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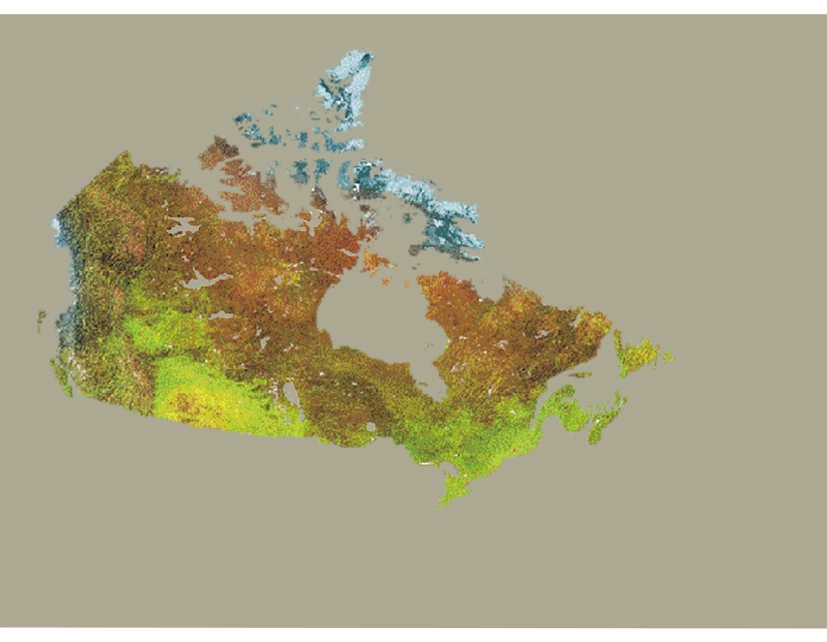

A BELT OF SEABED EROSION ALONG THE BEAUFORT SEA MARGIN, OFFSHORE NORTHWEST TERRITORIES, GOVERNED BY HOLOCENE EVOLUTION OF THE BEAUFORT SHELF-BREAK JET; GEOLOGICAL EVIDENCE, CURRENT MEASUREMENTS, AND INITIAL OCEANOGRAPHIC MODELLING

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Background: Drivers

Despite the diminished present activity from the hydrocarbon industry along the Beaufort continental slope, the interest in several plays remains. A GSC **Beaufort Sea Geohazards Activity** focuses on potential geo-engineering related issues.

The National Energy Board (NEB) requires assessment of potential geohazards related to safe drilling, anchoring and (eventually) production.

Sub-seabed and seabed-near permafrost

Permafrost and a changing thermal regime play a strong role in many of the geohazards. Sub-seabed zones where permafrost and gas hydrate, initially formed or stable during glaciation, are since degrading (melting) following marine incursion. These processes can generate elevated pressures at depth with resultant migration and seabed release of free water and gas including sediment entrainment.

These processes, include the generation of pingo-like features PLFs, marine pingos (ice-cored), and related mounds, ridges, troughs and holes, the result of various forms of efflux and sediment/fluid diapirism, and likely thermokarst.

Concerns at the Shelf Break

Oceanographic processes

Understanding the processes, pathways and fate of muds at the shelf break has implications for age-dating of large sediment gravity mass failures, seabed conditions for potential engineering infrastructure, and fate of natural compounds (e.g. carbon) and potential pollutants.

Currents have been studied largely through long-term and numerous anchored moorings. These help characterize the Beaufort Jet and related amplifying processes such as up- and downwelling (thermohaline, or dense water cascading with sea-ice formation and wind-driven coastal set-up).

Geological evidence for currents

Until now, erosion was tentatively attributed to either sea-level low-stand, glacial outburst flooding and/or oceanographic currents. Recent correlation of radiocarbon dates demonstrates, from the time frame, that only the post-glacial processes are at play; the Beaufort Shelfbreak Jet and associated amplifying processes appear to be responsible.

This poster focuses on a **belt of erosion and non-deposition** outlined in a new **surficial geology map** and the **effects of shelf-break currents** on the distribution and pathway of the muds, ultimately derived from the Mackenzie River. The map also depicts the belt of permafrost degradation-related sediment disturbance phenomena (including over 2500 pingo-like features) present along most of the Beaufort Shelf margin. The new chronology framework better constrains the activity levels of the sediment disturbance.

The Beaufort Shelf-break Jet (BSJ)

The Beaufort Shelfbreak Jet (BSJ) is an eastward-flowing, seasonally-variable, near surface contouritic oceanographic current originating from a branch of Bering Strait Pacific water tracing the edge of the Alaskan and Canadian Beaufort Shelves (also the western Arctic boundary current). Secondary processes periodically accelerate the current, manifest as up- and downwelling and eddies.

Erosion by the Beaufort Shelf-break Jet (BSJ)

The BSJ pattern and location matches **a 300km long erosion and non-deposition belt** suggesting a causal relationship given that the age of erosion precludes glacial or sea-level driven erosion. Local topographic perturbations with accentuated erosion are also consistent with contouritic flow. However, **the BSJ alone cannot reach erosive states**; complementary and **accelerating processes** such as wind driving, ice-forming and other dense water cascading and other shelf-break phenomena must be periodically contributing. Preliminary modelling is able to "generate" both the BSJ and some of such processes though their contribution magnitudes and sensitivities need further model development.

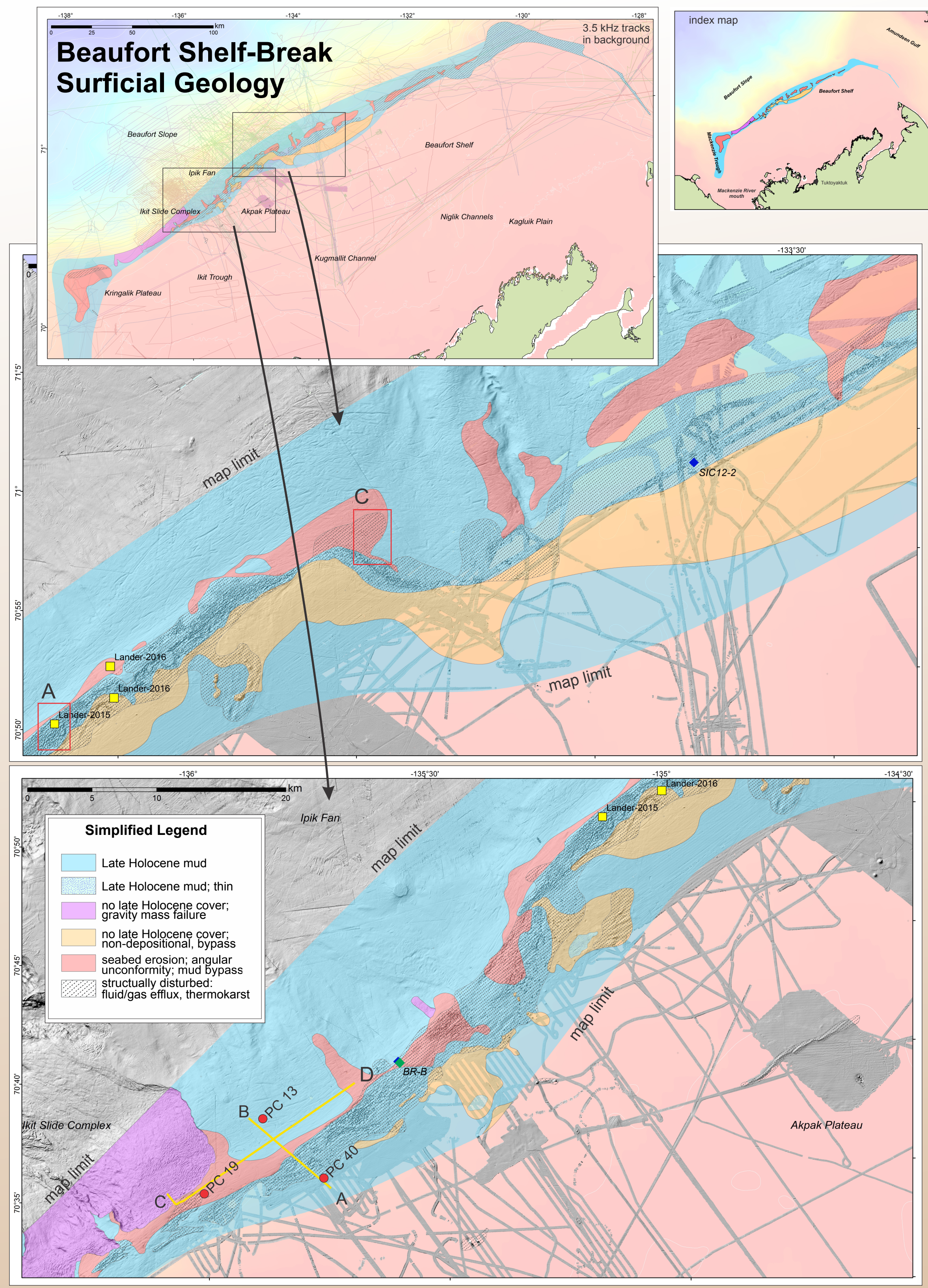
Science Highlights

Evolution of the BSJ

The shelf-break has undergone a **significant change in deposition pattern during the Holocene**. The geologic observations and their age constraints (despite various error sources in dating of the eroded strata), combined with the in-situ measurement of currents capable of mud erosion and the spatial superposition of the modelled BSJ indicates a **mid-Holocene evolution** of the BSJ and continued maintenance of shelf-break mud bypass.

Structural disturbance related to thermokarst and efflux

A broad band of structural disturbance of stratified sediments is mapped along the shelf-break. Processes responsible are not well understood but fluid and gas efflux, seabed waters at sub-zero temperature, local near-seabed permafrost, collapse phenomena, diapiric and associated flank failures are all observations that conform to a model of a degrading permafrost front at depth, liberating fluids. The new chronology framework demonstrates that the **disturbance is in thick Holocene age mud**, suggesting processes are ongoing.



Seabed Geological Evidence for Contour Currents

A preliminary **surficial geology map** of the shelfbreak and uppermost slope emphasizes a narrow belt of erosion on stratified Holocene and glacial age sediments and associated non-depositional or mud bypass along much of the shelf flank of this erosion. Radiocarbon-dated Holocene muds are strongly influenced by the current at the uppermost slope. The **temporal evolution** is presented in the adjacent panel, below.

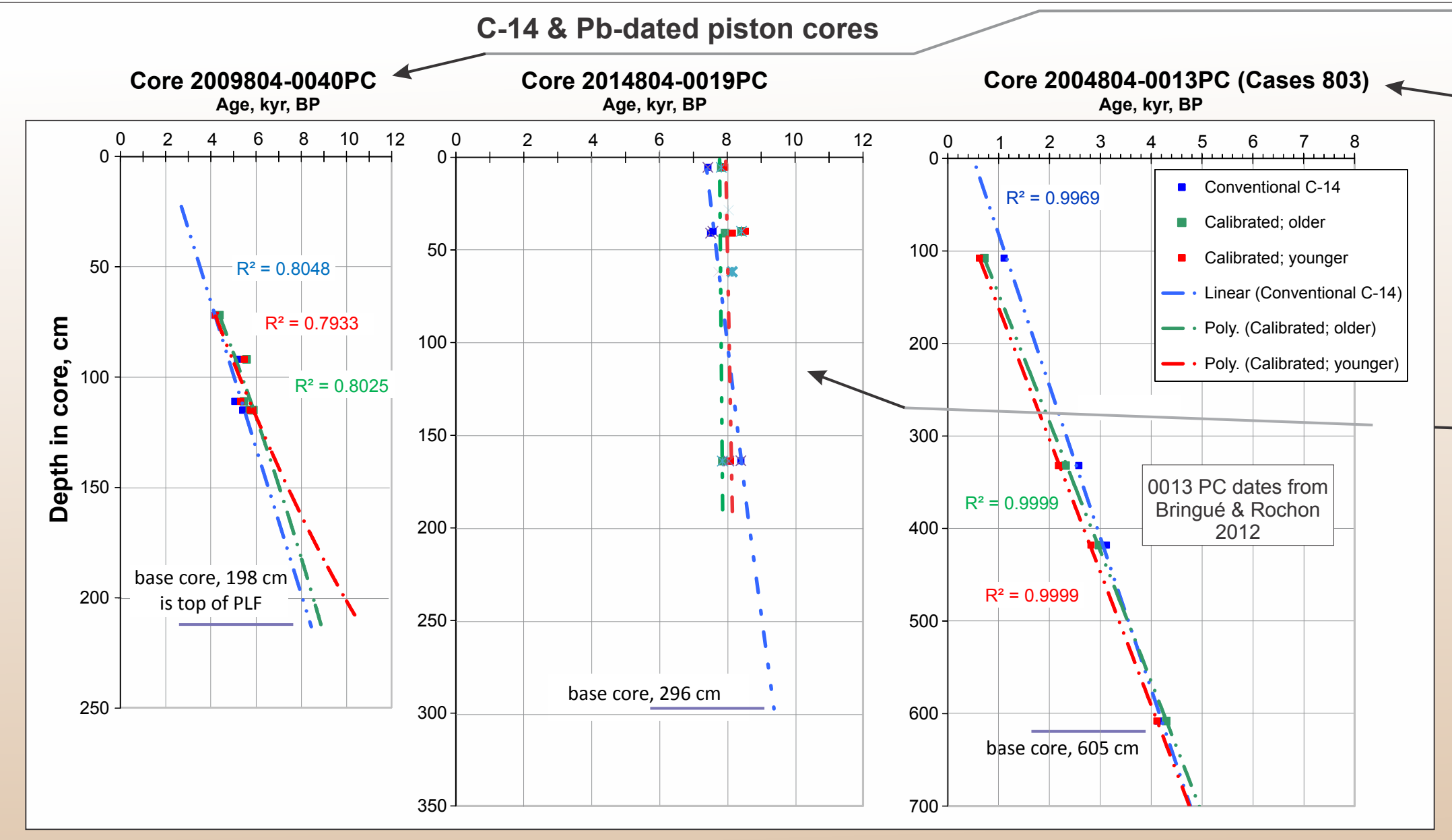
Legend

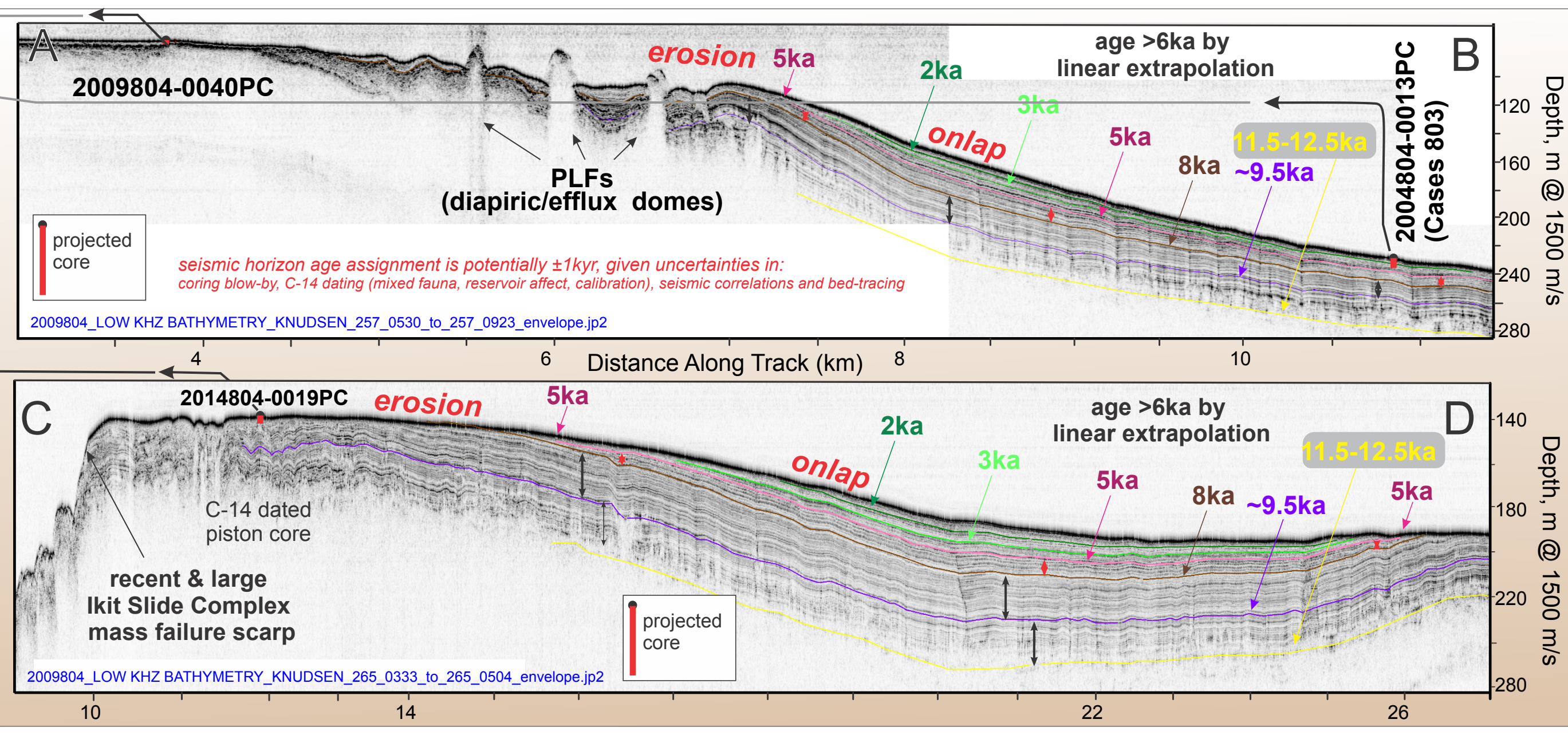
🟪	**Gravity Mass Wasting** The upper slope has large (1000-2000 sq km) slide complexes. Most are buried in the pre-glacial and de-glacial geologic section. However, many are at the seabed and so recent as to not register any Holocene mud cover on the sub-bottom profiles. Only these seabed occurrences are mapped here. The Holocene mud system must be understood to reconcile the paucity of mud cover (centimetres or decimetres) identified in cores with a real *or apparent* recent failure age.
🟦 thin	**Holocene Mud: Continuous blanket** 1-15m thickness Acoustically stratified on the slope where it covers a de-glacial blanket with similar character. However, the early Holocene mud depositional pattern changes at the uppermost slope from a uniform blanket to a ponded, onlapping and spatially and thickness-variable cover. The late de-glacial drape preserves buried morphology of iceberg scours, a process which was active until burial by about 12ka BP muds. Buried thermokarst and slide complex morphologies also image "through" the overlying muds. The deposit thins to decimetres beyond ~300m water depth.
🟨	**Non-deposition** The shelf-situated Holocene blanket is a wedge that commonly pinches out before the shelf-break. Here, the PLFs and related structures or the deglacial and early Holocene muds crop out. These are almost universally structurally disturbed but acoustic stratification remnants are common. Interpreted as bypass maintained by the currents responsible for the erosion belt.
🟥	**Seabed Erosion** Angular unconformity. Distribution is confined to a narrow belt along the shelf-break but exceptions occur across local topographic highs or where gross topographic features apparently influence the current turbulence, enhancing the width of the belt (e.g. at Kugmallit Canyon). Stratigraphically over a locally recognized sea-level low-stand horizon. There is no known lag associated with the erosion belt, likely because source material is generally distal fluvial mud or its re-transported equivalent.
▨	**Structural Disturbance** Shelf-situated mounds (Pingo-Like Features, PLFs), moats, buried mounds, arcuate and sinuuous ridges, trenches, including thermokarst mass-failure slides, thermokarst collapse. The de-glacial and Holocene muds are generally strongly structurally disturbed by this permafrost degradation-related process. This generally inhibits recognition of the map units. Where recognized, the mud is thin (0 to several metres) except where infilling a pre-existing slump scar, and locally ponded in moats and mini-basins between PLF mounds. The muds are iceberg scoured but not at the de-glacial intensity.

Surficial geological zonations in transparent colours over a seabed shaded relief image. Zones outline the erosion belt (red), a non-deposition area (brown) and mainly mud deposition (blue). The structurally disturbed (hatched) area commonly affects the stratigraphy sufficiently to mask the map units; continuity of the map units here is with lower confidence. Selected piston core locations (red circles), instrumented lander sites (yellow squares) and oceanographic mooring sites (diamonds) shown.

Though the map area benefits from multibeam bathymetric imaging, the geologic units are not well manifest by morphology or acoustic backscatter. Rather, they are defined and constrained by the accompanying 3.5kHz sub-bottom profiler data. The map limit does not imply map unit boundaries.

C-14 & Pb-dated piston cores





Geological Evidence for a Holocene BSJ Evolution

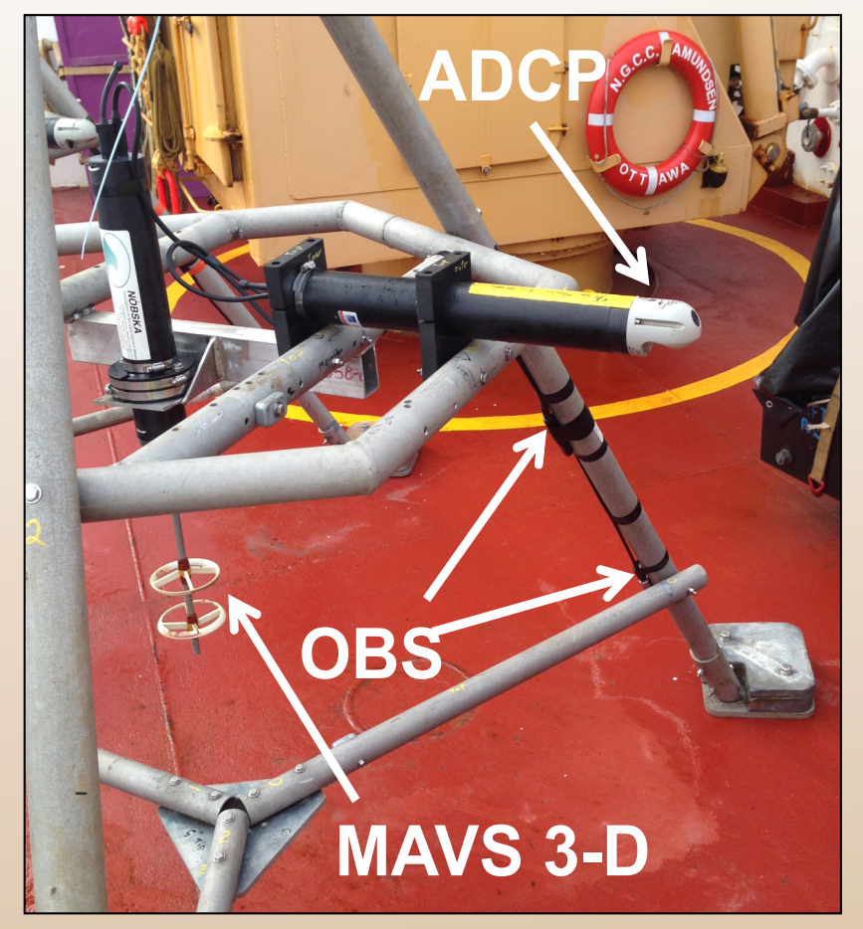
Dating of cores and their correlation to seismic horizons traced to the shelfbreak involves several error-prone assumptions and procedures that may limit precision to 1 or 1.5 kyr. Nevertheless, erosion in Holocene-aged muds is demonstrated. Furthermore, a change in depositional conditions occurred between 5 and 8ka BP (cal.) from a quiescent (draping) to a current-influenced mode (erosion, non-deposition and onlap). The surficial geology map shows the distribution of these zones. The pattern indicates that shallow (upper slope) current influence from the BSJ and related, amplifying processes, is responsible. The age indicates its evolution in mid to late Holocene time. A corresponding enhanced Holocene depocentre follows the uppermost slope suggesting that both erosion and bypass products deposit where the core of the BSJ weakens. However, this depocentre requires further mapping to establish patterns.

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 thickness is maintained at the shelf break (black double-headed arrows). Seismic profile locations are shown on the western (lower panel) surficial geology map.*

C-D: *As demonstrated in the dip line, A-B, a uniform blanket thickness (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 continues to the present day, albeit diminished, while erosion and/or bypass is maintained nearby at the shelf break.*

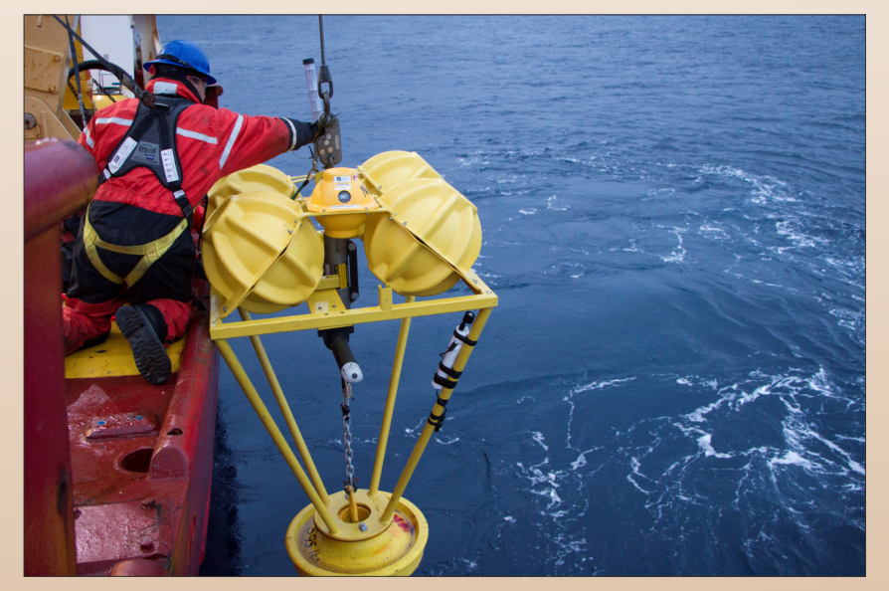
Direct Measurement: Nearbed Currents & Effects

The geological evidence indicated the need for direct observation of the currents and sediment transport at the seabed. Two landers were deployed in Sept 2015 and one recovered in Sept. 2016. Analysis from this is underway. Both the future modelling and the direct oceanographic measurements will attempt to decipher those (combinations of) processes which most directly influence the seabed.



The Instruments

- Optical BackScatter (OBS) for sediment concentration data at 0.5 and 1 m
- SeaBird MicroCat CTD sensor or a RBR CT sensor at 1.6 m height
- AquaDopp 2 MHz ADCP at 1.5 m; hourly current profile with 10 cm cell
- Nobska MAVS-3D or 4D current meters at 1 m height; high frequency velocity data at a fixed height
- Pressure sensors on both units for depth and wave data

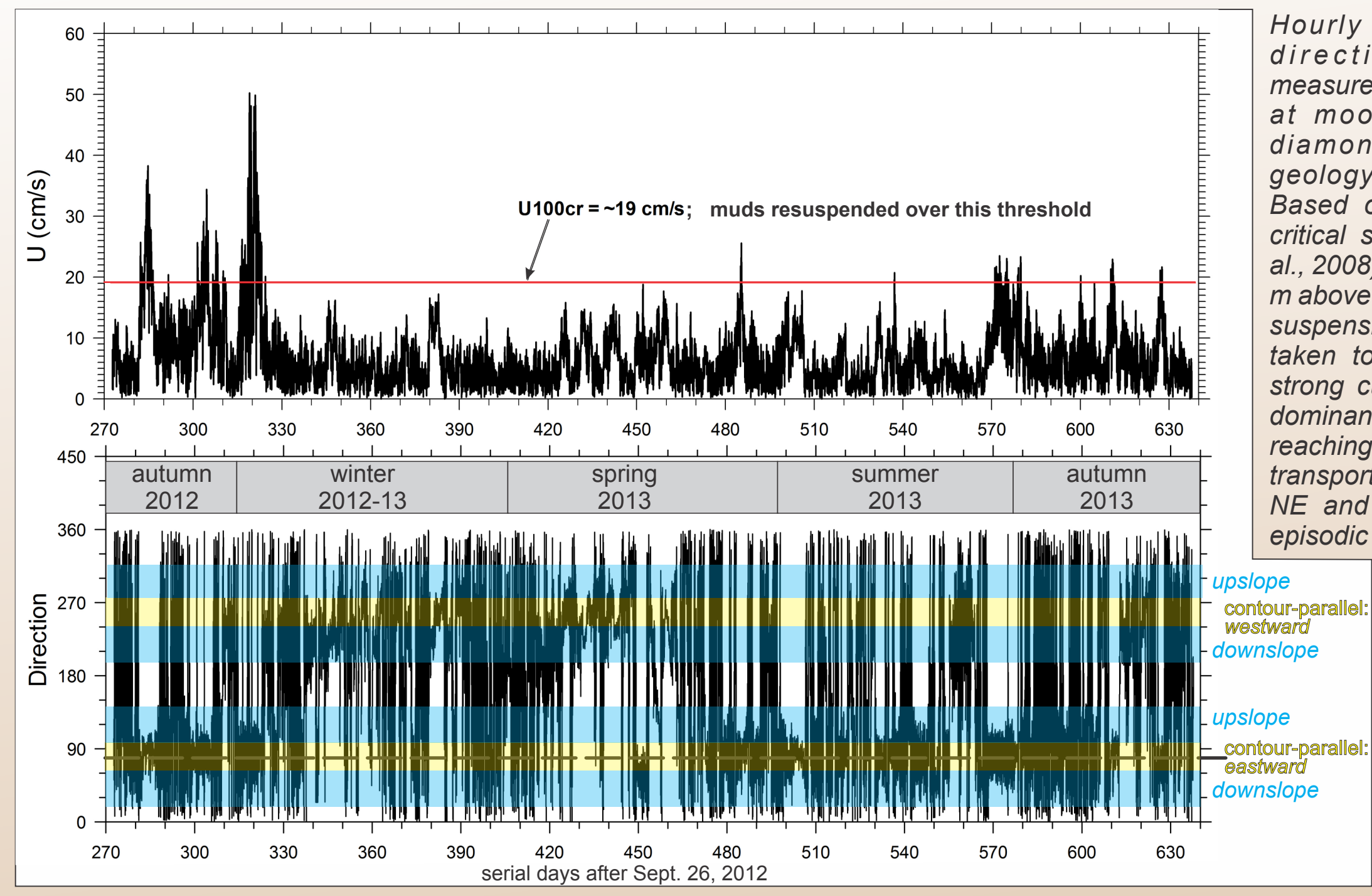


Anchored tripods and a free-fall (yellow) frame have been deployed at the outermost shelf (in the non-deposition zone) and the uppermost slope (on the erosion belt). Locations are shown (yellow squares) on the surficial geology map, left.

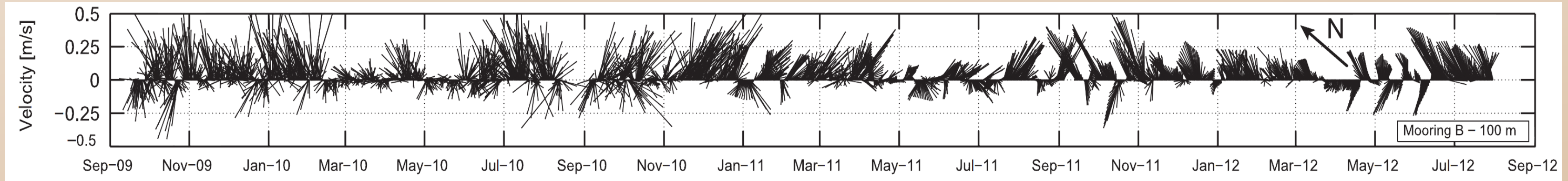
Oceanography from Moorings

Long-term taught-line moorings have been deployed by Fisheries and Oceans Canada and ArcticNet, jointly with Golder Associates guidance and supported by the **E**nvironmental **S**tudies **R**evolving **F**und (ESRF), **B**eaufort **R**egional **E**nvironmental **A**ssessment (BREA), ArcticNet, and Imperial Oil Canada. Numerous publications (by co-authors et al.) establish the types and magnitudes of current-generating processes.

Most taught-line moorings are water column rather than near-bed focused but provide the context for seabed current interaction. They demonstrate numerous autumn and winter events, and thus the need for year-round deployment of GSC-A instrumented landers (panel above).



Hourly mean currents and direction for 2012-2013 measured 8m above the seabed at mooring SIC12-2 (blue diamond, eastern surficial geology map, upper panel). Based on the field measured critical shear stress (Walker et al., 2008), the critical velocity at 1 m above seabed for sediment re-suspension/erosion, U100cr, is taken to be 19 cm/s. Several strong current events occurred, dominantly to the NE, with some reaching 30-50 cm/s. This would transport sediment preferentially NE and is sufficient to cause episodic erosion of outermost shelf muds ~3.2% of the time annually. It should be noted that comparing current speed at 8 m above bottom with u100cr slightly over-estimates the frequency of sediment erosion.



Current vectors (up is northeastward and along the contours, down is opposite direction) from a 100m deep instrument taught-line mooring from Sept. 2009 - 2012) at site BR-B (green diamond, western surficial geology map, lower panel). The strongest and most frequent direction is along the depth contours. Excerpted from Forest et al., 2015, fig. 7b.

Ultra-high Resolution Seabed Topography

The first autonomous underwater vehicle (AUV) based multibeam bathymetry images, collected by Monterey Bay Aquatic Research Institute and Geological Survey of Canada - Pacific in 2013 (A and B) demonstrate the benefits of resolution for process understanding.

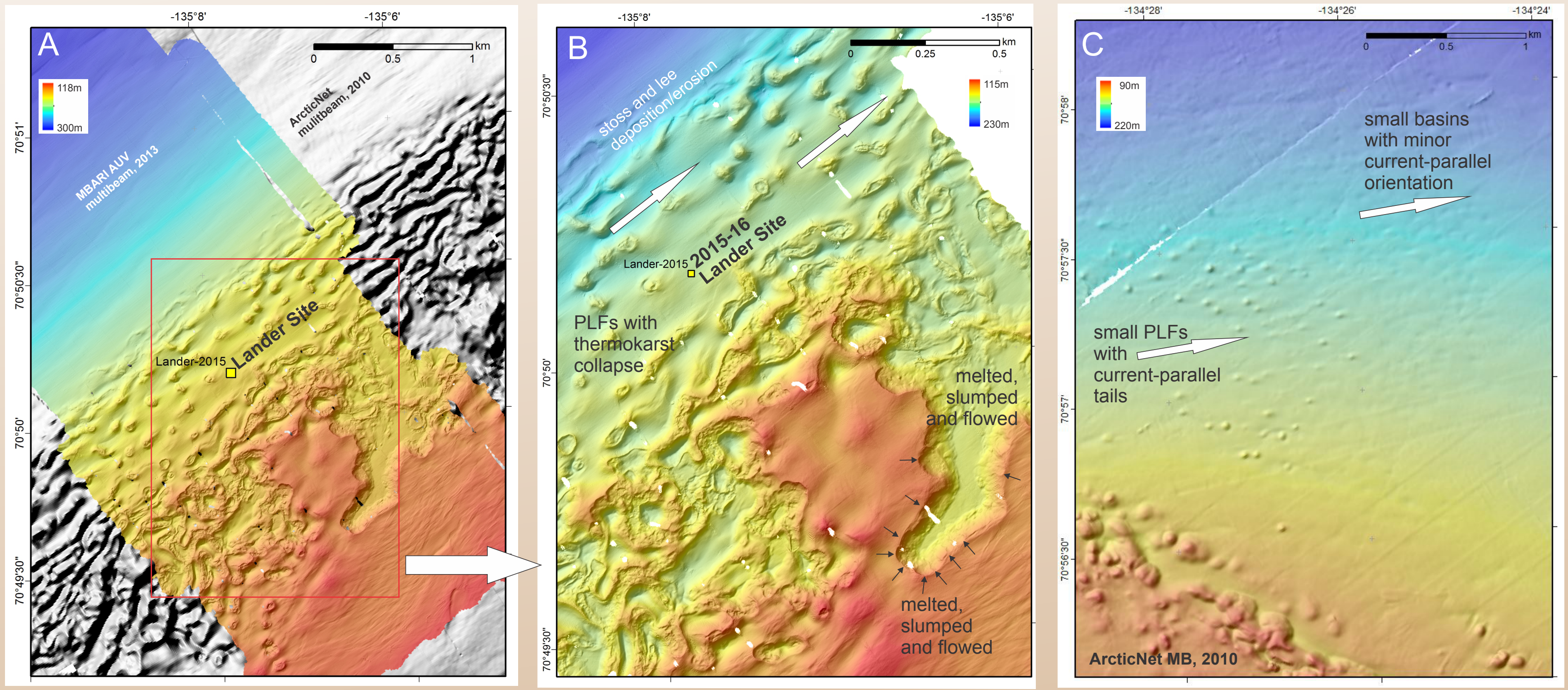
Sediment transport:

The lee and stoss accumulations were the first strong indicators of current influence. Hence the 2015 lander placement here. Conventional hull-mounted multibeam images (C) also show a preferred lineation in both the mounds (PLFs) and pockmark-like mini-basins.

AUV and multibeam bathymetry imagery at the 2015-16 instrumented lander site (A and zoom, B, locations on surficial geology map, upper panel) showing a preferred direction of mud features against the PLFs. This is consistent with a residual contour-parallel transport of muds from the BSJ but the PLFs are complex and poorly understood; some form ridges perhaps unrelated to seabed currents. A more subtle preferred orientation is manifest in small craters or basins, off the shelf break (C).

Pingo-Like Features (PLFs), Thermokarst and the Effect of Currents:

The PLFs only factor into the BSJ scenario because they appear to record a contour-parallel preferred orientation of lee-side mud deposits (B). Otherwise they complicate the recognition of the erosion and non-deposition zones. This is also an indicator of the activity level of the PLF process; the stratigraphic dating confirms that the disturbance continued throughout the Holocene. PLFs are not only at the seabed; their acoustic signature is also recognized buried in the Holocene strata. There is some evidence in the erosion belt that the currents cap the tops of those PLFs which have reached the seabed; they maintain a flat upper PLF surface where one might otherwise expect a seabed mound. Samples and ROV probes targeted from the AUV data were conducted on the PLFs, demonstrating seabed conditions capable of *growth* though freezing fluid efflux. Thermokarst-induced *collapse* is also common though, in the form of the hill-top craters and scarps with debris flow. The pockmark-like mini-basins (C) might also be interpreted as buried thermokarst.



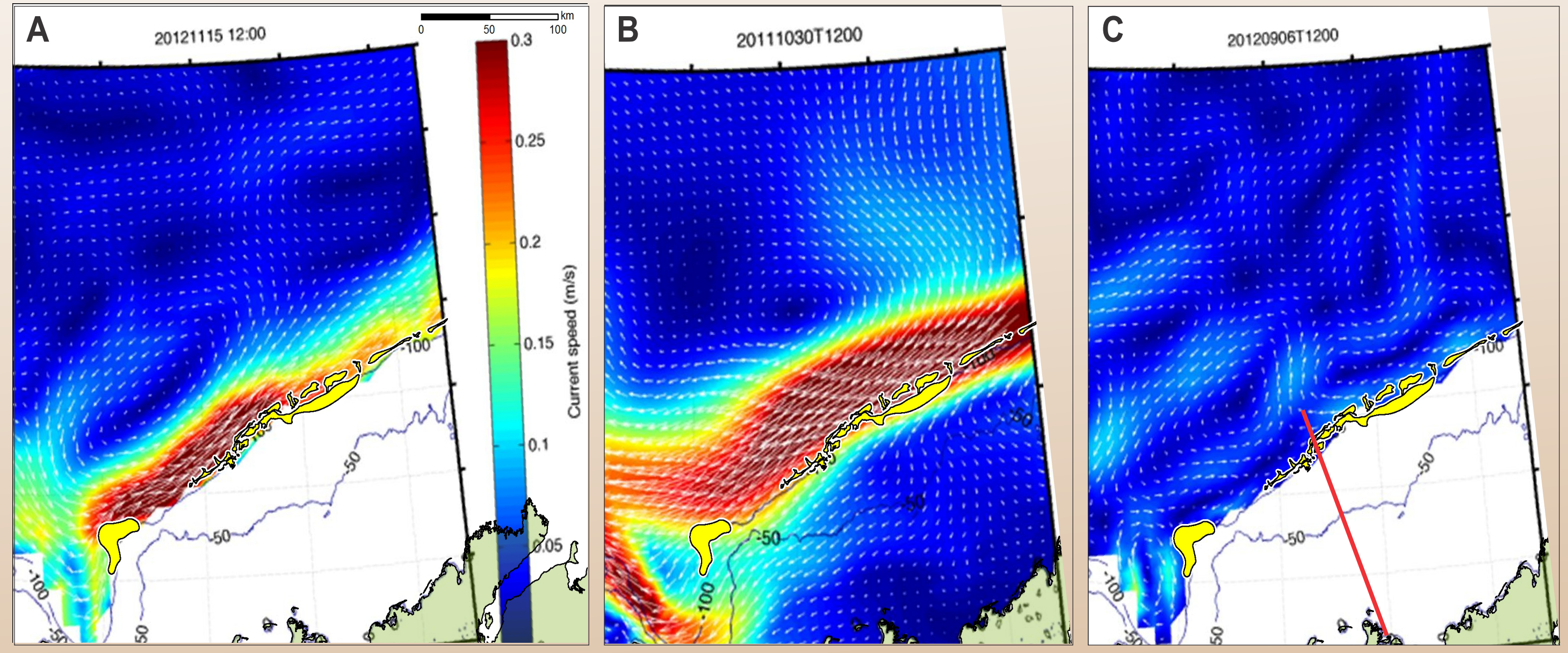
Preliminary Oceanographic Modelling

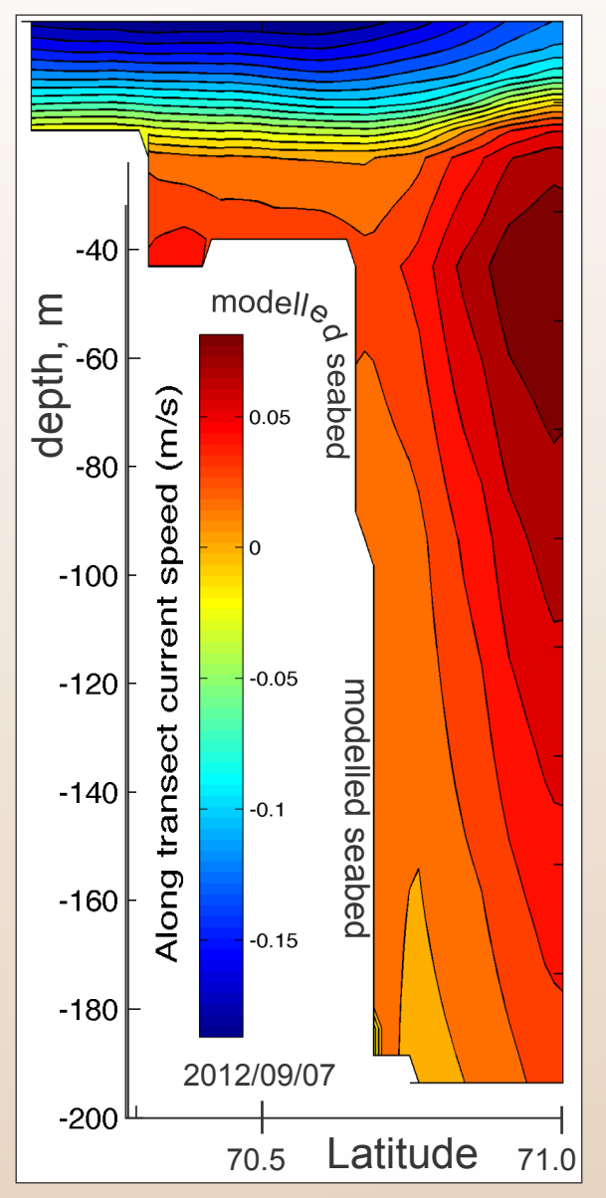
DFO and NRCan collaborated to apply a 3-D model of the Beaufort Sea towards demonstrating the geologic phenomena. This is the first such modelling study of the BSJ. The modelled BSJ generally flows eastward, along the depth contours, with occasional reversal. The non-deposition zone is found to be within the impact zone of the BSJ. 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.

The Model

Modelling efforts aim to utilize the predictions of an existing coupled ocean sea ice data assimilation system ocean model, TOPAZ, to confirm the presence of the BSJ and to quantify the spatial patterns, intensity and frequency of BSJ surges, eddies, and upwelling/downwelling events. Output is 3-D, daily mean fields of temperature, salinity, velocity and other ocean and ice parameters at 12.5km resolution. It was validated (especially for stronger currents) by *in situ* current data measured at 8m above the seabed (site SIC 12-2, blue diamond, on the central surficial geology map). It has produced the first representations of the BSJ with a core between 40 and 100m water depth impinging on the shelf break.

below; Snapshots (date & time, top) of modelling results showing A) BSJ with dominant NE direction at 100m depth, sufficient to erode mud, B) strong (but infrequent) reversed direction, C) quiescent minor meso-eddies. The yellow polygons represent the mapped erosion and non-deposition belt.





above: Velocity profile normal to the BSJ (along panel C red line transect) illustrating the BSJ core impinging the shelf break seabed (positive current direction is landward). This example emphasizes an autumn wind-driven current event with an otherwise weak contouritic component.

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