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Disparity between measured and BSR heat flow in the Xisha Trough of the South China Sea and its implications for the methane hydrate

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ABSTRACT

We calculate the heat flow from the depth of bottom-simulating seismic reflectors (BSRs) on a seismic profile in the Xisha Trough of the South China Sea, and compare them with the probe heat flow measurements. The BSR heat flow turn out to be 32–80 mW/m^2, significantly lower than the measurements of 83–112 mW/m^2. Such big disparity cannot be ascribed only to the errors from parameters (parameter errors) that traditionally believed to influence the BSR heat flow. Besides the parameter errors, we discuss emphatically the errors coming from the theoretical assumption for the BSR heat flow determination (theoretical errors), which occur when the BSR depth does not coincide with the base of the methane hydrate stability zone (MHSZ). If BSR stays bellow the base of MHSZ, lying at the top of free gas zone, the derived heat flow would be underestimated. Compared with the parameter errors, the theoretical errors would be relatively larger in some geological settings. The disparity between measured and BSR heat flow in the Xisha Trough might be mainly due to the theoretical error. Based on the theoretical model, assuming that the BSR lying at the top of the free gas zone, the methane flux along the Xisha seismic profile is estimated, and the thickness of the methane hydrate occurrence zone is predicted.

1. Introduction

Bottom-simulating reflectors (BSRs) commonly occur several hundred meters beneath the seafloor in continental slope sediments. These reflectors were inferred to mark the base of the region for methane hydrate stability zone (MHSZ), and the heat flow derived from them is called BSR heat flow in this paper. Yamano et al. (1982) initially put forward a method which used the pressure (P)/temperature (T) relation of the gas hydrate phase change and the depth of BSR to calculate heat flow. After that, numerous studies have been made on heat flow estimates based on the BSR depth (Davis et al., 1990; Fisher and Hounslow, 1990; Hyndman et al., 1992; Ashi and Taira, 1993; Townend, 1997; Ganguly et al., 2000; Kaul et al., 2000). Regional studies of BSR heat flow have identified regional trends in several accretionary prisms, such as the Barbados (Fisher and Hounslow, 1990), Nankai (Ashi and Taira, 1993) and Cascadia (Davis et al., 1990; Hyndman et al., 1992). BSR was even used as calibration for heat flow estimates (Hyndman et al., 1992). In many cases, there is general agreement between the regional trend and BSR heat flow, and the method of heat flow calculation, might be less accurate, but much easier than the heat flow probe techniques.

However, comparisons of measured and BSR heat flow reveal that they are not always identical. For example, on the lower slope of the Cascadia accretionary prism (Davis et al., 1990), a consistent discrepancy was observed between the probe heat flow measurements and the estimates from BSR. In the Makran accretionary prism of Pakistan (Kaul et al., 2000), the estimated BSR heat flow in all basins are significantly higher than the measured values.

The discrepancy between measured and BSR heat flow was usually explained by the calculation errors from parameters, such as the applicable P/T relationship for hydrate stability, the seafloor temperature to obtain the temperature gradient, the thermal conductivity–depth relation, and the density model for the pressure at the depth of BSR. We define this kind of error as parameter error in this paper. Uncertainties coming from these factors are listed in Table 1. The cumulative effects of uncertainties in several parameters are approximately 25% by Yamano et al. (1982), 10% reported by Minshull and White (1989), and 25% by Zwart et al. (1996), 22% reported by Townend (1997), 20% by Ganguly et al. (2000), and 10% by Kaul et al. (2000).

In fact, the discrepancy might also source from the theoretical assumption for the determination of BSR heat flow that the BSR marks the base of the MHSZ. In some cases, there is general agreement between the BSR and the base of the MHSZ. However, BSR may lie at the base of the methane hydrate zone (MHZ) and wholly within the MHSZ, if the impedance contrast associated with it is produced by the seismic velocity contrast between hydrate-bearing

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Table 1
Source and range of parameter errors.

Source	Error range (%)
Seafloor temperature	12 (Townend, 1997); negligible (Hyndman et al., 1992)
Reflection time	2 (Davis et al., 1990)
Velocity–depth relationship	<5 (Ganguly et al., 2000)
Thermal conductivity	10 (Ganguly et al., 2000)
Lithostatic/hydrostatic pressure model	8–12 (Ganguly et al., 2000)
Hydrate stability *P*–*T* relationship (pure water/seawater)	5 (Davis et al., 1990)
Hydrate stability *P*–*T* relationship (advective system)	12 (Ganguly et al., 2000)

sediments above and hydrate-free sediments below, which have been known for many regions of the world (Stoll and Bryan, 1979; Dvorkin and Nur, 1993). BSRs may sometimes occur below the MHSZ, at the top of the free gas zone (e.g., Minshull et al., 1994; Holbrook et al., 1996). Xu and Ruppel (1999) have achieved two significant results from their theoretical analysis: (1) the base of the zone in which gas hydrate actually occurs in marine sediments will not usually coincide with the base of the stability zone but rather will lie at a more shallow depth than the base of the stability zone. If the BSR represents the base of the methane hydrate-bearing layer, then the BSR may occur wholly within the MHSZ. (2) If the BSR marks the top of the free gas zone, then the BSR should occur substantially deeper than the base of the stability zone in some setting. Therefore, this basic theoretical assumption for the determination of BSR heat flow is not always proper, and may lead to errors defined as theoretical errors here.

In this paper, we firstly calculate the heat flow based on the BSR depth along a seismic profile in the Xisha Trough of South China Sea (SCS), and compare them with the probe heat flow measurements. And then, we put emphasis on the discussion of the possible factors yielding to discrepancy between the estimates and measurements, aiming to explain the difference between the measured and BSR heat flow in the Xisha Trough. Finally, we estimate the methane flux along the Xisha seismic profile based on the model of Xu and Ruppel (1999), and predict the thickness of the methane hydrate occurrence zone.

2. Background

2.1. Geological setting

The Xisha Trough (Fig. 1) situates near 18°N in the northwest of the SCS. It is located to the north of the Xisha Islands, south of the Pearl River Mouth Basin, east of the Qiongdongnan basin, and northwest of the Northwest (NW) Sub-basin of the SCS. The trough is 430 km long and 14 km wide, deepens eastwards from 1500 m to 3300 m. It is considered as a Cenozoic rift (He et al., 1980), whose evolution is closely related with the NW sub-basin, most likely had been mainly developed before 30 Ma and became a failed rift with the cease of the NW sub-basin (Shi et al., 2002). Though its neighboring area has developed igneous activities later and some faults may be active now, the Xisha Trough has substantially experienced thermal subsidence since 30 Ma, and has accumulated about 4 km of sediments in the center. The basement of the trough contains pre-Cenozoic metamorphic and granitic rocks, covered by upper Cretaceous – Quaternary sediments. The layer of upper Cretaceous to Eocene formation is 1000–5000 m thick, Oligocene – mid-Miocene formation is 500–2500 m, and upper Miocene – Quaternary formation is 200–600 m.

The Xisha Trough is adjacent to several oil–gas basins, such as the Qiongdongnan basin and the Pearl River Mouth basin. The organic carbon concentration bearing in the shallow sediments is 0.41–1.02%, showing great potential of hydrocarbon resources (Zhu et al., 2005). Since 1999, the Guangzhou Marine Geological Survey has developed several geological and geophysical investigations aiming for gas hydrate, and found many BSRs in this region. Along a seismic profile (Figs. 1 and 2), a discontinuous BSR is observed, and the heat flow are measured by the marine heat flow probe (Xu, 2005; Xu et al., 2006).

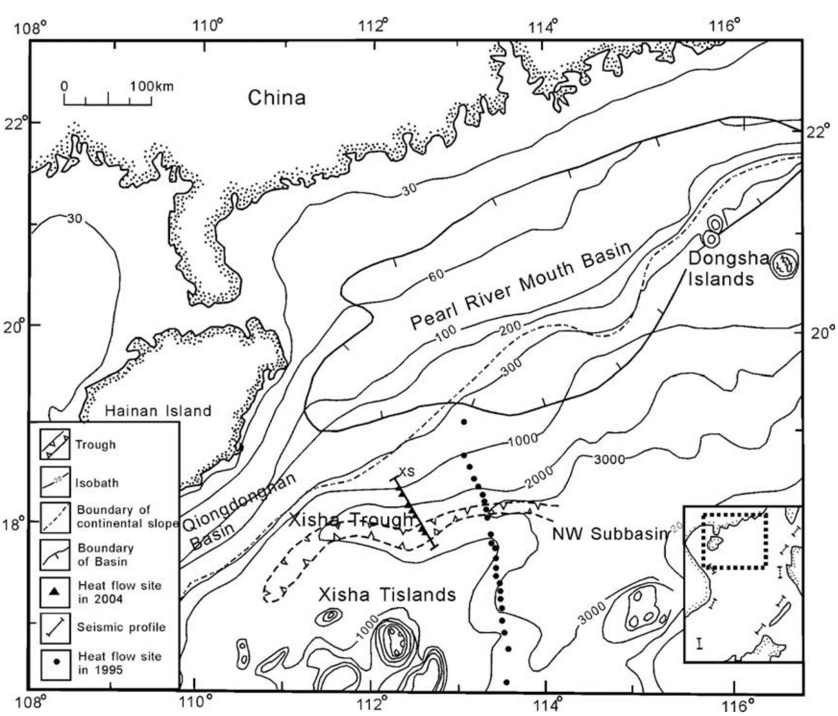

Fig. 1. Location of the Xisha Trough in the SCS.