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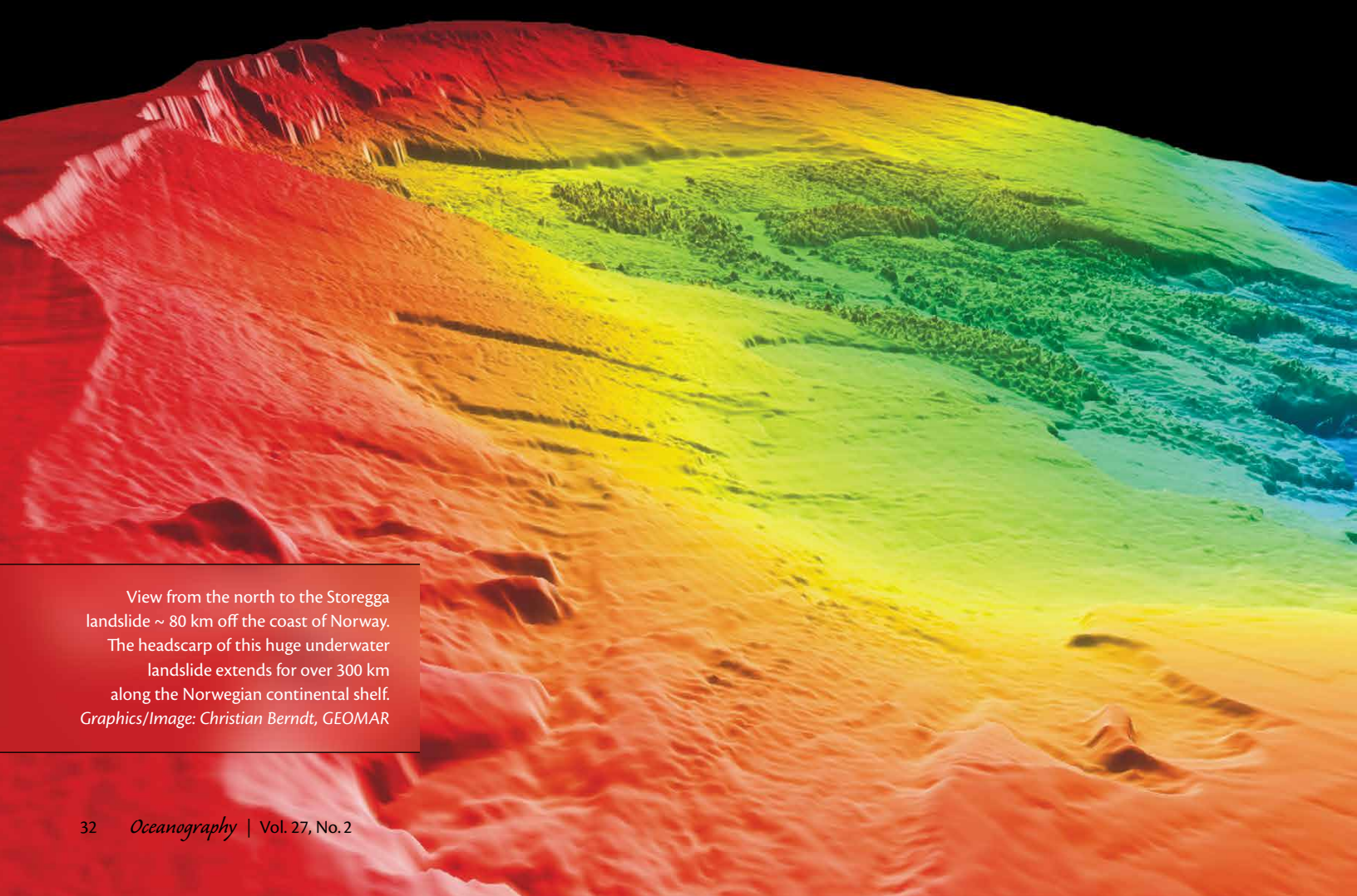
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Large Submarine Landslides on Continental Slopes

Geohazards, Methane Release, and Climate Change

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View from the north to the Storegga landslide ~ 80 km off the coast of Norway. The headscarp of this huge underwater landslide extends for over 300 km along the Norwegian continental shelf. Graphics/Image: Christian Berndt, GEOMAR

Landslide is used as a general term for the results of slope failure. Hampton et al. (1996) and Locat and Lee (2002) provide detailed terminology for slope failures and resulting mass movements.

Open continental slopes are those that lack deeply incised canyons.

Large landslides are defined here as those with volumes $>1 \text{ km}^3$.

ABSTRACT. Submarine landslides on open continental slopes can be prodigious in scale. They are an important process for global sediment fluxes, and can generate very damaging tsunamis. Submarine landslides are far harder to monitor directly than terrestrial landslides, and much greater uncertainty surrounds their preconditioning factors and triggers. Submarine slope failure often occurs on remarkably low ($< 2^\circ$) gradients that are almost always stable on land, indicating that particularly high excess pore pressures must be involved. Earthquakes trigger some large submarine landslides, but not all major earthquakes cause widespread slope failure. The headwalls of many large submarine landslides appear to be located in water depths that are too deep for triggering by gas hydrate dissociation. The available evidence indicates that landslide occurrence is either weakly (or not) linked to changes in sea level or atmospheric methane abundance, or the available dates for open continental slope landslides are too imprecise to tell. Similarly, available evidence does not strongly support a view that landslides play an important role in methane emissions that cause climatic change. However, the largest and best-dated open continental slope landslide (the Storegga Slide) coincides with a major cooling event 8,200 years ago. This association suggests that caution may be needed when stating that there is no link between large open slope landslides and climate change.

INTRODUCTION

Submarine landslides on open continental slopes can be exceptionally large, with volumes that far exceed those of any terrestrial landslide (Table 1). For instance, the Storegga landslide that occurred 8,200 years ago offshore Norway covers an area of seafloor that is larger than Scotland, and it contains over $3,000 \text{ km}^3$ of sediment (Figure 1a; Haflidason et al., 2005). This volume is more than 300 times the annual sediment flux transported to the ocean by all of the world's rivers (Table 1). The headwall of the Storegga landslide,

marking the upper boundary of failed material, is over 300 km long (Figure 1a). The often extreme scale of continental slope landslides may be due to the long continuous slopes found on such margins and to extensive weak horizons in layer-cake stratigraphy (Figure 1c). However, the most remarkable feature of large continental slope landslides is that they often occur on gradients of $< 2^\circ$ (Figure 1d; Hühnerbach et al., 2004). Such low gradients are almost always stable on land.

Following advances in seafloor mapping, large ($> 1 \text{ km}^3$) submarine

landslides have been mapped on continental slopes in numerous locations worldwide (Hühnerbach et al., 2004; Urlaub et al., 2013). Submarine landslides are a threat to seafloor infrastructure used for recovering oil and gas that can be worth many tens of millions of dollars (Barley, 1999). The Ormen Lange gas field, which currently provides $\sim 20\%$ of the United Kingdom's gas supplies, is located directly below the headwall of the Storegga Slide (Figure 1a). Landslides may disintegrate and mix with seawater to form even more mobile sediment flows, called turbidity currents. Turbidity currents can break seafloor telecommunication cables (Piper et al., 1999; Carter et al., 2012), which now carry $> 95\%$ of global data traffic, including the Internet. Tsunamis are most commonly generated by underwater earthquakes, but they can also result from submarine landslides. Debate surrounds the magnitude of landslide tsunamis, but deposits linked to the Storegga Slide record a tsunami that inundated surrounding coasts to heights of 6–20 m (Figure 1b; Bondevik et al., 2005, 2012), and landslide tsunamis have caused loss of life in recent times. A submarine landslide with a volume of $\sim 5 \text{ km}^3$ located offshore Papua New Guinea produced a localized tsunami that killed 2,200 people in 1999 (Tappin et al., 2008).

A fundamental question for geohazard assessment is what causes large continental slope landslides? It is important to distinguish between factors that precondition a slope to fail

and the final triggers. A wide variety of hypotheses have been proposed for how large-scale continental slope failure is preconditioned or triggered. These hypotheses are difficult to test

conclusively because of the infrequent nature of submarine landslides and our current inability to forecast their precise timing or location. This limits our knowledge of slope properties around the time of failure. Monitoring efforts are also hindered by the fact that landslides may destroy or damage local monitoring equipment. Therefore, we have yet to monitor detailed subsurface conditions just before failure, or the resulting landslide motion, for any large continental slope landslide. It is not easy to monitor terrestrial landslides, but there is stark contrast between the quality and number of direct observations available for terrestrial and submarine landslides.

A second key issue for geohazard analysis is the frequency of large continental slope landslides and whether it will change significantly in the future. Very few large continental slope landslides have been dated precisely (Urlaub et al., 2013). The main source of uncertainties in landslide ages is not associated with the dating techniques (such as radiocarbon dating) but rather with the locations of samples used for dating and the effects of sediment mixing by organisms (called bioturbation; see Urlaub et al., 2013). Indeed, only landslides that led to submarine cable breaks in the last century (Piper et al., 1999) or that have recently impacted coastal populations (L'Heureux et al., 2011), as well as the unusually well-studied Storegga landslide and tsunami deposit (Figure 1a,b; Haflidason et al., 2005; Bondevik et al., 2005, 2012), have age uncertainties of less than a few hundred years (Urlaub et al., 2013). It has been proposed that landslide frequency may increase as a result of warming climates and rising sea levels via processes including the melting of gas hydrate (Kennett et al., 2003; Maslin et al., 2004), an ice-like

Table 1. Volumes and frequencies of different types of events. See Talling (2014) for data sources.

Process	Volume	Average Frequency
SUBMARINE LANDSLIDES		
Storegga Slide offshore Norway	> 3,000 km ³	–
15 nonvolcanic slides in last 36,000 years > 100 km ³	> 100 km ³	Less than 2,400 years
1929 Grand Banks landslide-turbidite	~ 175 km ³	–
Volcanic island flank collapses of the western Canary Islands	50–500 km ³	1 per 150,000 years
SEDIMENT FLUXES DURING A SINGLE FLOOD OF INDIVIDUAL RIVER		
Largest floods of single rivers	0.03–0.06 km ³	1–50 years
Jokullhlaup in Iceland, 1996	0.07 km ³	–
AVERAGE ANNUAL RIVER SEDIMENT FLUXES		
Largest annual sediment flux from a single river (Amazon)	0.4 km ³	Annual
Sediment flux from all the rivers in world for a year	~ 6 km ³	
VOLCANIC PROCESSES		
Largest explosive volcanic eruptions (Magnitude > 8; e.g., Toba ~ 74,000 years ago)	> 350 km ³	100,000–800,000 years
Magnitude 6 explosive eruptions (e.g., Krakatau, 1883 CE)	~ 10 km ³	50–100 years
Magnitude 4–5 explosive eruptions (e.g., Mount St. Helens, 1980 CE)	~ 1 km ³	~ 10 years
OTHER PROCESSES		
Snow avalanches	Typically < 0.001 km ³	–
Sediment mobilized on land during a single major earthquake	5–15 km ³	–

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substance containing methane hosted in marine sediment (Maslin et al., 2010), or through changes in crustal loading that may trigger earthquakes and associated landslides (Brothers et al., 2013; Smith et al., 2013).

Finally, it has been suggested that large submarine landslides may play a role in climate change. Changes in levels of atmospheric methane, a strong greenhouse gas, have been attributed to melting of large volumes of marine gas hydrates (Kennett et al., 2003). This has been termed the “clathrate gun hypothesis” to distinguish it from a hypothesis that methane fluxes from wetlands primarily drive atmospheric methane levels (Kennett et al., 2003). It has been proposed that large submarine landslides are a key process for release of methane from the seafloor (Maslin et al., 2004).

This paper begins by evaluating the evidence for how large continental slopes are preconditioned to fail and, finally, triggered. It then outlines information on how landslides move, and the implications for tsunami generation. Key work on past landslide frequency is then summarized in order to help understand the factors that may control past landslide frequency and whether they have been temporally random or non-random. Implications for future landslide frequency are discussed briefly. Finally, we assess whether there is strong evidence that large continental slope landslides play a major role in determining atmospheric methane levels.

CAUSES OF LARGE SUBMARINE LANDSLIDES ON CONTINENTAL SLOPES

A key factor for slope failure in submarine or subaerial settings is excess pore pressure within the sediment that

is above the hydrostatic pore pressure, which acts to support the sediment overburden (Figure 2; Dugan and Sheahan, 2012). A rise in pore pressure leads to lowering of the vertical effective stress in the slope, which in turn undermines

the shear strength in the sediments and the slope stability. If excess pore pressure is supporting all of the overburden, then the slope is at the point of failure (Figure 2). Large continental slope failures often occur on much flatter (< 2°)

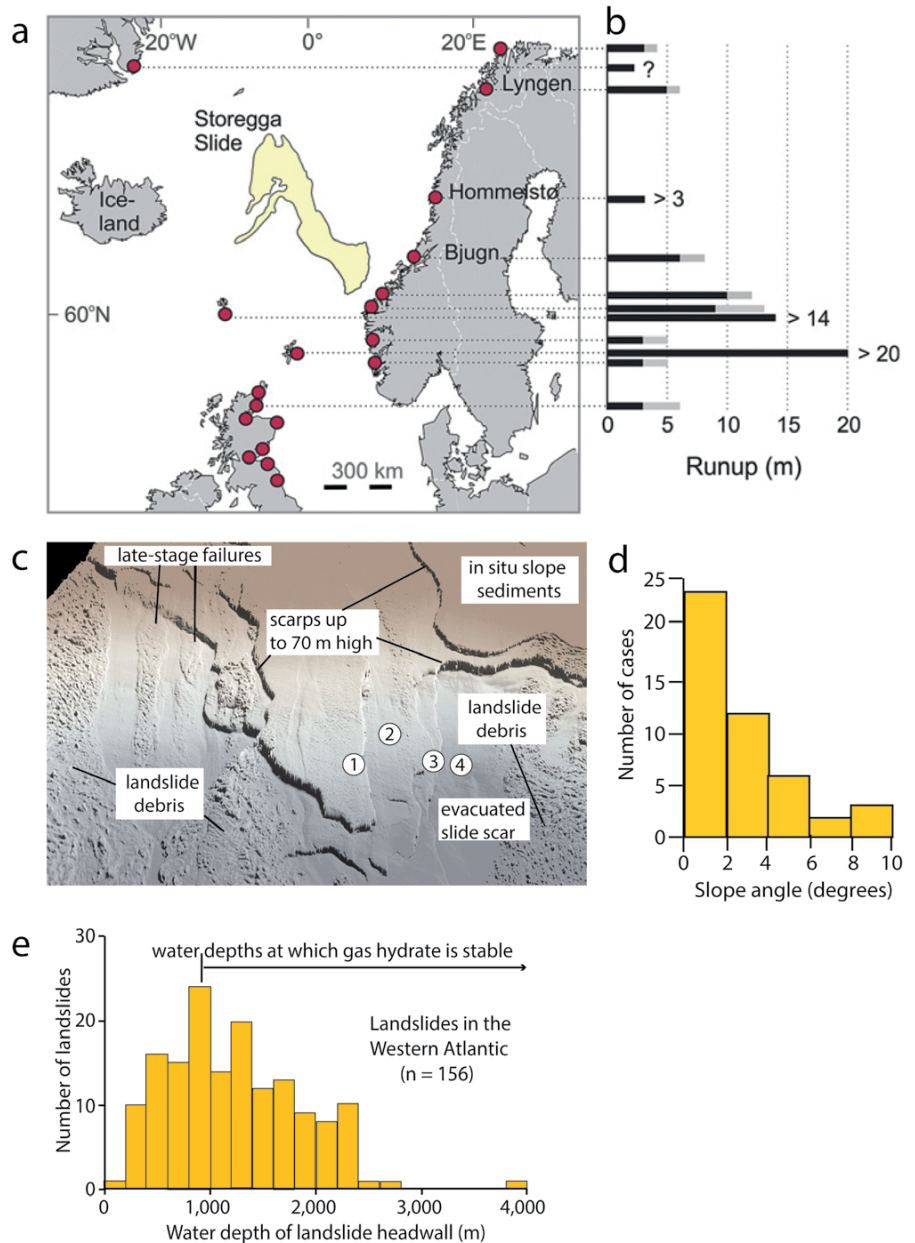


Figure 1. (a, b) Location of the Storegga Slide that comprises > 3,000 km³ of material and covers an area larger than Scotland. The red dots indicate locations of tsunami deposits associated with the Storegga Slide. Tsunami runup heights above sea level are indicated in (b). Black bars indicate minimum runup heights and gray bars maximum runup heights. From Bondevik et al. (2012) (c) Example from offshore Northwest Africa of stair-stepped landslide morphology resulting from failure along multiple weak layers (numbered 1 to 4). From Masson et al. (2010) (d, e) Frequency distributions of seafloor gradients and headwall water depths for large (> 1 km³) submarine landslides. After Hühnerbach et al. (2004)

gradients than terrestrial landslides. Excess pore pressures within submarine slope failures thus must in general support an even greater fraction of the overburden than in terrestrial slope failures.

Pore Pressures Due To Weight of Overlying Seawater

The weight of seawater might be invoked as a cause of submarine slope failure, such that failure is more likely as sea level rises (Smith et al., 2013). However, it is important to differentiate between hydrostatic pore pressure within the sediment and excess pore pressure (Figure 2; Dugan and Sheahan, 2012; Smith et al., 2013). Hydrostatic pressure results from the weight of an overlying water column,

and it acts equally in all directions. Hydrostatic pressure does not support overlying sediment, and changes in hydrostatic pressure alone do not make a slope more likely to fail. Sea level rise that only affects hydrostatic pressures would not cause slope failure. Nevertheless, if the rate of sea level rise is unusually rapid and the sediment has very low permeabilities, transient excess pore pressures could be generated (Smith et al., 2013). It could also be speculated that sea level fall triggers landslides. Low tides have been linked to slope failures in shallow water, in some cases probably due to expansion of gas bubbles within organic-rich sediment (Christian et al., 1997). However, there is no evidence that large landslides

in deeper water are associated with low tides, or indeed with long-term sea level falls (Urlaub et al., 2013).

Excess Pore Pressures Caused by Rapid Sedimentation and Fluid Flow

The most commonly invoked process for generating high excess pore pressures in continental slopes is rapid deposition of low permeability sediment (Dugan and Flemings, 2000; Stigall and Dugan, 2010; Dugan and Sheahan, 2012). Excess pore pressures result when fluid cannot dissipate quickly enough due to low permeability along drainage paths (Dugan and Sheahan, 2012). Rapid and prolonged sedimentation occurs offshore from major river mouths (Flemings et al., 2008) and at the terminations of glacial ice streams (Nygård et al., 2007). Sedimentation rates of up to 30 m per thousand years can be sustained for several thousand years in such settings. Numerical modeling shows that such fast sedimentation rates can result in excess pore pressures that approach the vertical effective stress, bringing low gradient (< 2°) continental slopes close to failure (Dugan and Flemings, 2000; Stigall and Dugan, 2010). This is consistent with direct measurement of excess pore pressures offshore from the Mississippi River delta (Flemings et al., 2008).

However, headwalls of large continental slope failures tend to occur in water depths of 1,000 m to 1,500 m or deeper (Figure 1e; Hühnerbach et al., 2004), much deeper than locations of highest sedimentation rates. It has thus been proposed that fluid is driven along permeable horizons toward the toe of slope due to asymmetric sediment loads that decrease offshore (Figure 3b; Dugan and Flemings, 2000; Masson et al., 2010; Dugan and Sheahan, 2012). This lateral

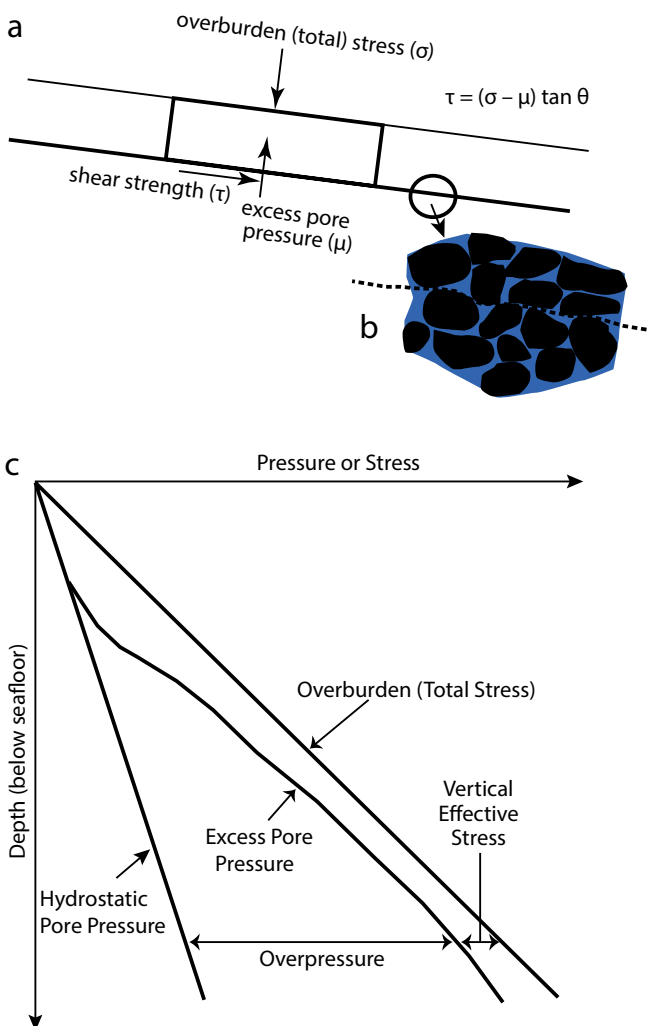


Figure 2. (a) Relationship between overburden (total stress; σ) and excess pore pressure (μ) acting normal to a failure plane, and shear strength (τ) along the failure plane, such that $\tau = (\sigma - \mu) \tan \theta$, where $\tan \theta$ is the friction coefficient. The slope comes closer to failure as the excess pore pressure approaches the overburden (total stress). (b) Schematic illustration of undrained (water-saturated) soil in which grain contacts bear the overburden (total stress). (c) Generalized example of change in overburden (total stress; σ), hydrostatic pore pressure, excess pore pressure (overpressure; μ), and vertical effective stress ($\sigma - \mu$) with depth below the seafloor. In this example, vertical effective stresses are small, such that the slope is close to failure.

fluid flow may produce excess pore pressure where the overburden is thinner in base-of-slope-locations, favoring slope failure in these regions (Dugan and Flemings, 2000). Excess pore pressures may peak within a few thousand years of maximum sedimentation rates, but some large landslides occur long after peak sedimentation (Urlaub et al., 2013). Thus, some uncertainty remains in the relationship between the timing of excess pore pressure generation and subsequent failure.

Failure in Areas of Slow Sedimentation: Loss of Sediment Structure?

Large submarine slope failures can also occur in areas with slow sediment accumulation (< 0.3 meters per thousand years), and the morphology of landslides in areas of slow or rapid sedimentation is similar (Urlaub et al., 2014). This suggests that high excess pore pressures can also develop where sedimentation rates are slow if the sediment is sufficiently impermeable. Urlaub et al. (2014) suggest that loss of structure within sediment layers can lead to rapid compaction during burial in such settings. This “destructuring” of the sediment can generate high excess pore pressures at realistic (50–250 m) depths below the seafloor and bring a continental slope toward failure (Urlaub et al., 2014). Various processes, such as early cementation that is favored by abundant calcareous microfossils or hydrate cements, could create the initial structure within the sediment, which is subsequently lost.

Cyclic Wave Loading

Cyclic wave loading commonly triggers relatively small submarine slope failures in shallow (< 200 m) water, such as those due to hurricanes that impacted

the Mississippi Delta (Bea et al., 1983). However, the headwalls of almost all large slope failures are well below the storm wave base (Figure 1e; Hühnerbach et al., 2004), and wave loading does not trigger these failures.

Earthquakes

It is known that major earthquakes can trigger large submarine landslides. A large (~ 150 km³) landslide offshore from the Grand Banks in 1929 coincided with a magnitude 7.2 earthquake (Piper

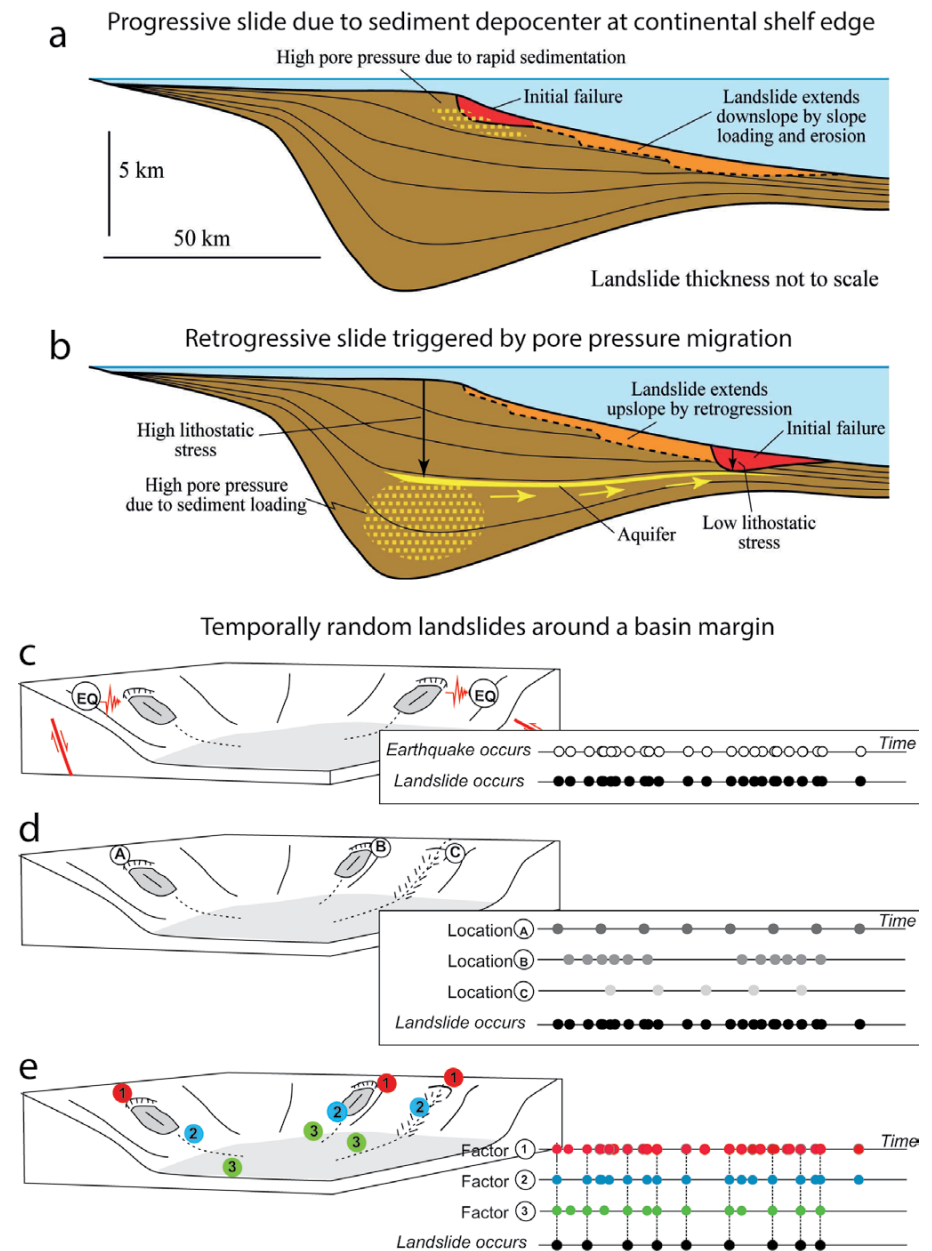


Figure 3. (a, b) Two models for continental slope failure due to rapid accumulation of low permeability sediment that generates high excess pore pressures. (a) A landslide initiates in shallow water where the sedimentation rate is rapid. (b) A landslide originates in deep water due to lateral flow of pore fluid toward the toe of slope, driven by the asymmetric sediment load. This results in retrogressive failure that migrates upslope. After Masson et al. (2010) (c–e) Three models to explain why large submarine landslides around a basin margin are temporally random due to (c) temporally random large earthquakes, (d) different tempos of failure in multiple locations, or (e) multiple factors causing failure at individual locations (e.g., sedimentation rate, earthquake frequency, weak layer development).

et al., 1999). Cable breaks recorded near-synchronous failure of steeper areas that extended over 100 km along the continental slope (Piper et al., 1999). Repeated earthquake shaking can also cause consolidation and strengthening of continental slopes (Locat and Lee, 2002). This may explain why few slope failures occurred near the epicenters of very large (M_w 8–9) earthquakes offshore Sumatra in 2004 and 2005 (Sumner et al., 2013) and offshore Chile in 2010 (Völker et al., 2011). Not all major earthquakes appear to generate large continental slope landslides. This conclusion is

gas hydrates to dissociate (“melt”) and release free gas and water within the sediment. Dissociation of a small amount of gas hydrate ($< \sim 6\%$ volume) can substantially weaken slopes for several reasons (Grozic, 2010). Weakening may occur through the presence of free gas bubbles and sediment volume expansion. The loss of solid hydrate cement may also lead to rapid sediment compaction and generation of excess pore pressures. More speculatively, freshwater generated during dissociation could leach marine clays, leading to quick clay behavior (Bull et al., 2008). The boundary between

stable (Grozic, 2010). It is thus unlikely that gas hydrate dissociation caused these slides (Hühnerbach et al., 2004).

Weak Horizons

There is little correlation between seafloor gradient and occurrence of large failures (Hühnerbach et al., 2004; Masson et al., 2010). However, many large continental submarine landslides have similar morphology in the source region, indicating failure along distinct planes that may have particular low-strength properties (Figure 1c; Masson et al., 2006, 2010; Locat et al., 2014). There are exceptions (Winkelmann et al., 2008), and a single landslide may also follow several basal planes at different stratigraphic levels, leading to a stair-stepped profile (Figure 2; Masson et al., 2010). It could be argued that consistent source-region morphologies indicate common global causes for landslides, or it may be that once failure occurs through various causes, it tends to follow discrete stratigraphic horizons or exploit layers with certain properties.

Identifying and understanding glide planes is key for modeling slope failure (Locat et al., 2014). Studies of a small (0.001 km^3) landslide in shallow ($< 60 \text{ m}$) water at Finneidfjord suggest that failure occurred at a subtle horizon that comprised an interface between fine sand and clay (L’Heureux et al., 2012; Vardy et al., 2012). However, sedimentology of weak horizons is not very well understood, mainly because they are destroyed in areas where landslides have occurred, and it is not known how to identify them before they fail (Masson et al., 2010). The steeper scarps that occur between glide planes indicate locally high slope stability (Figure 1c). These steeper scarps are enigmatic, and their presence suggests dissipation of

“ LARGE CONTINENTAL SLOPE LANDSLIDES HAVE POTENTIAL TO GENERATE VERY DAMAGING AND FAR TRAVELING TSUNAMIS, AS SHOWN BY THE STOREGGA LANDSLIDE AFTERMATH. ”

important because it has been proposed that turbidity currents associated with large landslides may provide a valuable long-term record of major earthquakes (Goldfinger, 2011; also see Atwater and Griggs, 2012) that extends further back in time than terrestrial records. More work is needed, but it appears that the earthquake record derived in this way may sometimes be incomplete.

Gas Hydrates

Methane hydrates form where there is a sufficient supply of gas, water at moderate pressure, and relatively low temperature conditions. Disturbance of the pressure-temperature regime causes

stable and unstable gas hydrate tends to reach the seafloor at water depths of 300–900 m (Mienert et al., 2005). Ocean warming causes migration of the hydrate stability zone into deeper water, while sea level rise tends to stabilize hydrate (Figure 4). Some slides occur in areas with sediment that presently or previously contained gas hydrate (Hornbach et al., 2007), but many large continental landslides occur where there is no evidence of gas hydrate (Urlaub et al., 2013). Importantly, most large continental slope slide headwalls occur in water depths greater than 1,000 m (Figure 1e; Hühnerbach et al., 2004), where gas hydrates are predicted to be

high excess pore pressures needed for initial slope failure. Weak intervals of sediment that are evacuated and flow away from the site of failure may be tens of meters thick in some locations (Bull et al., 2008), and their sedimentology is also poorly constrained.

Modeling shows how local failure may generate cracks that propagate very rapidly over much wider areas in a way similar to the progression of snow slab avalanches (Viesca and Rice, 2012). Lateral propagation can occur even where the overburden (vertical effective stress) is not fully supported by excess pore pressure, such that these parts of the slope were not on the point of failure. Together with the presence of failure-prone stratigraphic layers, such a process may partly explain why the basal glide plane of many open continental slope landslides is so extensive.

LANDSLIDE MOTION AND TSUNAMI HAZARDS

Large continental slope landslides have potential to generate very damaging and far traveling tsunamis, as shown by the Storegga landslide aftermath (Figure 1; Bondevik et al., 2005, 2012). However, it is not yet clear whether all large continental slope landslides generate major tsunamis. For instance, no tsunami deposit has yet been linked to the 900 km³ Traenadjupet Slide, north of the Storegga Slide (Stein Bondevik, University of Tromsø, *pers. comm.*, October 10, 2013). Understanding how these landslides move within the ocean is important, as this controls initial tsunami magnitude. Tsunami generation is especially dependent on (1) landslide volume, whether it is emplaced in one or multiple stages (Hunt et al., 2011); (2) landslide length and thickness; (3) water depth; and

(4) the initial acceleration and resulting speed of the landslide—especially in shallower water (Harbitz et al., 2006). Modeling of tsunami runup heights from the Storegga landslide indicates

slope failure with a duration of much less than an hour, and that the failed mass traveled at speeds of several tens of meters per second (Løvholt et al., 2005). Considerable uncertainty surrounds the

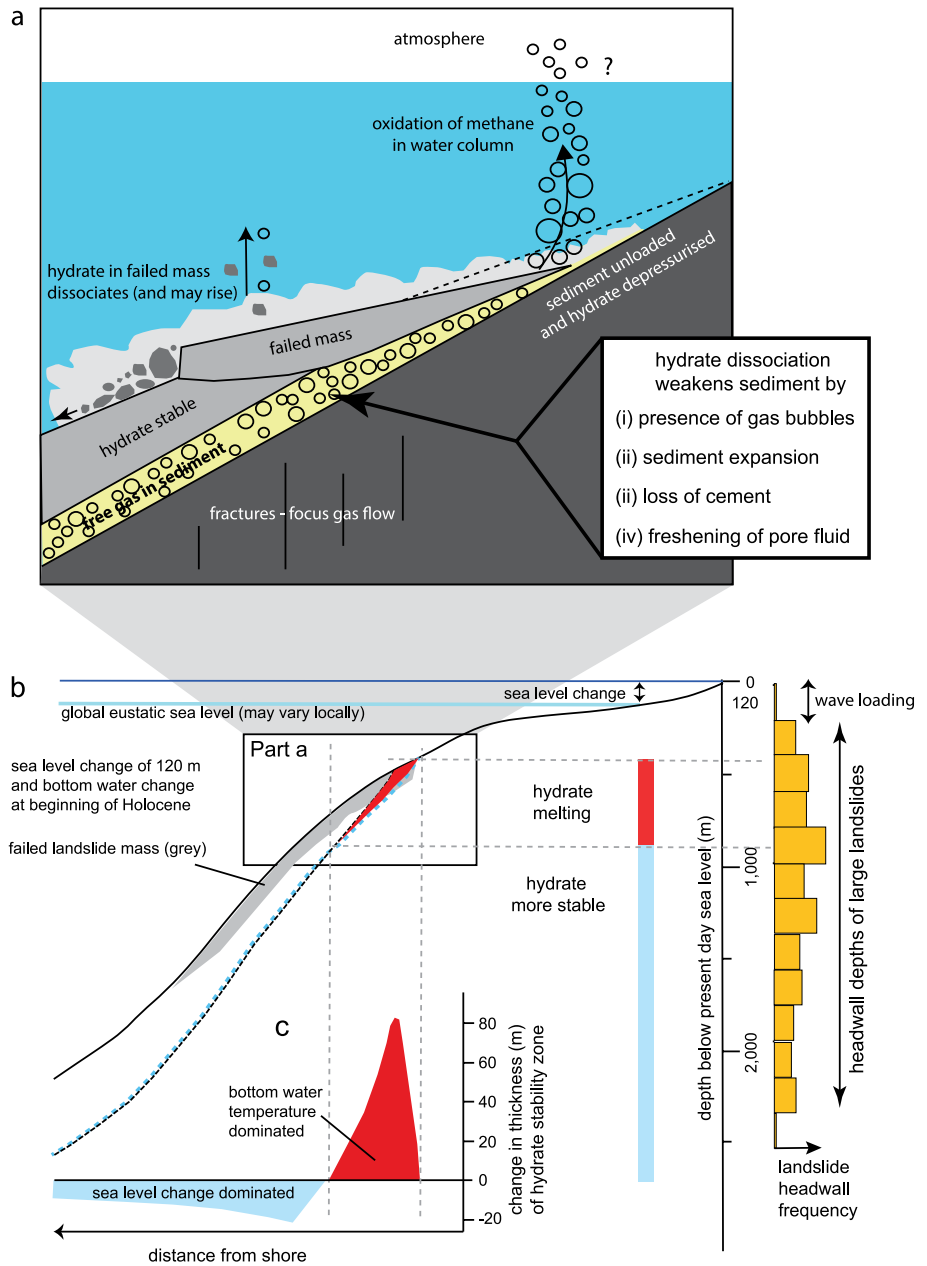


Figure 4. (a) Summary of previously inferred gas hydrate melting processes that may cause submarine landslides or cause methane emissions. (b) Continental slope profile showing variation in the gas hydrate stability zone that may cause realistic changes in bottom water temperature and sea level since the last glacial period (modified from Mienert et al., 2005). The range of water depths is shown in which gas hydrate melts (red) due to ocean warming or becomes more stable (blue) due to sea level rise. On the right is a plot of water depths for headwalls (orange histogram) of large landslides in the Western Atlantic showing water depths below which large landslides have occurred (from Hühnerbach et al., 2004).

motion of large underwater landslides due to a paucity of direct measurements (e.g., Piper et al., 1999).

A widely held view is that continental slope landslides are retrogressive, with failure propagating upslope (Locat and

Lee, 2002; Masson et al., 2006, 2010). Tongues of debris that drape across scarps between glide planes are strong evidence of such retrogressive failure, as they postdate evacuation of the underlying glide planes (Figure 1c). However, it is possible that most of the landslide mass was evacuated over a short period of time, followed by minor late-stage debris flows with small volumes. Snow slab avalanches show how fractures may initiate at the top or middle of slopes and expand rapidly down slope (Viesca and Rice, 2012). Failure of seafloor sediment can also migrate down slope when it is triggered by emplacement of volcanic island collapses, such as the El Golfo collapse that triggered the Canary debris flow (Masson et al., 2006). The existence of so-called frontally confined landslide deposits, which appear not to evacuate their source regions but rather to preserve deformed sediment bodies in situ, provide further evidence that some failures may originate near the heads, rather than the toes, of their source regions, with the driving force acting progressively, in a downslope direction. We thus take a cautious view of whether field evidence indicates that large open continental landslides are always retrogressive.

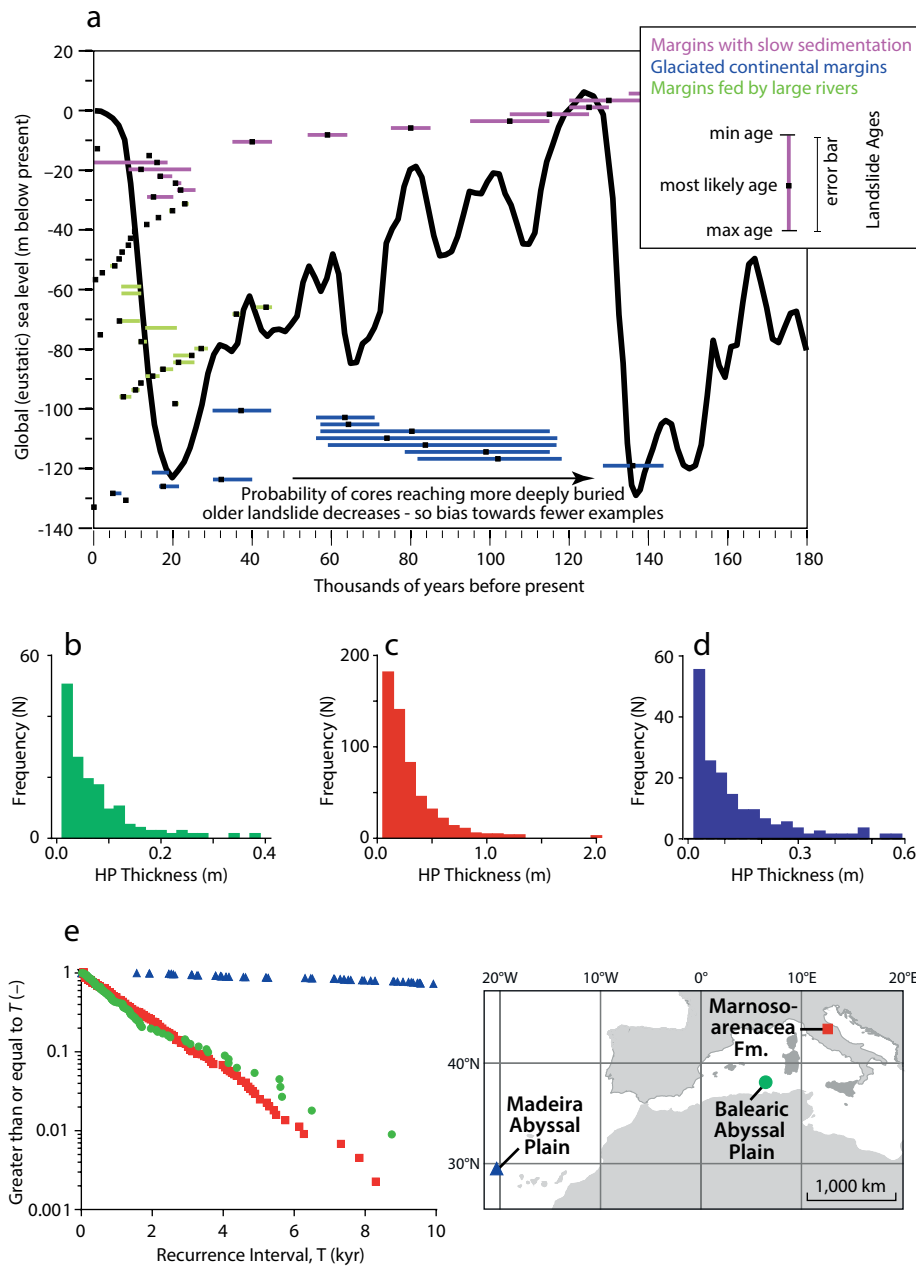


Figure 5. Recent insights in large submarine timing and frequency distribution of recurrence intervals. (a) Ages of large (> 1 km³) submarine landslides plotted against global (eustatic) sea level over the last 180,000 years. Maximum and minimum landslide ages are shown, together with the most likely actual ages. Landslides are colored according to the types of settings in which they occur. From *Urlaub et al. (2013)* (b–d) Histograms showing the frequency distribution of turbidite recurrence intervals measured by the thickness of hemipelagic mud (HP) between each turbidite unit in the (b) Balearic Abyssal Plain, (c) Marnoso-arenacea Formation, and (d) Madeira Abyssal Plain, which are inferred to be landslide triggered. (e) Plot showing cumulative frequency distribution of turbidite recurrence intervals (T) for the same data as in b–d. A straight line on such a log-linear plot indicates the landslides are approximately temporally random (Poissonian). The inset map shows the locations of these three data sets. *Parts b–e from Clare et al. (2014a)*

Locations in b to e
 ● Balearic Abyssal Plain
 ■ Marnoso-arenacea
 ▲ Madeira Abyssal Plain

2009). This proposal has been used to support a link between landslides and gas hydrate dissociation (Maslin et al., 2004) or increased seismicity due to flooding of continental shelves (Brothers et al., 2013). However, once realistic error bars for the available landslide ages are included in such an analysis (Figure 5a), either there is no strong correlation between landslide frequency and sea level or the available landslide dates are too imprecise to tell (Figure 5a; Urlaub et al., in press). There is also uncertainty whether landslide frequency covaries with atmospheric methane abundance (Maslin et al., 2010).

Clare et al. (2014a) used turbidity current deposits most likely generated by disintegration of large submarine landslides to analyze landslide frequency. The recurrence intervals for landslide turbidites exhibited temporally random (Poisson) distribution for three different deepwater basin plains (Figure 5e; Clare et al., 2014a). This suggests that the probability of a future landslide does not depend on the time since the last landslide, which would be inconsistent with a strong control from a single global factor such as eustatic (global) sea level change. It also appears that processes that covary strongly with eustatic sea level and climate cycles are not dominant single controls on landslide timing, such as hydrate dissociation driven by ocean warming (Clare et al., 2014a). Earthquakes may be an important cause of landslides, as large magnitude earthquakes have a roughly temporally random reoccurrence interval distribution (Clare et al., 2014a), although not all major earthquakes trigger large landslides (Völker et al., 2011; Sumner et al., 2013). Alternatively, large submarine landslides may be caused by yet unknown temporally random processes, by many disparate processes

acting locally along a basin margin, or by a series of processes that occur one after another at a single location (Figure 3c; Clare et al., 2014a).

Here, we propose a model for submarine landslide occurrence where some (but not all) areas of continental slope develop high excess pore pressures through a variety of processes, including rapid sedimentation and lateral fluid flow (Figure 3a,b; Dugan and Flemings, 2000) or destructuring in areas of slow sedimentation (Urlaub et al., 2014). These areas of continental slope are perched on the edge of failure where, for example, large earthquakes can trigger landslides (Figure 3c), resulting in temporally random recurrence intervals.

ROLE OF LANDSLIDES IN METHANE RELEASE AND CLIMATE CHANGE

We now assess evidence that large submarine landslides have played a significant role in methane emissions and climatic change. Some large landslides are associated with hydrate-rich sediment (Hornbach et al., 2007), but many large submarine landslides occur in water depths where gas hydrates are stable (Figure 1e; Hühnerbach et al., 2004), suggesting that many landslides are not triggered by hydrate dissociation. The occurrence of landslides may thus not indicate widespread hydrate dissociation, although it does not preclude the release of methane from seafloor sediment through other processes.

Large Submarine Landslide Frequency During Past Abrupt Climate Change Events

Compilations of global landslide ages during the last 30,000 years show no clear correlation between landslide frequency and global climate change

or atmospheric methane abundance in ice core records (Urlaub et al., 2013). However, this is not conclusive evidence against such links, due to the large error bars on most landslide ages (Figure 5a; Urlaub et al., 2013). It may be that these dating uncertainties mask such a relationship. The temporally random nature of landslide-triggered turbidity currents in three disparate deepwater basin plains (Figure 5e; Clare et al., 2014a) also suggests that landslide frequency is not linked strongly to climate cycles because climate cycles are non-random.

The Paleocene Eocene Thermal Maximum (PETM) is a well known example of very abrupt global warming and carbon release into the atmosphere ~ 55 million years ago, which has been attributed to dissociation of gas hydrates in marine sediments (Dickens et al., 1997; Kennett et al., 2003). Katz et al. (1999) concluded that landslide frequency increased during the PETM; however, the landslides that these authors studied are poorly dated, and they come from a single area in the Atlantic Ocean (Blake Plateau). A better-dated landslide-turbidite sequence that spans the PETM at Zumaia in northern Spain suggests that landslides and turbidity currents were actually much less frequent during the PETM (Clare et al., 2014b).

Carbon Isotope Excursions Associated with Individual Large Landslides

In the water column, dissolved methane that originates from gas hydrate dissociation has a strongly negative value of $\delta^{13}\text{C}$. Following consumption by bacterial metabolism, this anomaly can generate a negative $\delta^{13}\text{C}$ spike in benthic foraminifera shells (Bock et al.,

2012). It has thus been proposed that negative $\delta^{13}\text{C}$ excursions in benthic foraminifera may be a record of methane emissions from large landslides (Kennett et al., 2003; Maslin et al., 2004). This view has been contested, as negative $\delta^{13}\text{C}$ excursions might also result from diagenetic processes (Torres et al., 2003), so their significance is uncertain and

sources that have δD_{CH_4} values of ~ -290 (Sowers, 2006; Bock et al., 2012). If methane hydrates in seafloor sediments were a dominant source of atmospheric methane, a less negative value of δD_{CH_4} would be expected during such climate events. Analysis of ice cores shows that this is not the case, suggesting that the main drivers of atmospheric methane

result of climate change. However, there is a striking correlation between the best-dated large submarine landslide and the last major episode of abrupt climate change (Dawson et al., 2011; Bondevik et al., 2012; Smith et al., 2013).

The Storegga landslide and associated tsunami coincided with the coldest part of the 8.2 ka climate event (Figure 6; Dawson et al., 2011; Bondevik et al., 2012) during which temperatures fell by up to 6°C . The Storegga landslide is dated to within ~ 150 years (Bondevik et al., 2012) and could be associated with a rise in atmospheric methane abundance at the end of the 8.2 ka event (Figure 6a). However, methane emissions originally decreased in the 8.2 ka event, suggesting that the Storegga landslide could not have caused the climatic event (Bondevik et al., 2012).

It has been proposed that rapid sea level rise around the northern UK at ~ 8.2 ka triggered the Storegga landslide by loading the shelf and causing increased seismicity or increased excess pore pressures in sufficiently impermeable sediment (Figure 6; Smith et al., 2013). However, due to complex spatial and temporal variation in local sea level curves as a result of glacial rebound, it is not yet clear whether rapid sea level rise occurred in the source area of the Storegga landslide. There is evidence that the final trigger of the landslide was an earthquake that produced regionally extensive slope failures and turbidity currents (Bøe et al., 2004; Kvalstad et al., 2005). However, other factors such as rapid sedimentation were shown to have preconditioned the slope to failure (Figure 3a; Kvalstad et al., 2005). Further work is needed to determine if exceptionally rapid sea level rise can potentially increase excess pore pressures (Smith et al., 2013).

“ SUBMARINE LANDSLIDES ARE FAR HARDER TO MONITOR DIRECTLY THAN TERRESTRIAL LANDSLIDES, AND MUCH GREATER UNCERTAINTY SURROUNDS THEIR PRECONDITIONING FACTORS AND TRIGGERS. ”

complementary proxies are needed (Zeebe, 2007). Excursions in $\delta^{13}\text{C}$ values in benthic foraminifera are coeval with large landslides on the Amazon fan (Maslin et al., 2004) and in the Western Mediterranean (Panieri et al., 2012). However, other large landslides do not appear to be linked to an excursion in benthic $\delta^{13}\text{C}$ values. For instance, there is no $\delta^{13}\text{C}$ excursion associated with the huge Storegga landslide. Overall, there is no unambiguous evidence from marine $\delta^{13}\text{C}$ excursions that large submarine landslides are commonly linked to methane emissions from gas hydrates.

Deuterium Isotope Signal in Ice Core Records (Atmospheric Methane)

Methane hydrates have a deuterium isotopic signature (δD_{CH_4}) of -190 that distinguishes them from other methane

levels are emissions from other sources, such as wetlands (Sowers, 2006). This is perhaps the strongest line of evidence that increased landslide frequency due to dissociation of marine gas hydrates is not a major driver of climatic change. However, it is possible that although other processes drive atmospheric methane abundances, marine gas hydrates may respond to the resulting climatic changes, thus increasing atmospheric methane levels (Maslin et al., 2010).

Storegga Landslide and the 8.2 ka Climate Event


The preceding lines of evidence do not provide strong support for the hypothesis that landslides are linked strongly to climatic change, either as the driver of climate change through methane emissions (Kennett et al., 2003; Maslin et al., 2004) or as a more frequent

CONCLUDING REMARKS

Understanding huge open continental slope landslides remains a challenge for Earth science. Considerable fortune will be needed to monitor a continental slope immediately before large-scale failure and to recover data from intact instruments because it is hard to predict the timing of the infrequent failures, and they will tend to damage instruments. However, there have been major recent advances in monitoring pore pressures and other key parameters that affect slope stability (Flemings et al., 2008). Further in situ monitoring is needed to understand where very high excess pore pressures occur in other types of settings. For instance, can high excess pore pressures develop in areas of slow sedimentation and, if so, how? Recent work at Finneidfjord in Norway characterizes weak layers in which failure occurs (L'Heureux et al., 2012; Vardy et al., 2012). Similar studies of glide planes are needed for larger-scale and deeper-water slope failures, which will necessitate deeper ($\gg 50$ m) drilling below the seafloor. Cable breaks continue to provide valuable insights into the causes of landslides (Piper et al., 1999), together with seafloor surveys to determine where slope failure does (or does not) occur after major earthquakes (Völker et al., 2011; Sumner et al., 2013). Insights into the source of atmospheric methane from deuterium isotopes within ice cores provide the most unambiguous evidence against landslides (or indeed gas hydrates in marine sediments more generally) being a cause of climate change (Sowers, 2006). However, ice core records may smooth abrupt spikes in methane emissions (Bock et al., 2012), and further work is needed to compare large landslide timing to high-resolution ice core data

sets. The age of the Storegga landslide hints at a link between landslides and major climatic events or rapid sea level rise (Dawson et al., 2011; Bondevik et al., 2012; Smith et al., 2013). Dating of a greater number of landslides may uncover consistent associations between climate change and landslides, but such additional dates will need to be similarly precise (Urlaub et al., 2013).

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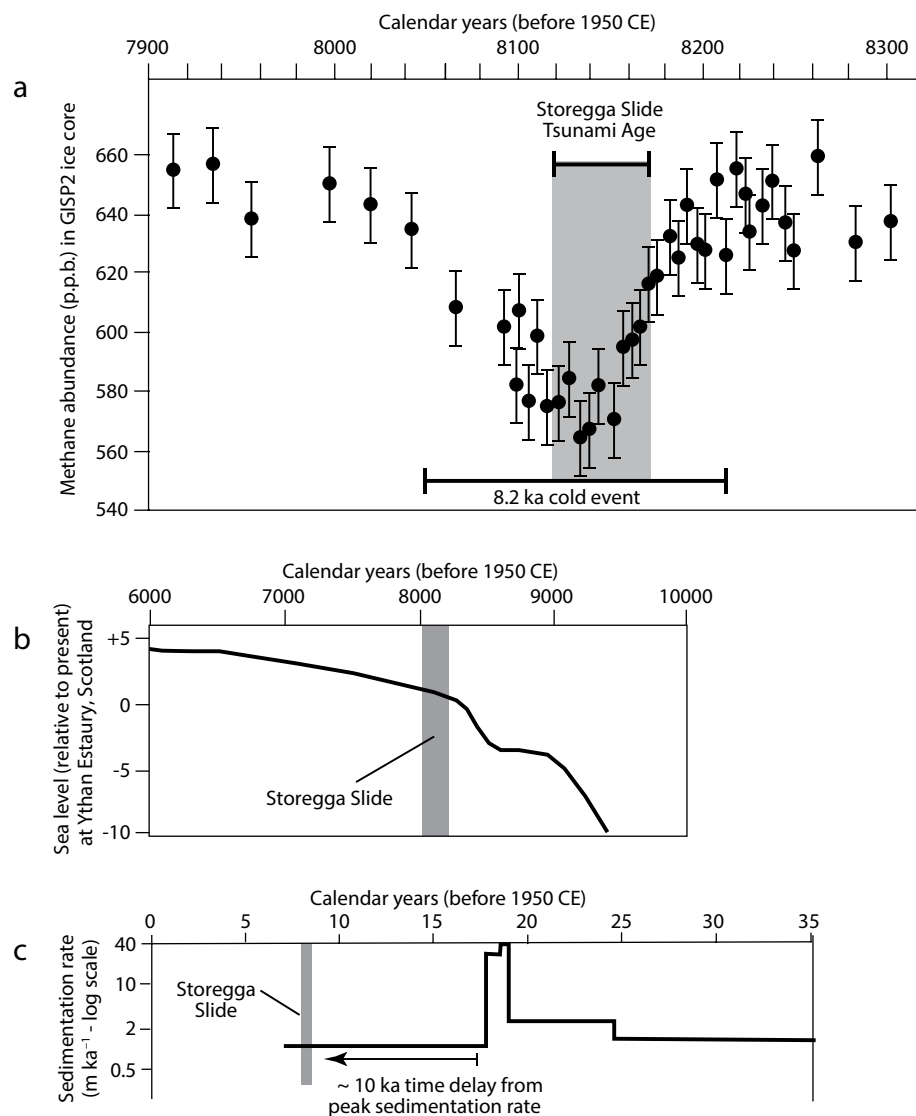


Figure 6. (a) Changes of atmospheric methane abundance during the 8.2 ka (ka = thousand years ago) cold event from the Greenland Ice Sheet Project (GISP) 2 ice core, and the best estimate of the age of the Storegga landslide. After Bondevik et al. (2012) (b) Changes in sea level at the Ythan Estuary in Scotland and the age of the Storegga landslide. From Smith et al. (2013) (c) Variations in sedimentation rate on the Norwegian shelf and the age of the Storegga landslide. After Urlaub et al. (2013)

REFERENCES

- Atwater, B.F., and G.B. Griggs. 2012. *Deep-Sea Turbidites as Guides to Holocene Earthquake history at the Cascadia Subduction Zone: Alternative Views for a Seismic-Hazard Workshop*. US Geological Survey Open-File Report, 2012-1043, 58 pp., <http://pubs.usgs.gov/of/2012/1043>.
- Barley, B. 1999. Deepwater problems around the world. *Leading Edge* 18:488–494, <http://dx.doi.org/10.1190/1.1438319>.
- Bea, R.G., S.G. Wright, P. Sircar, and A.W. Nidoroda. 1983. Wave-induced slides in South Pass Block 70, Mississippi Delta. *Journal of Geotechnical Engineering* 109:619–644, [http://dx.doi.org/10.1061/\(ASCE\)0733-9410\(1983\)109:4\(619\)](http://dx.doi.org/10.1061/(ASCE)0733-9410(1983)109:4(619)).
- Bock, J., P. Martinerie, E. Witrant, and J. Chappellaz. 2012. Atmospheric impacts and ice core imprints of a methane pulse from clathrates. *Earth and Planetary Science Letters* 349:98–108, <http://dx.doi.org/10.1016/j.epsl.2012.06.052>.
- Bøe, R., O. Longva, A. Lepland, L.H. Blikra, E. Sonstegaard, H. Haflidarson, P. Bryn, and R. Lien. 2004. Postglacial mass movements and their causes in fjords and lakes in western Norway. *Norwegian Journal of Geology* 84:35–55.
- Bondevik, S., F. Løvholt, C.B. Harbitz, J. Mengerud, A. Dawson, and J.L. Svendsen. 2005. The Storegga Slide tsunami—Comparing field observations with numerical simulations. *Marine and Petroleum Geology* 22:195–208, <http://dx.doi.org/10.1016/j.marpetgeo.2004.10.003>.
- Bondevik, S., S.K. Stormo, and G. Skjerdal. 2012. Green mosses date the Storegga tsunami to the chilliest decades of the 8.2 ka cold event. *Quaternary Science Reviews* 45:1–6, <http://dx.doi.org/10.1016/j.quascirev.2012.04.020>.
- Brothers, D.S., K.M. Luttrell, and J.D. Chaytor. 2013. Sea-level-induced seismicity and submarine landslide occurrence. *Geology* 41:979–982, <http://dx.doi.org/10.1130/G34410.1>.
- Bull, S., J. Cartwright, and M. Huuse. 2008. A subsurface evacuation model for submarine slope failure. *Basin Research* 21:433–443, <http://dx.doi.org/10.1111/j.1365-2117.2008.00390.x>.
- Carter, L., J. Milliman, P.J. Talling, R. Gavey, and R.B. Wynn. 2012. Near-synchronous and delayed initiation of long run-out submarine sediment flows from a record-breaking river flood, offshore Taiwan. *Geophysical Research Letters* 39, L12603, <http://dx.doi.org/10.1029/2012GL051172>.
- Clare, M.A., P.J. Talling, P. Challenor, G. Malgesini, and J.E. Hunt. 2014a. Distal turbidite records reveal a common distribution for large (> 0.1 km³) submarine landslide recurrence. *Geology* 42:263–266, <http://dx.doi.org/10.1130/G35160.1>.
- Clare, M.A., P.J. Talling, and J.E., Hunt. 2014b. What are the implications of rapid global warming for landslide-triggered turbidity current activity? *Geophysical Research Abstracts* 16, EGU2014-11579. Available at: <http://meetingorganizer.copernicus.org/EGU2014/EGU2014-11579.pdf>.
- Christian, H.A., D.J. Woeller, P.K. Robertson, and R.C. Courtney. 1997. Site investigations to evaluate flow liquefaction slides at Sand Heads, Fraser River delta. *Canadian Geotechnical Journal* 34:384–397, <http://dx.doi.org/10.1139/t97-004>.
- Dawson, A., S. Bondevik, and J.T. Teller. 2011. Relative timing of the Storegga submarine slide, methane release, and climate change during the 8.2 ka cold event. *The Holocene* 21:1,167–1,171, <http://dx.doi.org/10.1177/0959683611400467>.
- Dickens, G.R., M.M. Castillo, and J.C.G. Walker. 1997. A blast of gas in the latest Paleocene: Simulating first-order effects of massive dissociation of oceanic methane hydrate. *Geology* 25:259–262, [http://dx.doi.org/10.1130/0091-7613\(1997\)025<0259:ABOGIT>2.3.CO;2](http://dx.doi.org/10.1130/0091-7613(1997)025<0259:ABOGIT>2.3.CO;2).
- Dugan, B., and P.B. Flemings. 2000. Overpressure and fluid flow in the New Jersey continental slope: Implications for slope failure and cold seeps. *Science* 289:288–291, <http://dx.doi.org/10.1126/science.289.5477.288>.
- Dugan, B., and T.C. Sheahan. 2012. Offshore sediment overpressures of passive margins: Mechanisms, measurement, and models. *Reviews of Geophysics* 50, RG3001, <http://dx.doi.org/10.1029/2011RG000379>.
- Flemings, P.B., H. Long, B. Dugan, J.T. Germaine, C.M. John, J.H. Behrmann, D.E. Sawyer, and IODP Expedition 308 Scientists. 2008. Pore pressure penetrometers document high overpressure near the seafloor where multiple submarine landslides have occurred on the continental slope, offshore Louisiana, Gulf of Mexico. *Earth and Planetary Science Letters* 274:269–283, <http://dx.doi.org/10.1016/j.epsl.2007.12.005>.
- Goldfinger, C. 2011. Submarine paleoseismology based on turbidite records. *Annual Review of Marine Science* 3:35–66, <http://dx.doi.org/10.1146/annurev-marine-120709-142852>.
- Grozić, J.L.H. 2010. Interplay between gas hydrates and submarine slope failure. Pp. 11–30 in *Submarine Mass Movements and Their Consequences*. D.C. Mosher, R.C. Shipp, L. Moscardelli, J.D. Chaytor, C.D.P. Baxter, H.J. Lee, R. Urgeles, eds, Advances in Natural and Technological Hazard Research, vol. 28, Springer, Dordrecht, The Netherlands.
- Haflidarson, H., R. Lien, H.P. Sejrup, C.G. Forsberg, and P. Bryn. 2005. The dating and morphometry of the Storegga Slide. *Marine and Petroleum Geology* 22:123–136, <http://dx.doi.org/10.1016/j.marpetgeo.2004.10.008>.
- Hampton, M.A., H.J. Lee, and J. Locat. 1996. Submarine landslides. *Reviews of Geophysics* 34:33–59, <http://dx.doi.org/10.1029/95RG03287>.
- Harbitz, C.B., F. Løvholt, G. Pedersen, and D.G. Masson. 2006. Mechanisms of tsunami generation by submarine landslides: A short review. *Norwegian Journal of Geology* 86:255–264.
- Hornbach, M.J., L.L. Lavier, and C.D. Ruppel. 2007. Triggering mechanism and tsunamogenic potential of the Cape Fear Slide complex, US Atlantic margin. *Geochemistry, Geophysics, Geosystems* 8, Q12008, <http://dx.doi.org/10.1029/2007GC001722>.
- Hühnerbach, V., D.G. Masson, and COSTA Project Partners. 2004. Landslides in the north Atlantic and its adjacent seas: An analysis of their morphology, setting and behaviour. *Marine Geology* 213:343–362, <http://dx.doi.org/10.1016/j.margeo.2004.10.013>.
- Hunt, J.E., R.B. Wynn, D.G. Masson, P.J. Talling, and D.A. Teagle. 2011. Sedimentological and geochemical evidence for multistage failure of volcanic island landslides: A case study from Icod landslide on north Tenerife, Canary Islands. *Geochemistry, Geophysics, Geosystems* 12, Q12007, <http://dx.doi.org/10.1029/2011GC003740>.
- Katz, M.E., D.K. Pak, G.R. Dickens, and K.G. Miller. 1999. The source and fate of massive carbon input during the Palaeocene Eocene Thermal maximum. *Science* 286:1,531–1,533, <http://dx.doi.org/10.1126/science.286.5444.1531>.
- Kennett, J., K.G. Cannariato, I.L. Hendy, and R.J. Behl. 2003. *Methane Hydrates in Quaternary Climate Change: The Clathrate Gun Hypothesis*. American Geophysical Union, Washington, DC, 216 pp.
- Kvalstad, T.J., L. Andresen, C.F. Forsberg, K. Berg, P. Bryn, and M. Wangen. 2005. The Storegga Slide: Evaluation of triggering mechanics. *Marine and Petroleum Geology* 22:245–256, <http://dx.doi.org/10.1016/j.marpetgeo.2004.10.019>.
- L'Heureux, J.-S., S. Glimsdal, O. Longva, L. Hansen, and C.B. Harbitz. 2011. The 1888 shoreline landslide and tsunami in Trondheimsfjorden, central Norway. *Marine Geophysical Research* 32:313–329, <http://dx.doi.org/10.1007/s11001-010-9103-z>.
- L'Heureux, J.S., O. Longva, A. Steiner, L. Hansen, M.E. Vardy, M. Vanneste, H. Haflidarson, J. Brendryen, T.J. Kvalstad, C.F. Forsberg, and others. 2012. Identification of weak layers and their role for the stability of slopes at Finneidfjord, northern Norway. Pp. 321–330 in *Submarine Mass Movements and Their Consequences*. Y. Yamada, K. Ikehara, Y. Ogawa, R. Urgeles, D. Mosher, J. Chaytor, M. Strasser, eds, Advances in Natural and Technological Hazards Research, vol. 29, Springer, Dordrecht, The Netherlands.
- Lee, H.J. 2009. Timing of occurrence of large submarine landslides on the Atlantic Ocean margin. *Marine Geology* 264: 53–64, <http://dx.doi.org/10.1016/j.margeo.2008.09.009>.

- Locat, J., and H.J. Lee. 2002. Submarine landslides: Advances and challenges. *Canadian Geotechnical Journal* 39:193–212, <http://dx.doi.org/10.1139/t01-089>.
- Locat, J., S. Leroueil, A. Locat, and H.J. Lee. 2014. Weak layers: Their definition and classification from a geotechnical perspective. Pp. 3–21 in *Submarine Mass Movements and Their Consequences*. S. Krastel, J.-H. Behrmann, D. Völker, M. Stipp, C. Berndt, R. Urgeles, J. Chaytor, K. Huhn, M. Strasser, and C.B. Harbitz, eds, *Advances in Natural Hazard Research*, vol. 37, Springer, Dordrecht, The Netherlands.
- Løvholt, F., C.B. Harbitz, and K. Braaten-Haugen. 2005. A parametric study of tsunamis generated by submarine slides in the Ormen Lange/Storegga area off western Norway. *Marine and Petroleum Geology* 22:219–231, <http://dx.doi.org/10.1016/j.marpetgeo.2004.10.017>.
- Maslin, M., M. Owen, S. Day, and D. Long. 2004. Linking continental-slope failures and climate change: Testing the clathrate gun hypothesis. *Geology* 32:53–56, <http://dx.doi.org/10.1130/G20114.1>.
- Maslin, M., M. Owen, R. Betts, S. Day, T. Dunkley Jones. 2010. Gas hydrates: Past and future geohazard? *Philosophical Transactions of the Royal Society A* 368:2,369–2,393, <http://dx.doi.org/10.1098/rsta.2010.0065>.
- Masson, D.G., C.B. Harbitz, R.B. Wynn, G. Pedersen, and F. Løvholt. 2006. Submarine landslides: Processes, triggers and hazard prediction. *Philosophical Transactions of the Royal Society London* 364:2,009–2,039, <http://dx.doi.org/10.1098/rsta.2006.1810>.
- Masson, D.G., R.B. Wynn, and P.J. Talling. 2010. Large landslides on passive continental margins: Processes, hypotheses and outstanding questions. Pp. 153–165 in *Submarine Mass Movements and Their Consequences*. D.C. Mosher, R.C. Shipp, L. Moscardelli, J.D. Chaytor, C.D.P. Baxter, H.J. Lee, and R. Urgeles, eds, *Advances in Natural and Technological Hazard Research*, vol. 28, Springer, Dordrecht, The Netherlands.
- Mienert, J., M. Vanneste, S. Bünz, K. Andreassen, H. Hafidason, H.P. Sejrup. 2005. Ocean warming and gas hydrate stability on the mid-Norwegian margin at the Storegga Slide. *Marine and Petroleum Geology* 22:233–244, <http://dx.doi.org/10.1016/j.marpetgeo.2004.10.018>.
- Nygård, A., H.P. Sejrup, H. Hafidason, W.A.H. Lekens, C.D. Clark, and G.R. Bigg. 2007. Extreme sediment and ice discharge from marine-based ice streams: New evidence from the North Sea. *Geology* 35:395–398, <http://dx.doi.org/10.1130/G23364A.1>.
- Owen, M., S. Day, and M. Maslin. 2007. Late Pleistocene submarine mass movements: Occurrence and causes. *Quaternary Science Reviews* 26:958–978, <http://dx.doi.org/10.1016/j.quascirev.2006.12.011>.
- Panieri, G., A. Camerlenghi, I. Cacho, C. Sanchez Cervera, M. Canals, S. Lafeurza, and G. Herrera. 2012. Tracing seafloor methane emissions with benthic foraminifera: Results from the Ana submarine landslide (Eivissa Channel, Western Mediterranean Sea). *Marine Geology* 291–294:97–112, <http://dx.doi.org/10.1016/j.margeo.2011.11.005>.
- Piper, D.J.W., P. Cochonat, and M. Morrison. 1999. The sequence of events around the epicentre of the 1929 Grand Banks earthquake: Initiation of debris flows and turbidity currents inferred from sidescan sonar. *Sedimentology* 46:79–97, <http://dx.doi.org/10.1046/j.1365-3091.1999.00204.x>.
- Smith, D.E., S. Harrison, and T. Jordan. 2013. Sea-level rise and submarine mass failures on open continental margins. *Quaternary Science Reviews* 82:93–103, <http://dx.doi.org/10.1016/j.quascirev.2013.10.012>.
- Stigall, J., and B. Dugan. 2010. Overpressure and earthquake initiated slope failure in the Ursa region, northern Gulf of Mexico. *Journal of Geophysical Research* 115, B04101, <http://dx.doi.org/10.1029/2009JB006848>.
- Sowers, T. 2006. Late quaternary atmospheric CH₄ isotope record suggests marine clathrates are stable. *Science* 311:838–840, <http://dx.doi.org/10.1126/science.1121235>.
- Sumner, E.J., M.I. Siti, L.C. McNeill, P.J. Talling, T.J. Henstock, R.B. Wynn, Y.S. Djajidihardja, and H. Permana. 2013. Can turbidites be used to reconstruct a paleoearthquake record for the central Sumatran margin? *Geology* 41:763–766, <http://dx.doi.org/10.1130/G34298.1>.
- Talling, P.J. In press. On the triggers, resulting flow types and frequencies of subaqueous sediment density flows in different settings. *Marine Geology*, <http://dx.doi.org/10.1016/j.margeo.2014.02.006>.
- Tappin, D.R., P. Watts, and S.T. Grilli. 2008. The Papua New Guinea tsunami of 17 July 1998: Anatomy of a catastrophic event. *Natural Hazards and Earth System Science* 8:243–266, <http://dx.doi.org/10.5194/nhess-8-243-2008>.
- Torres, M.E., A.C. Mix, K. Kinports, B. Haley, G.P. Klinkhammer, J. McManus, and M.A. de Angelis. 2003. Is methane venting at the seafloor recorded by $\delta^{13}\text{C}$ of benthic foraminifera shells? *Paleoceanography* 18, 1062, <http://dx.doi.org/10.1029/2002PA000824>.
- Urlaub, M., P.J. Talling, and M. Clare. In press. Sea-level-induced seismicity and submarine landslide occurrence: Comment. *Geology*.
- Urlaub, M., P.J. Talling, and D.G. Masson. 2013. Timing and frequency of large submarine landslides: Implications for understanding triggers and future geohazard. *Quaternary Science Reviews* 72:63–82, <http://dx.doi.org/10.1016/j.quascirev.2013.04.020>.
- Urlaub, M., P.J. Talling, and A. Zervos. 2014. A numerical investigation of sediment destructuring as a potential widespread trigger for large submarine landslides on low gradients. Pp. 177–189 in *Submarine Mass Movements and their Consequences*. S. Krastel, J.-H. Behrmann, D. Völker, M. Stipp, C. Berndt, R. Urgeles, J. Chaytor, K. Huhn, M. Strasser, and C.B. Harbitz, eds, *Advances in Natural Hazard Research*, vol. 37, Springer, Dordrecht, The Netherlands.
- Vardy, M.E., J.S. L'Heureux, M. Vanneste, O. Longva, A. Steiner, C.F. Forsberg, H. Hafidason, and J. Brendryen. 2012. Multidisciplinary investigation of a shallow near-shore landslide, Finneidfjord, Norway. *Near Surface Geophysics* 10:267–277, <http://dx.doi.org/10.3997/1873-2012022>.
- Viesca, R.C., and J.R. Rice. 2012. Nucleation of slip-weakening rupture instability in landslides by localized increase of pore pressure. *Journal of Geophysical Research* 117, B03104, <http://dx.doi.org/10.1029/2011JB008866>.
- Völker, D., F. Scholz, and J. Geerson. 2011. Analysis of submarine landsliding in the rupture area of the 27 February 2010 Maule earthquake, Central Chile. *Marine Geology* 288:79–89, <http://dx.doi.org/10.1016/j.margeo.2011.08.003>.
- Winkelmann, D., W. Geissler, J. Schneider, R. Stein. 2008. Dynamics and timing of the Hinlopen/Yermak Megaslide north of Spitsbergen, Arctic Ocean. *Marine Geology* 250:34–50, <http://dx.doi.org/10.1016/j.margeo.2007.11.013>.
- Zeebe, R.E. 2007. Modeling CO₂ chemistry, $\delta^{13}\text{C}$, and oxidation of organic carbon and methane in sediment porewater: Implications for paleo-proxies in benthic foraminifera. *Geochimica Cosmochimica Acta* 71:3,238–3,256, <http://dx.doi.org/10.1016/j.gca.2007.05.004>.