Istituto Nazionale di Oceanografia e di Geofisica Sperimentale

Università degli studi di Trieste

LAUREA MAGISTRALE IN GEOSCIENZE

Classe Scienze e Tecnologie Geologiche

Curriculum: Esplorazione Geologica

Anno accademico 2021 - 2022

Analisi di Bacino e Stratigrafia Sequenziale (426SM)

Docente: **Michele Rebesco**

Istituto Nazionale di Oceanografia e di Geofisica Sperimentale

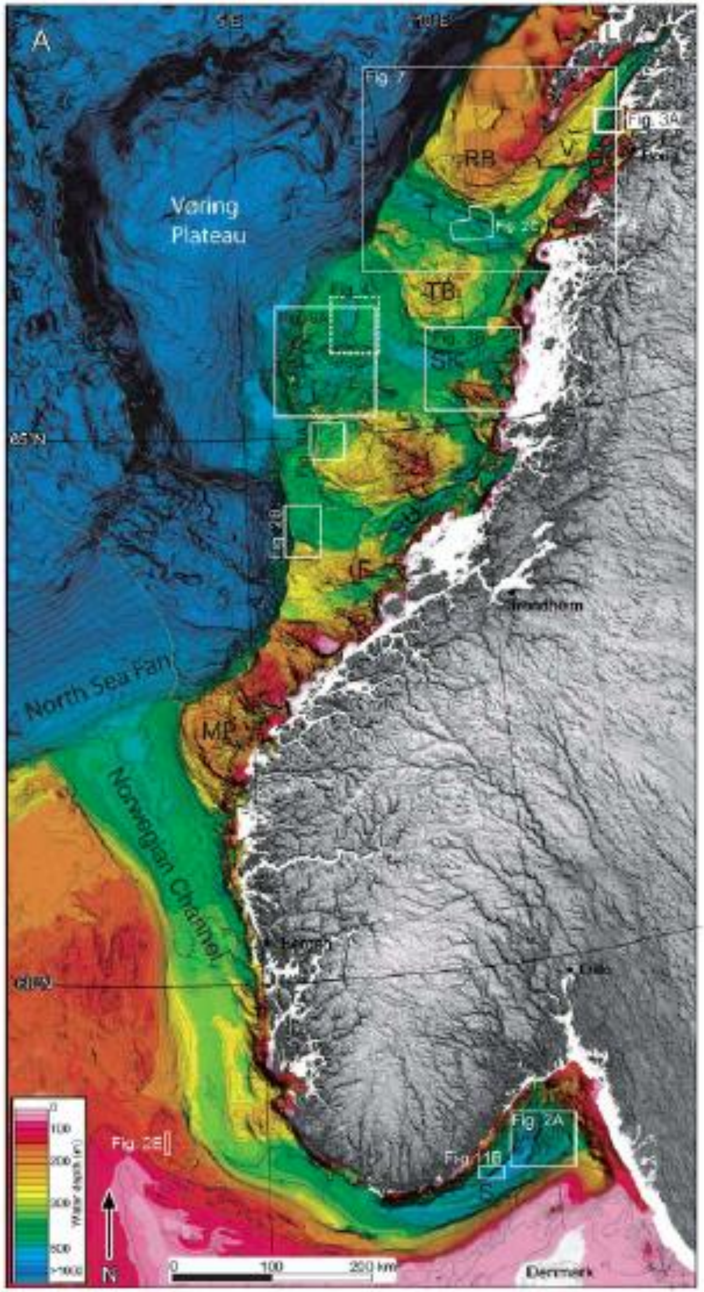
Modulo 3.6
Typical facies of depositional-erosional system in polar environment

Docente: **Laura De Santis**

Modulo 3.6 Typical facies of depositional/erosional system in polar environment

Docente: Laura De Santis

OUTLINE



Diagnostic features

- Glacial valleys and foredeepened surfaces
- Trough/bank topography
- Trough mouth fans
- Ice grounding zone wedge
- Glacial lineations
- Outwash channels

Modulo 3.6 Typical facies of depositional/erosional system in polar environment

Docente: Laura De Santis

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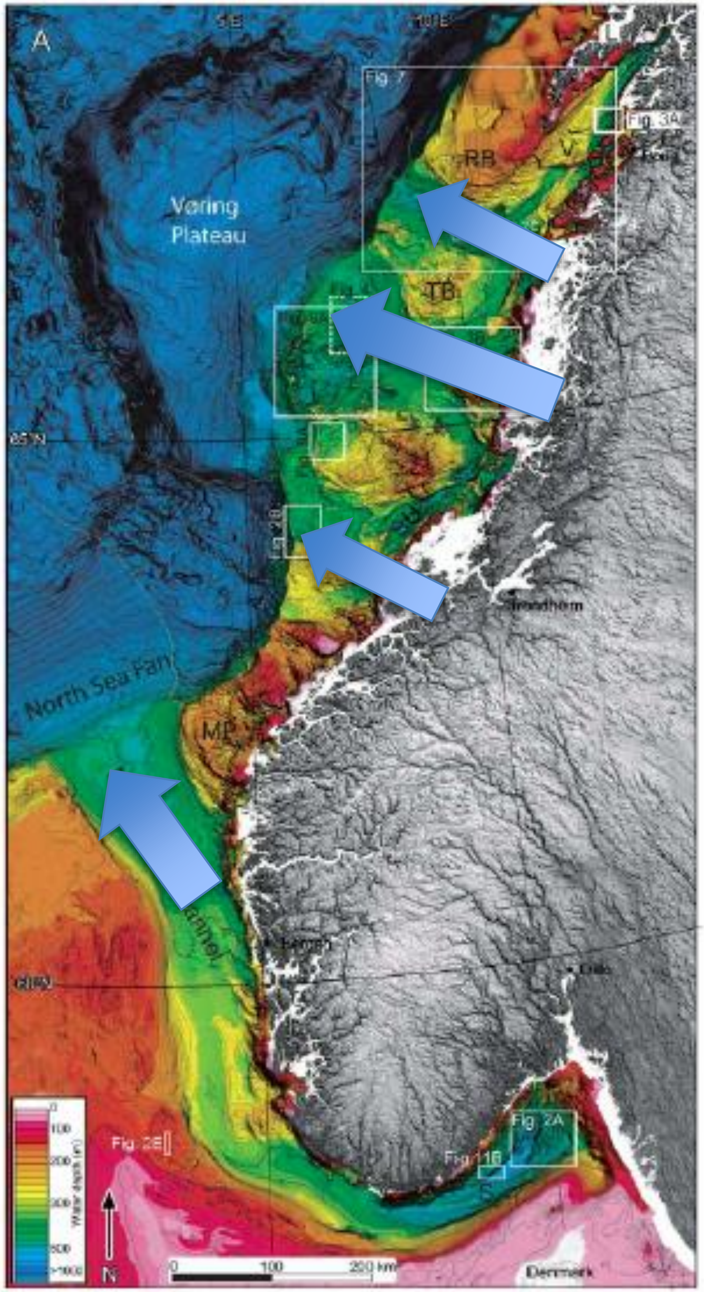

Diagnostic features

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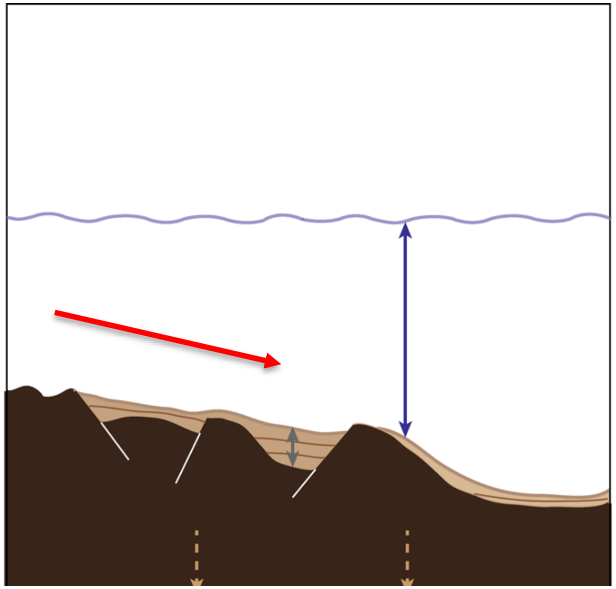
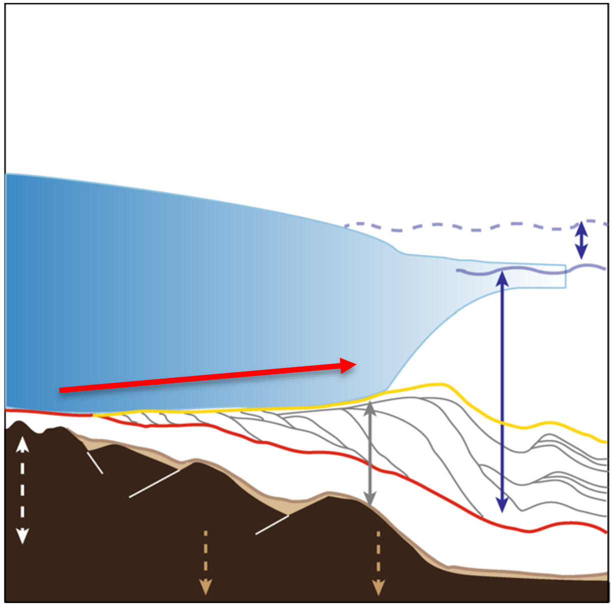
Glacial valleys and foredeepened surfaces



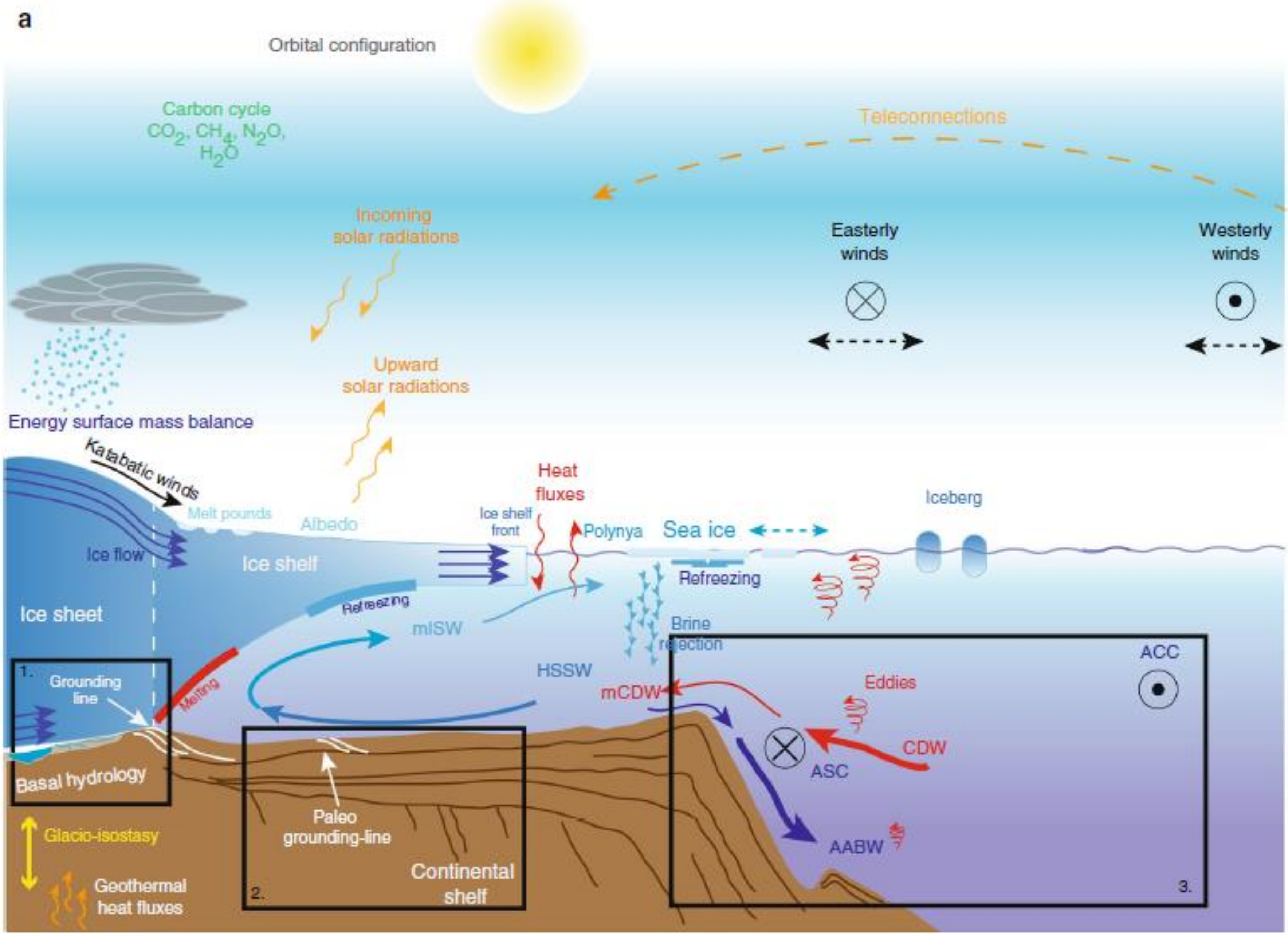
Piattaforma continentale medie-basse latitudini

= Fondo mare inclinato verso l'Oceano



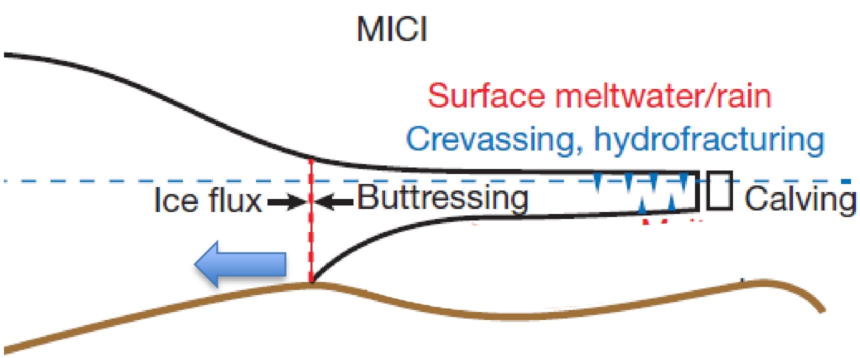
Peso calotta+erosione

= Fondo mare inclinato verso l'entroterra


a
Orbital configuration
Carbon cycle
CO_2, CH_4, N_2O, H_2O
Teleconnections
Incoming solar radiations
Easterly winds
Westerly winds
Upward solar radiations
Energy surface mass balance
Katabatic winds
Melt pounds
Albedo
Heat fluxes
Ice shelf front
Polynya
Sea ice
Iceberg
Ice flow
Ice shelf
Refreezing
Ice sheet
Refreezing
mISW
Brine rejection
HSSW
ACC
1.
Grounding line
Melting
mCDW
Eddies
CDW
ASC
Basal hydrology
Paleo grounding-line
AABW
Glacio-isostasy
Continental shelf
Geothermal heat fluxes
2.
3.

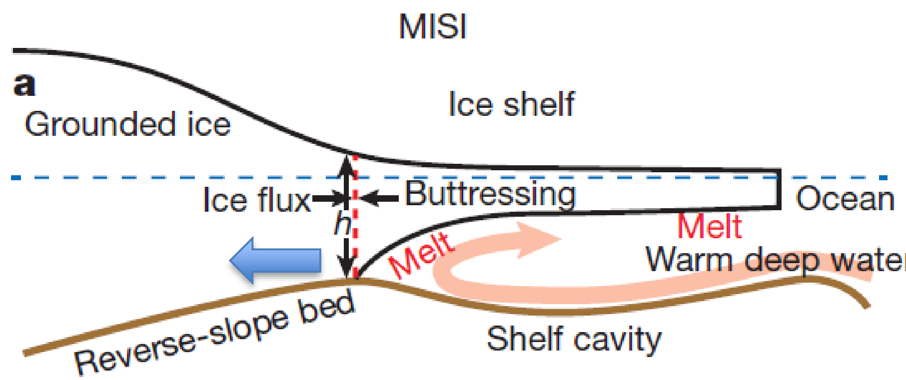
Marine Ice Cliff Instability (MICI)

Ice-shelf surfaces melting due to atmospheric warming causes thinning, crevassing and calving rates



Marine Ice Sheet Instability (MISI)

Sub-ice shelf melting due to ocean warming retreat onto a reverse-sloping bed runaway

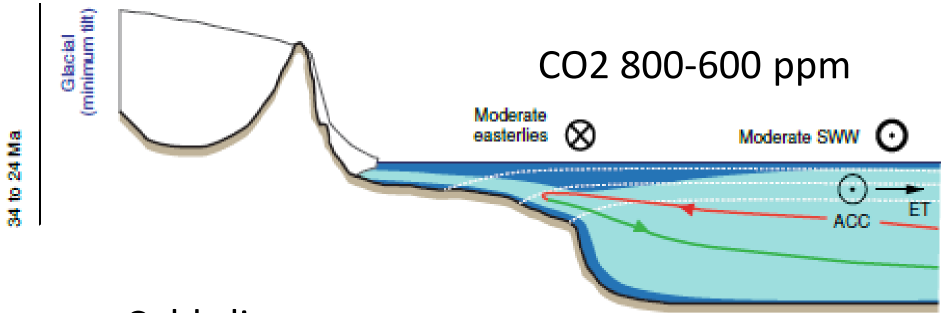


Including these processes was found to increase the previous model's contribution to Pliocene Global Mean Sea Level from +7 m to +17 m

DeConto and Pollard 2016

AIS sensitivity to ocean and climate dynamics

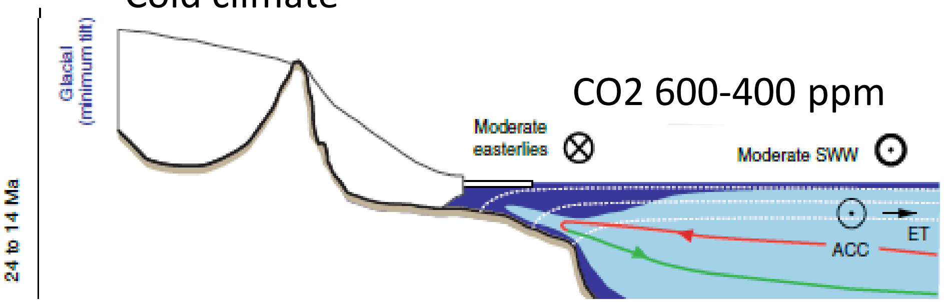
Cool climate



Levy et al., 2019

Terrestrial ice → low sensitivity to ocean warming

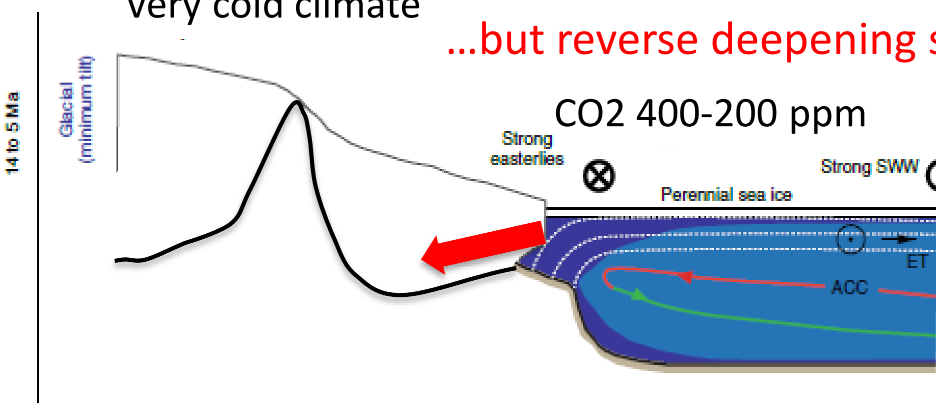
Cold climate



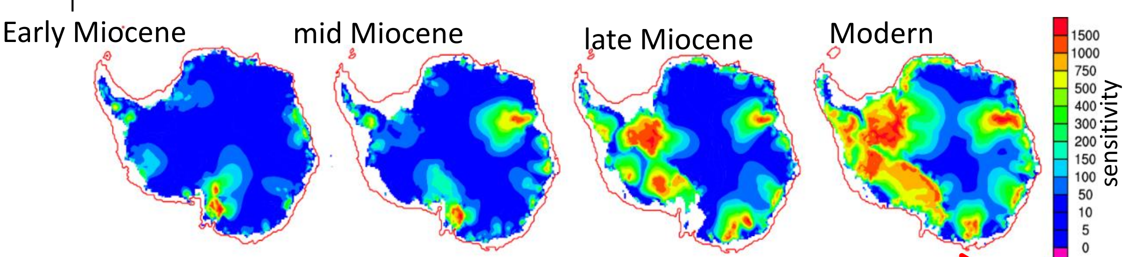
Marine ice-sheet extent → high sensitivity to ocean warming

Very cold climate

…but reverse deepening self profile



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

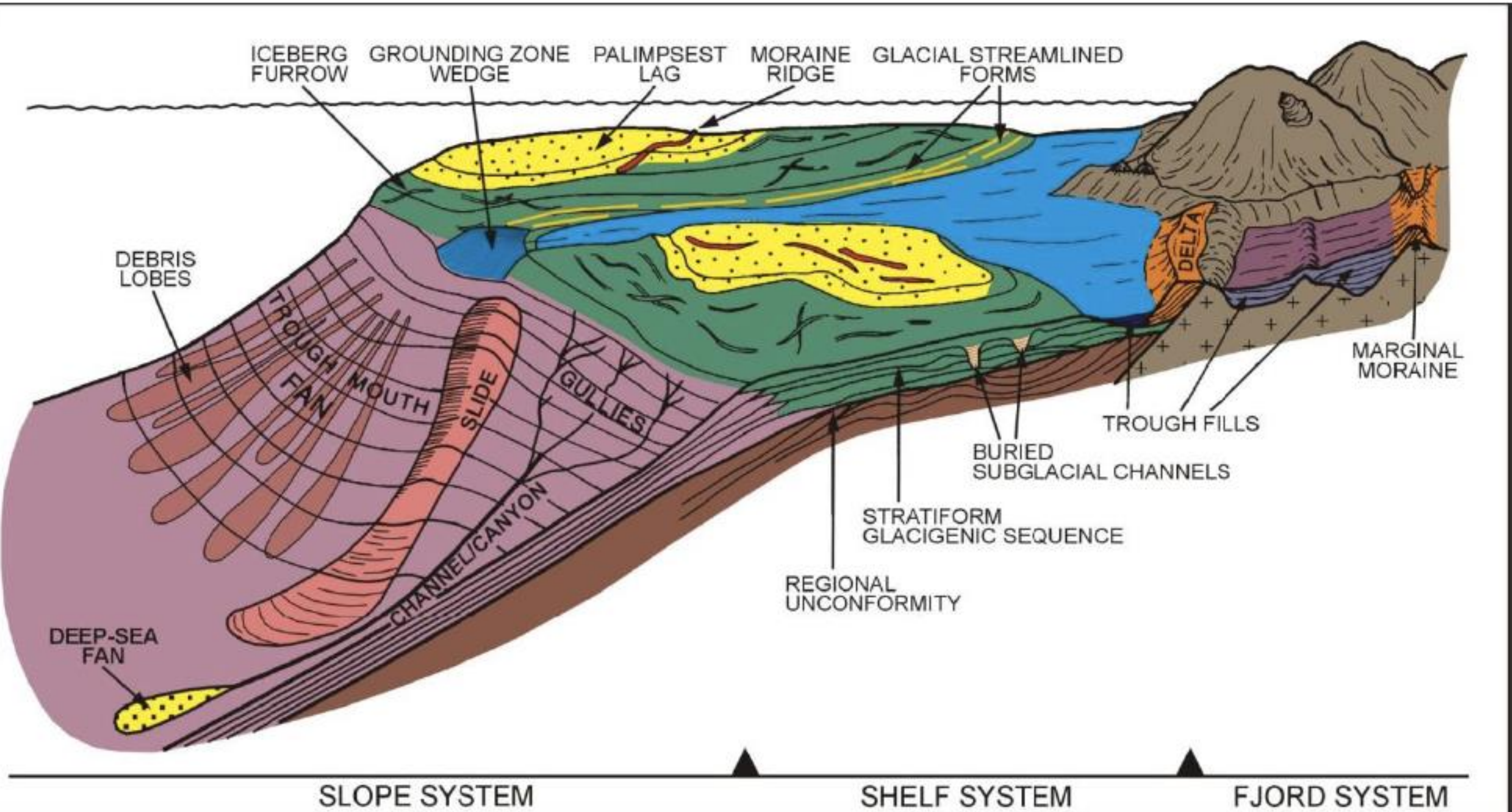


Bedrock deepening from terrestrial to marine based ice sheet

Colleoni, F., et al. 2018

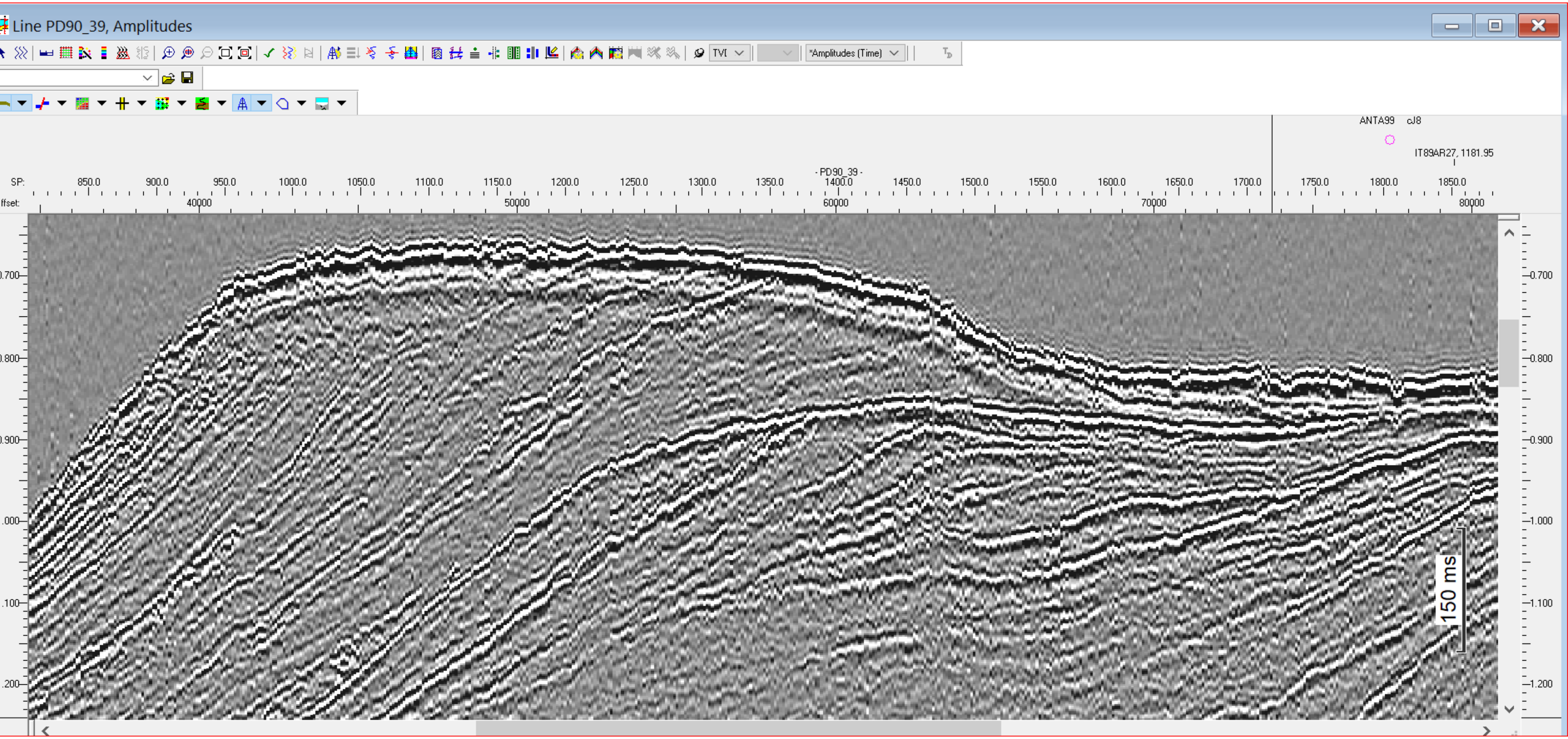
Topography/Bathymetry evolution => **increase ice sheet sensitivity to warming**

Trough/bank topography Trough mouth fans

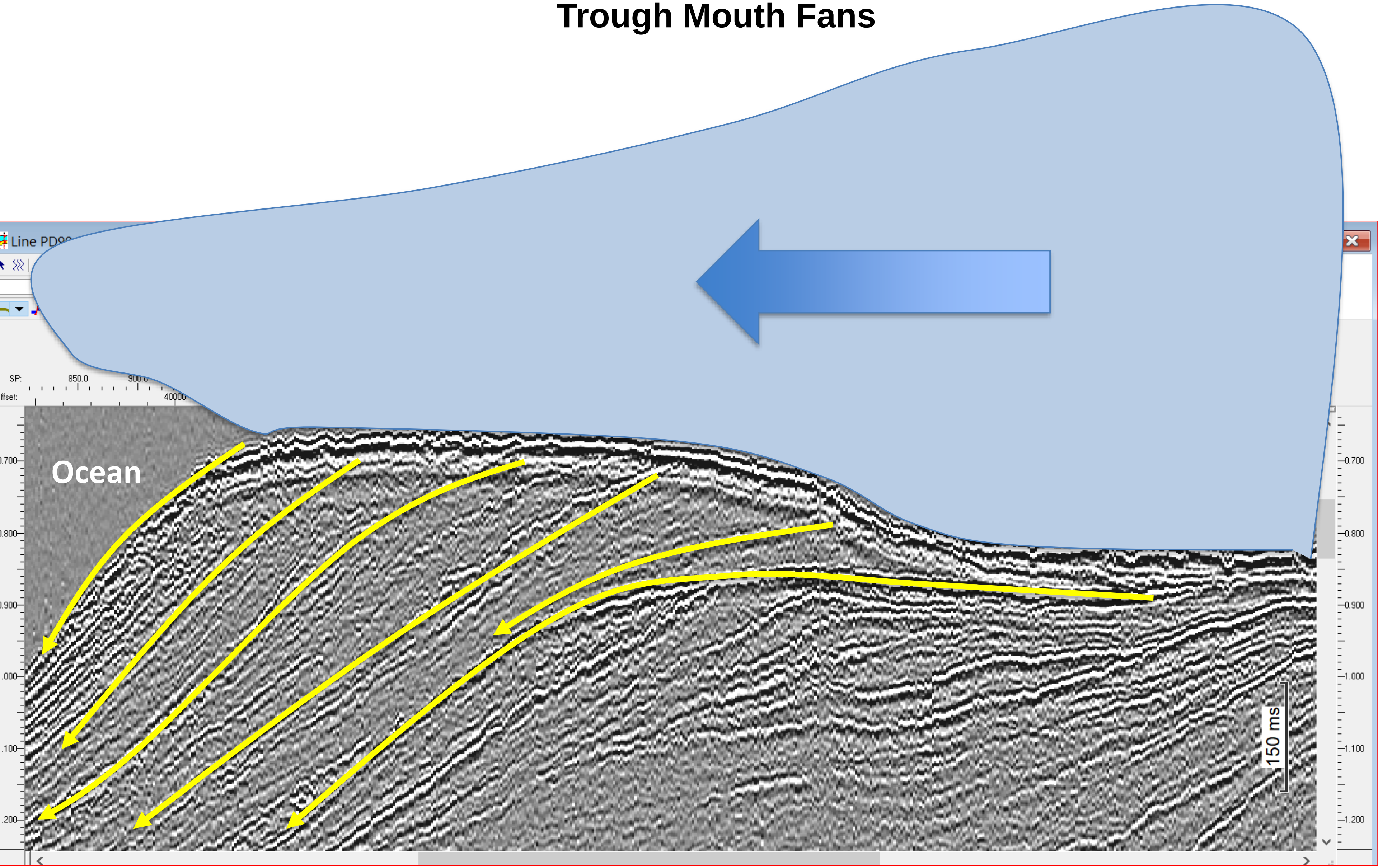


Vorren, 2003

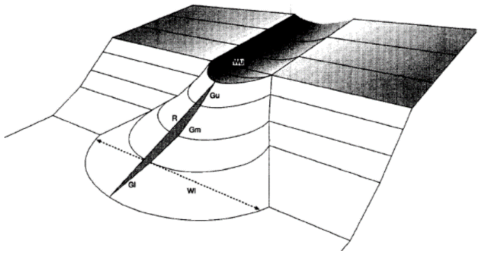
Trough Mouth Fans



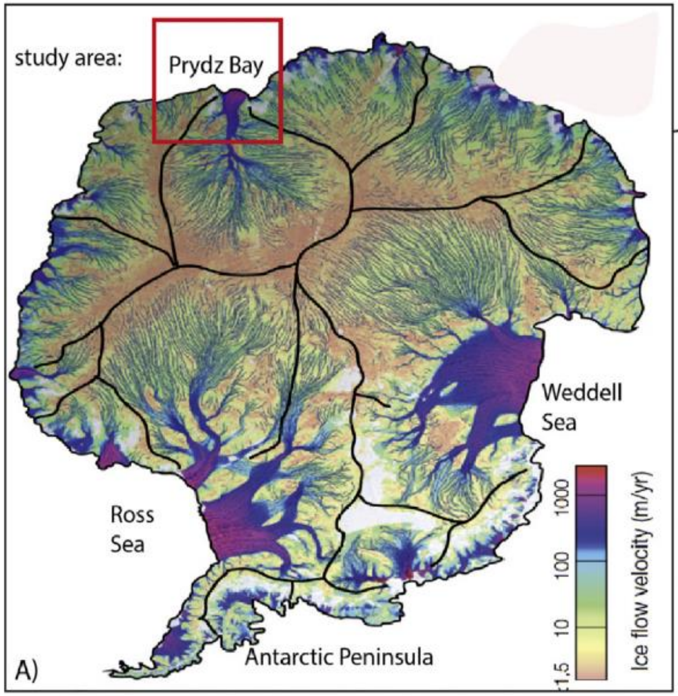
Trough Mouth Fans

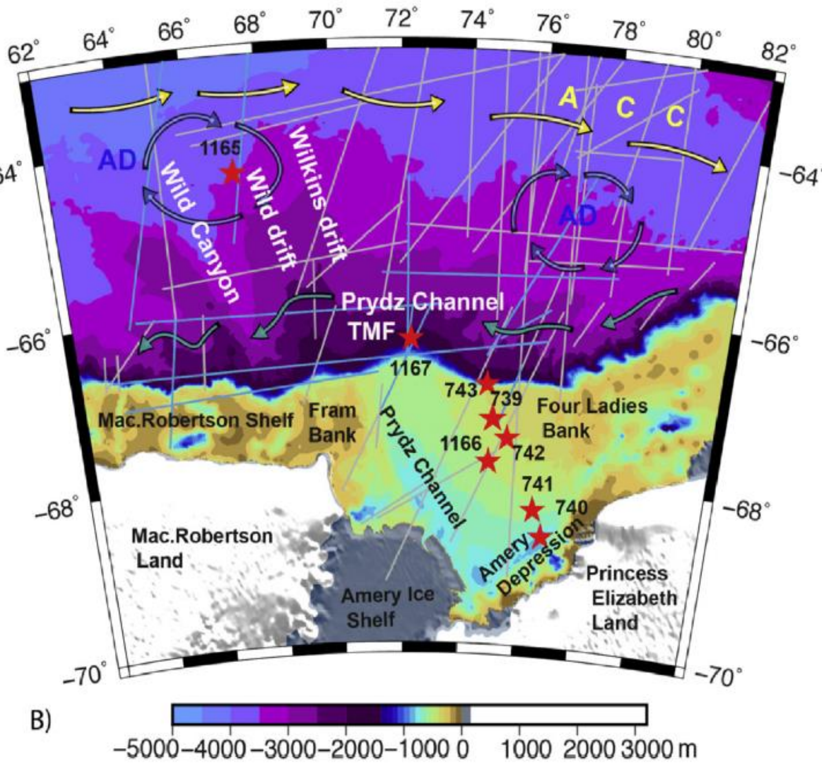


Trough/bank topography
Trough mouth fans

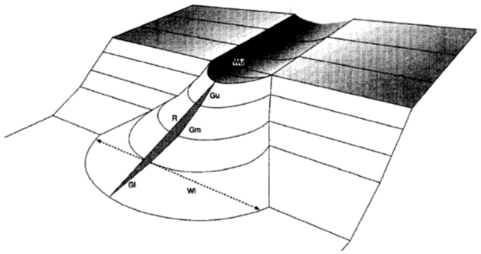


X. Huang, et al. *Marine Geology 430 (2020) 106339*





Trough/bank topography
Trough mouth fans



Prydz Bay Margin:

Shelf width: ~250 km (wide), the shelf edge prograded ~27 km from the early Pliocene to the present;

Slope gradient: < 2°;

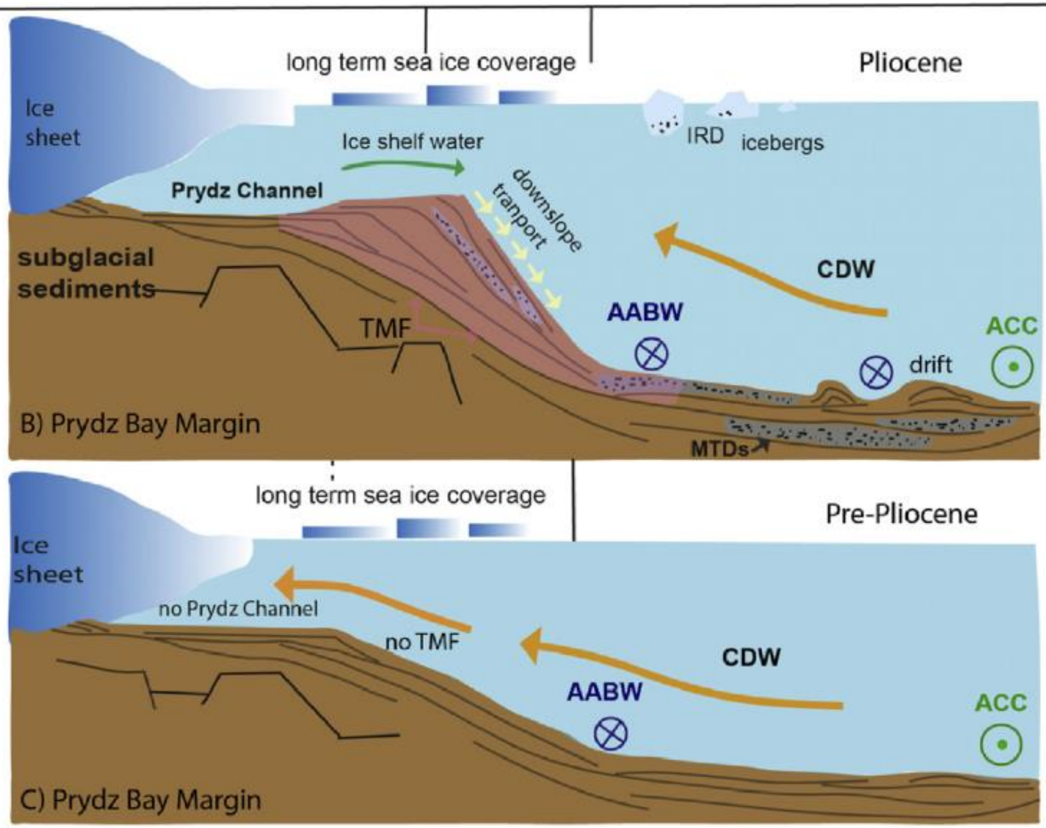
Prydz Channel formed during the Early Pliocene;

Large glacial system advances and retreats during Pliocene.

Pre-Pliocene:

Shelf width: (~ 223 km)

No Prydz Channel exist



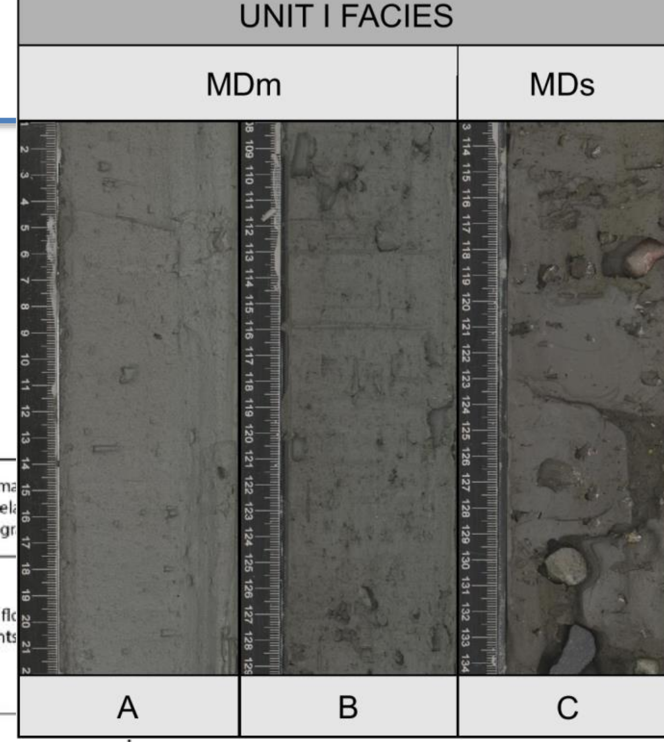
Late Pliocene to present: On the continental rise, the presence of drifts formed by AABW and CDW (Fig. 8)

Early to Late Pliocene: On the slope, episodic MTDs and other gravity flow dominated (Fig. 6);

TMF grew during the Pliocene (Fig. 5);

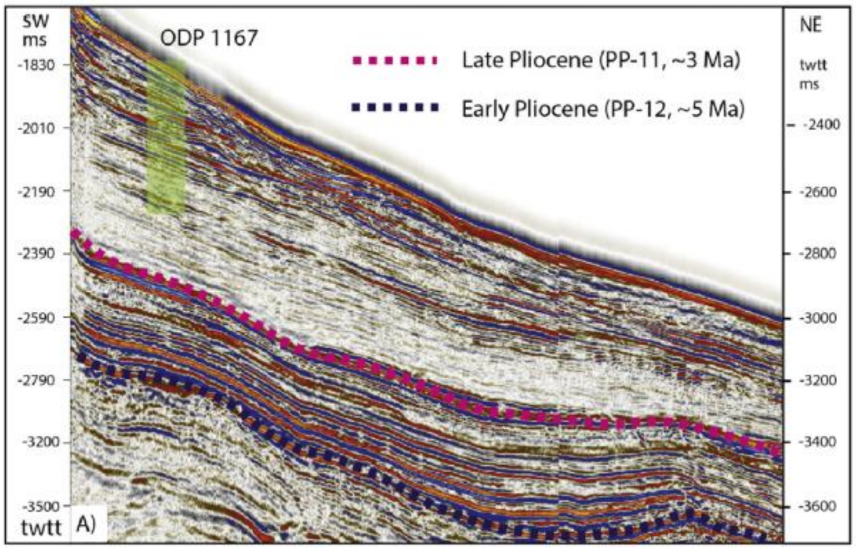
The onset of Prydz Channel TMF occurred in the Early Pliocene.

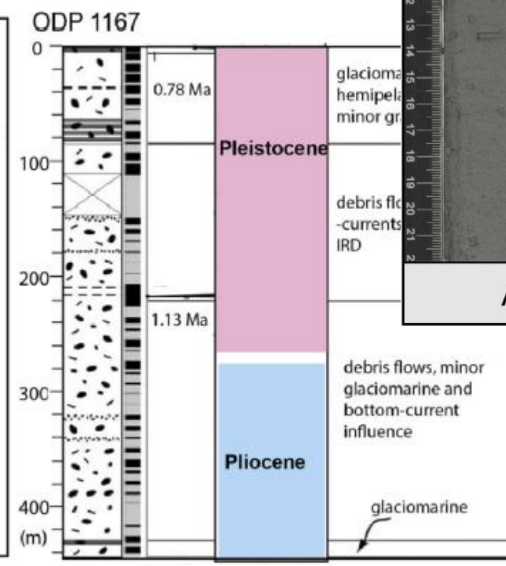
No TMF and Prydz Channel

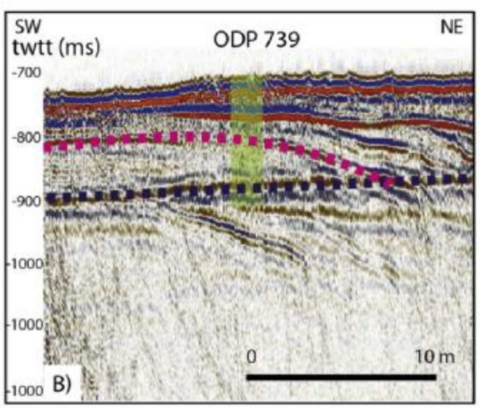


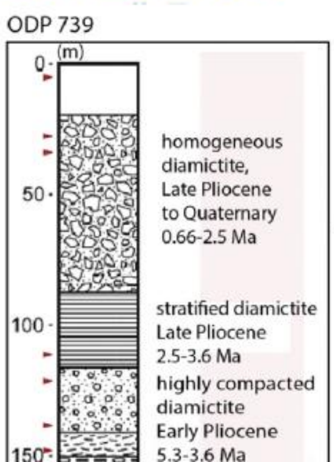
mud (55%) sand (32%) gravel (13%)
Ross Sea IODP U1525 unit I (King et al., 2021)

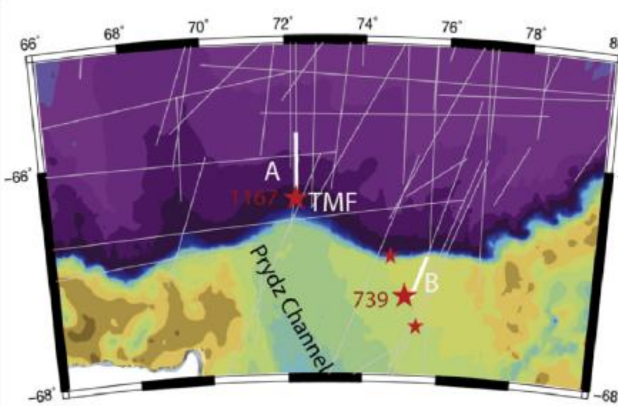
Huang et al., 2020



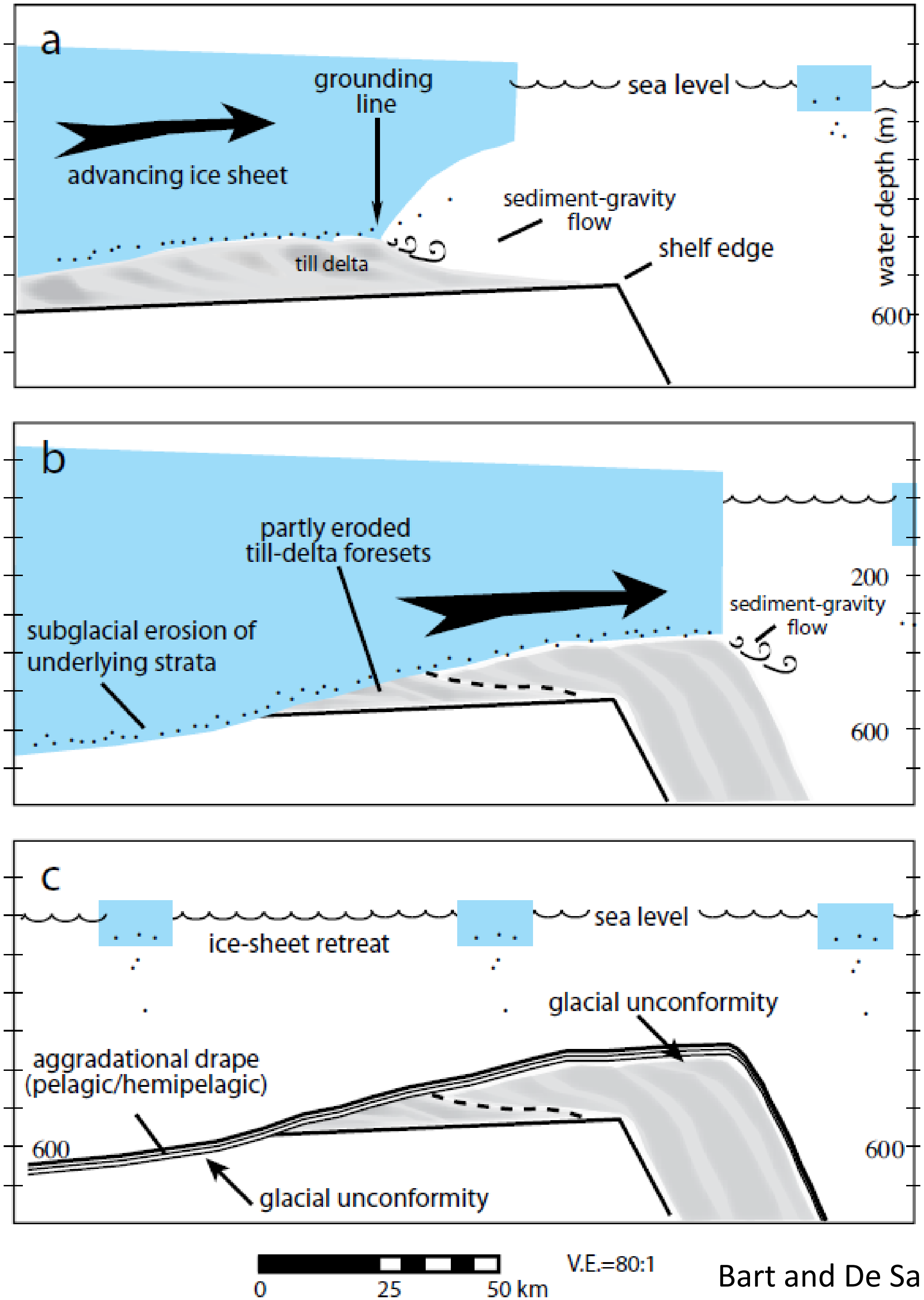




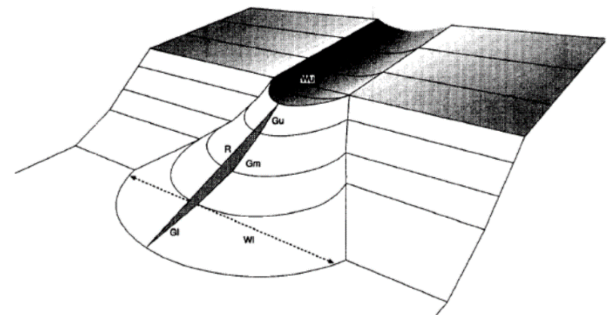




Ross Sea AND-2 (Mckay et al. 2009 GSA Bull.)



- Trough-mouth fans
- Till delta



Bart and De Santis 2012

Diagnostic features

- Glacial valleys and foredeepened surfaces
- Trough/bank topography
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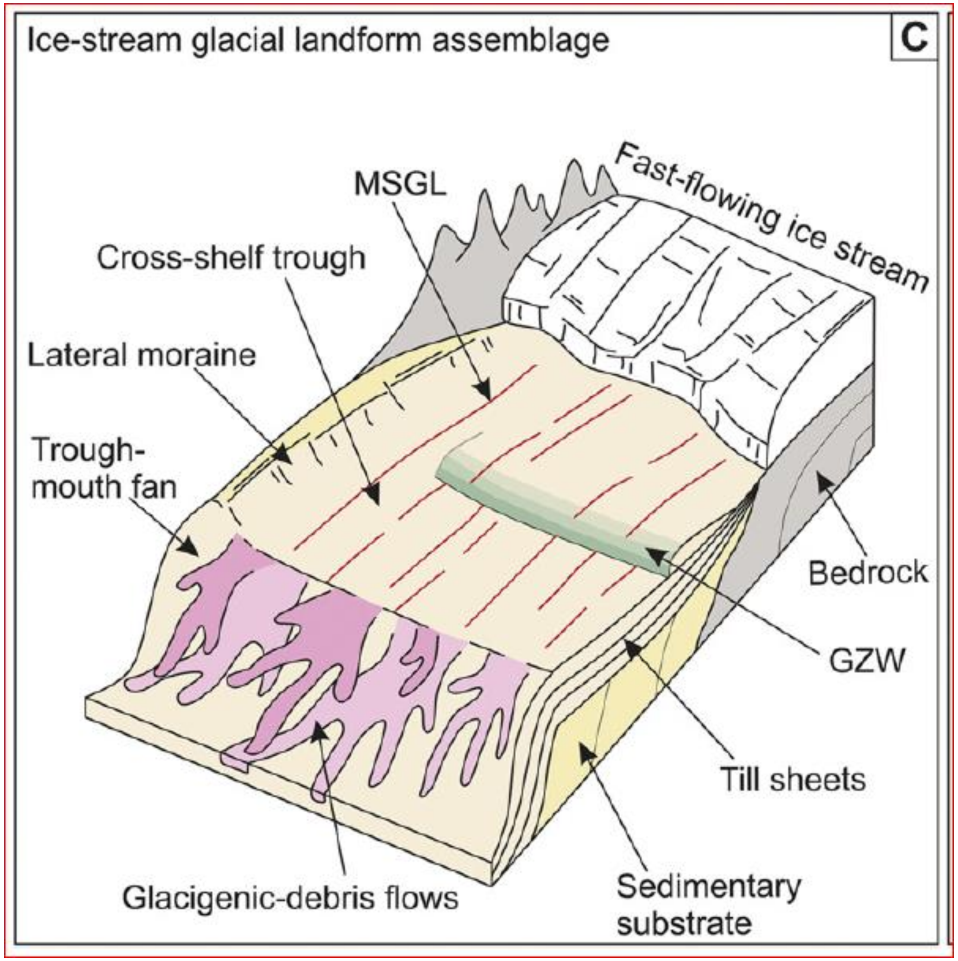
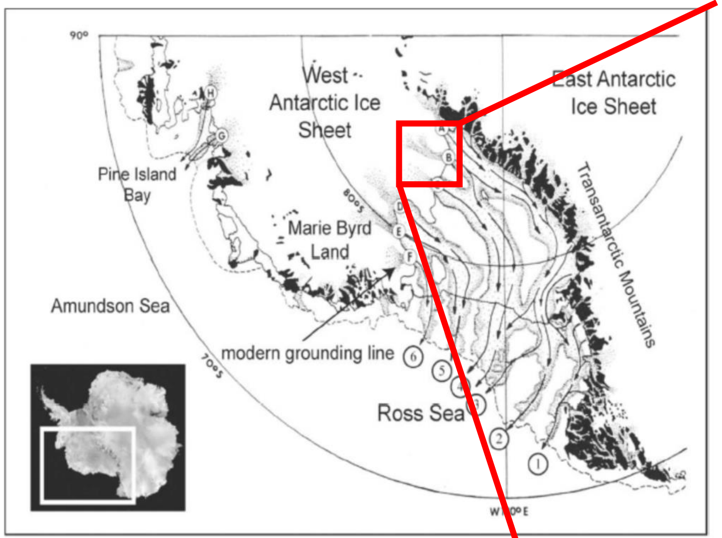
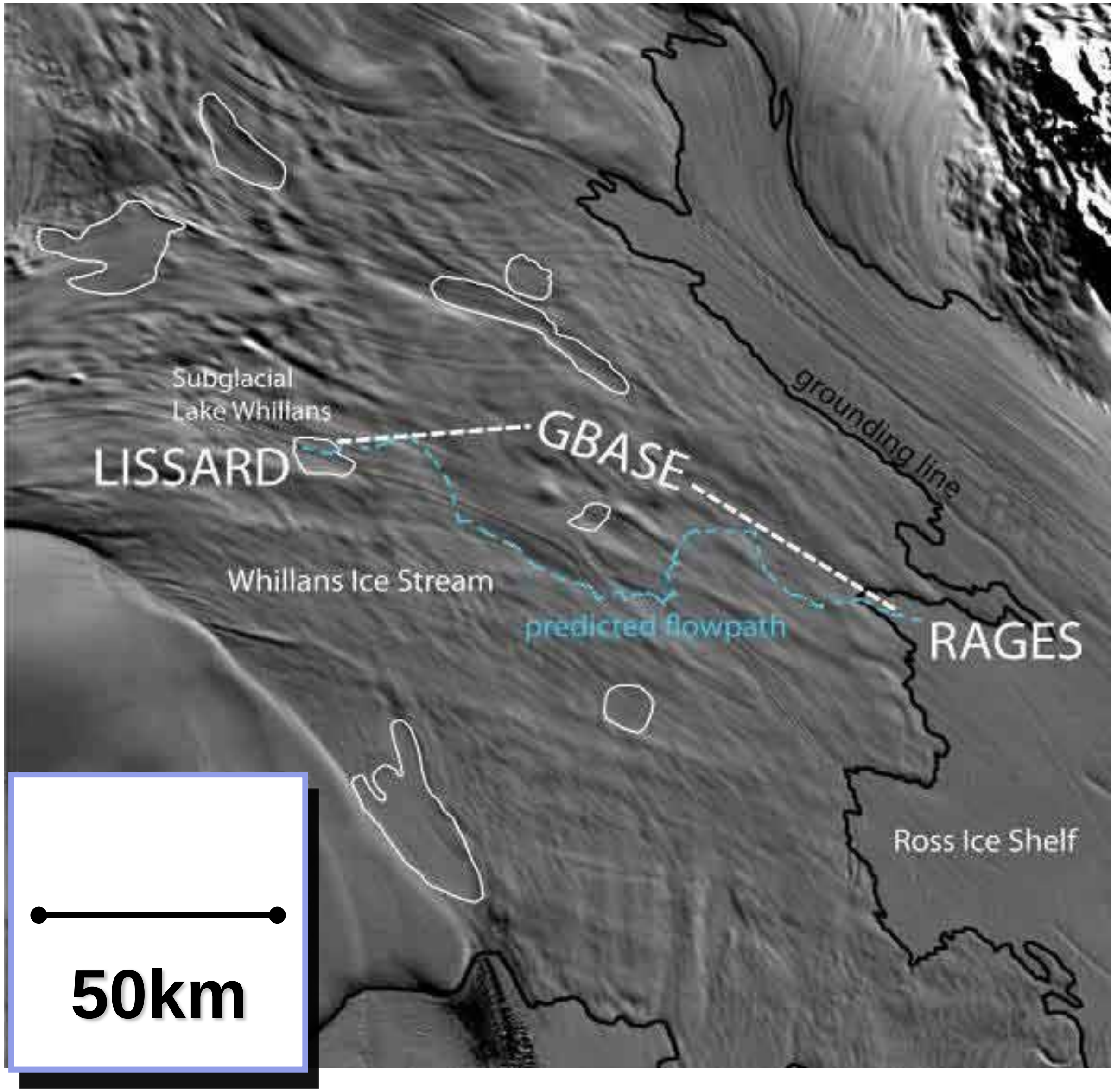
- Ice grounding zone wedge (GZW)
- Glacial lineations
- Outwash channels

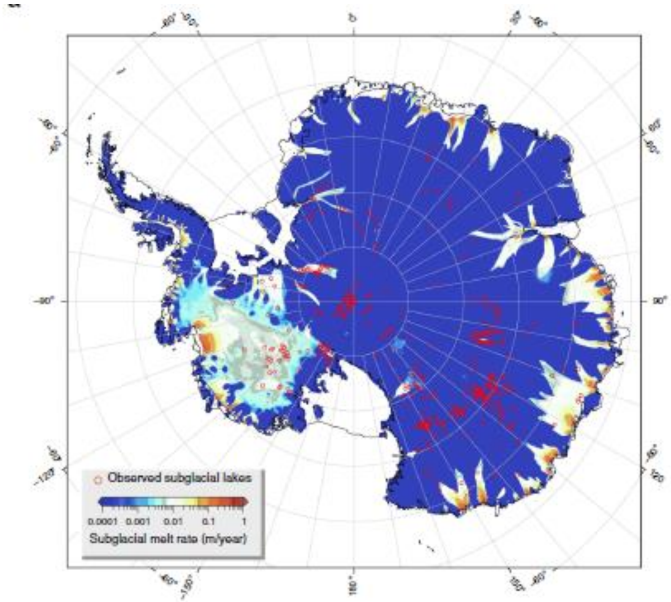


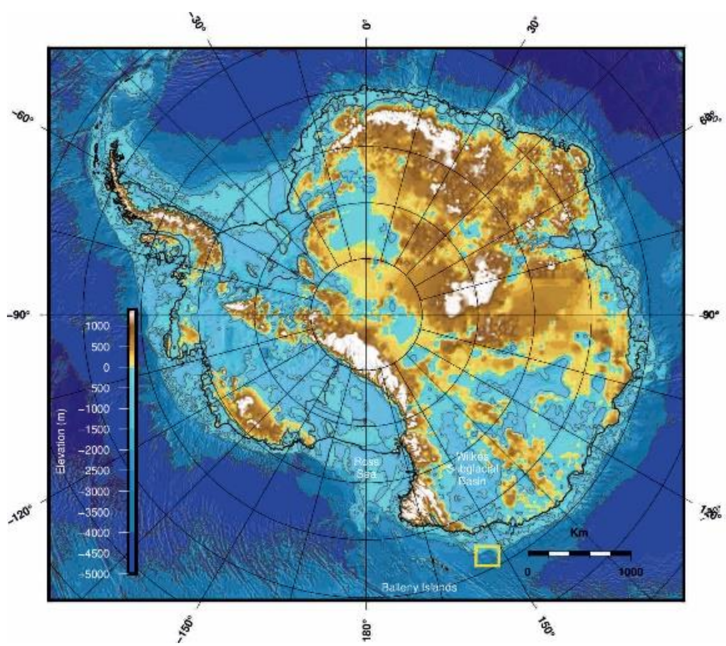


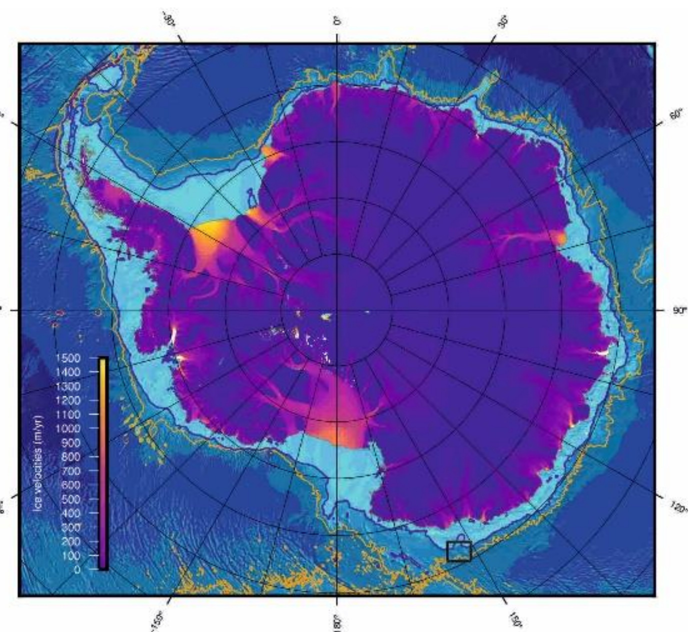


Whillans ice stream
150km large
500km long

(Anandrakrishnan et al., 2007)


Observed subglacial lakes
0.0001 0.001 0.01 0.1 1
Subglacial melt rate (m/year)


Elevation (m)
1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000
Ross Sea
Wilkes Subglacial Basin
Balleny Islands
Km
0
1000


Ice velocities (m/yr)
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0

The grounding zone of marine-terminating ice sheets is the transitional zone at which the ice-sheet base ceases to be in contact with the underlying substrate.

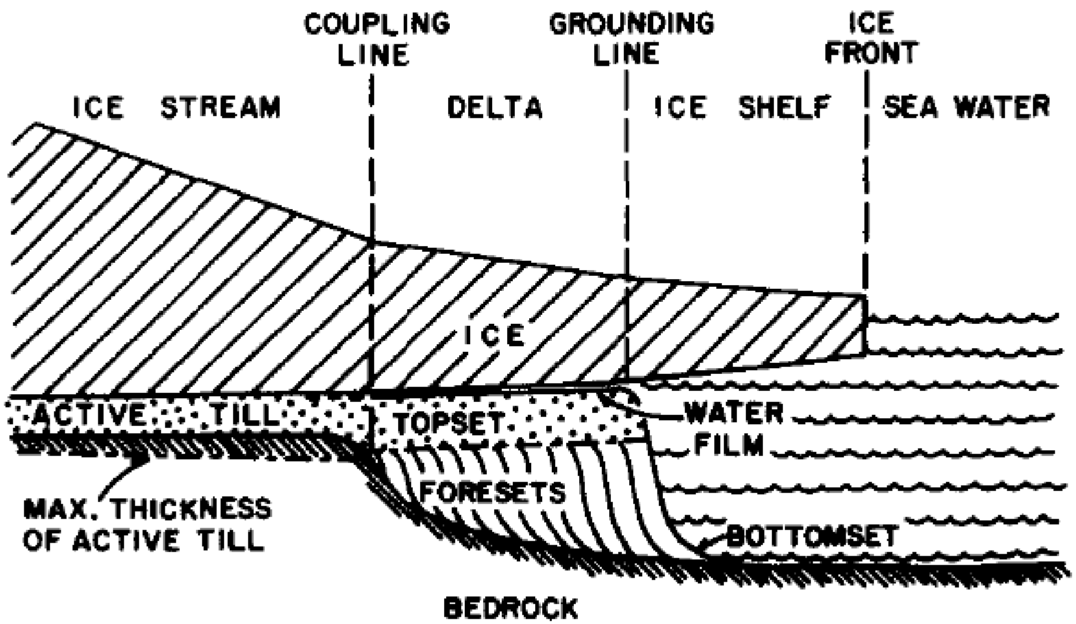


Fig.3. Cartoon of the likely configuration of the ice stream, till delta, and ice shelf.

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

For a rock flux of hundreds of cubic meters per year per meter-width of grounding line

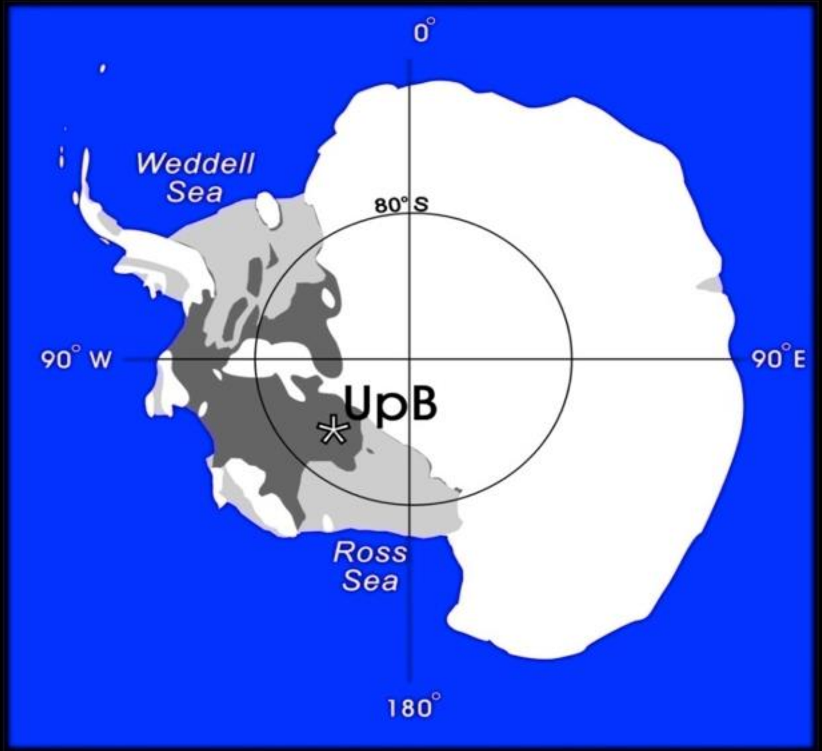
⇒ Formation of a sedimentary deposit tens of kilometers long into water tens of meters deep

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

Alley et al., 1987; 1989

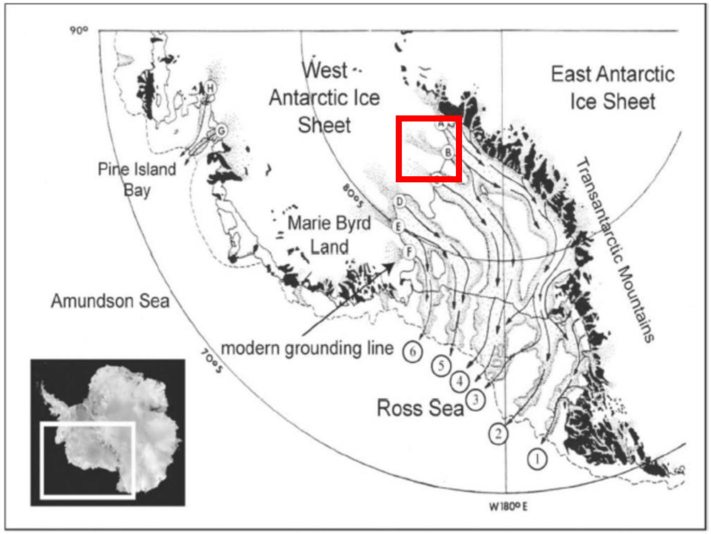
Sediments recovered from beneath the ice provided the only direct evidence of marine events in the West Antarctic interior

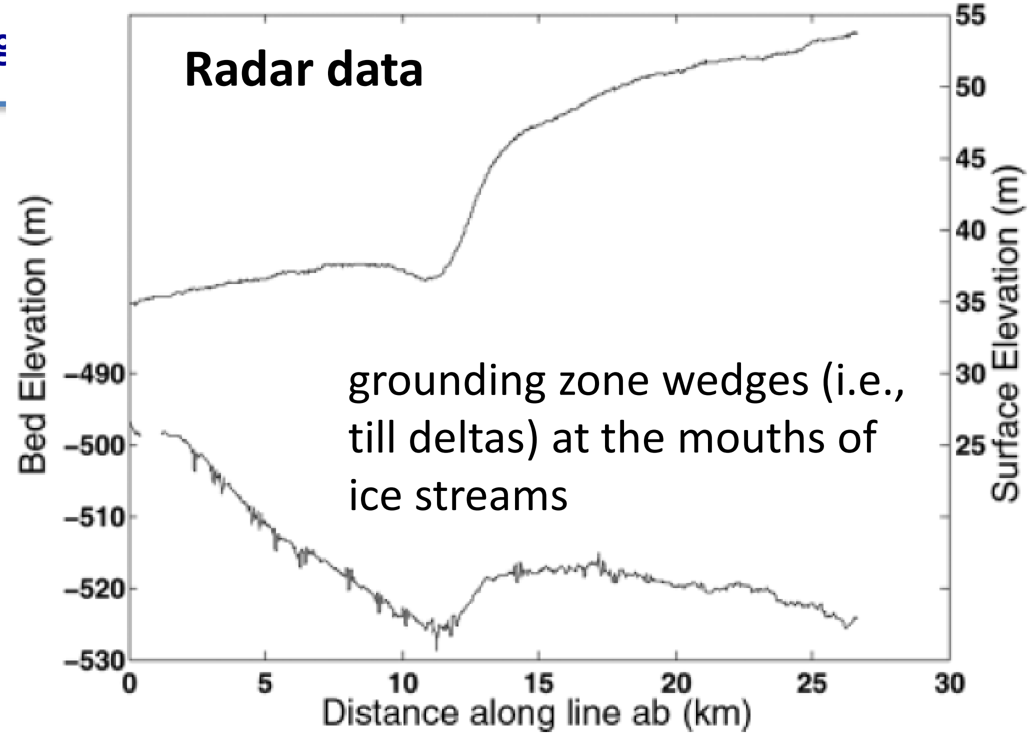
Caltech hot water drill at Upstream B, Antarctica, 1991

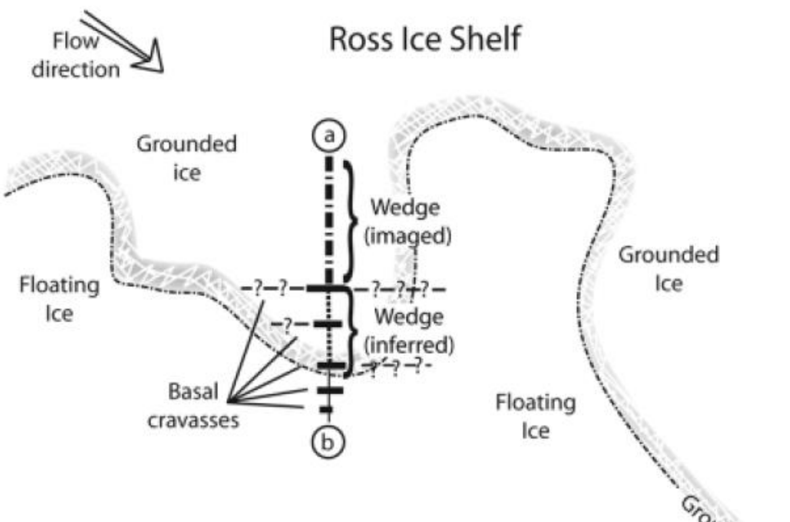


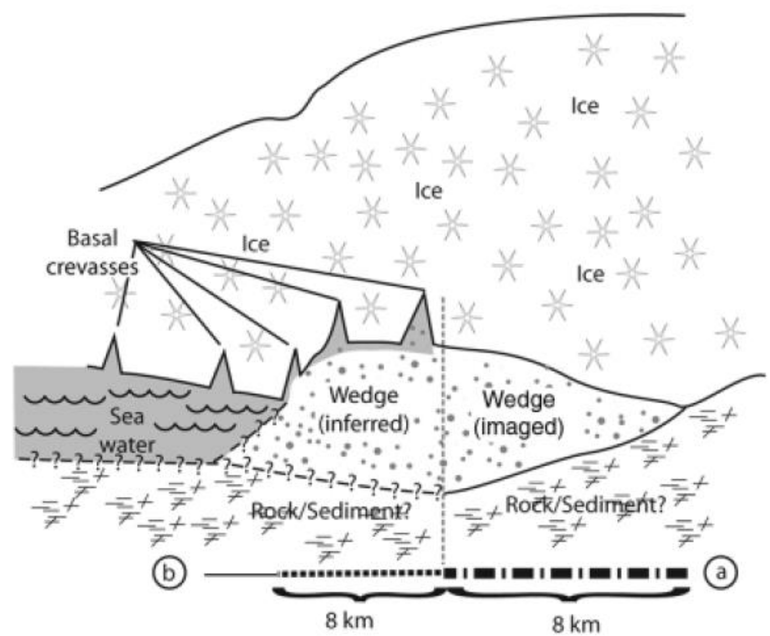
Scherer

Caltech system refurbished for WISSARD



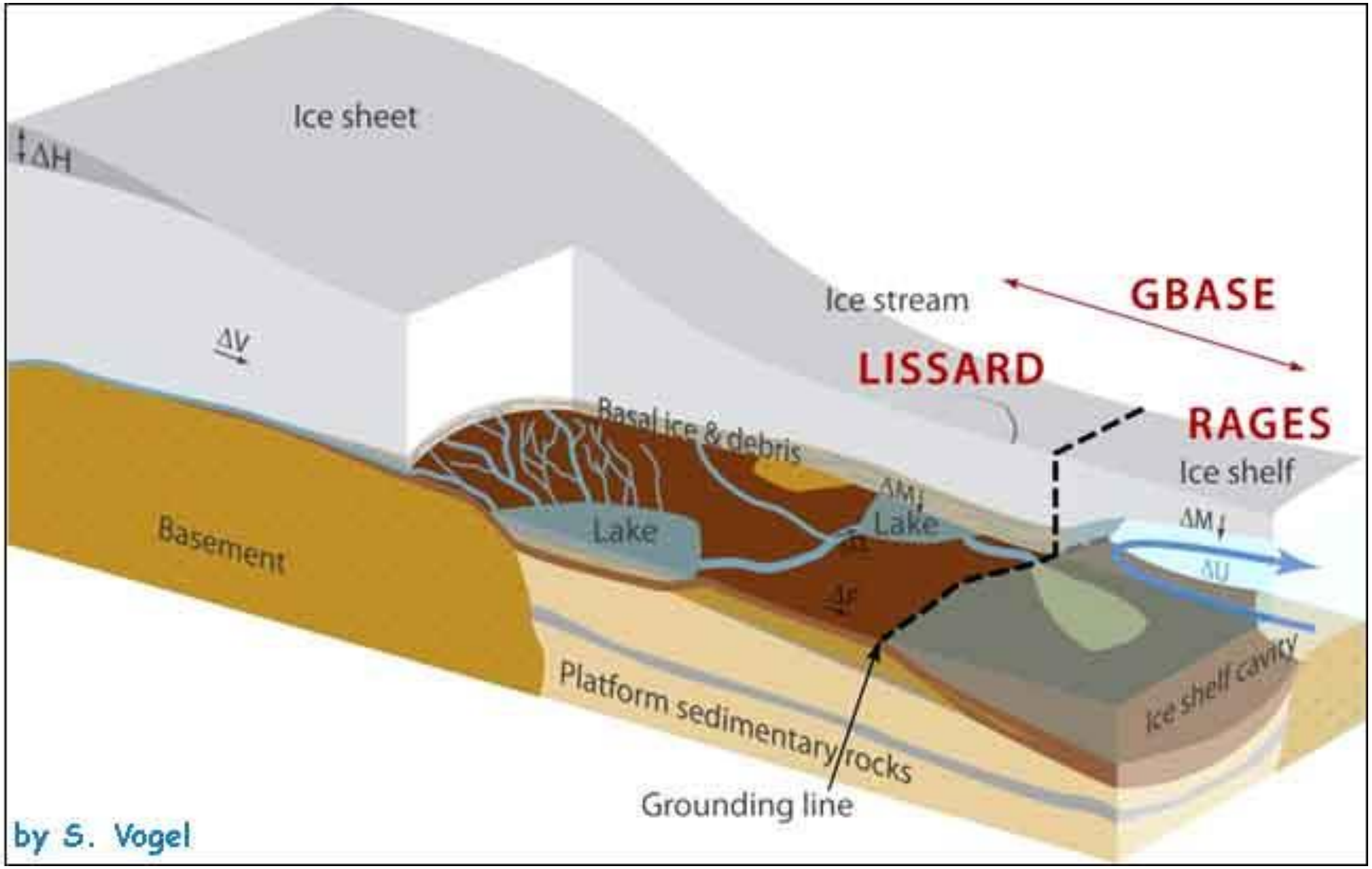






(Anandrakrishnan et al., 2007)

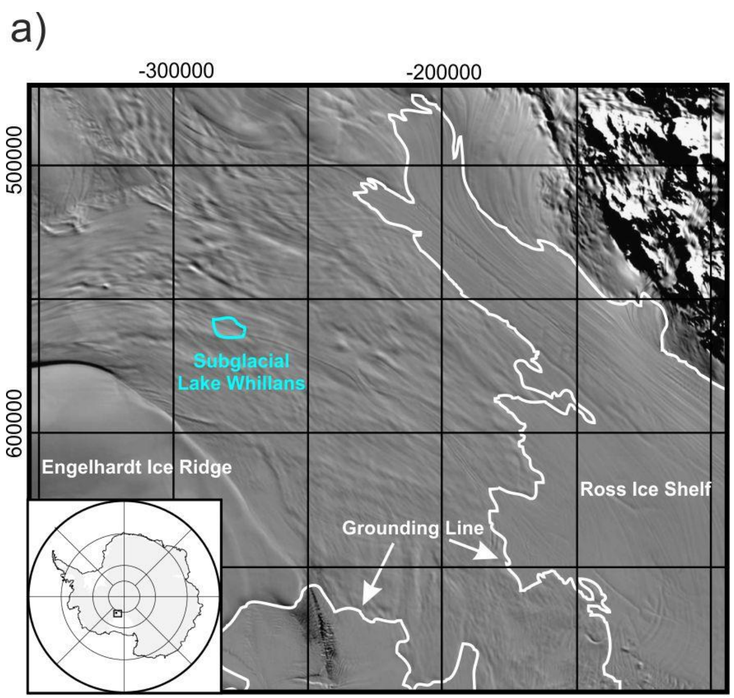
location of ice-sheet grounding is affected by short-term variations (e.g tides) and climatically-induced variations in thinning and rates of mass loss. The grounding zone is a key site for meltwater transfer from the ice sheet to the marine environment

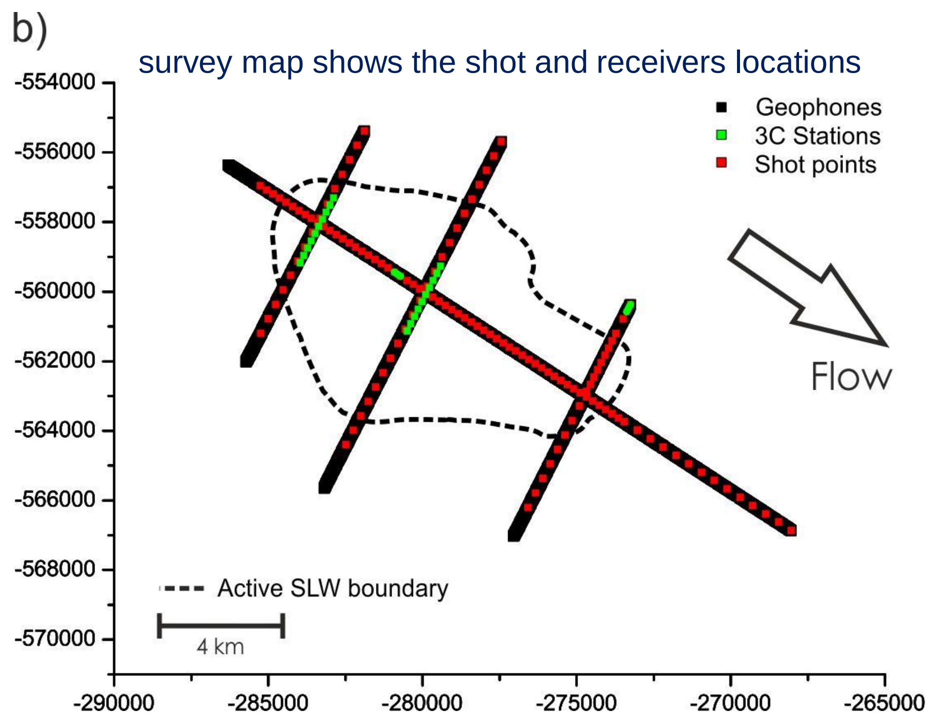


Subglacial and grounding-zone sedimentation aggradation may act as a negative feedback that counters dynamic thinning of the ice stream and stabilizes the ice-stream grounding zones (e.g., Alley et al., 2007).

Whillans Ice Stream – 2010-2011 Antarctic Campaign

Whillans Ice Stream is thousand of km long and hundreds of km wide. It flows towards the Ross Ice Shelf at over 300 m per year, with a tidally controlled stick-slip motion.





Objectives of the study: to verify the existence of the Subglacial Lake Whillans (SLW), and the presence of water-saturated sediments at the ice bottom.

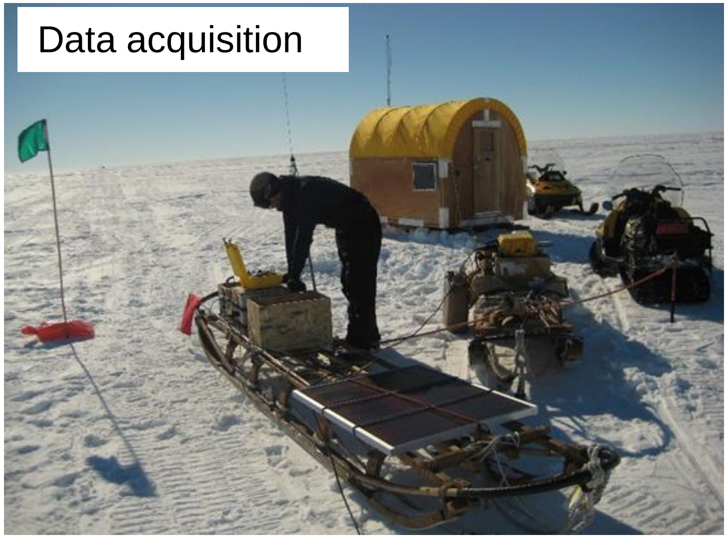
Whillans Ice Stream – 2010-2011 Antarctic Campaign

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


Base camp set up


The Base camp in the wind


Base camp skyline


Data acquisition

Whillans Ice Stream – 2010-2011 Antarctic Campaign

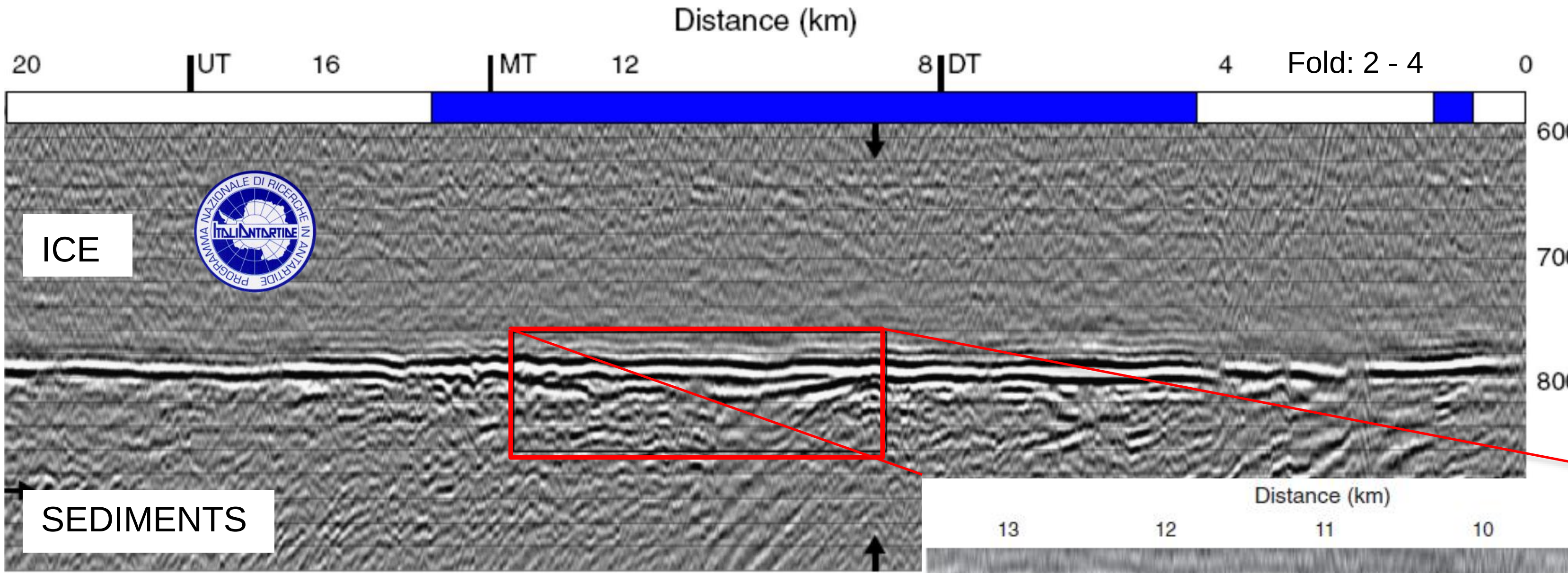
While drilling the holes for the explosive

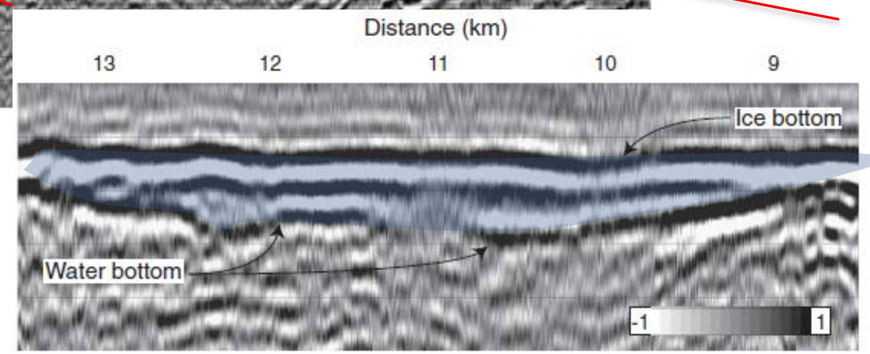
A hole in the ice for the explosive

Digging after the wind....!

3C Stations deployment

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





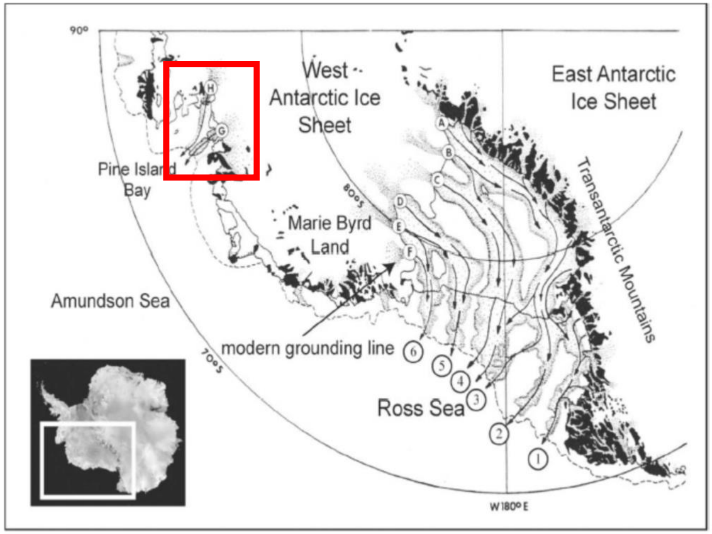
The survey, carried out in a low-tide period, evidenced that **the lake exists** and its water column is up to 8 m, along 5 km of the 45 km profiled. These findings were later confirmed by drilling operations.

In this case we observe the phase inversion between the Ice bottom reflection and the water bottom reflection.

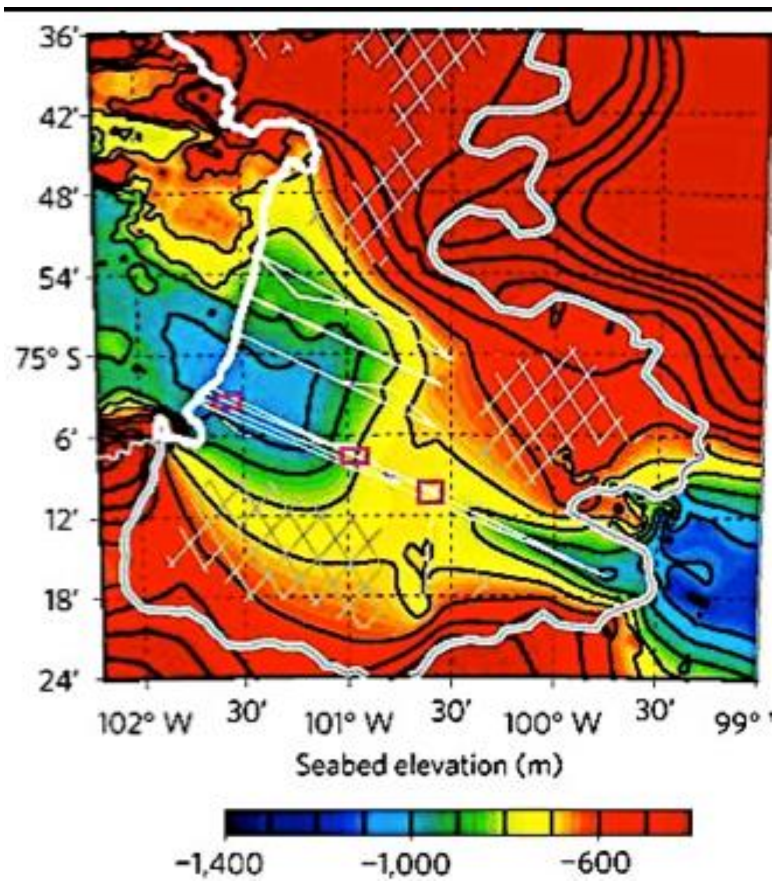
Moreover, AVO (Amplitude Versus Offset) analysis shows that the major part of the bed around the lake consists of soft sediments and thin water lenses.

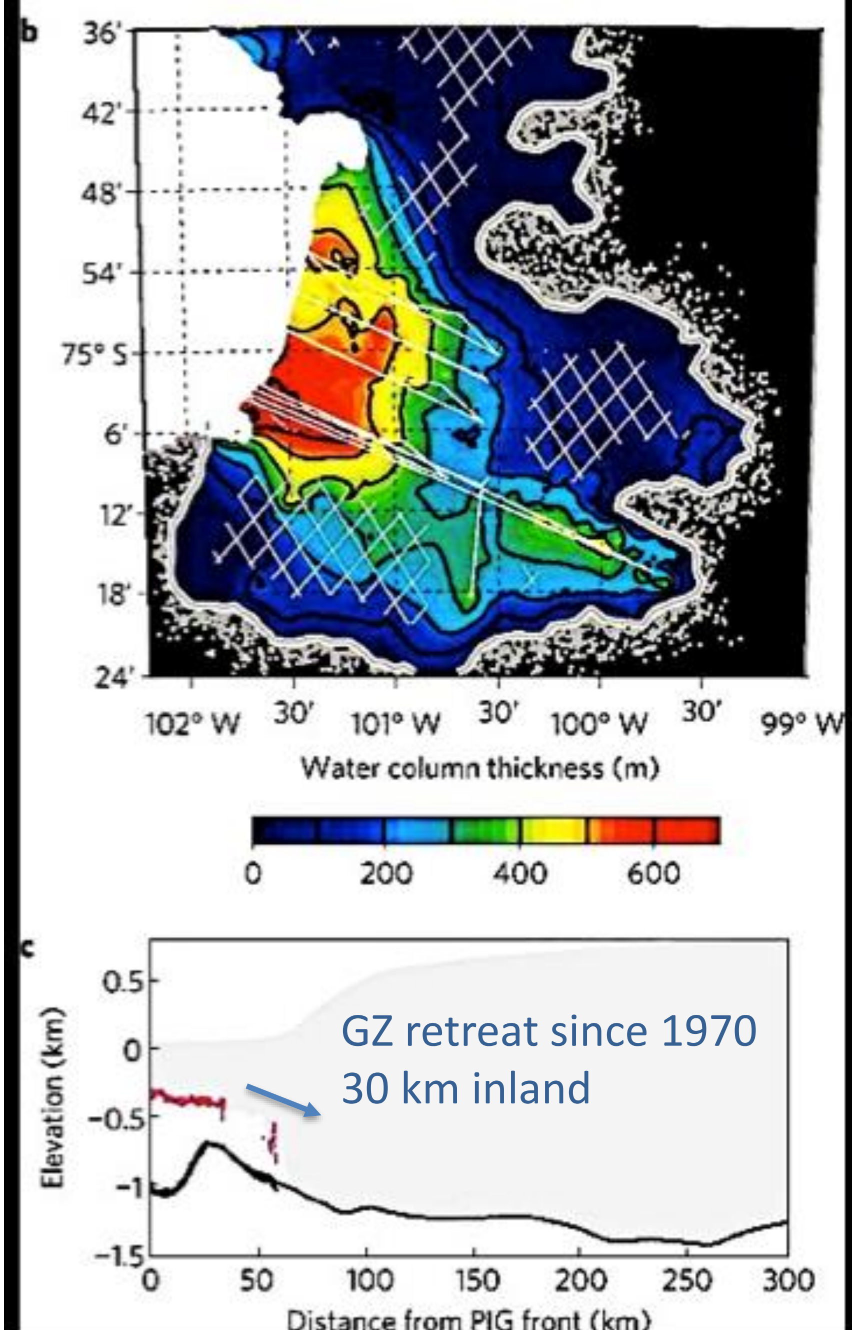
Picotti et. al 2011; 2015

Pine Island Glacier



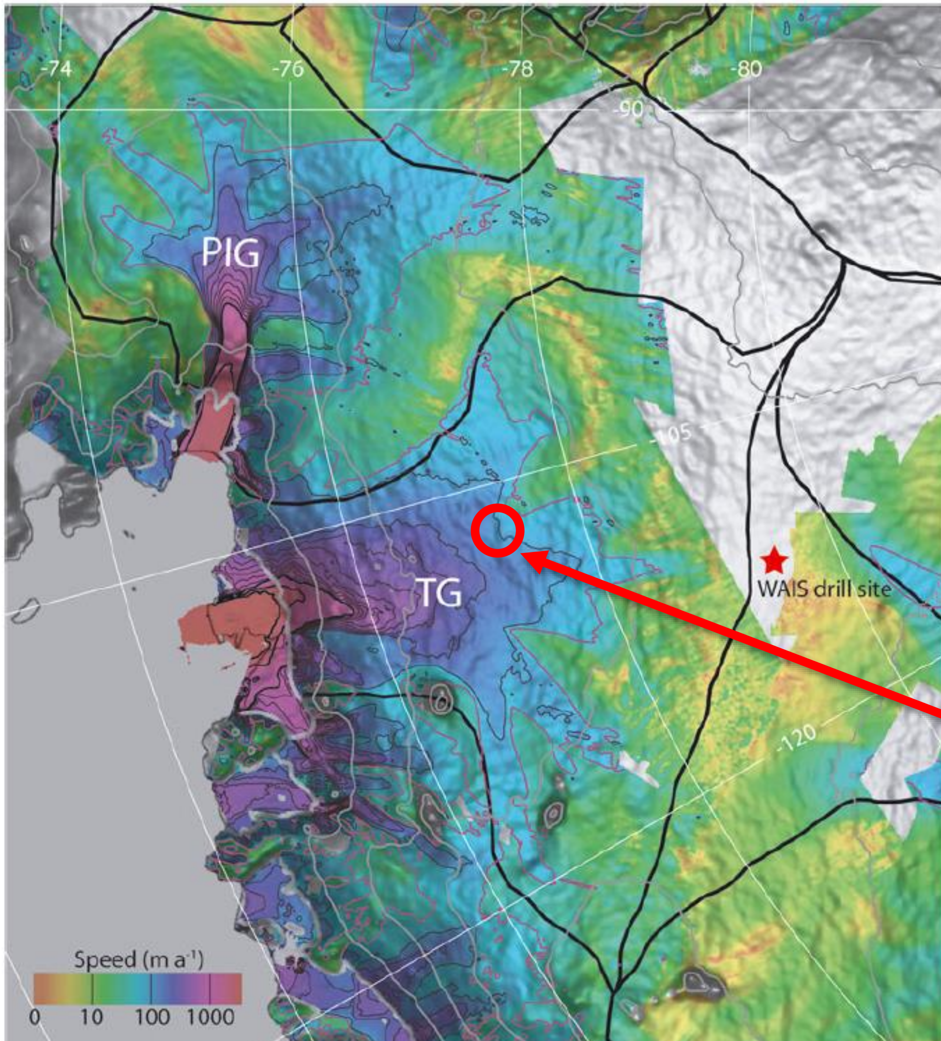
autonomous underwater vehicle





PIG - Jenkins et al. 2010

Thwaites Glacier (Amundsen-Scott coast - WAIS)



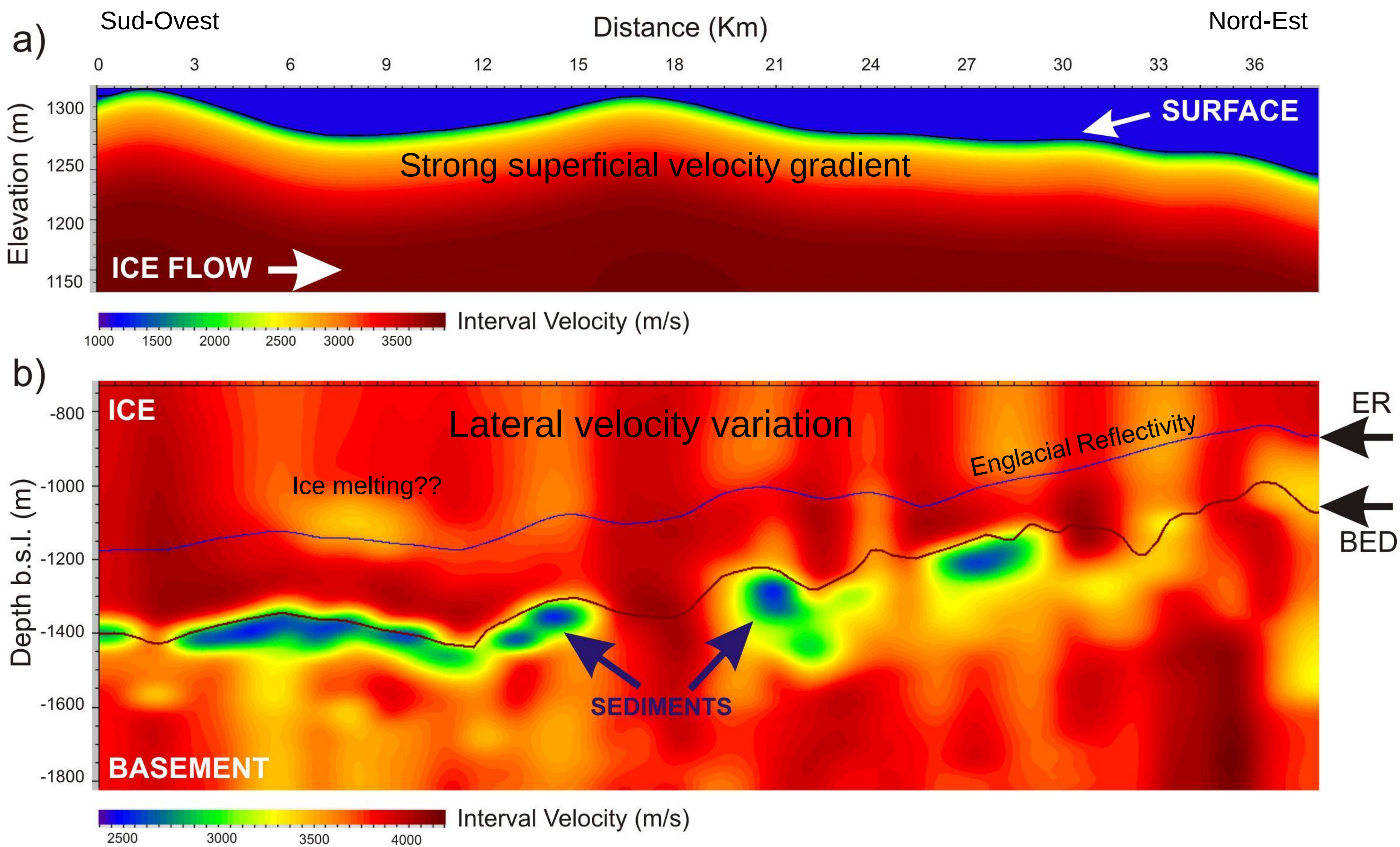
Flow speed (color) over the artificially shaded surface (grayscale) of a DEM produced from a combination of laser and radar altimetry for Pine Island (PIG) and Thwaites (TG) Glaciers. From Joughin et al. (2009).

Thwaites glacier and Pine Island glacier are two of the largest ice streams of the WAIS.

Joughin et al. (2009) indicates, with remote sensing techniques, that the Thwaites is more stable than the Pine Island, probably due to a more corrugated basement and the presence of a crystalline bedrock and consolidated sediments in the inner part.

The purpose is therefore to verify this hypothesis with a seismic line that crosses an area where Joughin et al. (2009) observed a change in baseline stress.

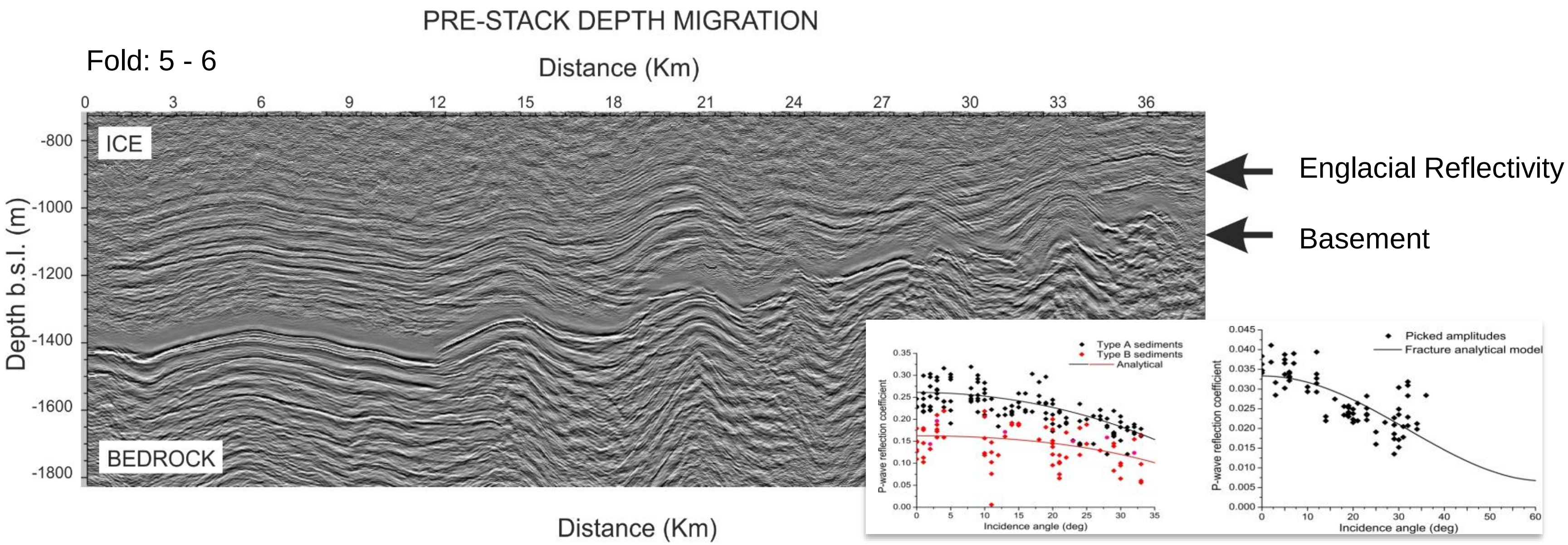
Thwaites Glacier: Interval velocity model

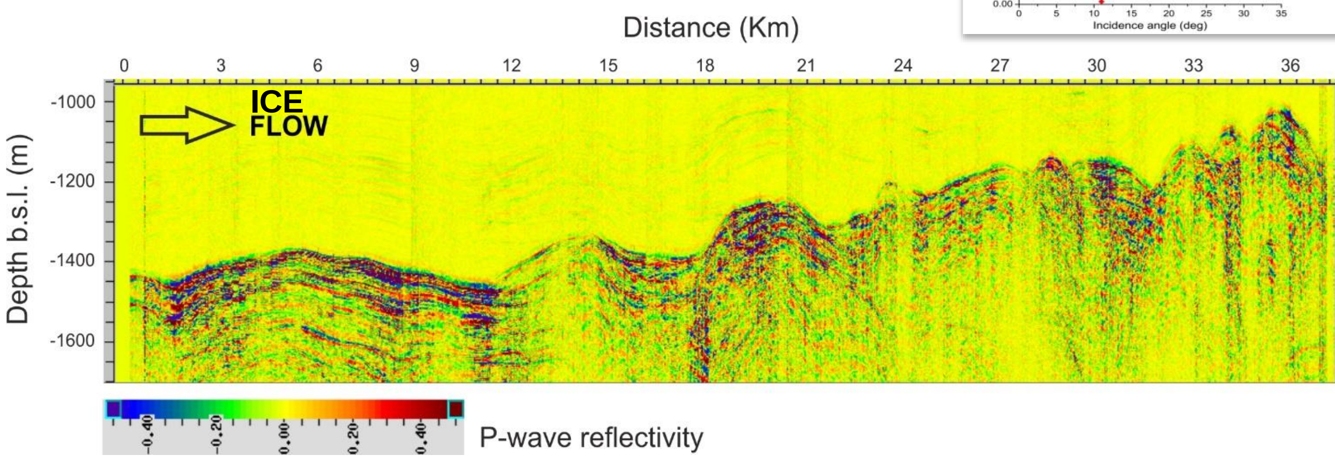


The strong superficial velocity gradient is due to the firn densification, while the lateral variation in depth are due to the stress distribution that generate ice deformation and local ice melting.

Seismic Imaging of Thwaites Glacier (Amundsen-Scott coast - WAIS)

This image shows a 2.5 km thick glacier flowing over a very rough basement located 1.5 km b.s.l...





the basement consists of crystalline bedrock or consolidated sediments,

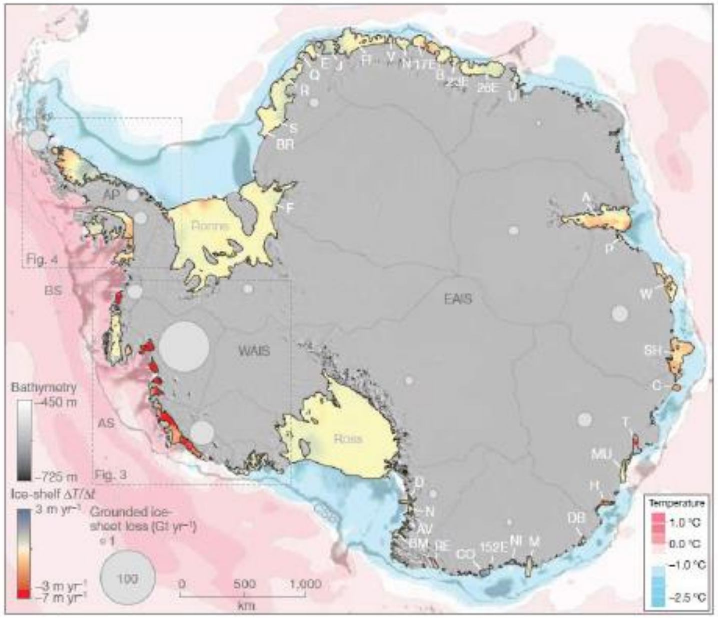
Englacial Reflectivity is due to fractures.

Fractures are propably produced by the huge stresses arising in the lower part of the glacier, indicating **that the principal component of the ice stream motion is deformation in the ice, rather than basal sliding.**

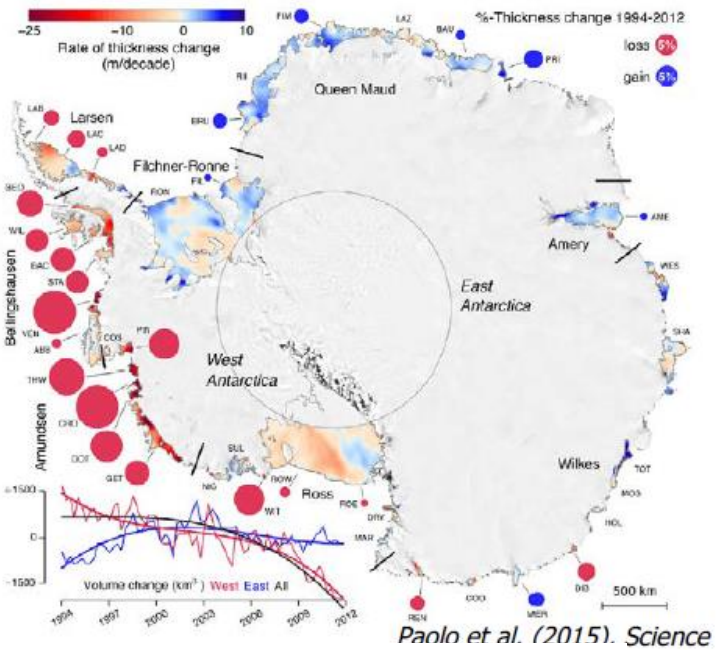
Southern Ocean is warming

Ice shelves are melting

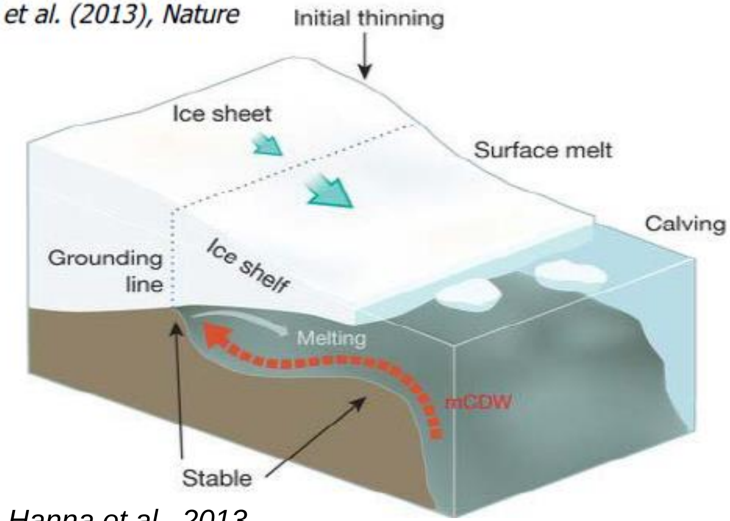
Istituto Nazionale di Oceanografia e di Geofisica Sperimentale



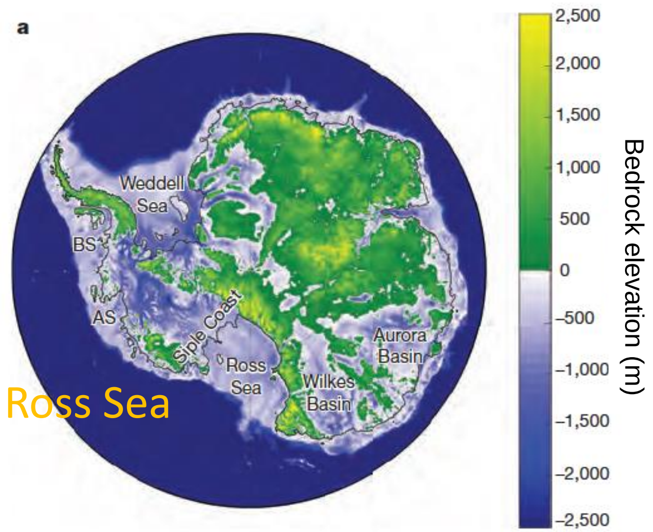
Pritchard et al. (2013), Nature



Paolo et al. (2015). Science

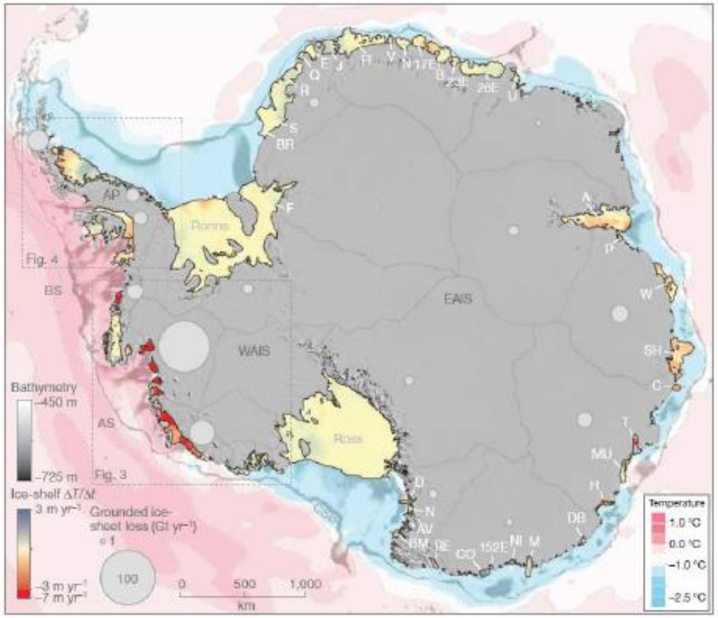


Hanna et al., 2013

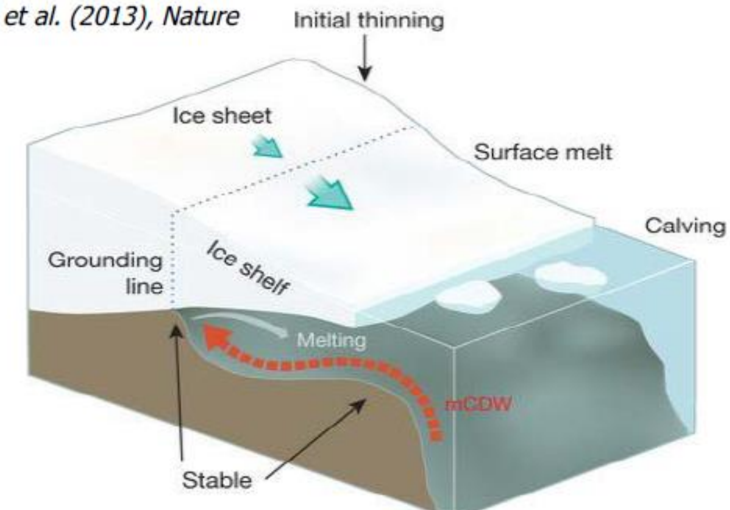


P. Fretwell etal. 2013

Southern Ocean is warming

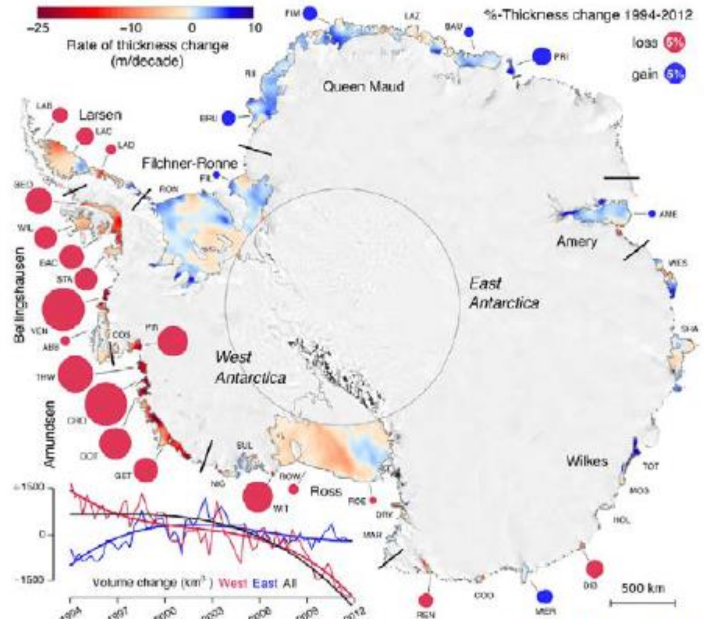


Pritchard et al. (2013), Nature

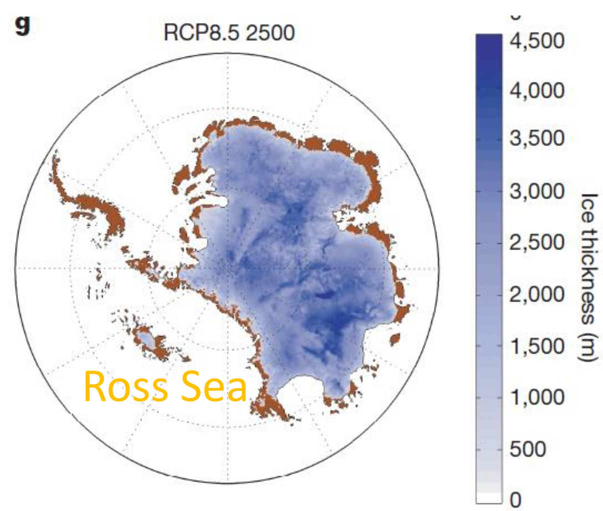


Hanna et al., 2013

Ice shelves are melting



Paolo et al. (2015), Science

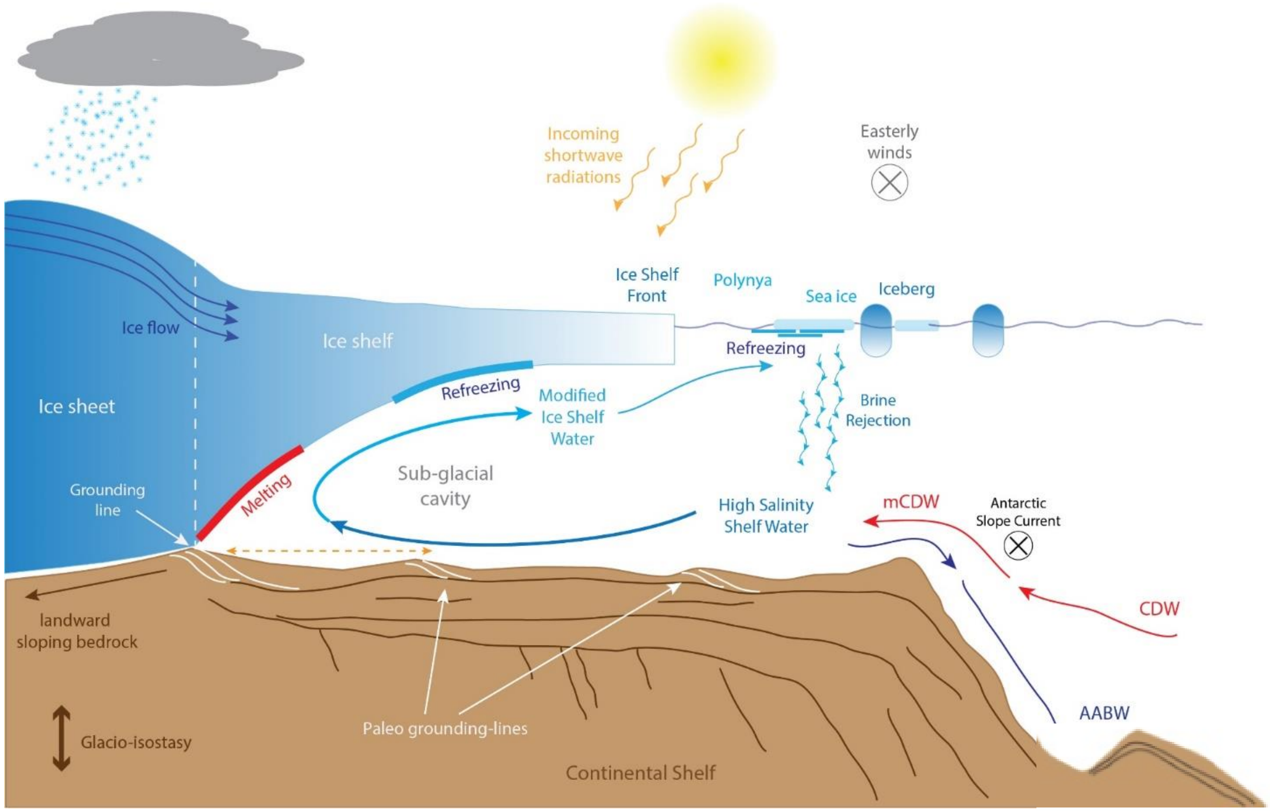


DeConto & Pollard (2016)

Mid-Pliocene warm period (Pollard, DeConto and Alley, 2015) predicted:

- **+17 m GMSL** 350-400ppm CO_2
- +3°C global average air, + 2°C SST
- +3-5°C Antarctic SST (Ross Sea)

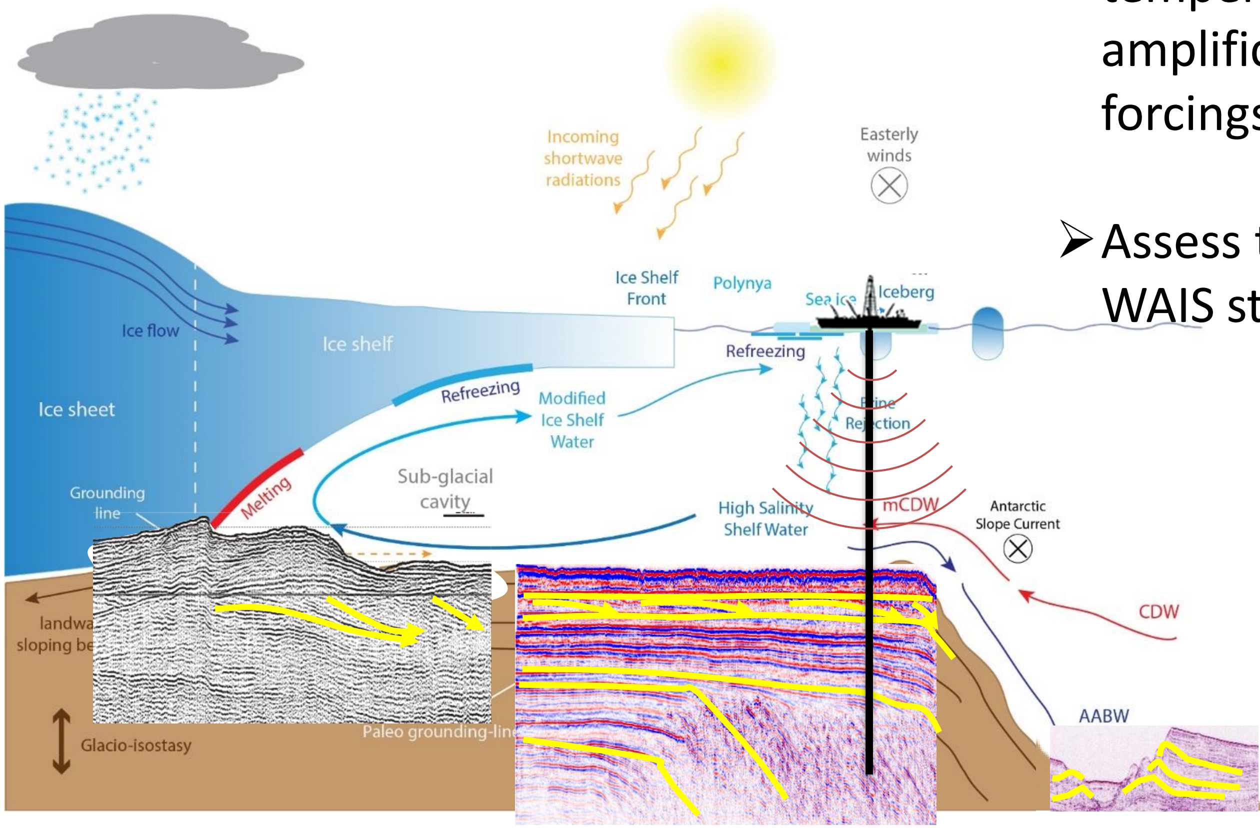
Palaeo-ice streams exerted a major influence on ice-sheet behaviour and had the potential to cause abrupt climatic change through the rapid delivery of ice and freshwater to the ocean.



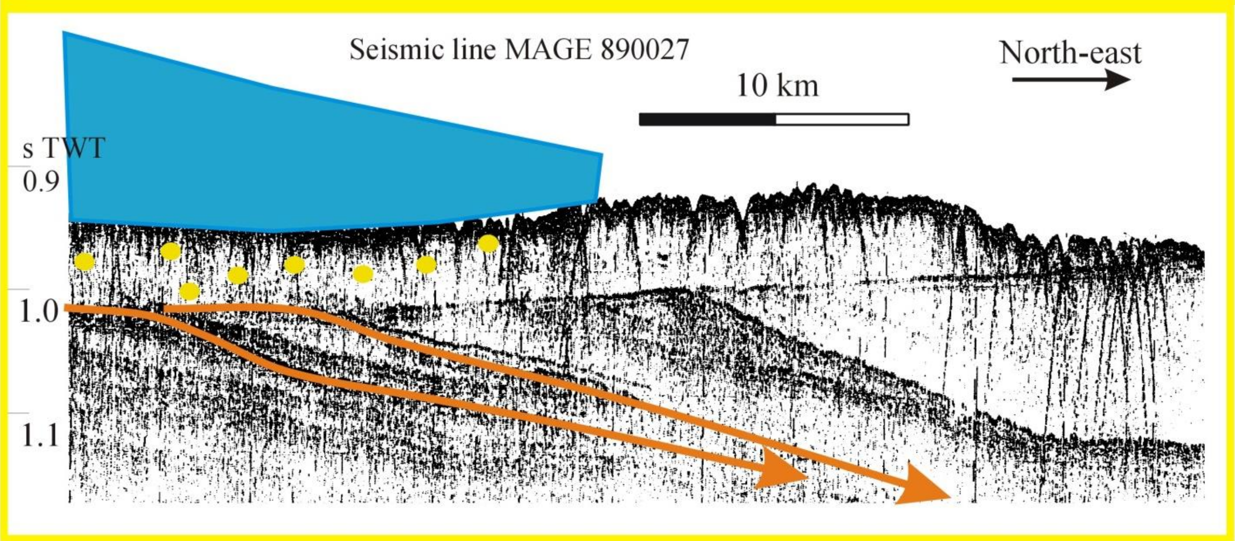
Colleoni et al., 2018

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

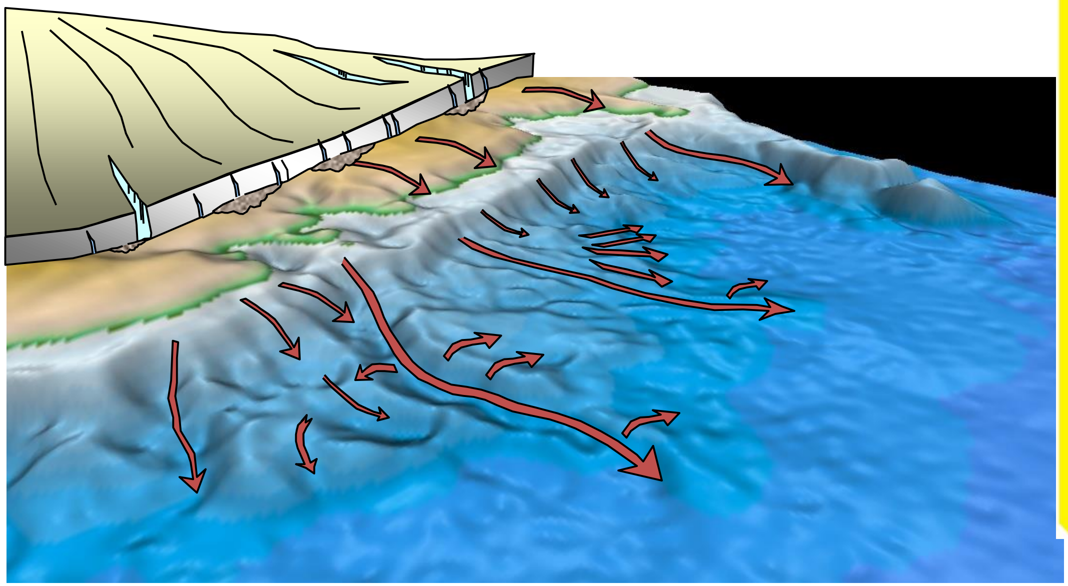
- Reconstruct ice volume change, atmospheric and oceanic temperatures to identify past polar amplification and assess its forcings/feedbacks
- Assess the role of oceanic forcing on WAIS stability/instability

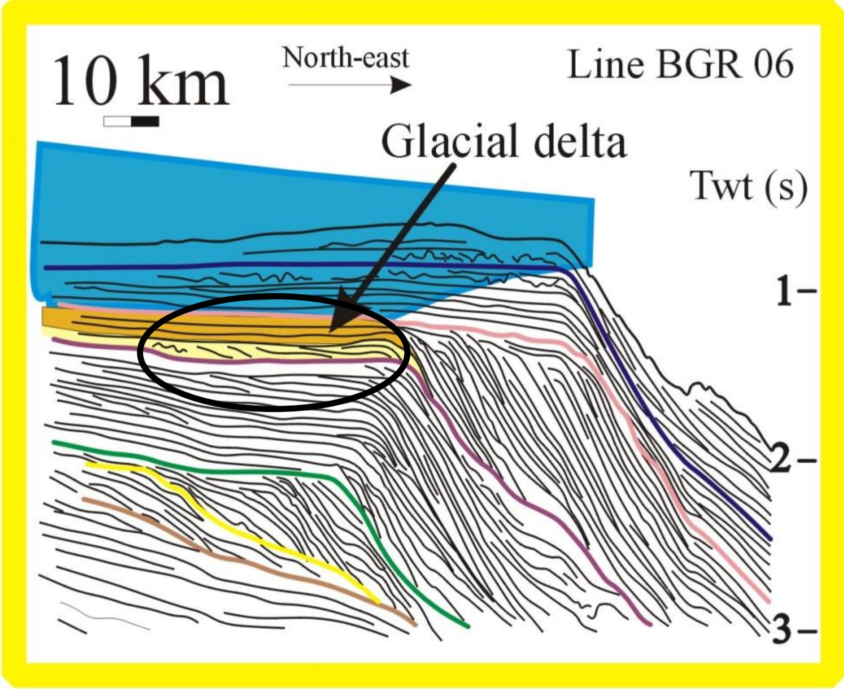


Colleoni et al., 2018



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 glacigenic 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).

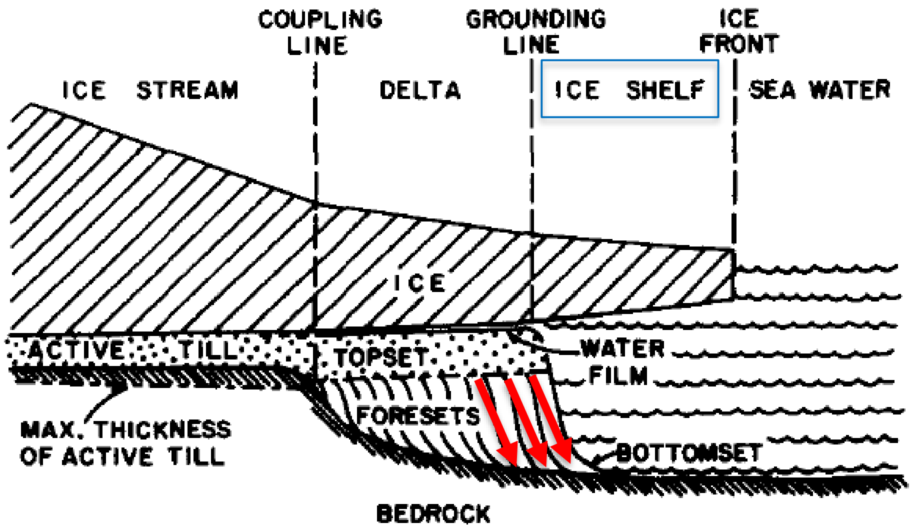
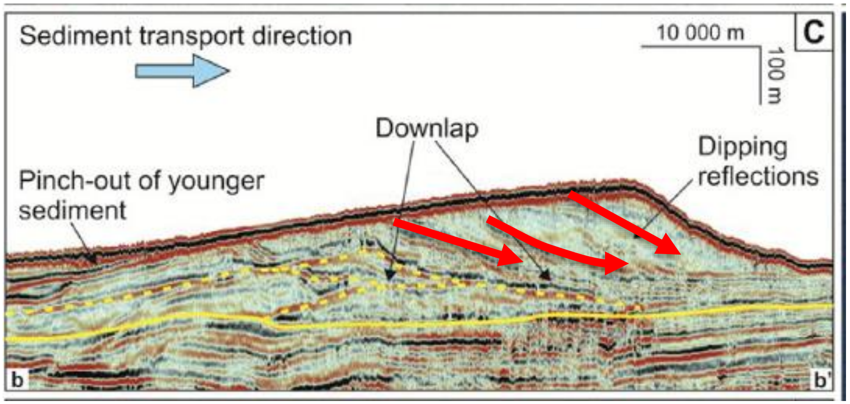
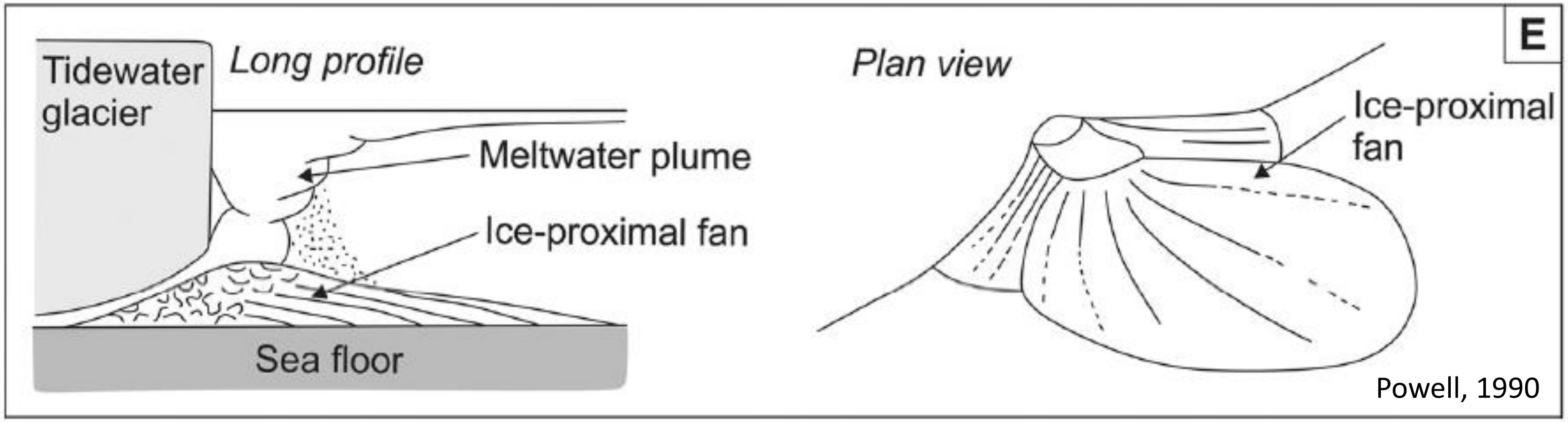


Fig.3. Cartoon of the likely configuration of the ice stream, till delta, and ice shelf.



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.

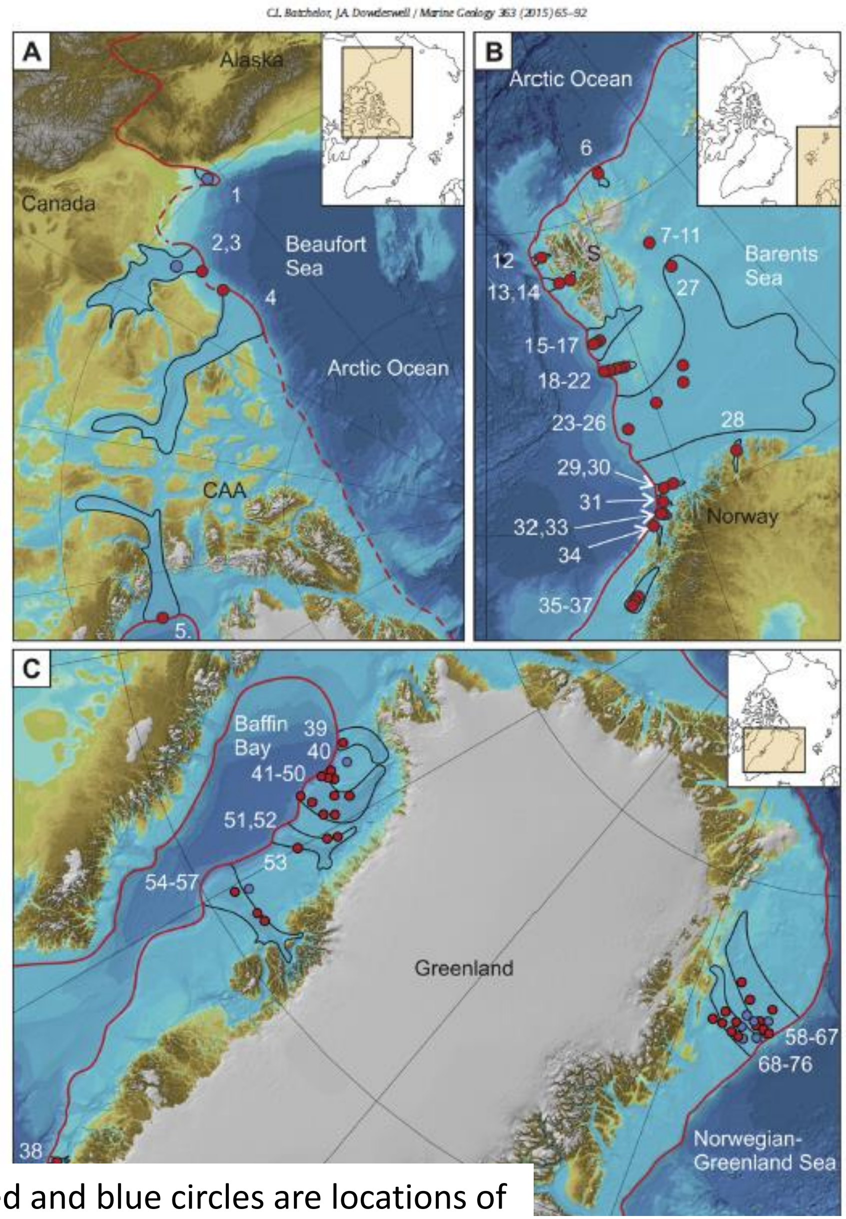
Moraine ridges and ice-proximal fans may also build up at the grounding zone during still-stands of the ice margin, but these require either considerable vertical accommodation space or sediment derived from point-sourced subglacial meltwater streams

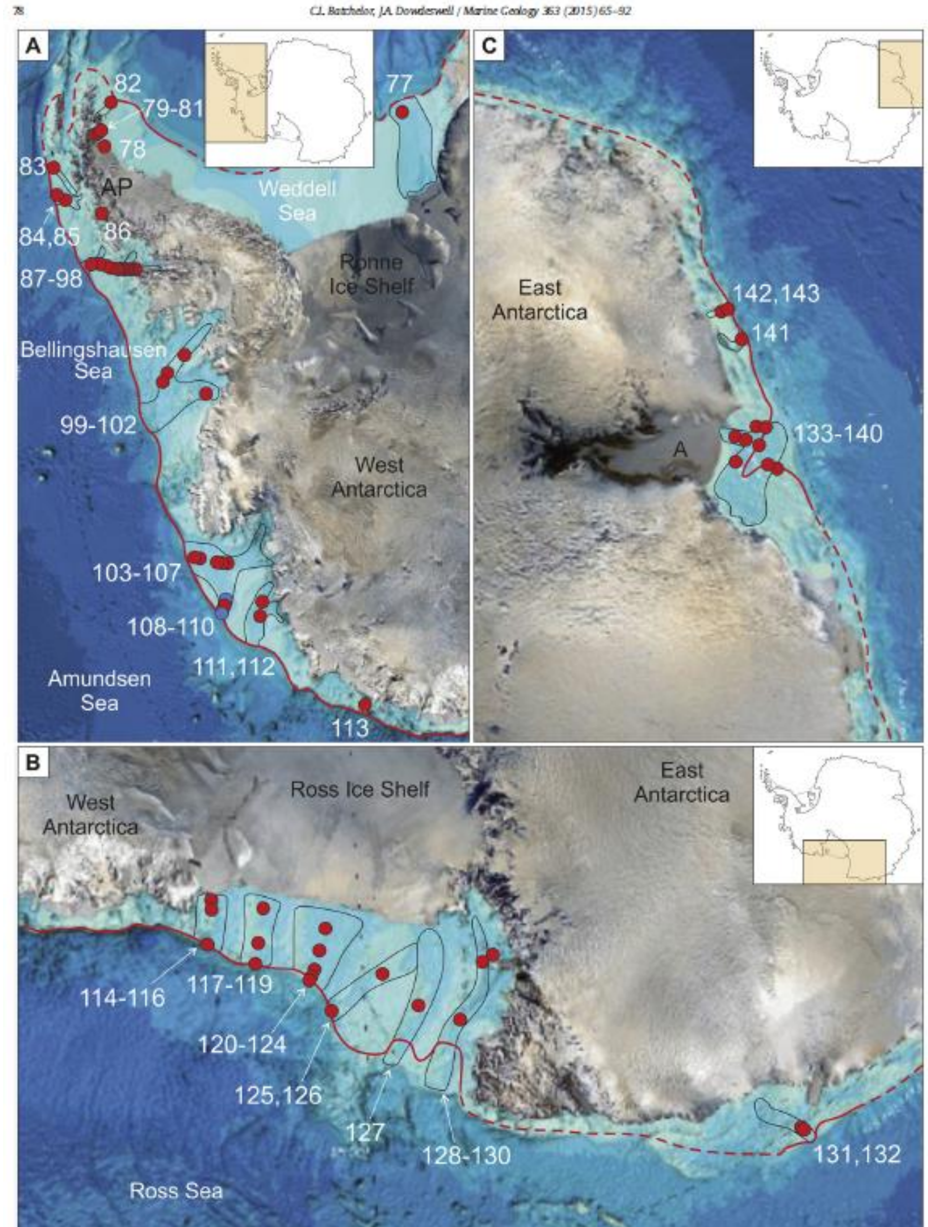


Powell, 1990

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.





Red and blue circles are locations of surface and buried GZWs

Batchelor et al., 2015

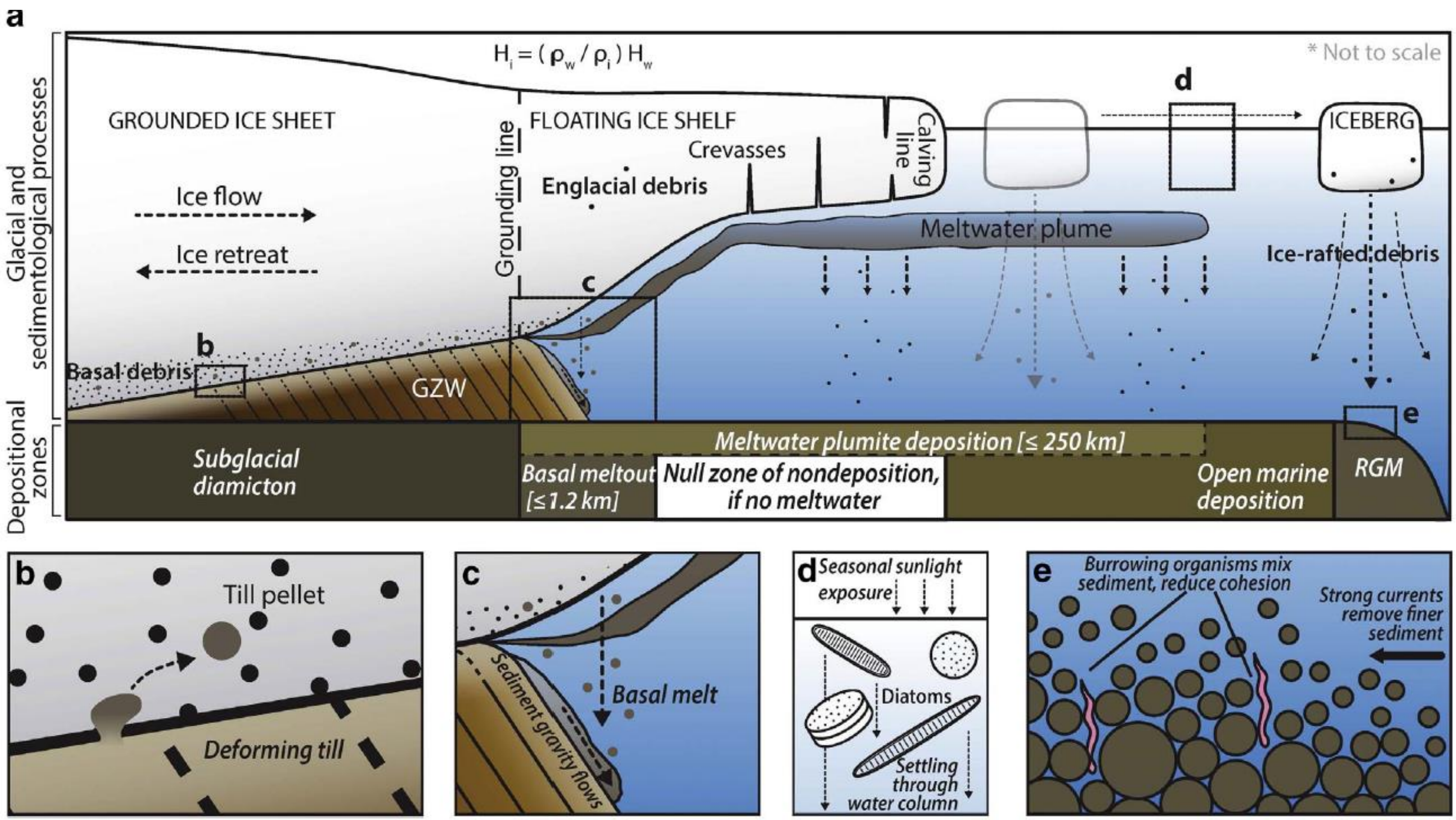
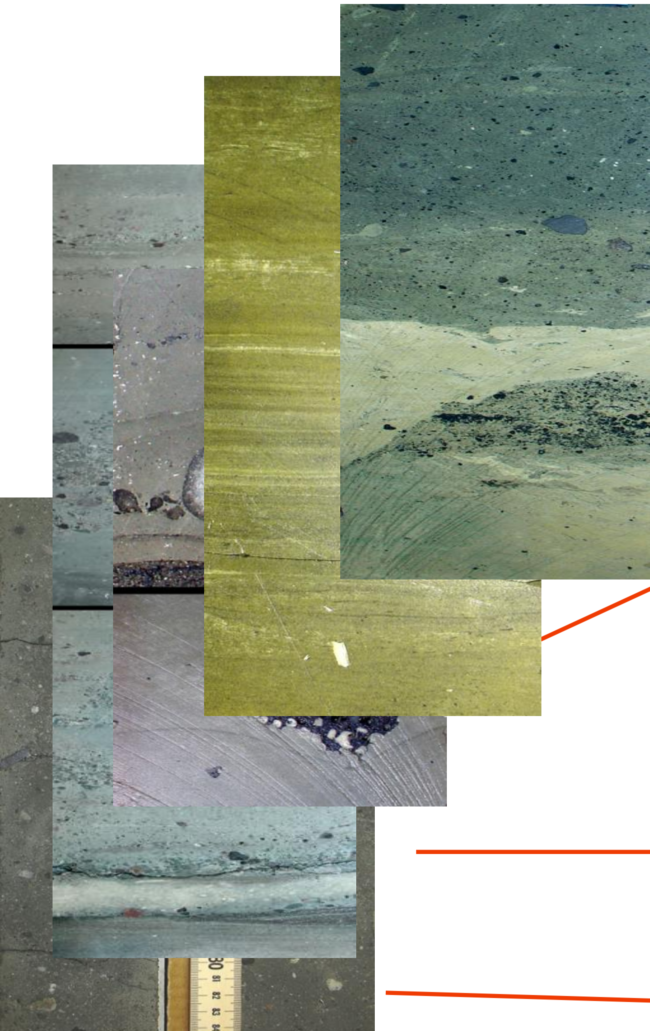


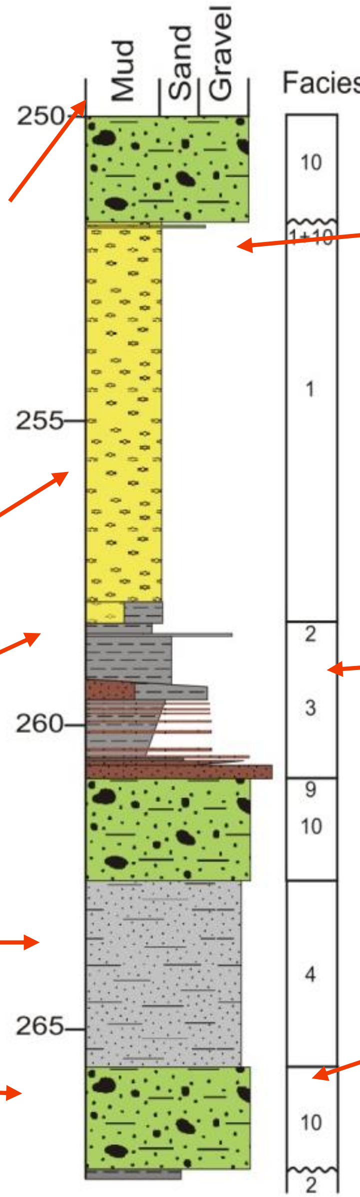
Fig. 2. (a) Conceptual diagram of a grounding-zone wedge (GZW) and proglacial environment, with associated glacial and sedimentary processes. Definitions of terms for buoyancy equation: H_i = ice thickness, Hw = water depth, ρ_i = density of ice (917 kg m^{-3}), ρ_w = density of seawater (~1025 kg m^{-3}—may 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 glacimarine sediments by marine currents on banktops and the shelf margin, facilitated by bioturbation or iceberg turbation.

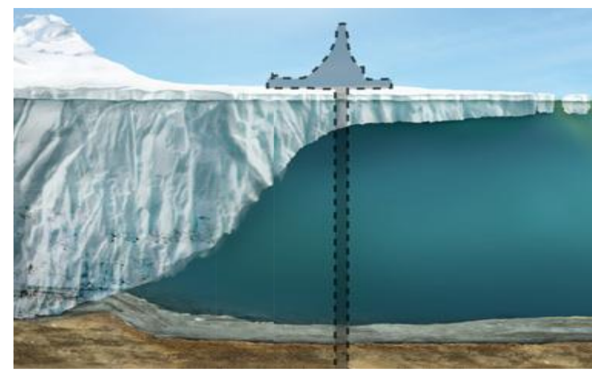
Prothro et al., 2018

Glacial-Interglacial glacimarine cycles

From Mckay et al. 2009 GSA Bull.

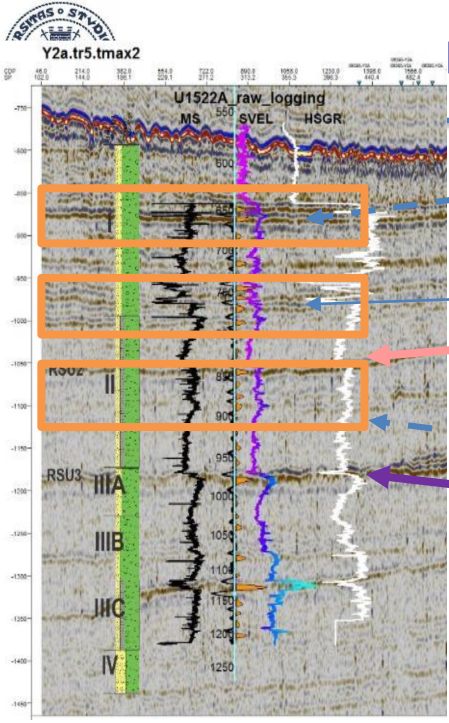


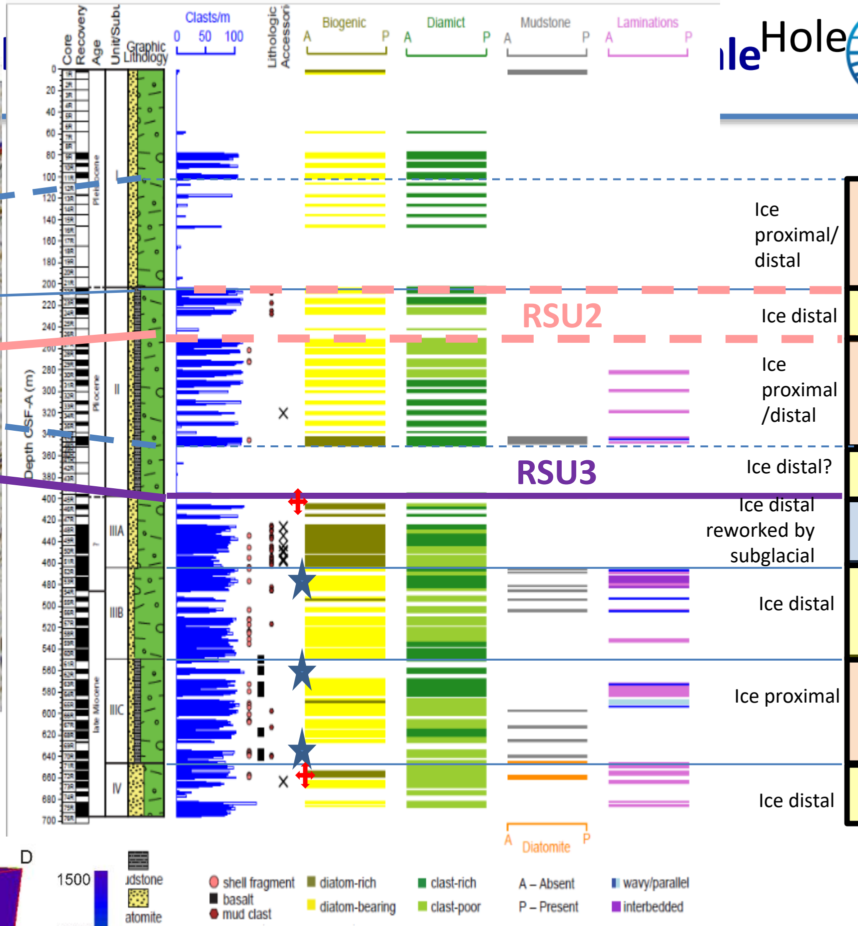


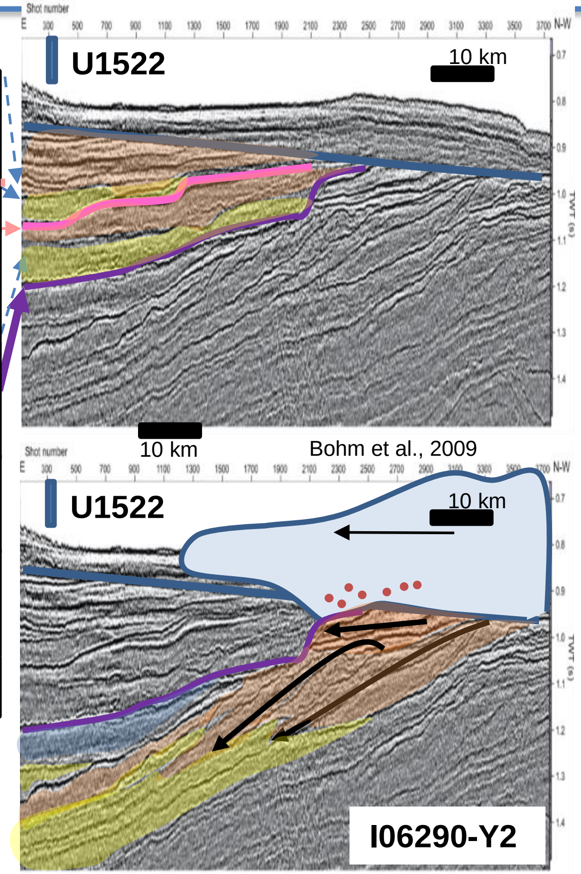


Hole U1522

Istituto Nazionale di Oceanografia e di Geofisica Sperimentale







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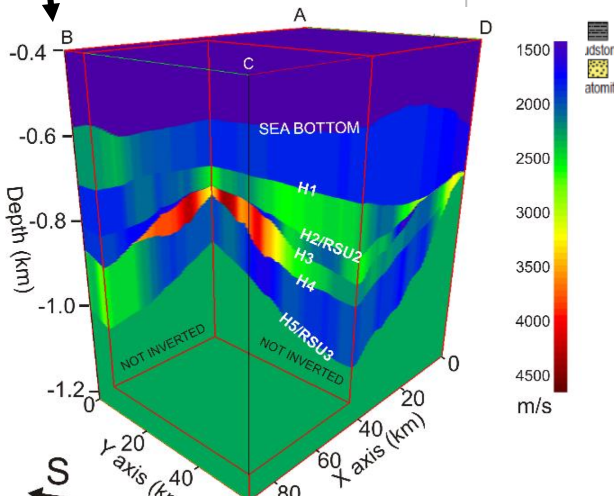
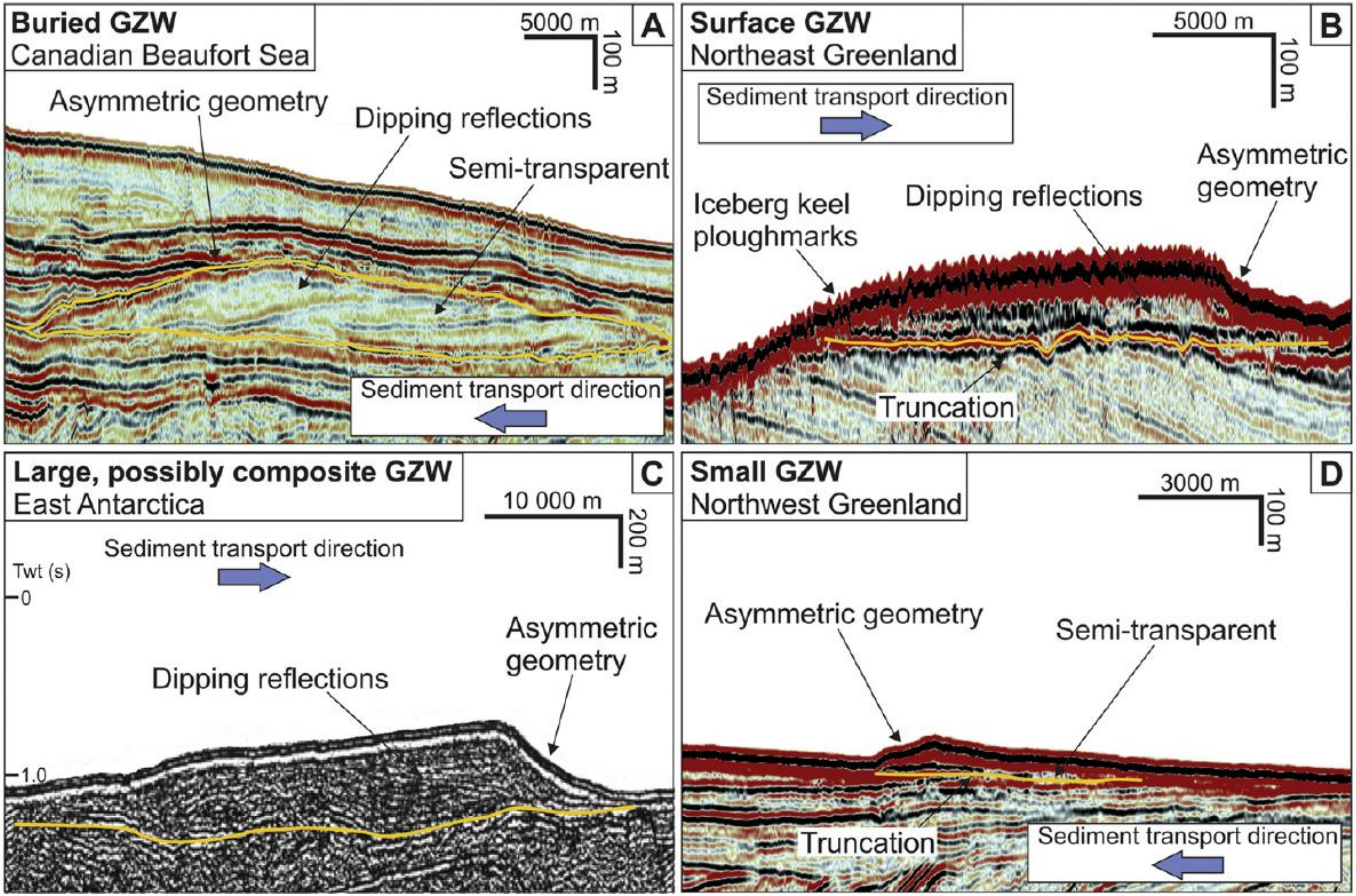


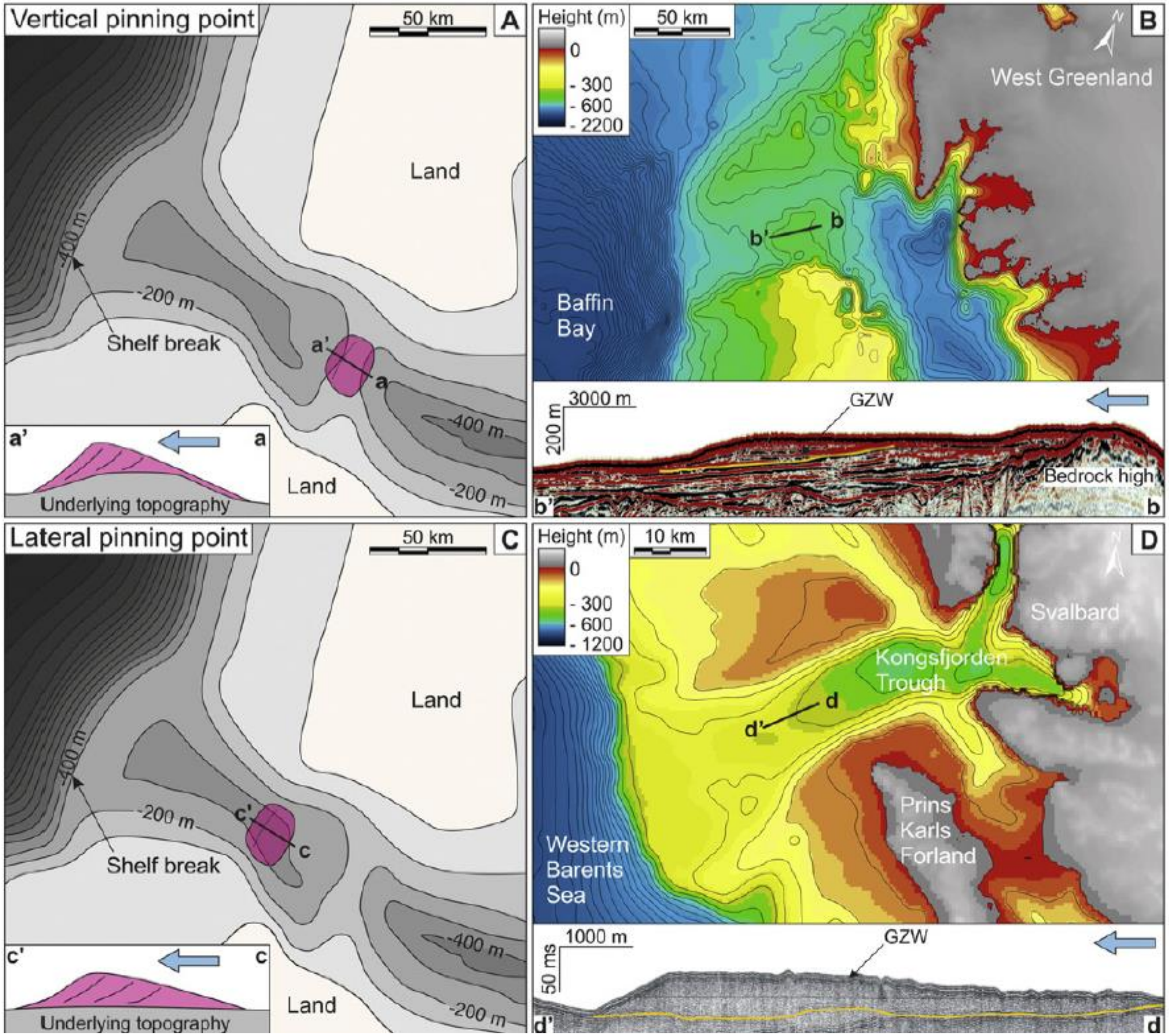
Boehm et al., 2009

INTERNATIONAL OCEAN DISCOVERY PROGRAM

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



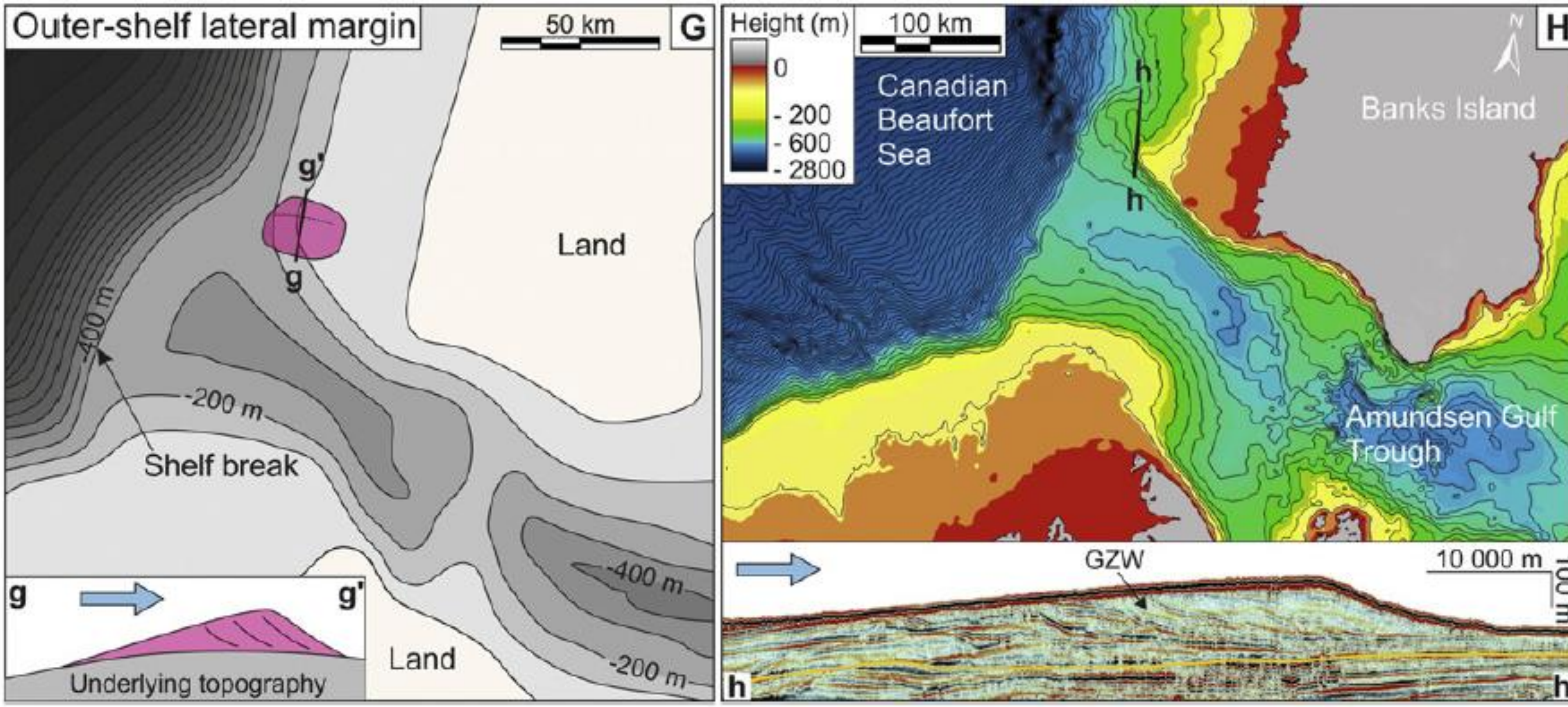
C.L. Batchelor, J.A. Dowdeswell / Marine Geology 363 (2015) 65–92



Bedrock outcrops on the seafloor can act as vertical pinning points

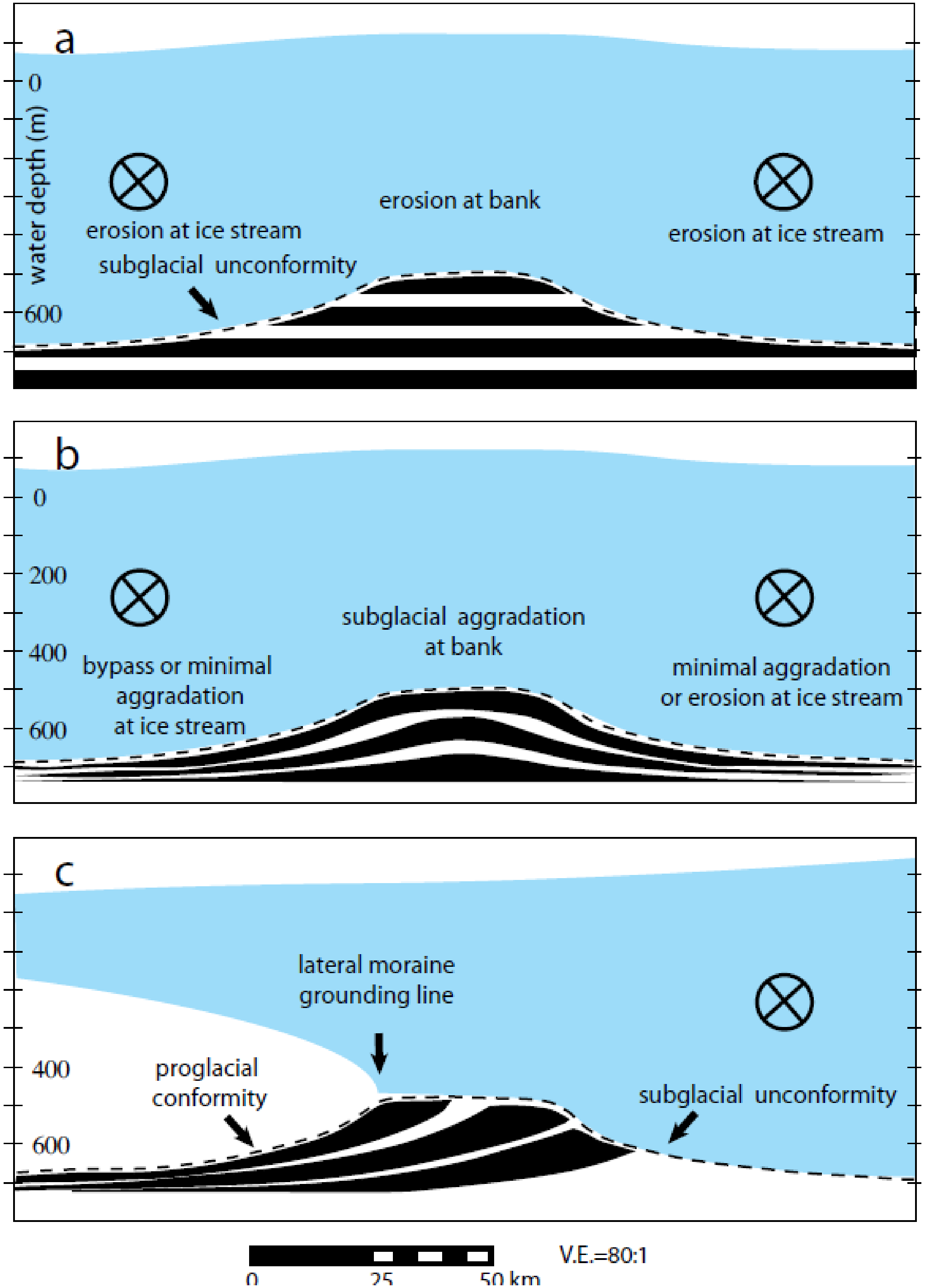
sediment aggradation within water-filled cavities below ice shelves may provide a mechanism **for ice-sheet stabilisation**

The lateral GZWs may represent the boundary between fast, icestreaming flow in the troughs and slower, cold-based ice on the adjacent shelf.



Batchelor et al., 2015

Paleotrough/sedimentary Bank



Conceptual models of erosion/deposition in strike-oriented view below grounded ice sheet on the outer shelf.

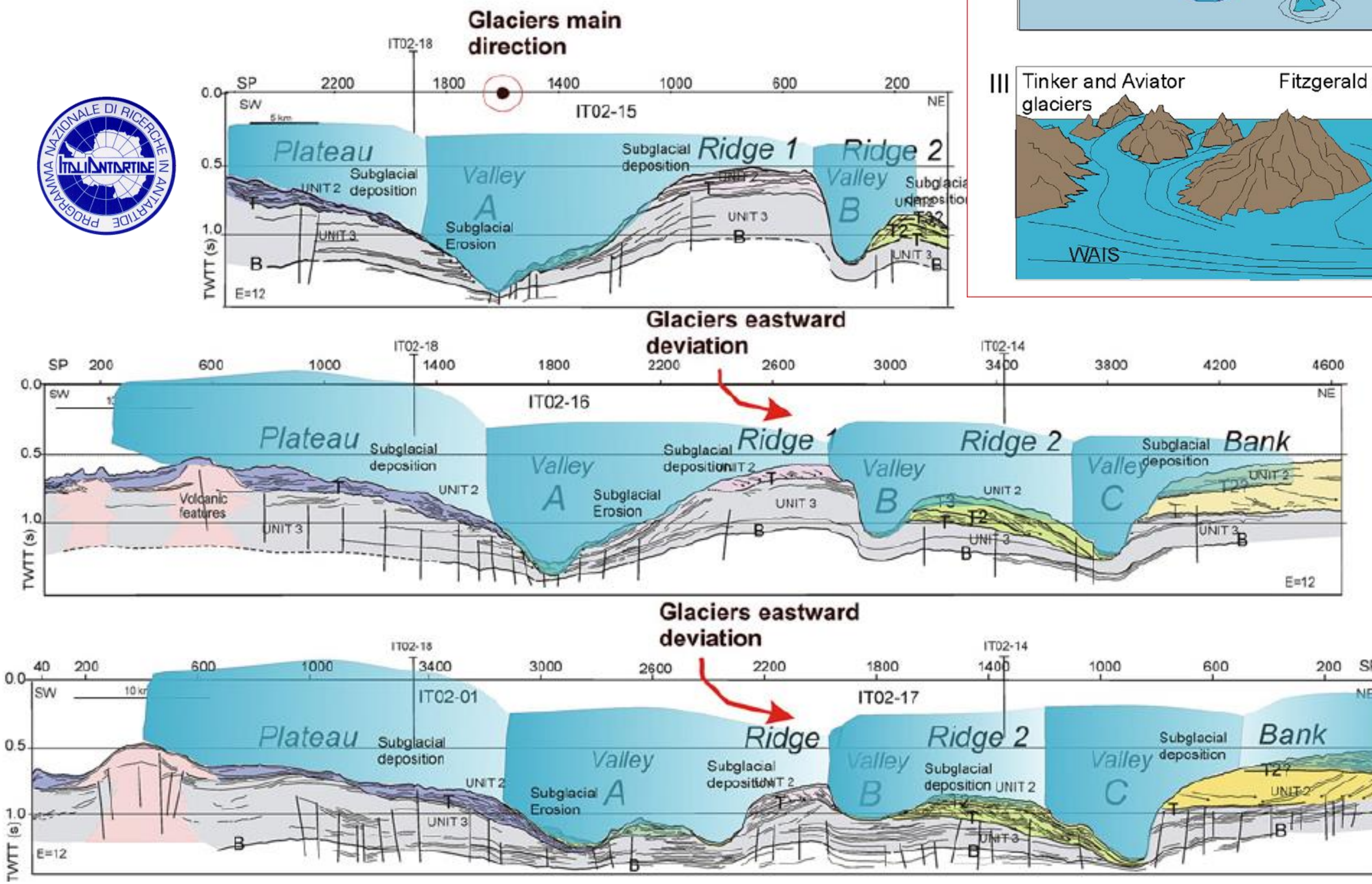
(a) Ice streams erode deep basins into the underlying strata whereas erosion between ice streams is minimal.

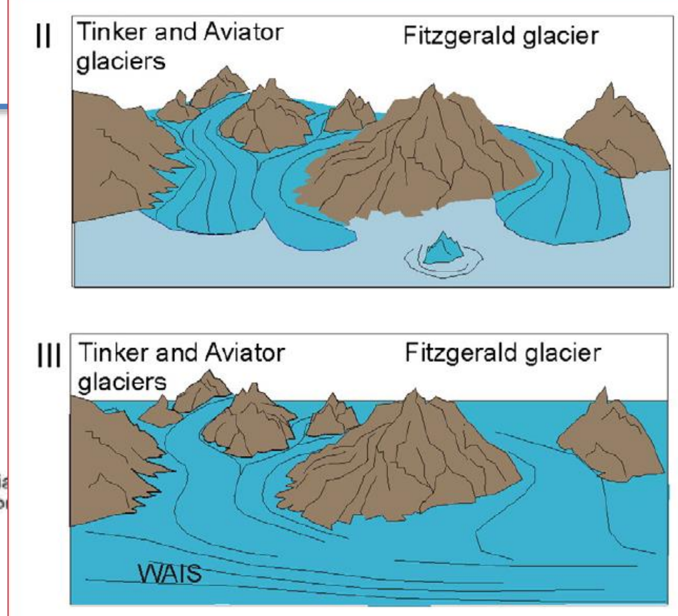
(b) Subglacial aggradation of sediment where ice flow is slowest between ice streams constructs a bank.

(c) Lateral accretion of till delta foresets into open water from a tongue of grounded ice.

Bart and De Santis 2012

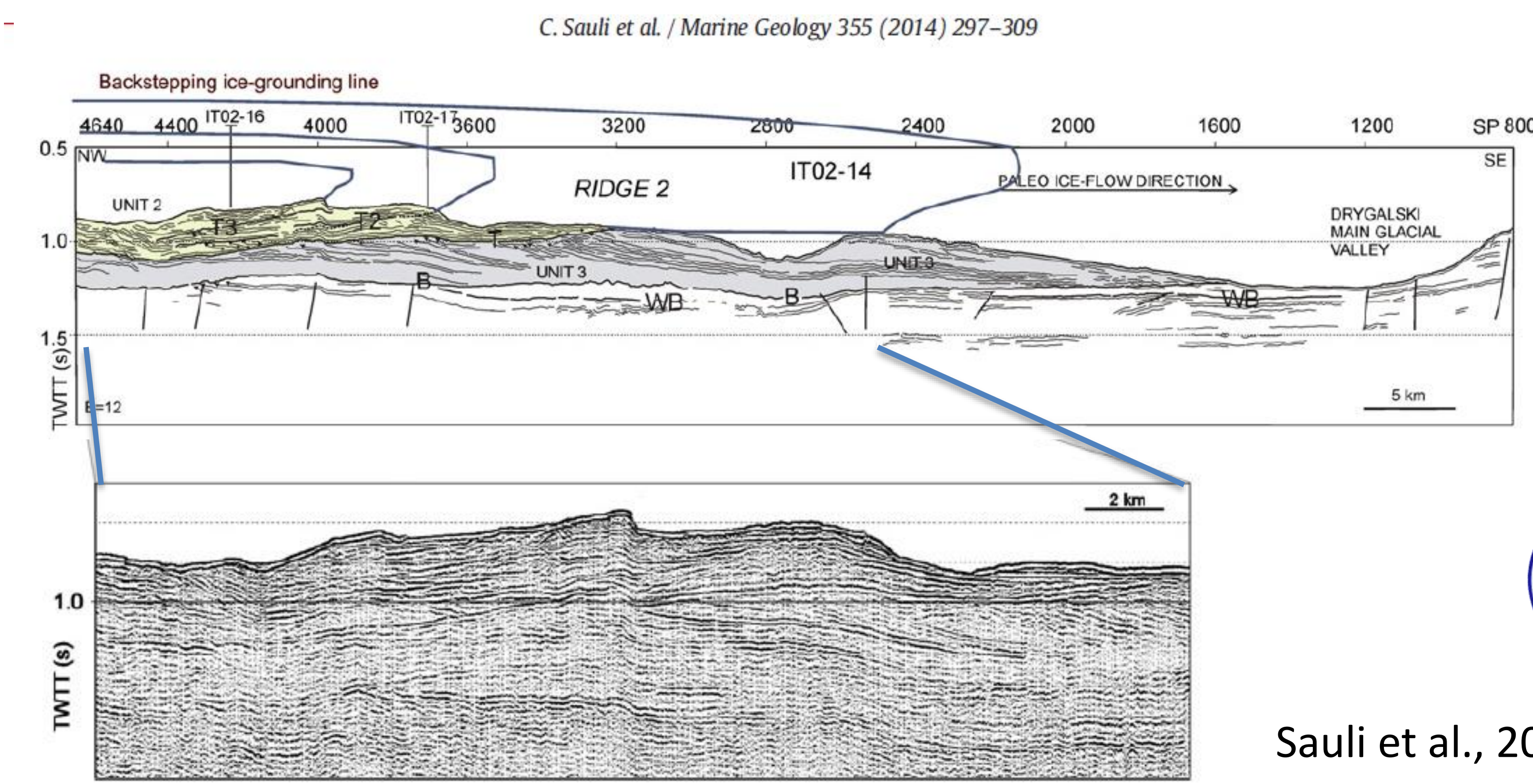
Sauli et al., 2014



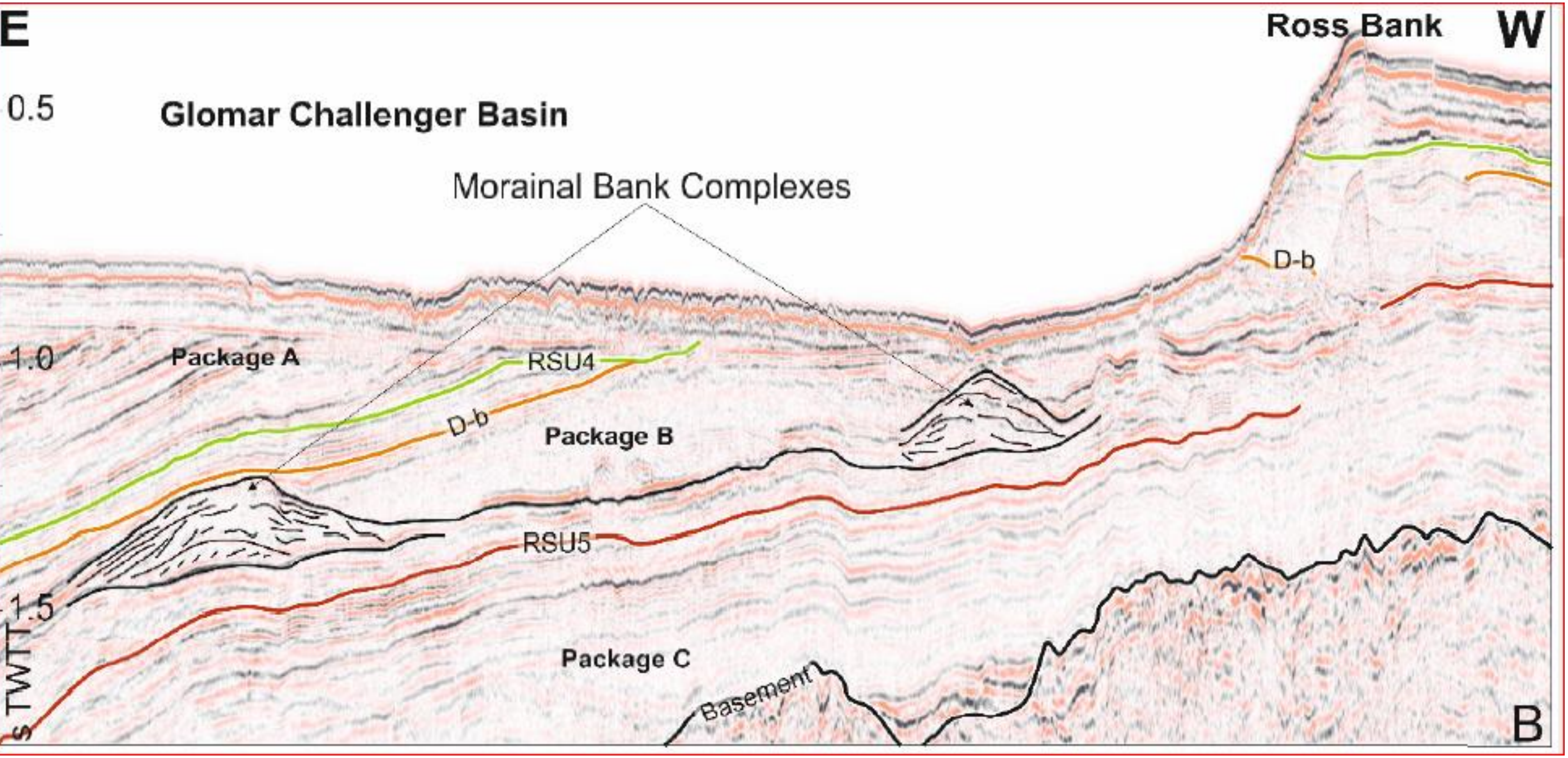


Moraines are typically composed of various unsorted ice-contact sediments and therefore possess a semitransparent to chaotic character on acoustic profiles.

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



Sauli et al., 2014


E
Ross Bank
W
0.5
Glomar Challenger Basin
Morainal Bank Complexes
D-b
1.0
Package A
RSU4
D-b
Package B
RSU5
1.5
s TWT
Package C
Basement
B

Oligocene development of the West Antarctic Ice Sheet recorded in eastern Ross Sea strata

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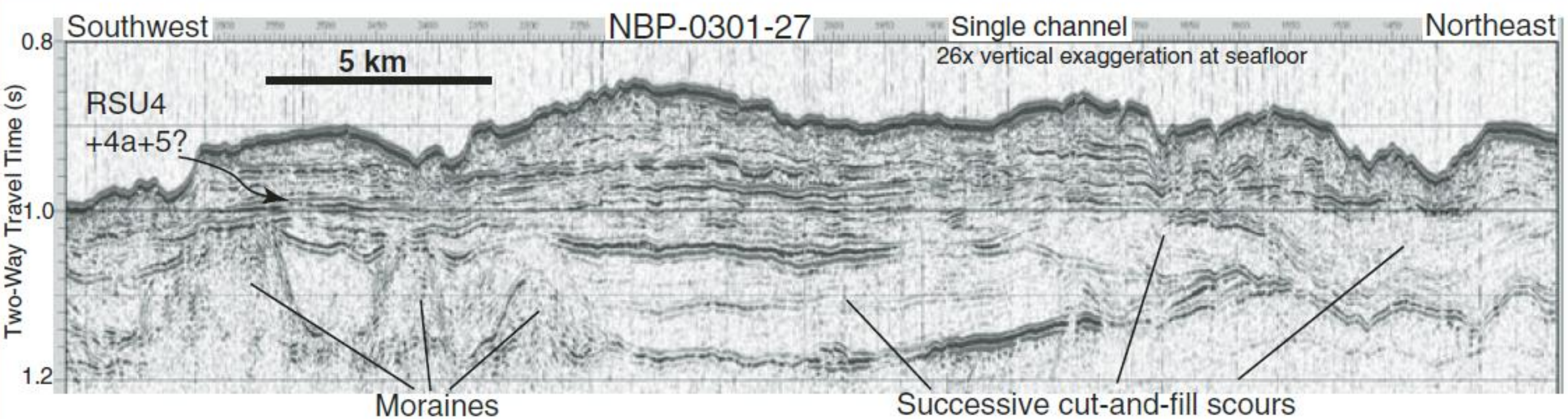
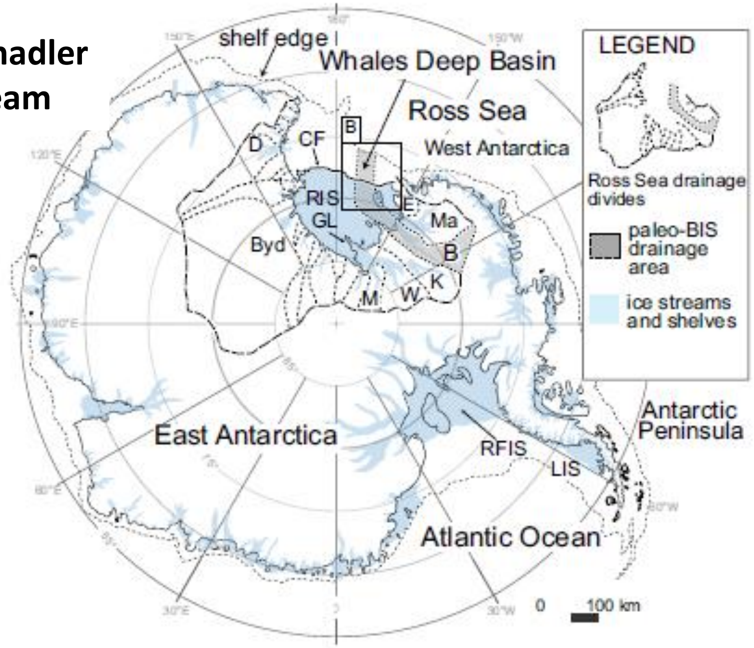
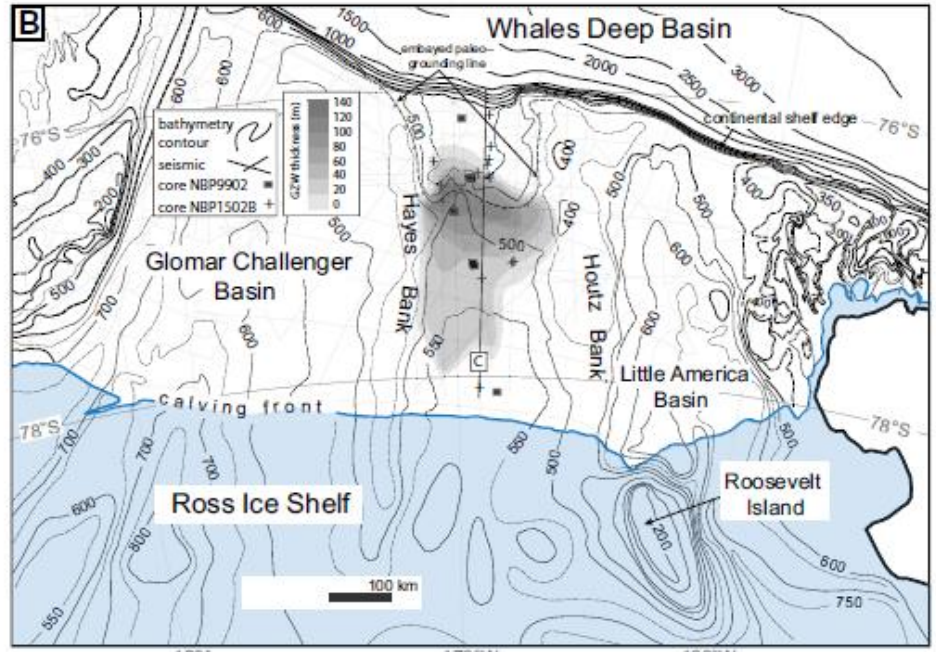
Bruce P. Luyendyk
Douglas S. Wilson
Robert C. Decesari* Department of Earth Science, University of California–Santa Barbara, Santa Barbara, California 93106, USA
Louis R. Bartek Department of Geological Sciences, CB 3315, University of North Carolina, Chapel Hill, North Carolina 27599-3315, USA
John B. Diebold Lamont-Doherty Earth Observatory, Columbia University, 61 Route 9W, Palisades, New York 10964-8000, USA



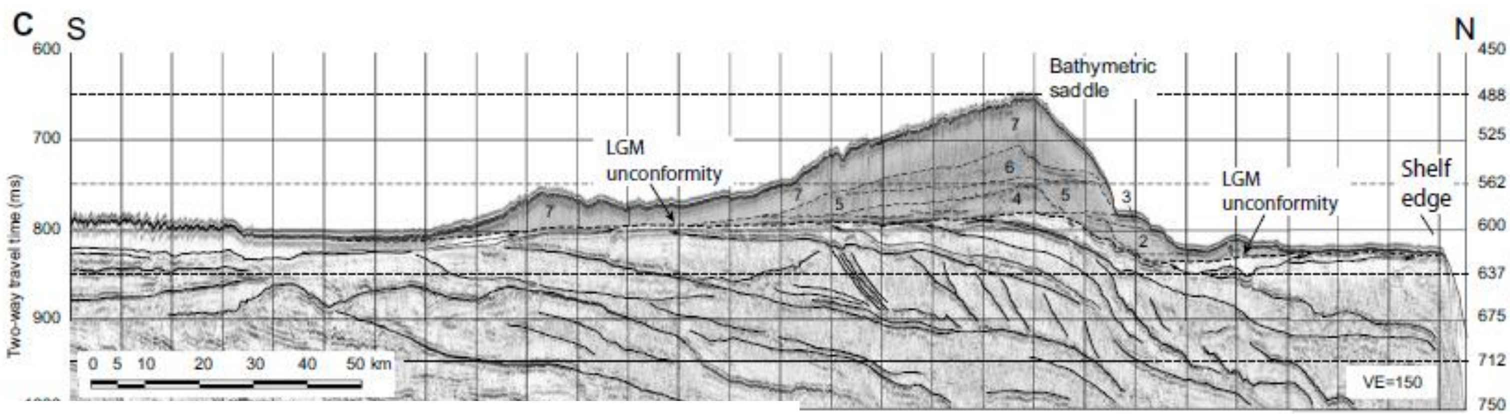
Geology 2007

paleo–Bindschadler Ice Stream



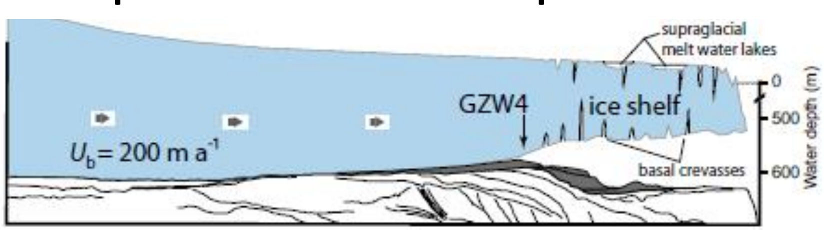


Most of GZW deposited in only 800 ± 300 years after the breakup of the fringing ice shelf

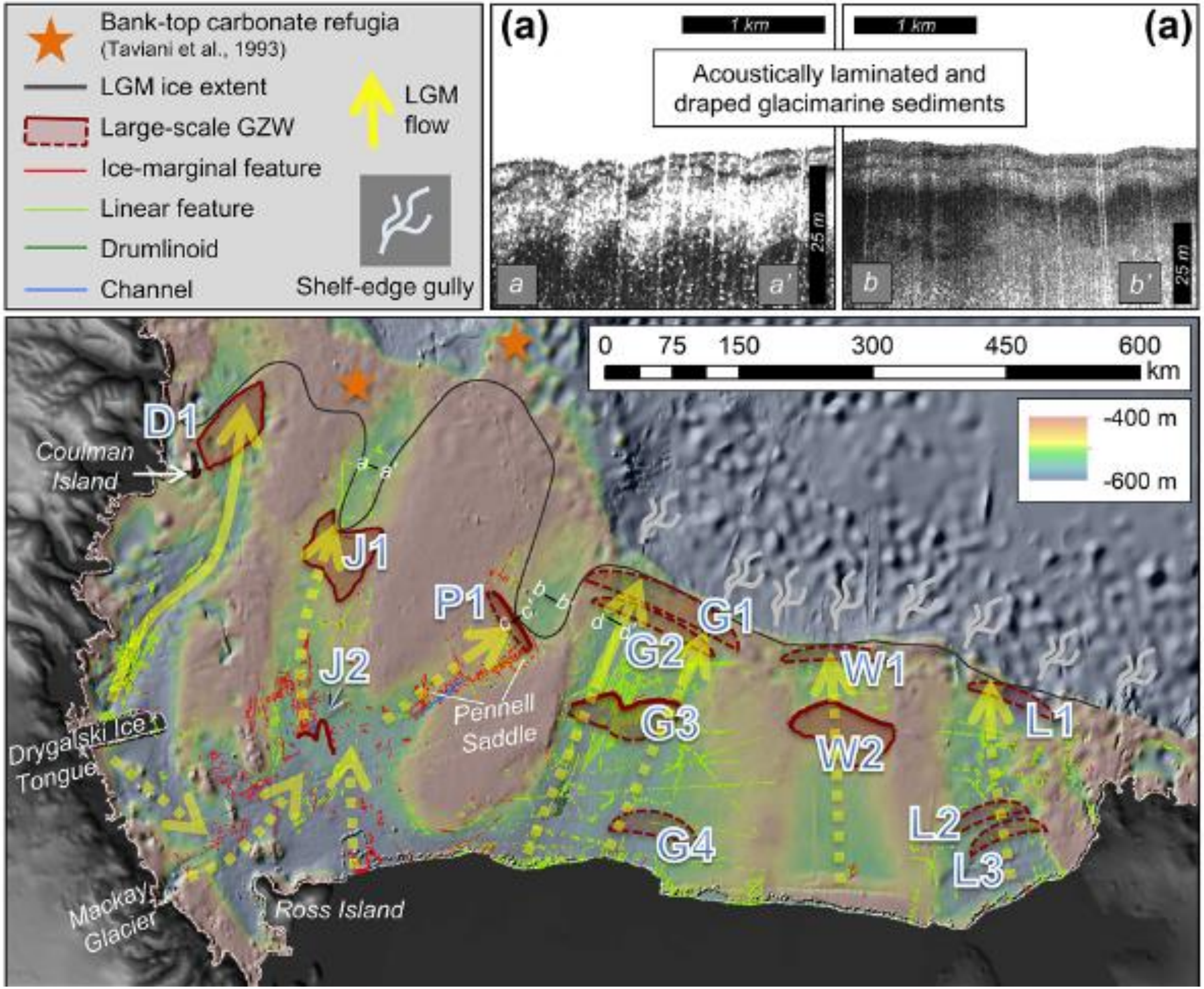


Bart, Tulaczyk, 2020

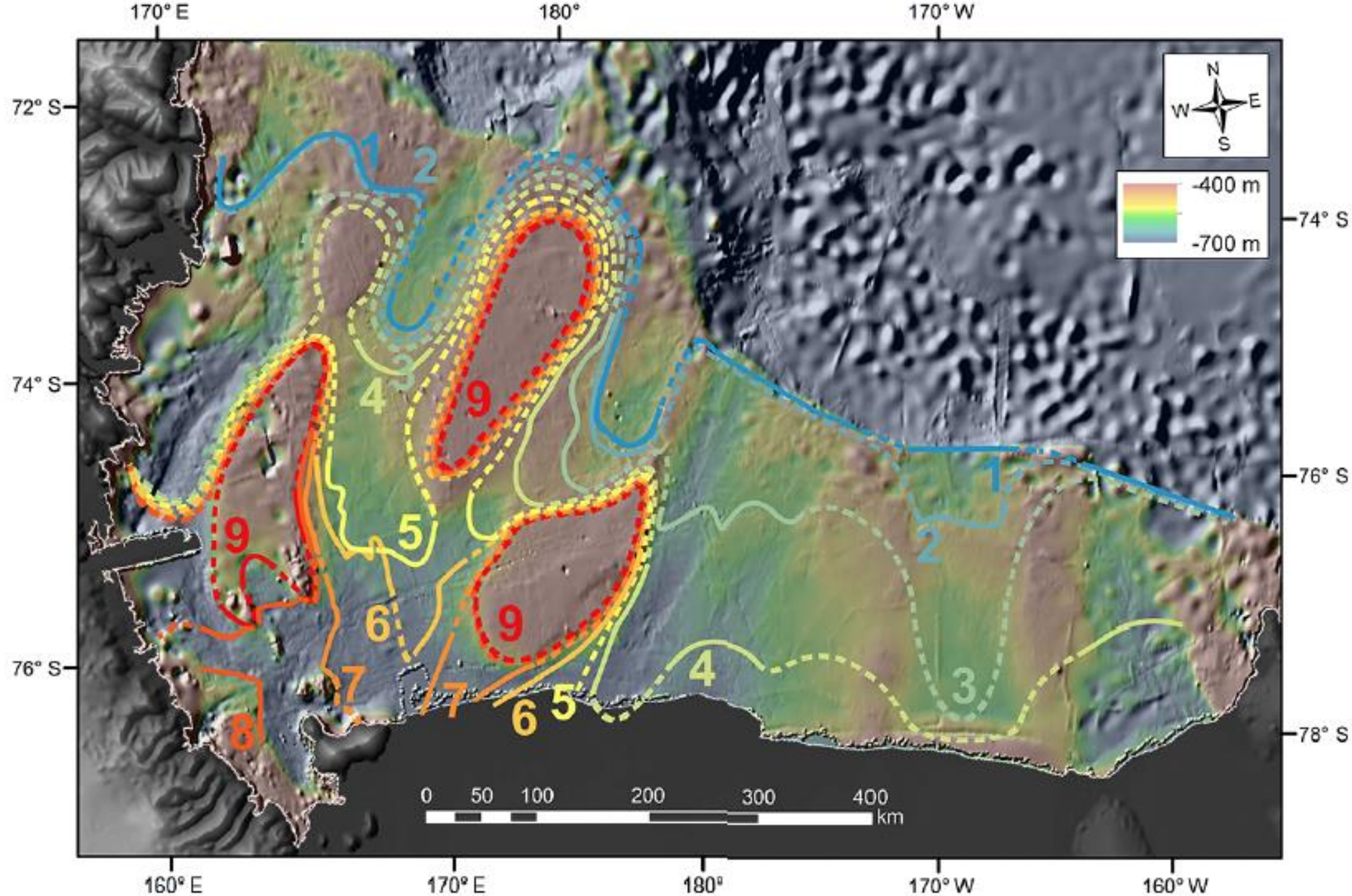
GZW4 prior to ice-shelf breakup 14.7-12.3 Ka



GZW7 after to ice-shelf breakup 12.3-11.5 Ka



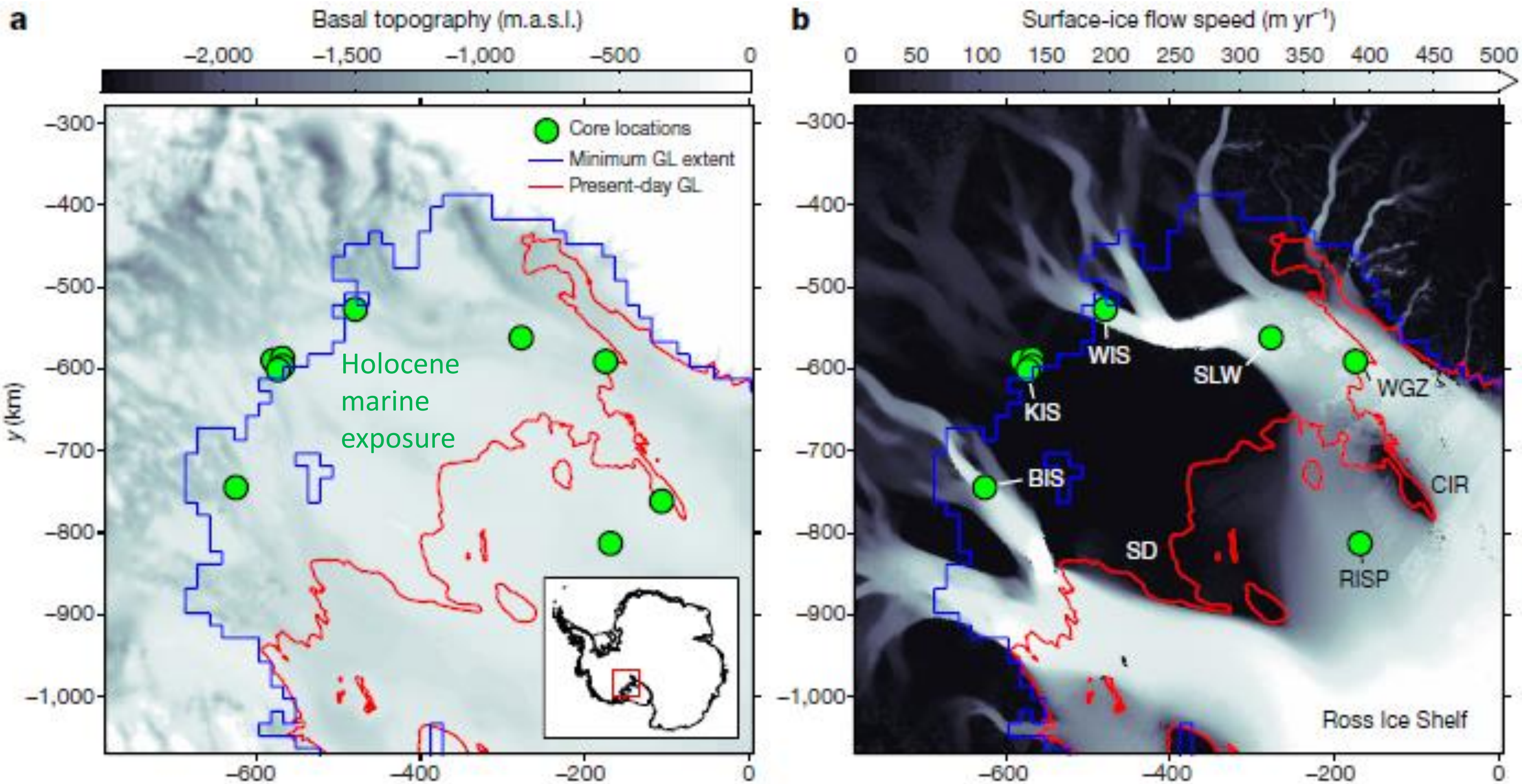
Halberstadt et al., 2016



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.

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

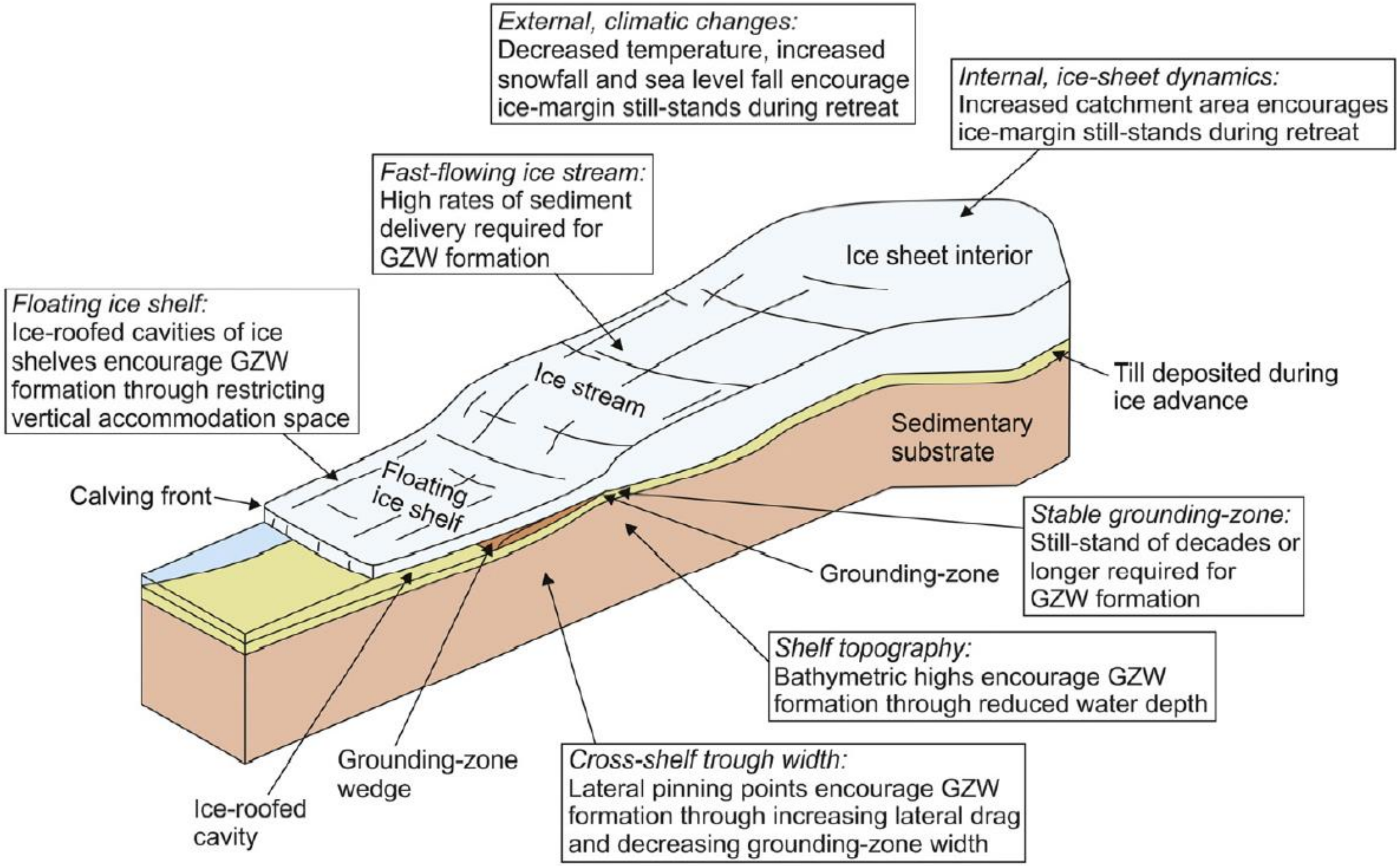
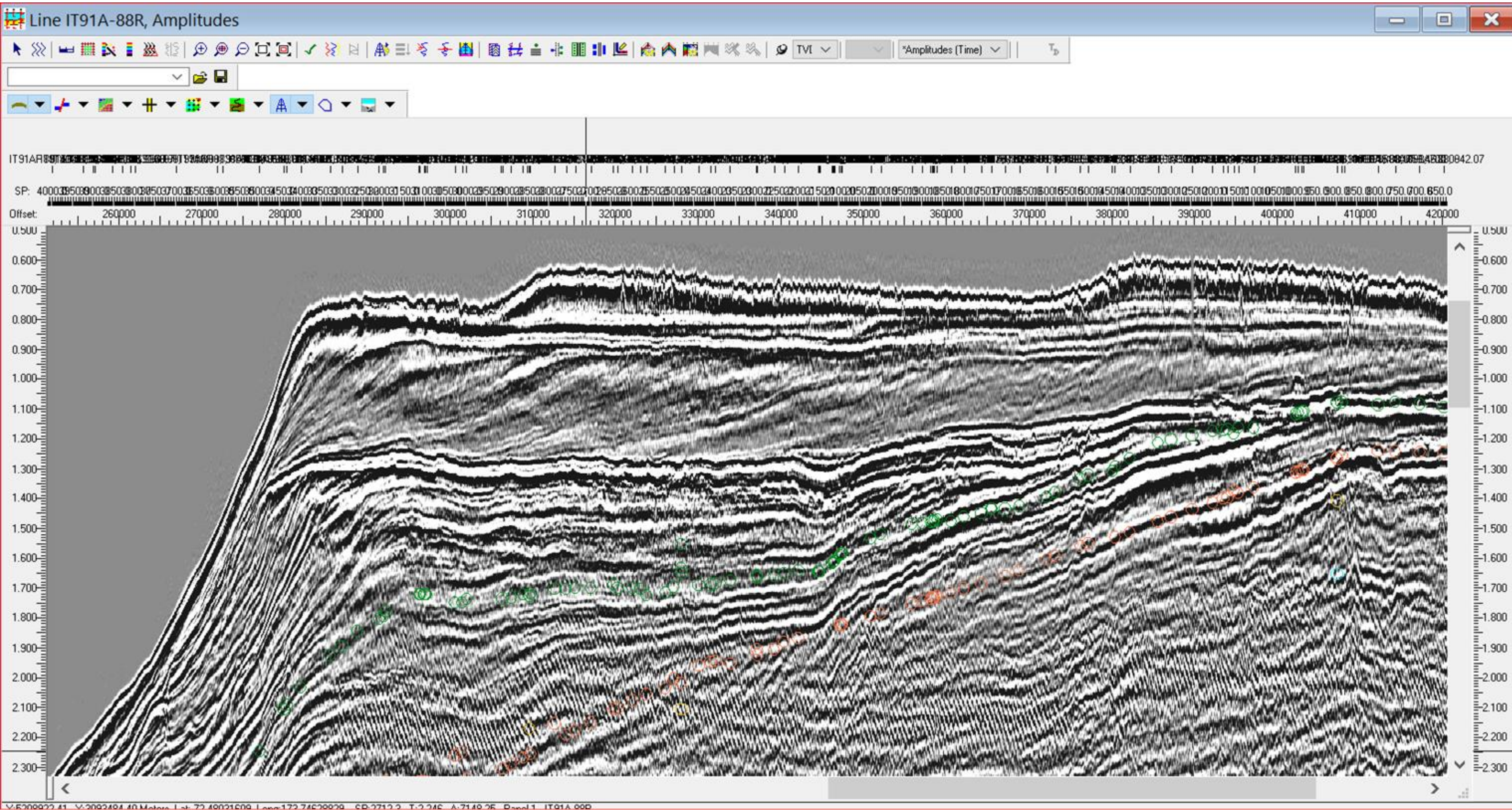


Fig. 11. Diagram illustrating the factors controlling the formation of GZWs on high-latitude continental margins.

Batchelor et al., 2015

EXERCIZE


Line IT91A-88R, Amplitudes
TVI
*Amplitudes (Time)
SP:
Offset:
260000
270000
280000
290000
300000
310000
320000
330000
340000
350000
360000
370000
380000
390000
400000
410000
420000
0.500
0.600
0.700
0.800
0.900
1.000
1.100
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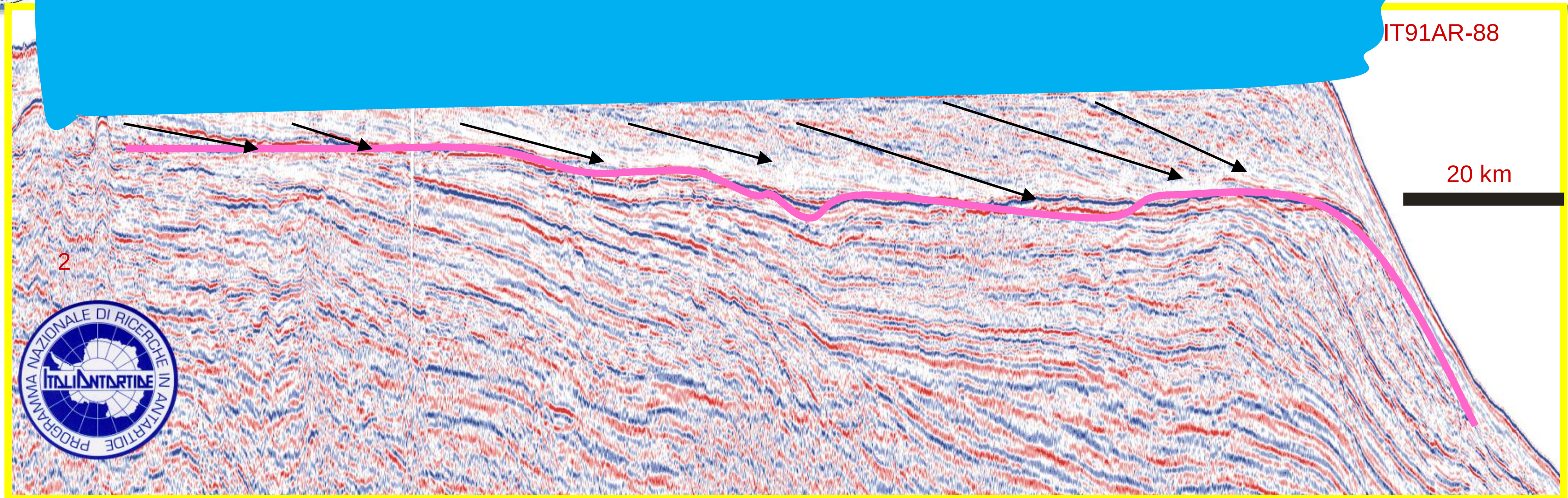
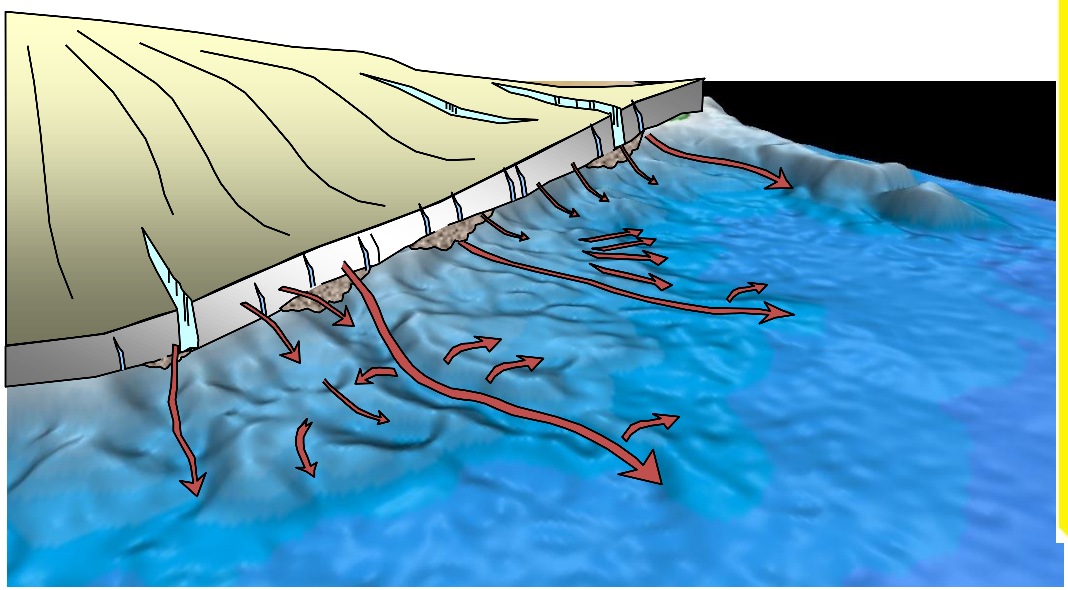
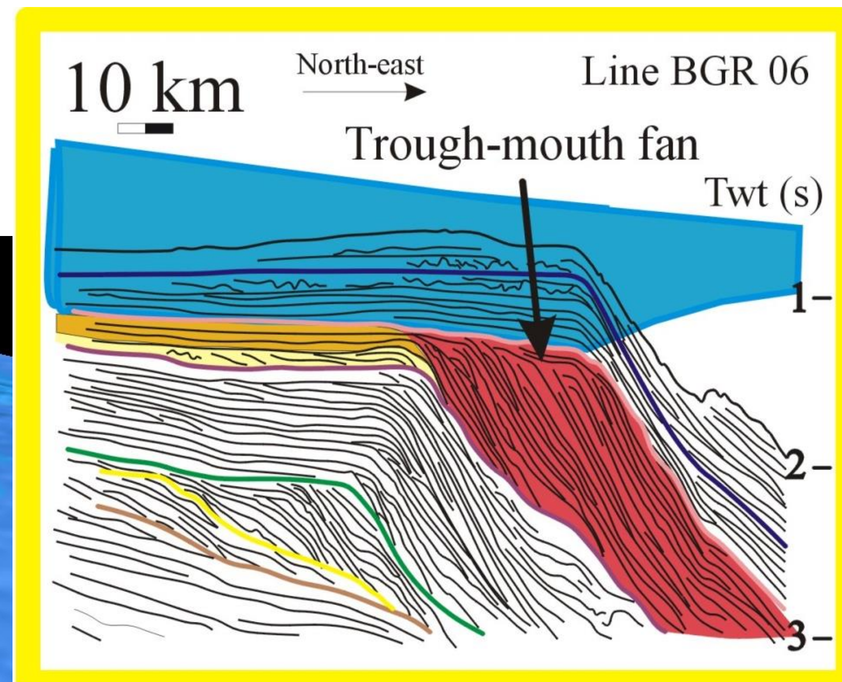
2.200
2.300



Sauli et al., 2014 (modified)

GZWs are only observed within cross-shelf troughs





L.O. Prothro et al.

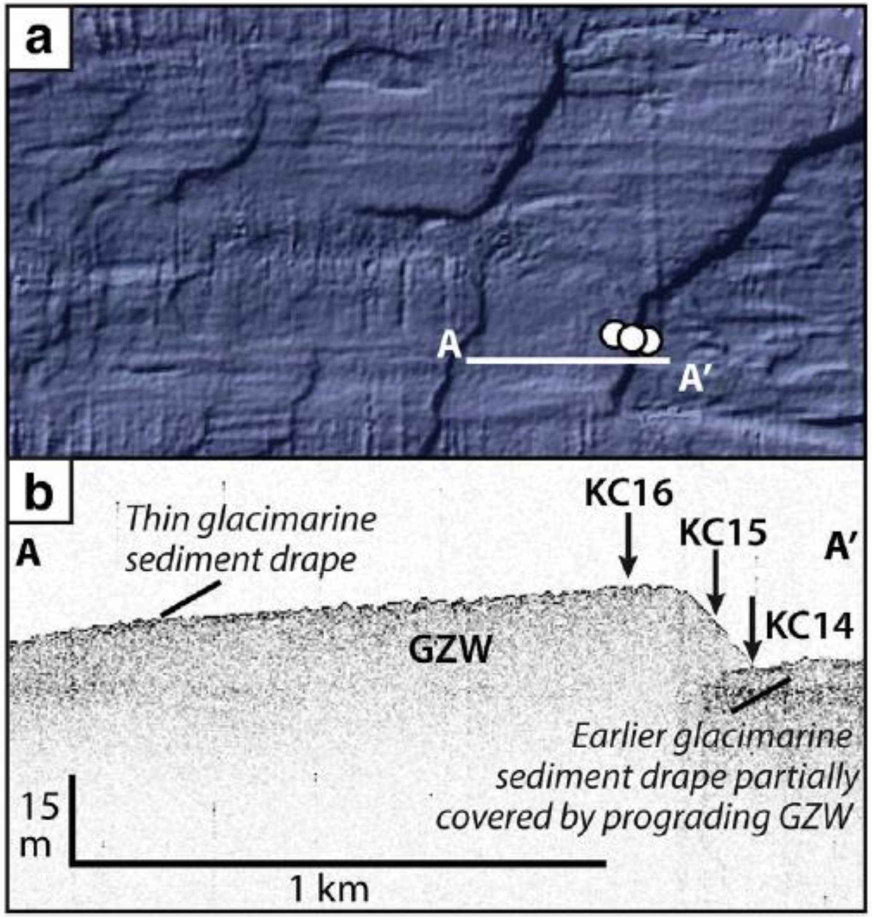
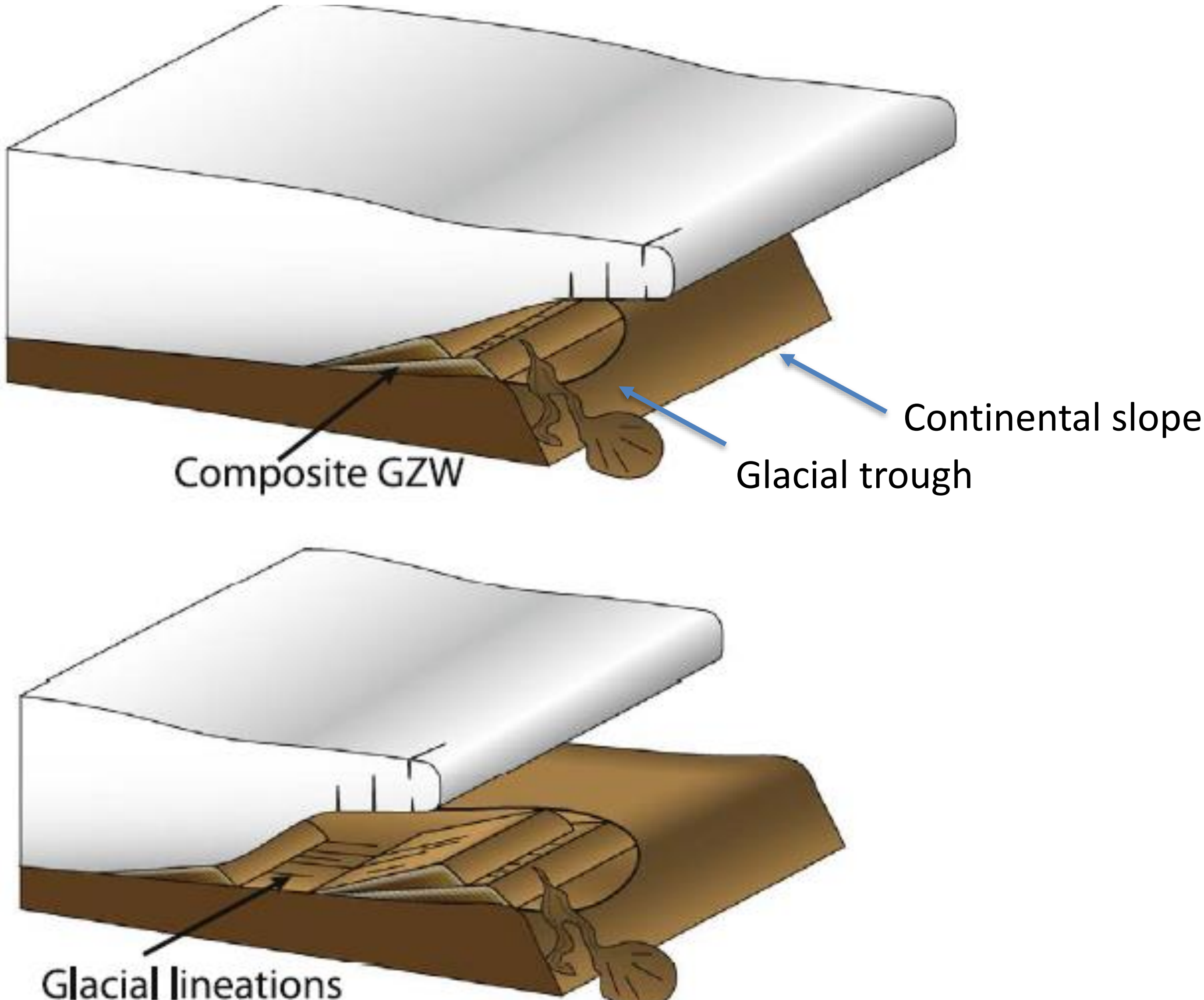


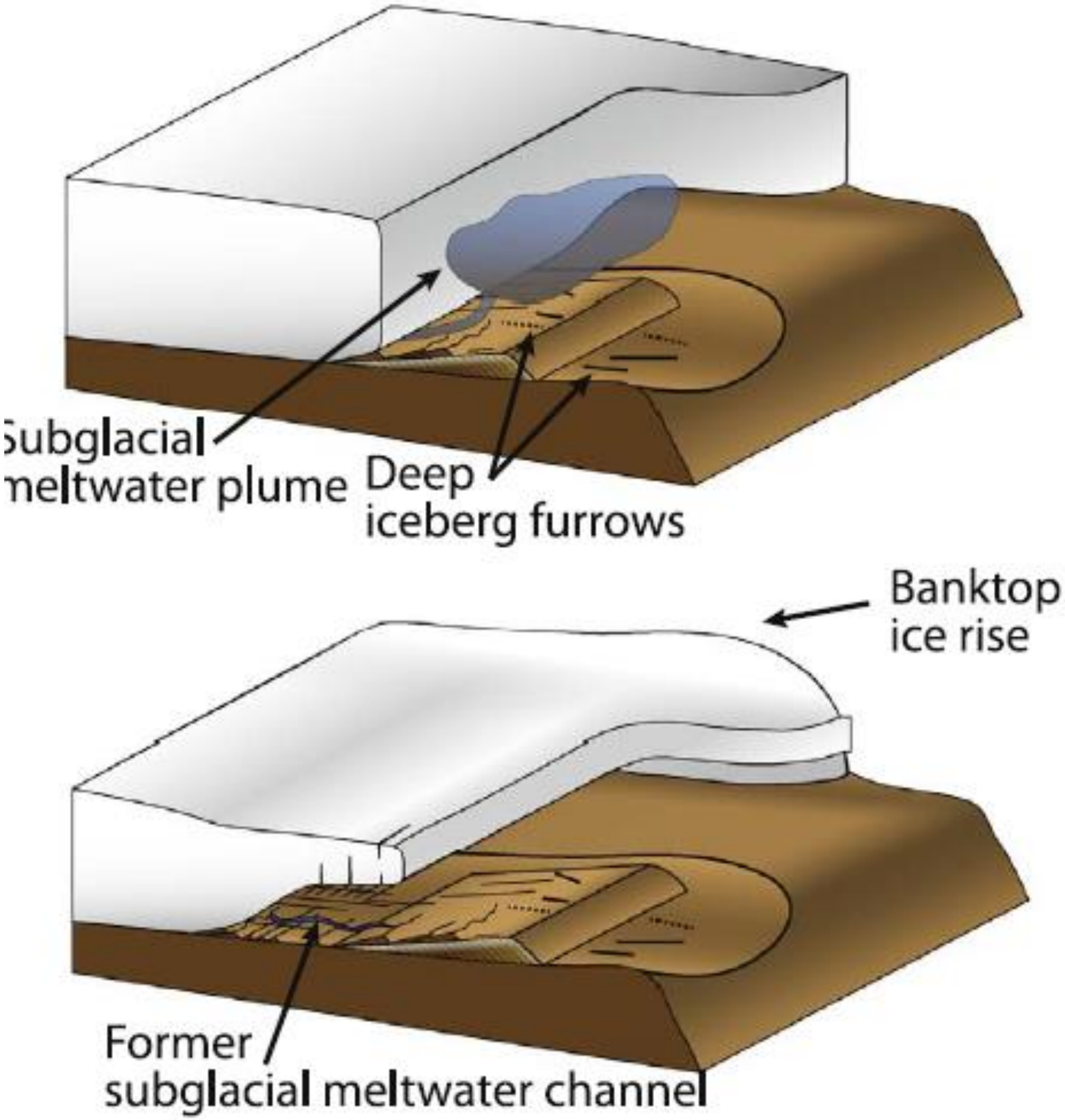
Fig. 3. Example of coring transect demonstrating targeted coring along a grounding-zone wedge using both (a) multibeam swath bathymetry and (b) CHIRP data. Core locations are shown in multibeam context in Fig. 3a, seismic context in Fig. 3b, and regional context in Fig. 1.

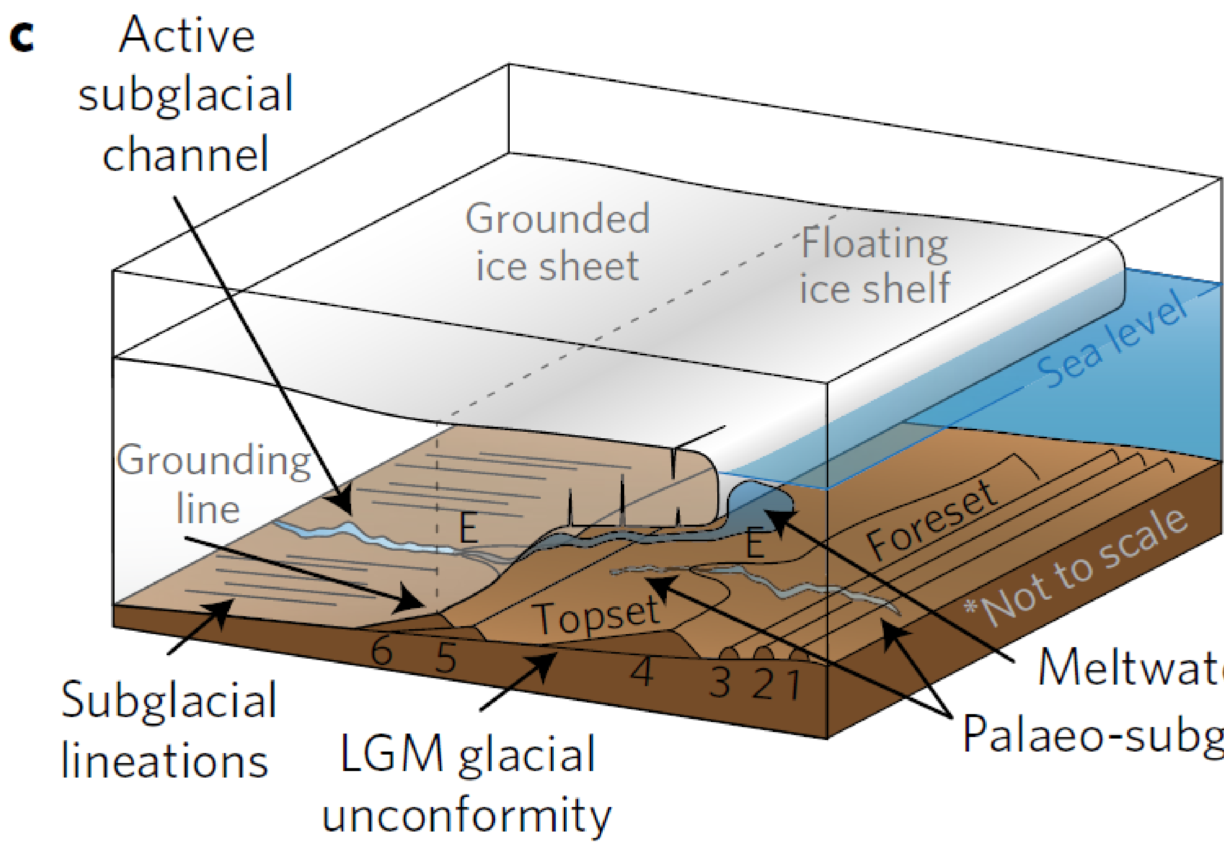
Prothro et al., 2018

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



Prothro et al., 2018


Subglacial
meltwater plume
Deep
iceberg furrows
Banktop
ice rise
Former
subglacial meltwater channel

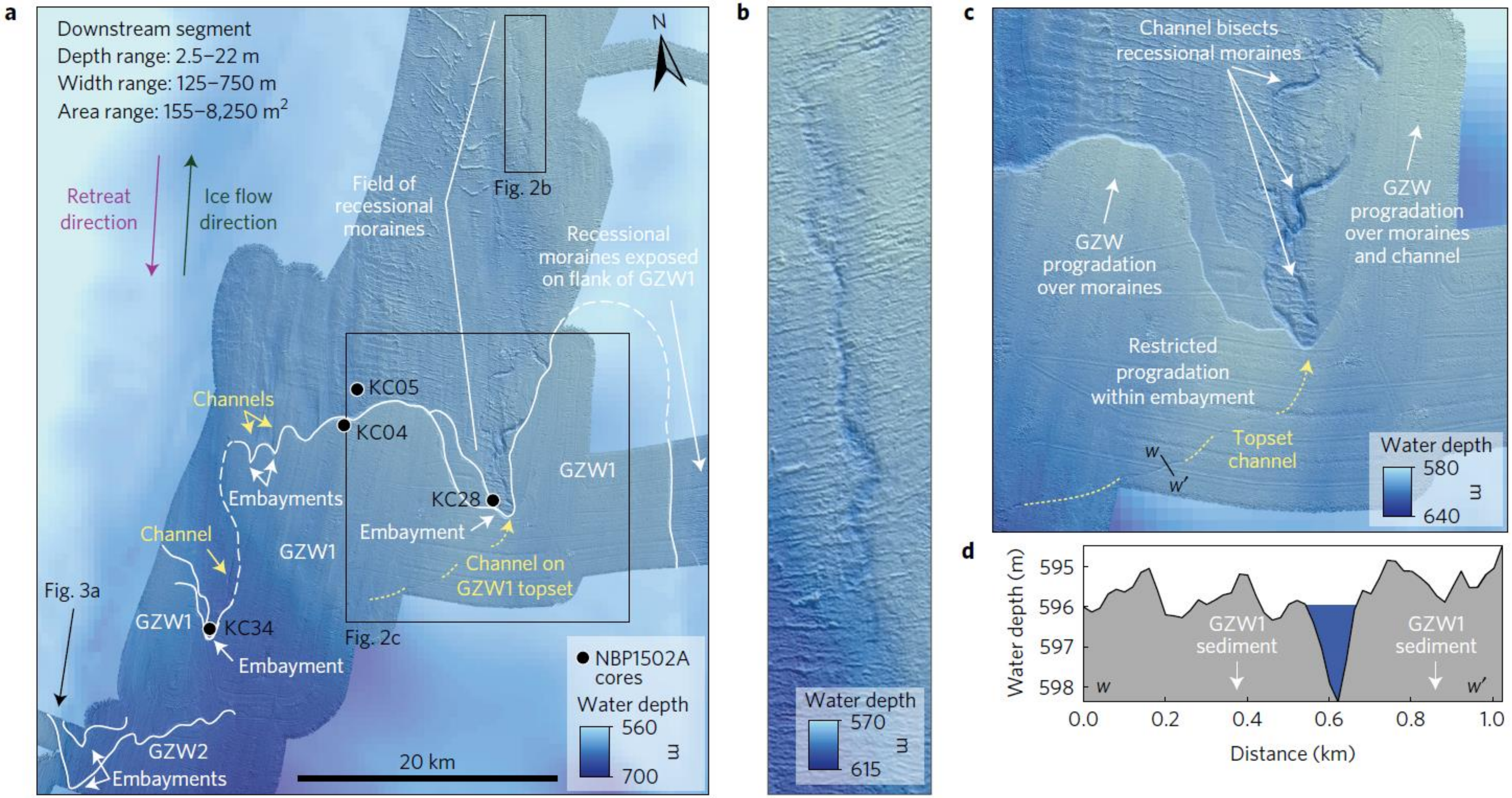


1–3: Recessional moraines (0.5–5 m amp., 20–160 m long, 150–1,700 m spacing)

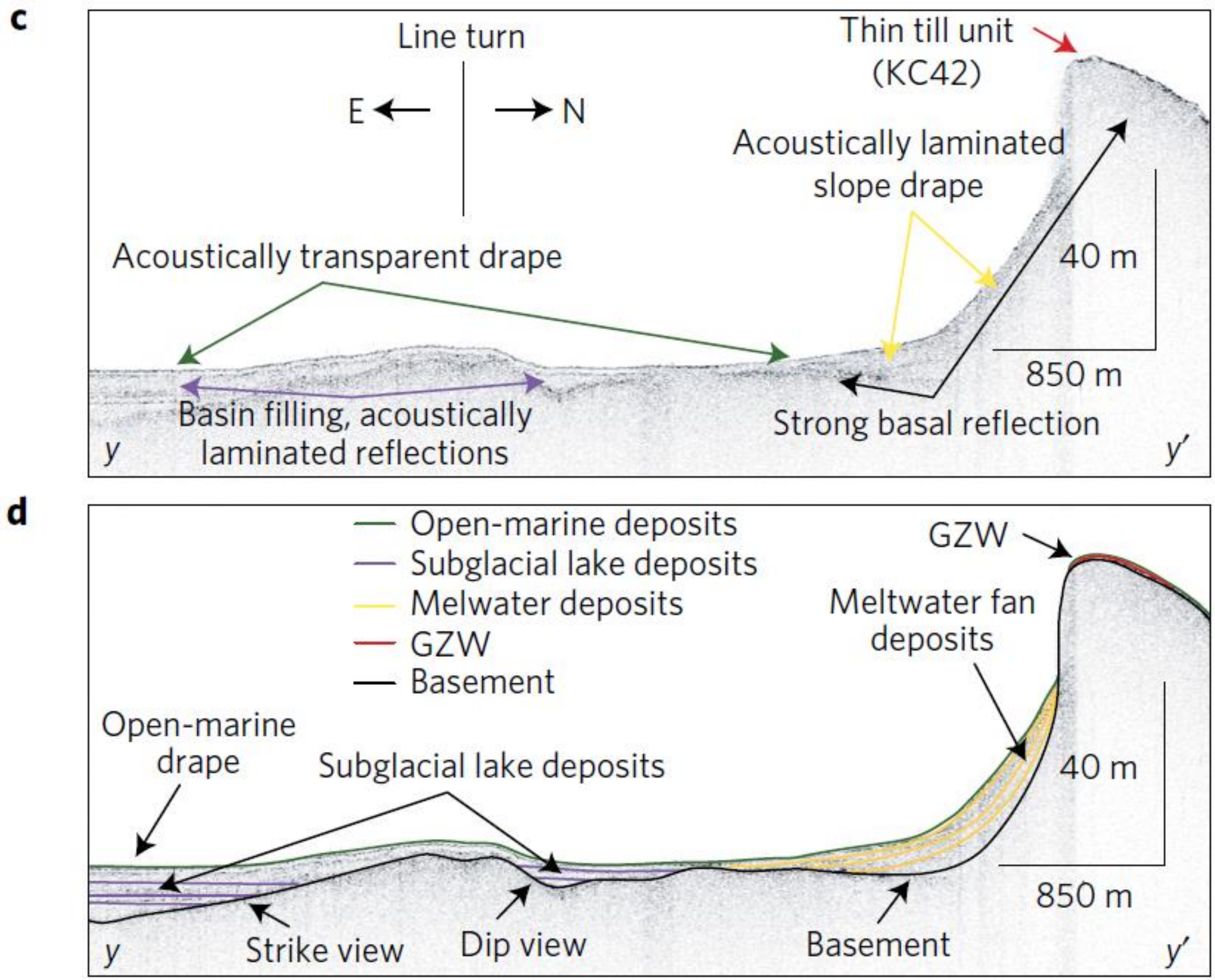
4–6: GZWs (2–20 m amp., 50–1,200 m long, 500–4,500 m spacing)

Grounding-line embayments (E)

Simkins et al., 2017



Simkins et al., 2017



Simkins et al., 2017

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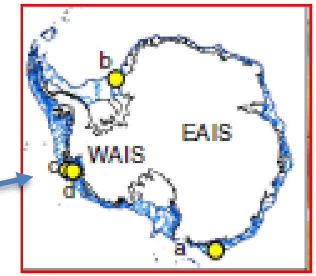
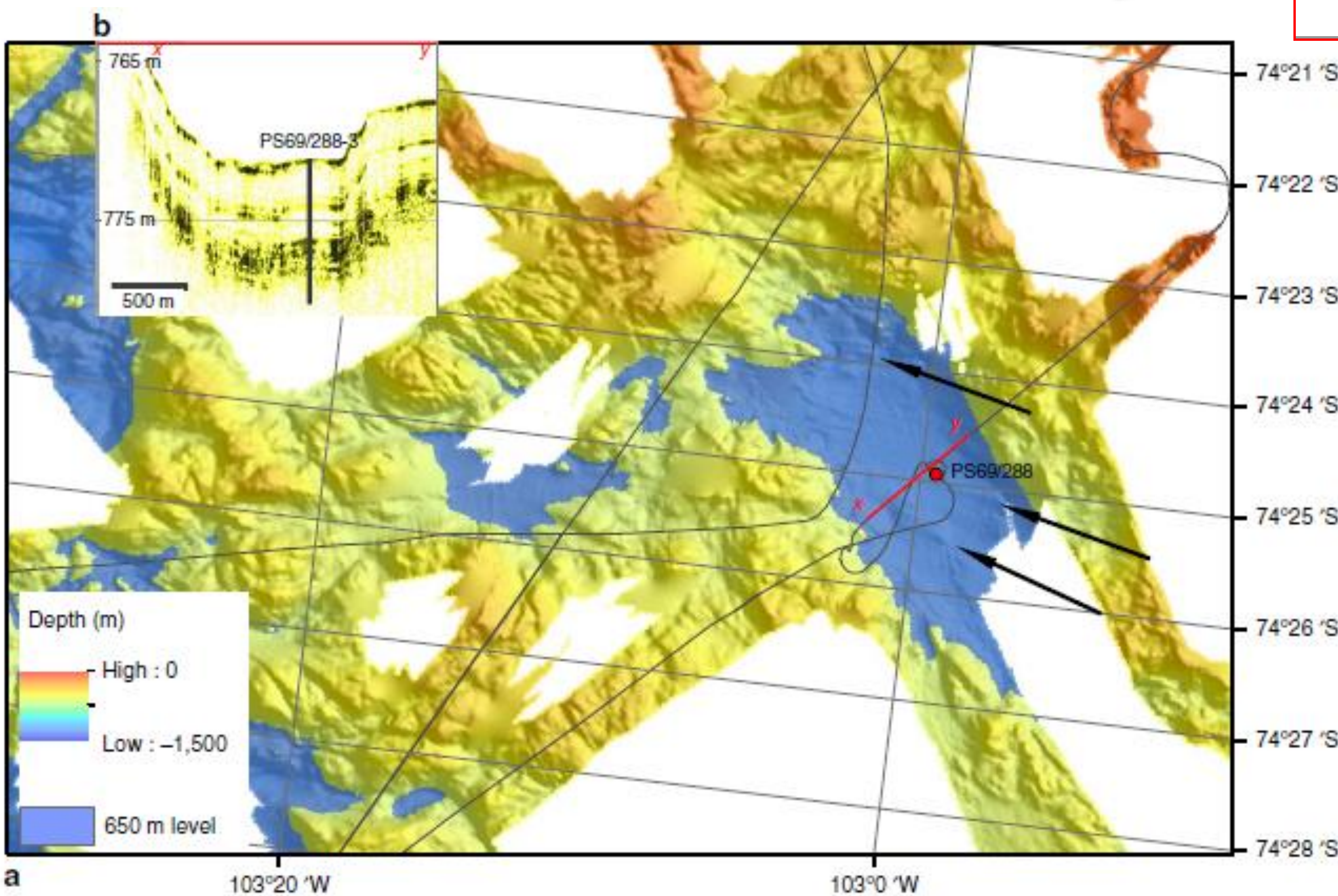
OPEN

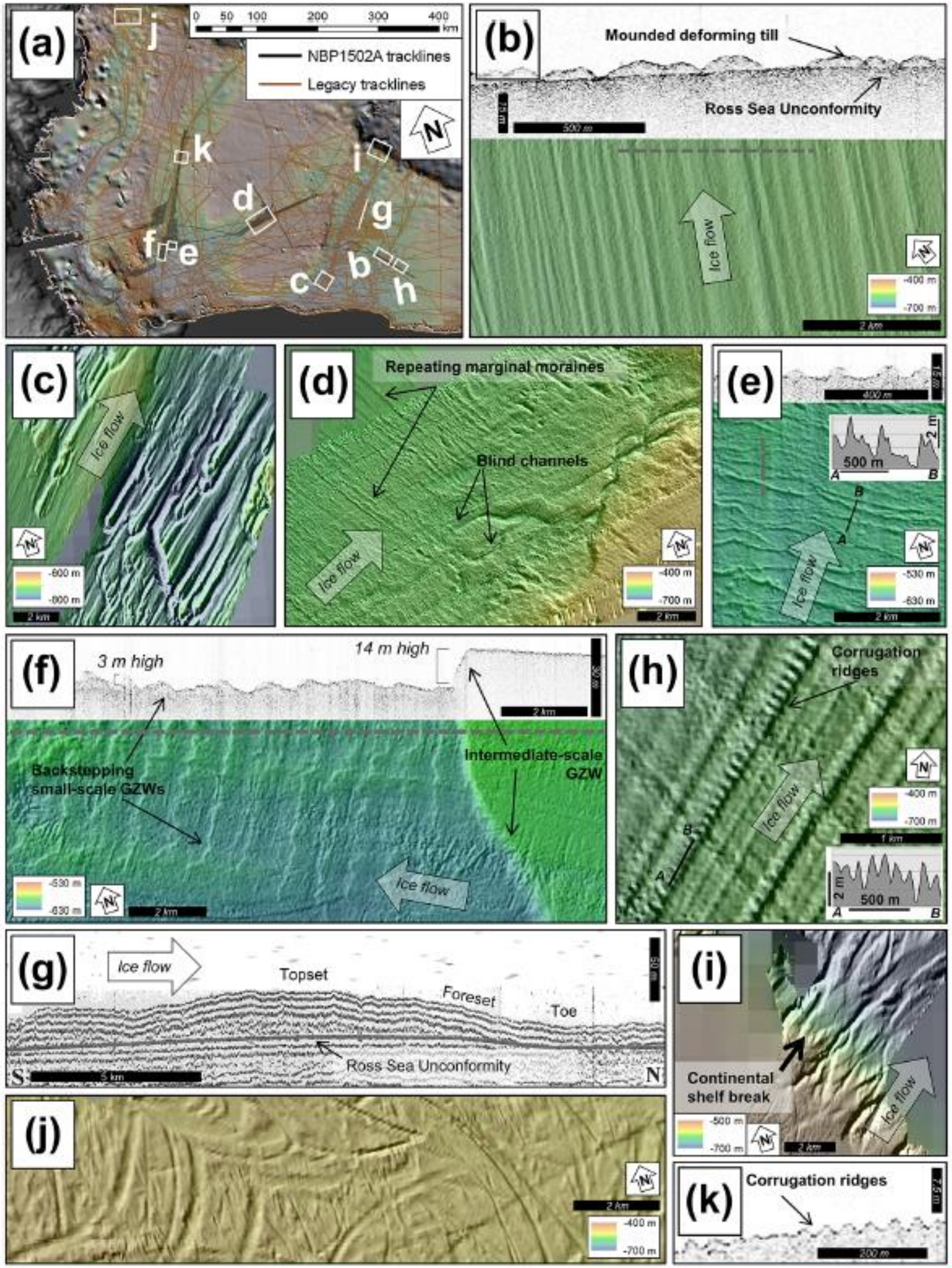
Evidence for a palaeo-subglacial lake on the Antarctic continental shelf

Gerhard Kuhn[1], Claus-Dieter Hillenbrand[2], Sabine Kasten[1], James A. Smith[2], Frank O. Nitsche[3], Thomas Frederichs[4], Steffen Wiers[4], Werner Ehrmann[5], Johann P. Klages[1] & José M. Mogollón[6]

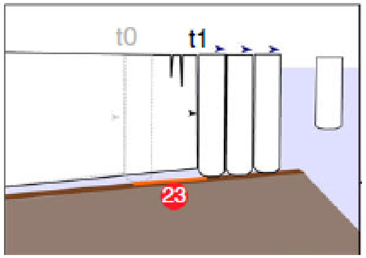




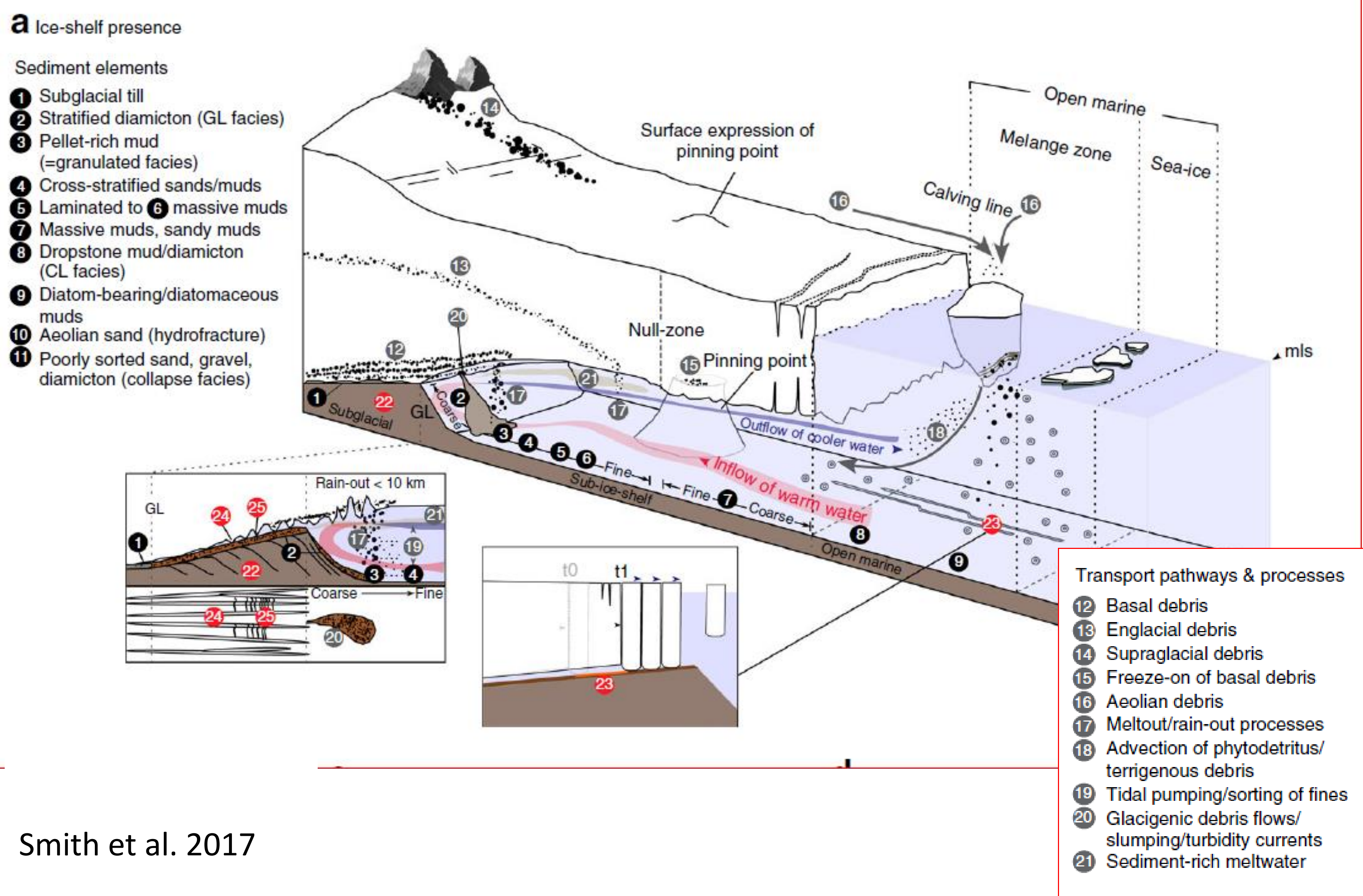
drumlins, crag and tails, and megaflutes



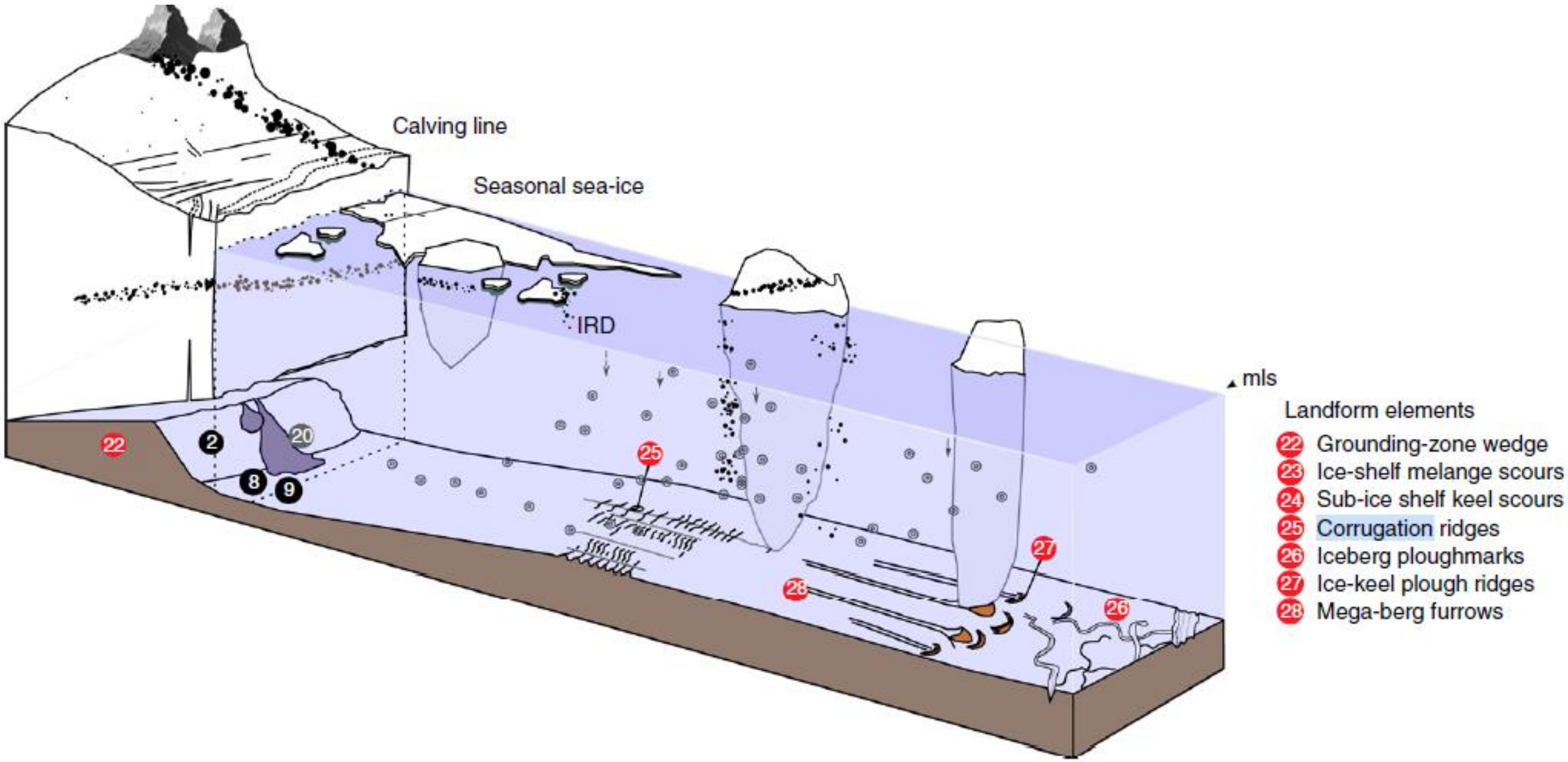
Megascale glacial lineations



Halberstadt et al., 2016

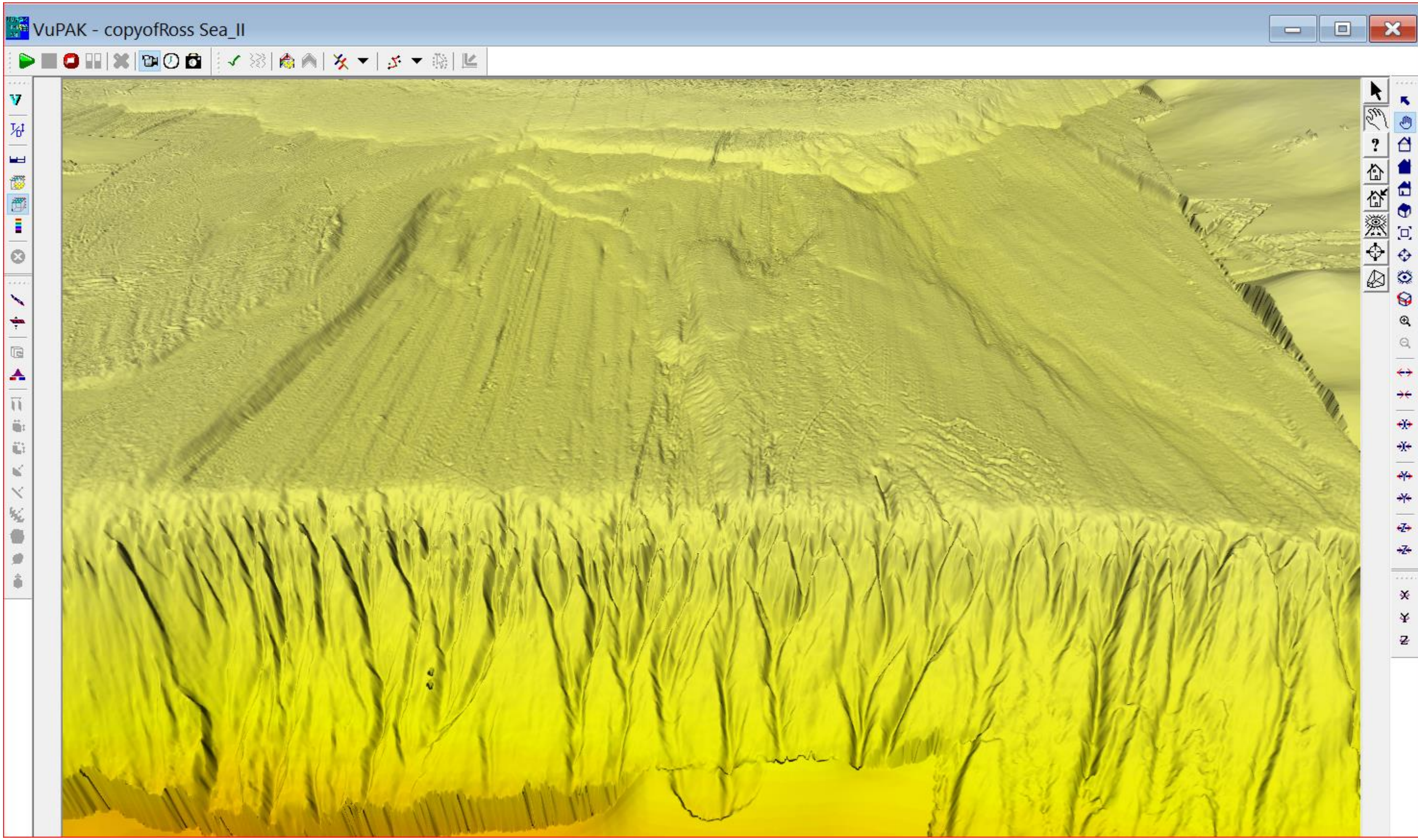


Smith et al. 2017



Smith et al. 2017

EXERCIZE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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

Post-LGM Grounding-Line Positions of the Bindschadler Paleo Ice Stream in the Ross Sea Embayment, Antarctica

Philip J. Bart[1], **John B. Anderson**[2], **and Frank Nitsche**[3]

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