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New evidence for a major late-Quaternary submarine landslide on the external western levee of Laurentian Fan

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Abstract: The Laurentian Fan is one of the largest submarine fans on the western margin of the North Atlantic. Recently acquired high-resolution multibeam bathymetric data (60 m horizontal resolution) reveal a major mass transport deposit (MTD) on the Western Levee of Western Valley (WLWV), covering >14 000 km^2 in water depths from 3900 m to >5000 m. Typical submarine landslide features are observed such as headscarps that in places reach the crest of the levee, crown cracks, extensional ridges, blocky debris and flow lineations. Multiple headwalls are observed on 3.5 kHz sub-bottom profiles indicating that the landslide retrogressed upslope. While the upper parts of the MTD consist of intact blocks that were displaced downslope as ridges and troughs, the lower parts exhibit a ~30 m thick incoherent to transparent acoustic facies typical of debris flows. Landslide geomorphology thus suggests that it was generated as a retrogressive spread and that slide blocks disintegrated downslope to become a blocky landslide with a surficial debris flow. The blocky landslide/debris flow extends downslope ~90 km and partially fills a submarine channel. The superposition of the MTD filling the channel and its location at the top of the stratigraphic succession in the levee suggests that it is late Quaternary in age, possibly Holocene. Deeper seismic reflection data also show that this is a rare event during the Quaternary; it is the largest MTD observed in the upper ~375 m of the levee succession and among the largest and deepest in the Western North Atlantic.

Introduction

Submarine landslides play an important role in the evolution of active and passive margins by transporting large volumes of sediment to the deep-sea. They commonly occur on steep slopes, where sedimentary deposits are thick (Hampton et al. 1996). Submarine canyon

environments are prime locations for the generation of landslides because they supply large volumes of sediment and are characterized by steep slopes (e.g., Jenner et al., 2007). Typically, landslides tend to be small and relatively frequent along canyon or channel margins (e.g., Smith et al., 2005) whereas they are typically much larger and infrequent in inter-canyon (or open) slopes (Lee, 2009).

Offshore Nova Scotia, large and infrequent submarine landslides have been reported on the Scotian margin through the analysis of multibeam bathymetry and seismic stratigraphy (e.g., Piper et al., 2003; Mosher et al., 2004). Landslide scars are widespread both on the open slopes and on the inner canyon environments. The Laurentian Fan valleys, extending from the Laurentian Channel, are no exception to the presence of submarine landslides. As an example, they were the main conduits for the 1929 Grand Banks failure (Piper and Aksu, 1987; Piper et al., 1999). Because the fan valleys were fed by glacigenic sediments originating from a large part of southeastern Canada throughout the Quaternary (Piper et al. 2016), they host some of the largest levees in the world (Skene et al., 2002; Skene and Piper, 2003). Levees are wedge-shaped sedimentary deposits formed by deposition along the margin of channels that confine sediment density flows (Kane *et al., 2010*). Levees consist mainly of an alternation of turbidites and hemipelagites and are often characterized by sediment waves (Migeon et al., 2001). Landslides on levees are generally localized and affect the inner levees, where the slope is steepest (e.g., Klaucke et al., 1997).

Canada is a signatory to the United Nations Convention on the Law of the Sea (UNCLOS); as a result, significant efforts have been made to map its extended continental shelf during the past decade. This systematic mapping has led to numerous discoveries on the seafloor, many of them related to geohazards. A large mass-transport deposit (MTD) on the Western Levee of Western Valley (WLWV), first recognized by Hughes-Clarke (1988) and Piper (1991), was recently mapped as part of Canada's extended continental shelf program. The extent of this MTD was previously unknown due to a lack of multibeam coverage and seismic stratigraphy in the region. In a region as well studied as the Laurentian Fan, such a large failure remained largely undocumented (Hughes-Clarke, 1988) and its significance in the stratigraphic record unknown.

In this paper, we document the slope failures on the WLWV of Laurentian Fan. Specifically, this paper addresses: 1) the geomorphology of the WLWV as a depositional and erosional environment; 2) the recurrence of submarine landslides in order to document the importance of the major WLWV MTD on external levee growth; 3) the failure style of this large MTD; and 4) its importance in the levee's stratigraphic record.

Regional setting

The Eastern Canadian continental shelf is characterized by the Laurentian Channel, a wide, deep, glacially carved cross-shelf trough (Todd, 2016). Seaward of the Laurentian Channel lies the large Quaternary Laurentian Fan (Piper, 2005). The Laurentian Fan is crossed by the Eastern and Western valleys (Fig. 1). The Eastern Valley is a 40 km-wide channel with its head starting at a depth of ~400 m; the Western Valley is narrower (≤ 20 km). Both valleys are connected by a narrow Central Valley that originates from a low point on the Eastern Valley near 3000 m and joins the Western Valley near 3800 m (Fig. 1). The western levees of both the Eastern and Western Valleys are among the largest in the World (Skene et al. 2002).

The sedimentology and stratigraphy is well known in the study area (Mosher et al., 2004). Proglacial sedimentation is characterized by grayish brown mud with silty turbidites and ice-rafted debris overlain by red brown mud with sandy intervals and ice-rafted debris. The late Quaternary stratigraphy of the Laurentian Fan reveals that turbidite deposition ceased around 14 ka ^{14}C BP (Skene and Piper, 2003). Brick red mud units linked with Heinrich events were deposited in the upper parts of this red brown mud facies and are dated to 14-13 ka ^{14}C BP. Holocene sedimentation is characterized by olive gray mud and silt, often bioturbated.

MTDs occur on canyon walls (Jenner *et al., 2007*), and occasionally on open slopes (Mosher *et al., 2004*). The largest MTDs are observed deeper in the stratigraphic record, two of the largest ones being MTD-J and the 150 ka BP MTD-D (Fig. 2A). They were hypothesized to have been triggered by earthquakes and preconditioned by high glacial sedimentation (Piper & Ingram, 2003).

Methods

Deep-water, high-resolution bathymetric data was collected by the Geological Survey of Canada (GSC) and the Canadian Hydrographic Service (CHS) in 2012 on board the R/V Atlantis (Expedition AT22-01) using a Hull mounted 12 kHz Kongsberg EM122 multibeam sonar coupled with a XYSEA PHINS integrated motion sensor. Positioning was provided by a satellite corrected CNav GPS and real-time sound speed at the transducer was acquired using a Seabird TSG velocity sounder. Expendable bathythermograph sound speed profiler casts were recalculated using the 2009 World Ocean Atlas (WOA) database salinity profiles and imported in real-time to the navigation and acquisition software (SIS). The EM122 has a 64° swath angle and 865 beams per ping. The data was imported into Caris HIPS and SIPS and gridded at a 60 m resolution. Backscatter intensity information was also recorded during the Atlantis cruise and was processed using Caris HIPS and SIPS Geocoder engine. The data were gridded at a 40 m resolution but the resolution decreases with increasing distance from nadir.

During the Atlantis cruise, 3.5 kHz Knudsen sub-bottom profiler data were acquired along the same lines as the multibeam data. These lines are roughly parallel to the depth contours, limiting the analysis of downslope features. In 2016, a GSC expedition on CCGS Hudson acquired seismic reflection data using a Huntec deep-tow system with a sparker source. The acoustic output was centered on ~1.5 kHz, with a 0.5-2.5 kHz bandwidth. 3.4 L Generator-Injector (GI) gun and single channel streamer data were collected to image deeper reflections. The sub-bottom data were imported and analyzed in The Kingdom Suite software.

Results

Morphology and internal architecture of the Western Levee of Western Valley

The WLWV has a relief, measured as the height above the floor of Western Valley, of 650 m at 3500 m water depth. Its relief progressively decreases downslope to less than 100 m at > 4700 m water depth (Fig. 1). The steep inner levee wall slope (5-6 °) consists of widespread and small scarps and gullies, even at depth of > 4500 m (Fig. 3). The eastern inner levee wall also consists of headscarps, although they are less common than on the

western one, where data are available. The headscarps do not appear to have a resulting deposit downslope since the latter may have been remobilized by density flows that eroded the Valley.

The external levee slope of WLWV has a much smoother surface compared to the inner levee slope, with a mean gradient ≤ 1°. This smooth appearance is due to the lower relief of the different geomorphological features observed. At a depth of ~ 3500 m, the levee is composed of an aggradational spillover channel that has a 20 km-wide head narrowing downslope to 3 km (Fig. 3, 4A). The head of this channel is located near the confluence of the Western and Central Valleys, where density flows likely overspill the levee. Downslope, an unnamed channel delimits the western extent of the levee (Fig. 3).

The upper 0.2 s TWT of seismic profiles collected over the levee can be separated into two distinct acoustic facies. The shallower undisturbed depths consist of generally continuous, parallel medium to high-amplitude reflections (Fig. 4A) whereas the deeper areas of the levee consist of discontinuous chaotic reflections (Fig. 4B). Wavy reflections observed in the shallower parts of the levee result from the draping of underlying chaotic reflections. Near the crest of the levee, the upper reflections, i.e., those at the seafloor, often appear chaotic, reflecting small MTDs (Fig. 3A). Seismic reflections across the levee reveal that the thickness of the sediment diminishes away from the valley, consistent with higher sedimentation rates at the crest during levee growth (Fig. 2B).

Surficial mass transport deposit characteristics

The main surficial MTD (WLWV MTD) was mapped from the bathymetry and backscatter imagery and has its shallowest headscarp at a water depth of ~ 4000 m and extends down to more than 5000 m. Its basinward limit is unknown since the multibeam coverage ends at a water depth of 5000 m (Fig. 3). The MTD is more than 100 km wide and extends downslope approximately 100 km (run-out length), encompassing an area of > 14 000 km^2. The headscarp of the landslide commonly reaches the crest of the levee; where it does not, it is amphitheatre shaped, arcuate to elongate in plan form, and has crown cracks along the headwalls (Fig. 5). The headscarps are 5-10 km wide and the scar slopes reach locally 10° but are typically < 5°, with heights of ~40 m. Its run-out ratio (headscarp height vs run-out

length) is 0.0005, making it a long running landslide relative to its height (McAdoo et al., 2000). The adjacent undisturbed slopes are ≤ 1°. The proximal domain is characterized by ridges and troughs spaced 300-400 m apart gradually increasing to more than 500 m (Fig. 5). The ridges and troughs morphology progressively disintegrate downslope into blocky debris and then to a smooth seafloor with lineations. In some cases, the shallower parts of the MTD have well-defined small lobe deposits that appear to overlie MTD sediments (lobe superposition; Fig. 5). The ridges and troughs lack any seismic internal structures and are chaotic. Where the headscarps reach the crest, ridges and troughs are absent and are replaced by an extensive field of blocky debris (Figs. 4B-5).

The backscatter response of the undisturbed sediment on the levee is relatively low and can be observed to the north (Fig. 6). The backscatter intensity increases substantially on the MTD. The multibeam bathymetry, in combination with the backscatter imagery, reveals the presence of flow lineations in a NE/SW direction. Downslope, these flow lineations abruptly stop where the MTD partly fills the unnamed channel. This channel is the westward limit of the MTD. The MTD is typically frontally confined since the unnamed channel limits frontal emergence (Fig. 4B-2A). Where the MTD does not reach this channel, frontal emergence is observed (Fig. 7A) and can easily be differentiated in the backscatter imagery (Fig. 6).

The 3.5 kHz acoustic stratigraphy reveals that the glide plane is a high-amplitude reflection (Figs. 4B,7). It is generally continuous from the mid levee to the toe of the MTD (Fig. 4B). Occasional erosional features, possibly grooves and erosional pits are observed (Fig. 7A). Upslope, the acoustic appearance is very chaotic, reflecting the presence of blocky debris near the crest of the levee. The thickness of the deposit is also more variable near the crest of the levee, ranging between 10 m on steeper slopes and 30 m on lower slopes. Where slopes are steeper, retrogressive headwalls are observed (Fig. 7B).

Discussion

Landslide behaviour

The landslide can be divided into three zones of different failure types (Figs 4, 5): 1) Zone 1 is characterized by extensional spreading of the seabed; 2) Zone 2 is characterized by an

extensive blocky debris field and; 3) Zone 3 consists of disintegrated blocks and likely represents a complex slide with a debris flow overlying a blocky landslide.

The ridge and trough morphology is characteristic of spreads, a type of failure characterized by the failure of sediment into coherent blocks displaced downslope along a glide plane (e.g., Micallef et al., 2007; Baeten et al., 2013). The spreading component of the MTD is confined to the amphitheater shaped scarps that did not reach the crest of the levee. These cohesive blocks were displaced downslope along a planar gliding plane. Spreading is also often indicative of headscarp retrogression, which is further observed by the presence of multiple headwalls in the sub-bottom profiles (Fig. 7B). The spreading retrogressed upslope and disintegrated downslope into a blocky debris MTD and finally into a debris flow. The spreading component of the MTD is absent in some places because the retrogression reached the crest of the levee and was completely evacuated as a blocky landslide (Fig. 4B). Retrogression to the levee crest may indicate little change in upslope sediment strength that would have been able to stop the retrogression. The possible grooves, or at least local erosion of the glide plane (Fig. 7A), indicate that large intact blocks within the blocky MTD eroded the seabed during downslope movement or that the glide plane was not confined to a single stratigraphic level. Such intact blocks are not observed on the sub-bottom data, perhaps because of the large acoustic footprint making it impossible to resolve such features or because they disintegrated following the localized erosion of the glide plane. The debris flow extends down the flank of the external levee, eventually terminating in an unnamed channel that runs parallel to Western Valley (Fig. 2). To the south, away from this unnamed channel, the MTD displays frontally emergent characteristics, that is, the deposit ramps up from its original basal shear surface (Frey-Martinez *et al., 2006*) (Fig. 6-7A).

The upslope spreading zone likely formed in two ways: 1) it could have resulted from the initial development of the large landslide during one main event with rapid retrogression of the headscarp; or 2) it could have formed following an initial phase of mass transport during multiple and distinct events. The sliding of material downslope can cause a loss of support for the upslope sediment, which can be reactivated during a later, distinct trigger event. There is also evidence from lobe superimposition that evacuation of the main MTD

led to a loss of support in the upslope part of the levees, which could have caused upslope spreading (Fig. 5).

In any case, the blocky debris flow is likely the result of disintegration of an initial spread. The blocks at the distal edge of the spread were displaced downslope and disintegrated when passing over the pre-existing headwalls (e.g., Piper et al., 1999; Micallef et al., 2007). This process is illustrated in Fig. 7B where a blocky debris field thins over a steeper slope with buried retrogressive headwalls and thickens as a homogeneous acoustic unit downslope. The 3.5 kHz consistently reveals incoherent acoustic reflections within the deposit, suggesting disintegration of the failed deposit and its homogenization during transport. These surficial sediments broke up easily during transport because of the presence of thin sand and silt turbidites that shear during downslope movement (Piper et al., 2012).

Timing of submarine landslides

Landslides on the internal slope of the WLWV are suspected to have occurred frequently during the Pleistocene according to the number of landslide scarps visible on the multibeam imagery. The presence of these landslides is also consistent with the frequent passage of sediment density flows in the channel during the glacial period (Skene and Piper, 2003) which caused erosion, undercutting and oversteepening of the channel wall. However, landslides are comparatively infrequent on the lower gradients (<1°) of the external levee. Small landslides are present near the crest of the levee but long-running ones reaching the base of slope are infrequent (Fig. 2B). The most recent MTD appears to be the largest on the levee.

Piper (1991) initially suggested that the largest landslide on the WLWV was triggered during the Holocene solely based on its presence in the upper stratigraphic succession. The high-resolution imagery presented here provides additional support for a late-Pleistocene / Holocene age of the MTD. The debris flow component of the MTD extends ~ 90 km downslope and partially fills an unnamed submarine channel. The filling of the channel and the location of the MTD at the top of the stratigraphic succession on the levee suggests that it occurred after major canyon flow events ceased and is possibly post-glacial in age.

The major gravity flows in submarine canyons along the Scotian margin have been active until *ca* 14 ka ^{14}C BP (Skene and Piper, 2003), which suggests that turbidity currents would have eroded/altered the MTD if it had been triggered prior to deglaciation.

Although the main event most likely occurred during the late-Pleistocene / Holocene, smaller components of the landslide may have occurred more recently. Evidence of smaller landslide activity following the main event is observed near the crest of the levee. For example, a deposit appears to overlie the main blocky MTD (Fig. 5). Additionally, the presence of crown cracks suggests that the landslide may not be in a stable state. Crown cracks typically indicate incipient failure that could be ongoing in the region (e.g., Micallef et al., 2007; Li et al., 2016). Therefore, although the main landslide may have been triggered during the late Pleistocene or early Holocene, it could have been reactivated locally after the initial failure.

Significance in the stratigraphic record and geohazard implications

A large MTD on the WLWV was first identified by Hughes-Clarke (1988) and Piper (1991) based on sparse echosounder profiles. At the time, its submarine extent, geomorphology and importance in the stratigraphic record was unclear due to lack of data. The newly acquired multibeam bathymetric data allows us to identify it as one of the largest MTDs observed in the Western North Atlantic with an area of > 14 000 km^2. According to Lee et al. (2007), only 2% of the landslides on the United States margin have an area larger than 1000 km^2 and the largest is estimated at 19 000 km^2. On the Canadian margin, it is the largest surficial landslide identified to date although larger landslides were identified in the stratigraphic record, namely the ~93 000 km^2 Montagnais landslide (Deptuck and Campbell, 2012). In the North Atlantic, this landslide is also among the deepest at 4000 m (Huhnerbach and Masson, 2004). Most landslides on the Scotian margin were initiated on the upper slope and evolved on the lower slope. The WLWV landslide initiated on the lower Scotian Slope and still led to one of the largest MTD in the region. Its presence in deep-water and on low angle slopes, its size and its young age make it a significant event to have occurred in the North Atlantic.

Small MTDs are recognized on the external levee of WLWV but are generally restricted to its upper parts. On the other hand, extensive MTDs disturbing the entire external levee appear to be extremely rare in the stratigraphic record. Deep seismic reflection data show that during the Quaternary, the shallowest MTD is also the largest one observed in the upper ~375 m of the levee succession. In the stratigraphic record of the Nova Scotia continental slope, the WLWV MTD is among the largest reported. Piper and Ingram (2003) described a series of Quaternary sediment failures on the east lower Scotian Slope, the largest, MTD-D (Fig. 4B), estimated to have occurred at ~150 ka BP. These MTDs were described as originating from the continental slope. The known extent of MTD-D is ~ 8 000 km^2. However, the new seismic profiles show that the areal extent of MTD-D may be two times greater. Therefore, in terms of areal extent, MTD-D and the WLWV MTD are similar. The volumes of failure are likely different since Fig. 2A clearly shows that MTD-D is much thicker than WLWV MTD. The volume of sediment involved in MTD-D is estimated at 800 km^3 whereas the volume of sediment involved in WLWV MTD is estimated at 300-400 km^3. Nonetheless, the WLWV MTD is the largest late-Pleistocene / Holocene MTD on the Scotian margin identified to date, making it much younger than the ones described by Piper and Ingram (2003). It also remobilized a much larger volume than the 1929 earthquake-induced turbidite, the latter involving 150 km^3 of failed material (Piper and Aksu, 1987). This giant landslide is thus a significant event in the late Quaternary record of the Scotian Slope.

Most landslides on the Scotian margin are believed to have been triggered by earthquakes (Piper and McCall, 2003). In this particular case, the earthquake trigger appears likely since two coeval MTDs are observed on the levee (Fig. 3). Unique geological setting may also be partly responsible for this event since it is located on one of the largest levees in the world, an emplacement that differs from other large MTDs. External levees are typically characterized by sediment waves with little evidence of MTDs (e.g., Migeon et al., 2001), which are generally observed on the inner levee walls. However, it is worth noting that the large accumulation of sediments on the levee as well as the alternation of hemipelagites and turbidites favour the presence of weak layers (Cauchon-Voyer et al. 2008) which in turn favour the occurrence of landslides. In this respect, levee MTDs are similar to

contourite drifts where failures may be due to low shear strength owing to high sedimentation rates and well sorted sediment, underconsolidation, and loading due to earthquakes and overlying sediment (Laberg and Camerlenghi, 2008). Although earthquakes are rare in the region, they do occur preferentially along the Laurentian Fan region, most notably being the M7.2 1929 event (Mazzotti, 2007). Other earthquakes may have occurred during the Holocene (e.g., Piper et al., 1985) but are insufficiently documented at present.

Conclusion

Recently-acquired multibeam bathymetry data expose the presence of one of the most extensive MTDs in the Western North Atlantic, covering an area of > 14 000 km^2. The results from this study reveal that:

1) The landslide initiated as a retrogressive spread that rapidly evolved downslope as a blocky debris landslide. The retrogression reached the crest of the levee in a large part of the region, leading to its disintegration as a debris flow;

2) The MTD filled an unnamed channel downslope and is located at the top of the stratigraphic succession, suggesting it is late-Pleistocene to Holocene in age, making it one of the most recent major landslides on the Scotian Slope;

3) The presence of multiple headwalls and lobe superimposition suggest that the landslide evolved in a multi-stage fashion. The crown cracks near the headscarp also suggest that the landslide may not be in stable state and that instability may still be ongoing;

4) This landslide event is a rare deep-water event. It is also a rare event to have occurred on the WLWV, a levee dominated by turbidite/hemipelagite deposition.

This giant MTD is thus the record of a major event in the late-Quaternary of the Scotian Slope and its significance was only just discovered as part of Canada's extended continental shelf program under UNCLOS. Such systematic mapping programs are thus vital for the evaluation of geohazards on continental margins. Further investigations of this

MTD should be accomplished in order to determine how it evolved during the Holocene and to evaluate whether or not it is in a stable state.

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References

BAETEN, N.J., LABERG, J.S., ET AL. 2013. Morphology and origin of smaller-scale mass movements on the continental slope off northern Norway. *Geomorphology*, **187**, 122–134, doi: 10.1016/j.geomorph.2013.01.008.

CAUCHON-VOYER, G., LOCAT, J. & ST-ONGE, G. 2008. Late-Quaternary morpho-sedimentology and submarine mass movements of the Betsiamites area, Lower St. Lawrence Estuary, Quebec, Canada. *Marine Geology*, **251**, 233–252, doi: 10.1016/j.margeo.2008.03.003.

DEPTUCK, M. & CAMPBELL, D.C. 2012. Widespread erosion and mass failure from the 51 Ma Montagnais marine bolide impact off southwestern Nova Scotia, Canada. *Canadian Journal of Earth Sciences*, **49**, 1567–1594, doi: 10.1139/e2012-070.

FREY-MARTINEZ, J., CARTWRIGHT, J. & JAMES, D. 2006. Frontally confined versus frontally emergent submarine landslides: A 3D seismic characterisation. *Marine and Petroleum Geology*, **23**, 585–604, doi: 10.1016/j.marpetgeo.2006.04.002.

HAMPTON, M.A., LEE, H.J. & LOCAT, J. 1996. Submarine landslides. *Reviews of Geophysics*, **34**, 33–59, doi: 10.1029/95rg03287.

HUGHES-CLARKE, J.E. 1988. *The Geological Record of the 1929 Grand Banks'' Earthquake and Its Relevance to Deep-Sea Clastic Sedimentation*. Dalhousie University.

HUHNERBACH, V. & MASSON, D.G. 2004. Landslides in the North Atlantic and its adjacent seas : an analysis of their morphology , setting and behaviour. *Marine*

Geology, **213**, 343–362, doi: 10.1016/j.margeo.2004.10.013.

JENNER, K.A., PIPER, D.J.W., CAMPBELL, D.C. & MOSHER, D.C. 2007. Lithofacies and origin of late Quaternary mass transport deposits in submarine canyons, central Scotian Slope, Canada. *Sedimentology*, **54**, 19–38, doi: 10.1111/j.1365-3091.2006.00819.x.

KANE, I.A., MCCAFFREY, W.D., PEAKALL, J. & KNELLER, B.C. 2010. Submarine channel levee shape and sediment waves from physical experiments. *Sedimentary Geology*, **223**, 75–85, doi: 10.1016/j.sedgeo.2009.11.001.

KLAUCKE, I., HESSE, R. & RYAN, W.B.F. 1997. Flow parameters of turbidity currents in a low-sinuosity giant deep-sea channel. *Sedimentology*, **44**, 1093–1102, doi: 10.1111/j.1365-3091.1997.tb02180.x.

LABERG, J.S. & CAMERLENGHI, A. 2008. The Significance of Contourites for Submarine Slope Stability. *In*: Rebesco, M. & Camerlenghi, A. (eds) *Contourites*. Elsevier, 537–556., doi: 10.1016/S0070-4571(08)10025-5.

LEE, H., LOCAT, J., ET AL. 2007. Submarine mass movements on continental margins. *In*: Nittrouer, C. A., Austin Jr, J. A., Field, M., Kravitz, J. H., Syvitski, J. P. M. & Wiberg, P. L. (eds) *Continental Margin Sedimentation: From Sediment Transport to Sequence Stratigraphy*. Malden, MA, Wiley, Book Section, 213–274., doi: 10.1002/9781444304398.

LEE, H.J. 2009. Timing of occurrence of large submarine landslides on the Atlantic Ocean margin. *Marine Geology*, **264**, 53–64, doi: 10.1016/j.margeo.2008.09.009.

LI, W., ALVES, T.M., ET AL. 2016. Morphology, age and sediment dynamics of the upper headwall of the Sahara Slide Complex, Northwest Africa: Evidence for a large Late Holocene failure. *Marine Geology*, doi: http://dx.doi.org/10.1016/j.margeo.2016.11.013.

MAZZOTTI, S. 2007. Geodynamic models for earthquake studies in intraplate North America. *The Geological Society of America, Special Paper*, **425**, 17–33, doi: 10.1130/2007.2425(02).

McAdoo, B.G., Pratson, L.F. & Orange, D.L. 2000. Submarine landslide geomorphology, US continental slope. *Marine Geology*, **169**, 103–136.

Micallef, A., Masson, D.G., Berndt, C. & Stow, D.A. V. 2007. Morphology and mechanics of submarine spreading: A case study from the Storegga Slide. *Journal of Geophysical Research: Earth Surface*, **112**, 1–21, doi: 10.1029/2006JF000739.

Migeon, S., Savoye, B., Zanella, E., Mulder, T., Faugeres, J.-C. & Weber, O. 2001a. Detailed seismic-refection and sedimentary study of turbidite sedimentwaves on the Var Sedimentary Ridge (SE France): significance forsediment transport and deposition and for the mechanisms ofsediment-wave construction. *Marine And Petroleum Geology*, **18**, 179–208.

Migeon, S., Savoye, B., Zanella, E., Mulder, T., Faugères, J.C. & Weber, O. 2001b. Detailed seismic-reflection and sedimentary study of turbidite sediment waves on the Var Sedimentary Ridge (SE France): significance for sediment transport and deposition and for the mechanisms of sediment-wave construction. *Marine and Petroleum Geology*, **18**, 179–206.

Mosher, D.C., Piper, D.J.W., Calvin Campbell, D. & Jenner, K.A. 2004. Near-surface geology and sediment-failure geohazards of the central Scotian Slope. *AAPG Bulletin*, **88**, 703–723, doi: 10.1306/01260403084.

Piper, D.J.W. 1991. Surficial geology and physical properties 6: deep water surficial geology. *In*: *Scotian Shelf*. 121., doi: 10.4095/210698.

Piper, D.J.W. 2005. Late Cenozoic evolution of the continental margin of eastern Canada. *Norwegian Journal of Geology*, **85**, 305–318.

Piper, D.J.W. & Aksu, A.E. 1987. The source and origin of the 1929 grand banks turbidity current inferred from sediment budgets. *Geo-Marine Letters*, **7**, 177–182.

Piper, D.J.W. & Ingram, S. 2003. Geological Survey of Canada Major Quaternary sediment failures on the east Scotian Rise, eastern Canada. *Current Research - Geological Survey of Canada*, 1–7.

Piper, D.J.W. & Mccall, C. 2003. A Synthesis of the Distribution of Submarine Mass

Movements on the Eastern Canadian Margin. *In*: Locat, J. & Mienert, J. (eds) *Submarine Mass Movements and Their Consequences*. Springer Netherlands, 291–298., doi: 10.1007/978-94-010-0093-2.

PIPER, D.J.W., FARRE, J.A. & SHOR, A. 1985. Late Quaternary slumps and debris flows on the Scotian Slope. *Geological Society of America Bulletin*, **96**, 1508–1517.

PIPER, D.J.W., COCHONAT, P. & MORRISON, M.L. 1999. The sequence of events around the epicentre of the 1929 Grand Banks earthquake: initiation of debris flows and turbidity current inferred from sidescan sonar. *Sedimentology*, **46**, 79–97.

PIPER, D.J.W., MOSHER, D.C., GAULEY, B.J., JENNER, K. & CAMPBELL, D.C. 2003. The chronology and recurrence of submarine mass movements on the continental slope off southeastern Canada. *In*: Locat, J. & Mienert, J. (eds) *Submarine Mass Movements and Their Consequences, Advances in Natural and Technological Hazards Research*. Springer Netherlands, 299–306.

PIPER, D.J.W., MOSHER, D.C. & CAMPBELL, D.C. 2012. Controls on the distribution of major types of submarine landslides. *In*: Clague, J. J. & Stead, D. (eds) *Landslides: Types, Mechanisms and Modeling*. Cambridge University Press, 95–107.

PIPER, D.J.W., CAMPBELL, D.C. & MOSHER, D.C. 2016. Mid-latitude complex trough-mouth fans, Laurentian and Northeast fans, eastern Canada. *In*: Dowdeswell, J. A., Canals, M., Jakobsson, M., Todd, B. J., Dowdeswell, E. . & Hogan, K. A. (eds) *Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient*. London, Geological Society, 363–364., doi: 10.1144/M46.93.

SKENE, K.I. & PIPER, D.J.W. 2003. Late Quaternary stratigraphy of Laurentian Fan: A record of events off the eastern Canadian continental margin during the last deglacial period. *Quaternary International*, **99**–**100**, 135–152, doi: 10.1016/S1040-6182(02)00116-7.

SKENE, K.I., PIPER, D.J.W. & HILL, P.R. 2002. Quantitative analysis of variations in depositional sequence thickness from submarine channel levees. *Sedimentology*, **49**, 1411–1430.

SMITH, D.P., RUIZ, G., KVITEK, R. & IAMPIETRO, P.J. 2005. Semiannual patterns of erosion and deposition in upper Monterey Canyon from serial multibeam bathymetry. *Geological Society of America Bulletin*, **117**, 1123–1133, doi: 10.1130/b25510.1.

TODD, B.J. 2016. The Laurentian Channel : a major cross-shelf trough in Atlantic Canada. *In*: Dowdeswell, J. A., Canals, M., Jakobsson, M., Todd, B. J., Dowdeswell, E. . & Hogan, K. A. (eds) *Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient*. London, Geological Society, 161–162.

Figures

Figure 1: Location of Laurentian Fan and the Western Levee of Western Valley (black frame) off of the eastern Canadian continental margin. EV: Eastern Valley, CV: Central Valley, WV: Western Valley

Figure 2: GI-gun seismic profiles illustrating A) the surficial MTD in relation to the unnamed channel and a large 150 ka MTD (MTD-D); B) the stratified levee deposits and the occurrence of mass-transport deposits (MTD). Red polygons represent buried MTDs.

Figure 3: Multibeam bathymetry (60 m grid) of the Western Levee of Western Valley illustrating the spillover channel and the large mass-transport deposit (WLWV MTD).

Figure 4: Sub-bottom profiles (3.5 kHz) of the two main acoustic facies observed in the upper stratigraphic succession of the levee: A) high-amplitude reflections with occasional small mass-transport deposits (MTD) and B) chaotic to incoherent acoustic facies representing the major WLWV MTD affecting a large part of the levee.

Figure 5: Multibeam bathymetry of the upper levee illustrating the different geomorphological features present, including ridges and troughs, blocky debris zone, crown cracks and lobe superposition.

Figure 6: Backscatter map of the Western Levee of Western Valley illustrating the higher intensity over the mass-transport deposit and flow lineations.

Figure 7: Huntec and sub-bottom profiles (3.5 kHz) of the Western levee illustrating A) erosion of the glide plane and emergence at the toe of the MTD and B) retrogressive headwalls in the upper parts of the levee. Red polygon represents a buried MTD.

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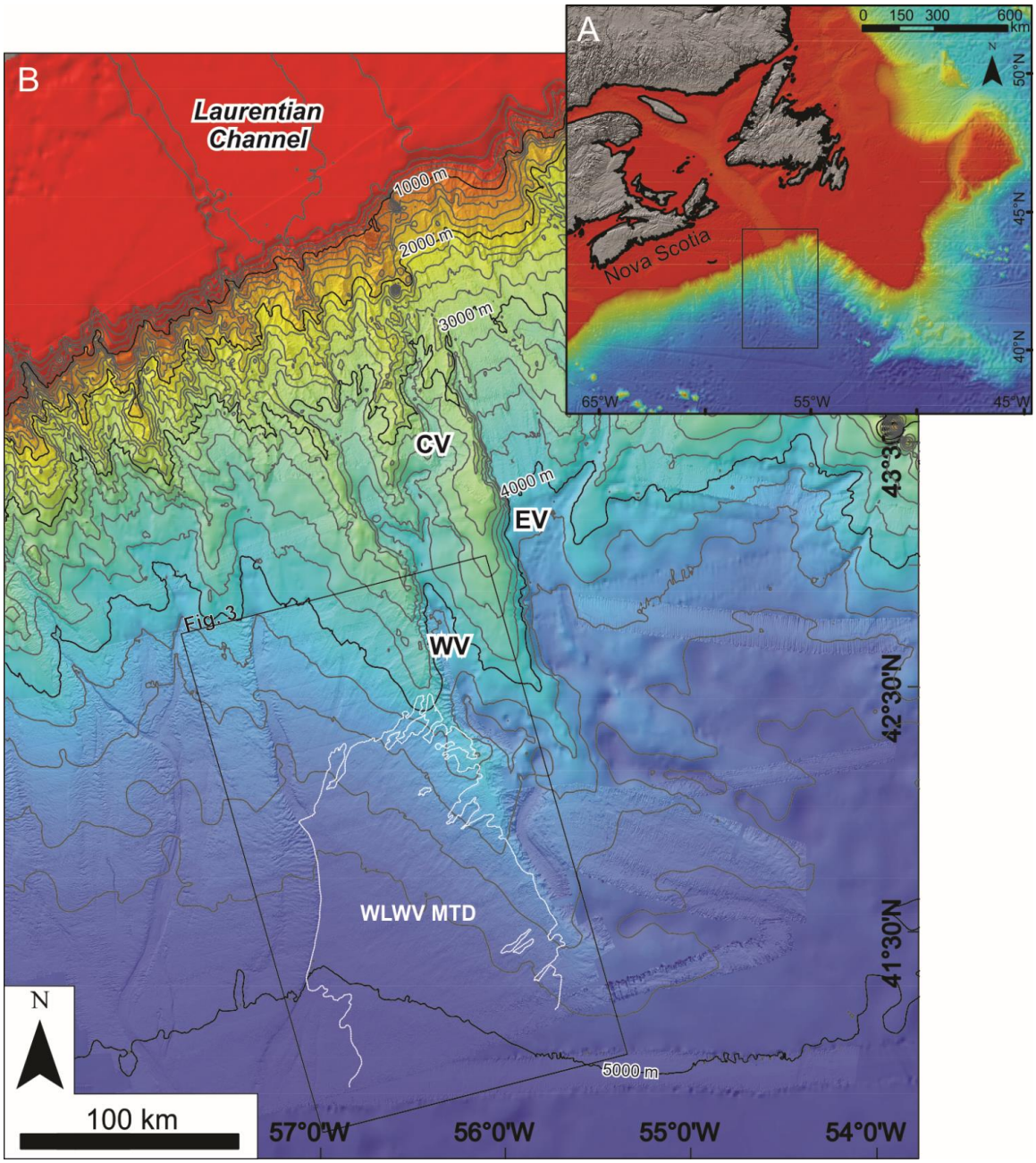
460 Figure 1



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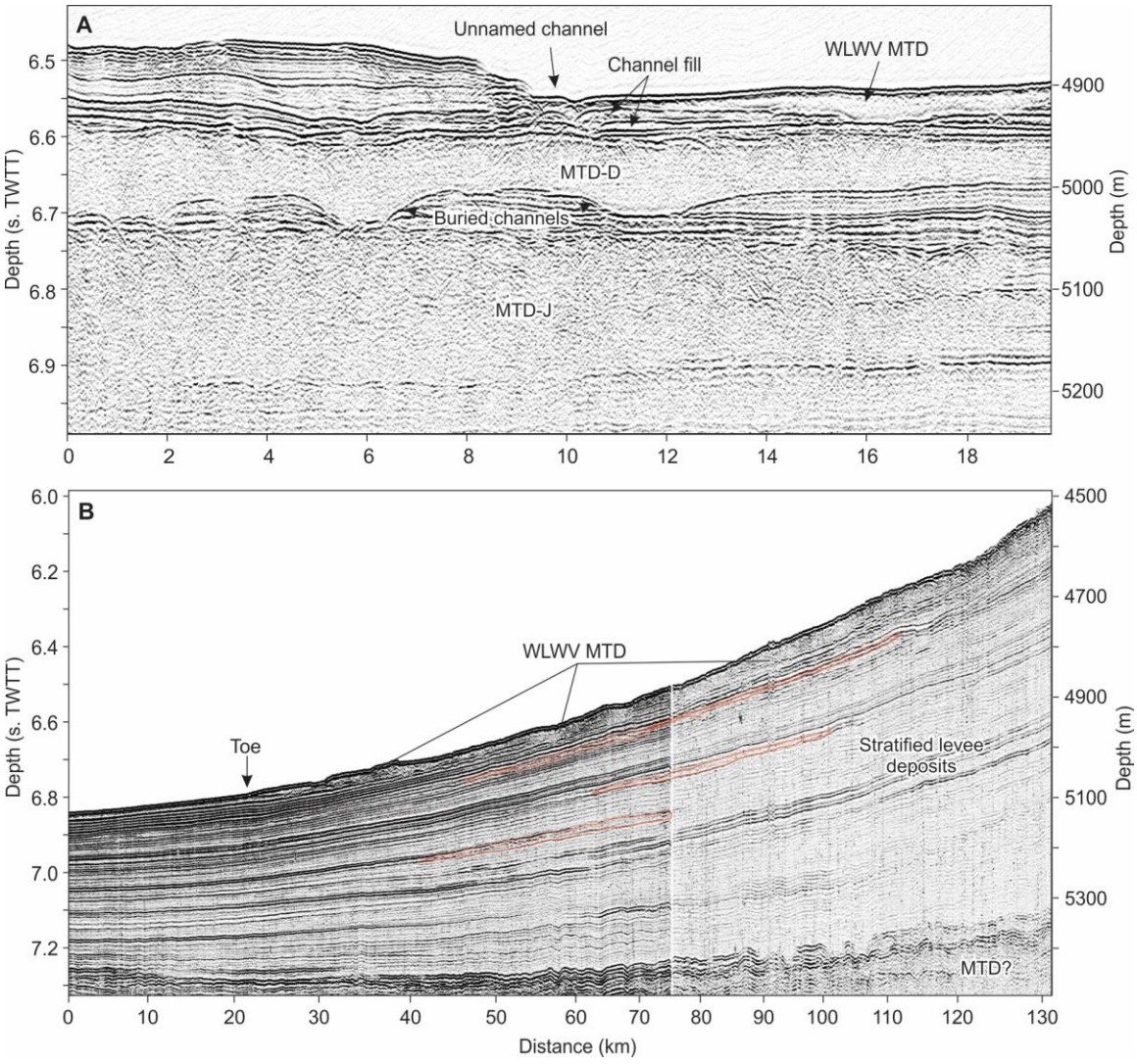
463 Figure 2



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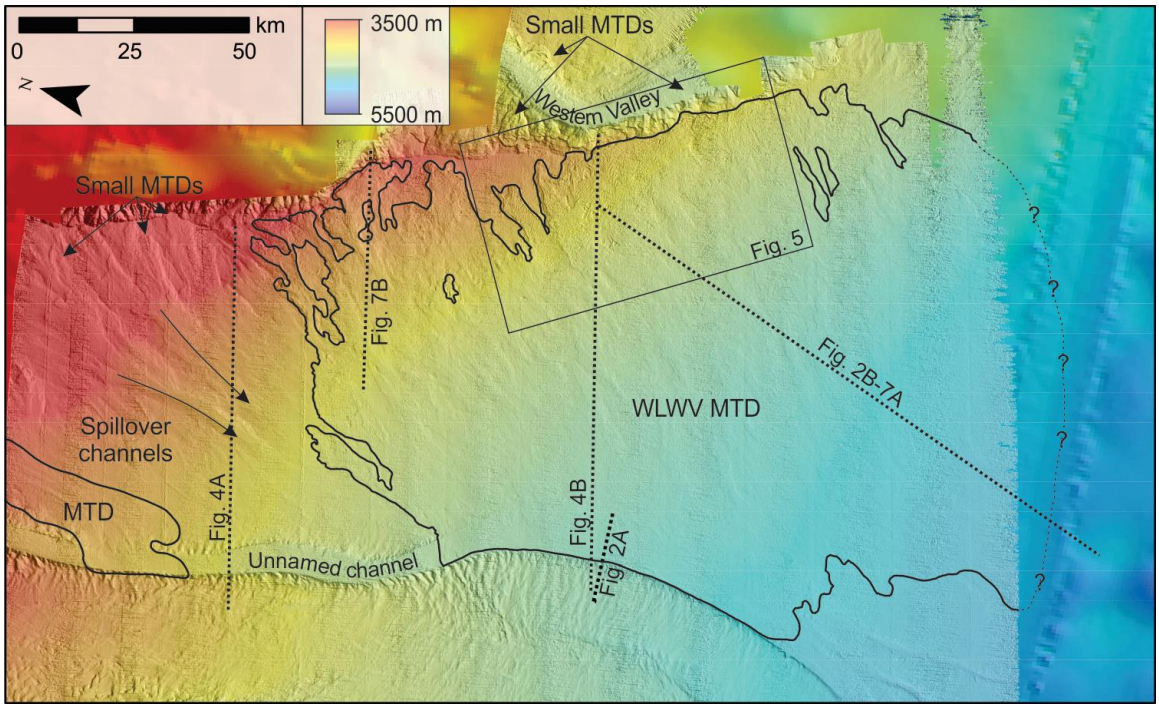
466 Figure 3



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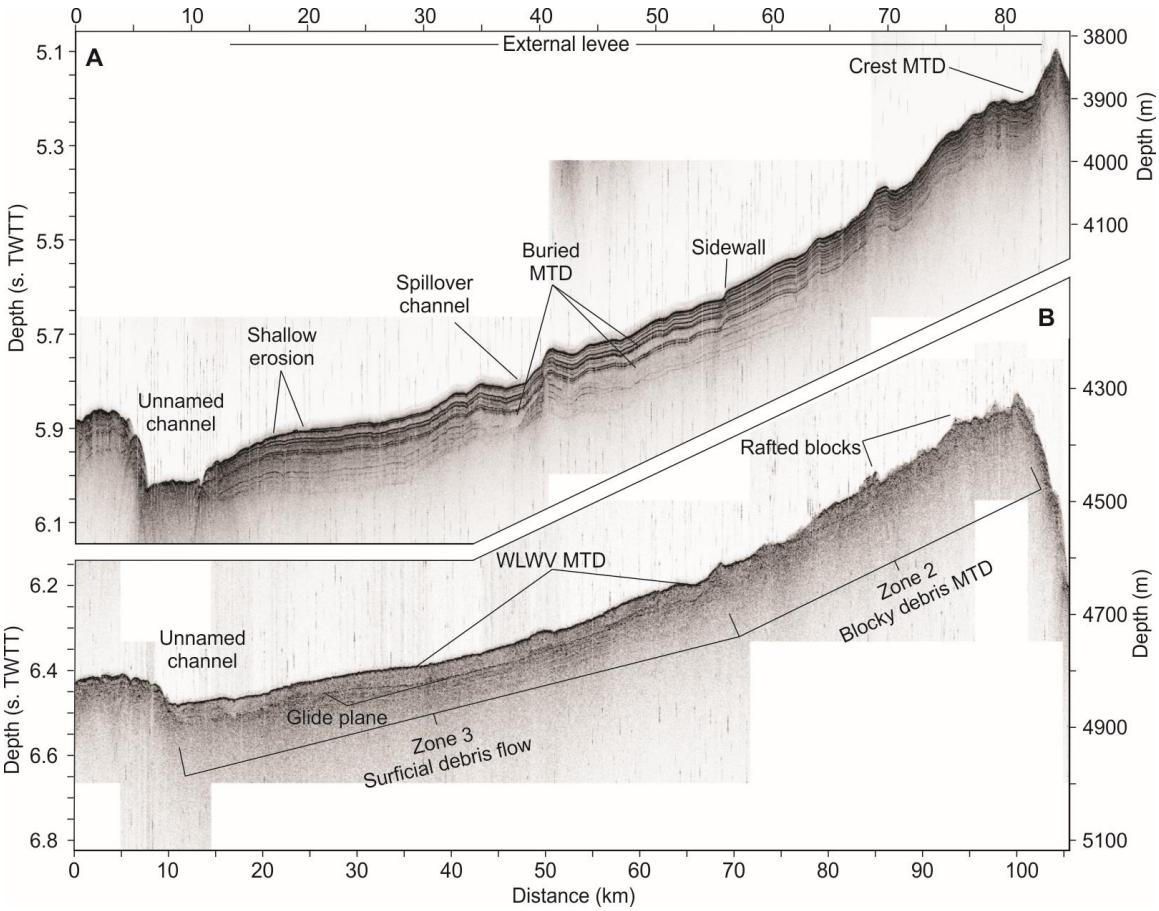

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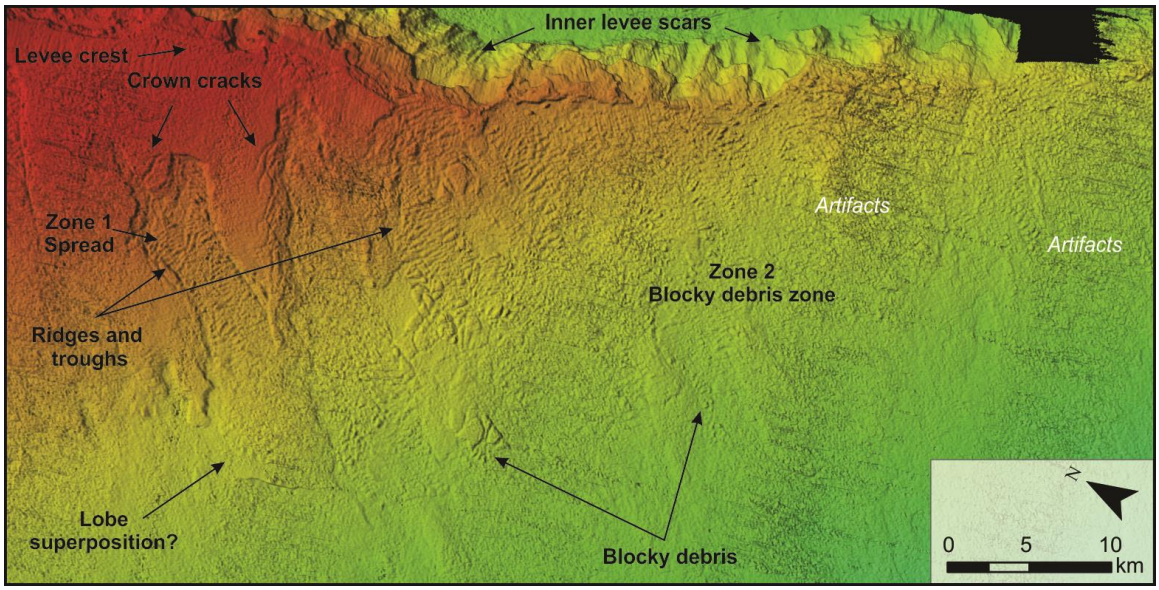

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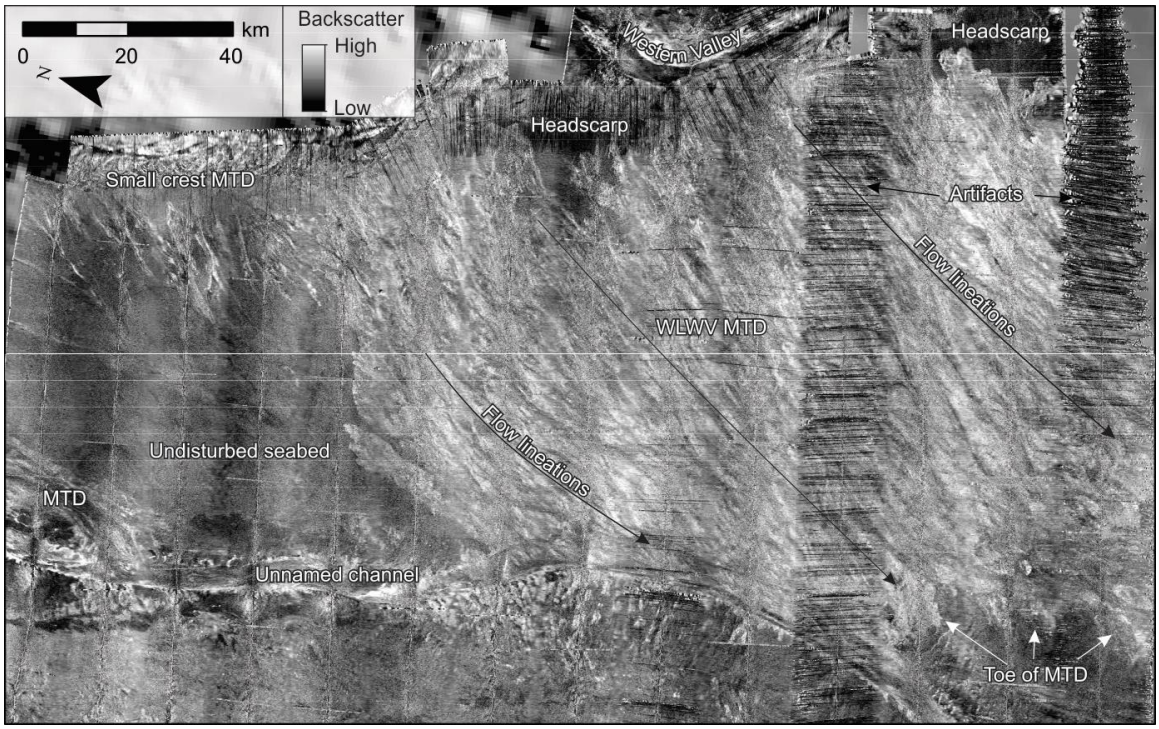

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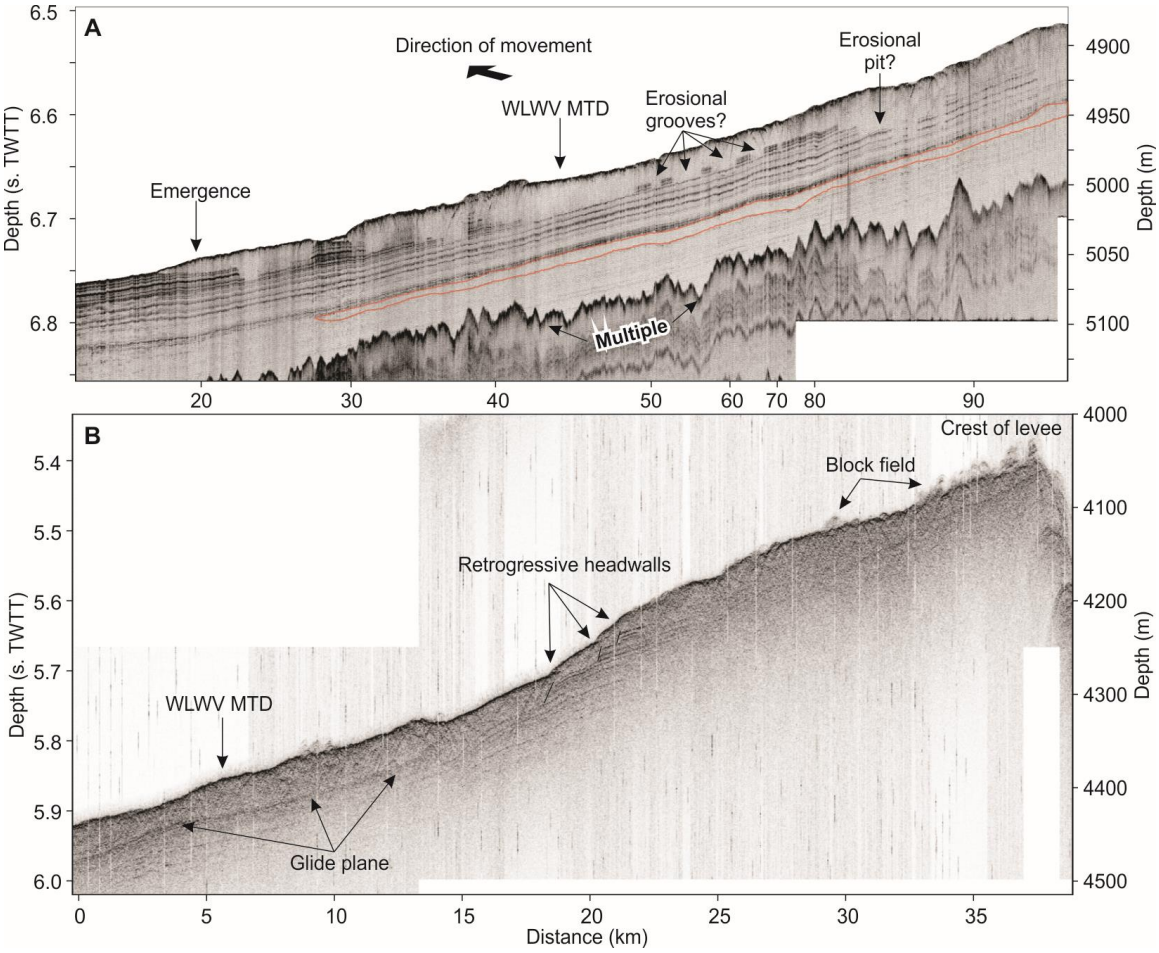
478 Figure 7



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