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The stability of gas hydrate field in the northeastern continental slope of Sakhalin Island, Sea of Okhotsk, as inferred from analysis of heat flow data and its implications for slope failures

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A B S T R A C T

The sudden release of methane from seas due to ocean warming and/or sea level drop, leading to extensive mass wasting at continental margins, has been suggested as a possible cause of global climate change. In the northeastern continental slope of the Sakhalin Island (Sea of Okhotsk), numerous gas hydrate-related manifestations have been reported, including hydroacoustic anomaly (gas flare) in the water column, pockmarks and mounds on the seafloor, seepage structures and bottom-simulating reflectors (BSRs). The gas hydrate found at 385 mbsl represents the shallowest occurrence ever recorded in the Okhotsk Sea. In this study, we modeled the gas hydrate stability zone (GHSZ) using methane gas composition, water temperature and geothermal gradient to see if it is consistent with the observed depth of the BSR. An important distinction can be made between the seafloor containing seepage features and normal seafloor in terms of their thermal structure. The depth of the BSR matches well with the base of GHSZ estimated from the background heat flow (geothermal gradient). A large slope failure feature is found in the northern Sakhalin continental slope. We explore the possibility that this failure was caused by gas hydrate dissociation, based on the past climate change history and inference from the GHSZ calculation. Prediction of the natural landslide is difficult; however, new stratigraphic evidence from subbottom profiles suggests that the landslide occurred at 20 ka which is roughly consistent with the late stage of the Last Glacial Maximum.

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1. Introduction

Gas hydrate is a gas clathrate consisting of water and gas molecules, commonly found in the modern-day seafloors in deep water (e.g., Matsumoto et al., 2011). Because it is stable under high pressure and cold temperature conditions, gas hydrate is frequently found in polar regions, below onshore permafrost and in arctic oceans, and in superficial section of marine sediments of continental margins (Kvenvolden, 1998). Gas hydrate has been suggested as a source of energy (Collett, 2002) and potential geohazard including mass wasting and ensuing tsunami (Bouriak et al., 2000; Paull et al., 2000), and as a factor affecting global climate change if a large amount of greenhouse gas is suddenly released into the atmosphere (Kennett et al., 2000).

Since the first finding of methane hydrate in the Okhotsk Sea in 1986 (Zonenshayn et al., 1987), numerous geophysical surveys have been carried out in this region by KOMEX (Kurile-Okhotsk sea Marine EXperiment) (Lüdmann and Wong, 2003; Obzhirov et al., 2004; Wong et al., 2003), and more recently, by CHAOS (hydro-Carbon Hydrate Accumulation in the Okhotsk Sea) and SSGH (Sakhalin Slope Gas Hydrate) projects. While the KOMEX project tried to elucidate the overall geologic features of the western Okhotsk Sea, the CHAOS and SSGH projects, have examined the detailed aspects of gas hydrate system in the northeastern continental slope of Sakhalin Island (Hachikubo et al., 2009; Jin et al., 2011; Shoji et al., 2005).

The northeastern continental slope of Sakhalin Island is also well known for its diverse manifestations of gas hydrate (Jin et al., 2011; Obzhirov et al., 2004; Shoji et al., 2005). A widespread occurrence of bottom-simulating reflectors and numerous seepage structures as well as pockmarks and mounds can be seen on the seafloor. Gas flares can also be frequently observed from echosounders. In this region, gas hydrate was recovered at a depth as shallow as 385 mbsl due to the cold water temperature, comparable to arctic regions (e.g., Biastoch et al., 2011). However, the

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spatial and temporal relationships among various gas-hydrate-related features are not well understood.

Understanding the extent of the gas hydrate stability zone (GHSZ) in this region would provide an important constraint in explaining the relationships among diverse features and their possible variations. Theoretically, the stability of gas hydrate depends on numerous factors including pressure and temperature, salinity (de Roo et al., 1983), gas composition (Sloan, 1990), gas concentrations in the pore water (Xu and Ruppel, 1999), dissolved ion contents (Dickens and Quinby-Hunt, 1997), pore size (Turner et al., 2005) and mineralogy of host sediment (Cha et al., 1988) to name a few. However, the factors affecting the GHSZ may be divided conceptually into regional and local factors. By considering that the effects of local factors can be averaged out over a wide region or assuming that they are pertinent to special features or phenomena, one may simplify the relationship. Of course, the validity of such an approximation or model needs to be checked. One of the goals of this study is to compare regional parameters with observed manifestations of gas hydrates. In particular, we investigate the role of background heat flow (geothermal gradient) on the stability of gas hydrate zone.

One of the important features in our study area is the evidence for massive landslide in the northern slope. If the landslide was really caused by gas hydrate dissociation, it would represent a rare modern-day example. Previously Wong et al. (2003) argued that this slide event occurred before 350 ka. However, a careful reexamination of subbottom profiler data together with reassessment on the sedimentation rate sheds a new light on the timing of this landslide.

2. Environmental setting

The Sea of Okhotsk is a marginal sea of the Northwest Pacific, semi-enclosed to the east by the Kamchatka Peninsula, to the west by the Sakhalin Island, and to the south by the Kuril Islands. The straits along the Kuril Islands serve as pathways for exchange of sea waters between the Okhotsk Sea and the Pacific. According to Kitani (1973) and Talley and Nagata (1995), the surface water flows inward along the west of Kamchatka Peninsula and outward along the east of Sakhalin Island, thus making a counterclockwise rotation before exiting to the Northwest Pacific.

Sea-ice forms during the winter as a result of an influx of fresh water from the Amur River and westerly cold winds (Katsuki et al., 2010). The formation of ice has a strong influence on the water temperature profile in this region especially at shallow depth. A subzero minimum-temperature (as low as −1.7 °C) develops at a depth of 50–150 mbsl by influx of cold water from melted ice. In the summer, the water temperature at shallow depth is largely affected by the halocline (Gorbarenko et al., 2002a). However, the water temperature stays almost constant (2.5–3 °C) below 800 mbsl.

Geologically, the Sea of Okhotsk is bounded by the North American, Eurasian, Amurian, and Pacific plates (Fig. 1a). Most of the large earthquakes in the Sea of Okhotsk are caused by the subduction of the Pacific plate and are located along the Kuril Island arc. In addition, many small earthquakes were recorded in the regions far away from the trench including the Sakhalin Shear Zone which runs N–S along the Sakhalin Island.

The Sea of Okhotsk can roughly be divided into two regions: a broad continental shelf/slope to the north with water depth less

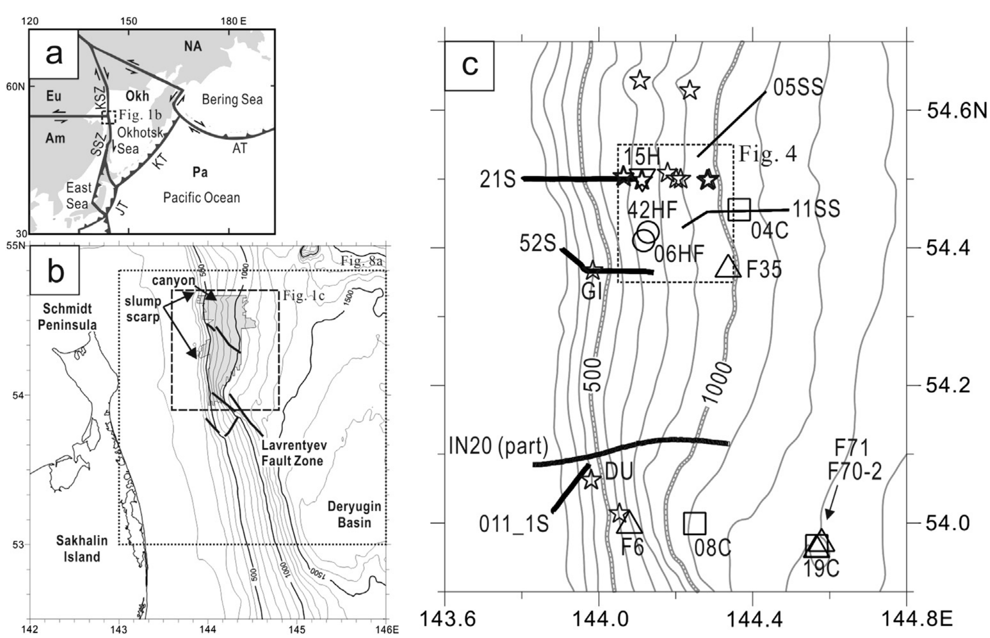

Figure 1. The location of the study area in the northern slope of Sakhalin slope, Sea of Okhotsk. (a) The Okhotsk plate (*Okh*) is bounded by 4 tectonic plates: North America (*NA*), Eurasia (*EU*), Amurian (*Am*), and Pacific (*Pa*) plates. Kashevarov Shear Zone (*KSZ*) and Sakhalin Shear Zone (*SSZ*) exhibit dextral movement. *JT* = Japan Trench, *KT* = Kuril Trench, *AT* = Aleutian Trench. The *box* represents the location of Figure 1b. (b) The study area, presented as *box*, is located in the northeastern continental slope of Sakhalin Island. The Deryugin Basin lies to the west. The *thick lines* indicate major faults in this region. *Lavrentyev Fault Zone* in the southern part of the study area divides cross-section slope morphology into 2 types: concave-upward to the north of itself, and convex-upward to the south (see text and Fig. 8). The *shaded area* represents the coverage of side-scan sonar survey. The *boxes* represent the location of Figures 1c and 8a, respectively. (c) The detailed map of survey area. The seismic survey lines (*thick lines*) conducted using the sparker instrument, the subbottom survey line (*thin line*), the locations of CTD casting sites to measure water temperature and salinity (*squares*), gas flare detected by hydroacoustic survey (*triangles*), and heat flow measurements (*circles*) are shown. The *reverse triangle* represents a site where core containing the gas hydrate was retrieved (see text). The bathymetric contour is shown at 100-m interval. Sites where sediment cores containing gas hydrates were taken are shown in *star* symbols: *DU* = Dungeon and *GI* = Giselle structure. The *box* represents the location of Figure 4.

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