Marine and Petroleum Geology 67 (2015) 785–794

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

BSRs, estimated heat flow, hydrate-related gas volume and their implications for methane seepage and gas hydrate in the Dongsha region, northern South China Sea

Lun Li [a, *], Haojie Liu [b], Xin Zhang [c], Xinhua Lei [c], Zhibin Sha [d]

[a] Earth and Atmospheric Sciences Department, University of Houston, TX 77204-5007, USA
[b] Bohai Oilfield Research Institute, CNOOC China Limited, Tianjin Branch, Tianjin 300452, China
[c] School of Information Engineering, China University of Geosciences, 29 Xueyuan Road, Beijing 100083, China
[d] Guangzhou Marine Geological Survey, China

ARTICLE INFO

Article history:
Received 27 April 2015
Received in revised form
1 July 2015
Accepted 7 July 2015
Available online 9 July 2015

Keywords:
Dongsha
South China Sea
Methane seepage
Gas hydrate stability zone
Double BSRs
Geothermal gradient
Heat flow
Gas volume

ABSTRACT

To investigate the relationship among methane seepage, subsurface gas hydrate, and heat flow and estimate hydrate-related gas amount in the Dongsha region, northeastern South China Sea, in this study we first identified Bottom Simulating Reflector (BSR) using multi-channel seismic data collected in 2004. Subsequently, the thickness of gas hydrate stability zones (GHSZ) was calculated from the observed BSR using time–depth conversion, ranging from 60 to 300 m in seawater depths of 600–1200 m. Additionally, a seismic feature of double BSRs is locally observed in this region, which is possibly caused by either the presence of mixed gas source (thermogenic and biogenic) or migration of a pre-existing base of GHSZ. Geothermal gradient, heat flow and hydrate-related gas volume are calculated based on the thickness of GHSZ. The estimated geothermal gradient and heat flow varies from 20 to 100 °C/km with an average of 48 °C/km, and from 20 to 120 mW/m^2 with an average of 54 mW/m^2, respectively. Both estimated geothermal gradient and heat flow are generally consistent with those from measurements. High geothermal gradient (up to 60 °C/km) and heat flow anomaly (up to 80 mW/m^2) are present in one methane seepage site, where BSR is clear and reliable. High heat flow could result in thin GHSZ in the continental slope. In this case, gas hydrate could form in the shallow sediments, making dissolved gas from hydrate and/or free deep-seated gas easy to migrate upwards to seafloor through faults, and thus resulting in the occurrence of methane venting. The hydrate-related gas volume is estimated as ~6×10^{11} m^3 over an area of ~400 km^2 with possible occurrence of BSR. This finding would shed lights on understanding potential amount of subsurface methane in the Dongsha region and place useful constraints for modeling GHSZ from measured heat flow data, especially in regions where no BSRs are present.

1. Introduction

Dongsha region is located in the continental margin of northeastern South China Sea (SCS) (Fig. 1a). Over the past decade, an increasing interest on the detection of gas hydrate in the Dongsha region has been triggered by a discovery of active methane seepages (or venting) at the seafloor (Suess, 2005). A cold seafloor methane seepage, Jiulong methane seepage (JMS), was discovered in this region in 2004 during the Chinese–German joint expedition (Suess, 2005; Han et al., 2008). Large seep carbonate, carbonate nodules and crust, biogenic shells, which infer the cold seep ecosystem, were observed (Chen et al., 2006, 2005; Han et al., 2008). Additionally, high methane concentration in bottom water in the JMS region has been inferred from water column samples, indicating that JMS is dramatically active (Yin et al., 2008). A number of studies have suggested that the occurrence of this methane seepage is related to subsurface gas hydrate (Li et al., 2013; Zhang et al., 2014a; Sha et al., 2015). Previous studies demonstrated that the tectonic and sedimentary conditions in the Dongsha region are beneficial for the formation and accumulation of gas hydrate (Song et al., 2000; McDonnell et al., 2000; Wu et al.,

* Corresponding author. Current address: ION Geophysical Corporation, Houston TX, USA.
E-mail addresses: lli19@uh.edu, lilun.cugb@gmail.com (L. Li).

http://dx.doi.org/10.1016/j.marpetgeo.2015.07.008
0264-8172/

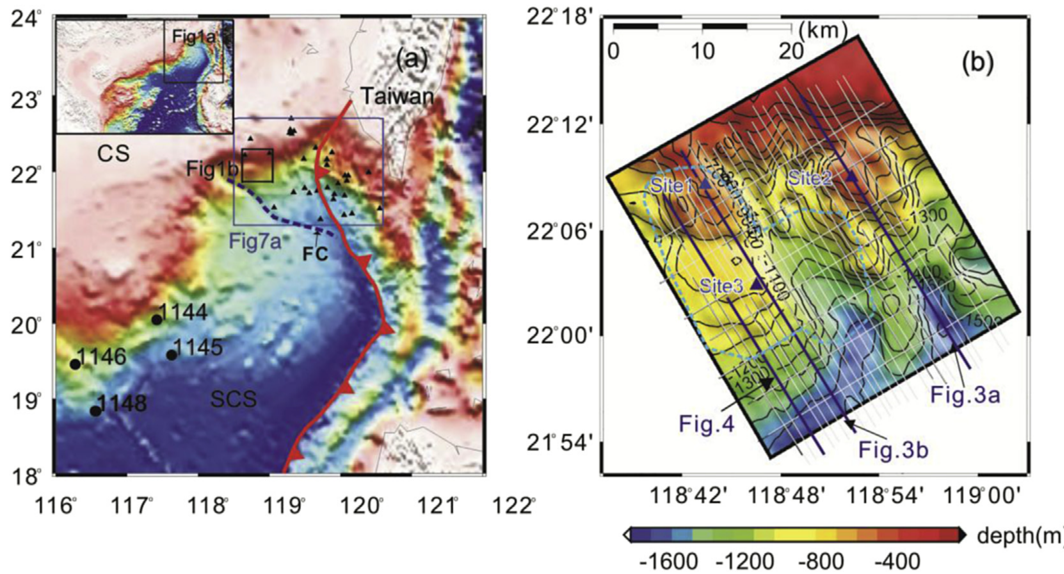

Fig. 1. (a) Topographic map of northeastern South China Sea. Location is shown as a solid black line box in the embedded map. The big blue box represents the location for Fig. 7a. The black box represents the study area, where multi-channel seismic lines in Fig. b were collected. Red line with triangles indicate Manila subduction belt. SCS, South China Sea; CS, Continental Shelf; FC, Formosa Canyon. Black points represent Ocean Drilling Program (ODP) drilling sites. (b) Bathymetric map of study area and multi-channel seismic survey. Location is shown in Fig. 1a. The blue lines indicate the location of multi-channel seismic lines in Figs. 3 and 4. Three methane venting sites are shown as blue triangles. The area outlined by blue dash lines is GMGS-2 expedition drilling region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2004; Yan et al., 2006; Wang et al., 2006; Lin et al., 2009; Schnürle et al., 2011; Li et al., 2012a, 2013). For instance, McDonnell et al. (2000) indicated that marine sediments in the Dongsha region located in passive continental margin have appropriate-thickness, methane-generating potential to host gas hydrate. Wu et al. (2004) suggested that debris flow and turbidity sediments are favorable for gas hydrate accumulation in an adjacent region. Yan et al. (2006) and Lin et al. (2009) analyzed geological features controlling the formation and distribution of gas hydrate. Furthermore, Li et al. (2013) presented seismic evidence for the existences of hydrate and free gas beneath JMS and demonstrated that the seafloor seepages in this region are a result of upward migrating free gas from dissolved hydrate and/or deep-seated gas source through mud diapirs and fault systems. Gas hydrate samples were recovered in the Dongsha region in a recent expedition (GMGS-2 expedition) conducted by Guangzhou Marine Geological Survey (GMGS) in the June–September 2013 (Zhang et al., 2014a, 2014b; Sha et al., 2015; Zhang et al., 2015). Totally 13 exploration sites were drilled at water depths of 664–1420 m. Gas hydrate samples were obtained at 5 sites and well log data at 8 sites inferred the existence of gas hydrate (Zhang et al., 2014a; Sha et al., 2015). Single-layer or double-layer gas hydrate samples are distributed in silty clay with coarse grain sizes with geometries of massive blocks, thin layers, veins, nodular or disperse particles (Zhang et al., 2014a; Sha et al., 2015). This expedition combined with other seismic and geochemical evidences confirmed the existence of gas hydrate in the Dongsha region. In this study, we used multi-channel seismic data collected in 2004 to further explore relationship among methane seepage, subsurface gas hydrate, and heat flow, and investigate hydrate-related gas volume in the Dongsha region, where multi-channel seismic data coverage is available.

The seismic survey region situates in the Tainan rift basin, northeastern South China Sea. A series of normal faults with a trend of northeast–east (NEE) have developed in this region and some of the faults were active during Pliocene and Quaternary (Yan et al., 2006; Wu et al., 2004). The seafloor morphology is characterized by complex, highly variable topography, and a large number of canyons, gullies and bathymetric ridges with NNW–SSE trend are well developed (Liu et al., 1998, 2004; Suess, 2005). The sea water depth ranges from 300 m to over 2000 m. The multi-channel seismic data used in this study have been previously reported in the paper of Li et al. (2013). Gas hydrate and free gas hydrate were inferred through identifying BSR in these seismic dataset combined with seismic attributes (Li et al., 2013). In this study, we further described various geological features associated with BSR. Additionally, the geothermal gradient and heat flow maps are constructed from the observed BSR. The relationship among methane venting, subsurface hydrate, and heat flow is investigated, which would shed lights on the detection of hydrate in regions where no BSR is observed or BSR is discontinuous. Additionally, we analyzed the causes of double BSRs, which are locally observed in seismic profiles. Hydrate-related gas volume is estimated, which would have implications for future studies on potential amount of gas releasing to atmosphere and their environmental effects.

2. Data and data processing

Approximate 1200 km multi-channel seismic (MCS) data (Fig. 1b) were acquired in the Dongsha region by Guangzhou Marine Geological Survey (GMGS) in 2004. These data were collected with 3000 m streamers at a depth of 5 m towed with 25 m shot spacing, 12.5 m trace spacing and a 160 cubic inches airgun array at a depth of 3 m giving full fold of 60. The sample rate is 1 ms and the record length is 6 s. The seismic data processing flow includes common depth point (CDP) sorting, prefiltering, spherical divergence amplitude compensation, predictive and surface-consistent deconvolution, velocity analysis, Dip-moveout correction (DMO) stack, and migration. More details regarding to the seismic processing strategy and parameters are given by Li et al. (2013).