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Heat flow in the rifted continental margin of the South China Sea near Taiwan and its tectonic implications

Wei-Zhi Liao [a], Andrew T. Lin [a,*], Char-Shine Liu [b], Jung-Nan Oung [c], Yunshuen Wang [d]

[a] Department of Earth Sciences, National Central University, No. 300, Jhongda Rd., Jhongli City, Taoyuan County 32001, Taiwan
[b] Institute of Oceanography, National Taiwan University, No. 1, Sec. 4, Roosevelt Rd., Taipei 10617, Taiwan
[c] CPC Corporation, Taiwan. No. 3, Songren Rd., Sinyi District, Taipei City 110, Taiwan
[d] Central Geological Survey, MOEA, No. 2, Lu. 109, Huaxin St., Zhonghe Dist., New Taipei City 235, Taiwan

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ABSTRACT

Temperature measurements carried out on 9 hydrocarbon exploration boreholes together with Bottom Simulating Reflectors (BSRs) from reflection seismic images are used in this study to derive geothermal gradients and heat flows in the northern margin of the South China Sea near Taiwan. The method of Horner plot is applied to obtain true formation temperatures from measured borehole temperatures, which are disturbed by drilling processes. Sub-seafloor depths of BSRs are used to calculate sub-bottom temperatures using theoretical pressure/temperature phase boundary that marks the base of gas hydrate stability zone. Our results show that the geothermal gradients and heat flows in the study area range from 28 to 128 °C/km and 40 to 159 mW/m^2, respectively. There is a marked difference in geothermal gradients and heat flow beneath the shelf and slope regions. It is cooler beneath the shelf with an average geothermal gradient of 34.5 °C/km, and 62.7 mW/m^2 heat flow. The continental slope shows a higher average geothermal gradient of 56.4 °C/km, and 70.9 mW/m^2 heat flow. Lower heat flow on the shelf is most likely caused by thicker sediments that have accumulated there compared to the sediment thickness beneath the slope. In addition, the continental crust is highly extended beneath the continental slope, yielding higher heat flow in this region. A half graben exists beneath the continental slope with a north-dipping graben-bounding fault. A high heat-flow anomaly coincides at the location of this graben-bounding fault at the Jiulong Ridge, indicating vigorous vertical fluid convection which may take place along this fault.

1. Introduction

The South China Sea rifted margin is characterized by highly attenuated continental crust and in typical rifted continental margins, heat flow may range from 40 to 70 mW/m^2 in average (Allen and Allen, 2005). The magnitude of heat flow and its distribution are combined effects of tectonic development and sedimentation in the continental margin (e.g., Cloetingh et al., 2010). A study of the spatial heat-flow distribution in a rifted margin may therefore reveal important tectonic features and shed lights on the tectonic development of the studied margin. The northern continental margin of the South China Sea (SCS) is occupied by rift basins that extend from beneath the continental shelf to continental slope. From east to west, the rift basins are the Tainan Basin (Yang et al., 1991; Lee et al., 1993; Tzeng et al., 1996), Pearl River Mouth Basin (Watson et al., 1987; Wu, 1988; Yu, 1990, 1994), and Qiongdongnan Basin (Wu, 1988). The study area lies in the northeastern corner of the SCS continental margin where the rifted continental margin (i.e. the Tainan Basin) has been overridden by the Taiwan orogenic wedge in the east since the late Miocene (Lin and Watts, 2002; Lin et al., 2003, 2008). The oblique impingement of the orogenic wedge on top of the rifted continental margin has turned the rifted continental margin into a mature foreland basin in the north (Lin and Watts, 2002) and an incipient foreland basin in the south, especially in the continental slope (Yu and Hong, 2006). The superposition of foreland basin on top of the rifted continental margin may result in a significant change of heat-flow patterns from typical rifted continental margins.

The western part of the northern continental margin (i.e. the Pearl River Mouth Basin and the Qiongdongnan Basin) of the SCS is a region of high heat flow compared to other rifted continental margins; with heat flow ranging from 50 to 120 mW/m^2 (Yuan et al., 2009). There is a general trend that heat flow increases from the inner margin to the outer margin (Shi et al., 2003). One reason for the high heat flow in this margin is that it is geologically young, merely 32 Ma old (Taylor and Hayes, 1983; Briais et al., 1993). Another reason may be vigorous magmatic activities associated

* Corresponding author. Tel.: +886 3 4227151x65618; fax: +886 3 4222044.
E-mail address: andrewl@ncu.edu.tw (A.T. Lin).

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with rifting processes occurring especially in the outer margin (Yuan et al., 2009). In addition, recent episodes of Miocene and Pliocene crustal extensions (He et al., 2001; Clift and Lin, 2001) may also assist to raise the heat flows in this margin.

The heat flow pattern in the eastern part of northern continental margin near Taiwan (i.e. the Tainan Basin) is unclear due to a lack of study. While the heat flows in the submarine accretionary wedge has been reported in the literature (Chi et al., 2003; Chi and Reed, 2008; Shyu et al., 2006) using the lower phase boundary of the gas hydrate stability zone inferred from seismic sections as Bottom Simulating Reflectors (BSRs). Past studies show that the average heat flow ranges from around 64 mW/m^2 (Shyu et al., 2006) to 43 in mW/m^2 (Chi and Reed, 2008) in the submarine accretionary wedge neighboring the rifted continental margin.

The studied continental margin (i.e. the Tainan basin) lies in the junction area between the rifted continental margin in the west and the accretionary wedge in the east. In terms of tectonic development, this area evolved from a rifted margin to a foreland basin. In this study, we first establish thermal gradients using data of bottom hole temperatures, measurements from hydrocarbon exploration wells in the shelf region and BSRs beneath the continental slope. These thermal gradients are then converted to heat flows with inferred thermal conductivities for studied sediment sections. The spatial distribution of heat flow allows us to gain a better understanding of the thermal regime in this tectonic transition zone.

2. Regional geological setting

The Tainan Basin is a Paleogene rift basin in the northeastern margin of the South China Sea, consisting of three tectonic elements, namely, the Northern Depression, Central Uplift Zone, and Southern Depression (Fig. 1; Tsao et al., 1992; Lin et al., 2003). The Northern Depression and Central Uplift Zone lie beneath the shelf region (Yang et al., 1991; Lee et al., 1993; Tzeng et al., 1996; Tang et al., 1999; Lin et al., 2003) while the Southern Depression lies largely beneath the continental slope (Fig. 1). A series of ENE-trending normal faults developed beneath the shelf

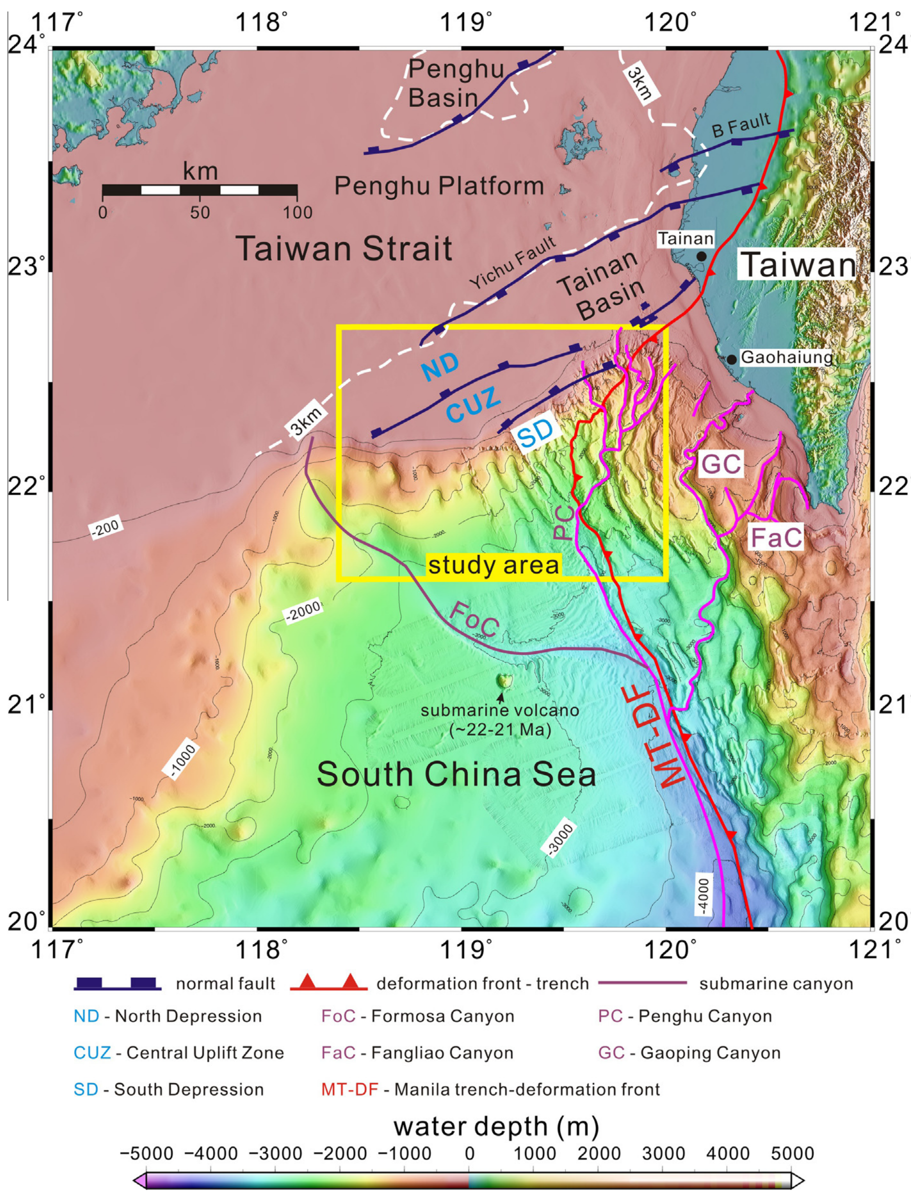

Fig. 1. Bathymetry and tectonic features off southwest Taiwan. Tectonic elements and sediment isopach of 3000 m are from Lin et al. (2003). The age of a submarine volcano south of the Formosa Canyon is from Wang et al. (2012) Purple lines reveal the course of submarine canyons. The yellow rectangle marks the study area.