Geological Survey of Canada
Scientific Presentation 100

A FULL SUITE OF SEABED AND SHALLOW GEOHAZARDS ON THE BEAUFORT SLOPE AND OUTER BEAUFORT SHELF, OFFSHORE NORTHWEST TERRITORIES: GLACIAL, PERMAFROST, AND TECTONIC CONTROLS

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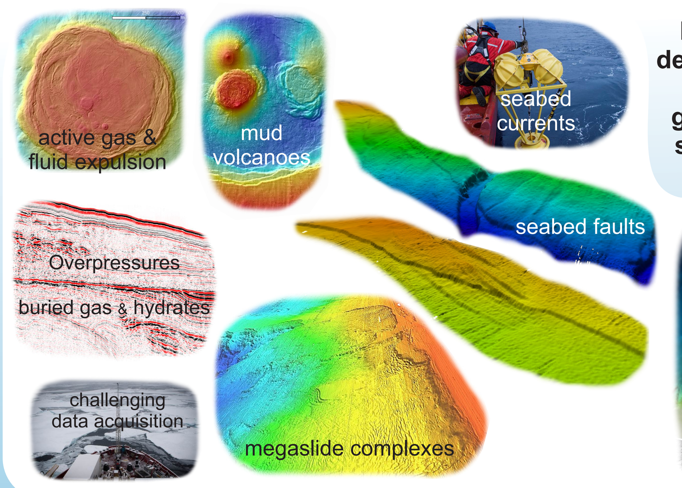
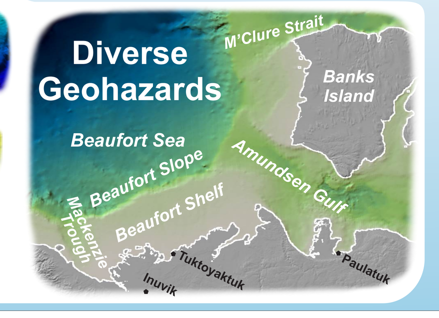


Public safety and infrastructure design in the Beaufort Sea requires understanding potential geohazards, many or which have seabed and shallow sub-surface manifestations.



Potential Geohazards are diverse and widespread; the existence of many has been known for decades, some for over a decade and some only recently. Their understanding has advanced significantly under recent focus.

Shallow overpressures on the slope generate widespread mud volcanoes, some actively fluxing gas, warm and fresh fluids with the mud. Overpressures in the Mackenzie Trough are linked to a paleo ice stream regional unconformity.

Mass failure events diminished following glaciation but continued periodically with the largest, most widespread and numerous, in recent time. Large seabed slide valley complexes involved multiple, retrogressive events following large deep-cutting initial failures, possibly tsunamigenic.

Large-scale rotational/slide activity 1350 yrs ago is followed by retroactive failure only 100s years old. Fresh porewater influx from permafrost degradation and/or long-traveled meteoric sources, and high sedimentation rates are likely pre-conditions to the failures. Epicenter proximity and failure periodicity suggest seismic triggering.

Deep-seated post-glacial faulting is also been recognized recently, with seabed throw exceeding 14 m along scarps traced for 10s km and potentially tsunamigenic.

Periodic and erosive bottom currents in a narrow band at the shelf break have evolved since glaciation and are deduced from mapping, oceanographic modelling, age-dating and seabed instrumentation approaches.

Densely-spaced hills, Pingo-Like-Features (**PLFs**), commonly with both growth and collapse components, are developing within Holocene age mud, mainly at the degrading buried permafrost front. Some are ice-cored while some leak methane. They are diapiric and likely active.

Advancement is being made on the **glacial framework**, including sediment type and distribution mapping in Mackenzie Trough, Amundsen Gulf and M'Clure Strait. Direct evidence of offshore ice margin deposits, flowpaths, stratigraphy, chronology (limited precision due to long C-14 age extrapolations back in time), retreat pattern, and ties to the land are now much better understood. Central Beaufort Shelf, much of Banks Shelf and the Yukon Shelf still present challenges.

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Advances in Glacial Framework

A regional development of the shallow geologic framework is advancing, mainly based on interpretations from multi-channel and very high-resolution sub-bottom profiler data and C-14 dated sediment cores.

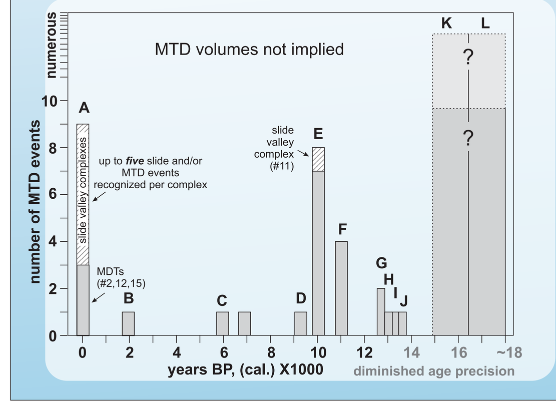
- The Canada Basin has a **very thick** and complex fill, highly accelerated with glaciations and clearly emanating from the Beaufort Shelf and Amundsen Gulf. These experienced **mega-scale deep-water buried failure complexes** (Mosher et al. 2012 and subsequent investigations by King). The base of the late Cenozoic Iperk Formation (mainly glacially derived) has now been mapped across the entire Canadian Beaufort Sea, reaching over 4 km thick and extending over 850 km north of the Tuktoyaktuk shoreline.
- The Yukon Shelf has only **limited remnants of glacial deposits**, much eroded across the inner shelf where there are also indications of very shallow permafrost (King et al. 2019).
- New and concrete delineation of glacial margins is emerging. Last glacial maximum and retreat margins are now recognized in Mackenzie Trough, followed by late and post-glacial sedimentation in Mackenzie Trough whose distribution varies strongly with space and time. A thin glacimarine mud blanket in the outer portions is followed by a thick and rapid influx from the eastern bank driven by bank erosion with sea-level rise. The river-dominated deposition dominates in the inner portions.
- An **ice shelf** (floating glacier) emanating from Amundsen Gulf flowed westward along the Beaufort Slope, carving long erosional lineations (Reidel et al. 2021). The shelf was likely buttressed by both a shelf-situated glacier and a basin-wide melange. Subsequently, a till tongue deposit along 170 km spanning the entire mouth of Amundsen Gulf, attests to a thin ice-stream calving margin of uniform thickness at 440 m present water depth.
- **Shelf-crossing glaciations** across Banks Island Shelf number only two, contrasting strongly with multiple phases in adjacent Amundsen Gulf (Batchelor et al 2014), but in addition to the single phase they identified. A prominent inner-shelf terrace, clearly low-stand formed, has a complex internal stratigraphy and may span multiple glacial phases.
- M'Clure Strait, north of Banks Island Shelf, has very limited preservation of glacial sediment, represented by broad till blankets, locally built into moraines, and an enigmatic mid-trough moraine that may emanate from the Innuitian Ice Sheet, to the north (King et al. 2014, 2015).

Sub-seabed Slope Mass Failures: Spanning Post-glacial Age

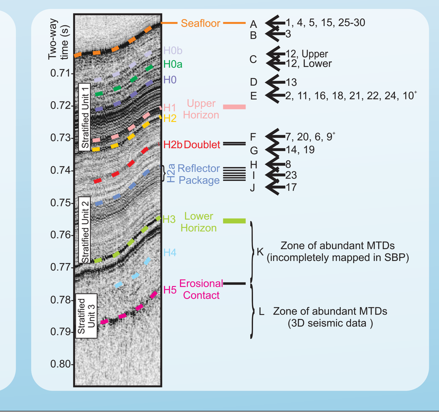
Buried Mass Transport Deposits (MTDs) are mapped over part of the Beaufort Slope and correlated though horizon tracing on high resolution (ArcticNet) sub-bottom profiler transects to an undisturbed type-section area. The overlying MTDs are mapped and grouped at stratigraphic levels. This provides a spatial and stratigraphic MTD overview to which selected C-14 dated sediment cores are similarly correlated (within ~1ka or better).

Numerous but undifferentiated MTDs at the base of the stratified unit represent a period of multiple glacial or earliest post-glacial failures. Yet **failures continued periodically**, spanning the Holocene, including a very large failure complex (mauve) at about 10 ka (cal.). However, none reach the extent and magnitude of the surficial failure complexes (panel below).

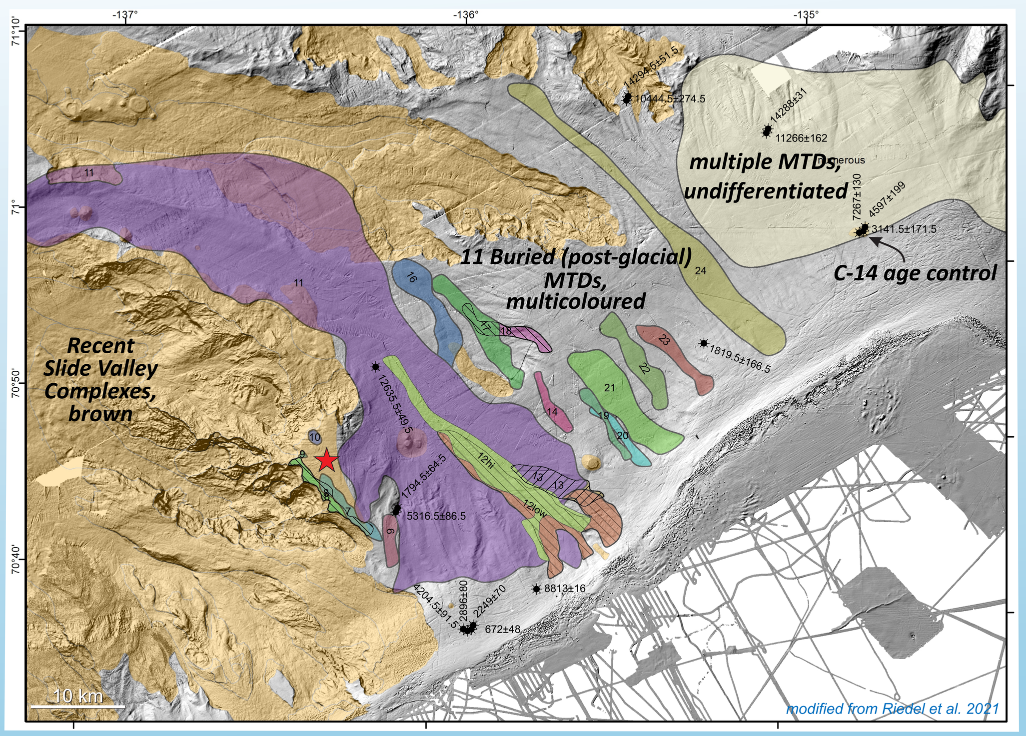
Mass failure deposit frequency during deglacial and post-glacial time. Unmapped but numerous failures dominate late glacial time but numbers and ages are not quantified (panels modified from Riedel et al. 2021).



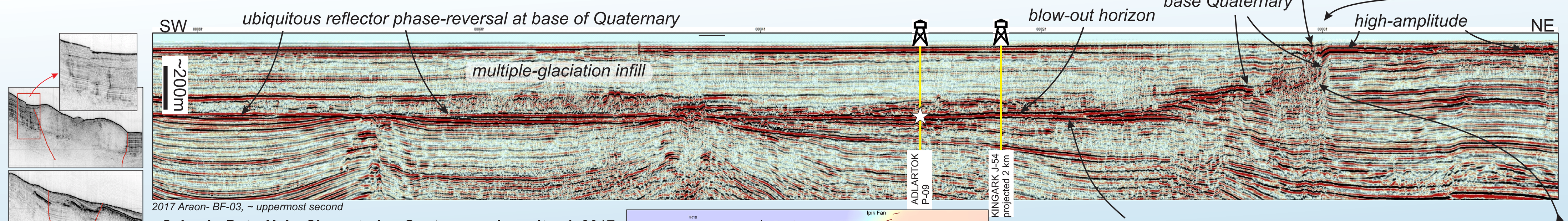
Buried MTDs are grouped stratigraphically and tied to this "type section", an entirely undisturbed "island" located at the red star.

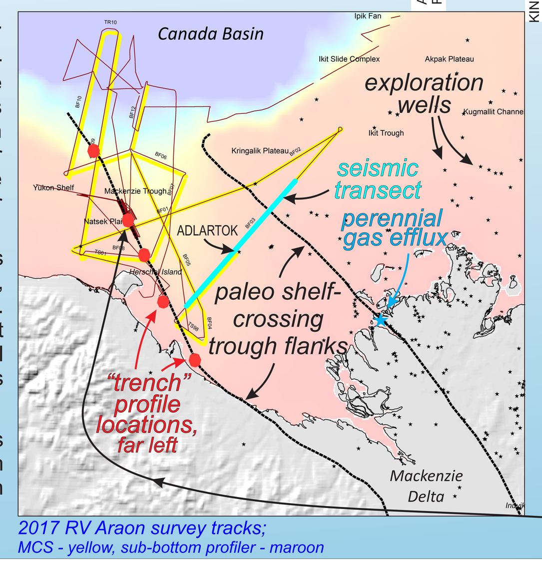


Buried MTDs: Numerous MTD events, bounded by undisturbed, stratified late and post-glacial mud, are mapped. Numbering subject to change as MTD in other areas are incorporated.



Recent Multi-channel Seismic (MCS) across the Yukon Shelf and Mackenzie Trough; Drilling Blowouts at the base of Quaternary and Fluid Efflux at the Paleo-trough Flanks





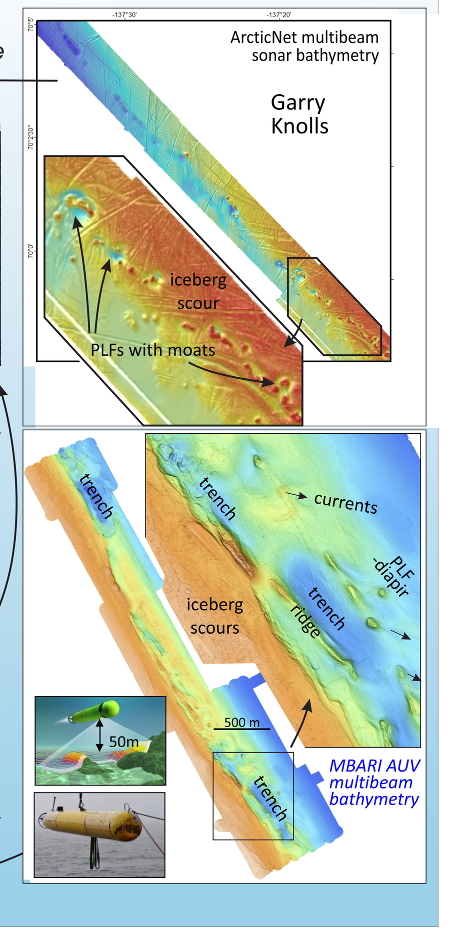
Seismic Data Help Characterize Quaternary deposits: A 2017 KOPRI and NRCan collaboration collected a suite of 890 km high-resolution MCS, map on right, aboard Research Vessel *Araon*, the first academic-driven survey here for decades (Jin et al. 2018). This transect of the Mackenzie Trough provides improved resolution along an industry line. The trough was much larger under earlier glaciations (Bachelor et al. 2013) and is largely infilled. Multiple glaciations are preserved (Duchesne et al. 2020) but their depositional environment is not well understood.

Fatal Drilling Blow-out: A review of past drilling logs and reports indicate a serious drilling incident occurred at this horizon (see star), involving full blow-out and a fatality (Malloy and Dallimore in prep.). The nature of change in sediment conditions at this interface is not clear but decreased permeability, from ice and/or clay-rich glacial sediments clearly confines fluids and gas on a regional basis as manifest by the phase-reversal on seismic lines (above).

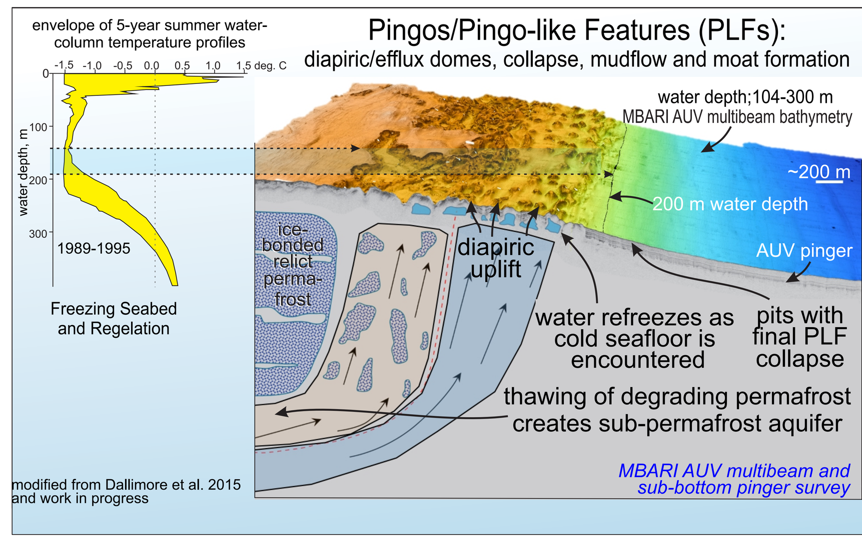
Trough-Flanking Trench: Sub-bottom profiler (3.5 kHz) transects (left) across a ubiquitous "trench" along the western paleo-ice stream erosional flank. Disturbance outlined in red. Locations, red dots on map. Vertical scale applies to all. See also AUV multibeam, far right.

Trapped Shallow Gas: Gas, fluids and permafrost are manifest as high-amplitude or bottom-simulating reflections (BSRs) arising from free gas, hydrates, and/or permafrost, meteoric water or their combinations. In the Mackenzie Trough a **regional phase-reversed reflector** marks the base of Quaternary deposits. The reversal arises from gas and perhaps permafrost at this horizon, either capped by less permeable glacial deposits or partly frozen sediments. Buried permafrost plays a strong but poorly understood role, including on bottom-simulating reflectors. Improved seismic imaging of buried permafrost in the area can help such knowledge gaps (Grob et al. 2023; Duchesne, et al. 2023).

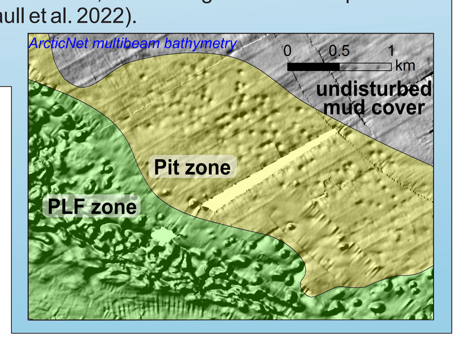
Gas/Fluid efflux conduit: Despite local "leaks" manifest as enhanced amplitude in overlying Quaternary units, apparently much of the gas/fluid is re-directed by the steep, buried flanks of the paleo-ice stream-formed trough. There, fluid efflux is concentrated, forming PLFs and narrow ridges, many with collapsed crests and moats but the main elements are linear trenches. All features are strongly **aligned with both flanks**. Even a long-known perennial gas efflux at the shoreline falls on this lineation (blue star on map). Various types of seabed structural disturbances at Garry Knolls (east flank) and all along the western flank (panel, far left) are now linked to this continuous, and steep geologic contact. This efflux appears unrelated to active slope-situated mud volcanoes (Paull et al. 2015).



Pingos/Pingo-like Features (PLFs):
diapiric/efflux domes, collapse, mudflow and moat formation



Regelation: Ice in sediment cores from PLFs apparently substantiates a model of relict permafrost melting from below (geothermal flux) and migrating to a front now located at the shelf break. Some of this efflux, on encountering freezing near-seabed temperatures re-freezes in the PLF. **Allochthonous Gravel and Diapirism:** MBARI ROV and AUV backscatter demonstrate gravel on the PLF flanks but dating indicates entirely Holocene age host sediments. Even near the Mackenzie River mouth, such sediments contain no gravel, so it is believed to originate from glacial sediments at depth, through diapiric action. The mechanism of density difference and rising glacial sediment is unclear; fresh fluid, ice and gas may all be involved. **Final PLF collapse:** Recently recognized zones of pits, just beyond the shelf break and partially mud-infilled (below), represent the fully collapsed and final stage of PLF evolution. Collapse events, mimicing calderas, some with associated mudflows, are recognized as frequent and ongoing (Paull et al. 2022).

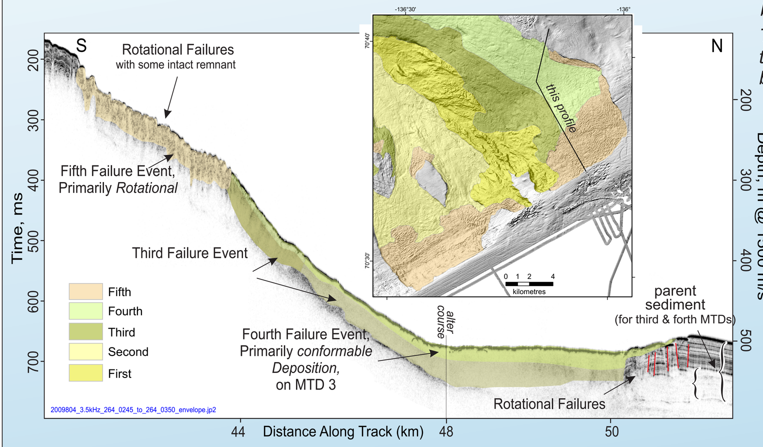


Slope Mass Failure: Dating the Most Recent Events

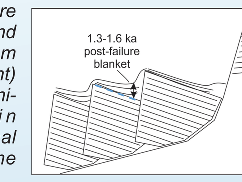
Known for over a decade, multiple and extensive Slide-Valley Complexes have no discernable sediment cover on sub-bottom profiler transects, suggesting **a recent age**. Their relative age has been unravelled (Cameron and King 2018) but absolute age determination is challenging. A thin (~20 to 40 cm) red-banded regional blanket is now recognized, both within and outside the failures. C-14 dating within one large retrogressive failure yields ~1.3 ka while widespread Pb and Cs dating (Cameron et al. 2017, Douglas 2017) yield "dates" **from 230 to 410 years**, summarized below.

Present interpretation is that **large failures occurred approximately in the last millennium** while smaller, widespread retrogressive failure, not generally recognized at multibeam bathymetry resolution, occurs in the last hundreds of years. Some periodicity in this suggest seismic triggering.

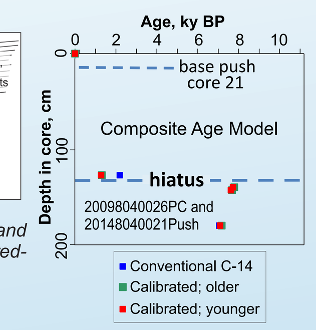
Numerous events within a Slide Complex have been unravelled from cross-cutting relations from both sub-bottom profiler and mutibeam imagery (Cameron and King, 2018). Unfortunately, this is resolution-dependant and gives little absolute age information, unlike in the buried MTDs in the panel above. All surficial failures have no sediment cover and all head- and side-walls fully cut the uppermost sediment horizons on the sub-bottom profiler data. The high resolution in targeted AUV-surveyed failure areas allow further individual event differentiation.

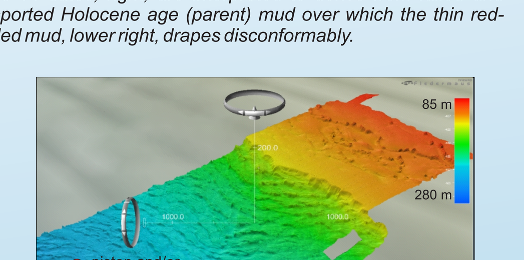


Schematic of rotational failure sampled by a piston core and undisturbed box core from which the push core (right) was sub-sampled. The mini-basins collect a thin (decimetres) post-rotational banded mud providing the basis for failure dating.

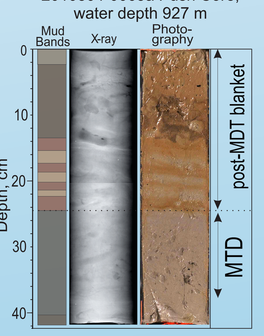


The C-14 dates, right, are interpreted to derive from failed and transported Holocene age (parent) mud over which the thin red-banded mud, lower right, drapes disconformably.

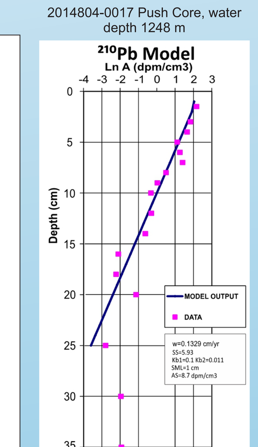




AUV-collected multibeam bathymetry perspective in shelf-break rotational retrogressive failure zone, similar to the setting for the core at right.

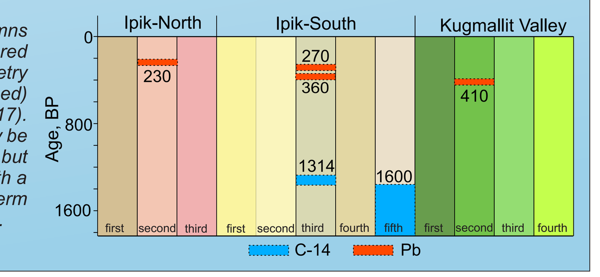


Example of one of five directly Pb-dated cores, right, spread across two major Slide Valleys and the intervening, un-failed area. The red-banded blanket has distinctive and roughly correlatable digital colour character across tens of km. Here it covers a massive MTD.

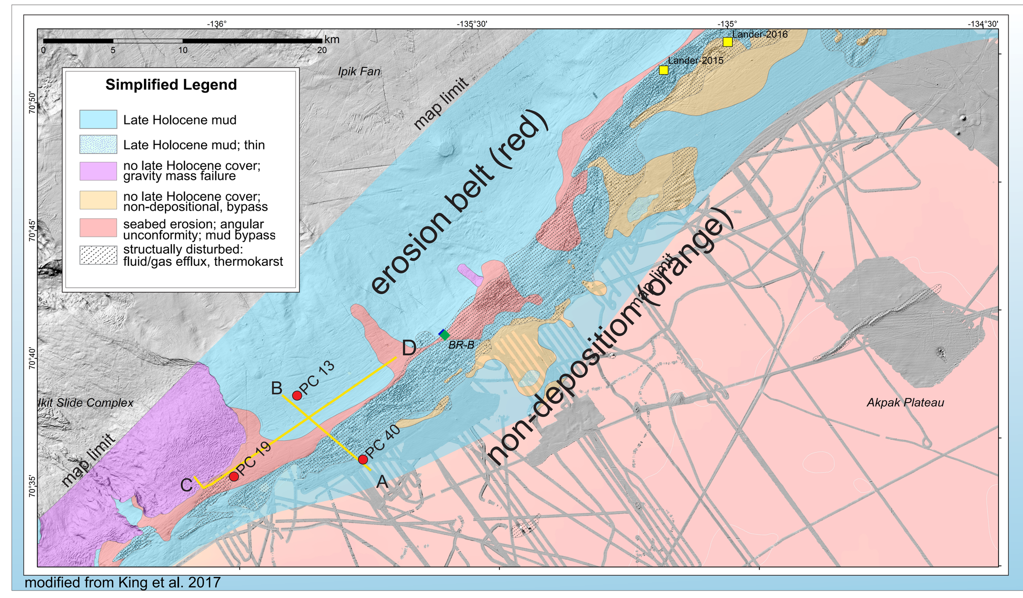


Pb and Cs analyses, left, yield a reliable trend in this selected example and match those of Bringue and Rochon (2012). C-14 derived sedimentation rates are linear and those of Bringue and Rochon (2012). This suggests reliable age derivations. However, recognition of a basal MTD in the core is not always straightforward.

Failure Age Summary: *(right) Vertical columns represent individual MTD events deciphered from cross-cutting relationships in bathymetry and seismic profiles for each of three (named) Slide Valley Complexes (Cameron et al. 2017). Age dating is shown. Note that erosion may be such that as few as two events occurred, but these are widespread. This is compatible with a seismic trigger and matches the longer-term (post-glacial) episodic nature of mass failures.*



Shelf-break Erosion Events: Evolution of the Beaufort Sea Jet (BSJ)

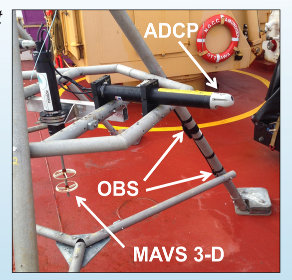


Belt of erosion: Mapping of an angular unconformity in the Holocene mud sequence (King et al. 2017) depicted extensive erosion with locally up to 40 m (typically 5-10 m) mud removal. Strongest in the west and diminishing eastward, it is confined to a belt at the shelf break. Coincidence with the Beaufort Shelf Jet suggests a causal relationship. However, the geostrophic current process alone cannot explain currents sufficient for erosion. Modelling and instrumented landers further approach this challenge. The **landers confirm periodic seabed current sufficient to exceed derived erosion thresholds** (Li et al. 2020, excerpt, right). These are not only open water phenomena; winter events can be strong.

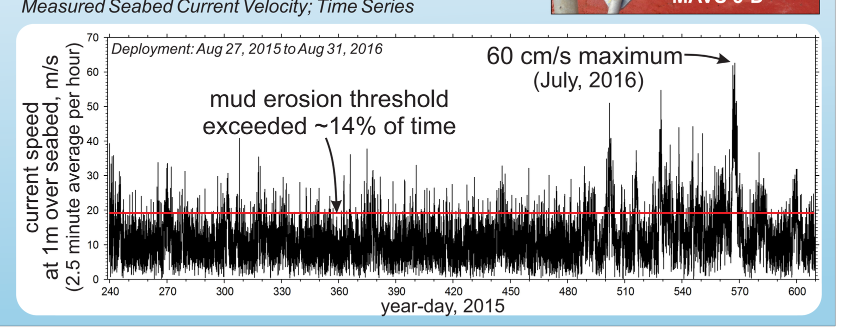
Post-8ka current evolution: Dating of cores and their correlation to seismic horizons traced to the shelf break demonstrate that the erosion cuts into Holocene-aged mud. A **change in depositional conditions occurred between 5 and 8ka** BP (cal.) from a quiescent (draping) to a current-influenced mode (erosion, non-deposition and onlap), see panel below. The surficial geology map, left, shows the distribution of these zones. The pattern, confined to the shelf-break and coincident with the modelled BSJ, is interpreted to be causal. The age indicates **initiation of the proto-BSJ**, likely as the Bering Strait opened for Pacific waters. Enhanced Holocene deposition follows along the uppermost slope, where the core of the BSJ weakens and thus juxtaposes the erosion-bypass belt with enhanced deposition.

Further Current Erosion Evidence: 2017 Araon sub-bottom profiler and MBARI AUV data near Herschel Island confirm that related currents matching modelled BSJ directions sweep the Yukon Shelf (lower, right on panel above). Their presence here (far from the shelf-break) suggests that other periodic high-energy current events, such as breaking internal waves at the shelf-edge, are a less-likely alternate interpretation.

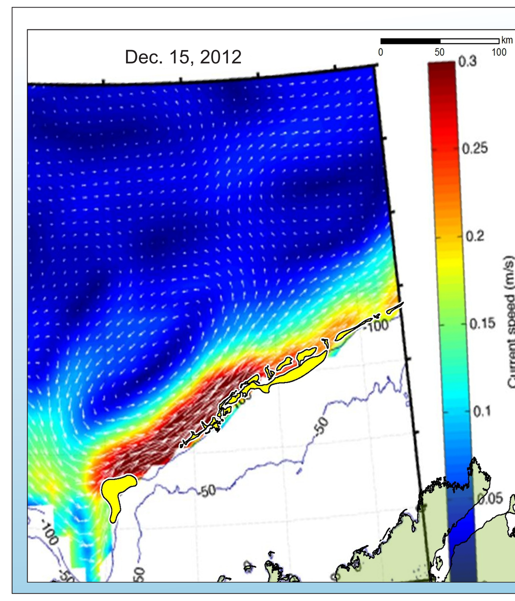
The Lander Instrument



Measured Seabed Current Velocity; Time Series



Modelling The Beaufort Sea Jet

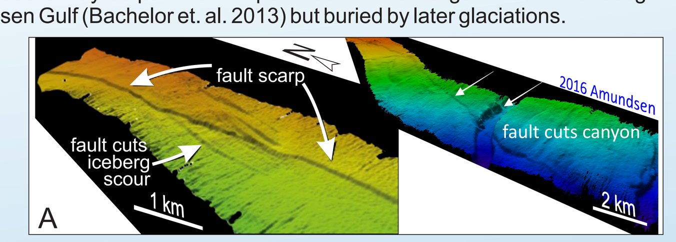


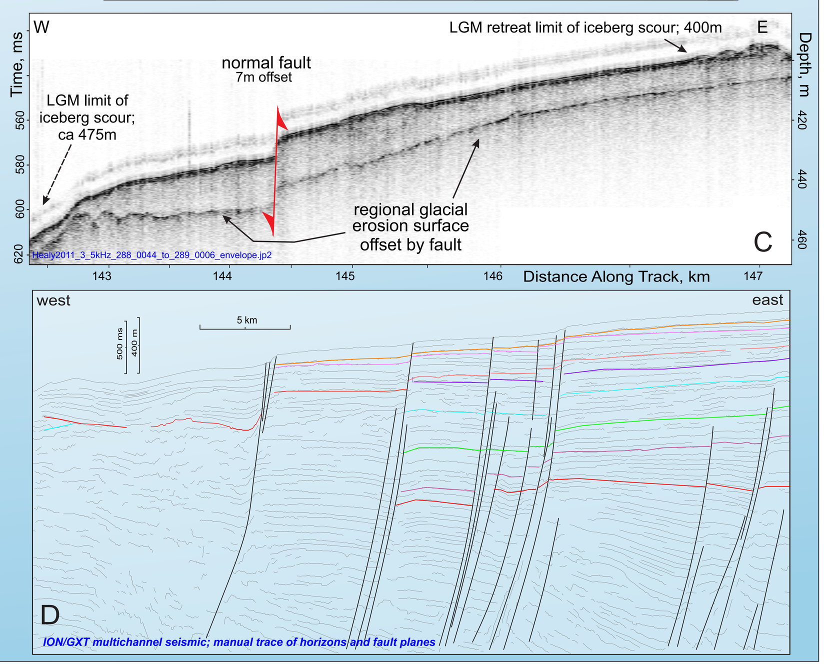
DFO and NRCan collaborated to apply a 3-D model of the Beaufort Sea towards demonstrating the geologic phenomena. This is the first such modelling study of the BSJ (Ding and Wu, 2017). The modelled BSJ generally flows eastward, along the depth contours, with occasional reversal. The non-deposition and erosional zone (red and orange on the adjacent map) occurs within the seabed impact zone of the BSJ (King et al. 2017). The 3D model successfully represented both up- and down-welling currents during storms, dense water cascading and formation of meso-scale eddies due to thermohaline convection associated with fall and winter sea-ice formation and a breakup event. Sensitivity experiments suggest wind-driven currents are the most important accelerator of the BSJ.

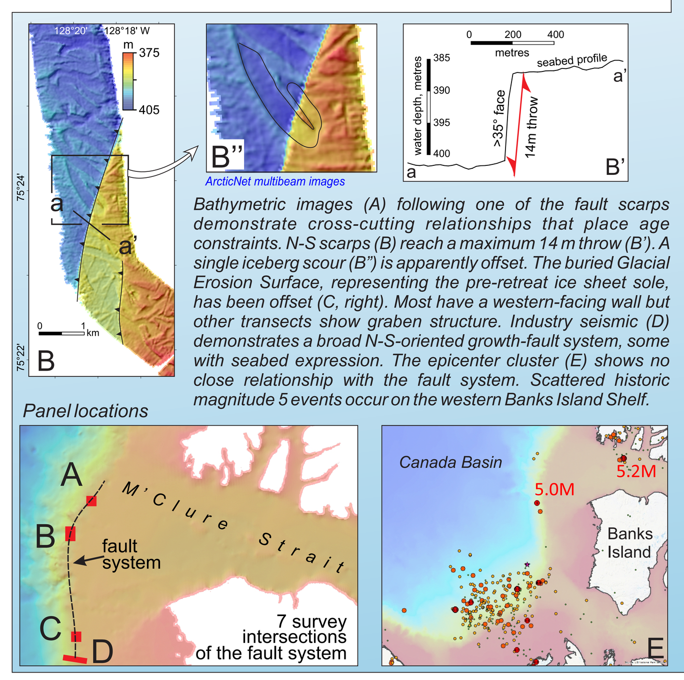
Snapshot of modelling results showing the BSJ with dominant NE direction at 100m depth, sufficient to erode mud. Yellow polygons represent the mapped erosion and non-deposition belt.

Neotectonics; deep-seated post-glacial reactivation

Seabed Fault Scarp: Early Post-glacial Age: Seven sub-bottom profiler transects across a fault complex show **offset at the seabed from 3 to 14 m**. The MCS demonstrate a broad system seated in basement. An argument can be made for **early post-glacial activity** because iceberg scours and late-glacial canyons are offset yet some scours may be penecontemporaneous. Even larger offsets are recognized in Amundsen Gulf (Bachelor et. al. 2013) but buried by later glaciations.

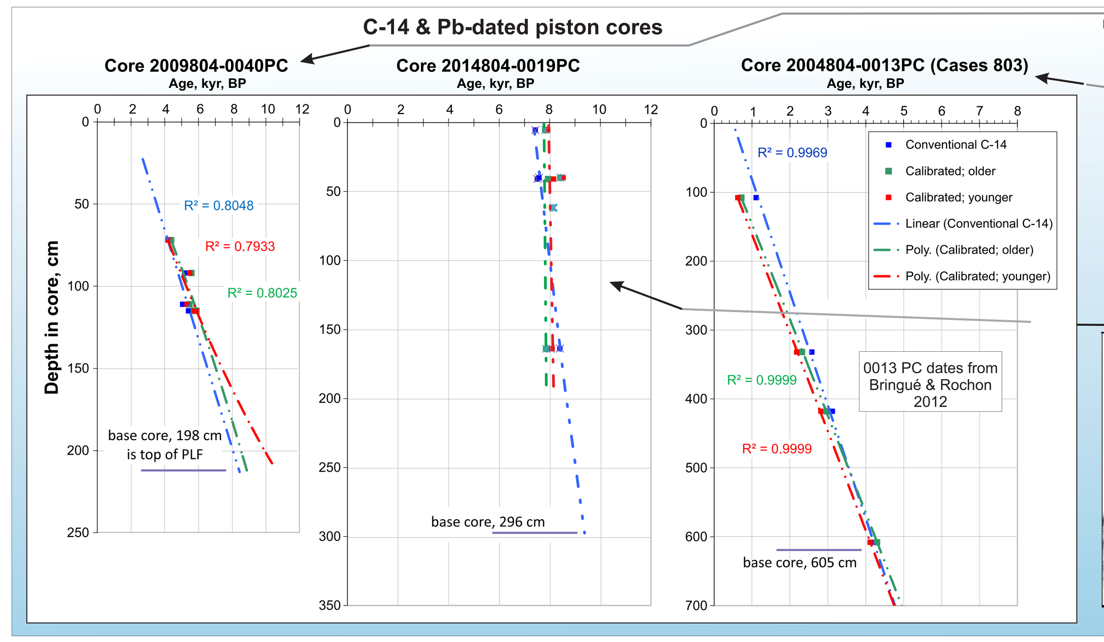


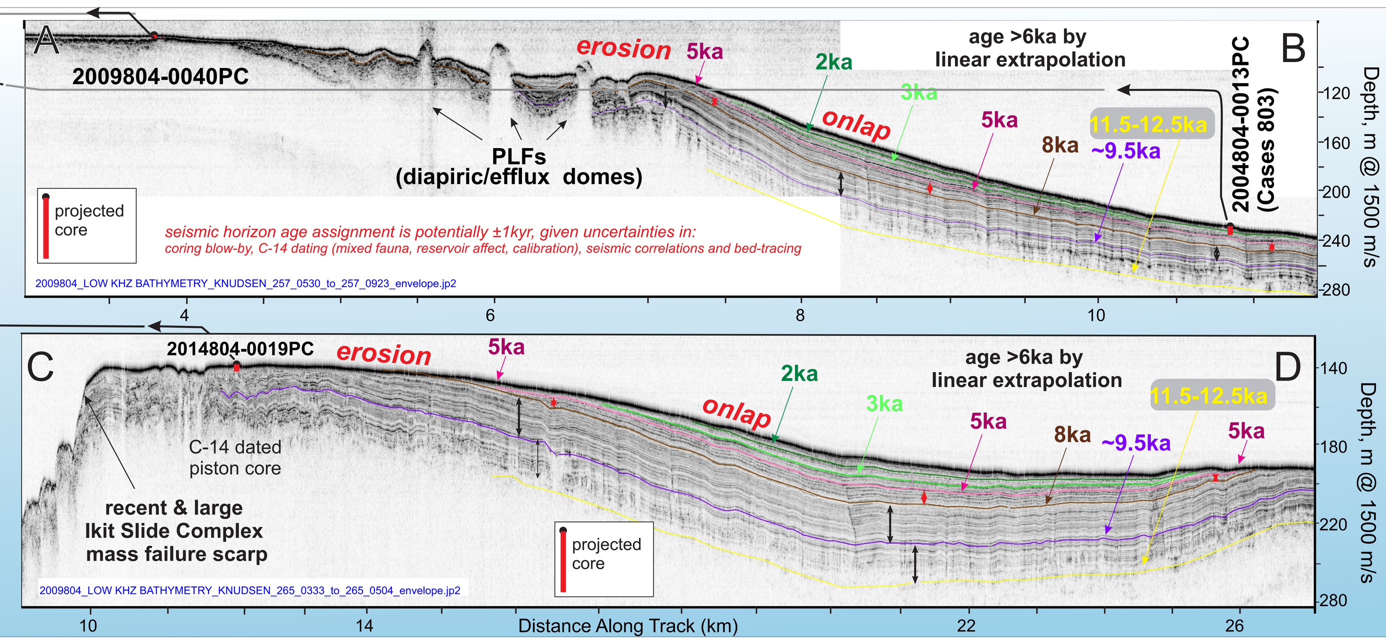




Bathymetric images (A) following one of the fault scarps demonstrate cross-cutting relationships that place age constraints. N-S scarps (B) reach a maximum 14 m throw (B'). A single iceberg scour (B') is apparently offset. The buried Glacial Erosion Surface, representing the pre-retreat ice sheet sole, has been offset (C, right). Most have a western-facing wall but other transects show graben structure. Industry seismic (D) demonstrates a broad N-S-oriented growth-fault system, some with seabed expression. The epicenter cluster (E) shows no close relationship with the fault system. Earthquakes Historic magnitude 5 events occur on the western Banks Island Shelf.

C-14 & Pb-dated piston cores





Dating the Shelf-break Erosion

A-B: *High resolution 3.5kHz sub-bottom profiler collected by ArcticNet with C-14 dated cores projected and initial seismostratigraphic horizons with assigned ages. Strata from about 11.5 to 12.5ka BP Cal., in yellow, drape a buried iceberg scoured surface and until ~8ka (brown) maintain a uniformly draped blanket deposit. The 9.5 to 5ka interval thins gradually toward deeper water but truncates at the shelf-break (black double-headed arrows). Seismic profile locations are shown on the western (lower panel) surficial geology map.*

C-D: *A dip line, A-B, demonstrates a uniform blanket thickness (vertical black arrows) was maintained for several millennia (to younger than 8ka), draped over the ~11.5 to 12.5ka yellow horizon. The 8 to 5 ka interval, by contrast, thins preferentially at the shelf break (red arrows). This eventually evolved to magnitudes capable of erosion (here >10m removal); the older strata began to be truncated at the shelf-break while local deposition was maintained on the immediately adjacent slope. This is interpreted as a temporal increase in shelf break energy and evolution from drape, through bypass and to erosional conditions. The change occurred shortly after ~7ka and was well established by before 5ka. Just below the shelf break, deposition continued to the present day; diminished in later Holocene but enhanced below this. Erosion and/or bypass is maintained nearby at the shelf break.*

References

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Acknowledgements

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