (Table 1).

The $\varepsilon Hf_{(T)}$ values are plotted against the U–Pb zircon ages for all the measured grains to delineate possible sources of zircon (Fig. 5). It is noted that the ~437 Ma zircons possess $\varepsilon Hf_{(T)}$ values similar to those from Caledonian granitic and gneissic rocks in Southeast China (−2.8 to −9.3; Xu et al., 2005). Further taking the whole-rock $\varepsilon Nd_{(T)}$ values into consideration, younger zircons (~60 Ma) are present in volcanic rocks with relatively constant $\varepsilon Nd_{(T)}$ values (−1.9 to −1.3), whereas older zircons (~437 Ma) are in association with a magma that has a higher $\varepsilon Nd_{(T)}$ value (+3.9). Since the $\varepsilon Nd_{(T)}$ values of the Caledonian rocks in southeast China are mainly in the range of −5 to −14 (Shen and Lin, 2002), such an incoherency between zircon $\varepsilon Hf_{(T)}$ and whole-rock $\varepsilon Nd_{(T)}$ values in these samples is best explained by contrasting genesis for the older and younger groups of zircon in Huayu volcanics.

4.4. Geochemistry and isotope compositions of andesites

Geochemistry of Huayu volcanics based mainly on the major elements has been described by Yang (1989). Basically, their geochemical behaviors are very similar to the calc-alkaline rocks in common orogenic belts and volcanic arcs. As exemplified by the K_2O vs. SiO_2 plots (Fig. 6), the andesite lava and dacite and rhyolite dikes belong to the medium-K calc-alkaline series, in which the trend of above-mentioned K-enrichment can also be unraveled. On this basis, those fall into the shoshonitic and perhaps high-K calc-alkaline fields as well are probably the influence of the K-enrichment due to propylitization. Here, we supplement with trace

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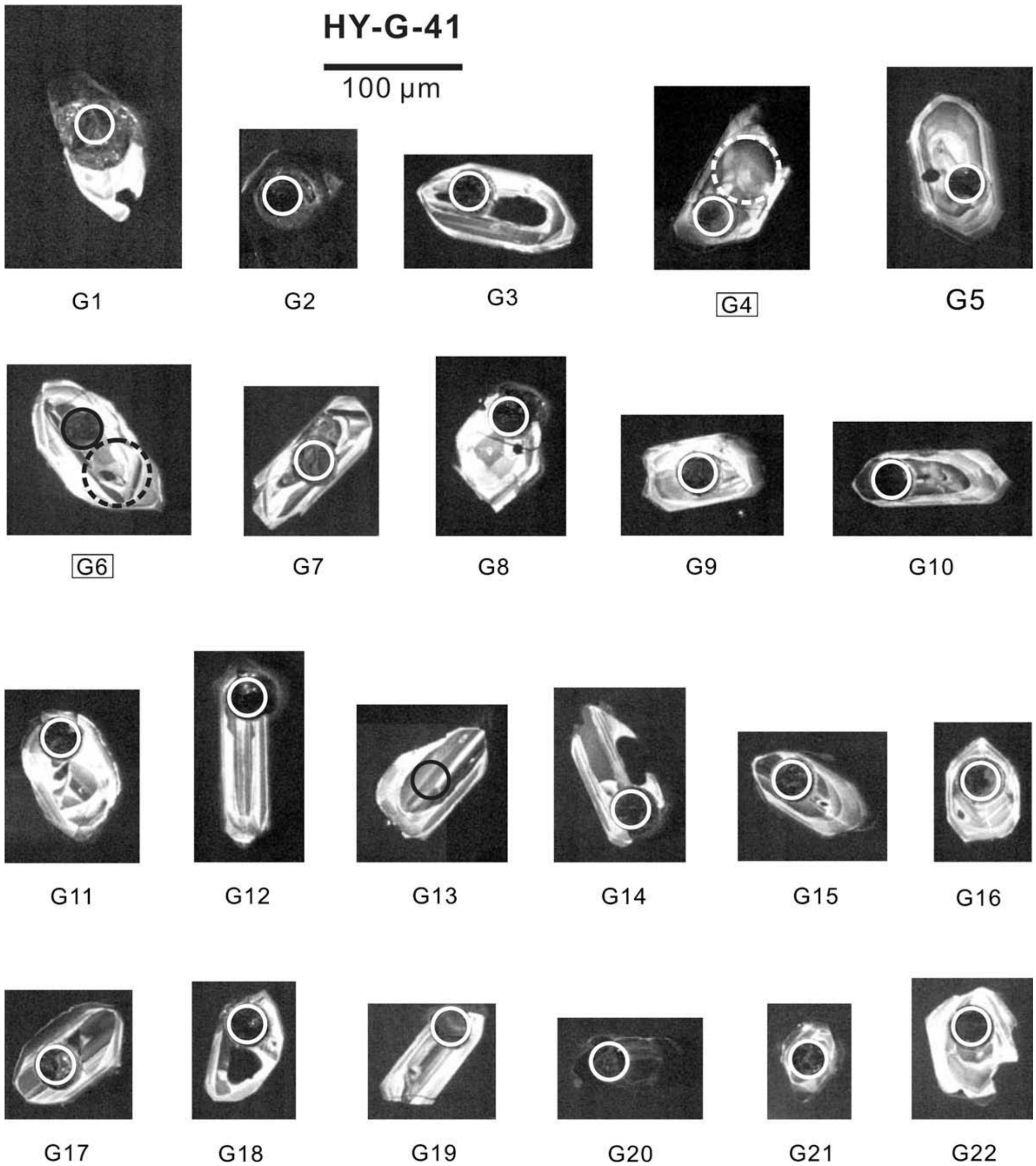

Fig. 4. Cathodoluminance (CL) images for dated zircons: (a) andesite lava (HY-G-41); (b) tuff-like rock (HY-L-07); and (c) rhyolite dike (HY-L-06) from Huayu. Subrounded cores in (a), e.g., G4 and G16, indicate inherited zircons. Zircon grains that Hf isotope analysis has been carried out are boxed. Positions of laser pits for U–Pb age dating and Hf isotope analyses are shown by solid circles and dotted circles, respectively.

element data (Table 3) to demonstrate that these rocks are diagnosed for a volcanic arc environment by the tectonic discriminating plots. To minimize the influence of alteration, relatively immobile trace elements, such as Nb, Ta, Y and Yb, are chosen as the major discriminators (Fig. 7a and b). High Rb concentration of samples HY-L-07 and -05 indicates the Rb–K elemental coherency of these rocks (Fig. 7c and d). As viewed from the overall elemental behavior in these discriminating diagrams, Huashu volcanics are closer to the Late Cretaceous dacite–rhyolite in Zhejiang-Fujian than the Late Cretaceous/Early Cenozoic andesite–dacite in eastern Guangdong (except Lienping; Chung et al., 1997) in the entire Southeast Coast Magmatic Belt.

Calculated ISr and $\varepsilon Nd_{(T)}$ values of sample HY-G-41 critically depend on the time of magma eruption: ISr = 0.7034 and $\varepsilon Nd_{(T)} = 3.9$ if $T = 437$ Ma, and ISr = 0.7057 and $\varepsilon Nd_{(T)} = 1.3$ if $T = 63$ Ma. For samples HY-L-05 (ISr = 0.7051 and $\varepsilon Nd_{(T)} = -1.3$) and HY-L-07 (ISr not available due to very high Rb/Sr ratio after extensive sericitization and $\varepsilon Nd_{(T)} = -1.9$), their Nd isotopic compositions are basically alike (Table 4). When compared with the Late Cretaceous/Early Cenozoic volcanic rocks in the Southeast Coast Magmatic Belt, Huayu andesites are more depleted than rhyolites in Zhejiang (ISr = 0.7084–0.7087 and $\varepsilon Nd_{(T)} = -4.9$ to -7.3; Xing et al., 1999; Lapierre et al., 1997), but close to the dacitic and rhyolitic rocks in Fujian (ISr = 0.7056 and $\varepsilon Nd_{(T)} = -0.6$ to -2.9; Xing et al., 1999; our unpublished data). Isotopic compositions of the Late Cretaceous/Early Cenozoic basalt–andesite–(dacite) rocks in eastern Guangdong (e.g., ISr = 0.7039-0.7063 and $\varepsilon Nd_{(T)} = 6.4$ to -0.5 for Sanshui rocks, ISr = 0.7106–0.7136 and

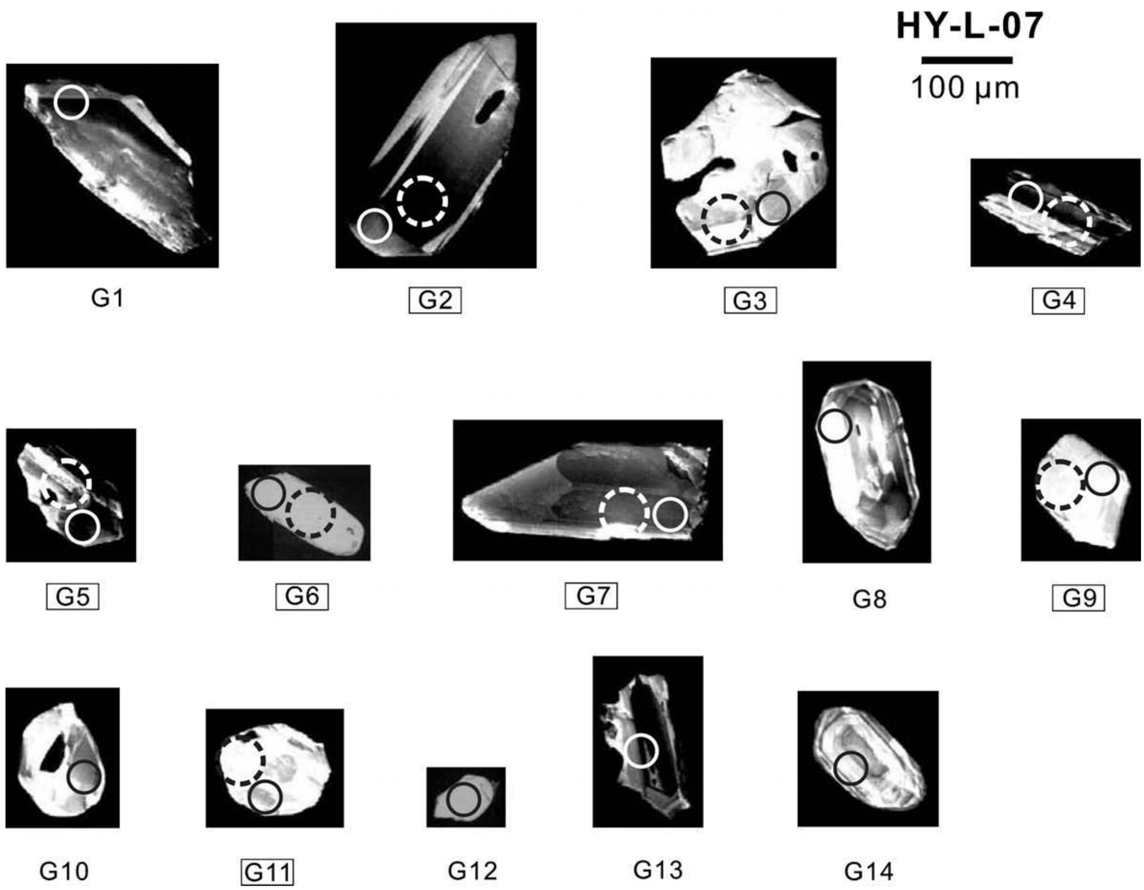

Fig 4. *(continued)*

$\varepsilon Nd_{(T)}$ = 0.5 to −11.5 for Maoming rocks, ISr = 0.7075–0.7114 and $\varepsilon Nd_{(T)}$ = −2.5 to −4.8 for Lienping rocks, and ISr = 0.7048 – 0.7052 and $\varepsilon Nd_{(T)}$ = 1.1–0.3 for Heyuan rocks) (Chung et al., 1997; Zhu et al., 2004) are too heterogeneous for a direct correlation. Combining both the elemental and isotopic geochemistry, Huayu andesites may be best correlated to those in the southern Fujian section of the Late Cretaceous/Early Cenozoic magmato-tectonic province that vastly covers the southeast China coastal area.

5. Discussion

5.1. Identification of sample HY-L-07

Lithology of the rock similar to sample HY-L-07 has been previously described as shale (Yang et al., 2008) or a tuff-like rock based on the field observation (Fig. 1b). As shown in Fig. 2, this sample does not contain detectable quartz but is dominated with hydrous mica and some amounts of ore minerals, making it difficult to be referred as shale. Chemically, it is very high in Al_2O_3, Fe_2O_3 and K_2O but low in SiO_2 contents (Table 3). Assuming all the Al_2O_3 content (29.7 wt%) of this sample is entirely the contribution of sericite, the K_2O content compensated for a theoretical sericite composition (9.1 wt%) is very close to the K_2O value (9.4 wt%) as shown in Table 3. Hence, sericite should occupy ~80% of the sample based on the proportion of the Al_2O_3 content to the theoretical Al_2O_3 value (38.5 wt%) in the sericite formula. The rest SiO_2, TiO_2, Fe_2O_3 and MgO contents can then be allocated to the ilmenite and titaniferous magnetite that commonly present in this sample. Therefore, on the basis of mineral constituents and whole-rock chemical compositions, it most likely represents a potassic alteration zone of andesite lavas that have undergone extensive propylitization.

5.2. The age of Huayu volcanics

Using the cation coordination in chlorites, Yang (1989) suggested that the Huayu andesite body was subjected to a thermal condition of 250–300 °C as a consequence of low-grade metamorphism. Therefore, FT zircon ages previously reported for the andesite lavas, dacite and rhyolite dikes in Huayu, 65 ± 3 Ma, 62 ± 4 Ma and 61 ± 2 Ma, respectively, by the same author render a general believe that metamorphism occurred at the earliest Cenozoic. Besides, the age of 56 Ma obtained from the Rb–Sr isochron of whole-rock, plagioclase and chlorite reported for a rhyolite dike from Huayu (Jahn et al., 1976) would be the formation age of chlorites during metamorphism. On the observation that similar felsic dikes had intruded into a gneissic rock of 93 Ma in Lehsu (Hsiaochinmen), Chen and Chang (1995) postulated that the age of Huayu andesites shall fall within the time span of 95–55 Ma.

Because of the high closure temperature of the U–Pb zircon system (~900 °C; Dahl, 1997), the U–Pb zircon age is often used to delineate the time of magma emplacement or magma eruption for igneous rocks. Now that our U–Pb zircon dating results yield two contrasting age groups among the Huayu volcanics, the dated zircons need to be examined concerning their sources. In the coastal area of Fujian, there are some metamorphosed Paleozoic volcanic rocks along the Changle-Nanao Metamorphic Belt juxtaposing the Southeast Coast Magmatic Belt (Fig. 1a). They are collectively called Aojiao Rock Group and have been suggested to be the representatives of the metamorphosed calc-alkaline basalt-andesite

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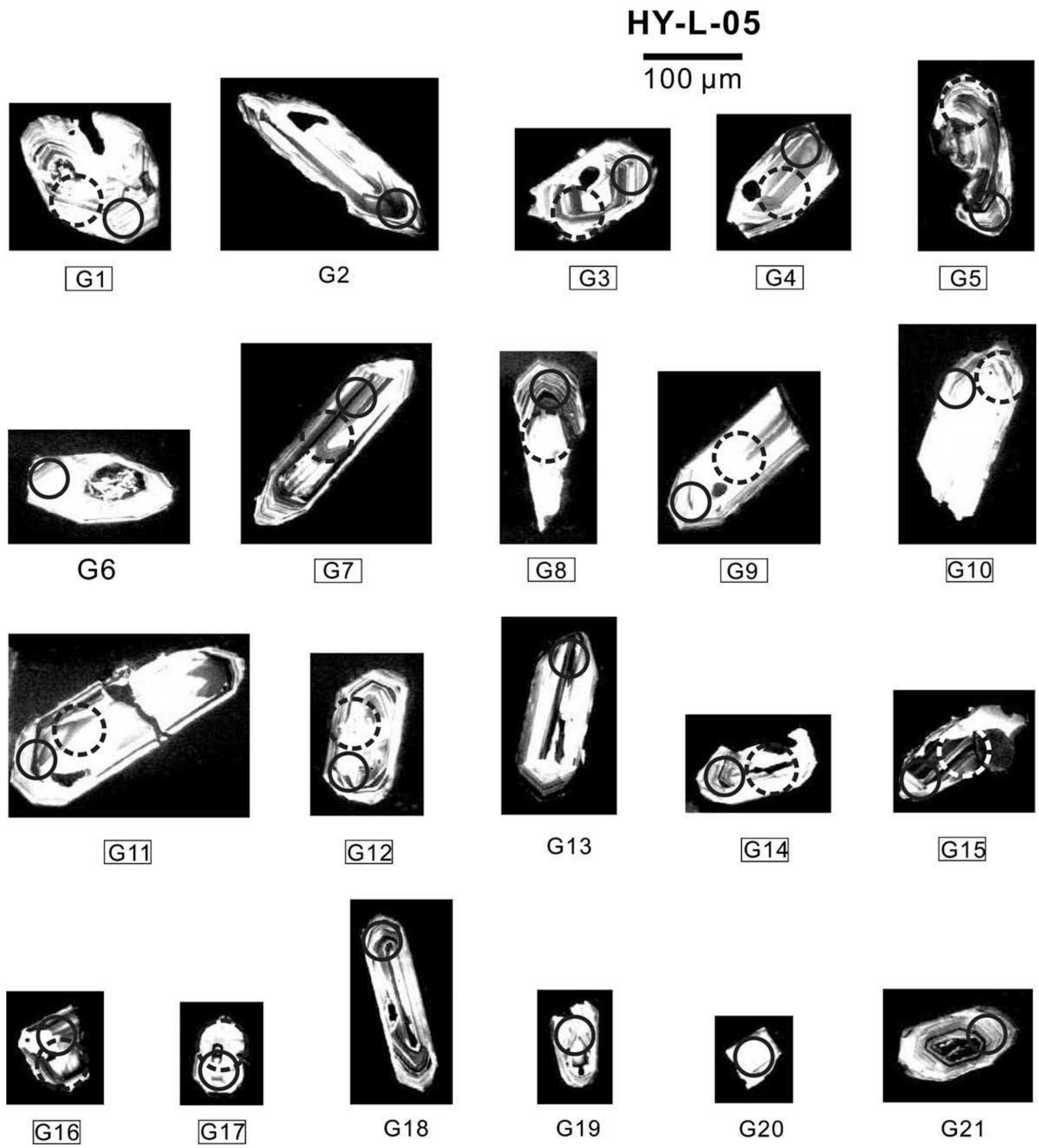

Fig 4. *(continued)*

rock association pertaining to the Late Caledonian orogenic cycle (Ordovician to Silurian) (Huang et al., 1998). For resolving the meaning of the old U–Pb zircon age group in Huayu andesites, one trace may be the linkage between Huayu volcanics and the Aojiao Rock Group due to similarity of ages.

However, there are some evidences that disprove the possibility of ∼437 Ma to be the eruption age of Huayu volcanics: (1) CL images of dated zircon grains in sample HY-G-41 show unparallel zones in the inner portion (particularly G4, G10 and G15 in Fig. 4a), indicatives of possible inherited cores where the age and $\varepsilon Hf_{(T)}$ data were taken. (2) In spite of a large population of dated zircon grains indicates an age cluster of 437 Ma, some younger ages do exist. Besides, a few data seem to be somewhat discordant in the age concordia diagram (Fig. 3a). (3) The whole-rock Nd isotope composition of sample HY-G-41 ($\varepsilon Nd_{(T)} = 3.9$ for $T = 437$ Ma) is more depleted than other two samples from Huayu ($\varepsilon Nd_{(T)} = -1.9$ to -1.3). Usually for magmatic zircons, their $\varepsilon Hf_{(T)}$ values are greater than the corresponding whole-rock $\varepsilon Nd_{(T)}$ value (Salters et al., 2002; Thompson et al., 2004). A reverse relationship between the whole-rock $\varepsilon Nd_{(T)}$ (3.9) and zircon $\varepsilon Hf_{(T)}$ (−9) in sample HY-G-41 indicates that the ∼437 Ma zircons are unlikely of magmatic crystals. (4) Although the Late Ordovician/Early Silurian (Caledonian) igneous rocks are present in the Changle-Nanao Metamorphic Belt and wide spread in the Cathaysia Block (Xu et al., 2005, 2007), the possibility for correlating Huayu andesites with the Caledonian volcanics is small as judged from the more enriched Sr and Nd isotopic compositions (ISr = 0.706−0.720 and $\varepsilon Nd_{(T)} = -5$ to -14) for the latter rocks (Shen and Lin, 2002).

Alternatively, the younger U–Pb zircon ages determined for the altered andesite and dike are envisaged. We stress the similarity between FT and U–Pb zircon ages, 61 ± 2 Ma vs. 58.7 ± 0.8 Ma, for the rhyolite dike. This indicates that the presumably low-grade metamorphism for the Huayu volcanics was in fact a duteric alteration taken place soon after the rhyolite dike injection. The fact

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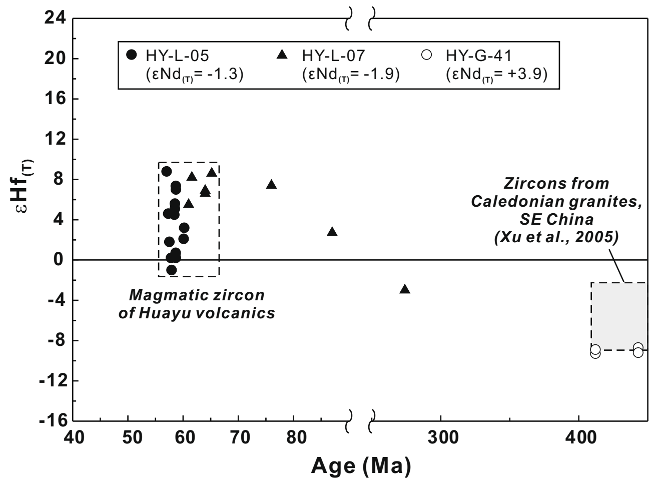

Fig. 5. $\varepsilon Hf_{(T)}$ vs. age plots of the dated zircons for Huayu volcanics. Decouple of low $\varepsilon Hf_{(T)}$ values (−9) for Silurain zircons enclosed in the host andesite (sample HY-G-41) that has high whole-rock $\varepsilon Nd_{(T)}$ values (+3.9 on $T = 430$ Ma) suggests that these zircons are unlikely magmatic in origin. Zircons from two other samples have high $\varepsilon Hf_{(T)}$ values (mostly > 0) are more comparable with their whole-rock $\varepsilon Nd_{(T)}$ values (−1.5 to −2.1 on $T = 60$ Ma).

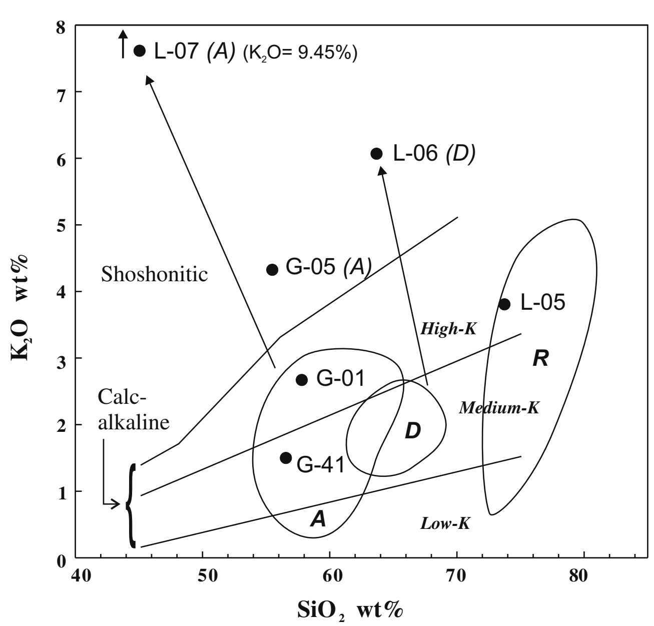

Fig. 6. The effect of sericitization (K-enrichment) on Huayu volcanics (black dots with sample number without the prefix HY-) in terms of K_2O vs. SiO_2 plots. Arrows show the trend of K-enrichment of andesite lavas and dacite dikes. Distribution fields for andesite (A), dacite (D) and rhyolite (R) are taken from Yang (1989).

that zircon $\varepsilon Hf_{(T)}$ values are relatively higher than the whole rock $\varepsilon Nd_{(T)}$ values in samples HY-L-07 and -05 is the supportive evidence. On this basis, the FT zircon ages for andesite lava (65 Ma) and dacite dike (62 Ma) are likewise adopted as the time of duteric alteration that occurred at the time close to the eruption of andesite and injection of dacite, respectively. This also explains the U–Pb zircon age of 63.3 ± 1.5 Ma for the altered andesite that is basically a record of its eruption time unaffected by the hydrothermal alteration. Therefore, magmatic activities of Huayu islet can be confined to a time span from 65 to 59 Ma, with the eruption time of andesite lava at 65–63 Ma.

5.3. Tectonic consideration

Tectonically, the Late Cretaceous/Early Cenozoic extensional environment in the Taiwan Strait caused the basement to be cut into a series of elongated grabens and horsts (Chen and Chang, 1995), and Huayu, like Penghu Islands, sits on the horsts. Since Penghu Islands locate in a place where the pre-Tertiary strata is the shallowest in the Taiwan Strait (Sun and Hsu, 1991; Yang et al., 2006), therefore, Early Cenozoic andesites of Huayu may represent a continuation of the Late Cretaceous volcanism occurred in the continental margin, or the Southeast Coast Magmatic Belt. Further because the Tungliang well (TL-1) in Penghu shows a predominance of Late Cenozoic basaltic lavas down to 626 m below the sea level (Huang, 1967; Chou, 1969), Huayu is apparently a high peak uncovered by these basaltic lavas in Penghu area.

Although the exposure of Late Ordovician/Early Silurian igneous bodies in southeast China coastal region is rare, detrital monazites in the Minjiang river mouth sediments (Fujian) and western Taiwan beach placers reveal two important age peaks of 450–430 Ma and 245–220 Ma (Chen et al., 2006). This indicates that, in addition to the Yanshanian magmatic products that overwhelm the southeast China coastal area, there must have accompanying Caledonian and Indosinian aluminous intrusive bodies (S-type granites) to account for the formation of such monazites. When subjected to erosion, disintegrated members were washed into the now Taiwan Strait and redeposited as the pre-Cenozoic (most probably Late Cretaceous) sedimentary sequences. Thus, the ~437 Ma and younger zircons in sample HY-G-41 are best explained as contributions from dismembered sedimentary xenoliths of predominantly Caledonian and subordinately Indosinian and Yanshanian igneous sources captured by the Huayu andesite lavas.

5.4. The high-magnetic anomaly belt southeast to Taiwan

Subsurface geology under the Neogene Formations of Penghu Islands has been revealed from the drilling information. The basement beneath the Penghu Islands (–626 to –898 m in the TL-1 well) was described as Mesozoic (?) rocks (Chiu, 1973) related to the Peikang High—a basement high east of Penghu that a drilled well had penetrated a pre-Miocene graben and reached the Cretaceous strata (Yang et al., 2006). Unlike Penghu main islands, Huashu is sitting on a high-magnetic anomaly belt extending in a NE-SW direction about 450 km long and 50–70 km wide (Fig. 1a inset). This belt is one of the most significant features of the Central Uplift Zone in the northeastern South China Sea that connects the Peikang High to the northeast, and can be correlated with the high velocity body through 3D velocity structure analysis (Cheng, 2004). This author further pointed out that this belt most likely represents the high velocity body of magmatic origin in the continental margin. Most recently, Hsu et al. (2008) also considered that high crustal magnetization zones in/around Taiwan generally reflect the nature of igneous rocks. Therefore, such a high-magnetic anomaly belt is highly possible a magmatic terrain situated in the northern flank of the South China Sea basin that opened up during 37–16 Ma (Taylor and Hays, 1983).

The fact that Huayu is situated on the high-magnetic anomaly belt, or a remnant magmatic belt, in Taiwan Strait provides a thought that this magmatic belt is mainly composed of Late Cretaceous/Early Cenozoic andesitic, dacitic, and rhyolitic rocks. A framework of magmatic evolution for the Late Yanshanian orogenic cycle of the Southeast Coast Magmatic Belt has been constructed based on the geochronological, element and isotope geochemical data (Chen et al., 2004). In particular, the epilogue

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Table 3
Major and trace element compositions for Huayu volcanics.

Sample no.	HY-G-01	HY-G-05	HY-G-41	HY-L-05	HY-L-06	HY-L-07
Lithology	Andesite	Andesite	Andesite	Rhyolite dike	Dacite dike	Potassic zone
(wt%)						
SiO_2	58.73	56.27	56.86	73.64	63.62	45.58
TiO_2	0.82	0.68	0.78	0.29	0.70	1.41
Al_2O_3	16.20	18.22	17.20	14.07	20.95	29.68
Fe_2O_3	7.63	7.49	7.67	2.38	5.61	10.07
MnO	0.15	0.14	0.13	0.05	0.02	0.04
MgO	3.99	3.41	3.47	0.71	0.58	1.10
CaO	3.66	4.55	5.37	1.20	0.25	0.09
Na_2O	3.01	1.84	3.88	3.46	0.24	0.23
K_2O	2.61	4.27	1.51	3.79	6.05	9.45
P_2O_5	0.18	0.15	0.15	0.10	0.18	0.06
LOI	3.15	2.44	1.87			
Sum	100.13	99.46	98.89	99.69	98.19	97.71
(ppm)						
Sc				8.3	25.4	27.2
V	124	114	159	51.2	116.4	311
Cr	52.1	32.0	33.6	67.1	39.9	50.3
Co	32.9	30.8	37.6	4.04	14.2	22.9
Ni	20.6	12.4	16.9	30.8	26.1	25.3
Ga	16.6	19.6	18.0	12.7	20.3	29.1
Rb	106	168	61.0	174	368	545
Sr	344	373	410	196	29.2	12.0
Y	27.9	22.6	42.9	17.4	41.9	16.4
Zr	138	126	119	135	165	271
Nb	5.64	4.57	3.93	6.60	7.40	11.1
Cs	1.44	1.28	2.11	1.87	7.45	9.35
Ba	657	928	315	523	430	851
La	21.6	17.7	17.2	23.4	65.8	23.4
Ce	44.7	35.8	31.0	44.7	126.4	24.2
Pr	5.09	4.09	4.25	4.86	17.3	8.03
Nd	21.3	17.0	19.1	16.7	66.8	29.6
Sm	4.60	3.60	4.47	3.10	13.0	6.07
Eu	1.21	1.12	1.20	0.700	2.29	1.38
Gd	4.45	3.52	5.02	3.03	11.0	4.36
Tb	0.714	0.570	0.844	0.430	1.46	0.650
Dy	4.27	3.40	5.11	2.66	7.99	3.78
Ho	0.885	0.720	1.14	0.590	1.63	0.800
Er	2.58	2.10	3.20	1.73	4.47	2.39
Tm	0.388	0.329	0.475	0.280	0.680	0.410
Yb	2.61	2.16	2.87	1.91	4.44	3.04
Lu	0.415	0.339	0.460	0.300	0.720	0.450
Hf	3.46	3.10	2.93	3.58	4.10	5.59
Ta	0.375	0.318	0.284	0.590	0.520	0.720
Pb	13.4	18.8	8.50	19.2	10.1	8.70
Th	7.65	5.57	3.66	12.7	9.85	11.4
U	1.58	1.49	0.92	3.31	2.26	1.52

Note: Rock elemental compositions were analyzed at National Taiwan University (Taipei).

of this orogenic cycle is characterized by the bimodal (basalt/rhyolite) volcanics dominated with the rhyolitic rocks in Zhejiang and northern Fujian and basalt–andesite–dacite association in southern Fujian and eastern Guangdong. Putting together all the age data for these rocks (Fig. 8a), the variability of lithology, time and space of volcanic eruption is seen: eruptions of Zhejiang-Fujian bimodal rhyolites peaked at 88–81 Ma, and those of Fujian-Guangdong basalt–andesite–dacite association occurred mainly at 72–56 Ma (Chen et al., 2008a; Zhu et al., 2004). Under this framework, the geochemical characters of Huayu andesites are closer to the andesitic rocks in southern Fujian, and different from eastern Guangdong rocks that have a within-plate tectonic characterization (Fig. 7). In other words, Huayu andesites can be included as a volcanic unit in Fujian developed during the late-stage magmatic evolution of the Southeast Coast Magmatic Belt.

Accordingly, we suggest that the high-magnetic anomaly belt may represent a torn-apart portion from the southern section of the Southeast Coast Magmatic Belt as a consequence of east-dipping subduction along the Manila trench (Fig. 8a). In other words, Huayu was originally sitting in the southeast coastal area of South China as a volcanic peak before the earliest breakup taken place along the current coastline at the Late Paleocene. Existence of the Pearl River Mouth Basin, a passive margin rift system composed of three sub-basins (known as Zhu I, II and III), along the continental shelf between the southeast China coastline and the high-magnetic anomaly belt (Fig. 8b) is the supportive evidence, because these sub-basins are generally believed to have formed by lithospheric stretching, and the main rift phase is in the Eocene and Oligocene (e.g., Xie et al., 2006 and references therein). After the opening of the South China Sea at 37–16 Ma (e.g., Chung et al., 1997), the high-magnetic anomaly belt was then dragged closer to its present position by the east-dipping subduction system. Such a tectonic evolution scheme is consistent with the idea of Jahn et al. (1992) who proposed that west Taiwan might have been situated at the

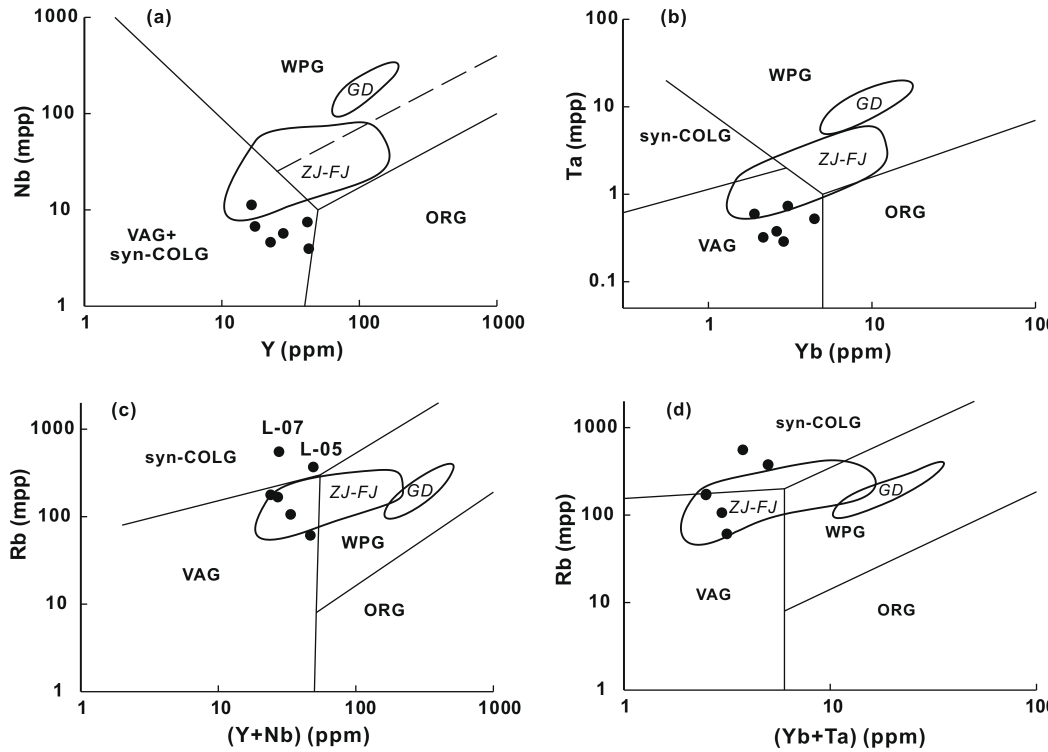

Fig. 7. The (a) Nb vs. Y and (b) Ta vs. Yb plots for Huayu volcanics in which the Late Cretaceous dacite–rhyolite in Zhejiang and Fujian (ZJ-FJ; our unpublished data) and Late Cretaceous/Early Cenozoic andesite–dacite in eastern Guangdong (GD; Chung et al., 1997) are compared. The discriminating boundaries are those set for granitic rocks, or intermediate to felsic compositions, after Pearce et al. (1984) with the fields of syn-collisional granites (syn-COLG), within-plate granites (WPG), volcanic-arc granites (VAG) and ocean-ridge granites (ORG). The (c) Rb vs. Y + Nb and (d) Rb vs. Yb + Ta plots for Huayu volcanics give same results providing the high Rb concentrations on samples HY-L-07 and -05 are the effect of Rb–K coherency as a consequence of K-enrichment. Thus, Huayu volcanics are best concluded as of a volcanic arc environment.

Table 4
Sr and Nd isotopic compositions of Huayu volcanics.

Sample no.	Rb (ppm)	Sr (ppm)	Sm (ppm)	Nd (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	2S.E.	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2S.E.	Isr	$\varepsilon Nd_{(T)}$
HY-L-05	174	196	3.10	16.7	2.57	0.707468	12	0.1122	0.512537	12	0.7051	−1.3
HY-L-07	545	12.0	6.07	29.6				0.1240	0.512510	12		−1.9
HY-G-41	61	410	4.47	19.1	1.30	0.706058	12	0.1280	0.512682	16	0.7057	1.3
HY-G-41											0.7034*	3.9*

Note: Sr–Nd isotopic compositions were analyzed at National Cheng Kung University (Tainan).
$\varepsilon Nd_{(T)} = [(^{143}Nd/^{144}Nd)_{sample}\ (T)/(^{143}Nd/^{144}Nd)_{CHUR}\ (T) - 1] \times 10^4$, $(^{143}Nd/^{144}Nd)_{sample}\ (T) = (^{143}Nd/^{144}Nd)_{sample} - (^{147}Sm/^{144}Nd)_{sample}\ (\exp\lambda T - 1)$, $(^{143}Nd/^{144}Nd)_{CHUR}\ (T) = 0.512638 - 0.1967\ (\exp\lambda T - 1)$, $\lambda = 0.00654\ Ga^{-1}$.
T = 63 Ma for all samples, except those with an asterisk that are calculated based on T = 437 Ma for comparison.

southern extension of Fujian based on the correlation of Pb isotope compositions between the Permo/Triassic limestone drilled from western Taiwan (Chia-Li No. 1 well in Fig. 8a) and Changxing limestone in west central Fujian. In sum, this scenario, on the basis of the new constraints that Huayu andesites belong to the same geochronological and geochemical provinciality as the Southeast Coast Magmatic Belt and the timing of terrain movement is later than 58 Ma, provides important information for establishing reconstructions in southeastern China continental margin. Following this line of thought, the puzzle for the provenance of 1.8 Ga monazites that occupy nearly 30% in western Taiwan beach sand monazite populations (Chen et al., 2006) and that are unlikely originated from the Paleoproterozoic Wuyishan basement in northwestern Fujian through Minjiang river system (Chen et al., 2008b) may be solved by examining the river systems in Guangdong, such as the Zhujiang (Pearl) River (Xu et al., 2007).

6. Conclusions

Huayu andesite exposed in the Taiwan Strait is the oldest volcanic rock so far documented in Penghu area. The whole-rock and zircon isotopic data and CL images suggest that the large cluster of ~437 Ma zircons are of xenocrystic origin. Alternatively, as compared with the FT zircon ages, younger U–Pb zircon age of 65–59 Ma would be more likely the indication of volcanic activity of Huayu. Geochemical characterizations indicate that they are related to a volcanic arc environment, and isotope compositions suggest the mantle origin of andesite but contaminated by crustal materials. Therefore, the high-magnetic anomaly belt, extending from northern margin of the South China Sea to western Taiwan and with the Huayu islet sitting on it, is suggested to be a remnant volcanic terrain developed at the earliest Cenozoic. This infers that a small part of the southeast China continent could have been drifted away due to rifting on the

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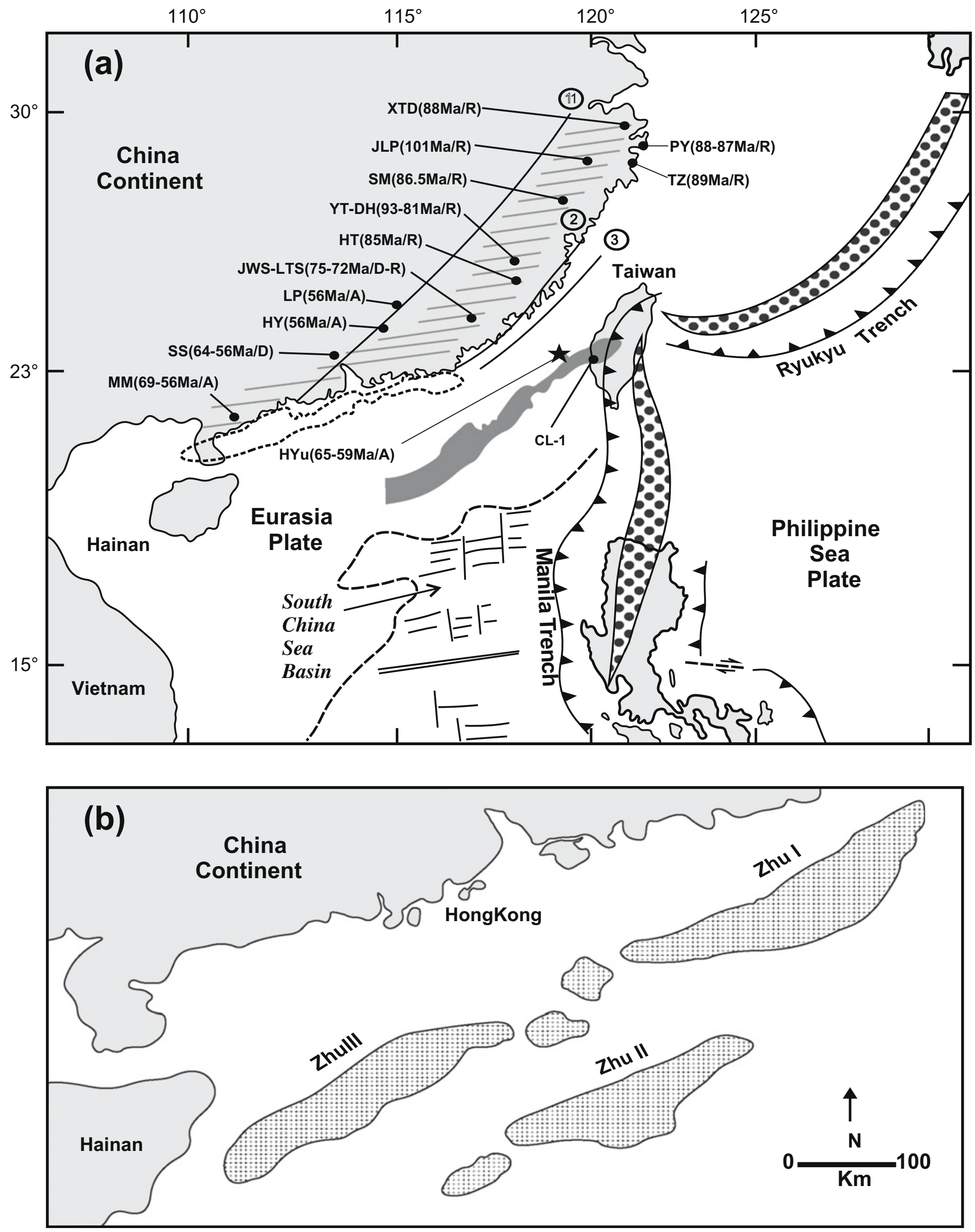

Fig. 8. (a) The high-magnetic anomaly belt (dark grey) and Taiwan island (Cheng, 2004) in the position of the Cenozoic tectonic framework of the Southeast Asia. Major fault systems in the vicinity include 1: Zhenghe-Dapu Fault; 2: Changle-Nanao Fault; and 3: Fujian Offshore Fault (modified from Chen and Chang, 1995). Based on the similarity of age and the $\varepsilon Nd_{(T)}$ values (see text), Huayu (HYu), denoted by the star, is suggested to be originally situated in the southern part of the Southeast Coast Magmatic Belt (stippled area) and the high-magnetic anomaly belt is thus explained as the torn-apart portion (area circled by small dots) of the Southeast Coast Magmatic Belt as a consequence of the east-dipping subduction due to sea-floor spreading (South China Sea basin) at 32–16 Ma (Chung et al., 1997). Noted that the peninsula north to the Hainan island is mainly composed of the Late Cenozoic basalts. Two young volcanic arcs (patterned with large dots) are also shown for comparison. Age data (Ma) and lithology (R = rhyolite, D = dacite, and A = andesite) for Xuantandi (XTD), Julipin (JLP), Shanmeng (SM), Yongtai-Dehua (YT-DH), Huangtang (HT), and Jianweishan-Lingtongshan (JWS-LTS) are taken from Chen et al. (2008a), and Lienping (LP), Heyuan (HY), Sanshui (SS), Maoming (MM), from Zhu et al. (2004). (b) Positions of some Eocene-Oligocene rift sub-basins (Zhu I, II and III) in the Pearl River Mouth Basin (modified from Xie et al., 2006). The high-magnetic anomaly belt in (a) is suggested to have been broken up first and then drifted away by this rifting system in the continental margin before opening of the South China Sea. CL-1: the site of Chia-Li No. 1 well.

passive continental margin in the early stage and opening of the South China Sea in later time.

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