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Topographic and sedimentary features in the Yap subduction zone and their implications for the Caroline Ridge subduction

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ABSTRACT

The Yap subduction zone in the western Pacific presents some unique features compared to normal intra-oceanic subduction zones such as the subduction of an oceanic plateau. However, due to the relative paucity of geophysical data, the detailed structure remains unknown in this area. In this study, we present the latest high-quality swath bathymetry and multi-channel seismic data acquired synchronously in 2015 across the Yap subduction zone. The topographic and sedimentary features are intensively investigated and a modified evolutionary model of the Yap subduction zone is proposed. The two-stage evolution of the Parece Vela Basin (PVB) produced fabrics that are N-S trending and NW-SE trending. Our seismic data clearly reveal landslide deposits at the upper slope break of the forearc, to the north of the Yap Island, which was identified as the fault notch denoting a lithological boundary in previous work. The swath bathymetry and seismic profile reveal detailed horst and graben structures, including a crescent-shaped fault zone near the contact between the Yap Trench and the Caroline Ridge. A simple geometric model is proposed to explain the structure formation, indicating that the higher topography of the Caroline Ridge resulted in enhanced bending-related extension. A seismic angular unconformity (named R1) is identified in the Sorol Trough, marking the onset of rifting in the trough. Based on the sequence thickness and deposition rate by Deep Sea Drilling Project (DSDP), it is deduced that the Sorol Trough formed at 10 Ma or even earlier. A modified model for the Yap subduction zone evolution is proposed, incorporating three major tectonic events: the proto-Yap Arc rupture in the Oligocene, the collision of the Caroline Ridge and the Yap Trench in the late Oligocene or middle Miocene, and the onset of the Sorol Trough rifting in the late Miocene.

1. Introduction

The Yap subduction zone lies in the south part of the Mariana arc-trench system, in the western Pacific, where the Caroline plate subducts northwestwards beneath the Philippine Sea plate in an intra-oceanic subduction setting. As the most prominent structure in the Caroline plate, the Caroline Ridge is a buoyant oceanic plateau with over-thickened crust, although the Sorol Trough, a spreading feature in the middle of the ridge, makes it like a spreading system, e.g., mid-ocean ridge. This oceanic plateau is thought to be subducting beneath the Yap trench at present (Sato et al., 1997; Fujiwara et al., 2000). There are numerous unique tectonic features in this subduction system compared with other intra-oceanic subduction settings, such as subduction of an oceanic plateau, the extremely slow convergence velocity estimated at 7–10 mm/yr (Kotake, 2000), the abnormally short arc-trench distance about 50 km (Nagihara et al., 1989; Ohara et al., 2002) and the lack of intermediate depth seismicity (no earthquakes deeper than 70 km in the north and few deeper than 70 km in the south, Lee, 2004). It is thought that the present Yap subduction zone is relatively young (Lee, 2004) or is a typical immature case (Kim et al., 2009). Therefore, the study of topographic, sedimentary and tectonic features in the Yap subduction zone may be important for gaining insight into the earlier subduction dynamic processes and for the comprehension of subduction of oceanic plateaus at deep oceanic trenches.

Scientists from the U.S. and Japan carried out the seismic explorations in the Caroline Basin in the earlier times (Bracey, 1975; Den et al., 1971), with a source of pneumatic sound and electric sparker. Then Japanese scientists launched multidisciplinary surveys in the Yap Arc

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and back-arc region in the 1980s, including gravity, heat flow, single channel and 12 channel seismic surveys (Nagihara et al., 1989). The Chinese R/V *Xiangyanghong10* carried out expeditions for gravity measurements from Shanghai to the Caroline sea twice (Wan et al., 1988). Despite such investigations, the region lacks comprehensive geophysical data across the Yap subduction zone, especially high-quality multichannel seismic data. Hence, the sedimentary structure and evolutionary details of the Yap subduction zone remain unclear.

The research vessel *Kexue* (*Science* in Chinese) from the Institute of Oceanology, Chinese Academy of Sciences, conducted integrated geophysical surveys across the whole Yap subduction zone in 2015 and 2016, and collected a wide range of datasets including multi-beam swath, gravity, magnetic, heat flow, and multichannel seismic data, as well as sub-bottom profiles. In addition, an array of seven ocean bottom seismometers (OBSs) was deployed on both sides of the Yap Trench for long-term observation. This study is mainly based on the multi-beam swath bathymetric data and multichannel seismic profiles of the surveys. We analyze the detailed topographic and sedimentary structures of the major tectonic units and propose a modified evolutionary model of the Yap subduction zone.

2. Geological setting

The Yap Trench represents the southeastern boundary of the Philippine Sea plate and is regarded as a part of the long continuous arcuate trench system, including the Izu-Bonin-Mariana (IBM), Yap and Palau Trenches (Fujiwara et al., 2000; Ohara et al., 2002). The northernmost end of the Yap Trench connects with the southwestern end of the Mariana Trench at 11°10′N and extends southwards in the NNE direction to 7°15′N, where it turns to the NWW direction and comes into contact with the Palau Trench (Fig. 1). The J-shaped Yap Trench is > 700 km in length. A complex SEE-NWW striking bathymetric high is present here on the Caroline plate, rising about 2 km above the surrounding seafloor. This prominent morphological feature is called the Caroline Ridge, and it is approximately 500 km long in the EW direction and 300 km wide in the N-S direction.

2.1. Plate kinematics

The subduction of the Pacific plate to the west is thought to have begun in the late Eocene (~40 Ma, Uyeda and Benavraham, 1972) or in the early Eocene (~55 Ma, Deschamps and Lallemand, 2002), leading to the Shikoku and Parece Vela Basin (PVB) formation at ~30 Ma later. Intense micro-seismic activity below the inner trench wall (Nagihara et al., 1989; Sato et al., 1997), high heat flow in the region east of the Yap Arc (Nagihara et al., 1989) and the absence of flat-lying sediments in the trench axis (Fujiwara et al., 2000) all indicated slow, yet active subduction at the Yap Trench. Earthquake slip vector inversion showed the convergence rate of the Caroline plate and Philippine Sea plate is merely 3–6 mm/yr in our study area (Seno et al., 1993). More recent GPS measurements on the Ulithi and Fais Atolls on CIR indicated that the Caroline plate is moving with respect to the Yap Island on the Philippine Sea plate at the rate of 7–10 mm/yr (Kotake, 2000) (Fig. 1). It is notable that the Caroline plate appears to subduct beneath the Philippine Sea plate at an oblique angle, which might contribute to the regional tectonics, but the detail mechanisms accommodating this oblique subduction are not well understood. The Caroline Ridge was considered to be a buoyant oceanic plateau formed by the Caroline hotspot in the late Oligocene (Keating et al., 1984) that then collided with the Yap Trench. However, there is still considerable uncertainty surrounding the timing of the collision, e.g., during the late Oligocene to early Miocene (McCabe and Uyeda, 1983), 18–14 Ma (Fujioka et al., 1998), ~25 Ma (Fujiwara et al., 2000; Ohara et al., 2002). Therefore, the collision time ranges from the late Oligocene to middle Miocene. This collision might have caused the eastern half of the southernmost PVB to thrust over the Yap Arc along the spreading rift towards the west (Ohara et al., 2002). However, it is also possible that the eastern half was offset by a transform fault and thus the region now lies to the west of the northern Mariana Trough (Okino et al., 2009). The Sorol Trough, a rift developed in the Caroline Ridge, divided the ridge into two sections, Caroline Island Ridge (CIR) in the north and West Caroline Rise (WCR) in the south (Lee, 2004). The trough is considered to be a failed rift, that is, the extensional rifting did not progress into final seafloor spreading (Altis, 1999).

2.2. Geology of the Yap Island

Petrological studies have indicated that the Yap Arc, west of the Yap Trench, consists primarily of metamorphic rocks and lacks active arc volcanism (Hawkins and Batiza, 1977; Shiraki, 1971), totally different from the typical oceanic island composed mainly of volcanic rocks. Hawkins and Batiza (1977) suggested that collision in the Tertiary appeared to have led to the obduction of oceanic crust and the subsequent metamorphic processes. Fujioka et al. (1998) considered that the Yap Island consisted of four major geological units, from bottom to top: metamorphic rocks of the Yap Formation, debris flow sediment of the Map Formation, Tomir volcanics and Garim limestone. He proposed that the debris flow sediments were related to the obduction of metamorphosed ophiolite caused by collision of the Caroline Ridge against the Philippine Sea plate, and thus constrained the collision event to 18–14 Ma. However, the collision timing remains far from certain as what mentioned in the above section.

2.3. Geology of the Caroline Ridge recovered from DSDP

Deep Sea Drilling Project (DSDP) Leg6 has drilled 3 sites, 55, 56 and 57 in the northern flank of the Caroline Ridge (Fig. 1) to test the character and age of the massive opaque unit in profiles revealed by *Glomar Challenge* (Heezen et al., 1971). Site 55 penetrated almost a complete section in the Neogene and the uppermost Oligocene sequence down to a total depth of 131 m, but did not reach the sediment base. The encountered sediment is chalk ooze dominated by nanoplankton. Site 56 cored a Neogene section resembling Site 55 down to a total depth of 270 m, and penetrated the upper Oligocene nanofossil oozes and chalks in the lower sequence. The Oligocene sequence rests on the opaque seismic unit, which is the rock too hard to penetrate. Site 57, however, sampled a fresh, coarse grained doleritic basalt below the unaltered upper Oligocene sediments down to a total depth of 335 m. The opaque reflector, found both at Site 56 and 57, is thus demonstrated to be igneous rock, representing the sediment base. It indicates that the basalt flow was emplaced before the end of the Oligocene. Thus the northern flank of the Caroline Ridge appears to consist of young basaltic flows, completely different from the much older Pacific oceanic floor in the north.

2.4. Subduction of the oceanic plateau in the western Pacific

Arrival of over-thickened crust at the subduction zone, such as aseismic ridge or oceanic plateau, could cause considerable dynamic and kinematic variations. Many over-thickened crusts at the subduction zone are distributed around the Pacific (Gutscher et al., 2000; Rosenbaum and Mo, 2011). Among them, the prominent intra-oceanic subduction of oceanic plateaus occurred mainly in the western Pacific, including Ontong Java Plateau (OJP), Ogasawara Plateau (see insert of Fig. 1 for locations) and Caroline Ridge (Rosenbaum and Mo, 2011). The OJP is the largest oceanic plateau in the world, comprising large igneous body. It is thought that the shallow part of the plateau is accreted in front of the Solomon Island Arc (SIA), but the lower part is still subducting at present, as indicated by many deep hypocenters (100–200 km) (Miura et al., 2004b). The North Solomon Trench (NST) is not a subduction zone anymore but a deformation front of accreted materials, and the “arc-trench” distance (from axis of NST to SIA) is