Antarctic ice sheet evolution

50 years of Ocean drilling and seismic stratigraphy discoveries

Laura De Santis
ldesantis@inogs.it
OGS National Institute of Oceanography and Applied Geophysics

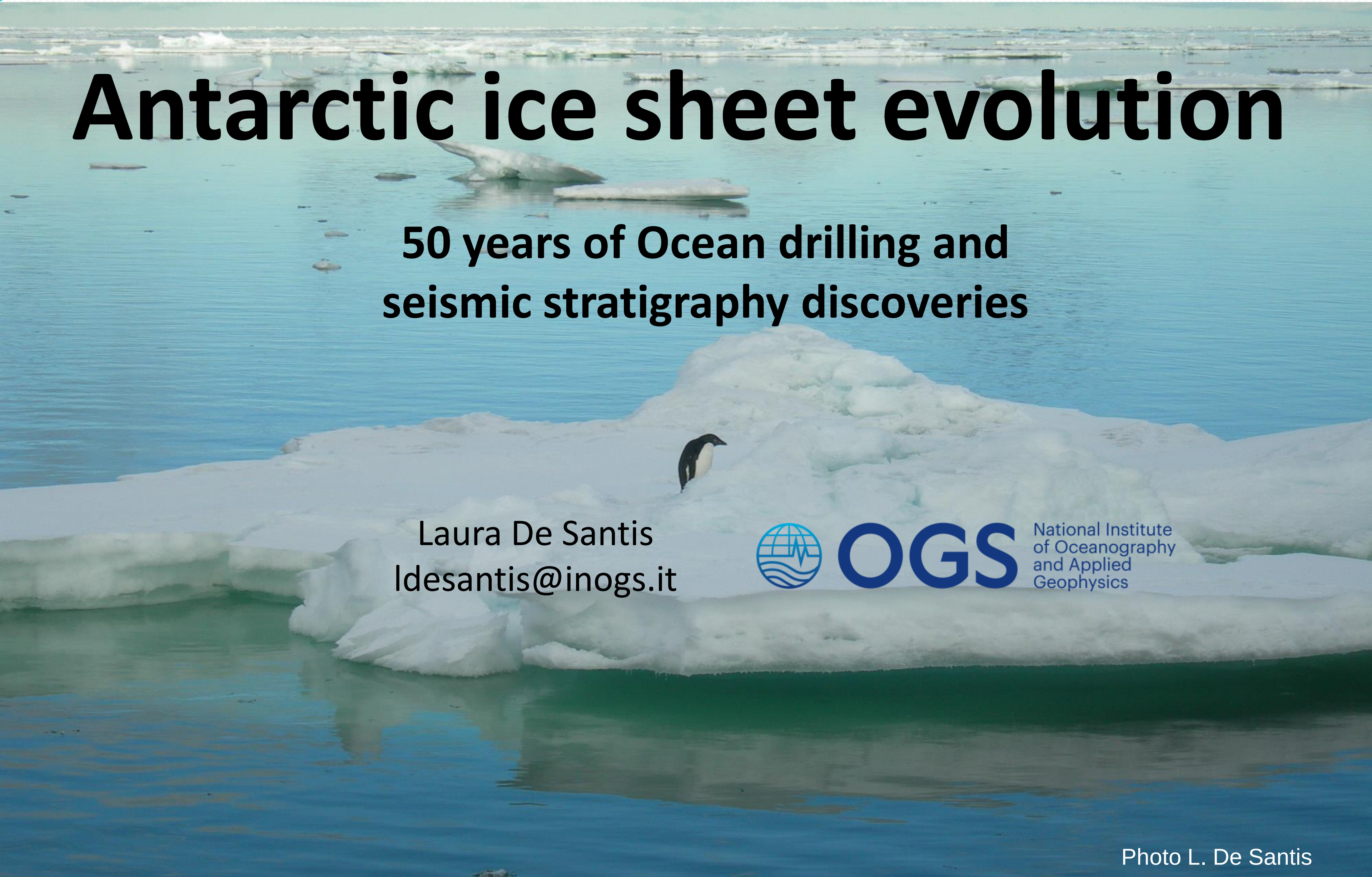


Photo L. De Santis

Expedition 374

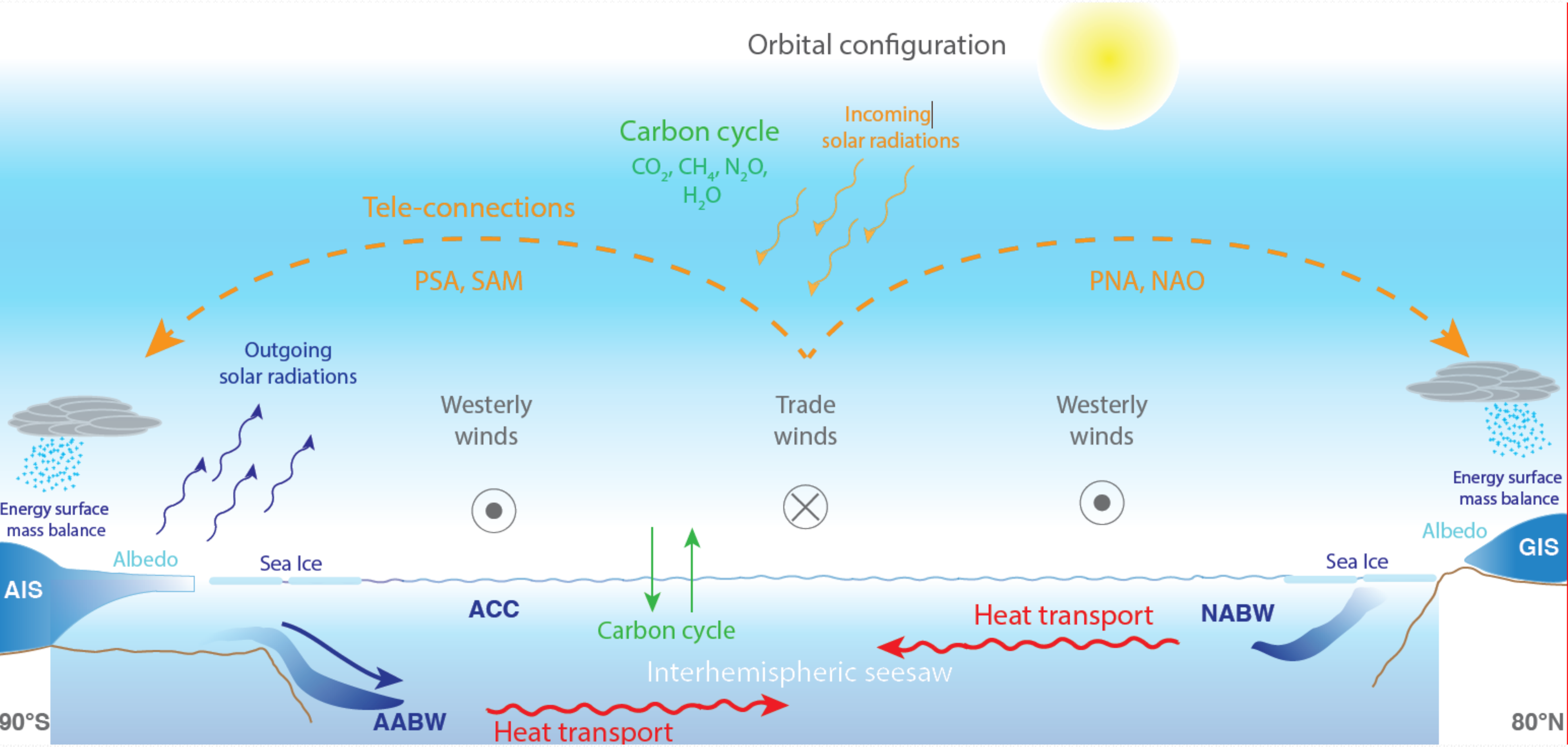
Ross Sea West Antarctic Ice Sheet History

INTERNATIONAL OCEAN DISCOVERY PROGRAM

January 4-March 8 2018

Lyttelton to Lyttelton, New Zealand

Changes in cryosphere affect the Earth System

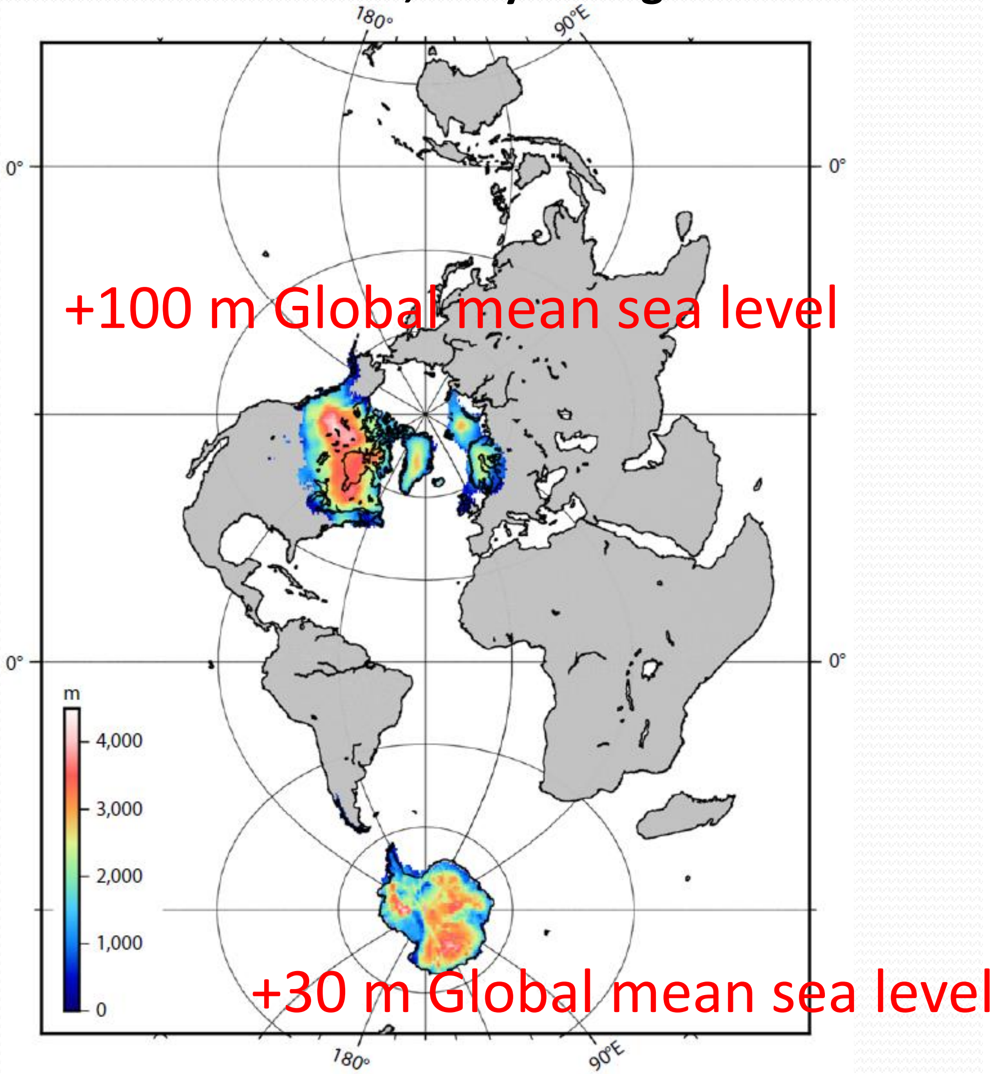


SAM: Southern Annular Mode
PSA: Pacific South-American oscillation
AIS: Antarctic Ice Sheet
GIS: Greenland Ice Sheet

AABW: Antarctic Bottom Water
NABW: Northern Atlantic Bottom Water
ACC: Antarctic Circumpolar Current

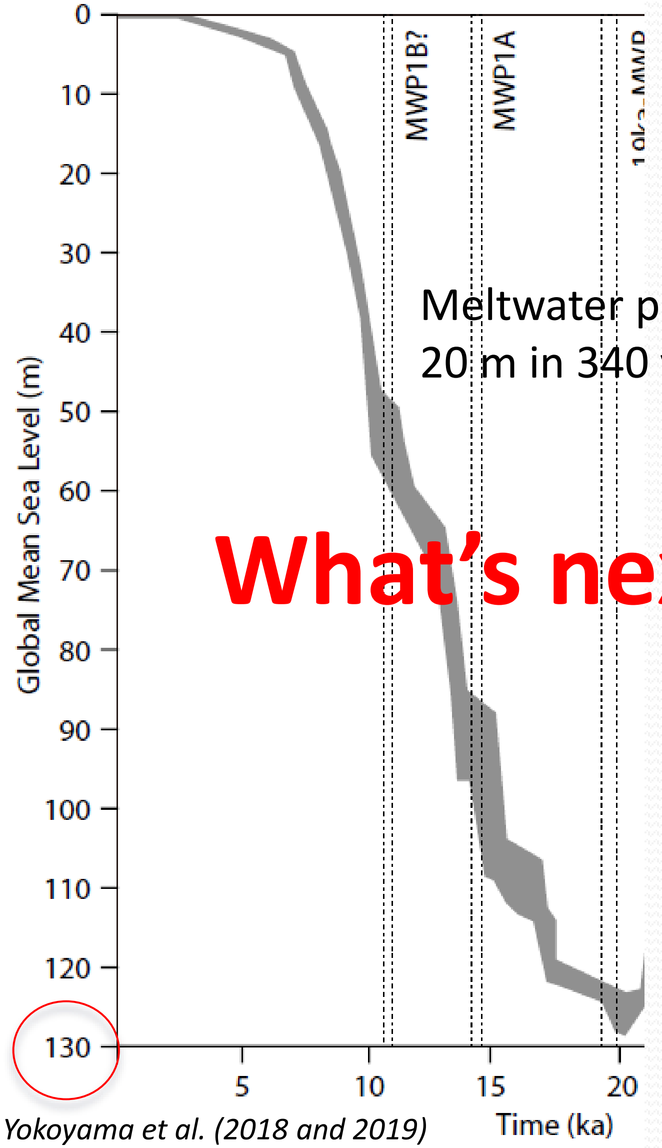
Colleoni et al., 2018 modified

ice sheet during the Last Glacial Maximum 21,000 years ago



Peltier et al., 2015, Yokoama et al., 2019

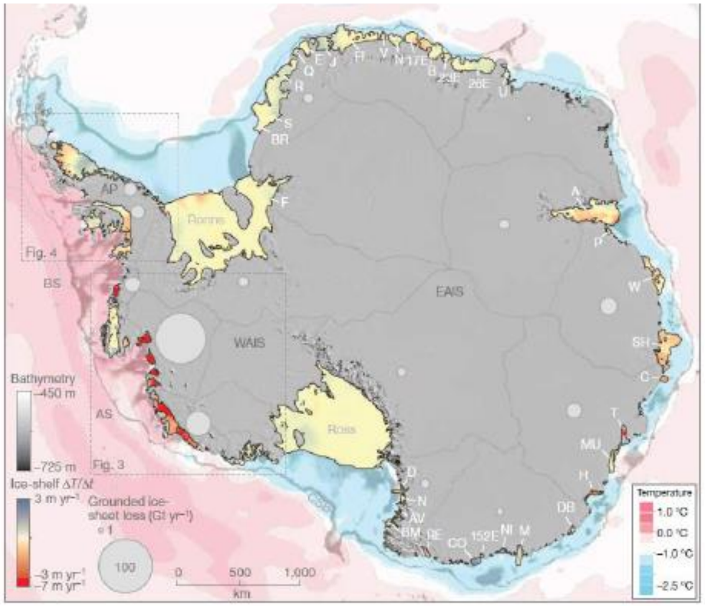
global mean sea level from Great Barrier coral Reef (ODP exp. 325)



Yokoyama et al. (2018 and 2019)

Is the ice mass loss due Ocean warming?

Ice shelves are melting



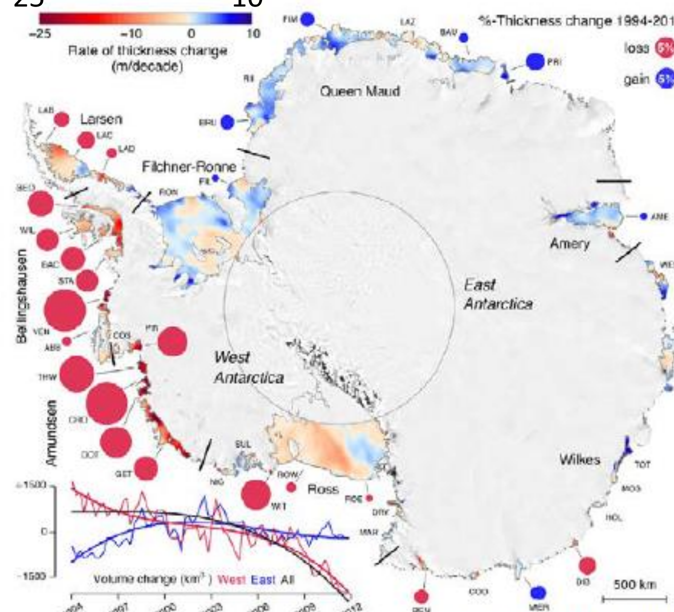
Pritchard et al. (2013), Nature

Rate of thikness change

-25 10

Loss 5%

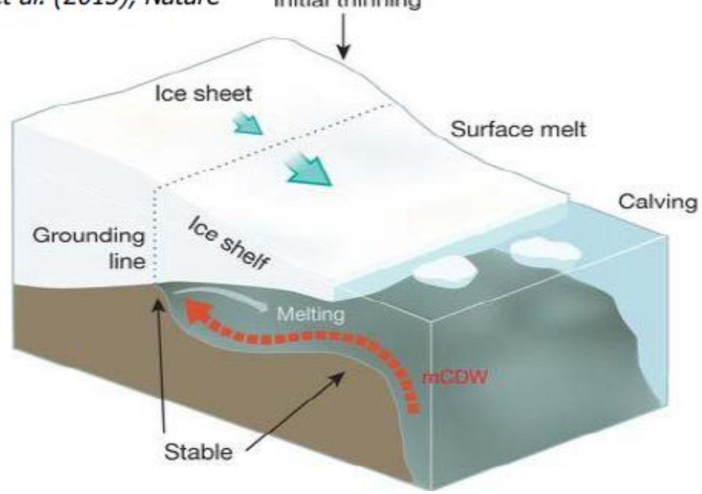
Gain 5%



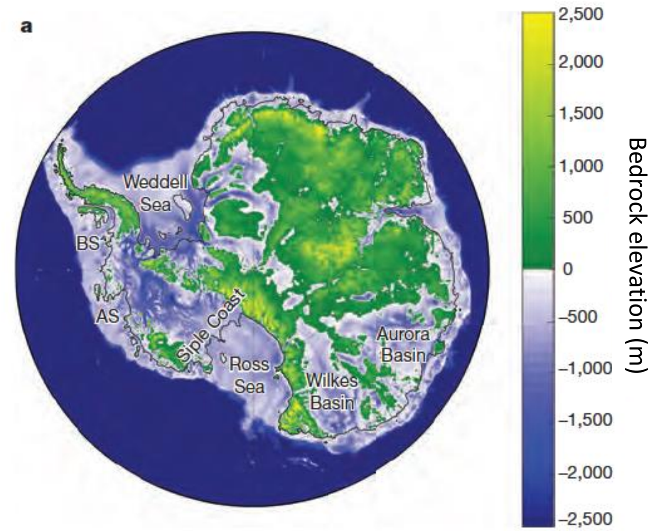
Volume change (km3)

1994 2012

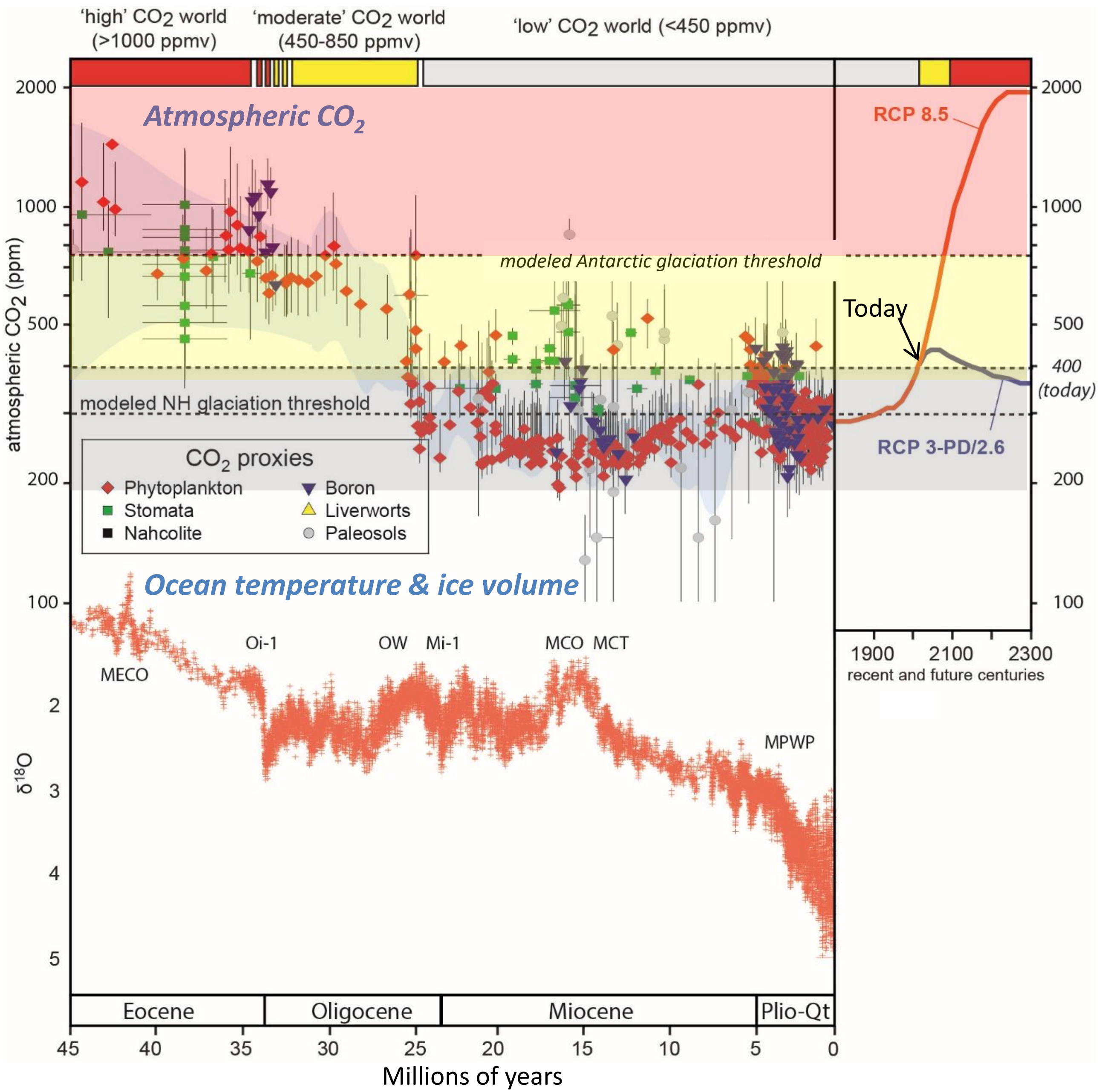
Paolo et al. (2015), Science



Hanna et al., 2013

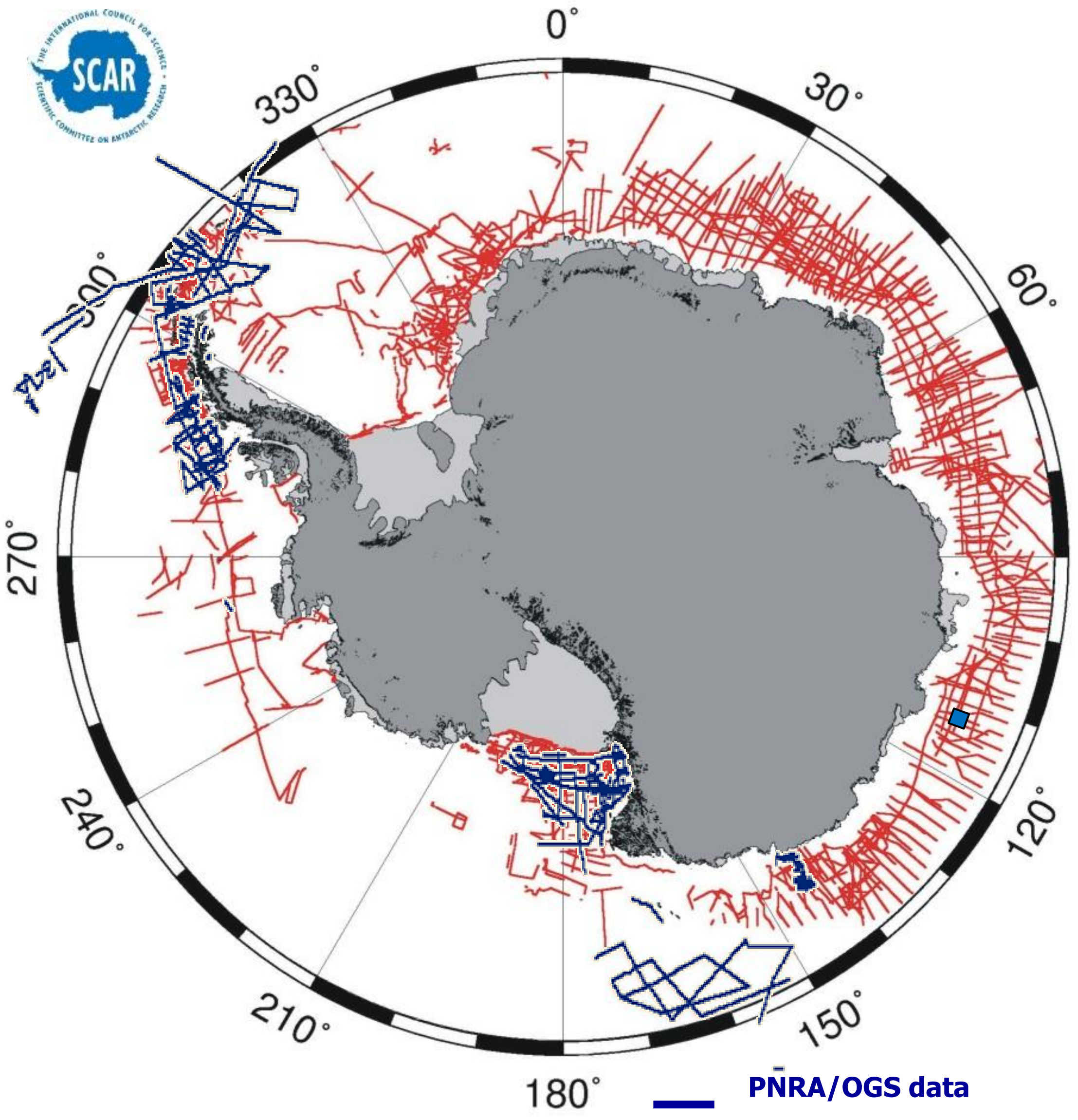


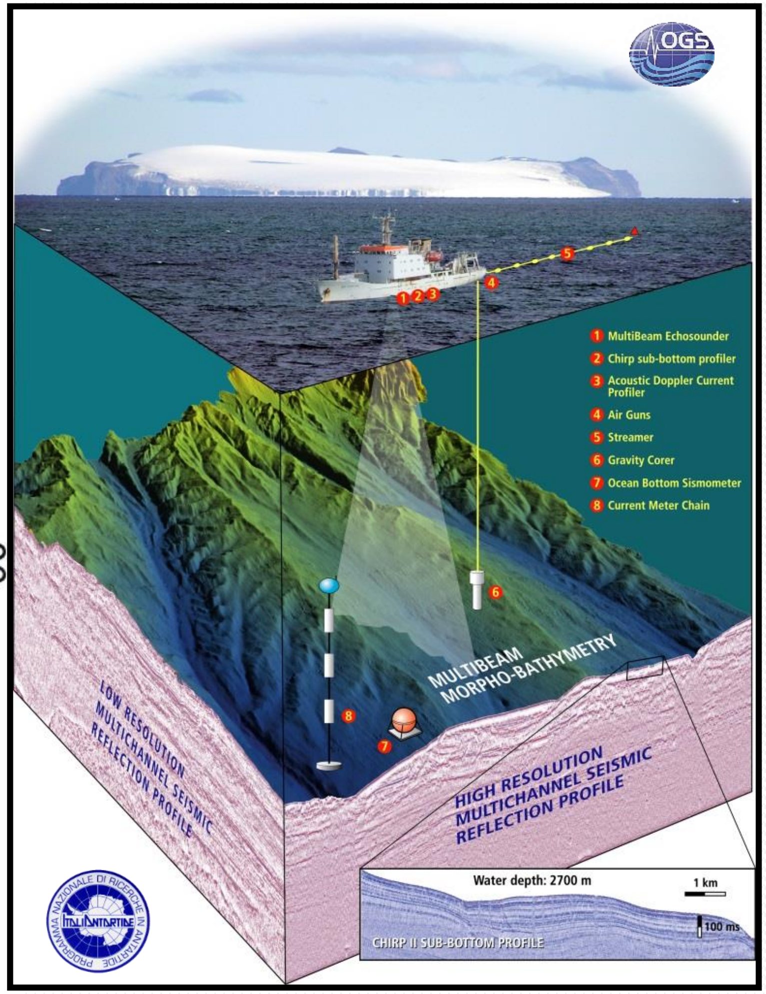
P. Fretwell etal. 2013



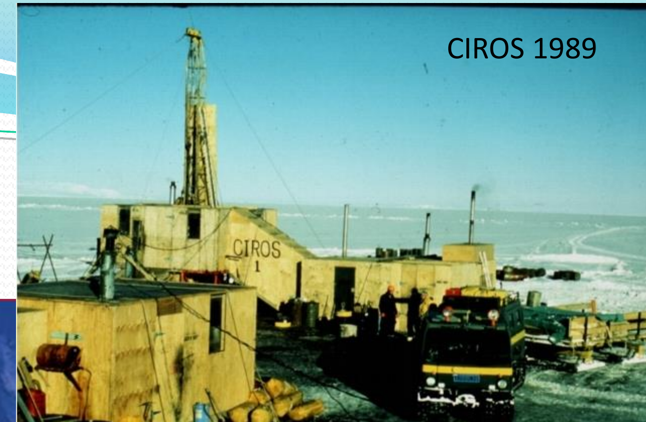
(IPCC, 2013; Zachos et al., 2008, DeConto et al., 2010)

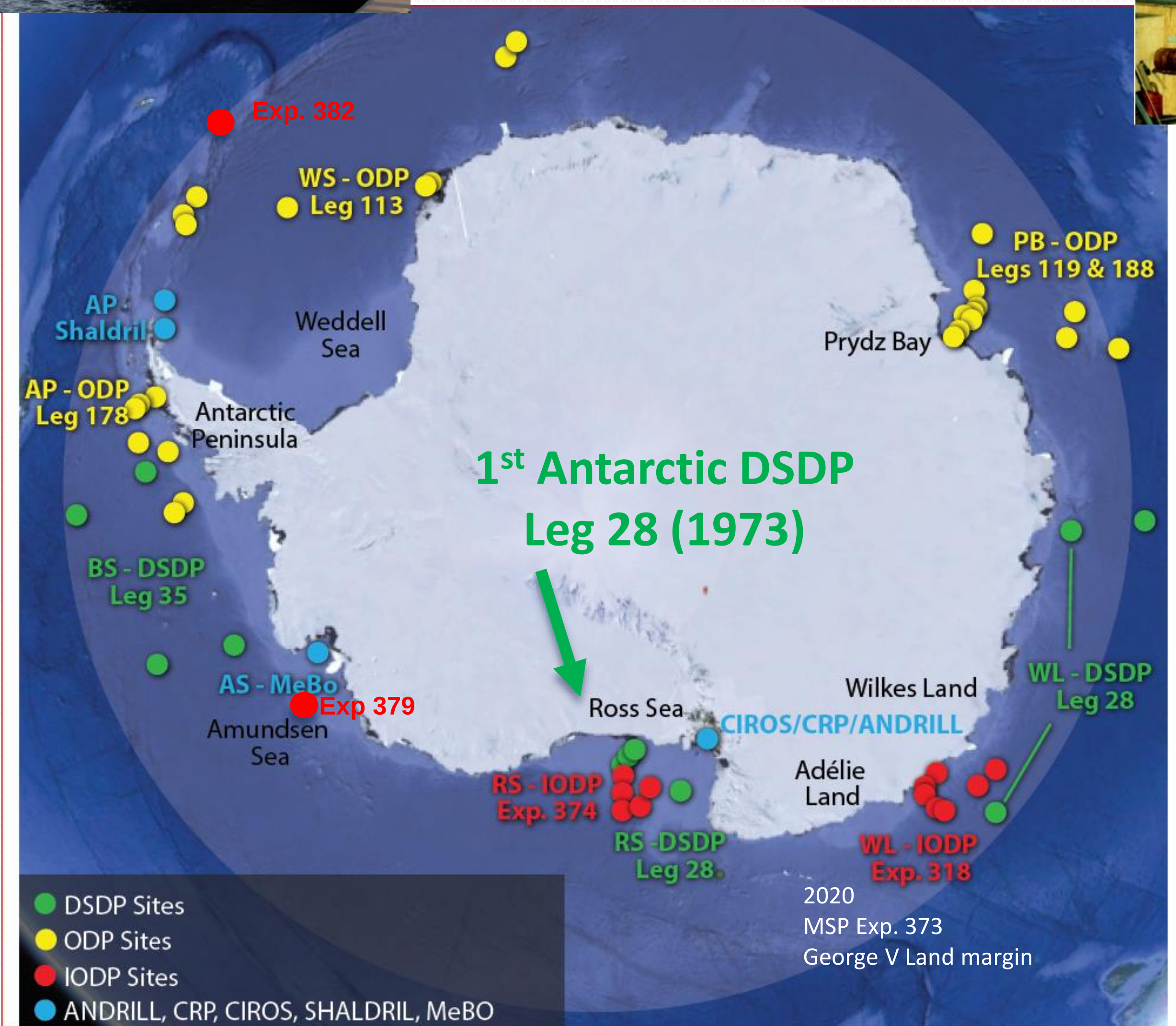
Antarctic Seismic Data Library System run by OGS and USGS/LDEO *http://sdls.ogs.trieste.it/*

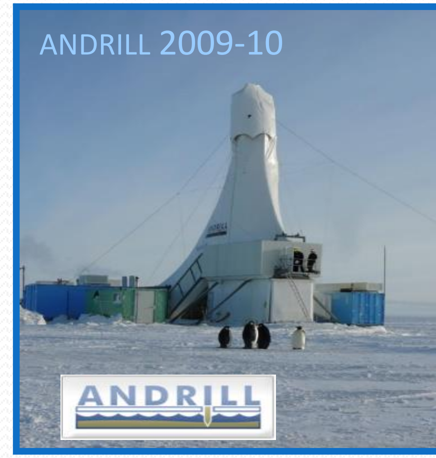




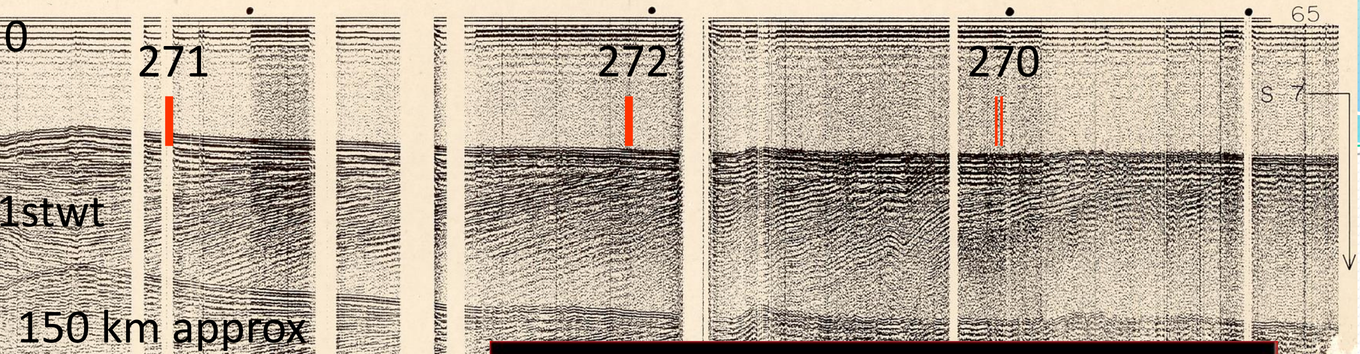
336000 km of seismic lines acquired by 16 Nations



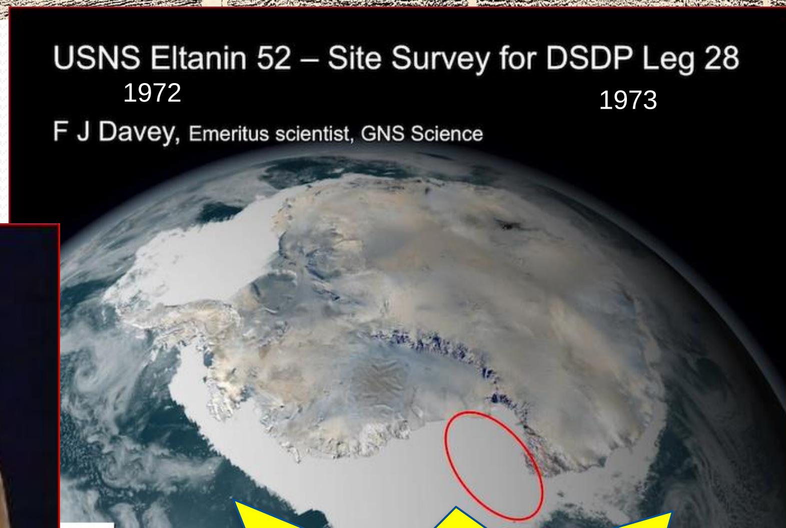


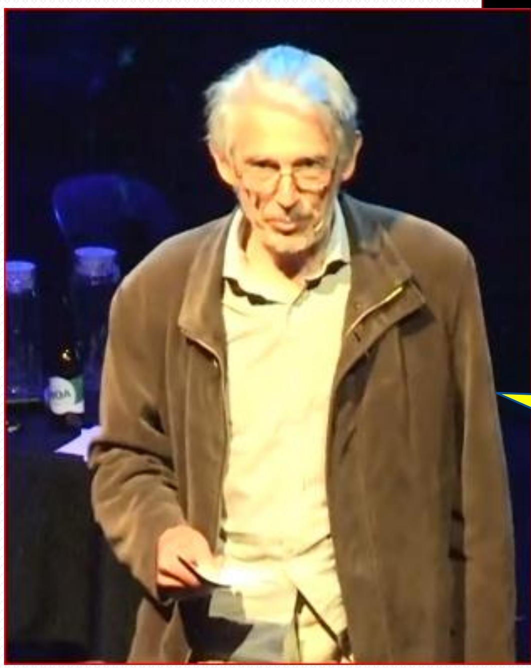


Escutia et al., 2019



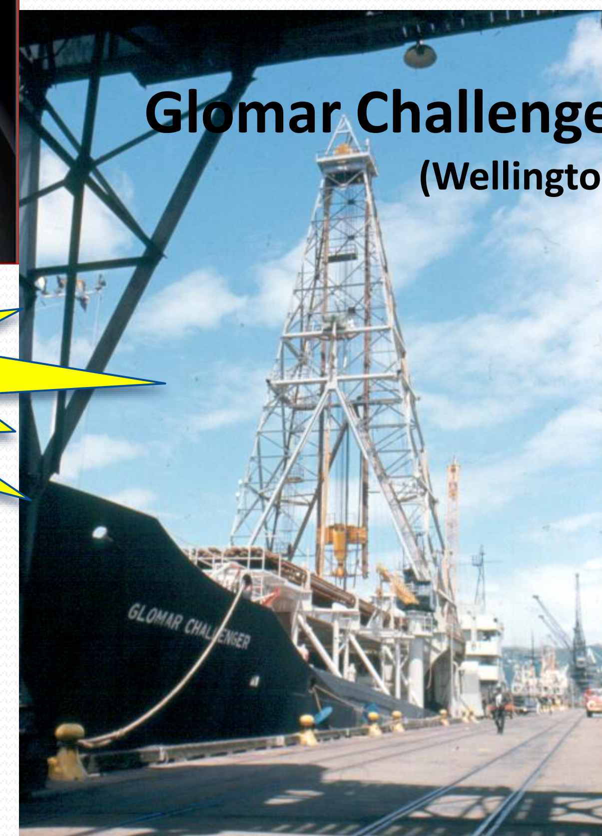
Fred Davey (GNS, NZ)
geophysicist





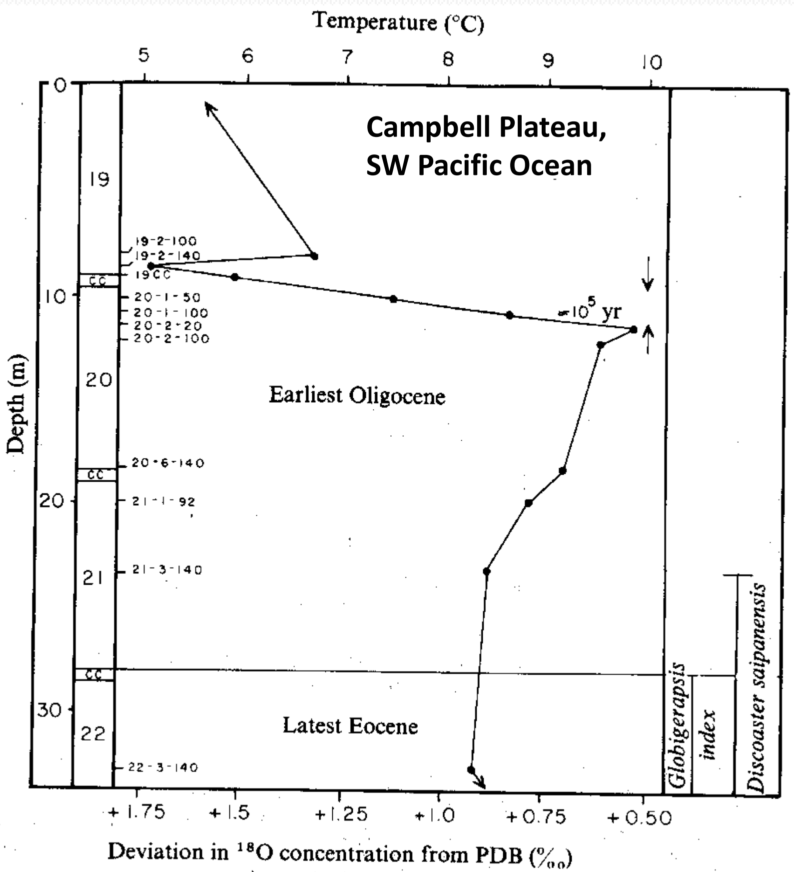
Ice existed 25 Ma ago

Peter Barrett
Sedimentologist
(Univ. Victoria, NZ)

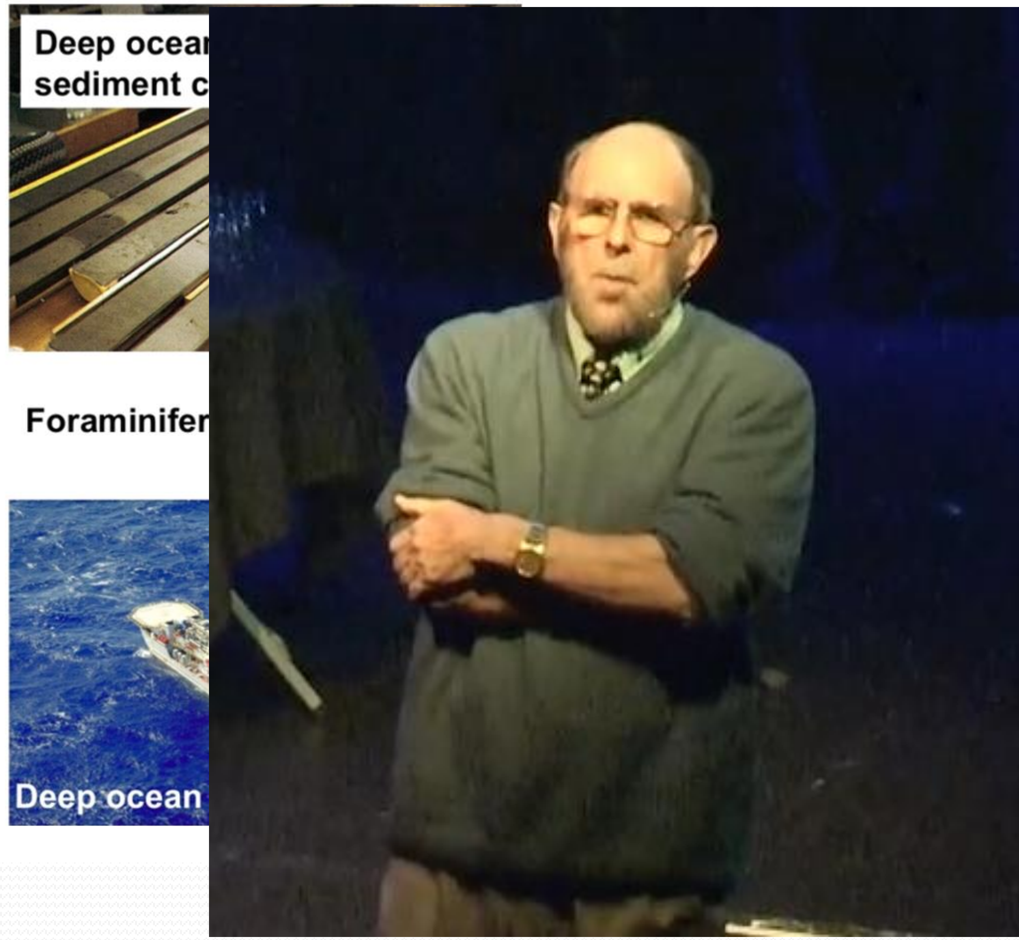


Video talks March 8th 2018
http://www.scar-pais.org/index.php/insights/video

DSDP Leg 29 Ocean Deep sea Geochemical evidence for the onset of Antarctic glaciations at c. 34 Ma

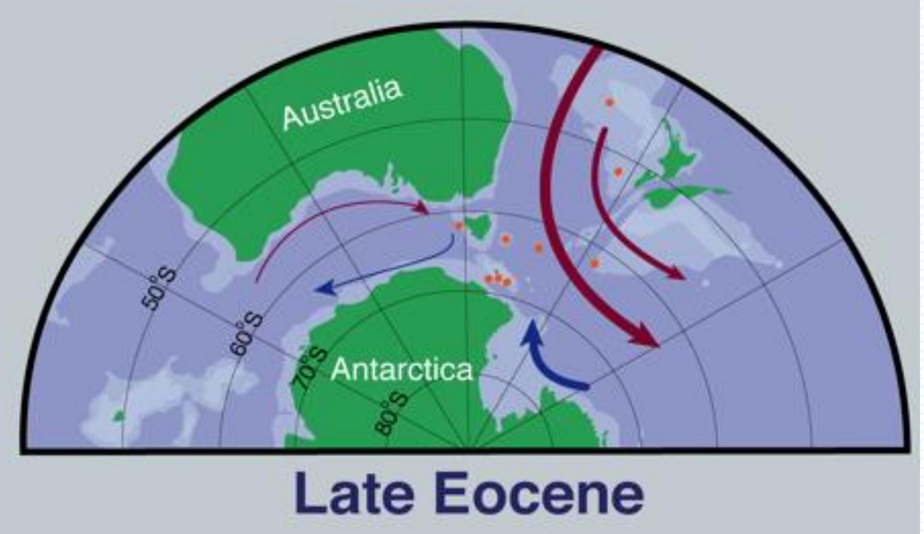


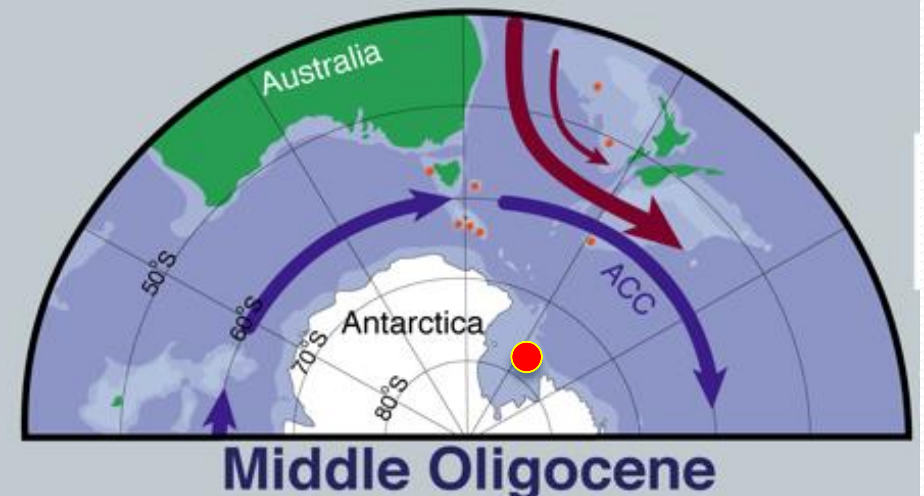
Kennett and Shackleton (1976),
Nature, DSDP Site 277



Talk by Jim Kenneth (Univ. California) March 8th 2018
http://www.scar-pais.org/index.php/insights/video

Thermal isolation of Antarctic ~35 Ma when ocean gateways opened – *James Kennett's hypothesis*





DSDP leg 28 (Hayes and Frakes, 1973)

Ocean Gateway Hypothesis

Warm Eocene
Ice free continent (greenhouse world)

Opening of the Tasmanian Gateway during the Eocene/Oligocene transition

Initiation of Circum Antarctic Current

Thermal isolation of Antarctica And Glacial Expansion

First evidence of grounding ice dated 25 Ma

ice albedo feedback amplified cooling => icehouse world

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†

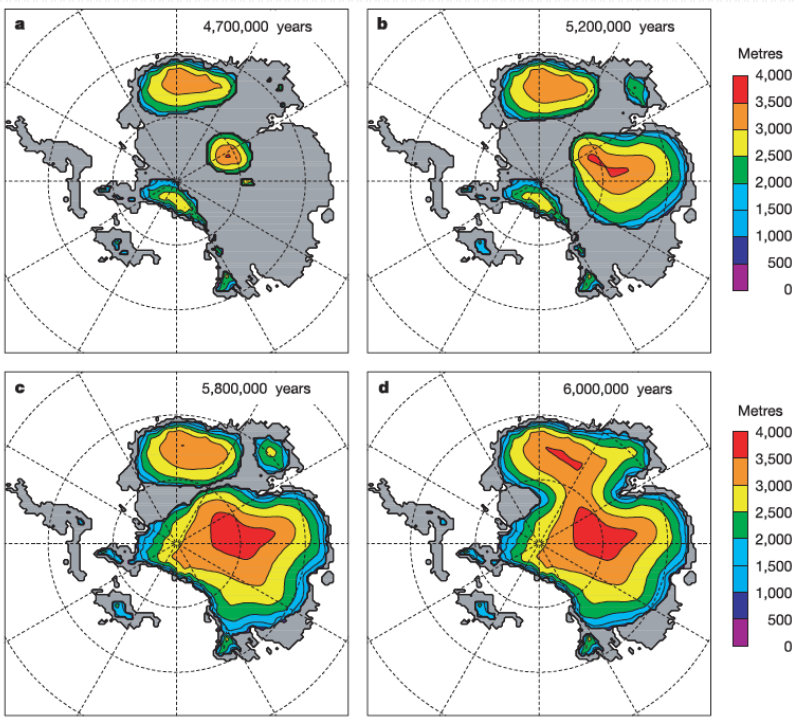
** Department of Geosciences, University of Massachusetts, Amherst, Massachusetts 01003, USA*
† EMS Environment Institute, The Pennsylvania State University, University Park, Pennsylvania 16802, USA

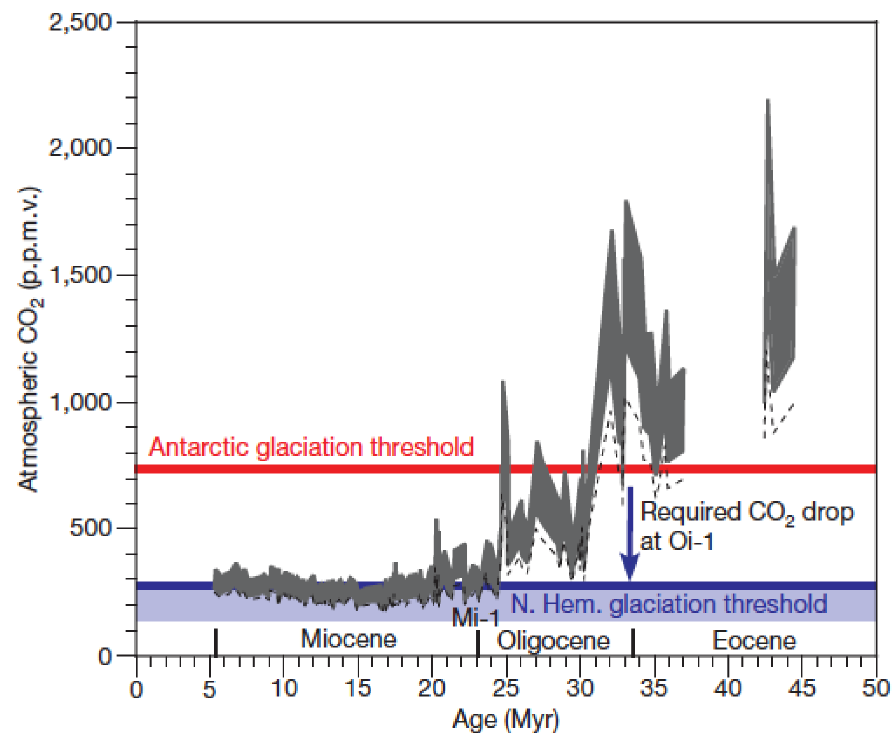
nature Vol 455|2 October 2008|doi:10.1038/nature07337

LETTERS

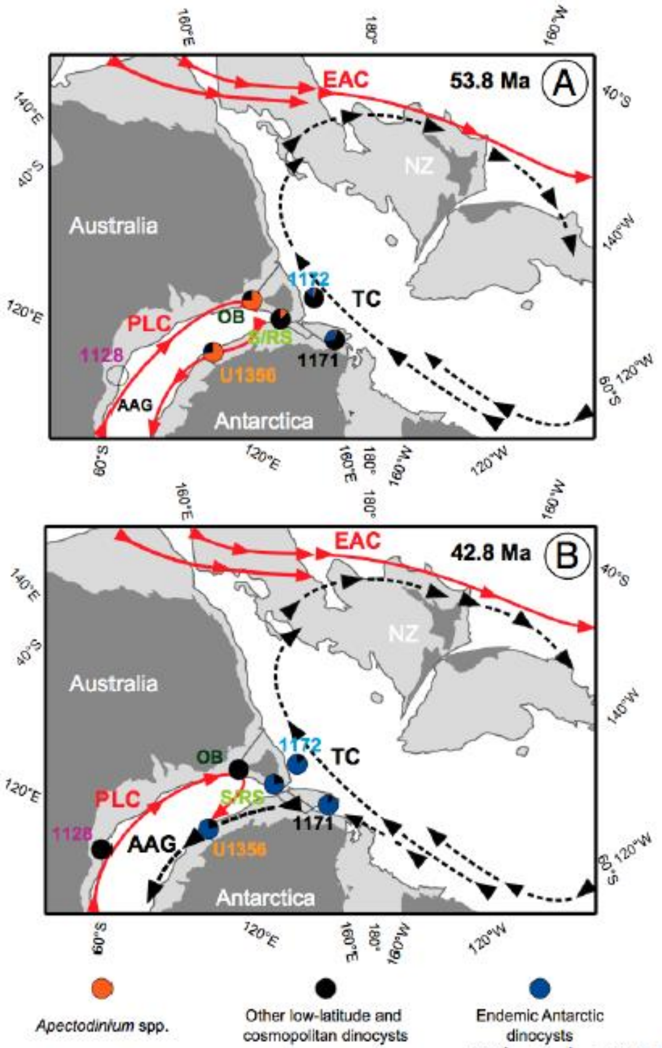
Thresholds for Cenozoic bipolar glaciation

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





Eocene paleogeographic, paleoceanographic and paleotopographic reconstructions



Bjil et al., 2013

Dinocyst assemblage and organic biomarker paleothermometry data from Site U1356

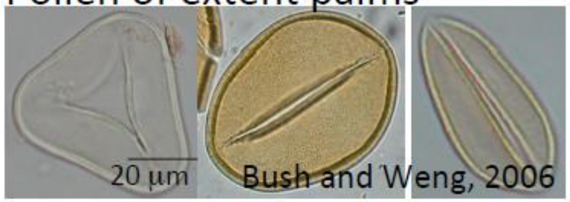
Cooling coincided with cold waters from the Ross Sea Gyre flowing through the incipient opening of the southern Tasman Gateway, following the Early Eocene Climatic Optimum

although atmospheric CO2 forcing alone might provide uniform middle Eocene cooling, the early opening of the Tasman Gateway is more consistent with Southern Ocean surface water and global deep ocean cooling in the apparent absence of (sub-) equatorial cooling

Proto-Leeuwin Current (PLC)
Tasman Current
Australo-Antarctic Gulf (AAG)

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

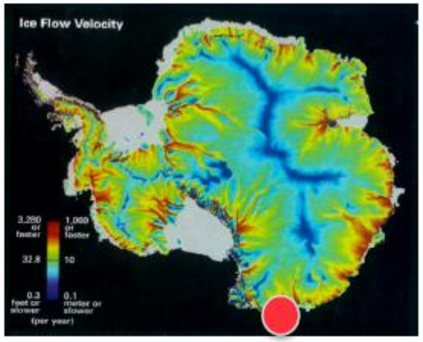
Pollen of extent palms



Pollen from Wilkes Land

despite polar winter darkness

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

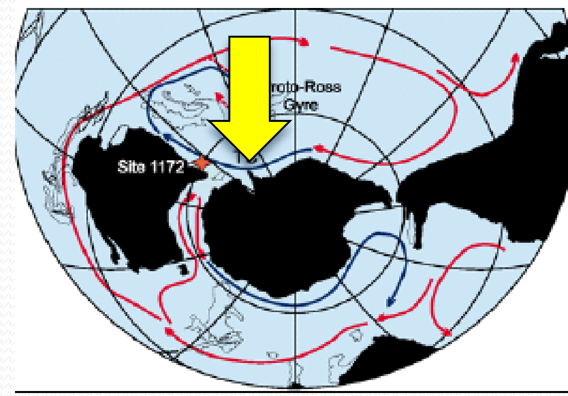
Pollen from Wilkes Land

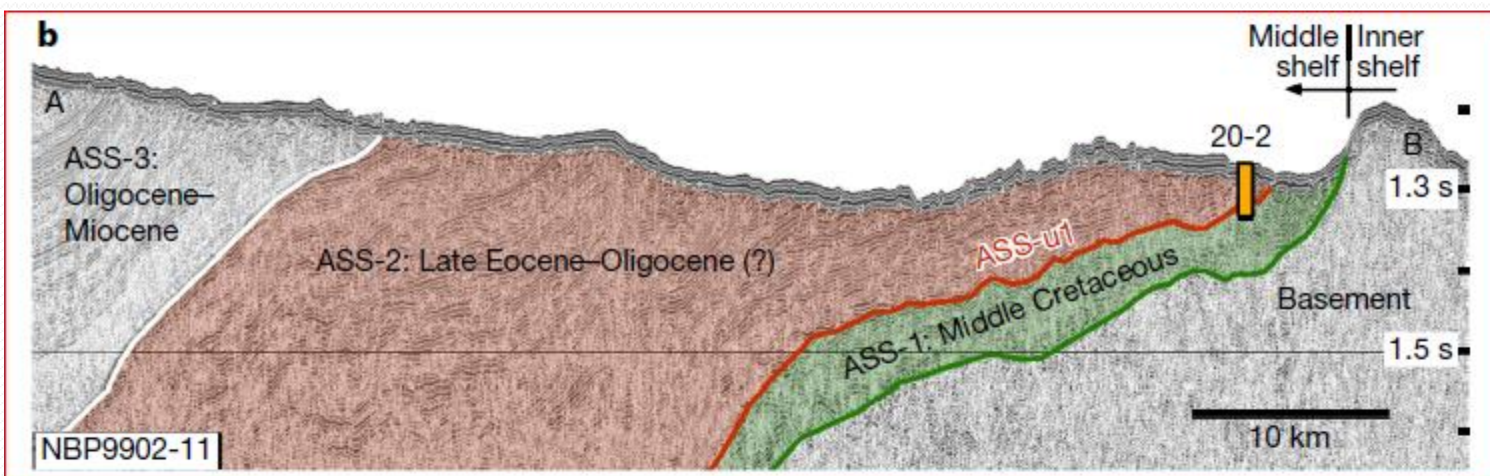
Mean Annual T: >16.8 ºC
Cold Month mean T: >10.6 °C + 3°C
Warm Month mean T: >21.5 °C

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

82° S Turonian–Santonian age (92 to 83 million years ago)

- mean annual temperature +13 °C
- precipitation of 1,120 mm yr−1
- 4 months fully dark
- CO_2 1,120–1,680 ppm
- **No ice**





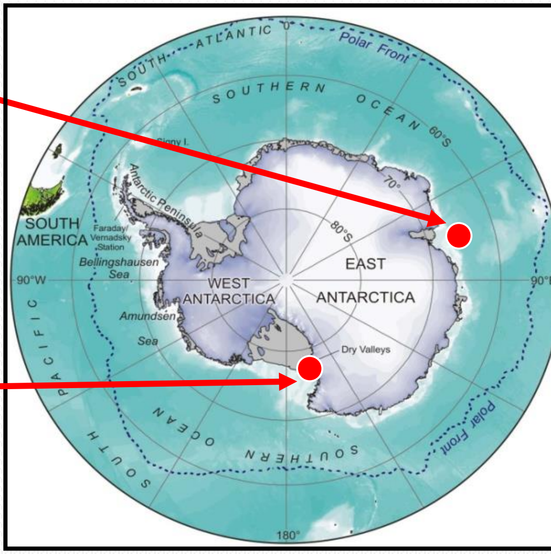
Klages et al., 2020

Proximal sedimentary evidence for earliest Oligocene Antarctic glaciation (33-35 Ma)

Hambrey et al (1991), ODP Leg 119, Prydz Bay
O'Brien, Cooper et al. (2004), ODP Leg 188

Iceberg rafted debris

Barrett et al. 1989



Australia, Germany, United Kingdom, The Netherlands, Italy, New Zealand, and USA

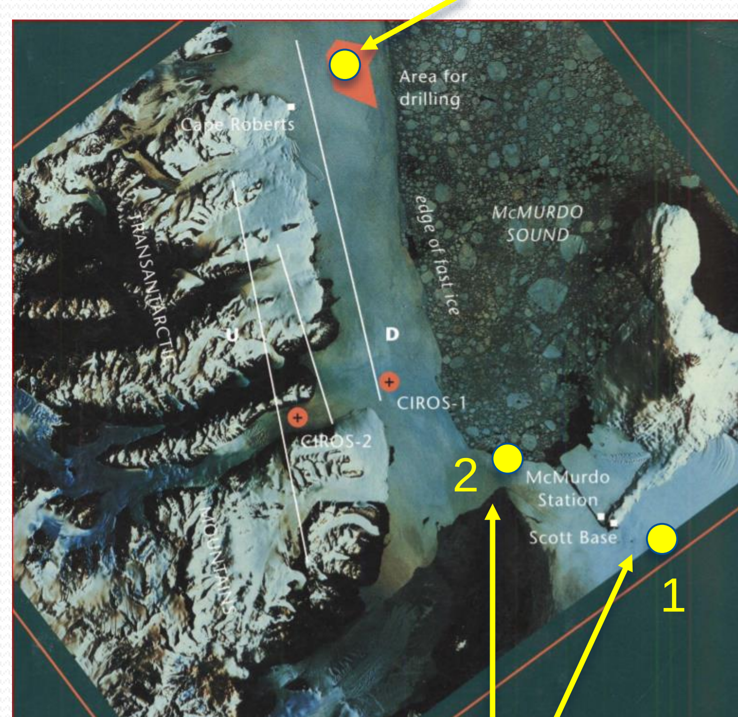
Cape Roberts project

1997-99

(1500 m) 34-17 Ma

from cool temperate to subpolar to polar climate

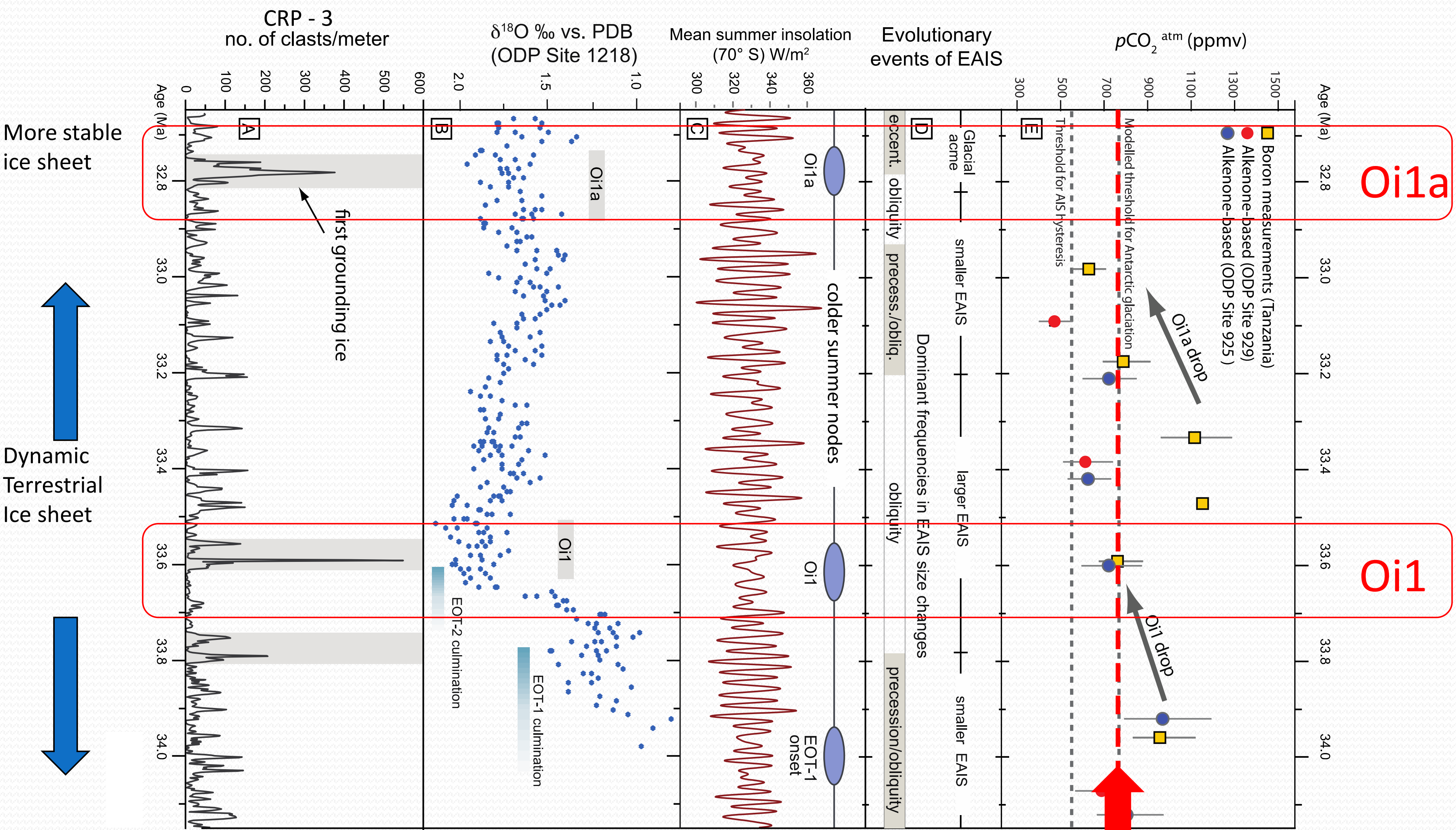
Crary Lab, McMurdo Station (Antarctica)



ANDRILL (**AN**tarctic **DRILL**ing Project 2006-07-08

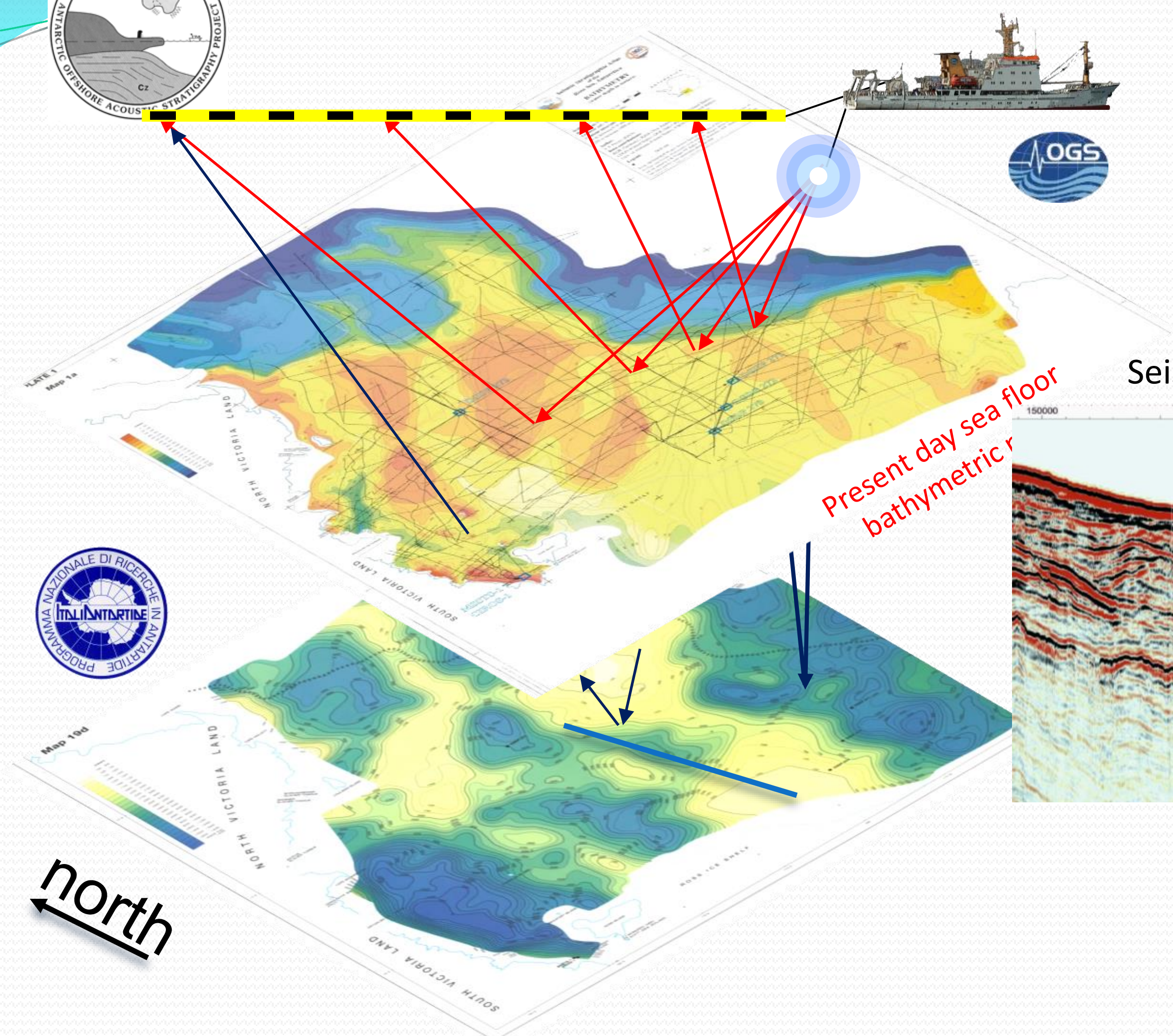
(2500 m) last 17 Ma

CO_2 threshold delays continental scale glaciation until Oi1a

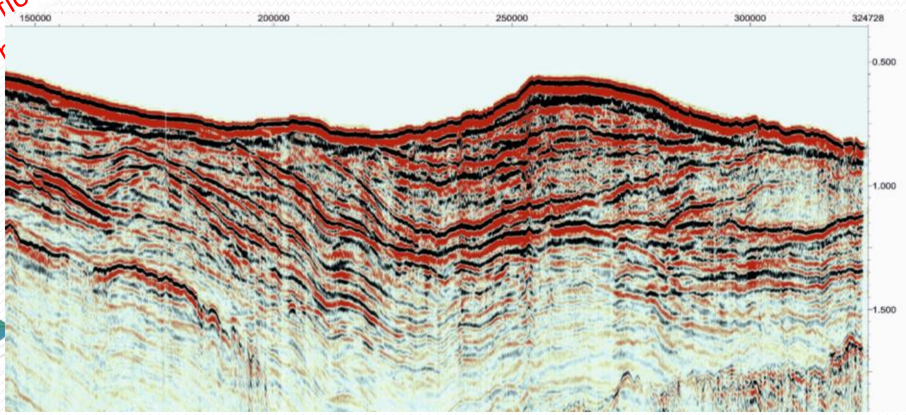


Galleoti, DeConto, Naish, Stocchi et al. (2016, Science)

600ppm CO_2 threshold not permanently crossed until Oi1a



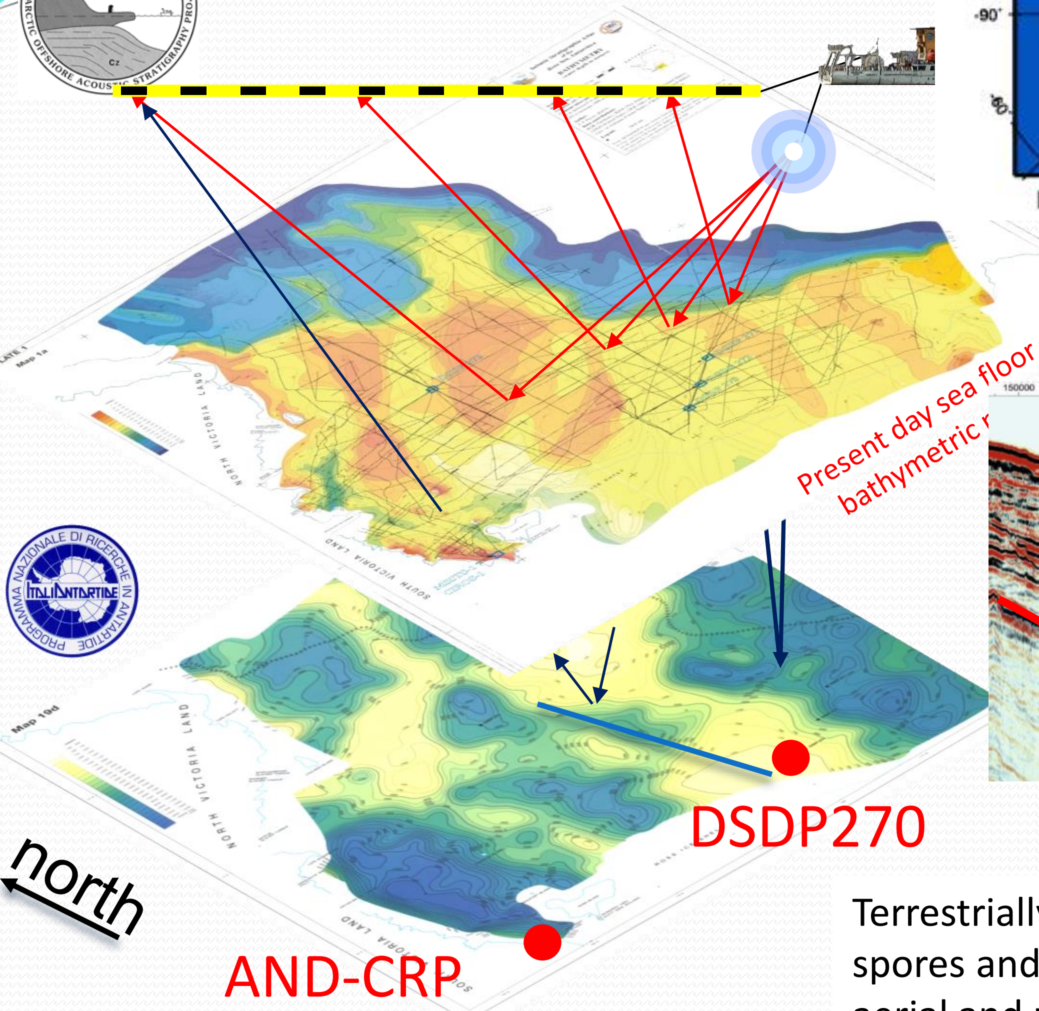
Seismic profile IT89-29



Ancient sea floor depth map.

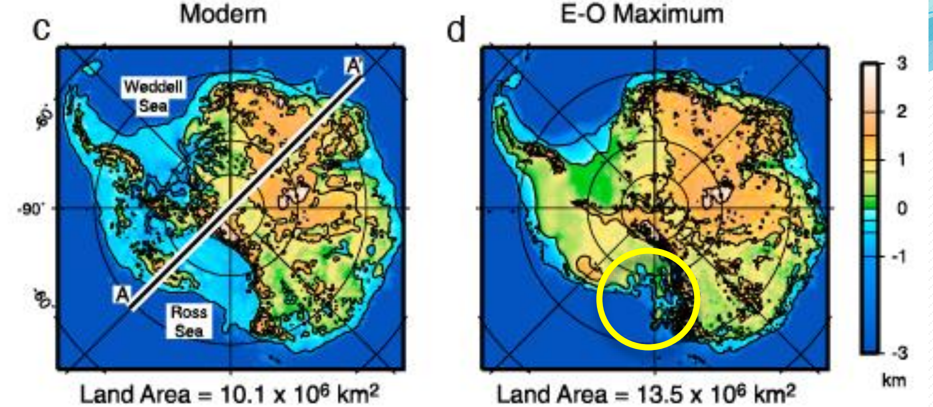
ANTOSTRAT project – Ross Sea Atlas . Brancolini et al., 1995

Antarctic Seismic Data Library System http://sdls.ogs.trieste.it/



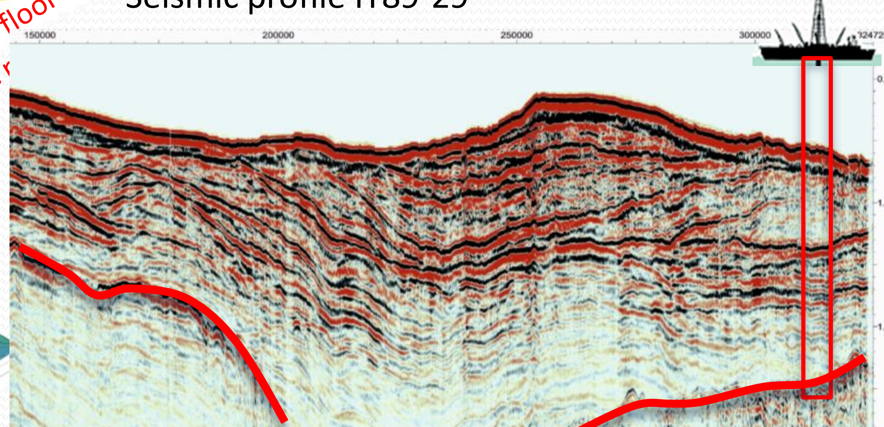
Ancient sea floor depth map.

ANTOSTRAT project – Ross Sea Atlas . Brancolini et al., 1995



Wilson et al. 2013

Seismic profile IT89-29



Terrestrially derived spores and pollen in sub-aerial and nearshore sediments above metamorphic basement

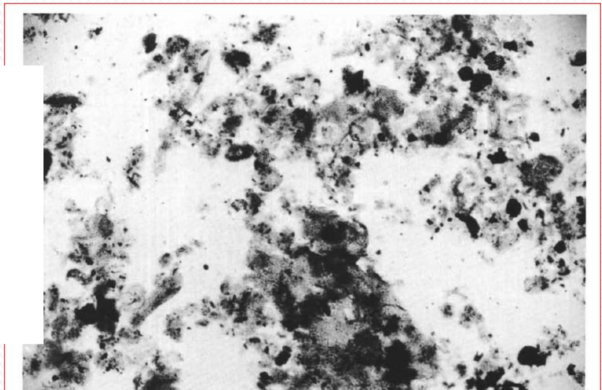
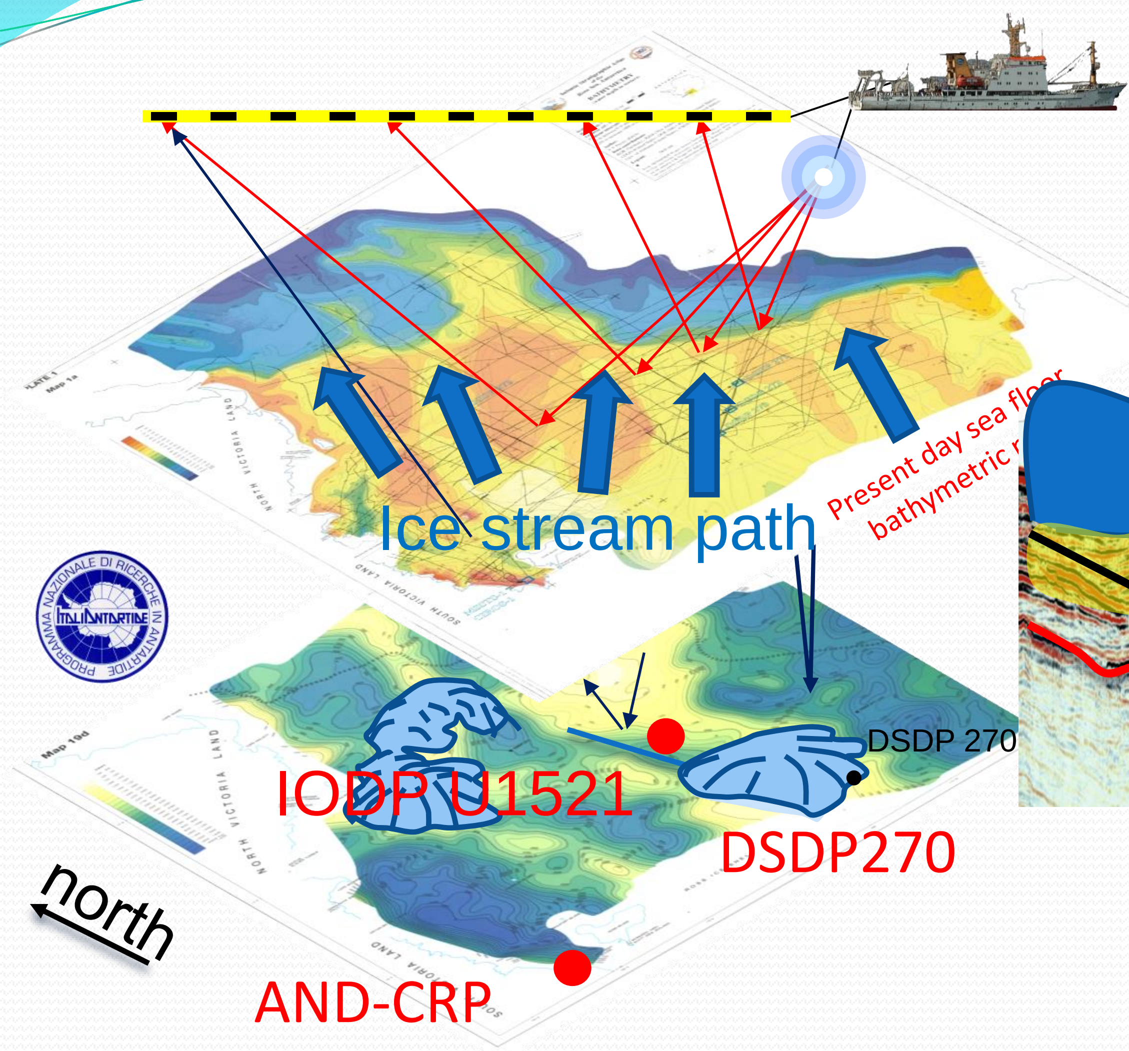
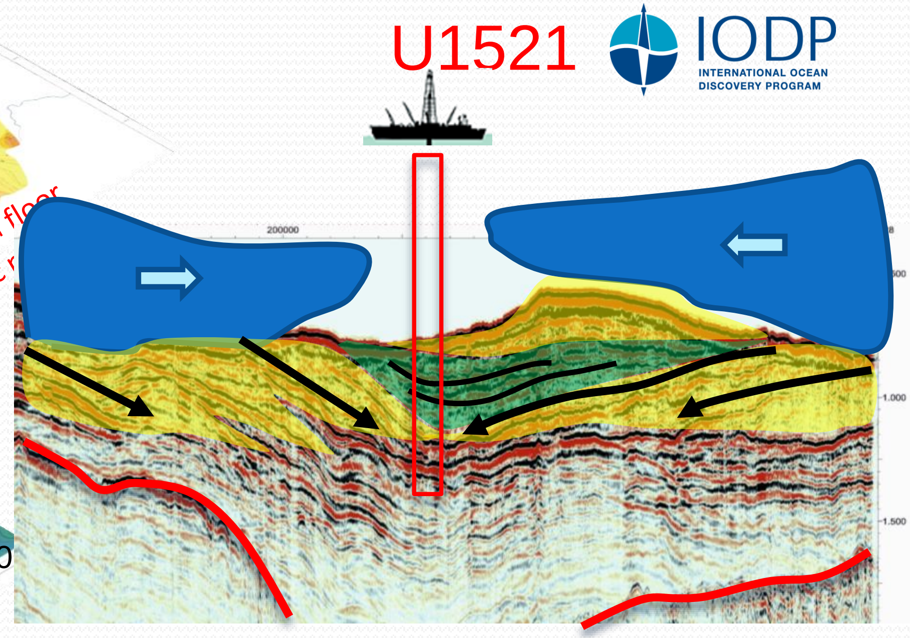


Figure 9. *Palynofacies with abundant, much degraded plant tissue; Site 270, Core 43.*





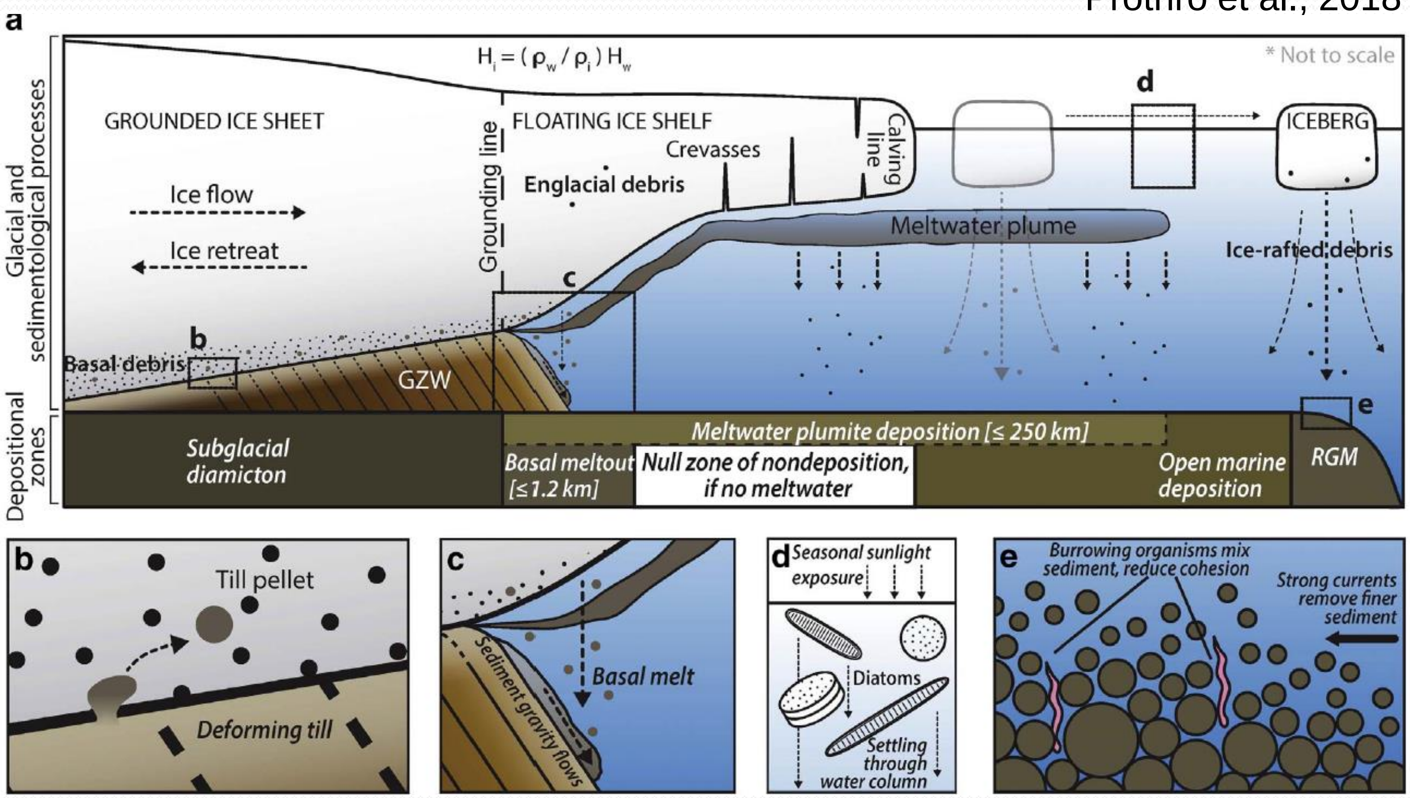
Seismic profile IT89-29

Ancient sea floor depth map.
ANTOSTRAT project – Ross Sea Atlas . Brancolini et al., 1995

PROXY (sediment cores)

- Ice/rafting record
- Geochemical changes
- Shift in biogeographic zones

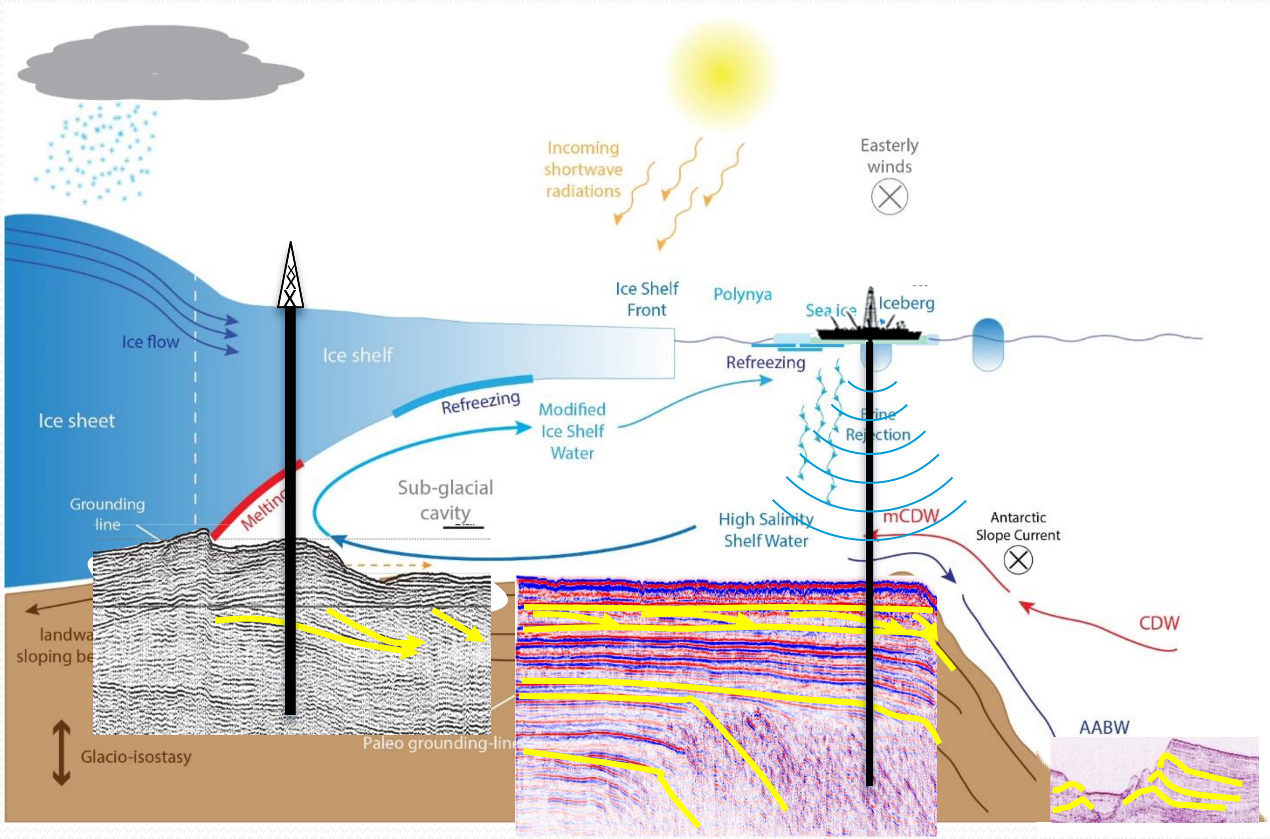
Prothro et al., 2018



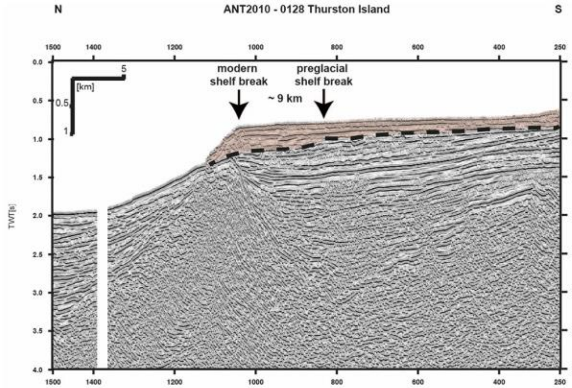
➢ Reconstruct ice- atmospheric-oceanic temperatures

➢ identify past polar amplification of climate change

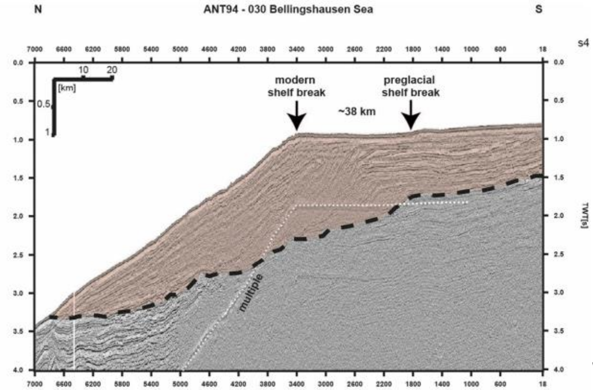
➢ assess forcings/feedbacks on ice sheet stability/instability



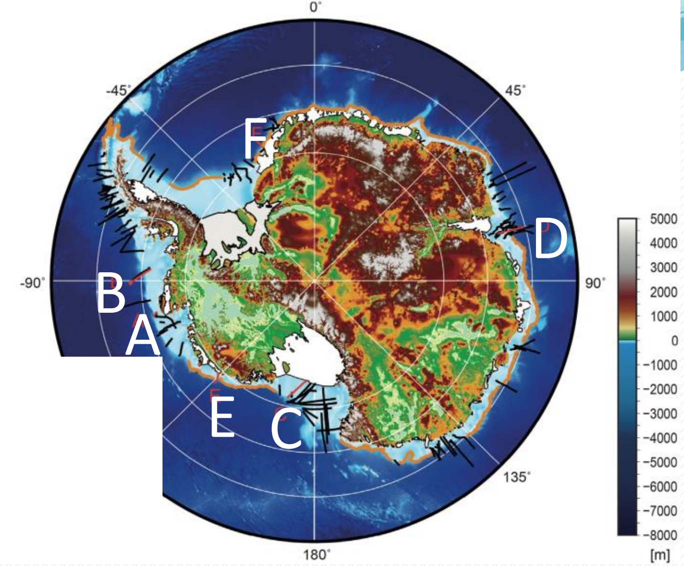
Colleoni et al., 2018 modified

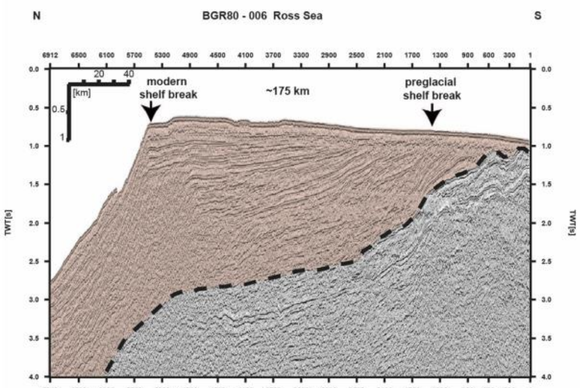


A minimal progradation limited by presence of basement high

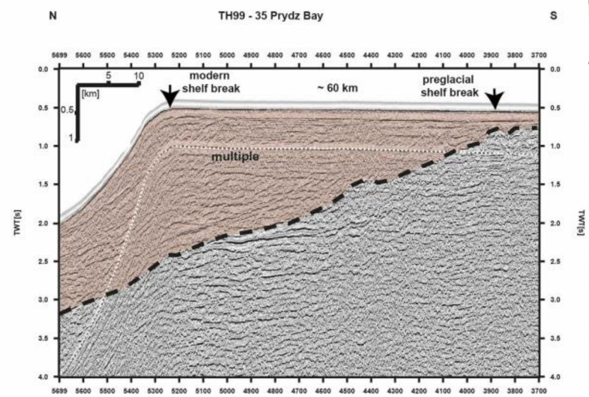


B progradation within minor glacial trough

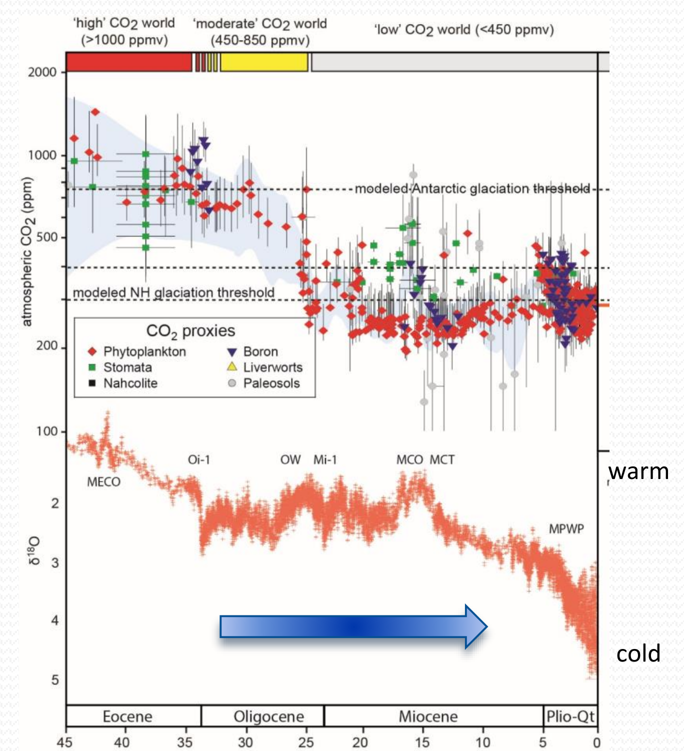


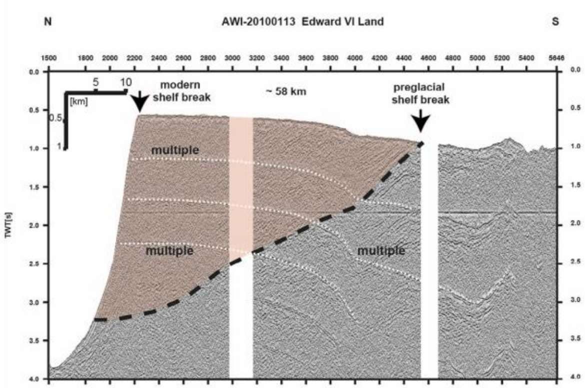


C strong progradation within the center of a major glacial trough

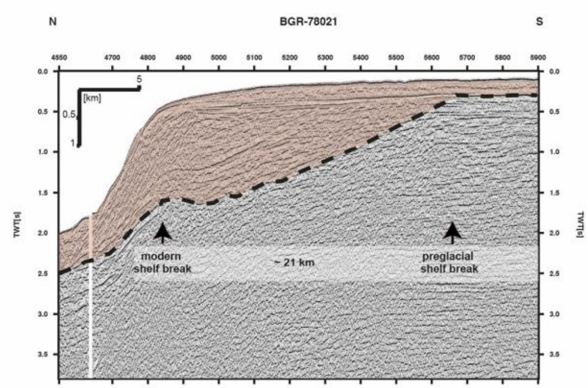


D progradation at the border of a major glacial trough





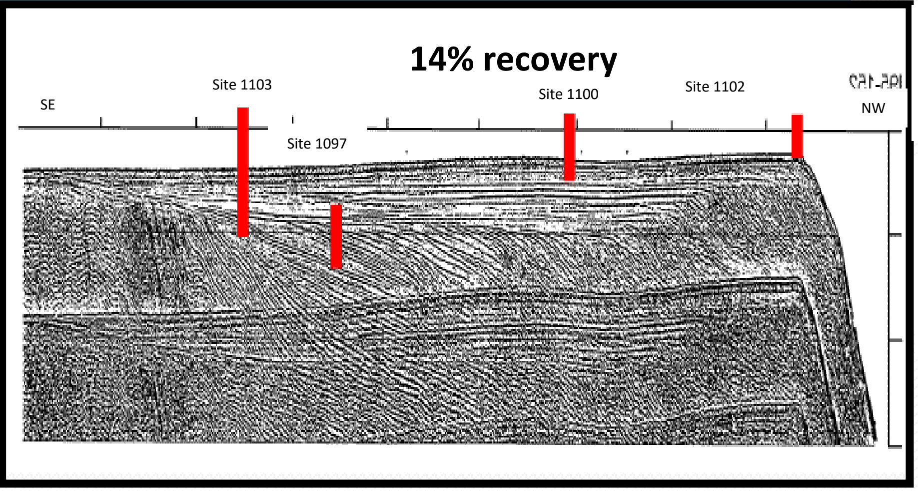
E progradation influenced by Neogene tectonic activity



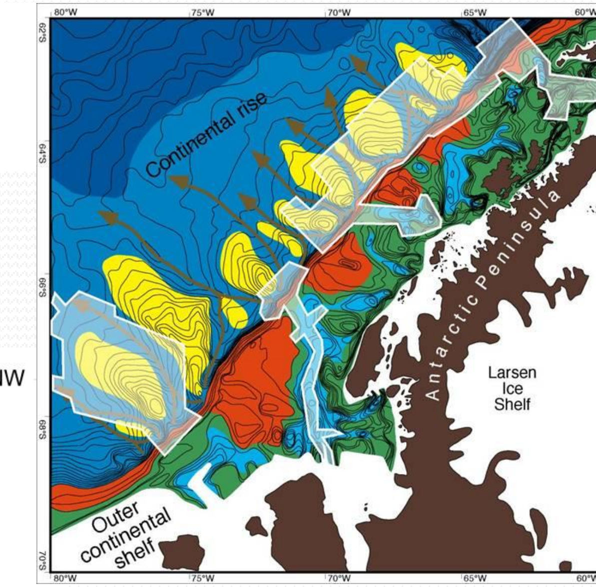
F minor progradation at a narrow shelf

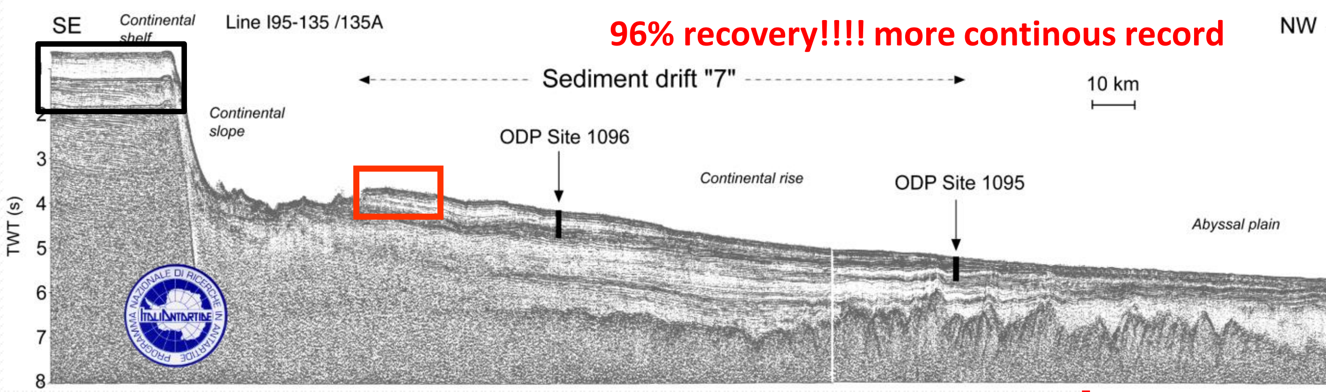
Hockmuth and Gohl, 2019

Barker, Camerlenghi, Acton, et al., ODP leg 178 (1999) Antarctic Peninsula

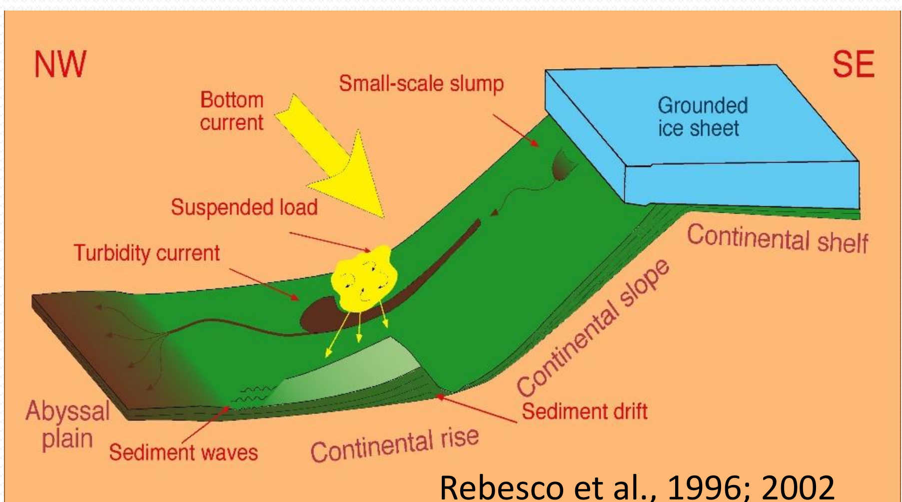


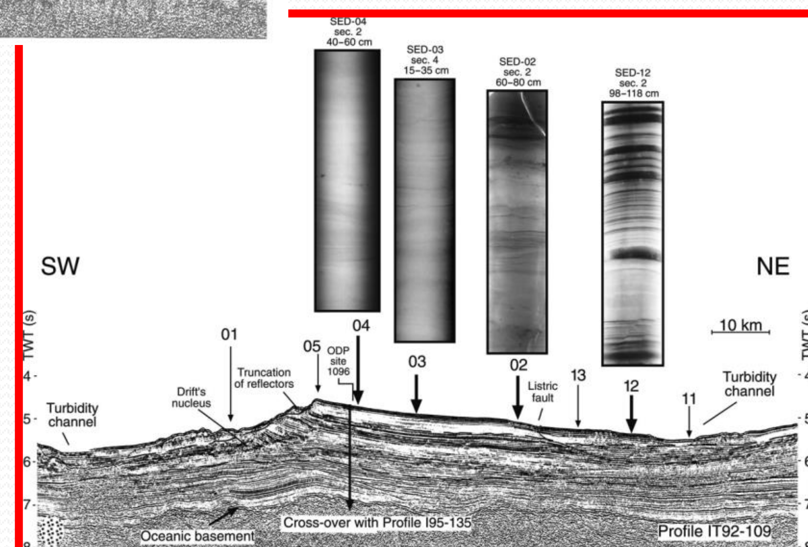
0.0
TWT
1.0
1.5
2.0

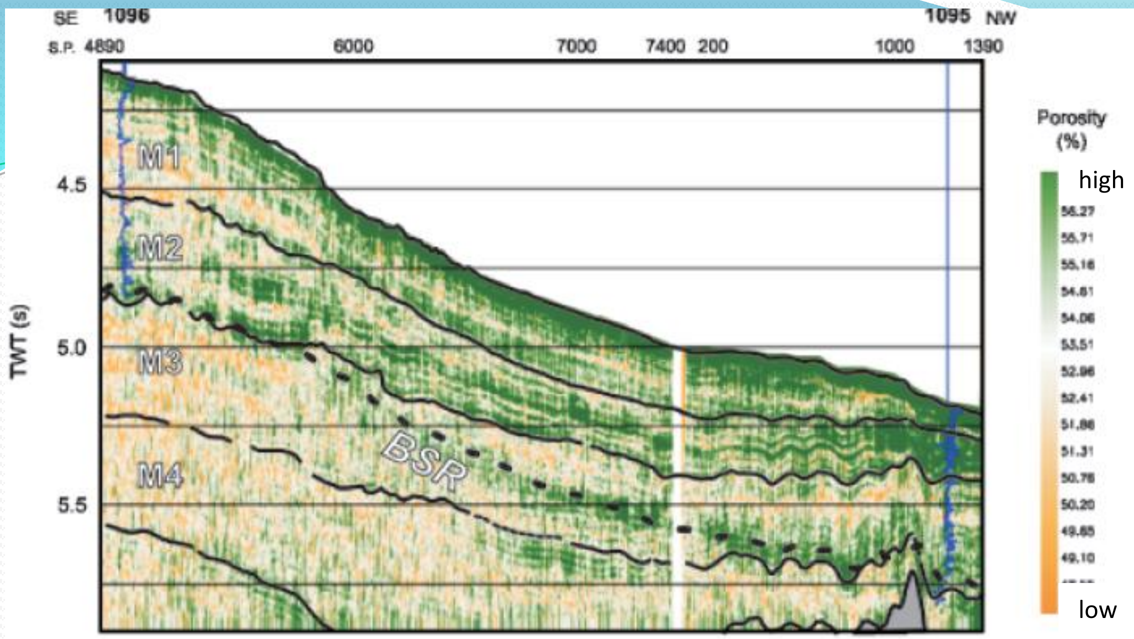




Rebesco et al., 2006
Lucchi and Rebesco 2007







Volpi et al., 2003

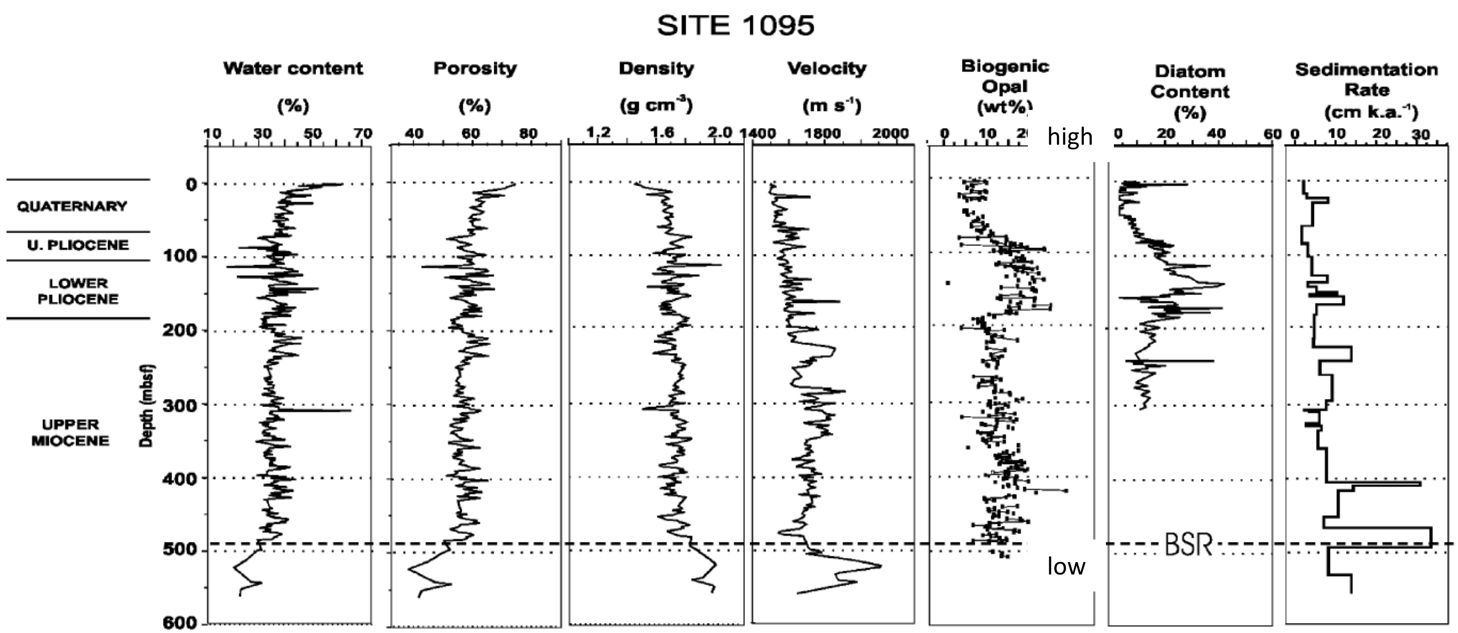
Bottom Simulating Reflector (BSR)

Diagenetic alteration of biogenic opal-A to opal-CT

$\Rightarrow$ reduction of porosity allowing sediments to consolidate at depth.

$\Rightarrow$ overpressuring and a decrease in the effective stress.

Effects of biogenic silica



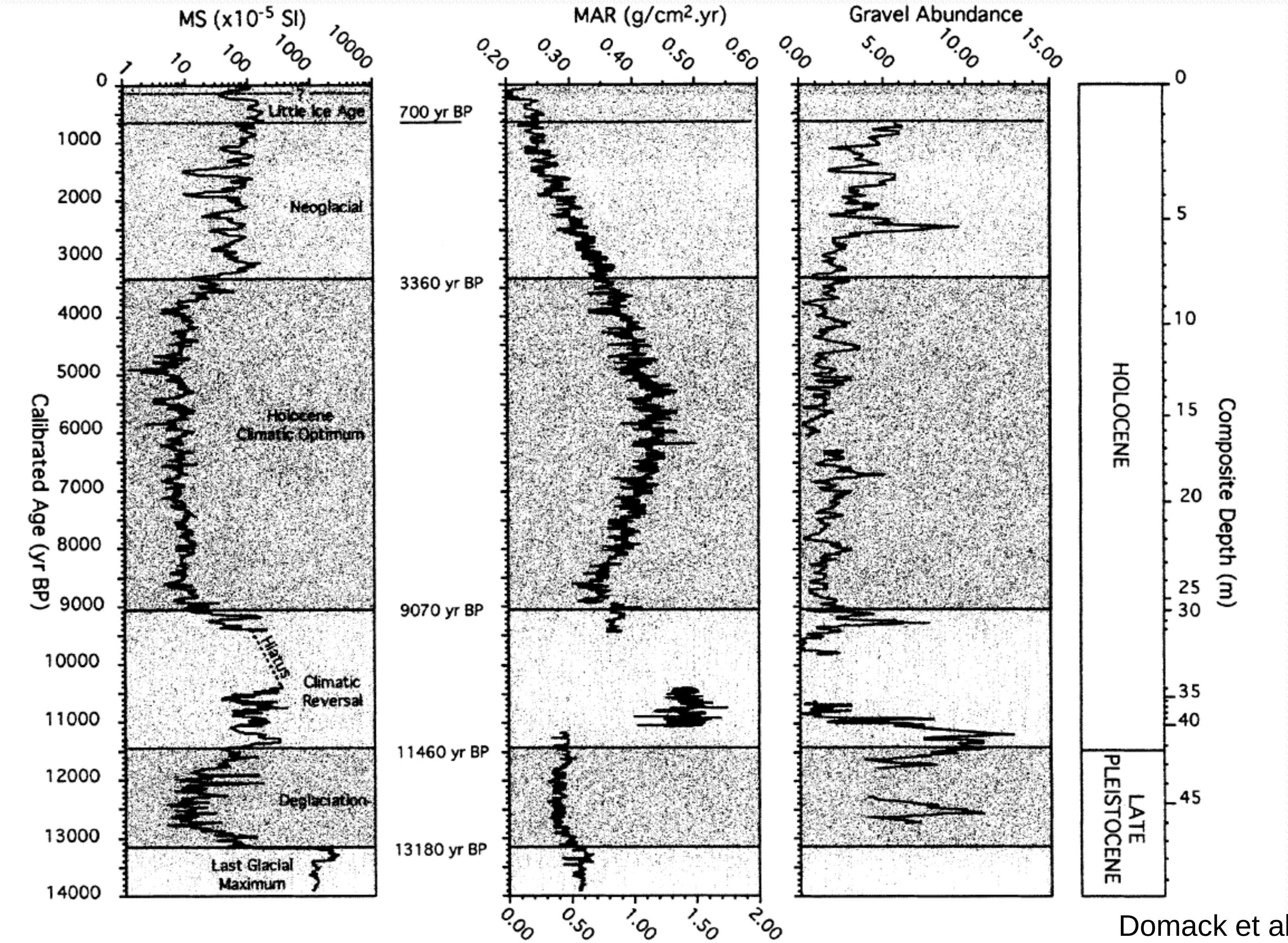
ultrahigh-resolution Holocene sedimentary record

Palaeoenvironmental proxies for ODP site 1098 in the Palmer Deep

Magnetic susceptibility

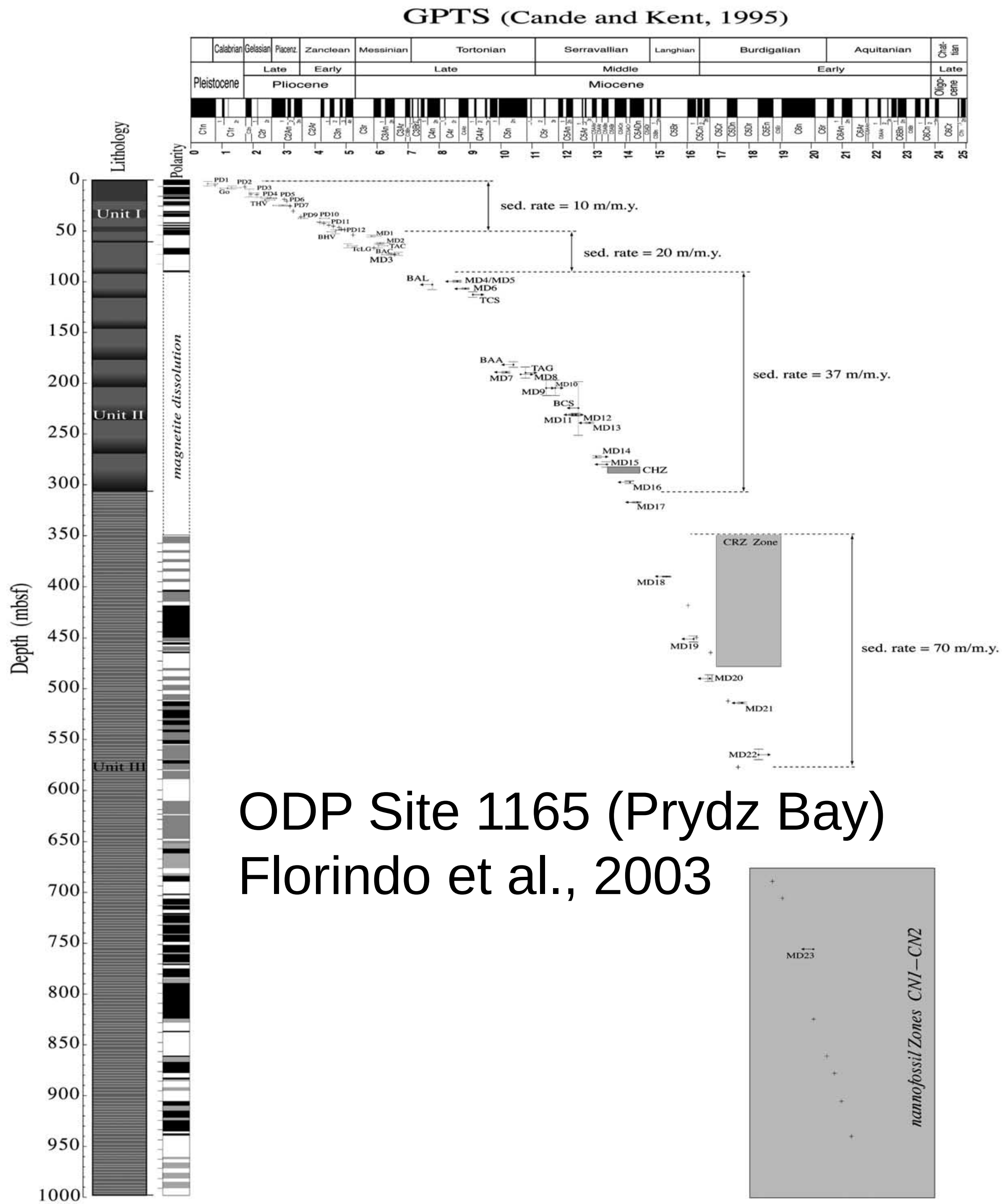
Mass accumulation rate

Ice-rafted debris concentration

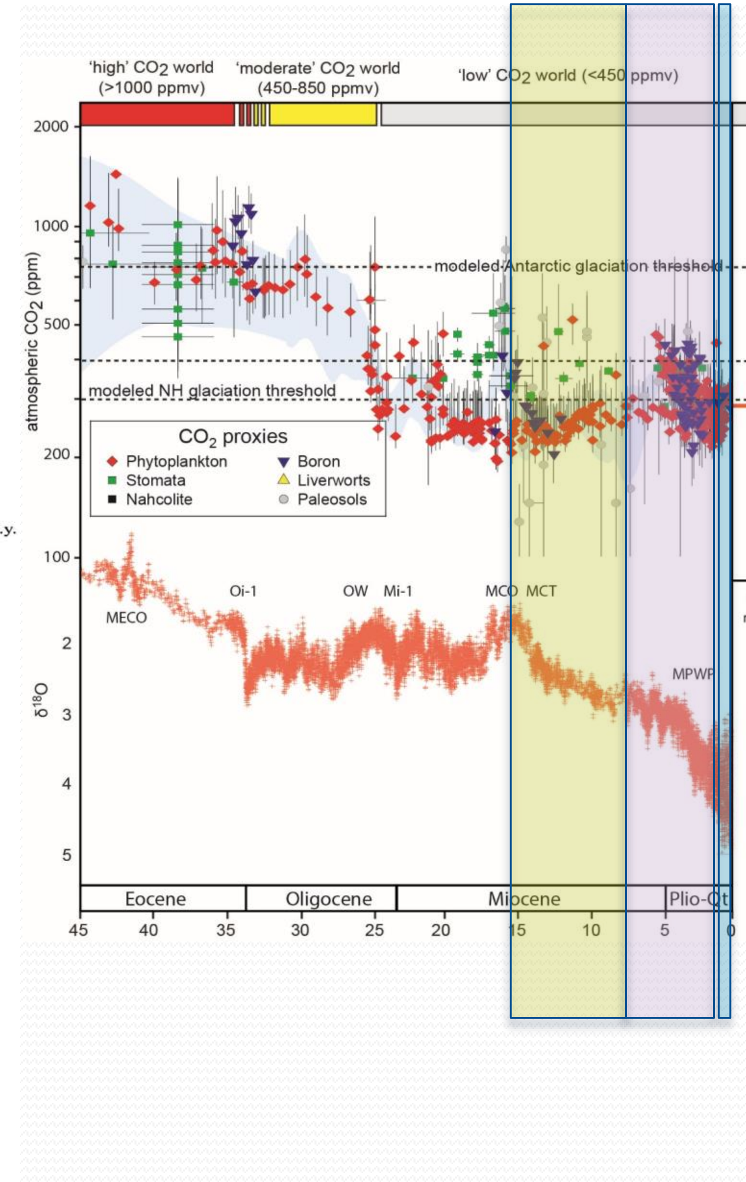


Domack et al., 2001

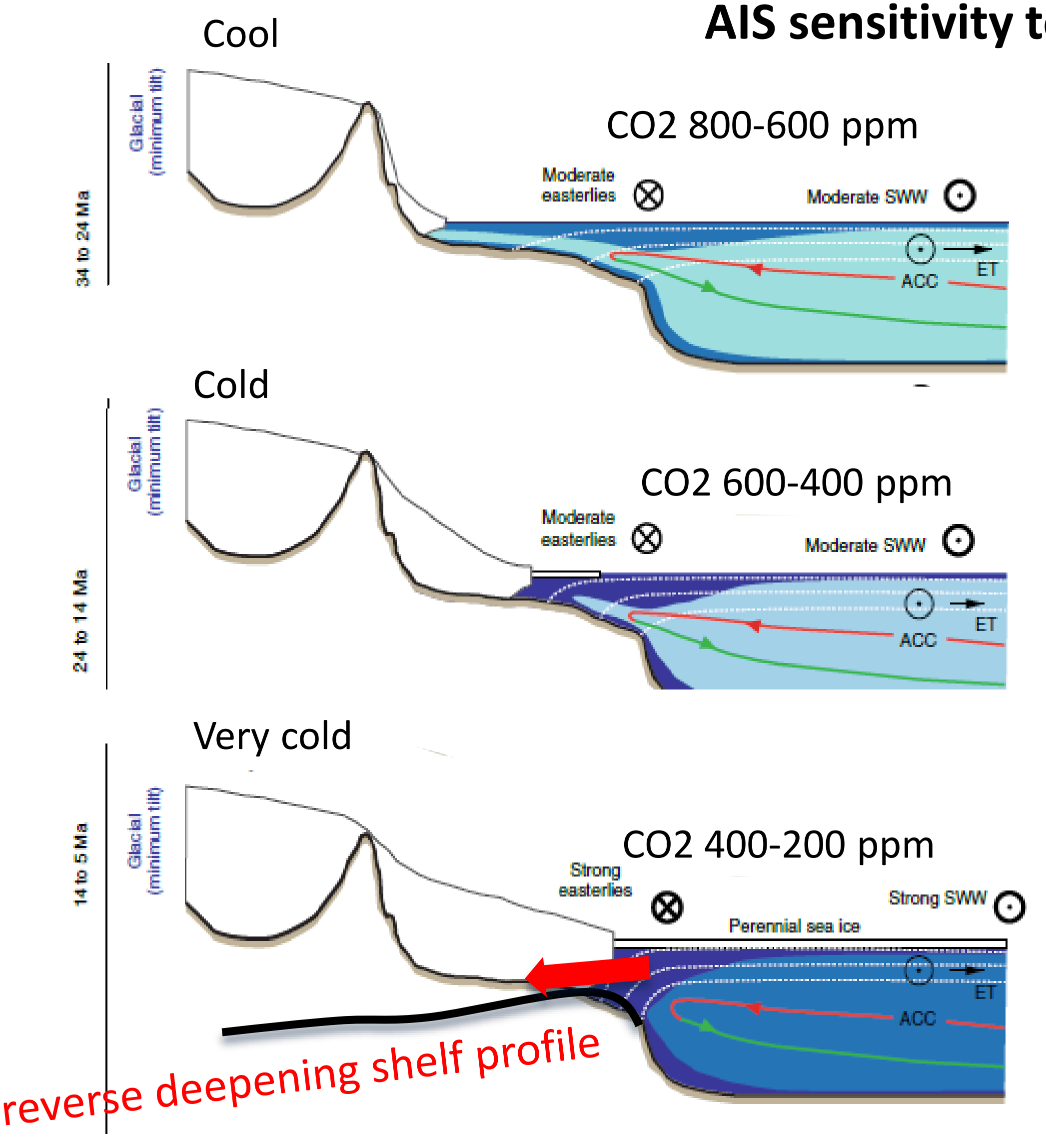
overall trend of decreasing sedimentation rates



ODP Site 1165 (Prydz Bay)
Florindo et al., 2003



AIS sensitivity to ocean and climate dynamics

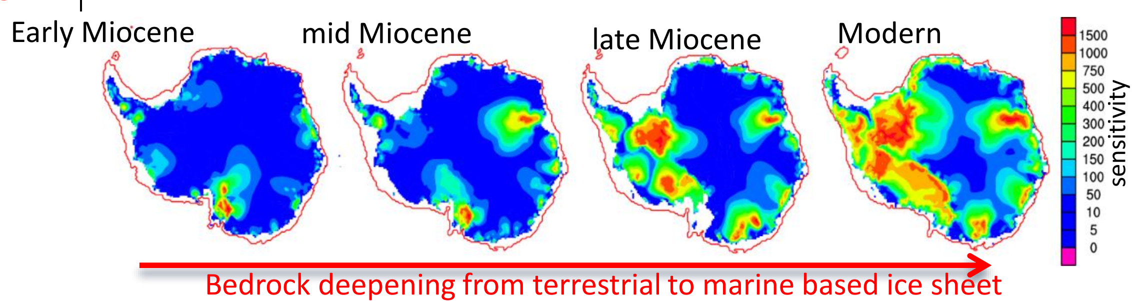


Levy et al., 2019

Terrestrial ice → low sensitivity to ocean warming

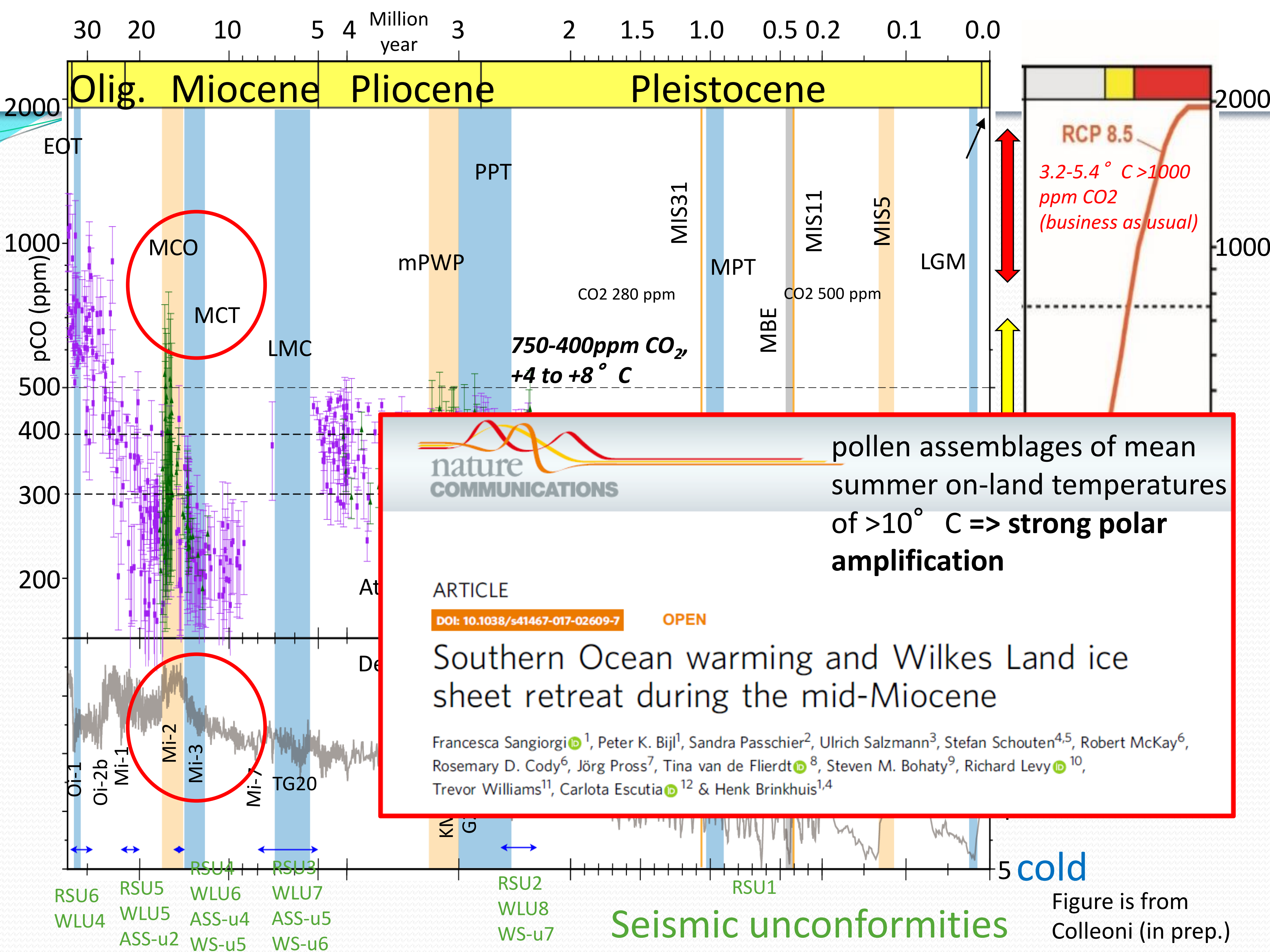
Marine ice-sheet extent → high sensitivity to ocean warming

Persistent terrestrial and variable marine ice sheets. Sea ice and deep pycnocline 'insulate' marine ice sheet from ocean = decreased sensitivity to ocean warming



Colleoni, F., et al. 2018

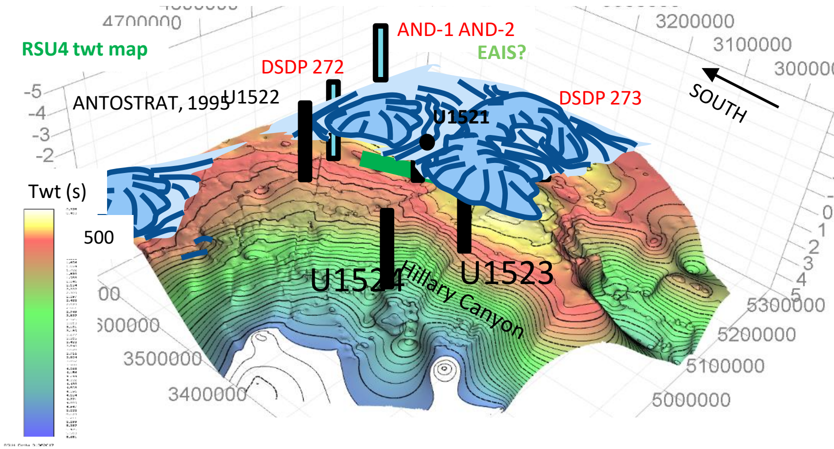
Bathymetry evolution => increase ice sheet sensitivity to ocean warming

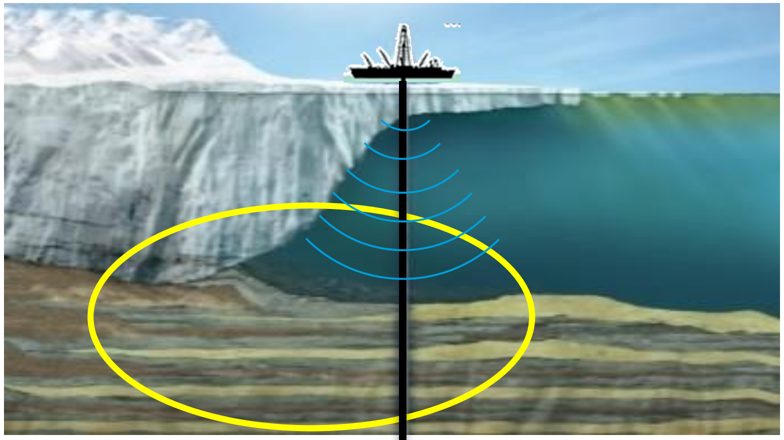


Million year
30 20 10 5 4 3 2 1.5 1.0 0.5 0.2 0.1 0.0
Olig. Miocene Pliocene Pleistocene
2000
1000
500
400
300
200
pCO (ppm)
EOT
MCO
MCT
LMC
mPWP
PPT
MIS31
MPT
MBE
MIS11
MIS5
LGM
CO2 280 ppm
CO2 500 ppm
750-400ppm CO2, +4 to +8° C
RCP 8.5
3.2-5.4° C >1000 ppm CO2 (business as usual)
Oi-1
Oi-2b
Mi-1
Mi-2
Mi-3
TG20
5 cold
RSU6 WLU4
RSU5 WLU5 ASS-u2
RSU4 WLU6 ASS-u4 WS-u5
RSU3 WLU7 ASS-u5 WS-u6
RSU2 WLU8 WS-u7
RSU1
Seismic unconformities
Figure is from Colleoni (in prep.)
nature COMMUNICATIONS
ARTICLE
DOI: 10.1038/s41467-017-02609-7
OPEN
Southern Ocean warming and Wilkes Land ice sheet retreat during the mid-Miocene
Francesca Sangiorgi[1], Peter K. Bijl[1], Sandra Passchier[2], Ulrich Salzmann[3], Stefan Schouten[4,5], Robert McKay[6], Rosemary D. Cody[6], Jörg Pross[7], Tina van de Flierdt[8], Steven M. Bohaty[9], Richard Levy[10], Trevor Williams[11], Carlota Escutia[12] & Henk Brinkhuis[1,4]
pollen assemblages of mean summer on-land temperatures of >10° C => strong polar amplification

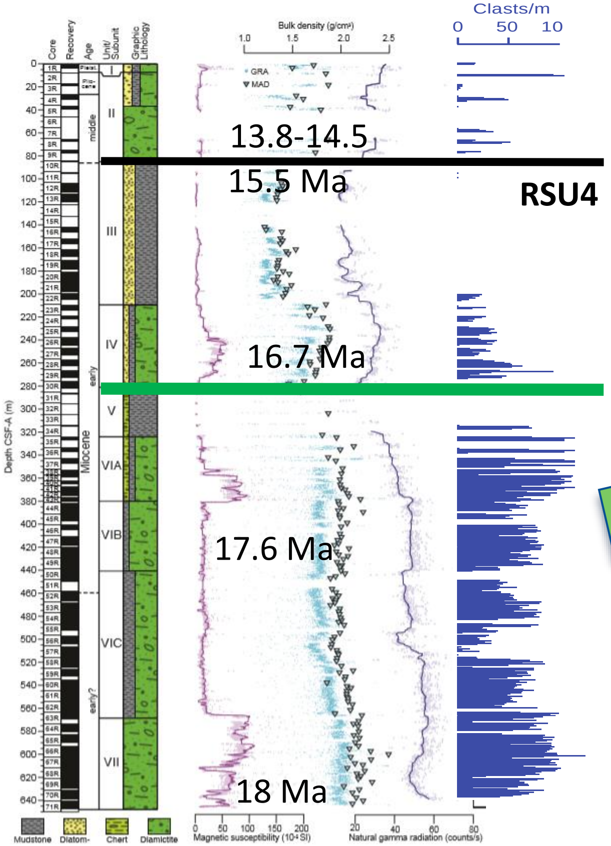
IODP Exp. 374 (Ross Sea)

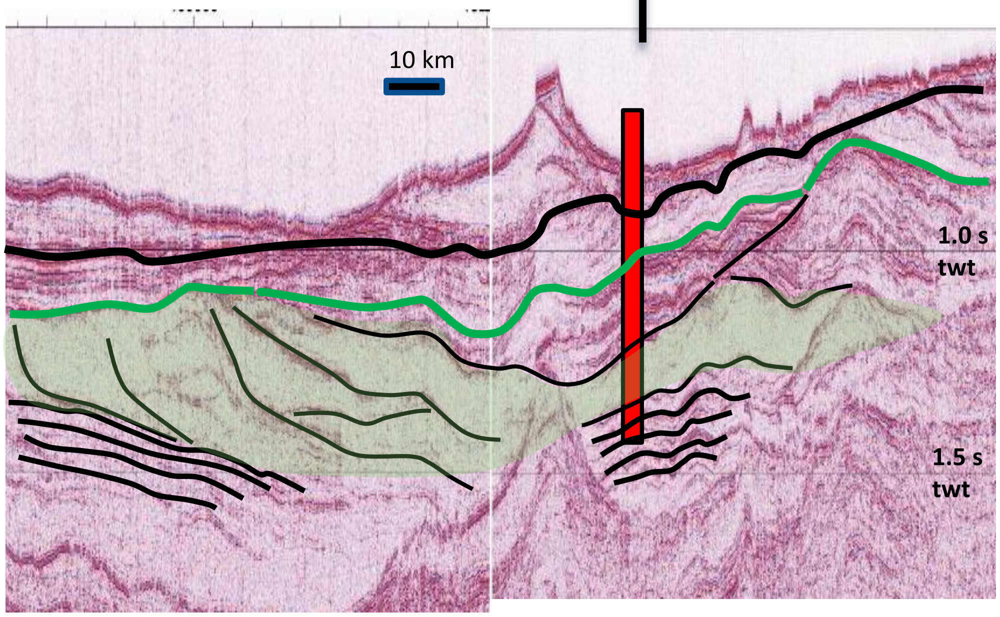
Early Miocene Climatic cooling





63% recovery!!

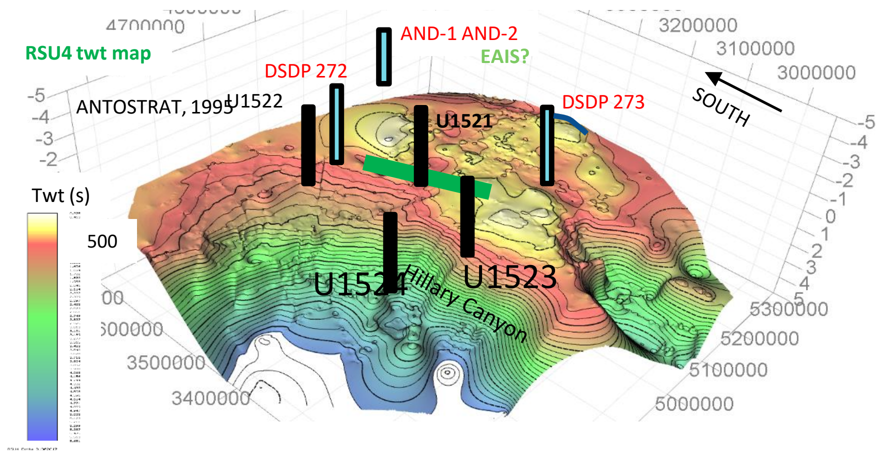


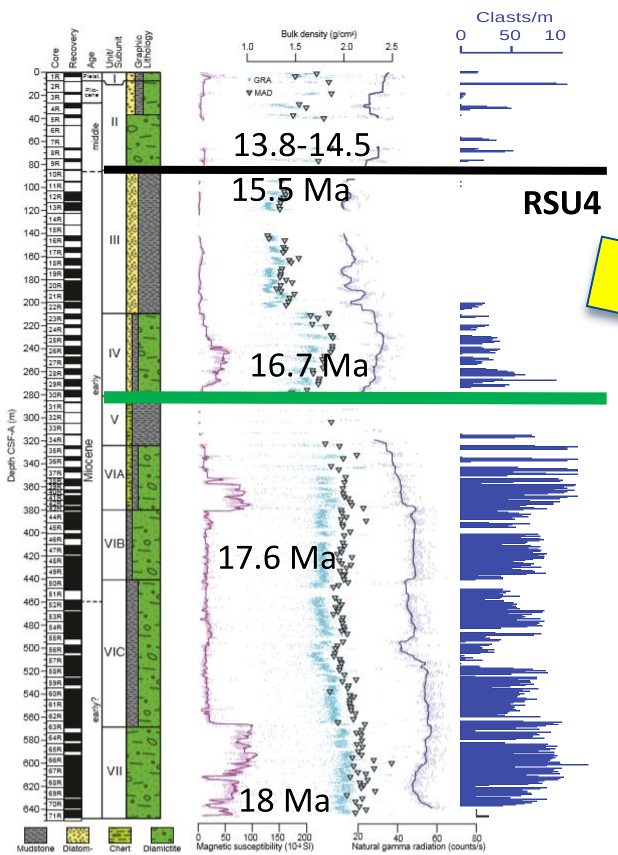


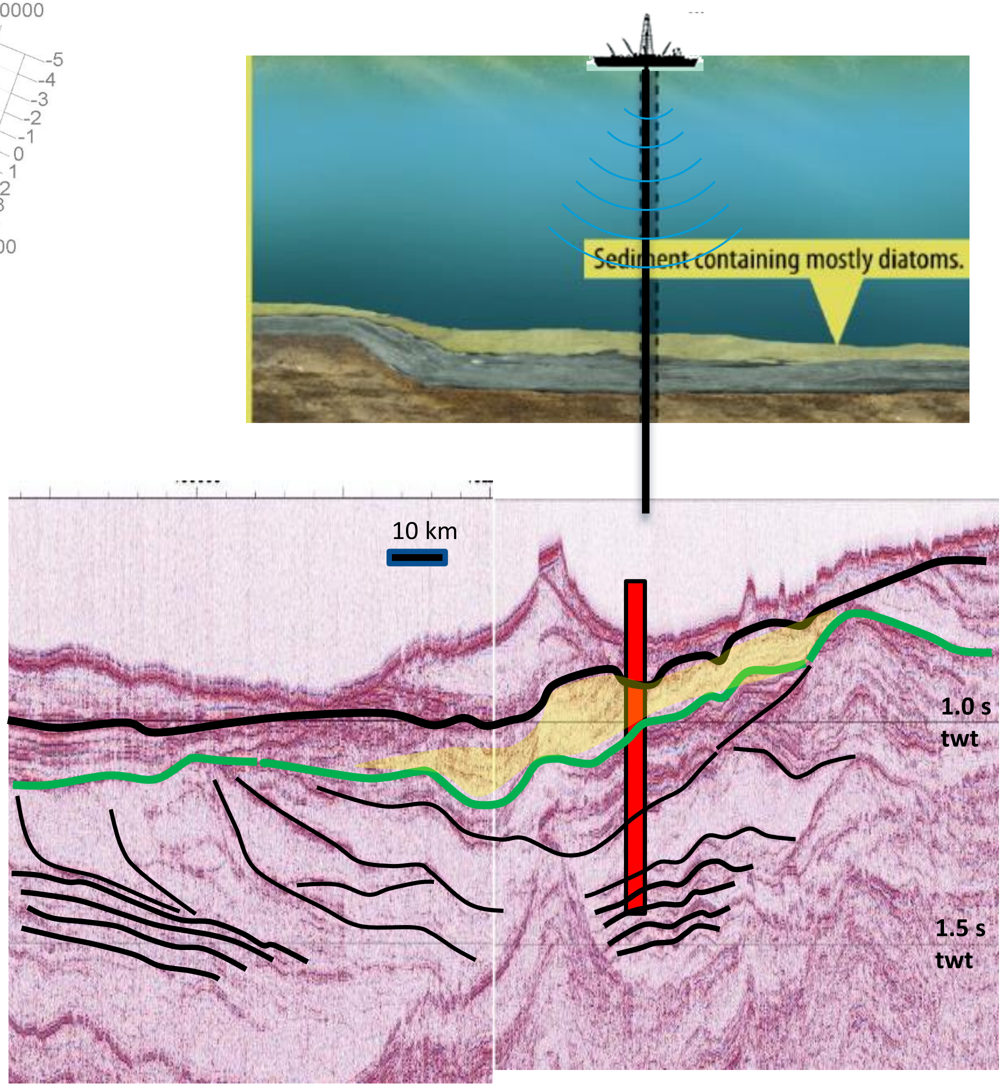
McKay, De Santis, Kulhanek et al., 2018, Perez et al., 2021 in press

IODP Exp. 374 (Ross Sea)

Mid Miocene Climatic Optimum

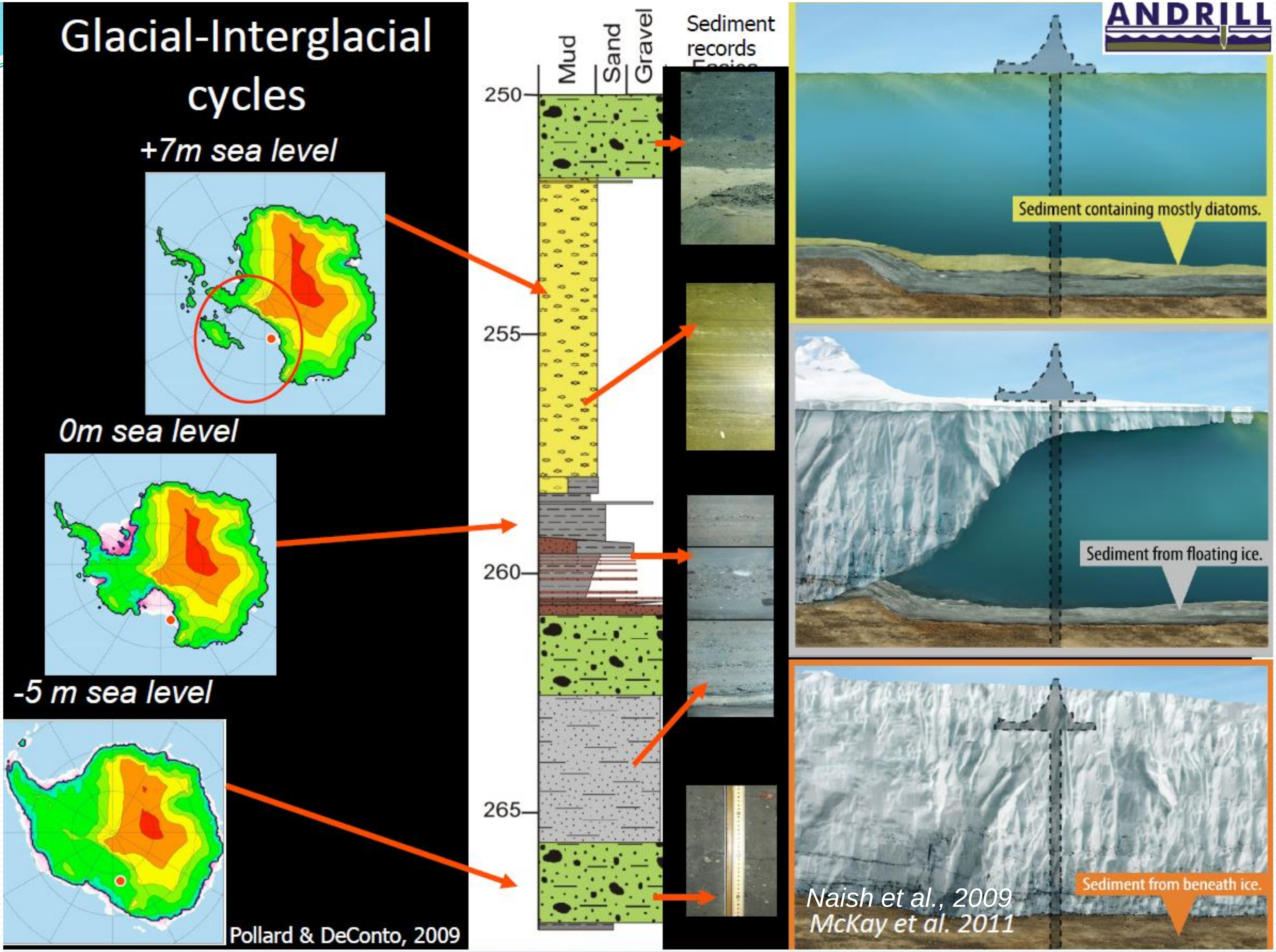


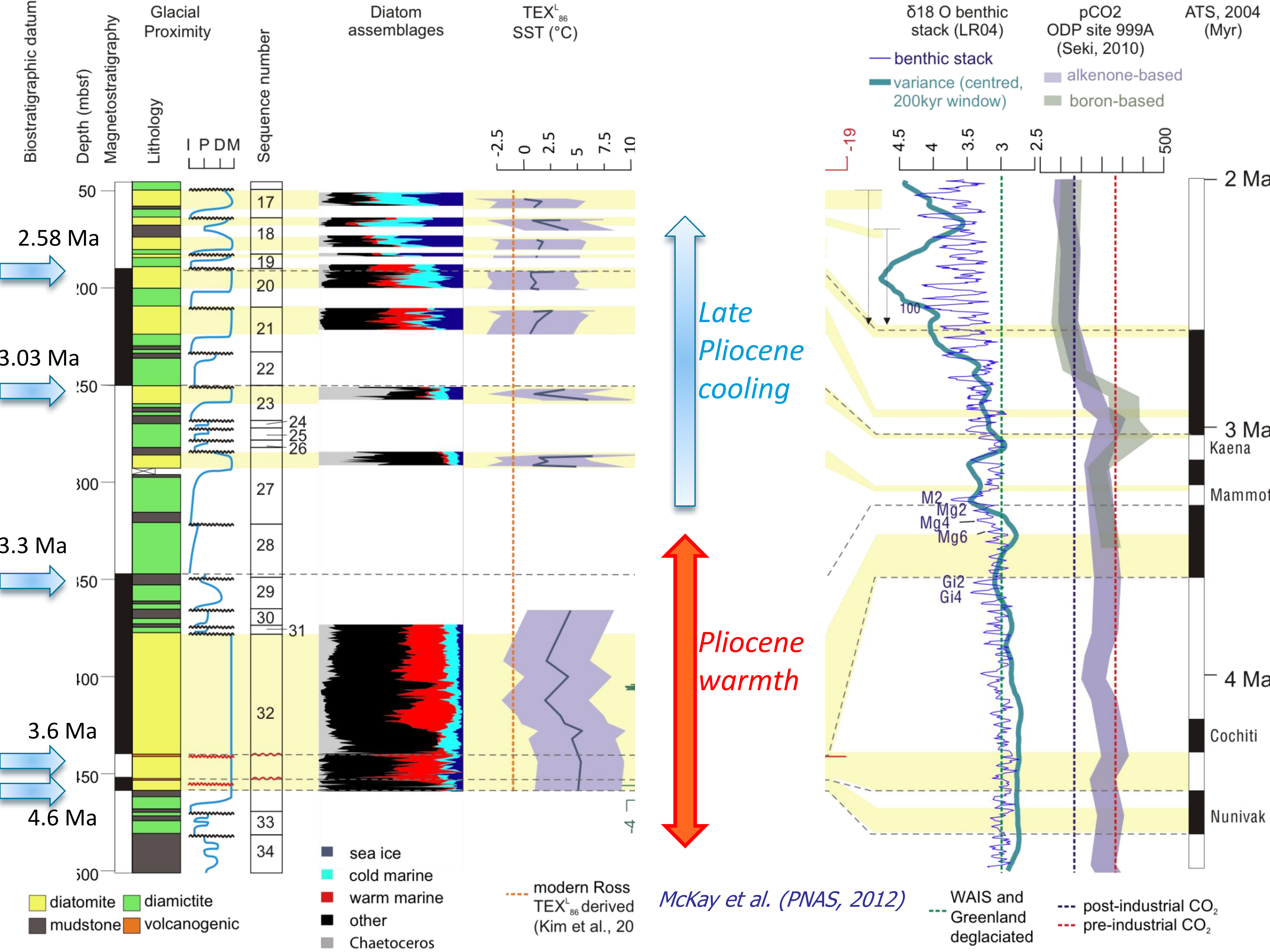




McKay, De Santis, Kulhanek et al., 2018, Perez et al., 2021, in press

ANDRILL evidence of marine-based ice sheet collapse 5-3 Ma

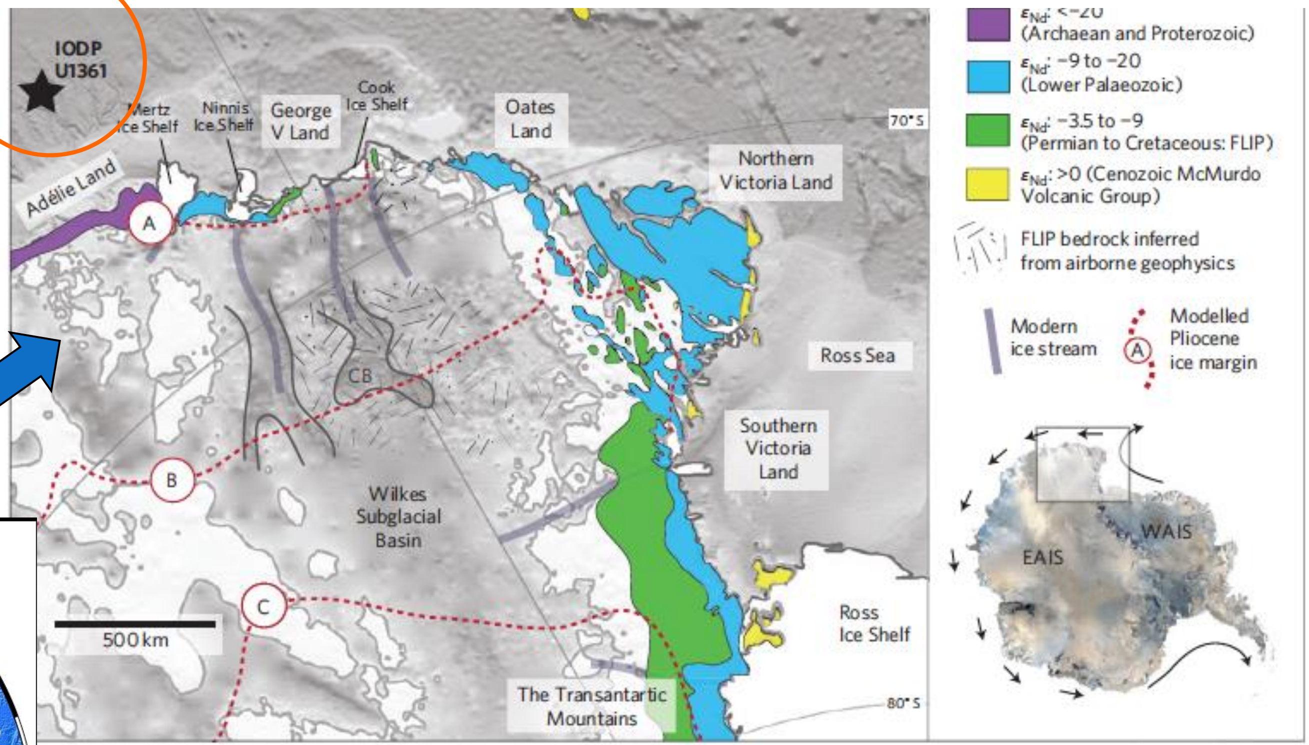


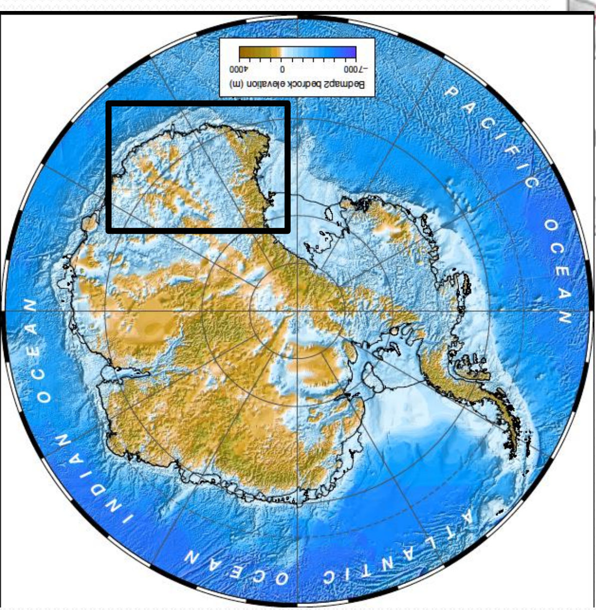


Biostratigraphic datum
Depth (mbsf)
Magnetostratigraphy
Glacial Proximity
Lithology
I P DM
Sequence number
Diatom assemblages
TEX$^L_{86}$ SST (°C)
δ18 O benthic stack (LR04)
benthic stack
variance (centred, 200kyr window)
pCO2 ODP site 999A (Seki, 2010)
alkenone-based
boron-based
ATS, 2004 (Myr)
2.58 Ma
3.03 Ma
3.3 Ma
3.6 Ma
4.6 Ma
Late Pliocene cooling
Pliocene warmth
2 Ma
3 Ma
4 Ma
Kaena
Mammoth
Cochiti
Nunivak
M2
Mg2
Mg4
Mg6
Gi2
Gi4
diatomite
diamictite
mudstone
volcanogenic
sea ice
cold marine
warm marine
other
Chaetoceros
modern Ross TEX$^L_{86}$ derived (Kim et al., 20
McKay et al. (PNAS, 2012)
WAIS and Greenland deglaciated
post-industrial CO_2
pre-industrial CO_2

Geochemical provenance of detrital material evidence for retreat of the EAIS 5-3 Ma

Cook et al., 2013



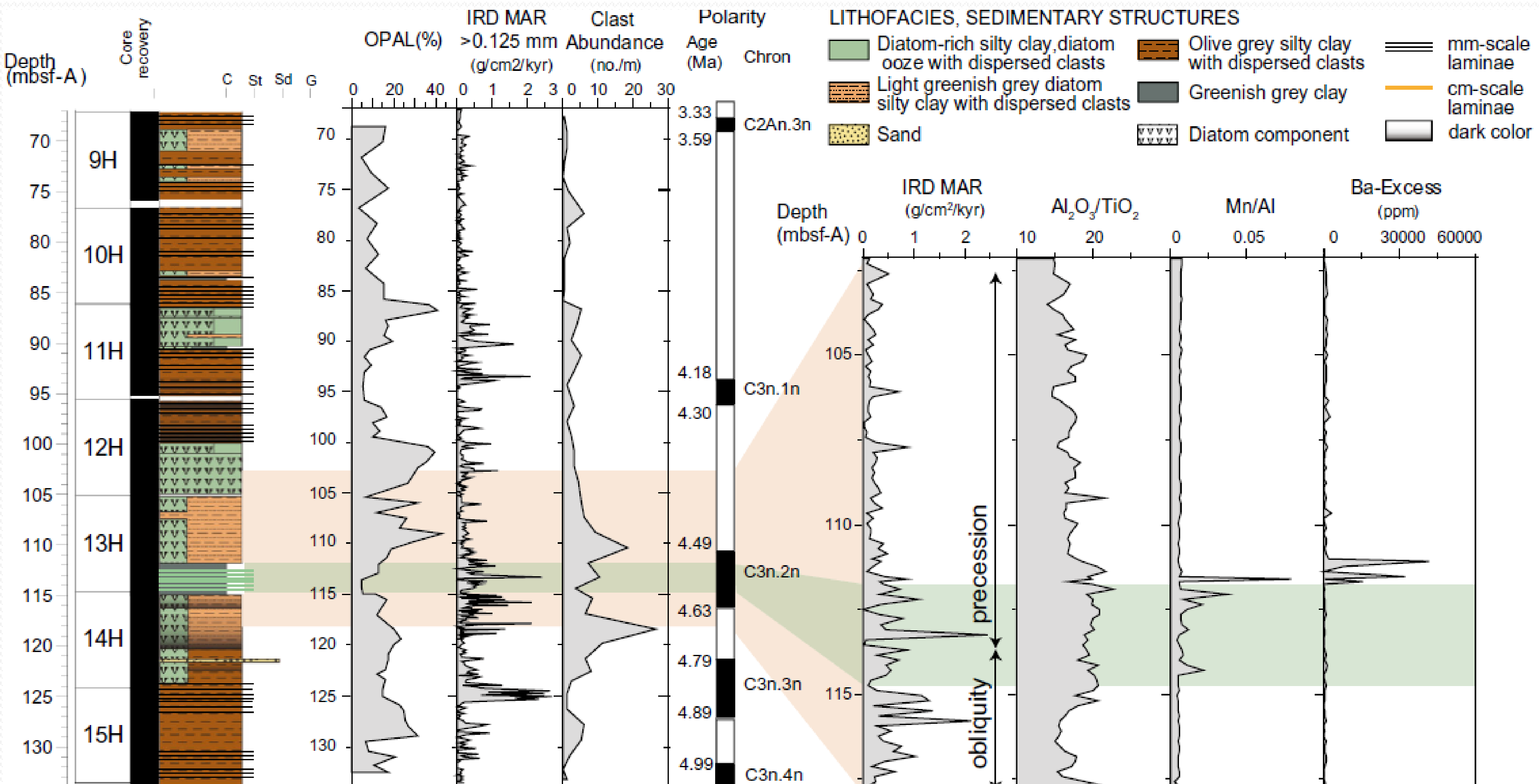


Evidence for iceberg armadas from East Antarctica in the Southern Ocean during the late Miocene and early Pliocene.

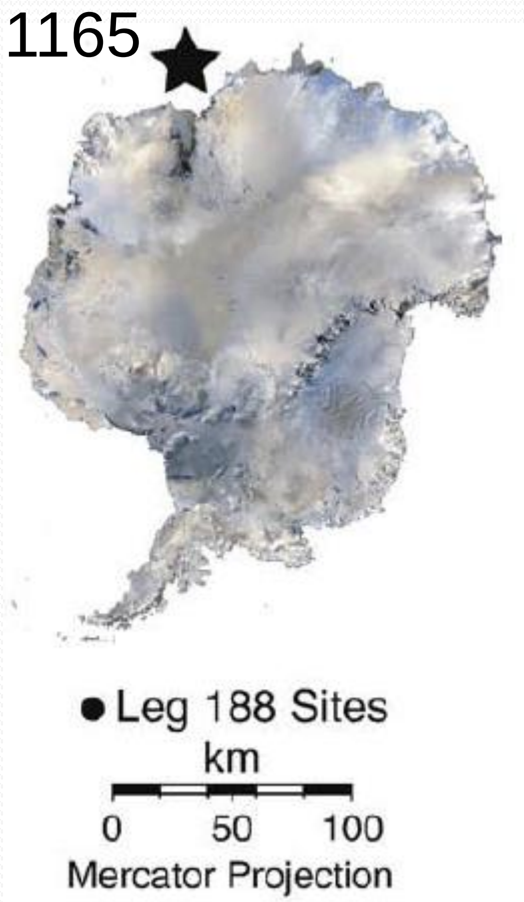
Williams, et al., 2010

enhanced upwelling of nutrient-rich Circumpolar Deep Water (CDW) affected ice discharge

Hansen et al., 2017



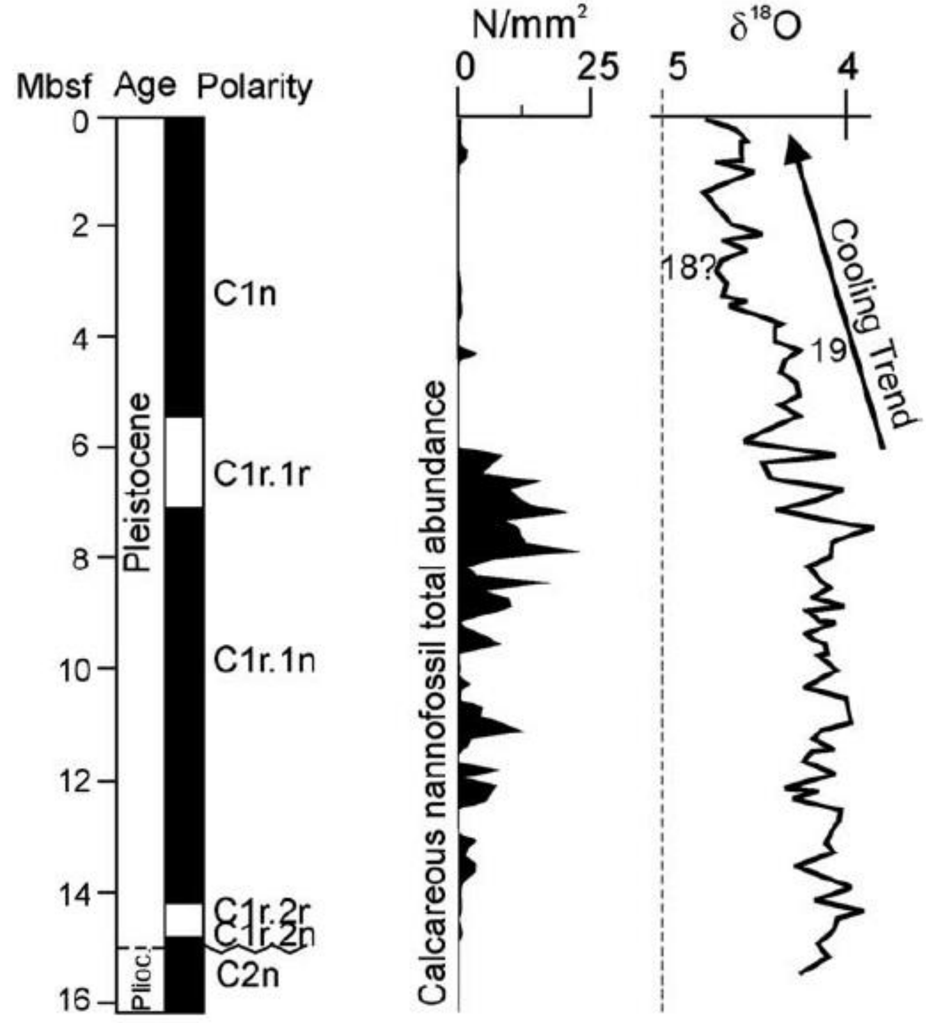
Marine Isotope Stage 31 at ~1 Ma



Magnetostratigraphy

nannofossil total abundance plot

oxygen isotope



Villa et al., 2008
Florindo et al., 2003
Warnke et al., 2004

AGU PUBLICATIONS

Paleoceanography and Paleoclimatology

RESEARCH ARTICLE

10.1002/2017PA003225

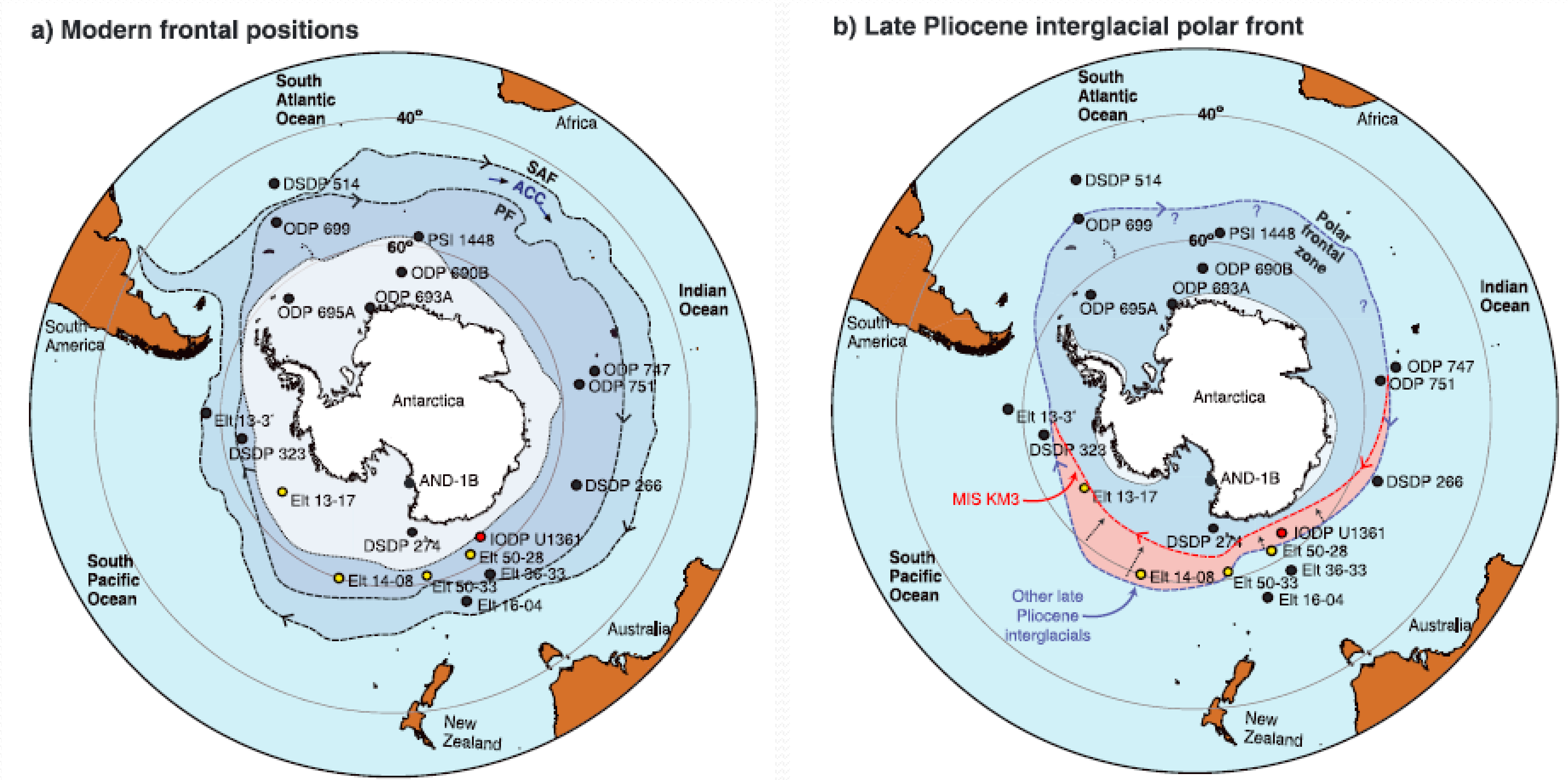
Key Points:
- Pliocene cooling on the Wilkes Land margin was interrupted by an excursion to warmer subantarctic conditions during the unique MIS KM3
- Revisiting published records shows that the KM3 excursion was produced

Polar Frontal Migration in the Warm Late Pliocene: Diatom Evidence From the Wilkes Land Margin, East Antarctica

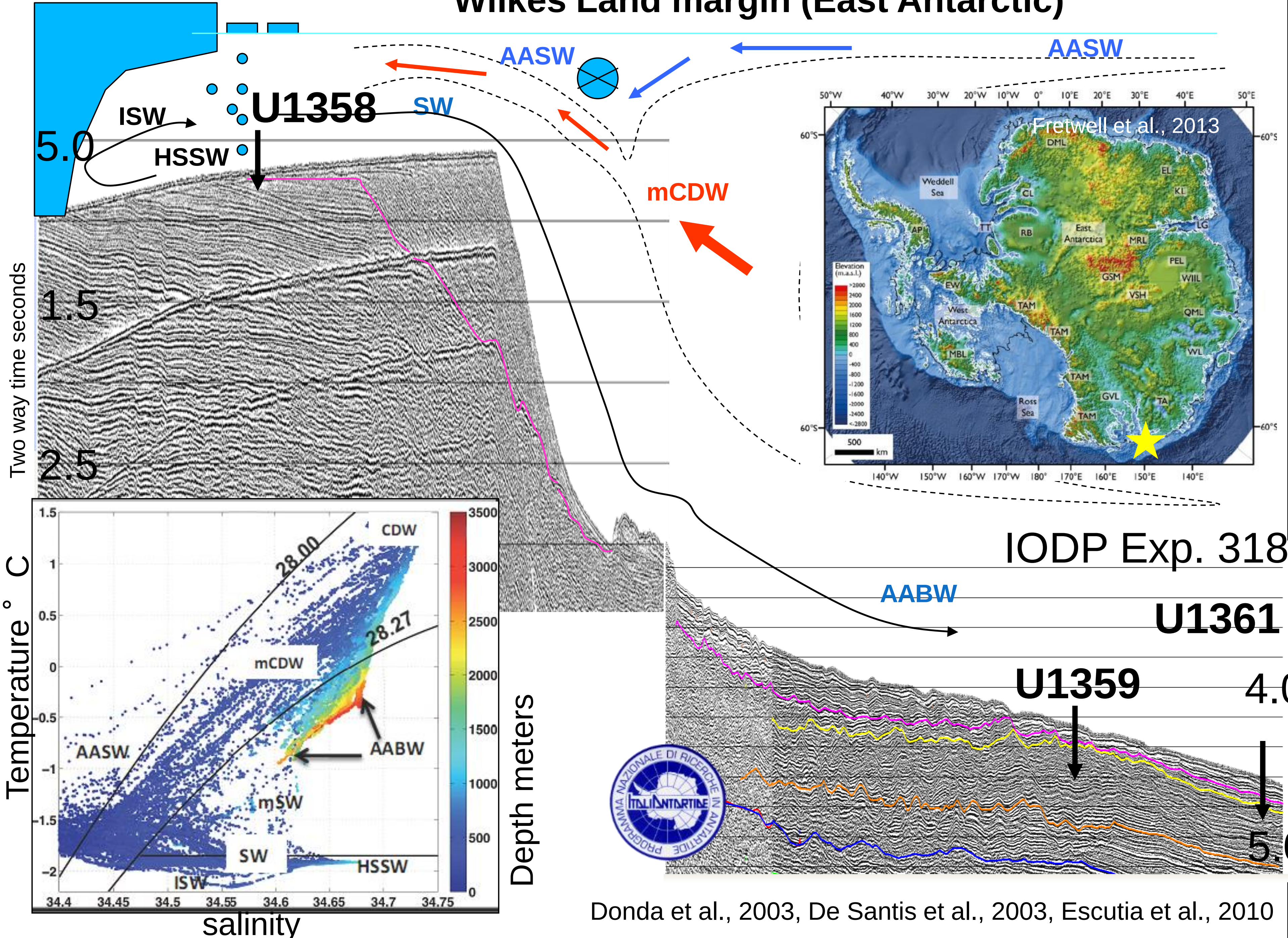
B. I. Taylor-Silva[1] and C. R. Riesselman[1,2]

[1]Department of Geology, University of Otago, Dunedin, New Zealand, [2]Department of Marine Science, University of Otago, Dunedin, New Zealand

marine isotope stage KM3 (3.17–3.15 Ma)

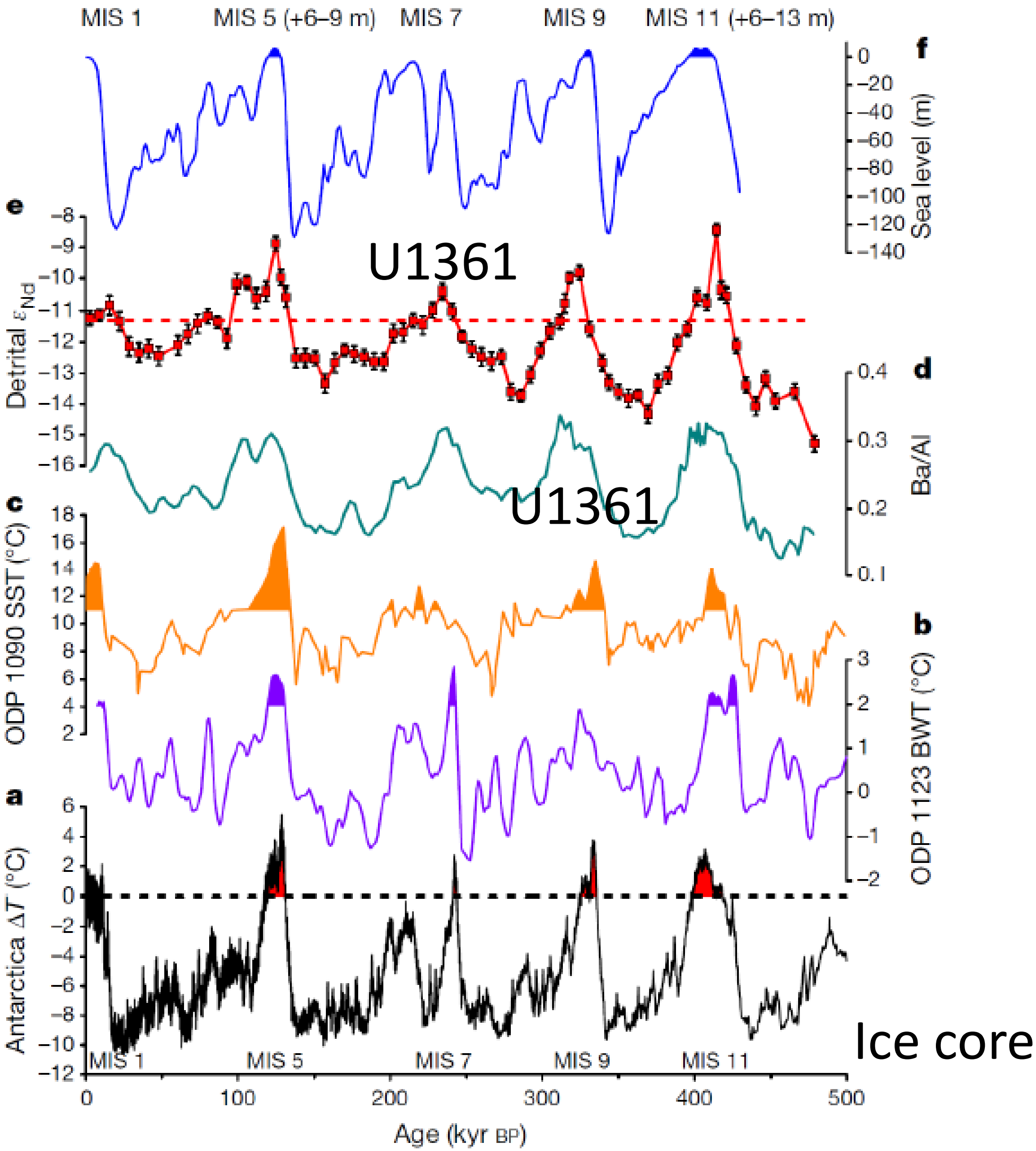


Wilkes Land margin (East Antarctic)



Donda et al., 2003, De Santis et al., 2003, Escutia et al., 2010

Link between extended Antarctic warmth and ice loss from the Wilkes Subglacial Basin



MIS 5, MIS 9, MIS 11:
ice sheet margin at the
Wilkes Basin retreated

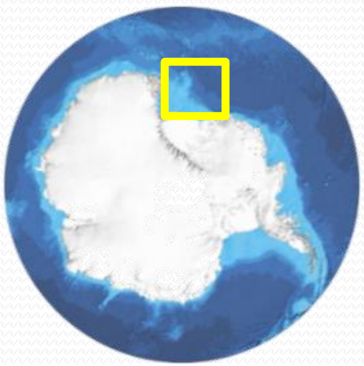
MIS 11:
→ ca. 700 kilometers
inland = + 3-4 m SLE

→ ca. + 2° C for 2500

Wilson et al., 2018 *Nature*
Blackburn et al., 2020, *Nature*

45 years after the Antarctic first leg…..

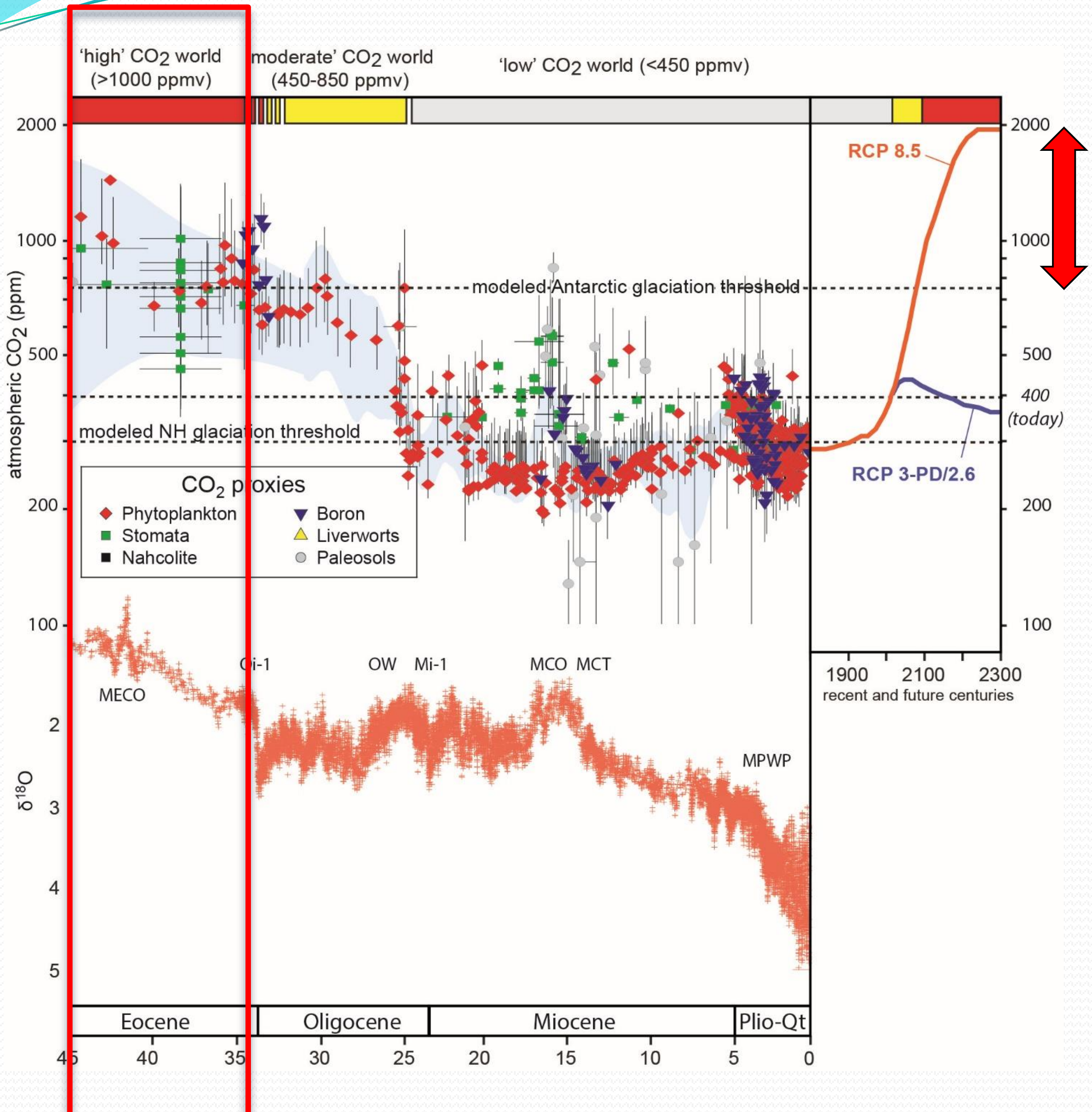
West Antarctic Ice Sheet History
IODP Exp. 374 (Ross Sea)



Exciting results are coming soon!!

Laura De Santis OGS Trieste, IT
Rob McKay Victoria Univ. Wellington, NZ
Denise Kulhanek Texas AM Univ., USA
all shipboard party

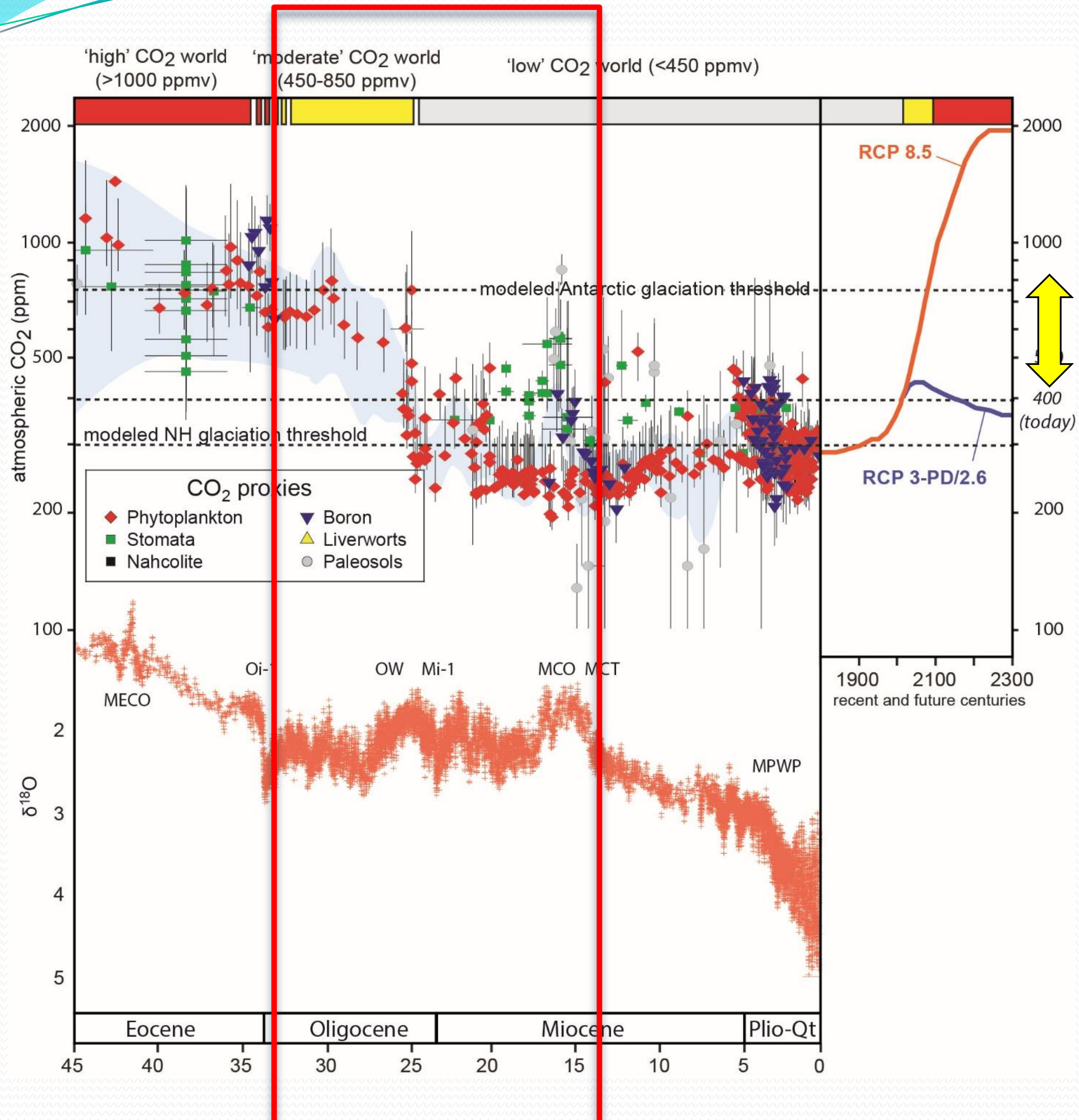
IODP
INTERNATIONAL OCEAN DISCOVERY PROGRAM



ice-free subtropical Antarctica

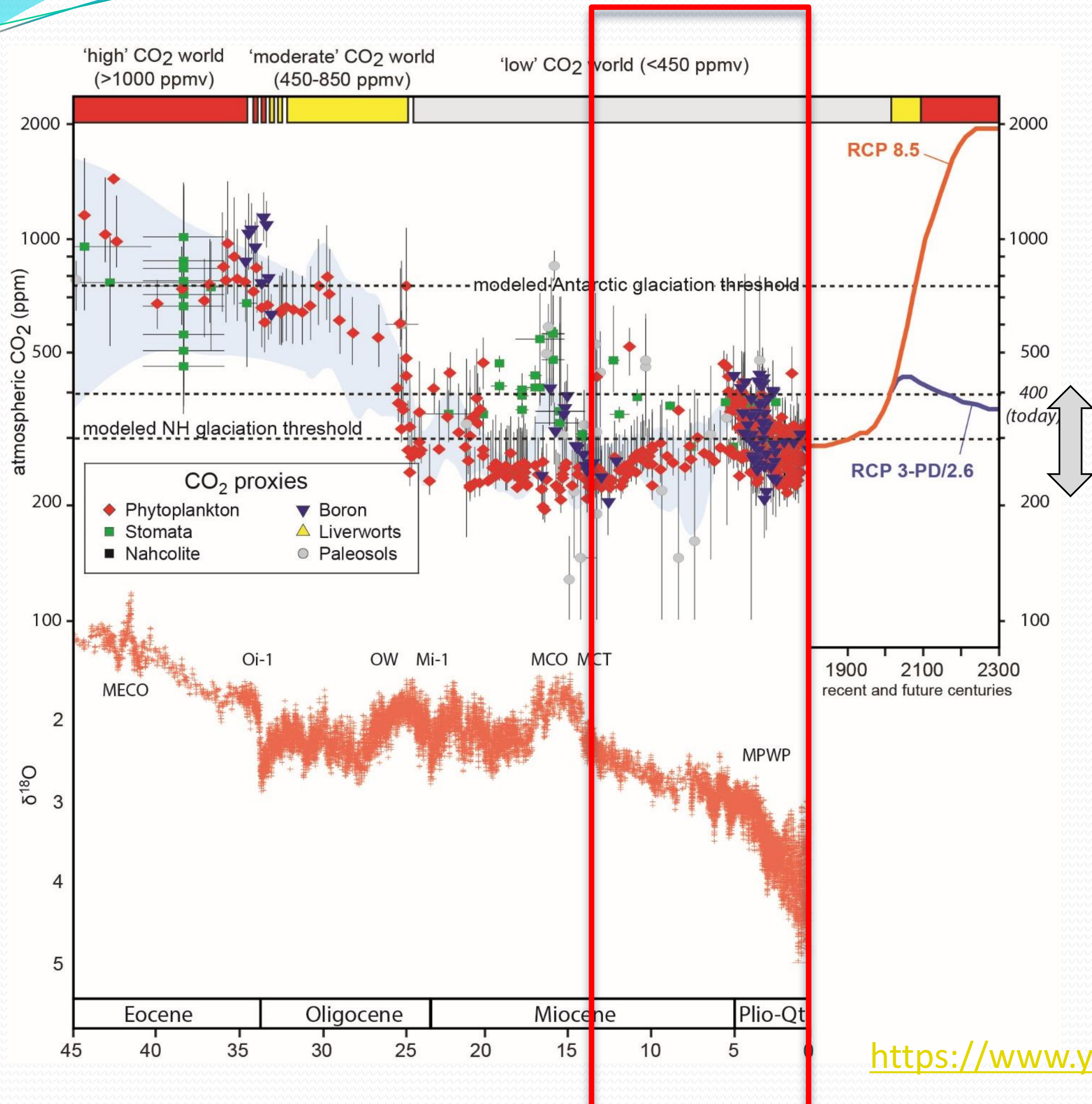
CO_2 ~1000 ppm
+8 to 12 ° C

initiation of continental-scale glaciations from alpine-type glaciers to mainly terrestrial ice sheets as CO_2 dropped below 800 ppm



750-400ppm CO_2 +4 to 8˚ C

terrestrial and marine ice sheet driving global sea level changes of up to 40 m amplitude



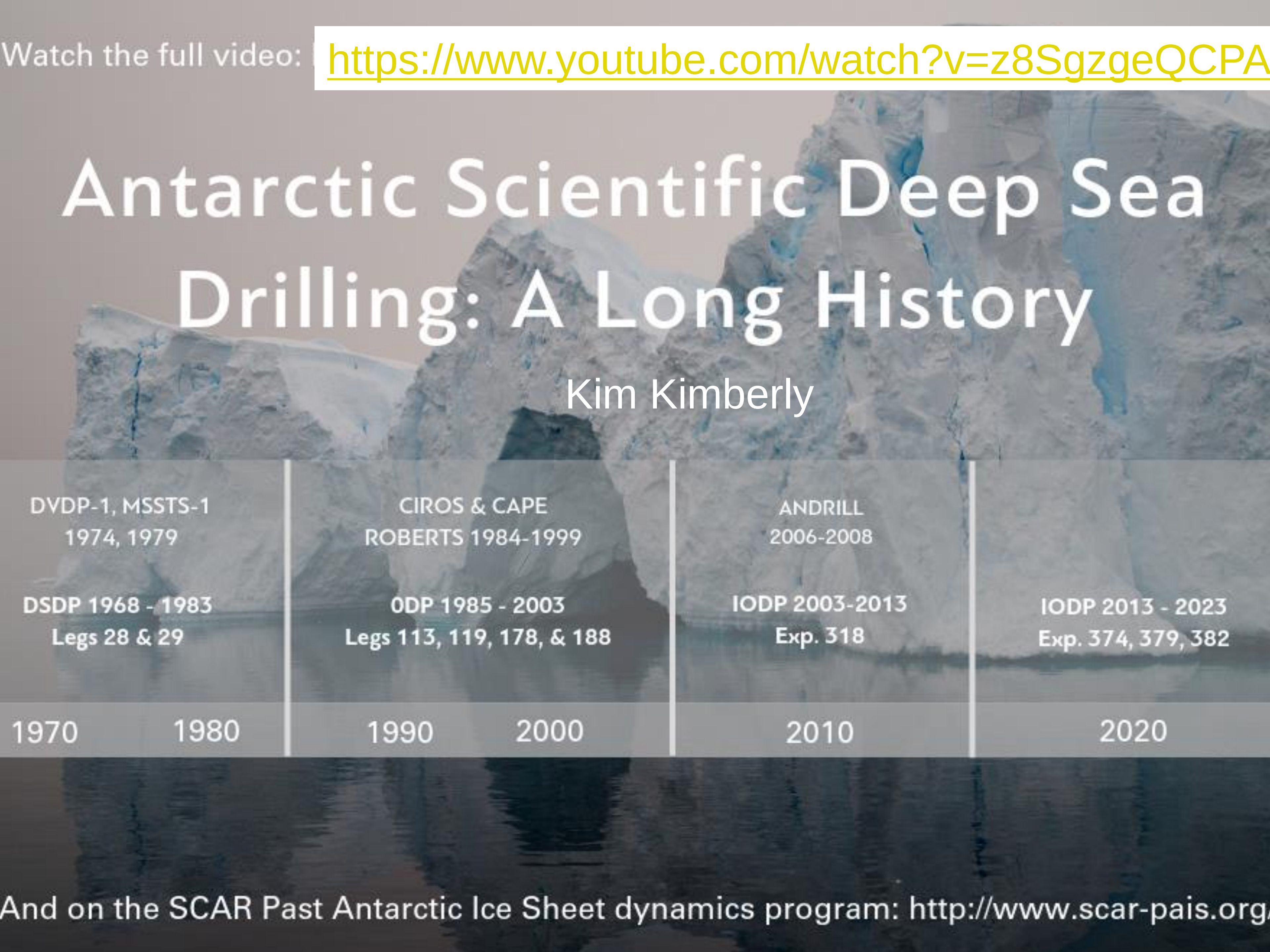
between ~14 and 3 million years ago: highly dynamic, mainly marine ice sheets contributing up to 20 m of global sea level rise

400-200ppm CO_2 -5 to+3° C

Since 3 million years ago: more stable ice sheet, but still fluctuating marine sheet

bipolar mode with Northern Hemisphere ice sheet driving global sea level changes of up to 20 m amplitude

https://www.youtube.com/watch?v=z8SgzgeQCPA


Watch the full video: https://www.youtube.com/watch?v=z8SgzgeQCPA
Antarctic Scientific Deep Sea Drilling: A Long History
Kim Kimberly
DVDP-1, MSSTS-1 1974, 1979
DSDP 1968 - 1983 Legs 28 & 29
CIROS & CAPE ROBERTS 1984-1999
ODP 1985 - 2003 Legs 113, 119, 178, & 188
ANDRILL 2006-2008
IODP 2003-2013 Exp. 318
IODP 2013 - 2023 Exp. 374, 379, 382
1970
1980
1990
2000
2010
2020
And on the SCAR Past Antarctic Ice Sheet dynamics program: http://www.scar-pais.org

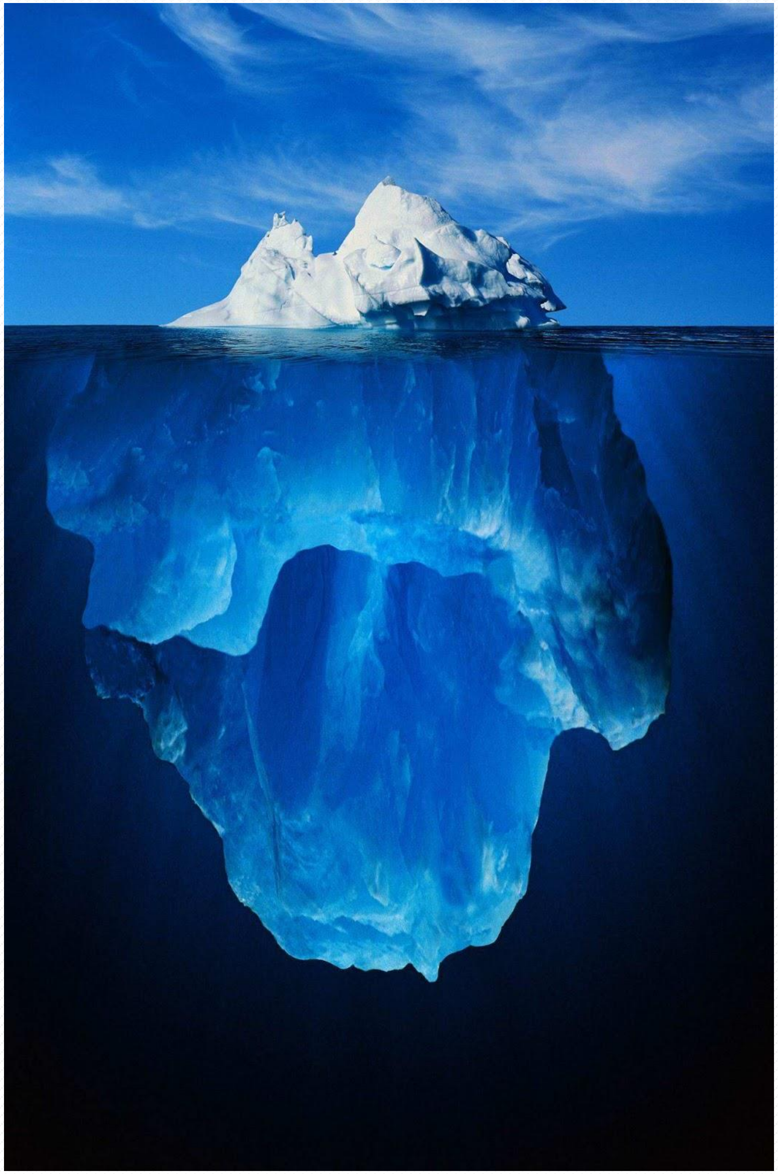
The first Antarctic DSDP
Leg 28 – 1973
12 scientists *2 females*
one as 1 scientist and
one as 1 typist

Happy birthday IODP

The IODP Exp. 374 – 2018
31 scientists 12 females (40%)
one as co-chief and
one as staff scientists
22 technical staff 8 females (36%)

Photo Courtesy: W. Crawford

INTERNATIONAL OCEAN DISCOVERY PROGRAM



…But we see just the tip of the iceberg!

- **What will be the rate of the future significant ice sheet disintegration?**

- **How far are we from the next ice sheet instability tipping points?**

- **Are there potential feedbacks mechanism that will counterbalance rapid ice mass loss?**

Photo L. De Santis