Geology of the Yap Trench: new observations from a transect near 10°N from manned submersible Jiaolong

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1. Introduction

The Yap Trench, which is located at the southern end of the Philippine Sea Plate, is a complex tectonic region of convergence among the Philippine Sea, the Pacific and the Caroline plates in the western Pacific (Figure 1). It has some apparent similarities to other subduction zones in the western Pacific with typical trench-arc-basin systems including deep trench, island arc (Yap arc), and back-arc basin (Parece Vela Basin) to the west (Nagihara et al. 1989; Sato et al. 1997). However, the Yap Trench also has some characteristics which are different from those of other subduction zones in the western Pacific (Sato et al. 1997; Fujiwara et al. 2000; Ohara et al. 2002). The distance with a length of about 50 km between the arc and trench axis is much less than those of other arc-trench systems. A typical trench–trench junction is formed at a nearly perpendicular angle near 11°07′N between the north of Yap Trench and the southern end of Mariana Trench (Ohara et al. 2002). There is a ridge called Caroline Ridge oriented in an ESE–WWW direction, consisting of a chain of seamounts on the down-going plate and intersecting the trench from the east. The Yap island arc consists largely of metamorphic rocks and has no active volcanism (Shiraki 1971; Hawkins and Batiza 1977). There is low seismicity and no deep-focus earthquakes occur along the Yap Trench area where cannot define a Wadati–Benioff zone between the down-going and over-riding plates (Sato et al. 1997).

There is a long debate about the subduction activity of the Yap Trench. A few cruises had been performed in the southern tip of the Parece Vela Basin and the Yap Trench (e.g. Bogdanov 1977; Hawkins and Batiza 1977; Dietrich et al. 1978; Beccaluva et al. 1980; Crawford et al. 1986; Tomoda 1986; Fujiwara et al. 2000; Ohara et al. 2002; Okino et al. 2009). It was suggested that the subduction had been terminated by collision of the Caroline Ridge in the early work of Hawkins and Batiza (1977) and McCabe and Uyeda (1983). Normally when igneous plateaus and volcanic islands collide with a subduction zone, a trench does not exist, and even if it exists, it should be shallow. However, similar to its adjacent intra-oceanic convergent margin, the Izu–Bonin–Mariana (IBM) Trench with 2800 km length extending from near Tokyo to Guam and the deepest trench ‘Challenger Deep’ (Stern 2002; Stern et al. 2003), the Yap Trench is only 1000 m shallower than the
Mariana Trench on average. Moreover, evidences from recent shipboard surveys and observations from islands arc show signs of uplift. The high heat flow value in the east of the Yap arc (Kinoshita and Kasumi 1989; Nagihara et al. 1989), lack of thick sediments at the bottom of the trench (Fujiwara et al. 2000), seismicity derived from earthquakes (Sato et al. 1997), presence of fresh volcanic rocks (Ohara et al. 2002), and GPS measurement data (Seno et al. 1993; Tsuji 1995) also support an active subduction zone in the Yap Trench.

Despite the importance of the Yap Trench, there are only few studies of morphology, deformation structure, and petrology (Hawkins and Batiza 1977; Beccaluva et al. 1980; Crawford et al. 1986; Fujiwara et al. 2000; Ohara et al. 2002; Lee 2004). Ohara et al. (2002) first reported a comprehensive petrology and geochemistry study in the Yap Trench. Their results showed that both peridotites and volcanics display arc-like affinities rather than spreading ridge affinities and proposed that the Yap arc and North Yap Escarpment seem to form as an incipient arc system at the propagating tip of the Parece Vela Basin (Ohara et al. 2002).

Newly geophysical data and rock samples were obtained from R/V Kexue integrated geophysical survey cruise in 2015 and submersible Jiaolong, R/V Xiangyanghong 09 Dayang 37th scientific survey cruise.
in 2016. In this study, we report new geophysical observations in the Yap Trench, island arc, and back-arc basin, and geochemical results for greenschists, peridotites, and basalt from both landward and ocean-ward slopes of the Yap Trench. These observations would provide new evidence of the subduction activity in the Yap subduction system and deepen our understanding of the tectonic evolution of the Yap Trench.

2. Geological background

The Izu–Bonin–Mariana–IBM–Yap–Palau trench systems, which define an obvious boundary among Philippine Sea Plate, Caroline Plate, and Pacific Plate, are one of the representative examples of intraoceanic converging plate margins (Karig 1971; Beccaluva et al. 1980). The Philippine Sea Plate lies on the west of the trench and the Caroline Plate and Pacific Plate are located in the east. The Yap Trench is about 700 km long and 50 km wide from the trench axis to island arc with a ‘J’ shape towards southeast (Lee 2004). The Yap Trench was divided into the northern and the southern segments, with 8°26′N as the boundary between these two parts, according to morphological characteristics (Fujiwara et al. 2000). The Caroline Ridge intersects the trench from the east and is a shallow NWW–SEE striking complex of ridge and trough structure as a most obviously geomorphic unit situated between Caroline Plate and Pacific Plate (Figure 1). It consists of three sub-parallel topographic textures. The Caroline Islands Ridge is located on the northeast and the West Caroline Rise lies on the southwest (Figure 1). The two ridges are separated by the Sorol Trough which is a rift-like feature of an approximate depth of 4000 m. Caroline Ridge began to subduct beneath Philippine Sea Plate along the Yap Trench since late Oligocene or early Miocene (McCabe and Uyeda 1983; Fujiwara et al. 2000; Kobayashi 2000, 2004; Lee 2004). Deep Sea Drilling Project (DSDP) site 57 established an Oligocene age for the Caroline Ridge (Gaina and Müller 2007). The Caroline Ridge and the Caroline Seamounts (located east of 144°E) have been formed by excessive volcanism on young and weak lithosphere of the Caroline Basin (Weissel and Anderson 1978; Hegarty and Weissel 1988). Altis (1999) confirmed this scenario for the Caroline ridge and proposed an Oligocene age for the formation of the Caroline Ridge and a late Miocene age for the rifting that led to the opening of the Sorol Trough.

The Pacific Plate subducted below the Philippine Sea Plate since middle Eocene (Uyeda and Ben-Avraham 1972), and the Shikoku–Parece Vela back-arc basin begun to open from about 30 million years because of the subduction. Previous models about Philippine Sea Plate motion showed that the rotation pole of the Philippine Sea-to-Caroline Plate is at the junction of the Palau Trench and Ayu Trough at nearly 6°N, 134°E (Ranken et al. 1984; Seno et al. 1993; Fujiwara et al. 2000). The rate of relative plate motion was estimated to be 0–6 mm/year along Yap Trench based on GPS monitoring (Seno et al. 1993). Hill et al. (1993) proposed that a slow and low-angle subduction probably occurred along the Papua New Guinea margin, at about 2000 km south of the northward subduction under the Caroline Plate during late Oligocene to late Eocene. Hill and Hall (2003) suggested that the northward moving Australian Plate was subducting under the westward moving Pacific Plate creating the Caroline back-arc basin from middle Eocene to late Oligocene. In a series of tectonic reconstructions, Hall (2002) models the inception of the Caroline plate on the east of the Philippine Plate as a result of a westward subduction of the Pacific Plate. In his model, the Caroline Plate is subjected to a clockwise rotation that relocated the trench from an NE–SW position to a more E–W location and subsequently the subduction of newly created crust north of Australia (in the so-called Solomon Sea). The age of the Caroline Basin crust has been determined by DSDP 62 and 63 drilling holes to be Tertiary (Winterer et al. 1971). The detailed subducting age of the Caroline Basin in the Caroline Plate was estimated to be 35–30 Ma (Bracey 1975; Hegarty and Weissel 1988; Yamazaki et al. 1994), while the age of overlying Parece Vela Basin of the Philippine Sea Plate was estimated to be 30–25 Ma (Mrozowski and Hayes 1979; Okino et al. 2009). At present, the Caroline Plate is moving with Pacific-like motions, as is the southern Philippine Sea Plate (Wu et al. 2016).

3. Observations and sample descriptions

3.1. Geophysical observations

The MCS lines performed by R/V Kexue integrated geophysical survey cruise in 2015 provided good information on the seafloor geomorphology and sub-bottom strata (Figure 3). The geomorphology of the trench shows asymmetric ‘V’ shape in which the ocean-ward slope is gentle while the landward slope is steeper (Figures 2 and 3). The maximum bathymetry water depth reaches 7528 m and the conform arc has a water depth of 1300 m along seismic profile YP15-1 where the distance between the trench axis and the top of volcanic arc is about 36 km (Figure 3). The ocean-ward slope of the Yap Trench is characterized by horst and graben structures (Figure 3). The landward slope can be divided into three parts according to the topographic relief where the slope angle greatly changed along the seismic profile YP15-1 at the water depth of 5300 and 6050 m. The upper part is from top of the arc to the first slope break (5300 m), with an average slope angle of 19°. The topography in the middle part between the first slope break (5300 m) and the second slope break (6050 m) is very...
gentle with an average slope angle of 4°. The lower part becomes steep again with an average slope angle of 13°. The seismic line YP15-1 revealed that the Parece Vela Basin had developed thick sedimentary strata with a thickness of 1.2 s (two-way travel time), about 1000 m (Figure 3). The West Caroline Basin has also accumulated sediments with 400 m thick based on seismic surveys and DSDP drilling cores (Bukry et al., 1969; Tokuyama et al. 1985), whereas the slopes of the Yap Trench are dominated by tectonic erosion except little and thin sediments developed in grabens and slope breaks. There are many normal faults facing towards trench developed on the ocean-ward slope along the seismic profile YP15-1. Some of these normal faults with large offsets form horsts and grabens and are sub-parallel to the trench axis of the Yap Trench (Figure 3).

Figure 2. Dive sites executed by submersible Jiaolong during Cruise 37-I and seismic profile YP15-1 across the Yap Trench. Dives 109, 110, 111, and 112 are located at landward slope of the trench, while Dive 113 lies at the ocean-ward slope of the trench. The rock samples collected from the Dives 109 and 113 are greenschists and basalts, respectively. Others sampled from Dive 112 are basalts and peridotites. No rock samples were collected from Dives 110 and 111.

Figure 3. YP15-1 seismic profile (a) and interpretations (b) across the Yap Trench. See Figure 2 for location. Red solid circles represent relative locations of the dives in the seismic profile.
3.2. Submersible observations and sample descriptions

Five dives (Dives 109, 110, 111, 112, and 113) have been performed along the northern segment of the Yap Trench by submersible Jiaolong, R/V Xiangyanghong 09 Dayang 37th-I cruise during 13–23 May 2016. Four dives (Dives 109, 110, 111, and 112) took place across the landward slope, whereas one dive (Dive 113) was performed in the ocean-ward slope along the northern segment of the Yap Trench (Figures 2 and 3). In this study area, the seafloor was covered by sediments which consist of debris flow deposits, suggesting that the submarine slide is still active in some places (Figure 4). We collected 10 rock samples as listed in the Supplementary Table 1. Metamorphic rocks are exposed on the trench slope shallower than 6200 m in Dive 109, whereas peridotites and volcanics are found at greater depth during Dive 112 (Supplementary Table 1, Figures 4–6). No rock samples were collected from the Dives 110 and 111 of which only sediments and macro-benthos were collected from the two dives (Figure 4(a,b)).

Dive 113 explored the ocean-ward slope along the northern Yap Trench segment where basalts are found only (Figures 2 and 3). This dive revealed that the subducting slab is only covered by thin sediments, but a lot of talus were found which mainly composed of volcanic breccia without significant Mn-oxide coating (Figure 5).

4. Analytical methods

The altered greenschist, peridotite, and fresh volcanic rocks were collected from the Yap Trench by Jiaolong submersible dives 109, 112, and 113. Rock samples were cut into slabs and the central fresh parts were then used for bulk rock analyses (Figures 2–5).

4.1. Major and trace element analysis

The samples were crushed to a roughly 200-mesh powder in a corundum mill. After grinding, a 1.0-g aliquot of powder was heated to 1100°C for 1 h for obtaining the weight loss on ignition (LOI). Major elements of whole-rock samples were analysed by X-ray fluorescence spectrometer at the China Ocean Sample Repository (COSR), the First Institute of Oceanography, State Oceanic Administration. The analytical precision was determined with the Chinese National Standard GSR-1, and the uncertainty was generally less than 5%. Trace elements were obtained using a PE DRC-e ICP-MS at the COSR. Powdered samples (50 mg) were dissolved in PTFE-lined stainless steel bombs using a HF + HNO₃ mixture for 48 h at ~190°C. Rhodium was used as an internal standard to monitor signal drift during counting. The international standards GSD-9 was used for monitoring analytical quality. The analytical uncertainty was generally less than 5%. The detailed analytical methods are described in Qi et al. (2000).

Figure 4. Photos taken by Jiaolong video camera. (a,b) Thin sediments observed during Dive 111, and (c,d) peridotite sample collected during Dive 112.
4.2. Sr isotopic ratios analysis

The Sr isotopic compositions of whole-rock samples were also analysed at the COSR. Whole-rock sample powders were spiked with mixed isotope tracers and dissolved in Teflon capsules with HF + HNO\textsubscript{3}. Strontium and rare earth element (REE) fractions were separated in the solution using cation ion exchange resin. The collected Sr fractions were then evaporated and analysed by multicollector-ICP-MS at COSR. The mass fractionation correction for Sr isotopic ratios is based on \(^{86}\text{Sr}/^{88}\text{Sr}\) of 0.1194. Repeated measurements of NBS 987 yielded \(^{87}\text{Sr}/^{86}\text{Sr}\) of 0.710265 ± 0.000006 (2\(\sigma\), \(n = 100\)).

4.3. Pb isotopic ratio analysis

In order to minimize contamination by the atmospheric Pb, whole-rock powders of less than 100 mesh were used for Pb isotope measurements. A 200-mg sample was spiked and dissolved in concentrated HF at 800°C for 72 h in a Teflon cup. The lead was separated and purified using conventional anion-exchange techniques with diluted HBr as an eluent (Zhang et al. 2002). The whole procedure blank was less than 0.4 ng Pb. Lead isotopic ratios were measured by a Finnigan MAT-261 Thermal Ionization Mass Spectrometer in the Laboratory of Radiogenic Isotope Geochemistry, Wuhan Institute of...
5. Petrology and geochemistry of rocks from the Yap Trench

5.1. Petrology

The greenschists are grey to green in colour. They consist mainly of Mg–Al chlorite, pistacite, oligoclase, or albite. Sphene and magnetite are common accessory phase in the groundmass. Their pronounced lineated texture is the results of elongated bundles of chlorite and albite or oligoclase (Figure 6(a)).

Recovered peridotites consist of angular or sub-angular pieces ranging in diameter from ~100 to ~200 μm. The peridotites are serpentinized harzburgites and dunites; no lherzolites were recovered (Figure 6(b,c)). Most of the original phases are serpentinized; olivine is totally serpentinized and orthopyroxene is completely replaced by bastite. Primary clinopyroxene is absent, indicating that these peridotites are highly depleted.

The volcanic rocks are black to dark green in colour, relatively fresh with weak carbonatization, and have a porphyritic texture and massive structure. They are porphyritic basalt or basaltic andesite. Phenocryst assemblages are olivine, clinopyroxene, and plagioclase. The groundmass textures are intersertal (Figure 6(d)).

5.2. Geochemical characteristics

The critical chemical data for the two greenschists discovered in Dive 109 are as follows: (1) SiO$_2$ ranges from 46.07 to 49.05 wt%, (2) Al$_2$O$_3$ is around 12.28–13.04 wt%, (3) MgO ranges from 7.14 to 8.03 wt%, and (4) higher abundances of light REE (LREE) relative to heavy REE (HREE). Thus, the greenschists were inferred to be derived from a mafic enriched parent material.

The three peridotites sampled by Dive 112 have low SiO$_2$ (39.32–40.46 wt%), high MgO (38.9–39.6 wt%), Cr (1680–2400 ppm), and Ni (1380–1900 ppm) contents. Their LOI values are high, ranging from 12.91 to 13.34. Most trace elements have been mobilized extensively by serpentinization (Figure 8 and Supplementary Table 2).

Five volcanic rocks, including the samples from the landward slope (Dive 112) and the ocean-ward slope...
(Dive 113), were fresh enough for detailed whole-rock geochemical study. Major and trace element results of these samples are summarized in Supplementary Table 2. The rocks are characterized by low K$_2$O contents (0.24–0.77 wt%) and K$_2$O/Na$_2$O ratios (0.07–0.24), classified as medium-K and low-K series (Figure 7). The LREE and large ion lithophile elements (LILE) show marked enrichment relative to the HREE and high field strength elements (HFSE) (such as Nb, Ta, and Ti) in primitive mantle normalized patterns (Figure 8(a)).

Strontium and Pb isotope results of the volcanics in Dive 112 and 113 are presented in Supplementary Table 3 and shown in Figure 9. The volcanic rocks have ($^{87}$Sr/$^{86}$Sr)i values of 0.7035–0.7051. The Pb isotopic compositions show a narrow range of ($^{206}$Pb/$^{204}$Pb)i (18.23–18.47) and unusually radiogenic ($^{207}$Pb/$^{204}$Pb)i (15.50–15.60) and ($^{208}$Pb/$^{204}$Pb)i (38.08–38.53), plotting well above the Northern Hemisphere Reference Line (Hart 1984). They display a shift towards the composition of enriched mantle (EMII) in the Sr–Pb isotopic systematics (Figure 9).

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**Figure 7.** K$_2$O versus SiO$_2$ diagram for the fresh volcanic rocks, modified after Gill (1981) and Peccerillo and Taylor (1976). Literature data are reported from the North Yap Escarpment volcanic rocks by Ohara et al. (2002). All the major elements are normalized to 100% on a volatile-free basis.

**Figure 8.** Primitive mantle normalized multi-element diagrams and chondrite-normalized rare earth element (REE) patterns for the fresh volcanic rocks from the Yap Trench. Literature data are reported from the North Yap Escarpment volcanic rocks by Ohara et al. (2002). Chondrite and primitive mantle normalized values are from Sun and McDonough (1989).
6. Discussions

6.1. Petrogenesis of the discovered rocks in the Yap Trench

The rocks sampled by Jiaolong submersible in different dives may represent the current lithologies in each area. Rocks of Dive 113 are dominated by basalt in the down-going oceanic plate. Dive 112 shows a lithospheric mantle signature with assemblages of basalts and peridotites below the slope break in the over-riding plate, while Dive 109 displays an upper crust signature with greenschist above the slope break, indicating that the slope break area may represent a lithologic boundary or transitional zone (Figures 2 and 11).

The peridotites obtained from the Jiaolong submersible dives display the characteristics including the absence of modal clinopyroxene in the primary assemblages and the irregular shape of spinels indicating that these peridotites from the Yap Trench landward slope were mostly mantle residual.

The basalts from both the landward (Dive 112) and ocean-ward (Dive 113) slopes of the Yap Trench have geochemical characteristics common to subduction-related volcanic rocks, characterized by selective enrichment in LILE and LREE, as well as depletion in HFSE (Figure 8). The subduction affinity was further confirmed by the shift from mid-ocean ridge basalt filed towards the composition of the enriched mantle in the Sr–Pb systematics (Figure 9). On the plot shown in Figure 10, the wide range of Ba/La values with the relatively constant (La/Yb)N values of the volcanics suggests that the mafic magmas in Yap Trench underwent a history of metasomatism, most possibly by hydrous fluid from subduction slab (Lin et al. 1989).

Ohara et al. (2002) reported that the Yap Trench peridotites are highly depleted subduction-related mantle residues, and the North Yap Escarpment volcanic rocks have arc-like affinities. These are mostly consistent with our new results, though the volcanic rocks from Dive 112 display less enrichment in LILEs (Ba, Rb, and Th), relatively gentle REE patterns ([La/Yb]N = 1.06–1.48), and also lower Ba/La values (Figures 8 and 10), indicating a less influence from the subduction.

6.2. Topographic modification of the subduction along the Yap Trench

The landward slope can be divided into three segments with two obvious slope breaks along the seismic profile YP15-1 across the Yap Trench according to the topographic relief. Similar observations also can be found in previous studies (Fujjwara et al. 2000; Lee 2004). Considering that little even no sediments are found in the trench and greenschists representing an upper crust sampled by Dive 109 near the first slope break, it seems that the sedimentary accretion cannot result in the basement highs. Therefore, these two slope breaks may represent fault notches in shape. The changing landward slope angle may related to the parameters of subduction of the
Caroline Plate, such as the subduction angle, rate, effective elastic thickness.

Numerous normal faults facing landward or ocean-ward displayed on the seismic profile YP15-1 across the horsts and grabens in the ocean-ward slope of the Yap Trench. These normal faults are parallel to the trench axis distribute on the ocean-ward slope of the trench. The presence of these normal faults is consistent with previous findings in the northern Yap Trench (Fujiwara et al. 2000; Lee 2004) and indicates that the front part of the Caroline Ridge has been an extensional environment. Lee (2004) outlined an extensional zone with 100 km long and 50 km wide in which the long axis is subparallel to the trench axis and the cross-section of the Caroline Ridge generally. The extensional zone in the northern Yap Trench was formed by bending of the down-going slab (Lee 2004). However, compression is the dominant mode on the front area of the down-going slab in the southern Yap Trench according to previous findings (Lee 2004). This difference between north and south Yap Trench may derived from the nature of subduction slabs which is consistent with ocean ridge (the Caroline Ridge) in the north and typical ocean crust in the south.

Tectonic erosion could resulted from continuing ocean ridge subduction that induced overriding plate uplift. The observations on down-going plate with normal faults, horsts, and grabens caused by bending of the oceanic plate detected by seismic profile and with no or little sediments covered imaged by Jiaolong submersible suggest that the Yap fore-arc has suffered tectonic erosion, the Yap Trench is still tectonically active, and the subduction of down-going plate with Caroline Ridge still continues. The earthquakes happened in tens of years also conformed the subducting activity.

7. Conclusions

The peridotites in the Yap Trench are highly depleted subduction-related mantle residues, and the wide range of Ba/La values with the relative constant \((La/Yb)_N\) value suggests that the Yap fore-arc rocks probably underwent a
history of metasomatism during Cenozoic subduction. There is a remarkable lithologic difference including an upper crust signature with greenschist above the slope break (Dive 109) and a lithospheric mantle signature with assemblages of basalts and peridotites below the slope break (Dive 112) can be found in the slope break area of the Yap landward slope, indicating that the slope break area may represent a lithologic boundary or transitional zone.

The Parece Vela back-arc basin deposits nearly 1000 m thick sediments, whereas the landward slope of the Yap Trench was covered by little and thin sediments which consist of debris flow deposits, indicating that the submarine slide is still active in some places and tectonic erosion dominate in the slopes of the northern Yap Trench. These mean that the Yap Trench is still active. The Caroline Ridge with low density is subducting beneath the Yap arc with the Philippine Sea Plate along the trench, although the convergence rate is very low.

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Disclosure statement

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References


Highlights

(1) The peridotites of Yap Trench are depleted subduction-related mantle residues whereas volcanoes in the northern segment have arc-like affinities.

(2) Jiaolong submarine vehicle observations and MCS data conformed thin sediment cover in the trench.

(3) Caroline Ridge with the Philippine Sea Plate is subducting beneath the Yap arc along the trench.