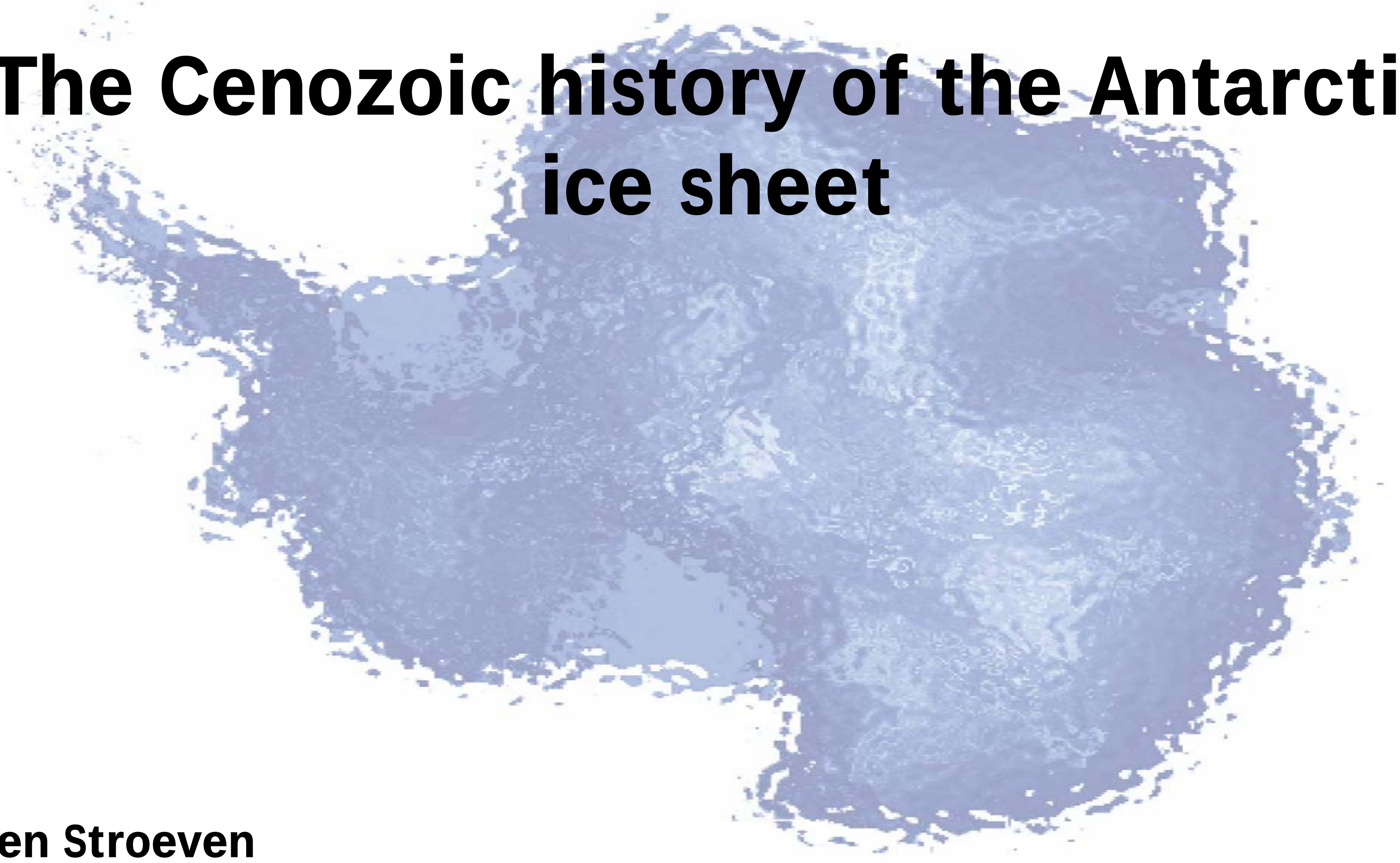
The Cenozoic history of the Antarctic ice sheet



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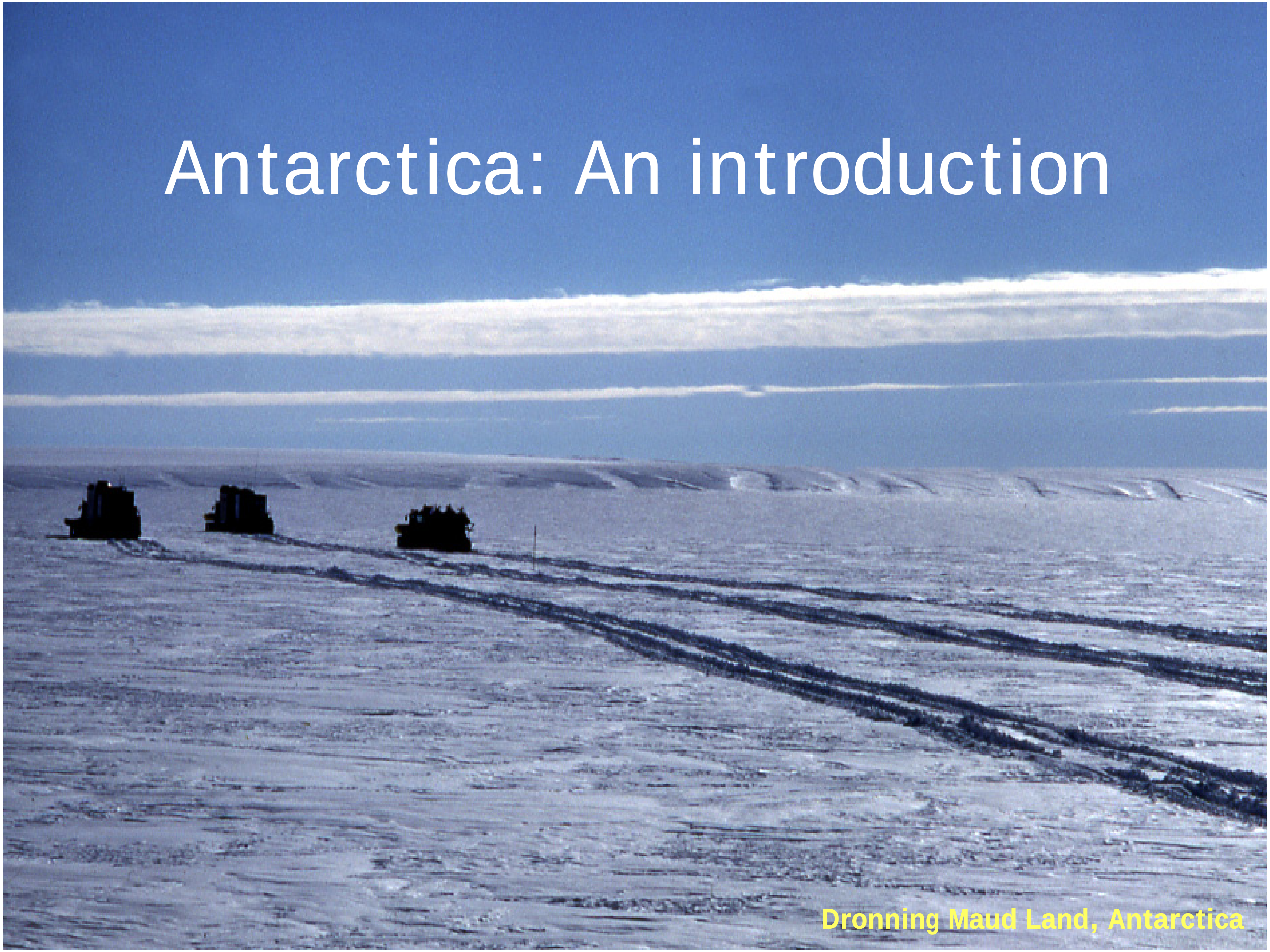
Structure of the lecture

- Antarctica: An introduction
- Antarctic geological history
  - plate tectonics
- Antarctic glacial history
  - how deduced?
  - what have we learned?
- Antarctic geomorphology
  - Dry Valleys
- Ice sheet modelling

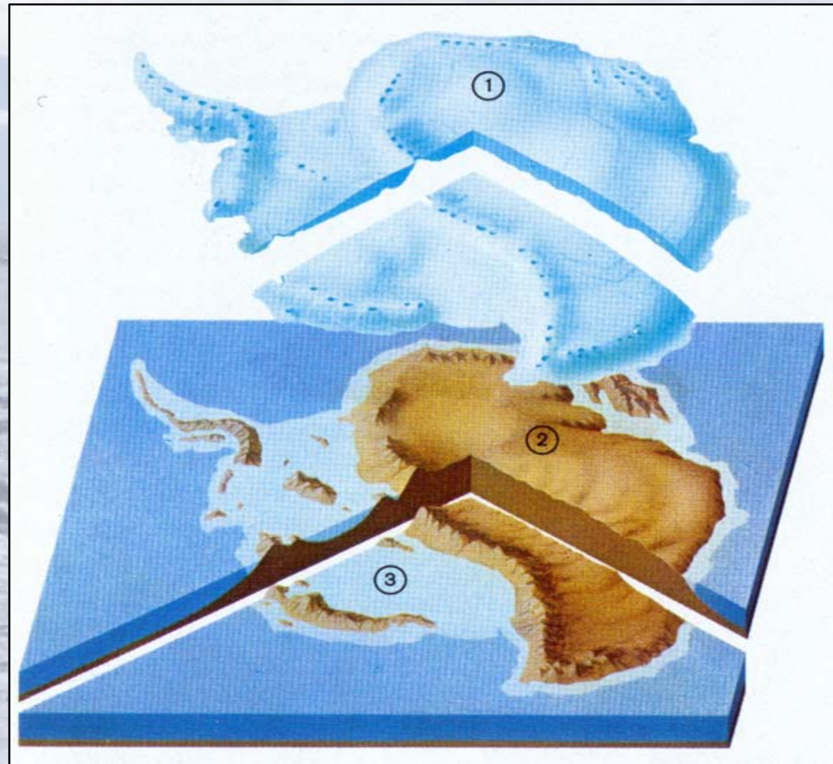
Antarctica: An introduction



Dronning Maud Land, Antarctica

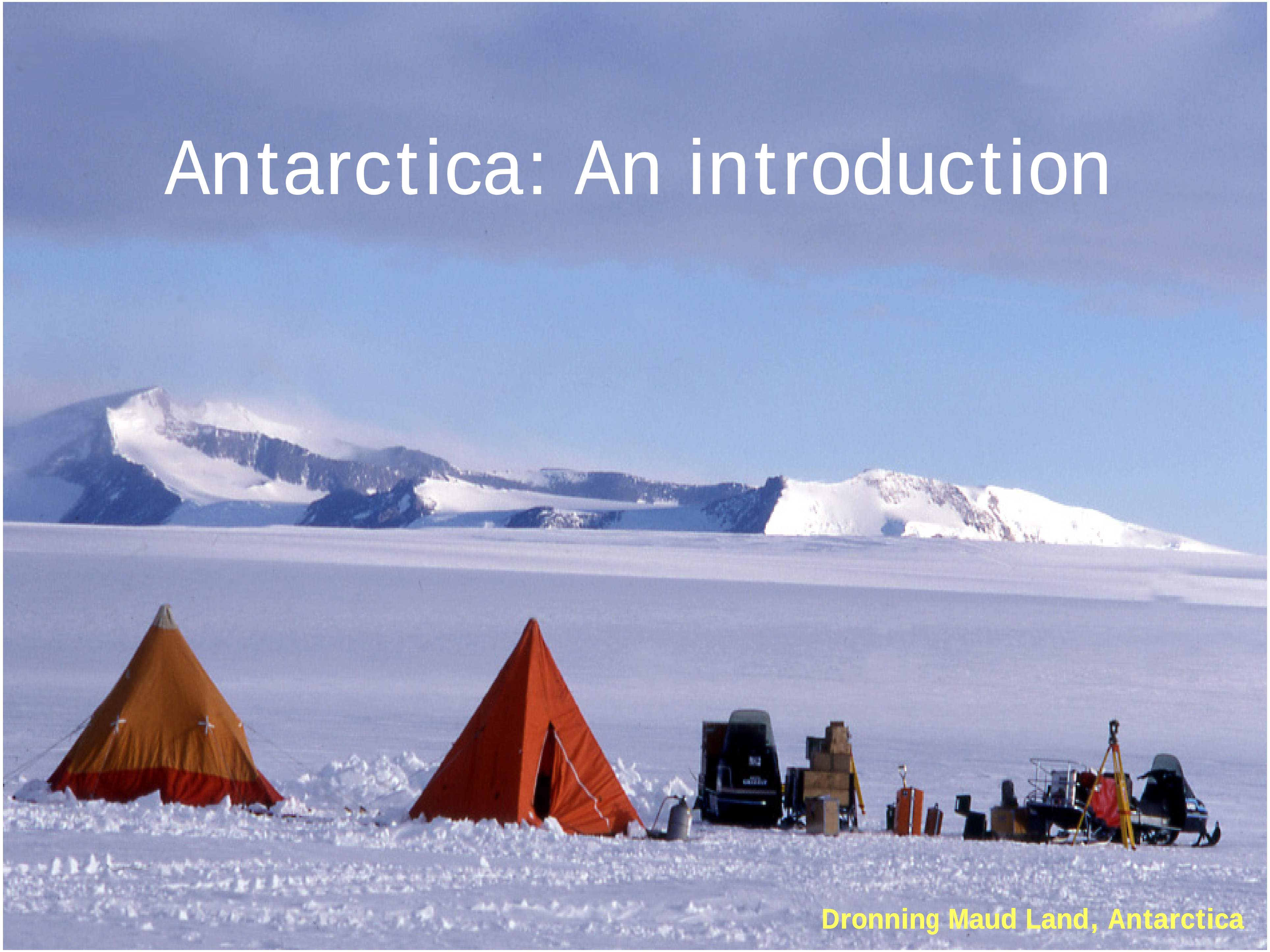
Antarctica: An introduction

- **East Antarctica (2):**
  continental
  -66 m water equivalent
- **West Antarctica (3):**
  marine
  -6 m water equivalent
- **Average thickness (1):**
  ~ 2,079 m (IPCC, 2001)



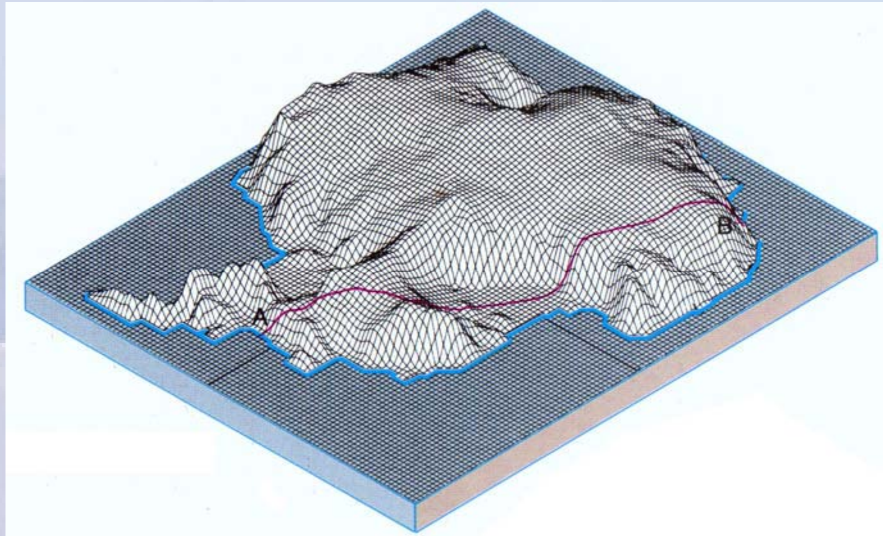
Dronning Maud Land, Antarctica

Antarctica: An introduction

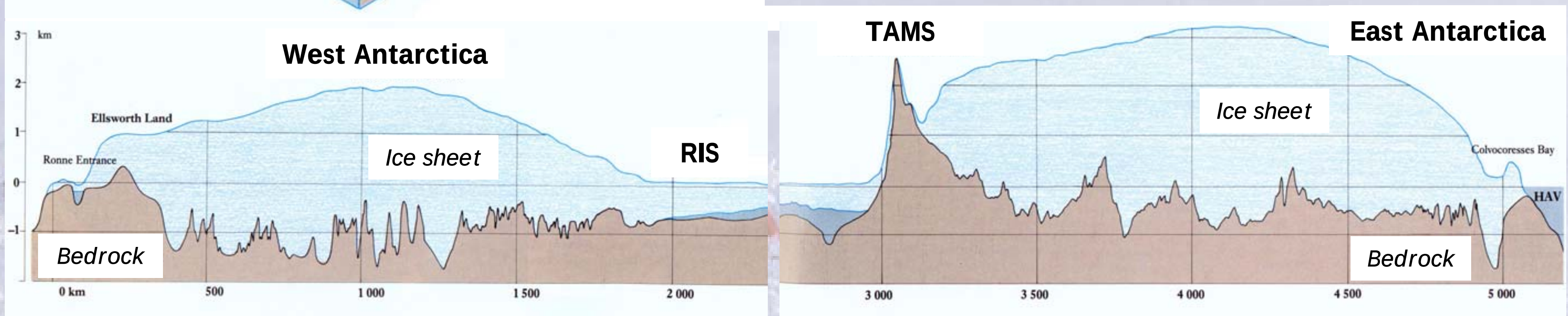


Dronning Maud Land, Antarctica

Antarctica: An introduction



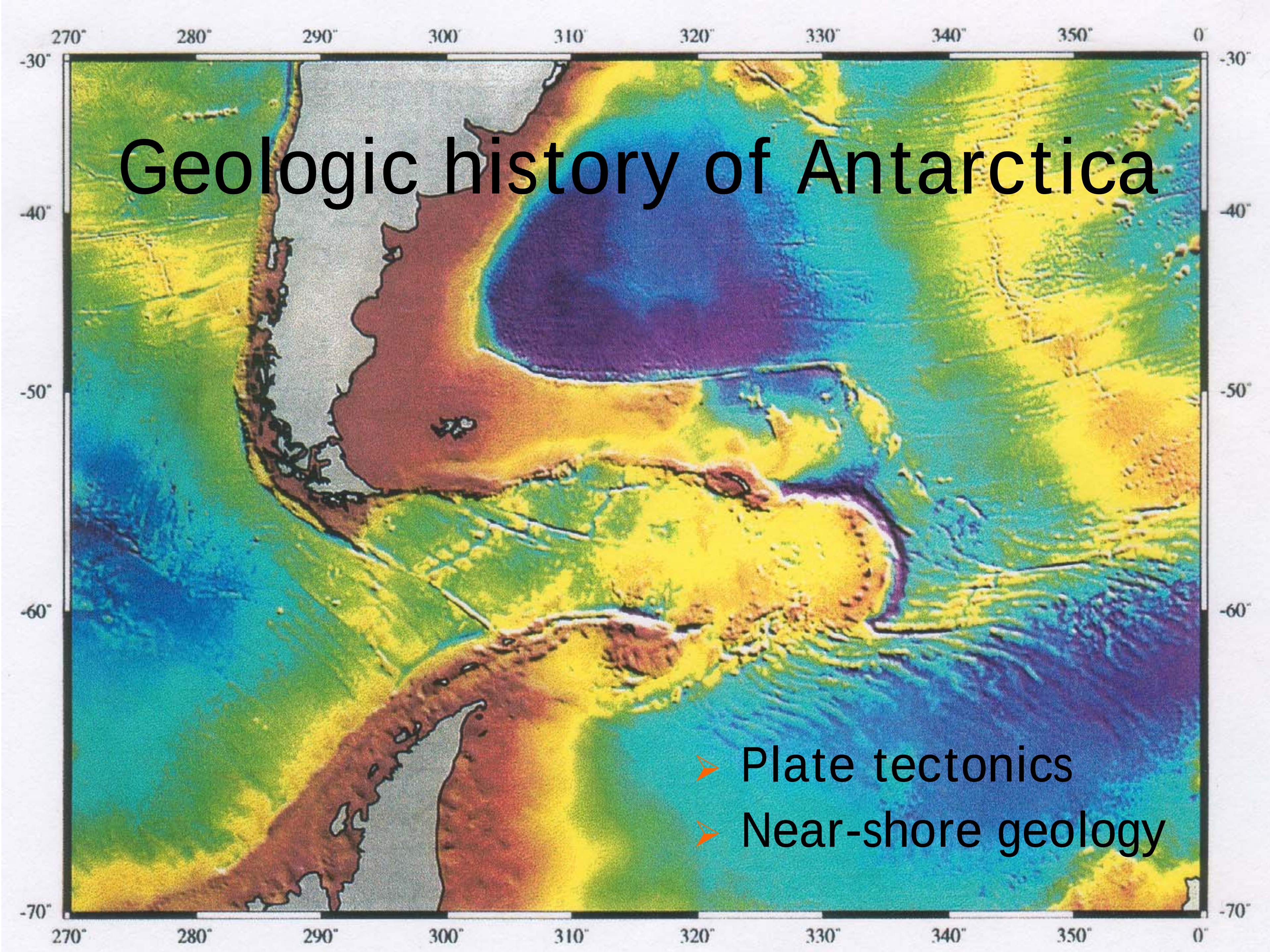
- Both ice sheets rest on bedrock below sea level - potentially sensitive situation
- Ice exits Antarctica through ice streams and ice shelves



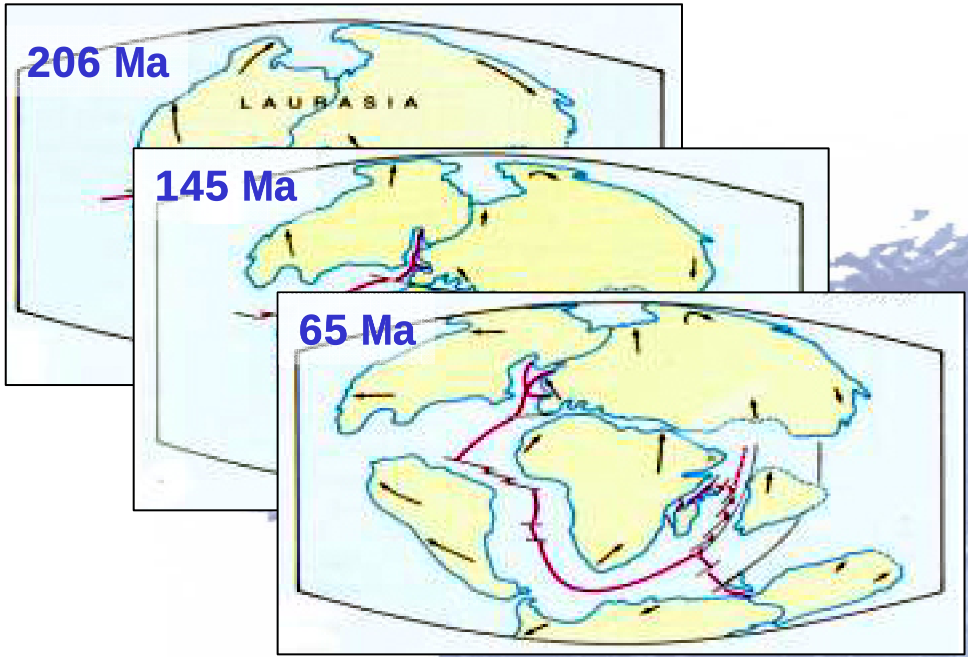
May (ed.) 1988, Dorling Kindersley Limited, London

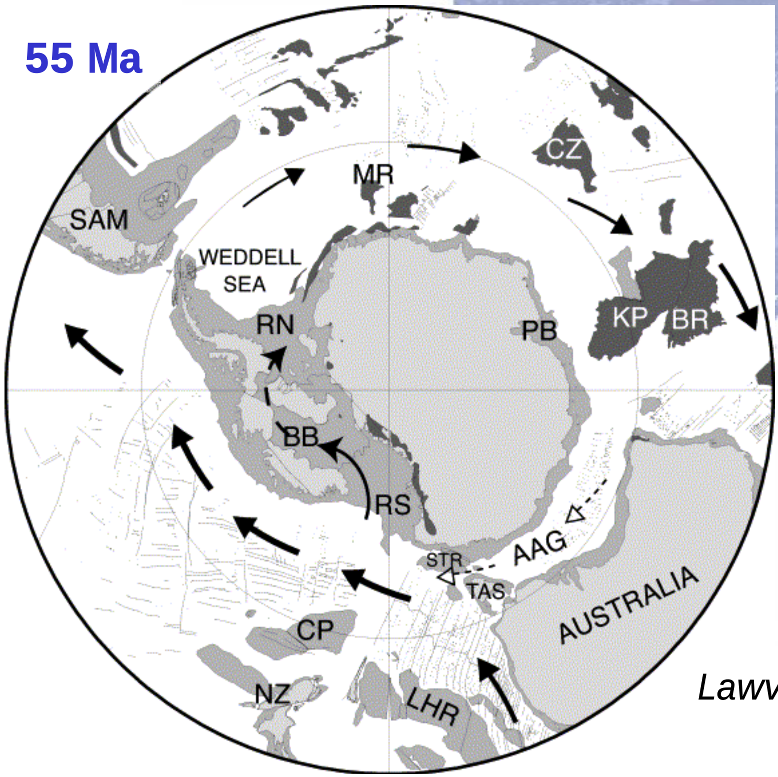

Highest continent
average elevation: ~2 km
Coldest continent
record: -89,5 °C
Driest continent
1.63 cm water equivalent/year
Windiest continent
average annual: 80 km/hour
Air Devron Six Icefalls, Dry Valleys, Antarctica

Geologic history of Antarctica



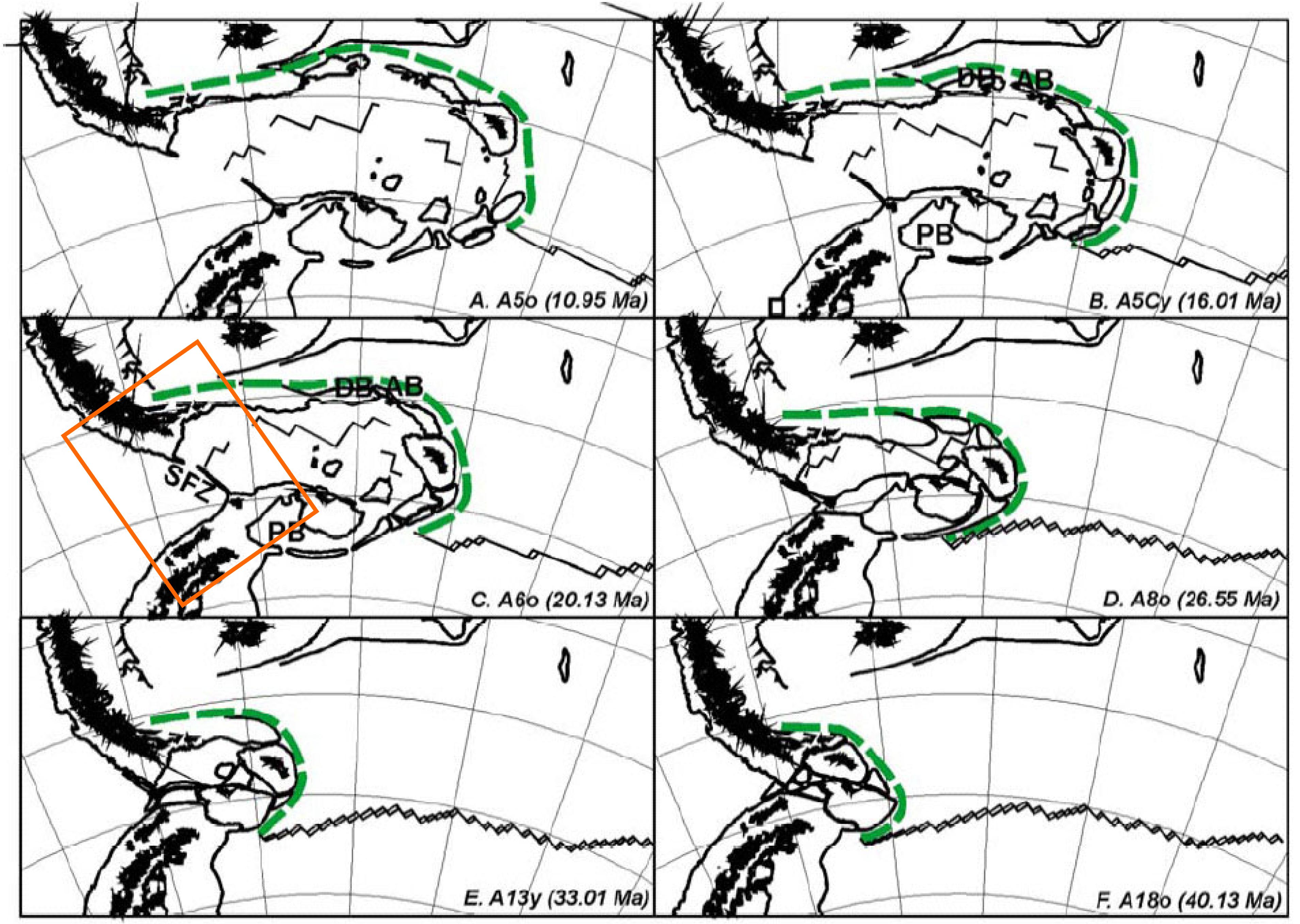
- Plate tectonics
- Near-shore geology





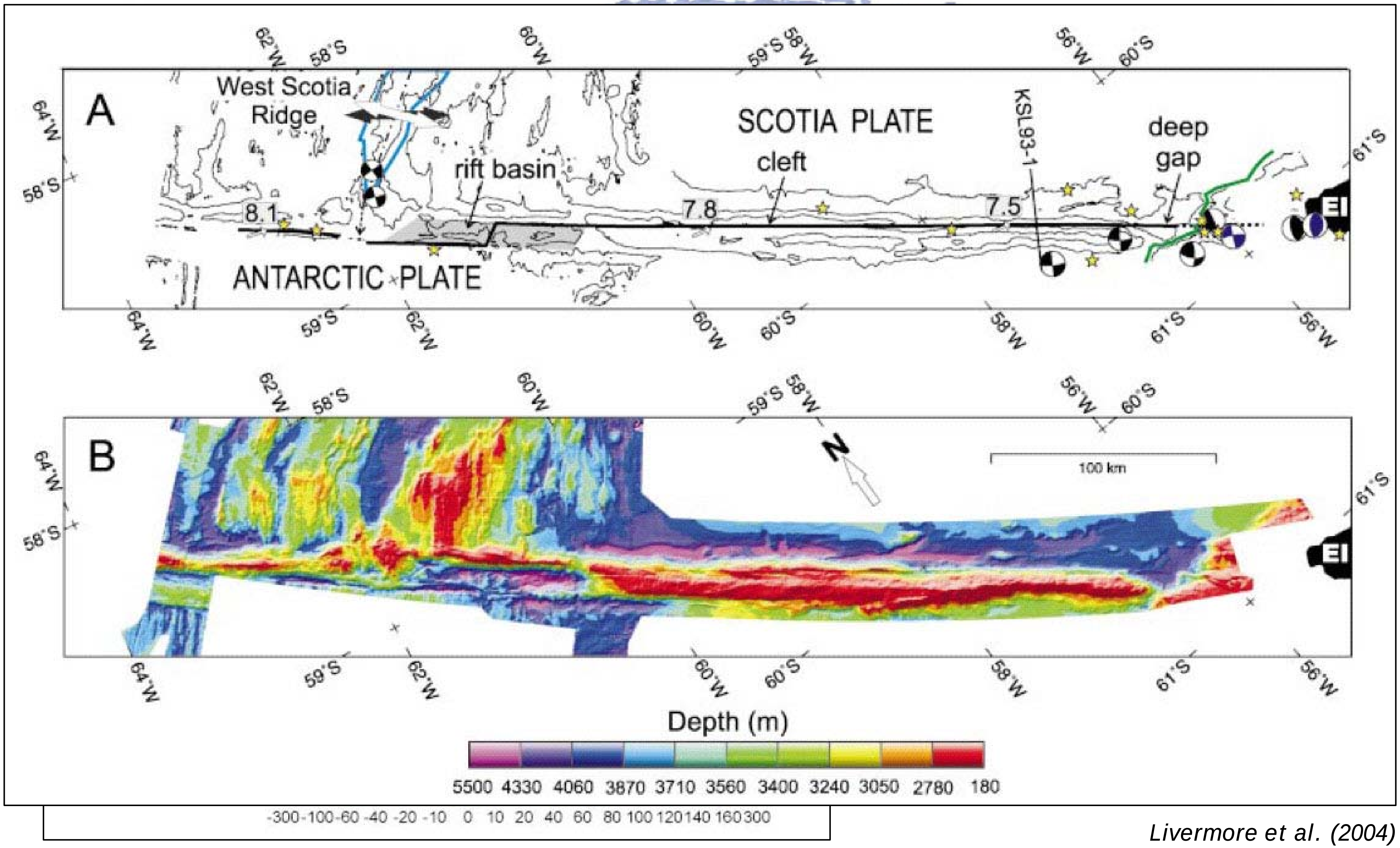
Lawver & Gahagan (2003)

ERA	PERIOD	EPOCH	YEARS AGO (millions)
Cenozoic	Quaternary	Holocene	The present
		Pleistocene	0.01
	Tertiary	Pliocene	1.8
		Miocene	5.3
		Oligocene	24
		Eocene	34
		Paleocene	55
Mesozoic	Cretaceous		65
	Jurassic		144
	Triassic		206
Paleozoic	Permian		248
	Carboniferous		290
	Devonian		354
	Silurian		417
	Ordovician		443
	Cambrian		490
	Precambrian		543
			3800

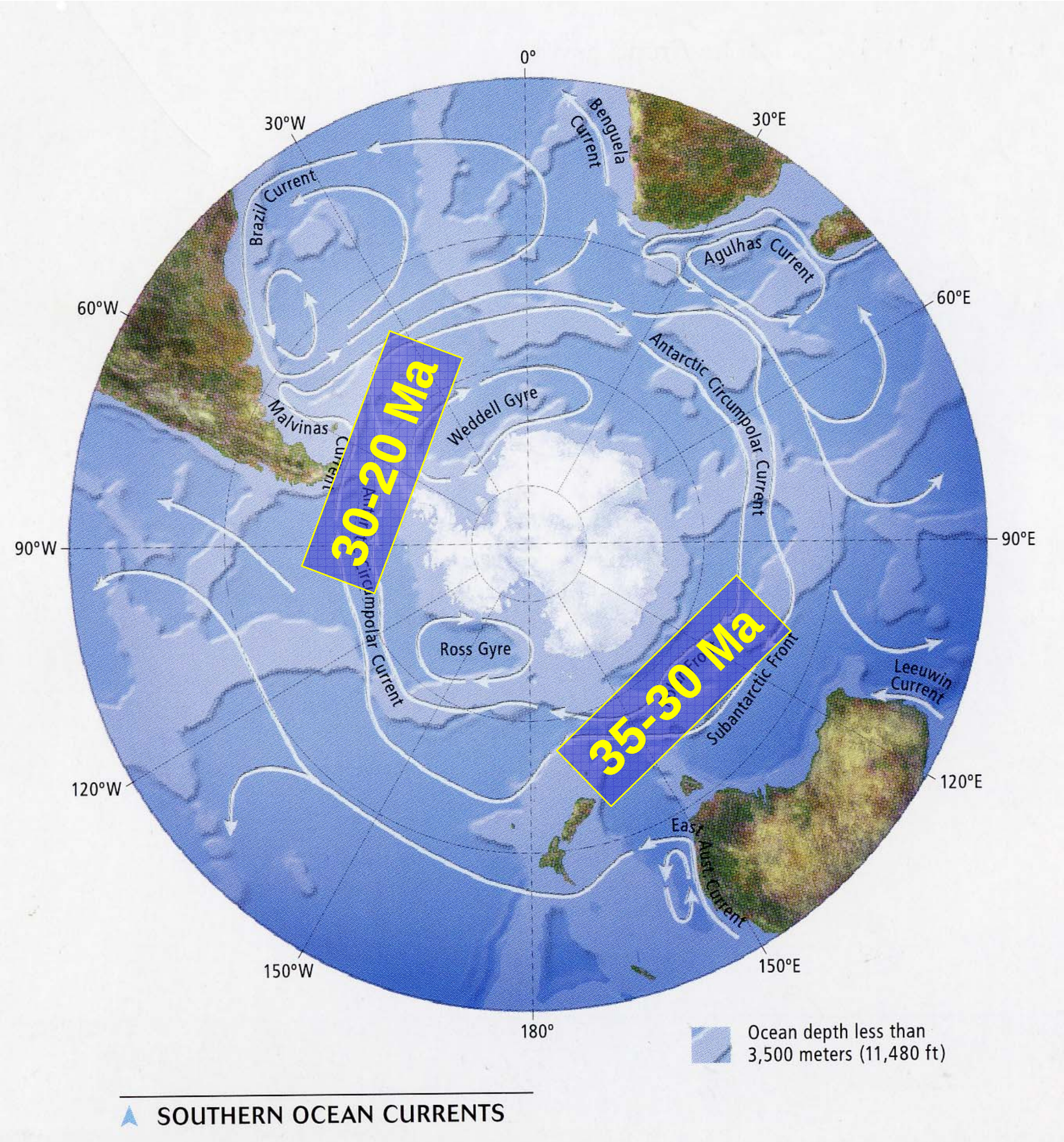


Barker and Thomas (2004)

Opening of the Drake Passage



Livermore et al. (2004)



McGonigal and Woodworth (2001)

Antarctic glacial history

- What are reconstructions based on?

- Sediment cores (ocean)
- sediment stratigraphy
  continental shelf
    -seismic studies
    -drill studies
- Sea level reconstructions (coral)

Reconstructions of the Antarctic glacial history

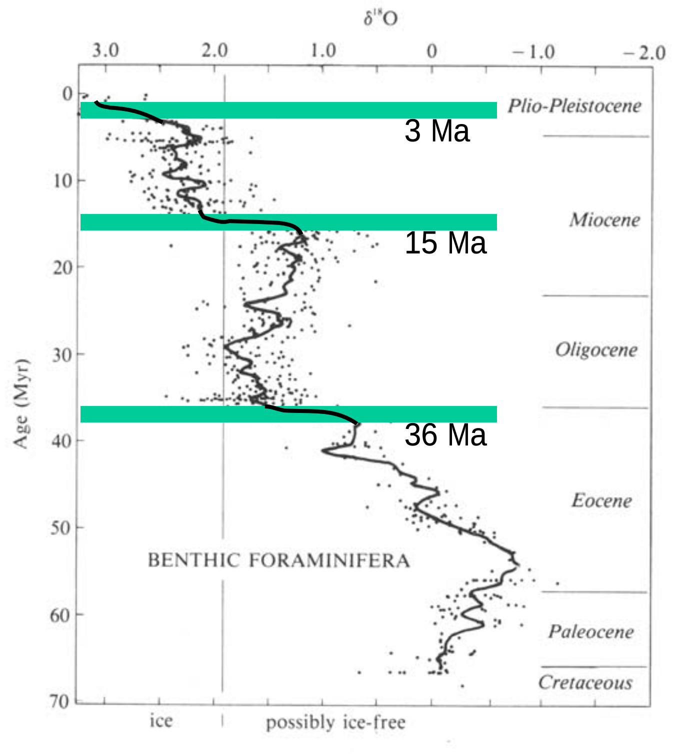
Far field evidence:

- indications from marine sediment cores
- indications from sea level data: far-field shelf stratigraphy & corals

Near field evidence:

- indications from Antractic shelf drill sites and stratigraphy
- indications from terrestrial sites: Mostly Pliocene
- Ice core records (not this lecture; 1 Ma presence)

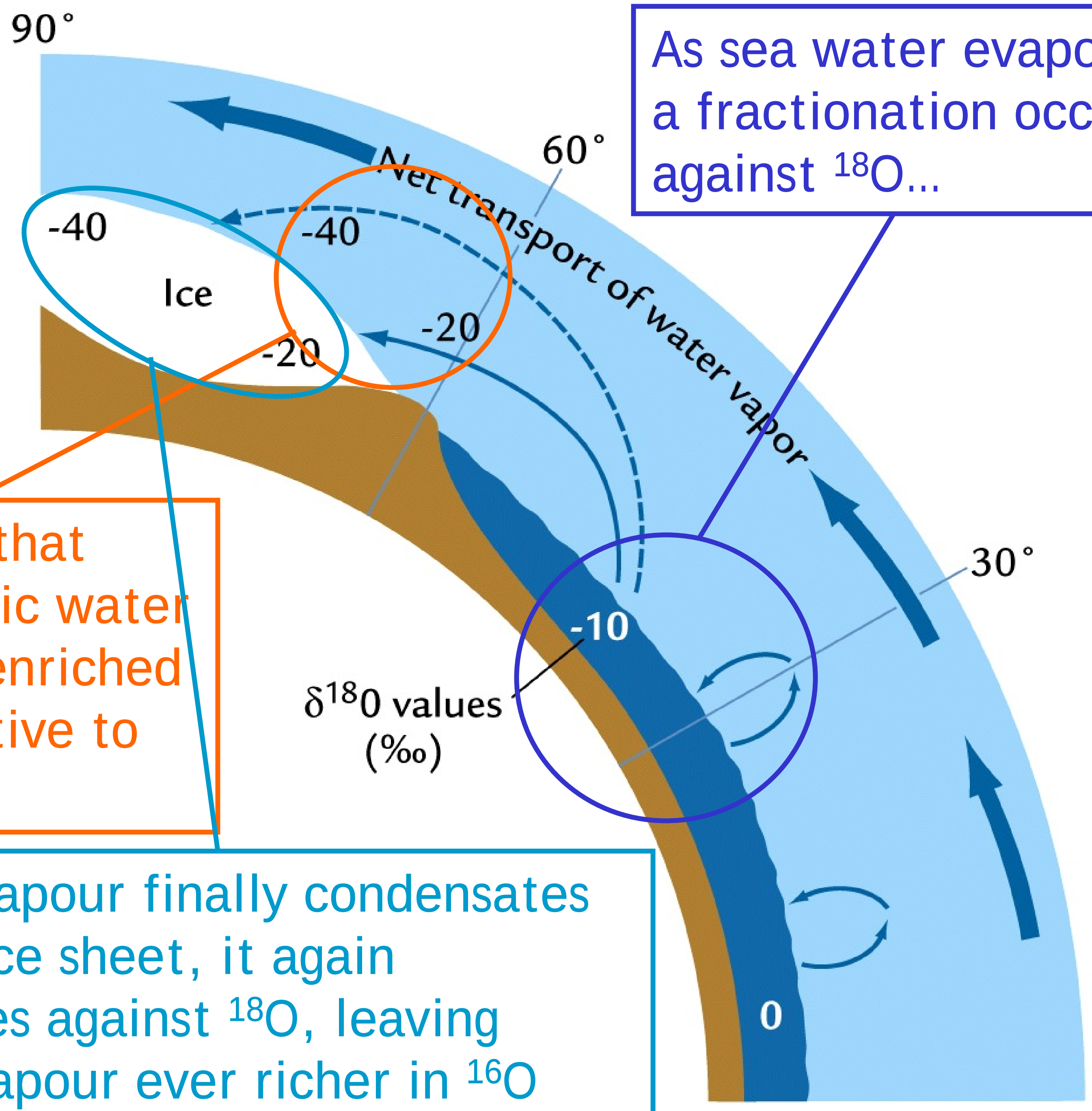
Indications from marine cores



Miller (1985)

- Oxygen isotopes are derived from:
  -planktonic
  -benthic foraminifer
- Oxygen isotopes are interpreted as:
  -ocean temperature
  -ocean isotopic signature
  -ocean circulation (cancels out)
- This could mean that changes imply a change in either of these two remaining properties

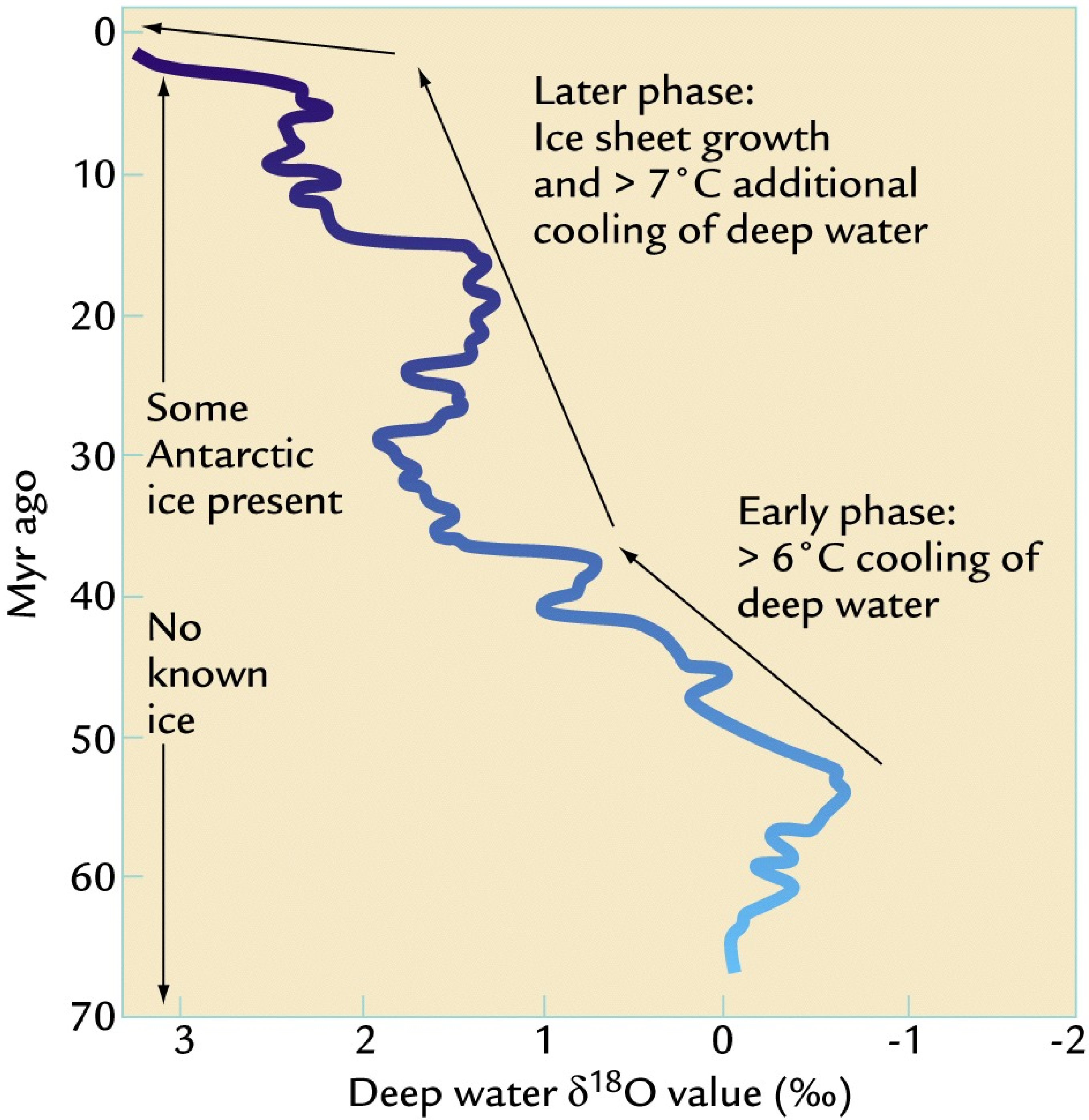
As sea water evaporates, a fractionation occurs against ^{18}O...



...yielding that atmospheric water vapour is enriched in ^{16}O relative to sea water

As water vapour finally condensates above an ice sheet, it again fractionates against ^{18}O, leaving remnant vapour ever richer in ^{16}O

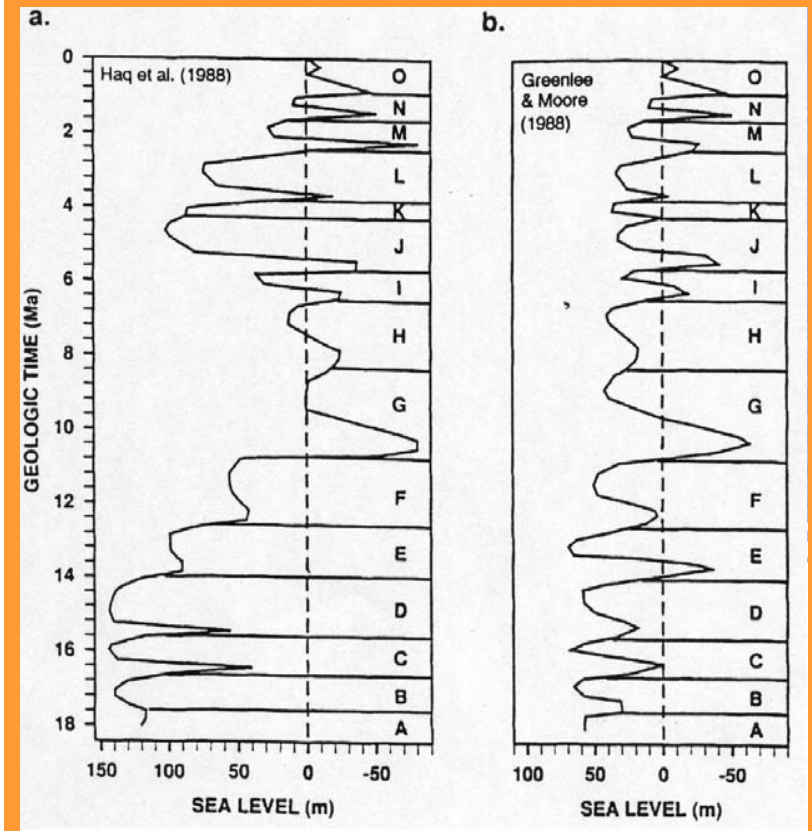
Ruddiman (2001)



About 1‰ $\delta^{18}O$ change during the Cenozoic is due to ice sheet growth, the rest is deep water temperature change

Ruddiman (2001)

Indications from sea level data from the continental shelf

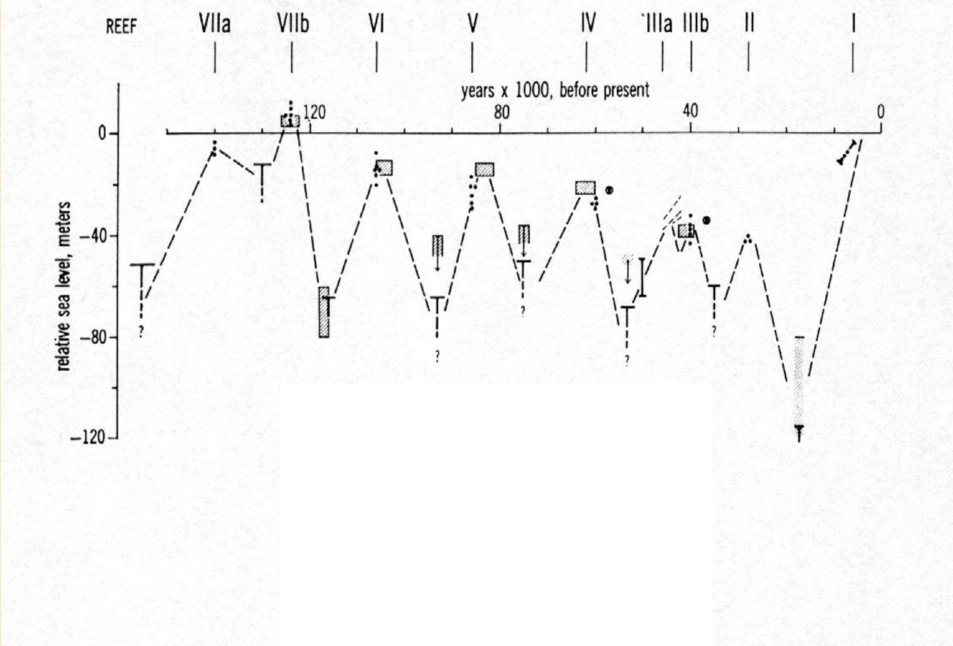


Schroeder & Greenlee (1993)

- Problems associated with sea level calculations:
  -**amplitude** of the signal (equated to ice volume)
  -**generalisation**, e.g. all of last 2 myr consists of two high "events", even though there were perhaps more than 20 glaciations.

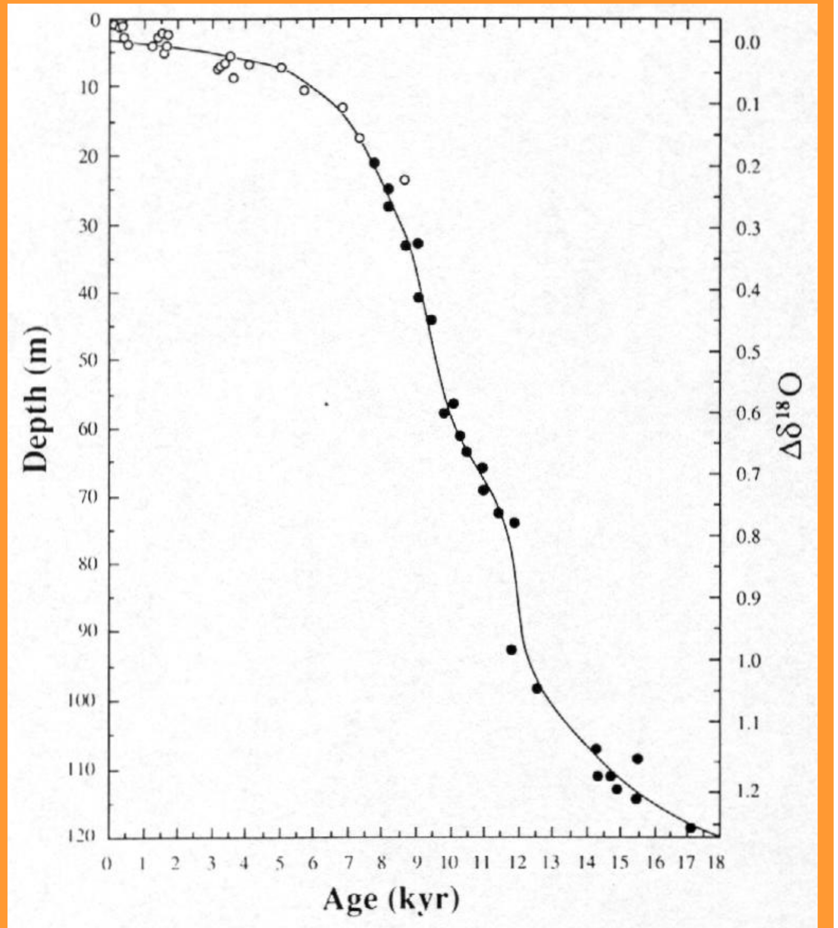
Indications from sea level data from corals

- (A) Eemian interglacial-today
  (B) late glacial
  global sea level history



(A)

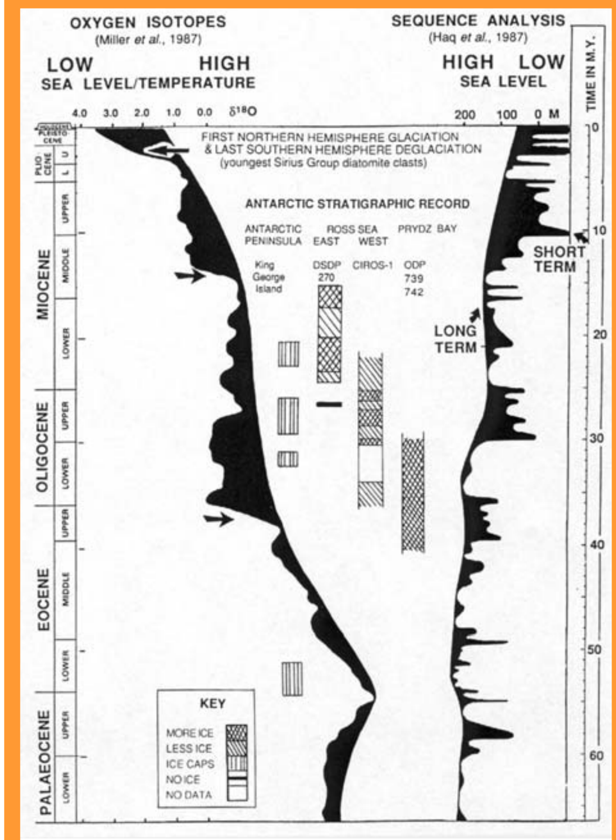
Bloom et al. (1974)



(B)

Fairbanks (1989)

Indications from sea level data: wrap-up

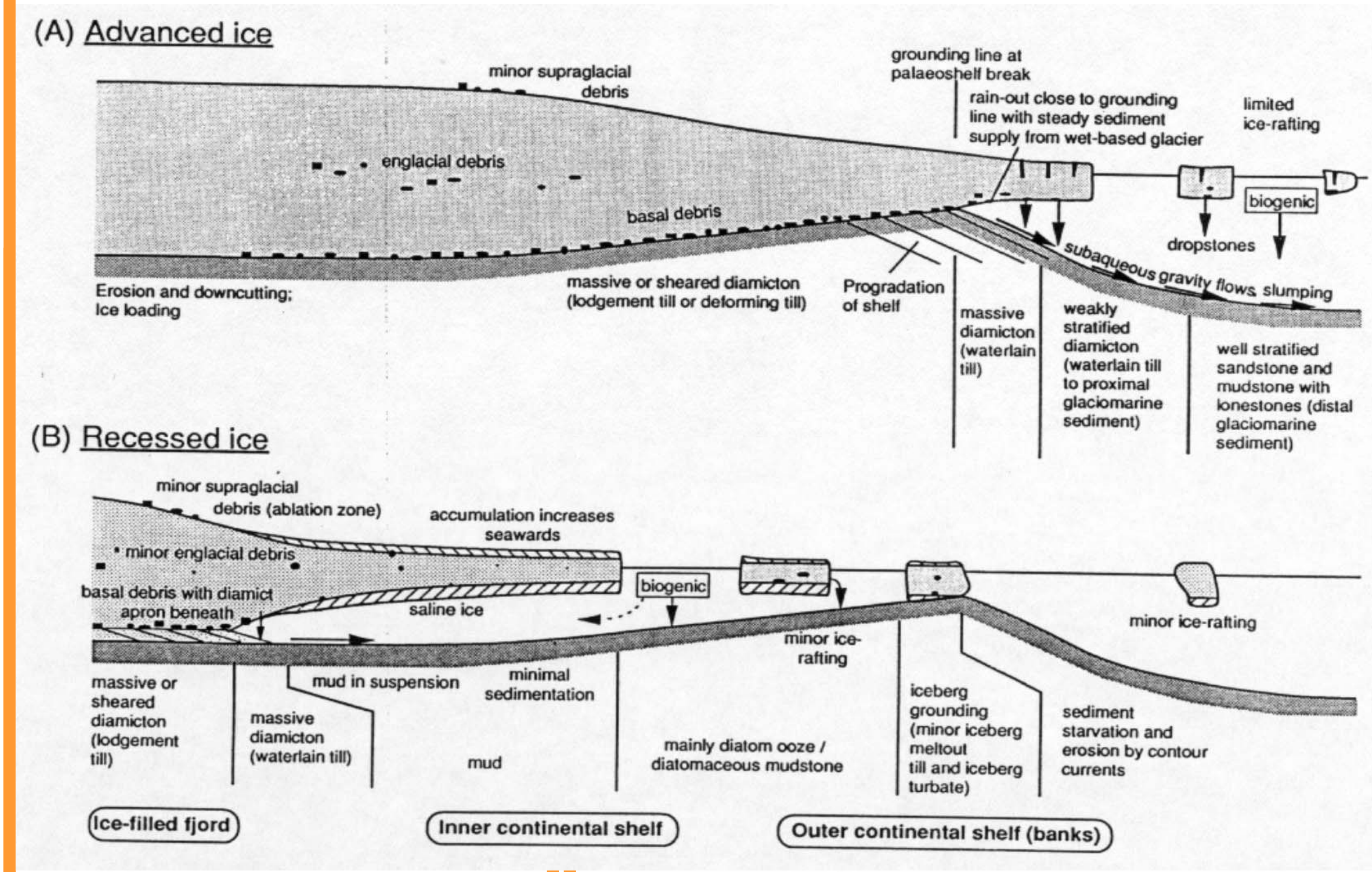


Barrett (1991)

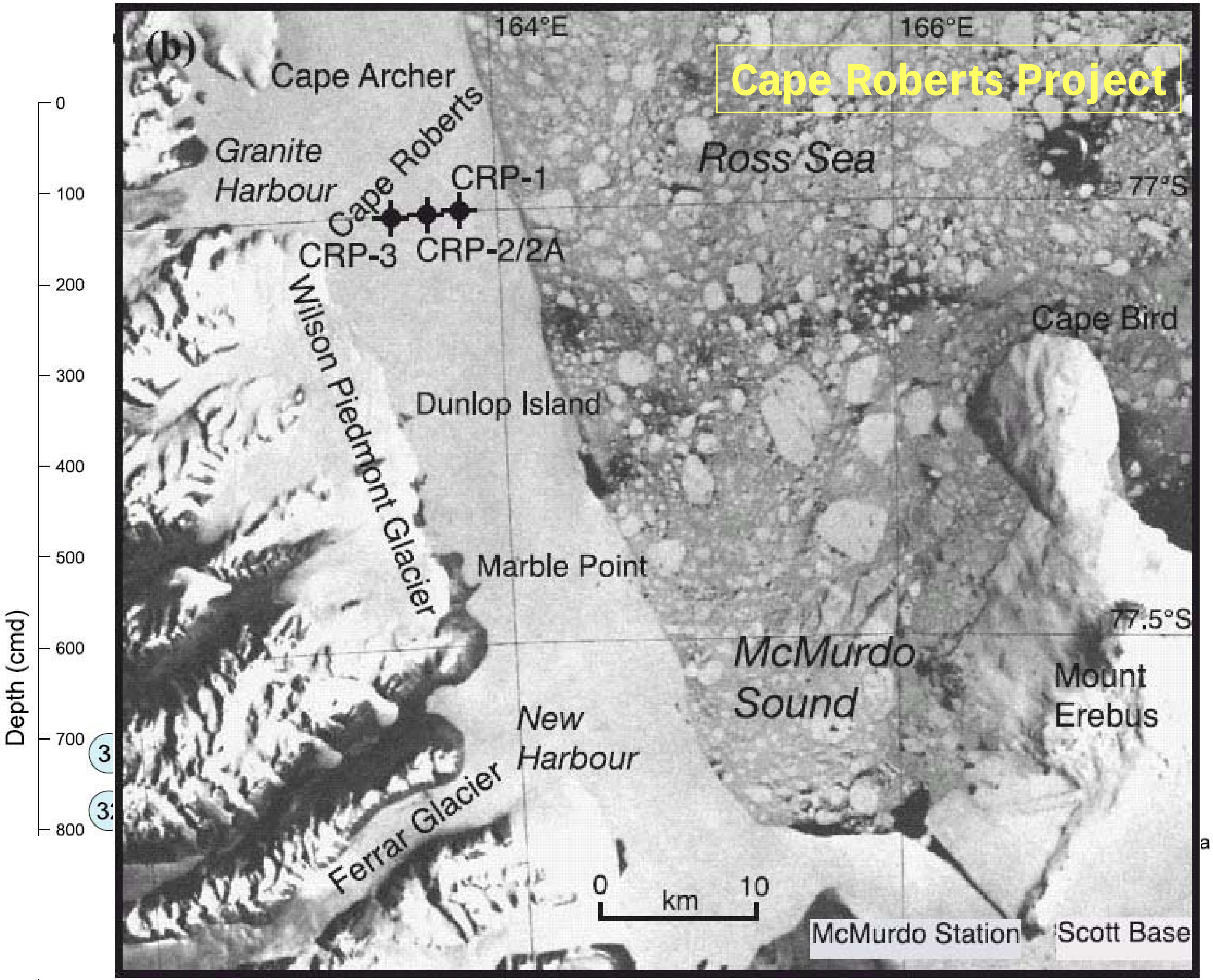
- Sea level changes are inferred from:
  - -corals
  - -depositional structures on the continental shelf, *i.e.*
    - -transgression: horizontal structures
    - -regression: erosion surfaces

But remember:

- Sea level changes are a function of:
  - -tectonics (trends- global)
  - -tectonics/isostacy (regional signature)
  - -ice sheet volume (global signature)



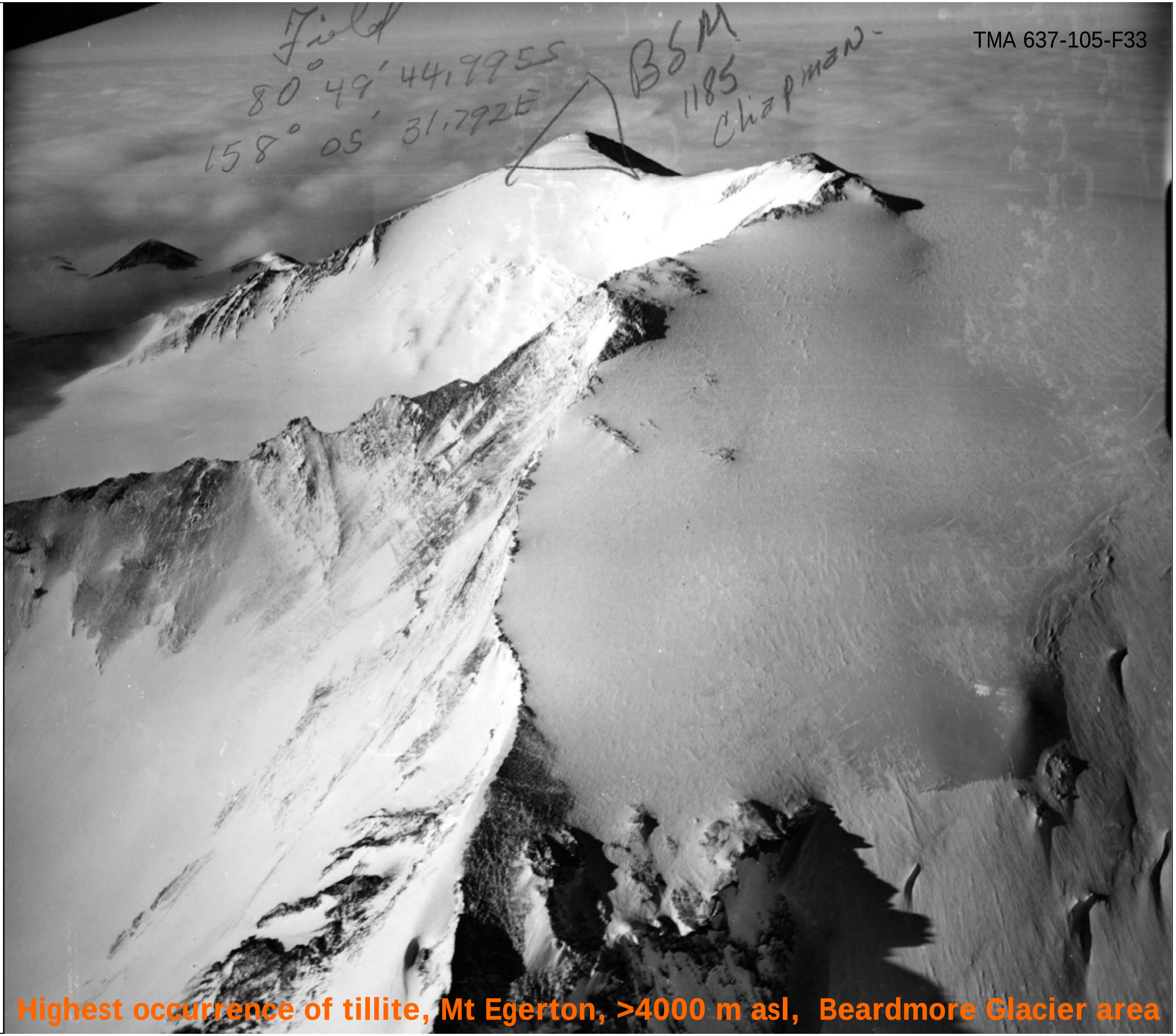
Hambrey (1992)



(b)
164°E
166°E
Cape Roberts Project
Cape Archer
Granite Harbour
Cape Roberts
CRP-1
CRP-3
CRP-2/2A
Ross Sea
77°S
Wilson Piedmont Glacier
Dunlop Island
Cape Bird
Marble Point
77.5°S
McMurdo Sound
Mount Erebus
New Harbour
Ferrar Glacier
0 km 10
McMurdo Station
Scott Base
Depth (cmd)
0
100
200
300
400
500
600
700
800

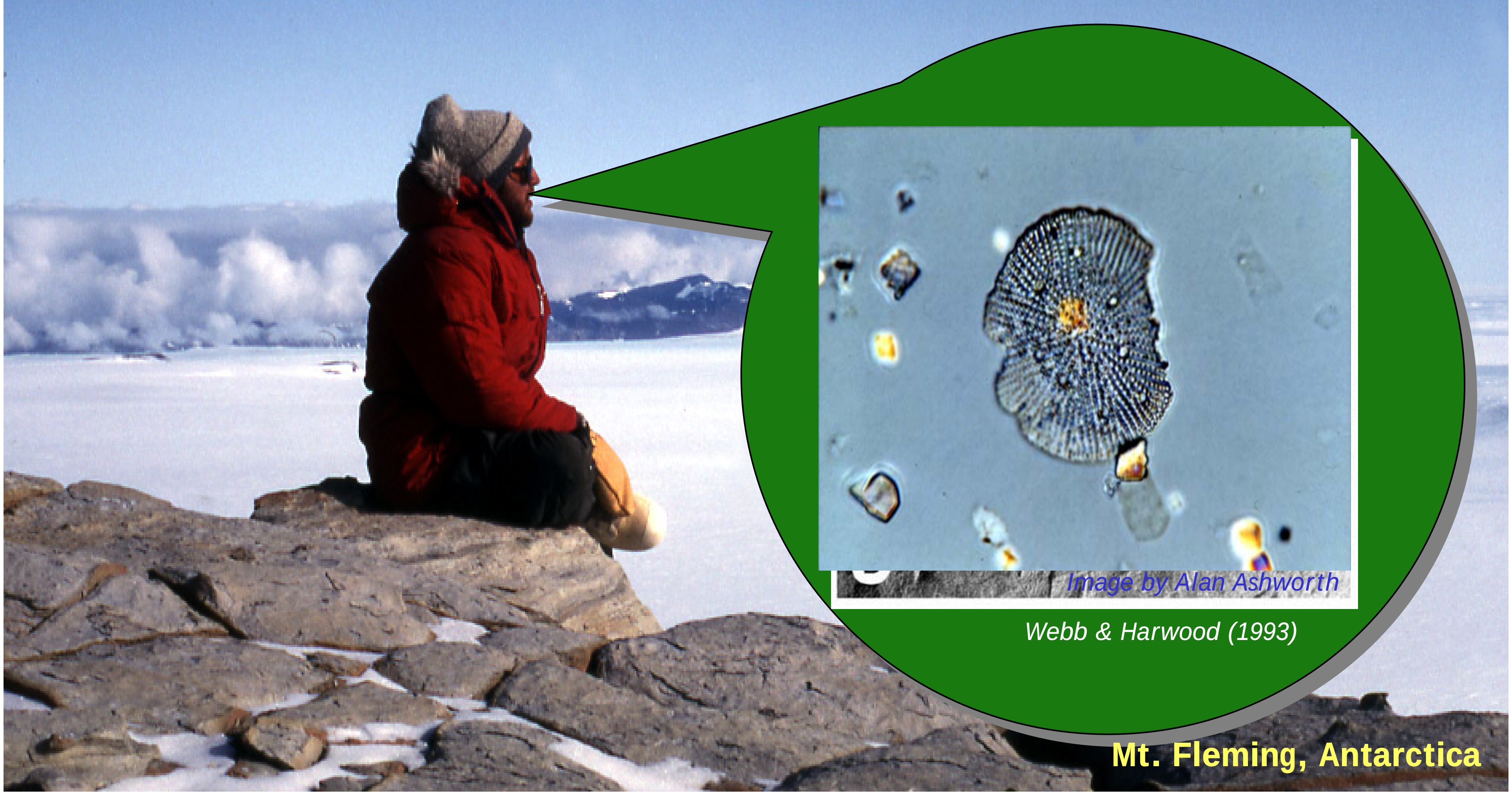
Indications from terrestrial sites: Near-coastal areas

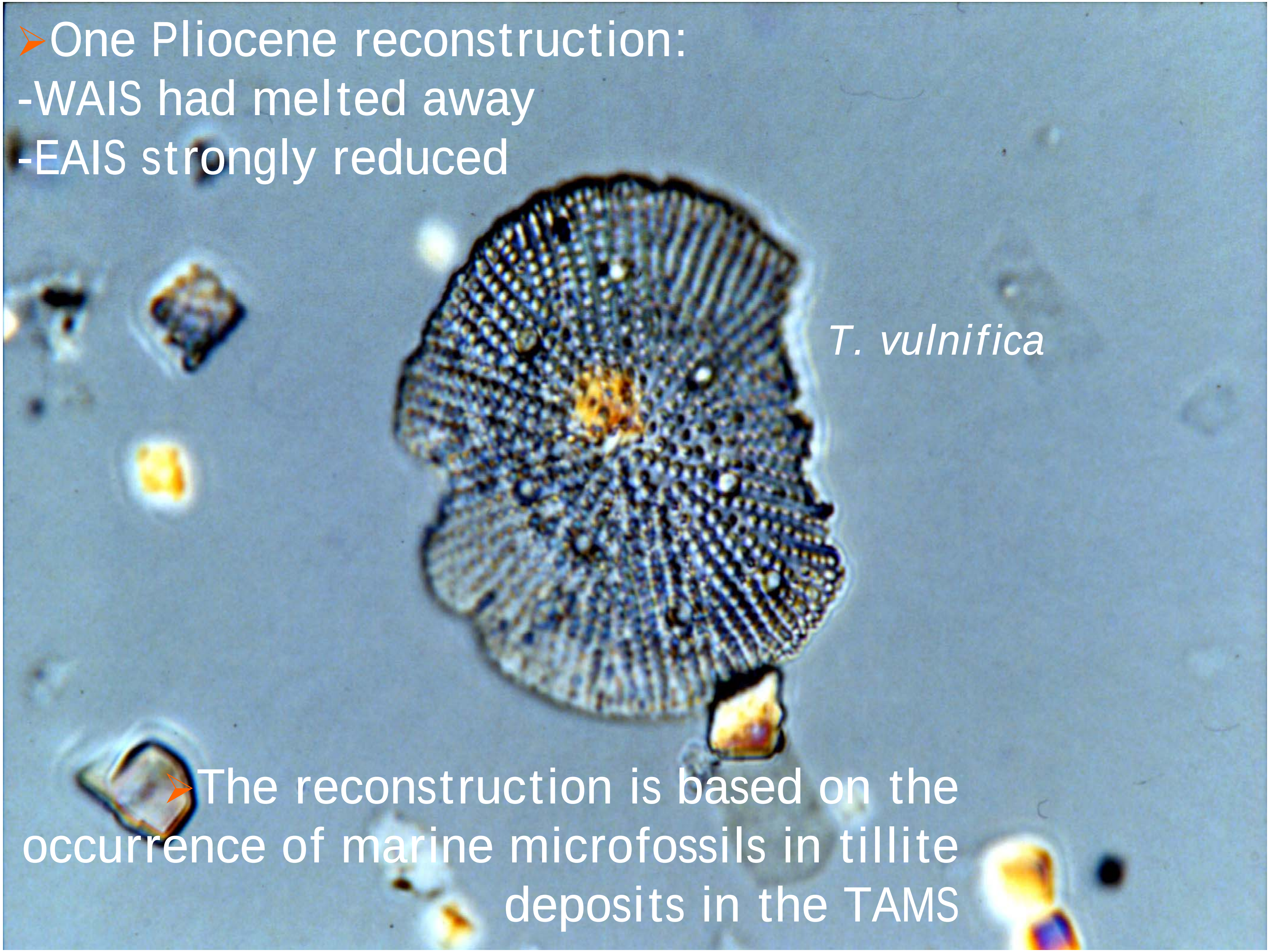
- Evidence from vegetation remains:
  -was there a Pliocene community?
- Terrestrial glacial stratigraphy
  - Lambert Graben area
  - Transantarctic Mtns
- N. Peninsula evidence of MAT leading up to inception of ice sheets, last warm period early Eocene: 7-15 °C.
- Deposits dating back to Oligocene - e. Miocene, mostly using microfossil, ash stratigraphy & TCN dating evidence

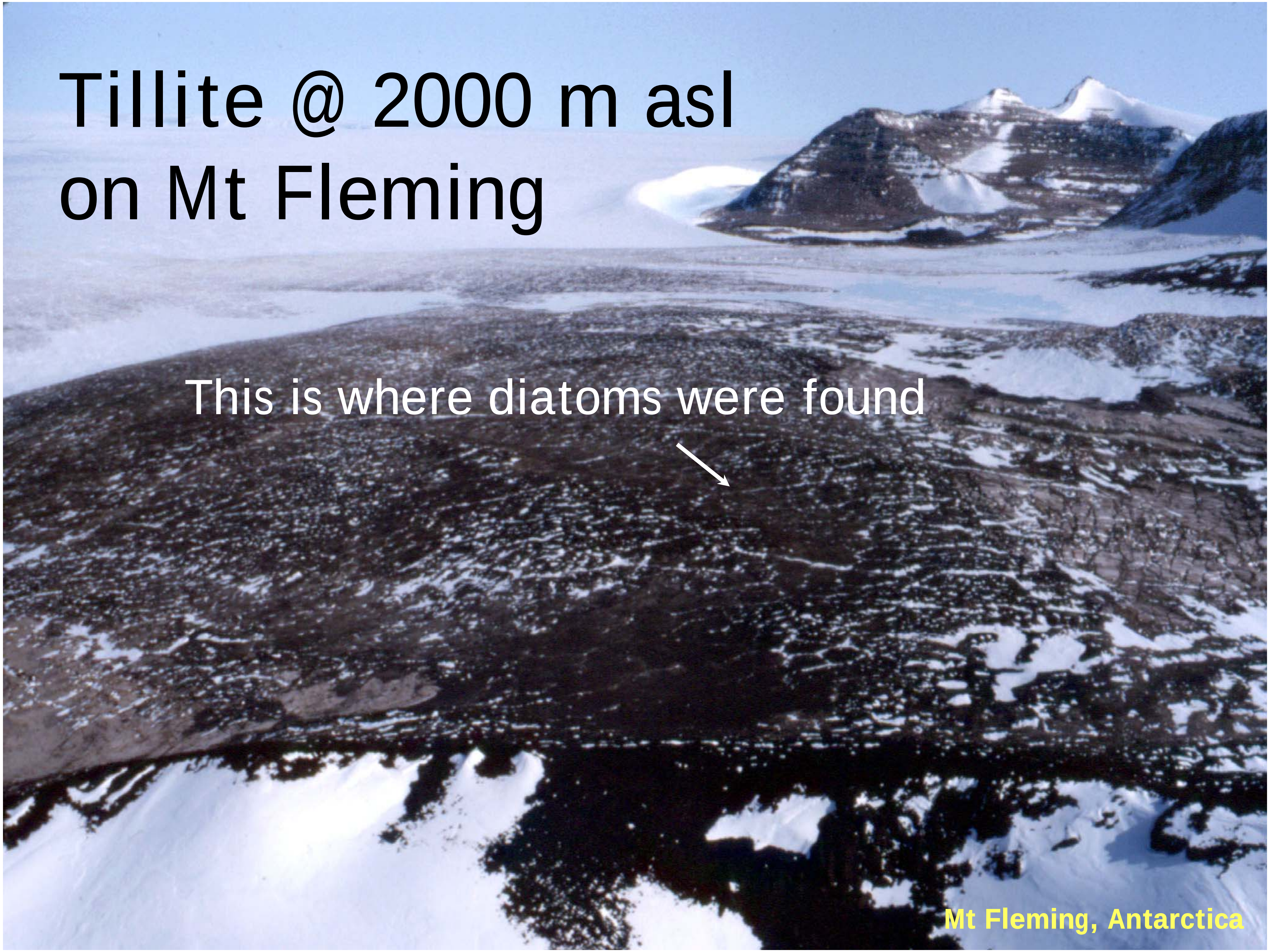


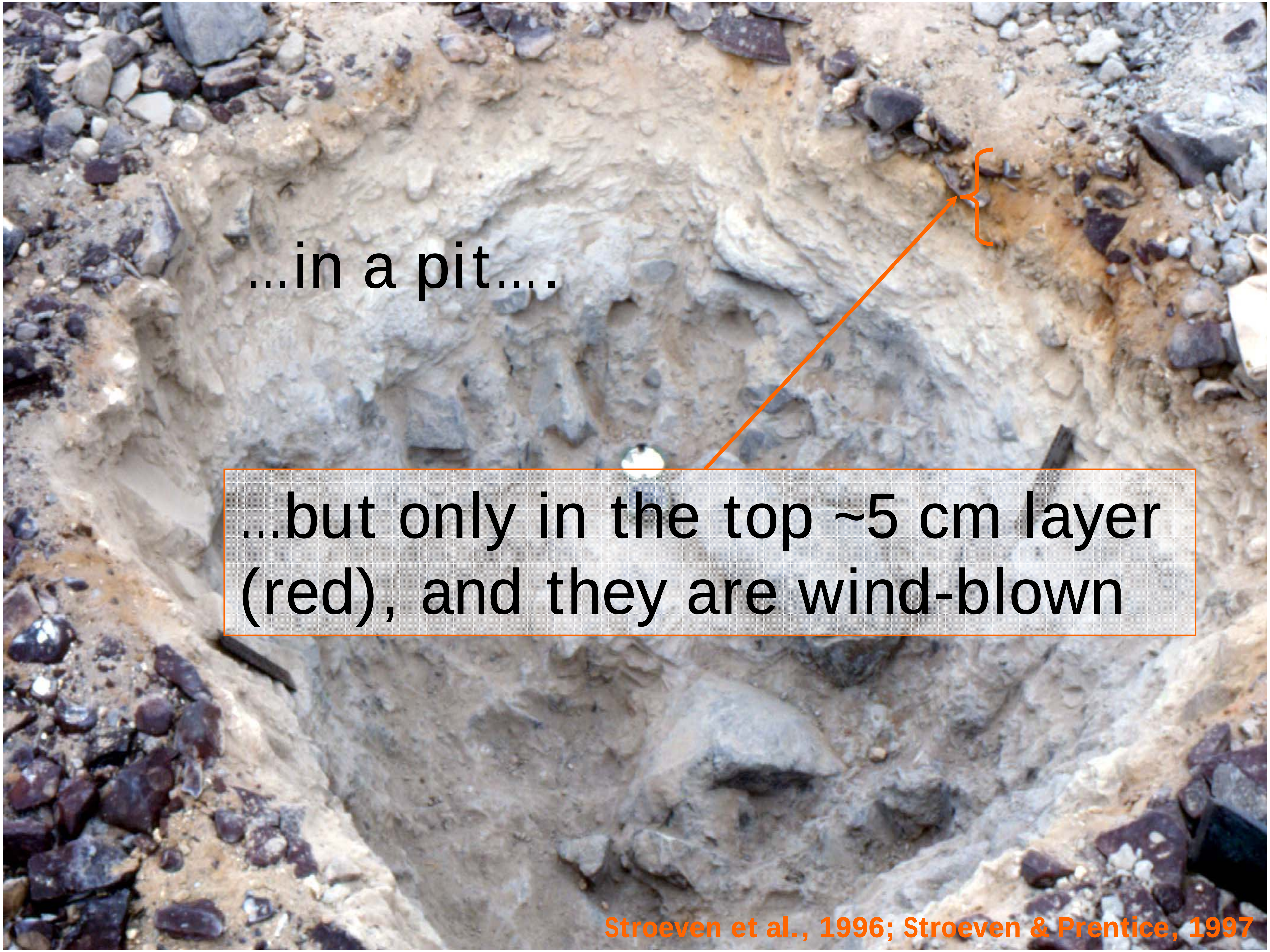
Highest occurrence of tillite, Mt Egerton, >4000 m asl, Beardmore Glacier area

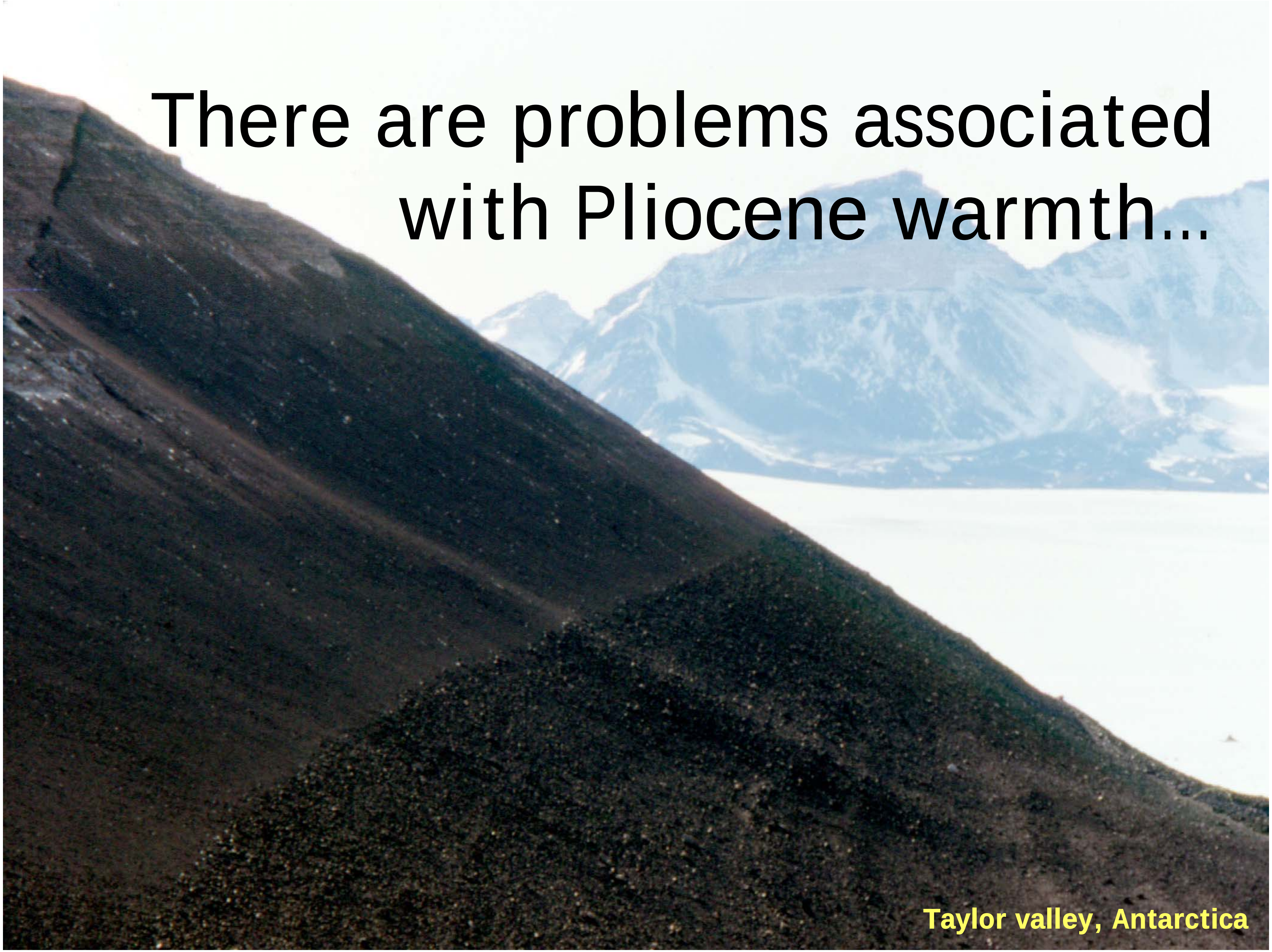
Indications from terrestrial sites: Transantarctic Mountains

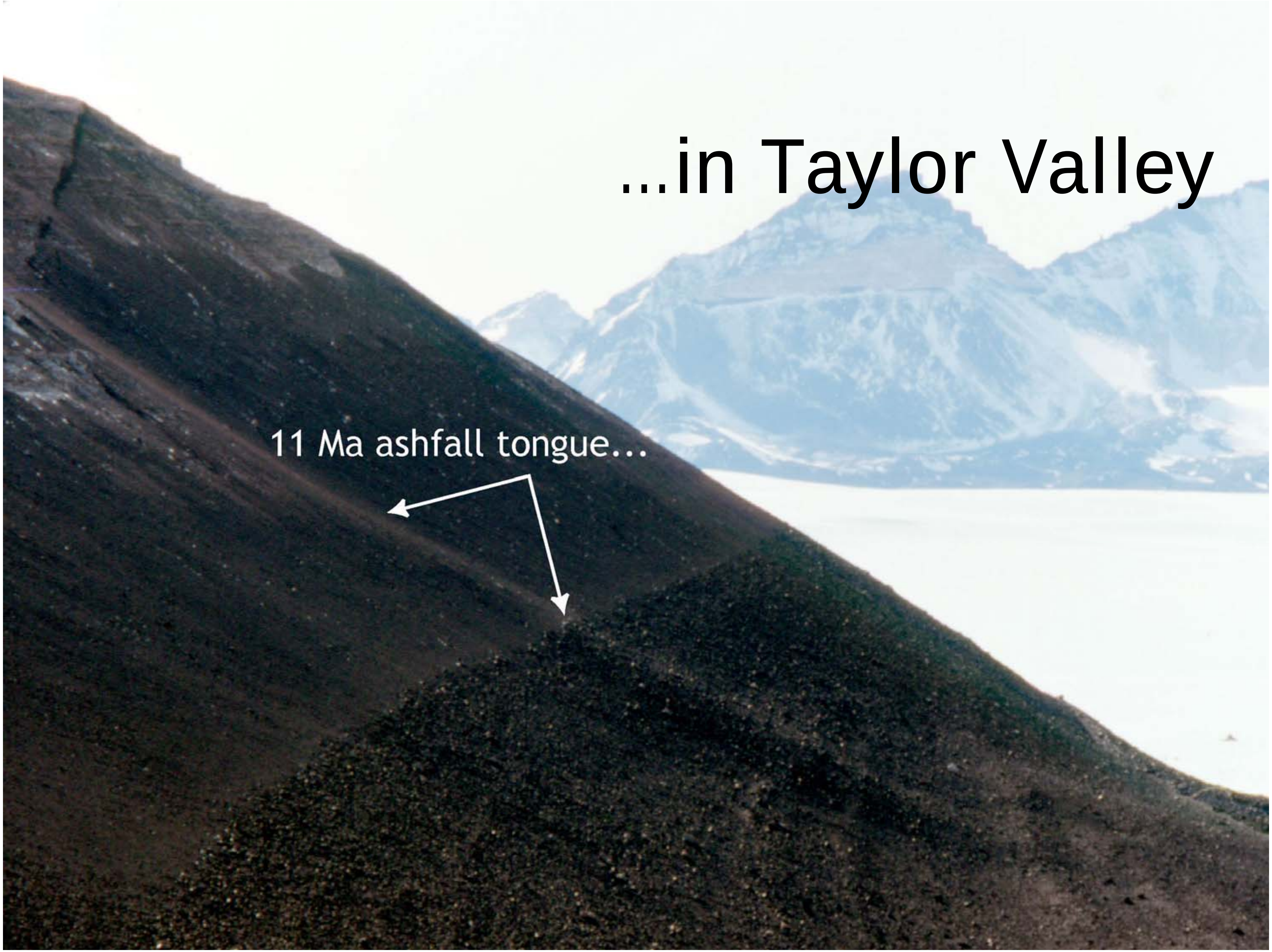


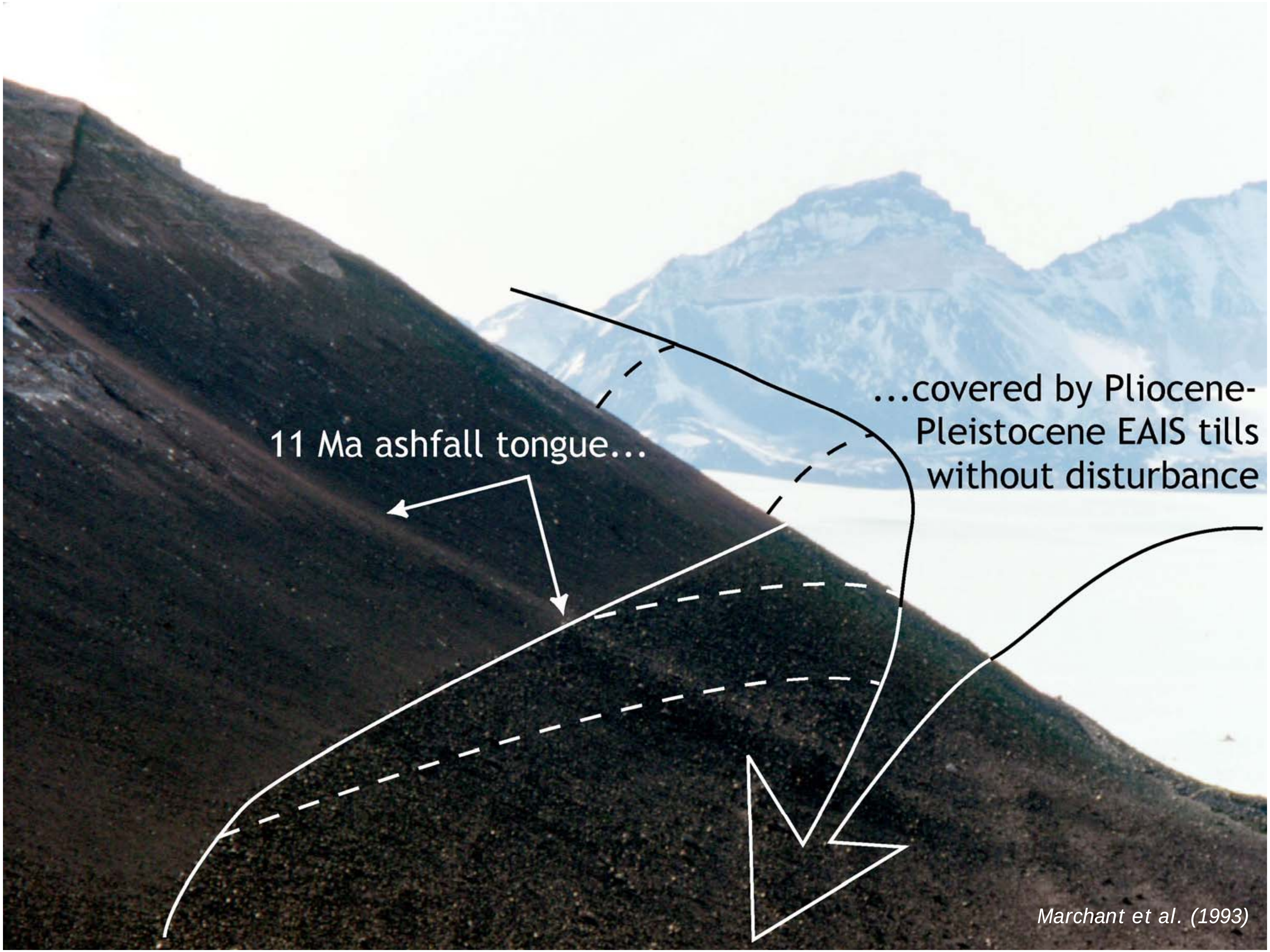

➢One Pliocene reconstruction:
-WAIS had melted away
-EAIS strongly reduced
T. vulnifica
➢The reconstruction is based on the occurrence of marine microfossils in tillite deposits in the TAMS


Tillite @ 2000 m asl
on Mt Fleming
This is where diatoms were found
Mt Fleming, Antarctica

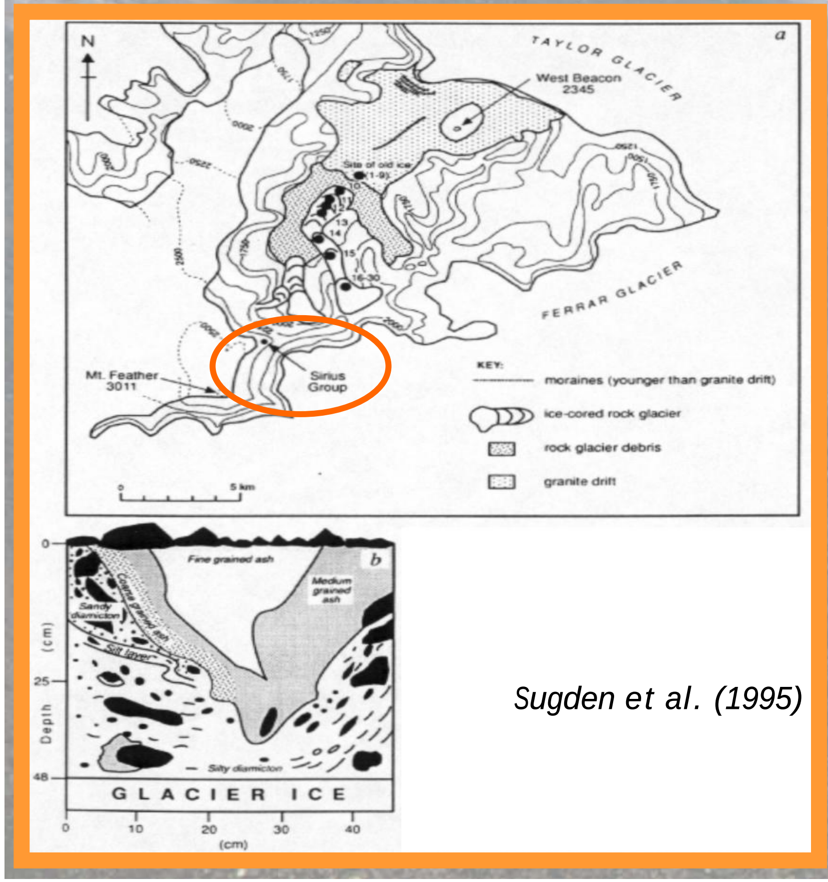

...in a pit....
...but only in the top ~5 cm layer (red), and they are wind-blown
Stroeven et al., 1996; Stroeven & Prentice, 1997


There are problems associated with Pliocene warmth...
Taylor valley, Antarctica


...in Taylor Valley
11 Ma ashfall tongue...


11 Ma ashfall tongue...
...covered by Pliocene-Pleistocene EAIS tills without disturbance
Marchant et al. (1993)

...and in Beacon Valley

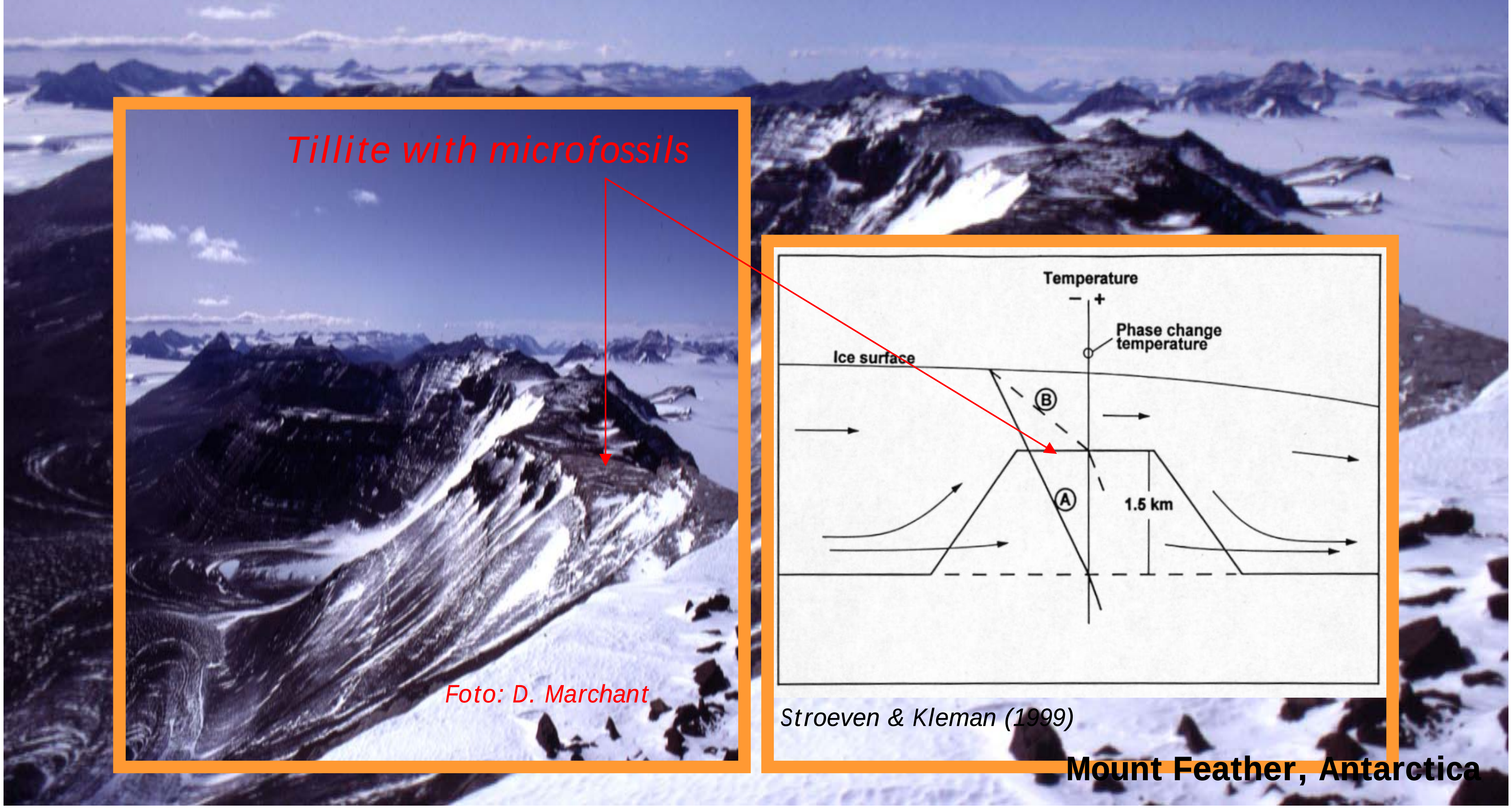


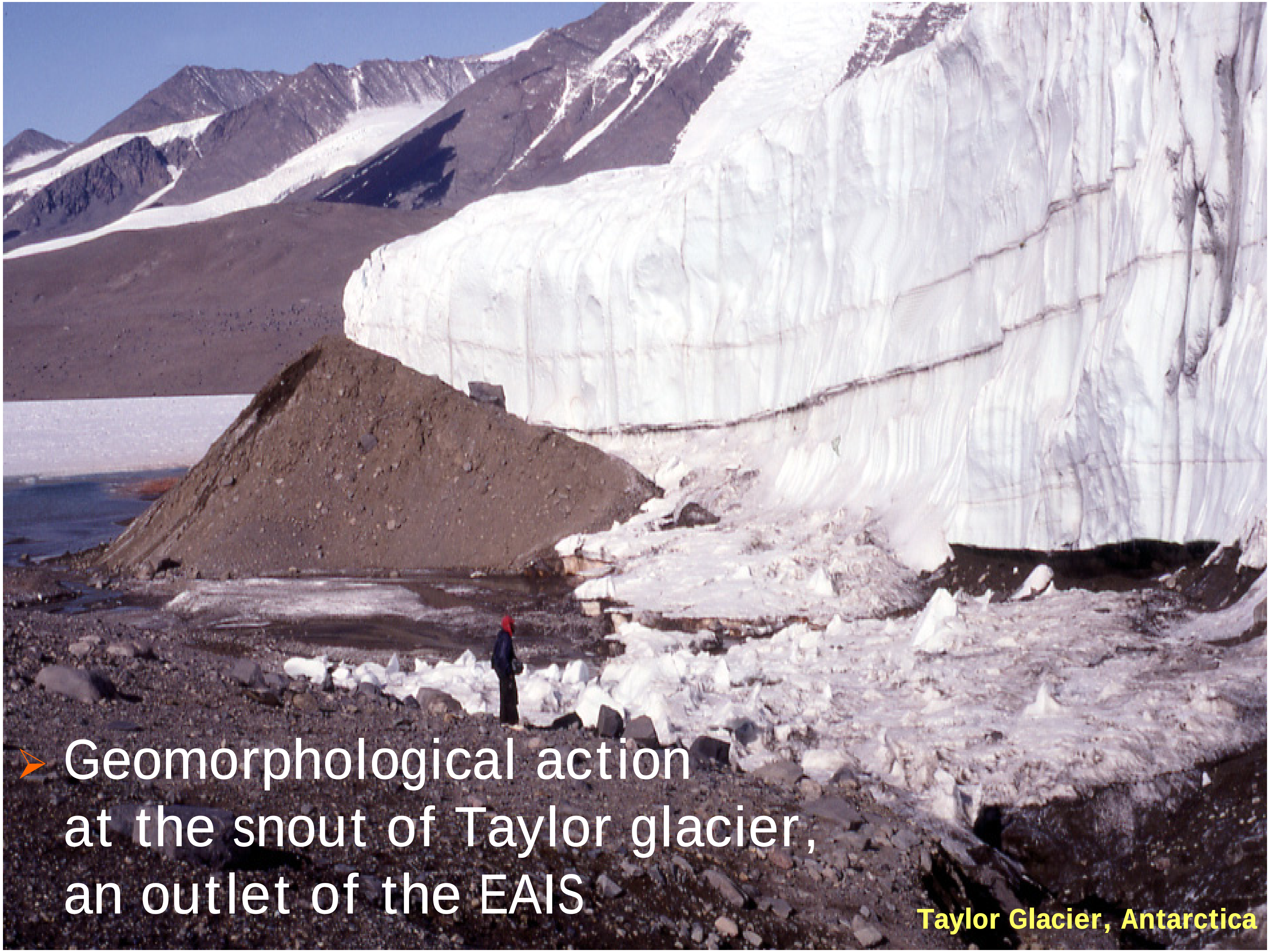
Sugden et al. (1995)

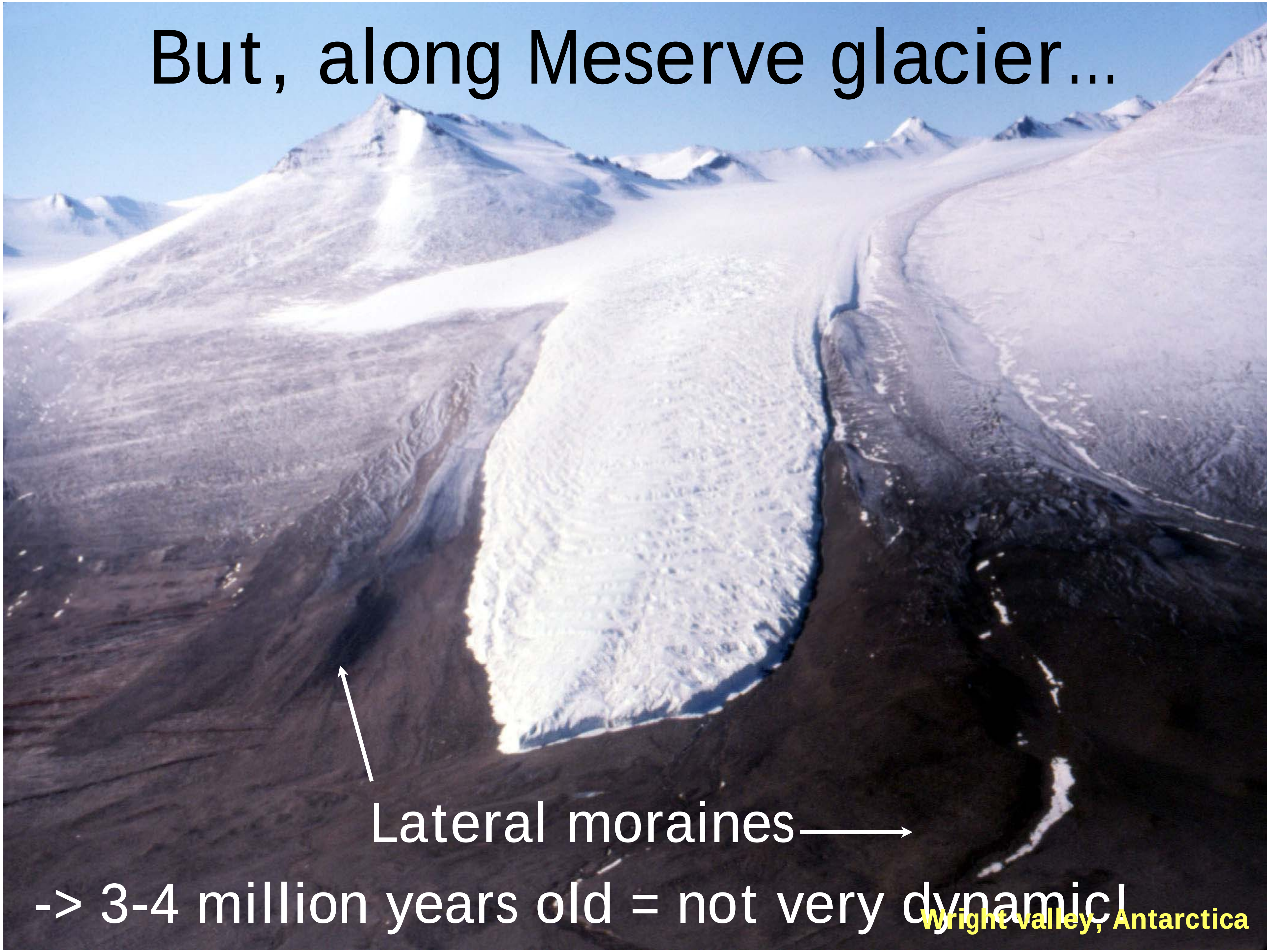
Current surface morphology in Dry Valleys appears to be at least 8 Ma, which implies that the tills must be older

Ice and ashes have been preserved since the Miocene. Hence it has been consistently cold and this appears to preclude an EAIS deglaciation during the Pliocene.

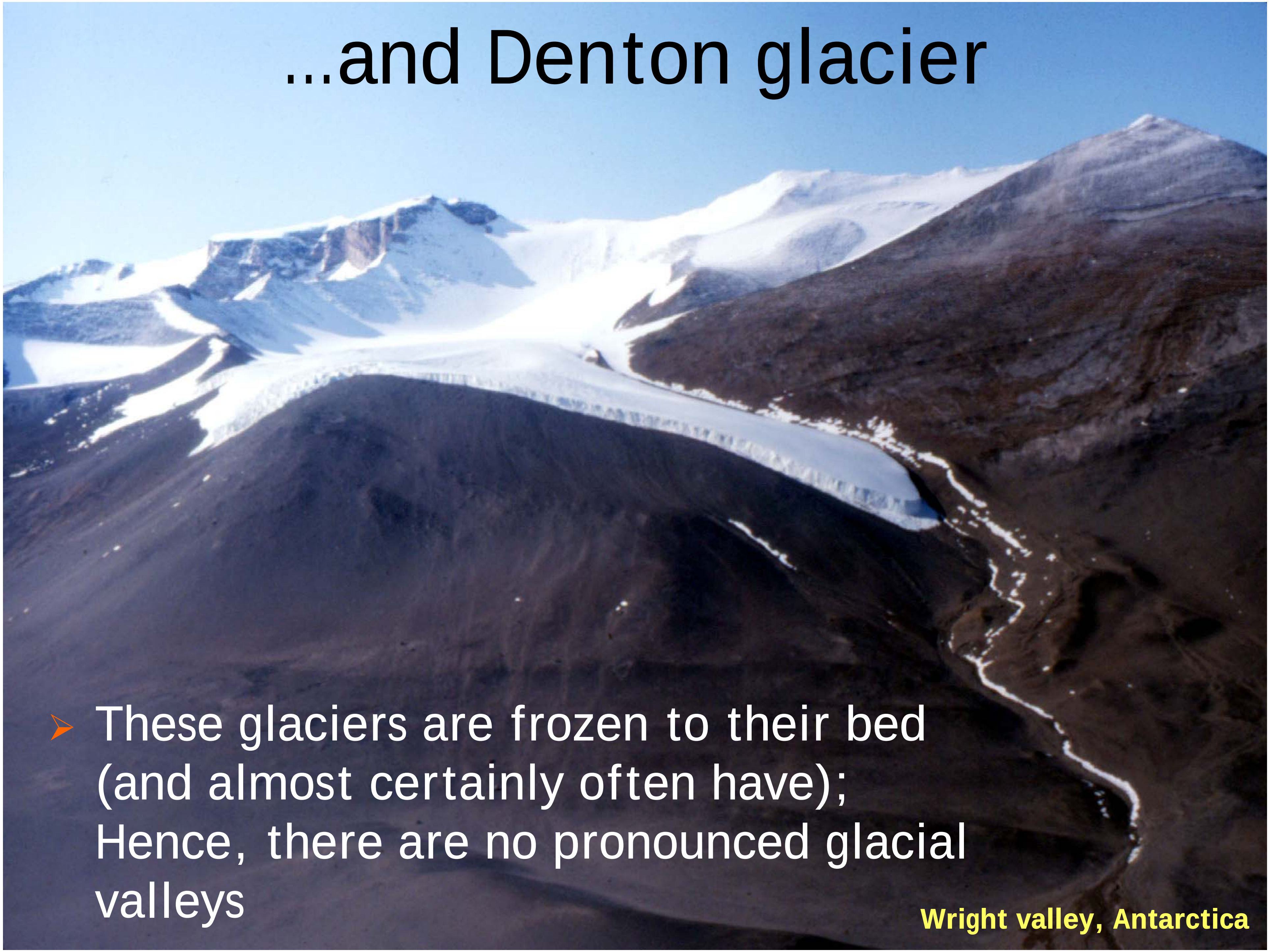
In addition, these diatoms occur in odd topographic situations…




Geomorphological action
at the snout of Taylor glacier,
an outlet of the EAIS
Taylor Glacier, Antarctica


But, along Meserve glacier...
Lateral moraines
-> 3-4 million years old = not very dynamic!
Wright valley, Antarctica

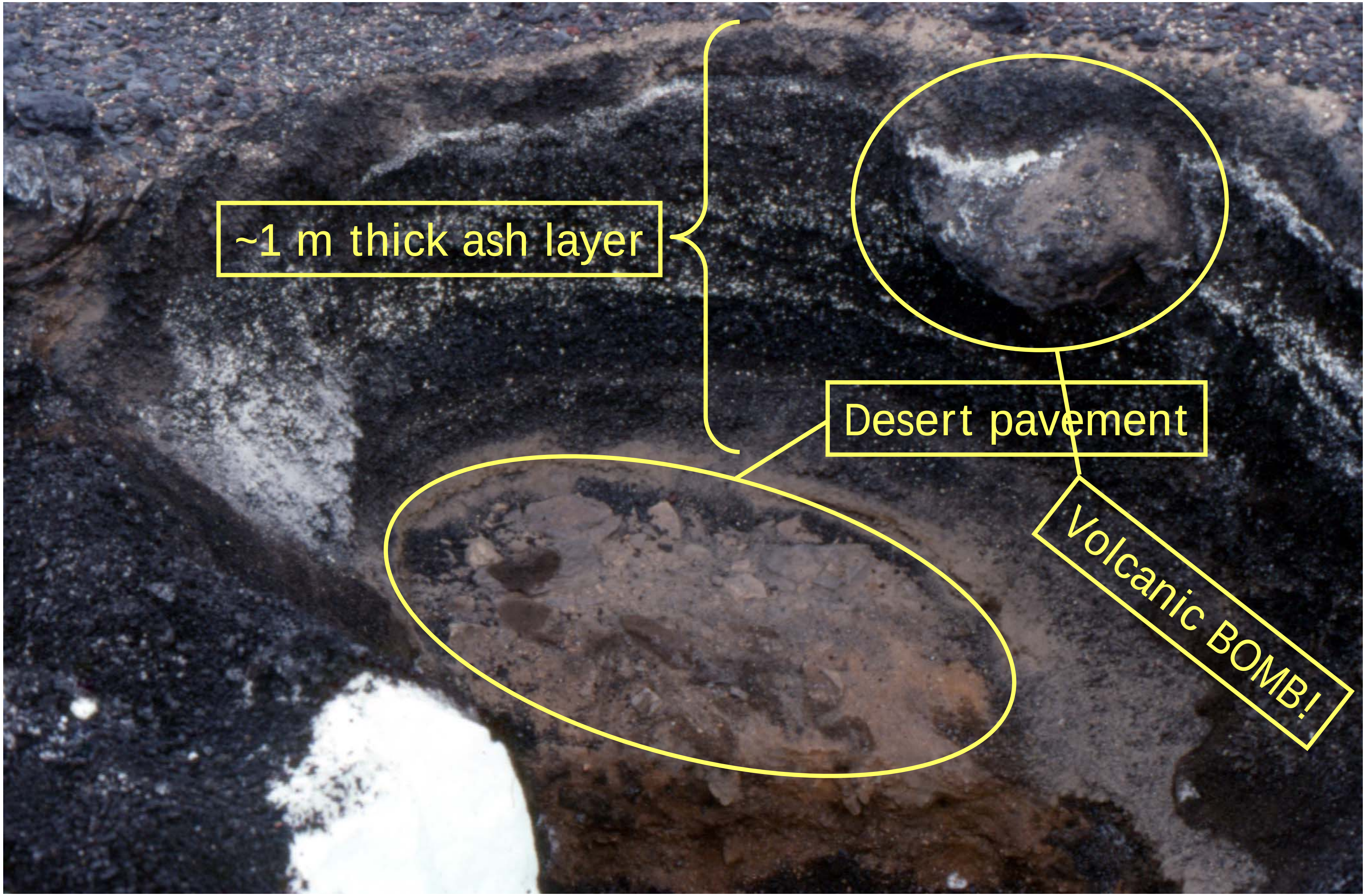
...and Denton glacier



- These glaciers are frozen to their bed (and almost certainly often have); Hence, there are no pronounced glacial valleys

Wright valley, Antarctica

Pliocene ashfall deposit in Taylor valley

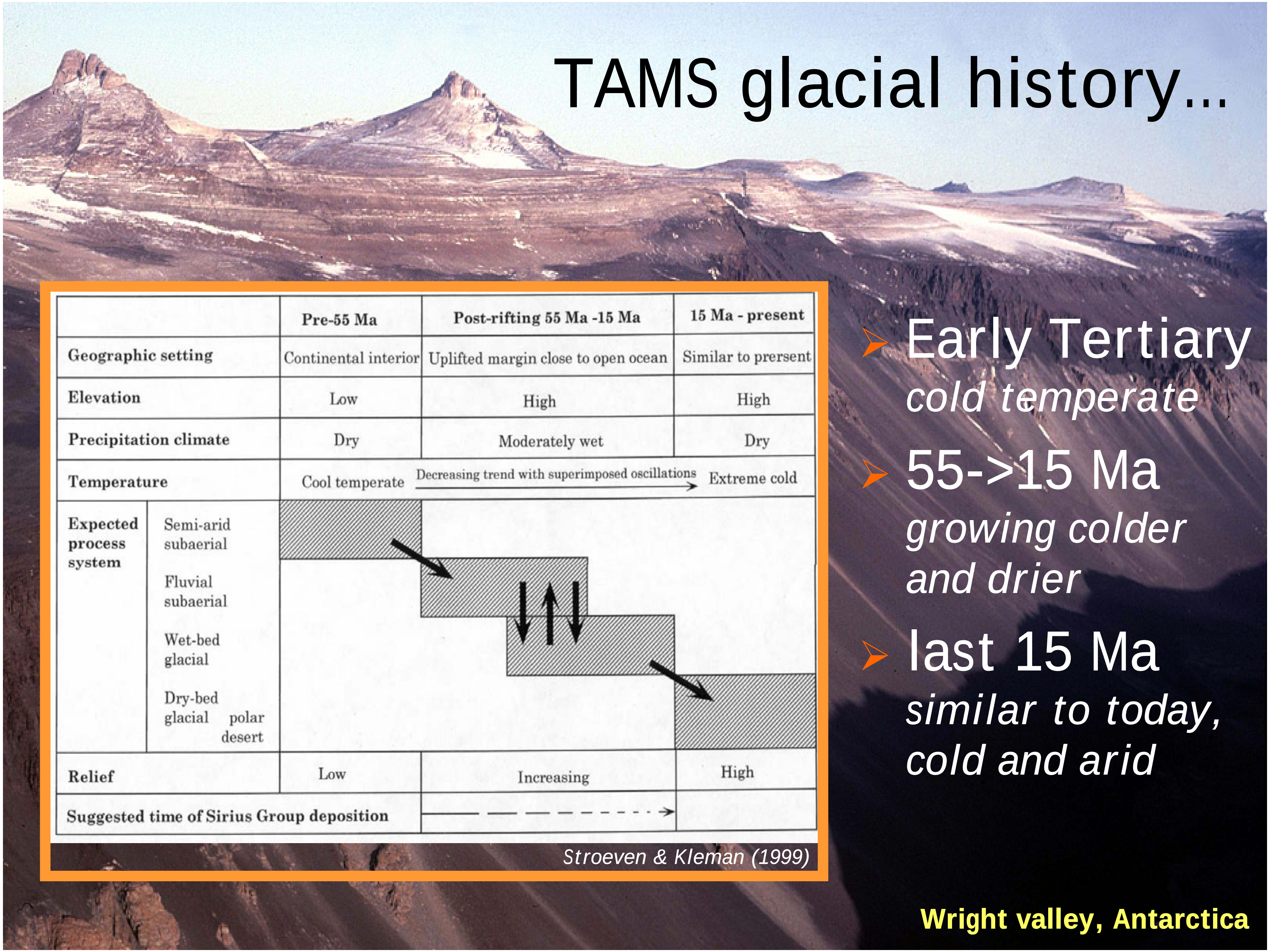


Antarctic geomorphology wrap-up

- Pliocene lateral moraines (and volcanic cones)
- 8-15 million years old ashes
- Geomorphological comparison w/ USA

- Trunk valley in which they are situated is older than the Pliocene: so are *its* tills
- Valleys, ice and sediment underneath the ashes are older, tills on top were deposited by cold-based ice
- EAIS has not everywhere left a definitive imprint

TAMS glacial history…



	Pre-55 Ma	Post-rifting 55 Ma -15 Ma	15 Ma - present
Geographic setting	Continental interior	Uplifted margin close to open ocean	Similar to present
Elevation	Low	High	High
Precipitation climate	Dry	Moderately wet	Dry
Temperature	Cool temperate	Decreasing trend with superimposed oscillations →	Extreme cold
Expected process system — Semi-arid subaerial; Fluvial subaerial; Wet-bed glacial; Dry-bed glacial polar desert			
Relief	Low	Increasing	High
Suggested time of Sirius Group deposition		— — — - - - →	

Stroeven & Kleman (1999)

- Early Tertiary
  cold temperate
- 55->15 Ma
  growing colder and drier
- last 15 Ma
  similar to today, cold and arid

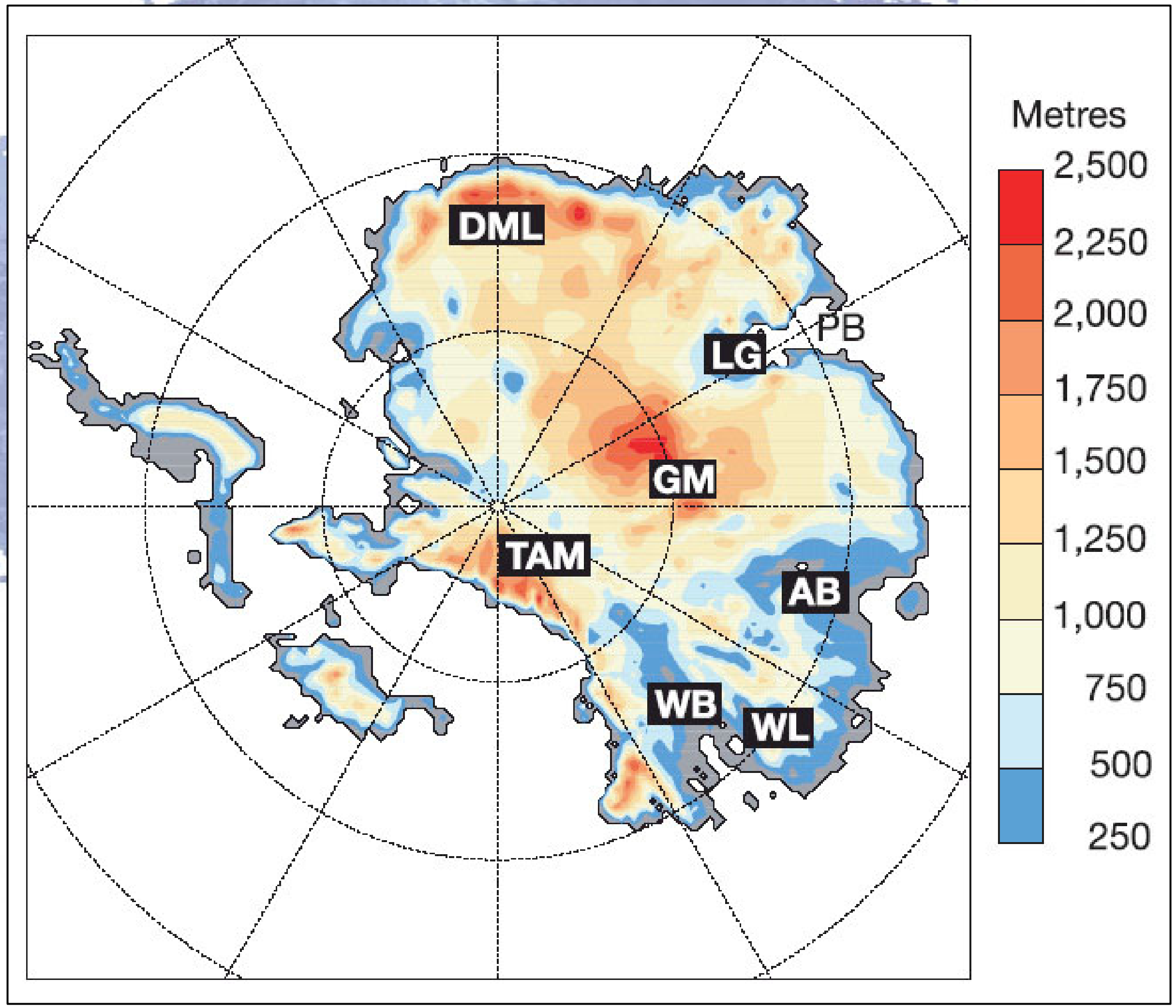
Wright valley, Antarctica

Ice sheet and climate modelling

• 34 Ma transition	• DeConto & Pollard (2003a, b), *P*[3], *Nature* Thorn & DeConto (2006), *P*[3]
• Pliocene warmth	• Huybrechts (1993): Geogr. Ann. *not shown*
• Cenozoic history	• Oerlemans (2004), *P*[3]

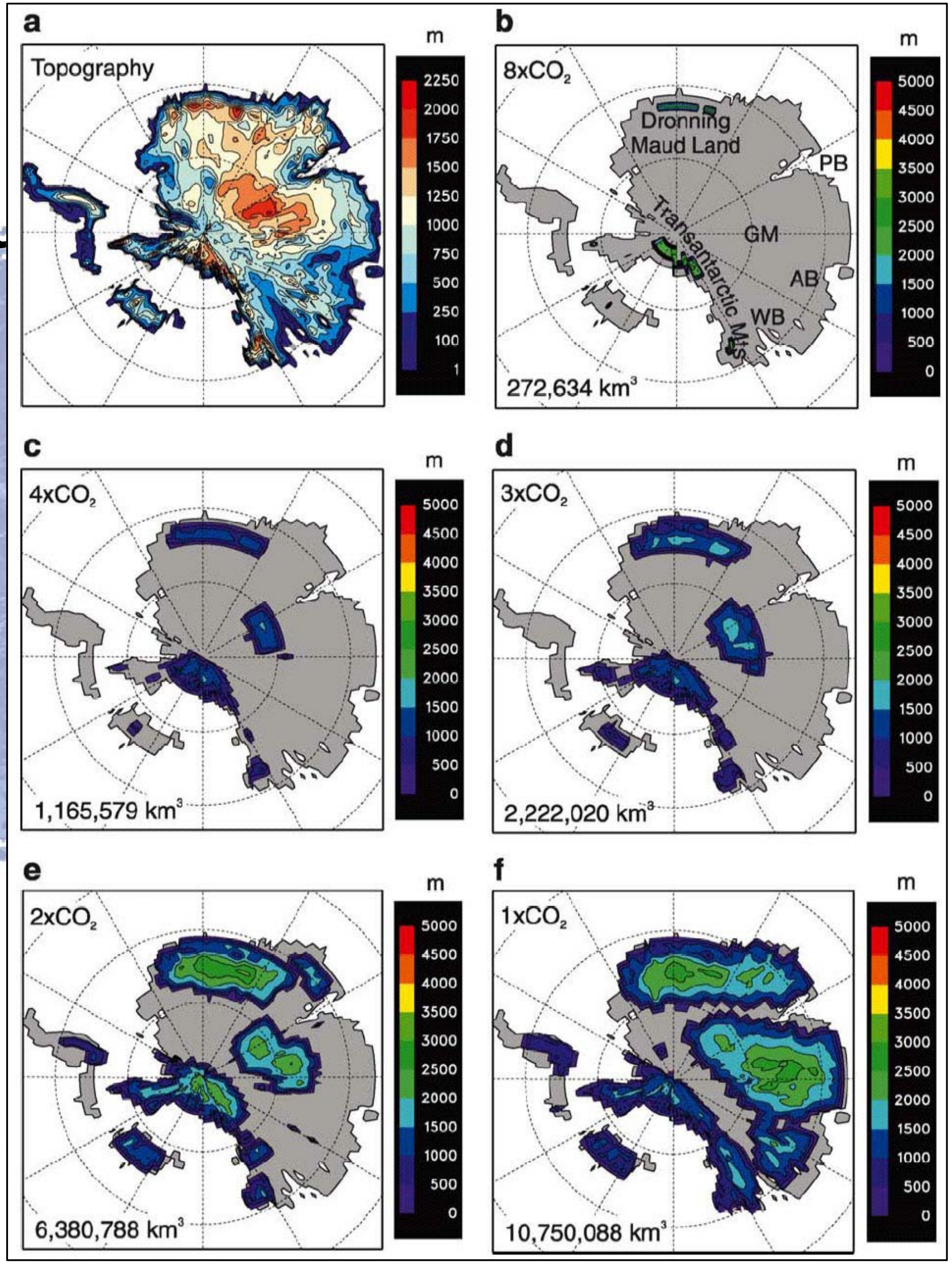
34 Ma glacial inception

Initial topography:



34 Ma gla

Ice sheets run to steady state following five different CO_2 boundary conditions: Non-linear response



34 Ma glacial inception

Effect of Drake Passage upon the inception of ice sheets on Antarctica

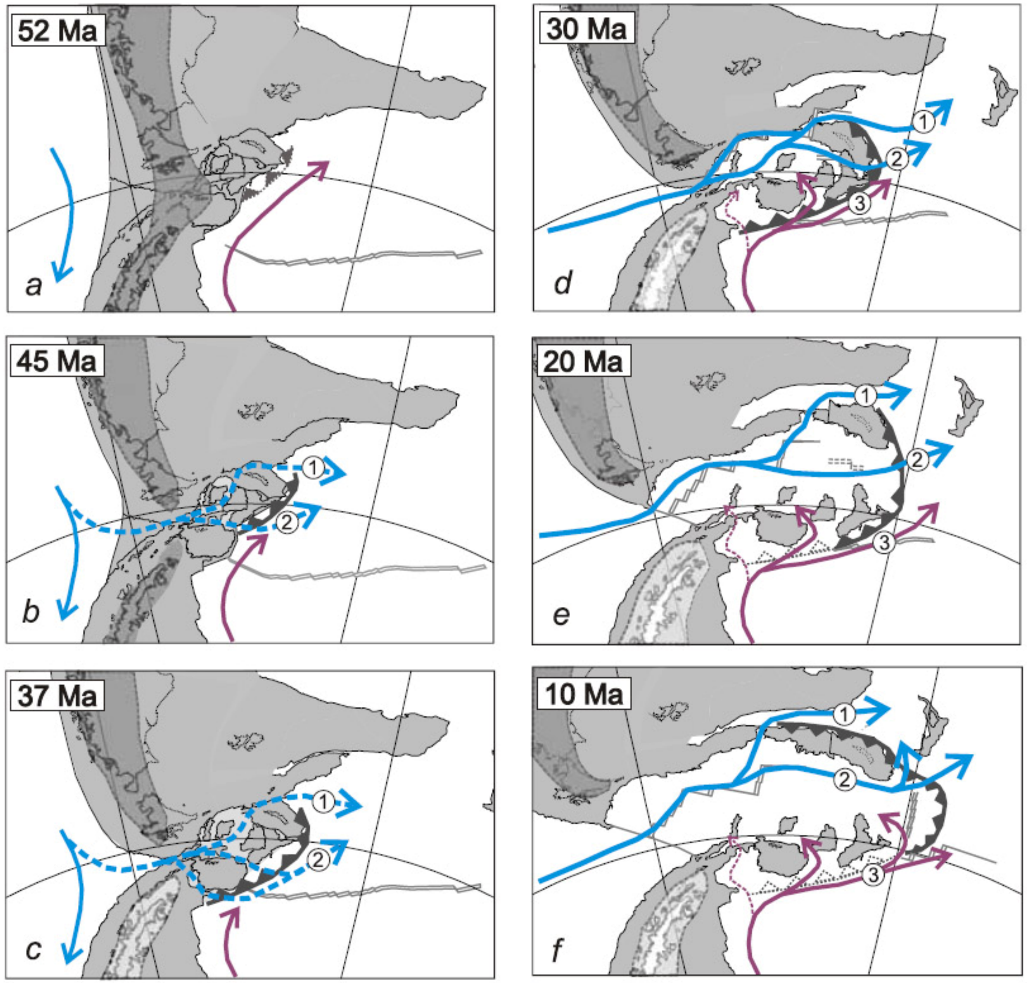
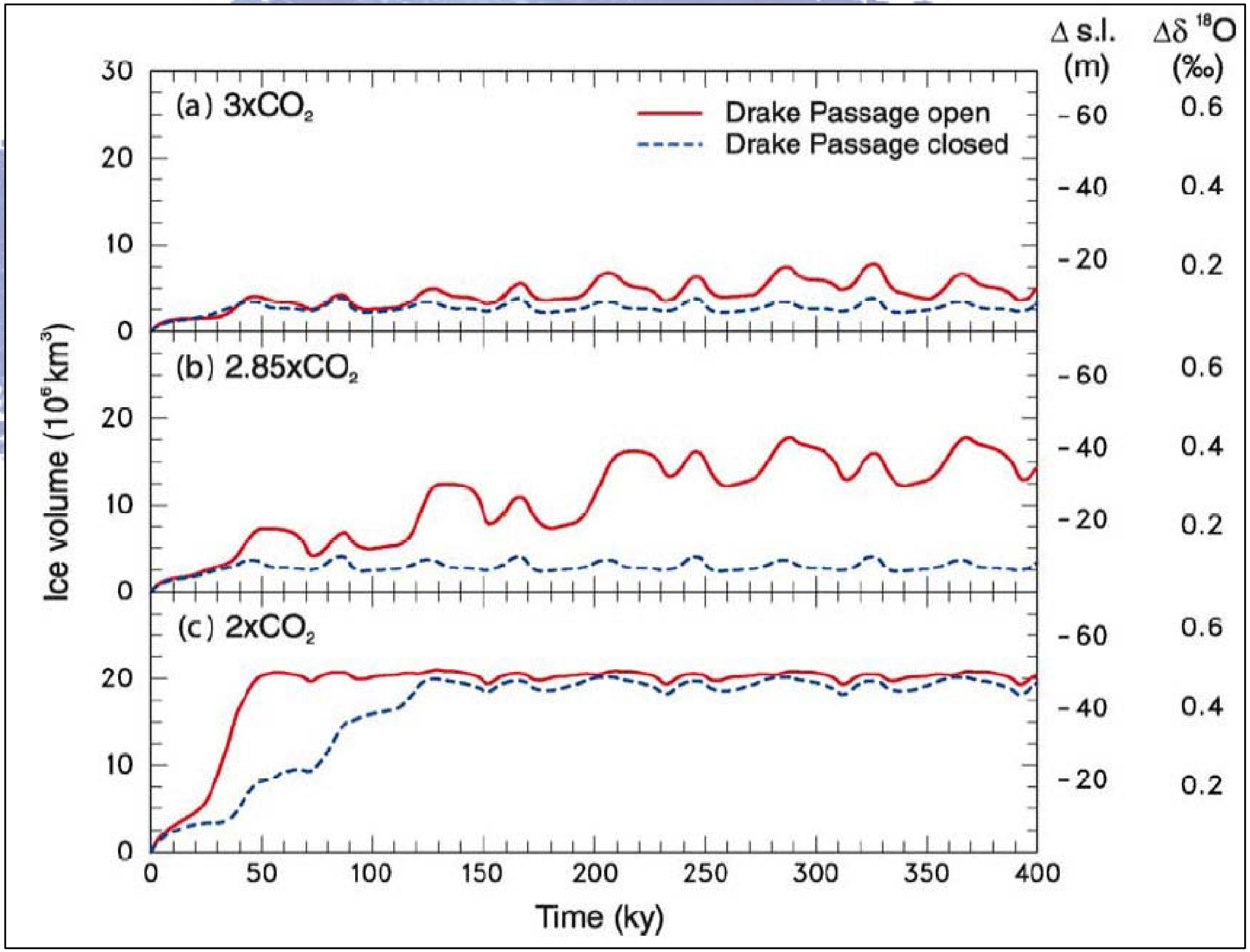


Fig. 2: Livermore et al. (2007)

34 Ma glacial inception

Effect of Drake Passage upon the inception of ice sheets on Antarctica



34 Ma

Effect of vegetation on 2-m surface temperatures on Antarctica for Evergreen and Tundra vegetation and ice sheet growth for 2 different CO_2 scenarios and 2 different orbital configurations

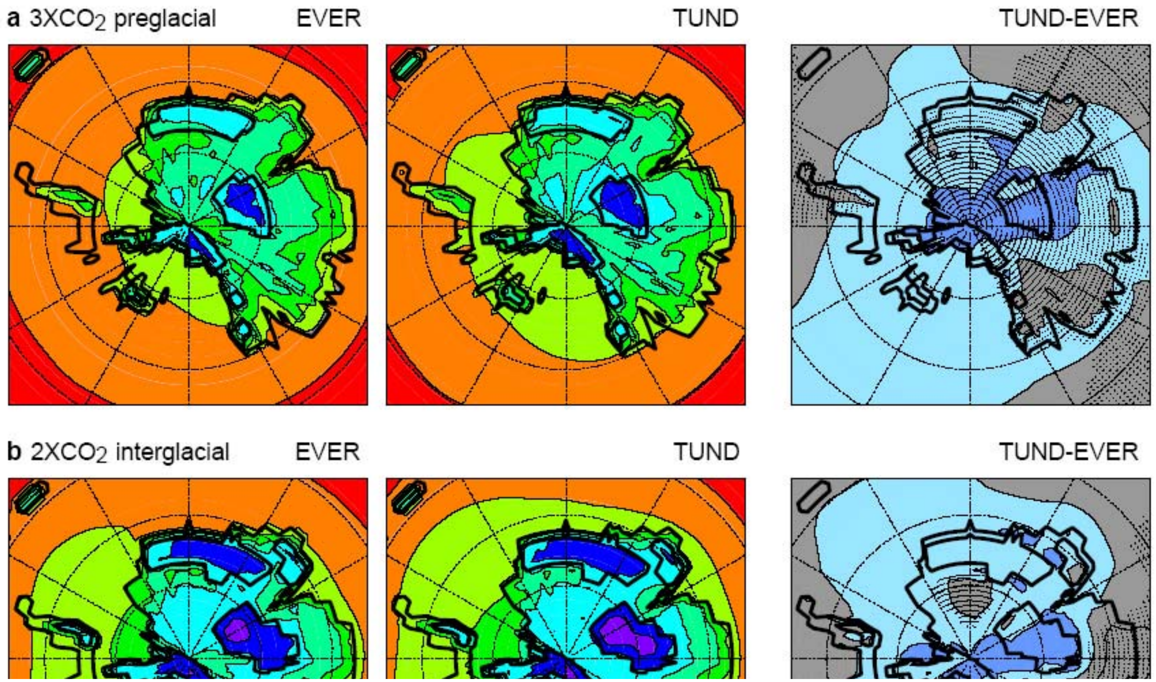


Table 2
Model simulations and relevant model inputs

Model run	CO_2 mixing ratio[a]	Orbital parameters (ecc., obl., pre.)[b]	Ice sheet geometry[c]	Antarctic vegetation[d]
1	$2 \times CO_2$	0.04, 23.5, 90	interglacial	TUND
2	$2 \times CO_2$	0.04, 23.5, 90	interglacial	EVER
3	$2 \times CO_2$	0.01, 22.5, 270.0	glacial	TUND
4	$2 \times CO_2$	0.01, 22.5, 270.0	glacial	EVER
5	$3 \times CO_2$	0.04, 23.5, 90	preglacial	TUND
6	$3 \times CO_2$	0.04, 23.5, 90	preglacial	EVER

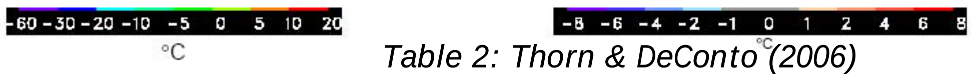
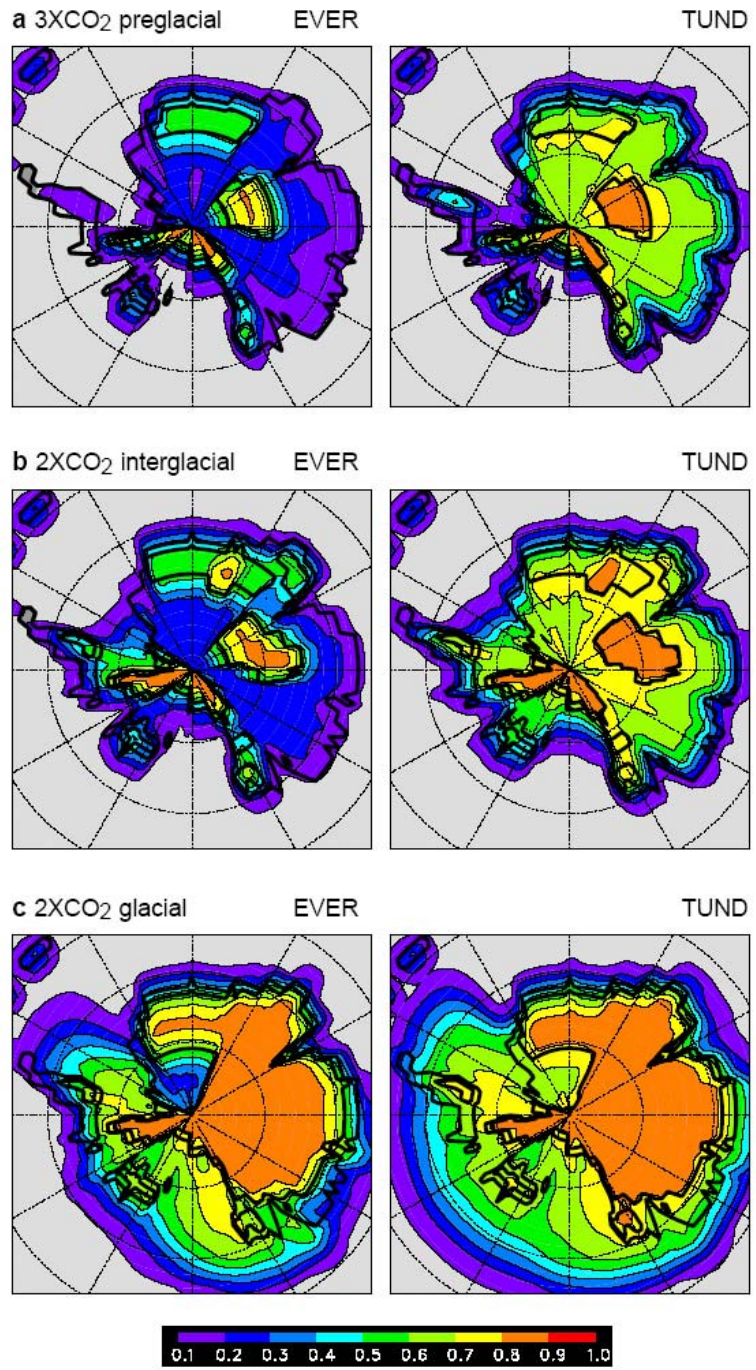


Table 2: Thorn & DeConto (2006)

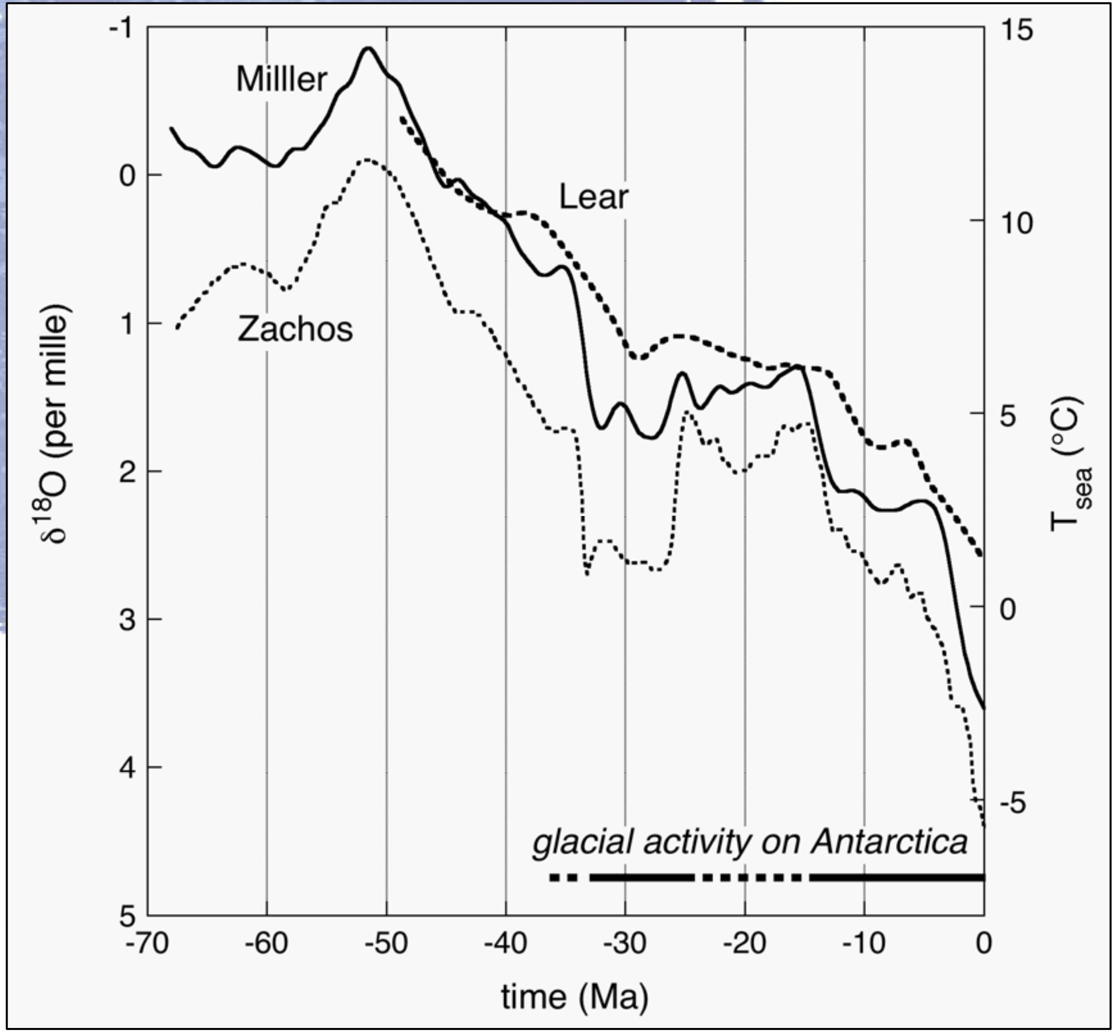
34 Ma glac

Effect of vegetation on surface albedo on Antarctica for Evergreen and Tundra vegetation and ice sheet growth for 2 different CO_2 scenarios and 2 different orbital configurations



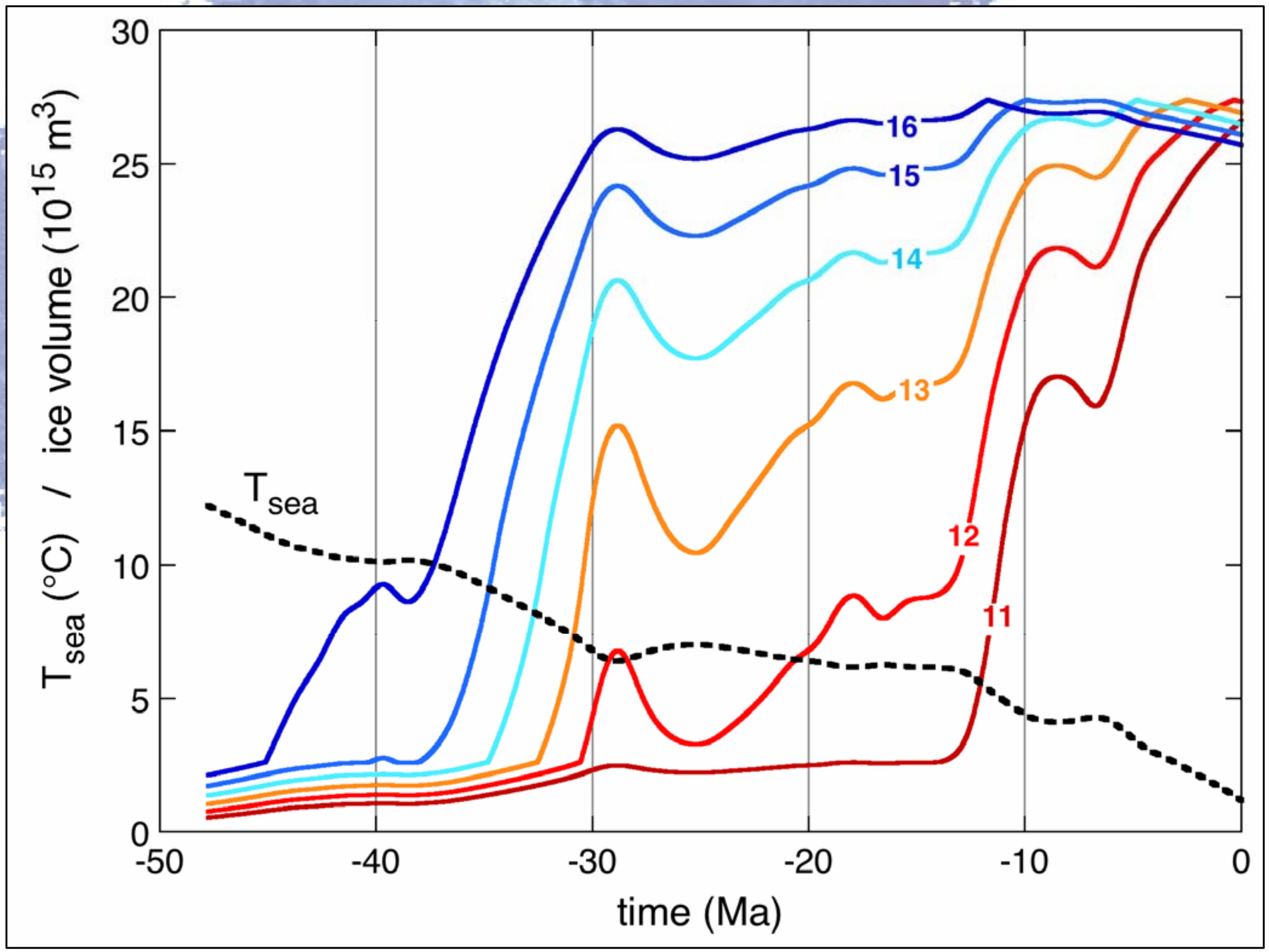
Cenozoic history

Forcing functions, Miller et al. (1987) and Zachos et al. (2001) deep sea temperatures (converted to Antarctic air temperatures) and Lear et al. (2000) sea surface temperatures.



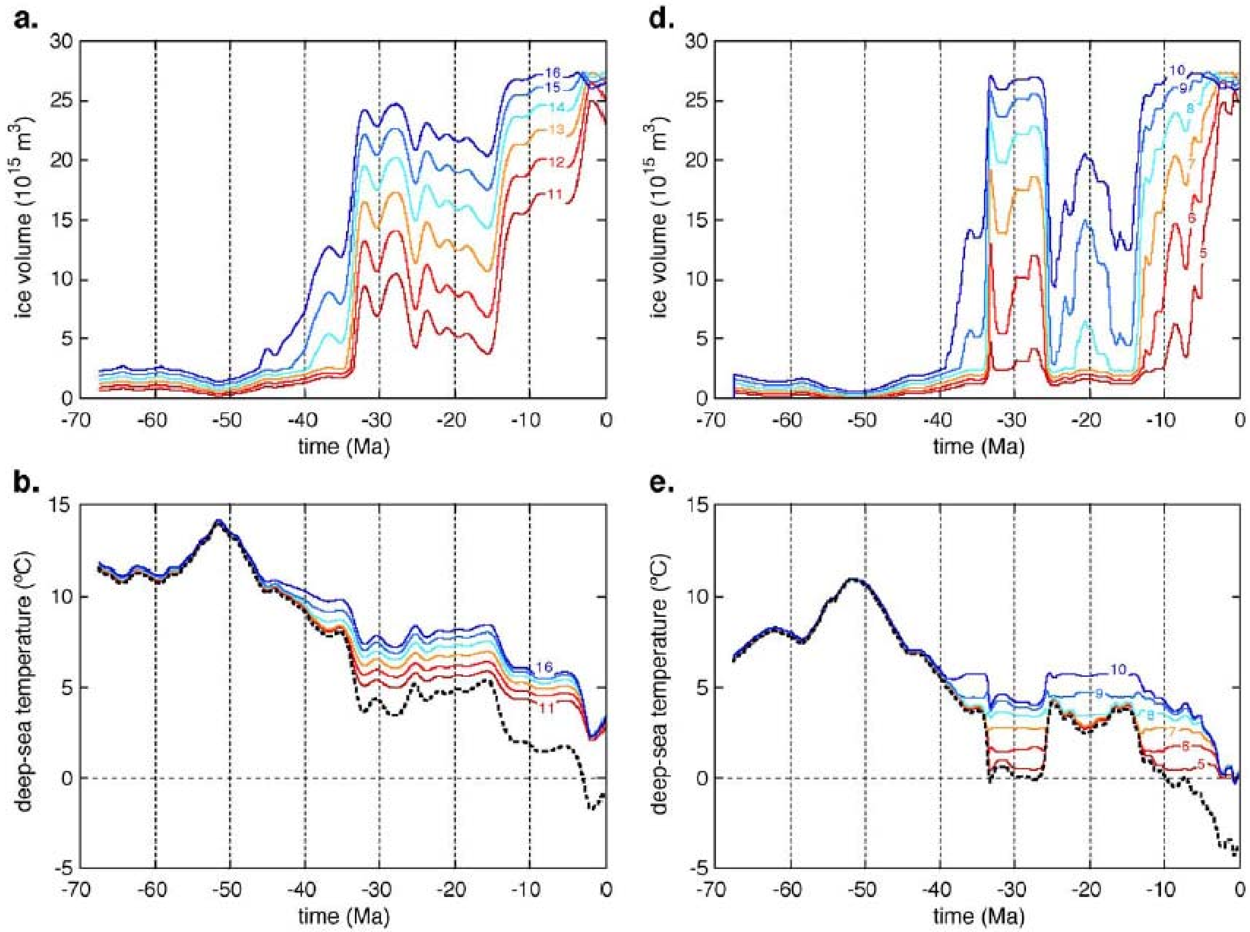
Cenozoic history

Strongly non-linear response of the Antarctic ice sheet for declining sea surface temperatures for different sensitivities



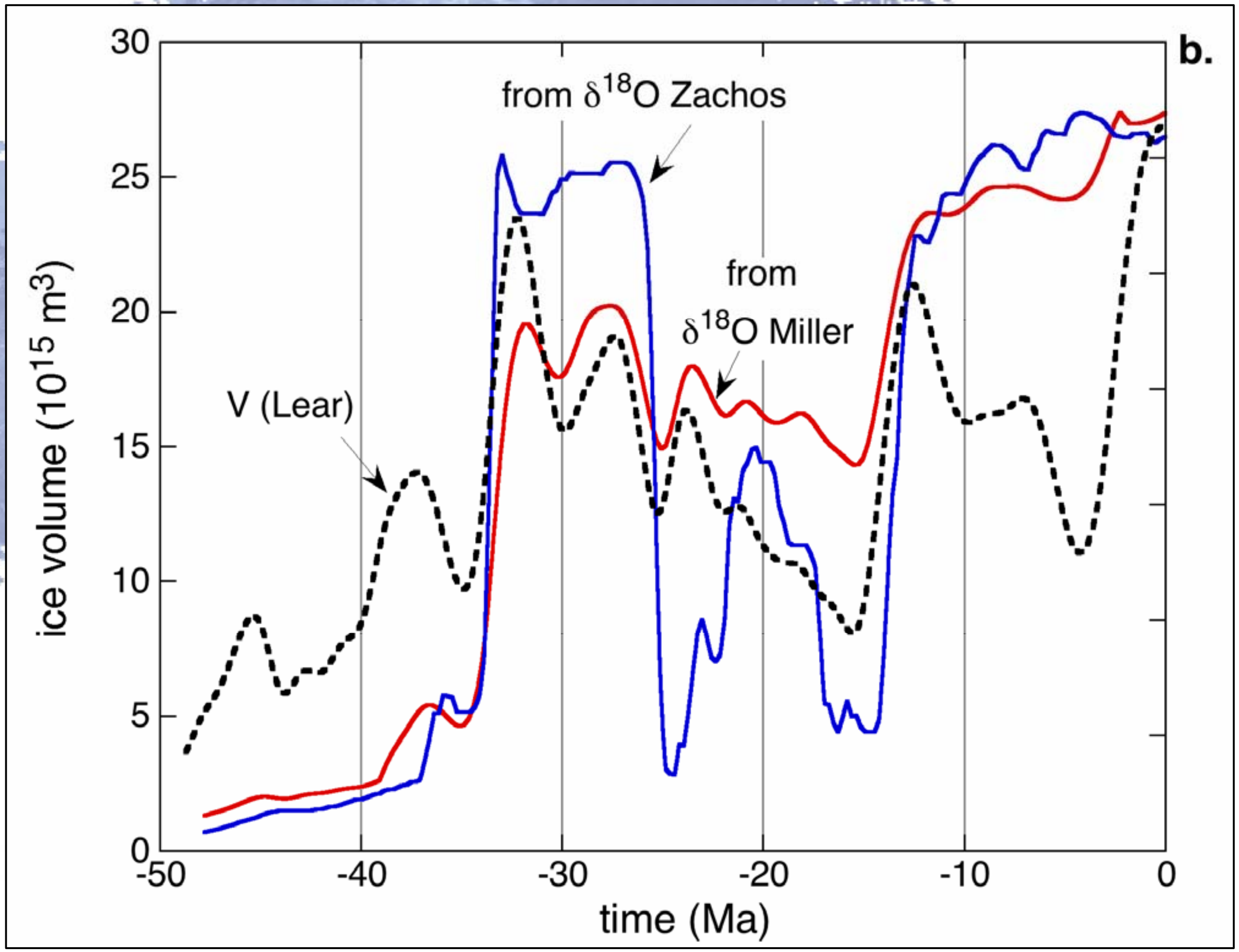
Cenozoic history

Strongly non-linear response of the Antarctic ice sheet using the Miller et al. 1987 forcing (a-b) or the Zachos et al. 2001 forcing (c-d).



Cenozoic history

Comparing Miller and Zachos best runs with Lear. Ice growth around 34 Ma for all 3 records and second/third pulses around 15 Ma and 3 Ma. Zachos decline in Miocene, Lear in early Pliocene.



Cenozoic history of Antarctica: Conclusions

Most important phases:

- Glaciation history spans the last 55 million years
- EAIS first formed ~34 million years ago (Ma); NLR
- Opening of Drake passage (?30-22 Ma)
  -> resulted in gradual thermal isolation, which implies that its climate became less and less sensitive to extra-Antarctic forcing
- Formation of a cold-based EAIS of current proportions first after 15 Ma
- Inception of bipolar glaciation around 3 Ma affected Antarctica only through sea level falls

References

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