



Università degli studi di Trieste

LAUREA MAGISTRALE IN GEOSCIENZE

Classe Scienze e Tecnologie Geologiche

Anno accademico 2025 - 2026

**Analisi di Bacino e
Stratigrafia Sequenziale
Docente: Michele Rebesco**



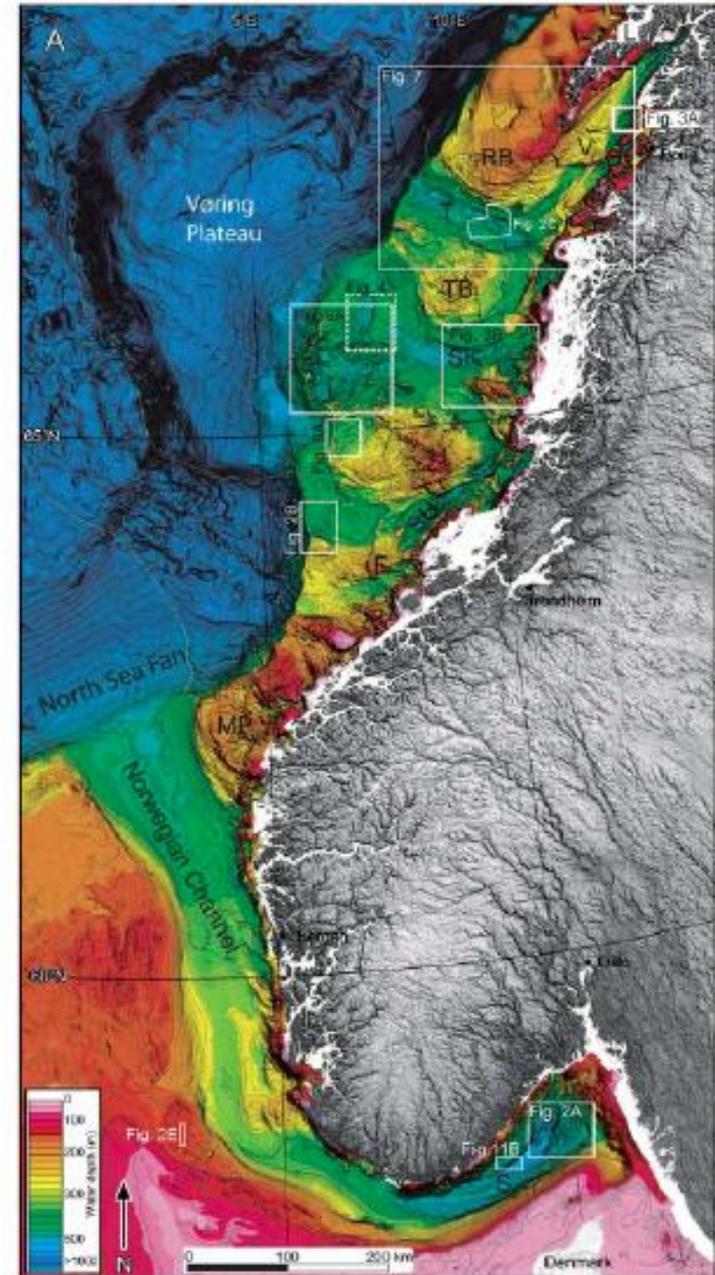
Modulo 3.8

Glacial depositional system

Docente: **Laura De Santis**

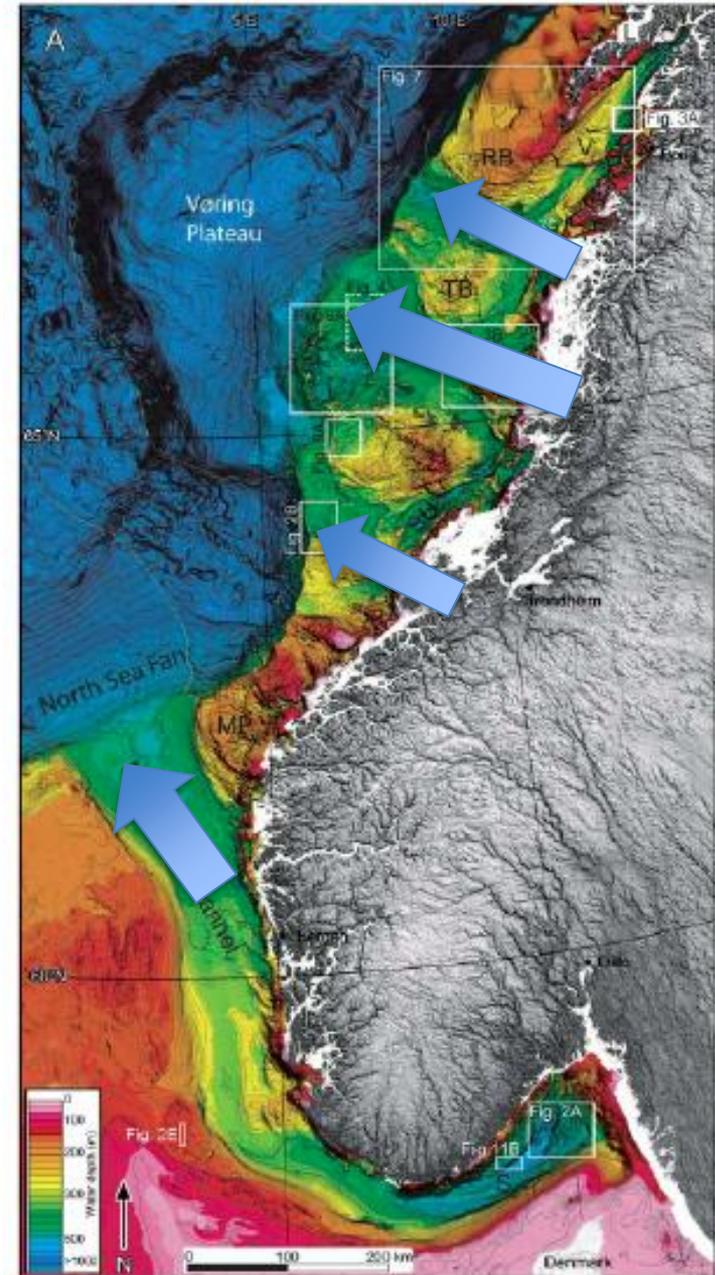
Diagnostic features

- Glacial valleys and banks topography
- Trough mouth fans
- Landward deepening continental shelf
- Ice grounding zone wedge
- Glacial lineations, outwash channels

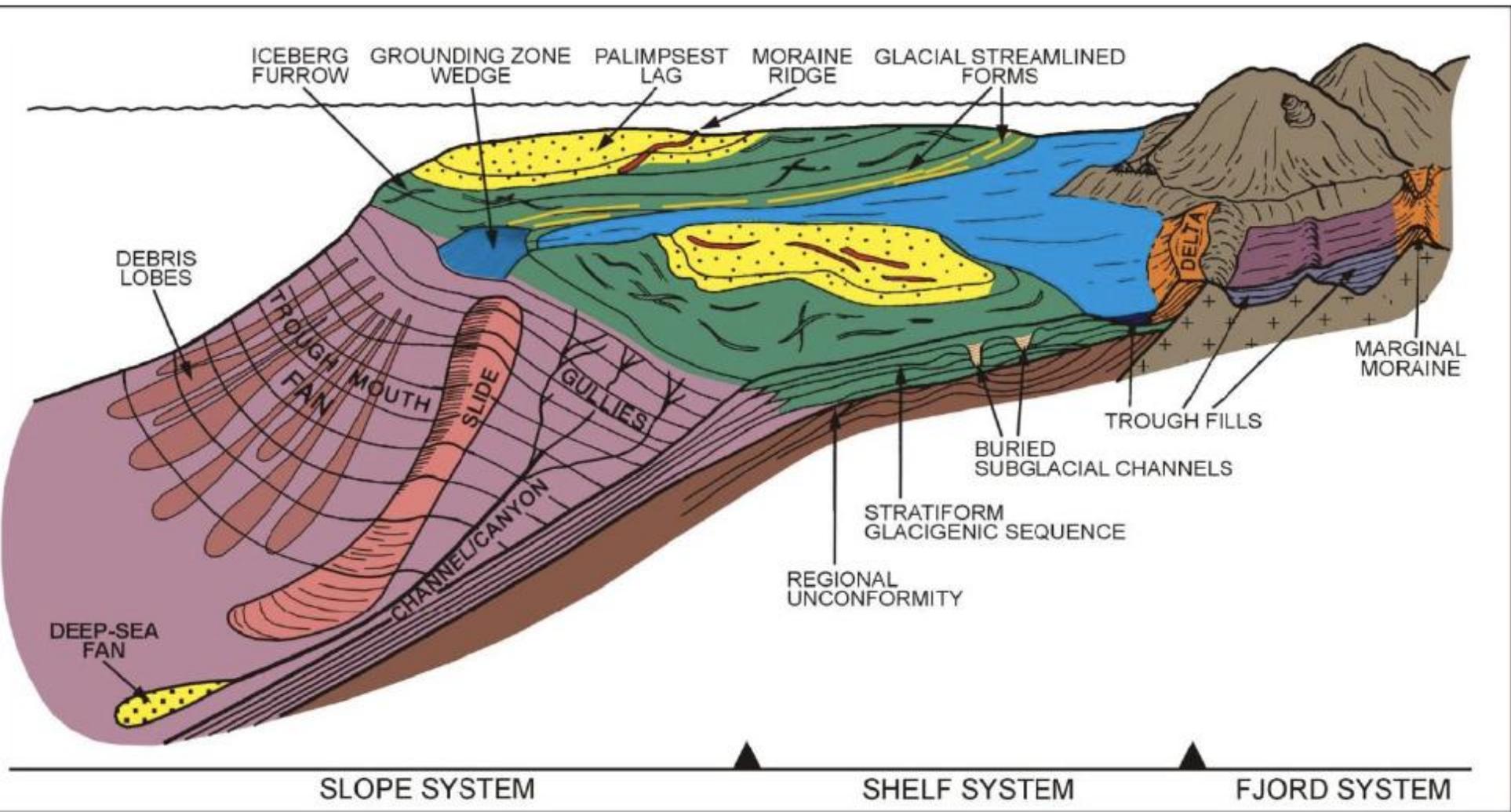


Diagnostic features

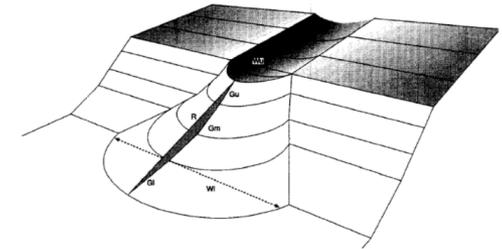
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Trough/bank topography Trough mouth fans

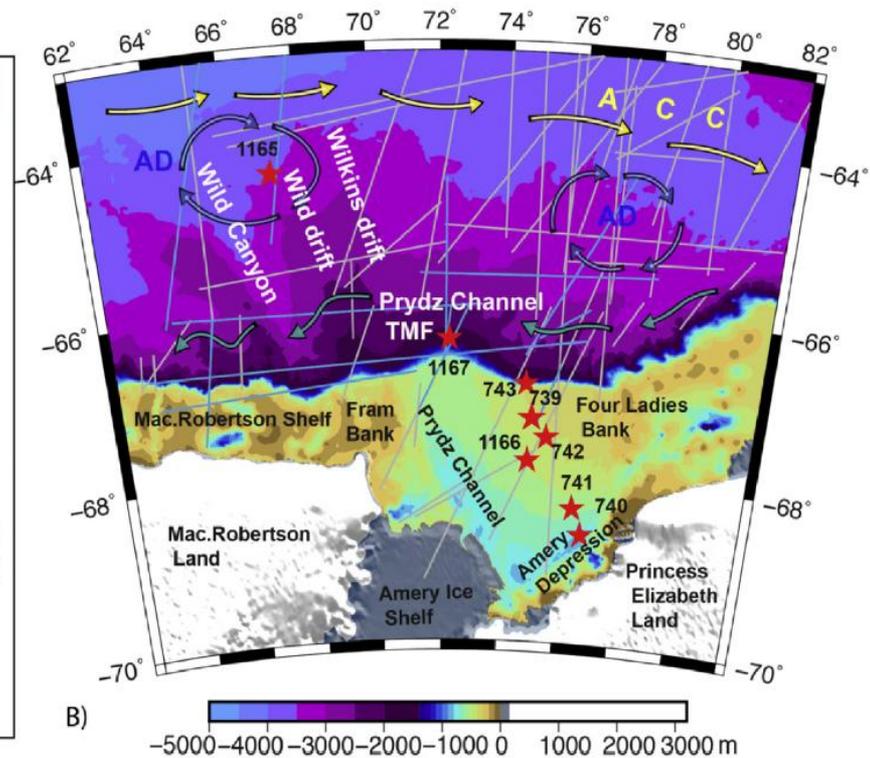
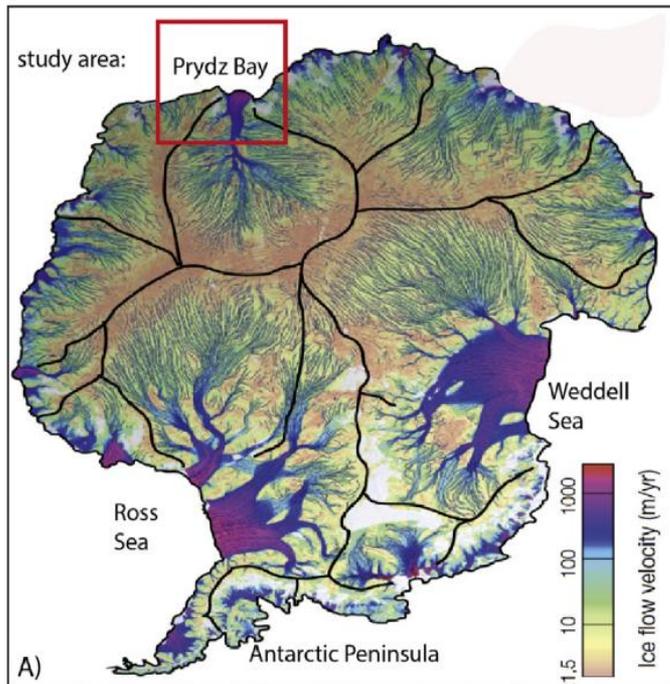


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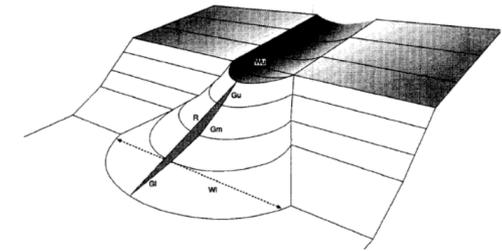


Marine Geology 430 (2020) 106339

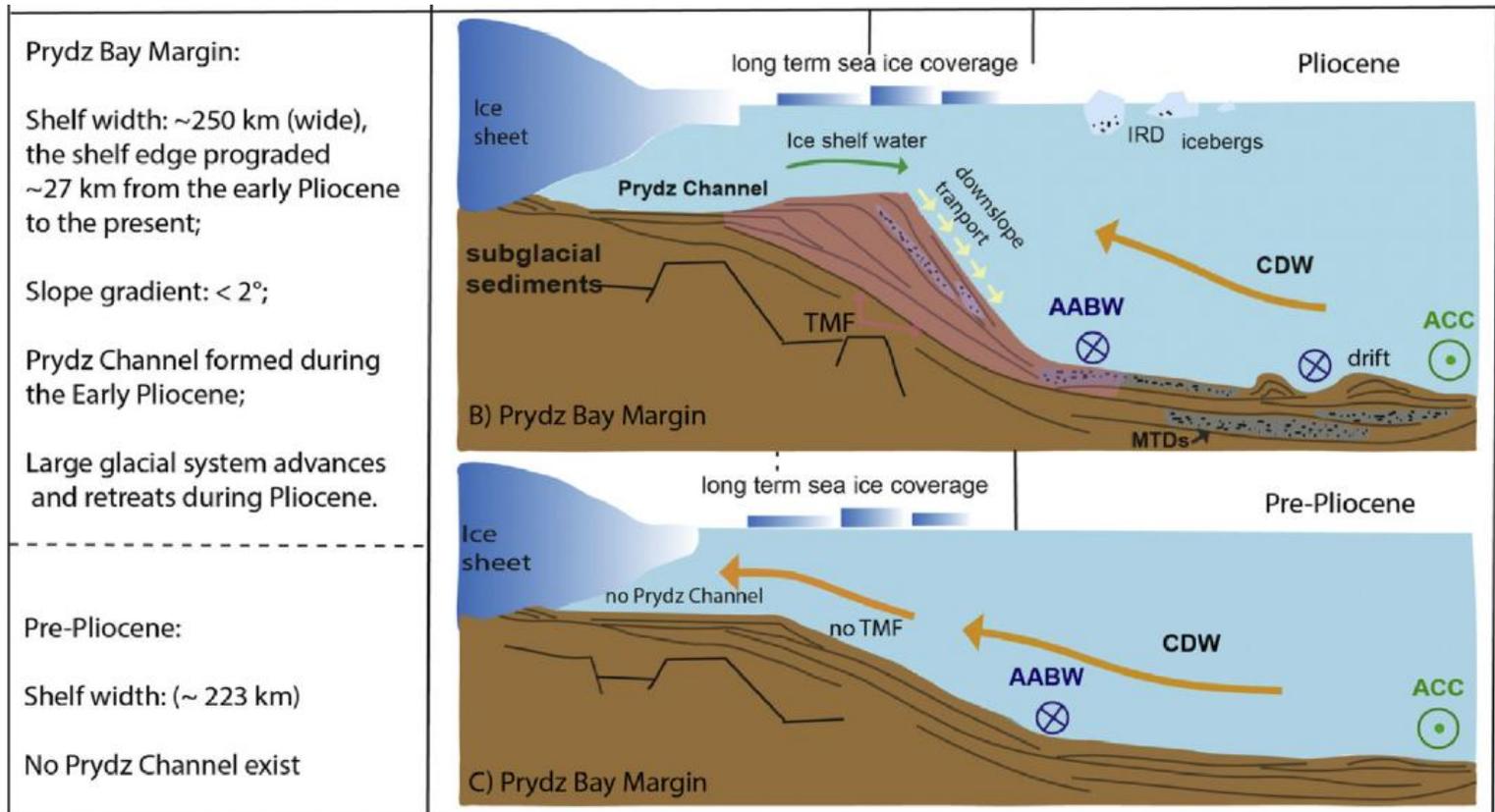
X. Huang, et al.

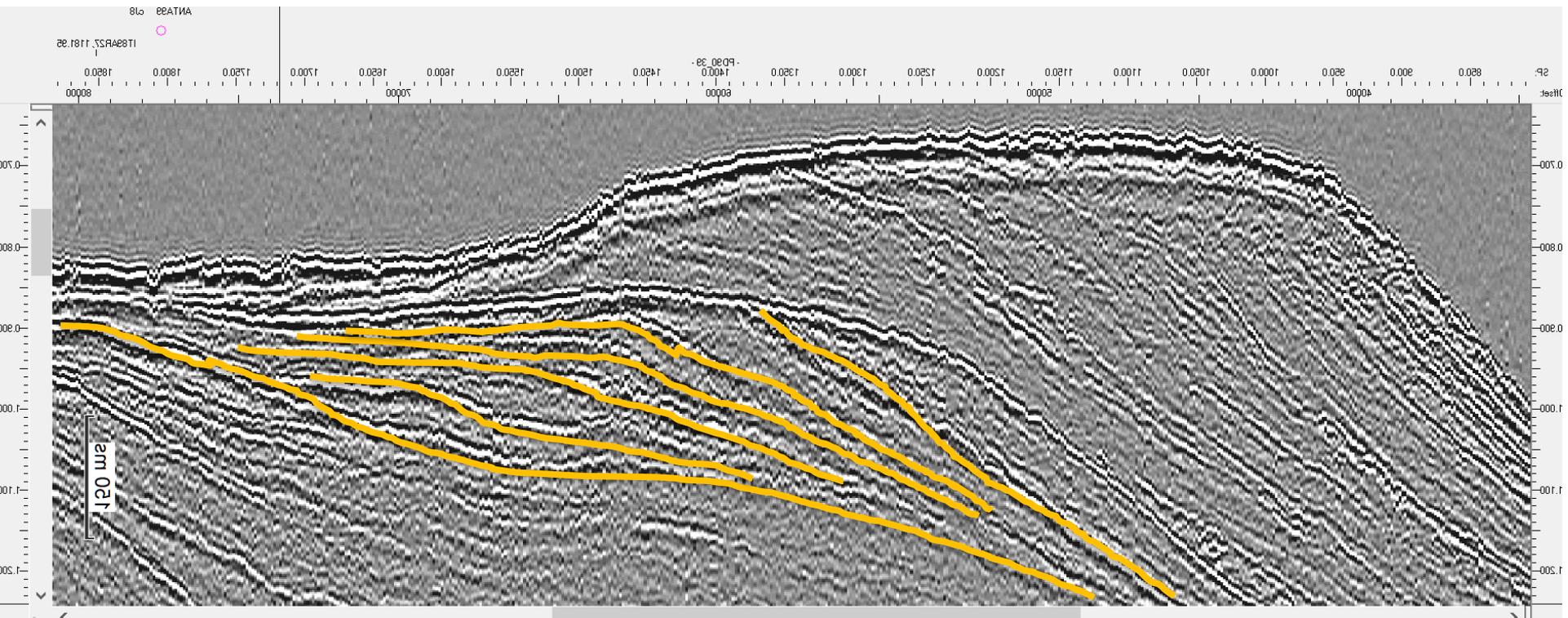
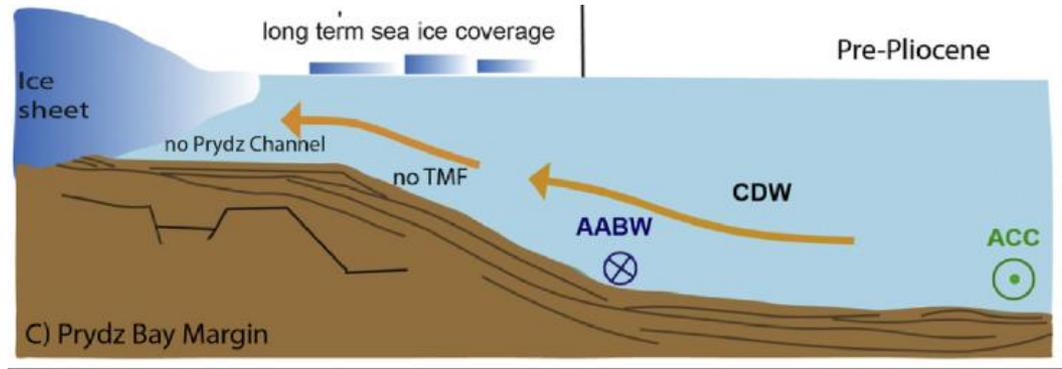


Trough/bank topography Trough mouth fans



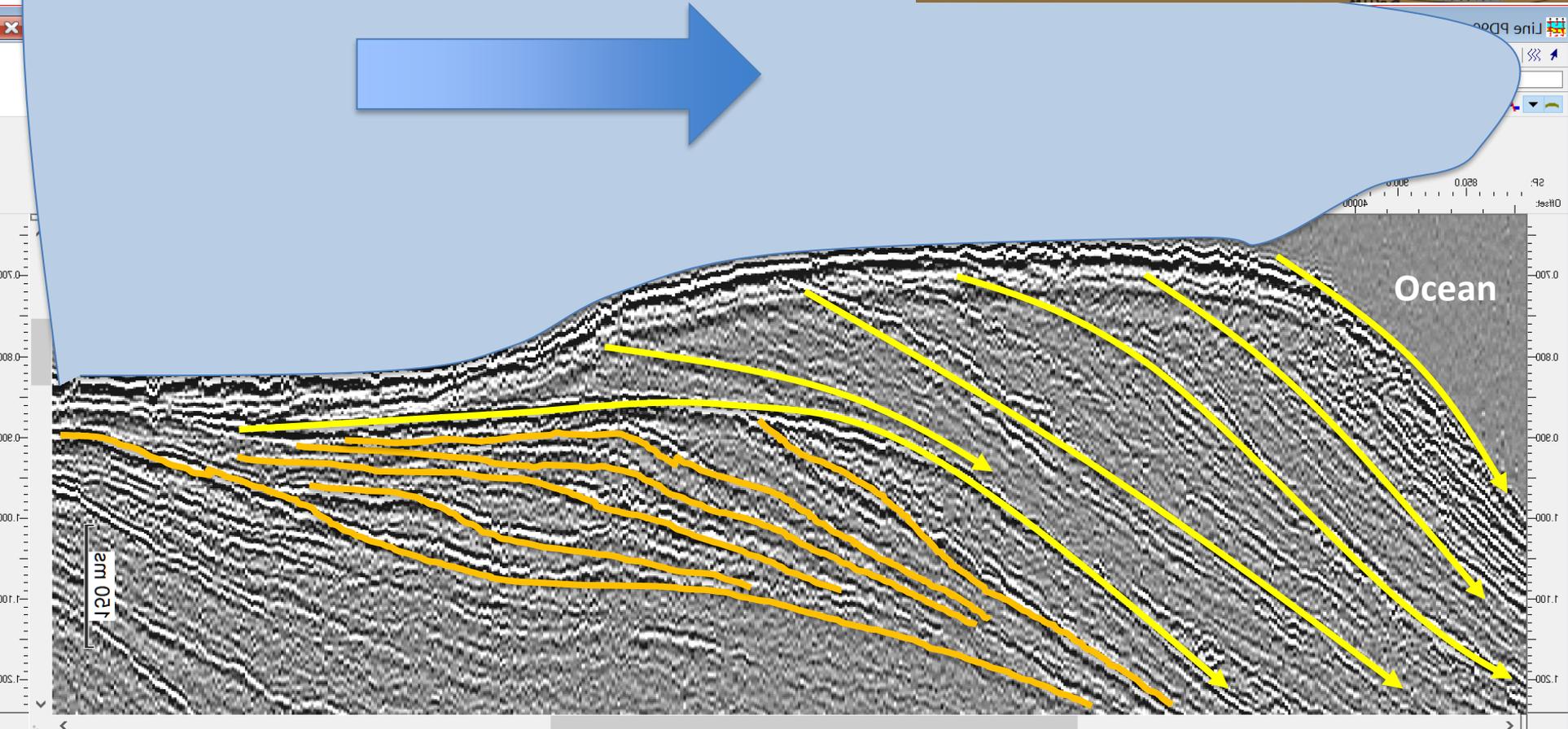
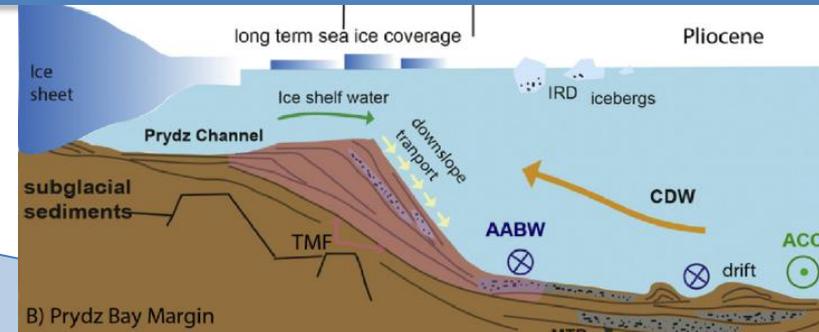
Glacial erosion (interior) and deposition (margin) => landward deepening cont. shelf



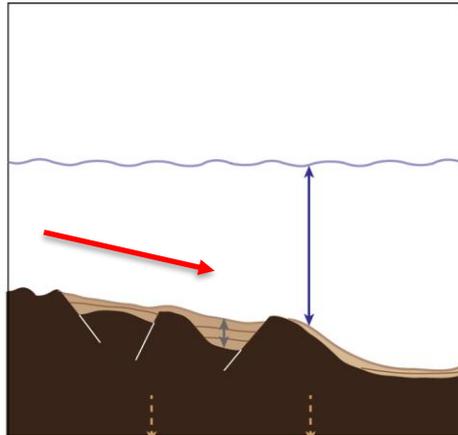


Trough Mouth Fans

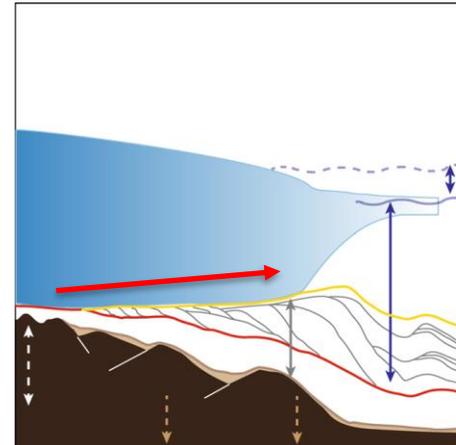
Glacial erosion (interior) and deposition (margin)
=> landward deepening cont. shelf



Glacial erosion and deposition => foredeepened and wide continental shelf



Seaward dipping profile

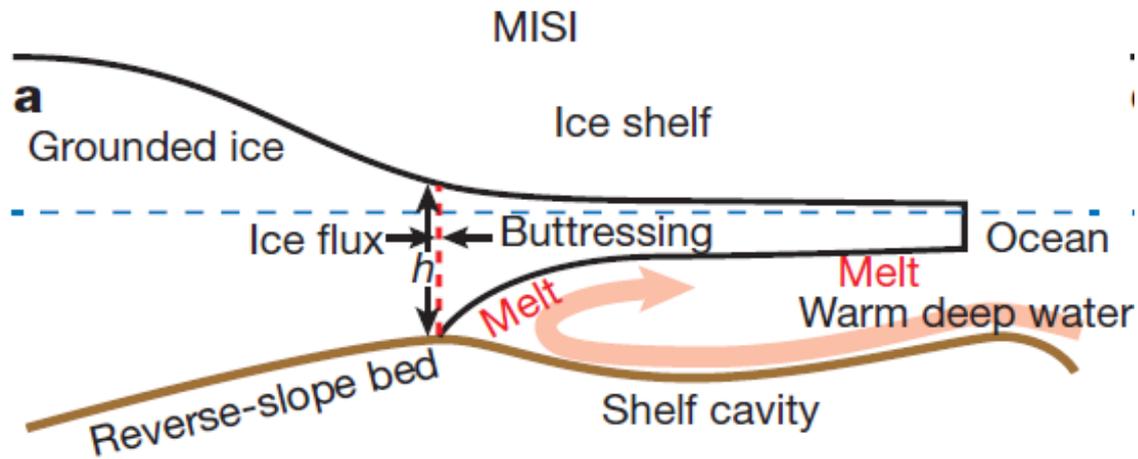


Landward dipping profile

Colleoni et al., 2018

Marine Ice Sheet Instability (MISI)

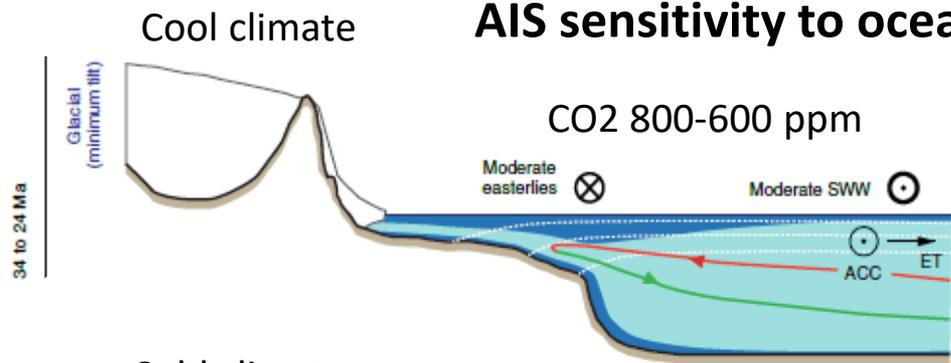
Sub-ice shelf melting due to ocean warming can trigger irreversible ice sheet retreat onto a reverse-sloping bed



Including these processes was found to increase the previous model's contribution to Pliocene Global Mean Sea Level from +7 m to +17 m

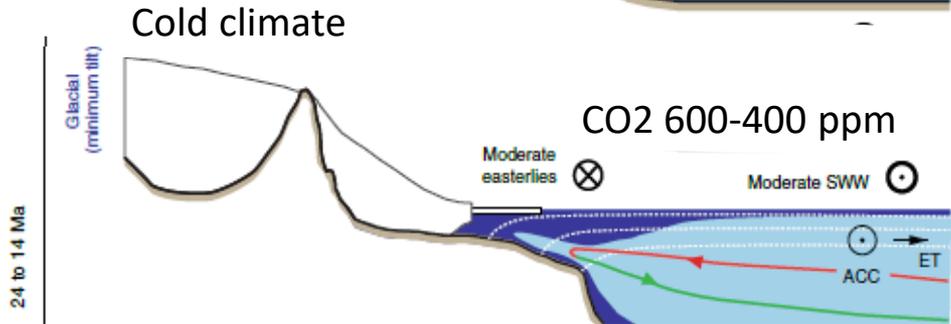
DeConto and Pollard 2016

AIS sensitivity to ocean and climate dynamics

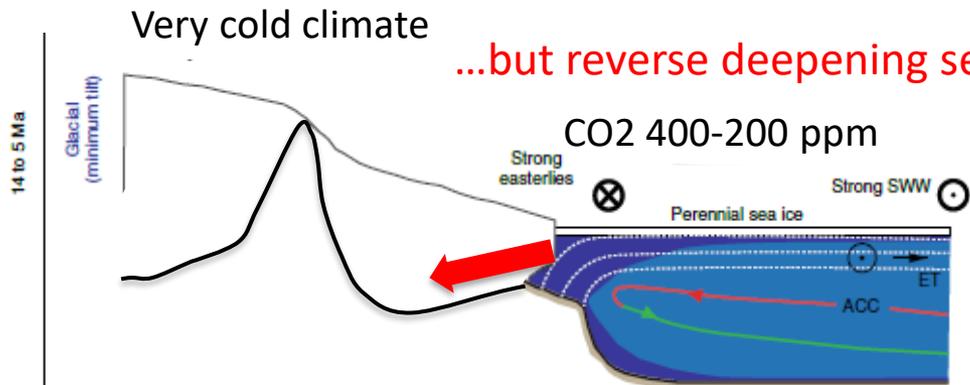


Levy et al., 2019

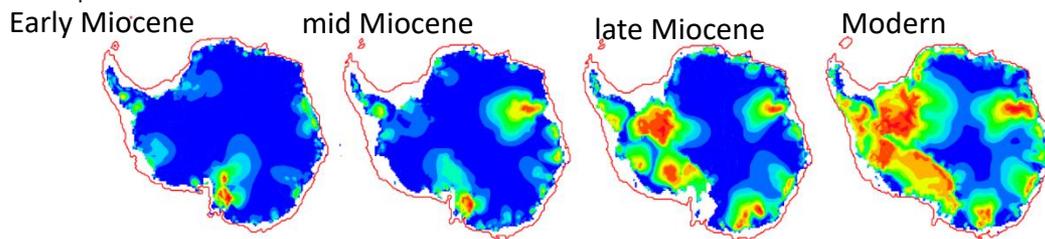
Terrestrial ice → low sensitivity to ocean warming



Marine ice-sheet extent → high sensitivity to ocean warming



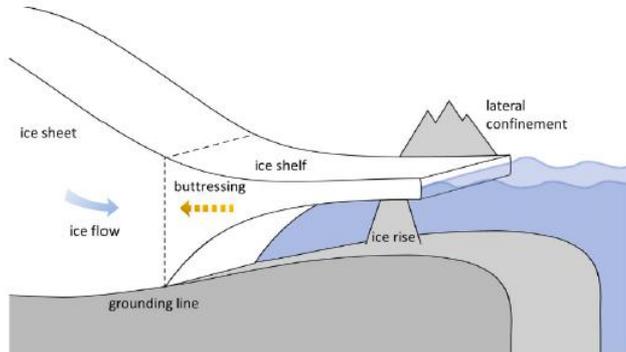
Persistent terrestrial and variable marine ice sheets. Sea ice and cold surface water 'insulate' marine ice sheet from warm ocean = decreased sensitivity to ocean warming



Colleoni, F., et al. 2018

Topography/Bathymetry evolution => increase ice sheet sensitivity to warming

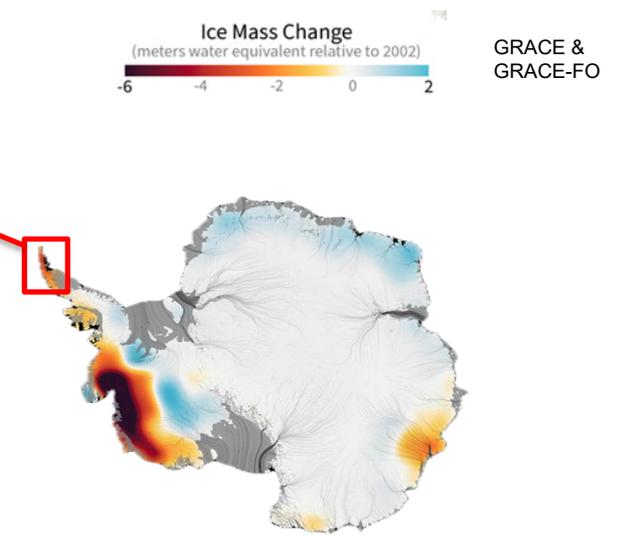
Bedrock deepening from terrestrial to marine based ice sheet

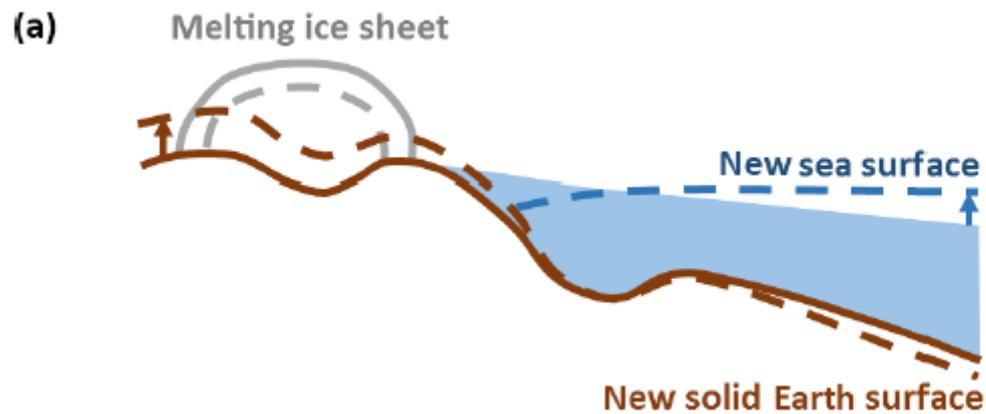


[Credit: Ronja Reese & Maria Zeitz]



Source: W. Rack





Whitehouse 2018

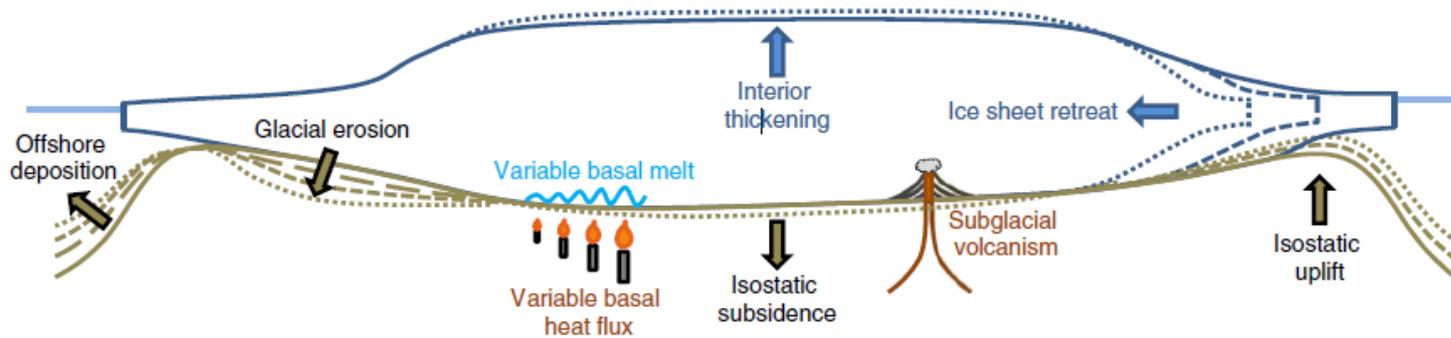
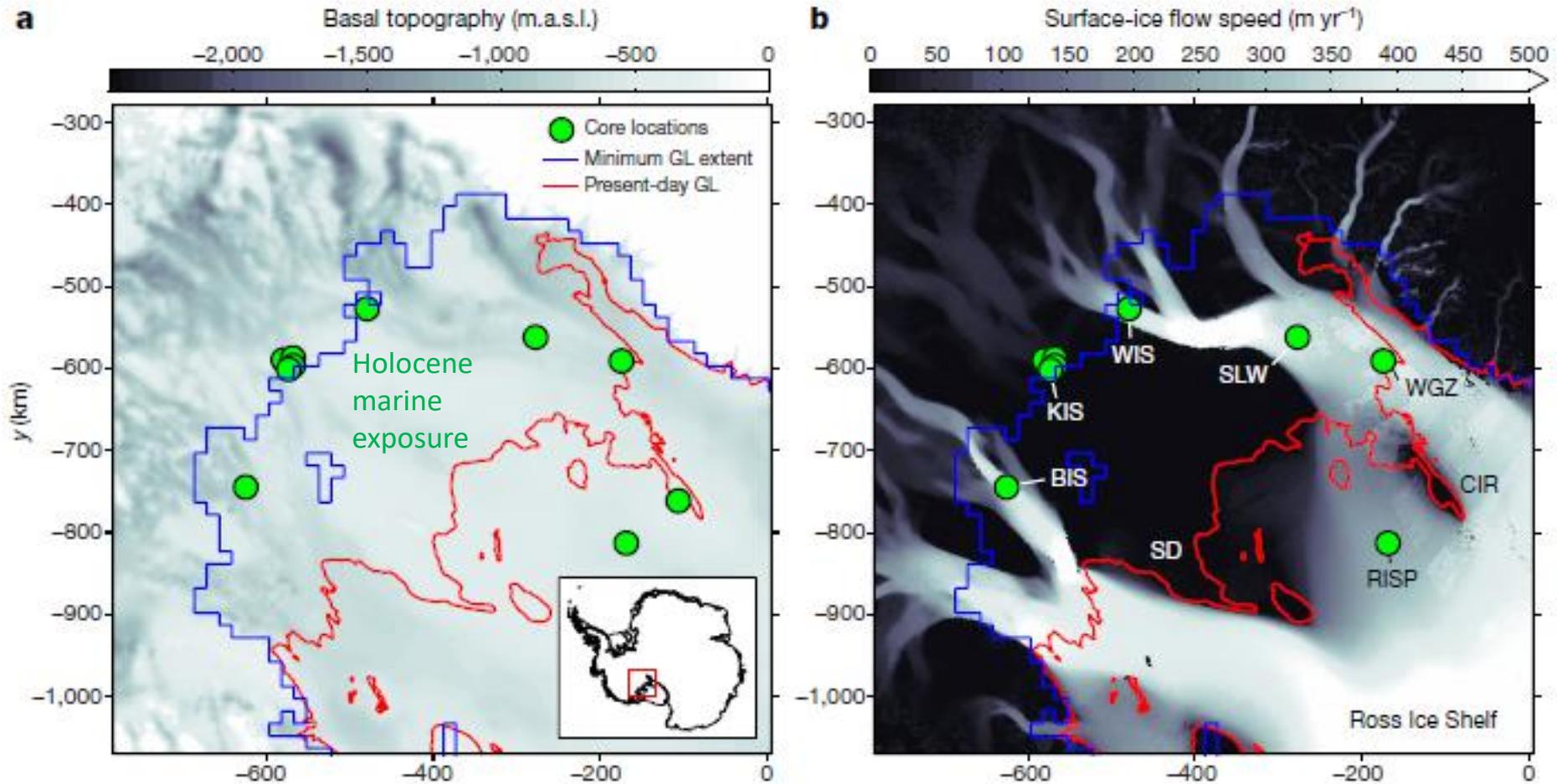


Fig. 1 Summary of interactions between the solid Earth and the Antarctic Ice Sheet. Local isostatic uplift occurs in response to ice-sheet thinning or retreat, isostatic subsidence occurs in response to ice-sheet thickening or advance. Subglacial volcanism and basal heat flux alter thermal conditions at the base of the ice sheet. Erosion and deposition also trigger an isostatic response (not shown). Increasing time indicated by finer dashed lines

Whitehouse et al., 2019

Presence or absence of **pinning points** influences ice sheet advances and retreat

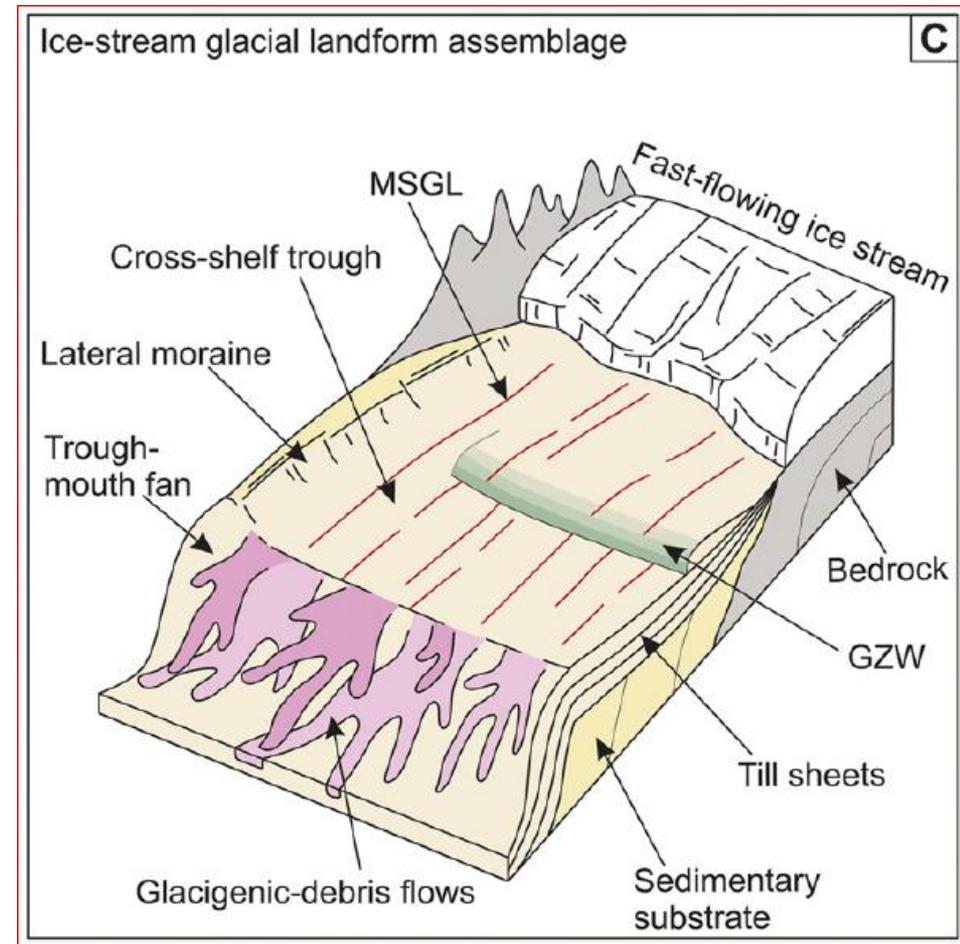


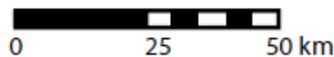
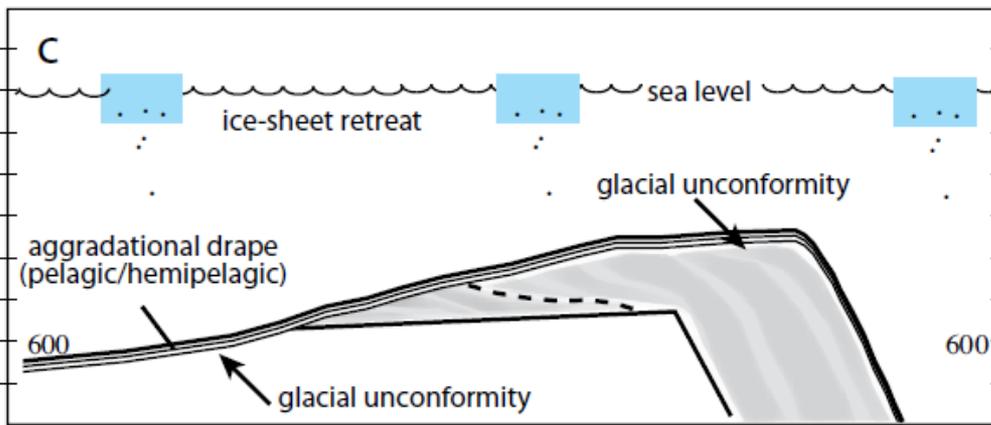
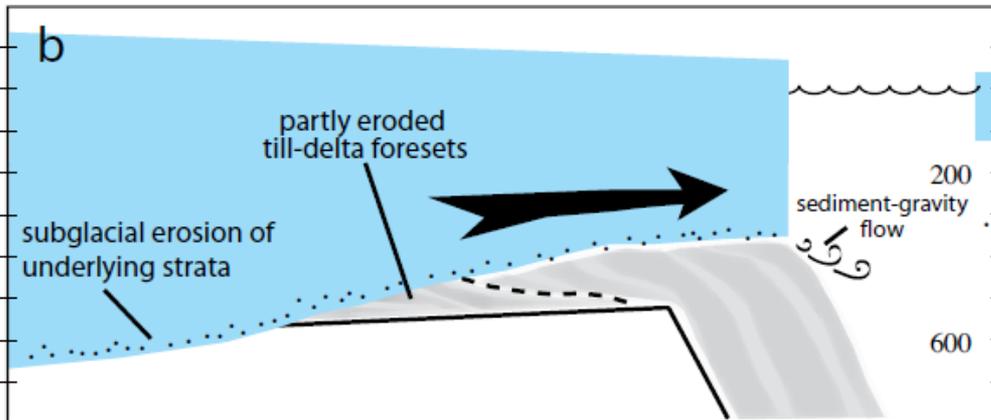
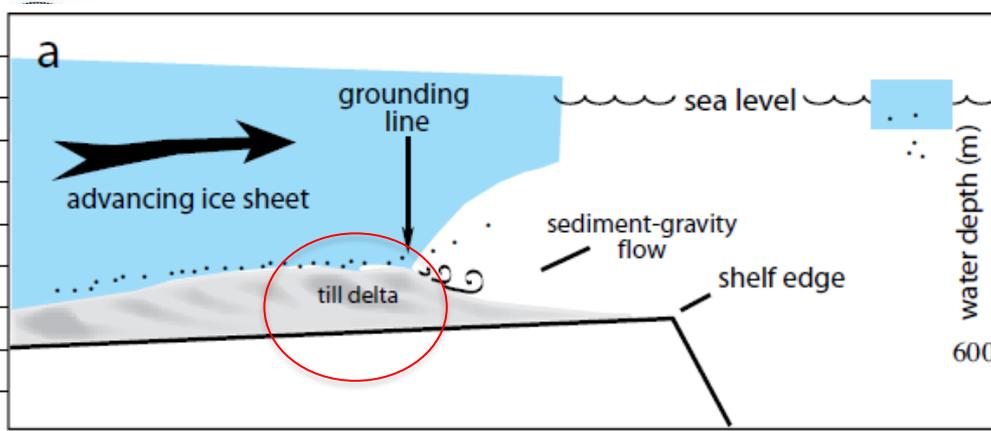
Grounding line retreated several hundred kilometres inland of today's position, before isostatic rebound caused it to re-advance

J. Kingslake et al., 2018

Diagnostic features

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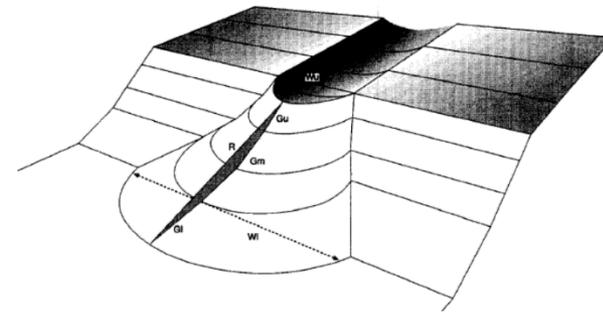




V.E.=80:1

Bart and De Santis 2012

- Trough-mouth fans
- Till delta



Discovery of a 6 m-thick layer of deforming till beneath the Whillans Ice Stream

If the grounding line has been near its present position for the last 5-10 ka

and assuming a constant rock flux of hundreds of cubic meters/year at the grounding line



A sedimentary deposit tens of kilometers long into water tens of meters deep formed

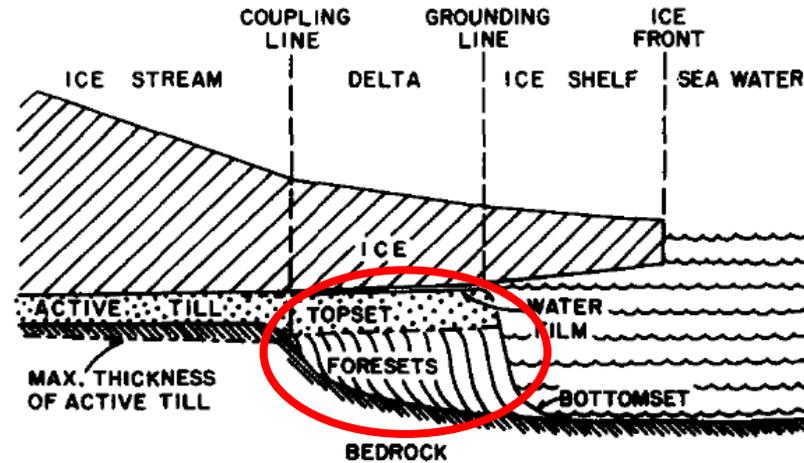
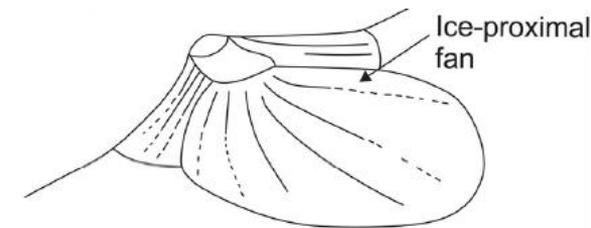
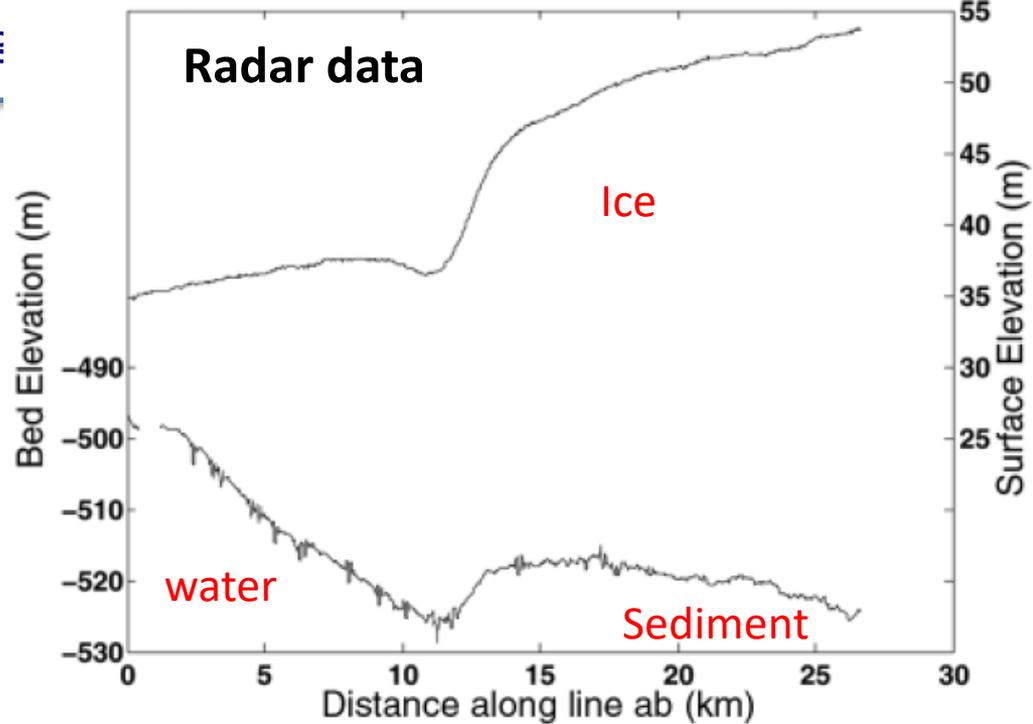
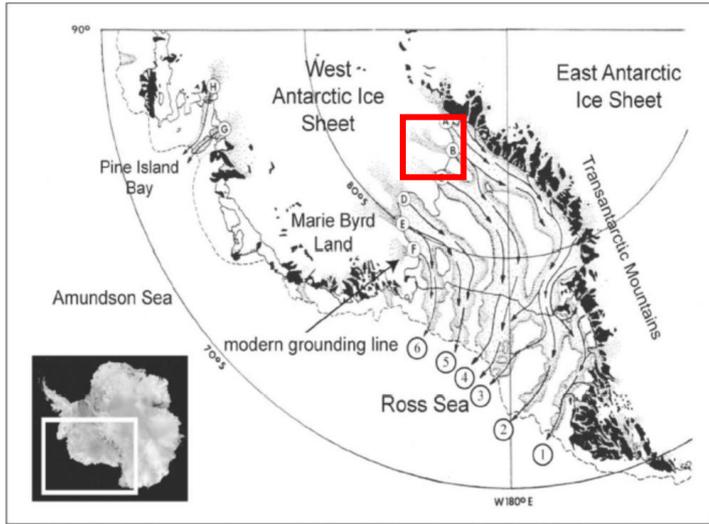


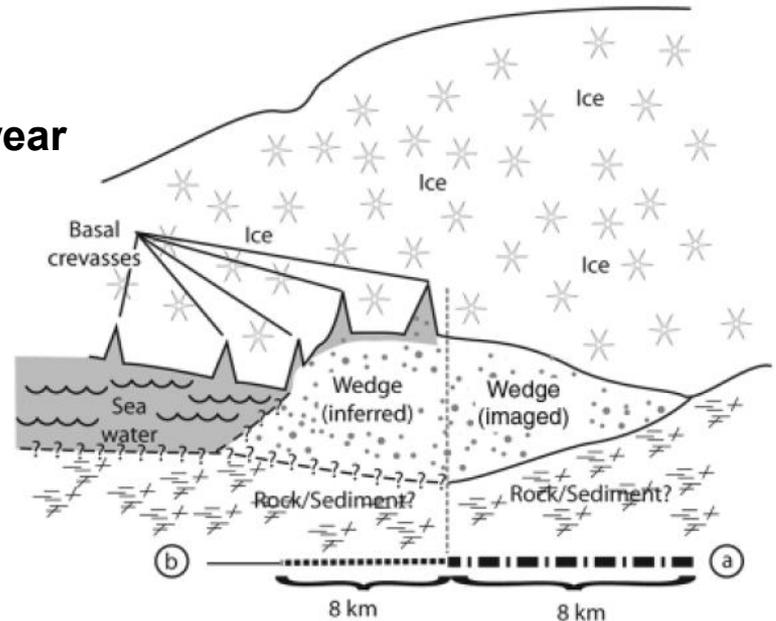
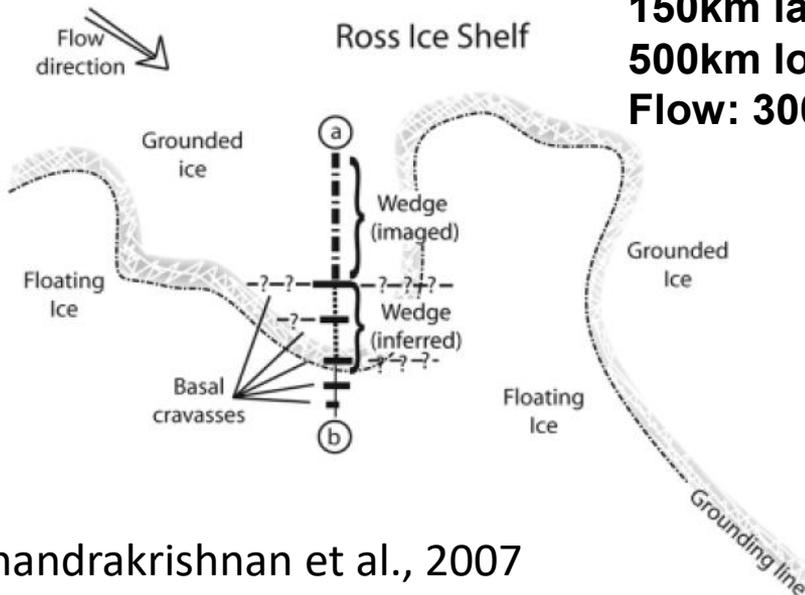
Fig.3. Cartoon of the likely configuration of the ice stream, till delta, and ice shelf.

Alley et al., 1987; 1989

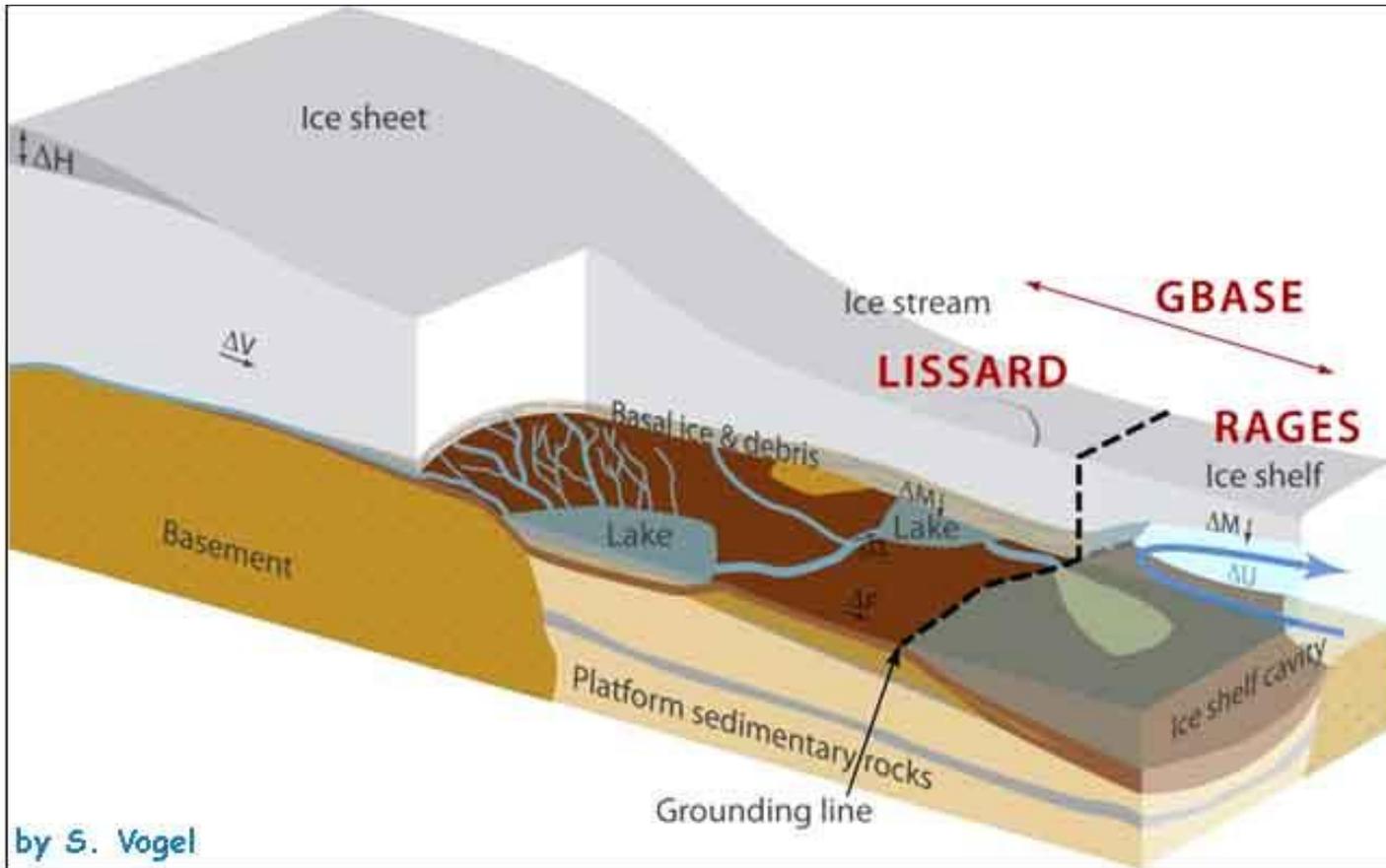




Whillans ice stream
150km large
500km long
Flow: 300 m/year

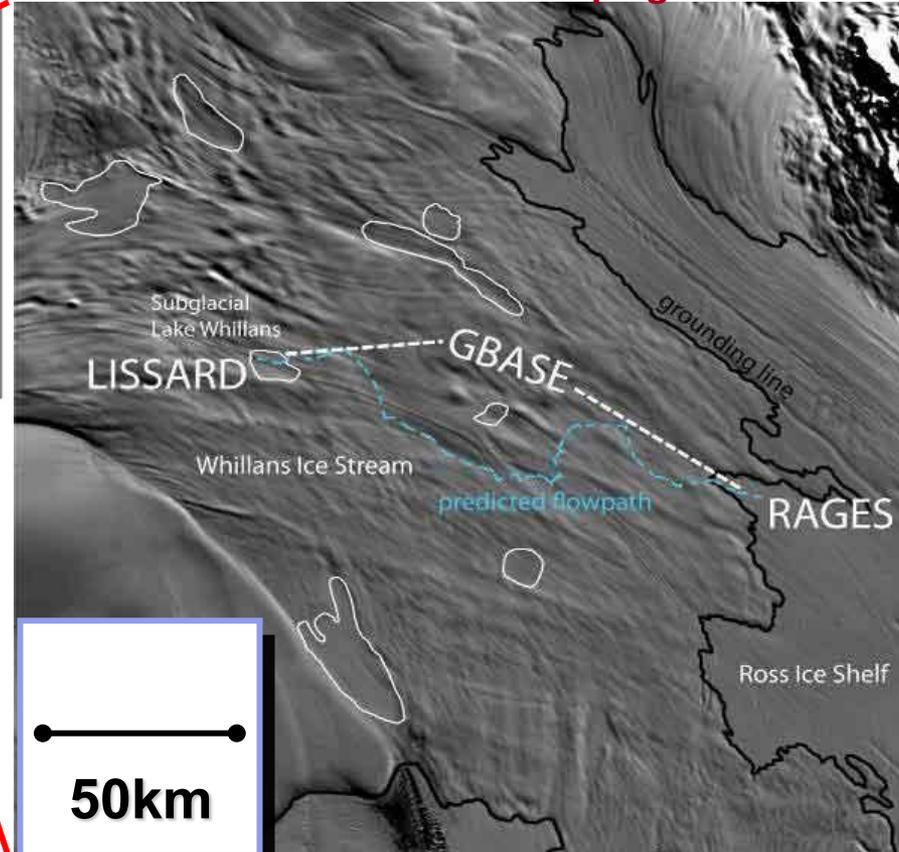
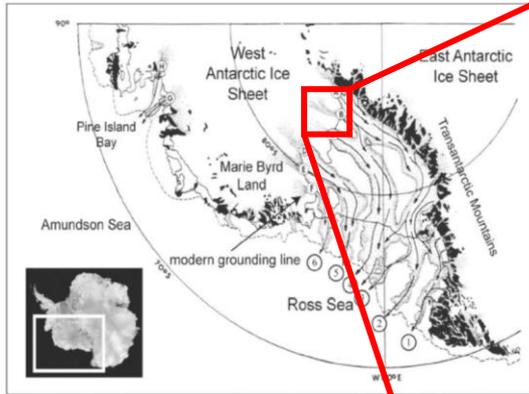


location of ice-sheet grounding is affected by short-term variations (e.g. tides) and climatically-induced variations in thinning and rates of mass loss. **The grounding zone is a key site for meltwater transfer** from the ice sheet to the marine environment



Subglacial and grounding-zone sedimentation aggradation may act as a negative feedback that counters dynamic thinning of the ice stream and stabilizes the ice-stream grounding zones (e.g., Alley et al., 2007).

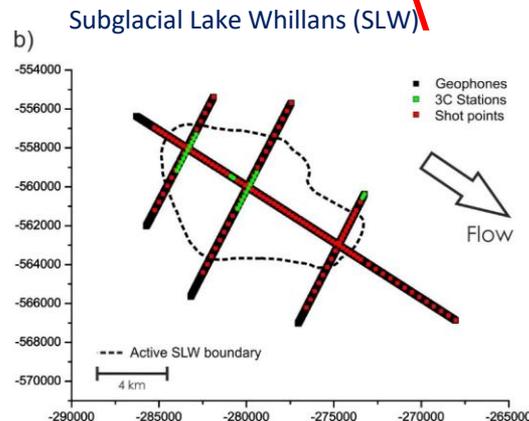
Whillans Ice Stream – 2010-2011 Antarctic Campaign



The Whillans Ice Stream is thousand of km long and hundreds of km wide.

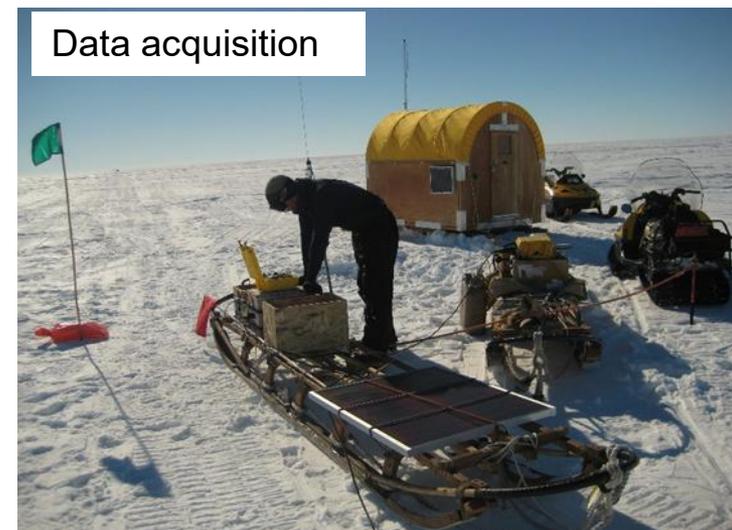
Flows towards the Ross Ice Shelf at over 300 m per year, with a tidally controlled stick-slip motion.

The water flows under the glacier, lubricating the basement and forming a network of subglacial lakes.



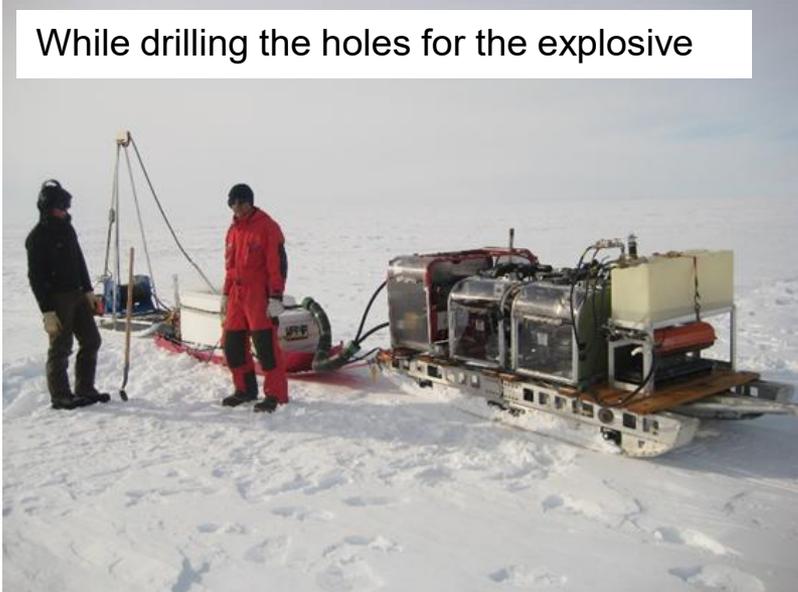
Whillans Ice Stream – 2010-2011 Antarctic Campaign

All the logistic was organized and financed by the US NSF (WISSARD Project).



Whillans Ice Stream – 2010-2011 Antarctic Campaign

While drilling the holes for the explosive



A hole in the ice for the explosive



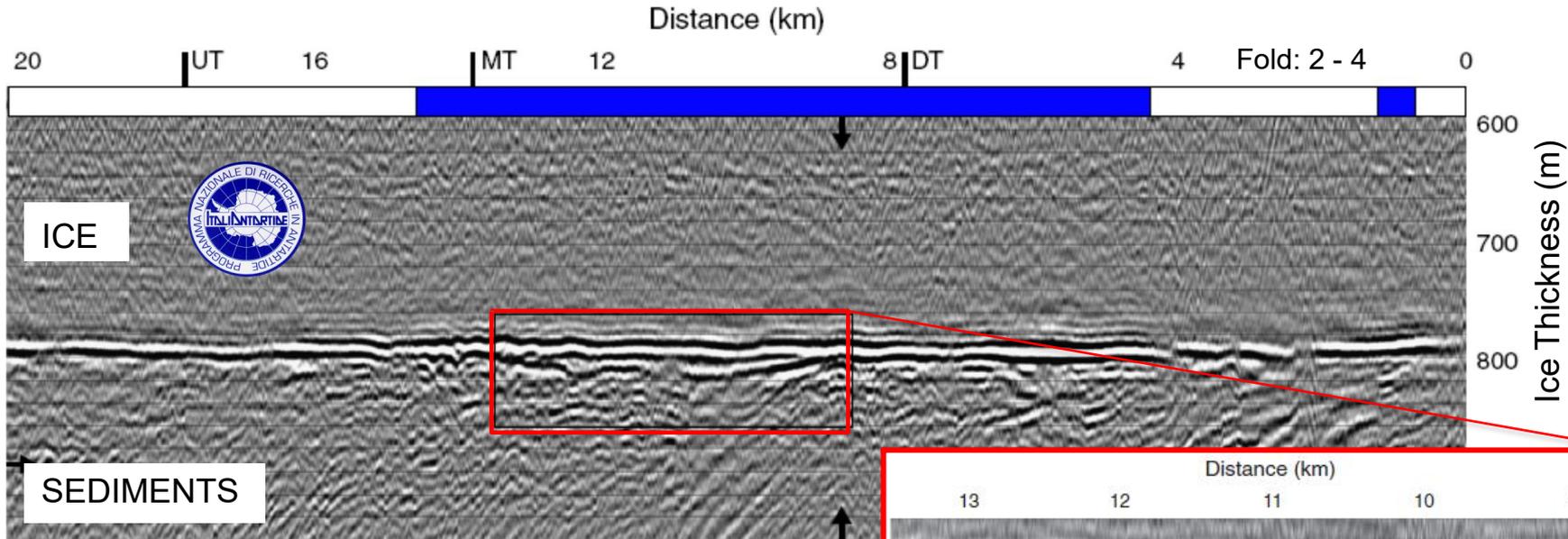
Digging after the wind....!



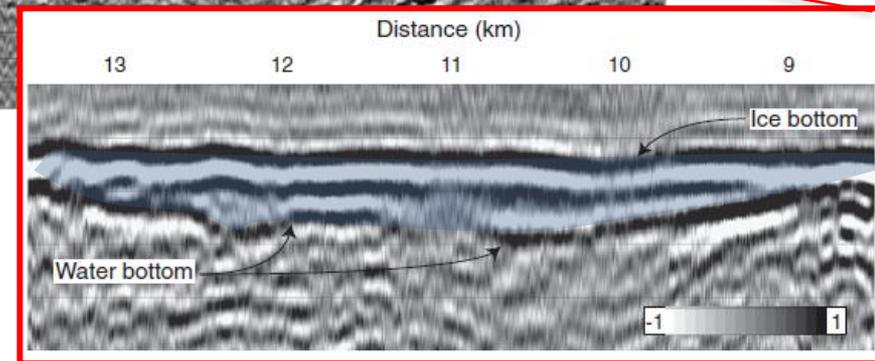
3C Stations deployment



Seismic Imaging of Subglacial Lake Whillans (Siple coast - WAIS)



The survey, carried out in a low-tide period, evidenced that **the lake exists** and its water column is up to 8 m thick, along 5 km of the 45 km profiled. These findings were later confirmed by drilling operations.

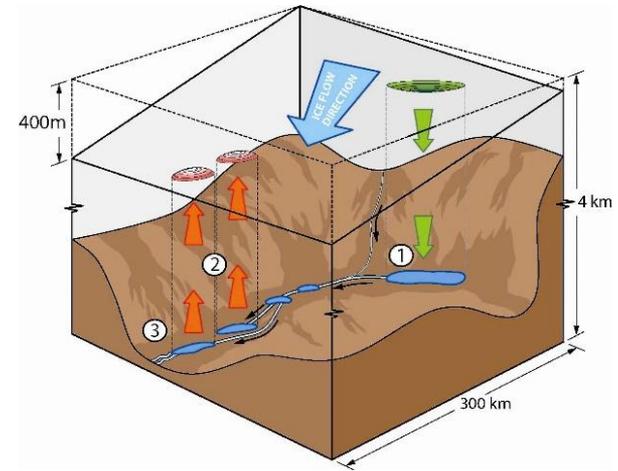
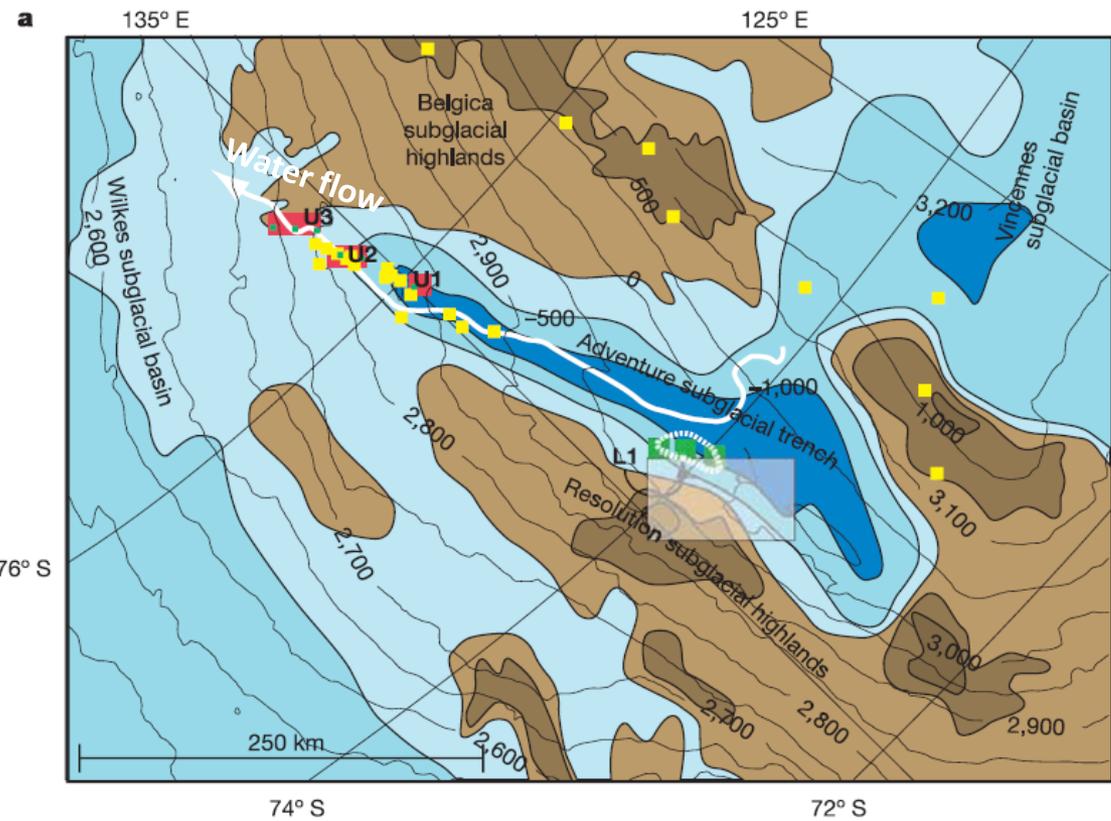
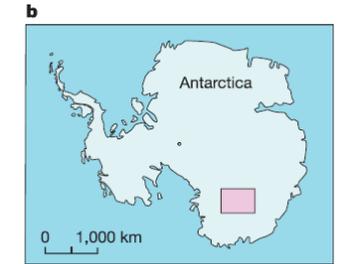


AVO (Amplitude Versus Offset) analysis shows that the major part of the bed around the lake consists of soft sediments and thin water lenses.

Topography of the Adventure subglacial trench region of Dome C, central East Antarctica

Water flow, calculated from the subglacial water pressure gradient

blue where the bed elevation is below sea level
brown where the bed is higher

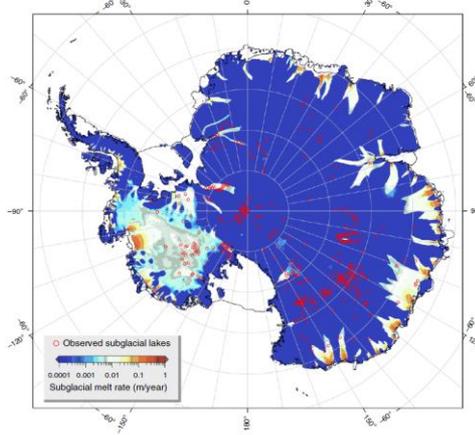


Satellite ERS-2 altimetric data between 14 August 1997 and 16 March 1998:

- 'L' sites lowering .1 m
- 'U' sites uplift .1 m.
- Subglacial lakes

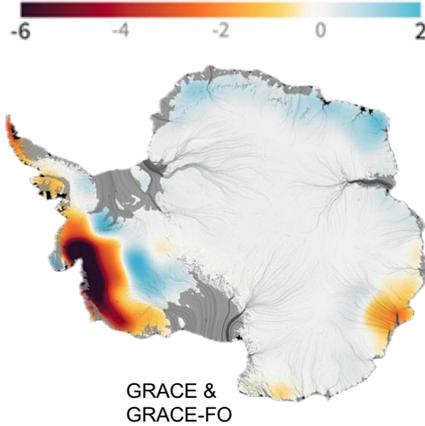
Duncan et al., 2006

Subglacial lakes (red circles) & basal meltwater production rate (ma⁻¹)

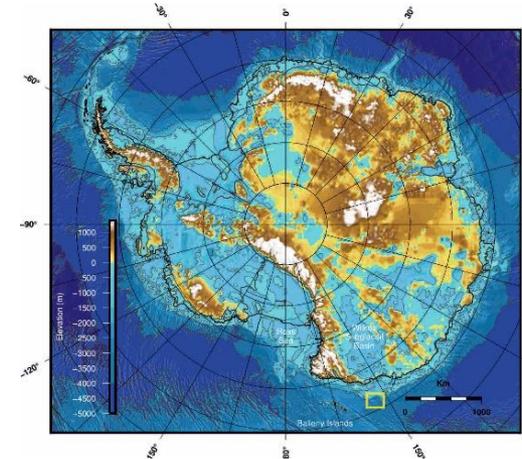


Colleoni et al., 2018

Ice Mass Change (meters water equivalent relative to 2002)

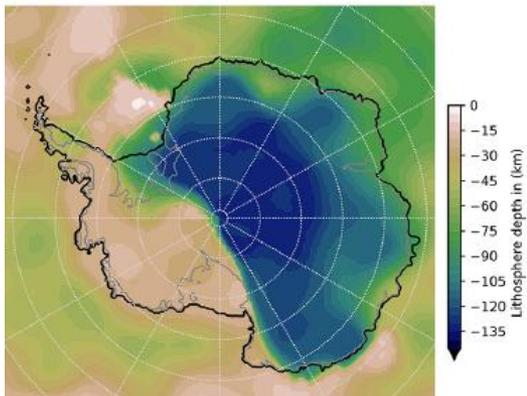


Topography and bathymetry



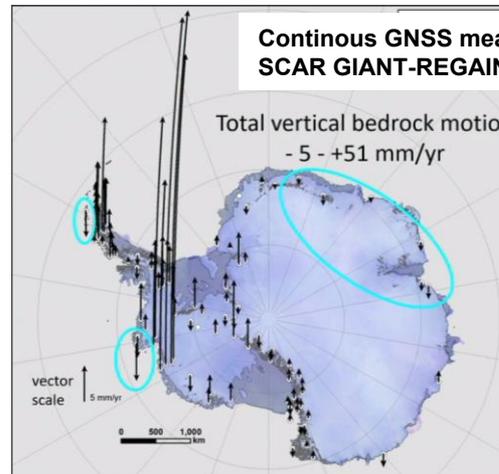
Morlighen et al., 2019, Dorschel et al., 2022

Lithosphere depth



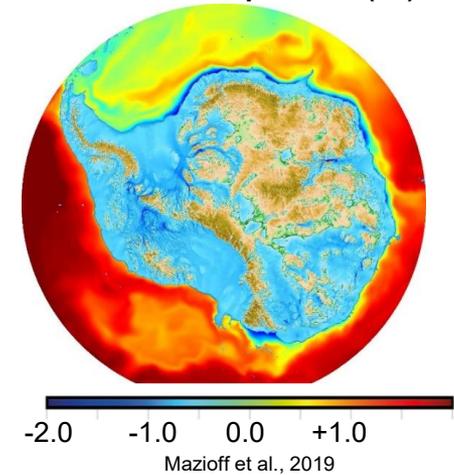
Albrecht et al., 2024

Continuous GNSS measures SCAR GIANT-REGAIN

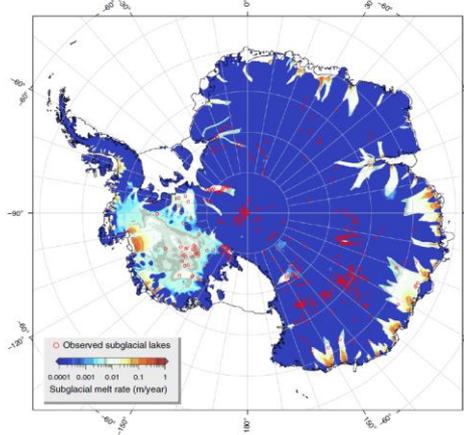


Wilson 2023

Southern Ocean temperature (°C) at 300 m

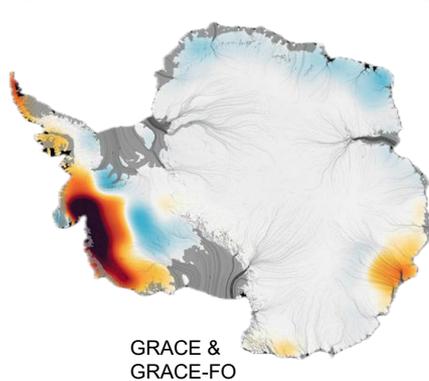


Subglacial lakes (red circles) & basal meltwater production rate (ma⁻¹)



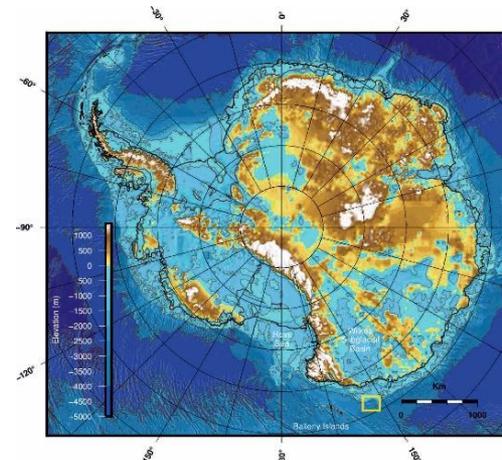
Colleoni et al., 2018

Ice Mass Change (meters water equivalent relative to 2002)



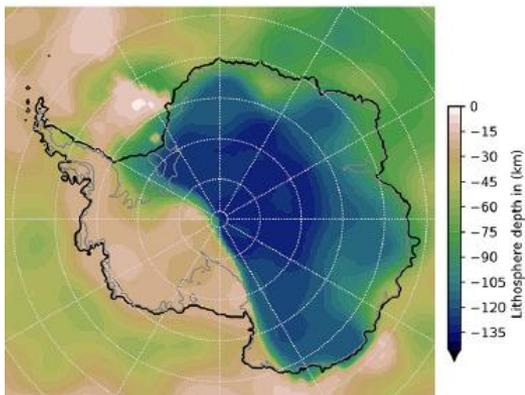
GRACE & GRACE-FO

Topography and bathymetry



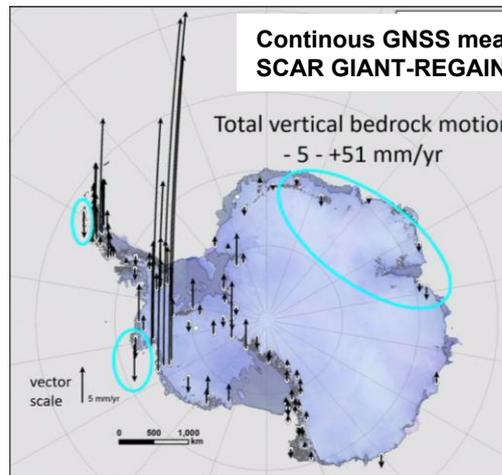
Morlighen et al., 2019, Dorschel et al., 2022

Lithosphere depth



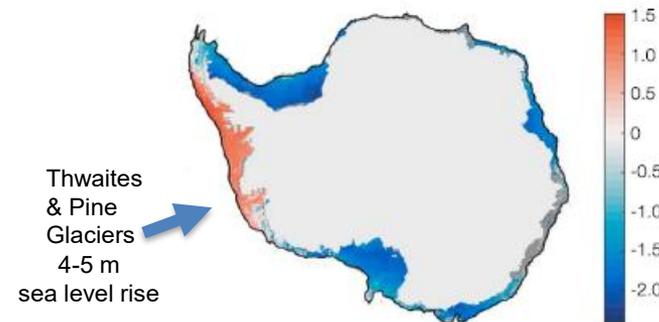
Albrecht et al., 2024

Continuous GNSS measures SCAR GIANT-REGAIN

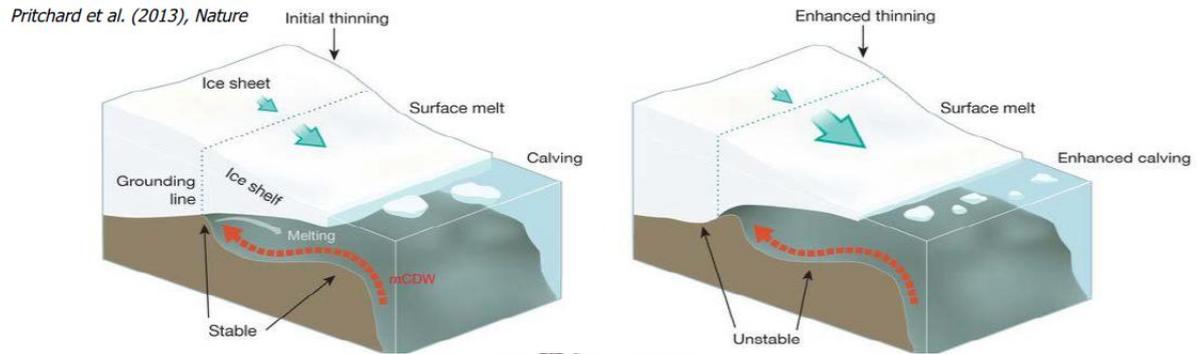


Wilson 2023

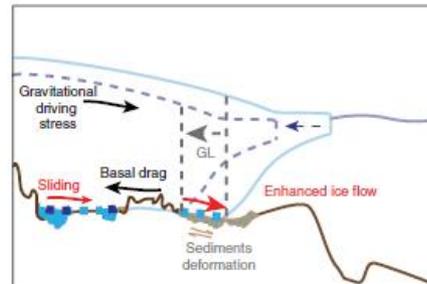
Continental Shelf bottom water (°C)



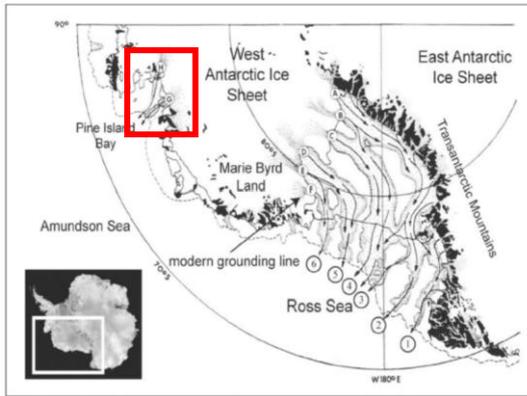
Thomson et al., 2018



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Colleoni et al., 2018

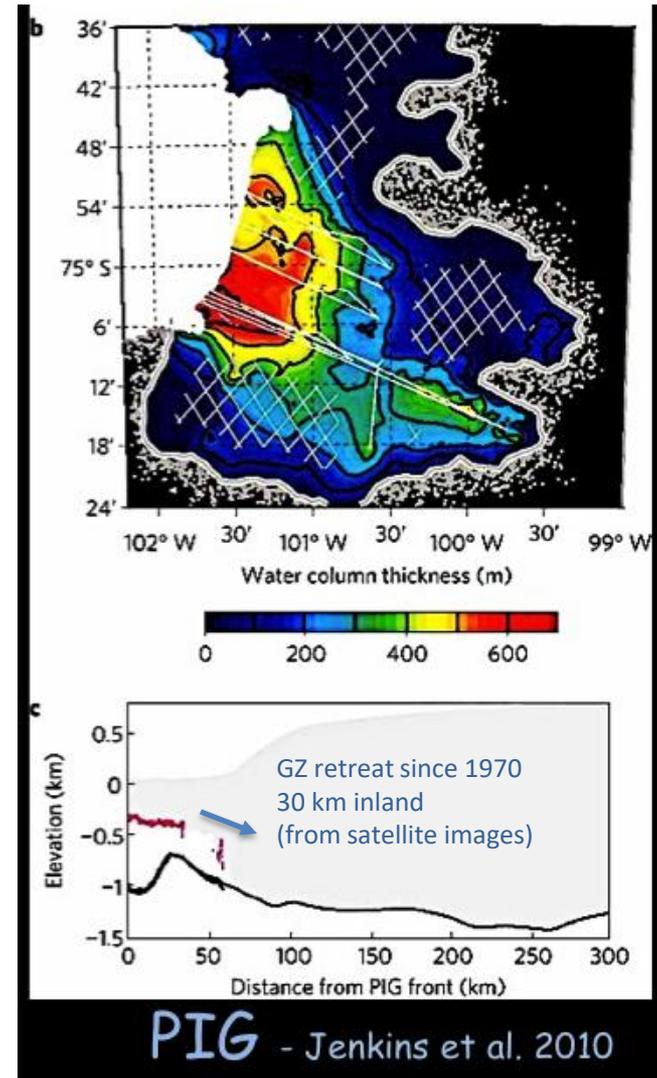
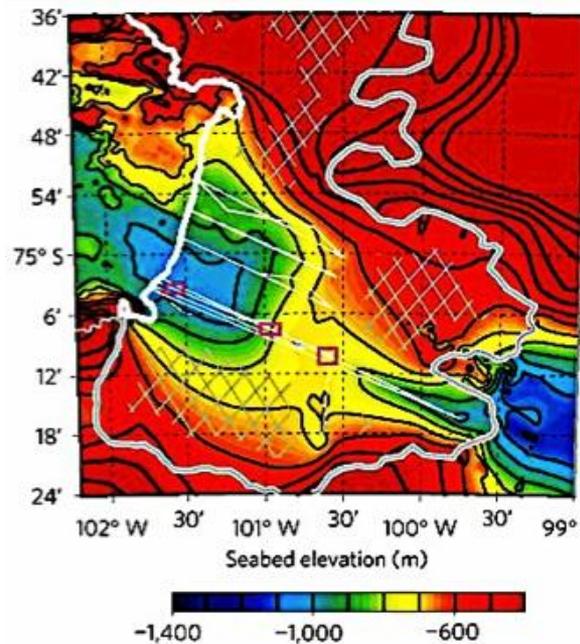


Pine Island Glacier

autonomous underwater vehicle

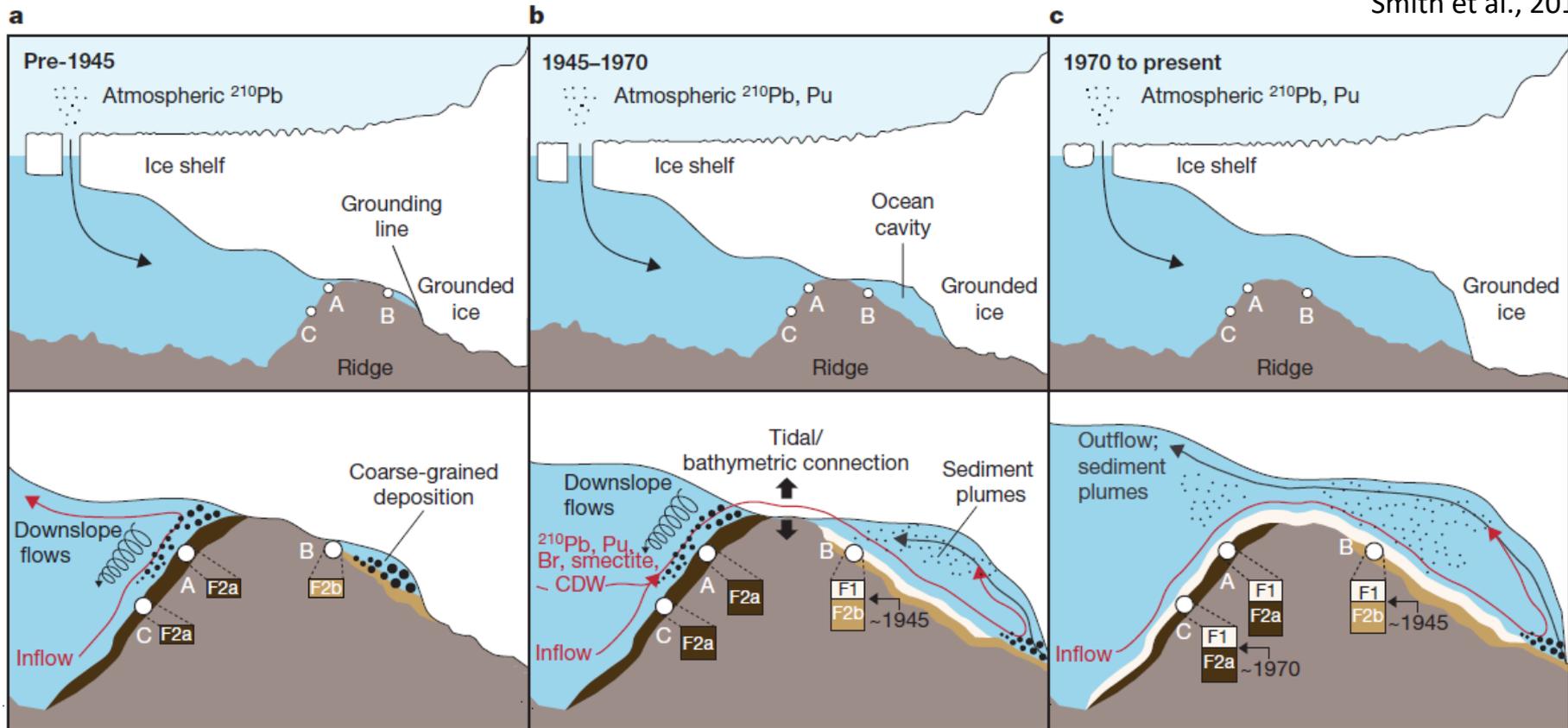
In the mid-1990s, the basal melt rate was estimated to exceed 50myr⁻¹

the input of ice from upstream of the grounding line has increased by at least 40% as a result of the glacier's acceleration



Pine Island Glacier

Smith et al., 2017



coarse-grained sediments

The inflow of marine water (CDW) over or around the ridge brings ^{210}Pb , Pu, Br, smectite and bromine (Br).

fine-grained sediments

ARTICLE

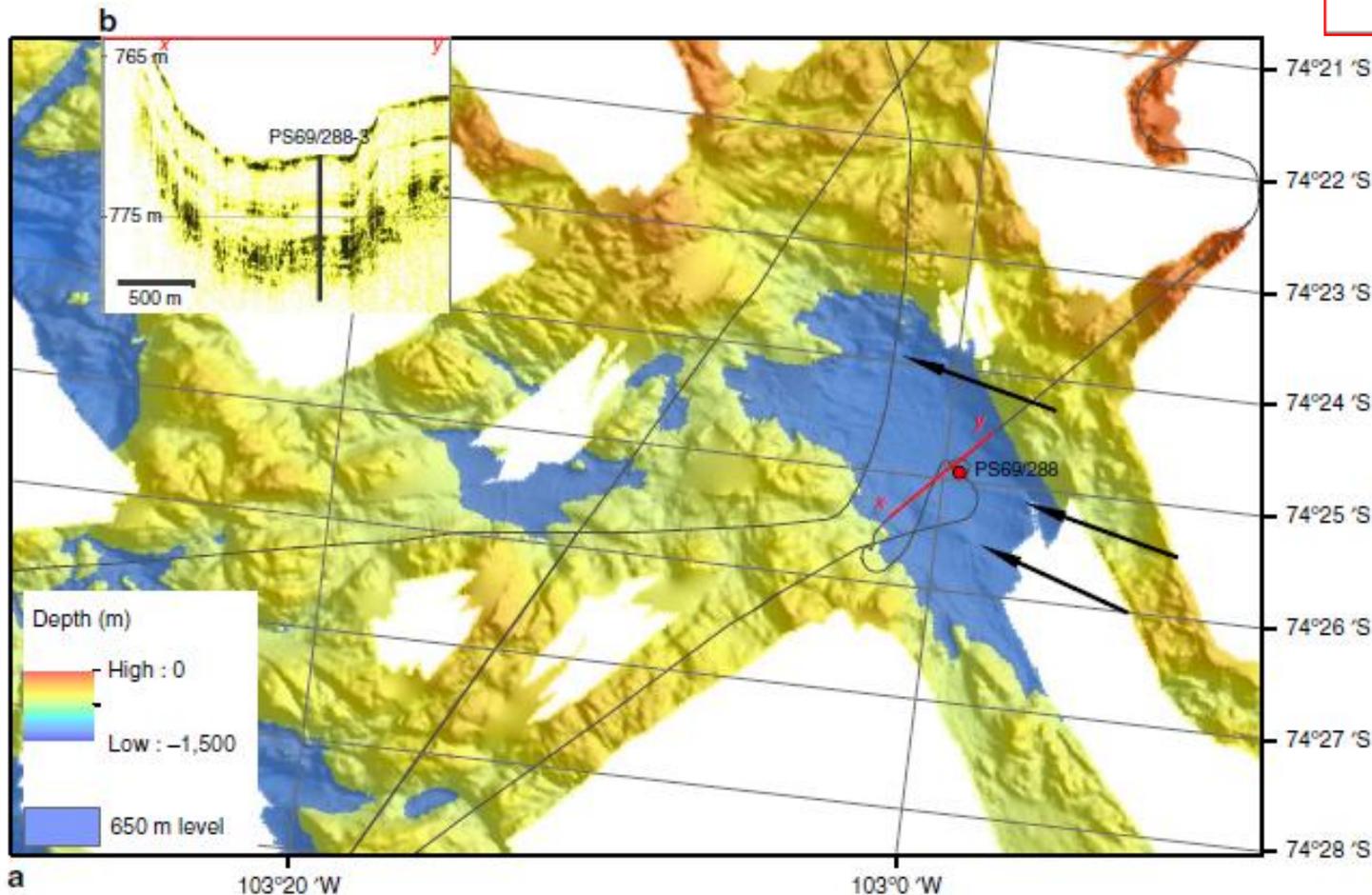
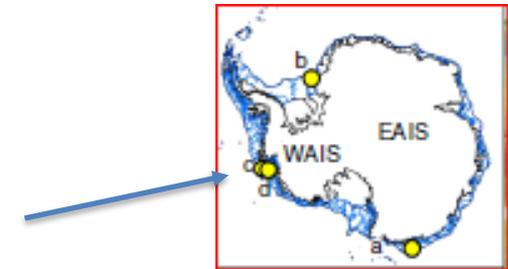
Received 23 Jun 2016 | Accepted 11 Apr 2017 | Published 1 Jun 2017

DOI: 10.1038/ncomms15591

OPEN

Evidence for a palaeo-subglacial lake on the Antarctic continental shelf

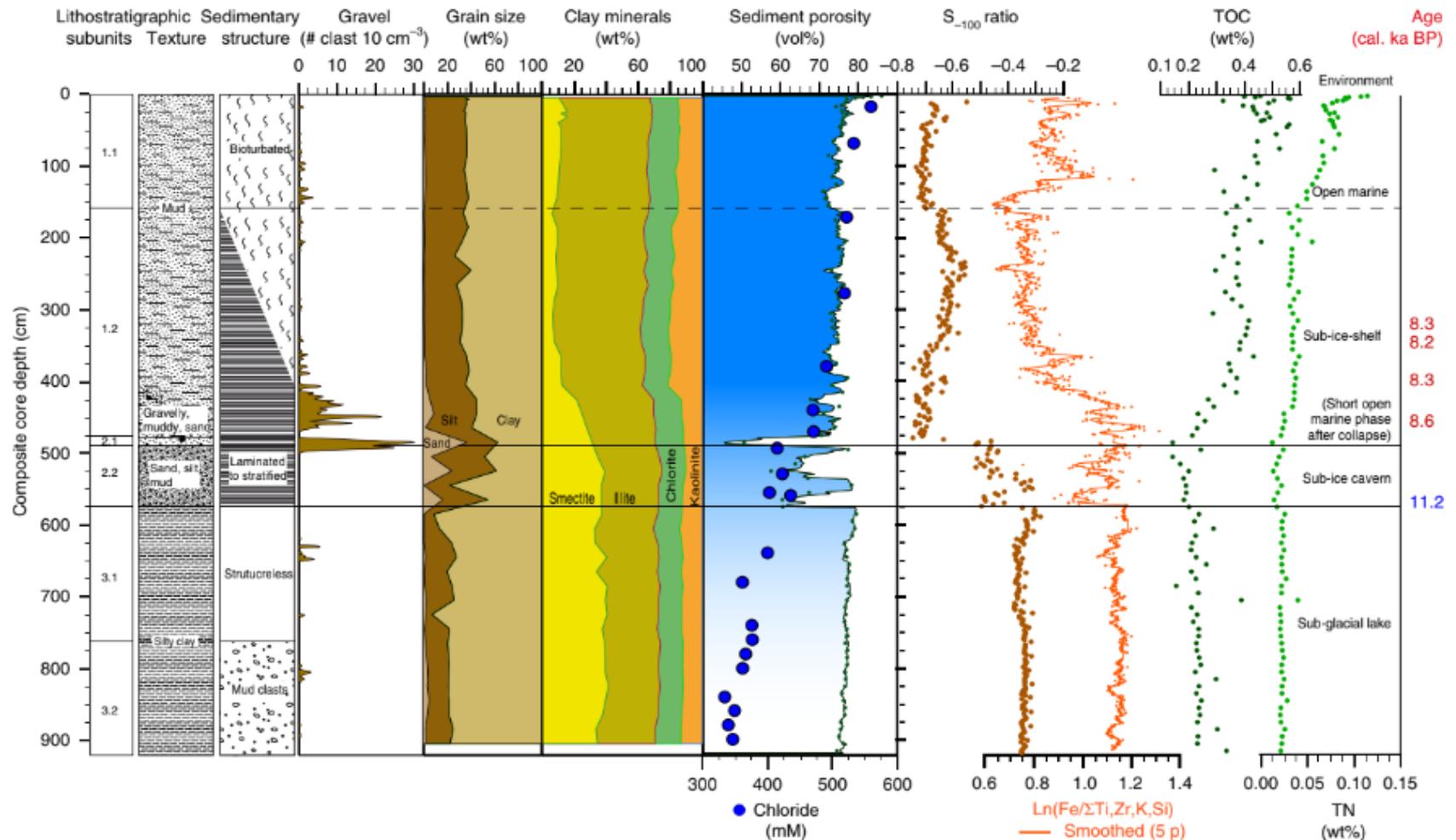
Gerhard Kuhn¹, Claus-Dieter Hillenbrand², Sabine Kasten¹, James A. Smith², Frank O. Nitsche³, Thomas Frederichs⁴, Steffen Wiers⁴, Werner Ehrmann⁵, Johann P. Klages¹ & José M. Mogollón⁶



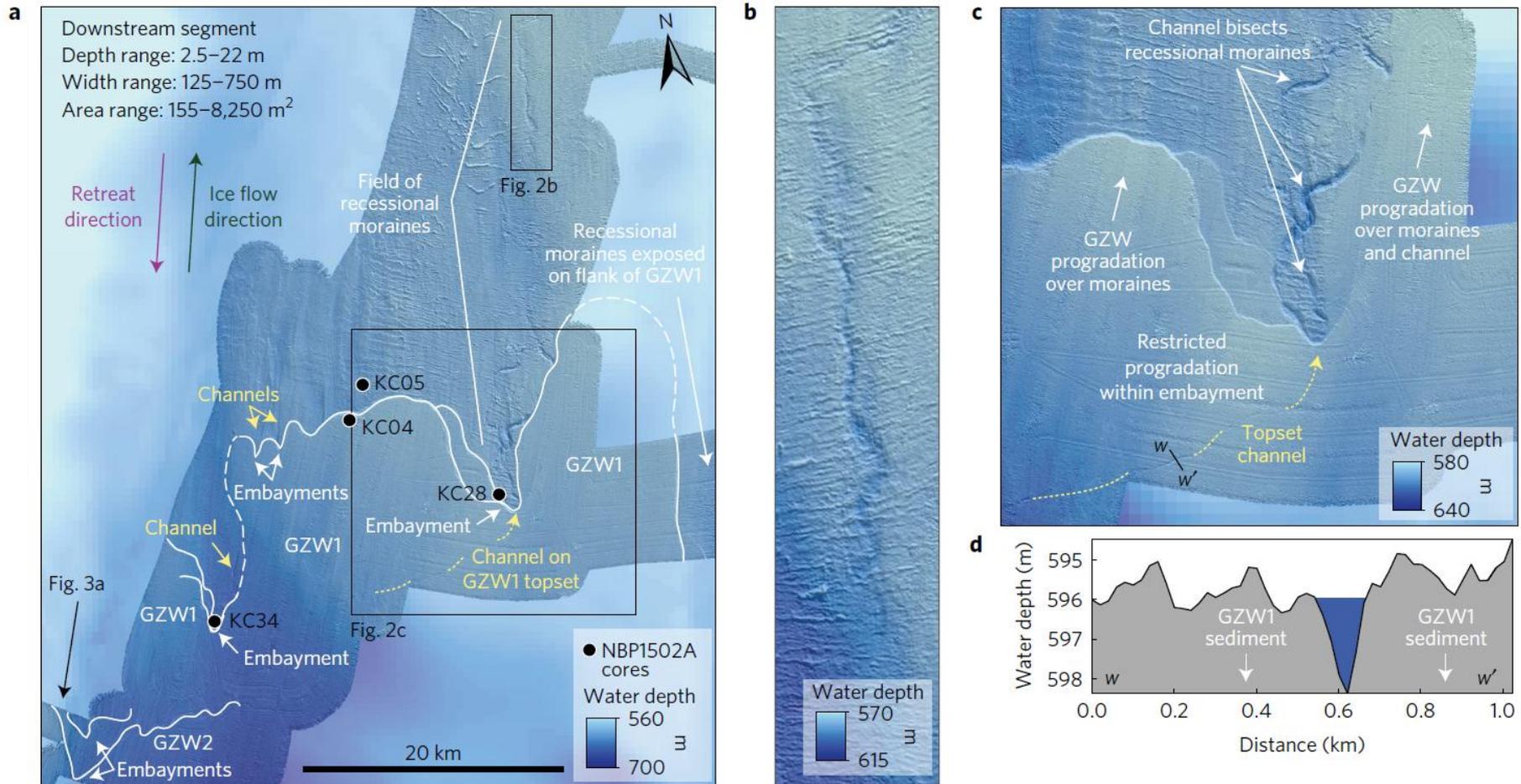
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NATURE COMMUNICATIONS | DOI: 10.1038/ncomms15591

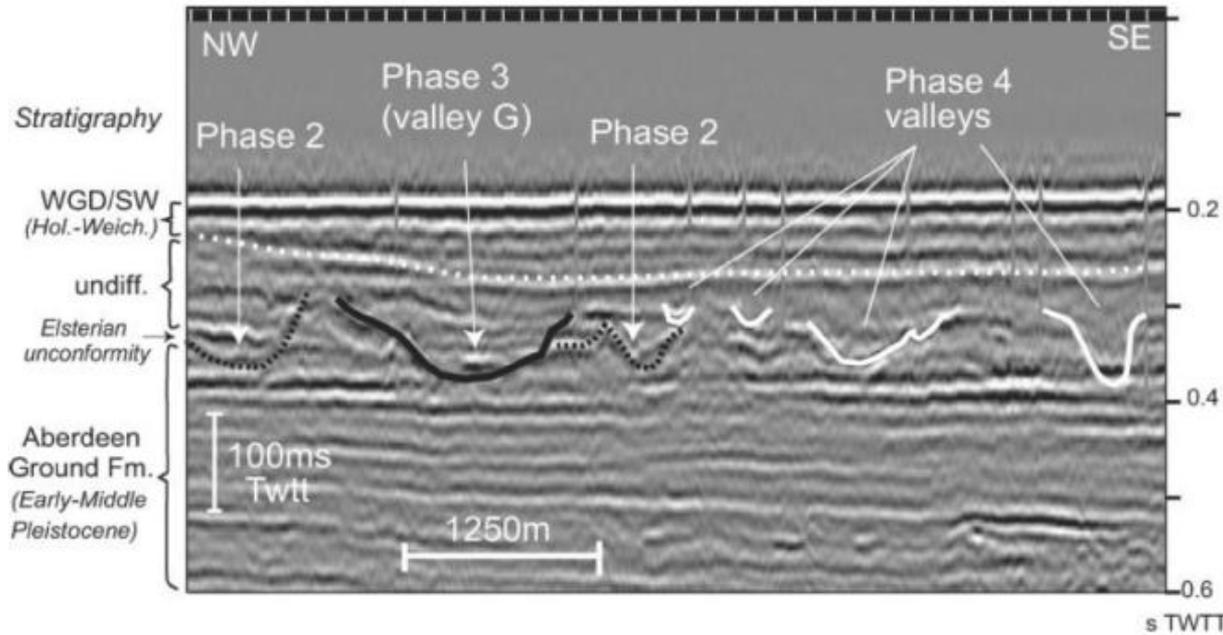


Outwash channels

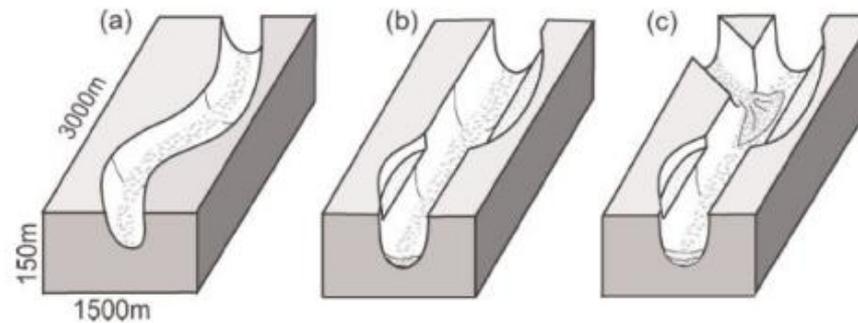


Simkins et al., 2017

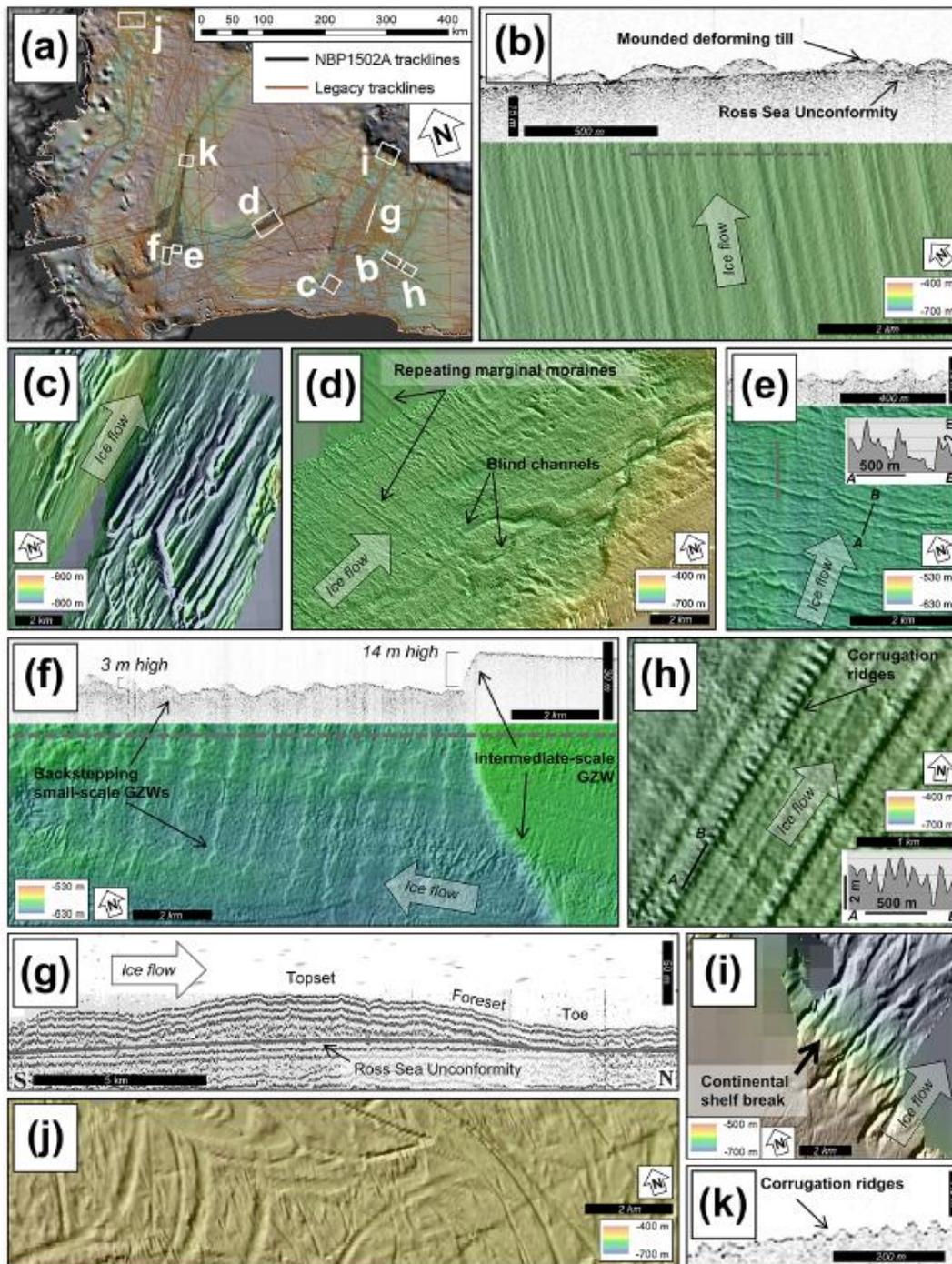
Outwash channels



Sand fill



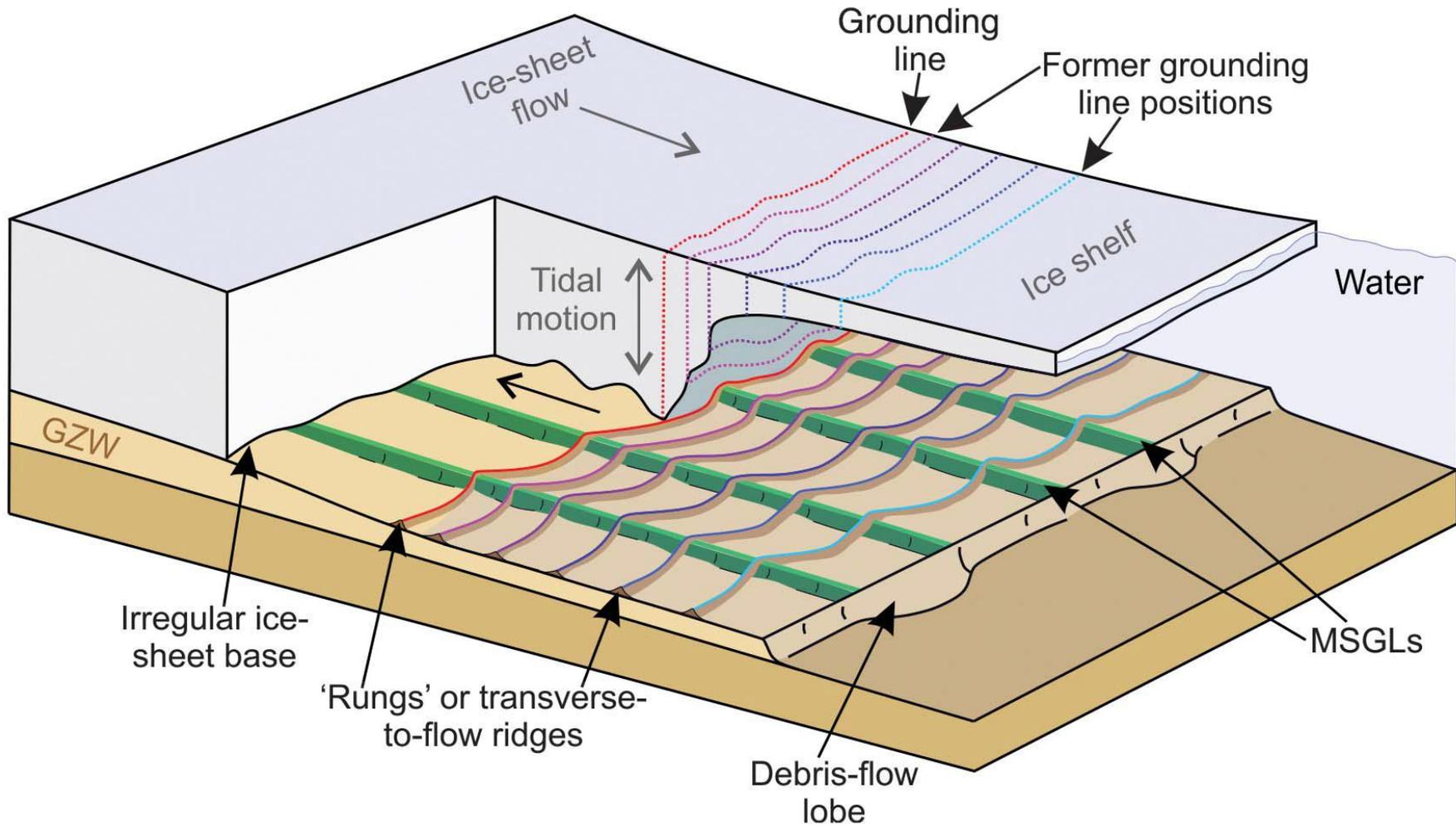
drumlins, crag and tails, and megaflutes



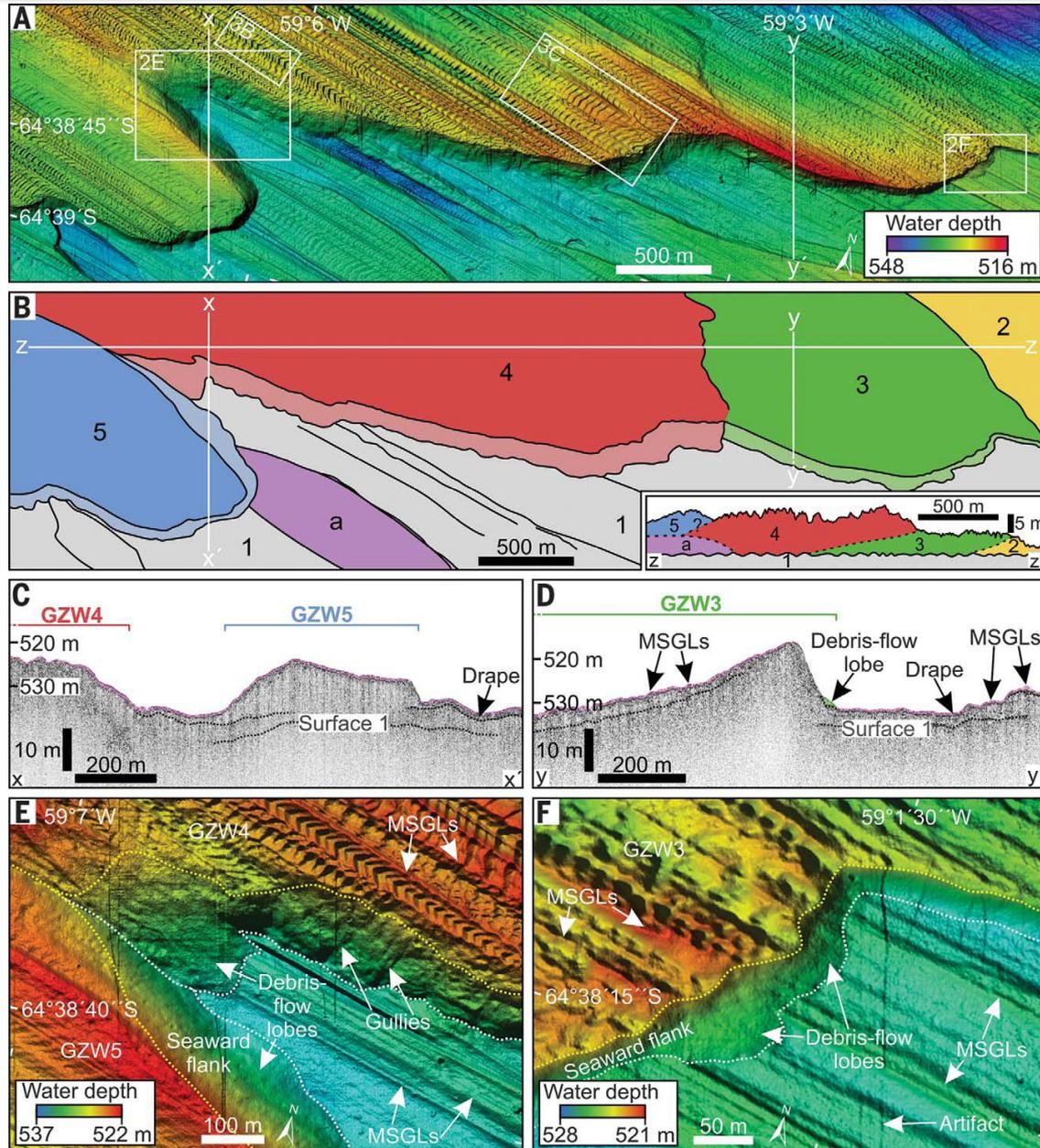
Megascale glacial lineations

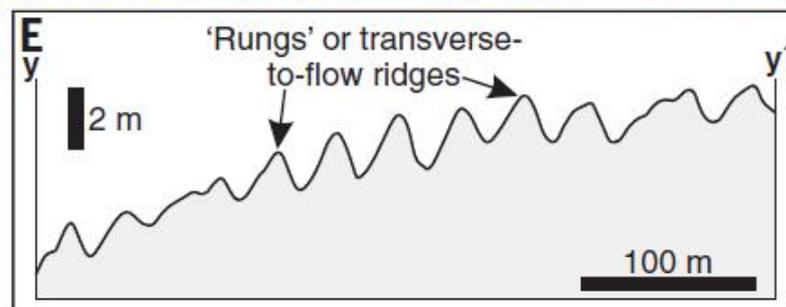
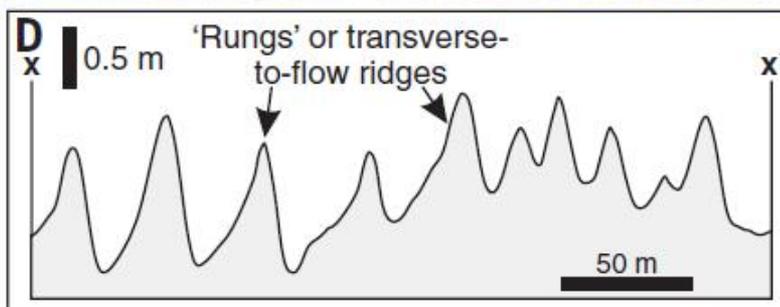
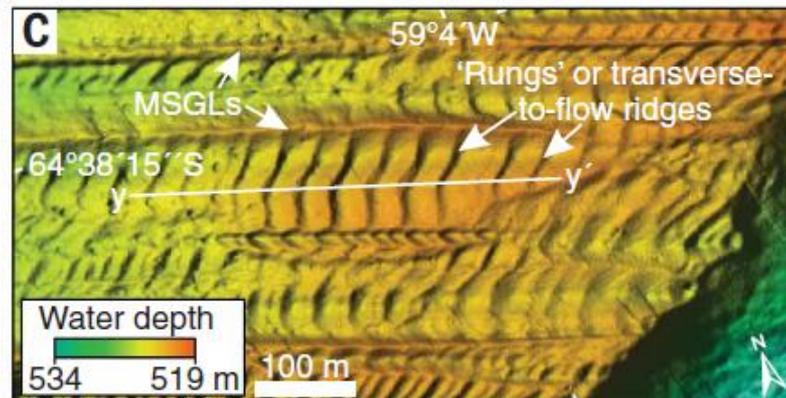
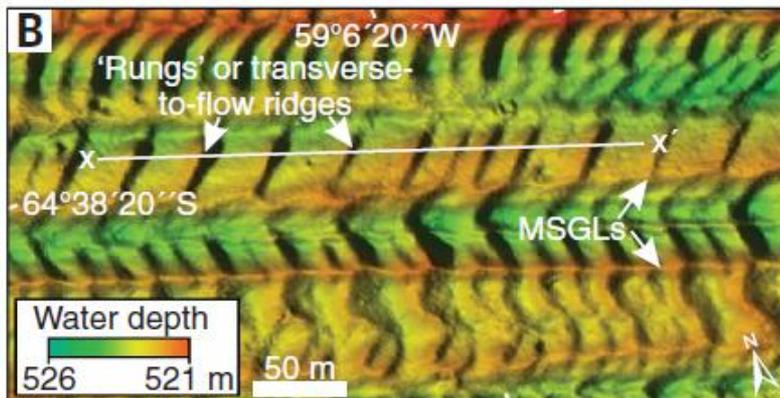
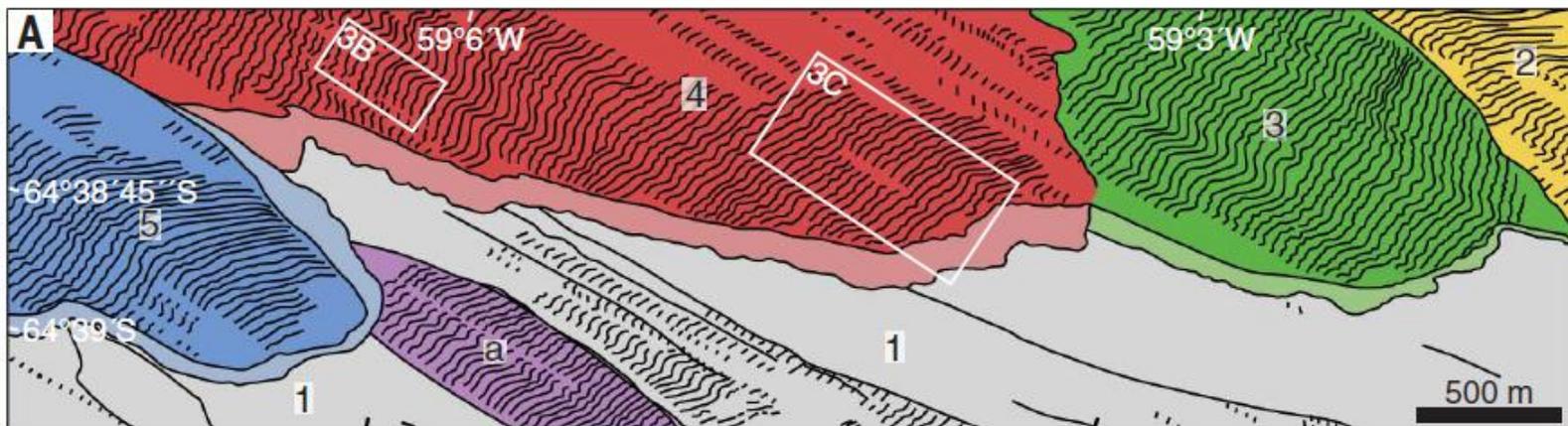
'corrugation ridges' are the expression of tidal lifting and settling of the ice shelf during scour formation

Halberstadt et al., 2016
Smith et al., 2019



Dowdeswell et al. 2020





L.O. Prothro et al.

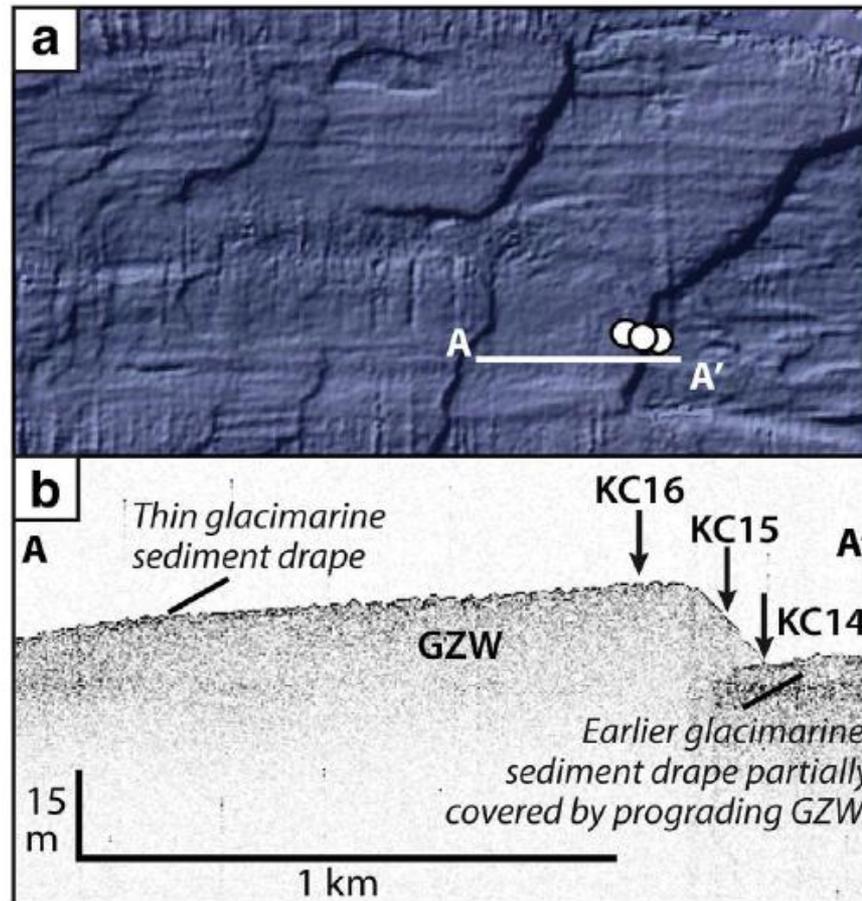
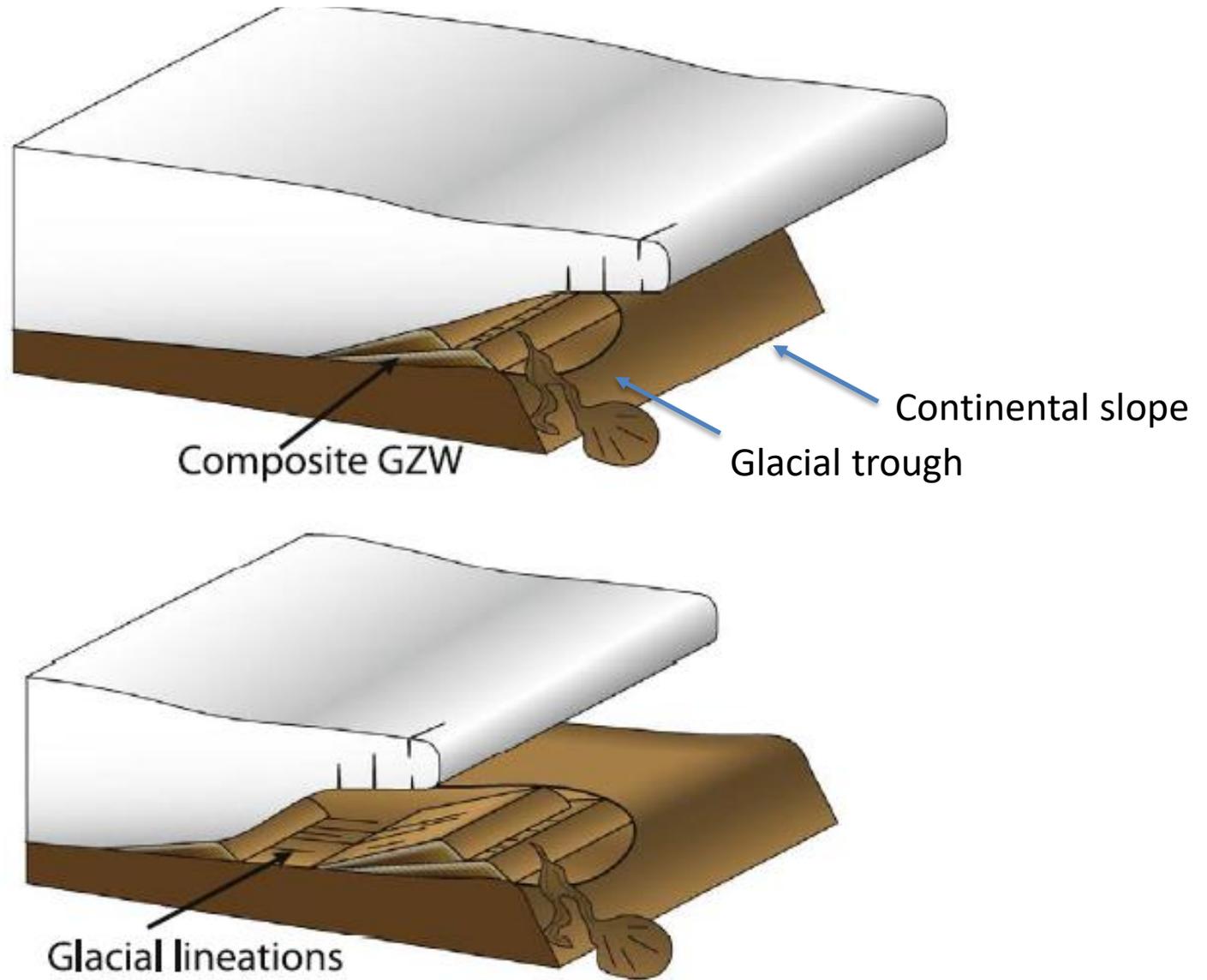
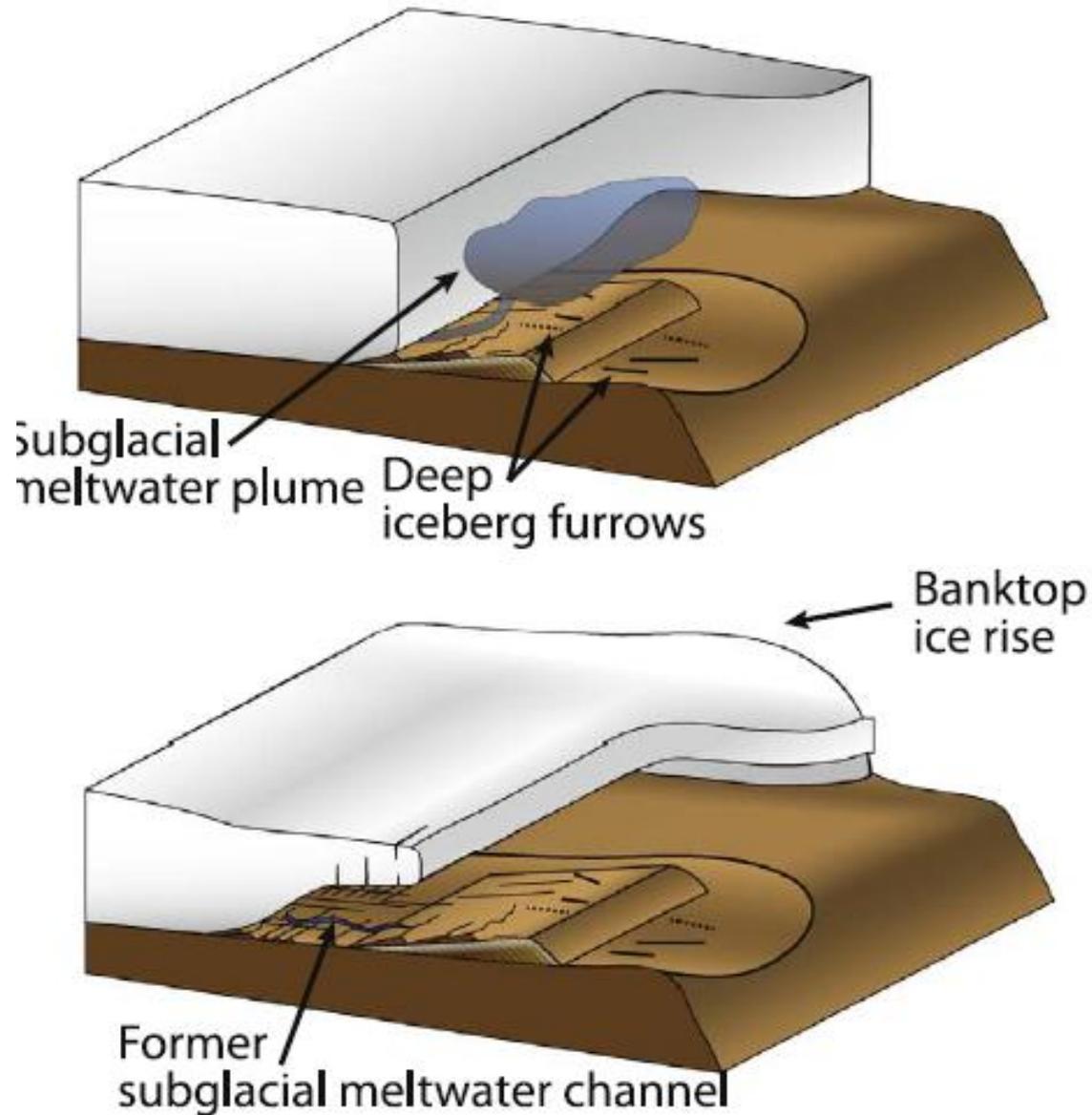
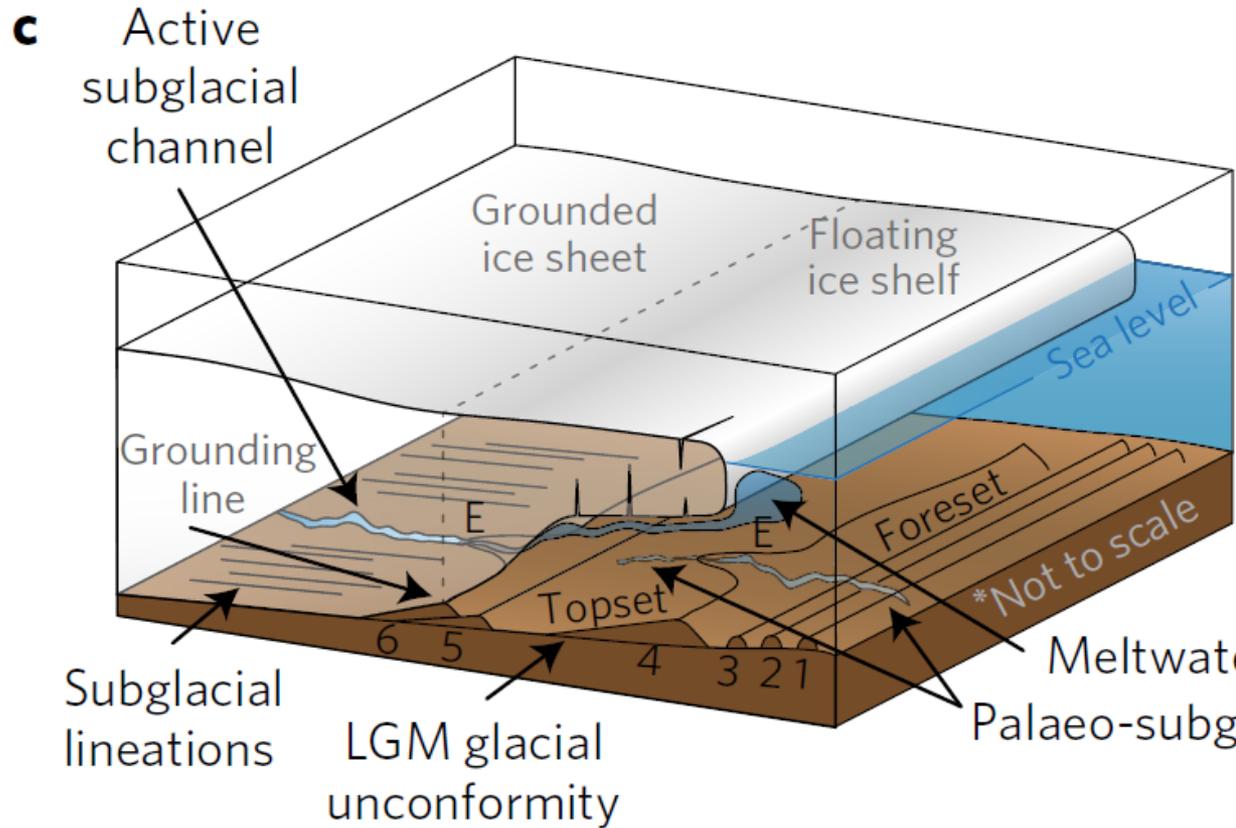


Fig. 3. Example of coring transect demonstrating targeted coring along a grounding-zone wedge using both (a) multibeam swath bathymetry and (b) CHIRP data. Core locations are shown in multibeam context in Fig. 3a, seismic context in Fig. 3b, and regional context in Fig. 1.

The presence of GZWs in the geological record indicates an episodic style of ice retreat punctuated by still-stands in grounding-zone position.







1-3: Recessional moraines (0.5-5 m amp., 20-160 m long, 150-1,700 m spacing)

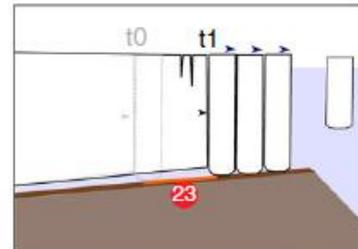
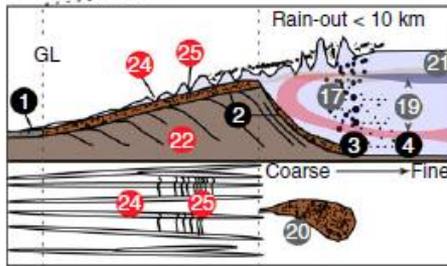
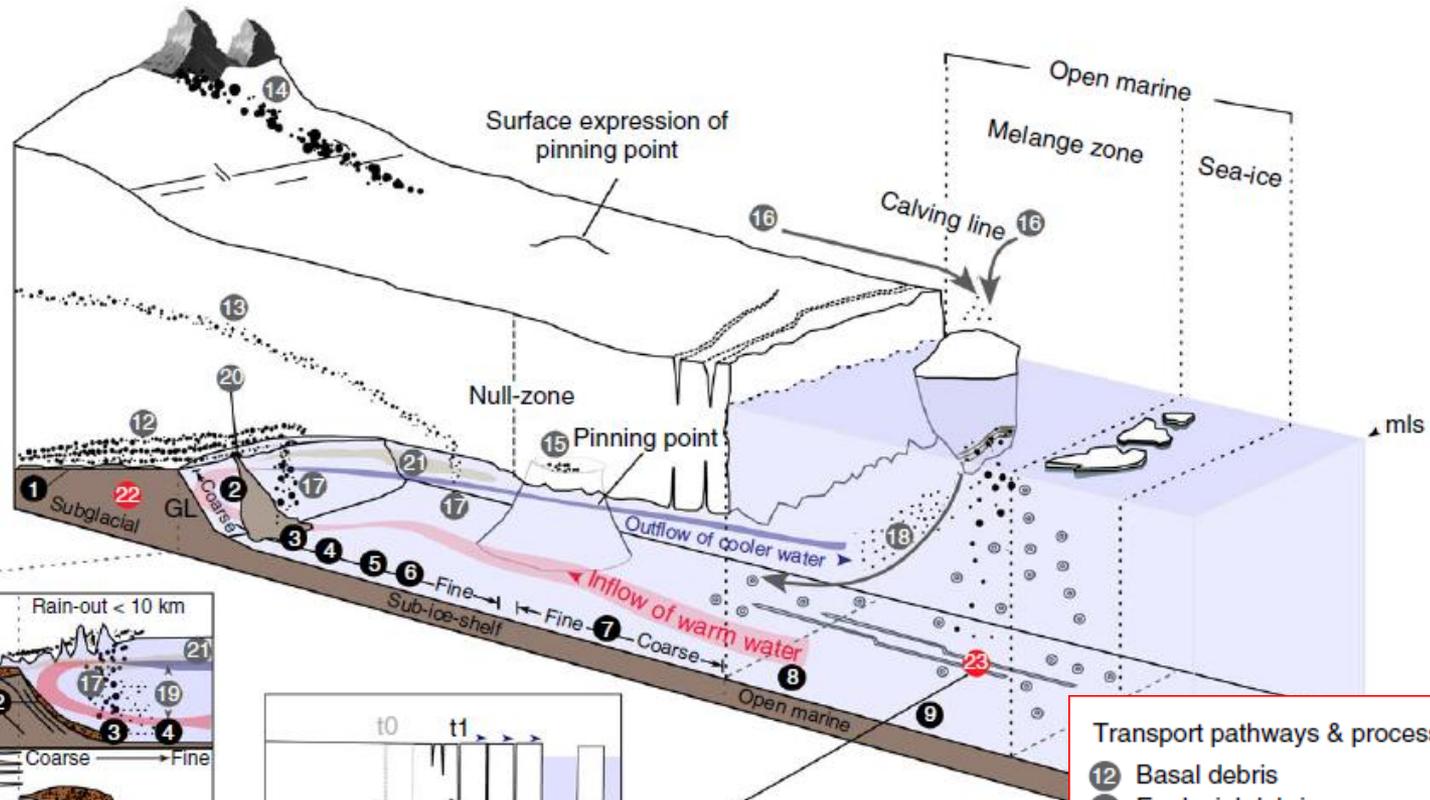
4-6: GZWs (2-20 m amp., 50-1,200 m long, 500-4,500 m spacing)

Grounding-line embayments (E)

a Ice-shelf presence

Sediment elements

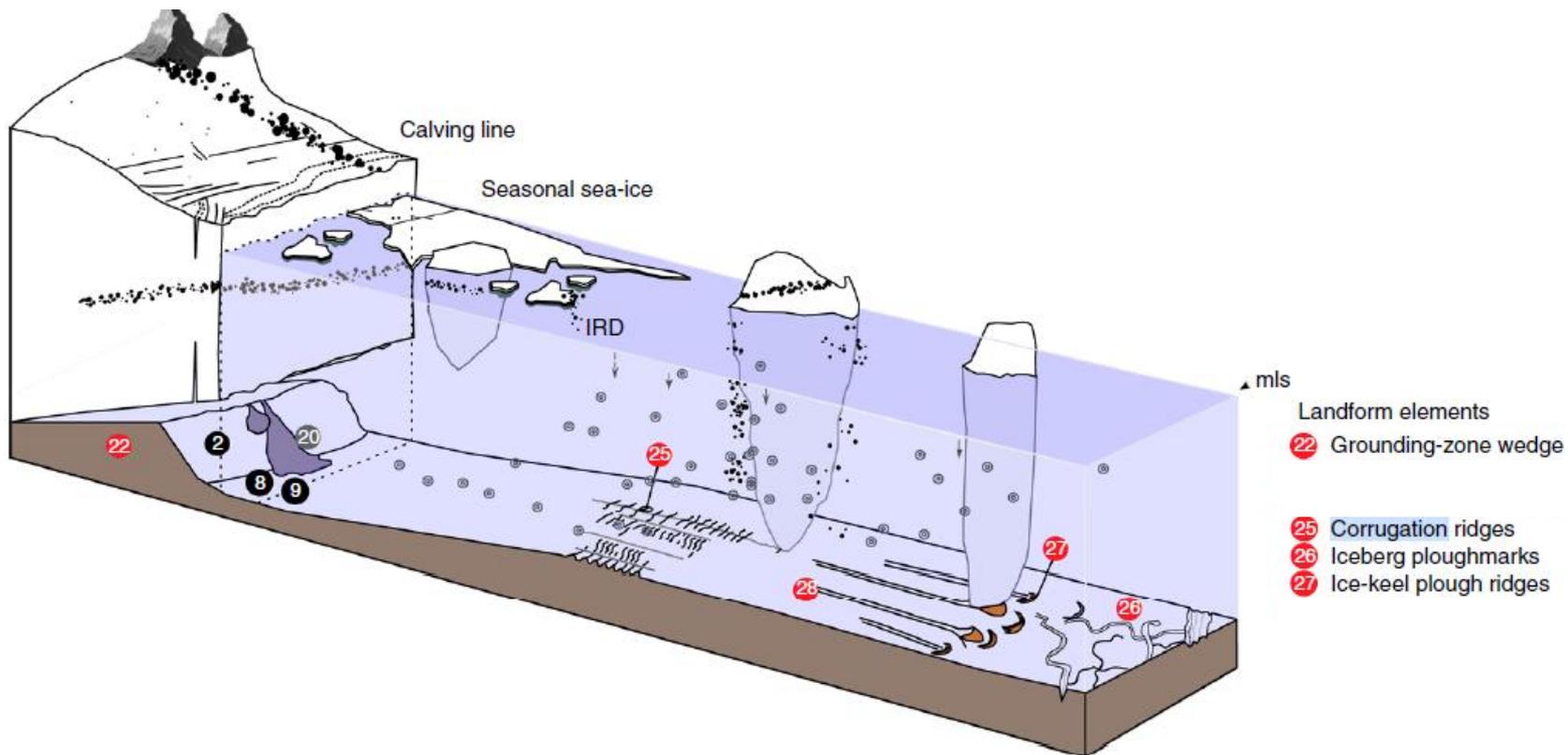
- 1 Subglacial till
- 2 Stratified diamicton (GL facies)
- 3 Pellet-rich mud (=granulated facies)
- 4 Cross-stratified sands/muds
- 5 Laminated to 6 massive muds
- 7 Massive muds, sandy muds
- 8 Dropstone mud/diamicton (CL facies)
- 9 Diatom-bearing/diatomaceous muds
- 10 Aeolian sand (hydrofracture)
- 11 Poorly sorted sand, gravel, diamicton (collapse facies)



- ### Landform elements
- 22 Grounding-zone wedge
 - 23 Ice-shelf melange scours
 - 24 Sub-ice shelf keel scours
 - 25 Corrugation ridges

Transport pathways & processes

- 12 Basal debris
- 13 Englacial debris
- 14 Supraglacial debris
- 15 Freeze-on of basal debris
- 16 Aeolian debris
- 17 Meltout/rain-out processes
- 18 Advection of phytodetritus/terrigeneous debris
- 19 Tidal pumping/sorting of fines
- 20 Glacigenic debris flows/slumping/turbidity currents
- 21 Sediment-rich meltwater



Smith et al. 2017

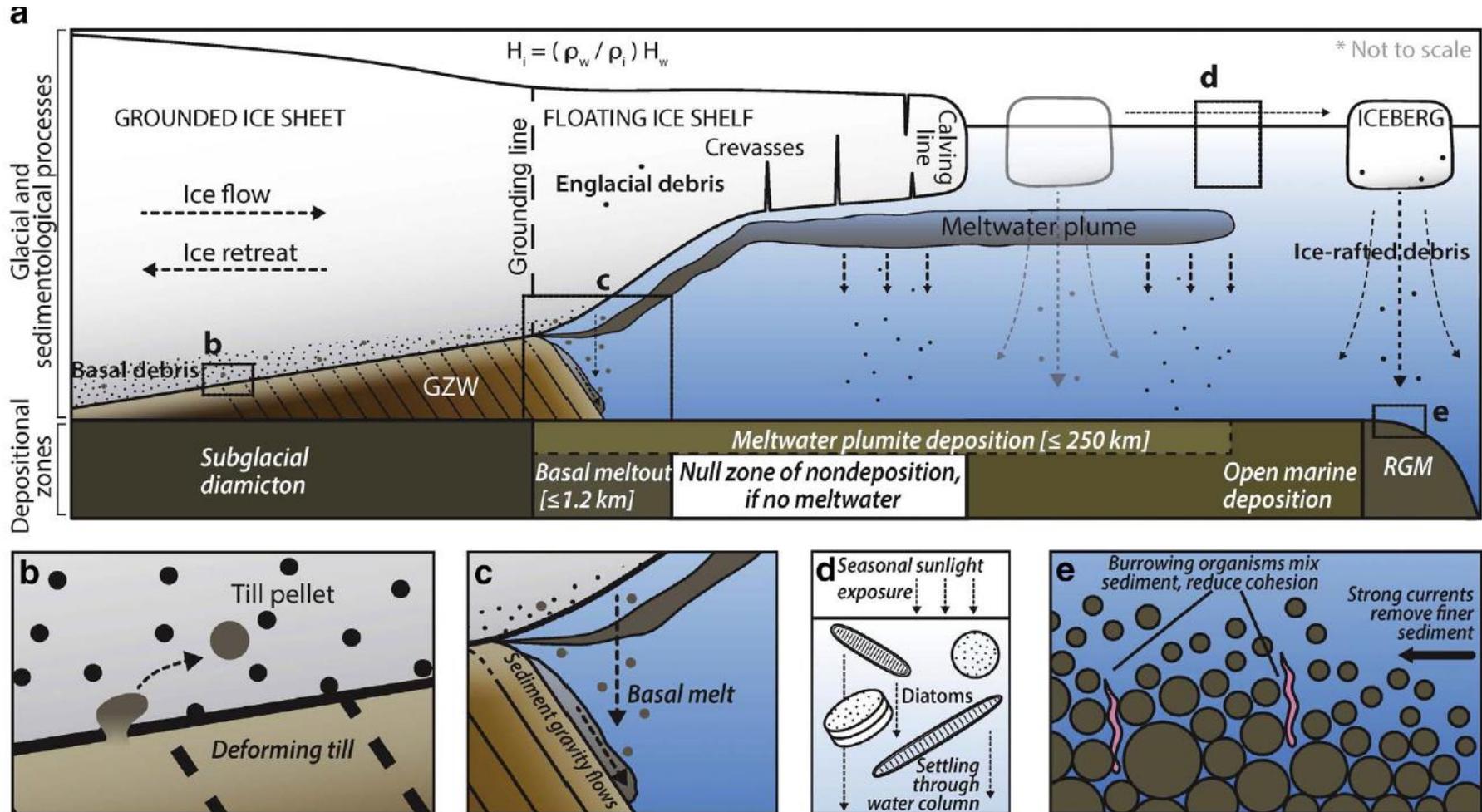
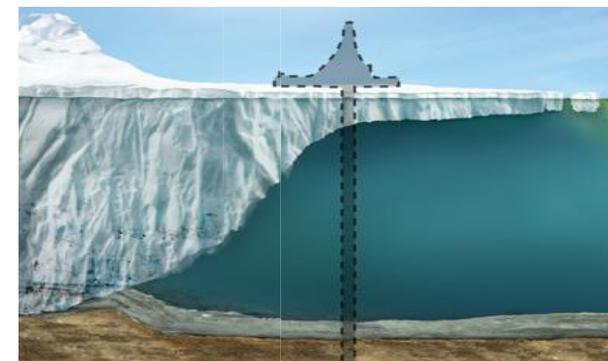
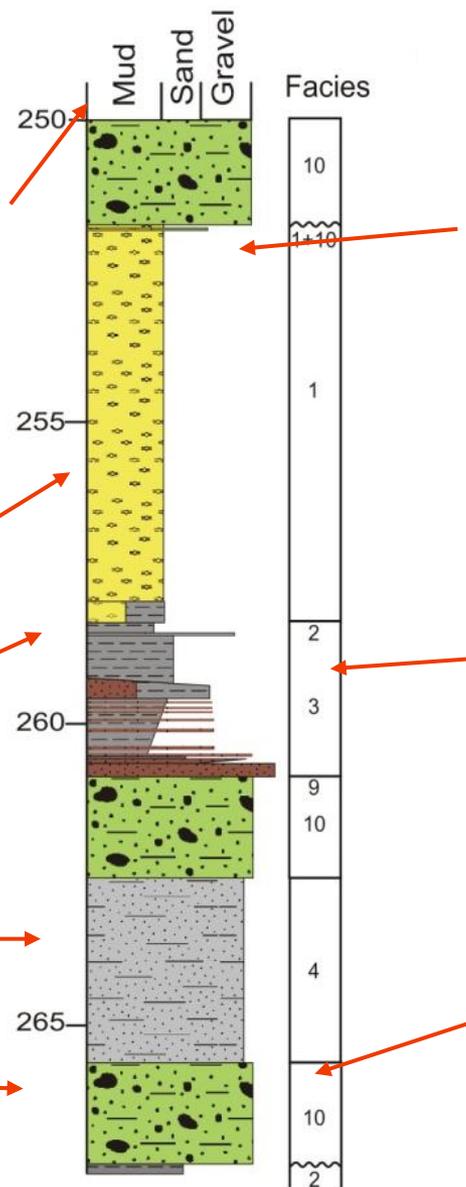
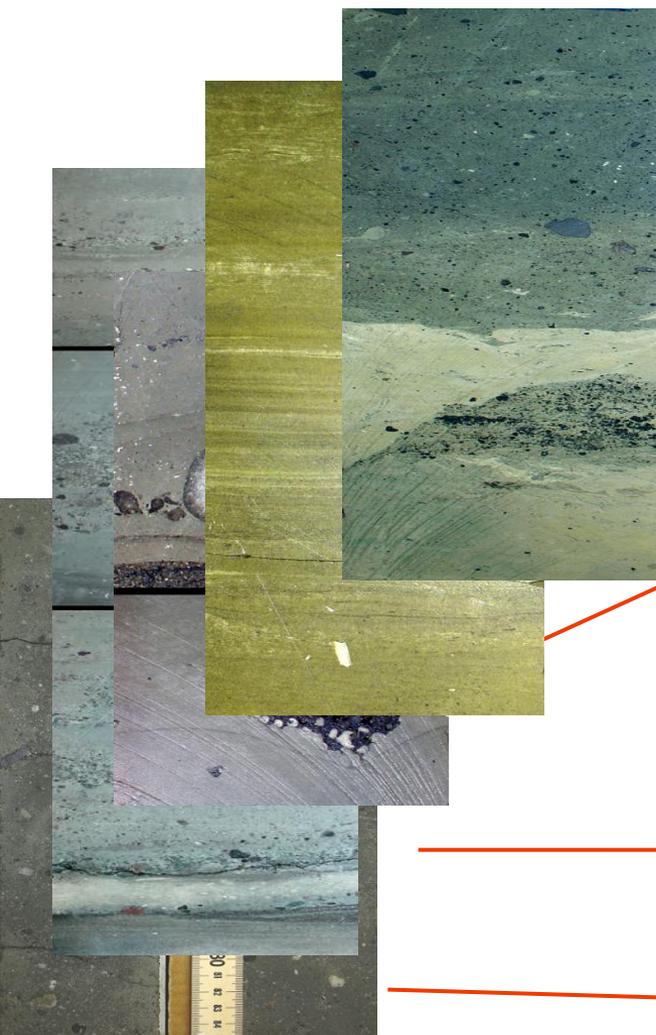


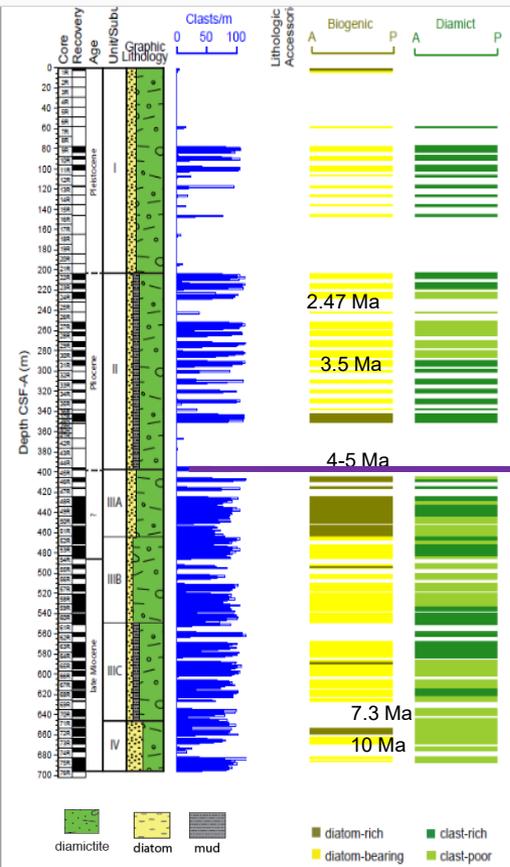
Fig. 2. (a) Conceptual diagram of a grounding-zone wedge (GZW) and proglacial environment, with associated glacial and sedimentary processes. Definitions of terms for buoyancy equation: H_i = ice thickness, H_w = water depth, ρ_i = density of ice (917 kg m^{-3}), ρ_w = density of seawater ($\sim 1025 \text{ kg m}^{-3}$ —may vary). Terrigenous input from meltwater plumes (level in water column unknown) is observed as far as 250 km from subglacial meltwater channels in the Ross Sea. (b) Formation of till pellets. (c) Deposition of basal meltout debris (limited to within 1.2 km of the grounding line) and debris flows (restricted to foreset length). (d) Open marine sedimentation dominated by rainout of organic detritus. (e) Reworking of glacial and glacialmarine sediments by marine currents on banktops and the shelf margin, facilitated by bioturbation or iceberg turbation.

Glacial-Interglacial glacimarine cycles

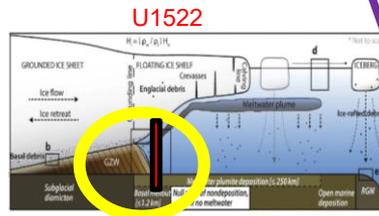
From Mckay et al. 2009 GSA Bull.



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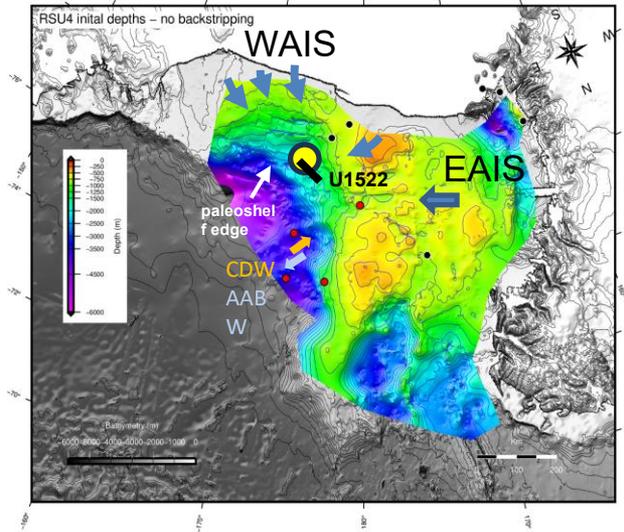


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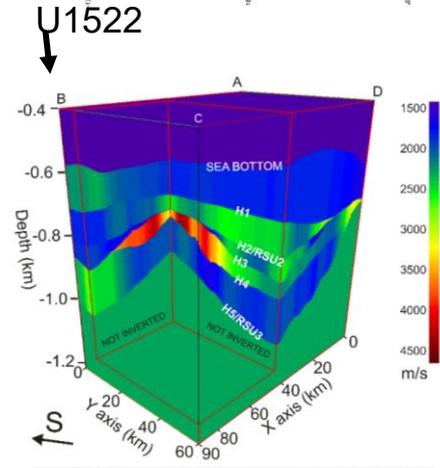
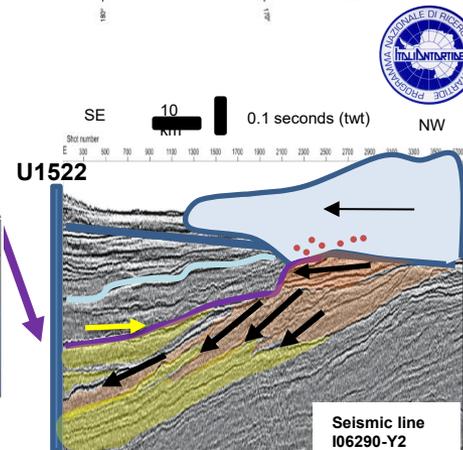
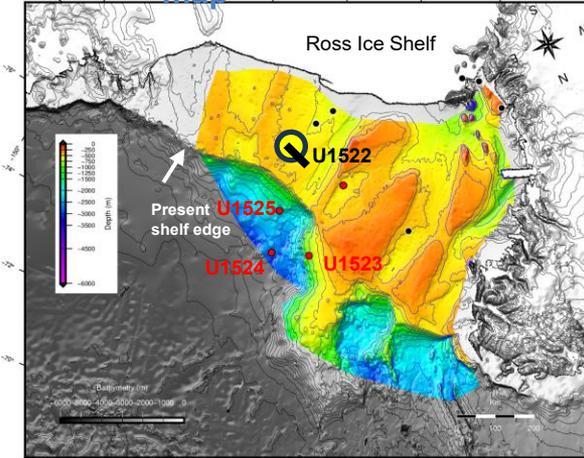


McKay, De Santis, Kulhanek et al., 2018

Tectonic boundary (Tinto et al., 2019)

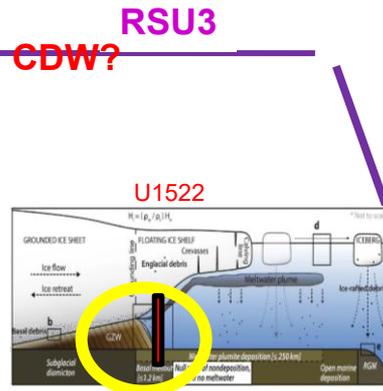
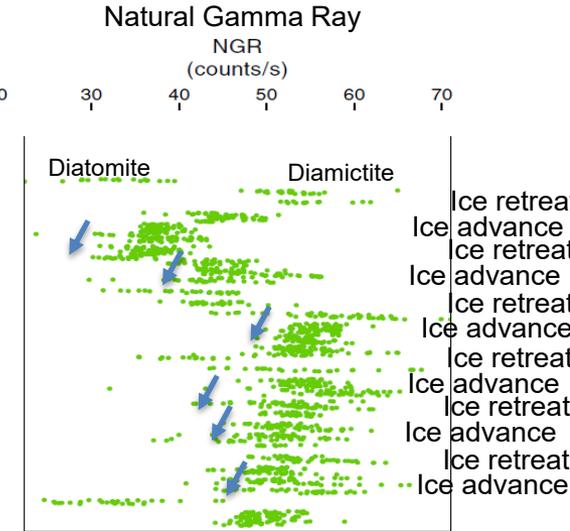
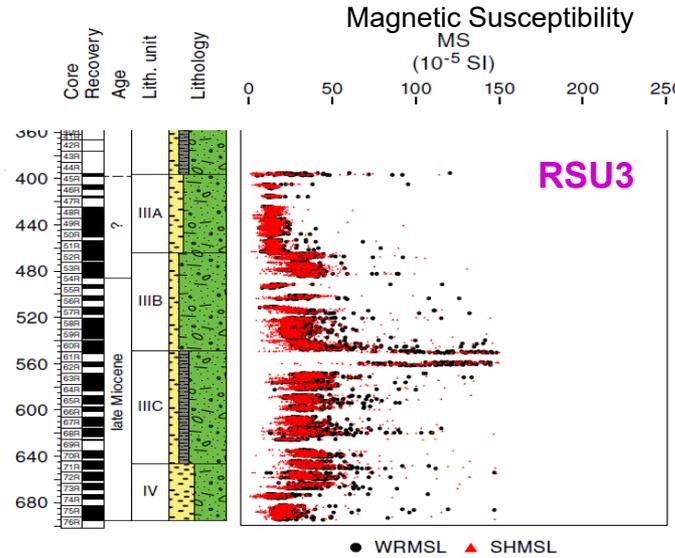
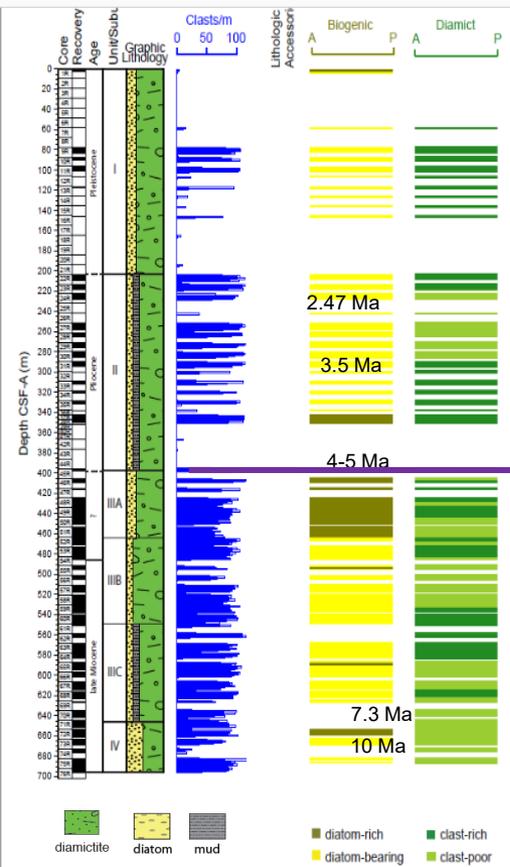


Present depth map

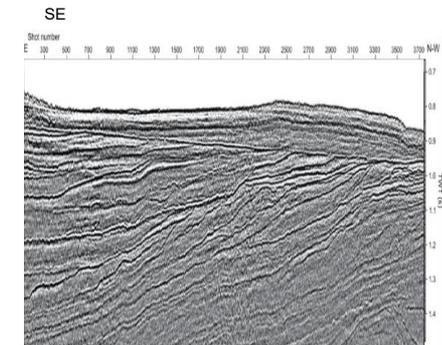
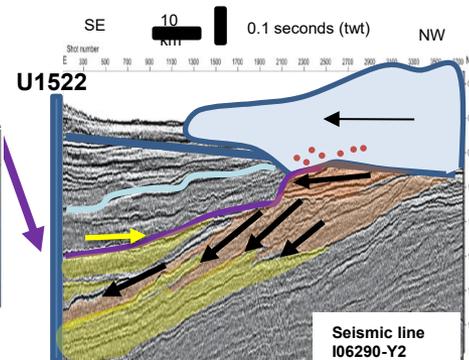


Boehm et al., 2009

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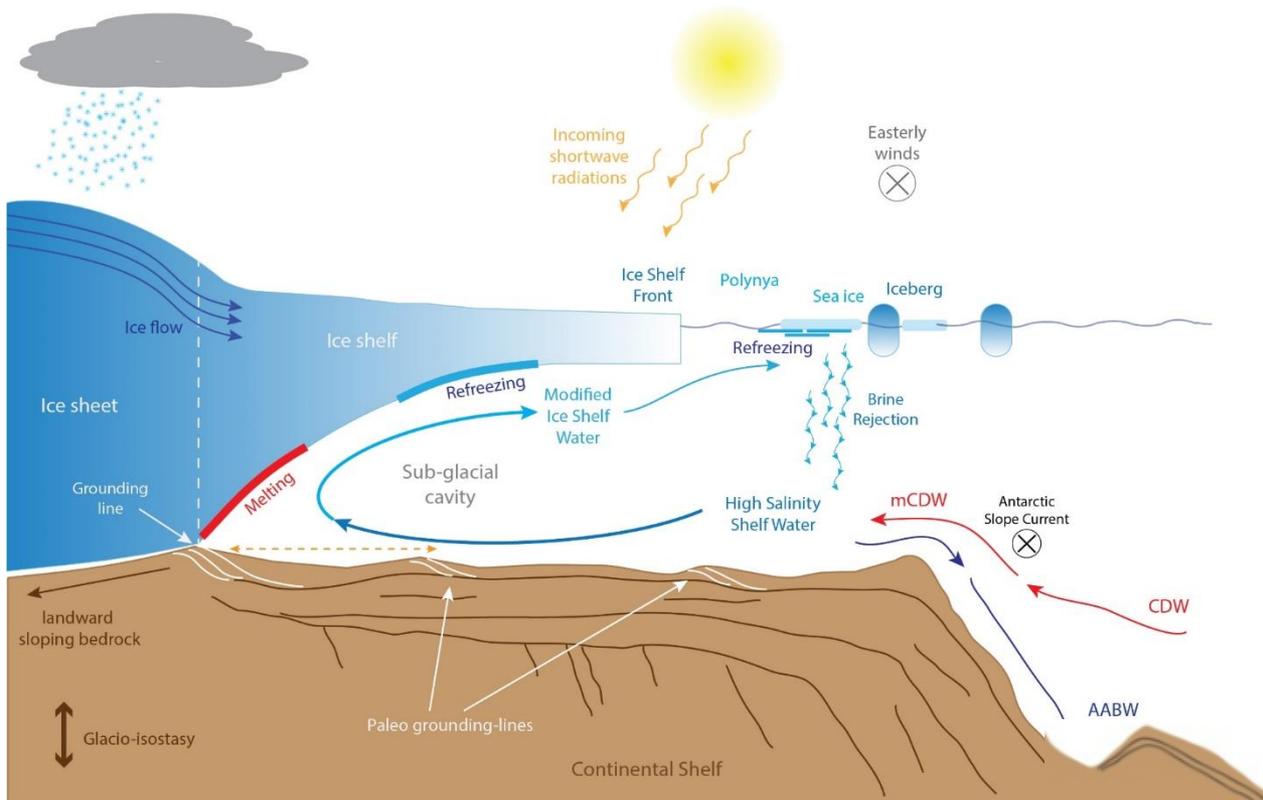


McKay, De Santis, Kulhanek et al., 2018



Boehm et al., 2009

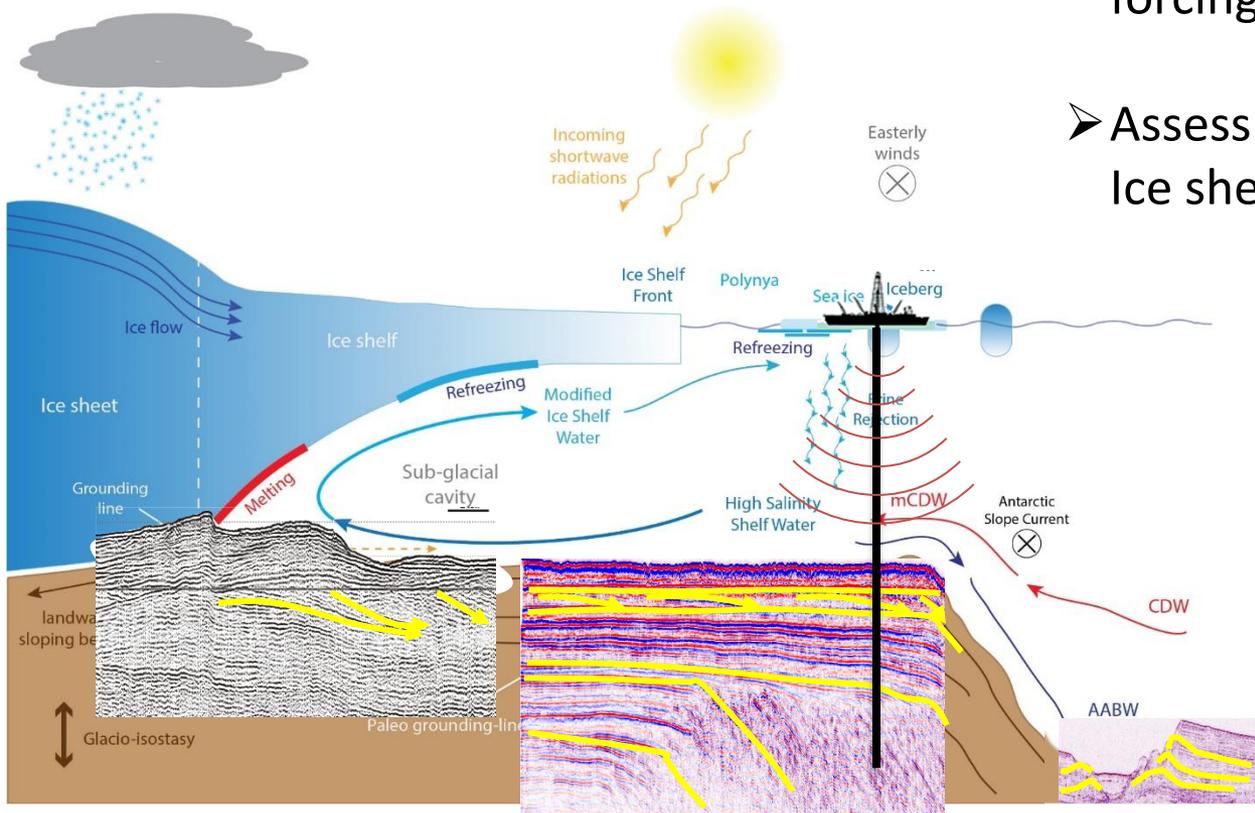
Palaeo-ice streams exerted a major influence on ice-sheet behaviour and had the potential to cause abrupt climatic change through the rapid delivery of ice and freshwater to the ocean.



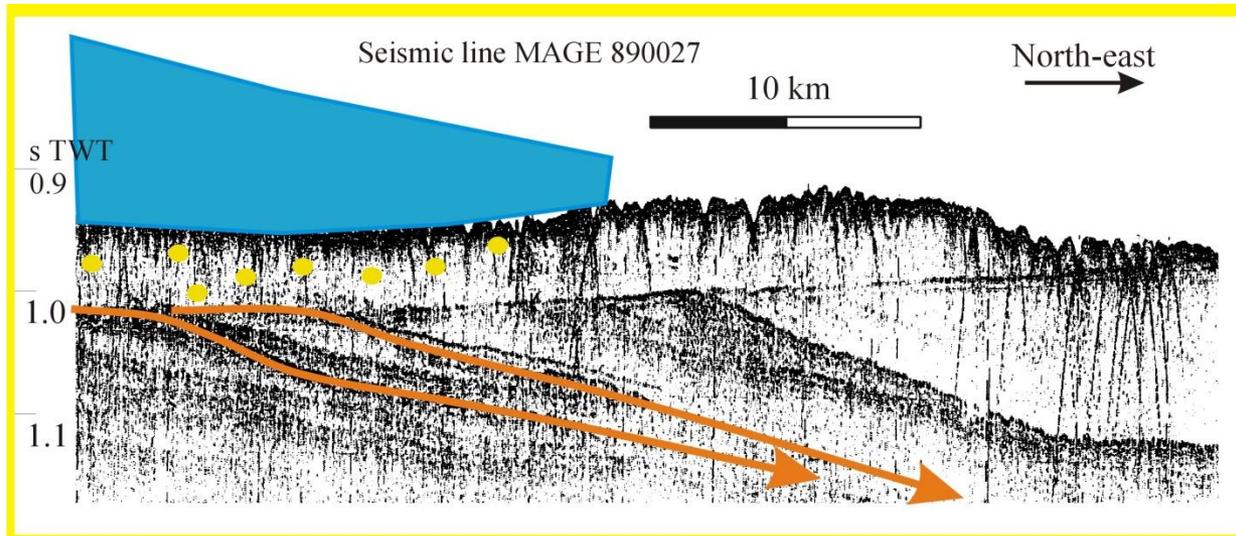
Paleo GZW indicate episodic palaeo ice-stream retreat punctuated by still-stands in the grounding-zone position (Dowdeswell et al., 2008; Ó Cofaigh et al., 2008).

Colleoni et al., 2018

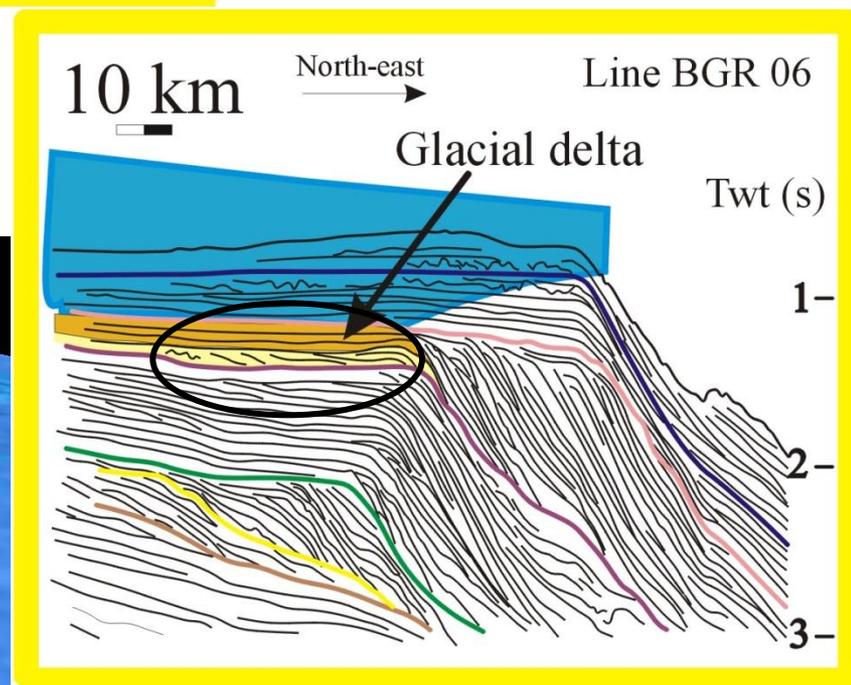
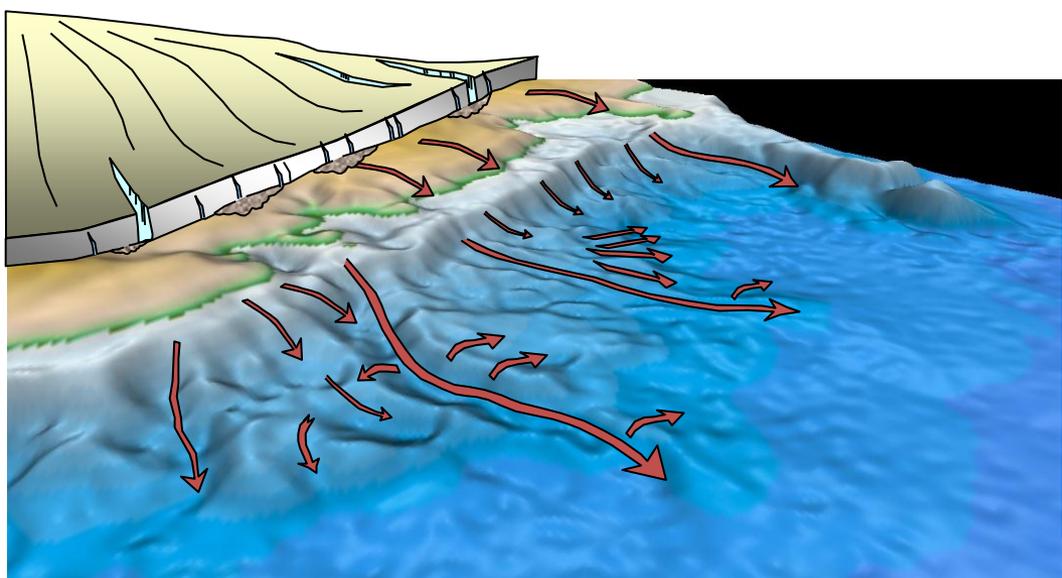
- Reconstruct ice volume change, atmospheric and oceanic temperatures to identify past polar amplification and assess its forcings/feedbacks
- Assess the role of oceanic forcing on Ice sheet stability/instability



Colleoni et al., 2018



Grounding-zone wedges form along a line-source at the grounding zone of marine-terminating ice sheets.



Grounding-zone wedges (GZWs) (replace “till delta”) are asymmetric sedimentary depocentres which form through the rapid accumulation of glacial debris during still-stands in ice-sheet retreat. GZWs form largely through the delivery of deforming subglacial sediments.

Foreset surfaces indicating that till deposition occurred by progradation (implying subglacial sediment transport-deformation conveyor belt).

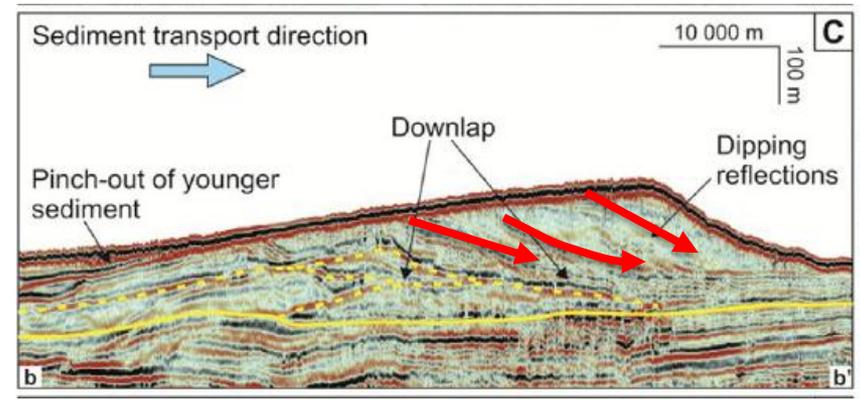
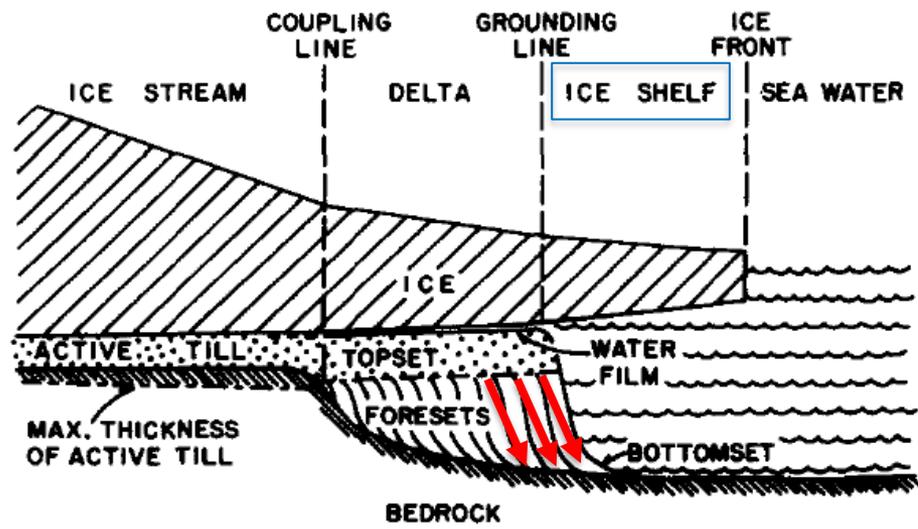
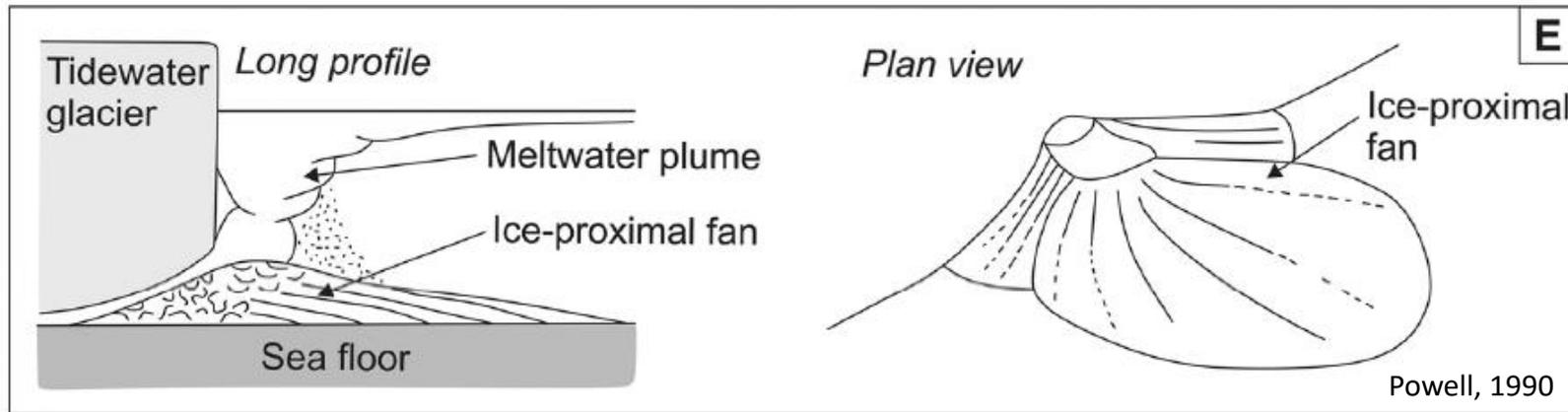


Fig.3. Cartoon of the likely configuration of the ice stream, till delta, and ice shelf.

GZW form mainly where **floating ice shelves** constrain vertical accommodation space immediately beyond the grounding-zone. The low-gradient ice roofed cavities of ice shelves restrict vertical accommodation space and prevent the aggradation of high-amplitude moraine ridges.

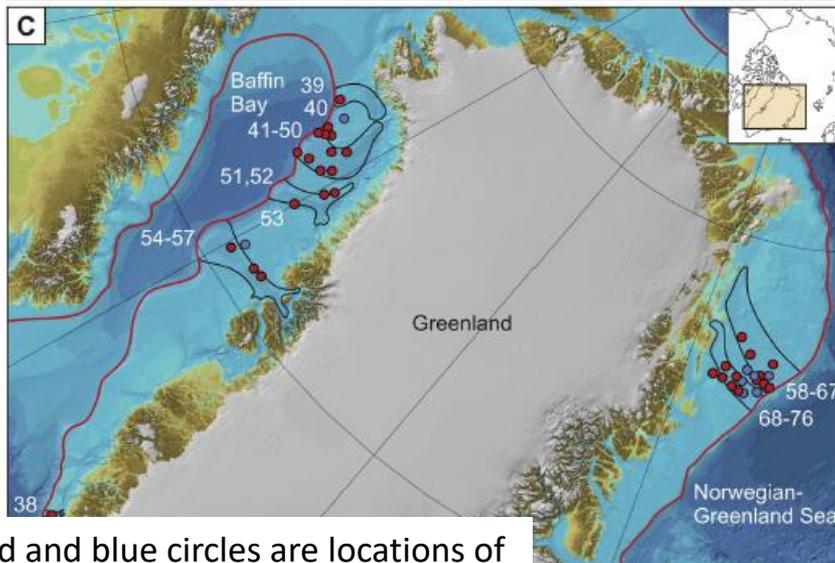
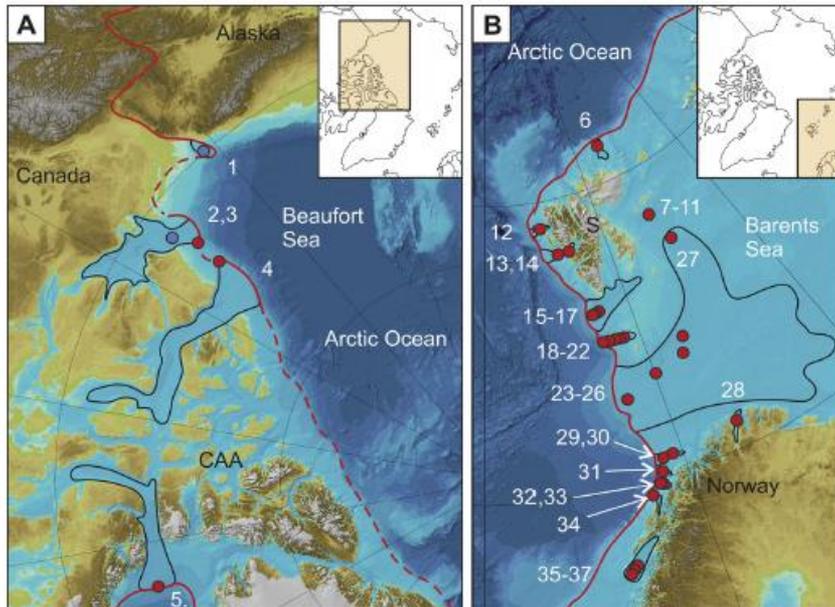
Moraine ridges and ice-proximal fans may also build up at the grounding zone during still-stands of the ice margin, but these require either considerable vertical accommodation space or sediment derived from point-sourced subglacial meltwater streams



Ice-proximal fans form **at the mouths of subglacial meltwater conduits** at the grounding zone of a marine-terminating ice mass (Powell, 1984). They are made of sub-aquatic outwash, gravity flow sediments and suspension settling deposits

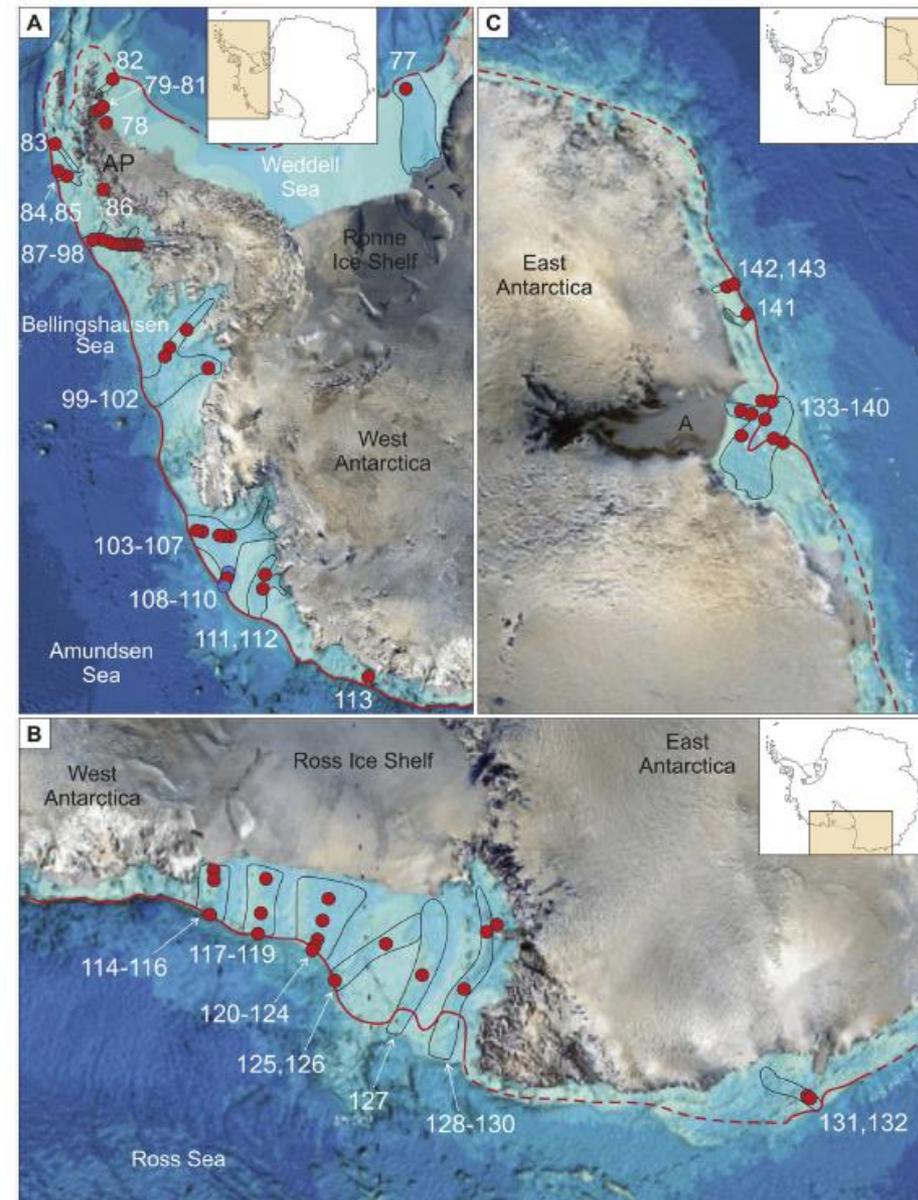
Ice-proximal fans that formed during the last glaciation to present interglacial have been described from the fjords of Alaska, Norway and Svalbard. They are typically up to a few tens of metres thick and up to a few kilometres in length.

C.J. Batchelor, J.A. Dowdeswell / Marine Geology 363 (2015) 65–92



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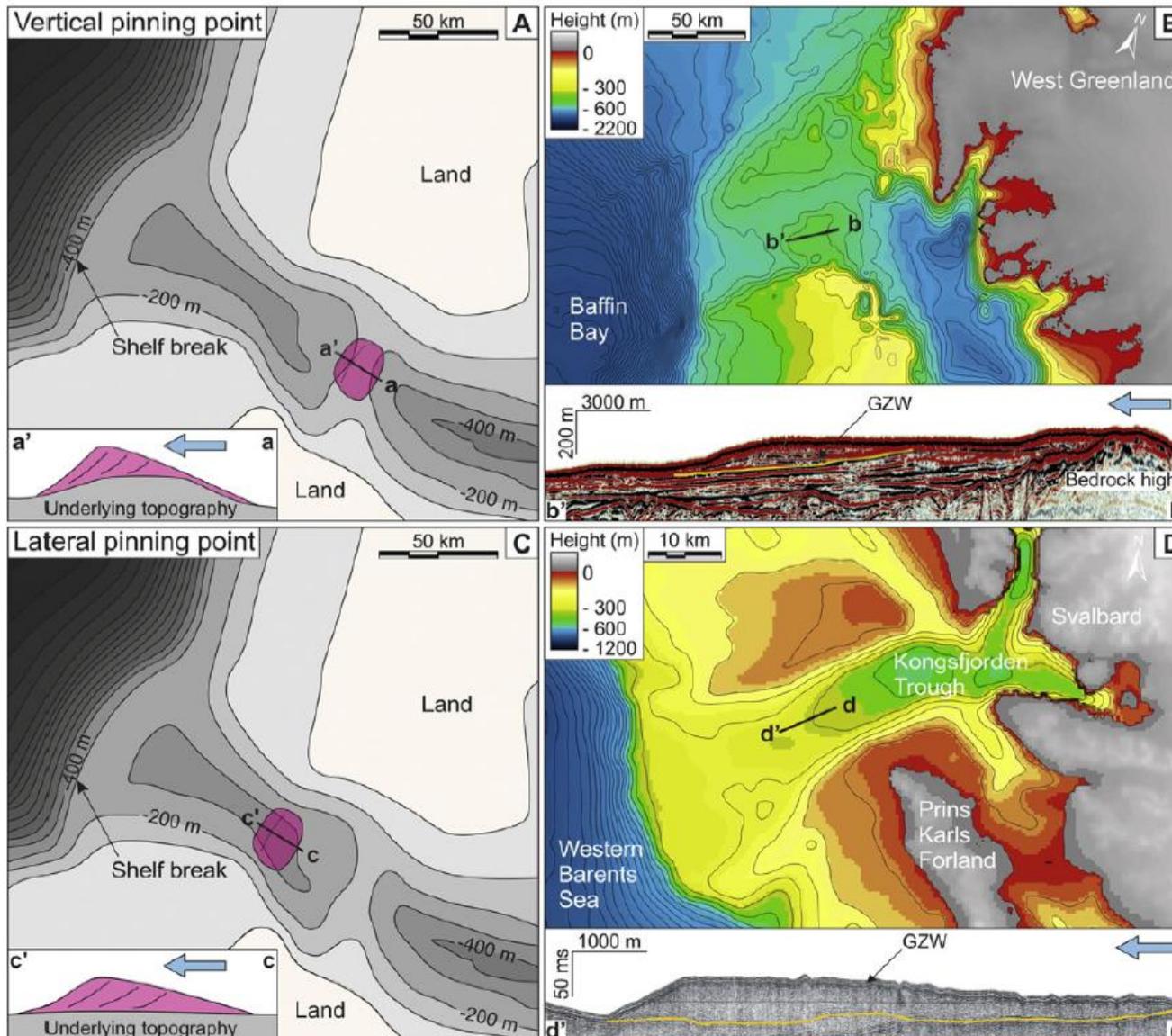
C.J. Batchelor, J.A. Dowdeswell / Marine Geology 363 (2015) 65–92



Red and blue circles are locations of surface and buried GZWs

Batchelor et al., 2015

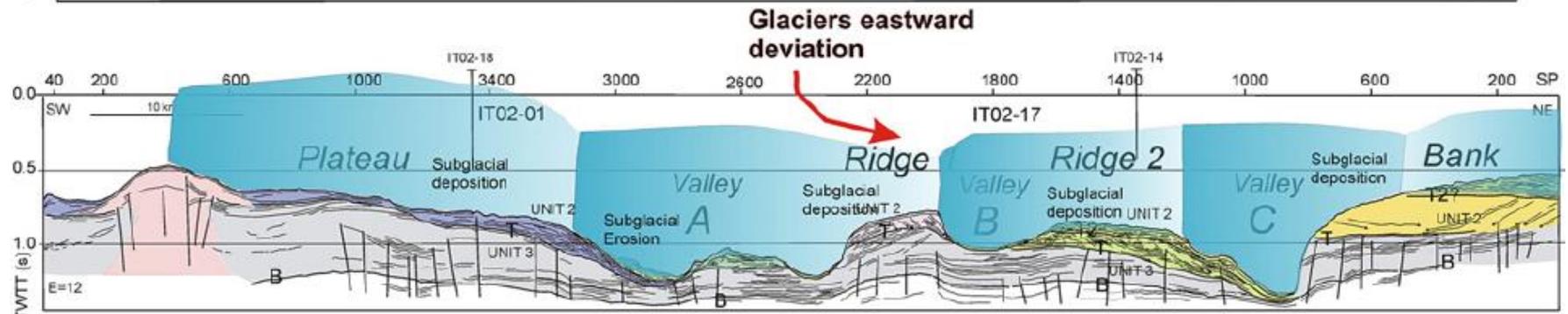
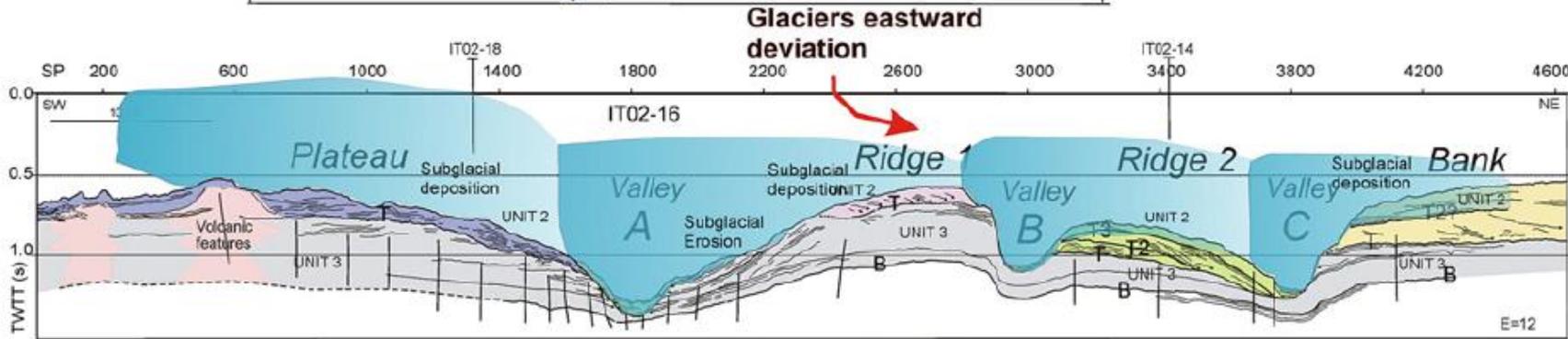
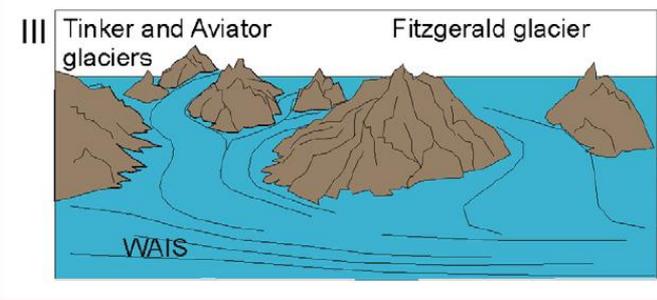
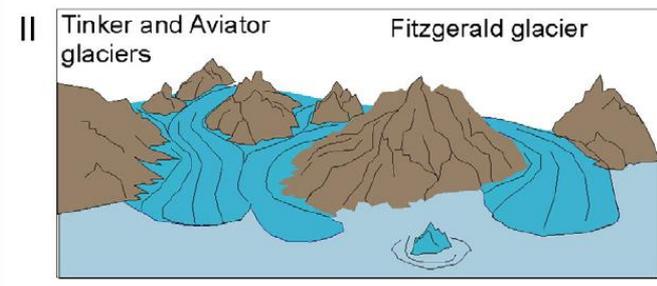
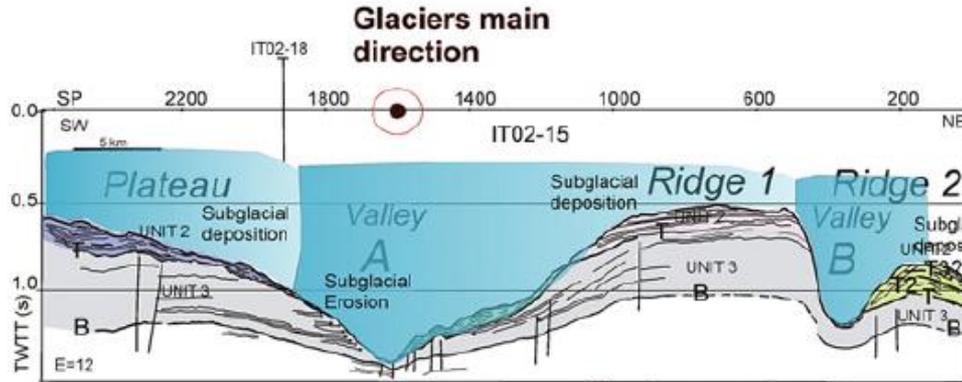
C.L. Batchelor, J.A. Dowdeswell / *Marine Geology* 363 (2015) 65–92



Bedrock outcrops on the seafloor can act as vertical pinning points

sediment aggradation within water-filled cavities below ice shelves may provide a mechanism for **ice-sheet stabilisation**

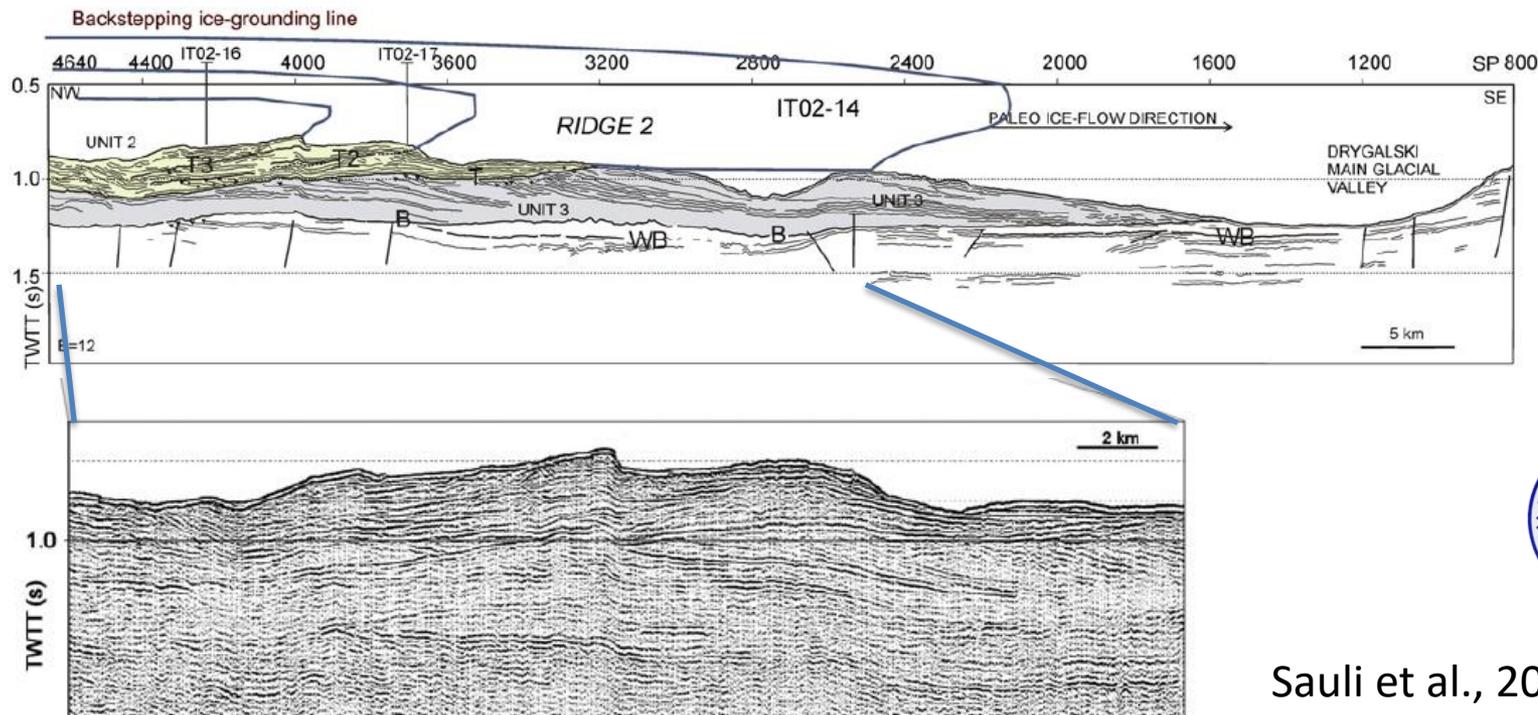
Sauli et al., 2014



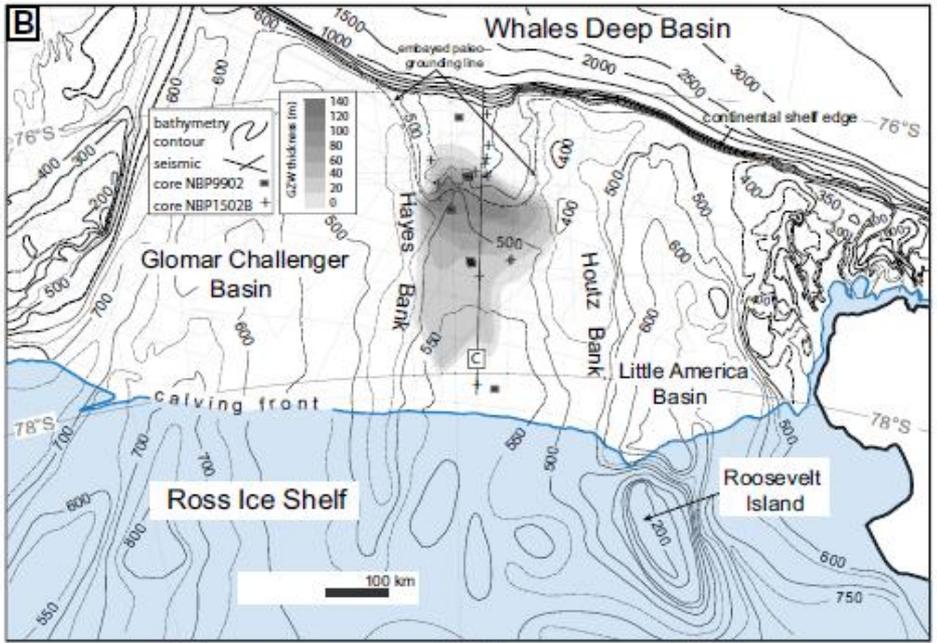
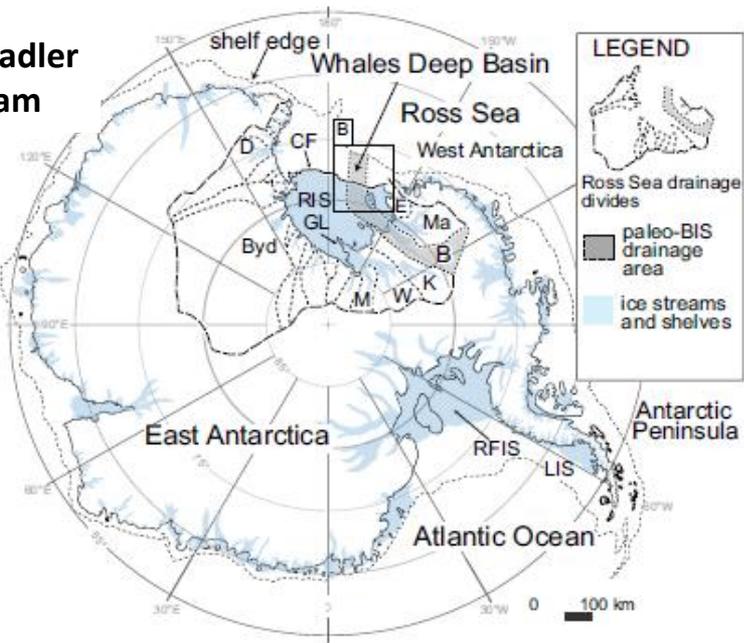
Moraines are typically composed of various unsorted ice-contact sediments and therefore possess a semitransparent to chaotic character on acoustic profiles.

Recessional-moraine ridges record the position of still-stands in the grounding zone during deglaciation

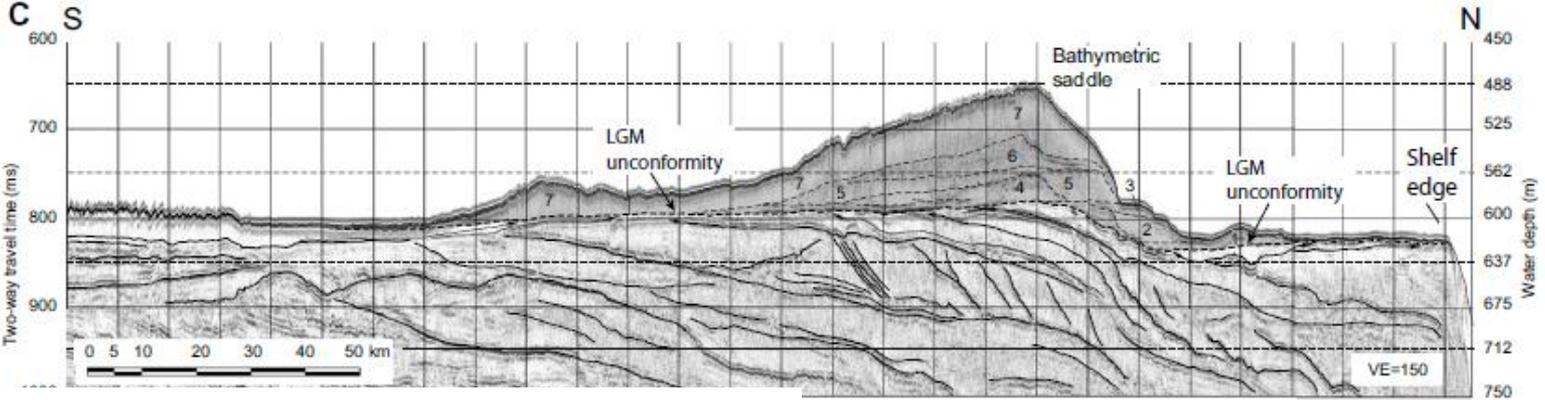
C. Sauli et al. / Marine Geology 355 (2014) 297–309



paleo-Bindschadler Ice Stream



Most of GZW deposited in only 800 ± 300 years after the breakup of the fringing ice shelf

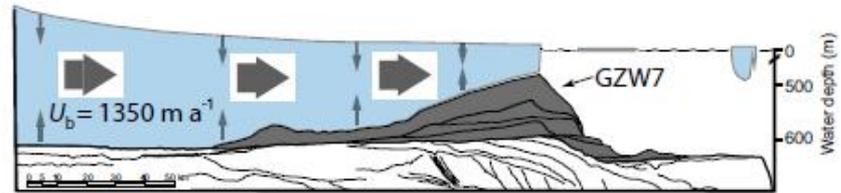


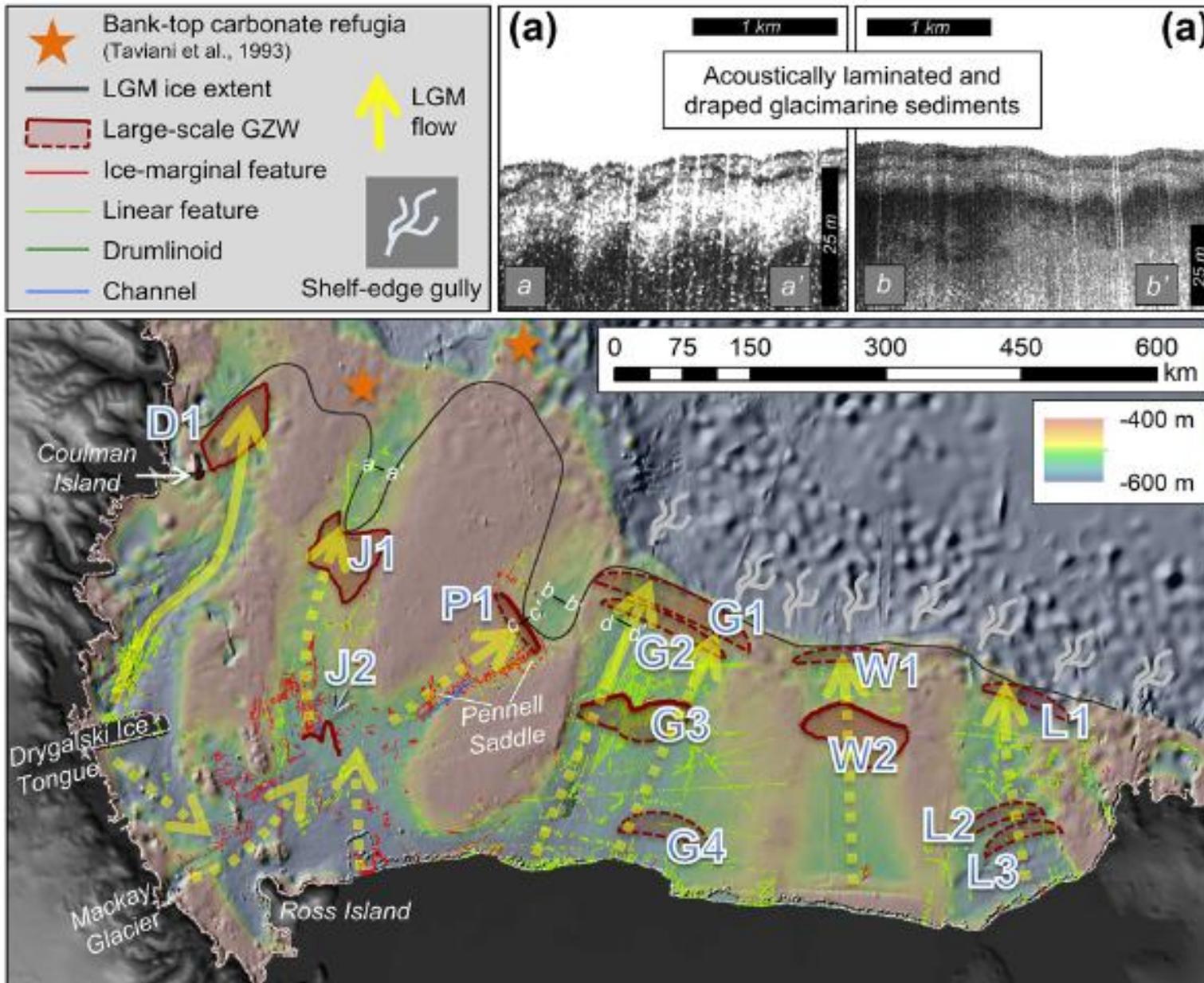
Bart,
Tulaczyk,
2020

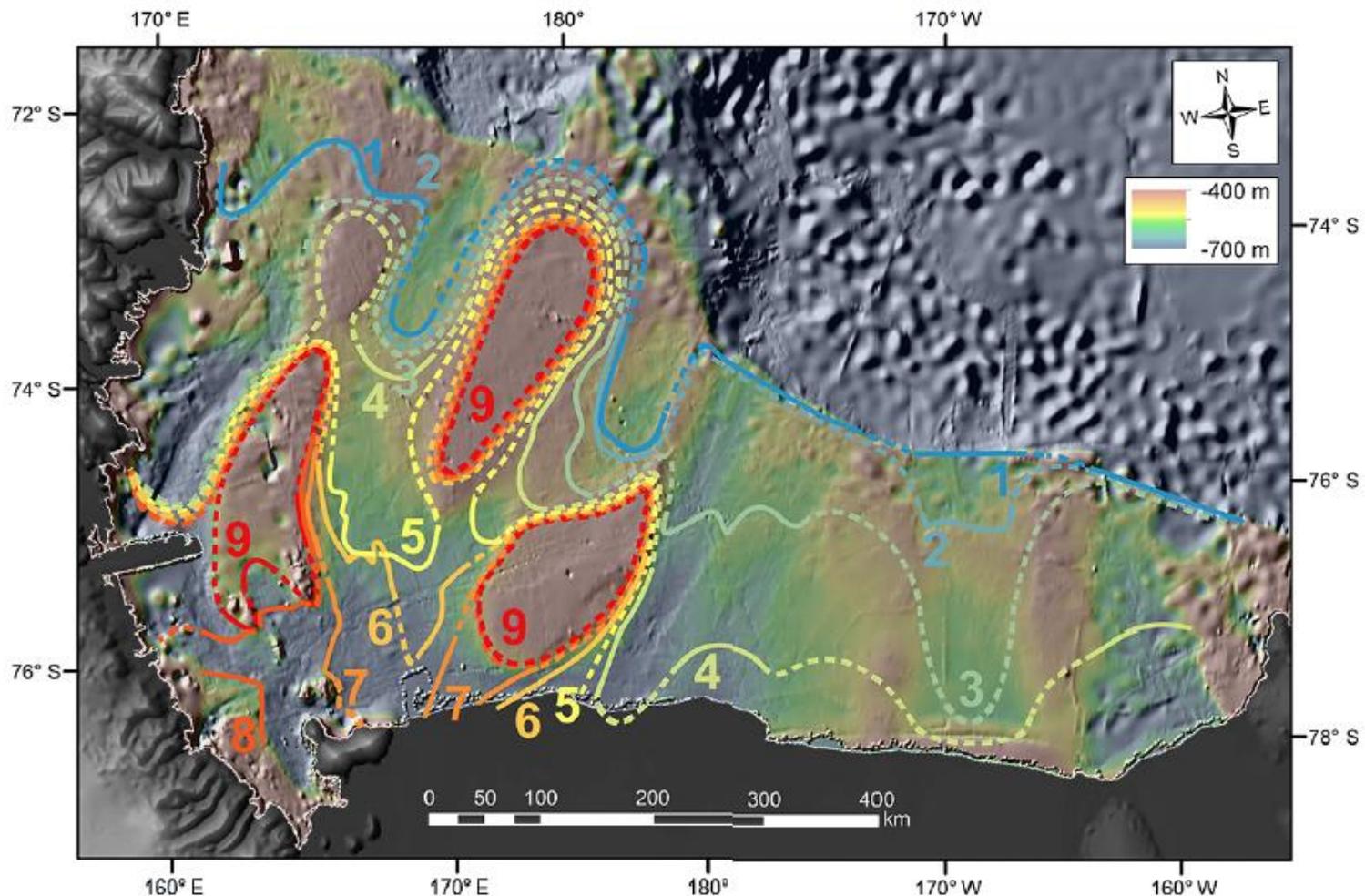
GZW4 prior to ice-shelf breakup 14.7-12.3 Ka



GZW7 after to ice-shelf breakup 12.3-11.5 Ka



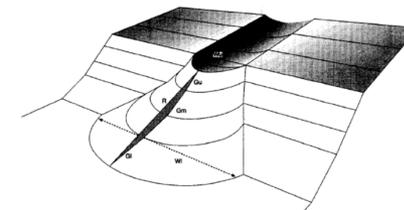
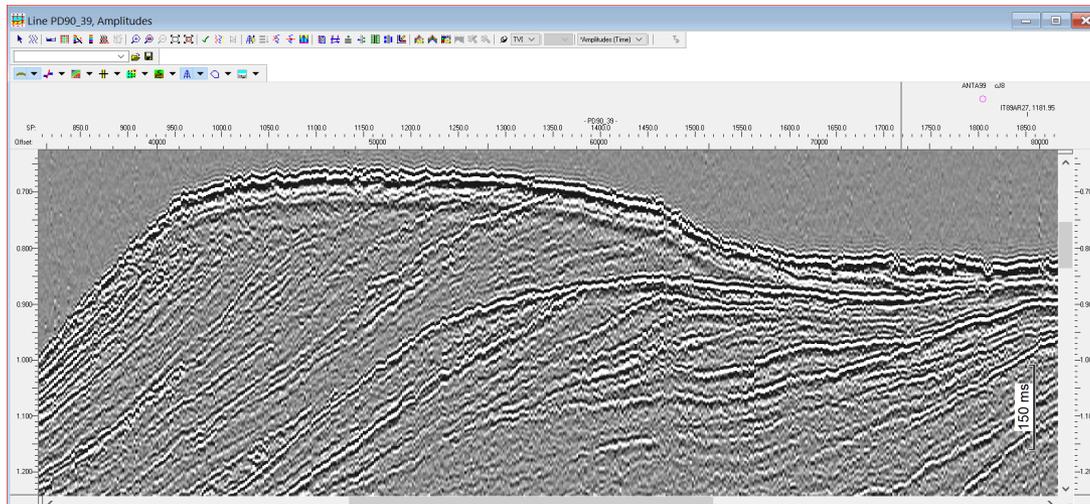
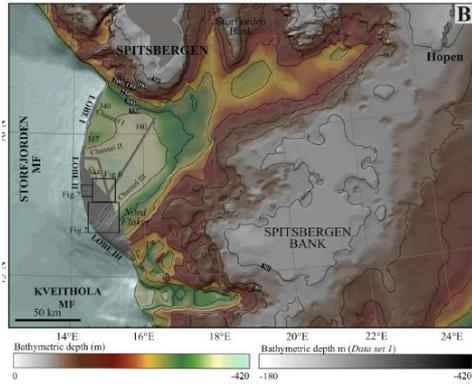




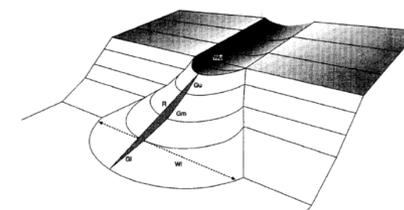
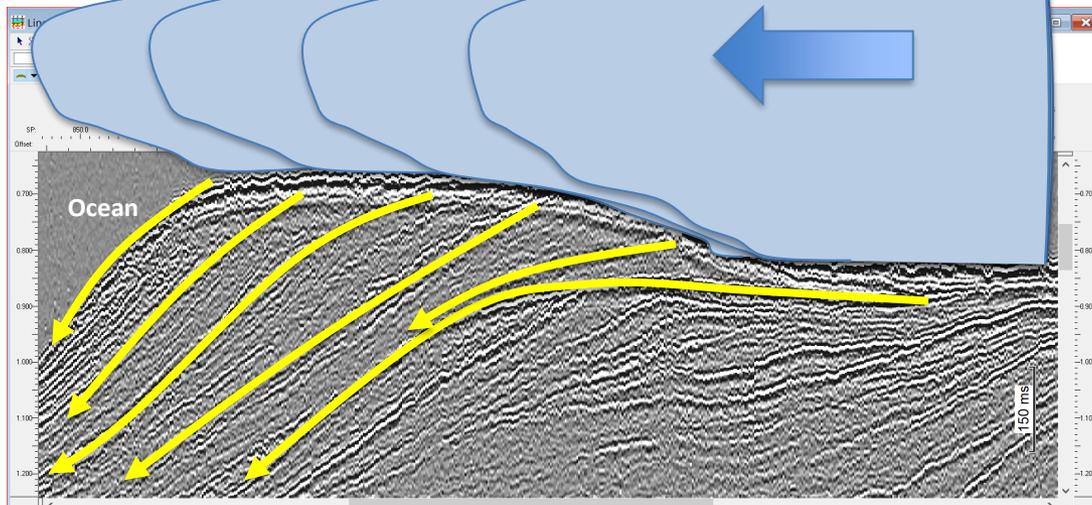
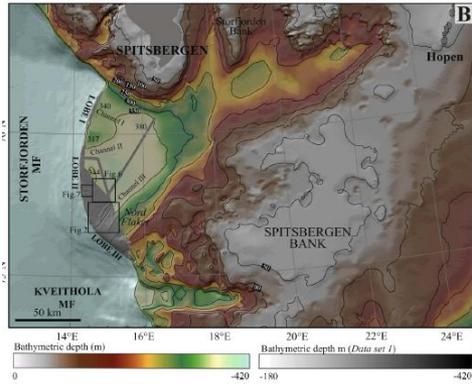
Halberstadt et al., 2016

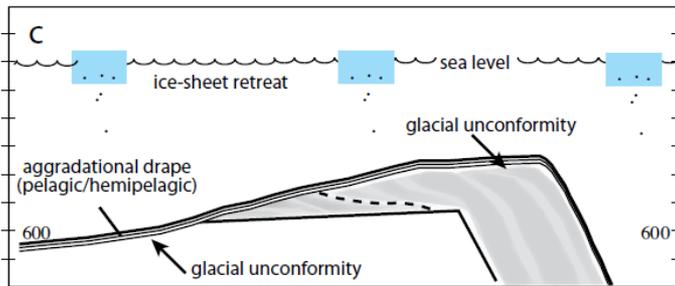
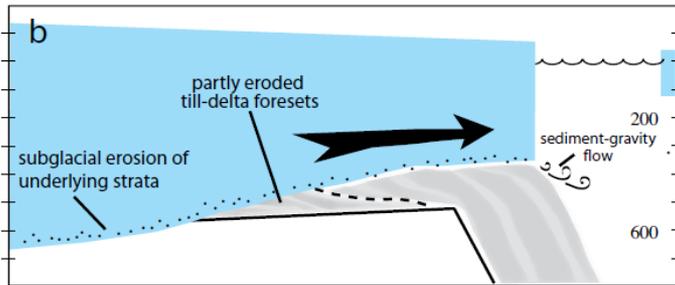
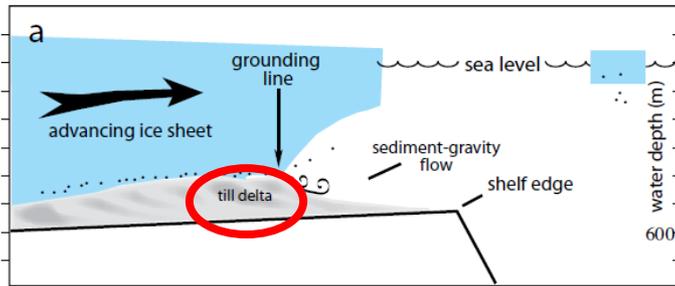
Figure 7. Reconstructed grounding-line retreat across the Ross Sea based on geomorphic indicators of grounding lines (solid lines) and inferred grounding-line locations (dashed). Each line marks a relative step in grounding-line retreat starting with step 1 at the LGM grounding line and ending with step 9 with ice pinned on banks.

Acoustic facies as expression of depositional system in polar environment: glacial trough-mouth fans



Acoustic facies as expression of depositional system in polar environment: glacial trough-mouth fans

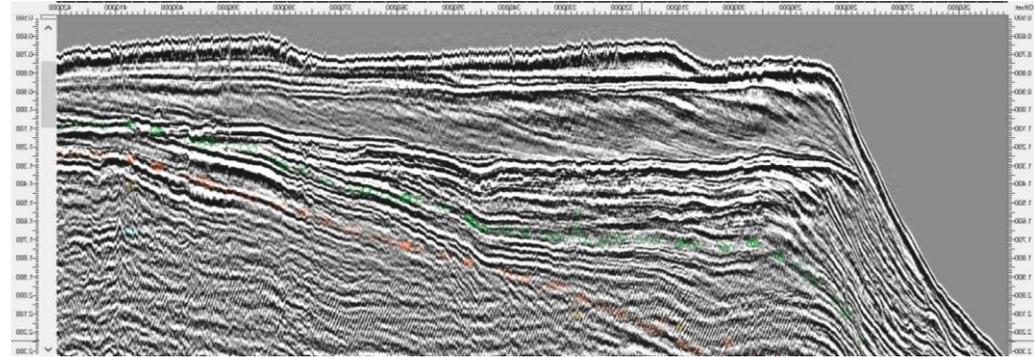




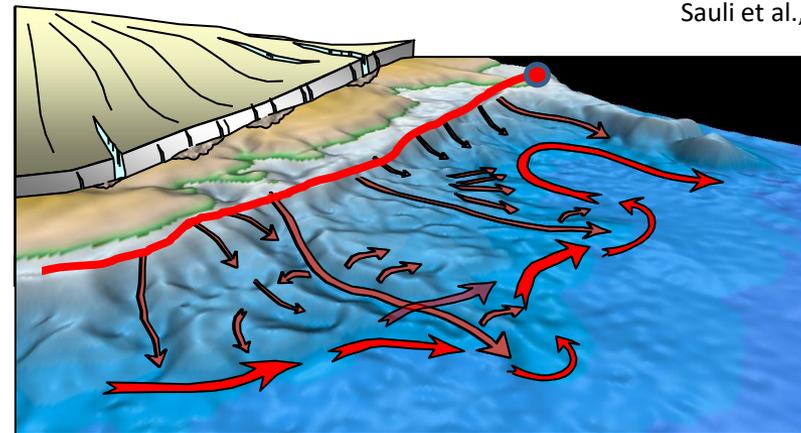
0 25 50 km V.E.=80:1

Bart and De Santis 2012

Acoustic facies as expression of depositional system in polar environment: Ice grounding zone wedges (till delta)



Sauli et al., 2014





EXERCIZE

Stratal terminations (model-independent)

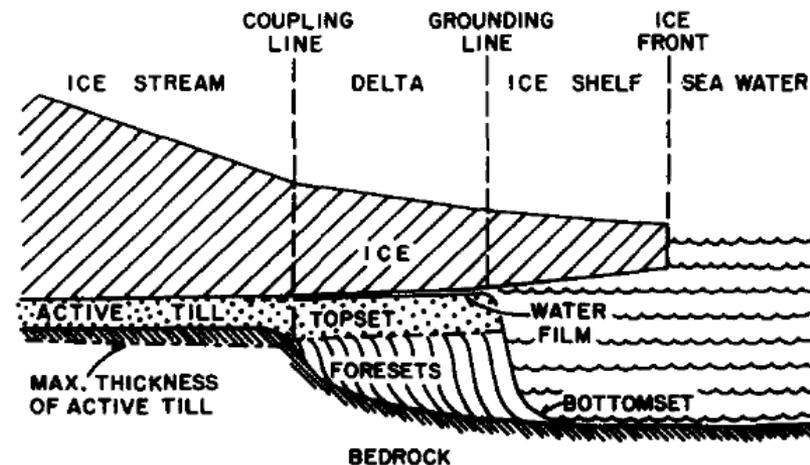
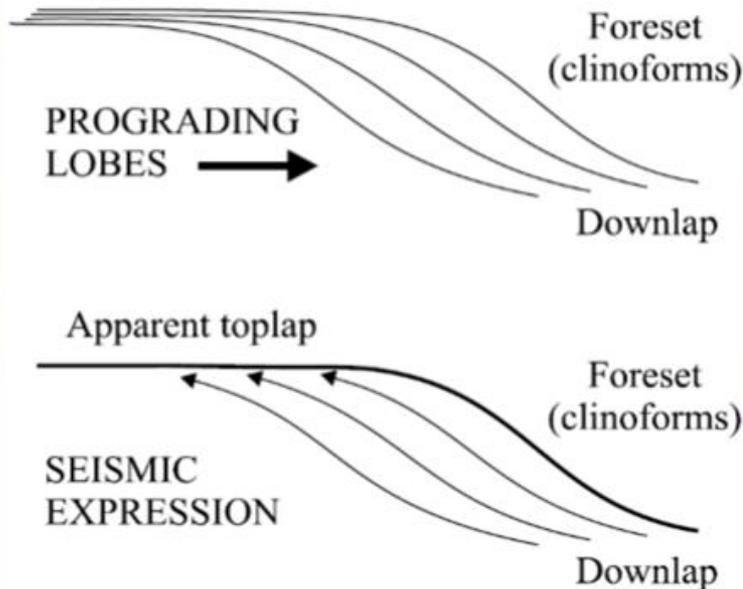
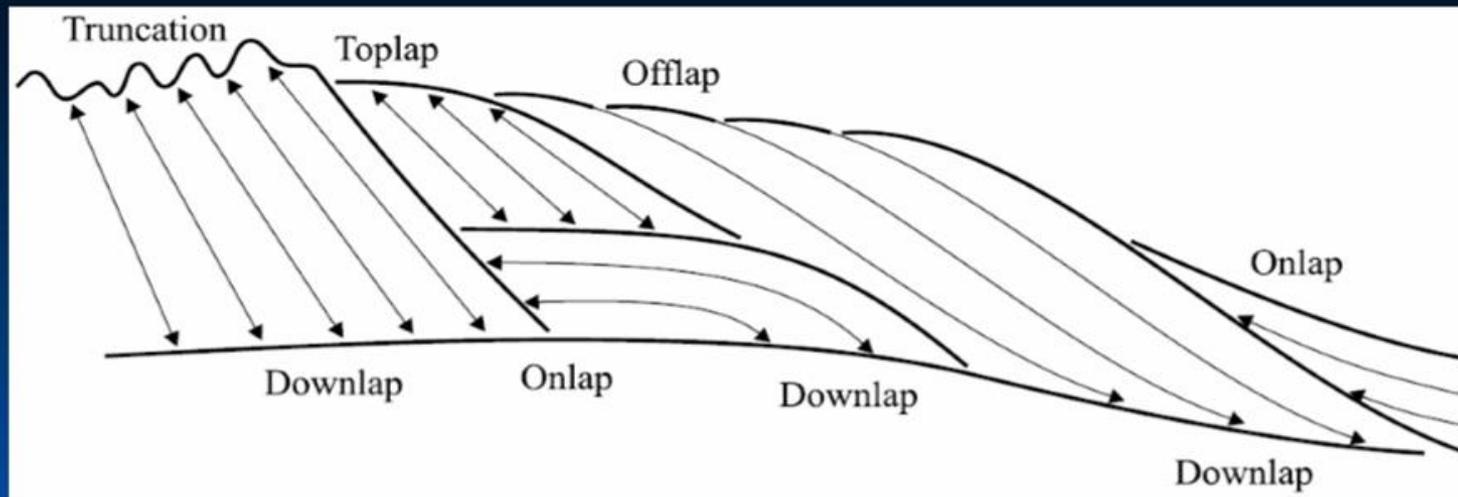
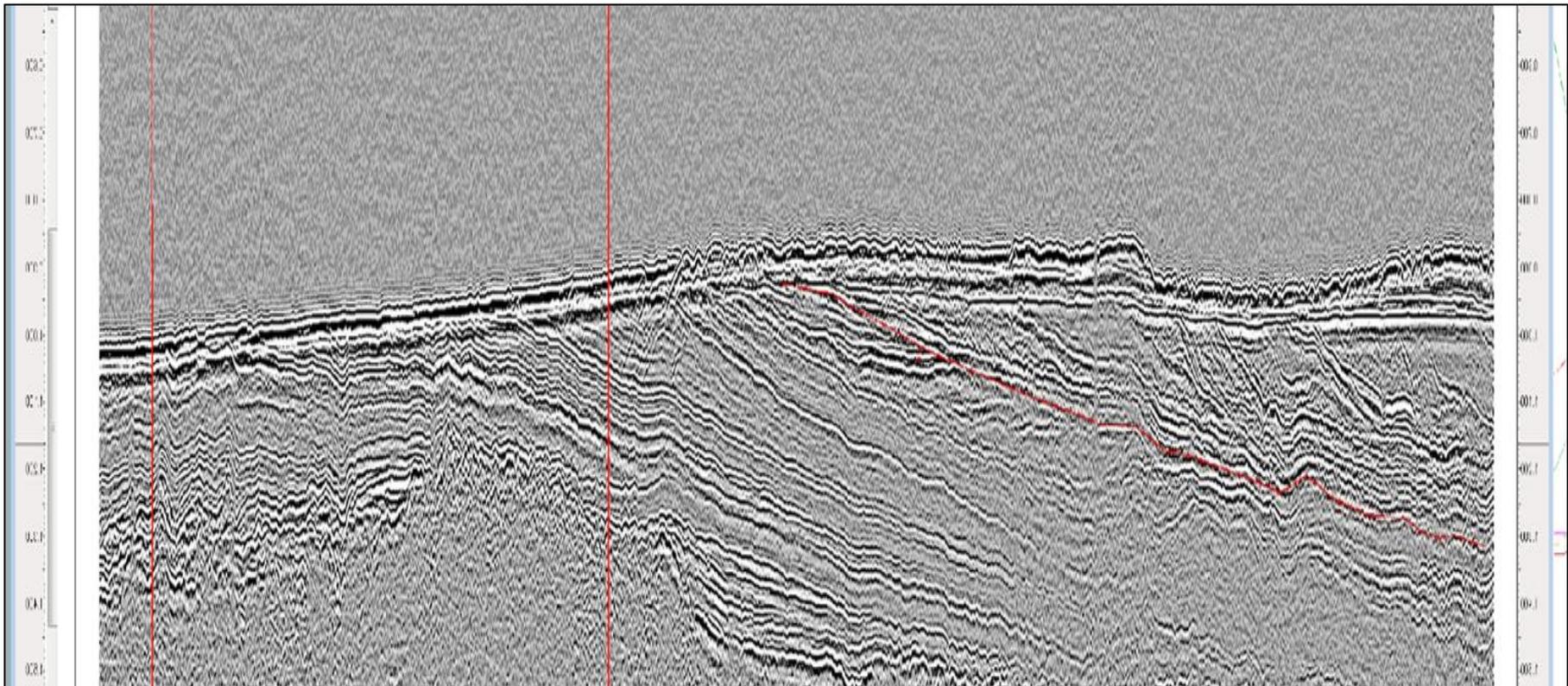
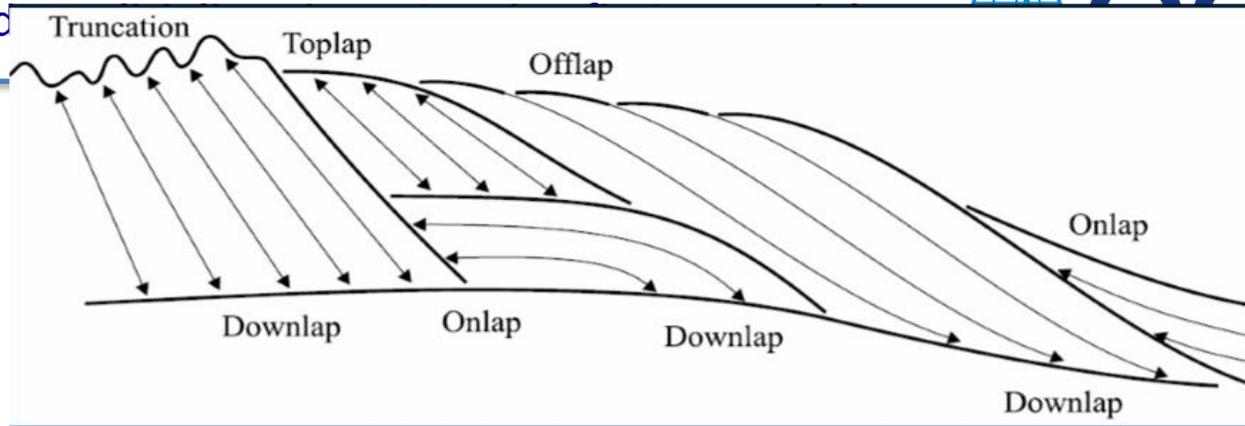
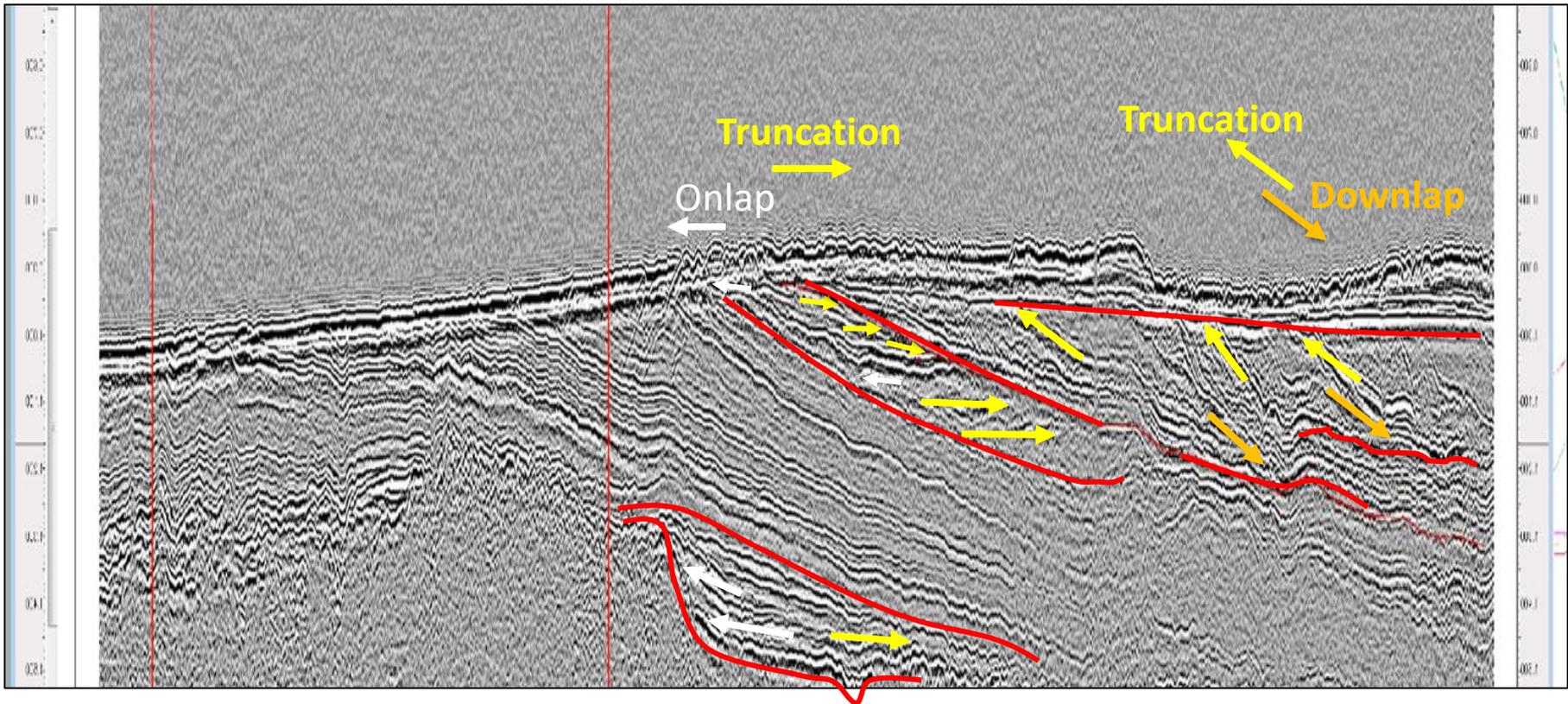
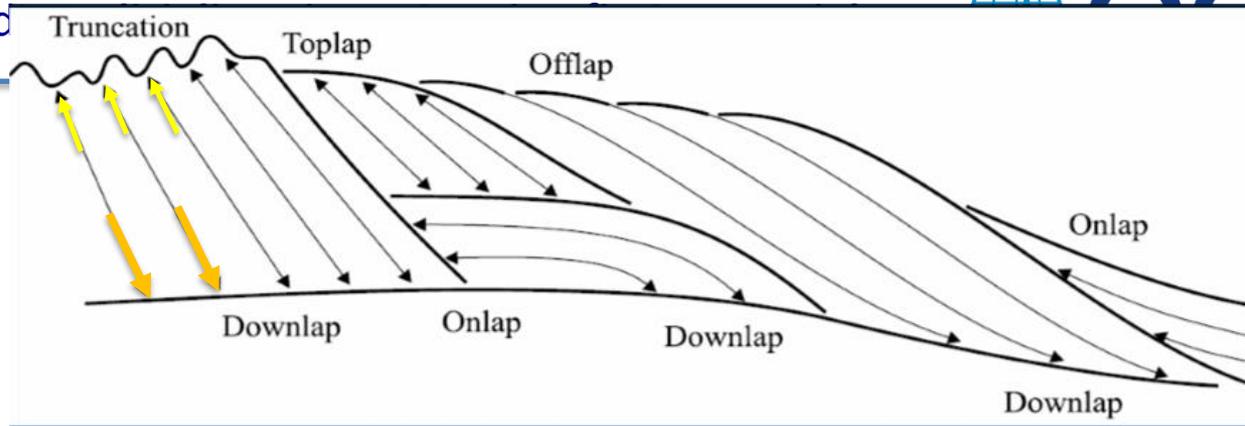
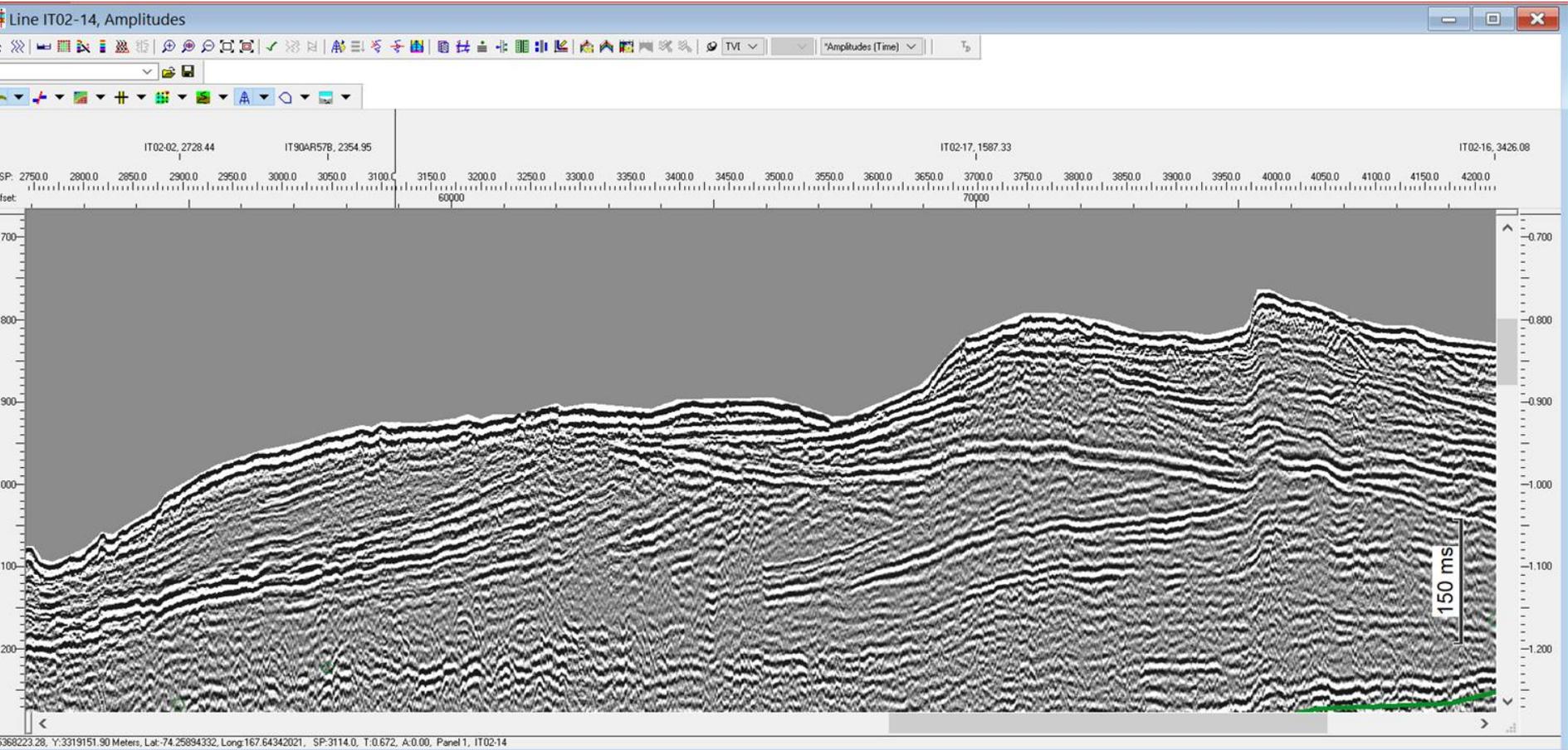
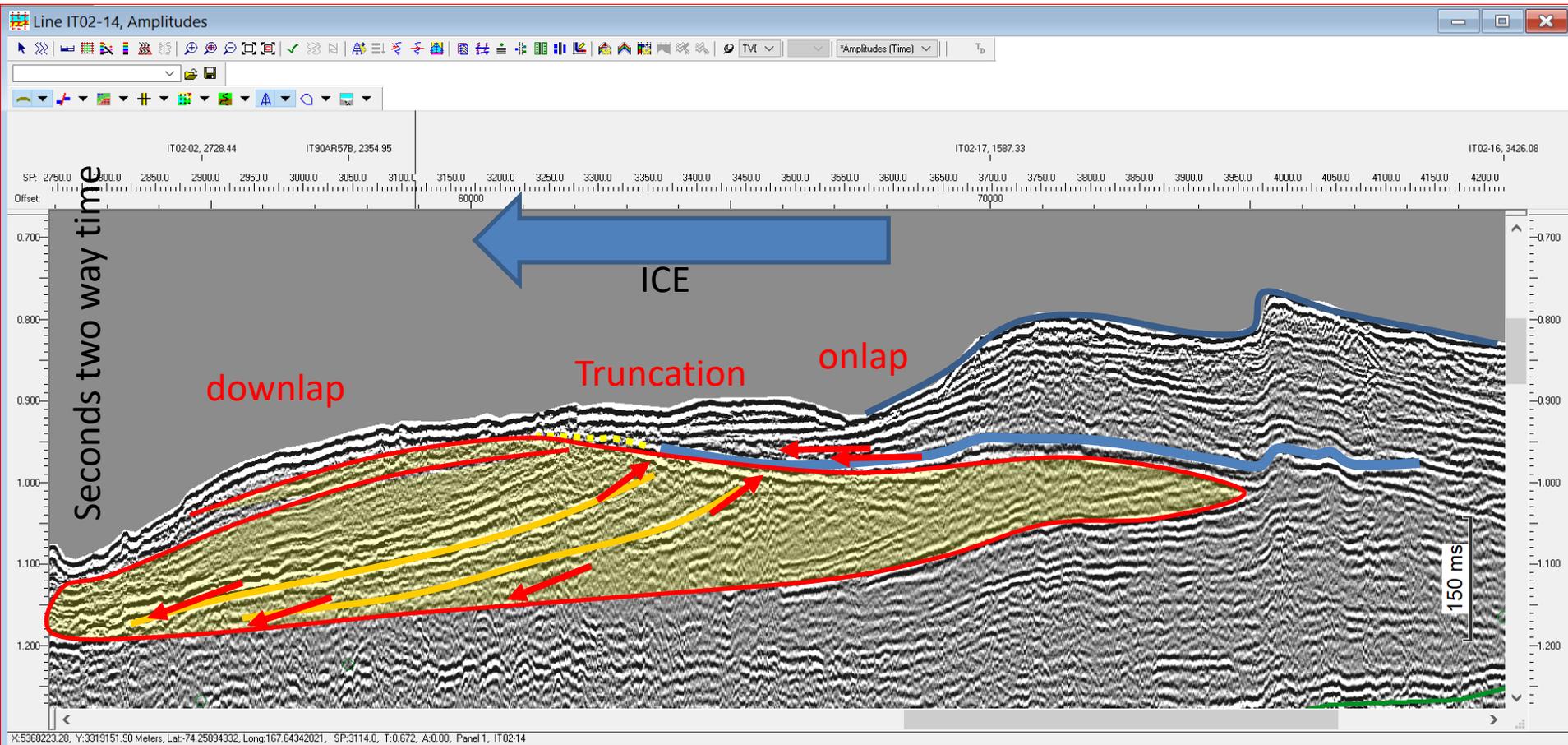


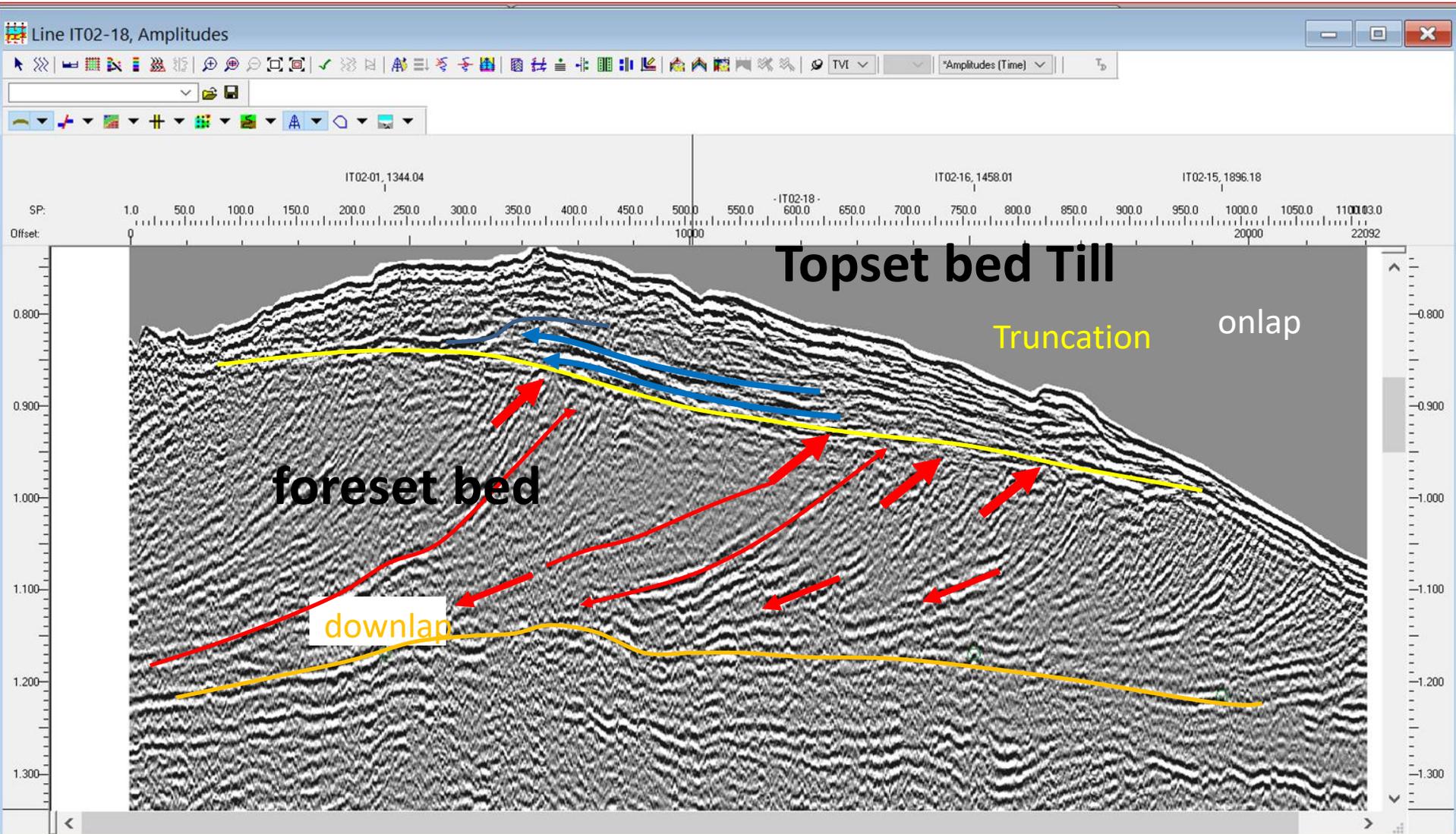
Fig.3. Cartoon of the likely configuration of the ice stream, till delta, and ice shelf.





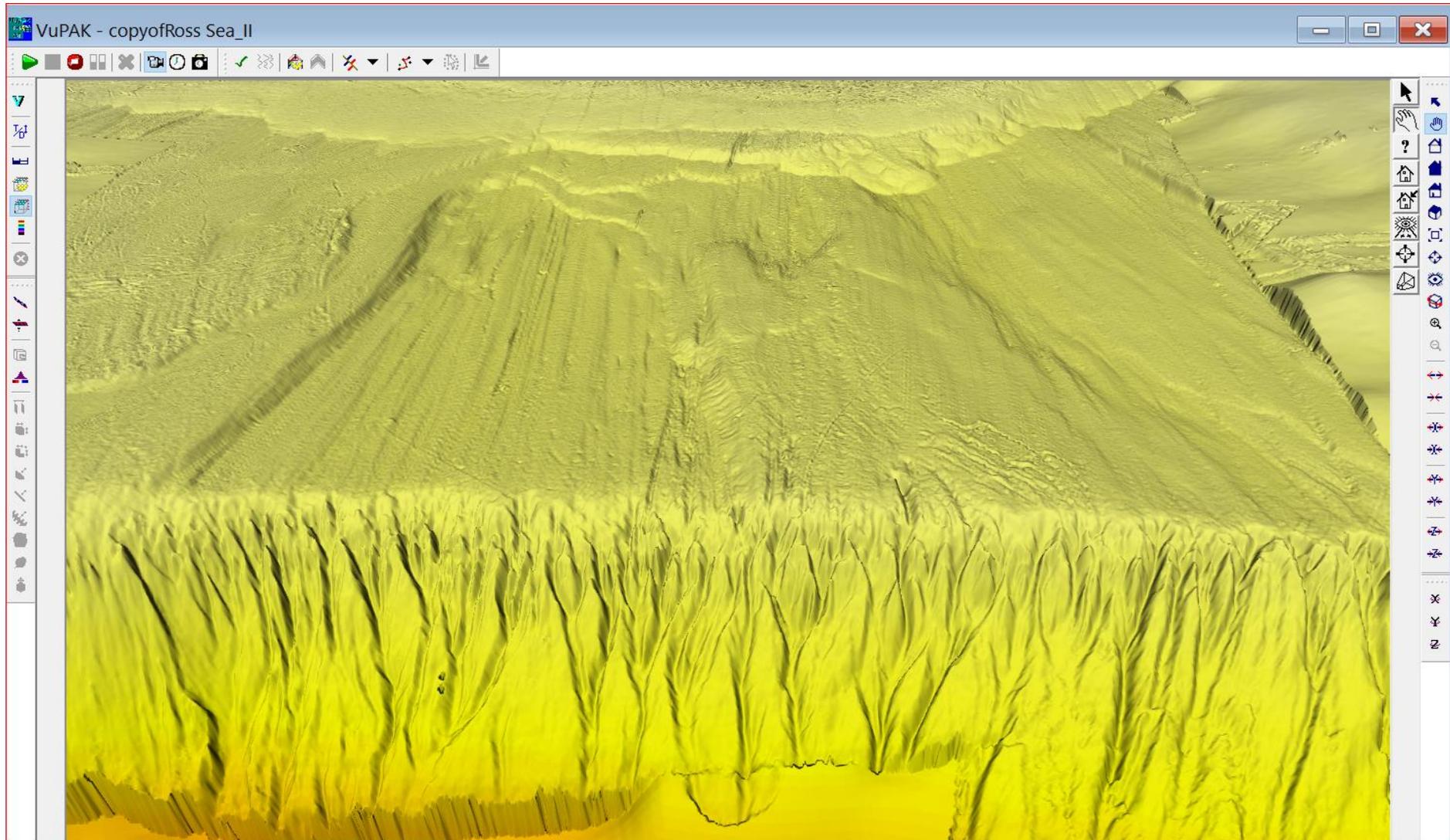








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RESEARCH ARTICLE

10.1002/2017JF004259

Post-LGM Grounding-Line Positions of the Bindschadler
Paleo Ice Stream in the Ross Sea Embayment, AntarcticaPhilip J. Bart¹, John B. Anderson², and Frank Nitsche³

Key Points:

- The Bindschadler Paleo Ice Stream occupied the Whales Deep Basin in eastern Ross Sea during the Last Glacial Maximum
- New multibeam and seismic data show that at least seven deglacial

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