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Research paper

Deep structures of the Palawan and Sulu Sea and their implications for opening of the South China Sea

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ABSTRACT

Compared to the northern South China Sea continental margin, the deep structures and tectonic evolution of the Palawan and Sulu Sea and ambient regions are not well understood so far. However, this part of the southern continental margin and adjacent areas embed critical information on the opening of the South China Sea (SCS). In this paper, we carry out geophysical investigations using regional magnetic, gravity and reflection seismic data. Analytical signal amplitudes (ASA) of magnetic anomalies are calculated to depict the boundaries of different tectonic units. Curie-point depths are estimated from magnetic anomalies using a windowed wavenumber-domain algorithm. Application of the Parker–Oldenburg algorithm to Bouguer gravity anomalies yields a 3D Moho topography. The Palawan Continental Block (PCB) is defined by quiet magnetic anomalies, low ASA, moderate depths to the top and bottom of the magnetic layer, and its northern boundary is further constrained by reflection seismic data and Moho interpretation. The PCB is found to be a favorable area for hydrocarbon exploration. However, the continent–ocean transition zone between the PCB and the SCS is characterized by hyper-extended continental crust intruded with magmatic bodies. The NW Sulu Sea is interpreted as a relict oceanic slice and the geometry and position of extinct trench of the Proto South China Sea (PSCS) is further constrained. With additional age constraints from inverted Moho and Curie-point depths, we confirm that the spreading of the SE Sulu Sea started in the Early Oligocene/Late Eocene due to the subduction of the PSCS, and terminated in the Middle Miocene by the obduction of the NW Sulu Sea onto the PCB.

1. Introduction

To better understand the opening processes of the South China Sea (SCS), an Atlantic-type marginal sea from continental rifting (e.g., Taylor and Hayes, 1980, 1983), it is critical to compare tectonics and deep structures of its two conjugate continental margins. The southern margin experienced a long history of Mesozoic paleo-Pacific subduction (Li and Li, 2007; Li et al., 2012), and Cenozoic subduction of the proto-South China Sea (PSCS) and its interactions with the Sulu Sea to the south. Different types of terrains (oceanic crust, continent–ocean transition zone, continental block, island arc) amalgamated here but their boundaries are not well defined and the origin of some tectonic units along the southern margin remains uncertain (e.g., Franke et al., 2008, 2011), because of complicated rifting and collision processes that have occurred.

The tectonic models for the southern margin involve two main types: collision–extrusion model (Briais et al., 1993; Replumaz and Tapponnier, 2003) and subduction–collision model (Hamilton, 1979; Lee and Lawver, 1995; Hall, 1996). The main differences of the two models are in the aspects of the mechanism responsible for rifting and seafloor spreading in the South China Sea, the amount of displacement along the Red River fault and the size of a pre-existing ocean basin (the proto South China Sea, PSCS) subducted beneath Borneo.

The southern South China Sea continental margin today is also in direct contact with the Sulu Sea, the tectonic evolution of which is still not well understood. Although ODP Leg 124 was implemented in the Sulu and Celebes Seas in 1990, many key issues are still unsolved (Rangin and Silver, 1991; Silver and Rangin, 1991). The origin of the NW Sulu Sea is rarely discussed in previous studies, and different hypothetic models are presented for the evolution of the SE Sulu Sea, either as a back-arc basin triggered by the subduction of the PSCS (Rangin and Silver, 1991) or the Celebes Sea plate (Rangin, 1989), or a marginal basin analogous to the SCS

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(Rangin and Silver, 1991). Moreover, the formation timing of the SE Sulu Sea, either the Early Miocene (Rangin and Silver, 1991) or the Oligocene (Roeser, 1991), is also in debate. Drilled at a location quite near to an arc (Cagayan Ridge), Site 769 of ODP Leg 124 (Fig. 2) did not sample the oldest oceanic basement of the Sulu Sea. Magnetic anomalies in the SE Sulu Sea are not parallel to the Cagayan Ridge (Fig. 3), and the oldest anomalies cannot be well recognized and have been largely subducted beneath the Negros Trench and Sulu Trench.

This paper explores topography, gravity, magnetic, and seismic data to better understand the tectonic complexity, deep structures, and hydrocarbon potential of the Palawan and Sulu Sea area and their surroundings. We have carried out various data processing and geophysical inversions, including analytic signal analysis and inversion of Curie depth and Moho depth.

2. Tectonic framework

The Palawan Continental Block (PCB) and Sulu Sea are surrounded by the SCS, Philippine Archipelago, Celebes Sea and Borneo (Figs. 1 and 2). The main Palawan Island is NE–SW trending and is made up of two parts, namely, the north Palawan formed by continent-originated sedimentary and metamorphic blocks drifted from the Eurasian continental margin with the opening of the SCS between ~32 Ma and ~16 Ma (Holloway, 1982; Taylor and Hayes, 1980, 1983; Sales et al., 1997; Almasco et al., 2000; Suzuki et al., 2000a, 2000b; Aurelio et al., 2012; Shi and Li, 2012), and the Early Cretaceous to Eocene oceanic rock formations (the Palawan Ophiolite Complex) exposed in the south Palawan (Raschka et al., 1985; Letouzey et al., 1988; Faure et al., 1989; Müller, 1991; Fuller et al., 1991; Encarnación, 2004). The Palawan Ophiolite Complex is equivalent in origin to the ophiolites of Borneo (Rangin et al., 1990; Schlüter et al., 1996; Cullen, 2010). The boundary between the north and south Palawan is partly defined by the Ulugan Bay fault (Figs. 1 and 2) (Yumul et al., 2009). Northeast of Palawan is a group of small islands that belong to the Calamian Island Group. The PCB contains the Reed Bank and the north Palawan. Borneo is located to the southwest of the Palawan Island, and Sabah sits on the northern portion of Borneo.

A linear trough called the Palawan Trough lies in the SCS southern coastal zone, and it connects with the Borneo Trough to the south. The Palawan and Borneo Troughs were interpreted as the extinct trench of the southern convergent margin of the Proto South China Sea (PSCS) (Hamilton, 1979; Hinz et al., 1989; Lee and Lawver, 1995; Hall, 1996, 2011; Morley, 2002; Hall et al., 2008), but the existence of the trench between the Reed Bank and the Calamian Island Group cannot be reconciled with the north Palawan continental strata as old as Permian that drifted southeastward from Eurasia (Taylor and Hayes, 1980, 1983; Fontaine, 1979; Mitchell and Leach, 1991; Almasco et al., 2000; Suzuki et al., 2000b; Li et al., 2007; Shi and Li, 2012). Therefore, it can be confirmed that the Palawan Trough was not associated with the

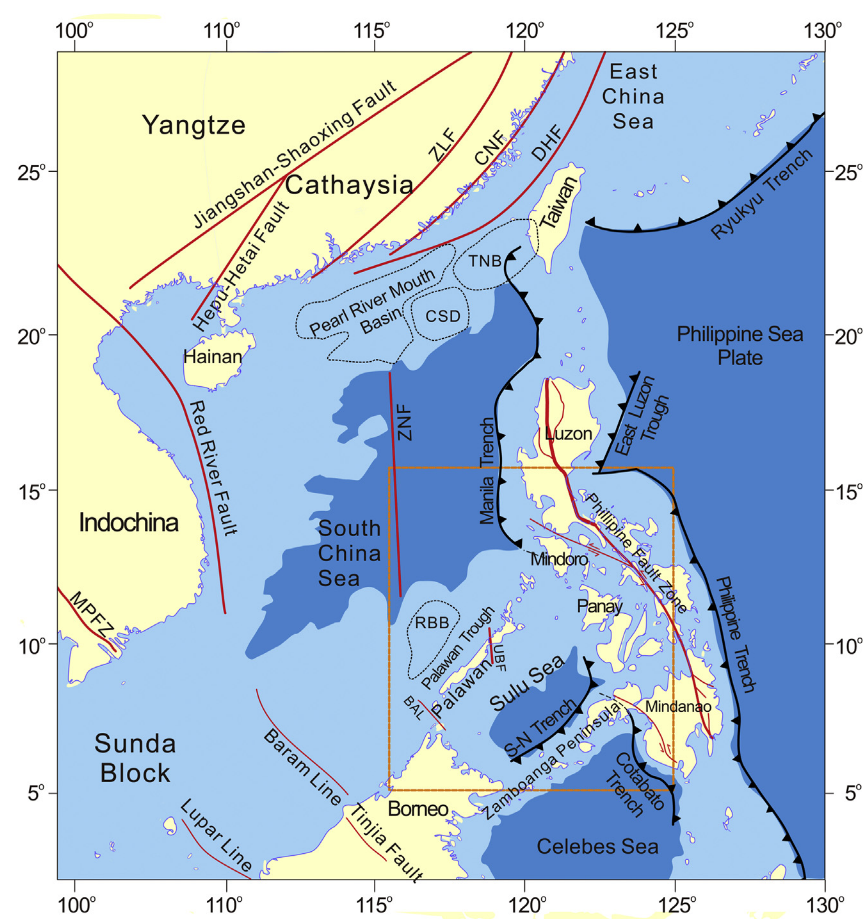

Figure 1. Regional tectonic and geological features of SE Asia. Major tectonic elements: ZLF = Zhenghe-Lianhuashan Fault, CNF = Changle-Nan'ao Fault, CR=Cagayan Ridge, DHF = Donghai Fault, ZNF = Zhongnan Fault, MPFZ = Mae Ping Fault Zone, BAL=Balabac Line, UBF=Ulugan Bay Fault, TNB = Tainan Basin, CSD=Chaoshan Depression, RBB = Reed Bank Basin. The box is the study area of this paper and details are shown in Fig. 2.