The Cenozoic evolution

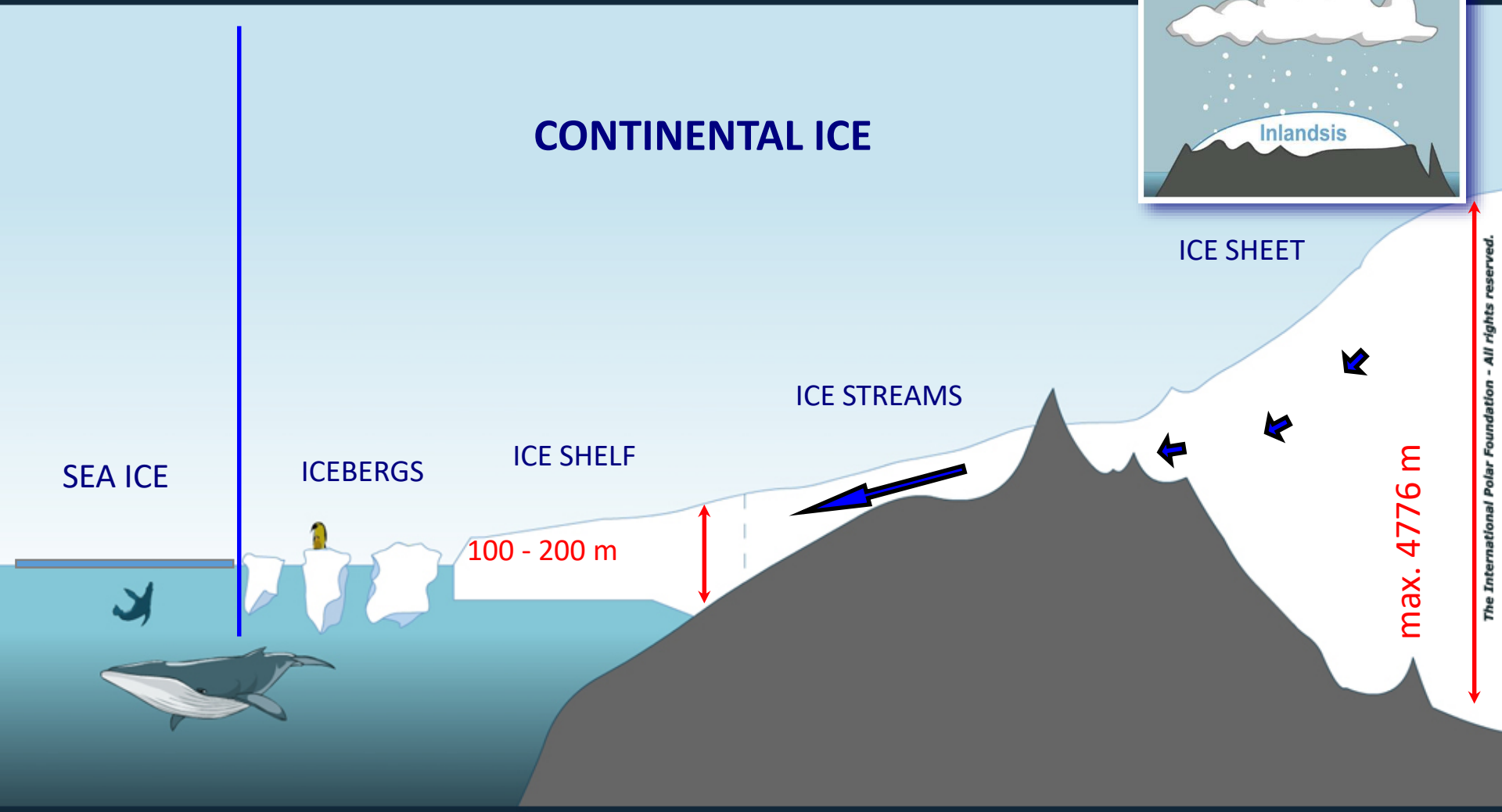
PROXY

- Oxygen isotope record
- Global sea level record
- Ice-rafting record
- Increased bottom current activity
- Shift in biogeographic zones

CONTINENTAL AND CONTINENTAL SHELF RECORD OF ICE SHEET EVOLUTION

- Seismic facies
- Sedimentary facies (till-open marine)

Types of ice



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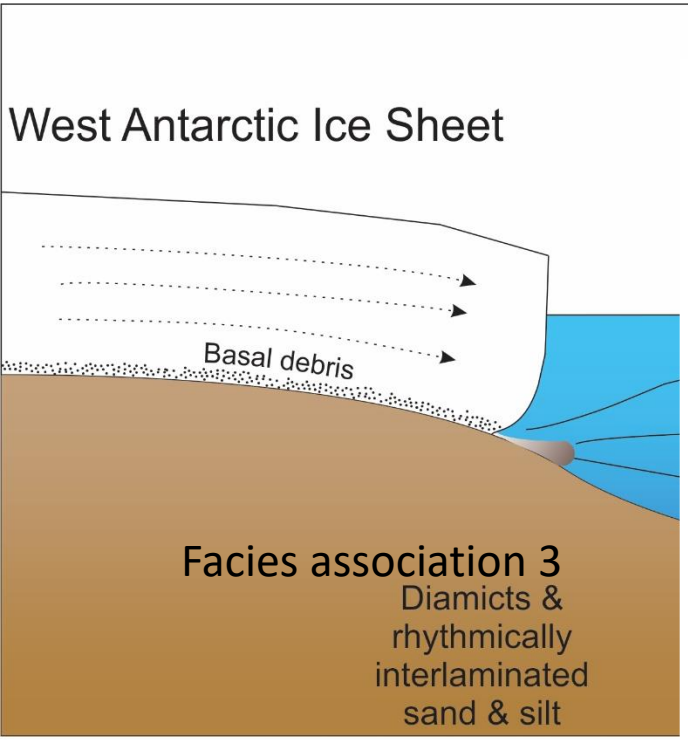
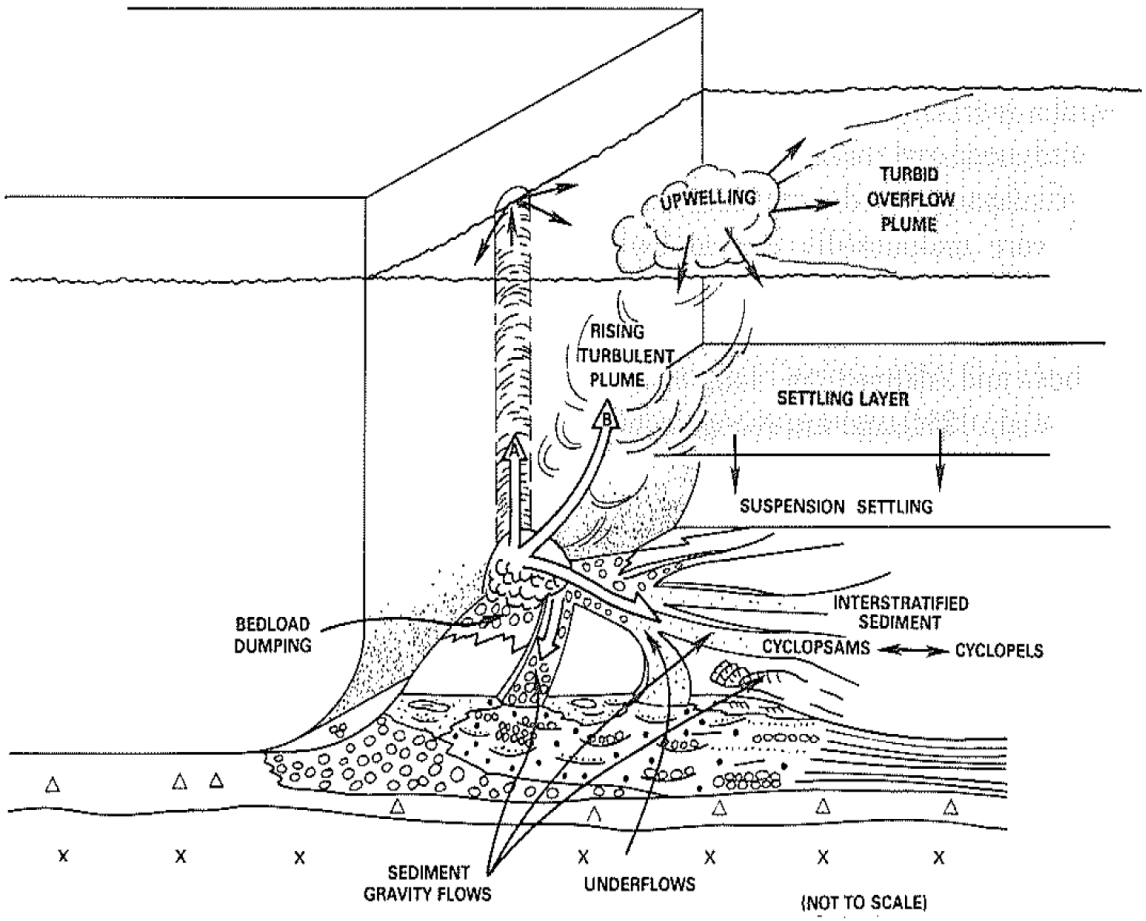
EducaPoles
The educational website of the International Polar Foundation
http://www.educapoles.org

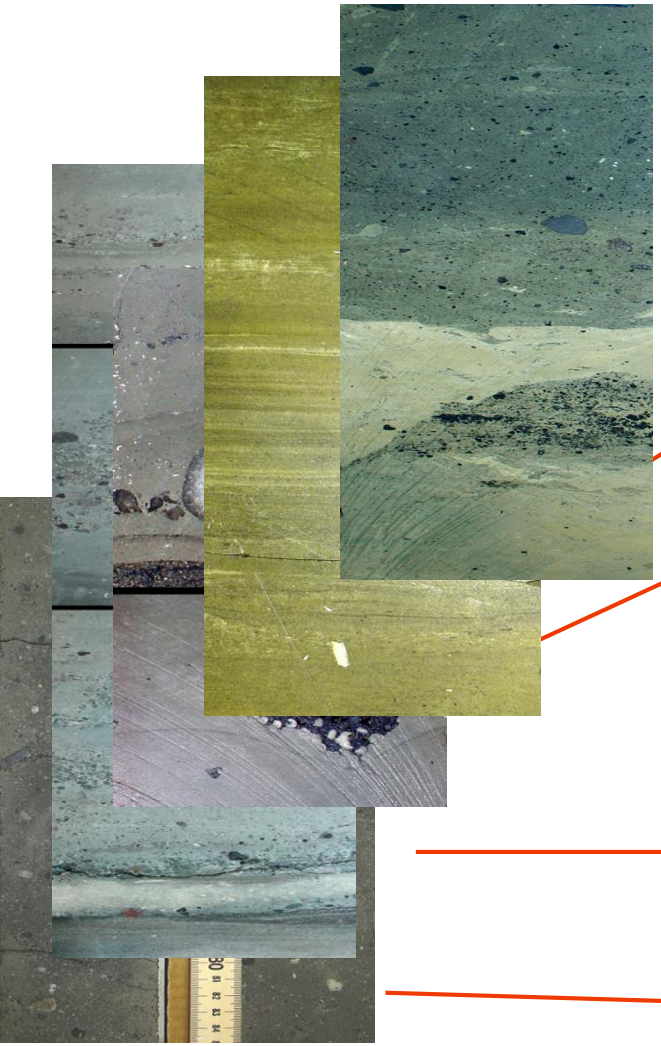
Facies scheme & depositional setting

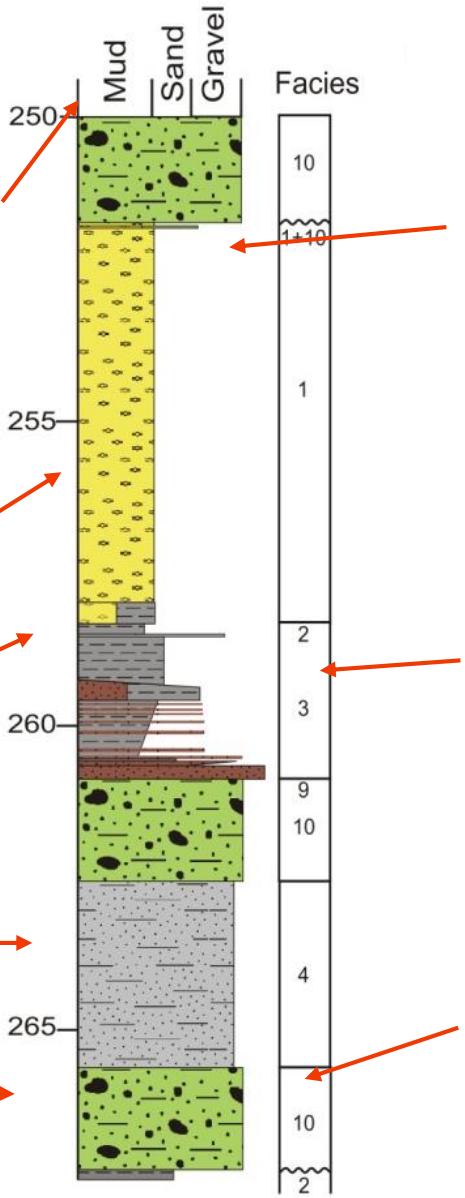


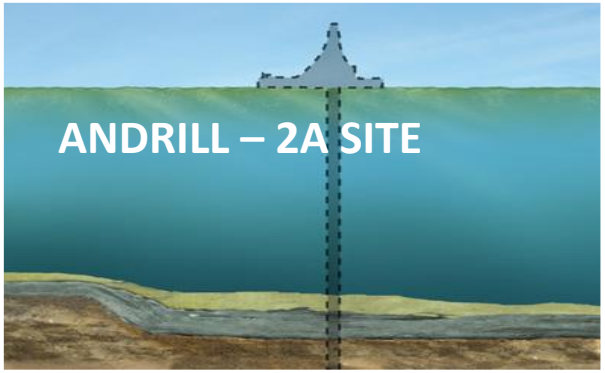


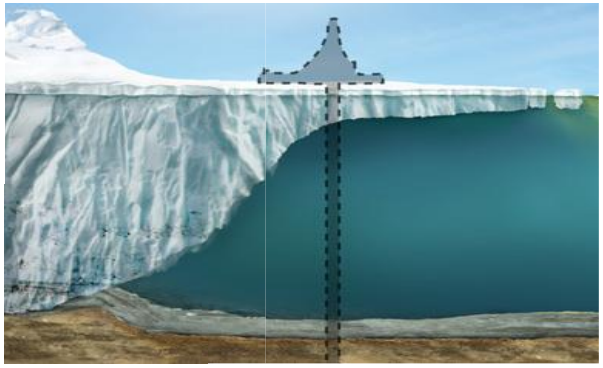
Glacial-Interglacial glacimarine cycles

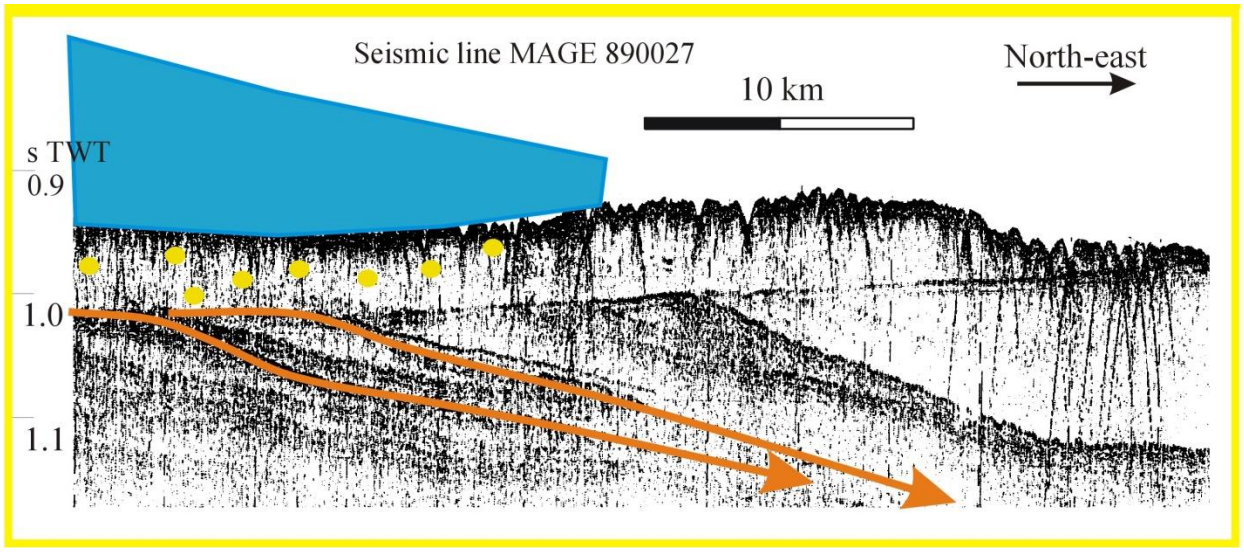
From Mckay et al. 2009 GSA Bull.

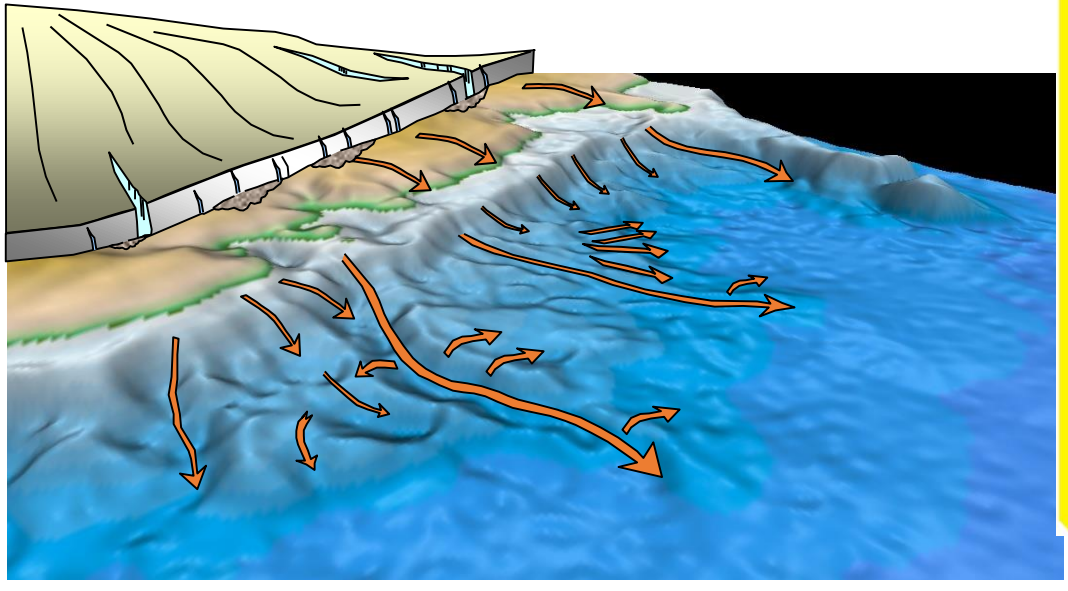


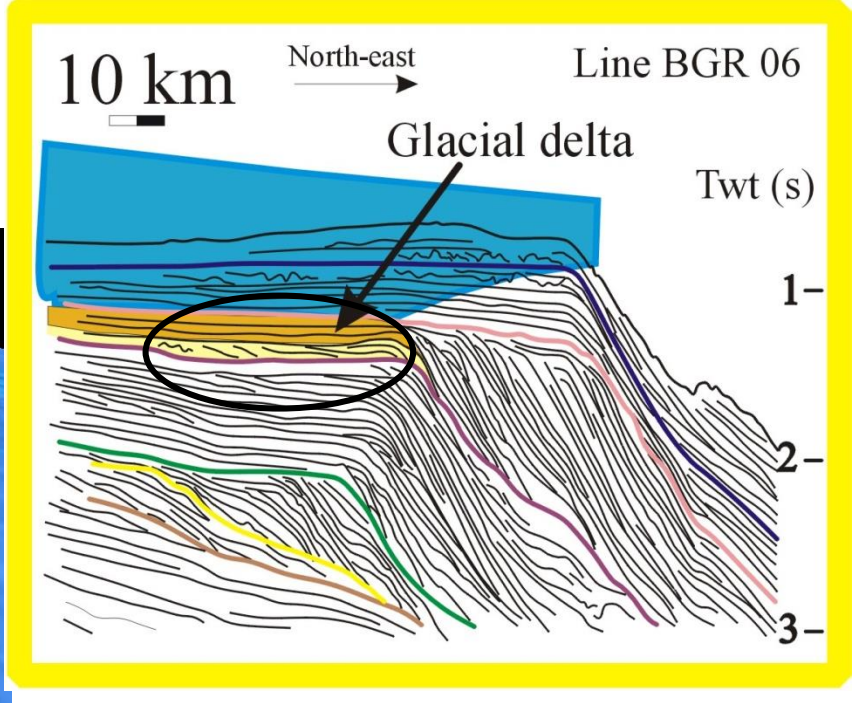


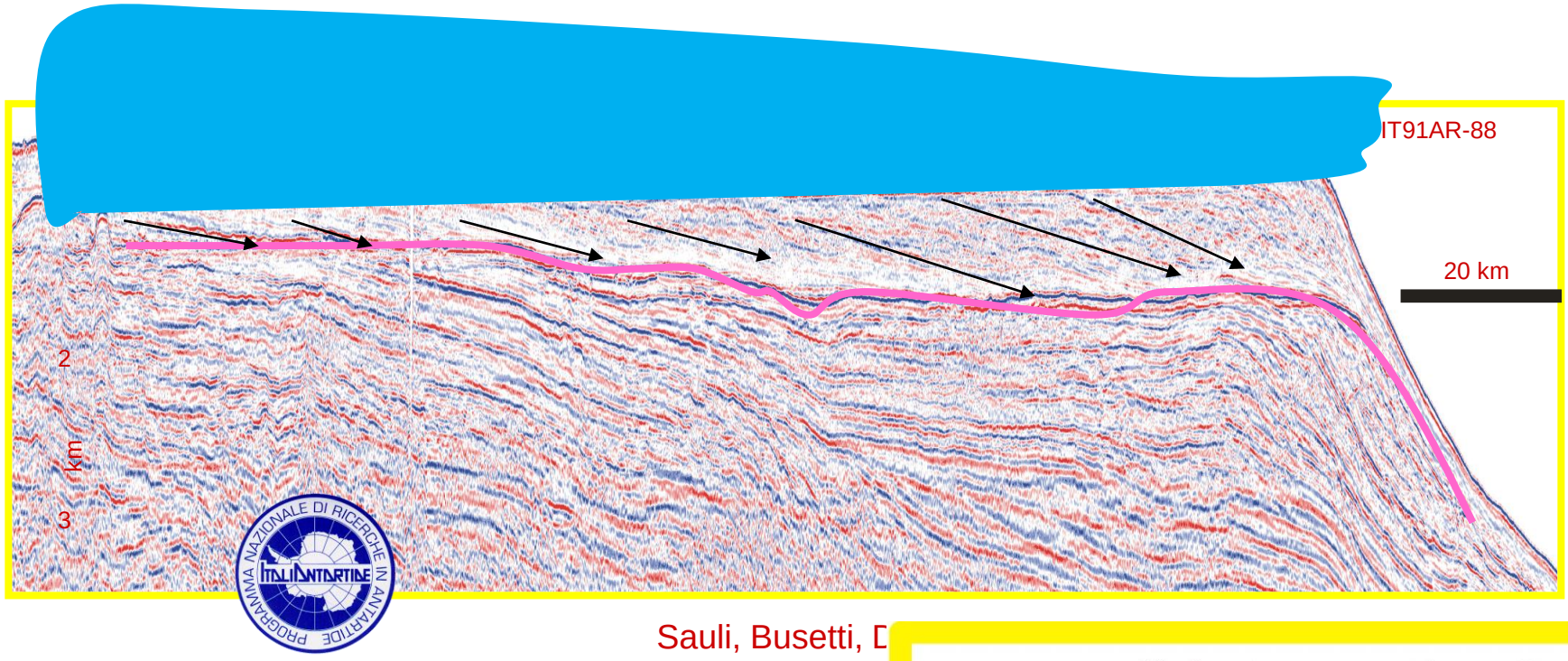




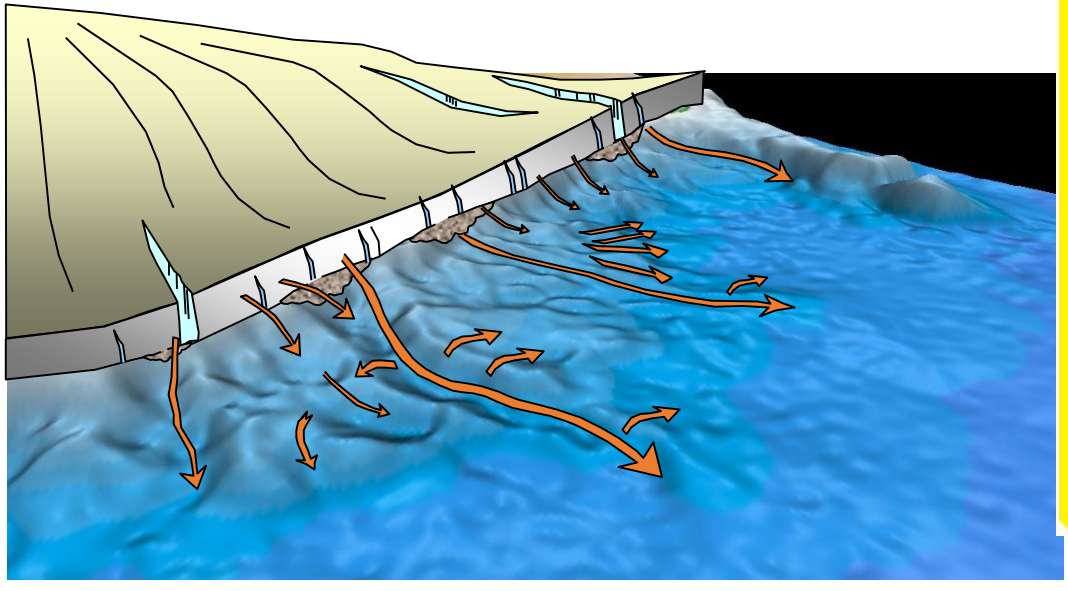

Seismic line MAGE 890027
North-east
10 km
s TWT
0.9
1.0
1.1

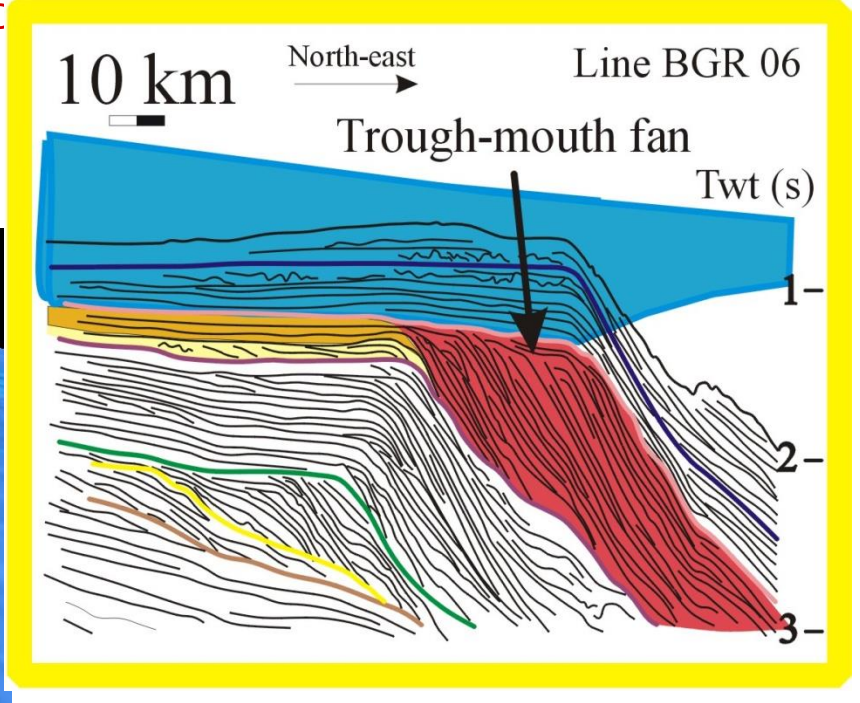



10 km
North-east
Line BGR 06
Glacial delta
Twt (s)
1
2
3

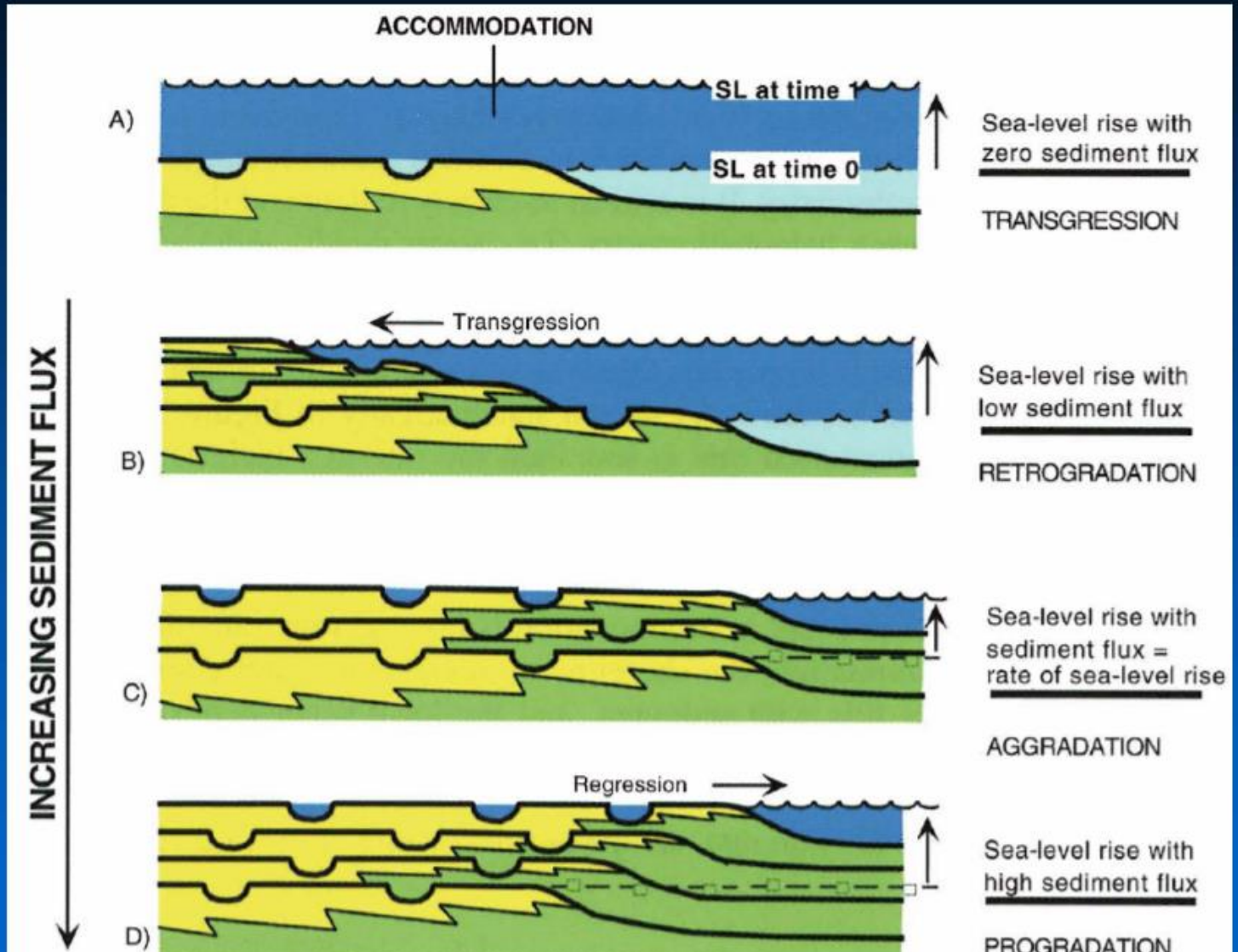


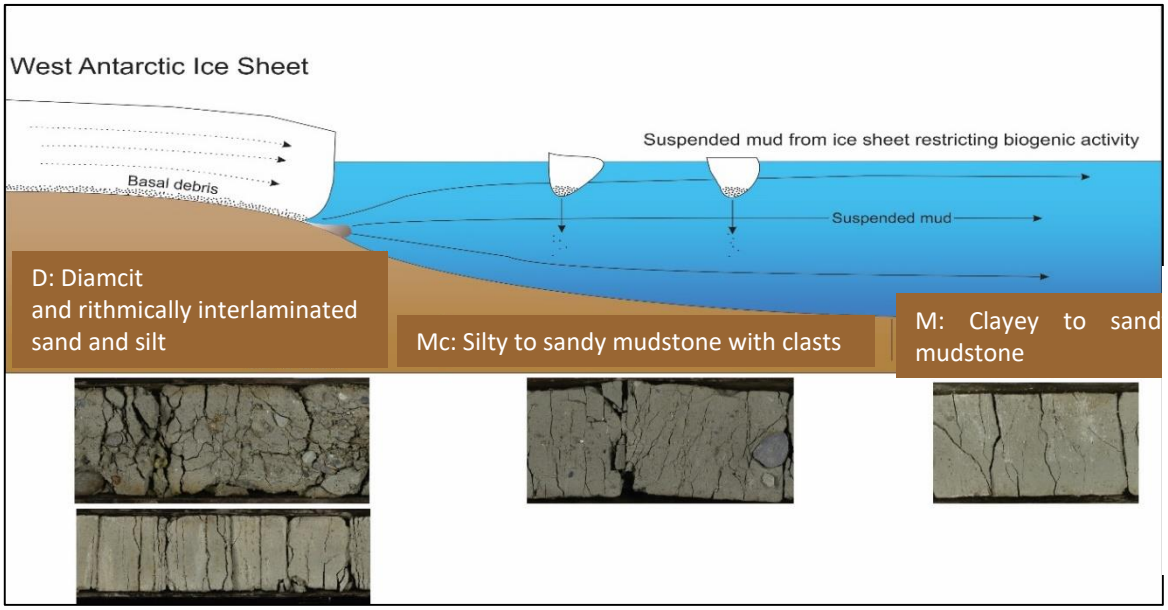
Sauli, Busetti, D



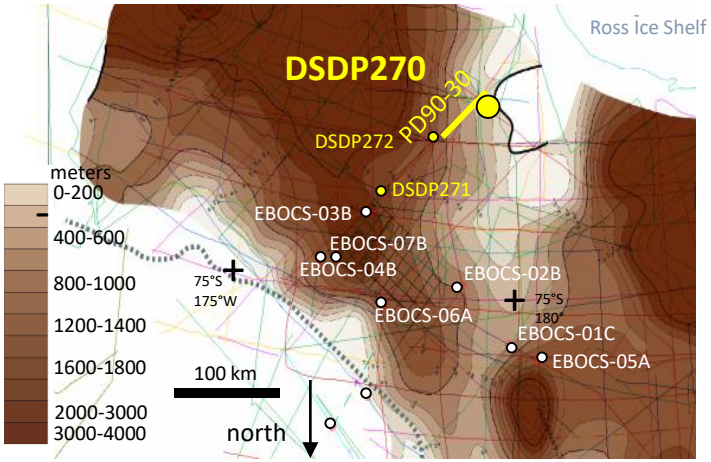


Accommodation and sediment supply

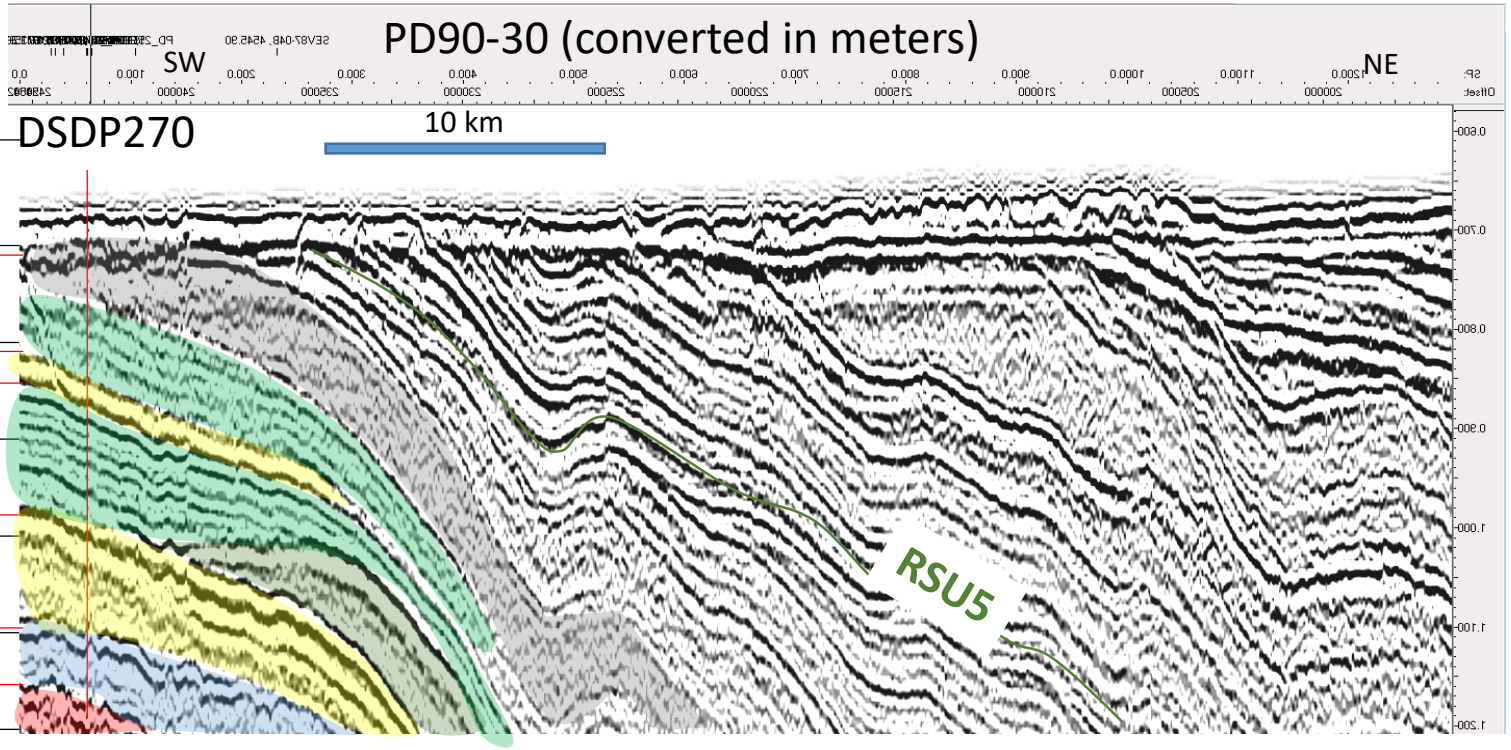




RSS-2 isopach map – early Miocene
(ANTOSTRAT, Brancolini et al., 1995)



Christopher Kraus,
Victoria Univ., NZ
Master thesis,
unpublished.
AGU poster 2015



M: Ice distal and
Very ice distal

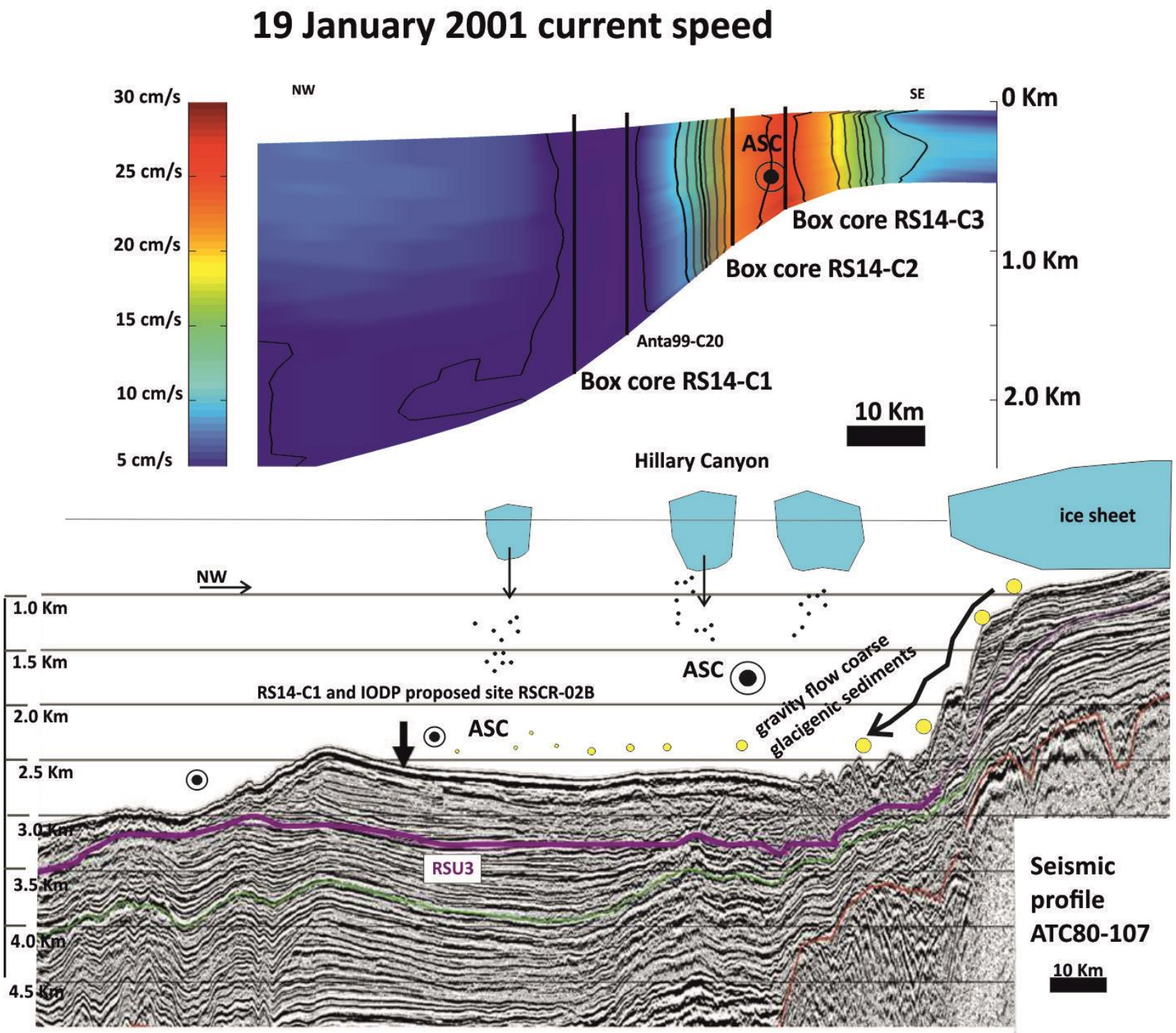
D: ice proximal

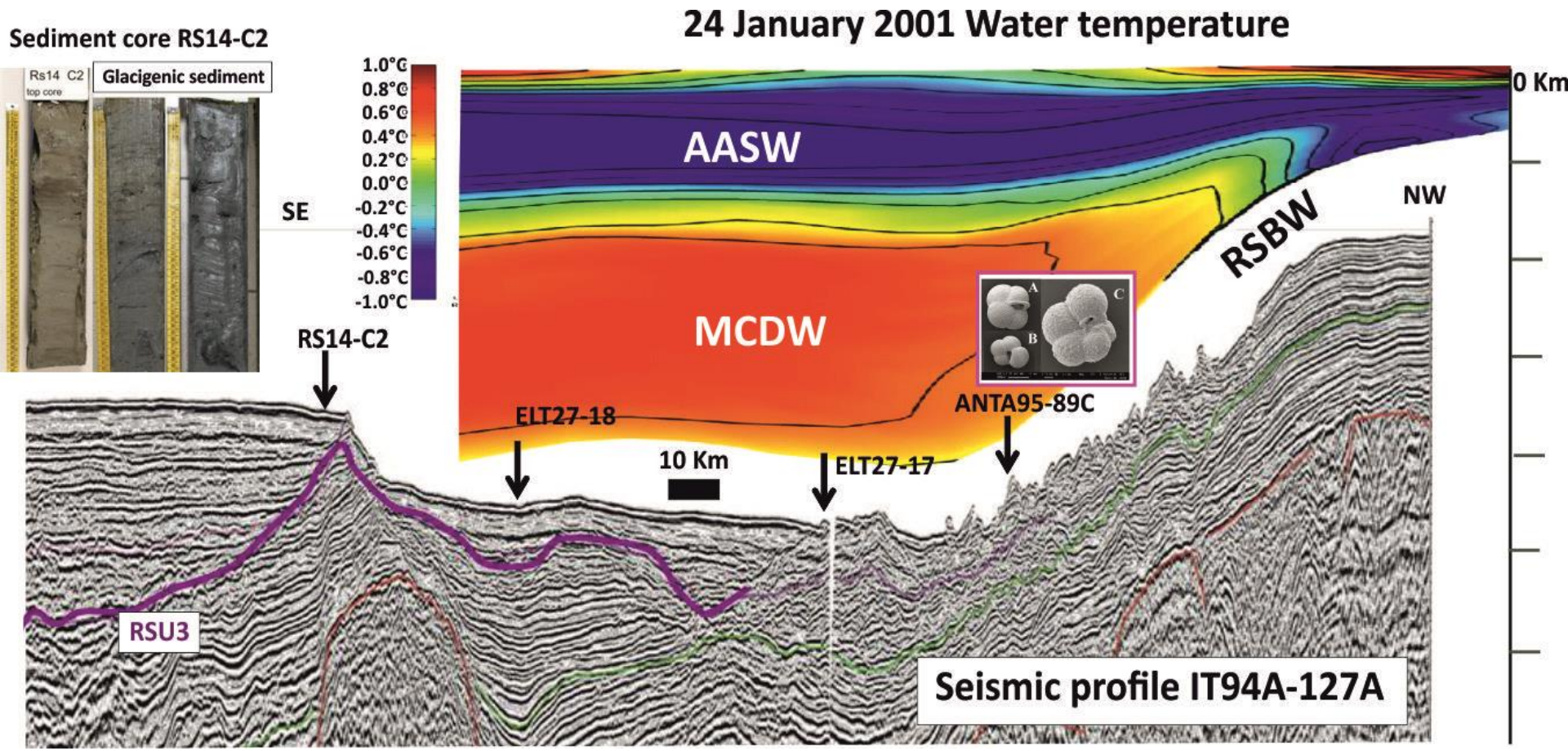
M: Ice distal (contourite?)

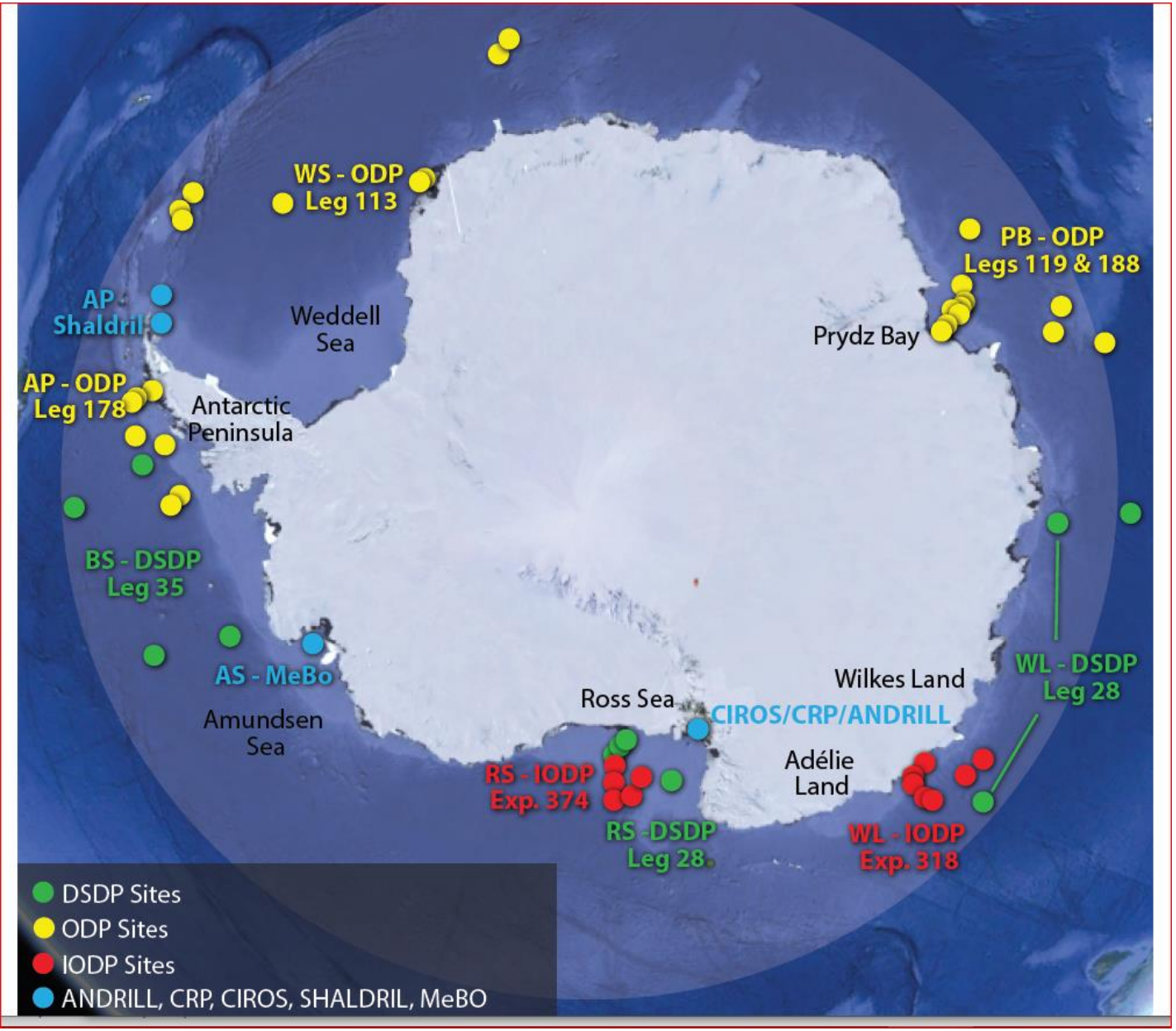
Shallow marine

Shallow marine non glacial?

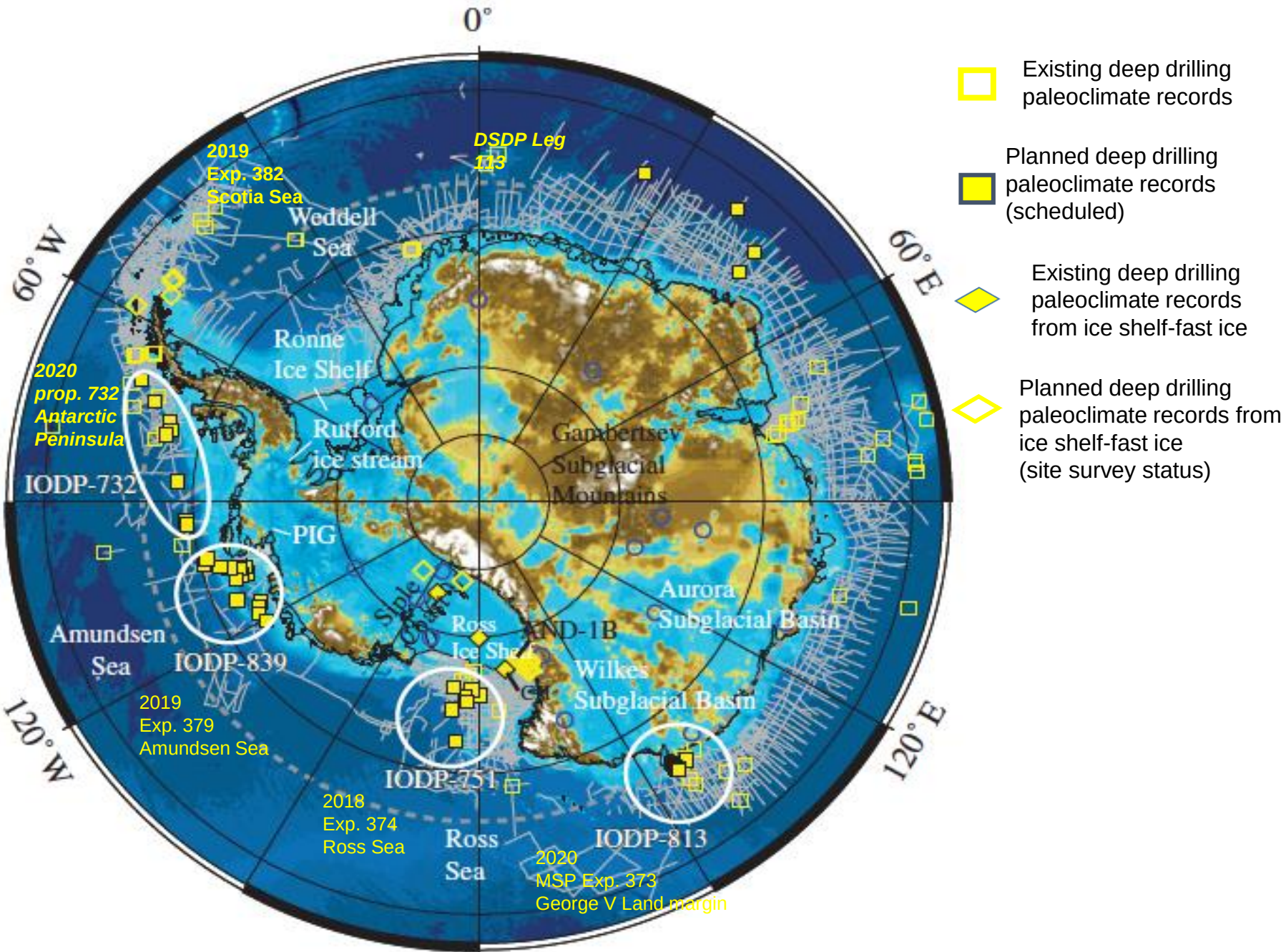
Metamorphic
basement

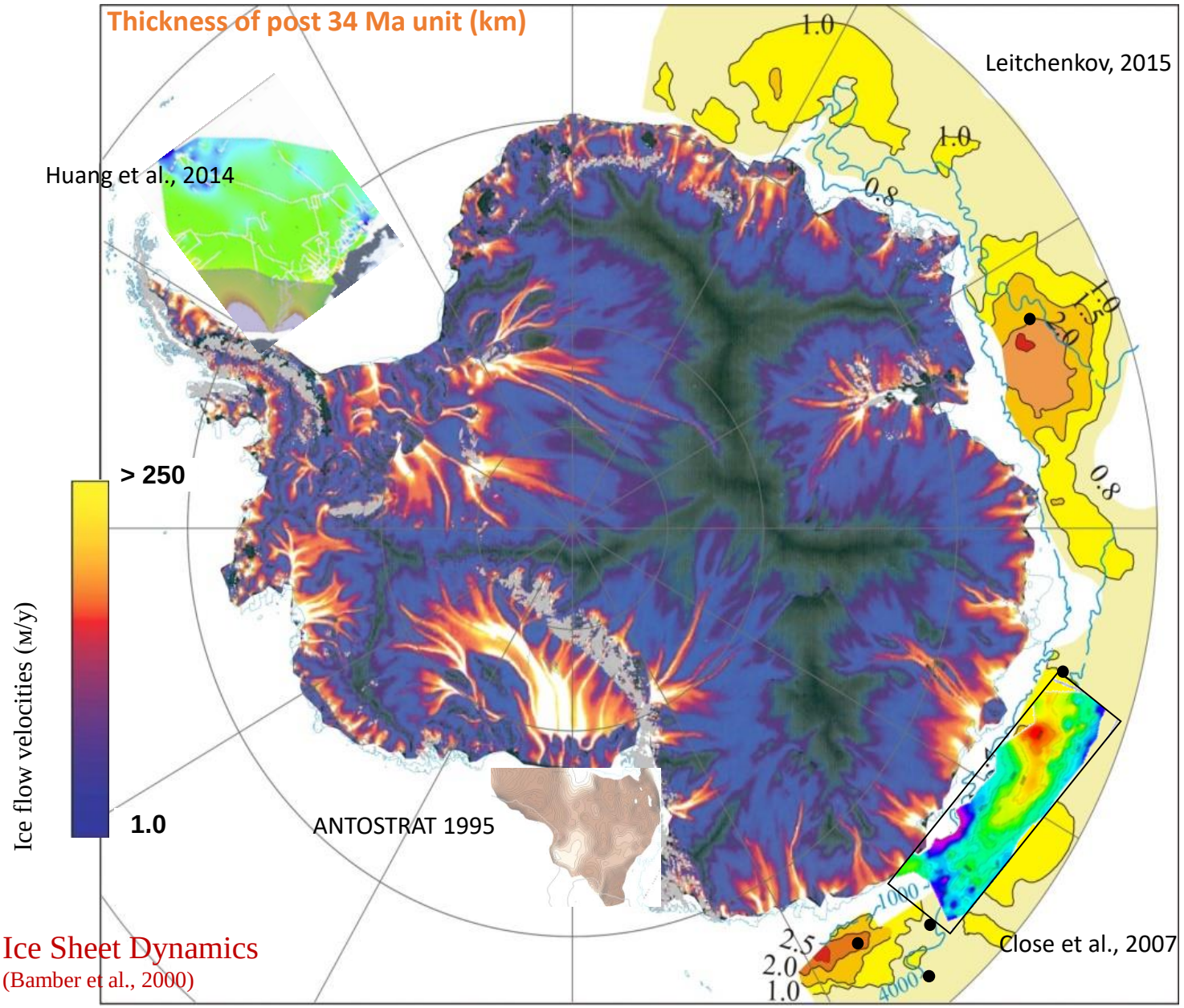

19 January 2001 current speed
30 cm/s
25 cm/s
20 cm/s
15 cm/s
10 cm/s
5 cm/s
NW
SE
0 Km
1.0 Km
2.0 Km
ASC
Box core RS14-C3
Box core RS14-C2
Anta99-C20
Box core RS14-C1
10 Km
Hillary Canyon
ice sheet
NW
1.0 Km
1.5 Km
2.0 Km
2.5 Km
3.0 Km
3.5 Km
4.0 Km
4.5 Km
ASC
RS14-C1 and IODP proposed site RSCR-02B
ASC
gravity flow coarse glacigenic sediments
RSU3
Seismic profile ATC80-107
10 Km


Sediment core RS14-C2
Rs14 C2
top core
Glacigenic sediment
24 January 2001 Water temperature
1.0°C
0.8°C
0.6°C
0.4°C
0.2°C
0.0°C
-0.2°C
-0.4°C
-0.6°C
-0.8°C
-1.0°C
SE
NW
0 Km
AASW
MCDW
RSBW
A
B
C
RS14-C2
ELT27-18
ANTA95-89C
10 Km
ELT27-17
RSU3
Seismic profile IT94A-127A



Escutia, C., R.M. DeConto, R. Dunbar, L. De Santis, A. Shevenell, and T. Naish. 2019. Keeping an eye on Antarctic Ice Sheet stability. *Oceanography* 32(1): 32-46, https://doi.org/10.5670/oceanog.2019.117. (Open Access)

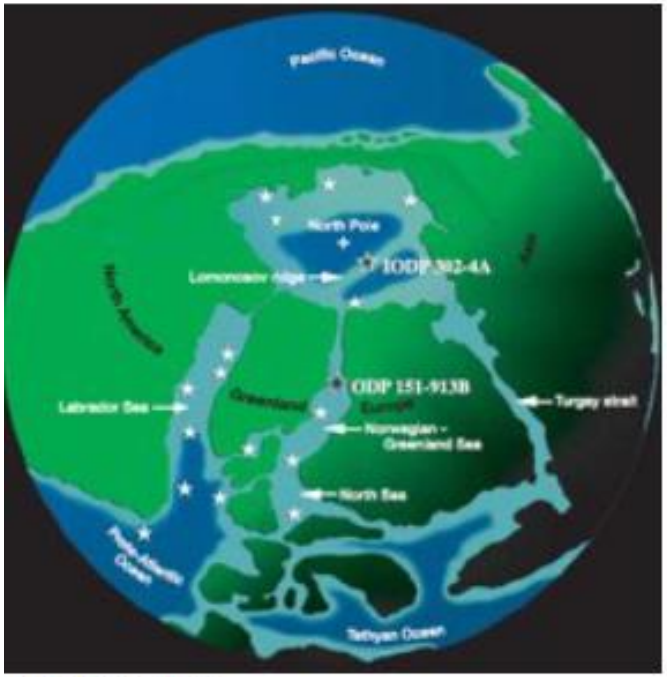

0°
60° W
60° E
120° W
120° E
2019
Exp. 382
Scotia Sea
DSDP Leg
113
Weddell
Sea
Ronne
Ice Shelf
2020
prop. 732
Antarctic
Peninsula
IODP-732
Rutford
ice stream
Gamburtsev
Subglacial
Mountains
PIG
Aurora
Subglacial Basin
Amundsen
Sea
IODP-839
Ross
Ice Shelf
AND-1B
Wilkes
Subglacial Basin
2019
Exp. 379
Amundsen Sea
IODP-751
2018
Exp. 374
Ross Sea
Ross
Sea
IODP-813
2020
MSP Exp. 373
George V Land margin
Existing deep drilling
paleoclimate records
Planned deep drilling
paleoclimate records
(scheduled)
Existing deep drilling
paleoclimate records
from ice shelf-fast ice
Planned deep drilling
paleoclimate records from
ice shelf-fast ice
(site survey status)

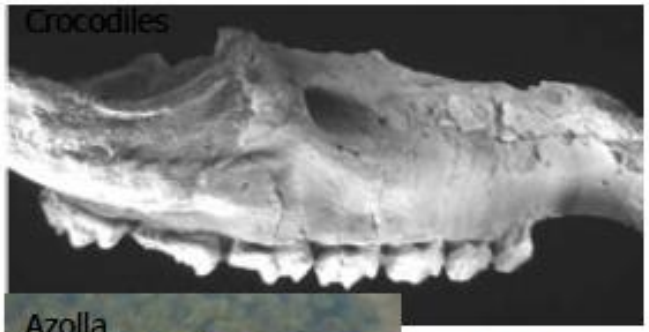


Ice Sheet Dynamics
(Bamber et al., 2000)

Paleo-data suggests near-tropical polar warmth ~50 Ma

Arctic



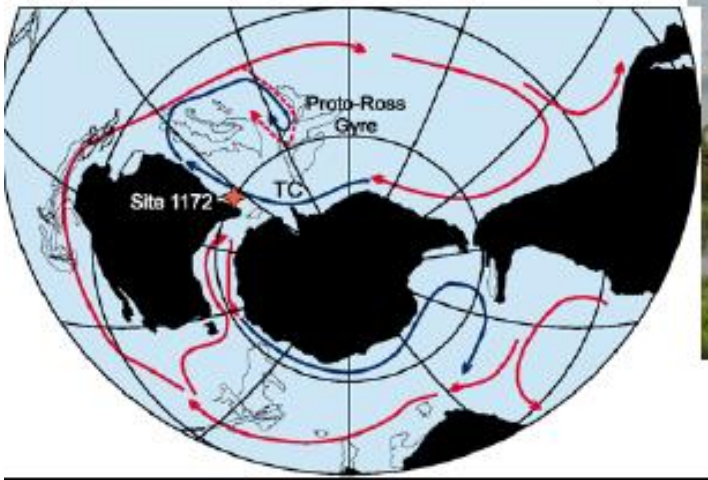


Sluijs et al., 2006
Brinkhuis et al., 2006
Moran et al., 2006

Bombacacoideae

Palms

Antarctic



LETTER

doi:10.1038/nature11360

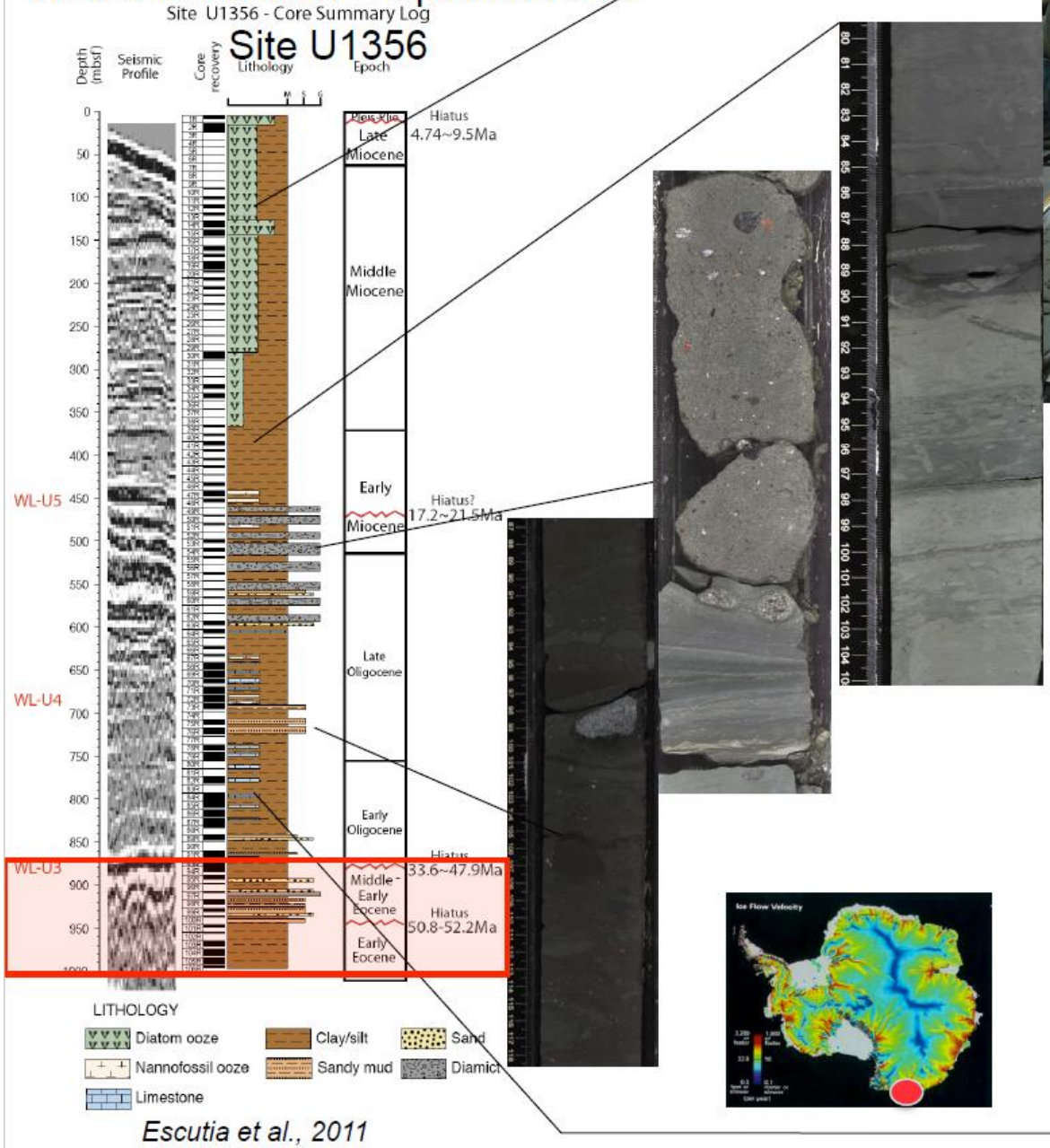
Persistent near-tropical warmth on the Antarctic continent during the early Eocene epoch

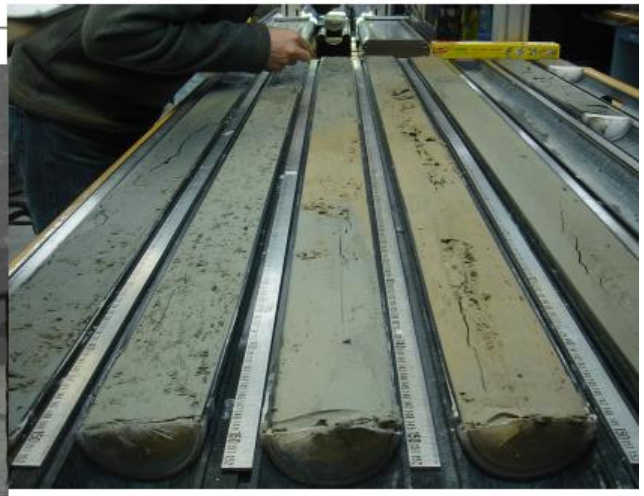
Jörg Pross[1,2], Lineth Contreras[1], Peter K. Bijl[3], David R. Greenwood[4], Steven M. Bohaty[5], Stefan Schouten[6], James A. Bendle[7],

Wilkes Land IODP Expedition 318

Site U1356 - Core Summary Log

Site U1356





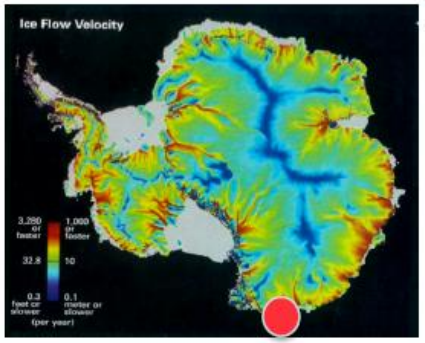
Escutia et al., 2011

Pollen from the e. Eocene peak greenhouse conditions
Wilkes Land IODP Site 1356

Pollen of extent palms

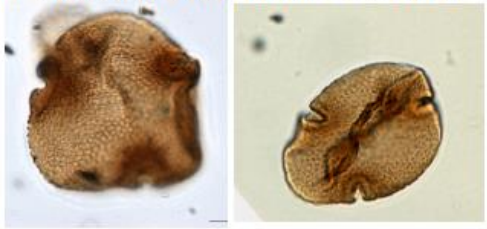
Pollen from Wilkes Land

Mean Annual T: >13.3 °C
Cold Month mean T: >5°C + 3°C
Warm Month mean T: >22.8 °C



Pollen of extent Bombacaceae plants

Pollen from Wilkes Land

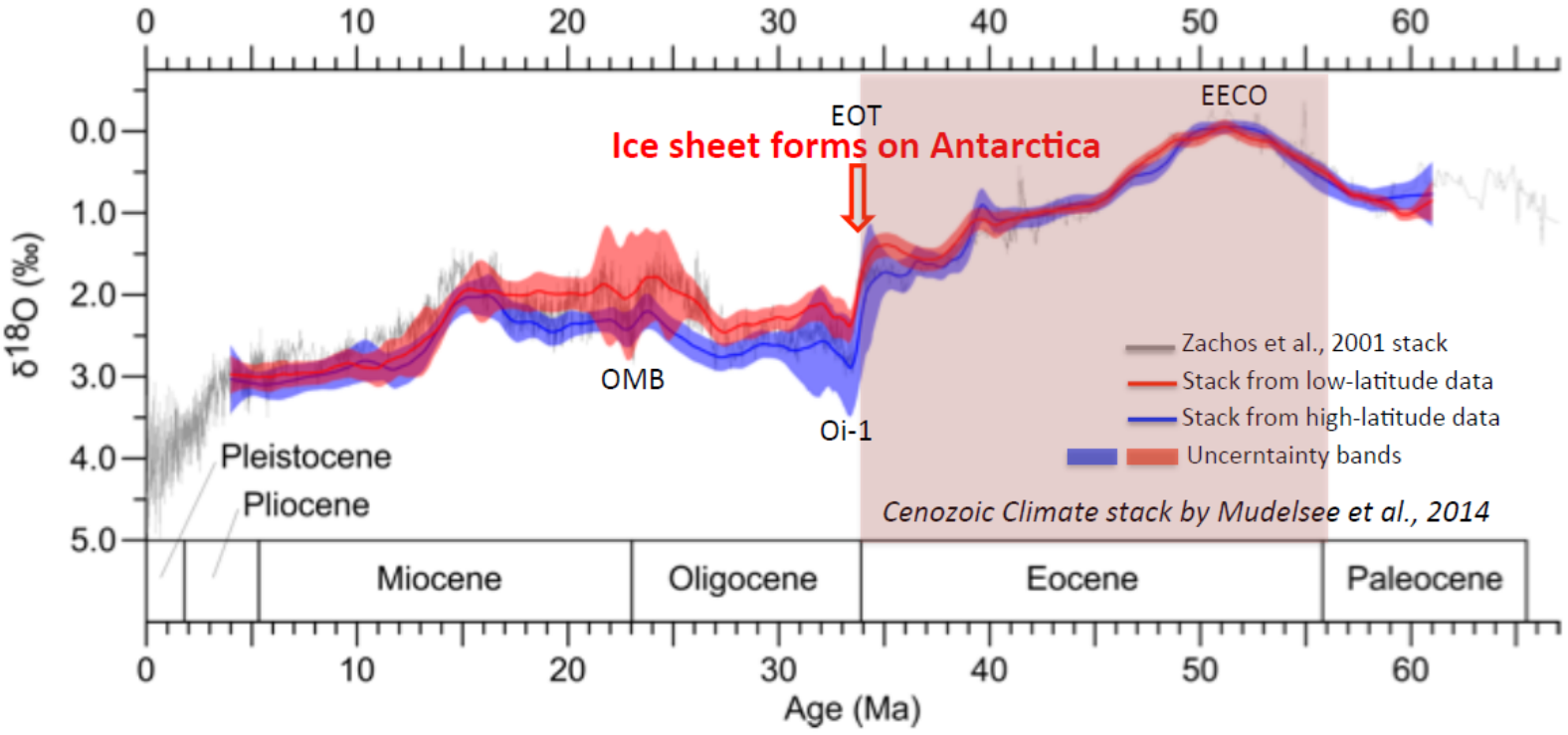


Mean Annual T: >16.8 ºC
Cold Month mean T: >10.6 °C + 3°C
Warm Month mean T: >21.5 °C

Pross et al., Nature, 2012
Contreras et al., 2013

Eocene (56-34 Ma) - High CO_2 Greenhouse World

CO_2 atmospheric concentrations reached >1000 ppm
No polar continental ice sheets
~60m equiv. SL (e.g., Fretwell et al., 2013; New Jersey)
EOT $\delta^{18}O$ enrichment in SO records of 1-1.2‰ (4-5ºC cooling)

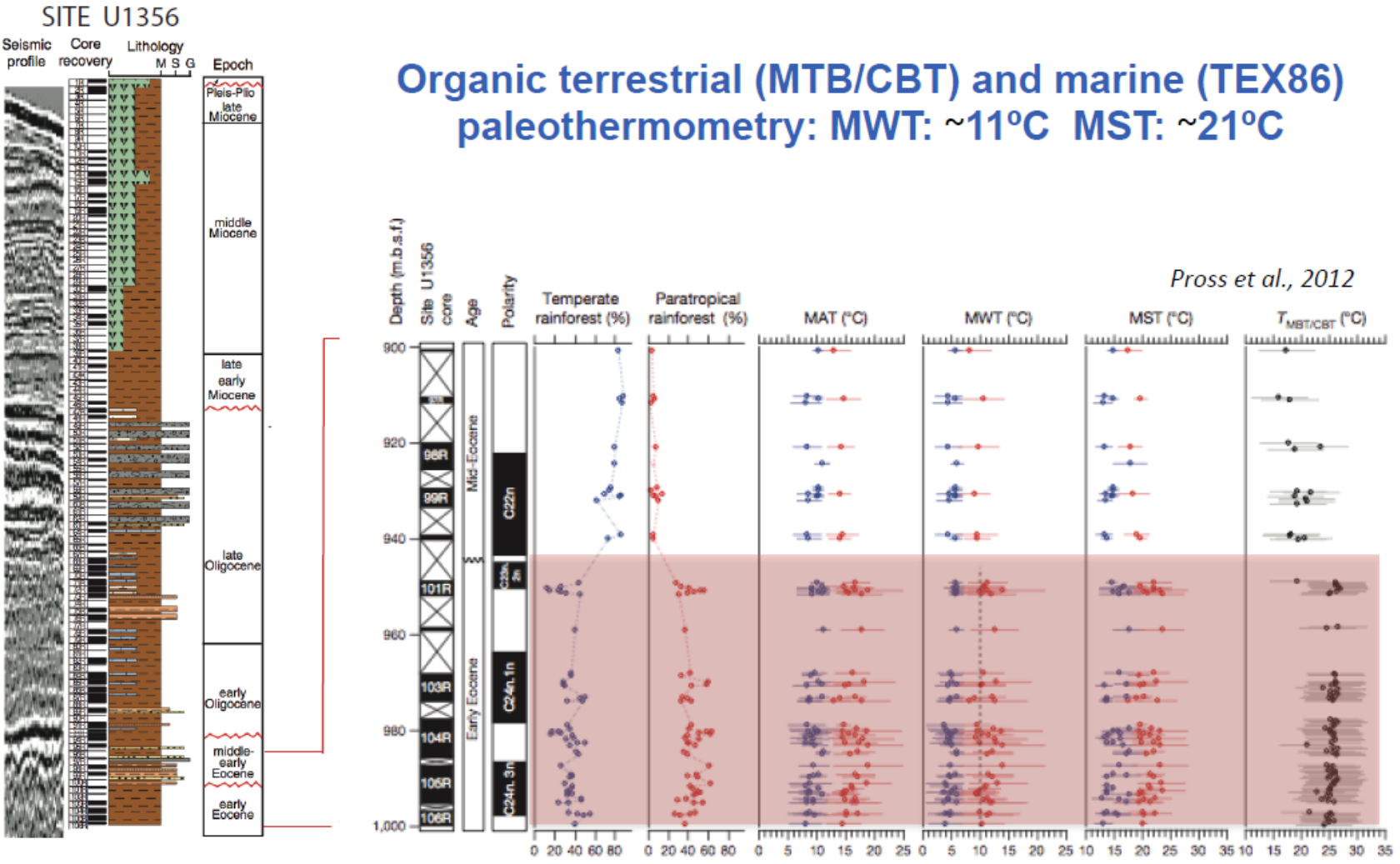


Early EOCENE (54-52 Ma): paratropical forests

Sporomorphs provide evidence for e. Eocene paratropical forests in lowlands/coasts of the Wilkes Land margin with temperate forests likely occupying the higher-elevation hinterlands.

But also …

Organic terrestrial (MTB/CBT) and marine (TEX86) paleothermometry: MWT: ~11ºC MST: ~21ºC

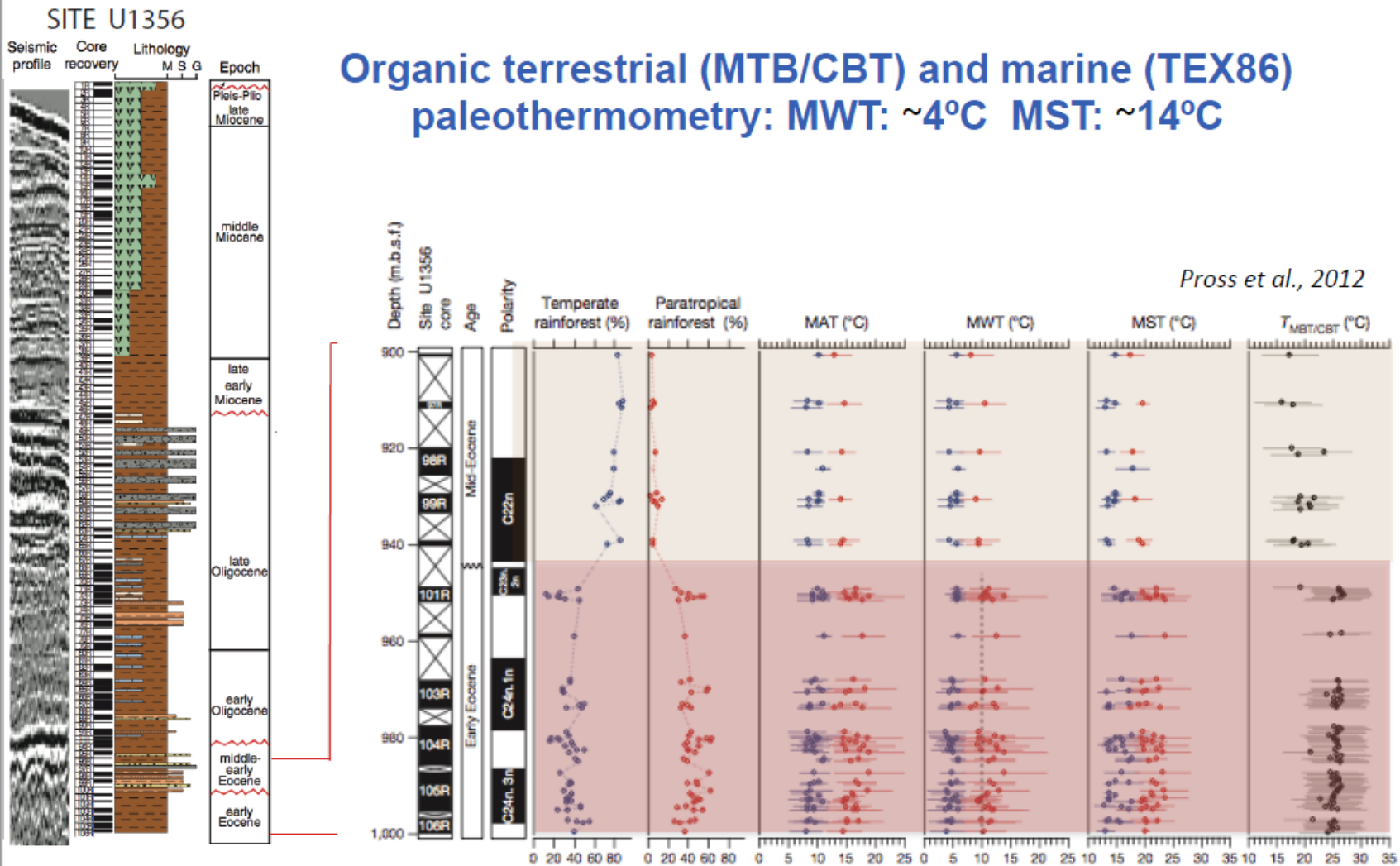


Latest early to middle EOCENE (49-46 Ma): temperate forests

Sporomorphs provide evidence for l. and m. Eocene temperate *Nothofagus and Araucaria araucana* forests in lowlands/coasts of the Wilkes Land margin

But also …

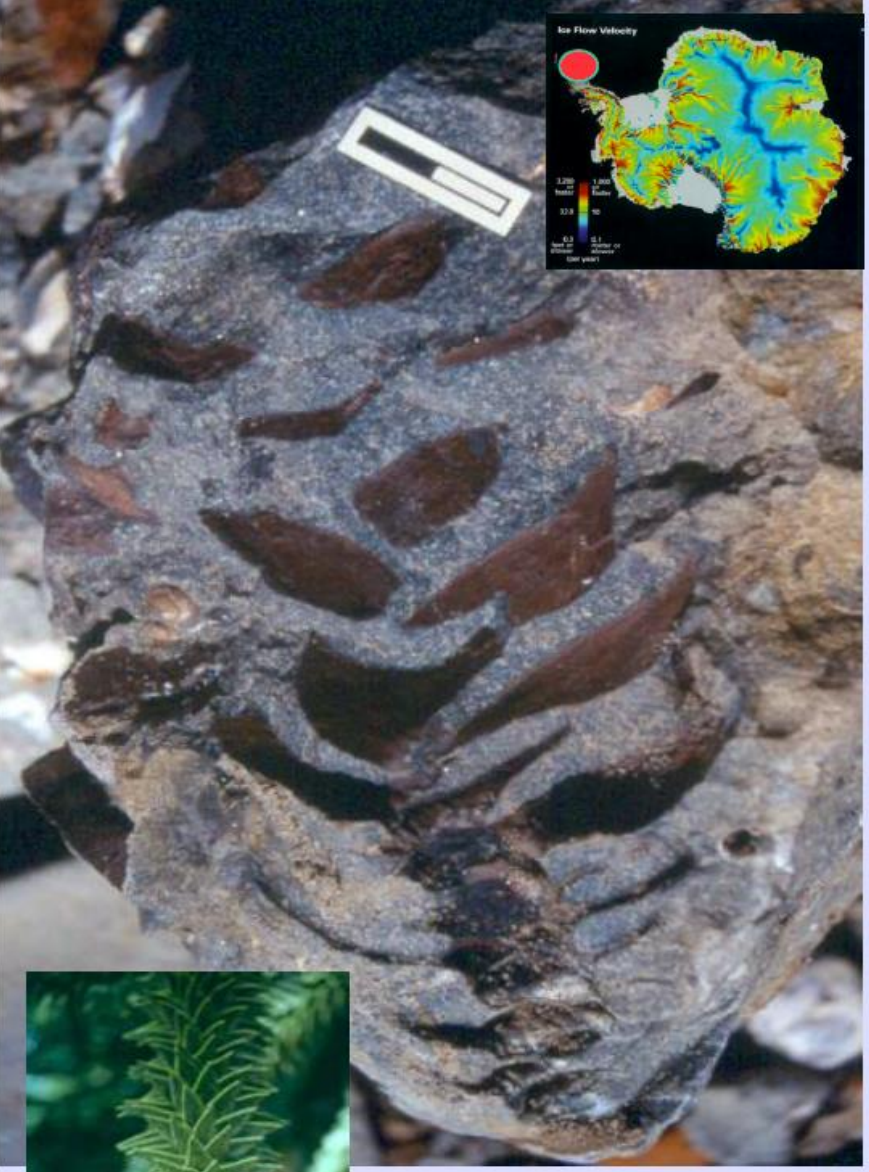
Organic terrestrial (MTB/CBT) and marine (TEX86) paleothermometry: MWT: ~4ºC MST: ~14ºC



Pross et al., 2012

3D preservation of conifer branches in concretions

middle Eocene



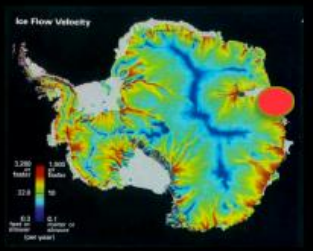
Araucaria araucana

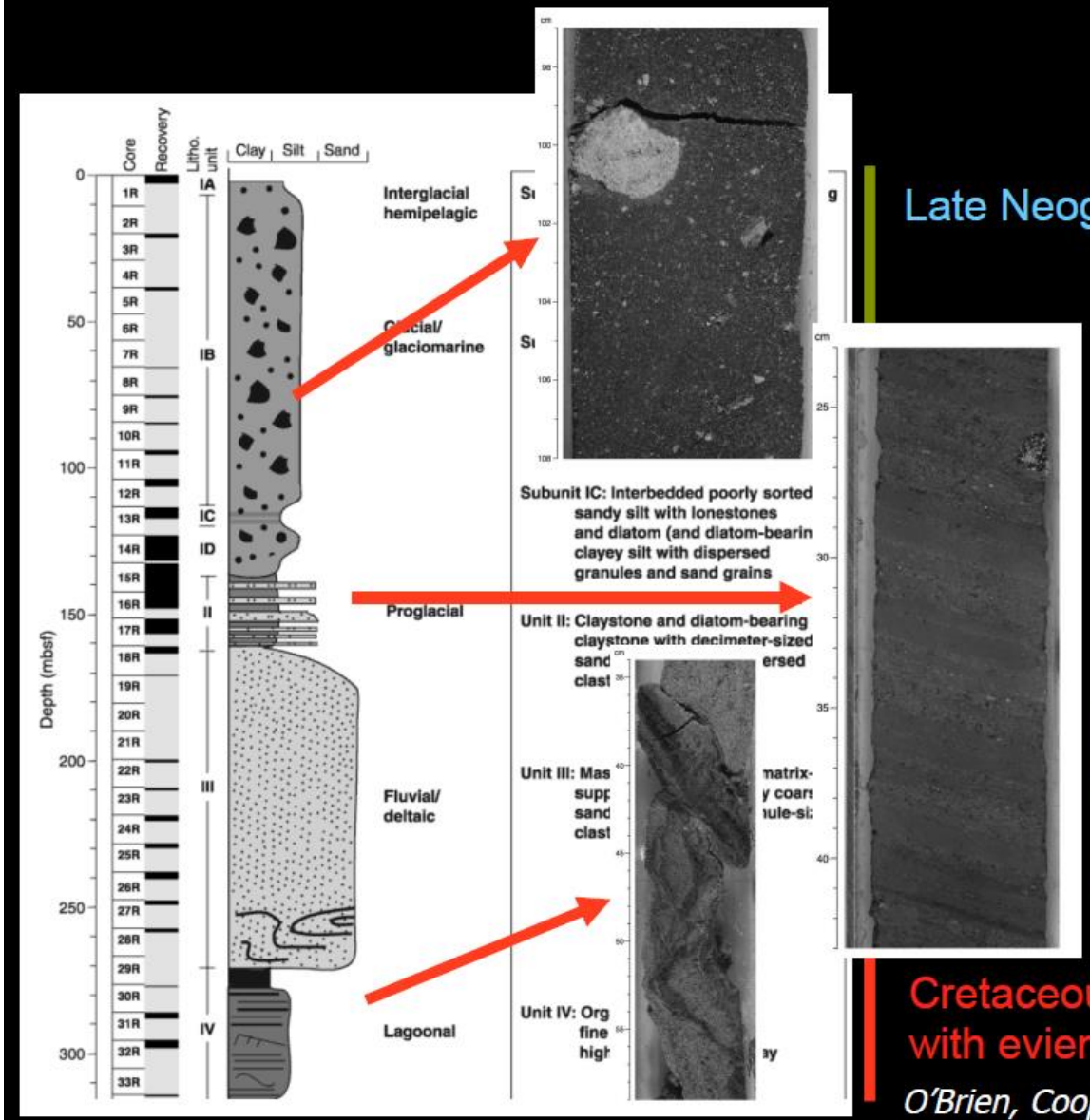
NLE *Araucaria araucana,* Monkey Puzzle, Chilean Andes, can withstand cool climates with snow

Slide courtesy of Jane Francis R. Stephens PhD

Ocean Drilling Program Leg 188, Prydz Bay:

Cooling trend recorded in changes in the sedimentary column





Late Neogene: cold!

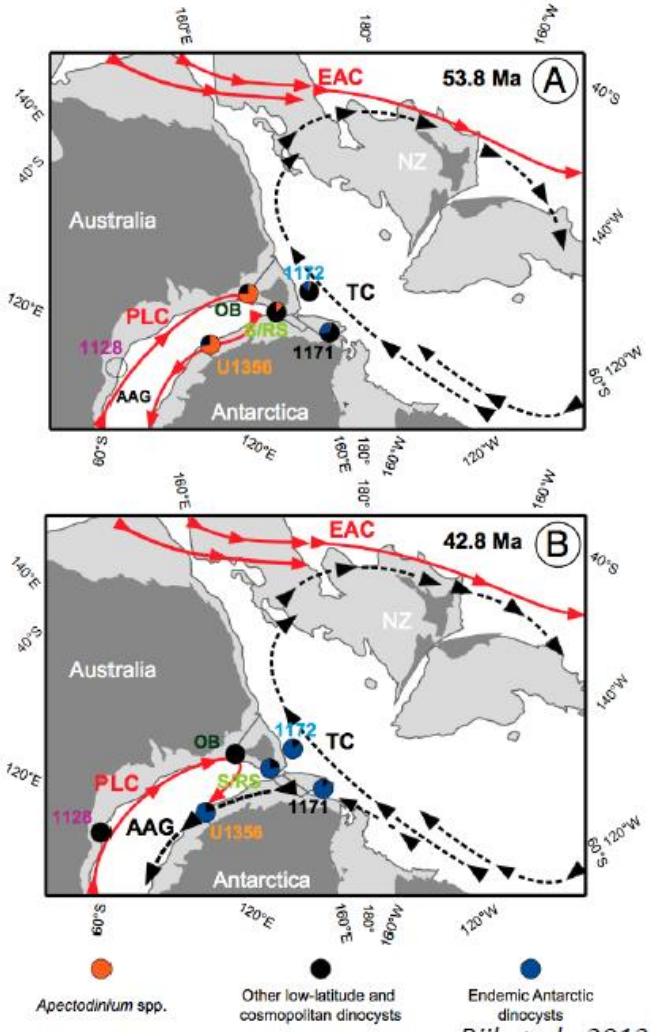
Ice sheet reaching the coastline: 35 Ma

m. Eocene (35-50 Ma): Cool environments: *Nothofagus*

Cretaceous (> 50 Ma): warm and with evience for connifers

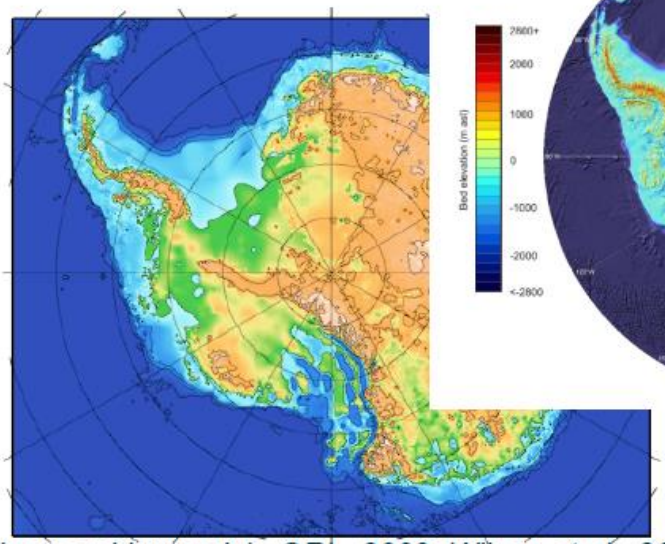
O'Brien, Cooper, Richter et al., 2001

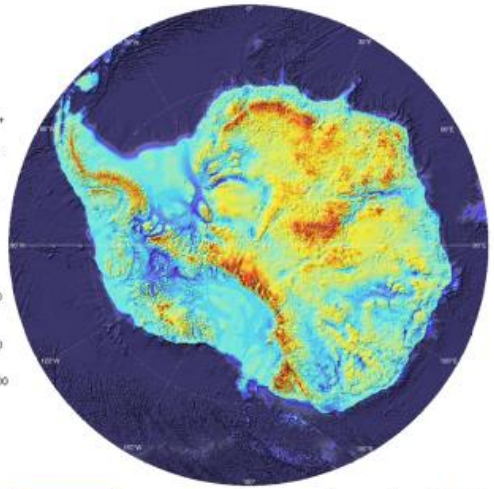
Eocene paleogeographic, paleoceanographic and paleotopographic reconstructions



Bjil et al., 2013

Bed corrected for ice load, thermal contraction, sedimentation, erosion, and horizontal motion



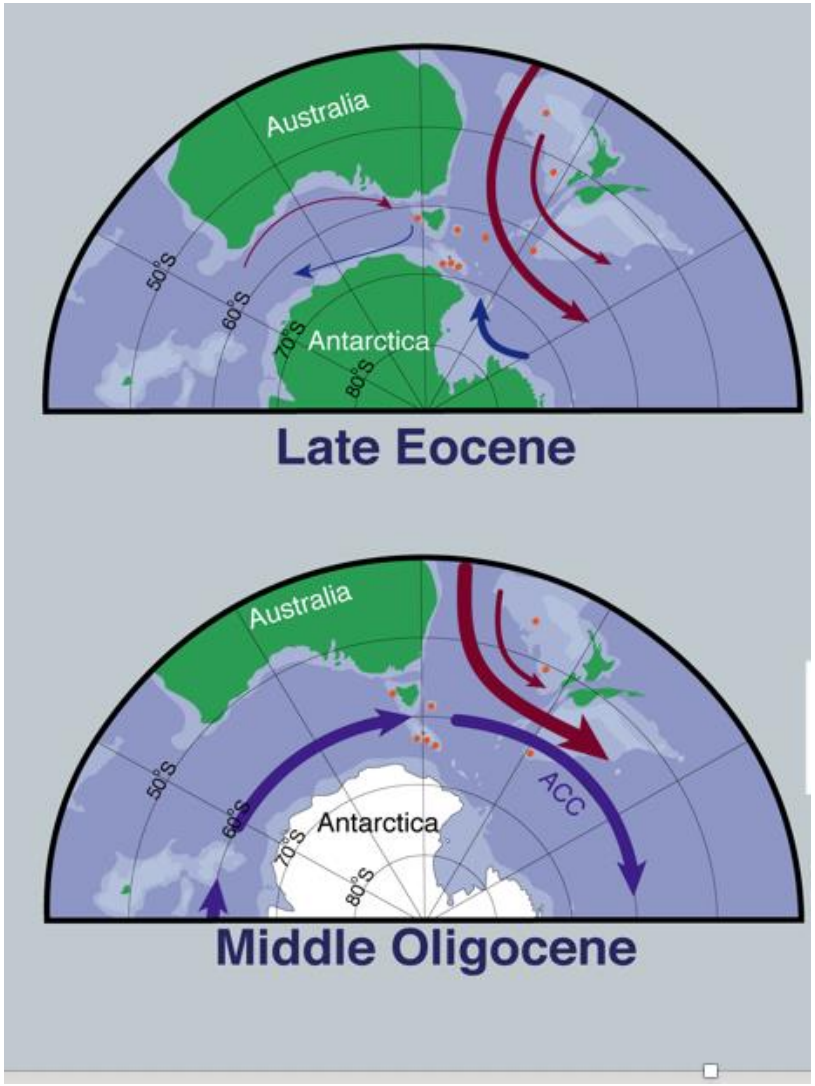


Fretwell et al., 2013

Wilson and Luyendyk, GRL, 2009; Wilson et al., 2012

-3000 -1000 -500 -250 0 250 500 750 1000 2000 3000

Total Antarctic land area in latest Eocene was 10–20% greater than generally assumed.



Ocean Gateway Hypothesis

Warm Eocene
Ice free continent

Opening of the Tasmanian Gateway during the Eocene/Oligocene transition

Initiation of Circum Antarctic Current

Thermal isolation of Antarctica And Glacial Expansion

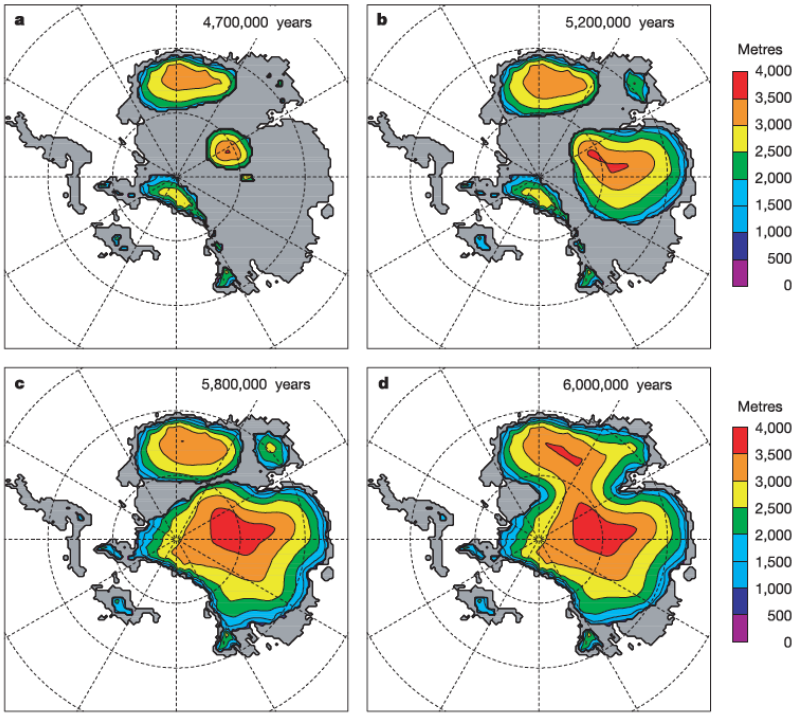
Atmopsheric carbon dioxide caused Antarctic glaciation
- *DeConto & Pollard's hypothesis*

letters to nature

Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2

Robert M. DeConto* & David Pollard†

** Department of Geosciences, University of Massachusetts, Amherst, Massachusetts 01003, USA*
† EMS Environment Institute, The Pennsylvania State University, University Park, Pennsylvania 16802, USA

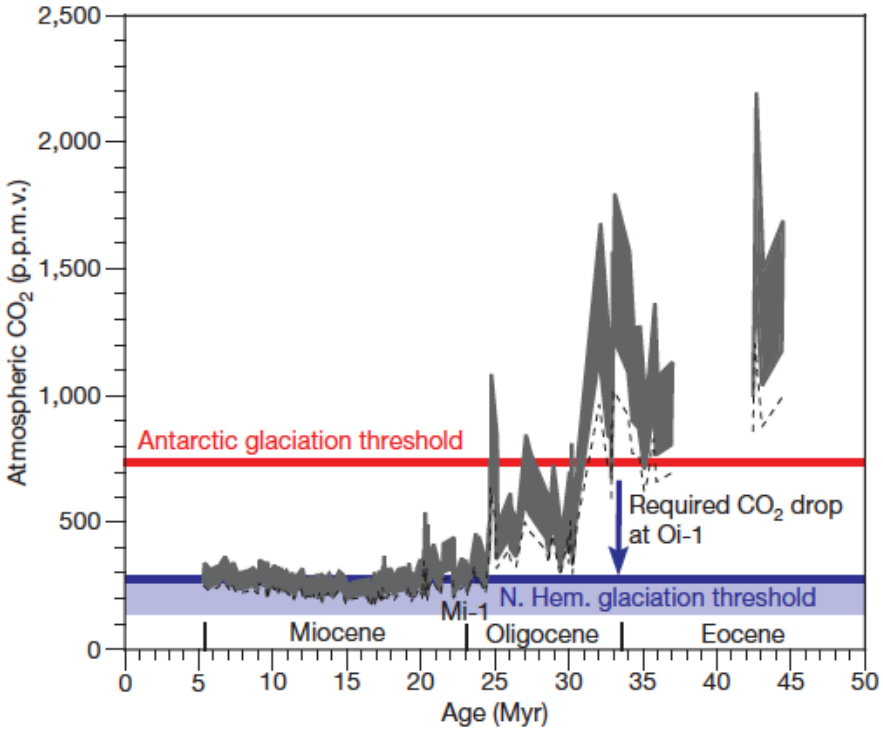


nature Vol 455|2 October 2008|doi:10.1038/nature07337

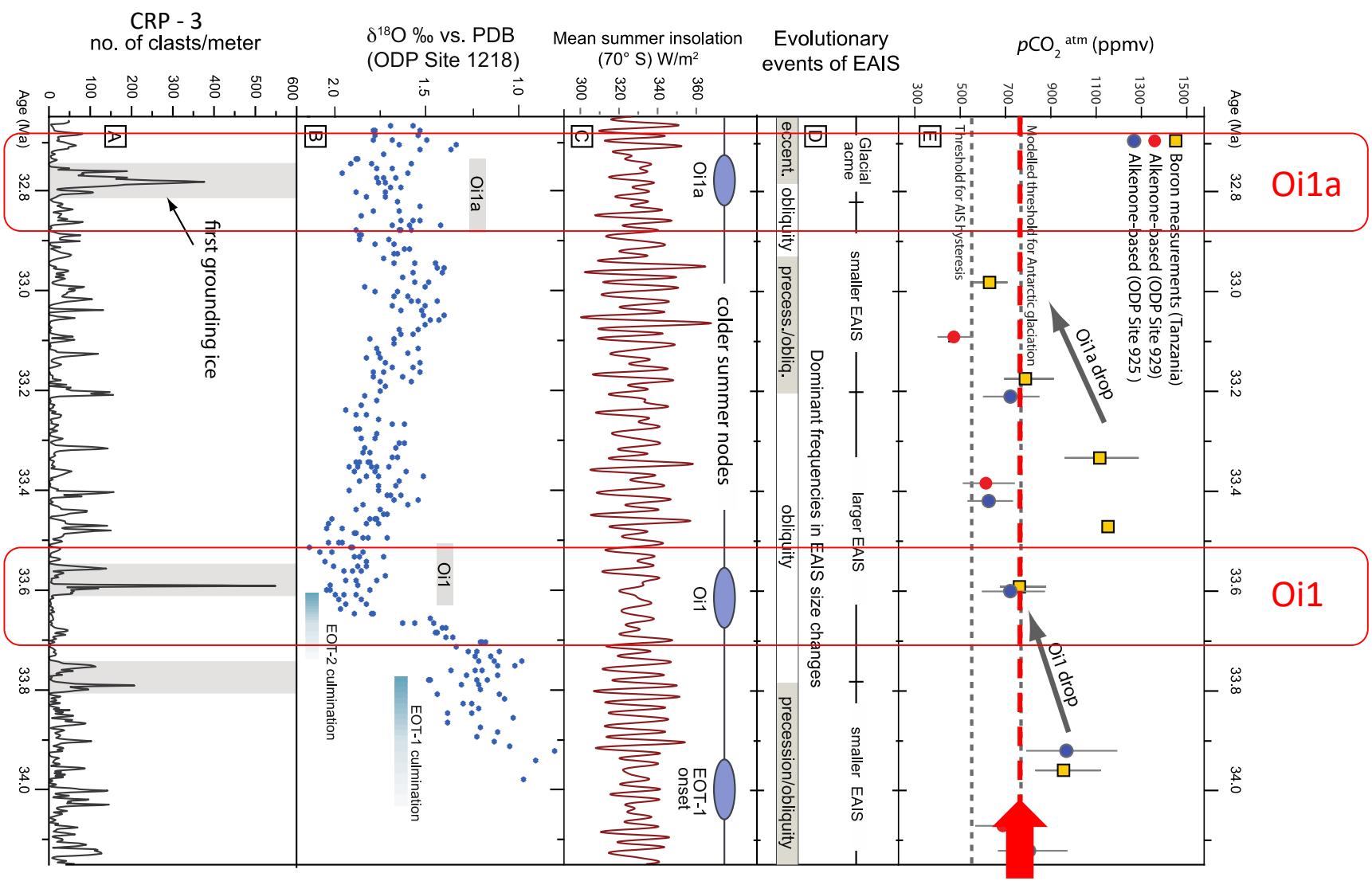
LETTERS

Thresholds for Cenozoic bipolar glaciation

Robert M. DeConto[1], David Pollard[2], Paul A. Wilson[3], Heiko Pälike[3], Caroline H. Lear[4] & Mark Pagani[5]

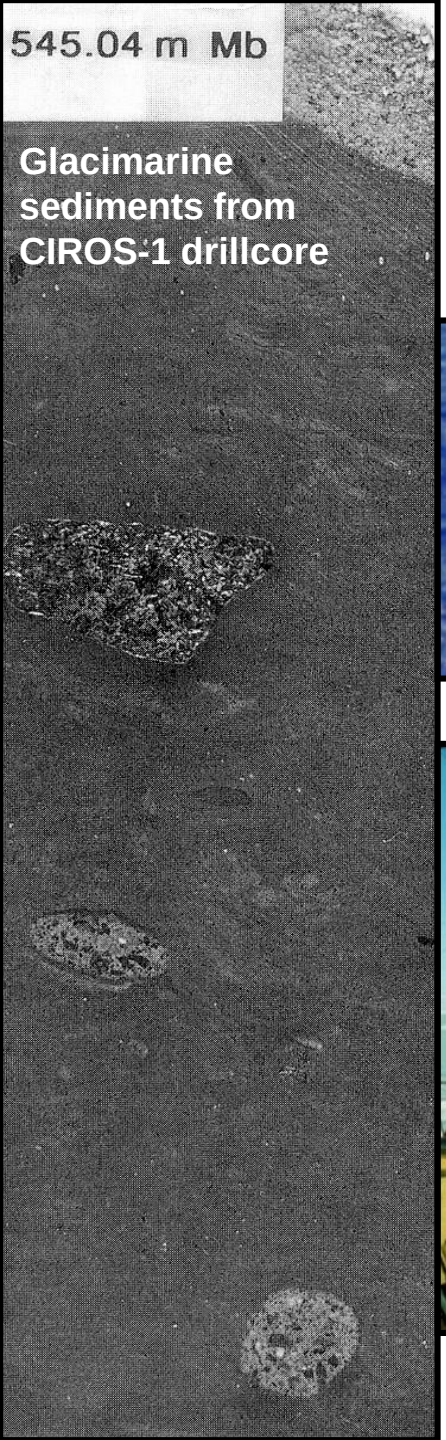


CO_2 threshold delays continental scale glaciation until Oi1a



Galeotti, DeConto, Naish, Stocchi et al. (2016, Science)

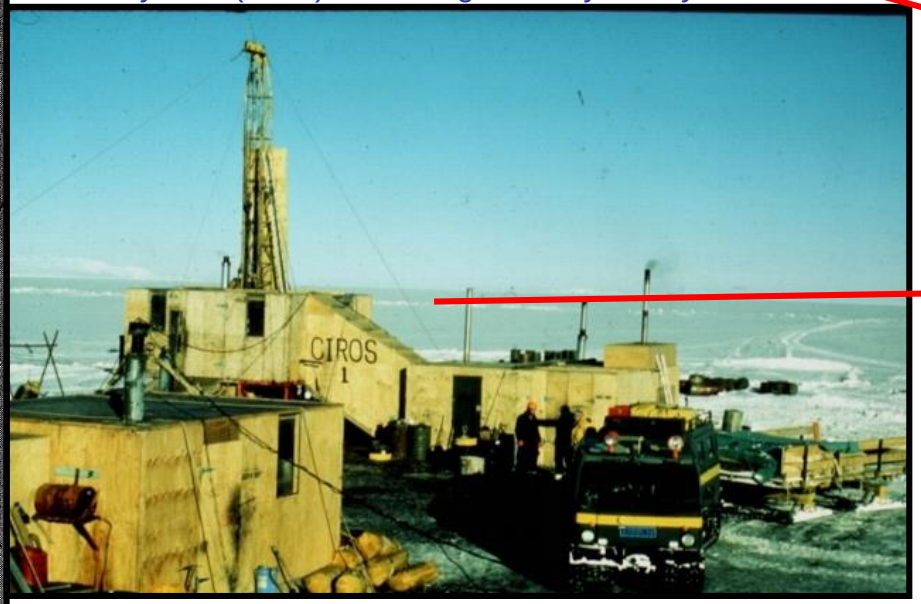
800ppm CO_2 threshold not permanently crossed until Oi1a

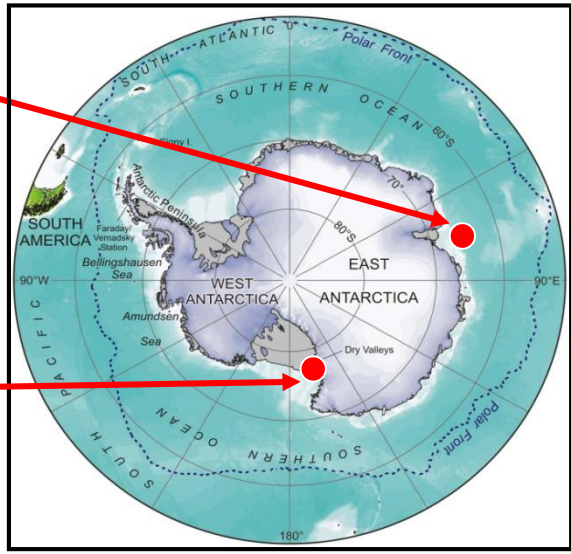


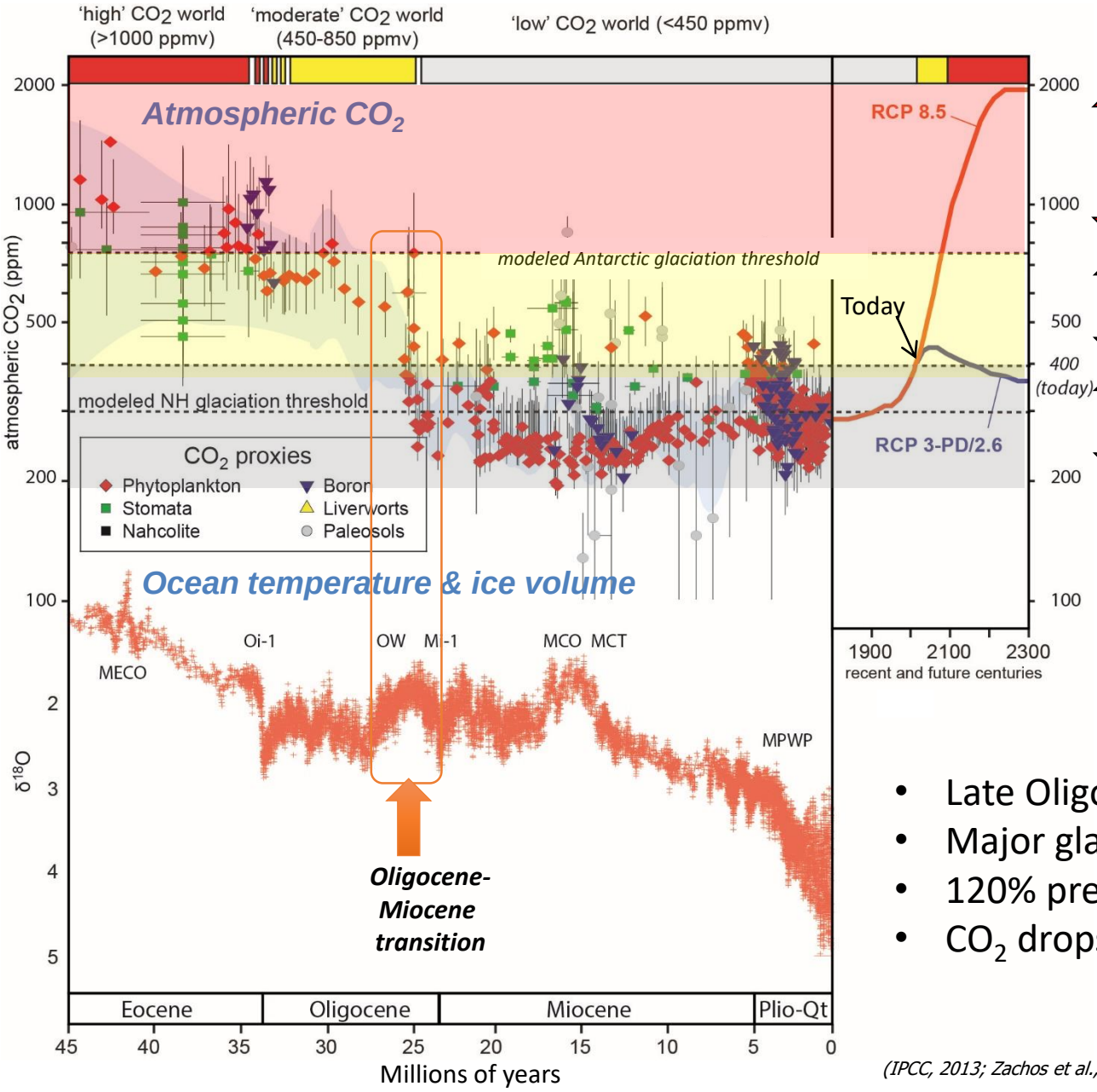
Glacimarine sediments from CIROS-1 drillcore

Proximal sedimentary evidence for earliest Oligocene Antarctic glaciation

Hambrey et al (1991), ODP Leg 119, Prydz Bay







Ice free Antarctica
(>1000ppm CO_2, +8 to 12°C)

Dynamic terrestrial EAIS
(750-400ppm CO_2, +4 to 8°C)

Dynamic marine-based EAIS/WAIS
(400-200ppm CO_2, -5 to+3°C)

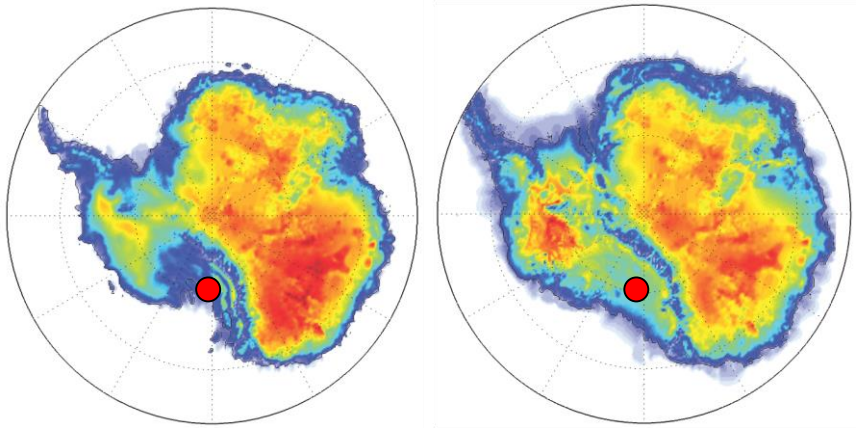
- Late Oligocene warm?
- Major glaciation in early Miocene
- 120% present day ice volume
- CO_2 drops below 400ppm

(IPCC, 2013; Zachos et al., 2008, DeConto et al., 2010)

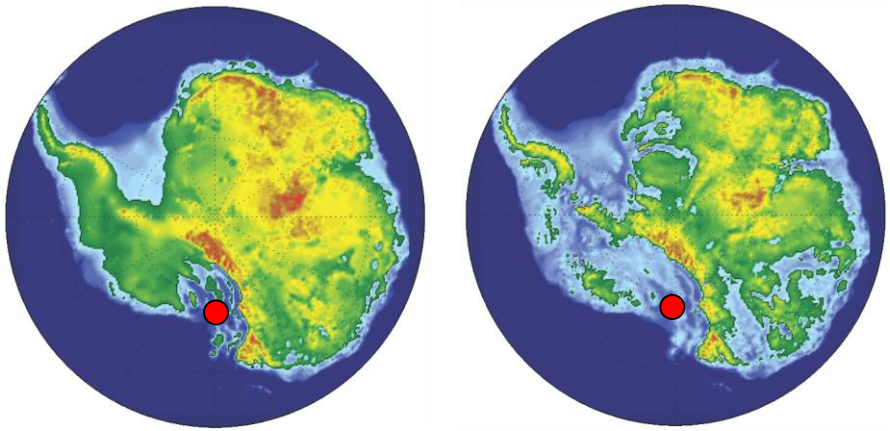
Oligocene – Miocene boundary climate transition summary

Early Oligocene *Early Miocene*

Glacial maximum ice extent

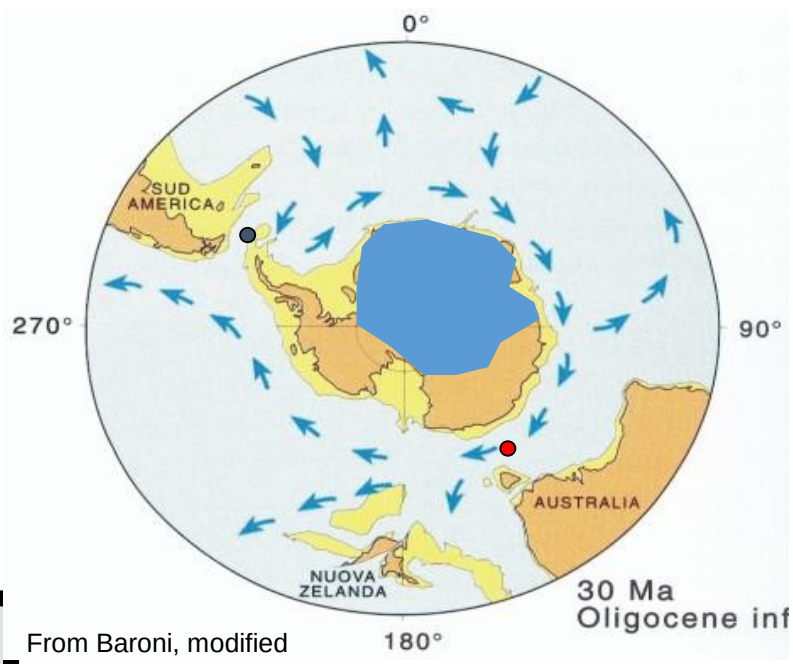


Bedrock topography reconstruction

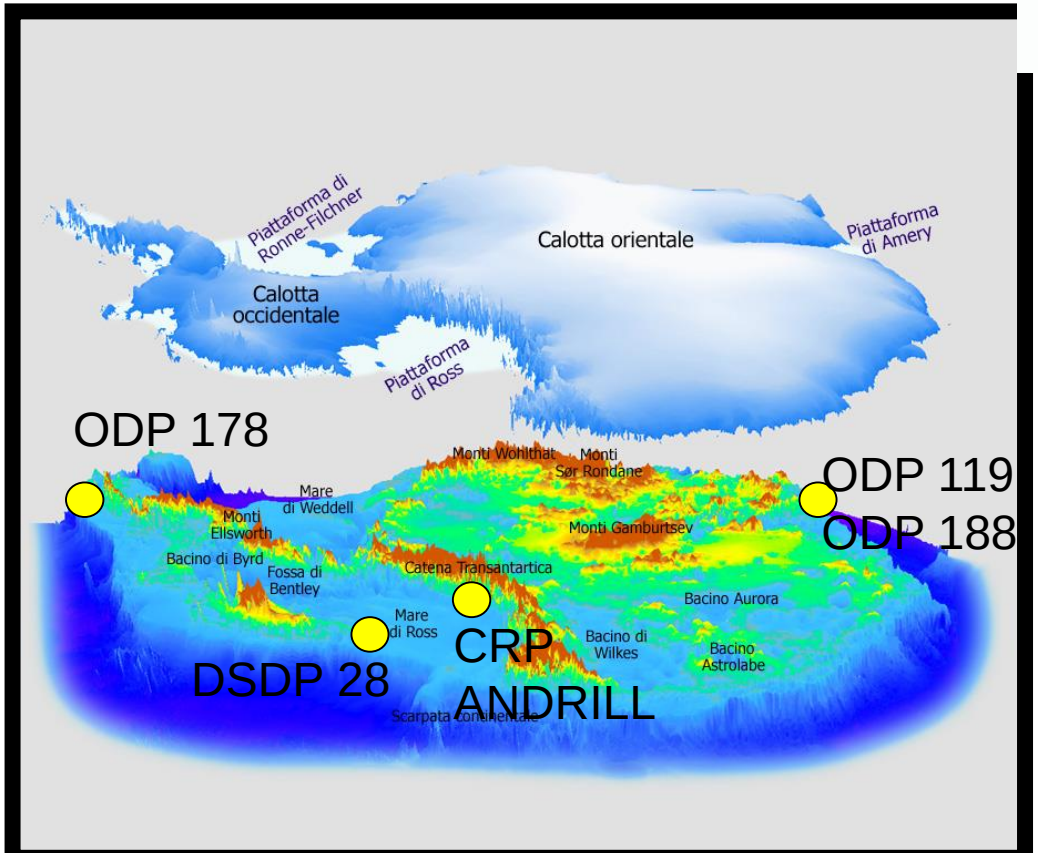


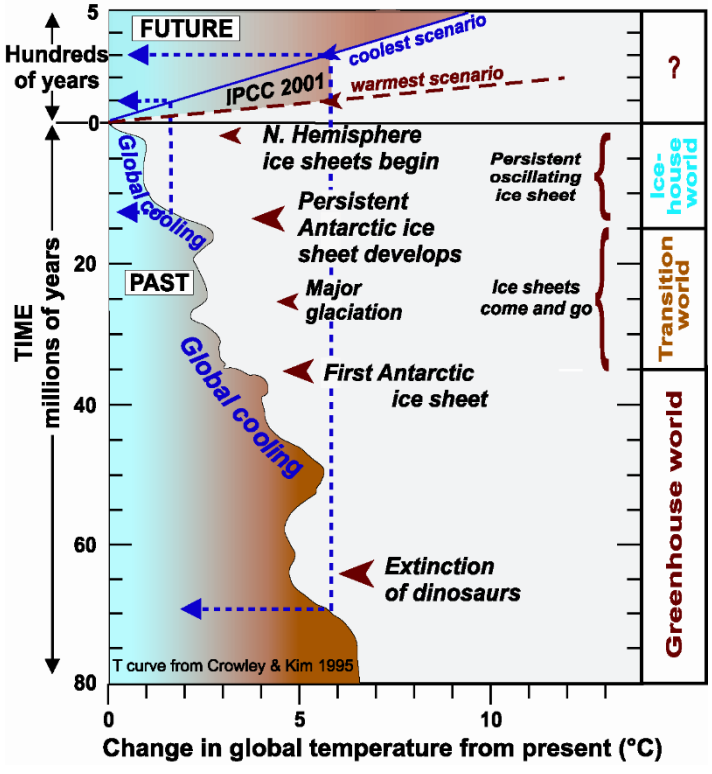
- Regional tectonic subsidence
- Atmospheric CO_2 drops below 400 ppm
- Up to 60m global sea-level fall
- -2-3°C bottom water temperature
- ***CO_2 Threshold crossed for growth of marine-based ice sheets***

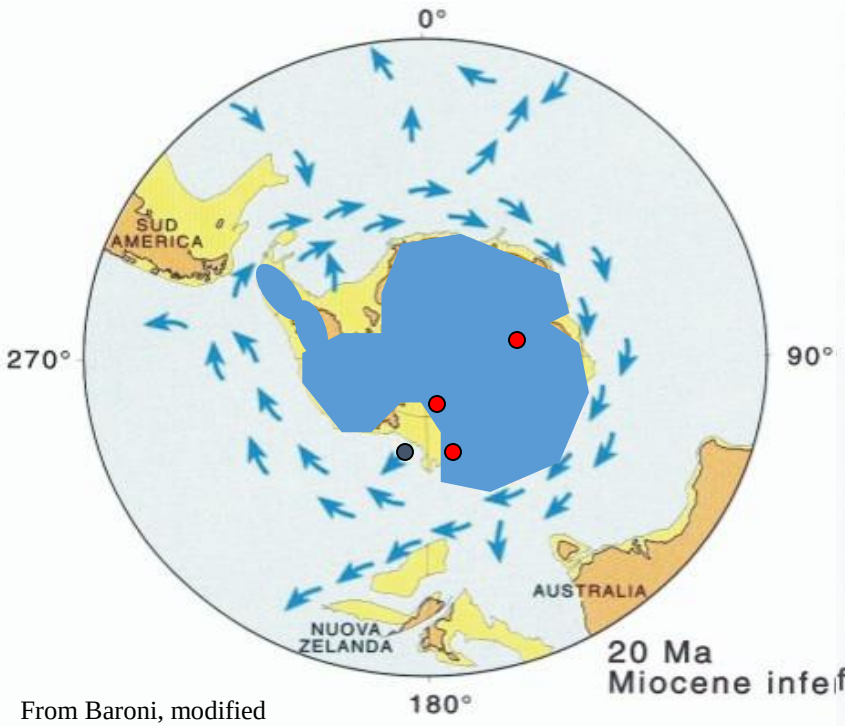
Transitional world



From Baroni, modified







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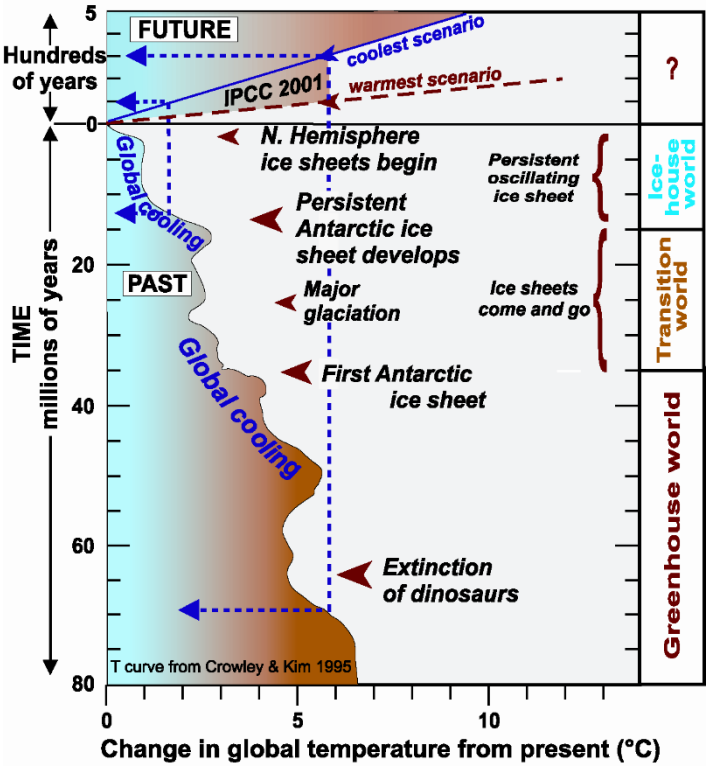
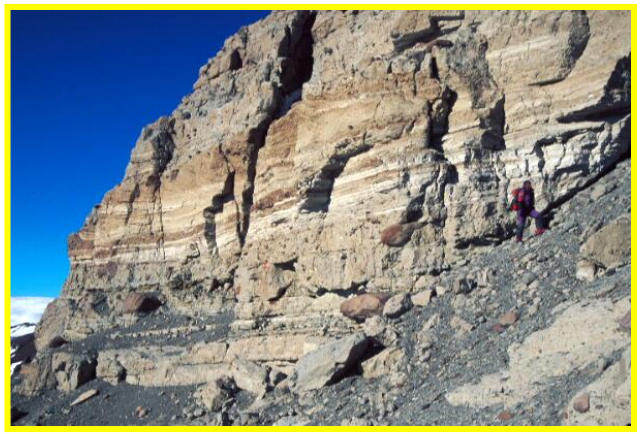
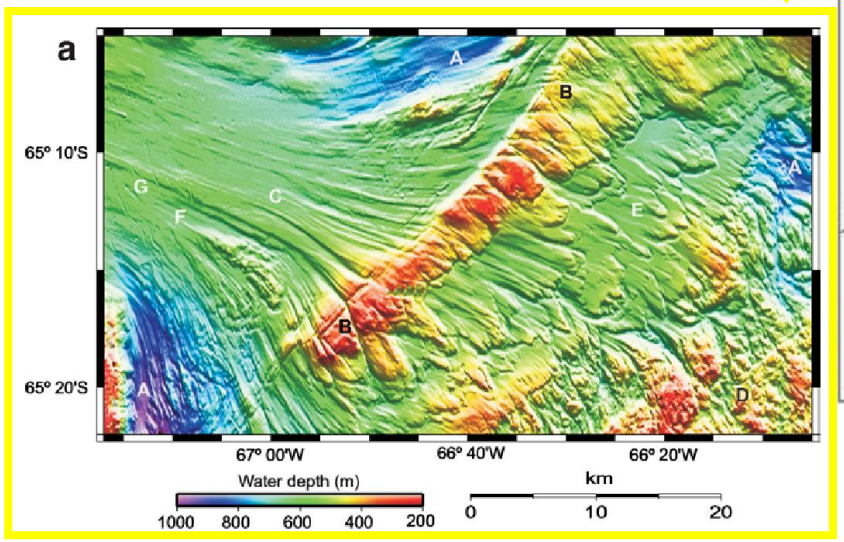
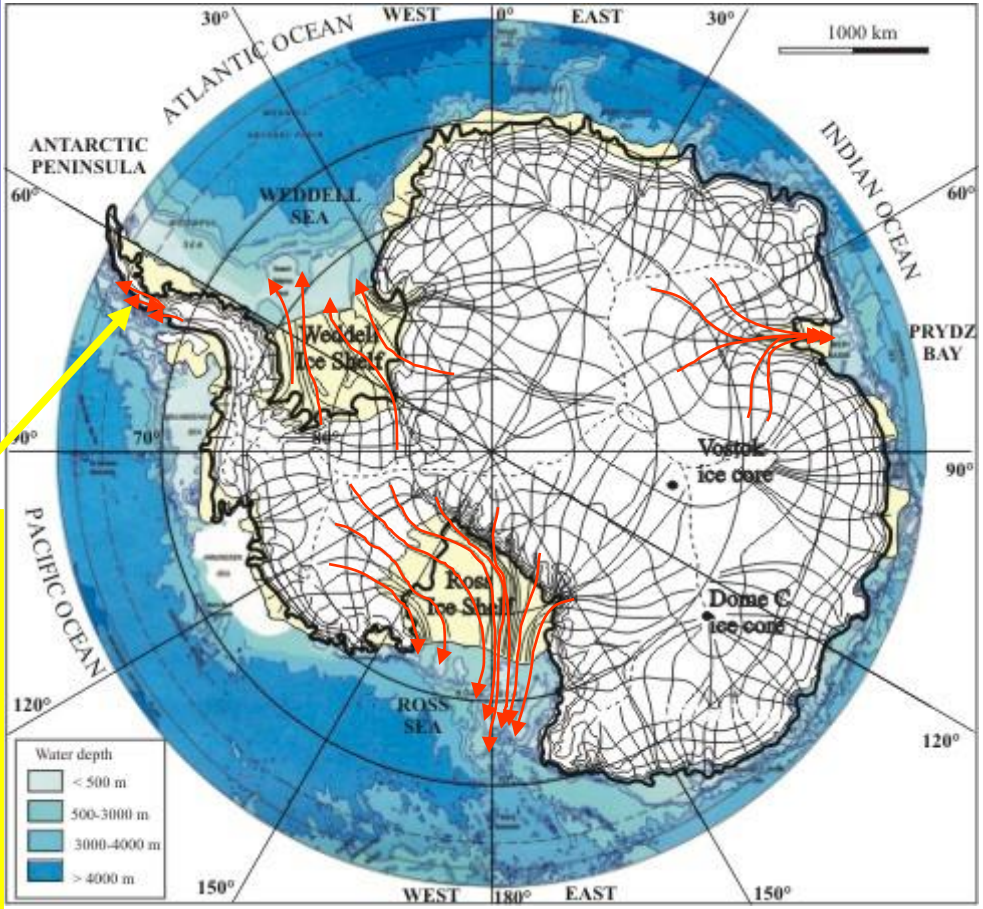
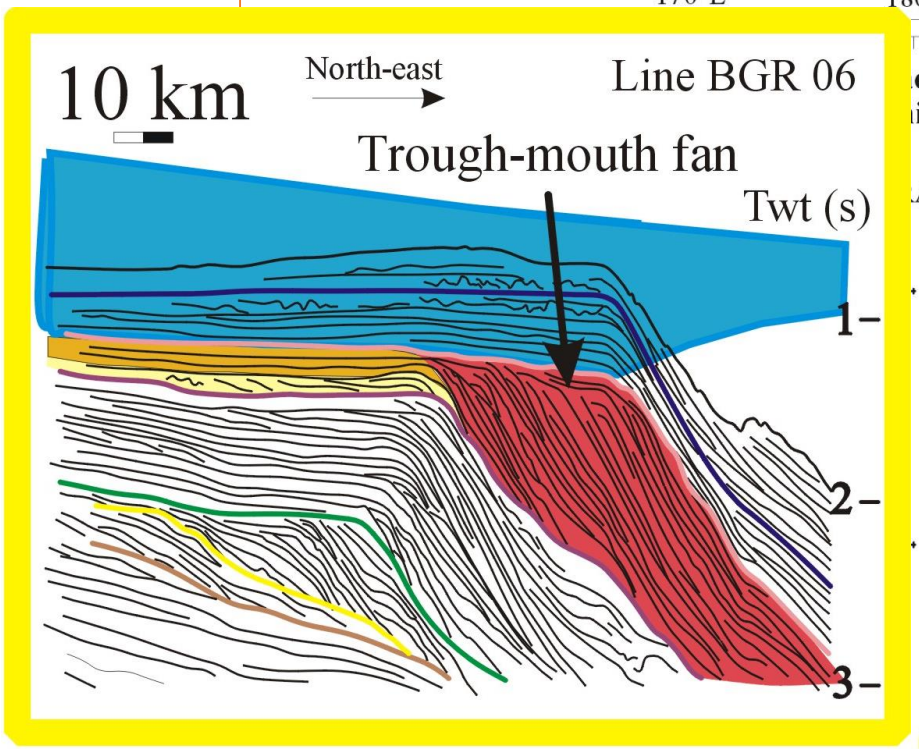


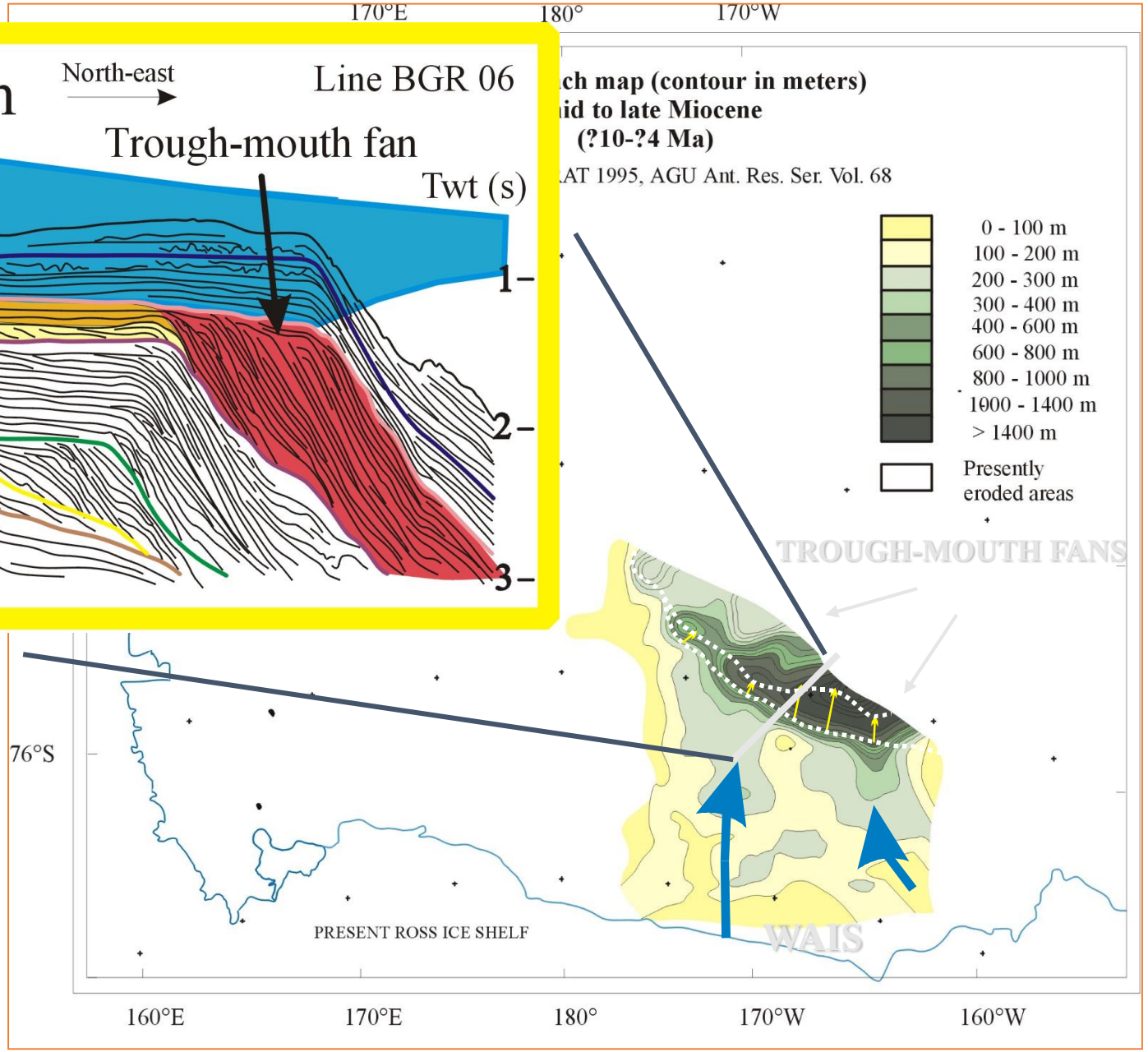


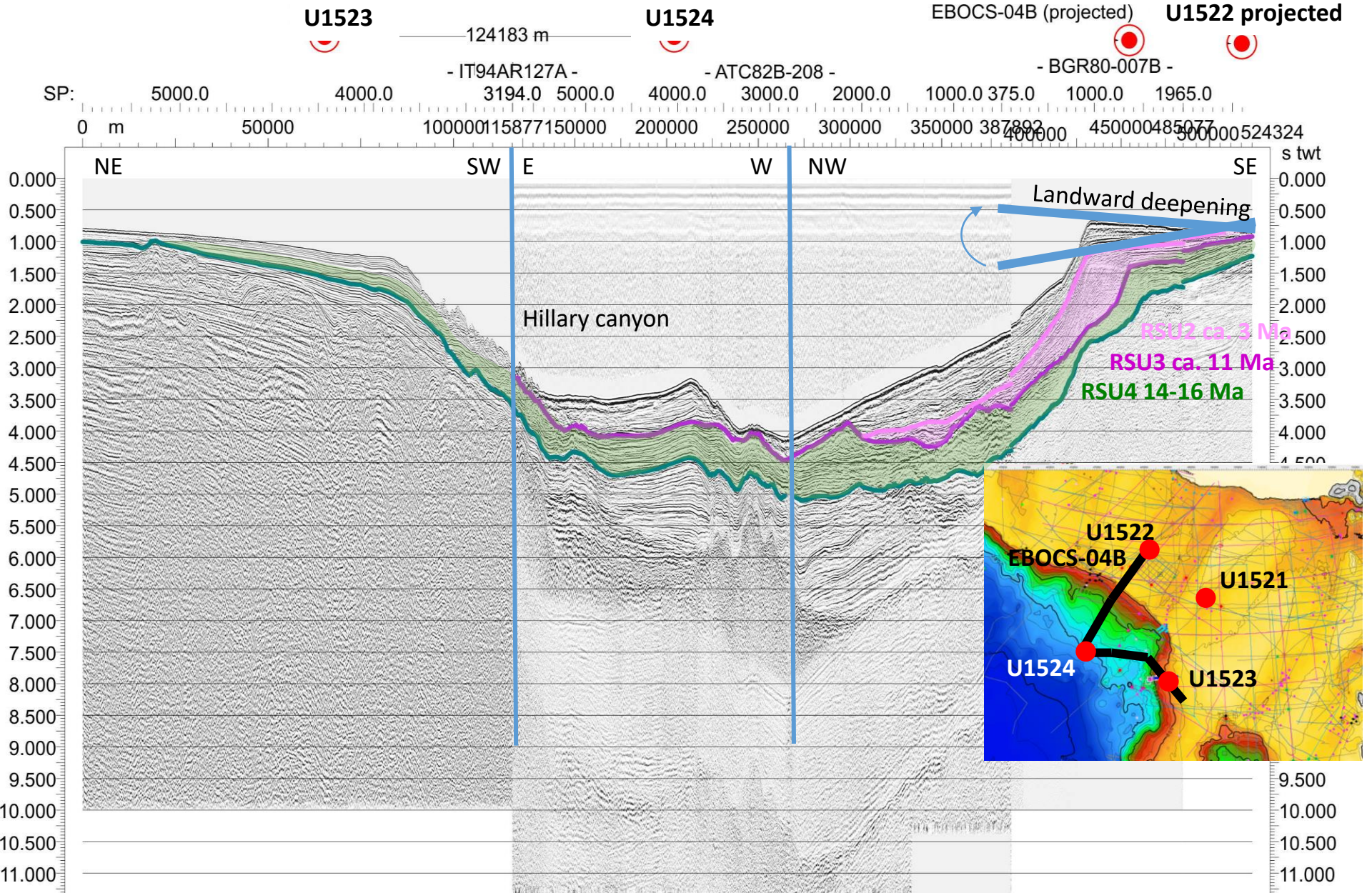
Sirius Formation - Foto by D. Harwood

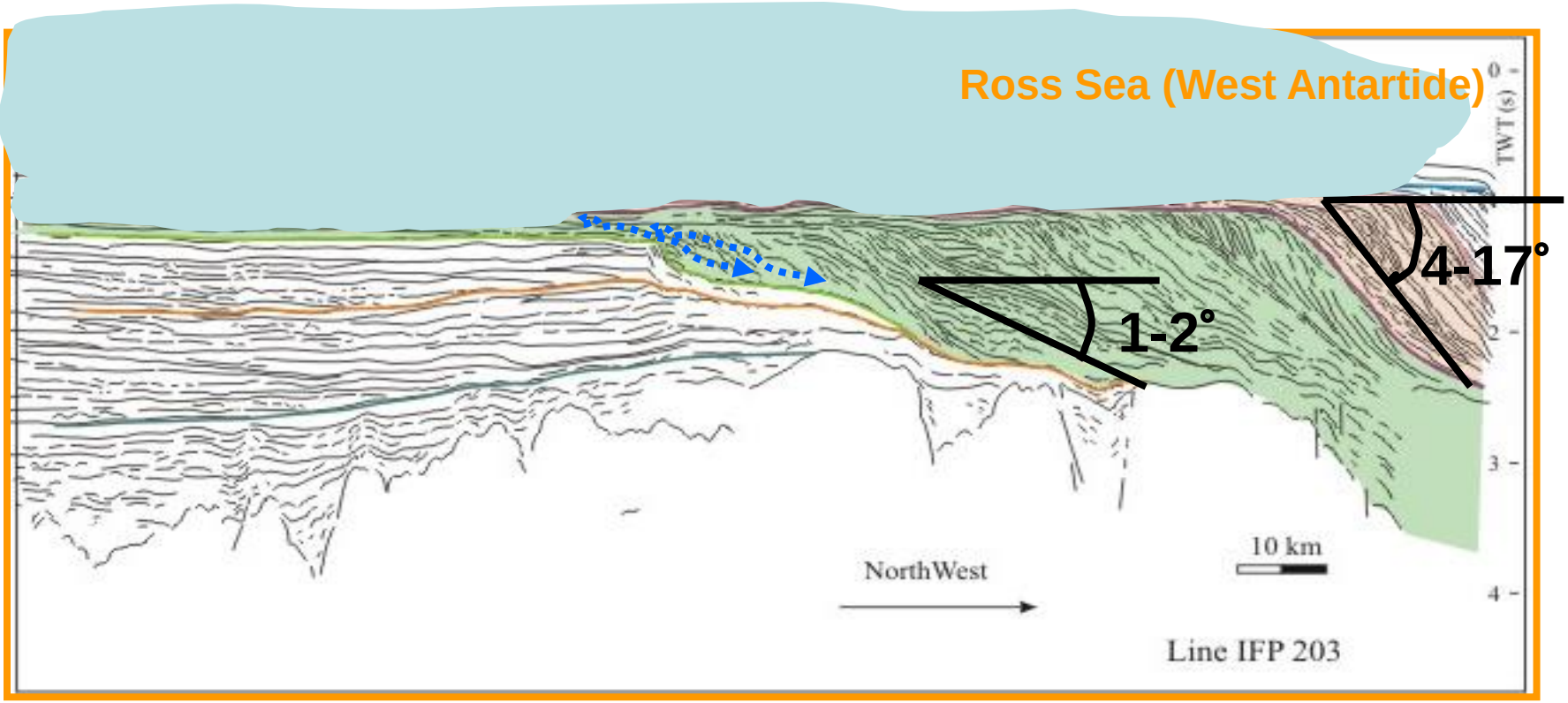

a
A
B
C
D
E
F
G
65° 10'S
65° 20'S
67° 00'W
66° 40'W
66° 20'W
Water depth (m)
1000 800 600 400 200
km
0 10 20

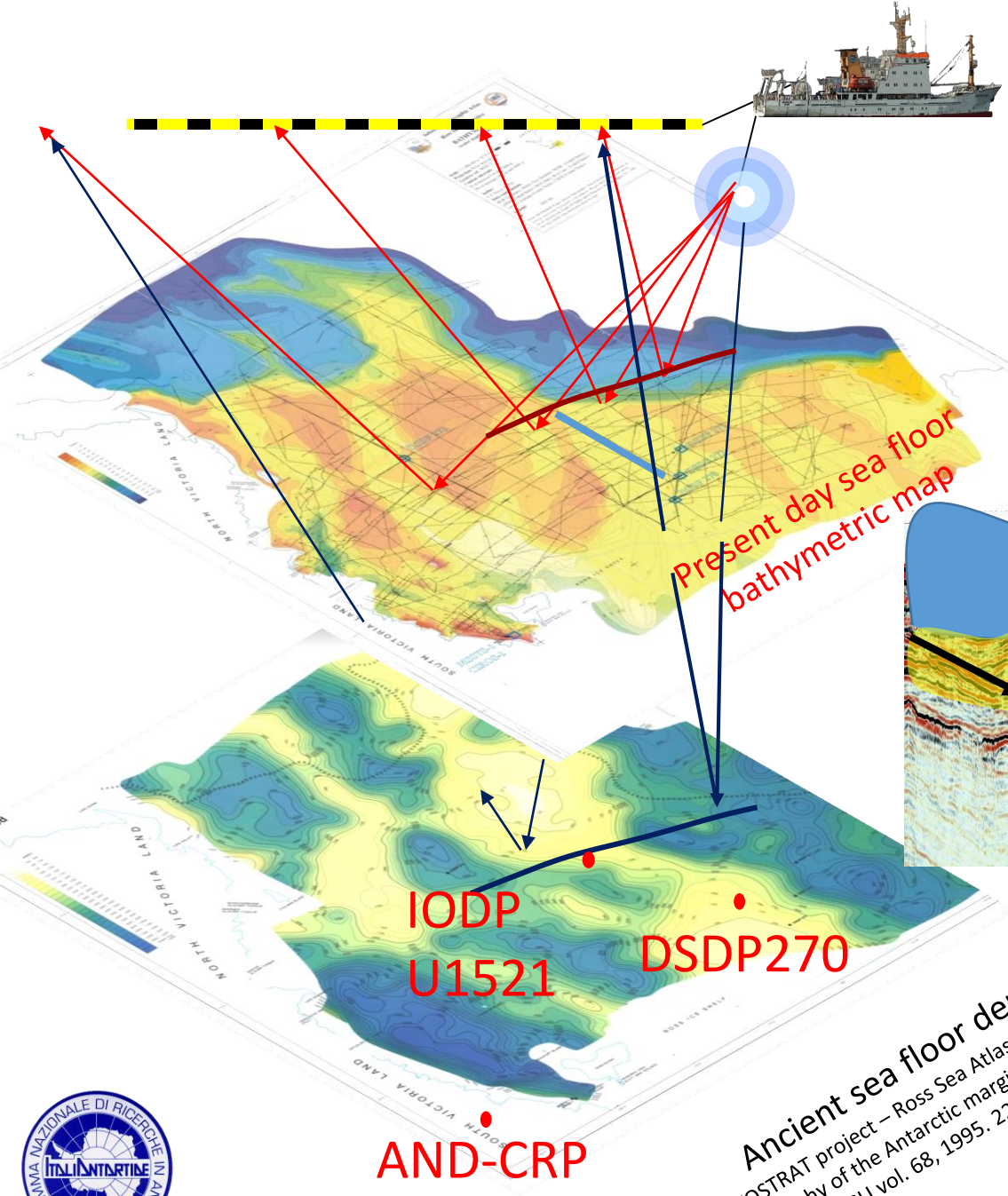

ATLANTIC OCEAN
WEST
EAST
INDIAN OCEAN
PACIFIC OCEAN
ANTARCTIC PENINSULA
WEDDELL SEA
Weddell Ice Shelf
Ross Ice Shelf
ROSS SEA
Vostok ice core
Dome C ice core
PRYDZ BAY
1000 km
30°
60°
90°
120°
150°
180°
Water depth
< 500 m
500-3000 m
3000-4000 m
> 4000 m


10 km
North-east
Line BGR 06
Trough-mount fan
Twt (s)
1
2
3


170°E
180°
170°W
ch map (contour in meters)
id to late Miocene
(?10-?4 Ma)
AT 1995, AGU Ant. Res. Ser. Vol. 68
0 - 100 m
100 - 200 m
200 - 300 m
300 - 400 m
400 - 600 m
600 - 800 m
800 - 1000 m
1000 - 1400 m
> 1400 m
Presently
eroded areas
TROUGH-MOUTH FANS
76°S
PRESENT ROSS ICE SHELF
WAIS
160°E
170°E
180°
170°W
160°W

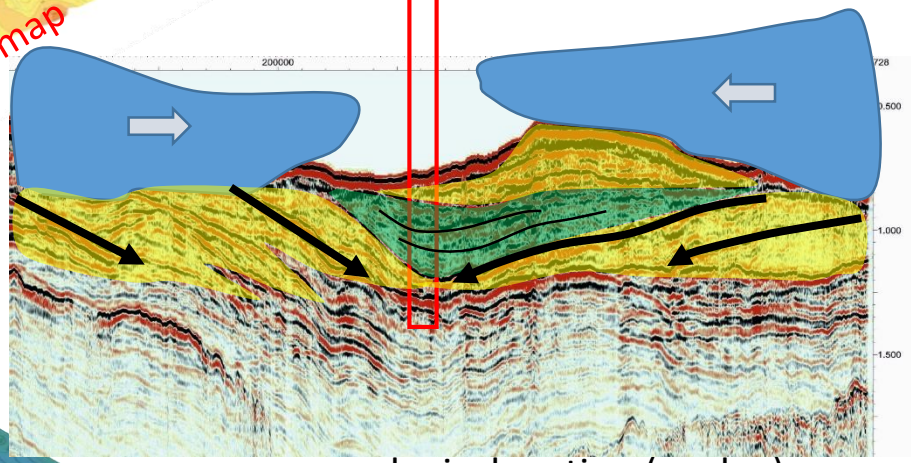

U1523
124183 m
U1524
EBOCS-04B (projected)
U1522 projected
- IT94AR127A -
- ATC82B-208 -
- BGR80-007B -
SP:
5000.0
4000.0
3194.0
5000.0
4000.0
3000.0
2000.0
1000.0
375.0
1000.0
1965.0
0 m
50000
100000
115877
150000
200000
250000
300000
350000
387892
400000
450000
485077
500000
524324
s twt
NE
SW
E
W
NW
SE
Landward deepening
Hillary canyon
RSU2 ca. 3 Ma
RSU3 ca. 11 Ma
RSU4 14-16 Ma
U1522
EBOCS-04B
U1521
U1524
U1523


Ross Sea (West Antartide)
TWT (s)
0
2
3
4
4-17°
1-2°
10 km
NorthWest
Line IFP 203



Seismic profile IT89-29

U1521

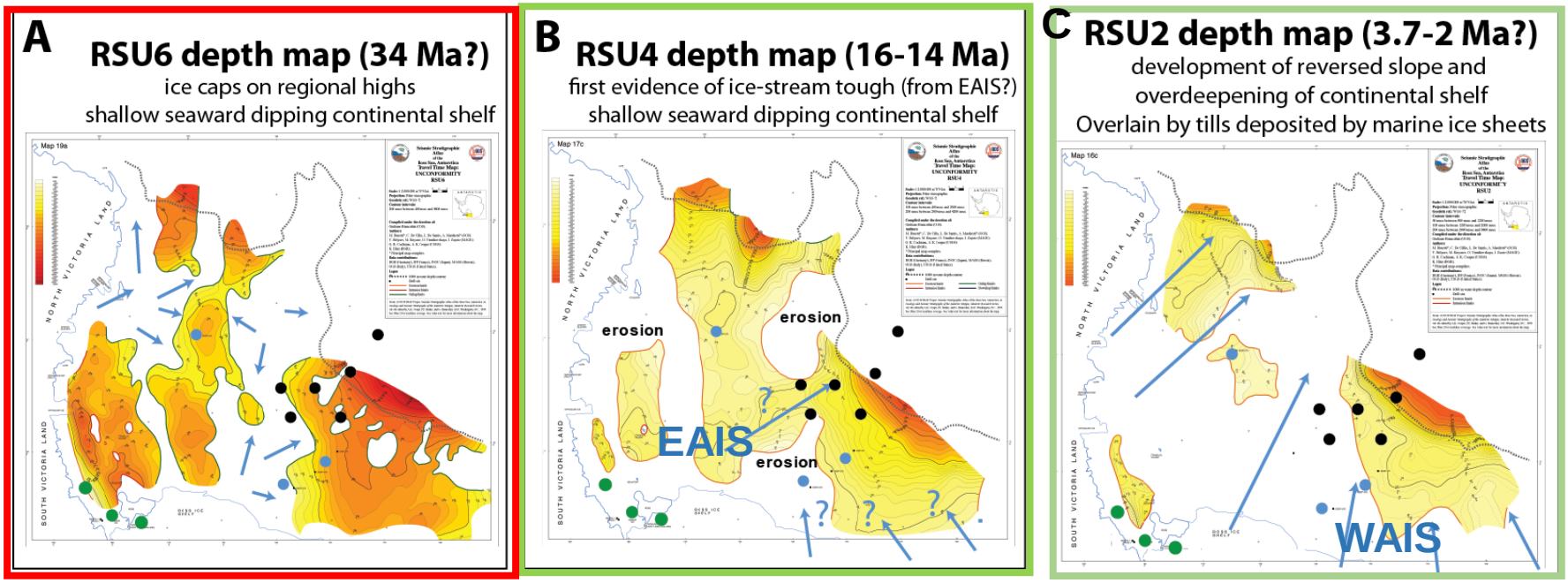


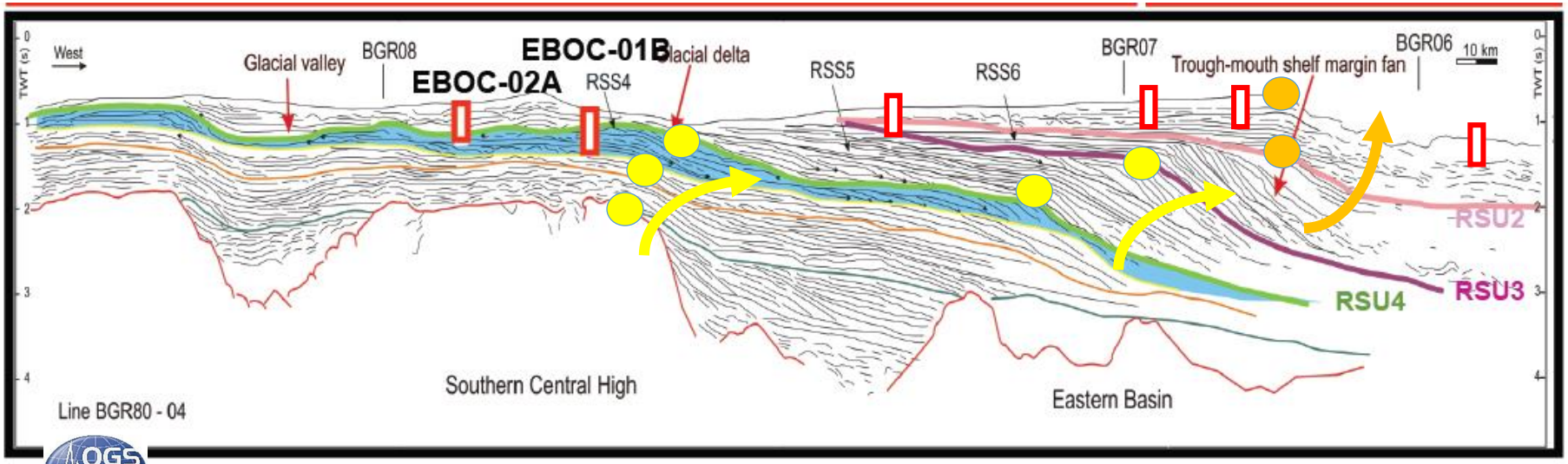
geological section (analog)

Ancient sea floor depth map.

ANTOSTRAT project – Ross Sea Atlas . Geology and Seimsic Stratigraphy of the Antarctic margin. In Cooper, Brancolini, Barker, AGU vol. 68, 1995. 22 maps and 2 CD Roms

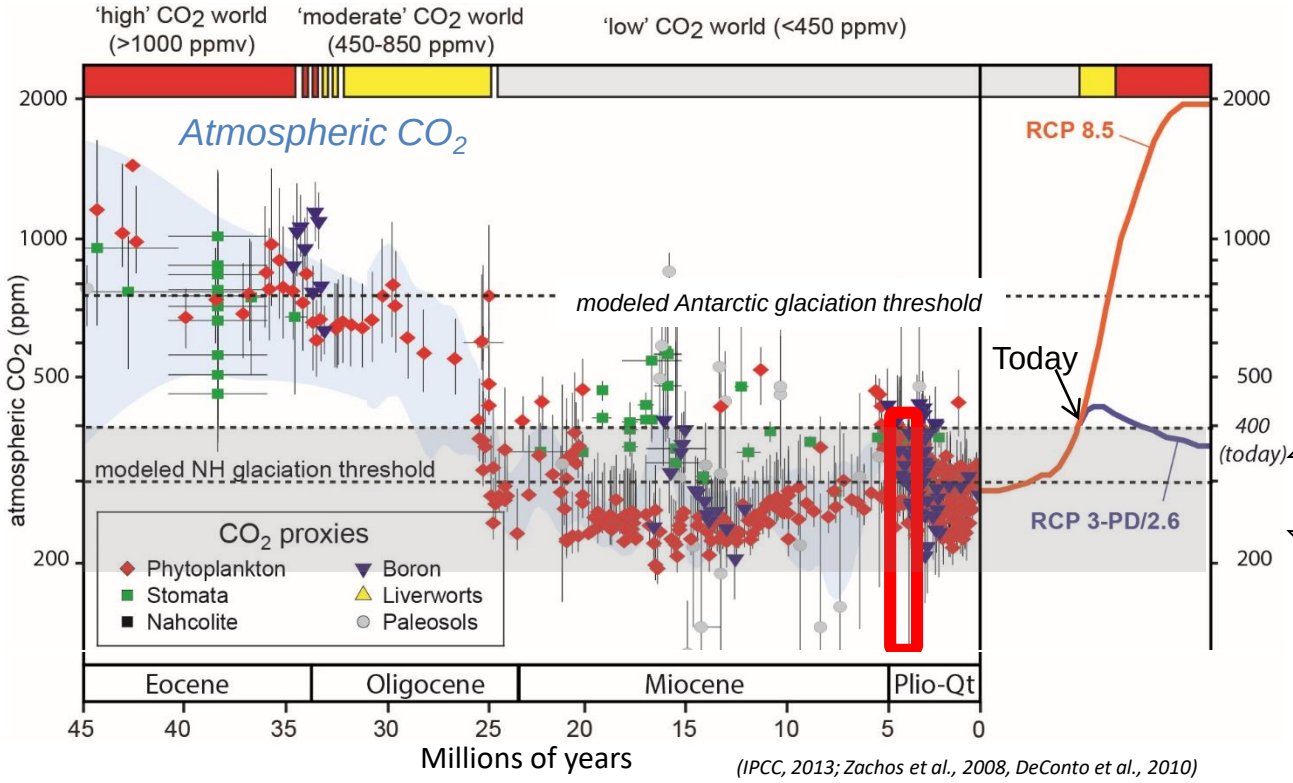
5. Reconstruct Eastern Ross Sea bathymetry to examine relationships between sea-floor geometry, ice sheet stability/instability, and global climate.





Brancolini et al., 1995; McKay et al., 2013

GLAISS provides model-data past simulations (when CO2 atmospheric content and temperature were higher) to predict Antarctic ice sheet future rate of changes

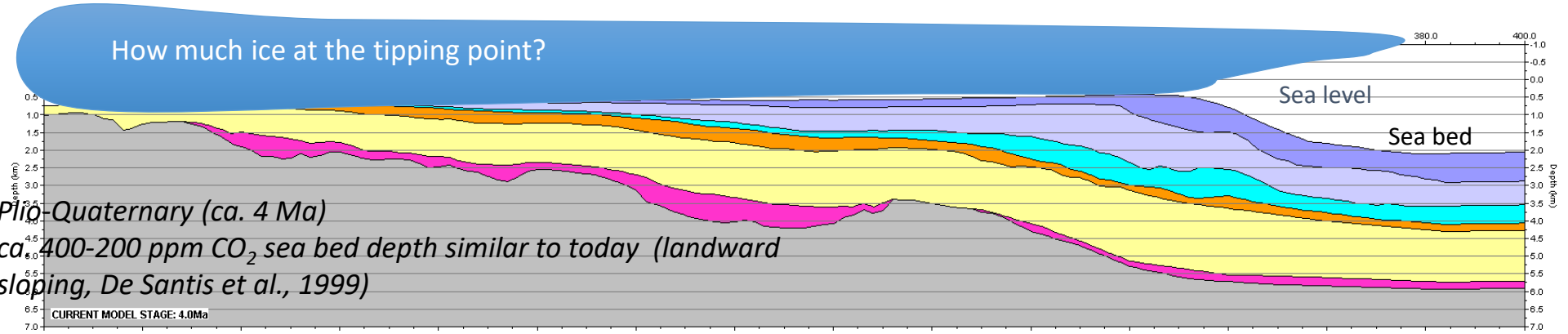


(IPCC, 2013; Zachos et al., 2008, DeConto et al., 2010)

RCP 8.5
(3.2-5.4 ° C >1000 ppm CO2 business as usual)

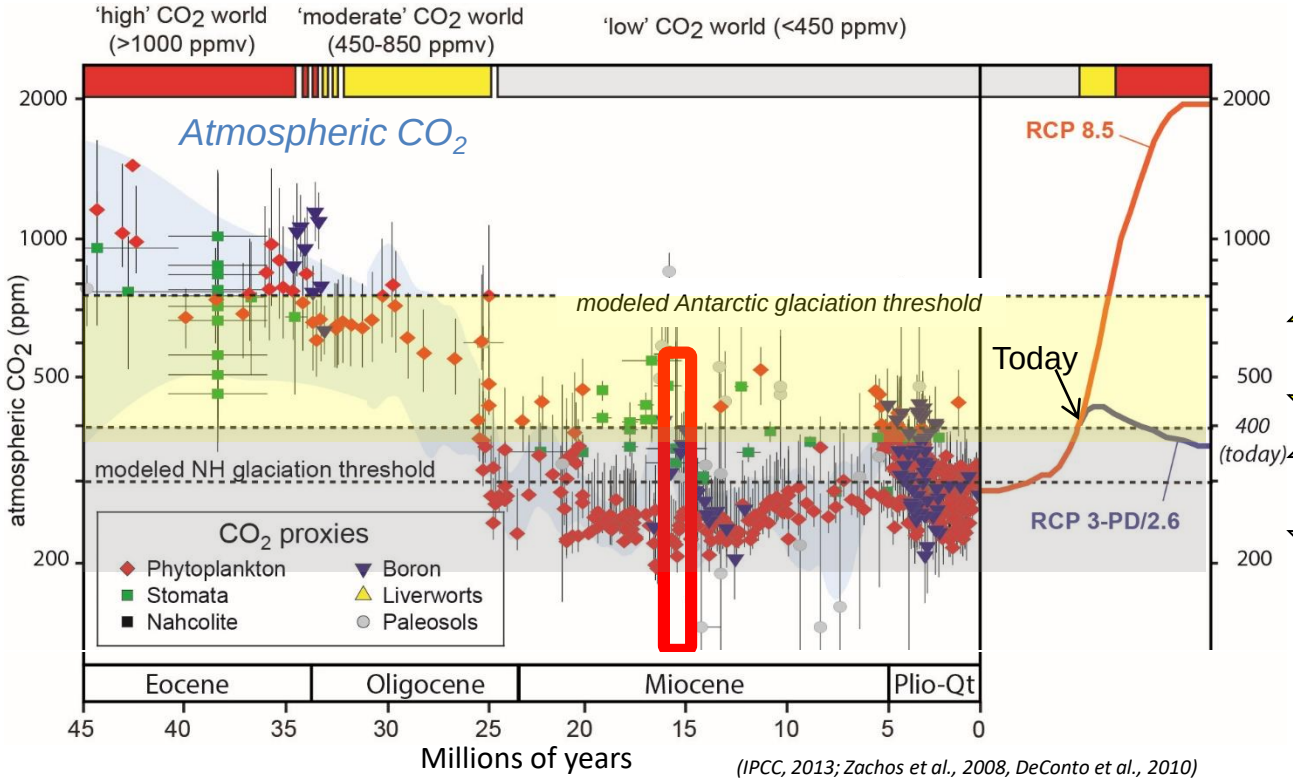
Antarctic marine-based EAIS/WAIS
(400-200ppm CO_2, -5 to+3°C)

RCP 2.6
(430-480 ppm CO2 1.5-2 ° C Paris agreement)



Plio-Quaternary (ca. 4 Ma)
ca. 400-200 ppm CO_2 sea bed depth similar to today (landward sloping, De Santis et al., 1999)

GLAISS provides model-data past simulations (when CO2 atmospheric content and temperature were higher) to predict Antarctic ice sheet future rate of changes



(IPCC, 2013; Zachos et al., 2008, DeConto et al., 2010)

RCP 8.5
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Ice free Antarctica
(>1000ppm CO_2, +8 to 12°C)

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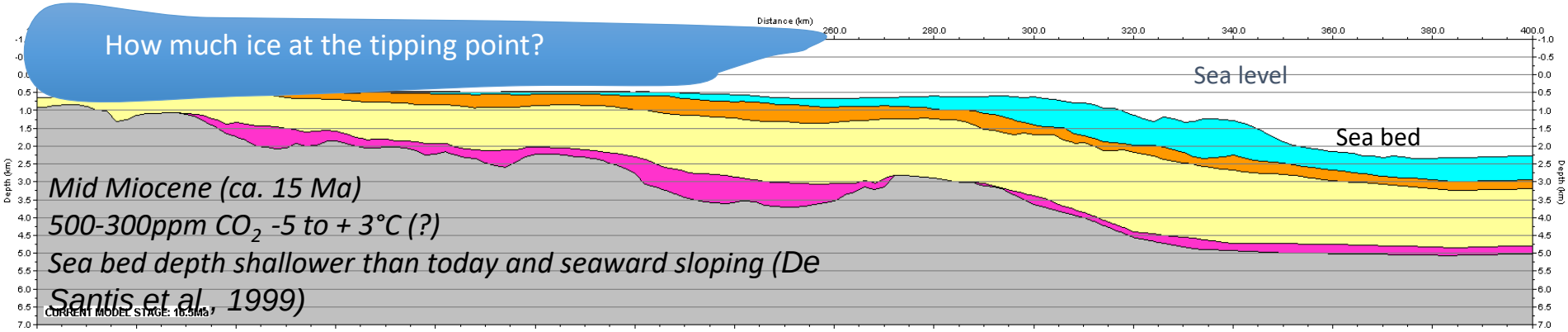
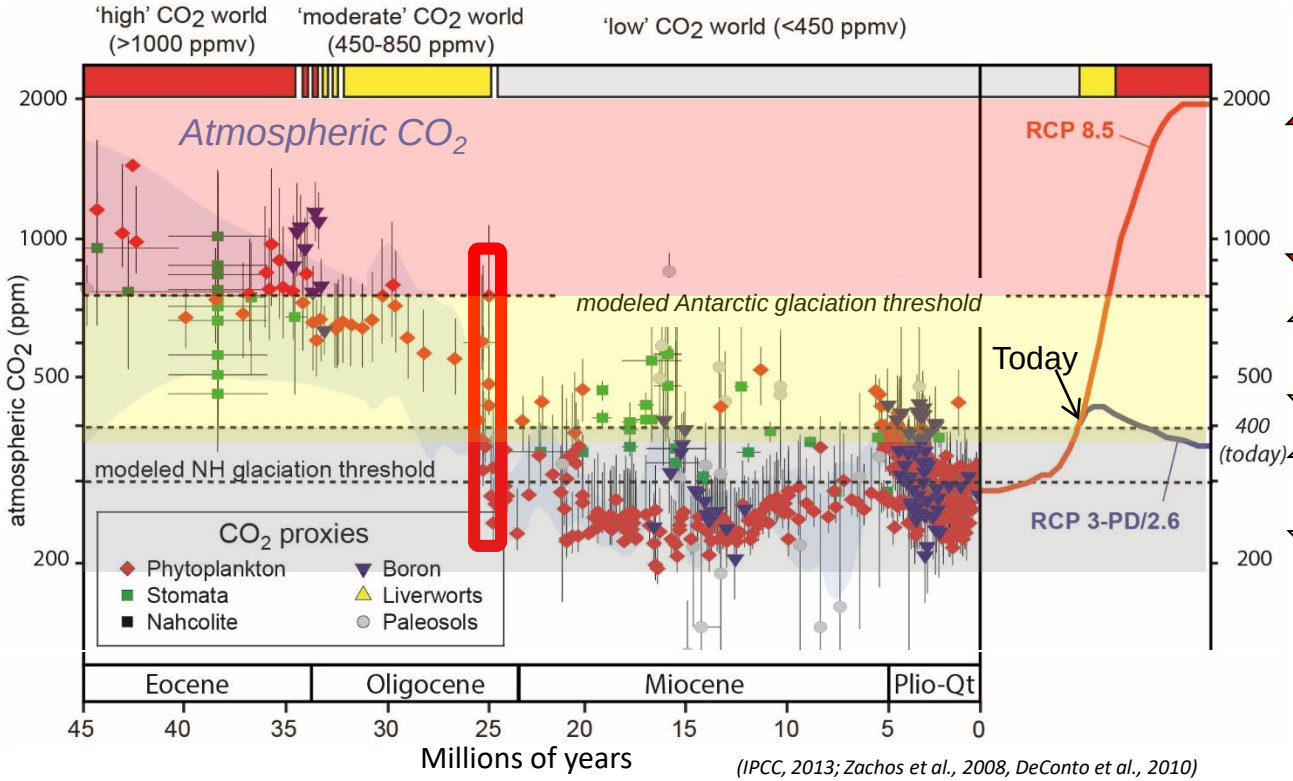


Mid Miocene (ca. 15 Ma)
500-300ppm CO_2 -5 to + 3°C (?)
Sea bed depth shallower than today and seaward sloping (De Santis et al., 1999)

GLAISS provides model-data past simulations (when CO2 atmospheric content and temperature were higher) to predict Antarctic ice sheet future rate of changes



(IPCC, 2013; Zachos et al., 2008, DeConto et al., 2010)

RCP 8.5
(3.2-5.4 ° C >1000 ppm CO2 business as usual)

ice free Antarctica
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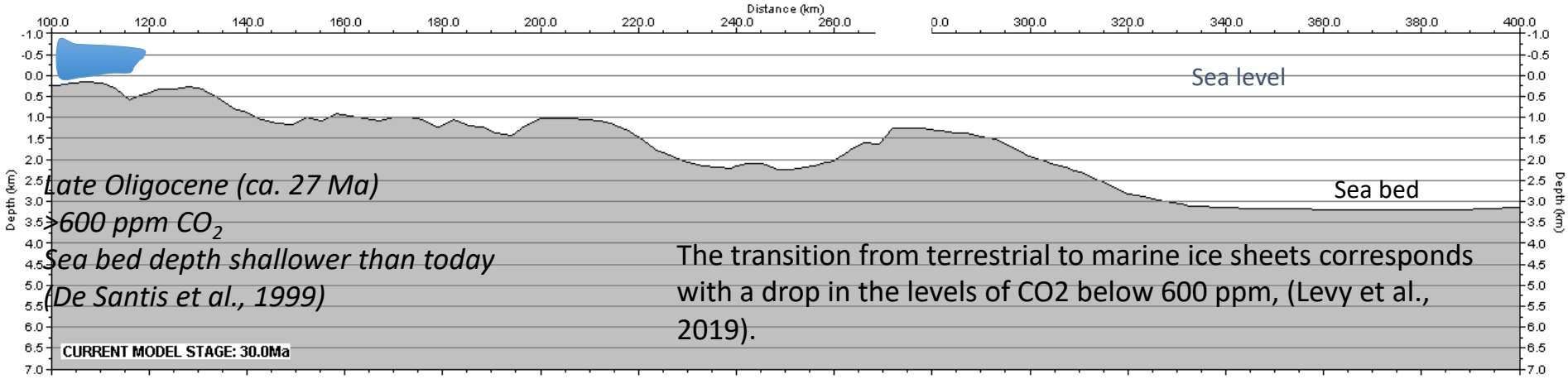
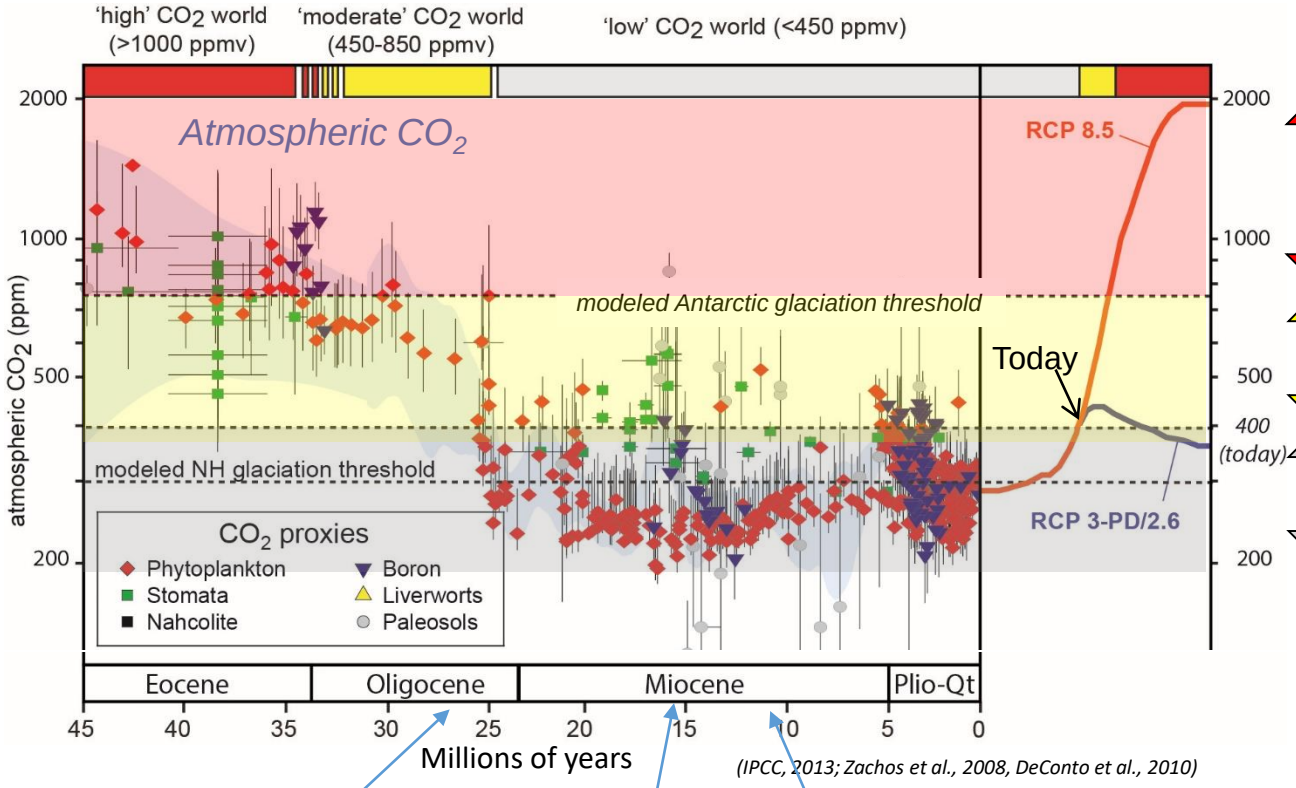


Late Oligocene (ca. 27 Ma)
>600 ppm CO_2
Sea bed depth shallower than today
(De Santis et al., 1999)

The transition from terrestrial to marine ice sheets corresponds with a drop in the levels of CO2 below 600 ppm, (Levy et al., 2019).

GLAISS provides model-data past simulations (when CO2 atmospheric content and temperature were higher) to predict Antarctic ice sheet future rate of changes



(IPCC, 2013; Zachos et al., 2008, DeConto et al., 2010)

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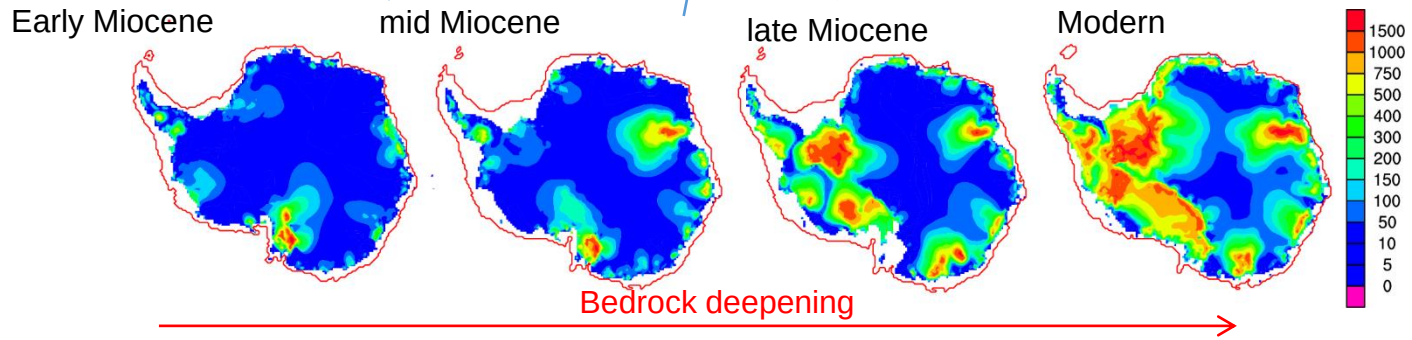
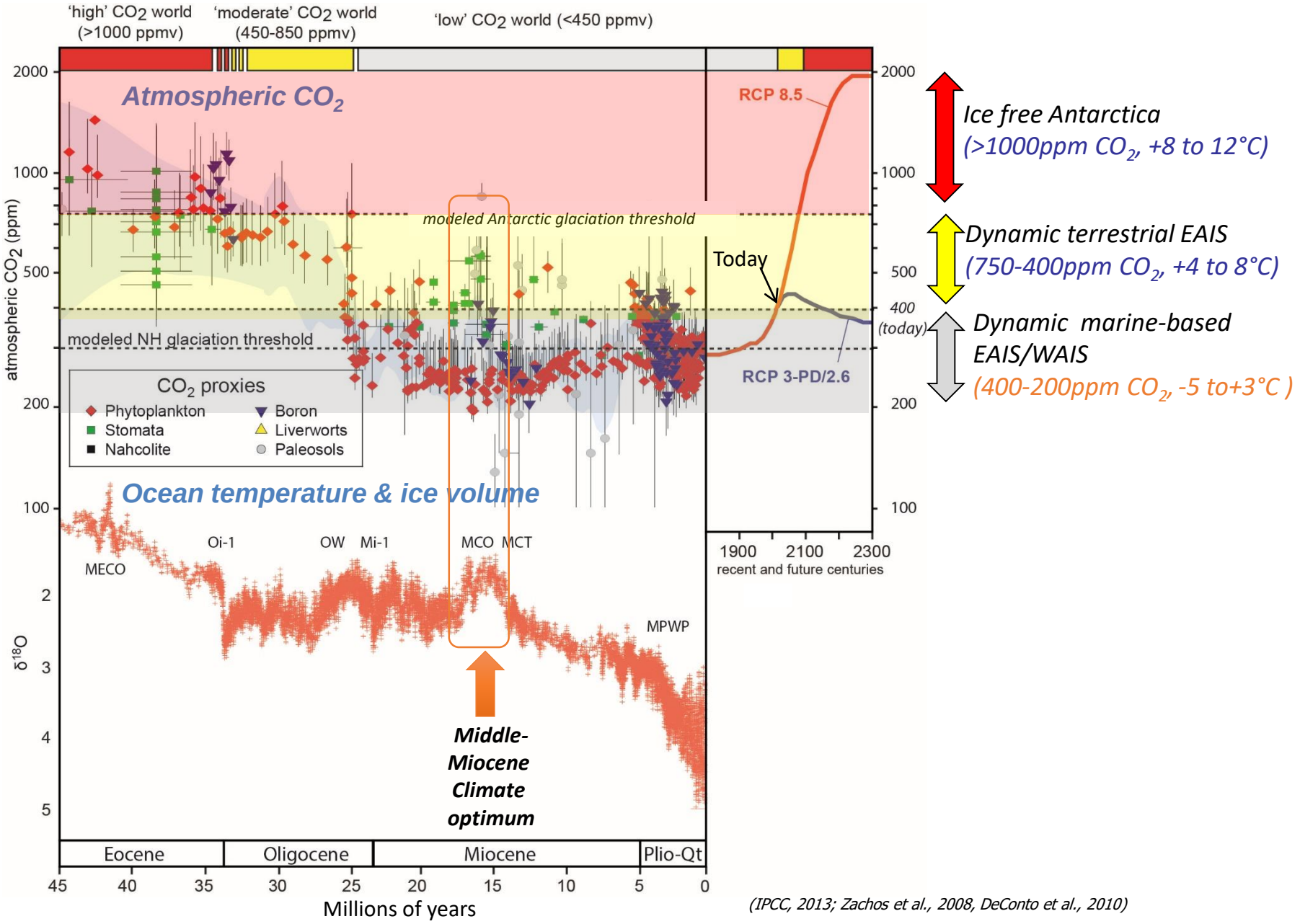


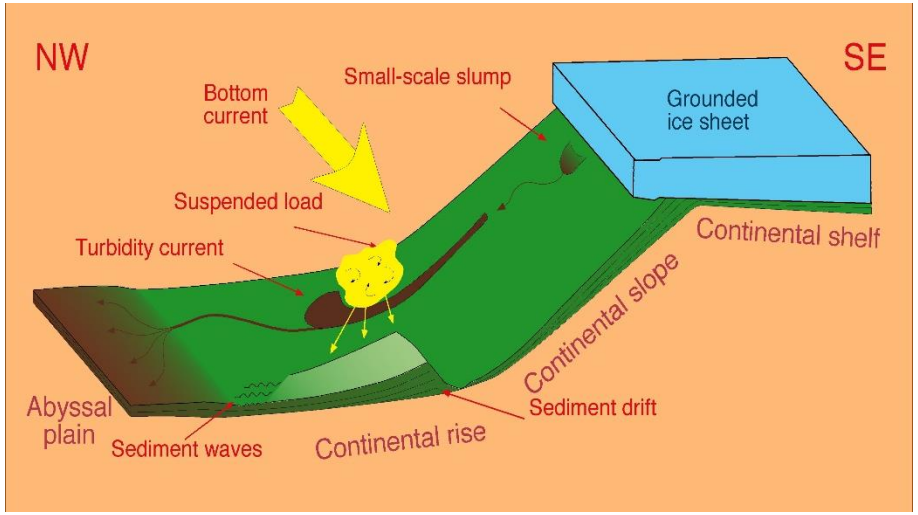
Simulated ice sheet sensitivity to climatic conditions

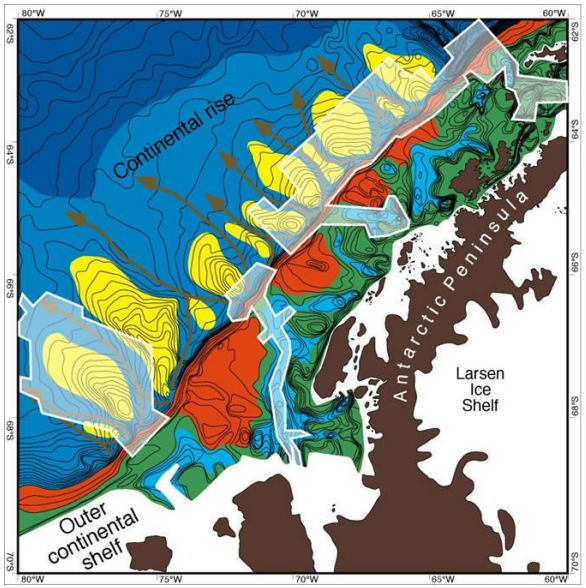
Colleoni, F., De Santis, L., Montoli, E., Olivo, E., Sorlien, C. C., Bart, P.J. Gasson, E. G. W., Bergamasco, A., Sauli, C., Wardell, N., Prato, S., Scientific Reports. 2018, volume 8, 11323

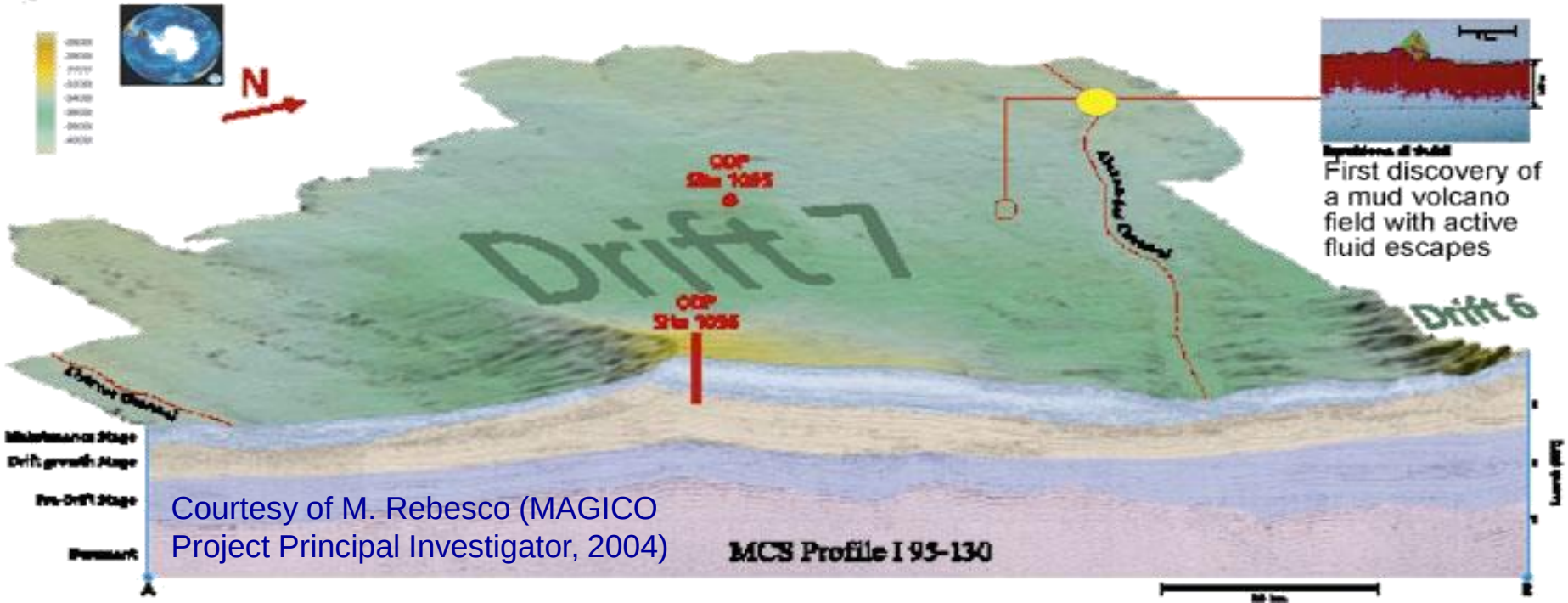


(IPCC, 2013; Zachos et al., 2008, DeConto et al., 2010)

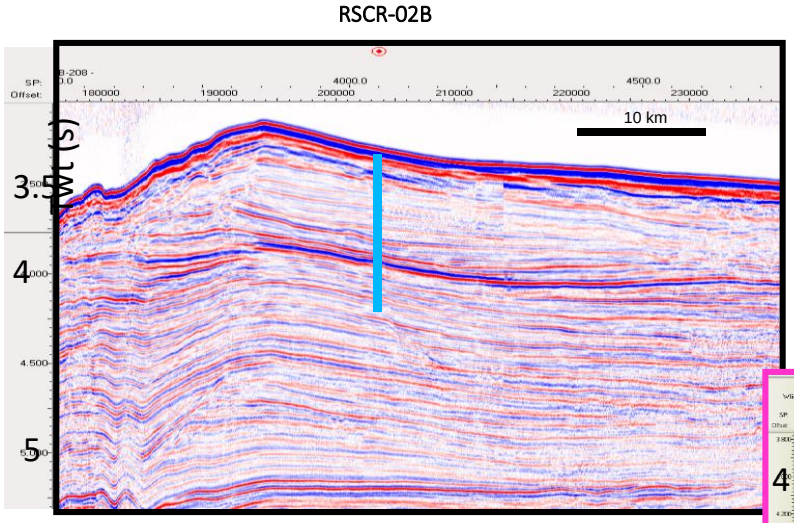
Investigating an antarctic dritf

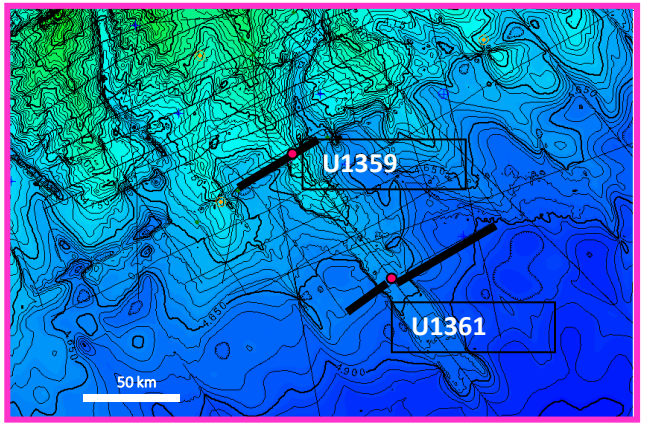


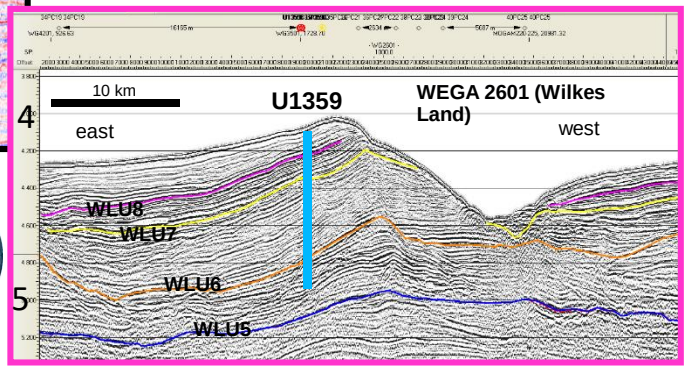


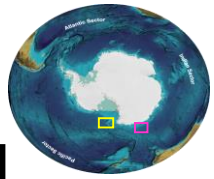


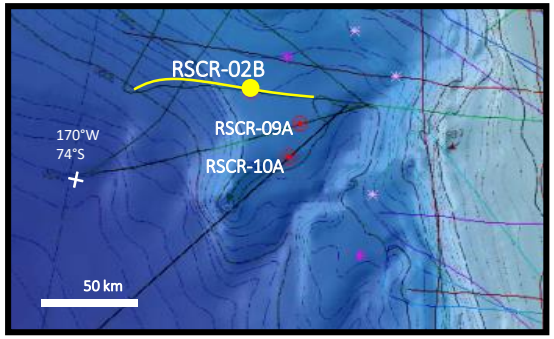
Courtesy of M. Rebesco (MAGICO Project Principal Investigator, 2004)

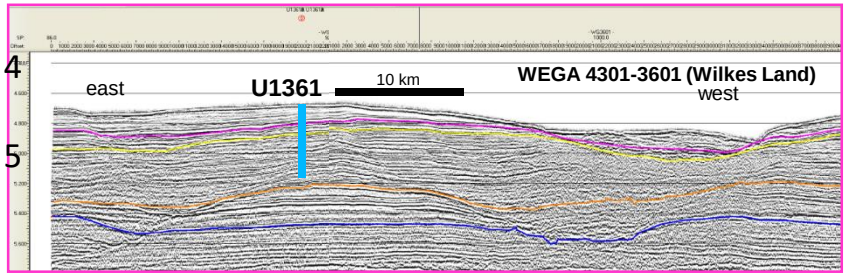

RSCR-02B
10 km
TWT (s)
3.5
4
5


U1359
U1361
50 km

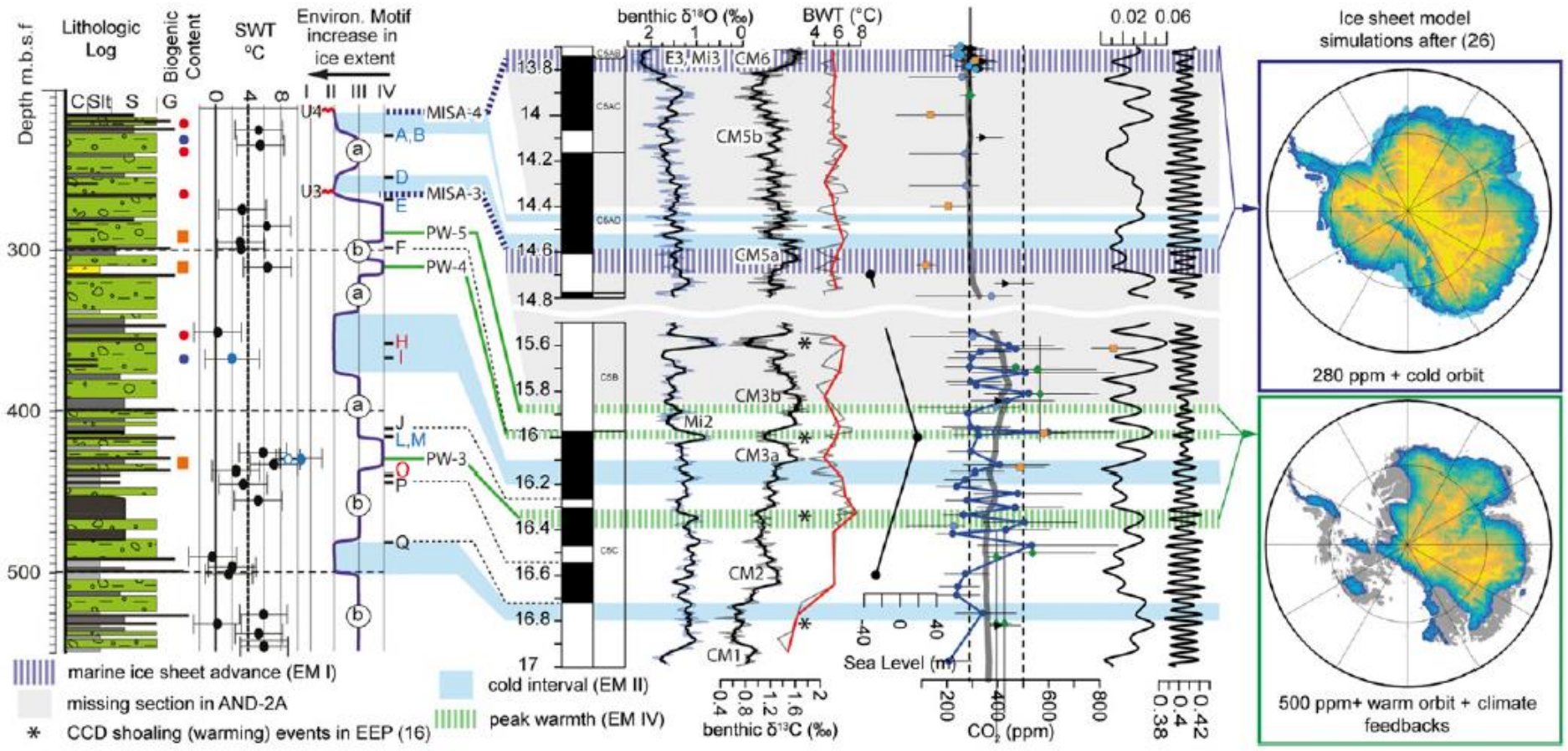

10 km
U1359
WEGA 2601 (Wilkes Land)
east
west
WLU8
WLU7
WLU6
WLU5
4
5




RSCR-02B
RSCR-09A
RSCR-10A
170°W
74°S
50 km


U1361
10 km
WEGA 4301-3601 (Wilkes Land)
east
west
4
5

The AND-2A record shows major variability of marine based ice in the Ross Sea between 17 to 14 Ma

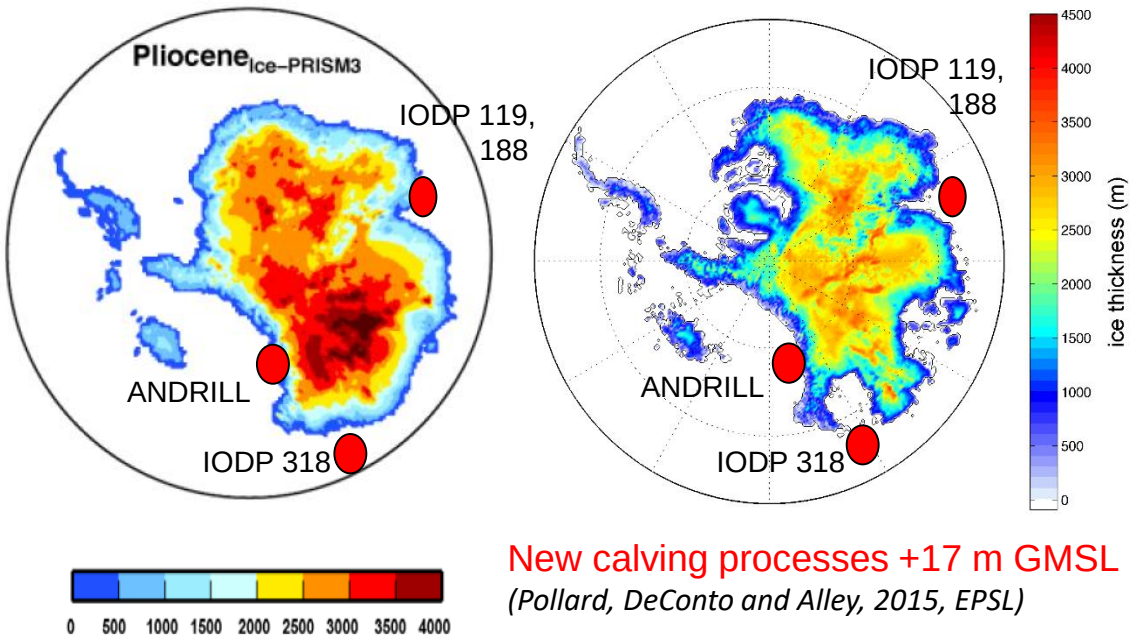


Levy at al. (2016, PNAS), Gasson et al. (2016, PNAS)

Mid-Pliocene warm period – 3.3-3Ma

- 350-400ppm CO_2
- +3°C global average air, + 2°C SST
- +3-5°C Antarctic SST (Ross Sea)
- +8°C Arctic SAT (Lake E)
- GMSL ~ +20m
- Up to 7m from GIS
- Up to +4m WAIS
- Up to +13m EAIS
- AIS contribution ???

Mid-Pliocene warm period model data comparison



New calving processes +17 m GMSL
(Pollard, DeConto and Alley, 2015, EPSL)

PLIS MIP +12 m GMSL
De Boer et al., 2015 (The Cryosphere)