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Slide structure and role of gas hydrate at the northern boundary of the Storegga Slide, offshore Norway

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Abstract

The Storegga Slide off the coast of Norway is one of the largest underwater slide complexes known and has been proposed as a significant source of past methane release into the atmosphere. We present pre-stack depth-migrated images from a new multi-channel seismic data set in the Storegga Slide. The northern scarp of the Storegga Slide has previously been interpreted as a single, large recent slope failure; however, our images show strong evidence for a composite structure consisting of a much older event and recent slumping. We observe onlapping features onto slide deposit highs, and layer thickening as post-slide sediments fill in accommodation space created at the slide scarp, both of which support this conclusion. Displaced fault blocks are overlain by undeformed, flat-lying sediments, also indicating considerable time between slide events. According to dating of the base of the Naust at this location, this older slide event occurred at a minimum of ~250 ka. The causes of submarine slope failure are poorly understood, but previous studies have proposed both earthquakes and dissociation of gas hydrates as triggering mechanisms. Pressure/temperature modeling shows that, assuming steady-state conditions, the bottom simulating reflector (BSR) would have been deeper than the glide plane at the time of slope failure. The base of the gas hydrate stability zone, and any gas that may have been present, likely played only a minor role, if any, in slide initiation at this locale.

Keywords: gas hydrate; submarine slide; Norwegian margin; slope stability; Vøring Plateau; bottom simulating reflector

1. Introduction

Large submarine landslides on continental slopes are important geologic features because they cause mass wasting, tsunamis and the possible rapid release of methane, a greenhouse gas, into the atmosphere (Nisbet and Piper, 1998; Paull et al., 1991). The North Atlantic and Nordic Seas are prone to large continental slope failures as a result of Quaternary ice sheets that once covered the area. Maslin et al. (2004) found that periods of high volume sediment slope failure, between 15–13 ka and 11–8 ka, correlate with rising sea levels and peaks in the atmospheric methane record. Their findings provide circumstantial support the clathrate gun hypothesis of Kennett et al. (2003), which suggests that the release of methane from marine sediments was a major source of atmospheric methane in the Quaternary. The conditions that trigger large submarine landslides are poorly understood. The gas hydrate system may induce seafloor instability either by providing a zone of weakness at the BSR that localizes the glide plane

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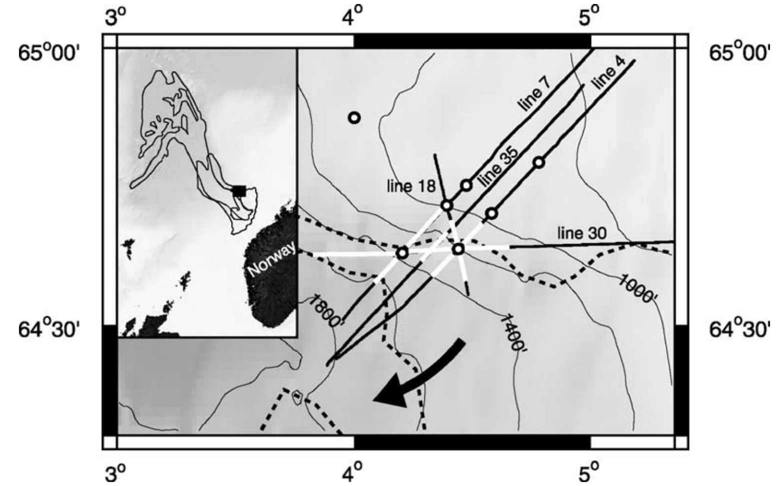

Fig. 1. Map of study area at the northern sidewall of the Storegga slide scarp. Black lines represent seismic lines recorded, while white lines indicate profiles shown in Figs. 2–4. Dotted lines represent the northern boundaries of the main Storegga slide events identified by Bugge et al. (1987). Proposed IODP drill sites are open circles. Direction of slide movement is indicated with a black arrow.

(Dillon et al., 1998) or by fluid and sediment liquifaction caused by gas hydrate dissociation immediately after a slide event (Berndt et al., 2005). In this paper, we investigate the possible influence of gas hydrates on failure of the northern sidewall of the Storegga Slide and the timing of multiple slide events there.

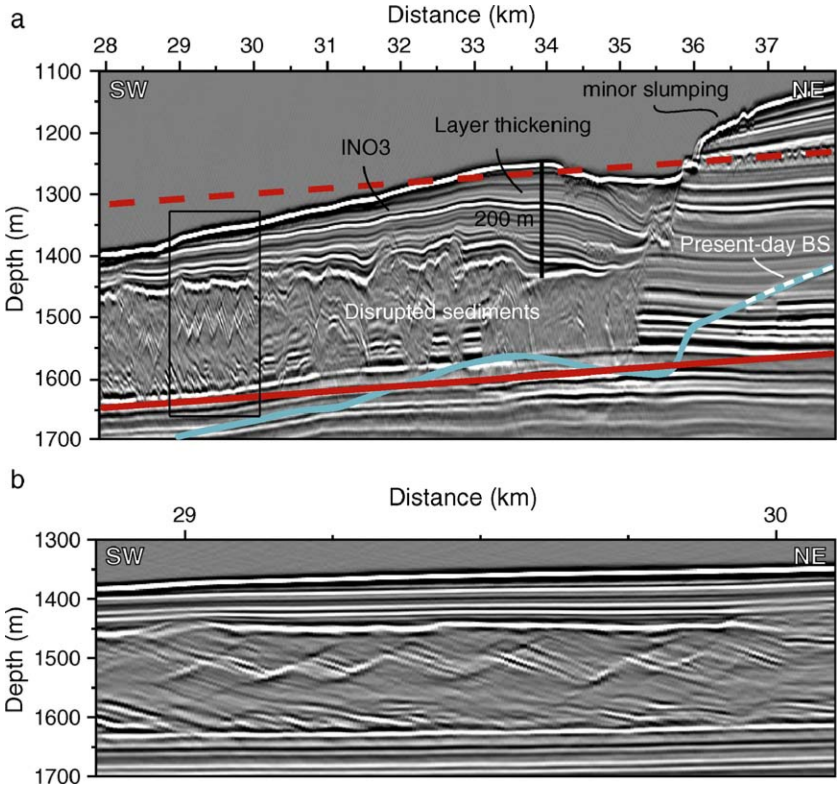

Fig. 2. (a) Pre-stack depth migration of slide scarp on line 4. Note that the present-day BSR, dashed white line, is not observed within the slide area. Sediment layers thicken towards the scarp. Black box indicates location of Fig. 3. Blue line represents the position the calculated BSR would be today. Dashed red line indicates location of pre-slide seafloor, while solid red line represents the position of the calculated pre-slide BSR. (b) Pre-stack depth migration of a portion of line 4 scaled 1:1. Tilted sediment blocks, between layers of undisturbed sediments, have undergone 30% extension.

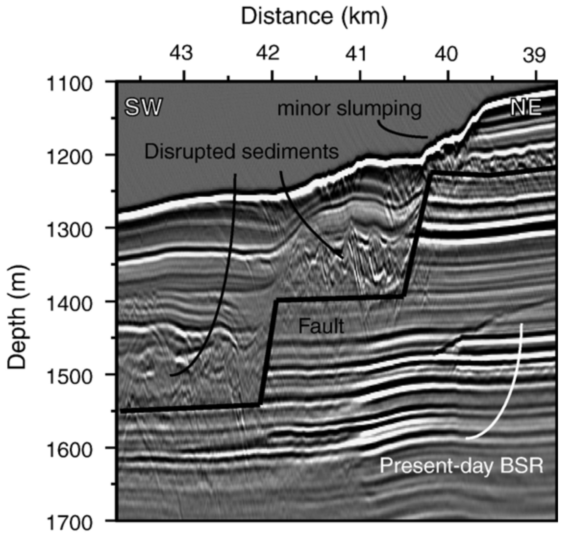

Fig. 3. Pre-stack depth migration of a portion of line 35. Stair-step pattern in fault.

Gas hydrates are an ice-like compound composed of a gas molecule, usually methane, surrounded by a rigid cage of water molecules (Sloan, 1998). They occur naturally when methane saturates pore water in marine sediments under particular pressure/temperature conditions, which usually occur on continental slopes at water depths greater than ~500 m. Hydrates are common on continental margins and may be the largest reservoir of methane on Earth (Kvenvolden, 1993). They are often found in close proximity to underwater landslides such as the Storegga Slide.

Since the gas hydrate stability zone (GHSZ) depends on pressure/temperature conditions, hydrate stability is sensitive to changes in both water temperature and sea level (Dickens, 2001). Small climate and sea level changes could make hydrate become unstable, breaking it down into free gas, which may weaken sediments and trigger landslides, from which methane might escape into the oceans and atmosphere. If significant quantities of methane, a greenhouse gas, are released into the

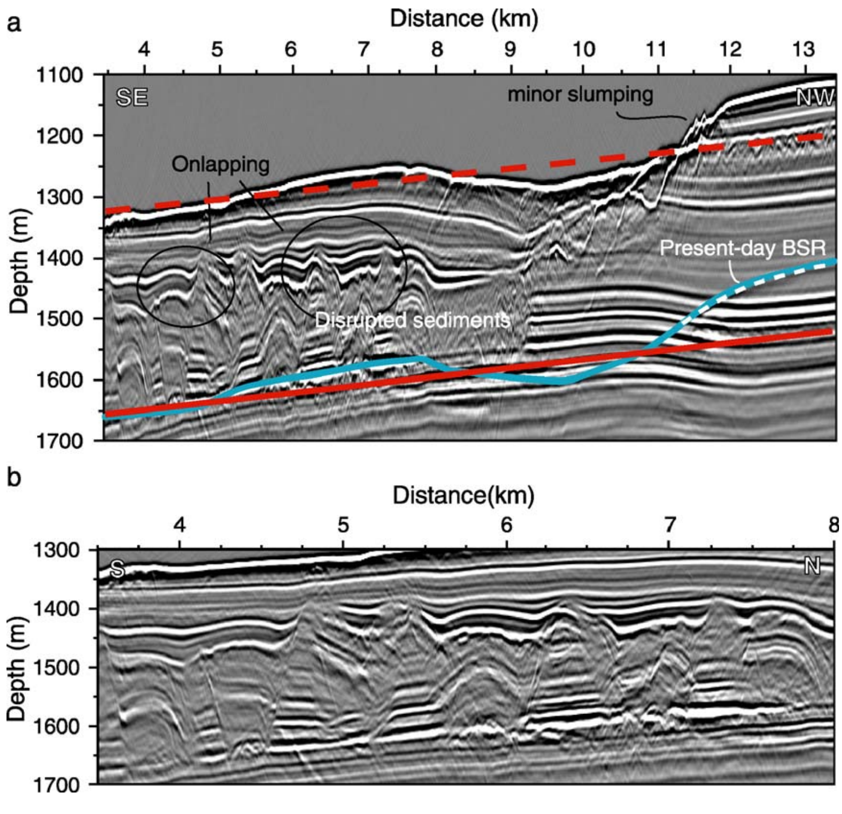

Fig. 4. (a) Pre-stack depth migration of line 18. On-lapping features observed over slide deposits. Dashed white line represents present-day BSR. Blue line represents position of calculated BSR today. Dashed red line indicates estimated location of pre-slide seafloor, while solid red line represents the position of the calculated pre-slide BSR. (b) Pre-stack depth migration of a portion of line 18. Coherent blocks of sediment have slid due to retrogressive failure. Note the distinct graben-like features.

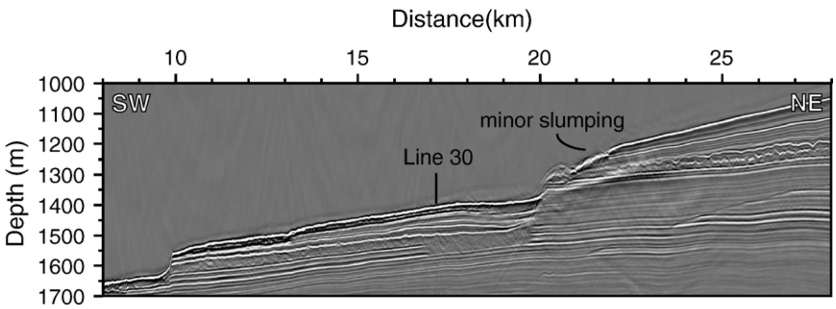

Fig. 5. Pre-stack depth migration of line 7. Intersection with line 30 occurs at the approximate location of step in glide plane. Recent slide cuts ~ 250 ka deposits at 10-km mark.

atmosphere by this mechanism, there could be important implications for Earth's climate (Kennett et al., 2003).

Here, based on new high-resolution seismic images and thermal modeling of hydrate stability conditions, we present evidence and analysis that suggests that (1) the northern boundary of the Storegga Slide is actually a much older event than previously thought, with minor recent slumping at the headwall, and (2) the base of the gas hydrate stability zone did not play a role as a glide plane.

2. Geologic setting

The Storegga Slide, located off the western coast of Norway (Fig. 1), is an 800-km-long submarine landslide (Bugge et al., 1987; Bugge et al., 1988) affecting an area of 95,000 km^2 (Haflidason et al., 2004) and displacing approximately 3500 km^3 of sediment (Bryn et al., 2003). Stratigraphy of the area consists of the Kai Formation and the Naust Formation. The Miocene/Early Pliocene Kai Formation is characterized by fine-grained hemipelagic oozes cut by polygonal faults formed by sediment contraction due to pore fluid expulsion (Bünz et al., 2003). The Naust Formation is mainly composed of Plio/Pliestocene contourites and hemipelagic sediments and glacial debris flows. Bottom simulating reflectors (BSRs), which indicate the presence of free gas and possibly hydrate in seismic data (Holbrook et al., 1996), have primarily been recognized in the Naust Formation (Bünz et al., 2003). Glacial sediments deposited on the southern Vøring Plateau, which sometimes interlayer with hemipelagics, inhibit upward fluid migration and possibly prevent gas hydrate formation (Bryn et al., 2003).

Our study focuses on the northern sidewall of the slide scarp at the southern edge of the Vøring Plateau (Fig. 1). This section was chosen because (1) a BSR indicates the presence of free gas in this area, (2) the close proximity of two main slide scarps provides an opportunity to study the interaction of submarine landslides with the methane hydrate system, and (3) this area is the focus of multiple proposed IODP drill sites. Although this area is frequently referred to as a "sidewall," the local transport direction (based on previous seafloor imaging and seismic lines; Haflidason et al., 2003) is perpendicular to the scarp. Therefore, this area can be treated as a headwall and lends itself well to the study of the interplay between gas hydrate and sediment failure.

3. Data acquisition and processing

In the fall of 2003, multi-channel seismic (MCS) data were collected using the R/V *Maurice Ewing* and a 6-km-long, 480-channel streamer. We used a six-element, 1340-in.^{3} air-gun array as a sound source, with a shot

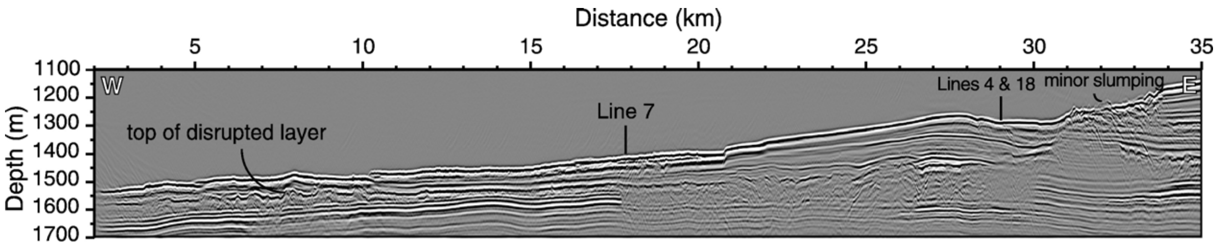

Fig. 6. Pre-stack depth migration of line 30. Top of disrupted layer is overlain by post-slide deposits that are continuous over more than 25 km. Note crossing points of lines 4, 18, and 7.

spacing of 37.5 m. A total of 62 seismic lines were collected across the Storegga Slide; five of these lines, 4, 7, 18, 30 and 35, will be discussed in this paper (Fig. 1). Line 4 strikes NE–SW across the northern scarp, parallel to the local transport direction of the slide. Lines 35 and 7 run roughly parallel to line 4 approximately 5 and 10 km to the west, respectively. Line 18 strikes NNW–SSE crossing line 4 at an angle of ~70°, and line 30 strikes E–W crossing the slide scarp on lines 4, 18, and 7. MCS processing was performed using the Paradigm processing packages Focus and GeoDepth and included pre-stack depth migrations (Figs. 2a–6). Our results are the first pre-stack depth-migrated images of the northern headwall of the Storegga Slide and show the structure of this area in unprecedented detail.

4. Seismic observations

4.1. Evidence for an older event

The most recent Storegga Slide has long been recognized as a composite of multiple large separate events and many minor events of approximately the same age (Bryn et al., 2003, 2005; Bugge et al., 1987). Submarine sliding on the margin probably began around 0.5 Ma and large slides continued to occur about every 100 ka (Solheim et al., 2005). Buried slide scars are found at both the main slide headwall and northern slide boundary, but it was previously unclear whether the scar at the northern boundary is from the most recent (8.2 ka) Storegga Slide event as suggested by Haflidason et al. (2004). The sedimentary relationships between deformed and undeformed layers on our seismic profiles (Figs. 2a–4b) show that the lower disrupted sediments by the northern sidewall are the deposits of a much earlier slide event. Disrupted hemipelagic deposits are identified by areas of low seismic reflectivity and less coherent stratigraphy on depth-migrated seismic sections. These deposits are distinctly different in character than the glacial debris flows commonly found on the Vøring Plateau, which are generally even more transparent and less stratified than mobilized hemipelagic units. Our results contrast with previous interpretations (Berndt et al., 2005; Haflidason et al., 2004, 2005; Mienert et al., 2005), which assume that the slide at this location is composed of one event containing a "sediment collapse structure" (Mienert et al., 2005). We summarize the observations supporting this new interpretation below.

Unlike previously published seismic images of this area (Berndt et al., 2005; Bouriak et al., 2000; Bryn et al., 2003), our migrations show a stair-step pattern in the fault on three lines, with steps of flat-lying sedimentary layers overlain by disrupted material and then draped with undisturbed deposits. This pattern is best observed on line 35 (Fig. 3), where fault steps are approximately 100 m high and 1200 m wide and is most likely related to the retrogressive nature of the slide as it backstepped along shallower clay layers (Kvalstad et al., 2005). The disturbed sediments at the base of the fault are approximately 100 m thick, with the top and bottom at ~1.45 km and ~1.55 km depth, respectively, and thicken slightly downslope. Approximately 200 m of undisturbed sediments lie directly on top of the slide deposits near the base of the fault scarp.

Four key observations indicate that the highly disrupted sediments at depth of 1450–1620 m in Figs. 2a–6 represent an older slide event that was subsequently covered by up to 200 m of undeformed sediment. (1) Undeformed sedimentary layers outside the slide area (Upper and Lower Naust O) correlate with a package of the same layering and seismic reflectivity inside the slide, indicating a significant time period of sedimentation across the scarp. (2) Undisturbed sediment layers above the slide deposits thicken towards the fault (Fig. 2a), filling in an area of greater accommodation space. Since it is impossible to accomplish layer thickening through deformation or "roll-over," this observation implies that these layers must have been deposited after the earlier slide event. (3) Clockwise-rotated fault blocks on line 4, and coherent slide blocks on line 18, are overlain by undeformed, flat-lying sediments; it is implausible that such block displacement could occur without deforming overlying sediments (Figs. 2b and 4b). (4) Seismic sections show onlapping features onto highs of deformed sediment, indicating later deposition onto pre-existing slide deposits (Fig. 4a and b).

Structures identified in our seismic images have been reproduced by the numerical simulations and modeling of Gauer et al. (2005) and Kvalstad et al. (2005), which illustrate the retrogressive and back-stepping behavior of slides in the Storegga region.

The base of the Lower Naust O Formation is dated at ~250 ka (Hjelstuen et al., 2004), leading us to estimate that the first slide occurred at a minimum of ~250 ka. We recognize the most recent slide event, dated at 8.2 ka (Haflidason et al., 2005), on line 7 as a younger event that clearly cuts the ~250 ka slide deposits and sediment the layers that cover them (Fig. 5). Slide deposits associated with the ~250 ka event are laterally continuous over 25 km as shown on line 30, an oblique cross section of the northern sidewall that ties line 4,18, and 7 (Fig. 6).

5. Phase boundary modeling

5.1. Methods

To determine the position of the present-day BSR inside the slide area we calculated the depth at which pressure/temperature conditions are sufficient for gas to exist. Using bottom-water temperatures from an expendable bathy-thermograph (XBT) deployed on line 4 (Nandi et al., 2004) and the depth of the BSR outside the slide (obtained from pre-stack depth-migrated images), we determined an average geothermal gradient of 54.4 °C/km for lithostatic conditions and 50.0 C/km for hydrostatic conditions. These values match those obtained by Bouriak et al. (2000), who performed similar analyses in the same region, and heat flow measurements by Sundvor et al. (2000). Because pressure at the edge of the Vøring plateau is likely between lithostatic and hydrostatic, we calculated the position of the hydrate stability boundary using each. We used a sediment density of 2.694 gm/cm^3 in order to determine lithostatic pressure with depth, a value derived from mineral percentages obtained from a nearby well log (NGI, 1997). The density of seawater with a salinity of 33.5 g/l is 1.035 g/cm^3. We determined porosity with depth with data from NGI (1997) (down to 300 m) and ODP leg 104 (300 m to 900 m) well logs. We calculated the pressure/temperature conditions at 0.1-m increments below the seafloor and compared the data with the methane hydrate stability curve for lithostatic conditions in Peltzer and Brewer (2000) to determine at what depth hydrate would become unstable. The equation used to calculate hydrate stability is $\ln(P/P_o) = -1205.907 + 44097.00/T + 186.7594 \ln T$, which was adjusted for seawater of 33.5 g/l salinity by adding 1.15 °C to the temperature, in accordance with Peltzer and Brewer (2000) and Dickens and Quinby-Hunt (1997). These depths were plotted on depth-migrated seismic sections to mark the position where a BSR would exist in present-day pressure/temperature conditions. The difference between the lithostatic and hydrostatic BSR depth prediction was only approximately 5–10 m, equaling the thickness of the line used to plot the boundary in Figs. 2a and 4a.

In order to calculate where the BSR existed in the pre-slide environment, we predicted the approximate location of the pre-slide seafloor by extrapolating the slope of the undisturbed sediments, which are outside the slide area to the north, across the scarp. From this extrapolation, we measure a pre-slide slope of approximately 1°; however, that assumes little sediment compaction or layer thinning commonly observed along the edges of the Vøring Plateau. The present-day slope of the seafloor at our location on the continental margin is 1.7°, steeper than our estimated pre-slide slope. Thus, a slope of 1° represents an upper boundary for the depth of the pre-slide seafloor and, therefore, an upper boundary for the depth of the calculated pre-slide BSR.

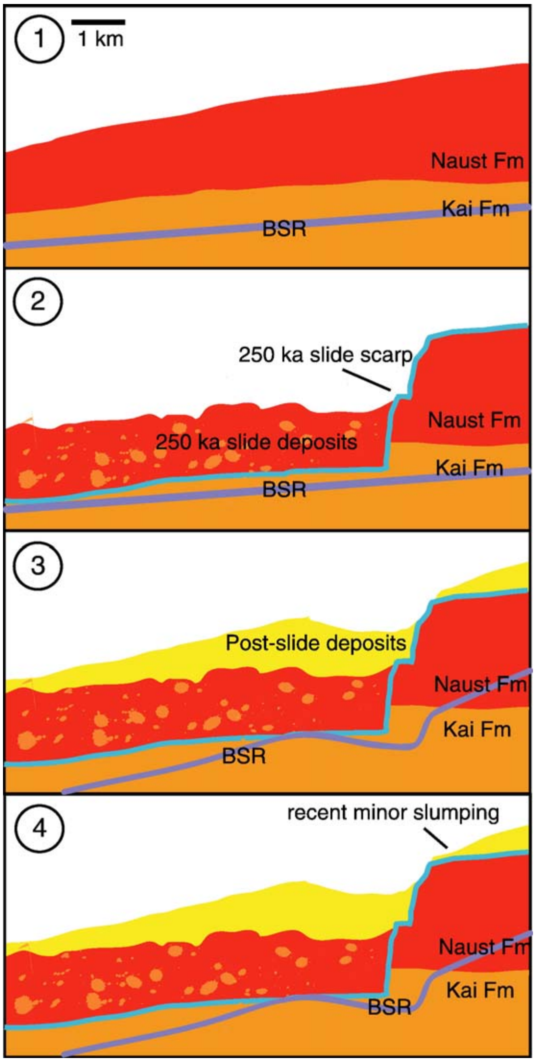

Fig. 7. Interpretation of sequence of events that occurred along line 4. (1) Pre-slide environment of the continental slope. Calculated BSR located below the Naust/Kai boundary. (2) ~ 250-ka slide occurs disrupting both the Naust and Kai Formations but does not slide along the base of the GHSZ. (BSR shown has not re-equilibrated.) (3) Post-slide deposition fills in areas of greater accommodation space on the slope. BSR adjusts to new pressure/temperature conditions. (4) Minor slumping occurs cutting deposits and small amount of Naust Formation. Calculated BSR re-equilibrates to current pressure/temperature conditions.

5.2. Present-day and past locations of the BSR

Today, at the northern sidewall, the BSR disappears as it enters the slide area on lines 4, 7, 18 and 30. The calculated position of the present-day BSR on line 4 follows seafloor bathymetry and dips below the ~250 ka scarp/glide plane intersection before running along the glide plane for about 1 km and then moving to greater depths (Fig. 2a). Line 18 shows that the predicted present-day BSR position approximately coincides with the glide plane of the ~250 ka slide (Fig. 4b). This coincidence has led some authors to suggest that gas hydrate dissociation played a role establishing the location of the northern sidewall and glide plane (Berndt et al., 2005).

However, based on the depth of the reconstructed pre-250-ka-slide seafloor, the calculated location of the pre-250-ka-slide BSR lies completely beneath the glide plane on line 4 (Fig. 2a). The pre-250-ka-slide BSR on line 18 runs close to the glide plane approximately 4 km downslope from the slide scarp. This is an upper limit for the depth of the BSR, and it is very likely that the BSR would have been deeper at that time, because the pre-slide slope was likely steeper than we have estimated, ignoring compaction (Fig. 4a). Assuming steady-state conditions, the glide plane did not develop as a result of the location of the base of the GHSZ and slope failure likely did not occur at the phase boundary. Our interpretation of the sequence of events at the northern sidewall is illustrated in Fig. 7.

Our results differ from those of Mienert et al. (2005), who performed similar modeling at the northeastern headwall. They concluded that the location of the headwall may be explained by hydrate dissociation; however, like us, they do not consider dissociation to be the primary cause of Storegga Slide slope failures.

6. Conclusions

Seismic evidence suggests that there was an ~250 ka event (previously interpreted as a 8.2 ka event) at the northern boundary of the Storegga Slide complex that has been covered with later deposits, cut by a more recent 8.2-ka slide scarp downslope, and disturbed by minor slumping and the headwall. Pre-stack depth-migrated images show that post-slide sediment deposition developed onlapping features over the slide deposits, and layer thickening occurred where areas with greater accommodation space were filled in. Faulted blocks of sediment have clearly been rotated during the slide event and later draped with undisturbed sediment layers. These observations support the conclusion that failure near the present-day northern sidewall of the Storegga Slide did not occur as a single large event but rather multiple events separated by significant time and sediment deposition. According to previous dating of the Naust Formation at the edge of the Vøring Plateau indicates that this older slide event occurred at ~250 ka. These results enhance the current interpretation of the timing of slope failures grouped together as the Storegga Slide complex, adding a considerable amount of time since the last major event at the northernmost boundary (Fig. 5). The large volume of sediment transported during this event implies that the amount of material moved during the 8.2 ka Storegga Slide may be less than previously estimated. Moreover, if large amounts of methane were released into the atmosphere at this locale, the most significant addition of gas would likely have occurred during the ~250 ka event, not at 8.2 ka. The escape of methane during the ~250 ka event, or elsewhere during the 8.2 ka event, remains an open possibility, as suggested by the disappearance of the BSR beneath the slide scar (Berndt et al., 2005; Mienert et al., 1998). Recent measurements from jumbo piston core samples within our study area indicate that pore water sulfate gradients do not correlate well with an 8.2-ka slide (Paull et al., submitted for publication); instead, they suggest that the methane gas on the margin may have been lost at an earlier point in time.

Finally, our images and pressure/temperature modeling show that the BSR would have been too deep at the time of initiation of the ~250 ka event to have intersected the glide plane. The base of the GHSZ, and the gas that may have been present, most likely did not play a strong role in slide initiation or regional slope failure at this locale. Most likely, the retrogressive nature of slope failure in this region indicates a triggering mechanism located in the toe area of the slide (Kvalstad et al., 2005).

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