ALONG SLOPE VARIATIONS IN MASS FAILURES AND RELATIONSHIPS TO MAJOR PLIO-PLEISTOCENE MORPHOLOGICAL ELEMENTS, SW LABRADOR SEA

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Abstract

The slope along the SW Labrador Sea is a prospective exploration frontier with limited legacy data and geoscience knowledge. Newly acquired seismic reflection and multibeam bathymetry data provide a better understanding of mass failure processes. A semicontinuous seismic section along the upper slope from Flemish Pass to north of Hamilton Spur shows an alternation of major morphological elements that includes canyons and failure corridors, inter-canyon ridges, ice-outlet trough mouth fans (TMFs), and sedimentary spurs. Preliminary geohazard investigation shows a wide variety of Plio-Pleistocene mass failure products including shallow detachment faults, head-scarps, creep folds, decollement surfaces, and a preponderance of mass transport deposits (MTDs) of various origins. Particularly noteworthy are two newly identified fans outboard the Hawke Saddle and Notre Dame Channel (believed to be TMFs constructed of mass wasted material), and a large shallow buried failure complex north of the Hamilton Spur, which contains many km-scale slide blocks dispersed over thousands of square kilometers.

Keywords: SW Labrador Sea, slope morphology, mass failures, giant slide blocks

1. Introduction

Renewed exploration interest in the SW Labrador Sea includes deep water areas of the slope where there is poor data coverage and limited stratigraphic control. New high resolution GI gun seismic reflection profiles collected during two cruises (Hud2005-033b and Hud2006-040) combined with 5500 km^2 of 30 kHz multibeam bathymetry collected between 2003 and 2006 were used to study the regional Plio-Pleistocene geology and potential geohazards along the slope (Fig. 1). These data suggest that mass-transport deposits (MTDs) form a significant part of the sedimentary succession. They occur at a variety of scales ranging from local failures that modified deposits dominated by other processes (e.g. contourite drifts) to more regional failure complexes that significantly altered the morphology of the margin (e.g. off Makkovik Bank). Some of the failures identified are amongst the largest yet observed off eastern Canada. The purpose of this paper is to provide a preliminary account of the MTDs and associated features and their influence in shaping major morphological elements along the slope.

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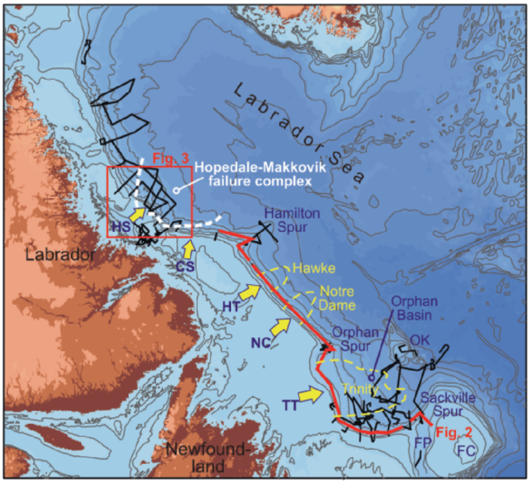

Figure 1. SW Labrador Sea showing profiles collected since 2003 and major morphological features. FC-Flemish Cap; FP-Flemish Pass; HT-Hawke Trough; HS-Hopedale Saddle; NC-Notre Dame Channel; TT-Trinity Trough; CS-Cartwright Saddle.

2. Slope between Sackville and Hamilton spurs

A semi-continuous 1330 km long composite seismic section was assembled from available high-resolution airgun profiles (Fig. 2). It shows dramatic changes in slope morphology between the Sackville and Hamilton spurs that are attributed to cross-slope ice-margin, along-slope contourite, and various mass wasting processes. Positive-relief fan-like deposits are found outboard the Trinity, Notre Dame, and Hawke shelf-crossing troughs (Fig. 1). They were deposited outboard major ice-outlets, probably during periods of maximum ice advance when large quantities of sediment were discharged onto the outer shelf (Hiscott & Aksu, 1996; Shaw et al., 2006; Tripsanas & Piper, submitted). Hence these features may be trough-mouth fans (TMFs; *sensu* O'Cofaigh et al. 2003). The most prominent bathymetric elements along the margin are the Sackville, Orphan, and Hamilton spurs. They are believed to be large contourite drifts (axial length >100 km; width > 50 km) deposited since at least the late Miocene, molded by a combination of the shallow south-flowing Labrador Current and the deeper Western Boundary Undercurrent (Myers & Piper, 1988; Kennard et al., 1990). Piston cores from their crests indicate late Pleistocene sediments consist predominantly of variably coloured clay to silty or sandy clay (e.g. Campbell et al., 2002; Goss, 2006; Tripsanas & Piper, submitted). The composition of older spur sediment is generally unknown. Canyons are also important morphological features. They are present on the upper slope south of the Trinity TMF, north of the Orphan Spur, between the Notre Dame and Hawke 'fans', and north and south of the Hamilton Spur (Fig. 2). In most places they are young, truncating shallow Pleistocene strata above thick largely canyon-less intervals of higher continuity Pliocene slope deposits. Hence, the prevalence of canyons at the seafloor is commonly a recent feature not widely observed in the subsurface, and like TMFs, is probably directly related to increased sediment supply associated with the growth and decay of the Laurentide ice sheet (Myers & Piper, 1988; Hesse et al., 1999). Canyons are commonly separated by inter-canyon ridges whose morphology ranges from narrow with sharp crests to wide with relatively flat-lying strata. Some consist of strata that aggraded contemporaneously with canyon incision, comprised of sediment that settles from meltwater surface plumes and spillover from fine-grained parts of turbidity flows (Hesse et al., 1999). Each of the above settings is, to varying degrees, influenced by mass failures, described in more detail below.

2.1 TROUGH-MOUTH FANS (TMFs)

Three prominent positive-relief (convex-upward) 'fans' are present on the upper slope outboard the Trinity, Notre Dame, and Hawke shelf-crossing troughs (Fig. 2). They are believed to be constructed predominantly of mass wasted material. The southern most of these is the Trinity TMF. It consists of a series of incoherent wedges, each with multiple lens-shaped bodies consisting of glaciogenic debris flow deposits (Hiscott & Aksu, 1996). On dip-oriented profiles the Trinity TMF progrades into the Orphan Basin with forsets inclined at 2 to 3°. Each incoherent wedge extends from the outer shelf, indicating debris flows were initiated near the ice-margin, perhaps from failure of till tongues during rapid delivery of glacial till to the upper slope (Piper & Brunt, 2006). The deepest incoherent interval may correspond to the initial excavation of the Trinity Trough (Campbell, 2005) during early shelf-crossing glaciations (beginning at about MIS 12; Piper, 2005). It is overlain by 4 other incoherent wedges, each separated by local erosion and intervals of stratified coherent reflections corresponding to hemipelagic drape deposited when the ice margin was far removed from the continental shelf-break (Hiscott & Aksu, 1996).

The newly identified deposits outboard the Notre Dame Channel and Hawke Saddle produce subtle seaward bulges on GEBCO bathymetric contours, which we used to approximate their perimeters (Fig. 1). The fan outboard the Notre Dame Channel is >100 km wide and 650 ms thick. The fan outboard the Hawke Saddle is 85 km wide and about 500 ms thick. They consist largely of incoherent higher amplitude seismic facies with lens-shaped 'patches' of low amplitude incoherent reflections. They were probably built through mass wasting processes, but lack the well-developed alternation of incoherent and coherent reflections seen in Trinity TMF. The more complex seismic facies may indicate a higher degree of gullying on the steeper slope in this area (2.5 to 4.0°), with poorer preservation of coherent hemipelagic intervals. Alternatively, they may have been supplied by a wider variety of mass failure deposits (e.g. glaciogenic debrites, slumps, slide blocks, turbidites). Sharply underlying both fans are higher-continuity slope deposits containing shingled reflections, sediment waves, and multiple prominent erosive surfaces indicative of marine deposition under the influence of ocean currents (Fig. 2e). Like the Trinity TMF, the abrupt change in deposition at their bases may correspond to the first shelf-crossing glaciations north of Trinity Trough. Canyon erosion south of the Notre Dame fan (Fig. 2a), however, prevents us from correlating seismic reflections to the south, and we are thus unable to determine the timing of the Trinity TMF relative to the deposits to the north. Their smaller dimensions might mean that the shelf-crossing troughs to the north were less important outlets for fast-flowing ice compared to the Trinity Trough, but more seismic profiles are required to better define their perimeters and seismic stratigraphy.

2.2 SPURS

The Sackville, Orphan, and Hamilton spurs are distinctly asymmetric and are dominated by highly continuous reflections, but also contain intervals of sediment waves and shingled and chaotic reflections. Oversteepening of their slopes through time, however, preconditioned the spurs to fail periodically either under their own weight, through ground shaking (Piper & McCall, 2003), or through gas hydrate dissociation (Mosher et al., in press). Consequently, their crests and flanks are variably truncated by head-scarps, bedding-plane detachments, and they locally contain MTDs.

The northern *upstream* sides (relative to prevailing ocean currents) of spurs are steeper and commonly erosive, where currents are most intense (Kennard et al., 1990). The upstream side of the Sackville Spur (up to 4.6°) periodically shed sediment into the Orphan Basin, with multiple failure scarps (some up to 200 m high) creating a stepped morphology with sharply truncated reflections periodically draped by continuous reflections. Prominent scarps are also present on the upstream (northern) sides of the Orphan and Hamilton spurs. Spur *crests* are variably truncated by failure scarps. At least one Pleistocene failure was sourced from the southern crest of the Sackville Spur (Campbell et al., 2002), but for the most part its crest remained intact throughout the Plio-Pleistocene, shedding surprisingly little sediment to the SE. In contrast, the more northerly spurs experienced more crest and flank failures. A chaotic MTD is found along the crest of the Hamilton Spur in >2800 m of water, presumably sourced from a crest failure initiated up-slope, and failure scarps are present off the seaward nose of the Orphan Spur. The southern *downstream* sides of spurs are commonly less steep and more depositional, with coherent reflections thinning away from their crests and in the seaward direction. Continuous seismic reflections on the downstream flank on the Sackville Spur were variably truncated by, and interfinger with, several erosive-based MTDs (up to 130 m thick; Fig. 2b). They were likely sourced from scarps on the Flemish Pass slope, south and east of the spur (Piper & Campbell, 2005). Similarly, the downstream flanks of the Orphan Spur interfinger with erosive-based MTDs from the adjacent Trinity TMF (Fig. 2d), and the southern flank of the Hamilton Spur is onlapped by MTDs in > 3000 m of water.

2.3 CANYONS AND INTER-CANYON RIDGES

Canyons are widespread across the southern Labrador margin. Their axes, margins and the ridges that separate them may be influenced by a variety of mass failures described in numerous previous studies (e.g. Josenhans et al., 1987; Piper & McCall, 2003; Mosher et al., 2004; Jenner et al., 2007). The northern side of the Orphan Spur and the northern and southern sides of the Hamilton Spur are particularly heavily eroded by canyons, exposing deeper Pliocene strata at the seafloor. Up-arching of seismic reflections in these areas indicates an underlying tectonic control may have caused uplift, with increased erosion and generally thin preservation of Plio-Pleistocene strata (Fig. 2). These areas may have been subjected to increased mass failures, but the lack of data in deeper water precludes mapping associated deposits. The slope south of the Trinity Trough is also cut by a series of seafloor canyons that coalesce downslope (Tripsanas et al., in press). Below them the slope is highly complex and contains prominent erosive surfaces that could represent much larger canyons (e.g. Campbell, 2005) or submarine erosion associated with intensified ocean currents as described by Piper & Normark (1989), Kennard et al. (1990) and Deptuck (2003) (e.g. Figs. 2b-f).

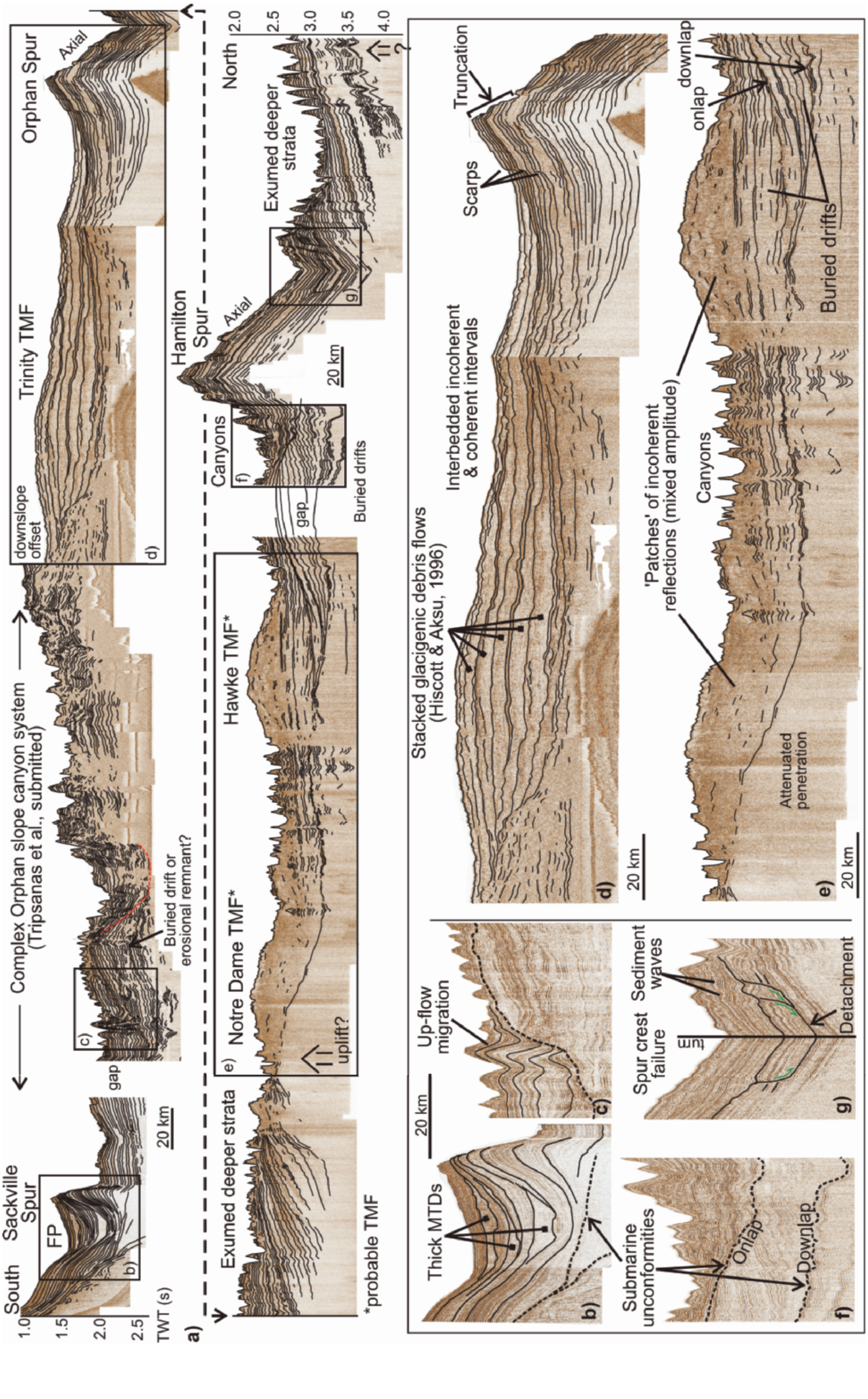

Figure 2. a) Along-slope profile extending from Flemish Pass (south) to north of Hamilton Spur (north), with close-ups (b-g). See text for details and figure 1 for location.

In either case, peculiar northward migrating sediment-wave-like geometries commonly develop along the steep incision surfaces, and can persist through > 600 ms of strata. They are believed to be caused by the interaction of failure-induced seafloor irregularities and south-flowing ocean currents. For example, slide blocks shed from the steep undercut slope probably initiated the complex northward migrating canyon margins in Fig. 2c, perhaps enhanced by continued motion along buried rotational detachments (Campbell, 2005). Similar geometries are found above headscarps on the Hamilton Spur, generating up-current migrating sediment waves (Fig. 2g).

3. Slope outboard Hopedale Saddle and Makkovik Bank

There is widespread evidence for mass failures at the seafloor and in the shallow subsurface north of the Hamilton Spur (Piper & McCall, 2003). Off Nain Bank several recent slope failures left up to 240 m high headscarps at the seafloor (Fig. 3a). Off Makkovik Bank the shelf-break forms a prominent indentation and the high gradient (> 5°) slope outboard it appears to have been unstable through the Pleistocene to recent. Amphitheater-like failure corridors, complex failure scarps, rotated slide blocks, and bedding plane detachments are observed. The 'bulge' in the outer shelf outboard the Hopedale Saddle (Fig. 3a) is a constructional feature formed during Pleistocene outbuilding of prominent clinoforms (Myers & Piper, 1988). It is up to 950 ms thick and may consist of glaciogenic debris flows similar to those found in TMFs. These deposits thin down-slope into a complex network of canyons and variably thick inter-canyon ridges (up to 400 ms thick). The thickest inter-canyon ridges, like the one identified in Fig. 3a, experience similar failures as the spurs. Some collapse under their own weight (perhaps initiated by ground-shaking), with multiple listric faults that sole out in shallow decollement surfaces that pass down-slope into creep folds (Mosher et al., 2004; Piper, 2005). Retrogressive rotated blocks off the flanks of steep ridges are also observed particularly outboard Makkovik Bank and the Cartwright Saddle (Praeg & Schafer, 1989) (e.g. Fig. 3f-g).

3.1 HOPEDALE-MAKKOVIK FAILURE COMPLEX

An interval of largely incoherent MTDs underlies Pleistocene canyon and inter-canyon deposits (e.g. Fig. 3c-d). They appear to have originated from widespread multi-phase Pliocene(?) collapse of the slope outboard Hopedale Saddle and Makkovik Bank, producing deposits covering > 28 000 km^2 (boundary identified by dashed line in Fig. 3a). We refer to these deposits collectively as the *Hopedale- Makkovic failure complex*, which is comprised of at least 4 separate failures. They contain angular blocks up to 6 km across with well-preserved internal stratification (Fig. 3d-e). The giant blocks are dispersed over thousands of square kilometres, extending into water-depths > 2500 m. At the time of deposition some blocks towered more than 350 m above the surrounding seafloor, with sides typically inclined between 4 - 6° (up to 20°). Pleistocene burial by turbidites, contourites and smaller MTDs reduced their present day relief, with the highly rugose topography strongly influencing depositional systems. Ponding is observed in the 'lows', with thicker deposits on the up-flow sides of some blocks and thinner deposits on their down-flow sides, in areas that were probably shadowed from sediment gravity flows. In some cases just the corners of angular blocks are exposed at the seafloor. In other cases long edges are exposed, producing 2-6 km lineations with up to 140 m of seafloor offset (Fig. 3c). Shallow detachment faults locally enhance their seafloor relief, with the Pleistocene overburden detaching along the steeply dipping faces of consolidated blocks (Fig. 3f).

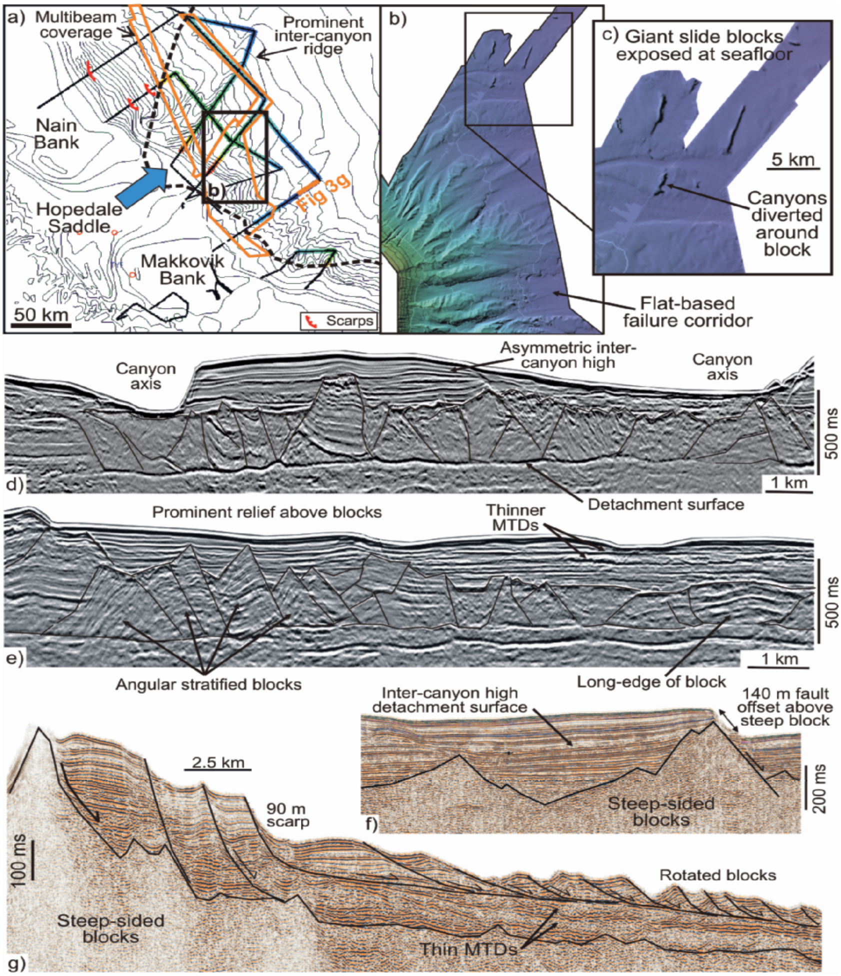

Figure 3. a) Location map; b-c) Multibeam bathymetry; d-e) Seismic profiles showing angular blocks within upper part of Hopedale-Makkovik failure complex (provided by GSI); f) High-resolution airgun profile above angular blocks below an inter-canyon high, onlapped by Pleistocene sediments; g) High-resolution airgun profile across recently collapsed inter-canyon ridge above blocky MTDs. See text for details.

The most recent failure in the complex forms above a bed-parallel detachment surface, constrained by lateral scarps as high as 280 m (Fig. 3d). The relatively low levels of deformation (subtle folding and tilting) and the angularity of blocks suggest strata were well-consolidated at the time of failure. We interpret the failure blocks to have formed through the break-up of a large detached slab consisting of relatively consolidated slope strata (perhaps above a weak layer). The dimensions of some blocks indicate the failed slab was more than 300 m thick. The failure probably originated near the Hopedale Saddle, where a 300 m high failure scarp is present below the more recent Pleistocene clinoforms. We speculate that the prominent indentation of the shelf-break outboard Makkovik Bank may also be a remnant scar associated with this failure complex. Stratigraphically similar chaotic deposits were mapped in vintage industry seismic profiles by Myers & Piper (1988) between their mid-Pliocene D and mid-Pleistocene A reflectors (their Fig. 10). If these are the same deposits, it indicates the failure complex could cover an area in excess of 85 000 km^2, in places be more than 700 ms thick, and reach >3500 m of water (their Fig. 12). This would place it amongst the largest failure complexes identified off eastern Canada, comparable to the Shelburne megaslump mapped off the Scotian margin (Shimeld et al., 2003).

4. Conclusions

The slope along the SW Labrador Sea is highly complex, and this brief study provides only a cursory overview of major morphological features and the range of mass failures that affect them. Sediment ages at present are poorly constrained, and more work is needed to define a regional Plio-Pleistocene stratigraphic framework and to map the distribution of mass failures and associated features. Mass failures on the predominantly depositional spurs, fans, and inter-canyon ridges are relatively local features. In contrast, the widespread Pliocene to early Pleistocene MTDs north of the Hamilton Spur are major failures that would have modified the seascape on a regional scale. The trigger for these large failures is unknown, but the slope outboard the Hopedale Saddle and on the northern side of the Hamilton Spur has experienced multiple magnitude 4 to 5.6 earthquakes over the past 50 years (USGS earthquake data-base). Hence earthquakes could have triggered these large failures (Piper et al., 2003), causing a multi-phase widespread collapse of a 200 km long segment of the Labrador slope, with transport of giant km-scale slide blocks far out into the Labrador Sea.

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