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"Uniform geothermal gradient" and heat flow in the Qiongdongnan and Pearl River Mouth Basins of the South China Sea

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A B S T R A C T

The Pearl River Mouth Basin (PRMB) and Qiongdongnan Basin (QDNB) are oil and gas bearing basins in the northern margin of the South China Sea (SCS). Geothermal survey is an important tool in petroleum exploration. A large data set comprised of 199 thermal conductivities, 40 radioactive heat productions, 543 measured geothermal gradient values, and 224 heat flow values has been obtained from the two basins. However, the measured geothermal gradient data originated from diverse depth range make spatial comparison a challenging task. Taking into account the variation of conductivity and heat production of rocks, we use a "uniform geothermal gradient" to characterize the geothermal gradient distribution of the PRMB and QDNB. Results show that, in the depth interval of 0–5 km, the "uniform geothermal gradient" in the PRMB varies from 17.8 °C/km to 50.2 °C/km, with an average of 32.1 ± 6.0 °C/km. In comparison, the QDNB has an average "uniform geothermal gradient" of 31.9 ± 5.6 °C/km and a range between 19.7 °C/km and 39.5 °C/km. Heat flows in the PRMB and QDNB are 71.3 ± 13.5 mW/m^2 and 72.9 ± 14.2 mW/m^2, respectively. The heat flow and geothermal gradient of the PRMB and QDNB tend to increase from the continental shelf to continental slope owing to the lithosphereic/crustal thinning in the Cenozoic.

1. Introduction

Geothermal gradient is a basic geothermal parameter used to describe characteristics of the geothermal field of sedimentary basins. In basin analysis, geothermal gradients can provide useful information for studying the development and evolution of sedimentary basins (Allen and Allen, 1990). In petroleum exploration, geothermal gradient has long been applied to estimate hydrocarbon generation of source rocks, which is closely associated with temperature (Tissot et al., 1987; Sweeney and Burnham, 1990). Up to now, there have been a lot of achievements in the study of geothermal gradient of sedimentary basins (Wang et al., 1985, 1990, 2003; Tissot et al., 1987; Wang and Shi, 1989; Wang, 1996; Hu et al., 1998; Majorowicz and Embry, 1998; Ren, 2000; Qiu et al., 2001; Xiao et al., 2001, 2004; Gong et al., 2003; Yang et al., 2003; Lu et al., 2005; Ascencio et al., 2006; Yuan et al., 2006). However, the body of work referenced above, generally did not address the fact that geothermal gradients are stratigraphical, and therefore depth dependent. Geothermal gradient data are nearly meaningless if depth intervals are ignored, since spatial comparisons are not relevant without depth limits. Geothermal gradient is significantly influenced by the thermal conductivity of rocks, in addition to the base heat flow and radioactive heat production.

The PRMB and QDNB are oil and gas bearing basins located in the northern margin of SCS of offshore China. Geothermal gradient data collected in the northern portion of the two basins originated from petroleum exploration wells drilled hundreds to thousands of meters deep. Conversely, geothermal gradient data from the southern portion are mainly from seafloor heat flow probes of 20 m or less into the seafloor. The two types of data derived from different depth intervals vary significantly. It is challenging to combine them to construct a contour map showing geothermal features of the PRMB and QDNB. This paper addressed this issue and introduced a "uniform geothermal gradient" parameter to replace the measured (conventional) geothermal gradient for contour map. Furthermore, this paper presents newly obtained geothermal data, e.g. thermal conductivity, radioactive heat production and heat flow useful for revealing the geothermal features of the PRMB and QDNB in the northern margin of SCS.

2. Geological settings

The South China Sea (SCS) is one of the largest marginal seas in the western Pacific. It has developed into a rhombic basin with

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a northern extensional margin, an eastern subduction margin, a southern compressional margin and a western sheared margin undergone the interactions of the Eurasian, Australian, and Pacific plates (Xia et al., 1995). In petroleum exploration, the northern margin is used to be divided into a shallow water area and a deep water area according to the 300 m bathymetric line (see Fig. 1). The northern shallow water area (water depth less than 300 m) is coincident with the continental shelf; the southern deep water area (water depth greater than 300 m) is coincident with the continental slope. The crustal thickness decreases from the north to the south, namely from the continental shelf to the continental slope (Yao, 1998).

There developed a number of Cenozoic extensional basins in the northern margin of SCS. Structural highs, such as the Hainan, Shenhu and Dongsha "uplifts", separate the individual basins, of which the PRMB and QDNB are two major oil-gas bearing basins. These highs are mainly composed of Mesozoic granites, overlain by approximately 1 km of Neogene deposits. The PRMB consisted of three distinct depressions; Zhuyi, Zhu'er, and Zhusan until the Oligocene time frame. The QDNB developed a series of interconnected deep depressions in the basin's center, known as Ledong, Lingshui, Songnan depression and Xisha Trough. The maximum thickness of Cenozoic deposits in these depressions is between 8 and 11 km (Wu et al., 1987; Yuan, 2007). The basement of the two basins is dominated by Yanshanian granite with a few Paleozoic sedimentary and metamorphic rocks. The oldest sedimentary sequence drilled in the QDNB is Yacheng formation of the lower Oligocene. Seismic interpretation techniques, however, reveal that the older formation, Eocene sequences widely spread in the rifted areas of QDNB. Hence, the sedimentary sequences in the QDNB, from bottom to top, are Eocene, Yacheng formation (early Oligocene), Lingshui formation (late Oligocene), Shanya formation (early Miocene), Meishan formation (middle Miocene), Huangliu formation (late Miocene), Yinggehai formation (Pliocene), and Ledong formation (Quaternary). The oldest sedimentary sequence drilled in the PRMB is Shenhu formation of the Paleocene. It is overlapped by the formations of the Eocene, Oligocene, Miocene, Pliocene and Quaternary in order from bottom to top.

It is generally believed that the basins in the northern margin of SCS evolved as a result of the Paleocene–Oligocene crustal extension and rifting processes forming the SCS Basin. The PRBM and QDNB experienced multi-episodic extensional rifting, and therefore multi-episodic heating events in Cenozoic time (He et al., 2001; Yuan, 2007) (see Fig. 2). The initial, early, and late rifting phases corresponded to the Paleocene, Eocene, and Oligocene heating events, respectively. After the Paleogene riftings, there followed a Miocene post-rifting phase which resulted in a contemporaneous thermal attenuation. A Neotectonic period occurred in the Pliocene (Zhang et al., 2007), which accounts for the extensive magmatic activities in the PRMB as well as the rapid subsiding in the QDNB since 10–5 Ma (Yuan, 2007). In the syn-rifting phases, non-marine sediments dominated by fluvial, lacustrine mudstones and sandstone interbeds were deposited from the Paleocene to Oligocene age. In the post-rifting phase, sedimentary environment turned to be marine facies with deposits dominated by clay with frequent light-colored, carbonate-rich layers.

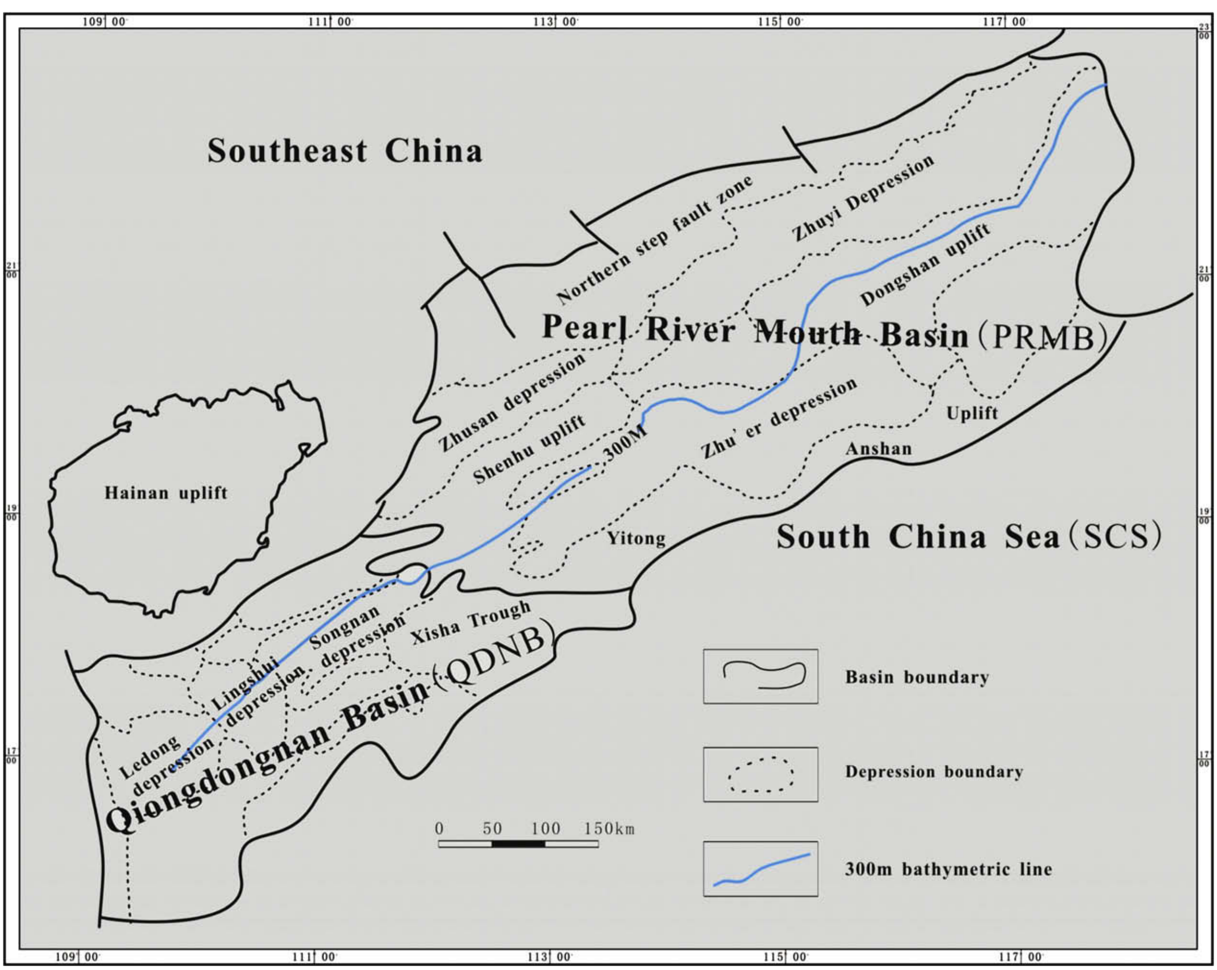

Fig. 1. Map showing the location and structural sub-units of the PRMB and QDNB.