# Site Survey Methods in Glacial Ice Drilling

**GESEP**
**EARTH PROBING SCHOOL 2011**

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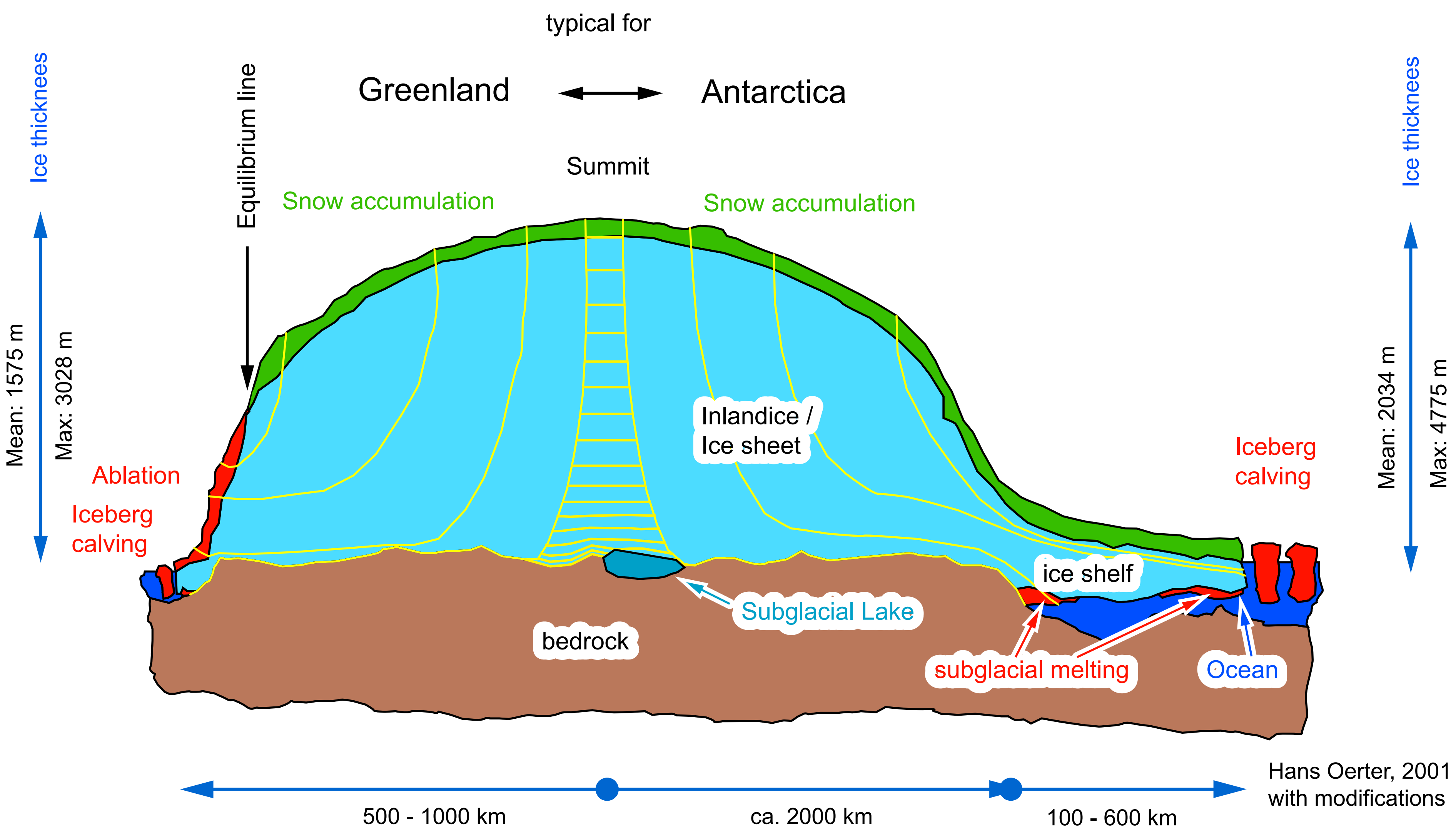
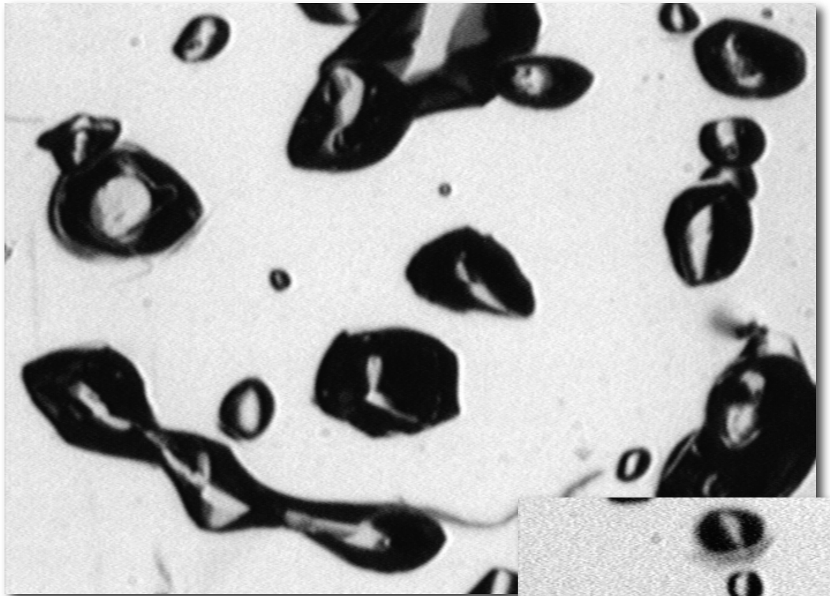
HELMHOLTZ
GEMEINSCHAFT

# Polar ice sheets

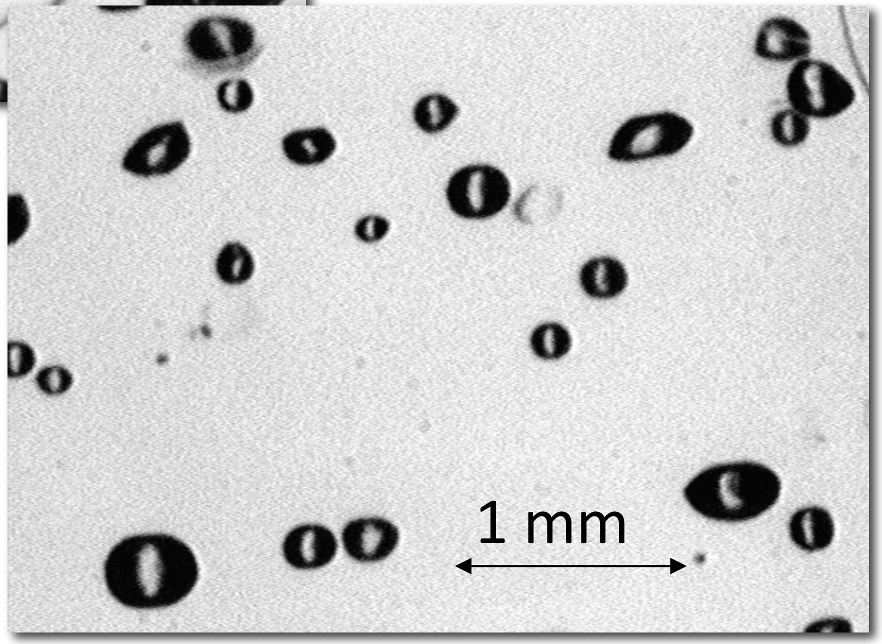



Hans Oerter, 2001
with modifications

# entrapped air bubbles in the ice

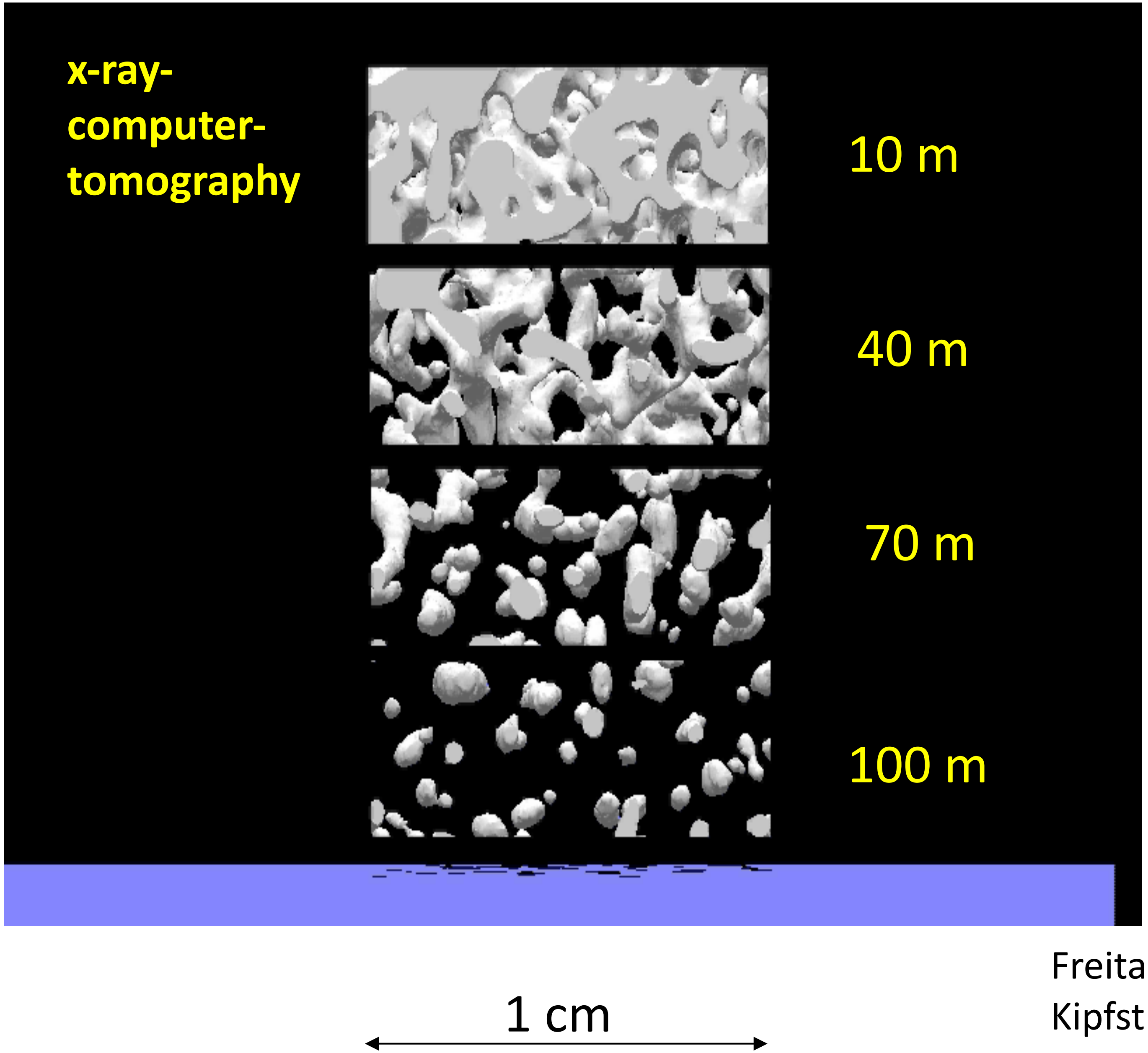


150 m



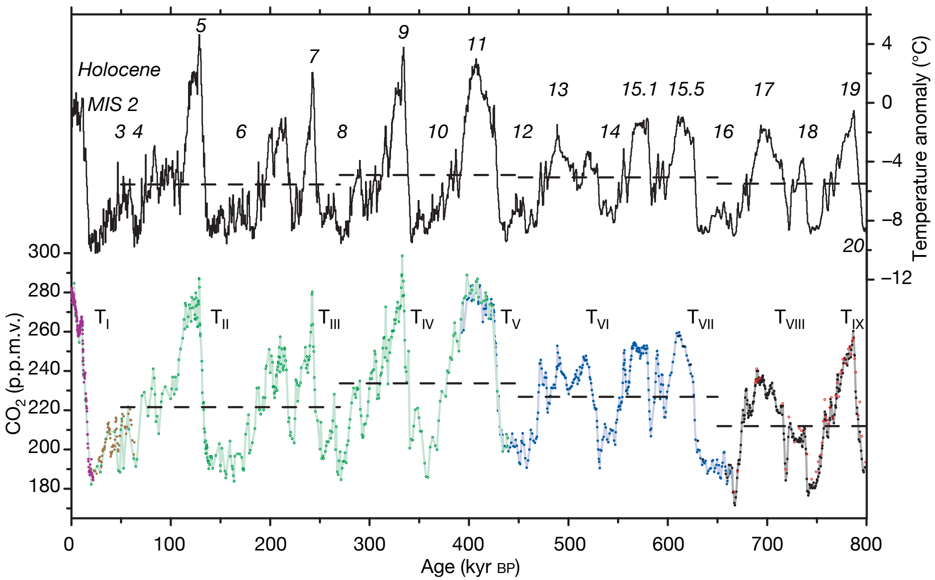

300 m

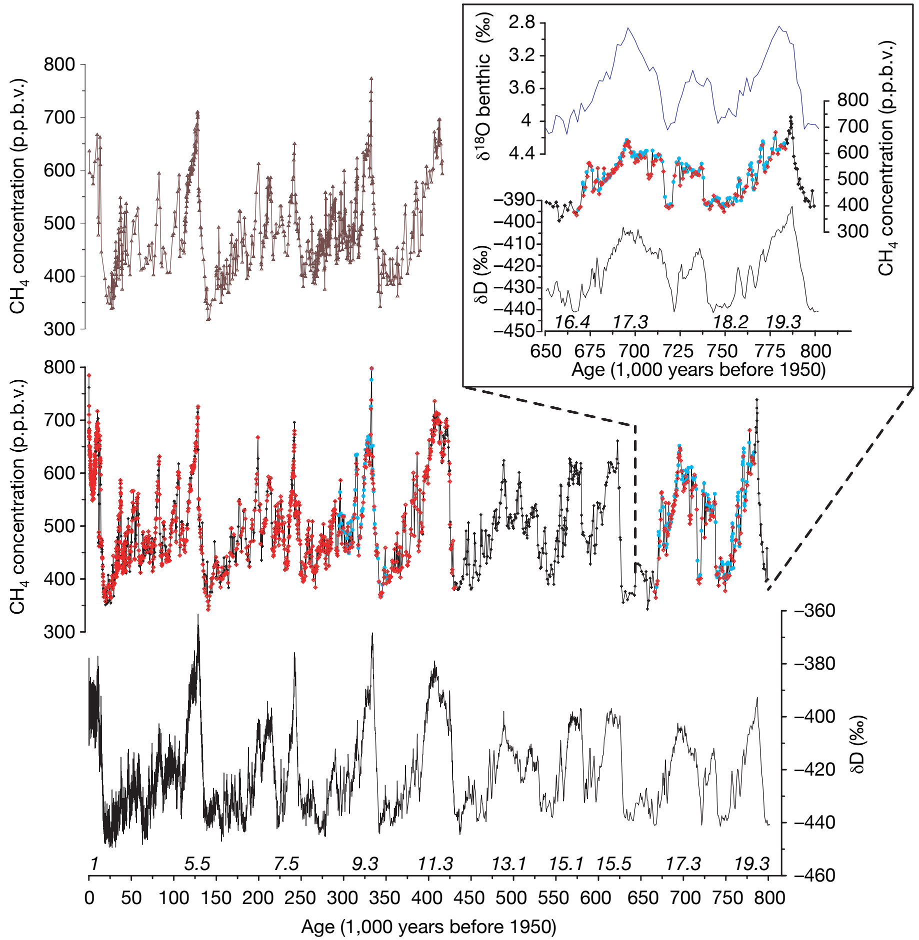
# the entrapment of air in the firn




Freitag, Wilhelms,
Kipfstuhl, JGlaciol, 2004

# Ice Cores are an archive of the past atmosphere



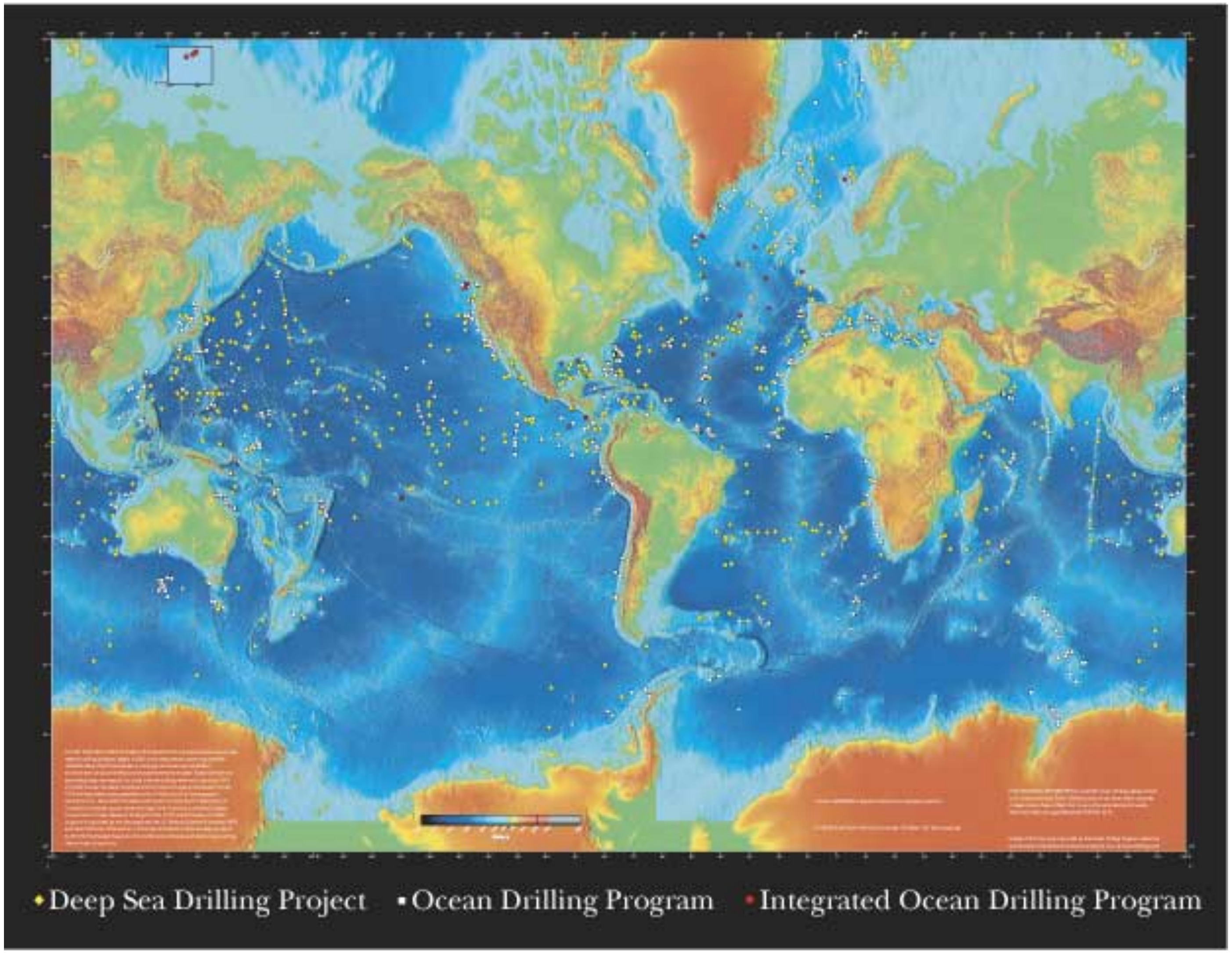



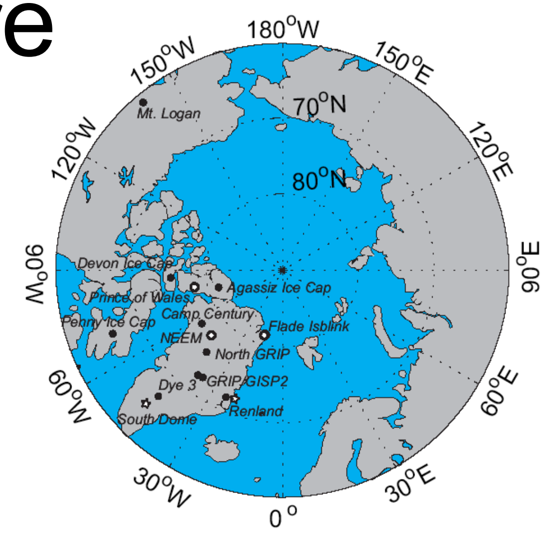

Lüthi et al., Nature, 2008

Loulerge et al., Nature, 2008

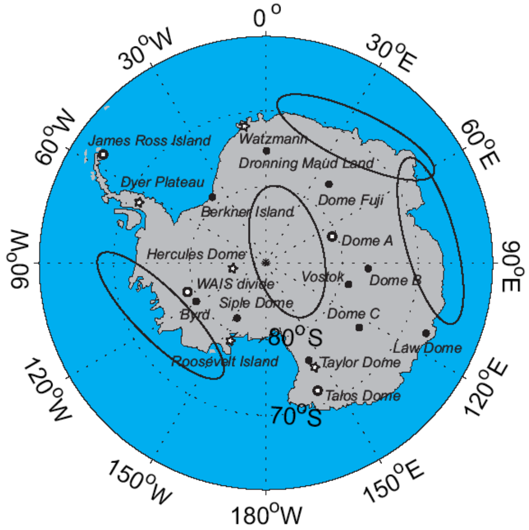
# Major sources of information on past ocean and atmosphere

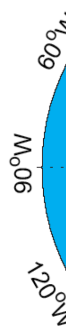
MARINE SEDIMENT CORES



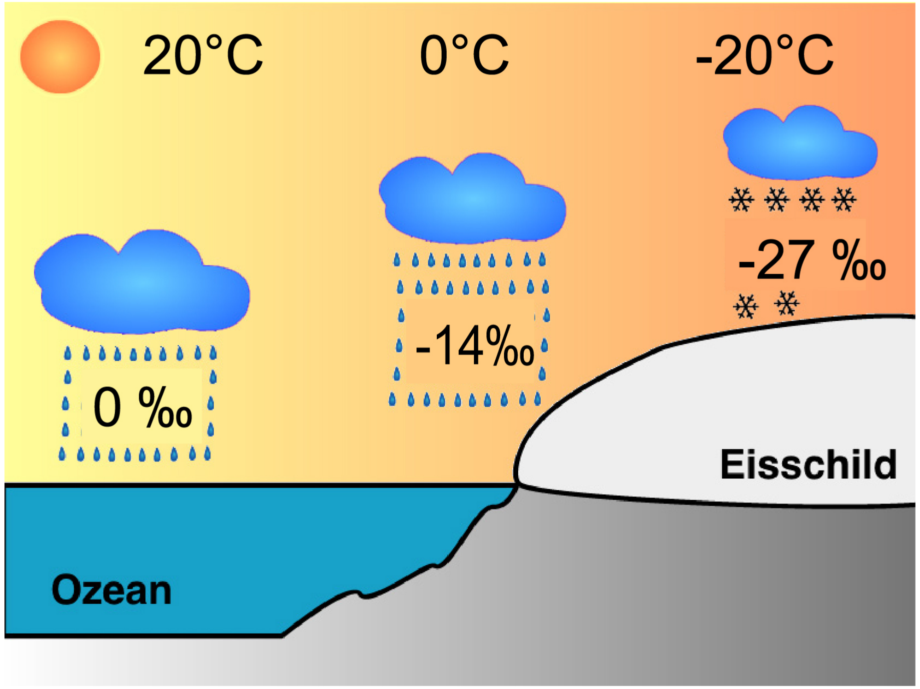




ICECORES

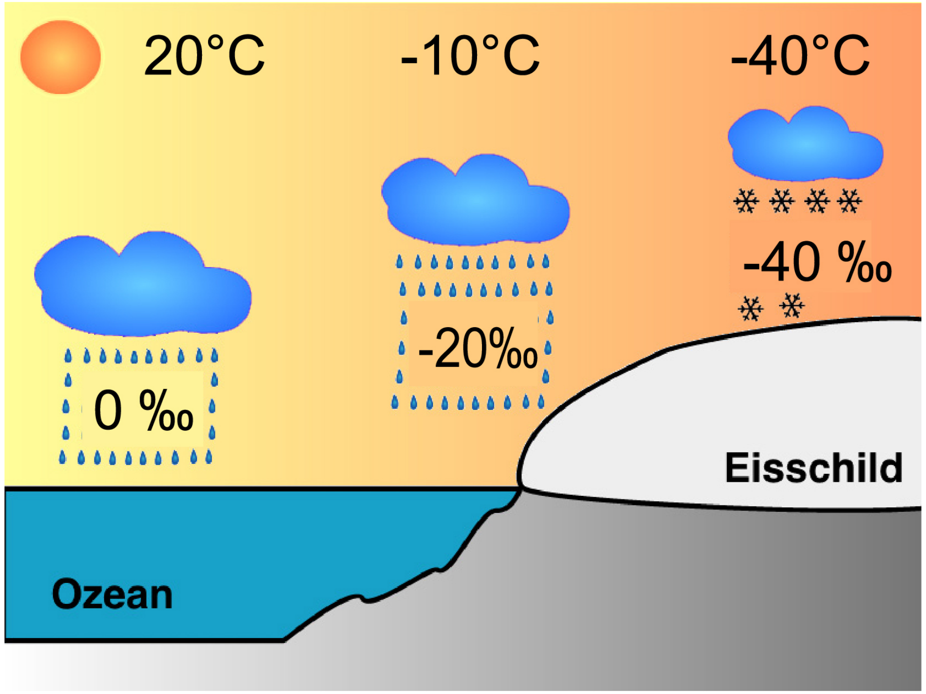


# Temperature archive: The isotope thermometer




summer



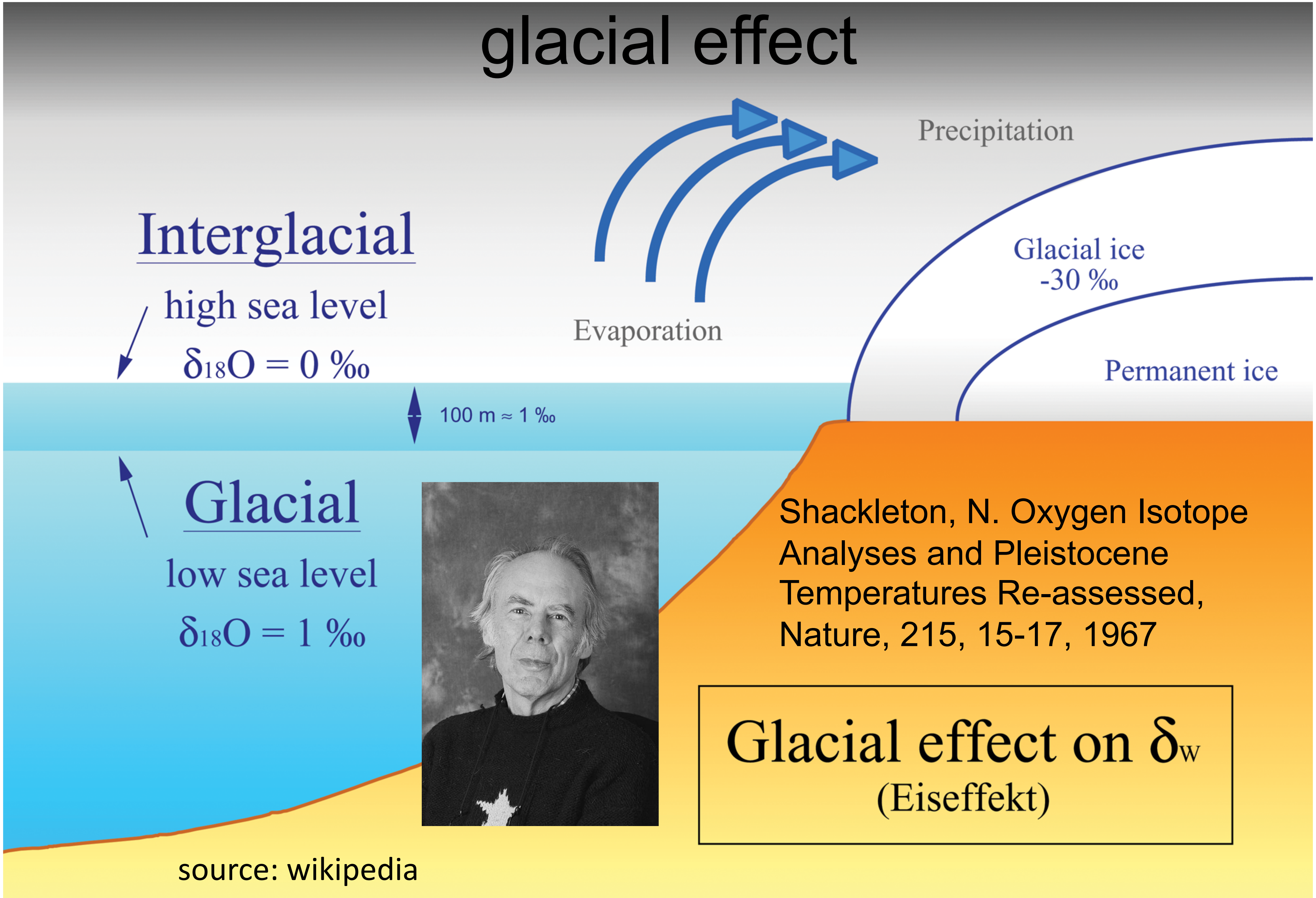

winter

after Stauffer, 2001

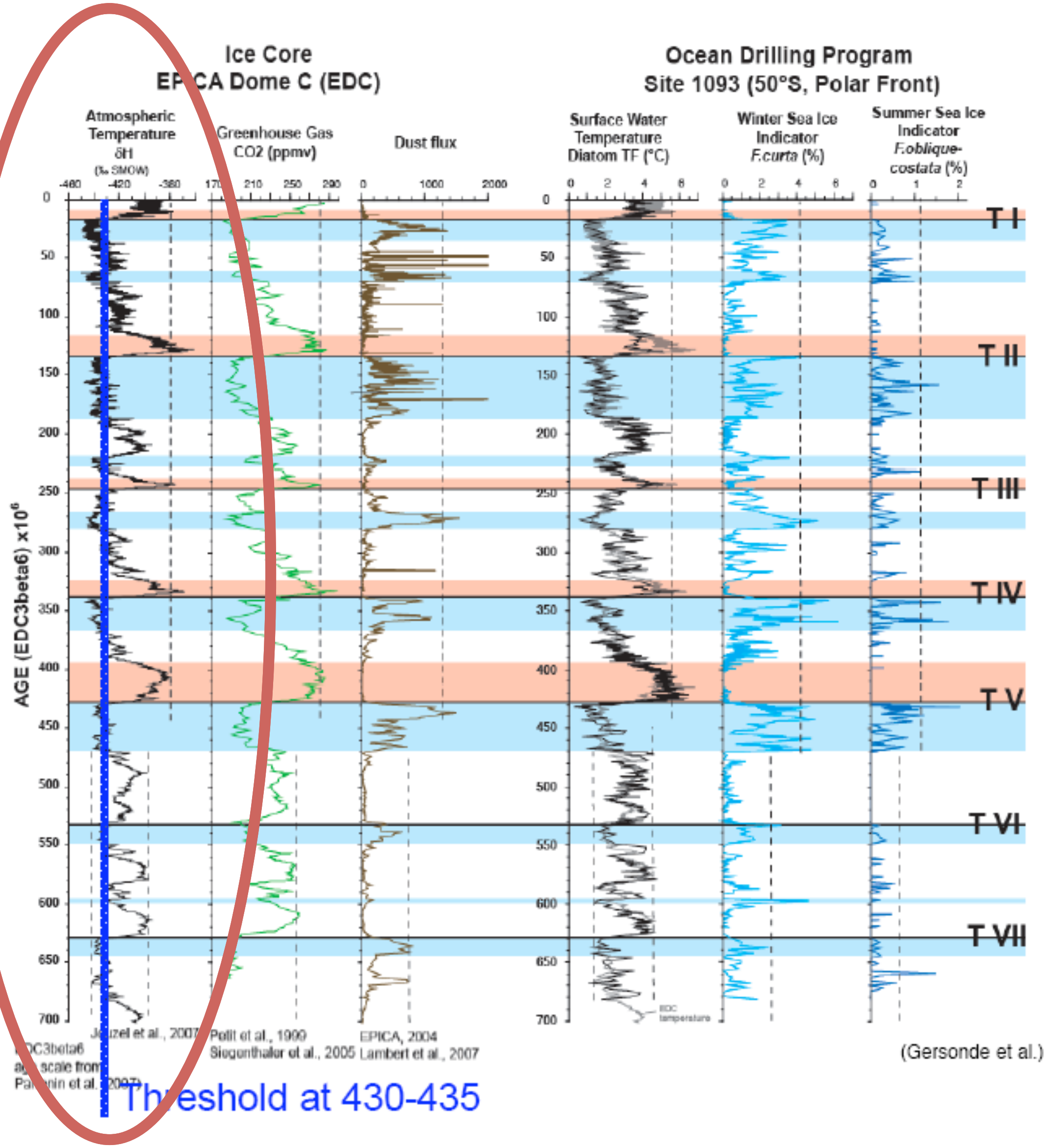
Fractionation of water isotopes during phase changes

Willi Dansgaard, The O18-abundance in fresh water, Geochim. et Cosmochim. Acta 6, 1954

# Ice sheets' sibling: The ocean The glacial effect



# EPICA-MIS: synchronization of ice and marine sediment records




SST - sea ice - dust (Fe) - $CO_2$ relationship

# Dating of ice cores

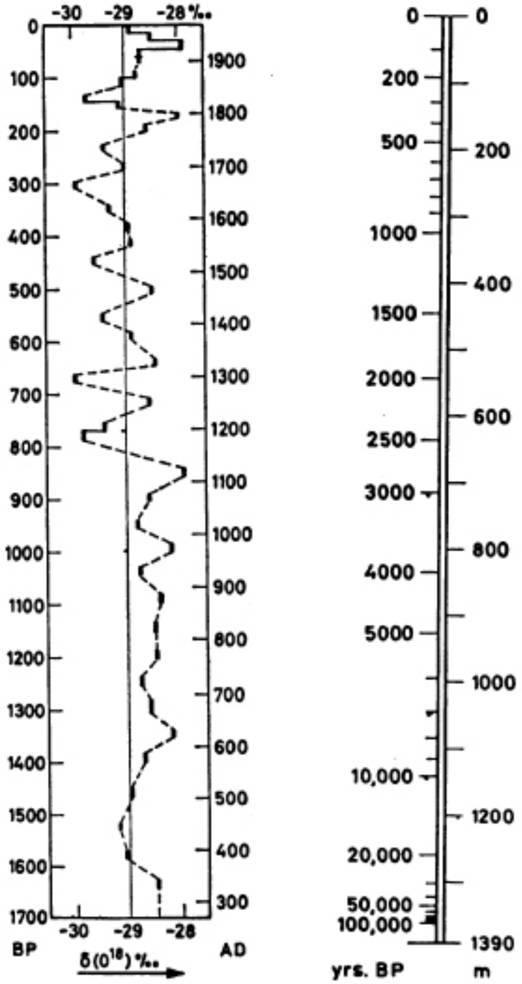



Fig. 2 (left). A depth-age nomograph for the 1390 m long Camp Century ice core. Fig. 3 (right). Variations in $\delta(O^{18})$ in the upper 470 m of the Camp Century ice core plotted against the calculated age of the ice. The lengths of the small vertical lines correspond to the number of years of accumulation represented and calculated as $-L/V_y$, $L$ being the length of the core section. A 120-year climatic cycle is observed.

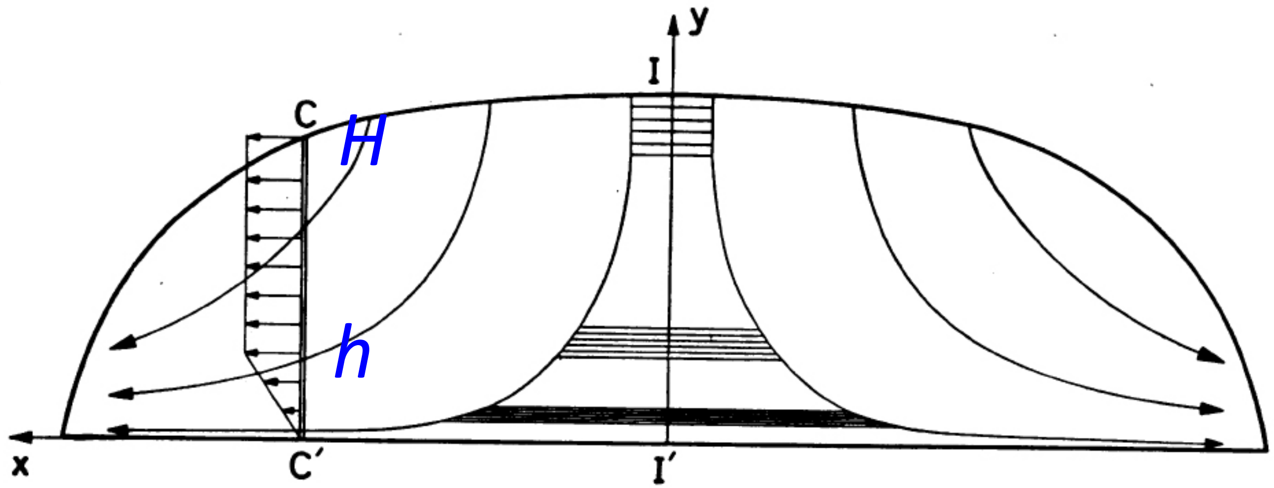



Fig. 1. Vertical cross section of an ice sheet resting upon a horizontal subsurface. Ice particles deposited upon the snow surface will follow lines that travel closer to the base the farther inland the site of deposition. An ice mass formed around the divide (*I–I′*) will be plastically deformed (thinned) with depth as suggested by the lined areas [compare (*35*)]. The horizontal arrows along the vertical ice core (*C–C′*) show the assumed profile of horizontal velocity component, $V_x$.

Dansgaard-Johnsen model: vertical speed w:

$$\frac{dw}{dy} = -rh \qquad ; h \le y \le H$$

$$\frac{dw}{dy} = -rz \qquad ; 0 \le y \le h$$

Dansgaard, Johnsen, Møller, Langway, Science, 1969

# solving the Dansgaard-Johnsen model

- integration of with constant rate thinning rate r

$$\frac{dw}{dy} = -rh \qquad ; h \le y \le H$$

$$\frac{dw}{dy} = -rz \qquad ; 0 \le y \le h$$

- yields for w:

$$w(y) = -\frac{r}{2}y^2 \qquad ; \; 0 \le y \le h$$

$$w(y) = -\frac{rh}{2}(2y - h) \qquad ; \; h \le y \le H$$

- and constant accumulation at surface *w(H)=-A* yields

$$r = \frac{2A}{h(2H - h)}$$

- time is the integral of inverse speed by height above bedrock

$$\mathrm{t}(y) = \int_H^y \frac{1}{w} dy$$

# Dansgaard-Johnson: depth-time relation

- just solving the integral yields

$$t(y) = \frac{2H-h}{2A} \ln \frac{2H-h}{2y-h} \qquad ; 0 \leq y \leq h$$

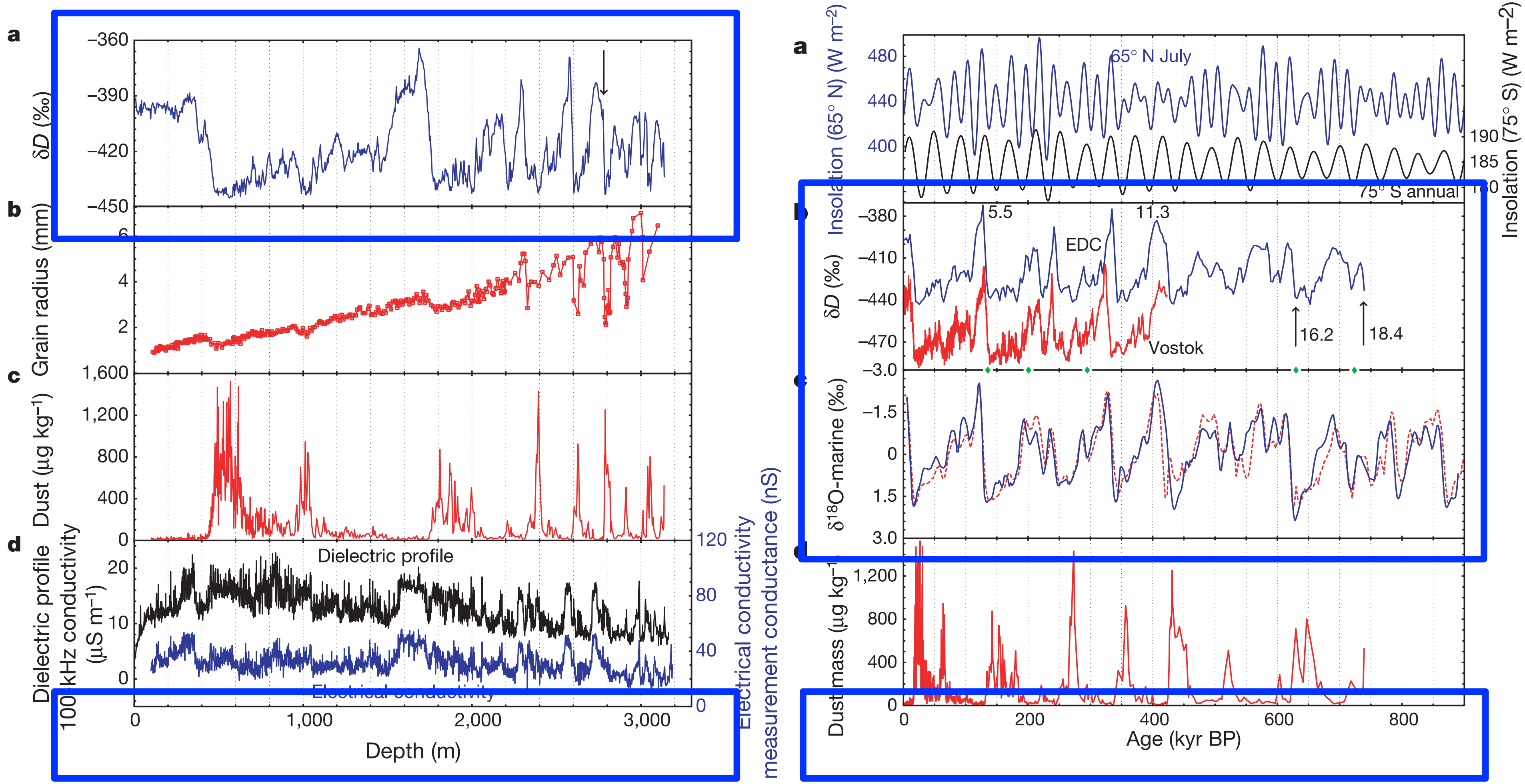
$$t(y) = \frac{2H-h}{2A} \ln \frac{2H-h}{h} + \frac{2H-h}{A}\left(\frac{h}{y}-1\right) \qquad ; h \leq y \leq H$$

- logarithmic age-depth relation within h above bed

  and an

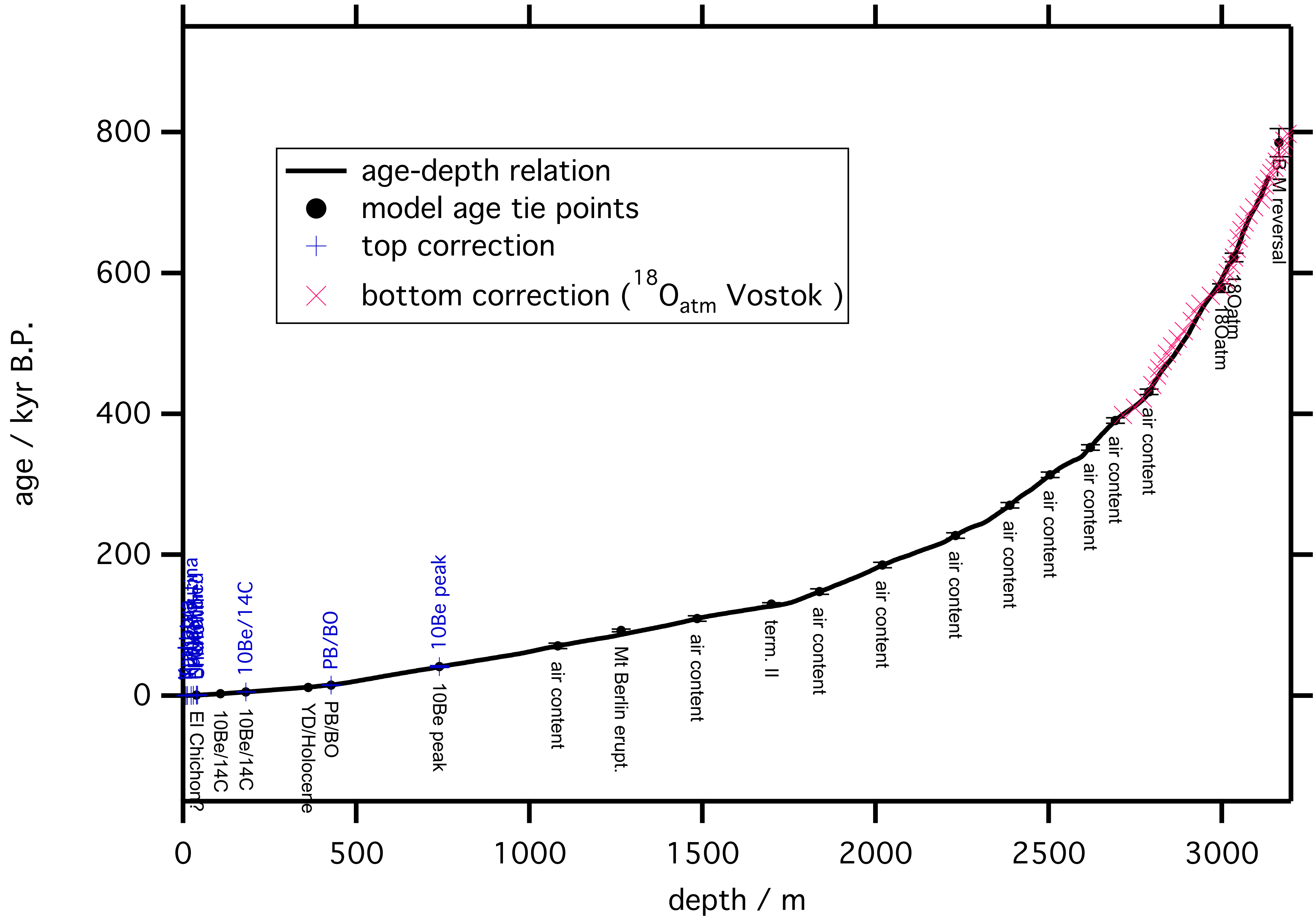
- inverse age-depth relation above h
- influenced by: accumulation, ice thickness, flow

# The depth scale in the data sets

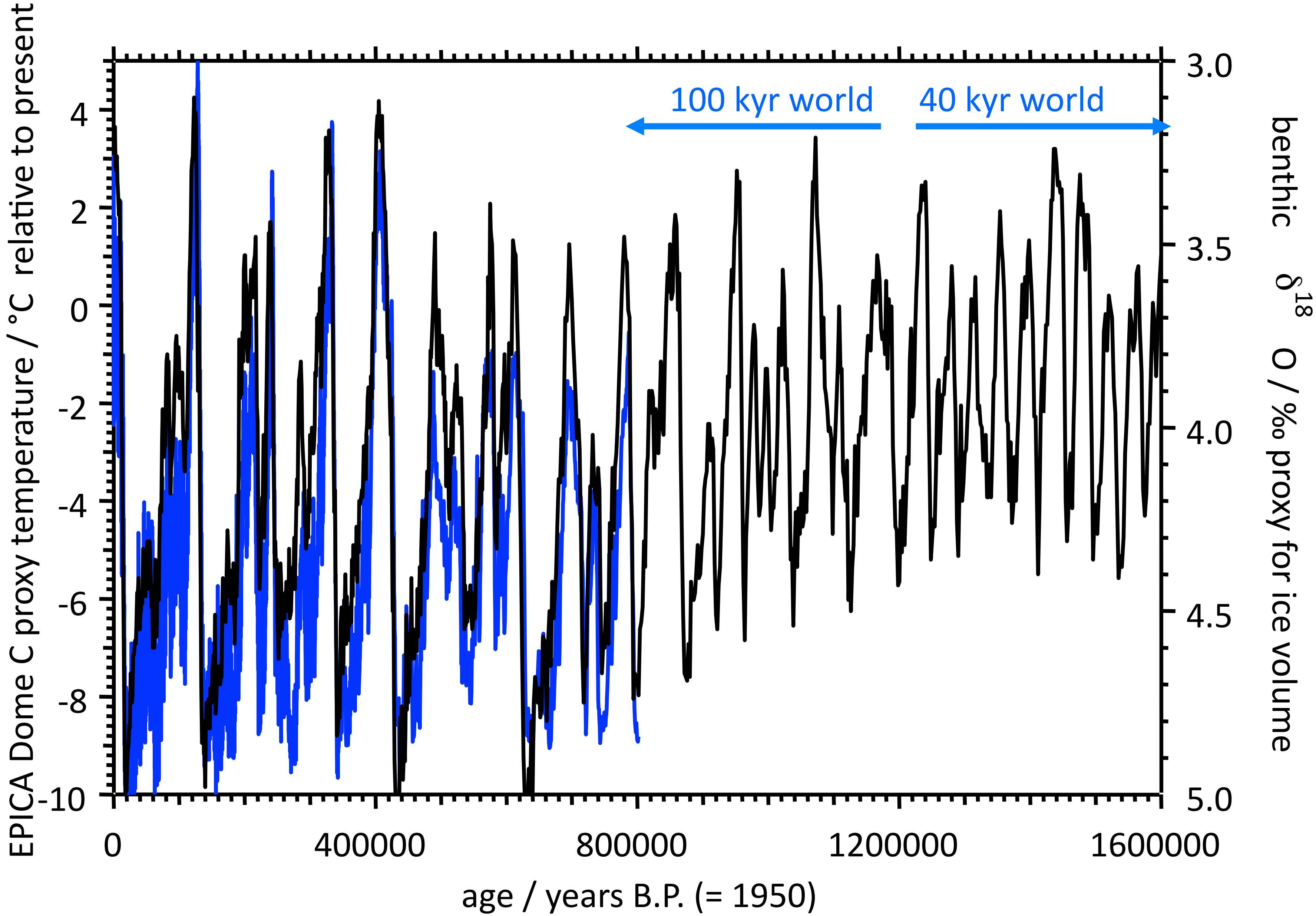



EPICA Community Members, Nature 2004

# EDC3 age-depth relation



# What to expect even earlier?




Jouzel et al. (2007)

Lisiecki & Raymo (2005)

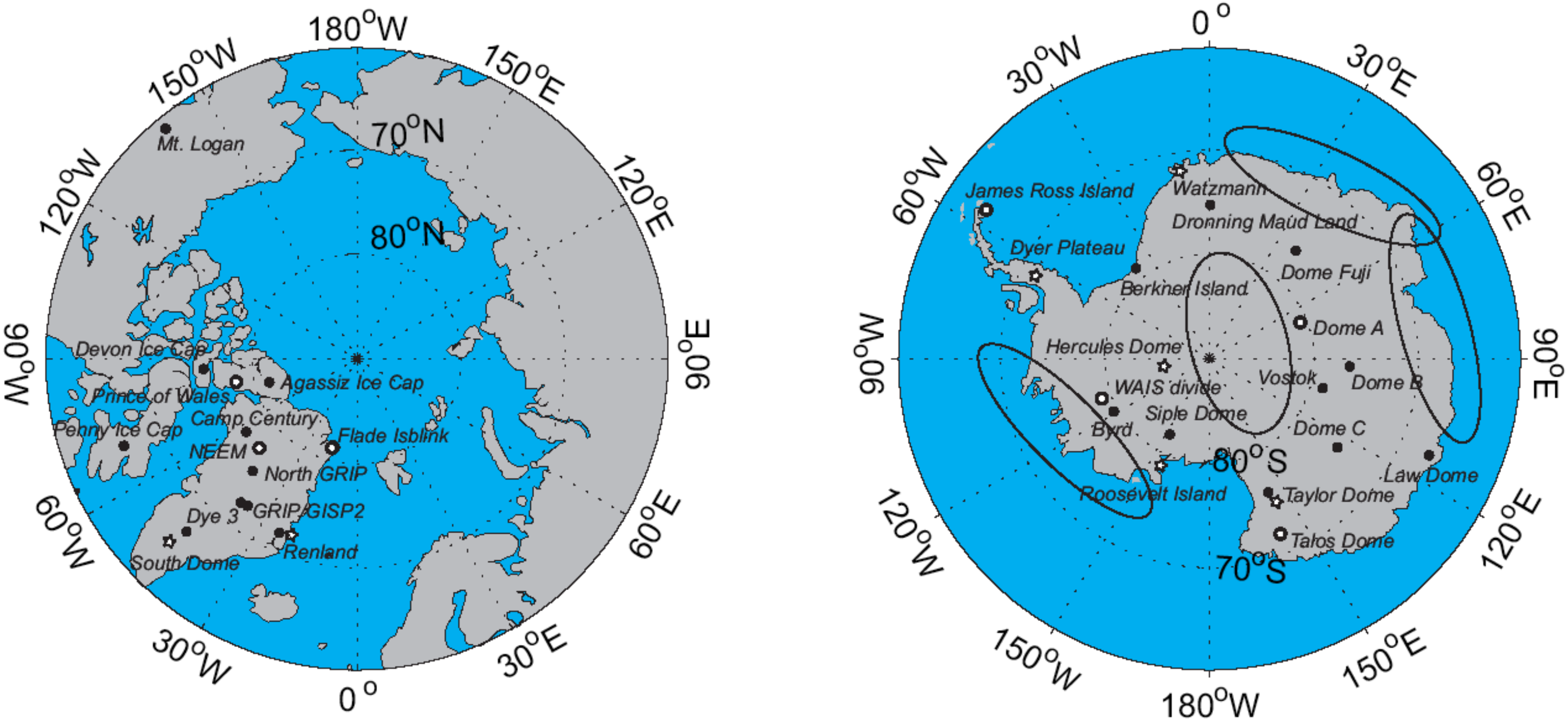
# The scientific goals - IPICS


1. The oldest ice core: A 1.5 million year record of climate and greenhouse gases from Antarctica (a time period where Earth's climate shifted from 40,000 year to 100,000 year cycles).
2. The last interglacial and beyond: A northwest Greenland deep ice core drilling project (a deep ice core in Greenland recovering an intact record of the last interglacial period).
3. The IPICS 40,000 year network: A bipolar record of climate forcing and response.
5. The IPICS 2k Array: A network of ice core climate and climate forcing records for the last two millennia

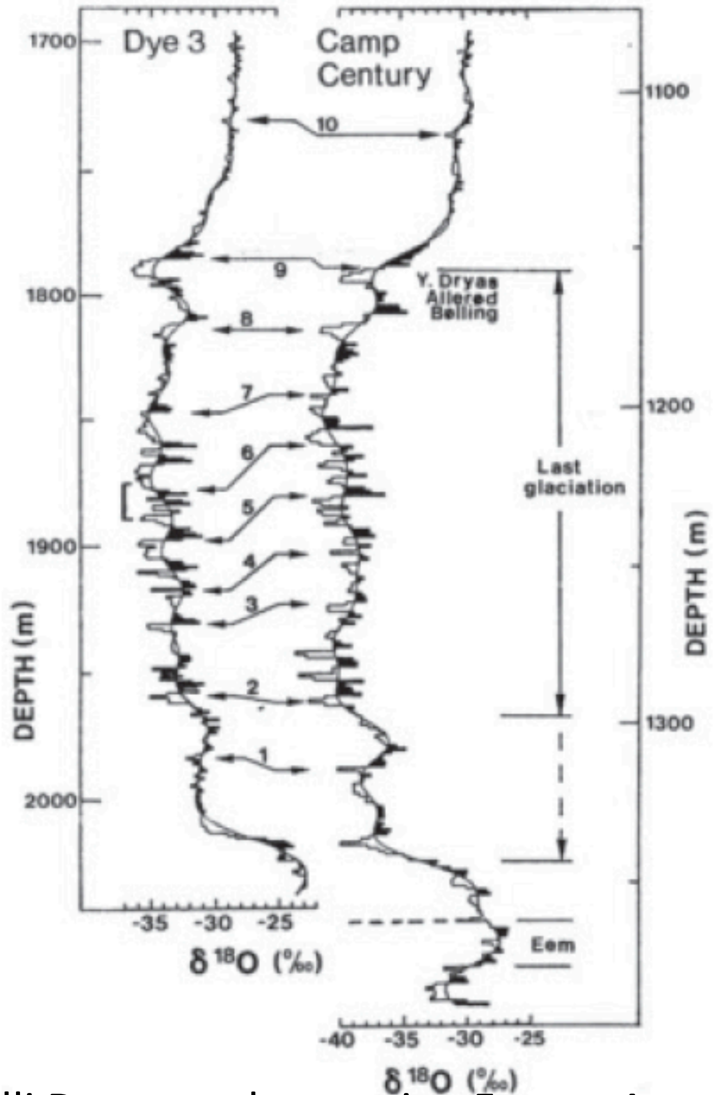
A fifth, and critical, element of IPICS is the development of advanced ice core drilling technology. A technical white paper, entitled "Ice Core Drilling Technical Challenges" addresses this.

www.pages.unibe.ch/science/initiatives/ipics

Non exclusive list, more will follow if promoted by science, e.g. biodiversity in ice cores, sub-glacial lakes, ice dynamics, etc.


180°W
150°W
150°E
70°N
80°N
120°W
120°E
90°W
90°E
60°W
60°E
30°W
30°E
0°
Mt. Logan
Devon Ice Cap
Agassiz Ice Cap
Prince of Wales
Penny Ice Cap
Camp Century
Flade Isblink
NEEM
North GRIP
GRIP GISP2
Dye 3
Renland
South Dome
0°
30°W
30°E
60°W
60°E
90°W
90°E
120°W
120°E
150°W
150°E
180°W
80°S
70°S
Watzmann
James Ross Island
Dronning Maud Land
Dyer Plateau
Dome Fuji
Berkner Island
Dome A
Hercules Dome
Vostok
Dome B
WAIS divide
Siple Dome
Byrd
Dome C
Law Dome
Roosevelt Island
Taylor Dome
Talos Dome

# The Greenland story





Willi Dansgaard memoirs: Frozen Annals http://www.iceandclimate.nbi.ku.dk/publications/frozen_annals/

# GRIP

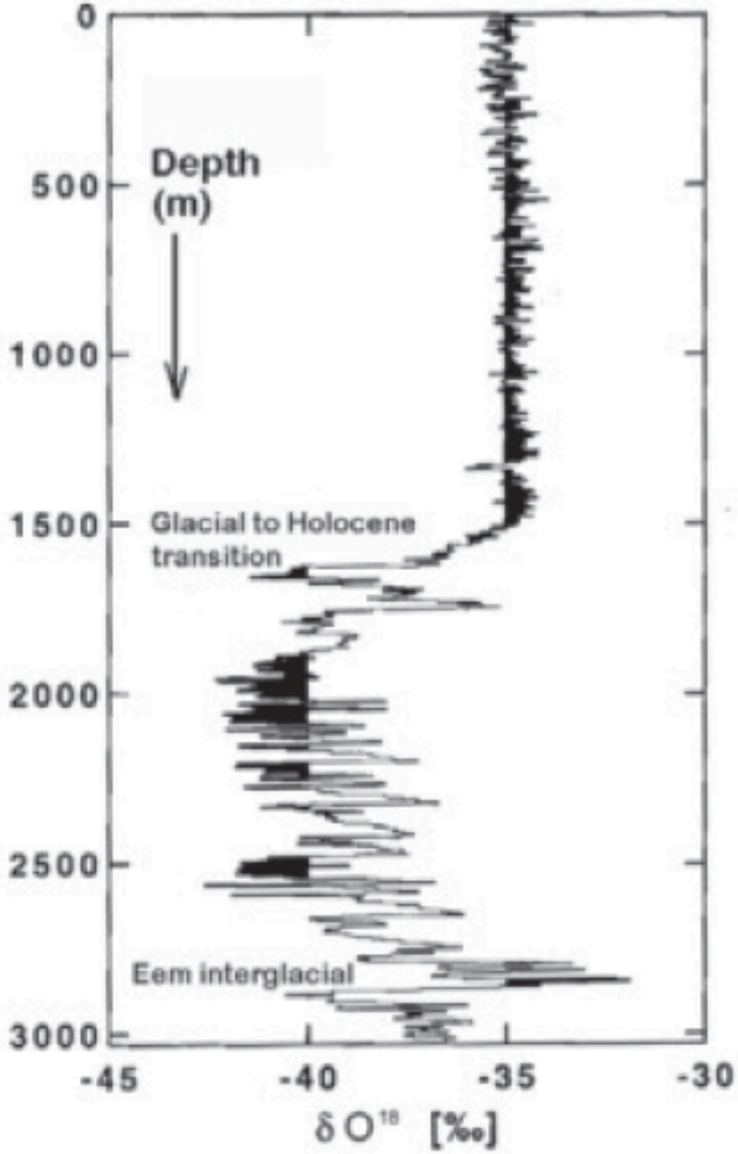



**Fig. 13.1.** *δ-profile along the GRIP ice core core. The wildly oscillating record from 1500 to c.2750 m depth reflects the turbulent glacial climate.*

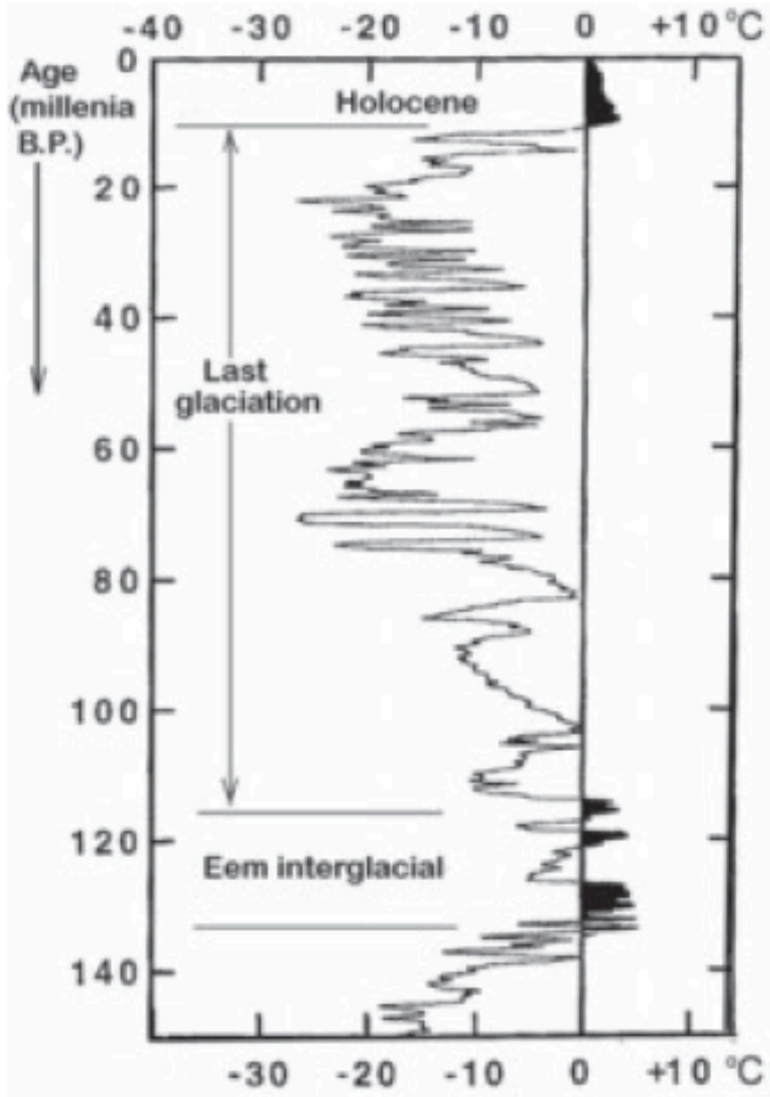



**Fig. 13.2.** *Calculated Greenland temperature deviations from present values through the last 150,000 years.*

# GRIP – GISP2

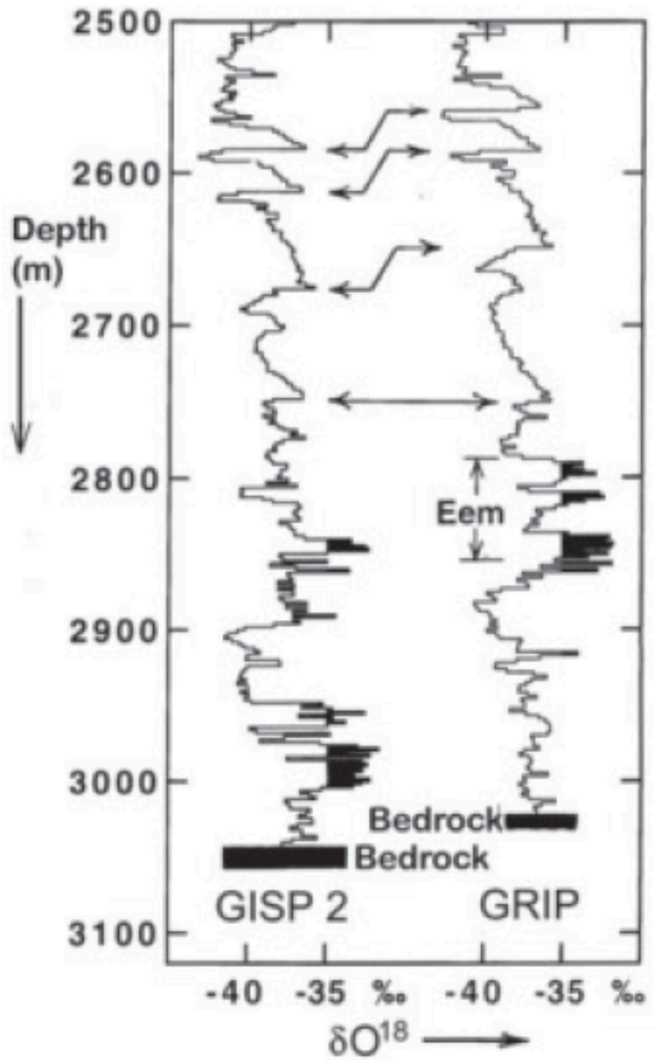
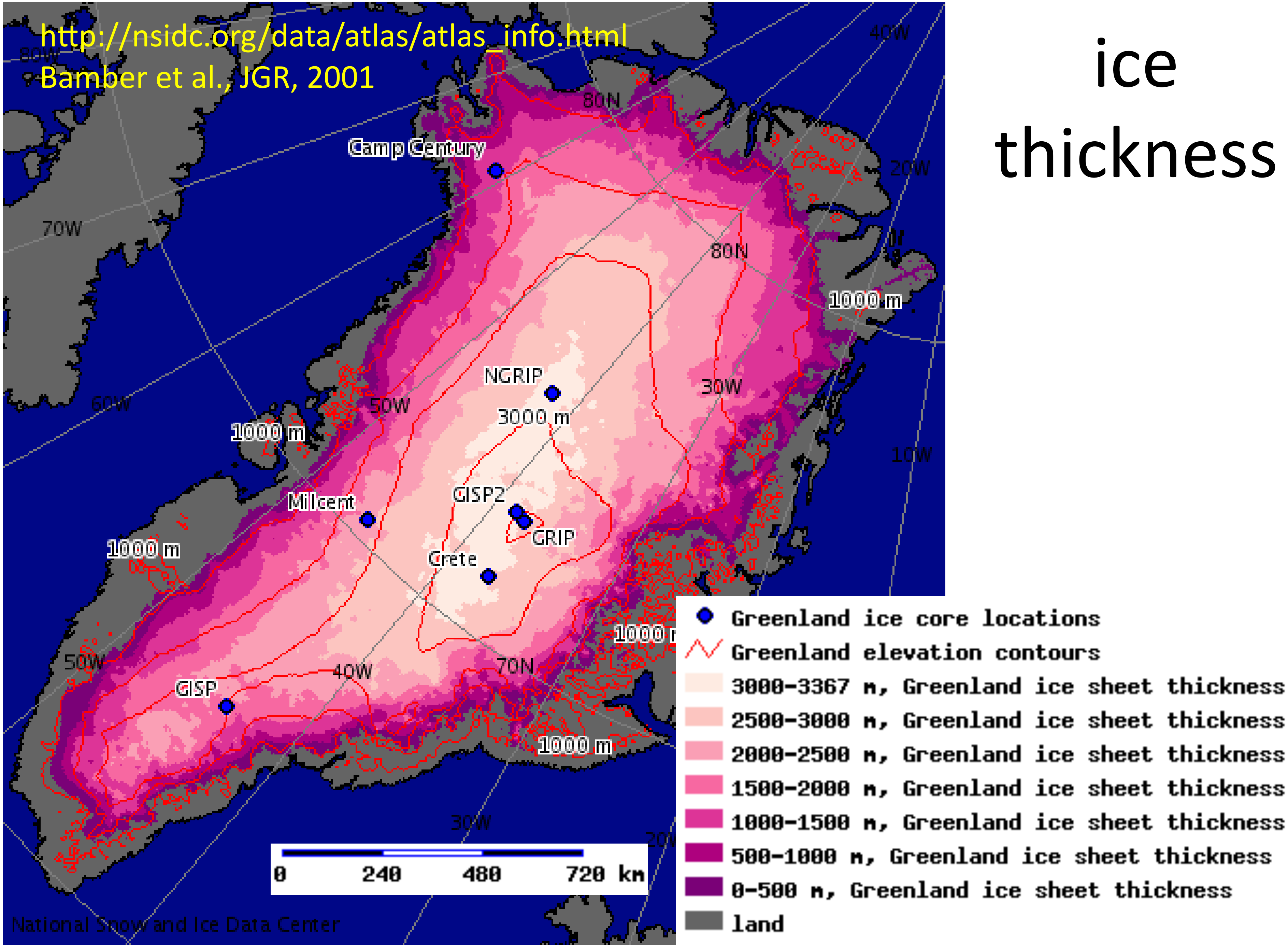


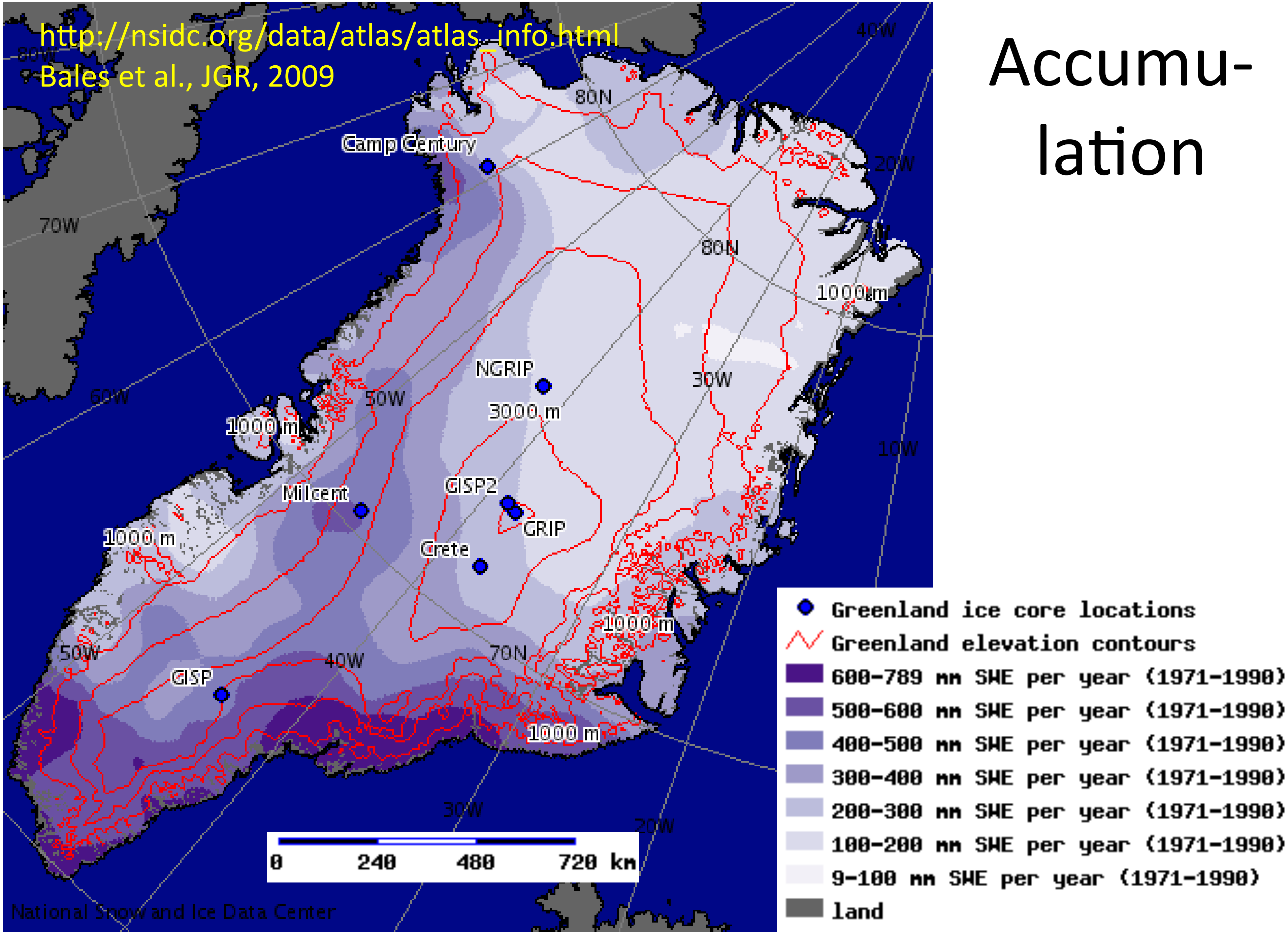

**Fig. 13.4** *δ profiles along the deepest parts of the GRIP ice core (to the right) and the American GISP2 core (to the left). Down to a depth of 2750 m the two profiles are essentially identical, but they are different in ice from the Eem period. The layer sequence is disturbed in the GISP2 core. Is this also the case for the GRIP core?*

Grootes et al., Nature 366, 1993

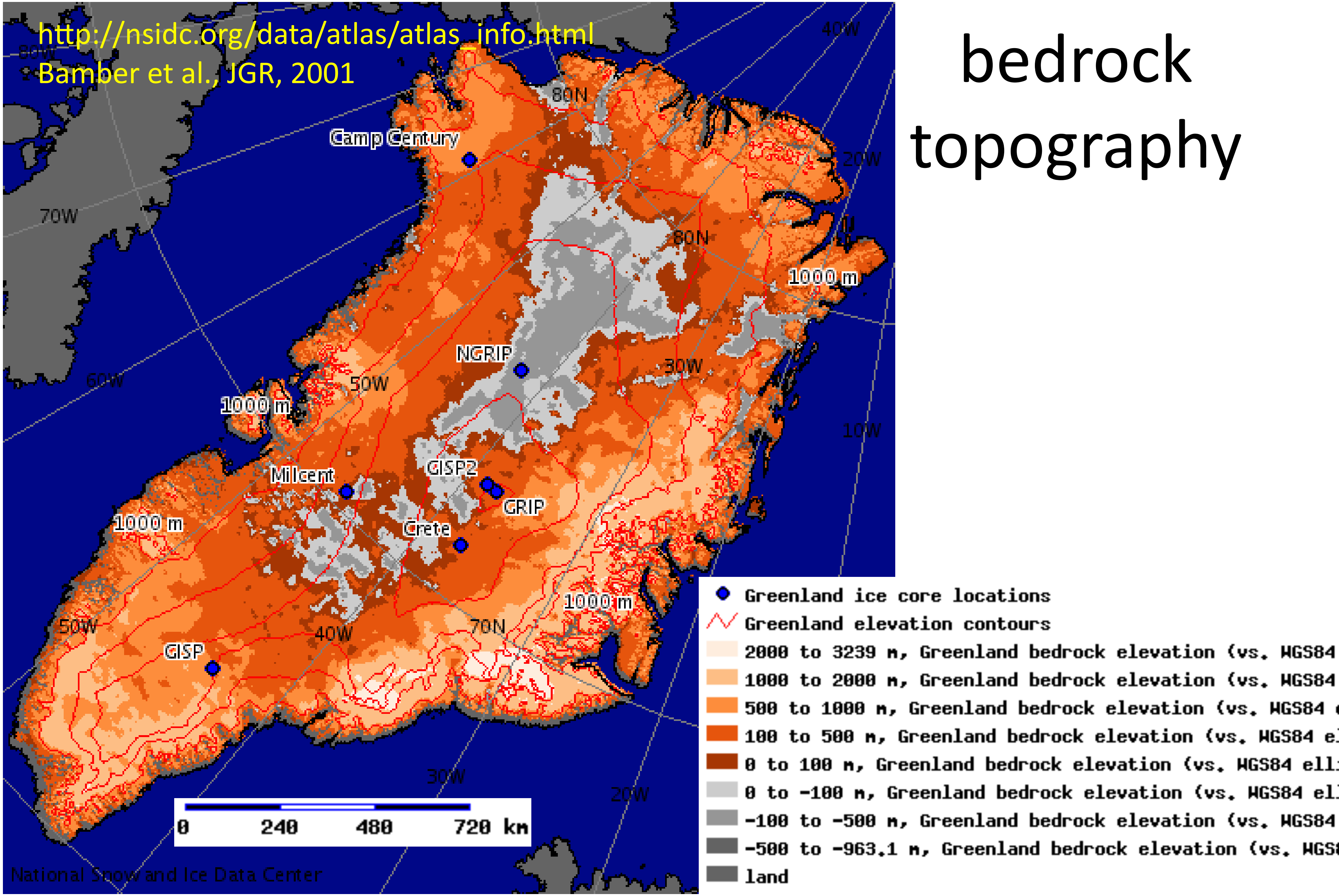
# ice thickness



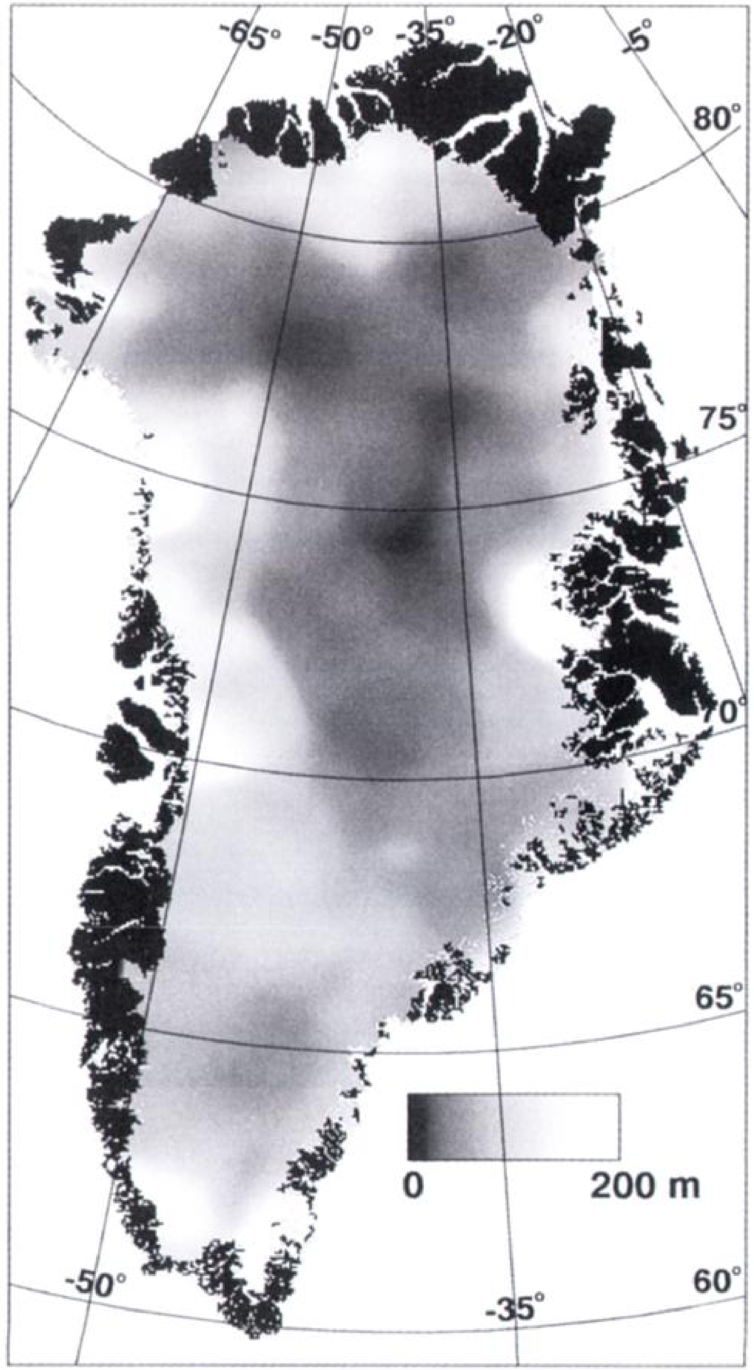
# Accumu-
lation



# bedrock topography

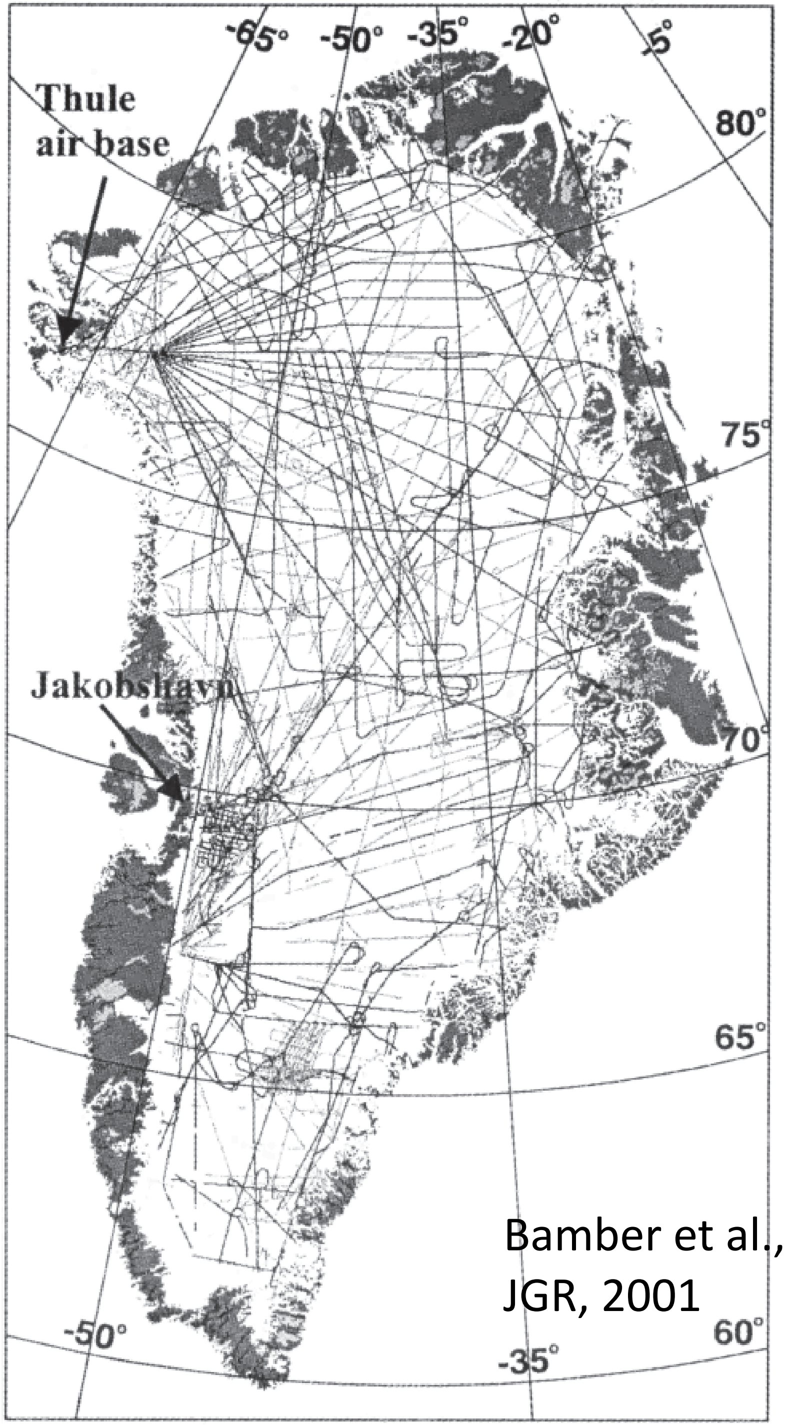


bedrock undulations at 20 x ice thickness

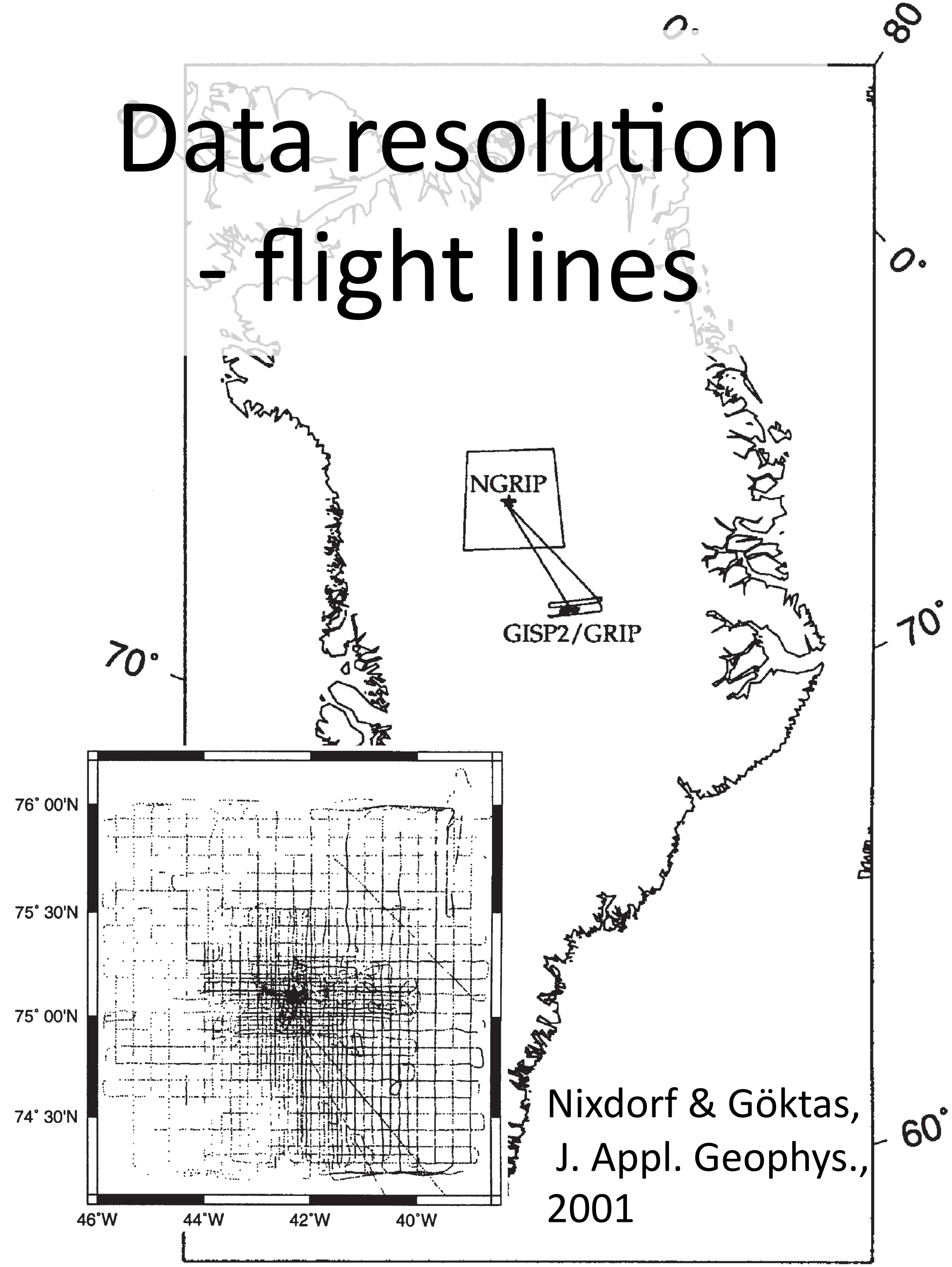



Layberry & Bamber, JGR, 2001

# Data resolution - flight lines

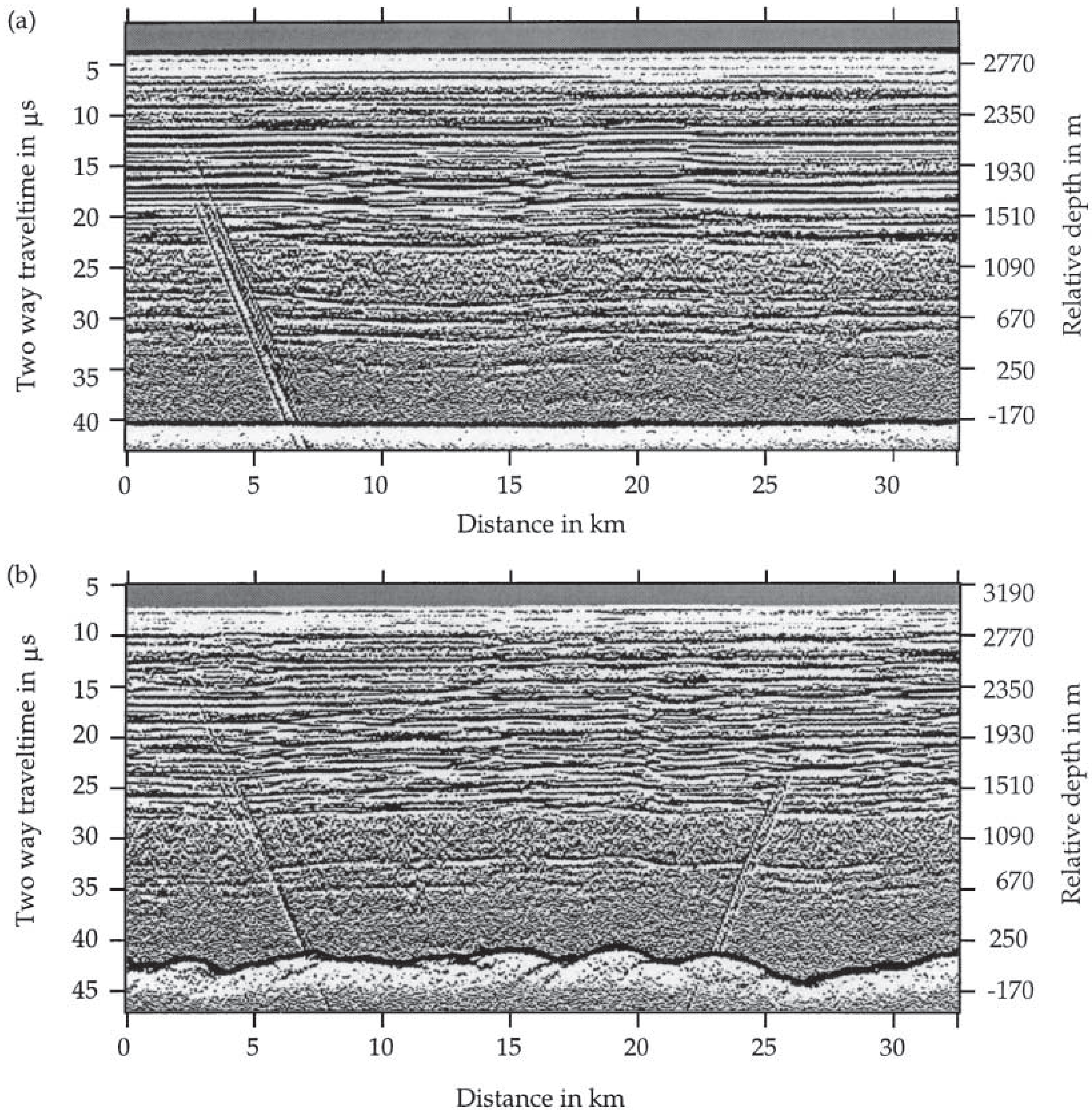


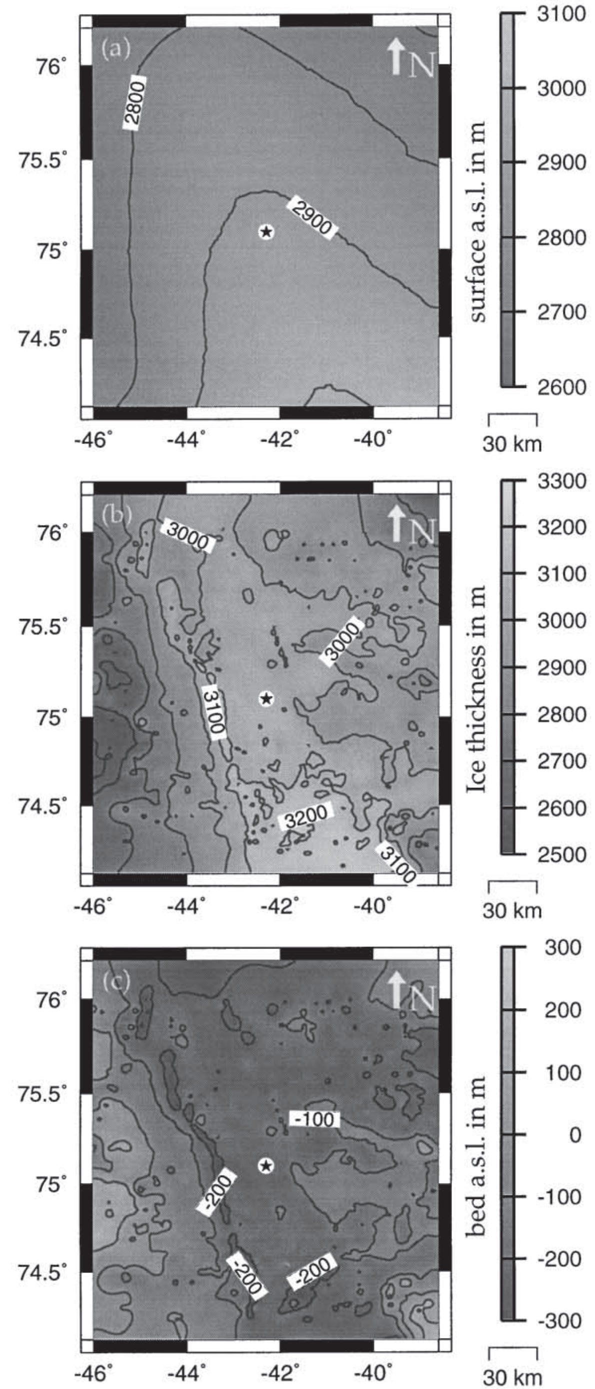

Bamber et al., JGR, 2001




Nixdorf & Göktas, J. Appl. Geophys., 2001

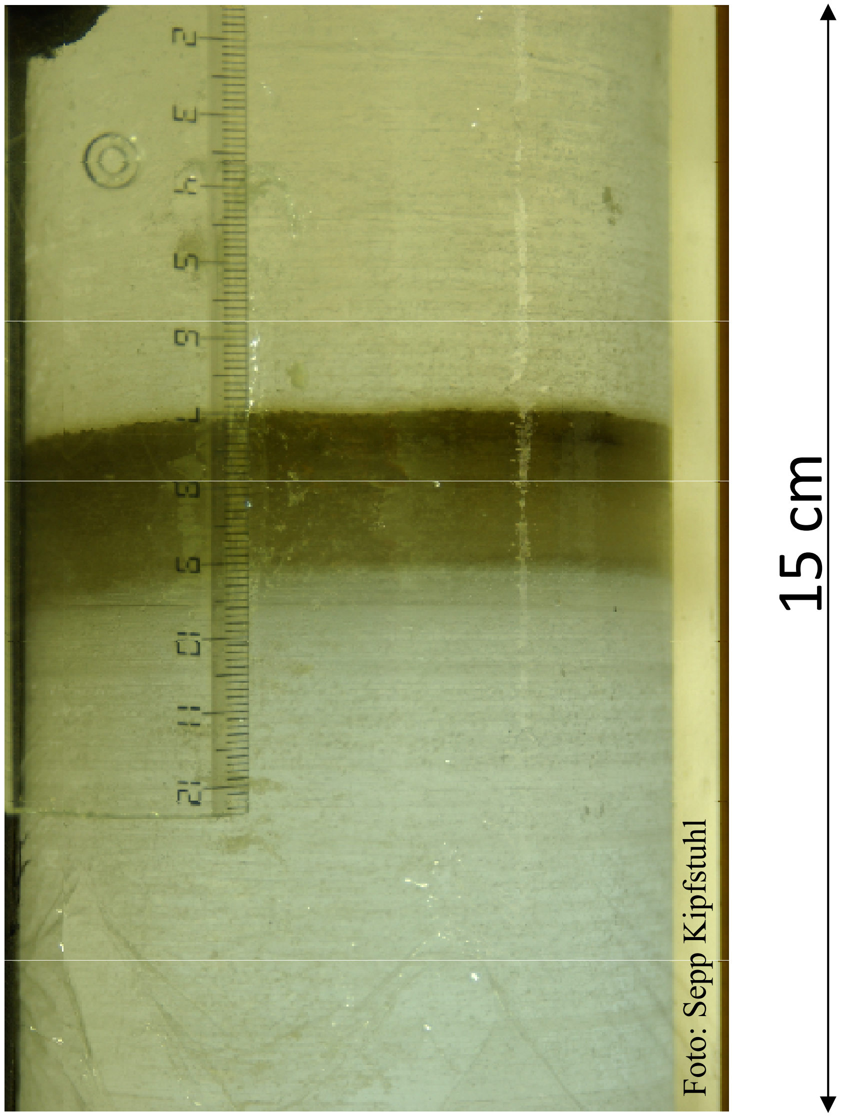
# Results of local studies




Nixdorf & Göktas, J. Appl. Geophys., 2001

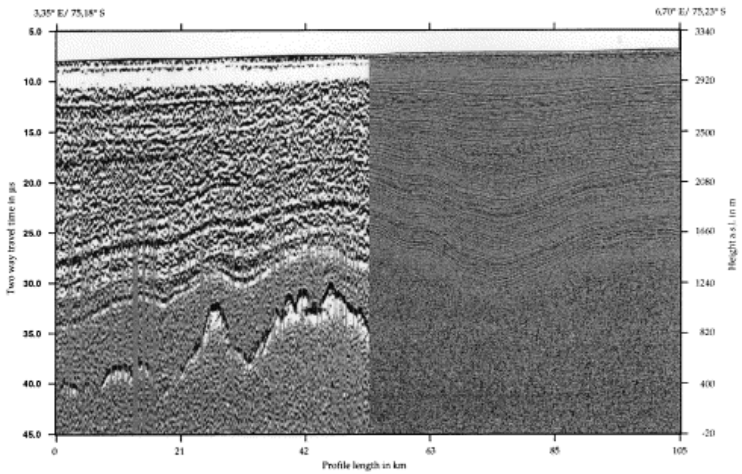
# volcanic horizons

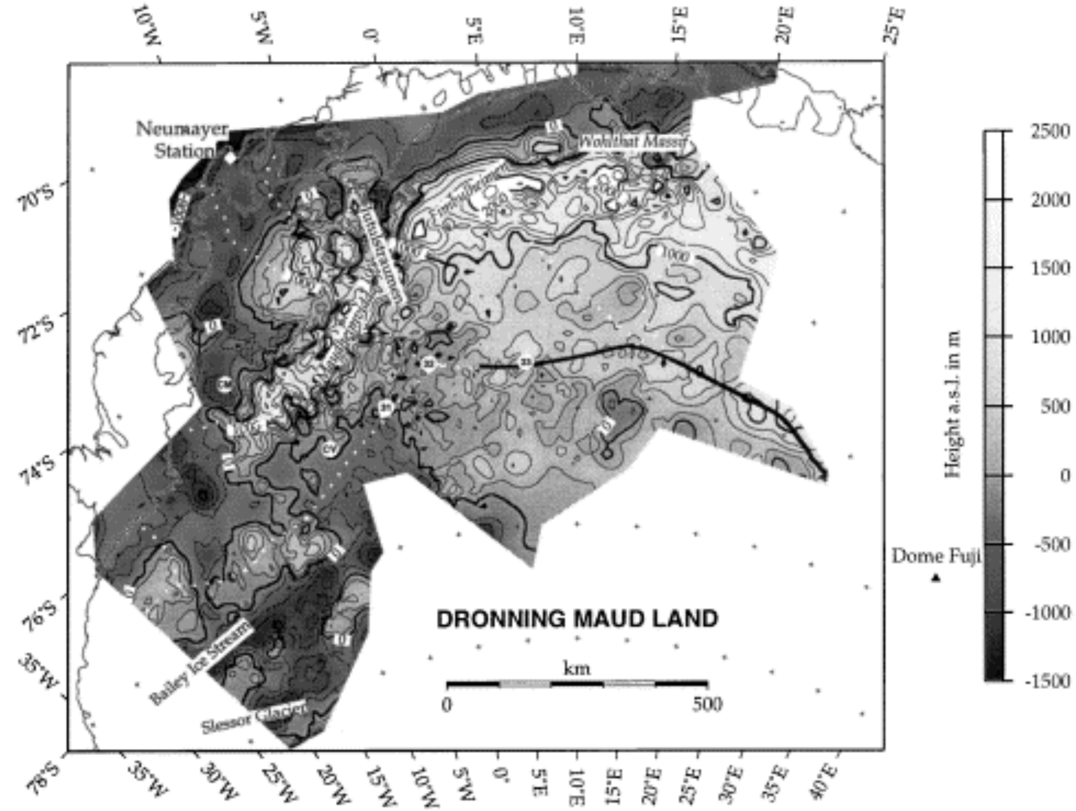



810 m depth (EDML)
(approx. 20 kyr BP)

# mapping the ice thickness and internal reflections

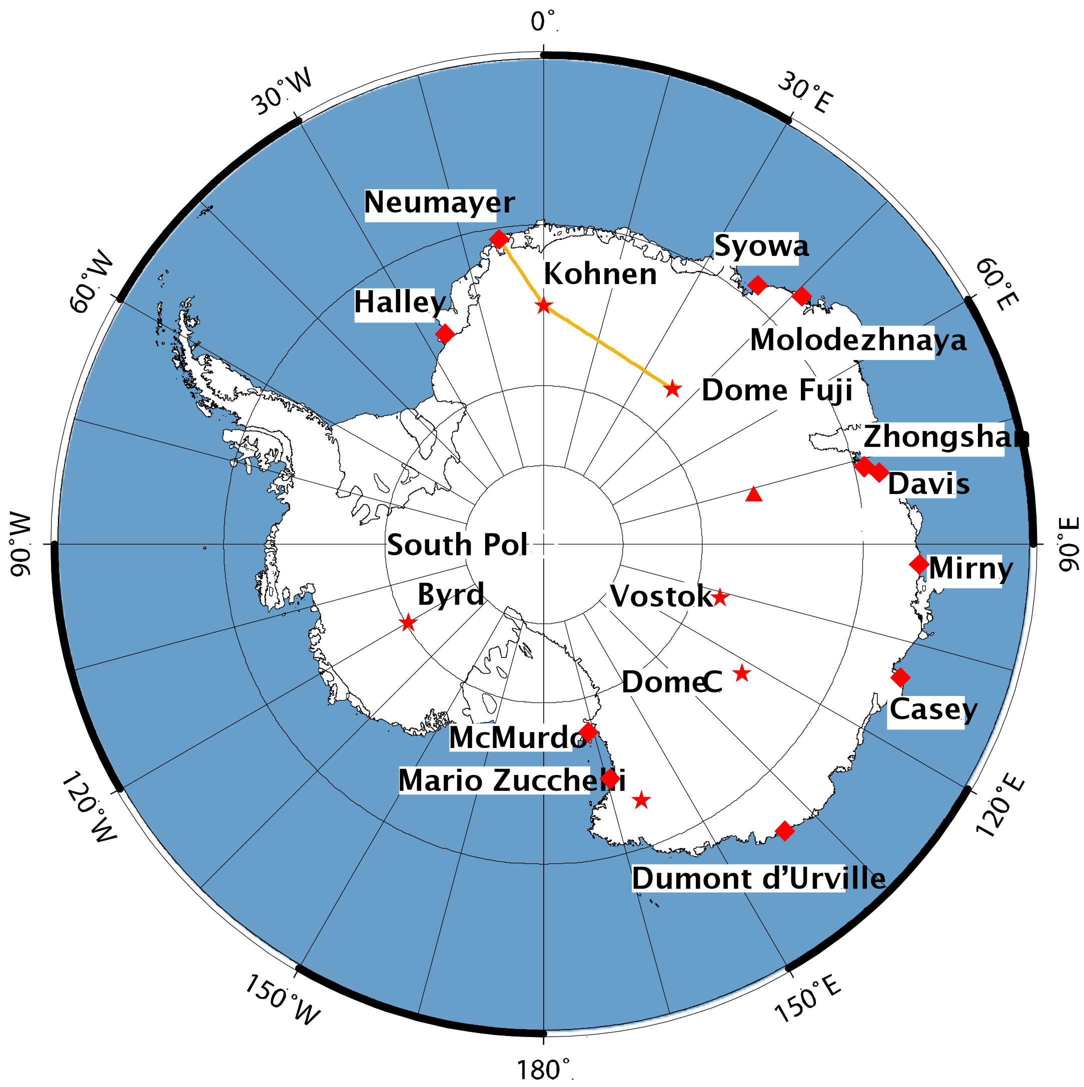

POLAR 2 (D-CAWI)

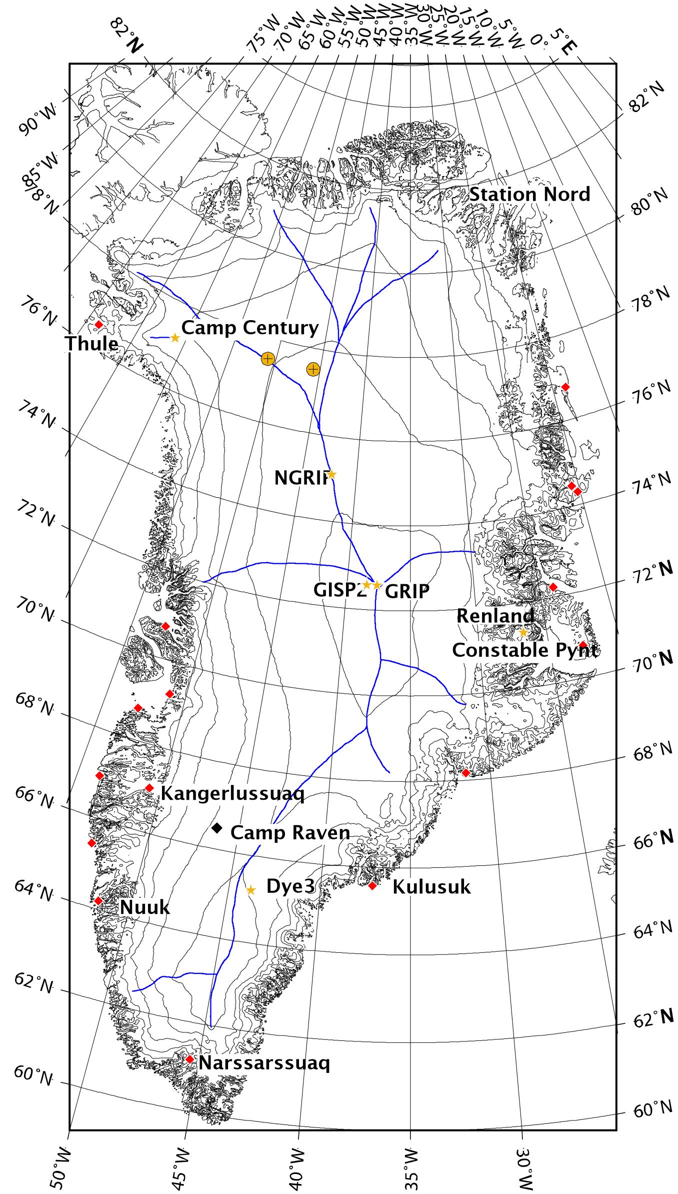



Steinhage *et.al., Journal of Applied Geophysics* 47 (3-4), pp. 183-189, 2001

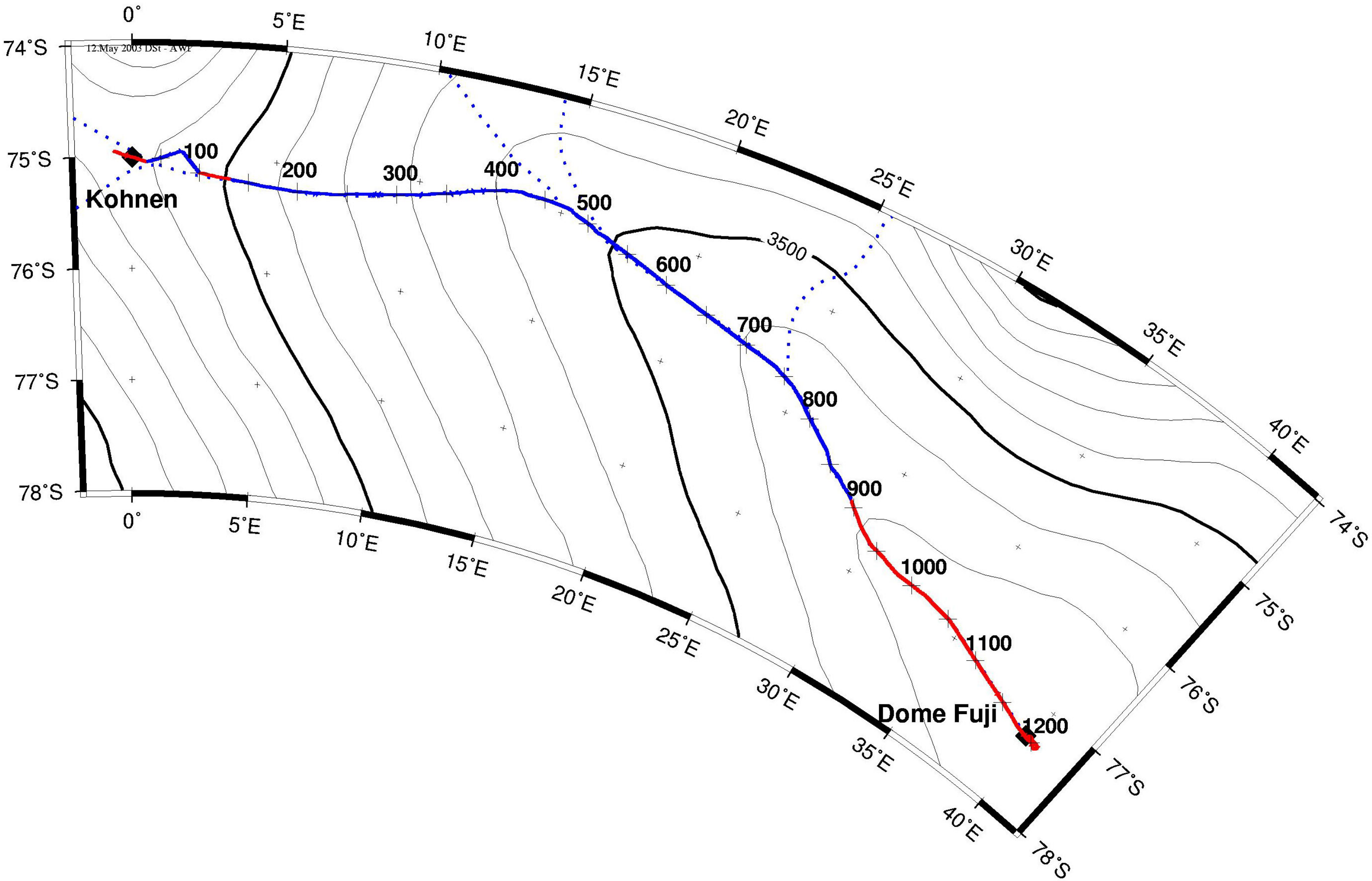
# Deep ice cores in Antarctica and Greenland



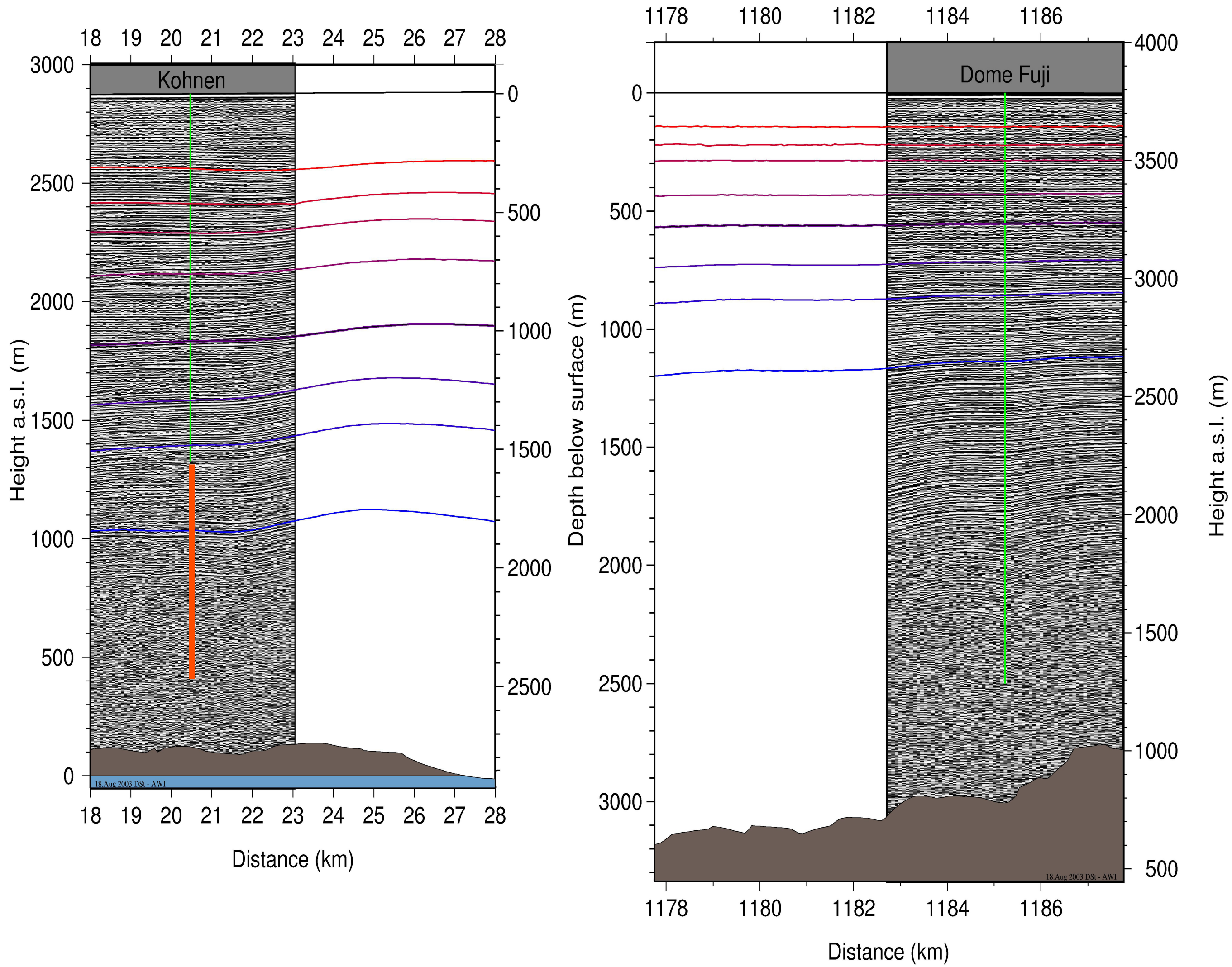




Antarctic Digital Database, Ekholm, 1998, maps by Steinhage with modifications

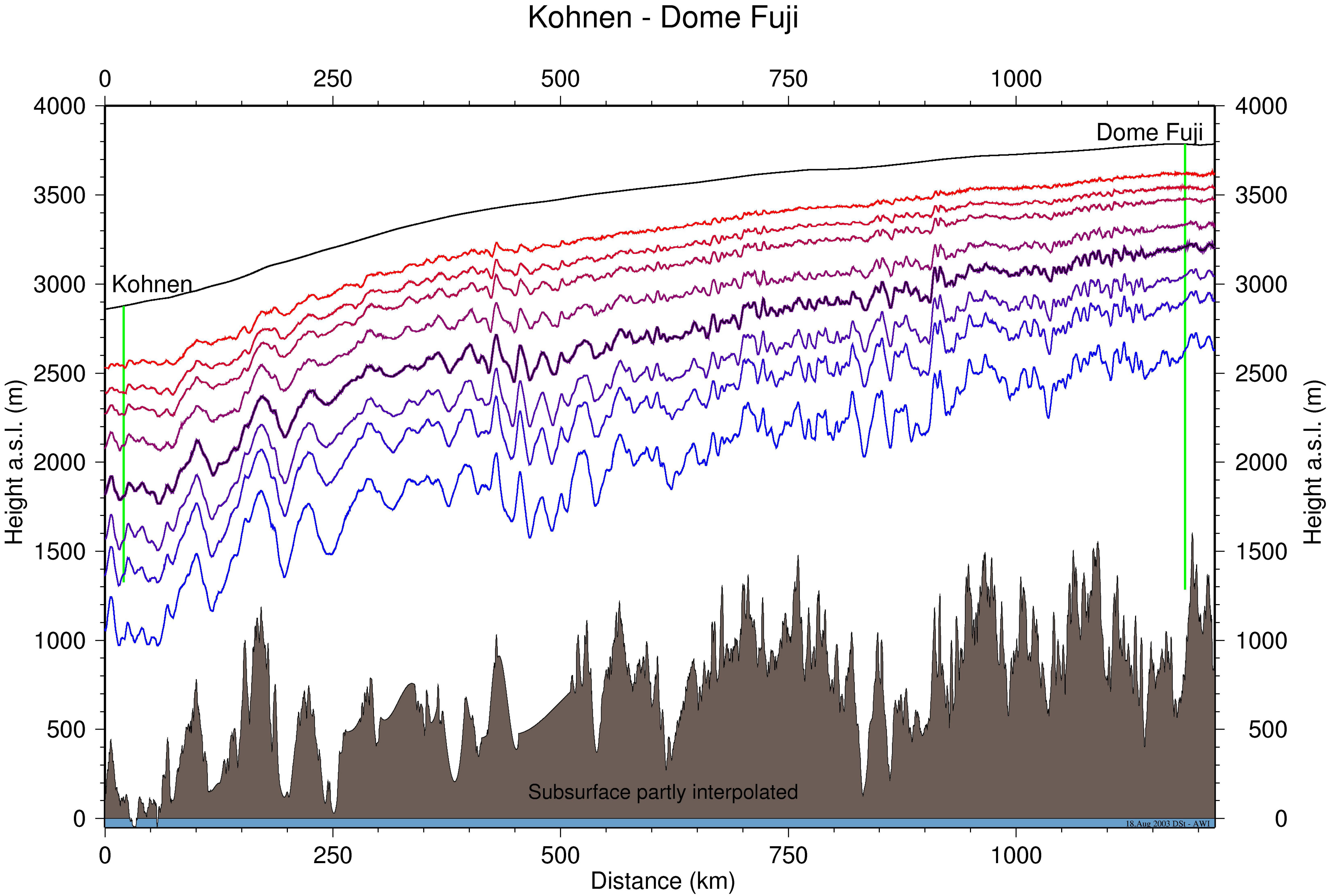
# Internal horizons at ice core drill sites



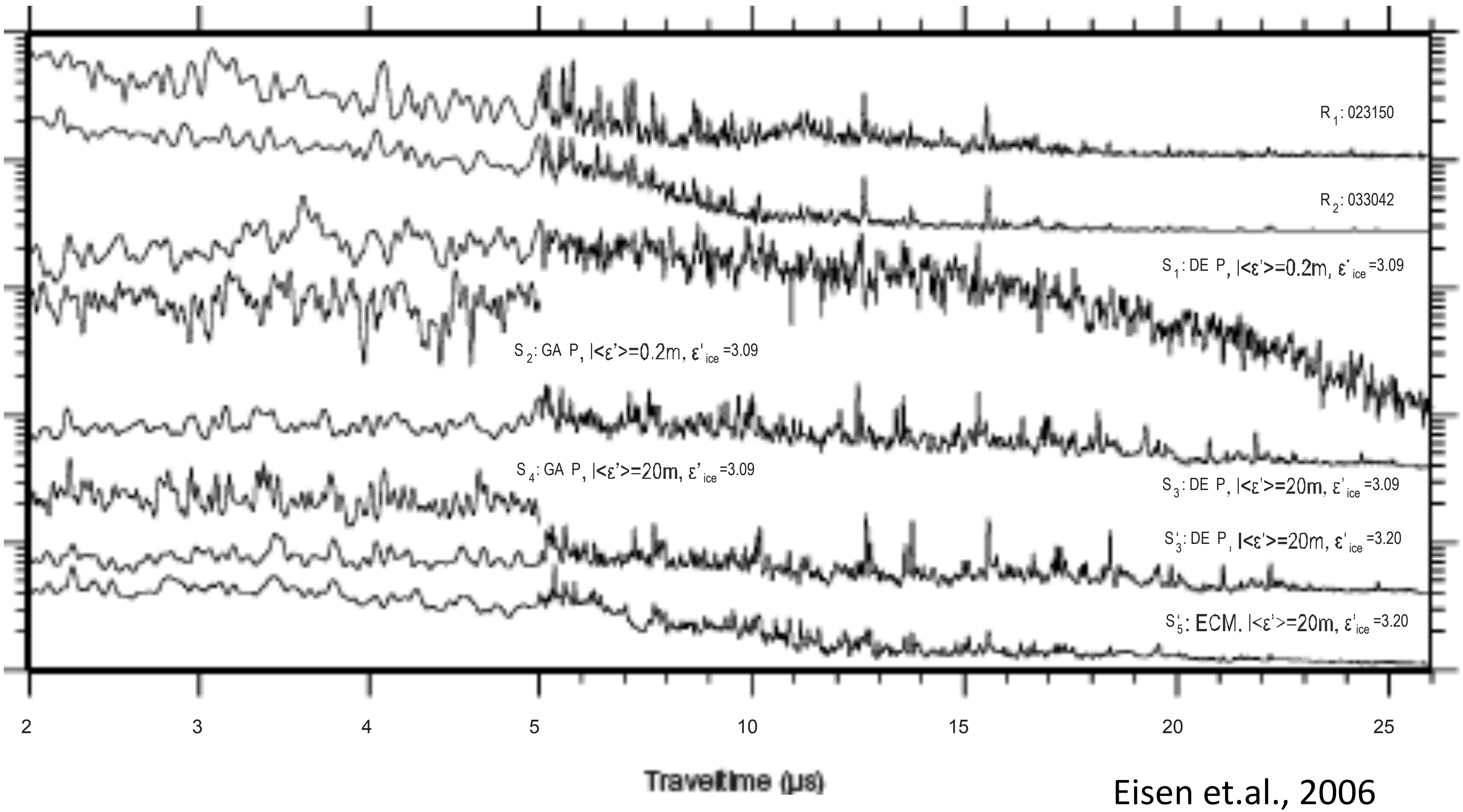
# Internal horizons at ice core drill sites



# Internal horizons at ice core drill sites

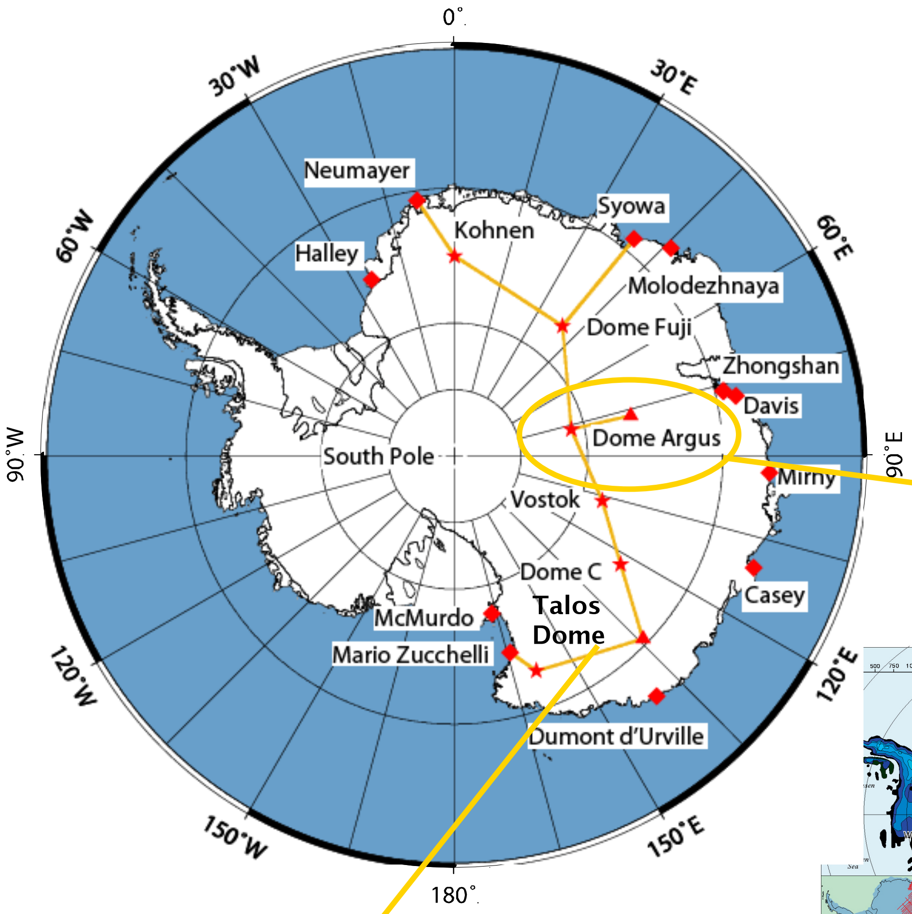


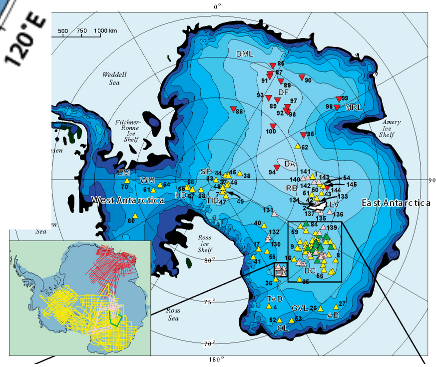
# FDTD synthetic radar traces to link ice-core and radar surveys




Eisen et.al., 2006

# Linking Ice Cores and surveys in East Antarctica



Siegert *et.al., Antarctic Science 17 (3), 453–460,* 2005

map: Daniel Steinhage
Data: Antarctic Digital Database

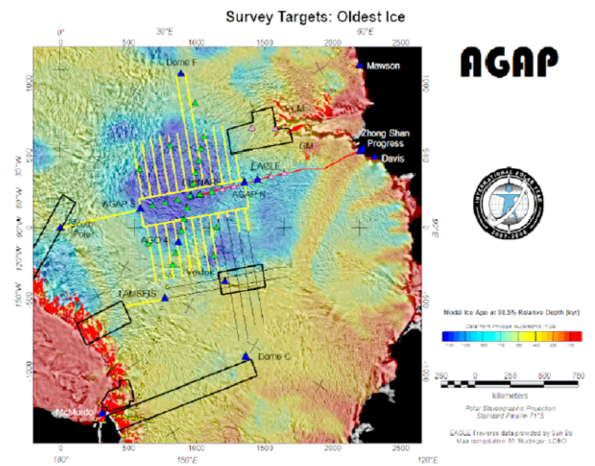
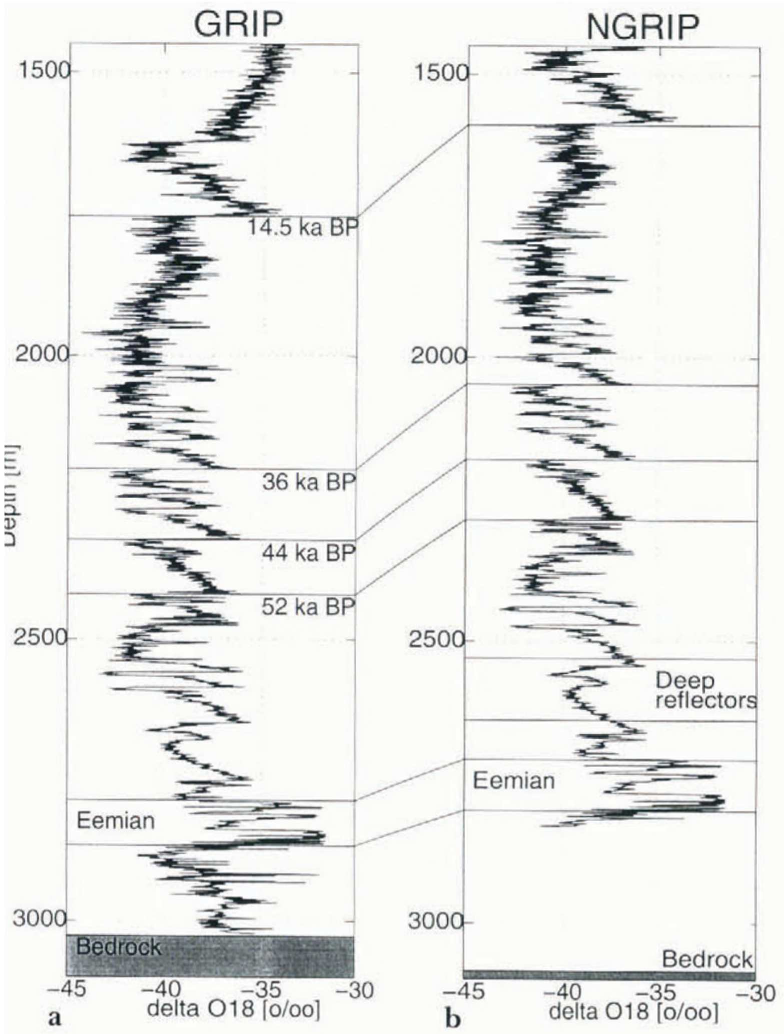
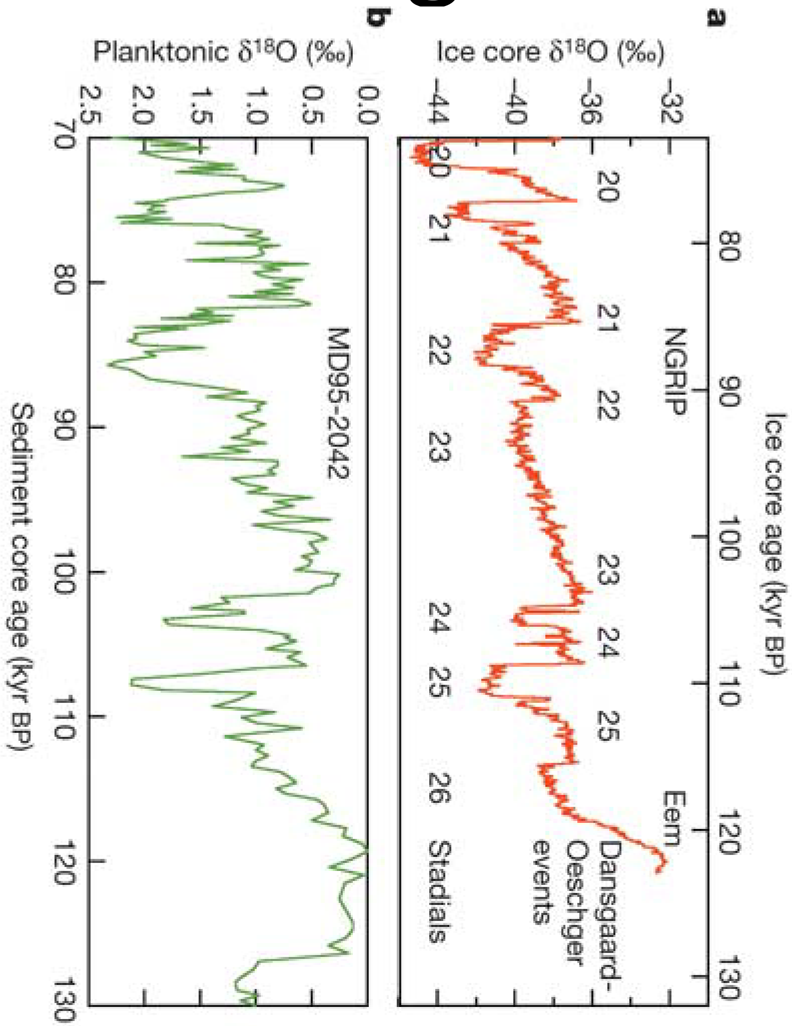



Figure 6. Possible flight lines for the AGAP survey, superimposed on the Huybrechts map of where oldest ice might be found.

We have the tools, but to bring the fuel is the challenge

# NorthGRIP – a warning



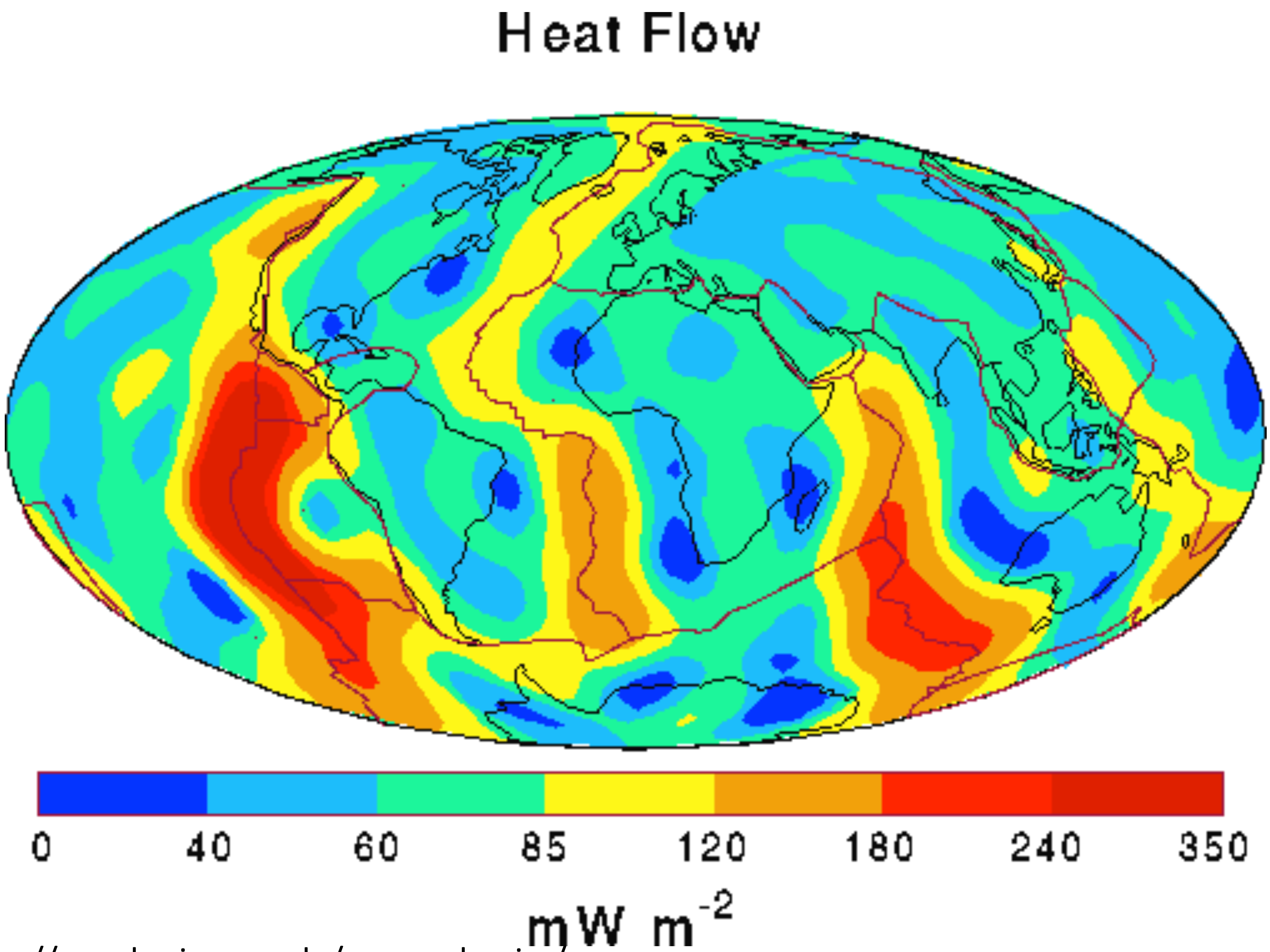




Dahl-Jensen et al., JGlaciol, 1997

NGRIP community members, Nature, 2004

Only really continuous radar layers may be used for tracing from one location to another!

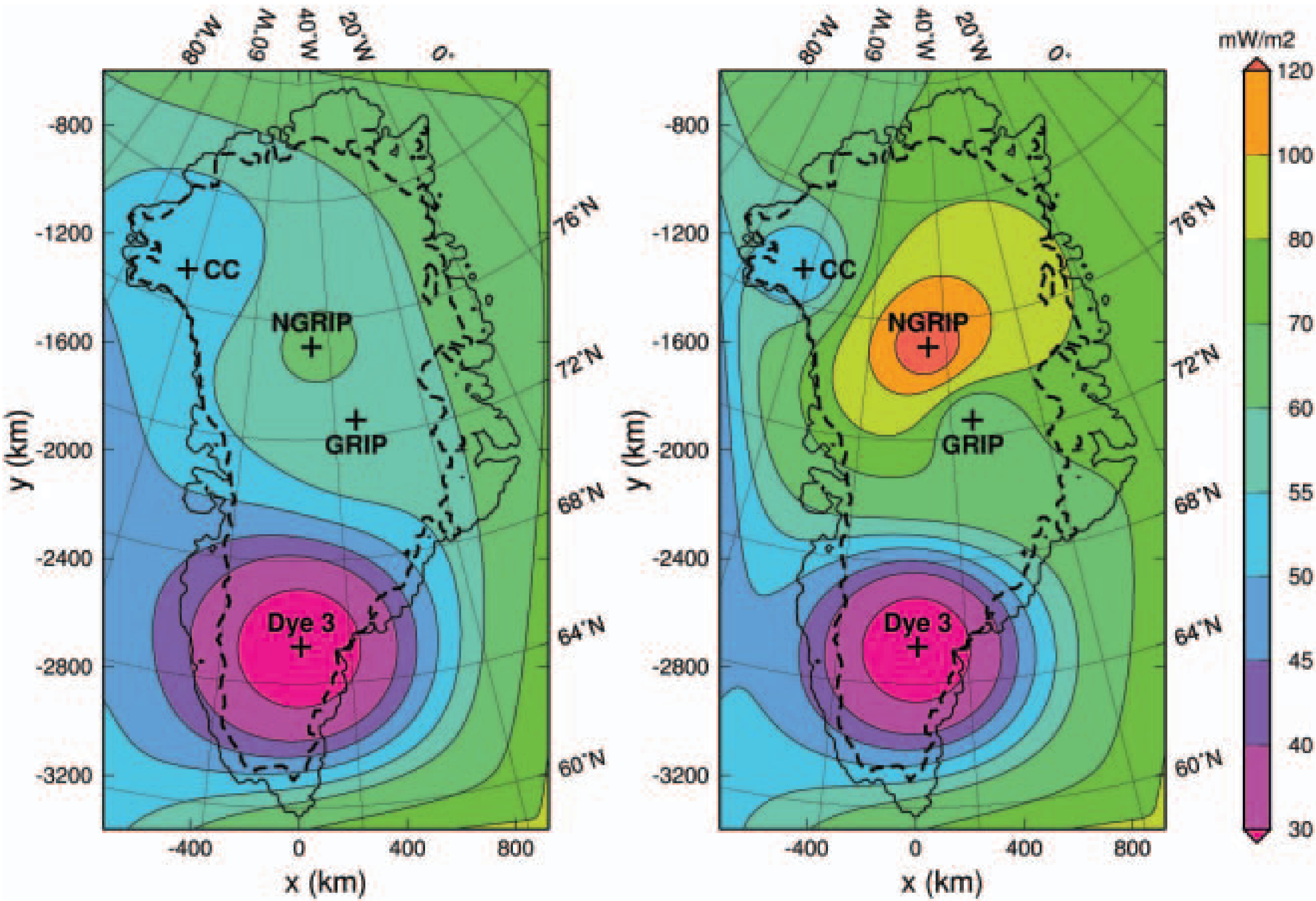
# NGRIP - melting at the bottom




http://geophysics.ou.edu/geomechanics/notes/heatflow/global_heat_flow.htm

Pollack et al., RG, 1993

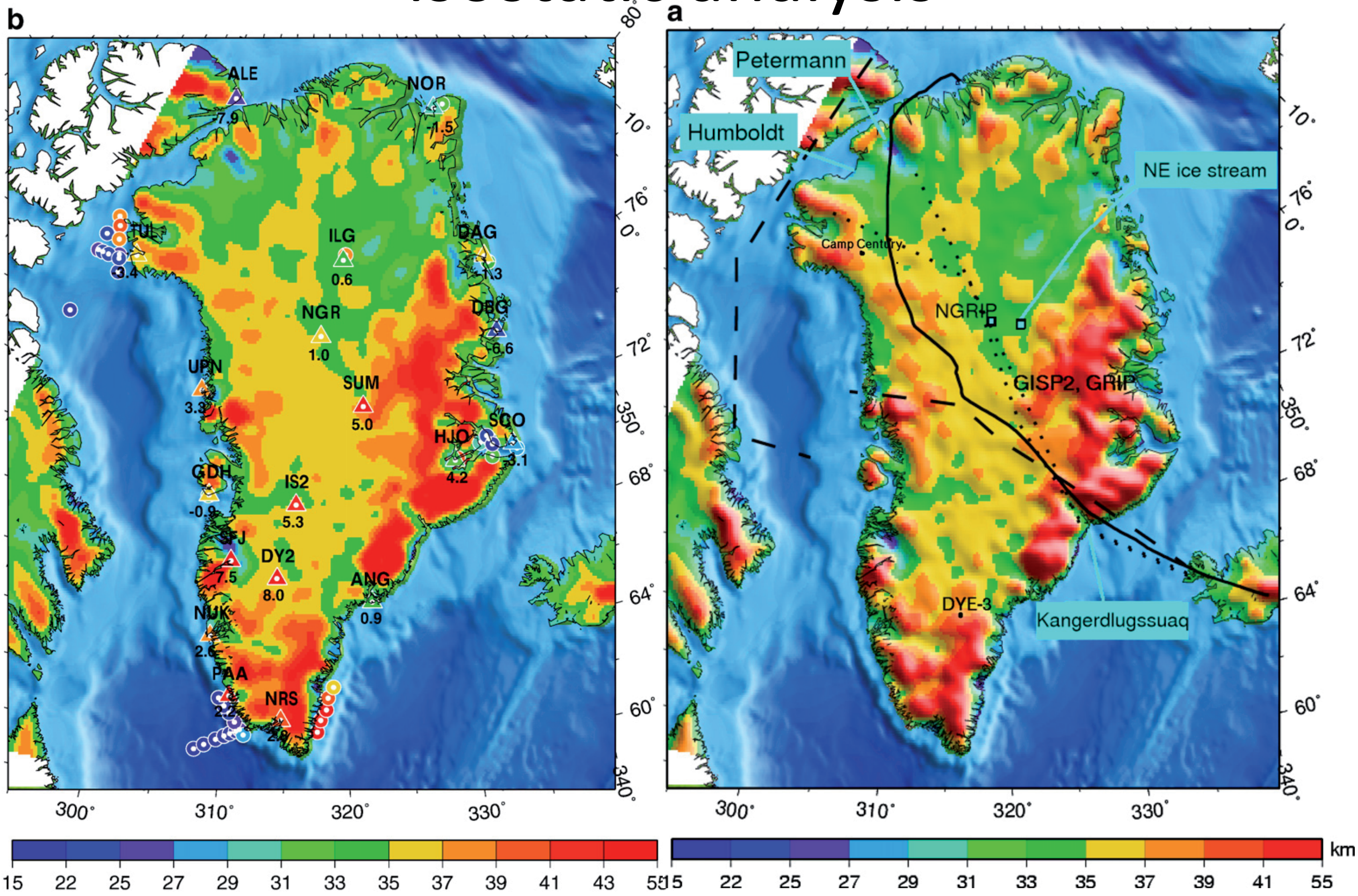
# Geothermal heat flux from model interpolation



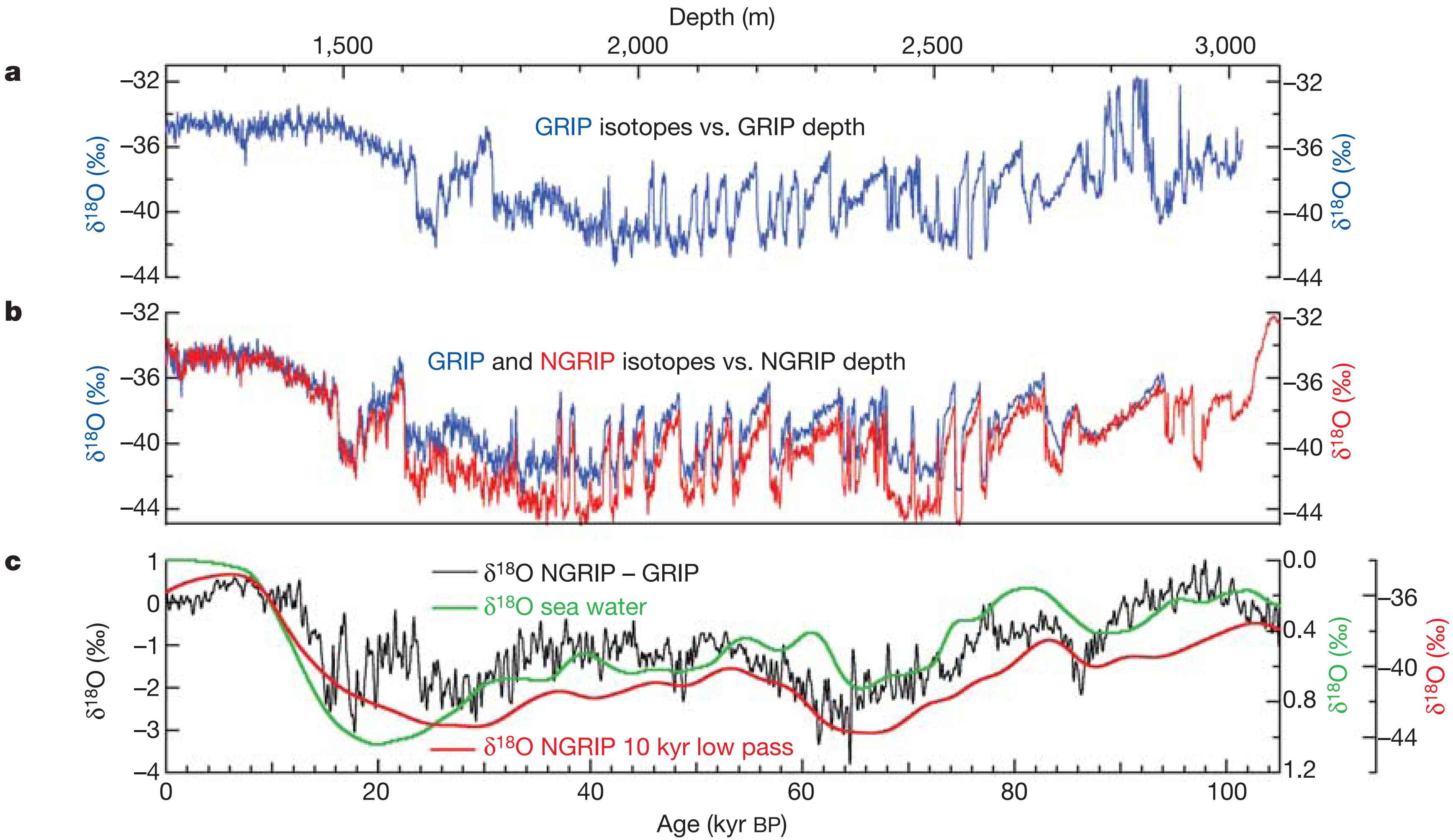

Greve, Ann. Galciol., 42, 2005

# crustal thickness from seismology an isostatic analysis

Braun et al., EPSL, 2007

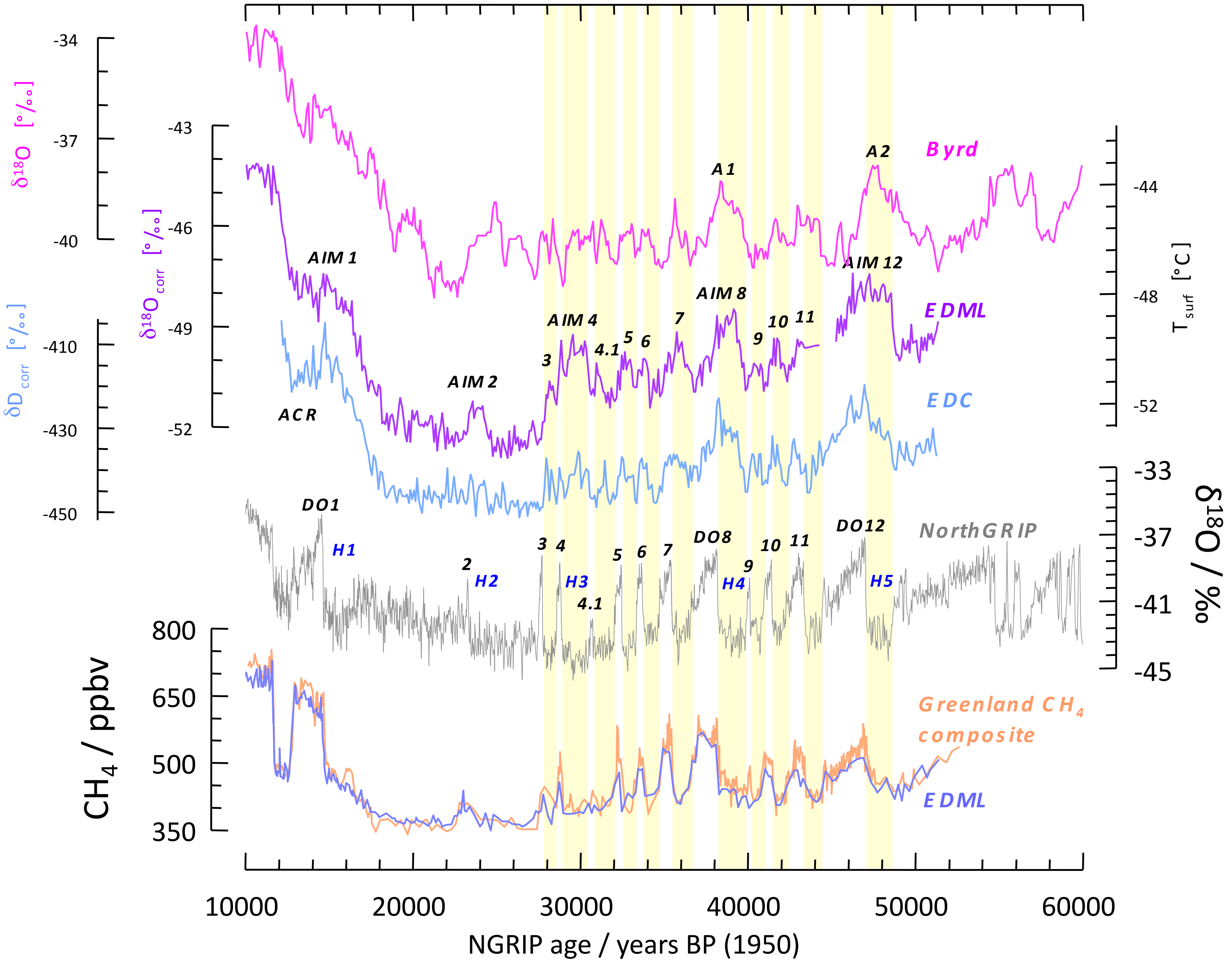


# NGRIP – anyhow good science




NGRIP community members, Nature, 2004

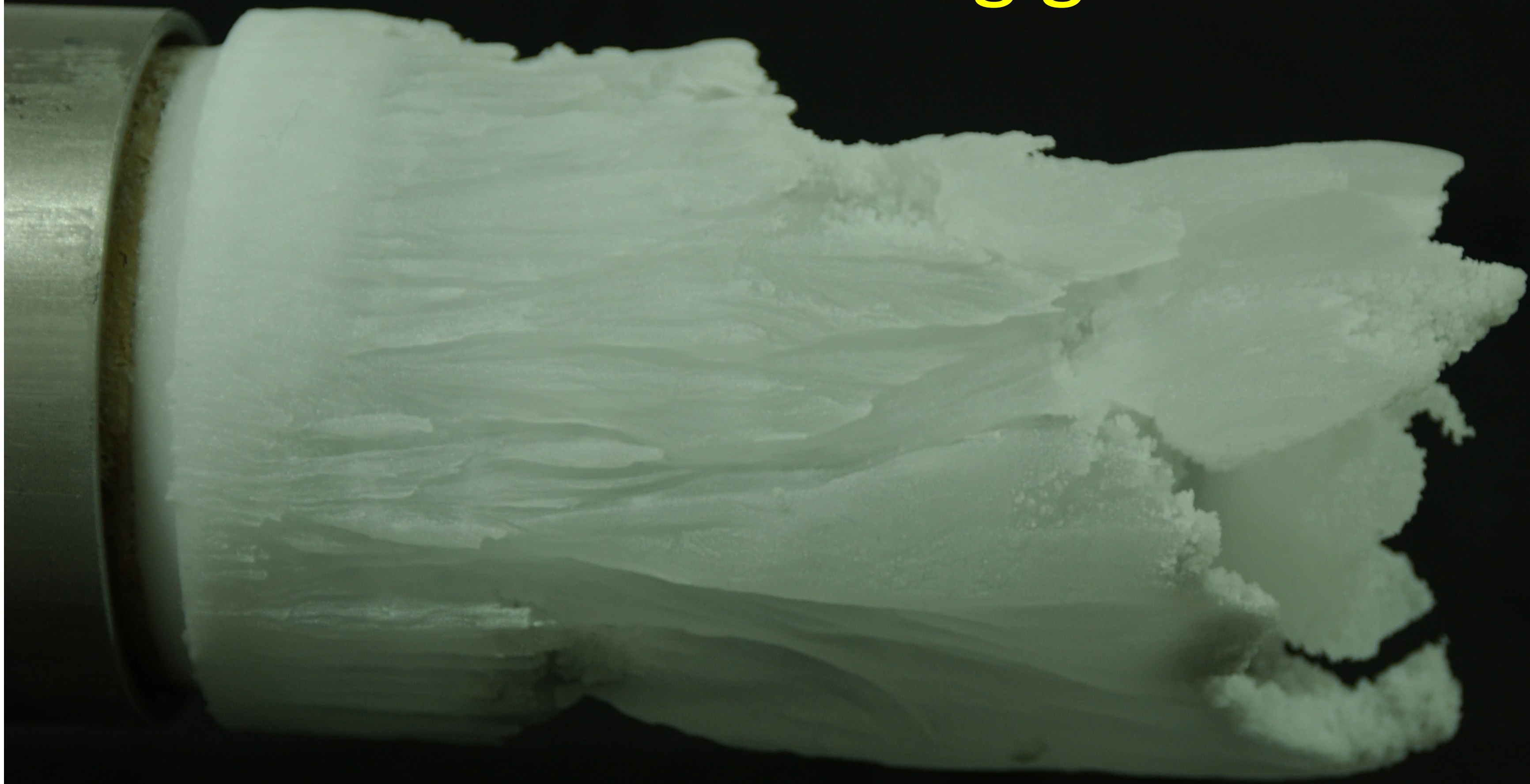
# Linking of Hemispheres

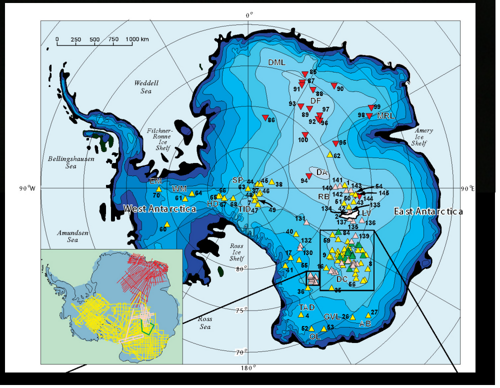



EPICA DML, NGRIP

EPICA community members, Nature 2006

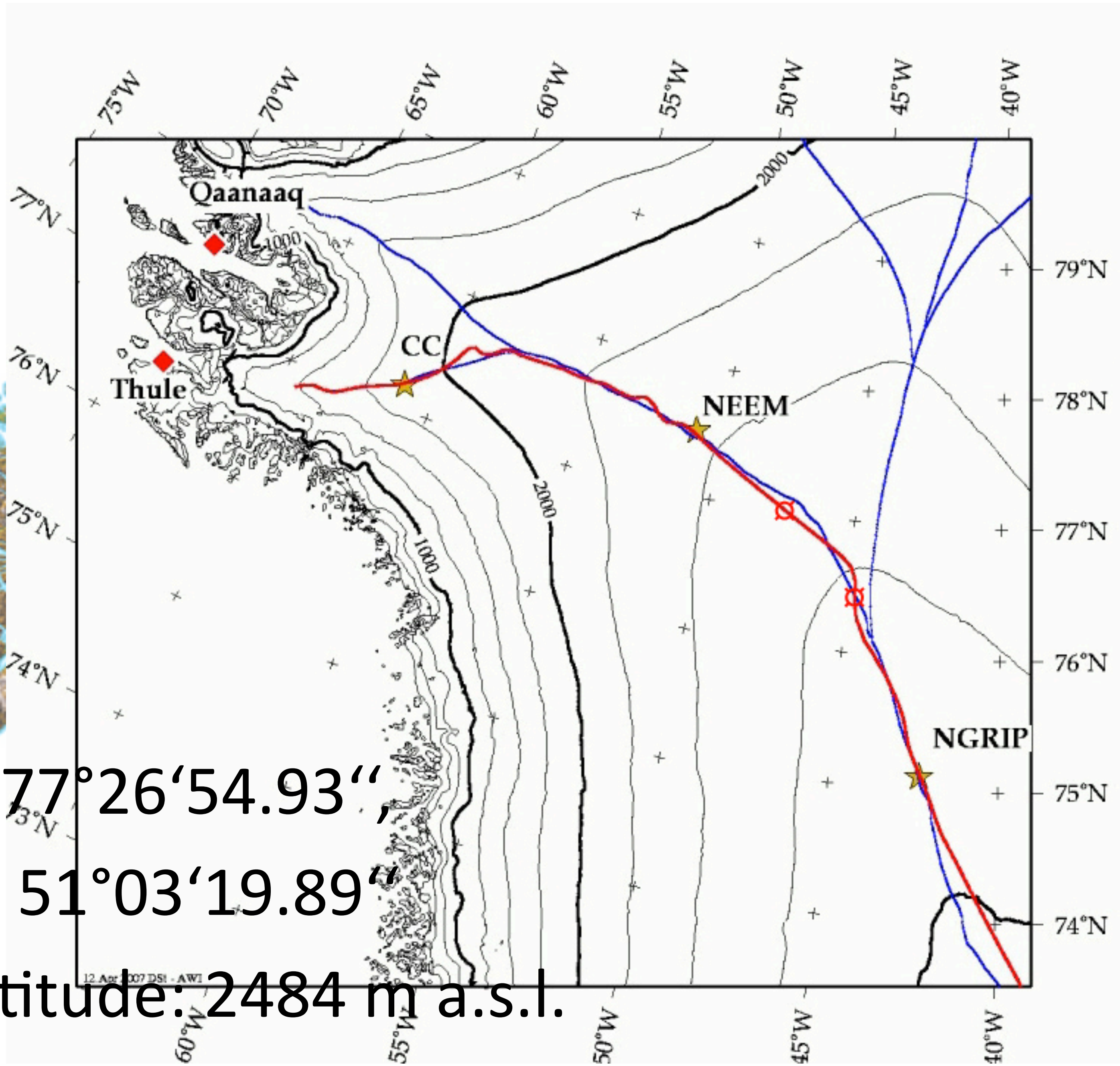
# EDML- Ice Coring goes arts





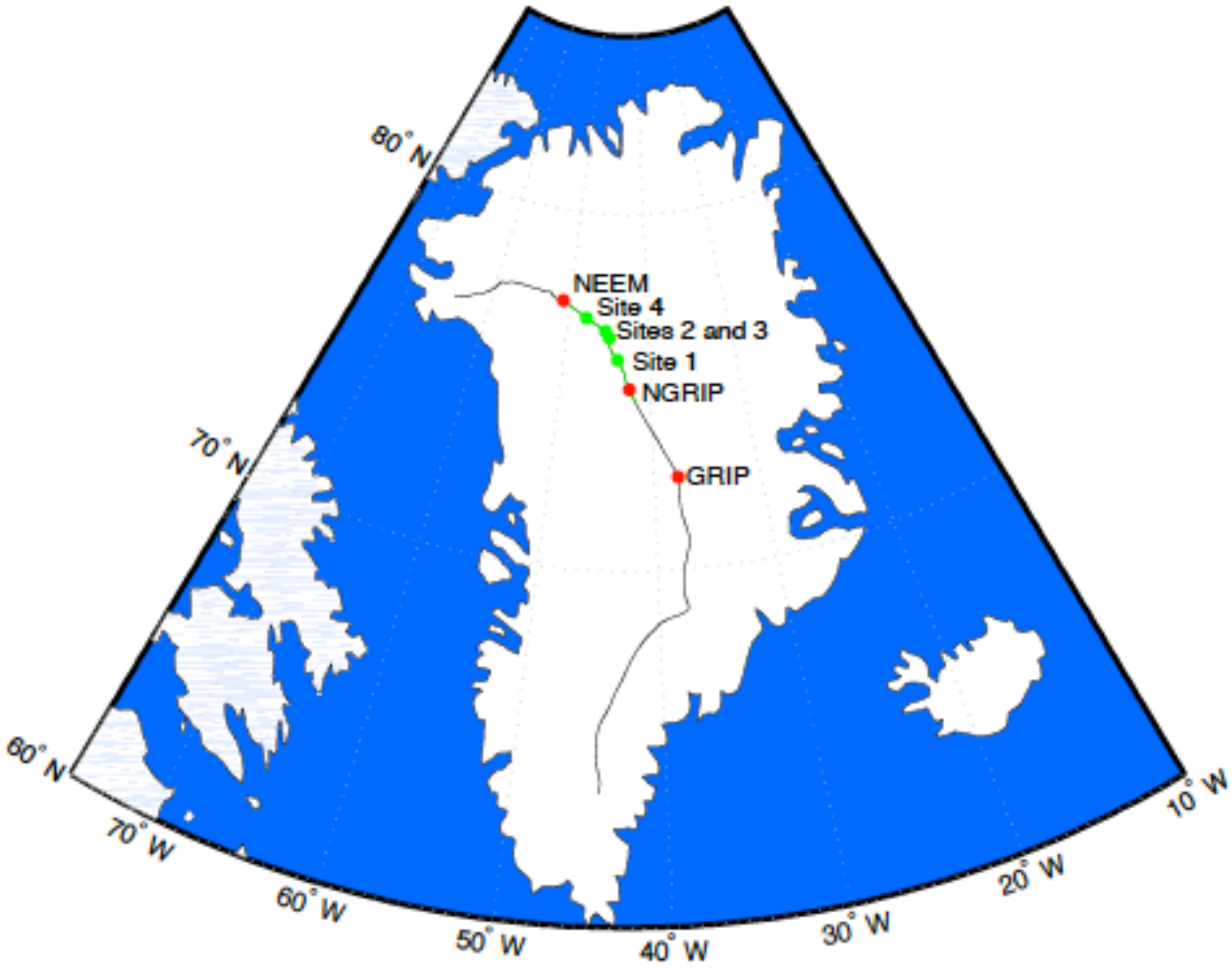

Siegert *et.al.*,
*Antarctic Science 17*
*(3), 453–460,* 2005

# NEEM


- N 77°26‘54.93‘‘,
- W 51°03‘19.89‘‘
- Altitude: 2484 m a.s.l.
- Ice Thickness: 2542 m

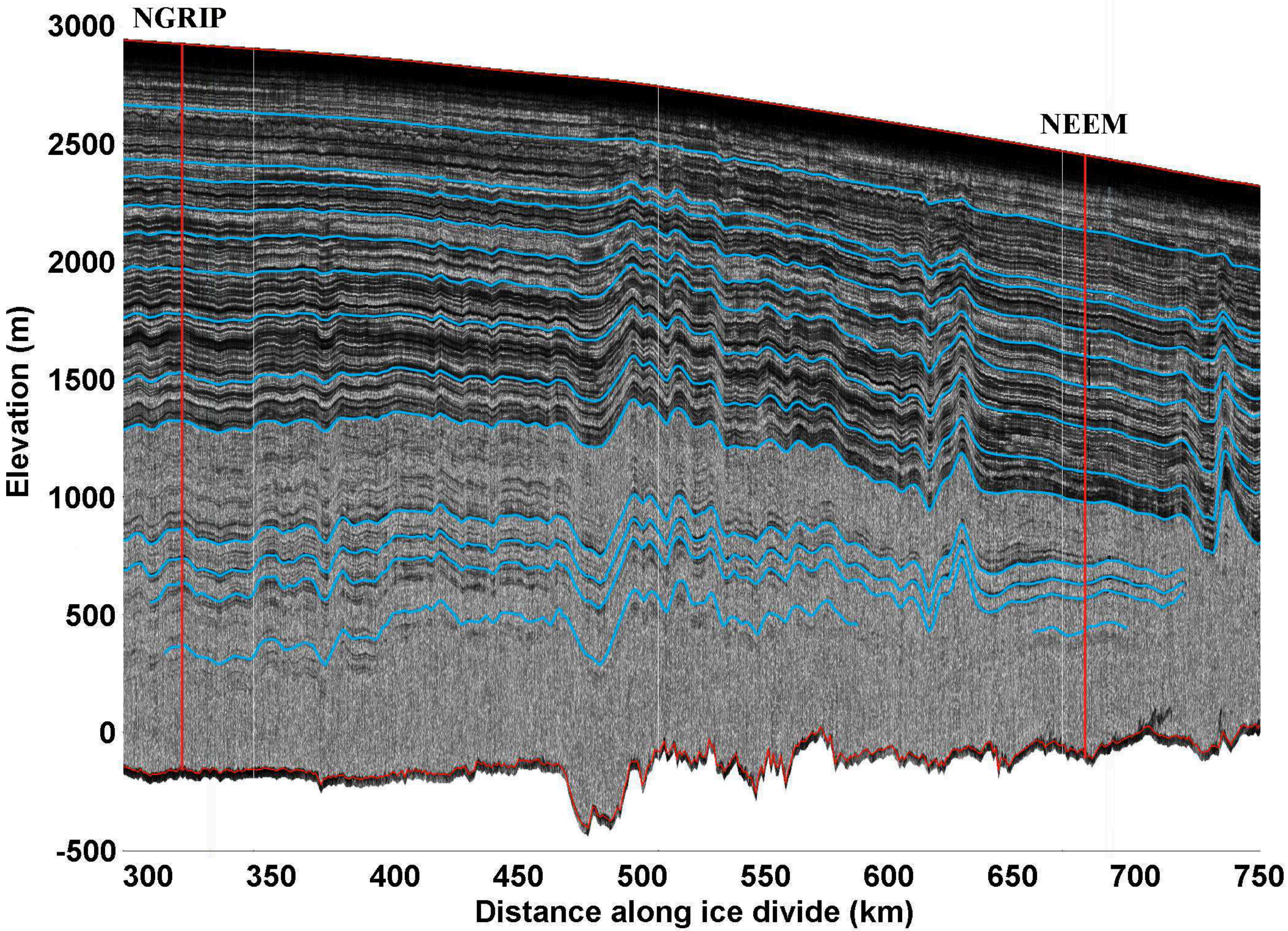
# Is there an Eemian?




Susanne Liljia Buchardt, PhD thesis, Ice and Climate Centre, Univ. København, 2009

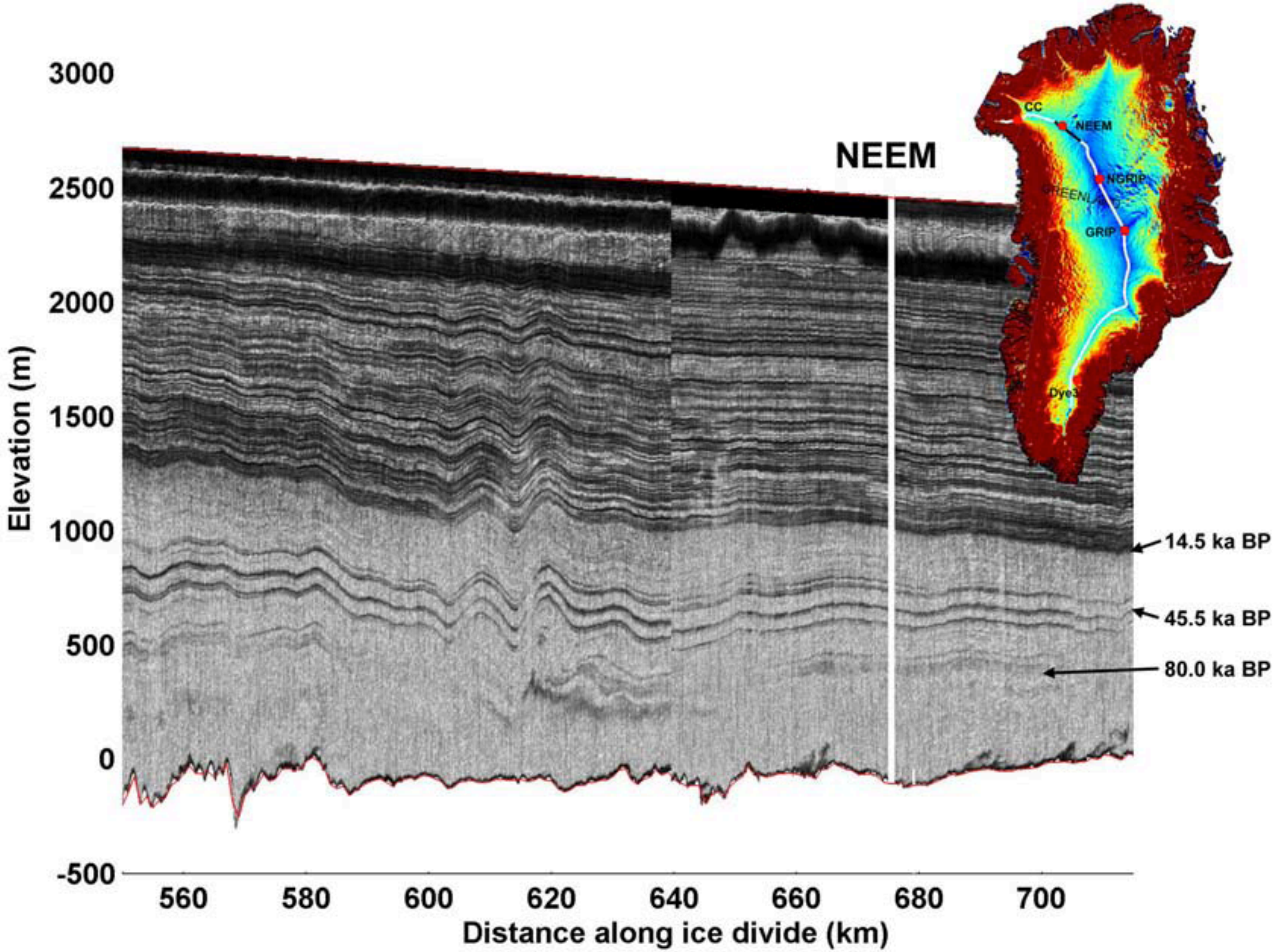
# Radar reflectors from NGRIP to NEEM

Susanne Liljia Buchardt, PhD thesis, Ice and Climate Centre, Univ. København, 2009



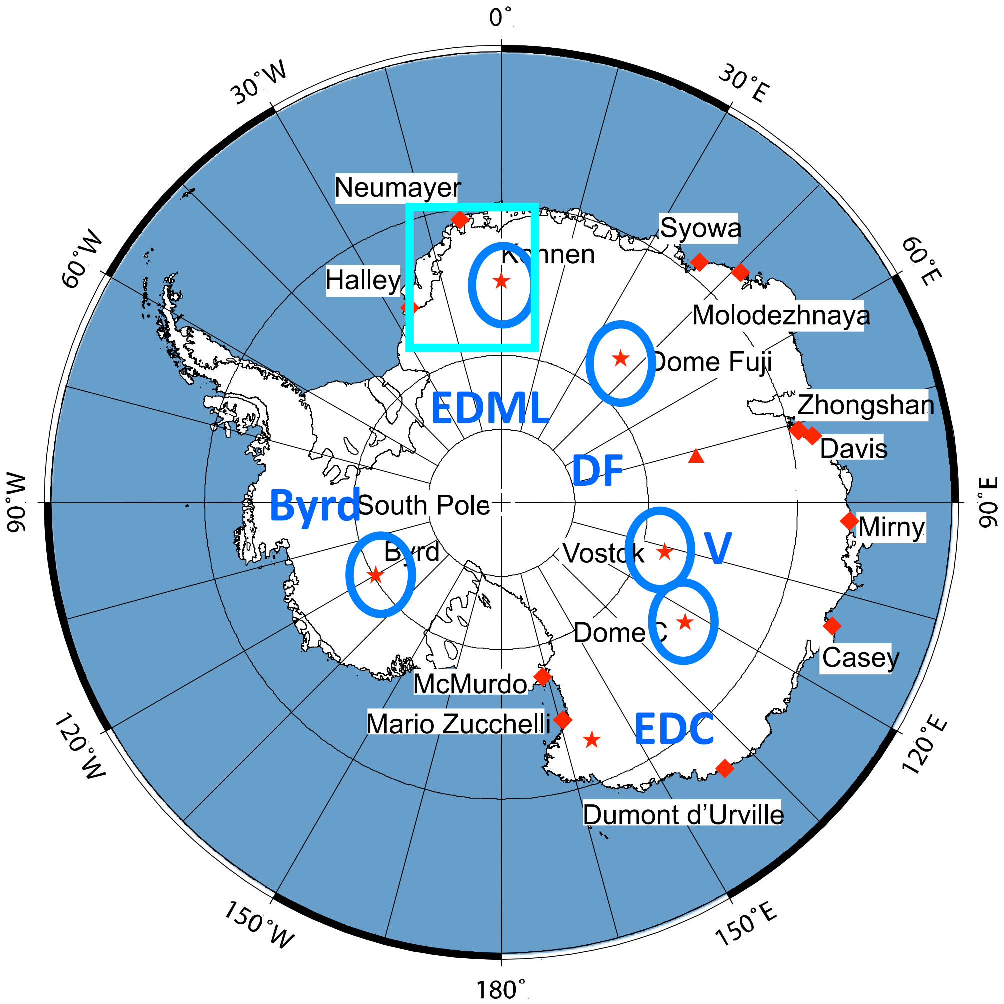

| Age (kyr) | Depth (m) | z (m) |
|---|---|---|
| 1.4 | 273 | 2644 |
| 2.7 | 501 | 2416 |
| 3.2 | 571 | 2346 |
| 4.0 | 689 | 2229 |
| 4.8 | 802 | 2116 |
| 5.9 | 955 | 1963 |
| 7.5 | 1146 | 1771 |
| 10.2 | 1396 | 1521 |
| 14.6 | 1600 | 1318 |
| 37.7 | 2055 | 863 |
| 45.0 | 2182 | 735 |
| 51.0 | 2284 | 633 |
| 74.6 | 2553 | 365 |

Age depth at NGRIP and elevation above sea level at NGRIP (Table 2.2)



NEEM
Elevation (m)
3000
2500
2000
1500
1000
500
0
-500
560
580
600
620
640
660
680
700
Distance along ice divide (km)
14.5 ka BP
45.5 ka BP
80.0 ka BP
CC
NEEM
NGRIP
GRIP
Dye3

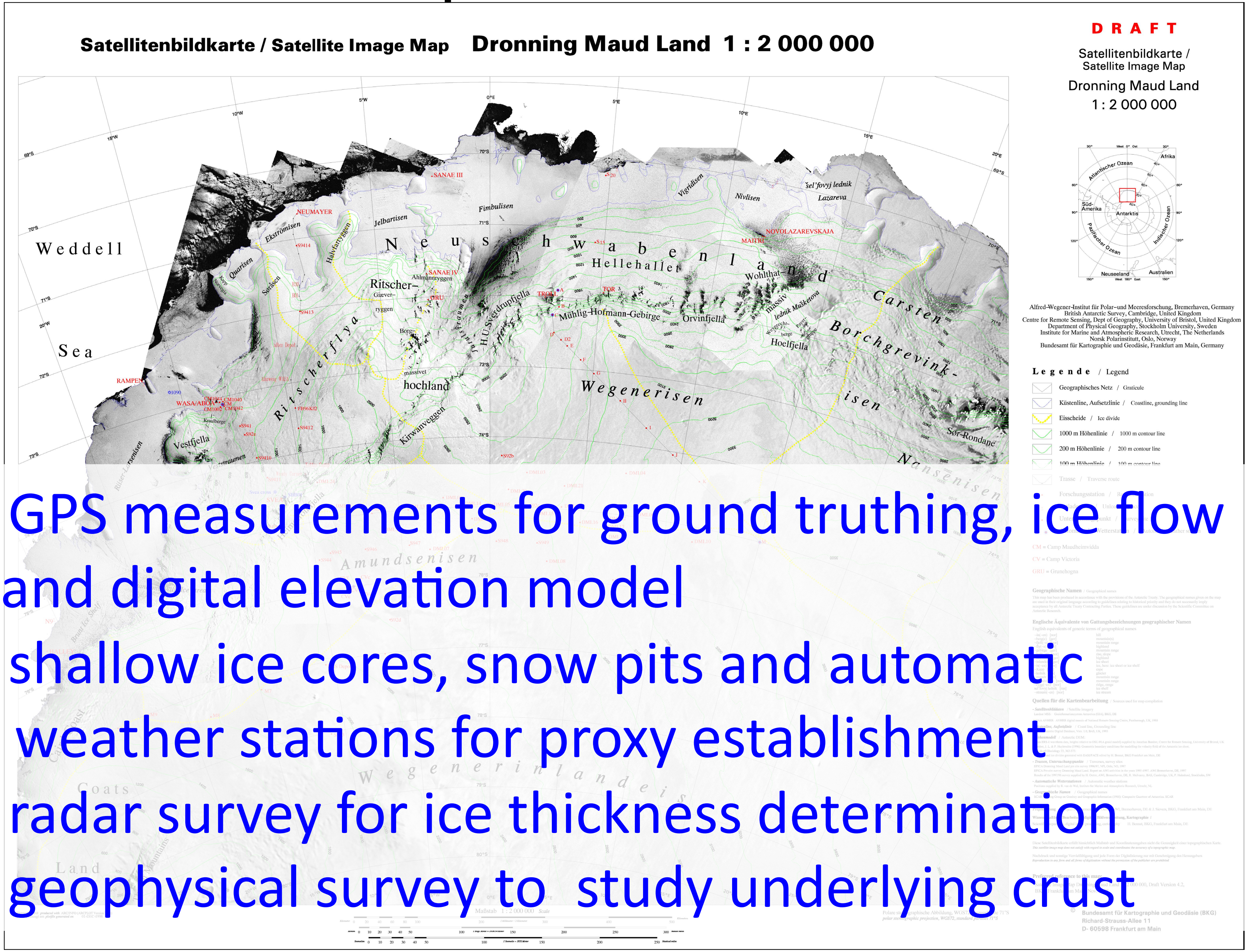
# The European Project for Ice Coring in Antarctica




EUROPEAN PROJECT FOR ICE CORING IN ANTARCTICA
EPICA
bottom
2774.15 m
17.01.2006
Dronning Maud Land
DOME CONCORDIA
DRONNING MAUD LAND

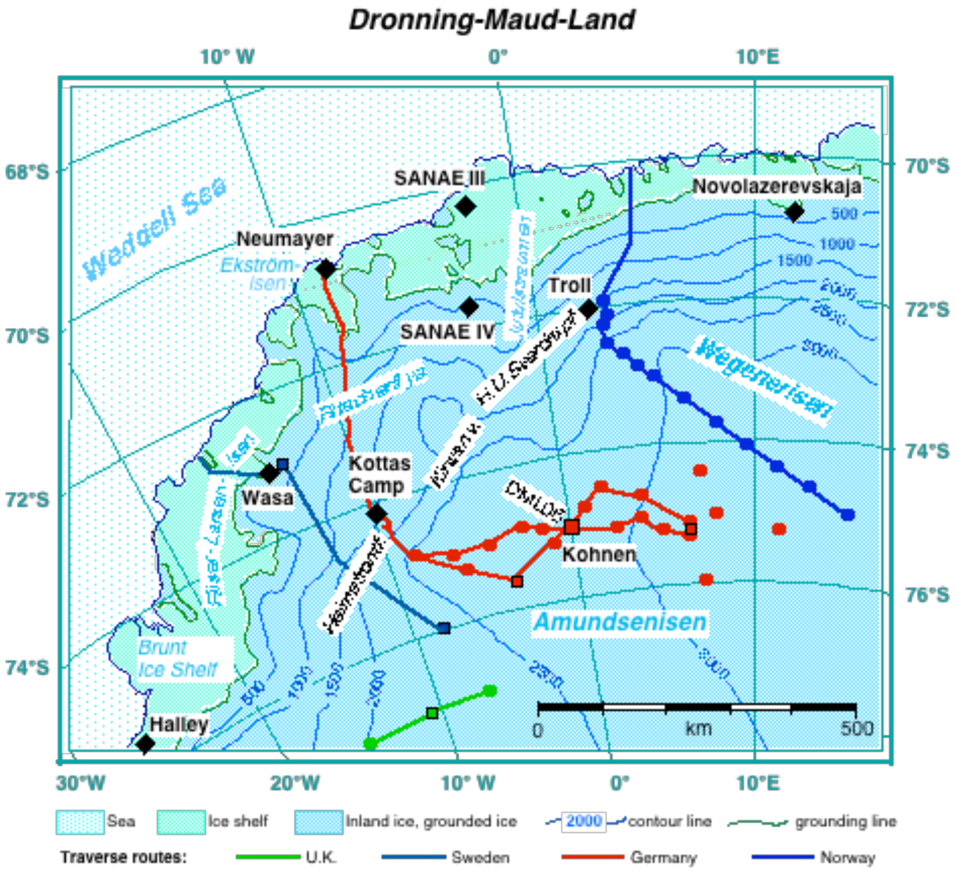
Antarctic Digital Database, Ekholm, 1998, map by Steinhage with modifications

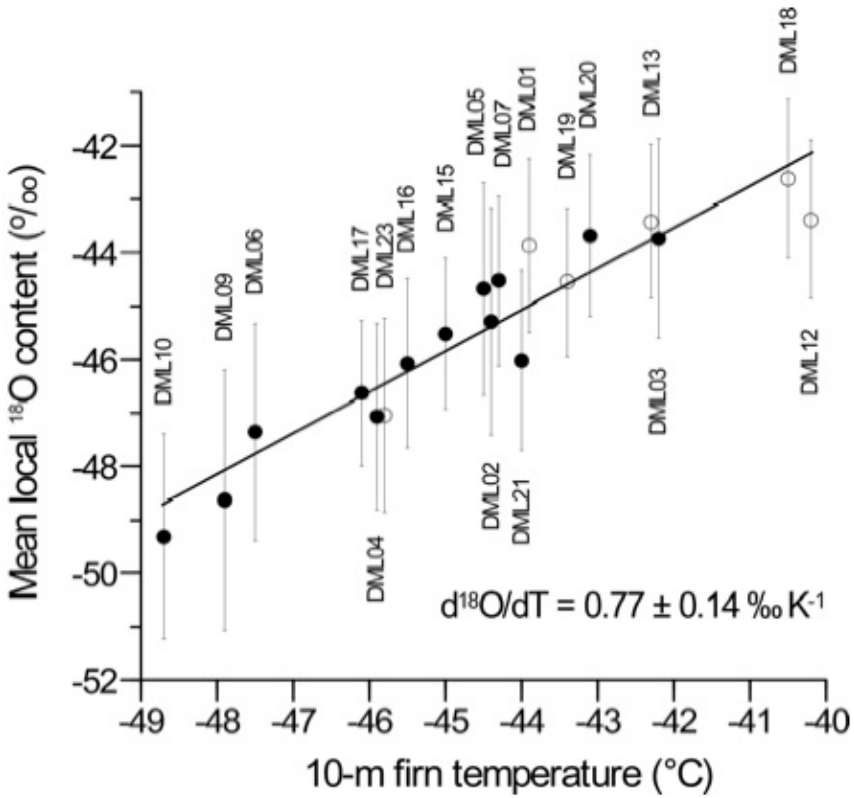
# Explore the area




- GPS measurements for ground truthing, ice flow and digital elevation model
- shallow ice cores, snow pits and automatic weather stations for proxy establishment
- radar survey for ice thickness determination
- geophysical survey to  study underlying crust

# isotope thermometer for EDML

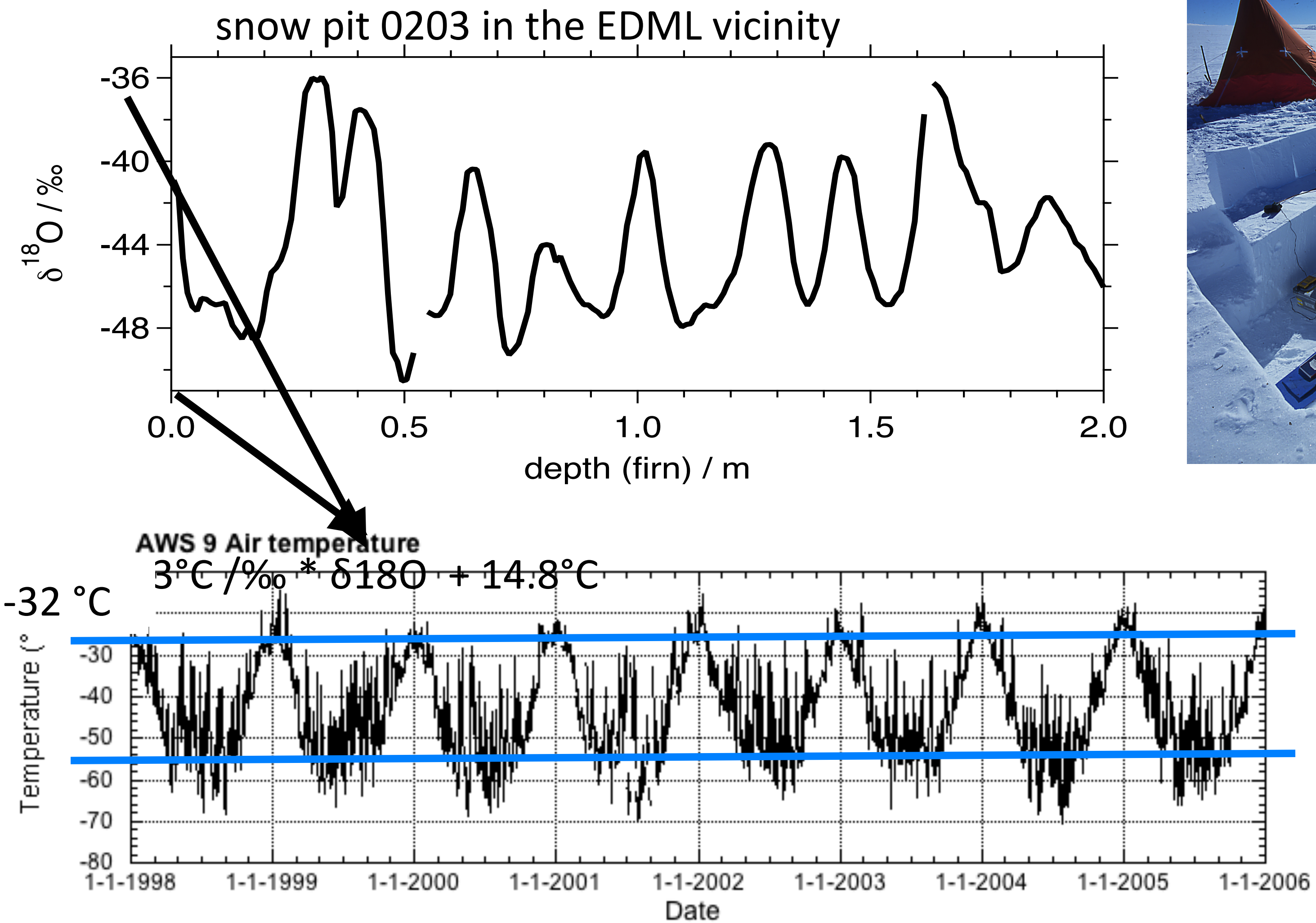


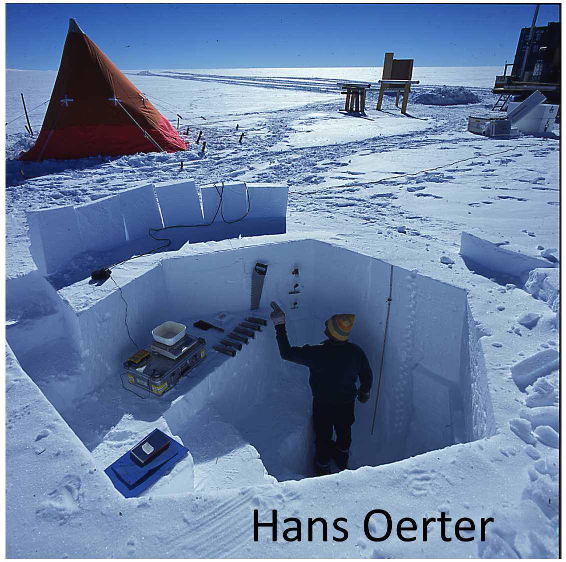



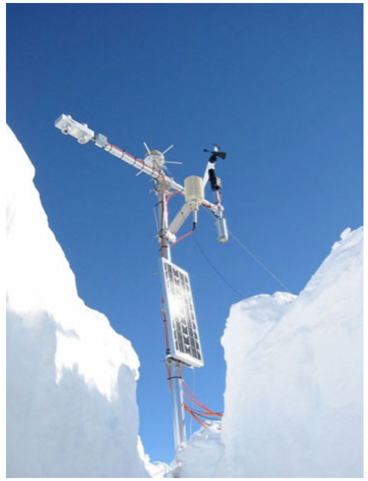

Antarktis (Dronning Maud Land) T =
1.3°C /‰ * $\delta^{18}$O + 14.8°C

Graf, W., Oerter, H., Reinwarth, O., Stichler, W., Wilhelms, F., Miller, H., Mulvaney, R. *Stable-isotope records from Dronning Maud Land, Antarctica*, Annals of Glaciology, 35, 195–201, 2002.

# seasonal variations

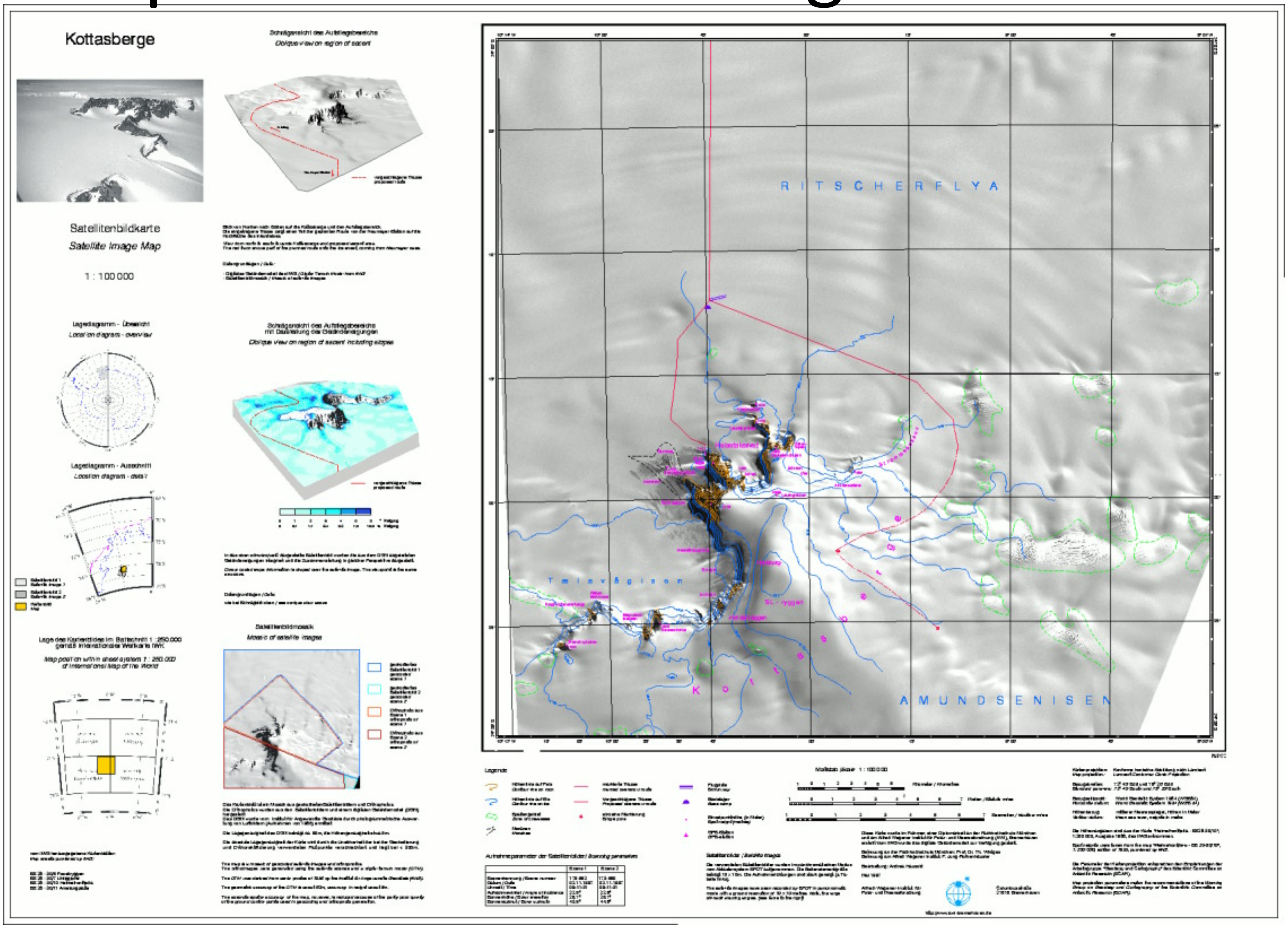


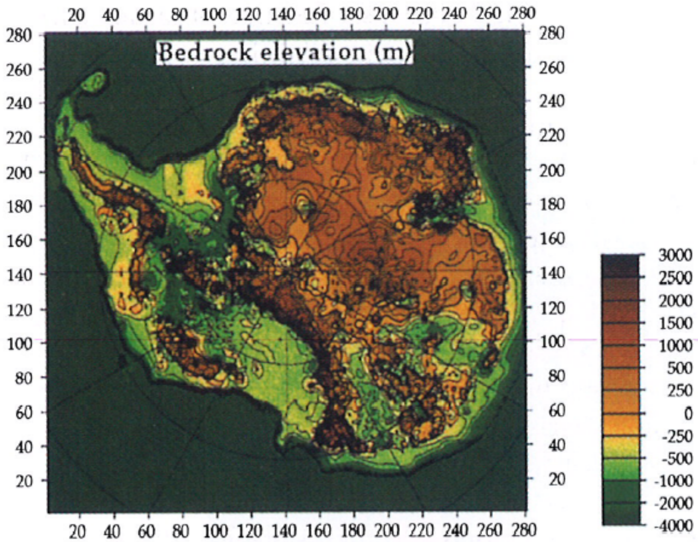



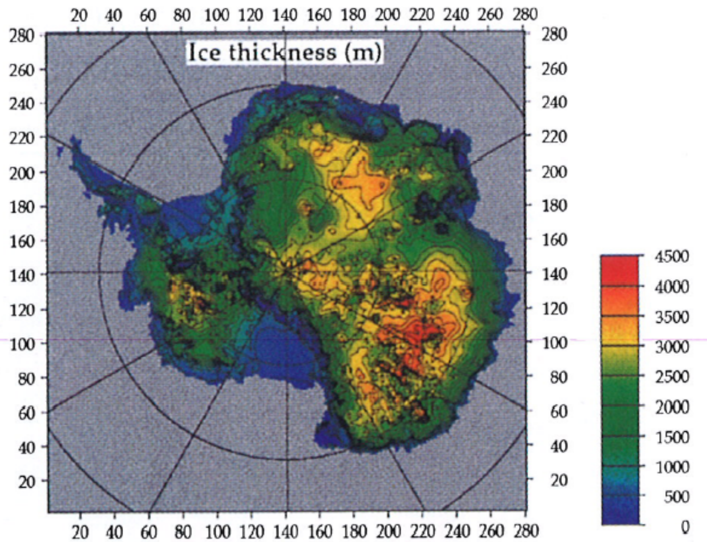
Oerter et al., Annals of Glaciology, 2004.
C. H. Reijmer et al., JGR, 2006: http://www.phys.uu.nl/~wwwimau/research/ice_climate/aws/antarctica_stations.html#aws9

# explore the area for logistic access

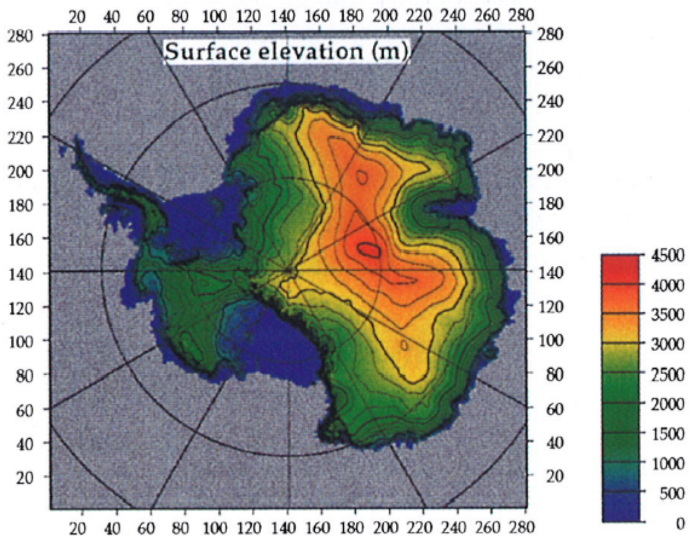


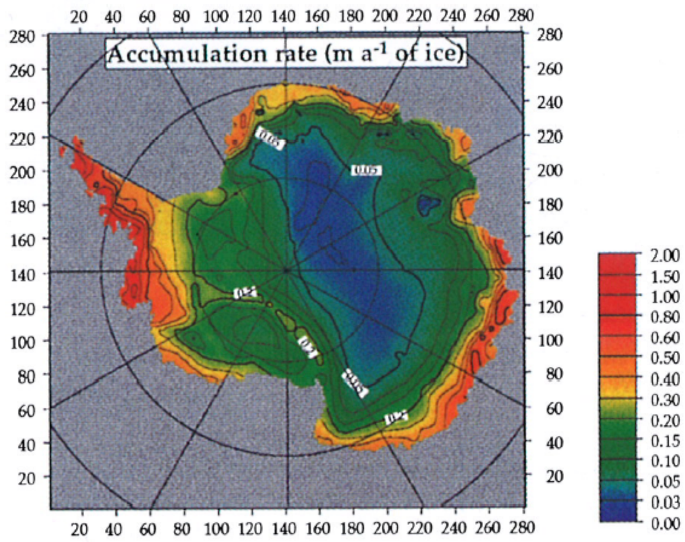
# Accumulation rate folio for modelling of the East Antarctic ice sheet



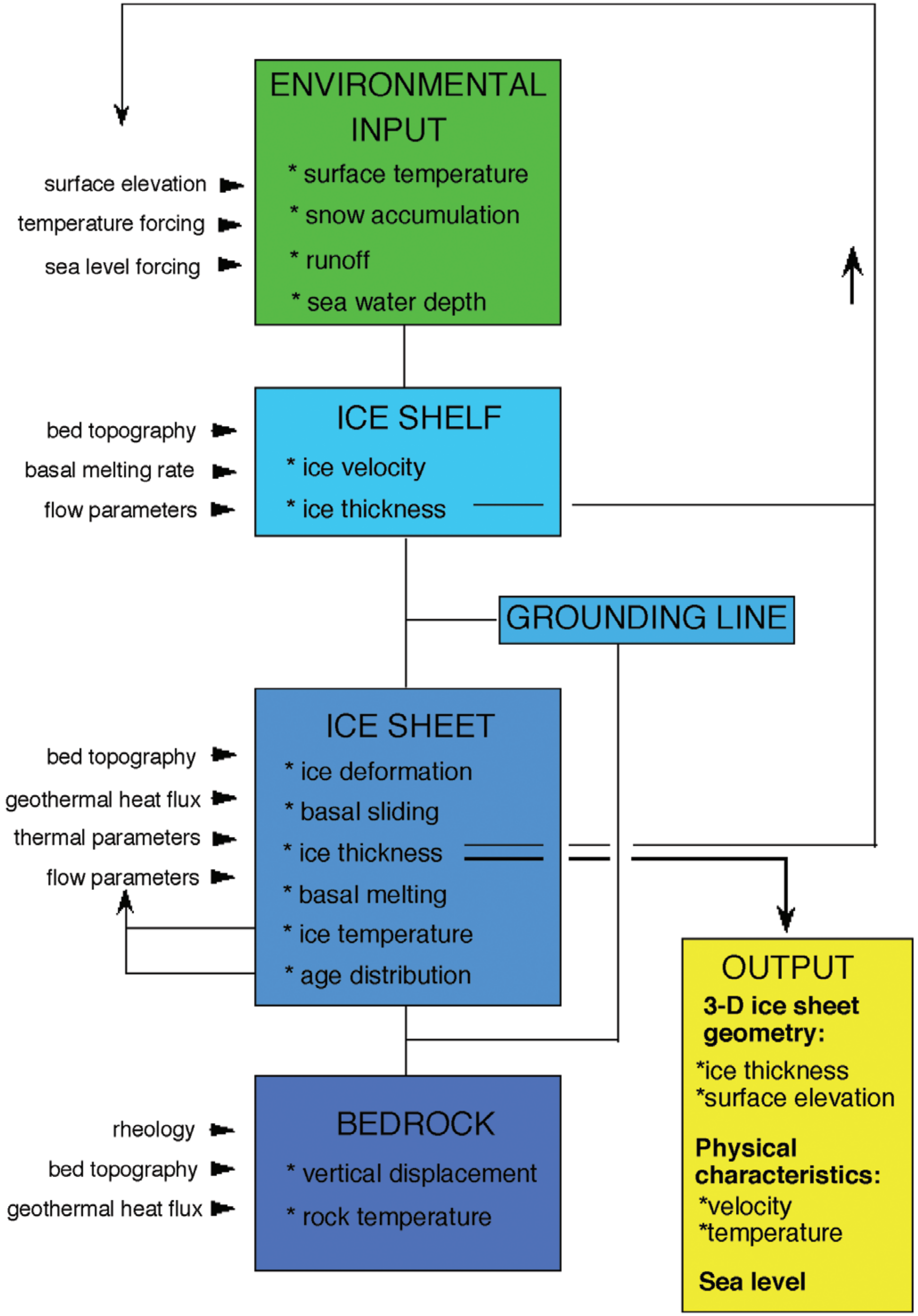




Huybrecht et al., AnnGlaciol 30, 2000



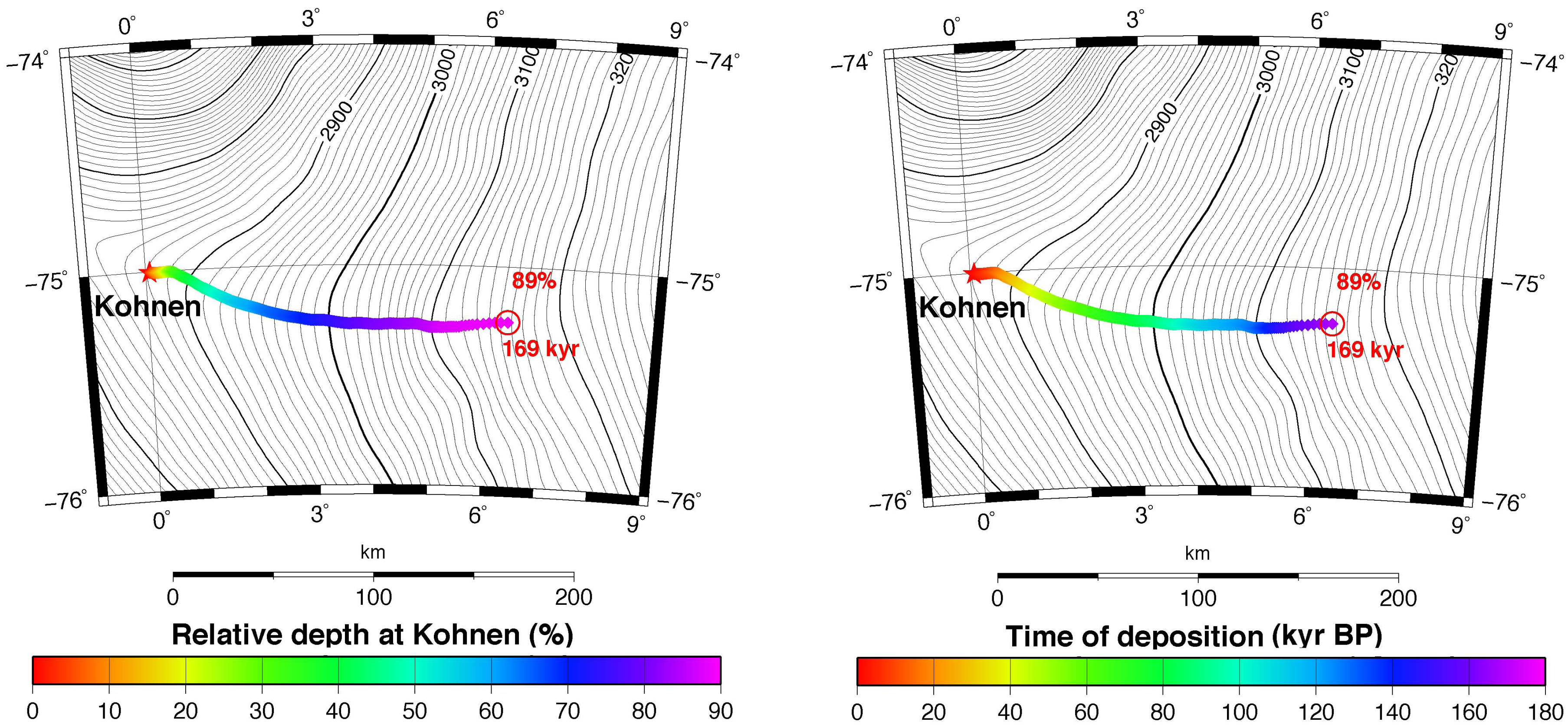



# ice sheet models



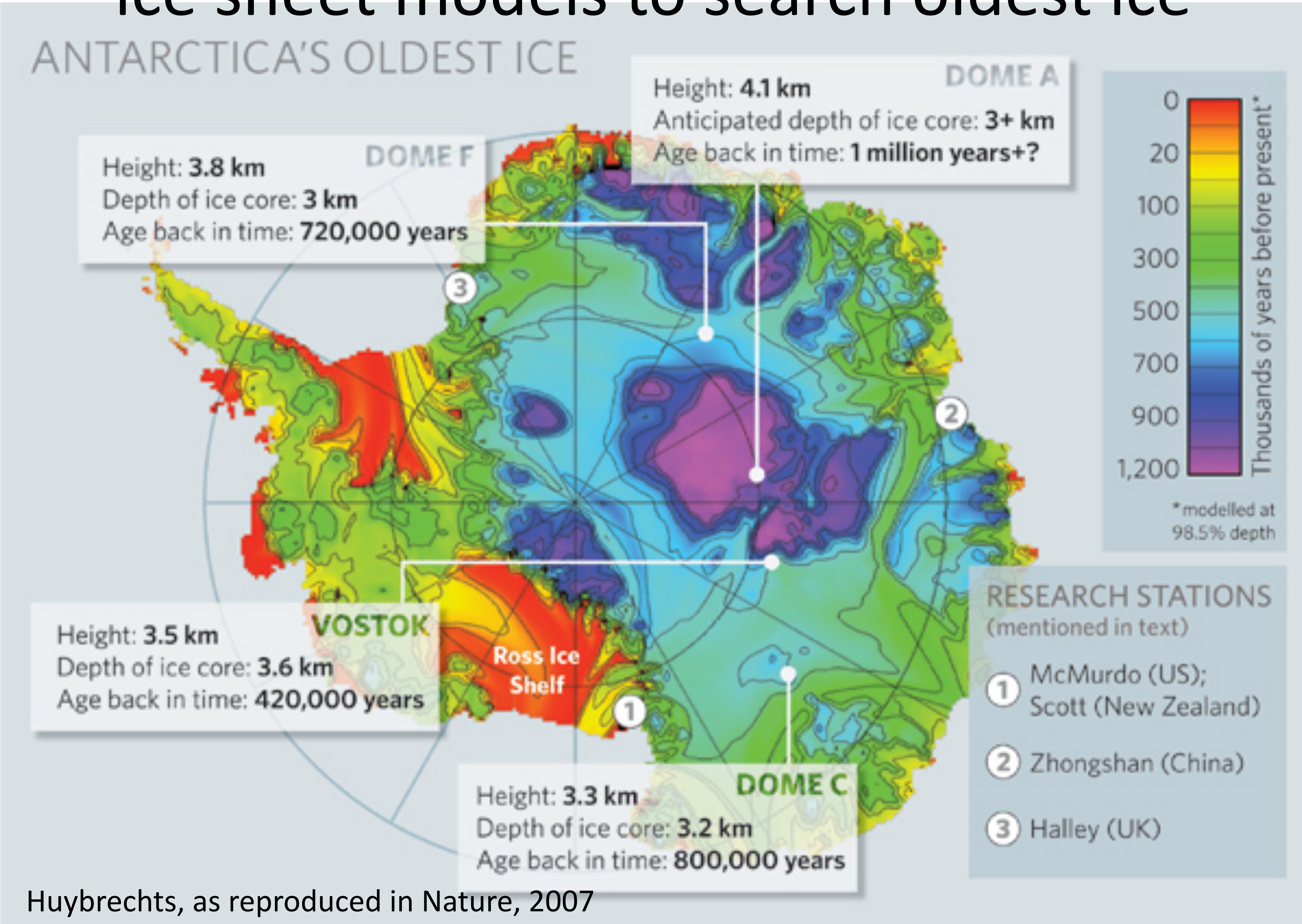

Huybrechts, Glacier Science and Environmental change, ed. P. Knight, Blackwell, 2006

# ice sheet models to improve the interpretation of the ice cores



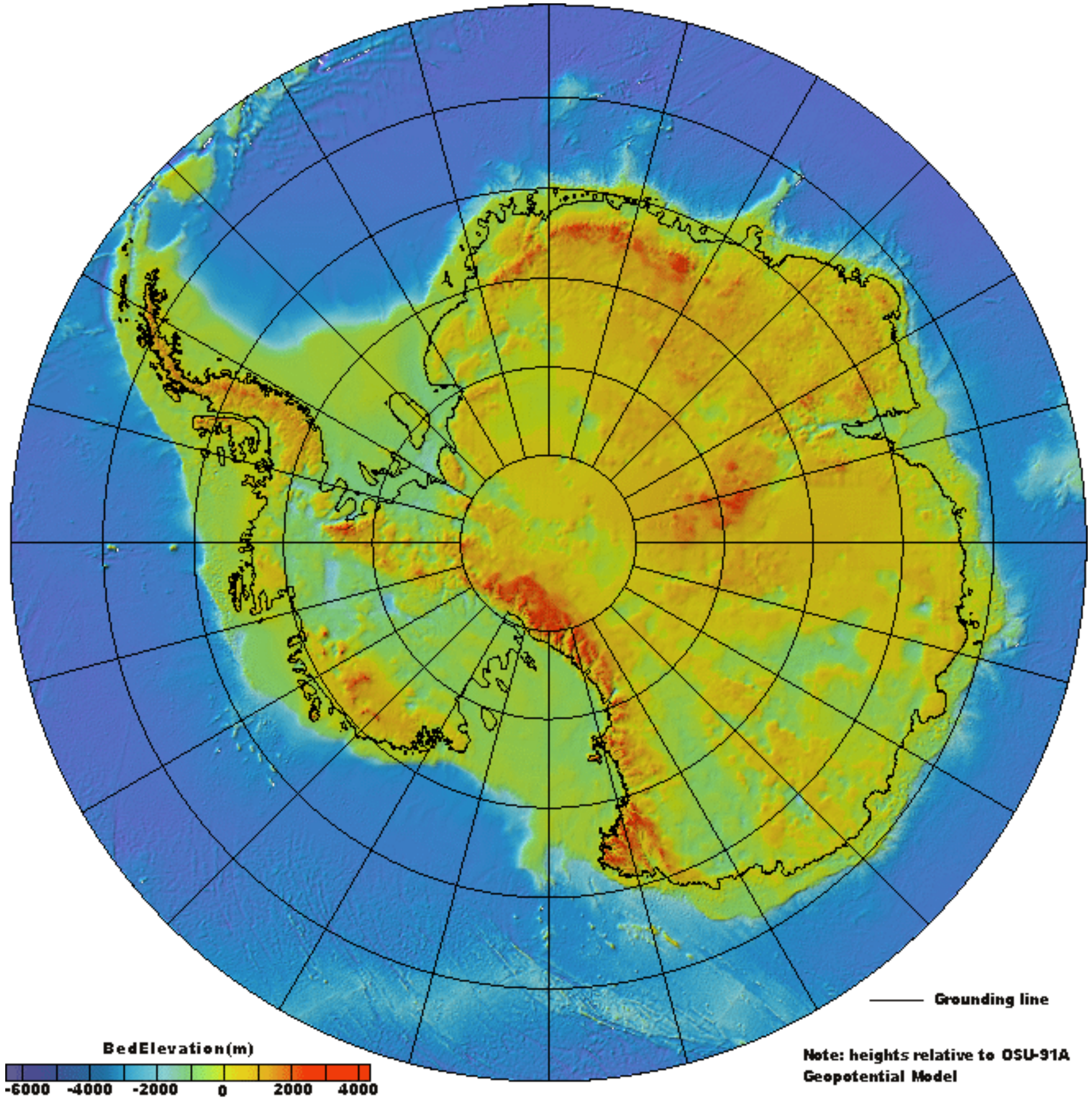

Huybrechts, Clim. Past, 2007

# ice sheet models to search oldest ice



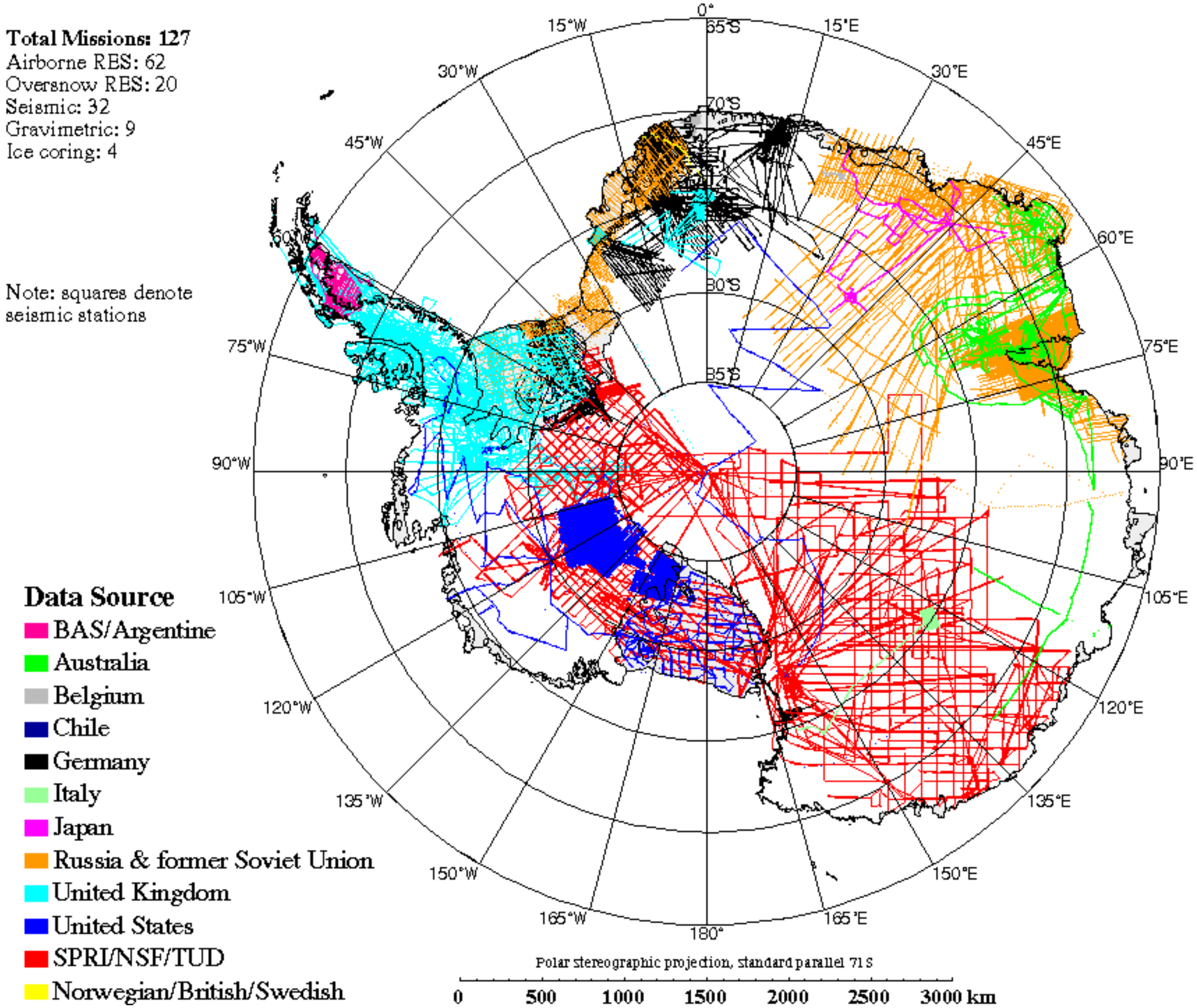

Huybrechts, as reproduced in Nature, 2007

# BEDMAP



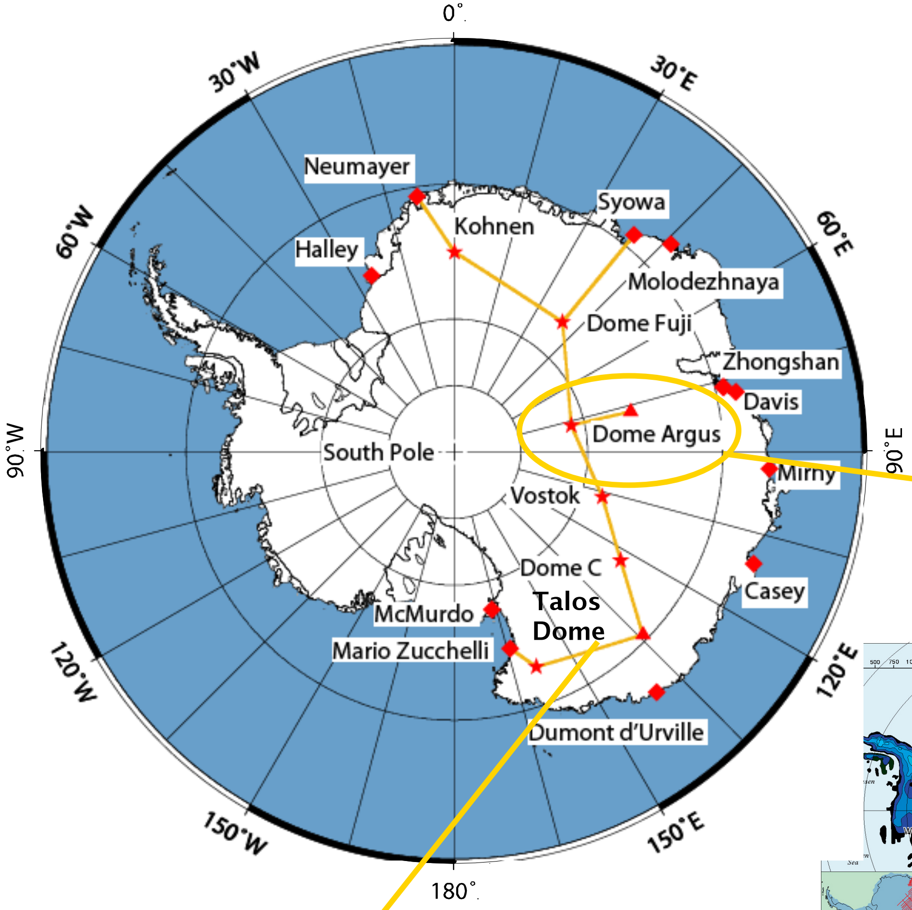

http://www.antarctica.ac.uk/Resources/AEDC/bedmap/examples/bed10.gif

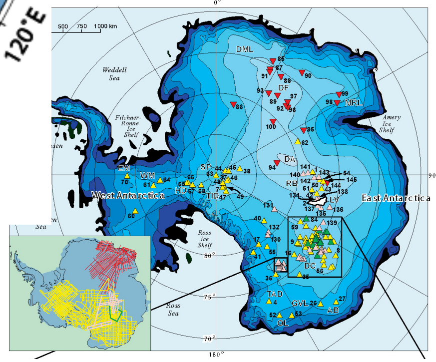
# Mapping of the ice sheet – BEDMAP dataset




http://www.antarctica.ac.uk/Resources/AEDC/bedmap/database/bedmap_coverage.html

# Linking Ice Cores and surveys in East Antarctica



Siegert *et.al.*, *Antarctic Science 17 (3), 453–460,* 2005

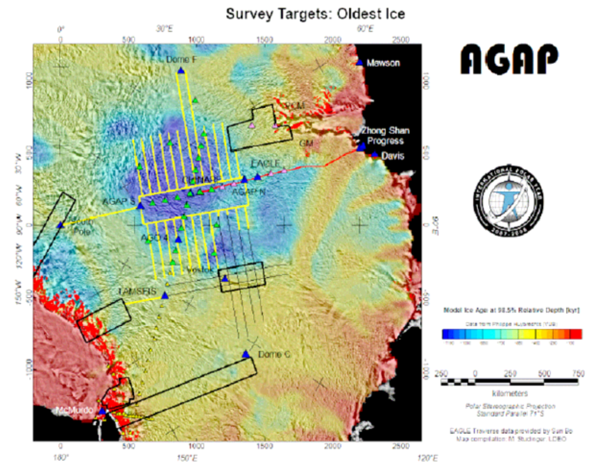


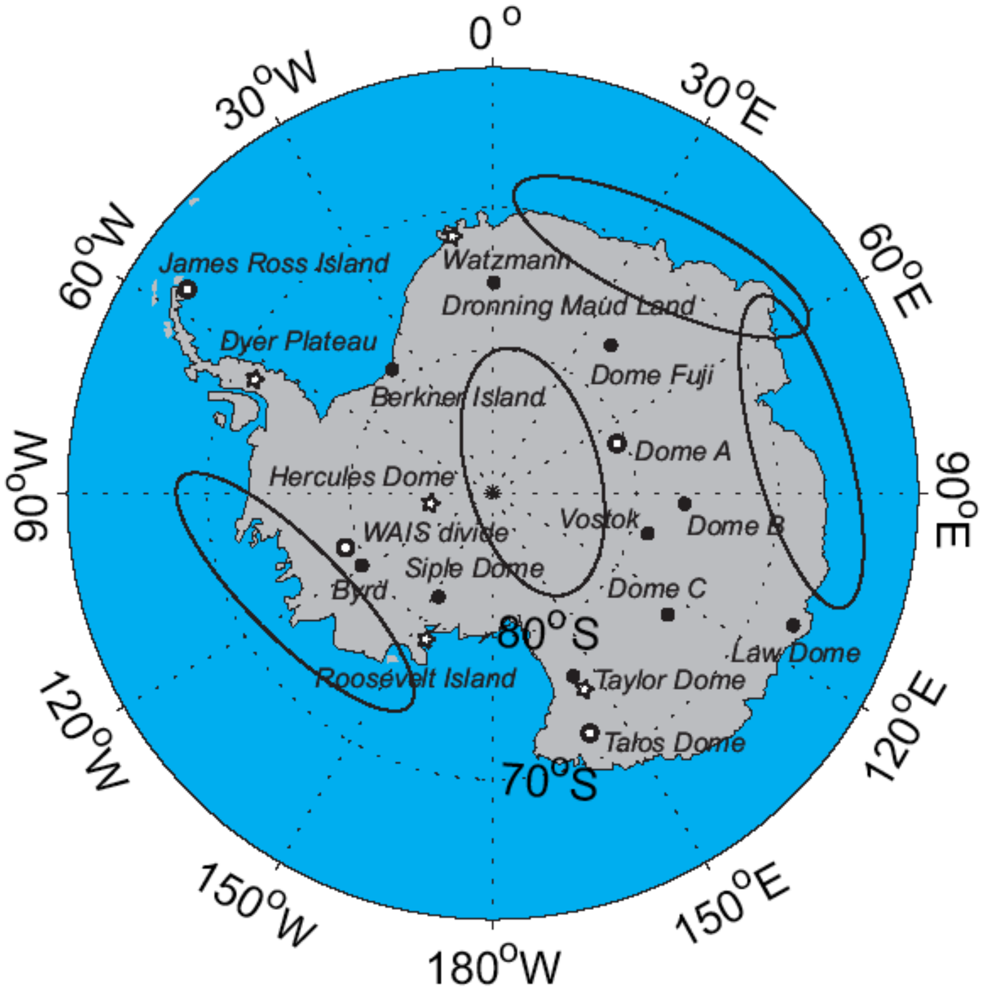

Figure 6. Possible flight lines for the AGAP survey, superimposed on the Huybrechts map of where oldest ice might be found.

map: Daniel Steinhage
Data: Antarctic Digital Database

We have the tools, but to bring the fuel is the challenge

# Logistics for 40k projects






Twin Otter DHC-6, Basler BT-67 based logistics, with ship supply to the coast, personnel moved through major air links. Approved by Berkner Island, Talos Dome, James Ross Island

# Operation in Antarctica – heavy equipment

European logistic means

Air drop capability by ALCI

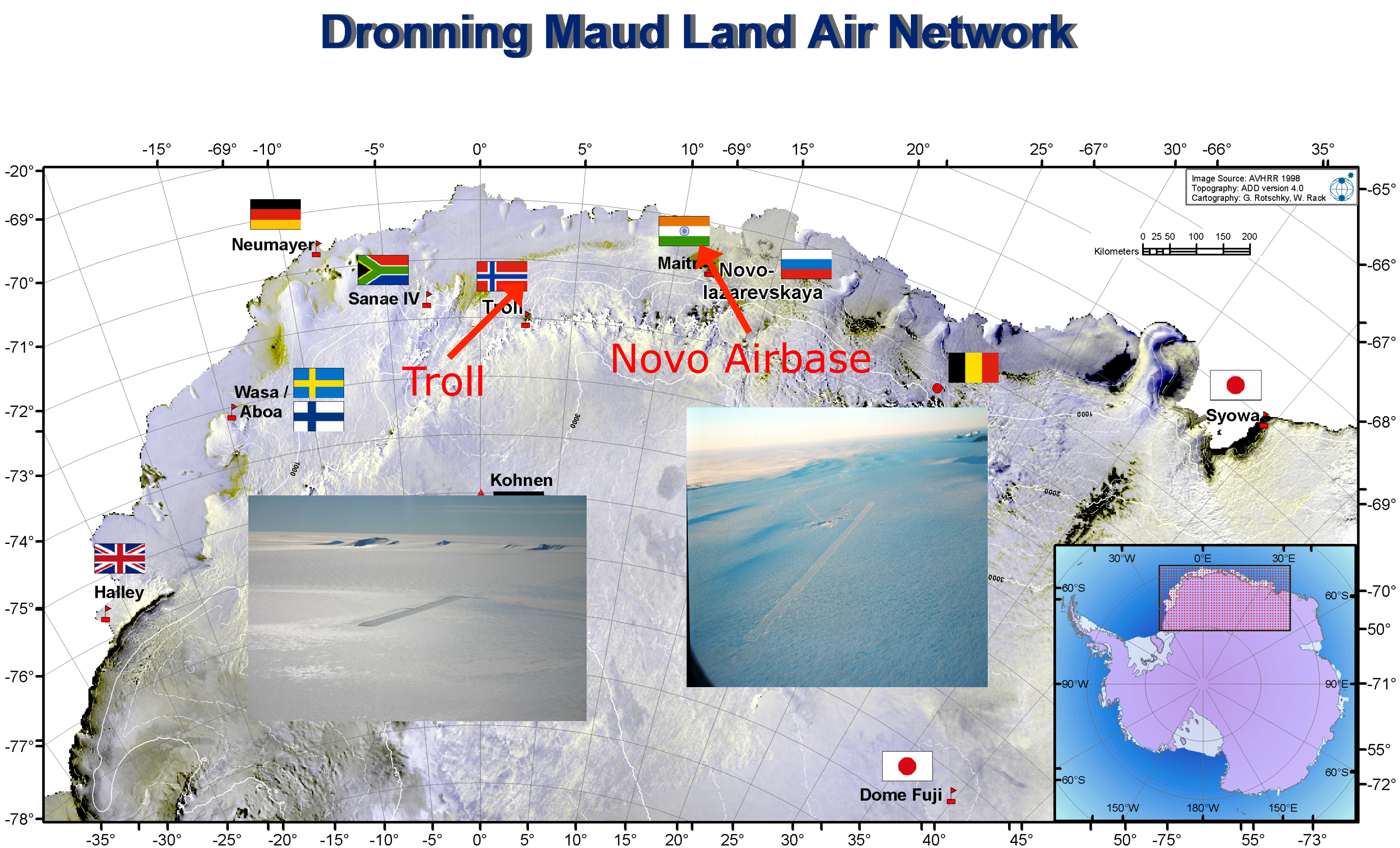
surface traverses

US logistic means additionally LC-130 heavy aircraft operation on the ice

Lightweight field camps

# Personnel to and from Antarctica

# DROMLAN AIR NETWORK




**THE GATEWAYS INTO ANTARCTICA**

# Infrastructure for Ice Coring

# Infrastructure for splitting cores and standard analysis

# socio-economic impact & outreach

# If you look for a drill site from scratch

- define the scientific question: age, resolution, represented area, etc.
- define feasible target area: logistics, safety, time, etc.
- geophysical mapping of the area: ice thickness, surface elevation, surface velocity, optional: gravity, magnetics, seismics, etc.
- shallow core suvey: proxies, accumulation rate, etc.
- if you look for a climatic record: look for an area with comprehension of ice movement (dome, ice divide etc.), appropriate accumulation, low surface velocity, high ice thickness and flat bed