

Petrogenesis and tectonic implication of lavas from the Yap Trench, western Pacific

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Abstract

We present major and trace element data of lava recovered from the northern Yap Trench in the western Pacific and discuss their petrogenesis and tectonic implications within the framework of interactions between the Caroline Ridge and Yap Trench. Rocks were collected from both landward and seaward trench slopes and exhibited geochemical characteristics similar to backarc basin basalt (BABB) and mid-ocean ridge basalt (MORB), including high Fe content, tholeiitic affinity, high TiO₂ value at a given FeO_T/MgO ratio, Ti/V ratio between 20 and 50, low Ba/Nb ratio and Th/Nb ratio, and trace element patterns commonly displayed by BABB and MORB, which are distinct from arc lava. These rocks seem to have been generated during mantle upwelling and decompression melting at a spreading center. However, compared with typical forearc lava produced by seafloor spreading in the Mariana forearc region, such as the early Eocene forearc basalts and late Neogene forearc lava in the southernmost Mariana Trench, the Yap Trench lava is derived from a more fertile mantle and feature a more minor subduction component; thus, they cannot be the products of forearc mantle decompression melting. We suggest that the landward slope lava represents backarc basin crust that was overthrust onto the forearc lithosphere during the collision of the Caroline Ridge with the Yap Trench (20–25 Ma), which played a key role in the evolution of the Yap subduction system. Moreover, the seaward slope lava represents the subduction plate crust that accreted onto the deep trench during the collision. This collision event resulted in the cessation of Yap Arc magmatism; thus, the Yap Trench volcanic rocks (<25 Ma) previously suggested to be arc magma products may actually represent the nascent island arc lava with a lower subduction component than in the mature Mariana Arc lava.

Key words: subduction zone, Yap Trench, forearc magmatism, subduction component, ridge subduction

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1 Introduction

Forearc lithosphere is thought to be generated in the nascent stage of subduction before the formation of a mature magmatic arc (Stern and Bloomer, 1992; Whattam and Stern, 2011; Stern and Gerya, 2018). Extensive forearc magmatism usually occurs during the earliest stages of plate subduction (Reagan et al., 2010, 2019; Shervais et al., 2019). In the forearc region of long-lived mature subduction zones, the mantle is strongly depleted and exceptionally cold due to its shallow depth and interaction with hydrous fluids released from the cold downgoing plate (Van Keken et al., 2002; Hulme et al., 2010; Wada et al., 2011). Thus, compared with magmatism in backarc basins and island arcs, forearc magmatism is rare in mature subduction systems (e.g., Ribeiro et al., 2013a, b; Stern et al., 2014). The origin of the forearc magmatism is poorly understood because it has few modern examples and requires interpretation within the framework of a specific evolution history of subduction systems. Multiple factors, such as

the subducting slab dehydration (Pearce et al., 1992), near-trench forearc spreading (Reagan et al., 2010), forearc lithosphere stretching (Ribeiro et al., 2013a, b), and tectonic emplacement (Hawkins and Batiza 1977; Fujiwara et al., 2000; Ohara et al., 2002), must be considered when examining the origins of forearc rocks.

The western Pacific subduction system is an ideal locality for examining the origin of forearc lithosphere. Early work on the Izu-Bonin-Mariana (IBM) subduction system suggested that boninite-series lava derived from the hydrous melting of highly depleted forearc mantle are ubiquitous rocks in the IBM forearc (Crawford et al., 1989; Pearce et al., 1992). These rocks are of Eocene age, i.e., older than other volcanic rocks of the IBM system, and may represent the initial melts (Meijer et al., 1983; Ishizuka et al., 2006). However, recent studies have proposed that mid-ocean ridge basalt (MORB)-like forearc basalts (FAB) are the oldest and most abundant igneous rocks in the IBM forearc (Reagan

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et al., 2010, 2019; Shervais et al., 2019). Slab sinking and rollback during the initial stages of IBM subduction facilitated lithospheric extension in the forearc region, which in turn triggered the asthenospheric upwelling and decompression melting of subduction-unmodified MORB mantle (Reagan et al., 2010, 2019). This process produced forearc basalts with MORB affinities, followed within less than 2 Ma by the flux melting of the subduction-influenced IBM mantle wedge peridotites that produced boninitic lava (Reagan et al., 2010, 2019; Shervais et al., 2019; Li et al., 2019). Another potential mechanism for the origin of the forearc magmatism is the eruption of lava in a forearc environment as an asthenospheric mantle flow, emanating from an active backarc region and penetrating into the forearc mantle owing to the forearc lithospheric extension (Ribeiro et al., 2013b; Stern et al., 2014; Martinez et al., 2018). A modern example of this process occurs in the southeast Mariana forearc rift (SEMPFR) near the Challenger Deep, where the forearc lithosphere has stretched to accommodate the opening of the Mariana Trough. This has led to the formation of the forearc rift, allowing the ambient mantle of the Mariana Trough, which represents the active backarc basin of the modern Mariana island arc, to flow southward and provide a supply of fresh, undepleted asthenosphere beneath the southern Mariana forearc. This led to the formation of forearc lava with a minor subduction component at ~3.7 Ma to 2.7 Ma (Ribeiro et al., 2013a, b; Stern et al., 2014).

The Yap Trench, located in the western Pacific, has evolved from the proto-IBM; thus, its forearc magmatism may have similar origins as the IBM forearc lava. However, compared with IBM, magmatism and tectonic evolution in the Yap Trench remain unclear. In addition to the mantle source composition and subduction component, other processes could have affected the Yap Arc and forearc magmatism, such as the subduction of the young Caroline Plate and the collision between the Caroline Ridge and trench. The collision between the Caroline Ridge and Yap Trench led to overthrusting of the backarc Parece Vela Basin lithosphere in the Yap Arc and forearc region (Hawkins and Batiza, 1977; Fujiwara et al., 2000; Ohara et al., 2002). Metamorphic rocks in the Yap Arc indicate source rocks composed of volcanic lithologies, including FAB, arc basalts, and lava from the subduction plate; this diverse range of lithology is associated with the collision of the Caroline Ridge with the trench (Zhang and Zhang, 2020). Some arc tholeiites collected in the Yap forearc are thought to have been generated by the abnormally shallow melting of forearc upper mantle owing to the subduction of the young, hot Sorol Trough crust in the Caroline Plate (Crawford et al., 1986). Therefore, tectonic processes such as the collision of the Caroline Ridge with the trench and the subduction of the young plate are of special interest because they may play a key role in the origin and evolution of forearc lithosphere in the Yap Trench.

In order to examine the nature of the forearc crust and the evolution of the Yap Trench, we present major and trace element geochemical data of lava from the northern Yap Trench slope. From these data, we determine the source mantle composition, influence of the subduction component, and origin of these forearc rocks. Through these analyses, we can better understand the mechanism of forearc magmatism and the evolution of the Yap Trench. Our results demonstrate that the Yap Trench lava was derived from an undepleted mantle similar to the backarc basin mantle and was not significantly affected by the slab-derived subduction component. The studied landward slope lava of the Yap Trench might represent the Parece Vela Basin crust that was overthrust in the forearc region owing to the collision of the Car-

oline Ridge with the Yap Trench.

2 Regional geology of the Yap Trench

The Yap Trench is located at the southeastern margin of the Philippine Sea Plate, where the Pacific and Caroline Plates subduct below the Philippine Sea Plate at an estimated rate of 0–6 mm/a (Seno et al., 1993; Fujiwara et al., 2000) (Fig. 1). The ~700-km-long Yap Trench has an east-facing arcuate shape and a maximum water depth of 8 946 m (Fujiwara et al., 2000). A volcanic island (Yap Arc) on the Philippine Sea Plate denotes the island arc magmatism associated with the W–NW subduction of the Caroline Plate at the Yap Trench (Fig. 1a) (Fujiwara et al., 2000). A W–NW-trending seamount chain (the Caroline Ridge) on the subducting Caroline Plate intersects the Yap Trench at a high angle, marking a collision event that started during the latest Oligocene–early Miocene (Fujiwara et al., 2000; Kobayashi, 2004). This ongoing collision led to the cessation of volcanism along the Yap Arc (Hawkins and Batiza, 1977; McCabe and Uyeda, 1983). The distance between the Yap Arc and the trench axis is only ~50 km, which is considerably shorter than the average (~115 km) in most western Pacific arc-trench systems, such as the Mariana Trench (~200 km) and Japan Trench (~300 km) (Kobayashi, 2000). This unusually narrow forearc basement is interpreted to have resulted from the significant tectonic erosion and subduction of the forearc mantle caused by the collision of the Caroline Ridge with the Yap Trench (Kobayashi, 2004; Zhang et al., 2019). There is little seismicity in the subduction zone and no earthquakes deeper than 40 km have been observed (Sato et al., 1997). Further, little sediment infill is present in the axial zone of the Yap Trench (Dong et al., 2018). The Yap Trench has evolved from the pro-IBM but is now offset hundreds of kilometers westward from the main IBM trend (Fig. 1) (McCabe and Uyeda, 1983).

Few petrological and geochemical studies have been conducted on rocks obtained from the Yap arc-trench system. The Yap Arc lacks any modern volcanic activity, and its basement is mainly composed of metamorphic rock (Hawkins and Batiza, 1977; Zhang and Zhang, 2020), which is unique in the western Pacific subduction zone system. An early study demonstrated that the Yap Trench metamorphic rocks originate from volcanic rocks overthrust from the backarc basin due to the collision of the Caroline Ridge with the trench (Hawkins and Batiza, 1977). A limited number of volcanic rocks obtained from the landward slope of the Yap Trench are island arc tholeiites (7–11 Ma) (Becaluva et al., 1980, 1986; Crawford et al., 1986), indicating arc volcanism in the vicinity of the Yap Trench during the early Miocene. Volcanic rocks recovered from the North Yap Escarpment (Fig. 1) and peridotites from the landward slope of the Yap Trench represent island arc tholeiites (~25 Ma) and highly depleted mantle residues, respectively (Ohara et al., 2002). Based on the nature of these igneous rocks, Ohara et al. (2002) proposed that the Yap forearc comprises two units. The upper part represents the Parece Vela Basin lithosphere that overthrust onto the forearc, although a minor amount of arc volcanic rocks is also present. The lower part is composed of mantle residues of arc magmatism (Ohara et al., 2002). Moreover, volcanic rocks and peridotites from the North Yap Trench were suggested to be subduction-related rocks that underwent metasomatism during later Cenozoic subduction (Yang et al., 2018). Based on peridotite geochemistry, Chen et al. (2019a, b) suggested that the Yap Trench mantle underwent a complex melting history, including an ancient melting event 1.16 billion years ago and a melting event during the earliest stages of subduction initiation. A recent study

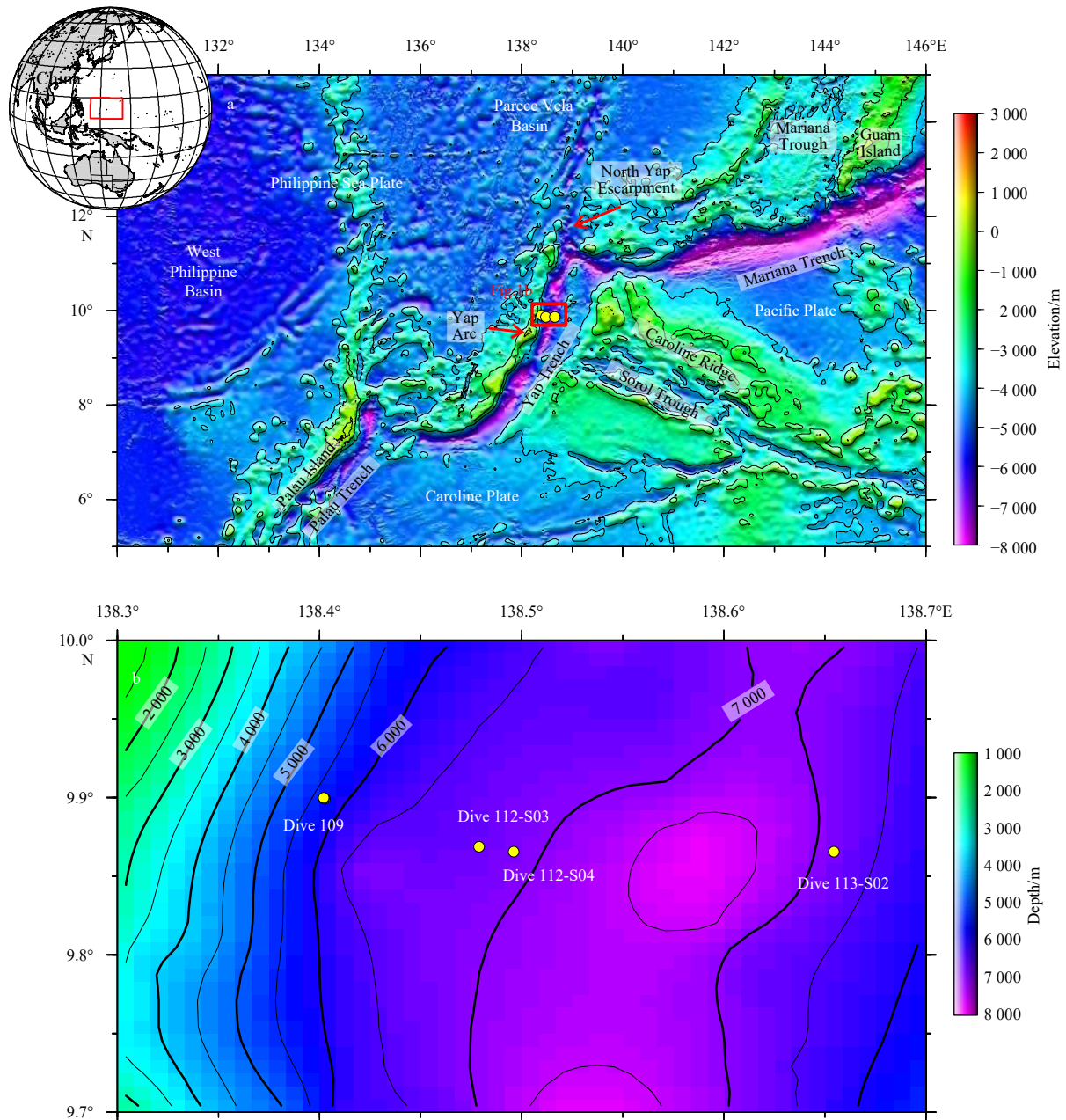


Fig. 1. Elevation and tectonic features of the study area (a) and detailed bathymetry around the sampling stations (b). Dive 109 in b includes 3 stations, which overlapped in map due to close distance. Refer to [Table 1](#) for detailed longitude and latitude information.

suggested that the metamorphic rocks in the Yap Arc are metamorphosed from volcanic rocks, such as forearc basalts of the nascent Yap forearc, basalts of the Caroline Plateau, and volcanic lava of the proto-Yap arc (Zhang and Zhang, 2020). According to these previous studies, the volcanic rocks in the Yap arc and forearc have a diversified nature and their petrogenesis processes—overthrust of the backarc crust to the arc and forearc area, subduction-related arc magmatism, forearc magmatism, and oceanic crust of their subduction plate—remain debatable.

3 Samples and methods

Volcanic rocks investigated in this study were collected from the northern segment of the Yap Trench using the Chinese manned submersible *Jiaolong* on Dives 109, 112, and 113 (Liu et al., 2010) during the DY125-37 cruise (Fig. 1). Dives 109 and 112

were on the landward side of the trench at water depths of 4 435–4 955 m and 6 035–6 351 m, respectively, whereas Dive 113 was on the seaward side at a depth of 6 532–6 578 m (Fig. 1b). Dives 109, 112, and 113 included 9, 8, and 7 stations, respectively, including stations where only biological samples were collected. For geochemical analyses, a total of 7 basaltic lava samples were collected from 6 stations (Dive 109-S02, Dive 109-S03, Dive 109-S05, Dive 112-S03, Dive 112-S08, and Dive 113-S02) (Table 1). Gabbroic rocks and greenschist associated with the basaltic samples were found on Dive 109, whereas the rock assemblages of Dives 112 and 113 were mainly basalts and peridotites. The bottom scene of the sampling site was photographed and is displayed in Fig. A1.

The basaltic samples are 5–10 cm in size and show massive and stomatal structures. Owing to seawater alteration and sea-

Table 1. Whole-rock major element and trace element concentrations in lavas from the Yap Trench

		Sample ID							GBW07316	AGV-2
		Dive 109-S02-1	Dive 109-S03-1	Dive 109-S05-1	Dive 109-S05-2	Dive 112-S03-1	Dive 112-S08-1	Dive 113-S02-1		
Dive station		Dive 109-S02	Dive 109-S03	Dive 109-S05	Dive 109-S05	Dive 112-S03	Dive 112-S08	Dive 113-S02		
East longitude/(°)		138.402 700	138.402 000	138.401 900		138.496 000	138.479 000	138.655 000		
North latitude/(°)		9.899 317	9.899 570	9.900 149		9.865 550	9.868 830	9.865 850		
Major element	SiO ₂ /%	45.94	49.91	54.50	52.08	50.55	48.73	49.50	31.21	
	TiO ₂ /%	1.62	2.08	1.77	1.71	1.83	1.93	0.95	0.37	
	Al ₂ O ₃ /%	11.73	13.26	11.82	13.75	13.29	12.97	17.75	7.89	
	TFe ₂ O ₃ /%	12.21	12.86	11.39	11.51	12.30	14.18	9.24	3.70	
	MnO/%	0.19	0.20	0.18	0.16	0.20	0.32	0.12	0.41	
	MgO/%	14.12	6.25	6.73	4.76	5.92	6.77	4.59	2.07	
	CaO/%	10.86	10.43	9.10	11.41	8.05	8.37	12.43	22.35	
	Na ₂ O/%	1.52	3.16	2.54	2.01	4.06	2.75	3.12	3.91	
	K ₂ O/%	0.14	0.34	0.39	0.20	0.81	0.29	0.24	1.54	
	P ₂ O ₅ /%	0.01	0.21	0.18	0.18	0.09	0.14	0.13	0.32	
	LOI/%	1.17	0.63	0.90	1.29	2.98	1.98	1.11	25.80	
	Sum/%	99.51	99.32	99.50	99.04	100.07	98.44	99.19	99.56	
Trace element	Li/10 ⁻⁶	3.1	4.6	4.7	4.1	22.3	29.7	10.9		10.6
	Ti/10 ⁻⁶	9 891	12 648	10 691	10 373	11 059	11 142	5 744		6 225
	V/10 ⁻⁶	327	392	340	354	464	452	236		118
	Rb/10 ⁻⁶	0.481	3.348	4.886	2.355	11.737	15.96	6.701		67.470
	Sr/10 ⁻⁶	97	387	358	492	143	112	168		659
	Y/10 ⁻⁶	18.5	31.9	27.1	31.3	26.7	31.8	24.1		19.9
	Zr/10 ⁻⁶	85.2	111.0	99.5	101.6	100.9	99.6	68.2		231.3
	Nb/10 ⁻⁶	13.50	12.05	11.40	14.00	5.00	4.92	2.57		14.31
	Cs/10 ⁻⁶	0.006	0.07	0.123	0.09	0.155	1.218	0.398		1.082
	Ba/10 ⁻⁶	20.6	100.4	122.3	65.2	57.7	18.1	15.7		1 115.3
	La/10 ⁻⁶	10.23	10.9	11.07	10.08	3.94	5.17	4.09		38.05
	Ce/10 ⁻⁶	22.7	25.9	24.3	24.9	10.0	12.9	8.5		69.1
	Pr/10 ⁻⁶	2.90	3.52	3.45	3.53	1.51	2.10	1.43		8.12
	Nd/10 ⁻⁶	13.22	17.26	16.75	17.23	8.05	10.45	7.44		30.22
	Sm/10 ⁻⁶	3.499	4.827	4.546	4.846	2.894	3.677	2.466		5.639
	Eu/10 ⁻⁶	1.308	1.672	1.514	1.636	1.24	1.384	0.998		1.524
	Gd/10 ⁻⁶	3.726	5.801	5.193	5.66	3.835	4.844	3.359		4.496
	Tb/10 ⁻⁶	0.582	0.939	0.846	0.922	0.707	0.888	0.588		0.615
	Dy/10 ⁻⁶	3.383	5.796	5.005	5.624	4.580	5.672	3.800		3.500
	Ho/10 ⁻⁶	0.682	1.185	1.021	1.136	0.968	1.198	0.826		0.655
	Er/10 ⁻⁶	1.862	3.358	2.829	3.211	2.903	3.528	2.480		1.840
	Tm/10 ⁻⁶	0.265	0.454	0.397	0.472	0.410	0.515	0.362		0.259
	Yb/10 ⁻⁶	1.743	3.015	2.556	2.945	2.812	3.404	2.408		1.653
	Lu/10 ⁻⁶	0.247	0.436	0.359	0.42	0.394	0.491	0.347		0.254
	Hf/10 ⁻⁶	2.295	2.936	2.646	2.618	2.744	2.757	1.687		5.243
	Ta/10 ⁻⁶	1.108	1.155	1.161	1.891	0.481	0.455	0.252		0.853
	Pb/10 ⁻⁶	10.30	8.24	3.63	4.57	0.77	0.94	0.77		13.13
	Th/10 ⁻⁶	0.969	0.928	0.937	0.806	0.255	0.322	0.234		6.232
	U/10 ⁻⁶	0.170	0.377	0.414	0.365	0.594	0.948	0.168		1.789

Note: LOI means loss on ignition. Measured major element contents for reference materials GBW07316 and trace element contents for reference materials AGV-2 are also presented.

floor weathering, these samples were black-gray and yellowish-brown and some samples were covered in black coatings of manganese (Fig. 2). The samples had a porphyritic texture with phenocryst assemblages of olivine, pyroxene, and plagioclase, and the groundmass was cryptocrystalline (Fig. 2). Both the phenocryst and groundmass were severely altered by seawater.

After cutting off their surfaces to remove any altered material, the samples were cut from the fresh section into ~5-cm rock slices. These rock slices were crushed into particles with size of

~5 mm and ultrasonically cleaned 3–5 times in ultrapure water until the surface dust was completely removed. Then, the cleaned samples were dried in a drying oven at 100°C for 24 h to remove moisture. Finally, the selected samples were crushed to a powder of 200 mesh size in an agate mortar for elemental analysis. Whole-rock major and trace element analyses were performed at the Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China. The major elements were analyzed using X-ray fluorescence with an analytical precision better than

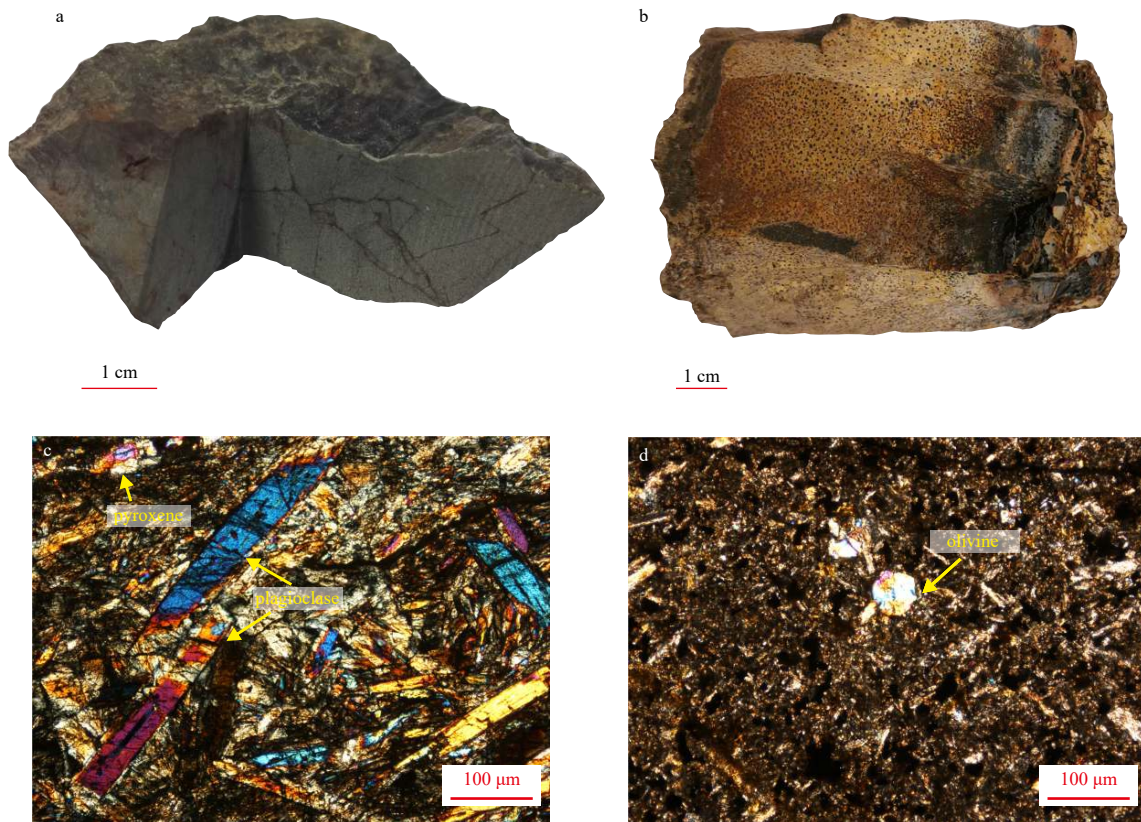


Fig. 2. Images of the Yap Trench lava. a and b. Hand specimens of Dive 112-S03-1 and Dive 113-S02-1 samples; and c and d. microimages of Dive 109-S02-1 and Dive 112-S03-1 samples in cross-polarized light.

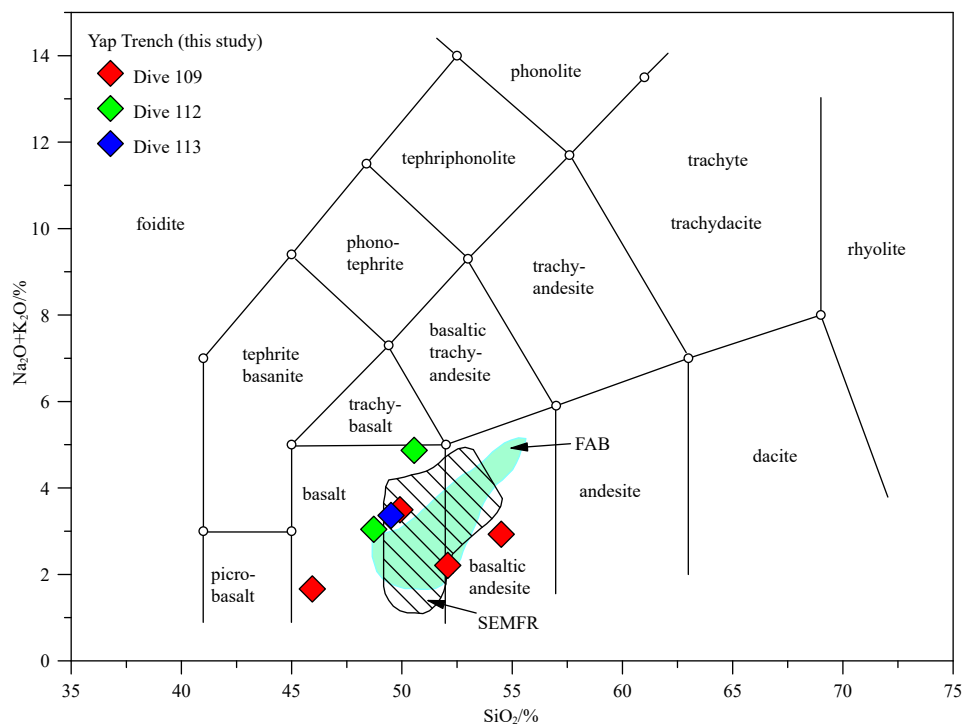


Fig. 3. SiO_2 vs. $\text{Na}_2\text{O} + \text{K}_2\text{O}$ diagram of the studied Yap Trench lava samples (after [Le Bas et al., 1986](#)). Lavas from the southeast Mariana forearc rift (SEMFR) ([Ribeiro et al., 2013b](#)) and typical forearc basalts (FAB) ([Reagan et al., 2010](#)) are shown for comparison.

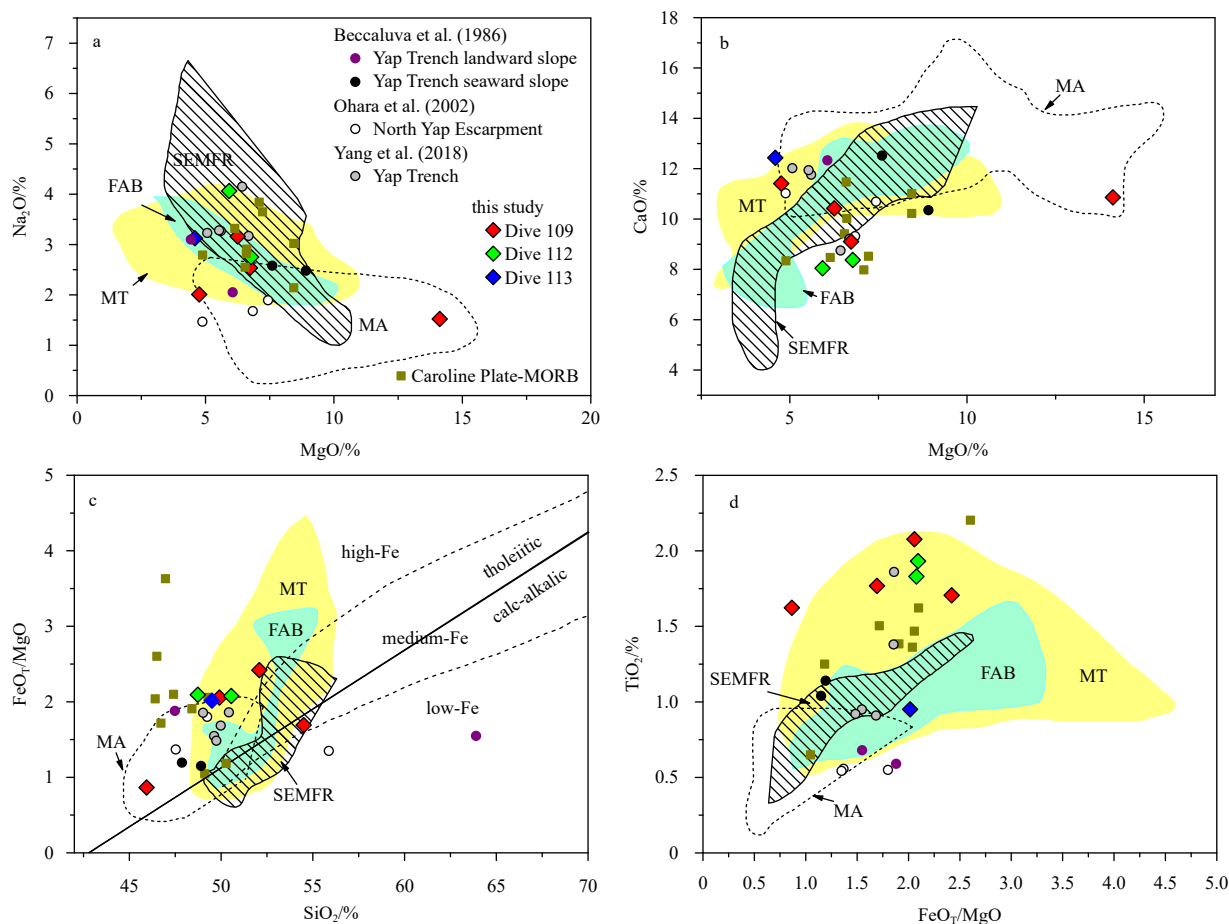


Fig. 4. MgO vs. Na₂O (a), MgO vs. CaO (b), SiO₂ vs. FeO_T/MgO (c), and FeO_T/MgO vs. TiO₂ (d) diagrams of the studied lava. The solid line and dashed lines in c distinguish the tholeiite and calc-alkaline suites (Miyashiro, 1974) and high-, medium-, and low-Fe suites (Arculus, 2003), respectively. Mid-ocean ridge basalt (MORB) samples dredged from the Caroline Plate are shown for comparison (Fornari et al., 1979; Zhang et al., 2020). The fields indicate lavas from the Mariana Arc (MA) (Stern et al., 2006; Tamura et al., 2014; Ikeda et al., 2016), Mariana Trough (MT) (Sinton and Fryer, 1987; Hawkins et al., 1990; Stern et al., 1990; Gribble et al., 1996, 1998; Ikeda et al., 2016), southeast Mariana forearc rift (SEMFR) (Ribeiro et al., 2013b), and typical forearc basalts (FAB) (Reagan et al., 2010). Other data sources are shown in the legend.

±2%. Whole-rock trace element analyses were conducted using Agilent 7700e ICP-MS at the Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China. The detailed sample-digestion procedure was as follows: (1) sample powder (200 mesh) was placed in an oven at 105°C and dried for 12 h; (2) 50 mg of sample powder was accurately weighed and placed in a Teflon bomb; (3) 1 mL of HNO₃ and 1 mL of HF were slowly added to the Teflon bomb; (4) the Teflon bomb was placed in a stainless steel pressure jacket and oven-heated to 190°C for more than 24 h; (5) after cooling, the Teflon bomb was opened and placed on a hotplate at 140°C and evaporated to incipient dryness, after which 1 mL of HNO₃ was added and evaporated to achieve dryness again; (6) 1 mL of HNO₃, 1 mL of MQ water, and 1 mL of internal standard solution with 1×10⁻⁶ In added, and the Teflon bomb was resealed and placed in the oven at 190°C for >12 h; and (7) the final solution was transferred to a polyethylene bottle and diluted to 100 g by adding 2% HNO₃.

4 Composition of the Yap Trench lavas

The whole-rock major and trace element geochemistry of the studied samples are presented in Table 1. Most samples are

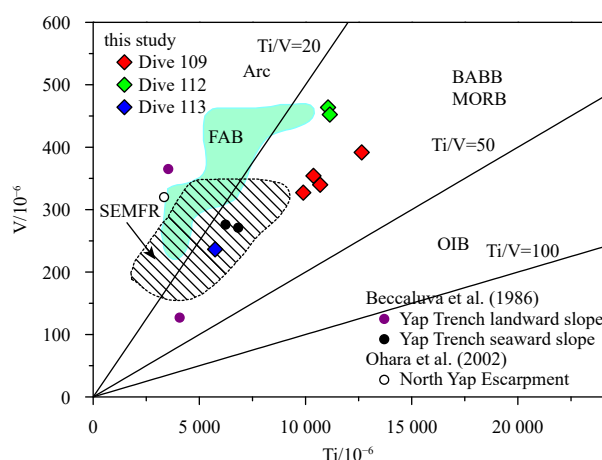


Fig. 5. Ti vs. V diagram of the studied Yap Trench lava. Lines of constant Ti/V distinguish arc lava (Ti/V < 20), backarc basin basalt (BABB), and mid-ocean ridge basalt (MORB) (20 ≤ Ti/V < 50), and ocean island basalt (OIB) (50 ≤ Ti/V < 100) (Shervais, 1982). Data sources are the same as in Fig. 3.

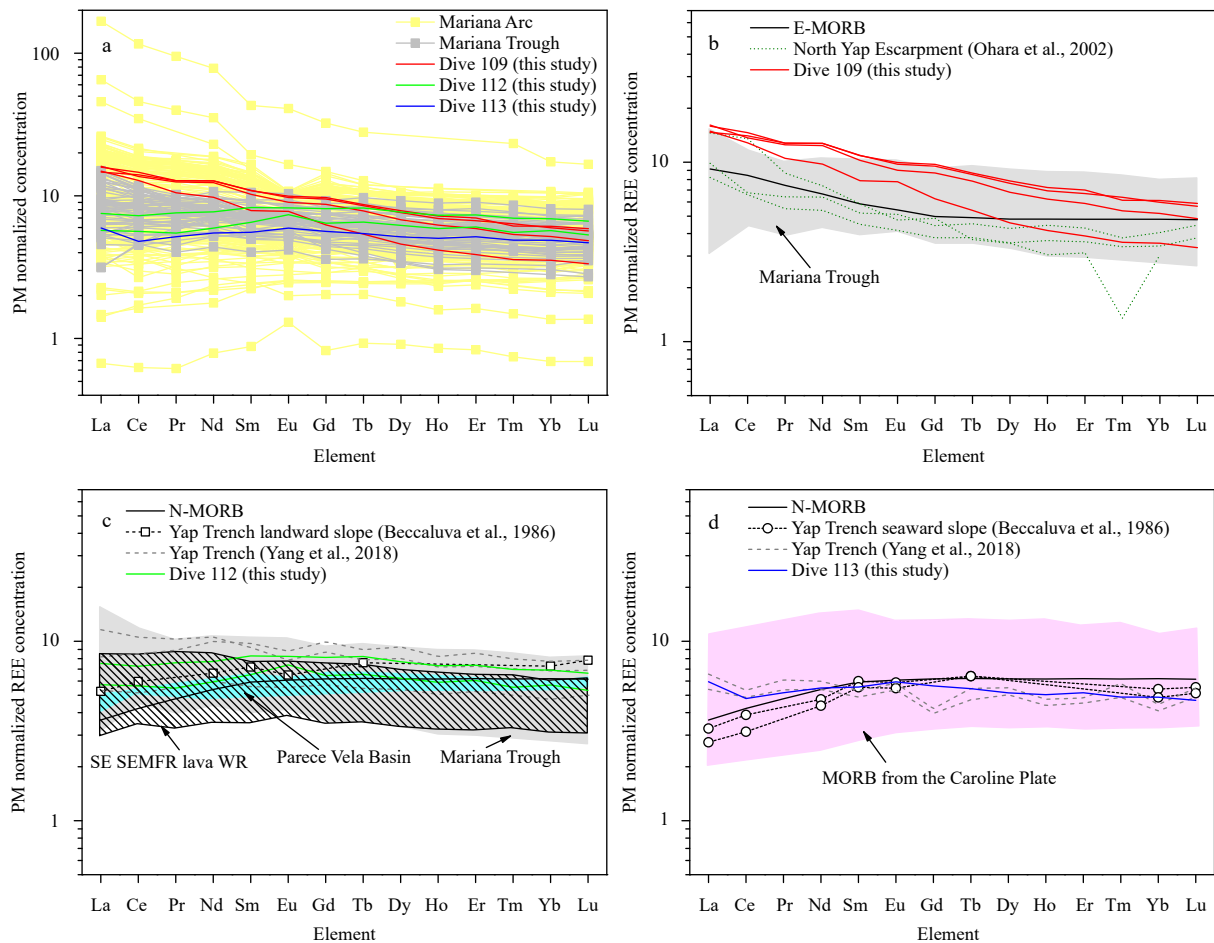


Fig. 6. Primitive mantle (PM)-normalized rare earth element (REE) concentrations of the studied lava. Lava data from the Mariana Arc (Turner and Langmuir, 2015; Ikeda et al., 2016) and Mariana Trough (Gale et al., 2013; Ikeda et al., 2016) are shown. Field of the whole-rock data of the southeast SEMFR lava (SE SEMFR lava WR) is obtained from Ribeiro et al. (2013b). Field of the N-MORB-type back-arc basin basalts in the Parece Vela Basin is obtained from Hickey-Vargas (1998). Field of the MORB-type basalts from the Caroline Plate is obtained from Zhang et al. (2020). Data for PM, N-MORB, and E-MORB are obtained from Sun and McDonough (1989). Other data sources are shown in the legend. SEMFR: southeast Mariana forearc rift, MORB: mid-ocean ridge basalt.

basalts; the exceptions are two samples that fall into the basaltic andesite field on a SiO_2 vs. $\text{Na}_2\text{O}+\text{K}_2\text{O}$ diagram (Fig. 3). On the MgO vs. Na_2O diagram, the Na_2O contents in most Yap Trench lava (those presented in this study and previously published data) are higher than those of the Mariana Arc lava, and plot close to those of FAB (Reagan et al., 2010) and the lava from the Mariana Trough and SEMFR (Ribeiro et al., 2013b; Ikeda et al., 2016) (Fig. 4a). The CaO contents of the Yap Trench lava are lower than those of the Mariana Arc and mostly plot within the compositional range of the Mariana Trough, SEMFR, and FAB lavas (Fig. 4b). On a SiO_2 vs. FeO_T/MgO diagram, most Yap Trench lava define a tholeiitic suite characterized by high Fe contents (Fig. 4c). The Yap Trench lava studied herein exhibit higher TiO_2 contents than the Mariana Arc lava, FAB, and SEMFR lava and their compositional field lies within the range of Mariana Trough lava (Fig. 4d). Lava from the North Yap Escarpment (Ohara et al., 2002) and landward slope of the Yap Trench (Beccaluva et al., 1986) was thought to represent island arc magma with low TiO_2 contents, similar to the Mariana Arc lava (Fig. 4d). MORB from the Caroline Plate show the same Na_2O and CaO contents as the Yap Trench lava and higher TiO_2 contents than

the Mariana Arc lava (Fig. 4). On a Ti vs. V diagram (Fig. 5), the studied Yap Trench lava plots as backarc basin basalts (BABB) and MORB with Ti/V ratios ranging from 20 to 50, i.e., differing from the arc lava field, which has Ti/V ratios lower than 20 (Shervais, 1982). The FAB and SEMFR lavas exhibit low Ti/V ratios and are plotted in the transition field between the BABB and arc lava field. These major and trace element data indicate that the Yap Trench basalts have geochemical features similar to those of BABB and MORB.

Generally, the Yap Trench lava is plotted in a field similar to the rare earth element (REE) range of the Mariana Trough lava in a primitive mantle (PM)-normalized REE diagram and lie in the relatively high REE endmember in the field of the Mariana Arc lava (Fig. 6). The Yap Trench lava dredged from the landward (Dive 109 and Dive 112) and seaward slopes (Dive 113) show distinct REE patterns (Fig. 6a). The Dive 109 lava exhibit a light REE (LREE)-enriched pattern, similar to enriched MORB (E-MORB) and lava from the North Yap Escarpment (Ohara et al., 2002) (Fig. 6b). The Dive 112 lava show a flat REE pattern plotting in the field of lavas from the southeastern SEMFR (Ribeiro et al., 2013a) and N-MORB-type basalts from the Parece Vela Basin (Deep Sea

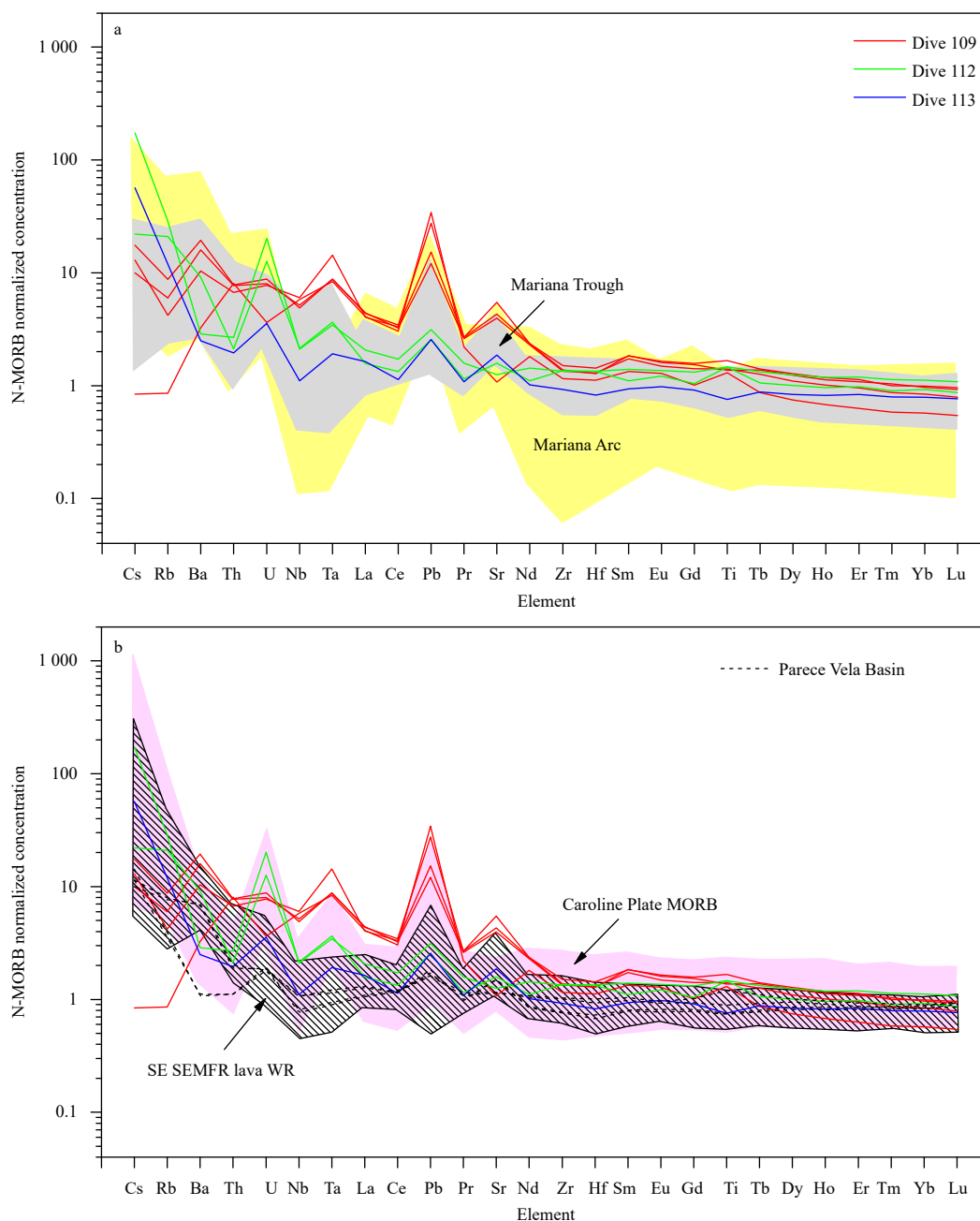


Fig. 7. N-MORB-normalized trace element diagram of the studied Yap Trench lavas. Fields of the Mariana Arc (Turner and Langmuir, 2015; Ikeda et al., 2016) and Mariana Trough (Gale et al., 2013; Ikeda et al., 2016) are shown for comparison. Field of the whole-rock data of the southeast SEMFR lava (SE SEMFR lava WR) is obtained from Ribeiro et al. (2013b). Field of the N-MORB-type basalts from the Caroline Plate is obtained from Zhang et al. (2020). Data of the N-MORB-type back-arc basin basalts in the Parece Vela Basin are obtained from Hickey-Vargas (1998). N-MORB data are obtained from Sun and McDonough (1989). SEMFR: southeast Mariana forearc rift, MORB: mid-ocean ridge basalt.

Drilling Project (DSDP) Sites 449 and 450 (Hickey-Vargas, 1998) (Fig. 6c). The lava from the landward slope of the Yap Trench (Beccaluva et al., 1986; Yang et al., 2018) exhibit REE patterns similar to those of the D112 lava (Fig. 6c). The seaward slope D113 lava also shows flat REE patterns with slightly higher LREE contents than the previously studied N-MORB-like lava from the seaward slope (Beccaluva et al., 1986), which shows REE pattern similar to those of the MORB-type lava from the Caroline Plate (Zhang et al., 2020) (Fig. 6d).

In a N-MORB-normalized trace element spider diagram, the

Yap Trench lava is plotted in the compositional range of the Mariana Trough lava and is distinct from the Mariana Arc lava owing to its higher moderately incompatible element content (Nb to Lu) (Fig. 7a). The compositional field of lava from the Southeast SEMFR was transitional between those of the Mariana Trough and Mariana Arc lavas; however, all of these lavas exhibit high contents of highly incompatible elements (Cs to U) (Fig. 7b). In general, the Yap Trench lavas are enriched in fluid-mobile elements (Cs, Rb, Ba, Sr, U, Pb); however, the D109-S02-1 sample shows lower Cs and Rb contents than N-MORB. High-field-

strength incompatible elements (HFSE), such as Nb, Zr, Hf, and Ti, show no systematic negative anomalies compared with the adjacent REE. Similar findings were reported in basalts from the Parece Vela Basin (Hickey-Vargas, 1998) (Fig. 7b). In general, the Yap Trench lavas have trace element patterns similar to those of the MORB-type lavas from the Caroline Plate (Zhang et al., 2020) (Fig. 7b).

5 Discussion

5.1 Petrogenesis of Yap Trench lava

The Yap Trench is considered to evolve from the proto-IBM subduction system (McCabe and Uyeda, 1983). Abundant lava samples were collected from the forearc area of this trench system, and their diversity can be summarized as follows.

(1) Forearc basalts were formed by forearc mantle upwelling and decompression melting during the initial stage of subduction in the early Eocene (Reagan et al., 2010, 2019; Shervais et al., 2019).

(2) Forearc lava was formed because of seafloor spreading related to the stretching of the pre-existing forearc lithosphere, such as the Pliocene lava from SEMFR (Ribeiro et al., 2013a, b). This lava is proposed to represent the nascent island arc magma (Ribeiro et al., 2020).

(3) The subduction-related island arc lava was affected by the slab-derived fluid and/or melt, such as the volcanic rocks collected from the landward slope of the Yap Trench (Beccaluva et al., 1980, 1986), intersection of the Yap and Mariana trenches (Crawford et al., 1986), and North Yap Escarpment (Ohara et al., 2002).

(4) The backarc basin crustal rocks were thrust over the island arc and forearc lithosphere owing to tectonic activities, such as metamorphic rocks from the Yap Arc (Hawkins and Batiza, 1977) and gabbroic rocks from the North Yap Escarpment (Ohara et al., 2002). The overthrusting of these rocks was related to the collision between the Caroline Ridge and Yap Trench (Hawkins and Batiza, 1977; Fujiwara et al., 2000; Ohara et al., 2002).

(5) The oceanic crust scraped from the subducting plate and accreted into the deep trench, such as rocks dredged from the seaward slope of the Yap Trench, was related to magmatism at diverging plate margins (Sorol Trough) or off-ridge volcanism on

the Caroline Plate (Beccaluva et al., 1980, 1986).

The studied Yap Trench lava samples were collected from both the landward and seaward slopes of the trench. Because the arc-trench distance is extremely narrow (Fig. 1), these lava samples could be derived from the backarc basin, island arc, forearc lithosphere, and subducting plate. The most prominent feature of the subduction-related volcanic rocks is enriched slab-derived components, such as the fluid-mobile large ion lithophile elements (LILE) relative to the subduction-immobile HFSE. Volcanic rocks from island arcs have depleted Nb, Ta, Zr, Hf, and Ti contents (e.g., Pearce et al., 2005). However, the studied Yap Trench lava show no systematic depletion in HFSE but high Ti and Ta contents relative to REE (Fig. 7). Thus, the influence of a subduction component, such as slab-derived fluid and melt, requires further evaluation. Incompatible element ratios, such as

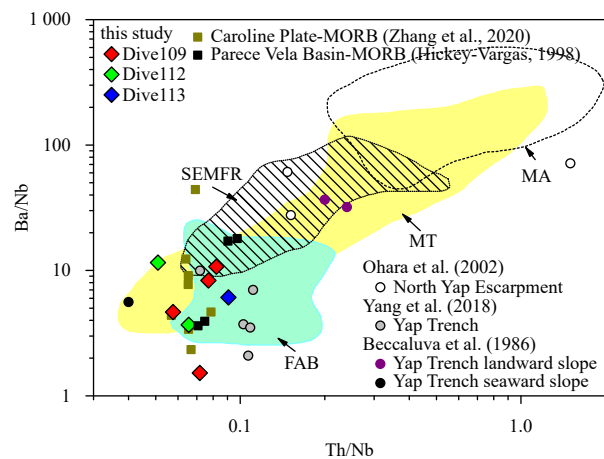


Fig. 8. Th/Nb vs. Ba/Nb diagram of the studied lava. Fields show lavas from the Mariana Arc (MA) (Stern et al., 2006; Tamura et al., 2014; Ikeda et al., 2016), Mariana Trough (MT) (Hawkins et al., 1990; Stern et al., 1990; Gribble et al., 1998; Pearce et al., 2005; Ikeda et al., 2016), southeast Mariana forearc rift (SEMFR) (Ribeiro et al., 2013b), and typical forearc basalts (FAB) (Reagan et al., 2010). Other data sources are shown in the legend. MORB: mid-ocean ridge basalt.

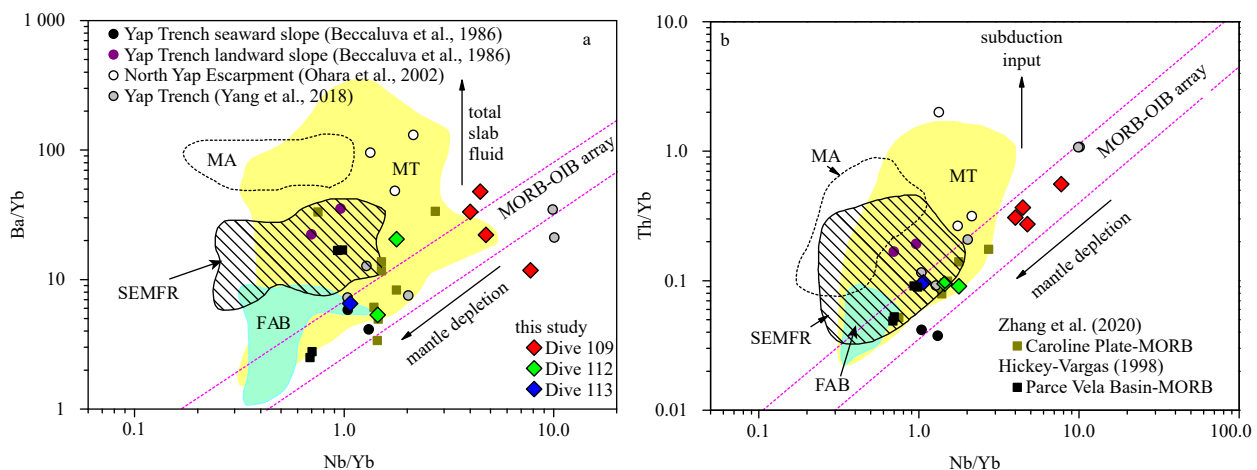


Fig. 9. Nb/Yb vs. Ba/Yb (a) and Nb/Yb vs. Th/Yb (b) diagrams of the studied lava. Fields show lavas from the Mariana Arc (MA) (Stern et al., 2006; Tamura et al., 2014; Ikeda et al., 2016), Mariana Trough (MT) (Hawkins et al., 1990; Stern et al., 1990; Gribble et al., 1998; Pearce et al., 2005; Ikeda et al., 2016), southeast Mariana forearc rift (SEMFR) (Ribeiro et al., 2013b), and typical forearc basalt (FAB) (Reagan et al., 2010). Other data sources are shown in the legend.

LILE/HFSE and LILE/HREE, were used as proxies to reflect the influence of slab-derived fluids during melt evolution (Hawkesworth et al., 1997; Pearce et al., 2005; Dilek et al., 2008; Ikeda et al., 2016). Considering that K, Rb, Cs, and U are more vulnerable to late-stage seawater alteration, Ba was selected as the most suitable LILE for evaluating the influence of slab-derived fluid on the subduction-related lava (Pearce et al., 2005). The melting of subducted sediments can transport some fluid-immobile elements such as Th into the mantle wedge (Elliott et al., 1997); therefore, most Th in arc volcanics was derived from subducted sediments (Hawkesworth et al., 1997). Consequently, Th/Nb and Ba/Nb have been widely used to evaluate the influence of subduction fluids and sediment melts in subduction-related lava (Pearce et al., 2005). In the Th/Nb vs. Ba/Nb diagram (Fig. 8), the FAB, SEMFR lava, and Mariana Arc lava exhibit a compositional trend with increasingly enriched slab-derived components (Ba and Th). The studied Yap Trench lava show low Ba/Nb and Th/Nb ratios and is plotted in the compositional field of FAB, indicating that similar to FAB (Reagan et al., 2010, 2019; Shervais et al., 2019), this lava was not significantly affected by the subduction component. The major and trace element compositions of the studied Yap Trench lava are consistent with those of BABB and MORB (Figs 4 and 5), suggesting that the lava was generated during decompression mantle melting.

If the studied Yap Trench lava represents FAB from the proto-Yap Trench, they would not be significantly affected by the subduction component (Fig. 8). However, the Yap Trench lava exhibit flatter, more LREE-enriched REE patterns than the FAB and N-MORB (Fig. 6). Furthermore, in the Nb/Yb vs. Ba/Yb and Th/Yb diagrams (Fig. 9), the studied Yap Trench lava is plotted in the MORB-OIB array but shows no subduction input, implying that they were either formed under lower degrees of mantle melting (high Nb/Yb) or derived from a less-depleted mantle source than FAB. Instead of flux melting of the mantle wedge of arc magma, FAB is thought to be generated by decompression melting of the forearc mantle during near-trench spreading, with little or no mass transfer from the subducting plate. However, the source mantle is more depleted than normal MORB mantle (Reagan et al., 2010, 2019; Shervais et al., 2019). Therefore, although the studied Yap Trench lava was unaffected by the subduction component, it did not represent the FAB of the proto-Yap Trench. This inference is supported by the higher Ti content in the Yap Trench lava than in the FAB (Fig. 5).

Forearc lava from SEMFR is thought to be derived from the adiabatic decompression of a BABB-like mantle flowing along the SEMFR owing to the stretching of the pre-existent forearc lithosphere in the Pliocene (Ribeiro et al., 2013a, b). This lava is different from the FAB because the latter is generated in the initial stage of subduction (early Eocene) before the formation of forearc lithosphere (Reagan et al., 2010; Shervais et al., 2019). This lava was proposed to represent the nascent island arc magma and showed an intermediate composition between FAB and mature island arc lava because the arc lava showed increasingly enriched subduction component as arc volcanism evolved (Ribeiro et al., 2020). The studied Yap Trench lava also exhibit BABB-like major and trace element compositions (Figs 4 and 5) but is less enriched in the subduction component compared with the SEMFR lava (Figs 8 and 9); thus, it may not have been produced during decompression mantle melting in the forearc region. The lava from both the North Yap Escarpment (Ohara et al., 2002) and the landward slope of the Yap Trench (Beccaluva et al., 1986) show compositions similar to the SEMFR lava (Ribeiro et al., 2013a, b) (Figs 8 and 9), indicating that it may represent the

nascent island arc magma instead of the mature island arc lava.

Previously studied lava from the seaward slope of the Yap Trench exhibit depleted LREE (Fig. 6d) and lower Ba/Yb and Th/Yb than lava from the landward slope and other volcanic arcs (Beccaluva et al., 1980, 1986) (Fig. 9). This lava was likely formed at a spreading center of the subducting Caroline Plate (Beccaluva et al., 1980, 1986). Generally, samples from the seaward slope of the Yap Trench (Dive 113) have compositions similar to the seaward slope lava studied by Beccaluva et al. (1980, 1986) (Figs 8 and 9) and may represent materials from the subducting plate. Volcanic rocks from the subduction plate include MORB-like tholeiites, ocean island tholeiites, and alkali basalts (Hawkins and Batiza, 1977; Fornari et al., 1979; Zhang et al., 2020). As the sample from the seaward slope of the Yap Trench shows low Na₂O and K₂O contents (Fig. 3) and was collected near the Sorol Trough (Fig. 1), it may represent MORB-like tholeiite generated in the spreading center of the Sorol Trough (Fornari et al., 1979), which is supported by the observation that it has composition similar to the MORB-type lavas from the subduction Caroline Plate (Zhang et al., 2020) (Figs 7–9). As previously discussed, samples from the landward slope of the Yap Trench (Dive 109 and Dive 112) exhibit compositions similar to those generated by decompression mantle melting but are derived from a more fertile mantle source than FAB (Reagan et al., 2010) and are less enriched in subduction components than lava produced by forearc spreading (Ribeiro et al., 2013a, b). Therefore, rather than arc and forearc magmas, the landward slope Yap Trench lava may represent backarc basin crust that thrust over the Yap forearc. This inference explains their compositional similarity to BABB while being insignificantly affected by subduction processes. Basalts from DSDP Sites 449 and 450 in the Parece Vela Basin were also insignificantly affected by the subduction component (Figs 8 and 9), and their REE and trace element patterns are similar to those of the D112 samples (Figs 6 and 7), supporting the backarc origin of the landward slope Yap Trench samples. The obduction of the Parece Vela Basin crust likely resulted from the continued westward motion of the Pacific plate and the collision of the Caroline Ridge with the Yap Trench (Hawkins and Batiza, 1977; Fujiwara et al., 2000). This collision resulted in the westward migration of the Yap Trench with respect to the Philippine Sea Plate and Mariana Trench and played a key role in its evolution. The detailed evolution history of the Yap Trench is discussed in the next section.

5.2 Implications for the evolution of the Yap Trench

The proto-Yap Trench is part of the proto-IBM trench system, which formed at ~52 Ma when the Pacific Plate began to subduct beneath the Philippine Plate (Ishizuka et al., 2011; Reagan et al., 2013; Ishizuka et al., 2018; Li et al., 2019). Magmatism associated with forearc seafloor spreading produced FAB during the first ~2 Ma after the initiation of subduction (Reagan et al., 2019; Shervais et al., 2019). Thereafter, the depleted mantle was affected by slab-derived fluids and further melted to generate boninites at 50 Ma to 40 Ma (Pearce et al., 1992; Reagan et al., 2019). Before the initiation of subduction, the proto-Yap-IBM forearc mantle experienced ancient mantle-melting events, as evidenced by the depleted radiogenic Os isotope in forearc mantle peridotites with Re-depleted ages older than 1 Ga (Parkinson et al., 1998; Chen et al., 2019b). As the subduction proceeded, the subducted slab rolled back and the Yap Trench migrated toward the east with respect to the Philippine Sea Plate (Fujiwara et al., 2000).

The Caroline Plate was formed at approximately 35 Ma to 30 Ma (Bracey, 1975; Hegarty and Weissel, 1988; Yamazaki et al., 1994),

and the Caroline Ridge originated from the activity of the Caroline hotspot at approximately ~33 Ma to 27 Ma (Keating et al., 1984; Hegarty and Weissel, 1988; Gaina and Müller, 2007). The Caroline Ridge migrated to the west with respect to the Caroline Plate before colliding with the Yap Trench. The collision of the Caroline Ridge and Yap Trench played a key role in the evolution of the Yap subduction system. However, the timing of this event remains debatable. Fujiwara et al. (2000) proposed that the collision caused the cessation of volcanism at the Yap Arc at approximately 25 Ma. Supporting this conclusion, the Yap Arc was formed from metamorphic rocks rather than volcanic rocks (Hawkins and Batiza, 1977). However, the volcanic rocks from the North Yap Escarpment were 25 Ma old (Ohara et al., 2002), suggesting that the collision occurred later than 25 Ma if the collision caused the cessation of the arc volcanism. Based on the age of metamorphic rocks of the Yap Arc, Zhang and Zhang (2020) proposed that the collision occurred at ~21 Ma, resulting in the metamorphism of the volcanic island rocks. This suggestion is supported by the dramatic changes in the spreading rate and direction at (20 ± 1.3) Ma in the Parece Vela Basin (Sdrolias et al., 2004), which were likely related to the collision. Therefore, the 25-Ma old volcanic rocks in the North Yap Escarpment (Ohara et al., 2002) are the products of island arc magmatism predating the collision with the Caroline Ridge.

Before the collision between the Caroline Ridge and the trench, the Yap-Mariana Trench migrated eastward with respect to the Philippine Sea Plate owing to trench retreat. After the collision, the Yap Trench drifted westward, while the Mariana Trench maintained an eastward migration owing to seafloor spreading of the Parece Vela Basin and Mariana Trough (Fujiwara et al., 2000; Okino et al., 1998). Owing to the relative displacement of the Yap and Mariana Trenches, the southernmost portion of the Mariana Trench curves from N-S to nearly E-W (Fig. 1), possibly representing a transformation boundary between the southern Mariana and the Caroline Plate (McCabe and Uyeda, 1983). Moreover, the collision changed the mode of backarc spreading in the Parece Vela Basin. After the collision, the spreading rate decreased and the spreading direction changed from E-W to

NE-SW at approximately 19 Ma (Okino et al., 1998; Lee, 2004). This collision enhanced the tectonic erosion and caused the narrowing of the distance between the Yap arc and trench. Additionally, the collision may have removed a section of the seafloor in the southern Parece Vela Basin. Supporting this suggestion, the Parece Vela Basin in the Yap backarc region was only half the size of its northern portion (Ohara et al., 2002) (Fig. 1). The removed backarc region of the southern Parece Vela Basin was thrust over the Yap Arc (Hawkins and Batiza, 1977; Fujiwara et al., 2000; Ohara et al., 2002). Therefore, the Yap Arc was principally composed of metamorphic rocks rather than volcanic rocks (Shiraki, 1971; Hawkins and Batiza, 1977; Zhang and Zhang, 2020).

Our geochemical data support that the Yap forearc region was overthrust by backarc crust formed during spreading of the Parece Vela Basin; accordingly, the composition characteristics of the studied Yap forearc lavas are unrelated to subduction. The Parece Vela Basin was spreading (29 Ma to 15 Ma) (Okino et al., 1998) when the Caroline Ridge collided with the Yap Trench (25 Ma to 20 Ma) (Fujiwara et al., 2000; Zhang and Zhang, 2020). The spreading process may have promoted overthrust of the back-arc crust. Swath bathymetry data have identified numerous horst and grabens at the collision front of the Caroline Ridge, i.e., the seaward slope of the Yap Trench (Fujiwara et al., 2000; Dong et al., 2018). A series of bending-related faulting and normal faulted structures along with the horst and graben may have exposed the volcanic rocks on the subducting plate (Fig. 10). Moreover, the existence of ridge, horst, and graben increased the roughness of the subducting plate, thus enhancing the subduction erosion of the Yap forearc and greatly shortening the arc-trench distance. Such intense erosion and extrusion was noted to steepen the slope at the landward side and facilitated the subsequent landslide in the forearc (Ohara et al., 2002; Dong et al., 2018; Zhang et al., 2019). Landslide bodies on the slope of the Yap forearc are clearly revealed in seismic data, indicating that submarine landslides are ongoing (Dong et al., 2018). After a landslide, overthrust back-arc rocks are deposited in the deep trench (Fig. 10).

According to previous studies, volcanic rocks from the landward slope of the Yap Trench and the North Yap Escarpment are

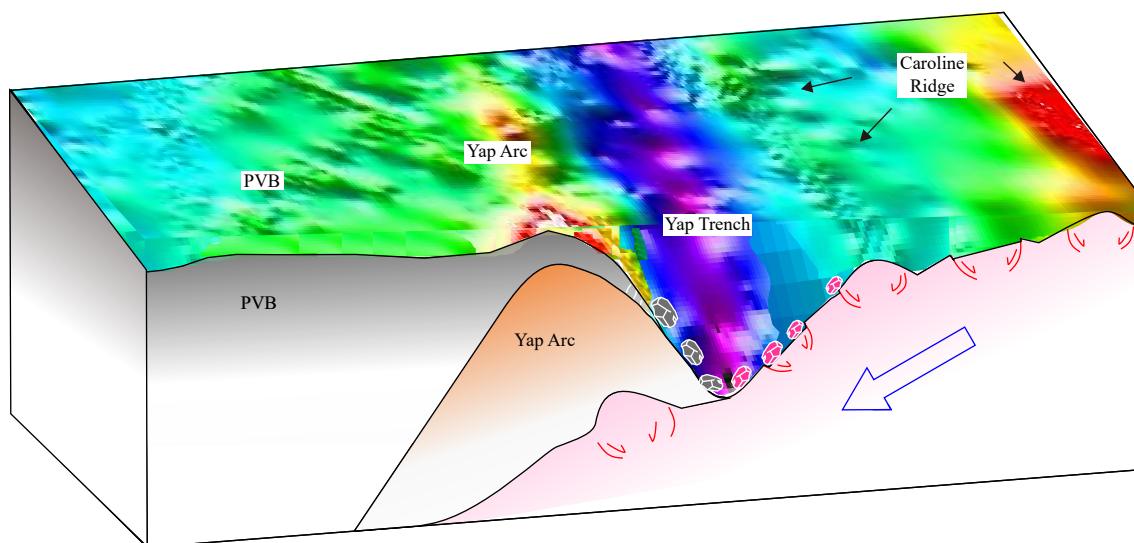


Fig. 10. Schematic showing overthrust of the Parece Vela Basin (PVB) crust onto the Yap Arc and forearc area due to the collision of the Caroline Ridge with the trench. Gray blocks indicate back-arc crustal rocks presented in the deep trench due to the overthrust of the Parece Vela Basin crust and landslides of the landward trench slope, and pink blocks indicate the volcanic lava exposed on the seafloor through faulting in the horst and graben (red arrows) on the subduction plate. Blue arrow indicates the subduction direction.

characterized by an elevated subduction component and probably represent island arc magmas (Beccaluva et al., 1980, 1986; Crawford et al., 1986; Ohara et al., 2002). However, these volcanic rocks involve a more minor subduction component than those of the Mariana Arc and their compositions resemble those of SEMFR lavas (Figs 8 and 9), which are intermediate between the FAB and the Mariana Arc lavas. Therefore, they have been interpreted as nascent island arc magma (Ribeiro et al., 2013a, b, 2020). We propose that either the mature arc magma of the Yap subduction system was overlain by the backarc crust or that no mature arc developed in the Yap Trench system (meaning that the volcanic rocks represent nascent island arc magma). The volcanic rocks from the North Yap Escarpment (aged 25 Ma; Ohara et al., 2002) post-date the formation of the Caroline Plate (35 Ma to 30 Ma) by only 10 Ma (Bracey, 1975). Thus, the Yap Arc may not have developed into a mature arc at 25 Ma because the subduction of the Caroline Plate was still in its early stage. Arc magmatism ceased at 21 Ma when the Yap Trench collided with the Caroline Ridge (Zhang and Zhang, 2020); this event further prevented the maturity development of the arc. After the collision, the subduction and arc magmatism rejuvenated, producing the observed 7 Ma to 11 Ma volcanic rocks (Beccaluva et al., 1980, 1986). This period of magmatism may represent another stage of nascent island arc magmatism linked to rejuvenated subduction; accordingly, these lavas were not significantly influenced by the subduction component. Because the rejuvenated subduction rate is very slow (0–6 mm/a; Seno et al., 1993), volcanic activity is now absent.

6 Conclusions

The studied Yap Trench lava show BABB-like major and trace element compositions, indicating a decompression mantle-melting origin. However, compared with the early Eocene forearc basalts (FAB) and late Neogene forearc lava produced by decompression mantle melting during the Mariana forearc seafloor spreading, the Yap Trench lava show a more fertile mantle composition (relative to the early Eocene FAB) and a more minor subduction component (relative to the late Neogene forearc lava). Therefore, these lavas were not produced by forearc decompression mantle melting. We suggest that the landward slope lava represents backarc basin crust that was overthrust onto the previously developed arc and forearc lithosphere, whereas the seaward slope lava was produced in the spreading center of the subducting plate. These lavas occurred in the deep trench owing to the collision of the Caroline Ridge with the trench, a process that caused the overthrusting of the backarc crust and the cessation of arc volcanism, thereby preventing the development of the Yap Arc into a mature arc. Consequently, although some previously studied volcanic rocks from the Yap Trench were thought to be the product of arc magmatism, they involved a more limited subduction component compared with the mature Mariana Arc lava and may instead represent the nascent island arc magma.

Acknowledgements

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Appendix:



Fig. A1. Image of the bottom scene at the sampling site of the Chinese manned submersible *Jiaolong* on Dive 112 during the DY125-37 cruise.