Change of Gas Hydrate Stability Zone in the Northeastern Continental Slope of Sakhalin Island, Sea of Okhotsk and Its Implications for Slope Failure

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Abstract

The sudden dissociation of gas hydrate within sediments at continental margin due to ocean warming and/or sea level drop has been suggested as a possible cause of global climate change as well as extensive slope failure. In the northeastern continental slope of the Sakhalin Island (Sea of Okhotsk), numerous gas hydrate-related manifestations in addition to gas hydrates have been reported, which include hydroacoustic anomaly through the water column, pockmarks and mounds on the seafloor, seepage structure and bottom-simulating reflectors (BSRs) in the sediment. The gas hydrate found at 385 mbsl is the shallowest occurrence ever reported in the Sea of Okhotsk. BSR depths matches well with the base of gas hydrate stability zone (BGHSZ) estimated under the current environmental conditions such as gas composition, water temperature and the background geothermal gradient. In terms of thermal structure, an important distinction can be made between seafloors containing the seepage structure or none. We explore the timing of a large slope occurred in the study area using new stratigraphic evidence from subbottom profiles. The timing of the failure seems to be much younger, 20 ka roughly corresponding to the late stage of the Last Glacial Maximum, than the previous estimate, older than 350 ka. The extent of the slope failure occurs up to much shallower depth than the intersection depth of BGHSZ with the seafloor at 20 ka, possibly indicating complexity of natural landslides. Furthermore, this region has witnessed a rapid sea water temperature increase in the last 50 years. If such a trend continues, additional slope failure can be expected in the near future, considering that the region is not far from a transform plate boundary where shallow seismicity occurs.

It is noted that the contents consist of the published material (Kim et al., 2013) together with newly-added discussion on the possibility of future slope failure in the study area.

1. Marine Surveys in the Sakhalin Continental Slope

Hydro-Carbon Hydrate Accumulations in the Okhotsk Sea
(2003-2006)

Focused on the northern Sakhalin continental slope and found lots of gas flares in the water column, gas fluid seepage structures on the seafloor, gas hydrate samples and gas hydrate-related structures in the sub-seafloor

Sakhlin Slope Gas Hydrate Project
(2007-2012)

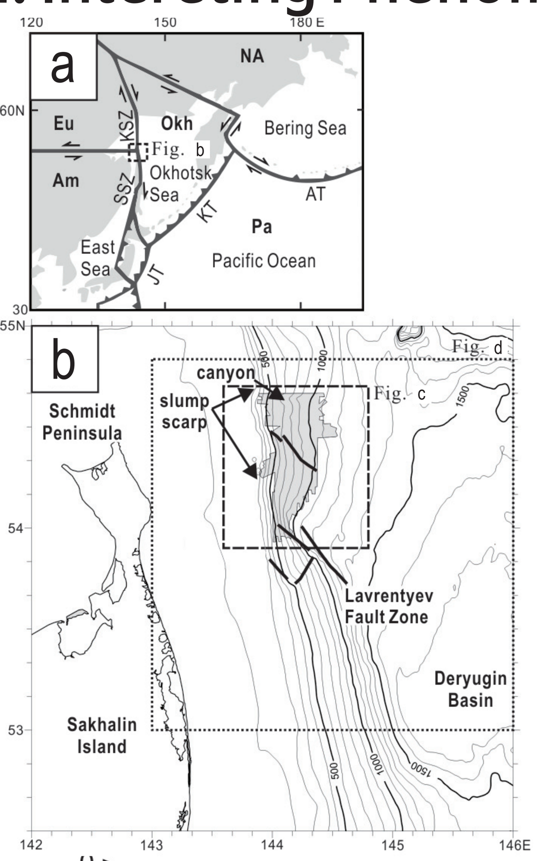
Devoted to mapping of seafloor and water column structures related to gas/fluid seeping phenomena on the northeastern Sakhalin continental slope for the first two years, and conveyed sediment coring to understand the formation mechanism of gas hydrate in sediments in terms of sedimentological and biogeochemical processes for the latter years

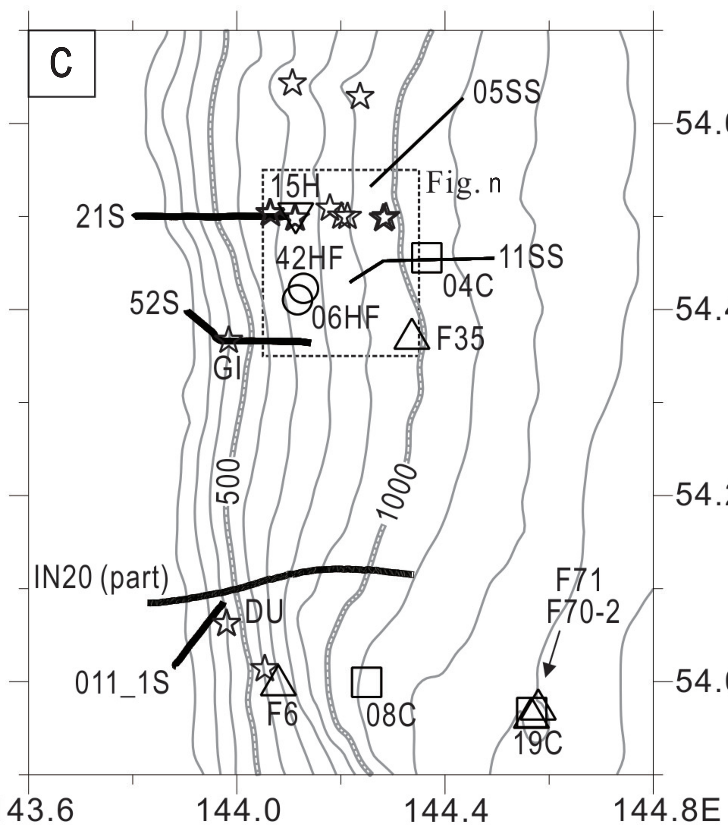
Sakhlin Slope Gas Hydrate Project II
(2012-2017)

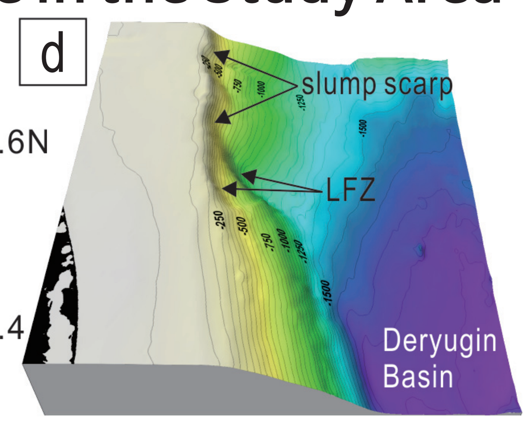
Main objectives are:
1. To characterize gas hydrates and gas hydrate-bearing sediments in Sakhalin Slope
2. To understand gas migration and gas hydrate formation mechanisms at methane seep areas
3. To trace methane migration from gas hydrate system to atmosphere through water column and its impact to global warming
4. To understand process of gas hydrate destabilization and its influence on slope failure as one of geological hazards
5. To establish a monitoring network for a long-term gas hydrate stability variation

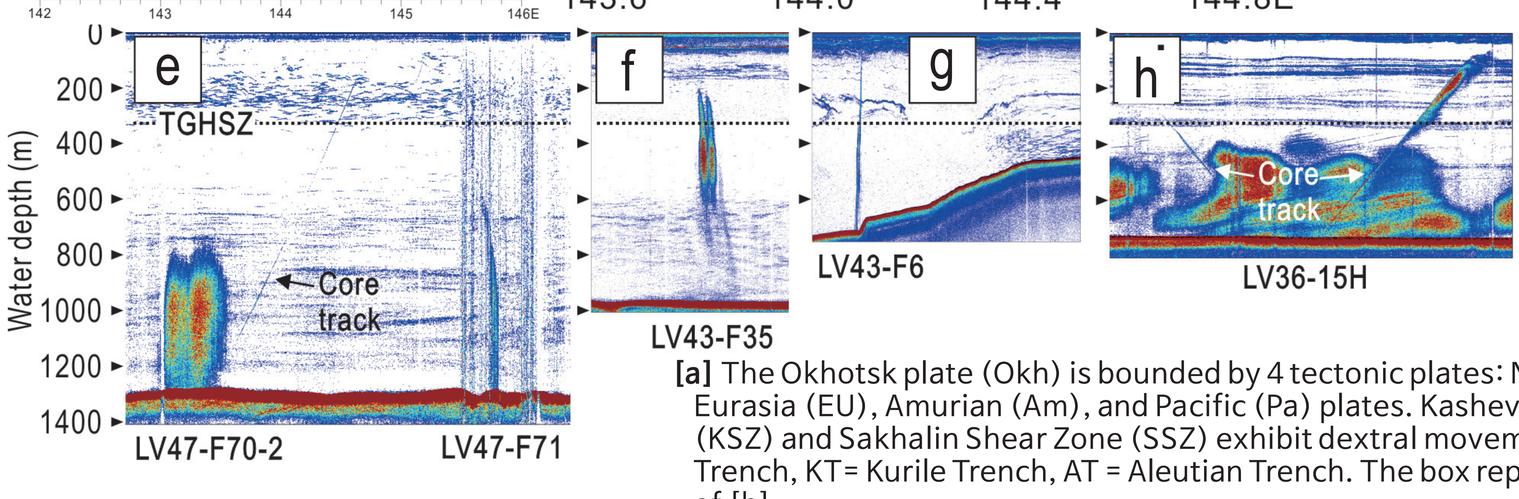
* In this study, we used survey results obtained from up to SSGH09.

2. Intereting Phenomena Related to Gas Hydrate in the Study Area









[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= Kurile Trench, AT = Aleutian Trench. The box represents the location of [b].

[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 divide cross-section slope morphology into 2 types: concave-upward to the north of itself, and convex-upward to the south (see [d], [q]). The shaded area represents the coverage of side-scan sonar survey. The boxes represent the location of [c] and [d], respectively.

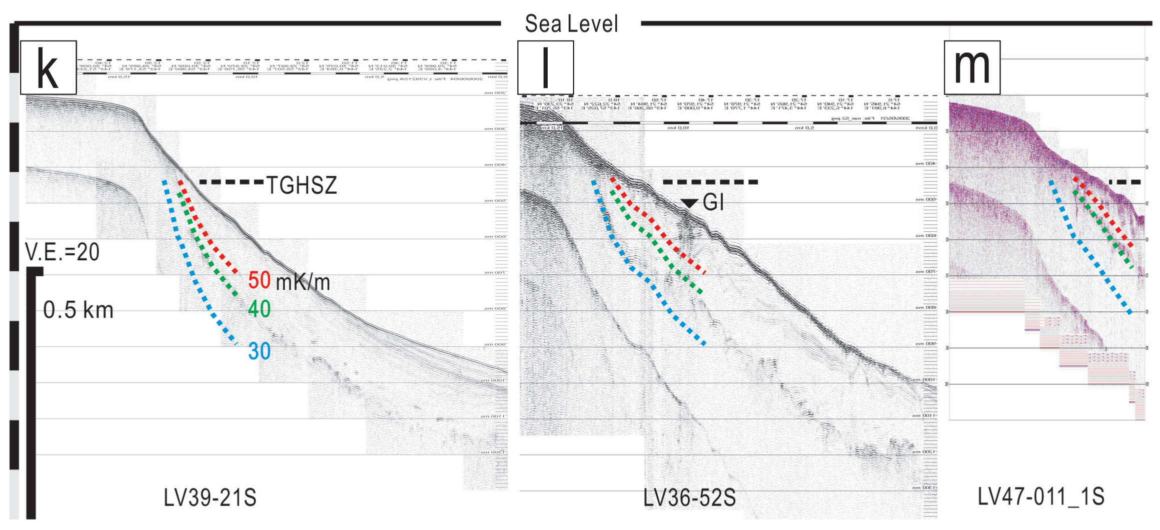
[c] The detailed map of survey area. The seismic survey lines (thick lines) conducted using the sparker instrument, the subbottom survey line (thin line), the locations of CTD casting sites to measure water temperature and salinity (squares), gas flare detected by hydroacoustic survey (triangles), and heat flow measurements (circles) are shown. The reverse triangle represents a site where core containing the gas hydrate was retrieved. The bathymetric contour is shown at 100-meter interval. Sites where sediment cores containing gas hydrates were taken are shown in star symbols: DU = Dungeon and GI = Gisella structure. The box represents the location of [n].

[d] The comparison of the slope between the continental margin to the north and south of the Lavrentyev Fault Zone (LFZ) (modified from Wong et al., 2003) in 3-dimensional aerial view. Note that slump scarp develops along contour lines 250-300 mbsl. See [b] for the location.

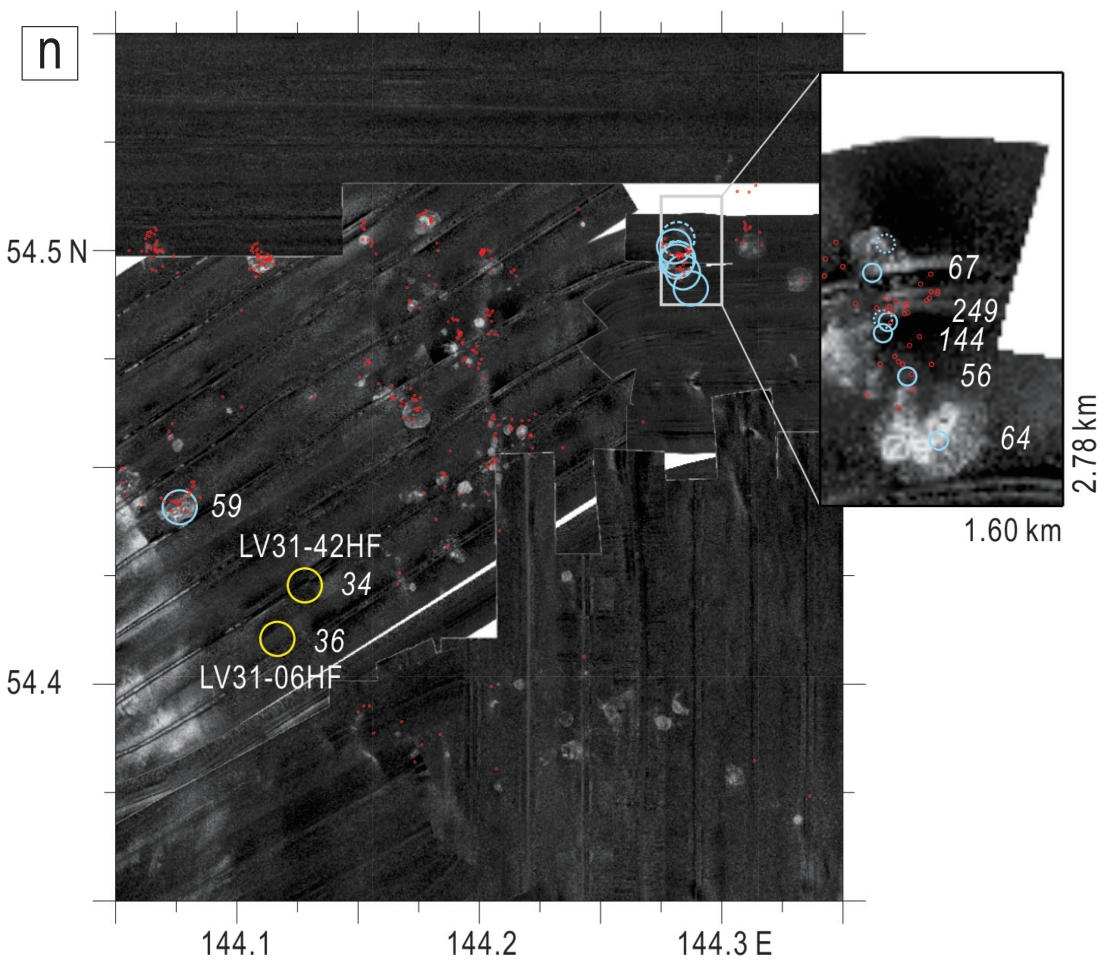
[e], [f], [g], [h] Gas flares as recorded by echosounder. The backscatter intensity is represented by colors from white for low to red for high. Reflection during the retrieval of cores can be seen (core track). The top of gas hydrate stability zone (TGHSZ) is depicted as a dotted line. Various shapes of gas flares are seen. The depth where flare begins sometimes coincides with TGHSZ.

[i], [j] The picture of gas hydrate samples from sediment core. See [c] for the location of the recovered gas hydrate samples. [i] from Dungeon (DU) and [j] from Gisella (GI) seepage structures are retrieved. The water depth at which these samples were recovered are 385 and 390 mbsl, the shallowest occurrence ever reported in the Sea of Okhotsk

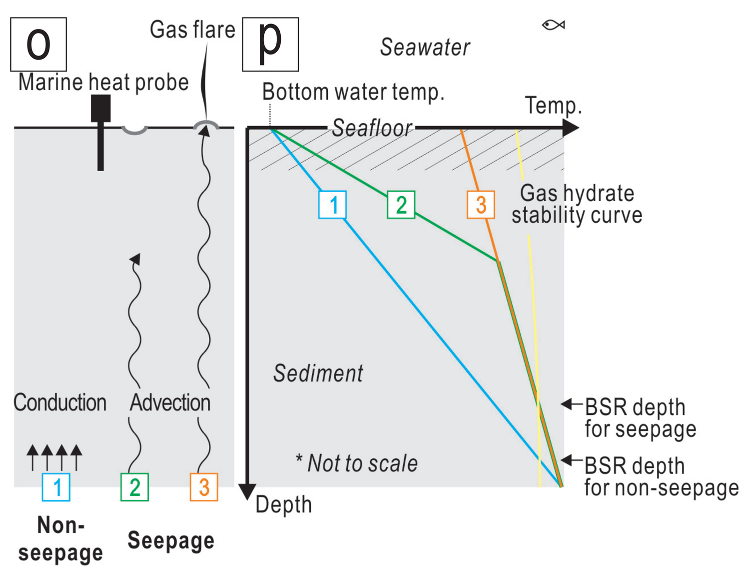
3. Estimated and Measured Heat Flow



[k], [l], [m] Seismic profiles showing the bottom-simulating reflectors (BSRs). The Dotted curves represent estimated BSRs based on geothermal gradients of 30 (blue), 40 (green) and 50 (red) mK/m using the stability curve by Tishchenko et al. (2005). The horizontal lines indicate the top of gas hydrate stability zone (TGHSZ). Gas hydrate sample was taken at Gisella seepage structure (GI, reverse triangle), which is shown in [c]. See [c] for the location of the echosounder profiles.

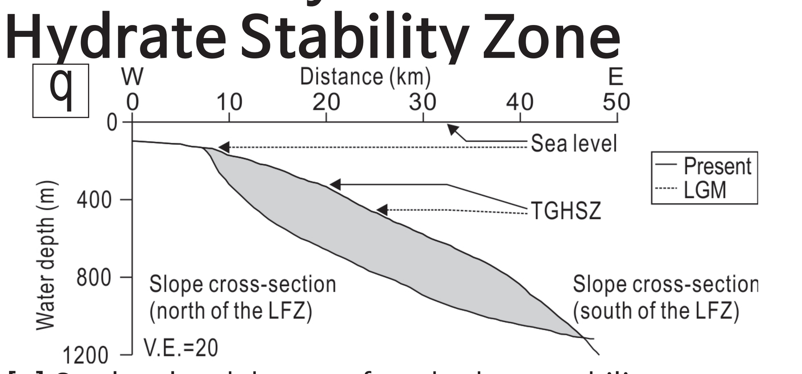


[n] The location of heat flow measurements. Measurements at seepage structure are marked as blue circles, and those at non-seepage as yellow circles on top of side-scan sonar image where light area represents the region of high backscatter. Dotted signs represent failed measurements. The Red dots indicate gas flares observed by the echosounder. Inset is a blow-up image of the box. The side-scan sonar image in the inset is the one below between overlapped two images. Numbers in italic represent geothermal gradient values. See [c] for the location of the heat flow measurements.

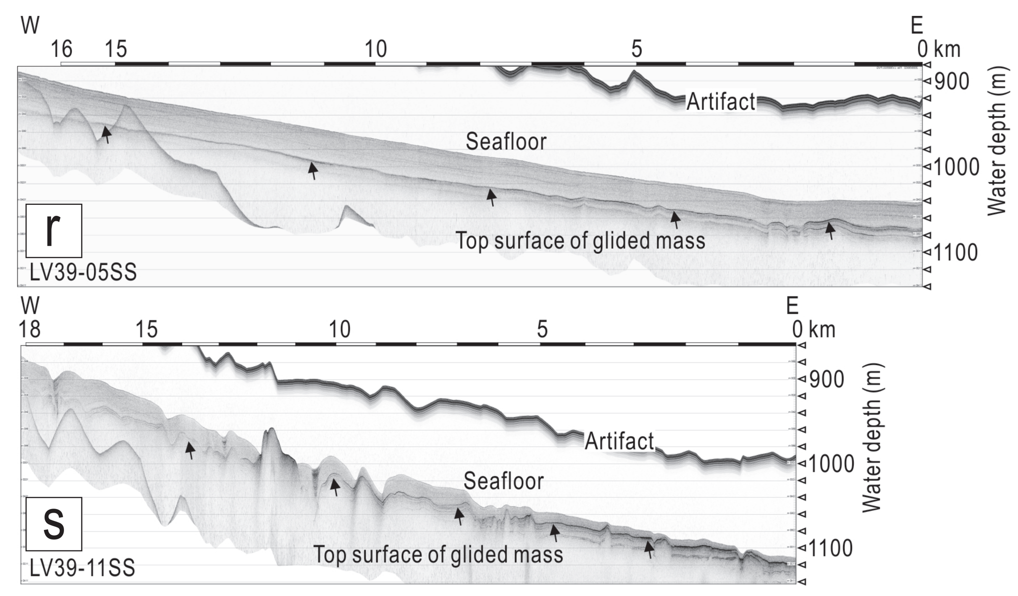


[o], [p] A schematic diagram illustrating the difference in heat transfer process and resulting thermal structure at non-seepage and seepage sites. [o] The dominant heat transfer process may vary between at a non-seepage site and at a seepage site. At a non-seepage site, conduction would be the dominant mode of heat transfer (Case 1). On the other hand, at a seepage site where convection by advective flow may play an important role, the warm fluid would rise up quickly to the surface (Case 3). Once the active venting has ceased, the convective fluid would not reach the seafloor and may be confined to the deeper portions of the sedimentary layer (Case 2). The sedimentary section may be divided into two: the upper part where conduction is dominant and the lower part where convection is dominant. [p] The temperature profile for active venting (Line 3) at the seepage site may be less steep than that at the non-seepage sites (Line 1). Hence, BSR depth can shoal up at the seepage site compared to at the non seepage site for given gas hydrate stability curve. When the active venting has ceased, the temperature profile at the seepage site may be shown a line bent at the depth where the convective fluid reaches (Line 2). Thus, the geothermal gradient corresponding to the conduction-dominant upper part is steeper than that to the convection-dominant lower part. Also, the geothermal gradient observed at the inactive or dormant seepage site becomes higher than that at the non-seepage site because a marine heat probe can penetrate into the topmost several meters below the seafloor (hatched area).

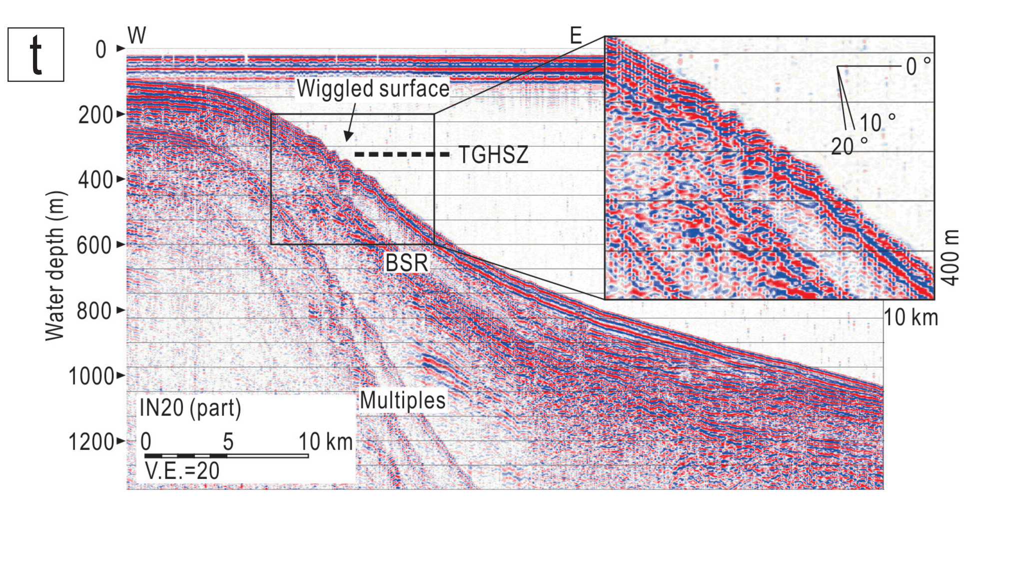
4. Possiblity of Past and Future Slope Failure due to Change of Gas Hydrate Stability Zone



[q] Sea level and the top of gas hydrate stability zone (TGHSZ) are represented for present-day (solid lines) and the Last Glacial Maximum (LGM: dotted lines). We do not know the exact mechanism for propagation of destabilization to non-hydrate bearing upslope at this stage due to lack of data.



[r], [s] Subbottom profiles showing a clear top surface of glided mass (arrows) at ~10-40 meters below the seafloor. The more deformed the less reflectors below the top surface of glided mass could be distinguished. Thickness of hemipelagite over the top surface is variable due to irregularity of the glided mass top surface: [r] rather constant at area with the flat top surface, and [s] thin or absent over highs/bumps as well as thinning-away offshore. Based on Biebow et al. (2003)'s sedimentation rate of 100 cm/kyr, the timing of landslide is estimated as 20 ka, consistent with that of the LGM.



[t] The wiggled surface as shown in the seismic profile. The location of the wiggled surface roughly agrees with the top of gas hydrate stability zone (TGHSZ). Inset is a blow-up image of the box. Careful interpretation of seismic data on the wiggled area may suggest that the surface does not have a current origin: 1) no change in seabed reflector amplitudes compared with one in non-wiggled area, and 2) steep (〉15 °) angle between the boundary of undulation and reflector of undulation (Berndt et al., 2006). See [c] for the location of the seismic profile.

Acknowledgments

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