Submarine slope-failure offshore Norway triggers rapid gas hydrate decomposition

Christian Berndt [(1)]*, Jürgen Mienert [(1)], Maarten Vanneste[(1)], Stefan Bünz[(1)] and Petter Bryn [(2)]

[(1)] Department of Geology, University of Tromsø, 9037 Tromsø, Norway
[(2)] Norsk Hydro ASA, Bygdøy allé 2, 0240 Oslo, Norway

2D-seismic data from the mid-Norwegian margin provide evidence for sediment liquefaction and fluid mobilisation within the sediments that were located at the base of the hydrate stability zone before the Storegga. The disturbed subsurface sediments are overlain by a prominent roll-over structure and sea floor collapse. This suggests that the landslide caused a pressure drop strong enough to dissociate the gas hydrates, and that it led to fluid escape from the formerly hydrated sediments. We calculate that this fluid escape must have taken place in less than 250 years, as the effect of pressure drop was afterwards compensated by a temperature decrease.

1 Introduction

Natural gas hydrates are clathrates of light hydrocarbons, such as the greenhouse gas methane, which are captured in water ice crystals. They occur under pressure / temperature conditions frequently encountered in ocean sediments at water depth greater than 500 m. Kvenvolden (1993) estimated that gas hydrates bound more than half of the Earth's carbon that could potentially influence climate. Therefore, it is necessary to assess the mobility of this reservoir. So far, evidence for natural gas hydrate dissociation is sparse and most reported examples are from settings in which gas hydrates dissociate slowly as for example in areas of rapid sedimentation (Dillon et al., 1998, Milkov, 2000) or tectonic uplift (von Huene and Pecher, 1999). Here, we present geophysical evidence from the hydrated sediments of the Norwegian Margin (Fig. 1) that gas hydrates have decomposed and released fluids adjacent to the side wall rapidly after the Storegga Slide event approximately 7300 ^{14}C years ago (Haflidason et al., 2001). Fast fluid escape is a prerequisite for rapid impact of gas hydrate dissociation on climate, and may support the "clathrate gun hypothesis" (Kennett et al., 2000).

2 Reflection seismic data

We use two seismic data sets in this study. The 96-channel data (Fig. 2a) are provided by Norsk Hydro ASA, whereas we acquired the single-channel data (Fig. 2b + c) in 1999 and 2000 ourselves. Both data sets image the top 500 m of sediment with high resolution, as the sleeve gun sources generated seismic signals with frequency bands from 10 to 130 and from 50 to 250 Hz, respectively. Both surveys have been processed including Stolt migration.

The high-resolution seismic reflection data show a distinct roll-over structure that is most pronounced towards a normal fault that coincides with the 110 m-high side wall of the submarine Storegga Slide (Fig. 2a + b). The roll-over involves the upper 150 ms two-way travel time (twt) of the seismic section, whereas the underlying strata are undisturbed. The throw of the fault is of the order of 60 ms twt or approximately 50 m. The seismic character of the strata directly above the uppermost undisturbed reflector at approximately 2.15 s twt is chaotic, and this chaotic seismic facies continues between 3 and 10 km downslope of the slide scarp. Beyond this zone the seismic reflectors are undisturbed. The depth of the base of this chaotic facies and the top of the undisturbed reflections coincide with the depth of a bottom simulating reflector (BSR) outside the slide area which has been

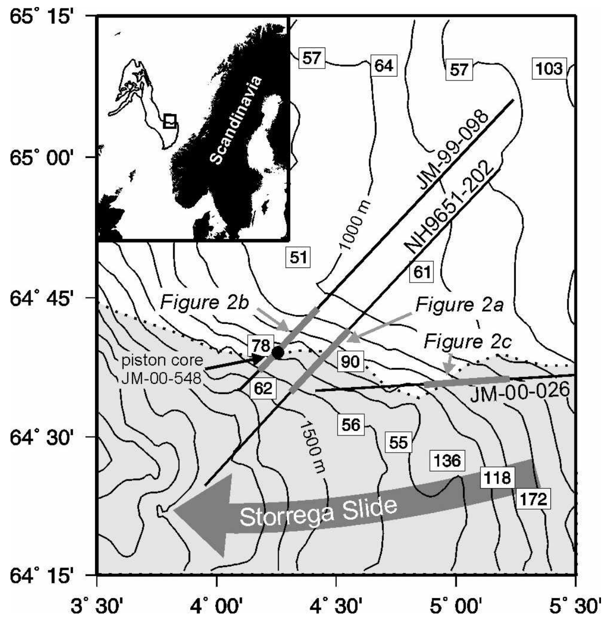

Fig. 1: Study area at the northern rim of the Storegga Slide. Gray lines indicate seismic profiles shown in Fig. 2. Numbers in boxes indicate heat flow measurements in mW/m^2 after Sundvor et al., 2000.

* Corresponding author. E-mail:cberndt@ibg.uit.no.

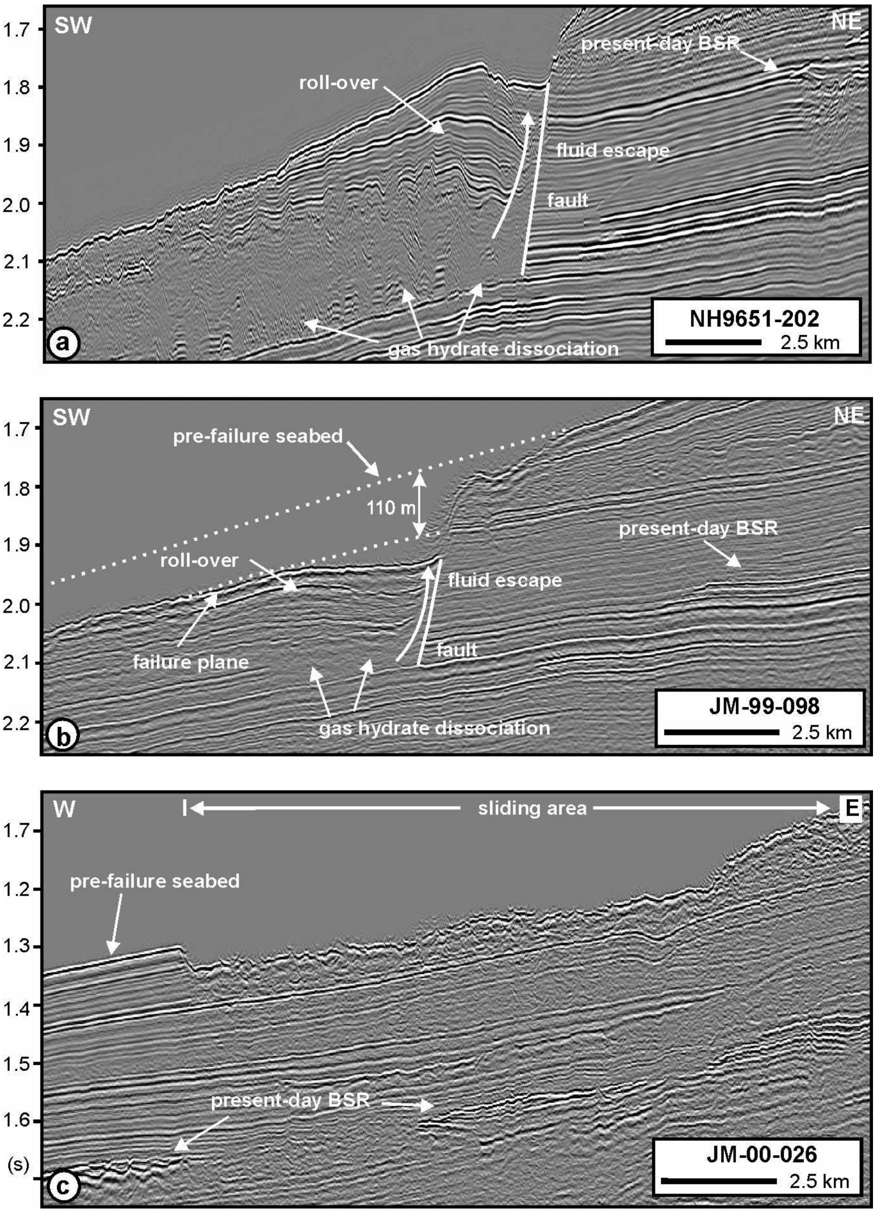

Fig. 2: Migrated high-resolution seismic data. a) multi-channel data. b + c) single-channel data. Note, that the bottom simulating reflector (BSR) within the slide area (c) mimicks the seafloor indicating that it has adapted to the new pressure/temperature conditions.

attributed to gas accumulation beneath gas hydrates previously (Mienert et al., 1998). Locally, a BSR is visible within the slide area (Fig. 2c).

3 Discussion

3.1 Evidence for subsurface mass movement. The fact that the strata underlying the roll-over structure are undisturbed (Fig. 2a + b) implies that mass has been transported away from the base of the roll-over structure. Subsurface transport of mass in a direction perpendicular to the seismic lines must have been minor, because all parallel lines show a lack of material at the base of the fault. Therefore, we conclude that most of the missing mass must have escaped to the surface. The most likely conduit for this transport is along the fault as there is no seismic evidence for other transport mechanisms such as mud diapirs. We interpret the chaotic seismic facies between the base of the roll-over structure and the top of the undisturbed sediments as the result of liquefaction of the sediments and mobilisation of fluids. It appears that both fault and roll-over structure developed as the result of sediment and fluid removal from the base of the roll-over structure as the seismic data shows no indications for a pre-existing fault at this location.

3.2 Mobilisation due to gas hydrate dissociation. The extent of the disturbed sediments is confined to the vicinity of the fault and our data do not show such features farther inside the slide area although this should be anticipated if the disturbance was caused by regional, seismicity-related liquefaction. Therefore, it appears more likely that a different mechanism has caused these structures. The disturbed sediments lie at the depth of the pre-slide gas hydrate stability zone. This is evident from their location just above the BSR observed outside the slide area (Fig. 2). The presence of gas hydrate-bearing sediments is commonly inferred from the presence of this characteristic reflector which is caused by the impedance contrast between hydrated sediments and free gas that is trapped underneath (Pecher et al., 1996, Mienert et al., 2001). The coincidence of the depth of disturbed sediments and the base of the gas hydrate stability zone strongly suggests that the sediment disturbance is related to gas hydrates.

The lithostatic pressure drop due to the multi-phase Storegga Slide event approximately 7300 14C years ago is a possible explanation for a sudden shoaling of the gas hydrate stability zone. As a result of the pressure drop, the lowermost hydrated sediments were no longer within the stability zone. Provided that the surrounding sediments supplied enough energy, the hydrates started to dissociate releasing fluids that could propagate upwards through the fault. Subsequently the geothermal field adjusted to the new conditions levelling out the temperature difference between the cold bottom water and the newly exposed, i.e. warmer, sediments at the sea floor. The sediments progressively cooled downwards until the conductivity-controlled geothermal gradient was re-established. Gas hydrate dissociation must have stopped when the thermal signal had reached the pre-landslide depth of the gas hydrate stability zone and re-stabilised the gas hydrates. This is evidenced by the observation of a re-adjusted BSR within the slide area (Fig. 2c).

3.3 Quantification of the thermal evolution. In order to estimate the maximum time of gas hydrate dissociation we calculate the thermal evolution of the sedimentary column since the sliding event. We assume an instantaneous sea floor temperature change imposed on a conductive medium (Vanneste, 2000). This does not take into account possible heat transport due to fluid flow. However, such heat transport will shorten the time available for dissociation because it will re-establish the thermal equilibrium faster than conductive heat transport alone. Given this caveat, the temperature *T* as a function of time *t* and sub-bottom depth *z* can be described by the initial conditions and a comple-mentary error function (Carslaw and Jaeger, 1959):

$$T(z,t) = T_0 + Gz + \Delta T \, Erfc\left(\frac{z}{2\sqrt{k\,t}}\right)$$

with T_0: the pre-landslide temperature at the slide plane, G: the geothermal gradient, ΔT the temperature difference at the new sea floor exposed by the slide, and k the average thermal diffusivity of the sediments involved. The physical sediment properties used in the calculation are based on loggging results of a piston core taken at the slide's side wall (Fig. 1) and from the seismic constraints (Table 1). The calculations indicate that the landslide initially moved the lowermost 8 m of sediment out of the pre-slide gas hydrate stability zone initiating gas hydrate dissociation within this layer (Fig. 3). After 60 years the thermal signal reached the pre-landslide depth of the gas hydrate stability zone beginning to re-stabilise the gas hydrates at the top of the 8 m layer and 180 years after the landslide the new base of the gas hydrate stability zone had reached pre-landslide depth. At that time gas hydrate dissociation must have terminated. Our model predicts that re-adjustment of the geotherm still continues. Today the base of the gas hydrate stability zone is 80 m deeper than the pre-slide base. The error of these calculations depends mainly on the thermal diffusivity, and is on the order of 40%. The errors of the remaining parameters, and the effects of additional physical processes such as latent heat generation, are small compared to this. This implies that fluid escape must have happened within a maximum of 180 + 70 years after the landslide and perhaps even faster.

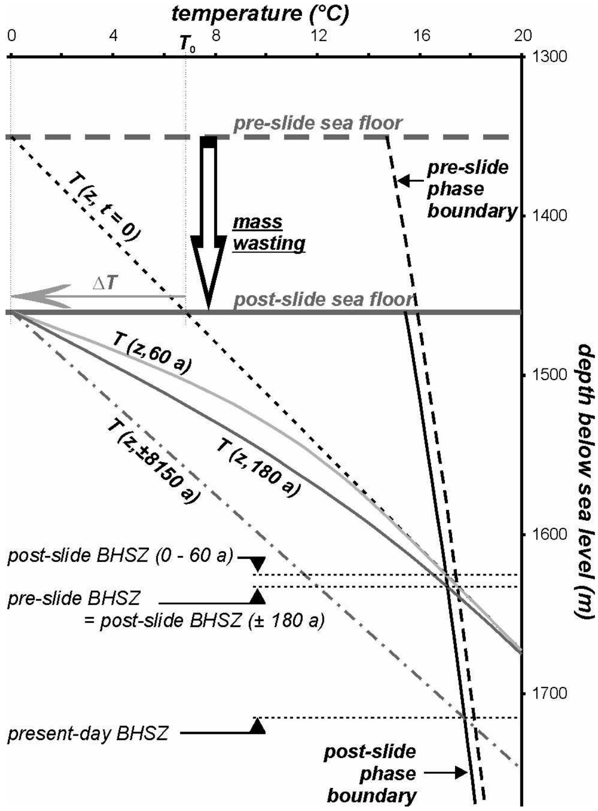

Fig. 3: Thermal evolution at the foot of the Storegga Slide side wall. Note the initial shoaling of the hydrate stability zone immediately after the occurrence of the landslide and subsequent deepening. Hydrate dissociation and fluid escape must occur within 180 +/- 70 years after the sliding event. BHSZ, base of the hydrate stability zone; T, temperature, T0, temperature difference at the sea floor due to the slides.

4 Conclusions

Sea floor collapse within the Storegga Slide region and above dissolved gas hydrates shows that the gas hydrate reservoir is highly dynamic. Our calculations show that it can release fluids from the base of the hydrate stability zone to the surface within decades. This makes the release of methane due to submarine landslides a process that potentially can influence climate. However, ice core data from Greenland show that it takes very large methane input, i.e. of the order of 4000 Tg, to increase global mean temperatures by 0.3 to 1 K (Thorpe et al., 1998). Moreover, given the present resolution of the ice core data evidence exists that the Storegga Slide events did not release enough methane from the gas hydrate reservoir to the atmosphere

Table 1: Modelling Parameters

Property	Value	Reference
bulk density	1850 kg/m^3	piston core JM-00-548
bottom water temperature	0ºC	Mienert et al., 1998
thermal conductivity	1.2 W/mK	Sundvor et al., 2000
bulk specific heat capacity	800-1300 J/kg K	Buntebarth, 1984
geothermal gradient outside the slide area	62 K/km	hydrate stability conditions
thickness of removed sediments	110 m	seismic line JM-99-098

to influence climate (Raynaud et al., 1998).

The Storegga Slide head wall extends for 300 km and developed simultaneously (Bugge et al., 1987). So far, it is not clear what caused slope failure at such large regional scale. The observation of induced sea floor collapse in the wake of landslides suggests a possible propagation mechanism: Initial local slope failure, possibly induced by an earthquake, may not only have started gas hydrate dissociation and fluid expulsion under the initial slide area but also in adjacent parts of the slope, because the pressure drop will also effect the vicinity of the slide. Subsequent sea floor collapse and rise of fluids perhaps decreased the shear strength of the sedimentary overburden leading to more regional slope failure.

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