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Multiple failure styles related to shallow gas and fluid venting, upper slope Canadian Beaufort Sea, northern Canada

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ABSTRACT

The continental slope of the Canadian Beaufort Sea presents an exceptional opportunity to study the relationship between the fluid venting and the formation of mass-transport deposits. The continental shelf was emergent and partially ice-free during the last glaciation and is underlain by widespread permafrost. Water-column backscatter has shown the locations of more than 40 active gas vents along seaward margin of the subsea permafrost at the shelf break and upper slope. New multibeam bathymetry and subbottom profiler data show shallow potentially late Holocene failures and mass-transport deposits on the upper slope. Upslope from a prominent headscarp, undulating seabed with apparent growth faults overlies an acoustically incoherent to stratified horizon at 50 m sub-bottom interpreted as a decollement surface over which progressive creep has occurred. Similar creep is present in places on the upper slope and in places seems to have evolved into small translational slides, involving more compacted sediment buried >25 m, or into muddy debris flows where sediments buried <25 m have failed. Much of the slope failed during a regional retrogressive event, the Ikit slump, likely initiated on steep channel walls on the lower slope. Characteristic ridge and trough morphology resulting from retrogressive spreading or rotational slumping are preserved on gradients <2° on the upper slope, but appear to have been completely evacuated on gradients of 3° on the mid slope, where muddy debris-flow deposits are found. Correlations between radiocarbon dated cores and sub-bottom profiles show that the retrogressive failure occurred in the last 1000 years. This study implies that Holocene shelf break and upper slope stability in the Beaufort Sea are strongly linked to the dynamics of the permafrost and the presence of weak, gas-rich sediments. It demonstrates that creep deformation evolves into either muddy debris flows or translational slides, dependent on sediment strength.

1. Introduction

Many authors regard earthquakes as the principal trigger of shallow slope failures, with increase in pore pressure by shallow gas as a preconditioning factor (Canals et al., 2004; Mosher et al., 2010). This topic has been the subject of hot debates during the past two decades over the key question as to what is the final trigger for submarine landslides (Canals et al., 2004). Where failure is widespread in multiple drainage systems, landslides are interpreted as triggered by earthquakes. In general, there is a lack of direct evidence for failures triggered by fluid circulation through sediment, although gas as the sole trigger cannot be entirely ruled out (Canals et al., 2004).

It has long been suggested that the presence of gas within shallow sediment could be the sole cause of certain slope failures (Sultan et al., 2004; Nixon and Grozic, 2007; Maslin et al., 2010; Li and He, 2012). Nevertheless positive feedback between fluid circulation and sediment deformation leading to failure is poorly documented. Recent work has highlighted gas seep anomalies where slope failures have recently occurred (Faure et al., 2006; Rogers and Goodbred, 2010). The spatial or temporal relationship between gas seeps and slope failures has been recognised in several shallow water areas, such as the U.S. Atlantic margin, New Zealand, Norway and Bay of Bengal among others (Best et al., 2003; Hill et al., 2004; Faure et al., 2006; Panieri et al., 2012). In those cases sub-surface sediment deformation coupled with active gas escape structures have been identified and linked to different mechanisms, for instance wave pumping or soft sediment creep. In the case of sediment creep, it is suggested that the progressive deformation of a shallow water delta results from gas migration upslope leading to a modification of the sediment pore pressure related to sediment overloading (Hill et al., 2004). Creeping of sediment is a common process in deep water, and is not necessarily related to the presence of gas (Hill et al., 1982, 2004; Syvitski et al., 1987; Correggiari et al., 2001; Canals et al., 2004; Shillington et al., 2012). Creep is a slow but gradual elastic deformation of the sediment, which occurs over a relatively long period of time and can evolve into different sorts of slides

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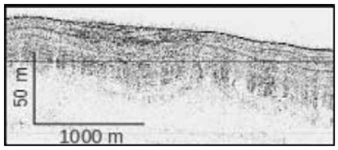
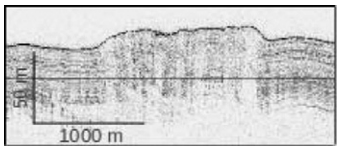
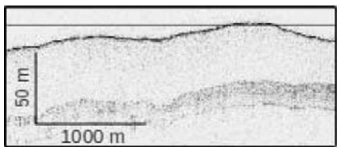
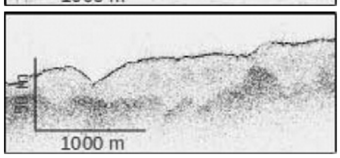
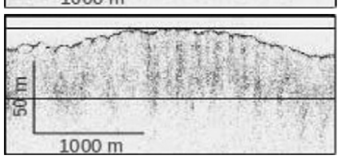
Table 1
Classification of 3.5 kHz acoustic facies.

Type		Detail	Description	Occurrence
Stratified	S1		Top unit consisting of numerous distinct continuous and parallel internal reflectors. Underlying (gas rich?) transparent basal unit with faint or indiscernible basal reflector.	Undisturbed or remnant topography.
	S2		Rugged seabed surface with disturbed top unit. Numerous acoustic voids and no basal reflector.	Terminal of debris flow.
Transparent	T1		Acoustic transparent facies covering basal unit with continuous and distinct internal reflectors.	Shelf, Slope, and mud volcano.
	T2		Acoustic transparent topunit. Irregular and faint or indiscernible basal reflectors.	Beyond slumps
Chaotic	C		Irregular seabed surface with disturbed sub-bottom. Occasional faint basal reflector.	Slumps from escarpments to gentle topography down slope and channels.

or into plastic to liquefied mass flow (Mulder and Cochonat, 1996). Creep does not necessarily lead to failure but causes permanent deformation to the sediment, although creep is characteristic of areas predisposed to failures. As for other classic failures, earthquakes can affect the creep in accelerating the process leading to the failure. Most of the documented examples of sediment creep in deep water involve muddy sediment deposited over a detachment layer (Correggiari et al., 2001; Shillington et al., 2012) and in some cases the detachment layer could be related to the presence of gas within a sandy unit overlaid by a thick clay rich unit (Hill et al., 2004). In such a case, the evolution from creep to failure relies on a positive feedback between the gas charge in the sandy layer and the load of the muddy unit. Yet, the interplay between gas and sediment in areas prone to failures is still not well documented.

In this study, we examine the upper slope seaward of the central Beaufort Shelf (Fig. 1), in the Arctic Ocean, where venting of fluids including gas is concentrated. The objectives of this study are: (1) to document the regional distribution of gas venting; (2) to characterise the style of recent sea-bed failure on the upper slope; and (3) to evaluate the role of shallow gas in the initiation and deformation of the mass-transport deposits.

2. Geological setting

The Mackenzie Delta occupies the central portion of the late Mesozoic to Cenozoic Beaufort-Mackenzie structural basin and today discharges onto a 100 km wide continental shelf in the Beaufort Sea. During the last glacial maximum, the continental ice sheet crossed the shelf to present day shelf edge for short time periods and left the shelf emergent for long periods (Blasco et al., 2013). Retreat of the ice front from the shelf edge resulted in the deposition of glaciomarine sediments, which pinch out at the shelf edge but thicken down slope. Although the Mackenzie River has the largest sediment load of any river discharging into the Arctic Ocean, ~127 × 10^6 Mt·a^{-1} (Carson et al., 1998), little sediment finds its way to the central shelf edge as the Coriolis force drives the sediment plume east along the inner shelf (Vilks et al., 1979; Blasco et al., 2012).

On the Beaufort Shelf, the top 100 m of sediment is no older than ~27 ka (Hill et al., 1985) and represent late Wisconsinan to Holocene deposition that continues down slope (Blasco et al., 2013). Sedimentation rates of ~1.4 m·ka^{-1} have been estimated for the uppermost Beaufort Slope in the late Holocene, highlighting the significant contribution of the Mackenzie River to the slope following deglaciation (Scott et al., 2009; Bringué and Rochon, 2012). A core at 671 m in the Mackenzie Trough shows 8 m of soft mid- to late Holocene silty muds overlying well laminated early Holocene to late Pleistocene muds (Schell et al., 2008). At 1000 m on the Beaufort Slope, the mid- to late Holocene silty muds are only 2 m thick and overlie rather uniform clays with thin sandy intervals (Scott et al., 2009).

Earthquake activity is quite low in the Canadian Beaufort region and is mostly related to the crustal response of a large uncompensated sediment load along the continental slope (Atkinson and Charlwood, 1988). Seismicity is usually of a low magnitude (<4) but a few events with magnitude greater than 5 have been reported in the 100 years of instrumental records (Lamontagne et al., 2008; Cassidy et al., 2010).

The Beaufort Shelf contains more than 700 m of ice-bearing sediments (Blasco et al., 2013). These frozen sediments pinch out at ~100 m water depth, coincident with the current shelf edge. The impermeable ice-bearing sediments form a barrier to migrating fluids. Over geologic time these fluids have migrated to the northern edge of the permafrost and escape to the seabed in the area of the shelf break. Concentrated fluid escaping at the permafrost edge has resulted in the formation of a linear array of over 700 mud volcanoes along the current shelf edge (Blasco et al., 2013).

3. Methods

Acoustic data were collected in 2009 and consisted of Kongsberg-Simrad 30 kHz EM302 multibeam sonar and Knudsen 3.5 kHz sub-