# Ice core science

# Ice cores & paleoclimate

*an introduction*

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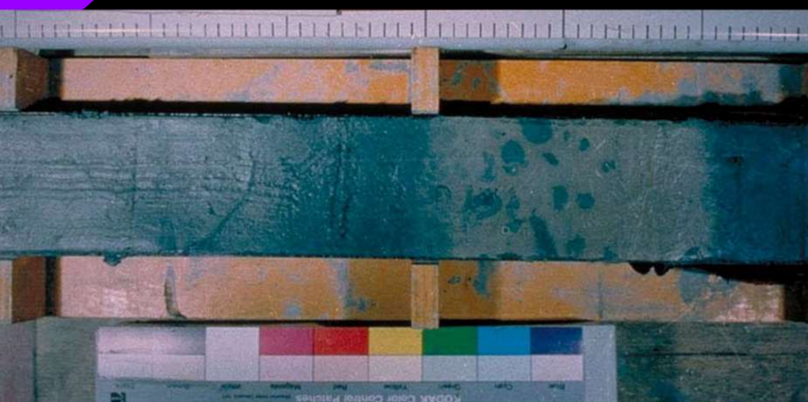
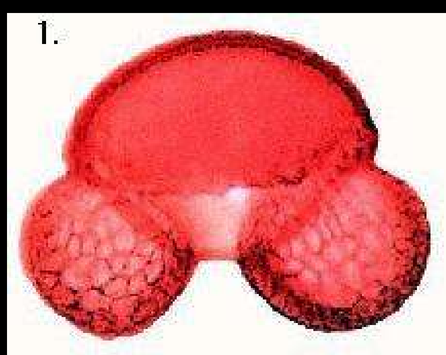
## *Why studying the climate of the past?*

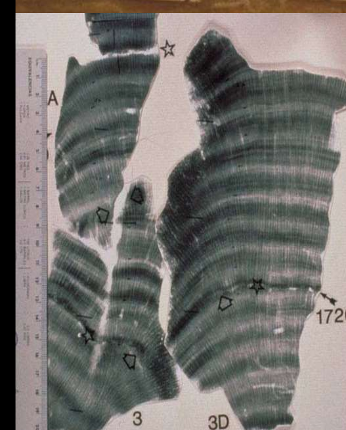
- The scientific community has the obligation to provide a realistic prediction of how climate will change in future.
- This requires a deep understanding of the Earth's climate system and an accurate modeling of how it works and responds to changes.
- This in turn requires a deep understanding the processes that can occur, and how they interact.
- This knowledge comes only from studying past climate variability

# Natural archives of climate information

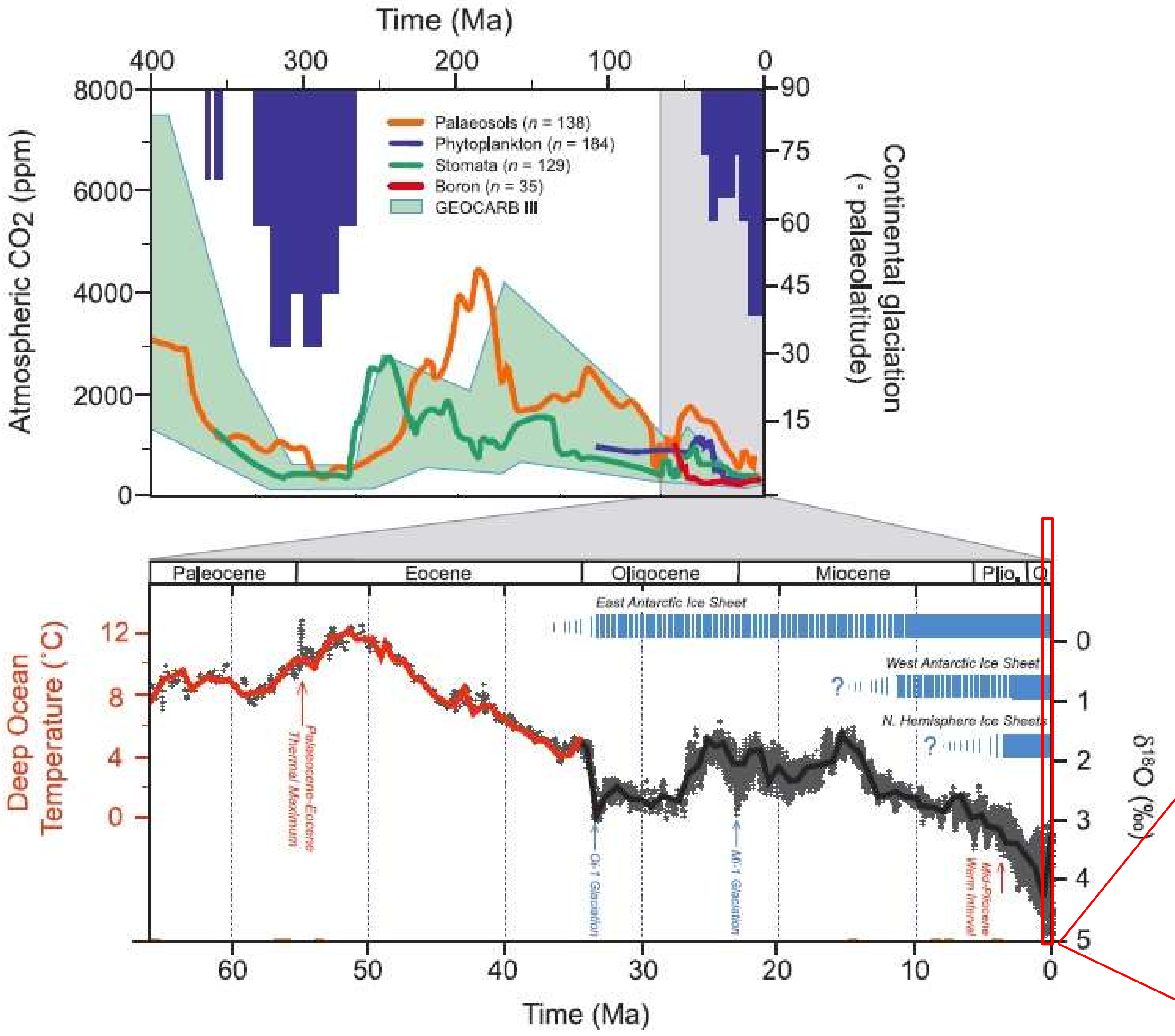
-Terrestrial: pollen and faunal records, loess series, lake sediments, speleothems, peat bogs, etc.
-Marine: deep sea core sediments, corals,..
-Glacial: ice cores



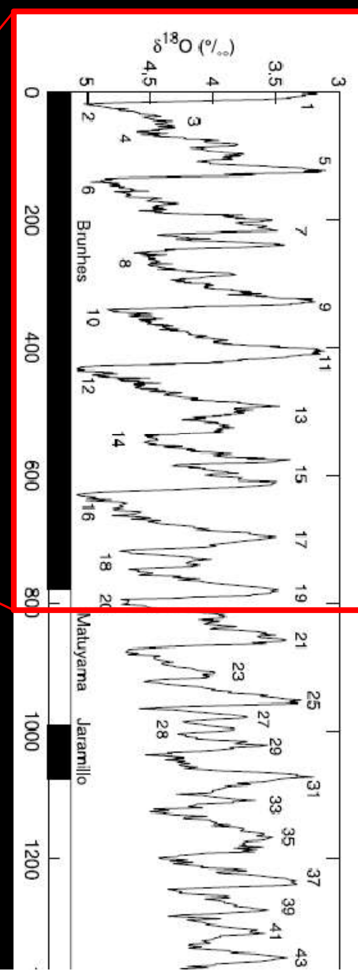



# Polar ice cores document late Quaternary climate changes




IPCC,2007




Lisiecki and Raymo, 2005

# FAQ

- What’s an ice core?
- Where can ice cores be drilled?
- Where are the most important drilling sites?
- Which proxies can be measured in ice?
- How can ice cores be dated?

# What's an ice core?

*Cores made of meteoric glacier ice.*

Meteoric ice from glaciers can be compared to a ***(meta)sedimentary rock*** deriving from the deposition of layers of snow (sediment), later hardened by compaction and pressure-sintering into firn and ice (sedimentary rock), eventually transformed into glacier ice by crystal growth and re-orientation in a temperature/pressure/stress field (metamorphic rock).

# Where can ice cores be drilled ?

## Temperate glaciers: not suitable

Made of "warm ice" (pressure melting point)

Presence of water throughout

"Isothermal" vertical profile acquired through repeated melting/freezing and release of latent heat

Original characteristics acquired by the snow *are not preserved*

# Where can ice cores be drilled ?

## Cold glaciers: suitable

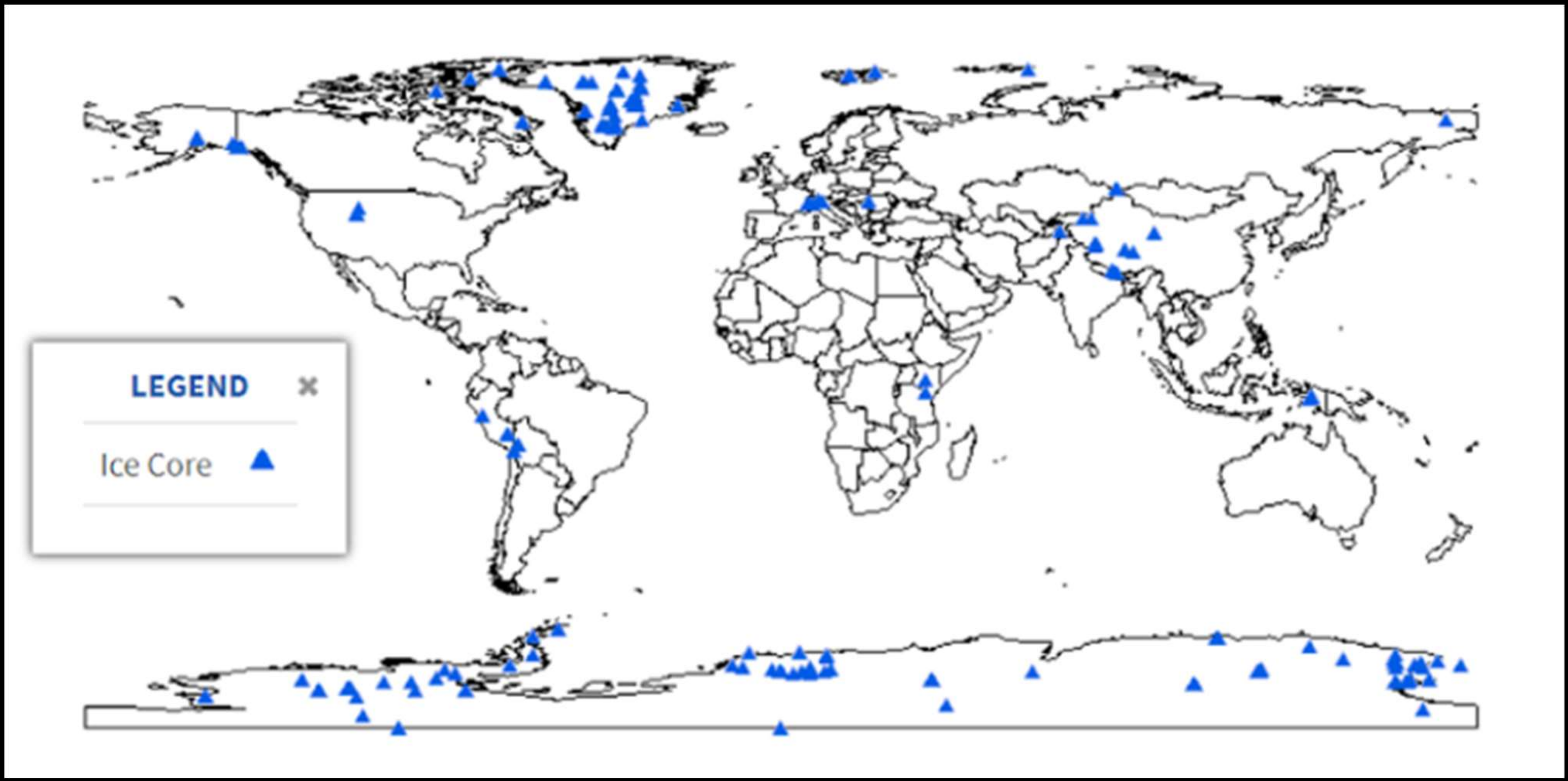
Cold ice below pressure melting point

Cold snow deposited and preserved without melting, trasformed into firn and metamorphosed into glacier ice

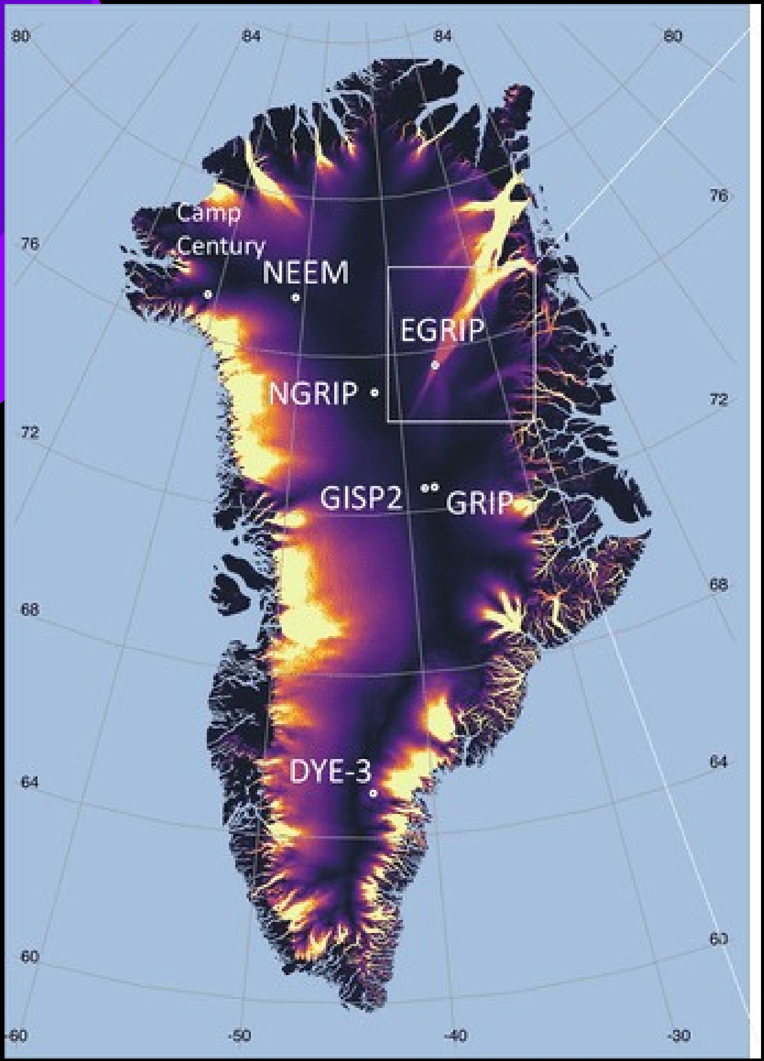
Vertical thermal profile depending on snow temperature and geothermal flux

Preservation of many of the original physico-chemical signals acquired by the snow from the air masses in which was formed.

# Ice core drilling sites



# Deep ice core drilling sites GREENLAND




**Camp Century**, 1387 m deep, year 1966

**Dye3**, 3037 m deep, year 1981

**GRIP**, 3029 m deep, year 1992

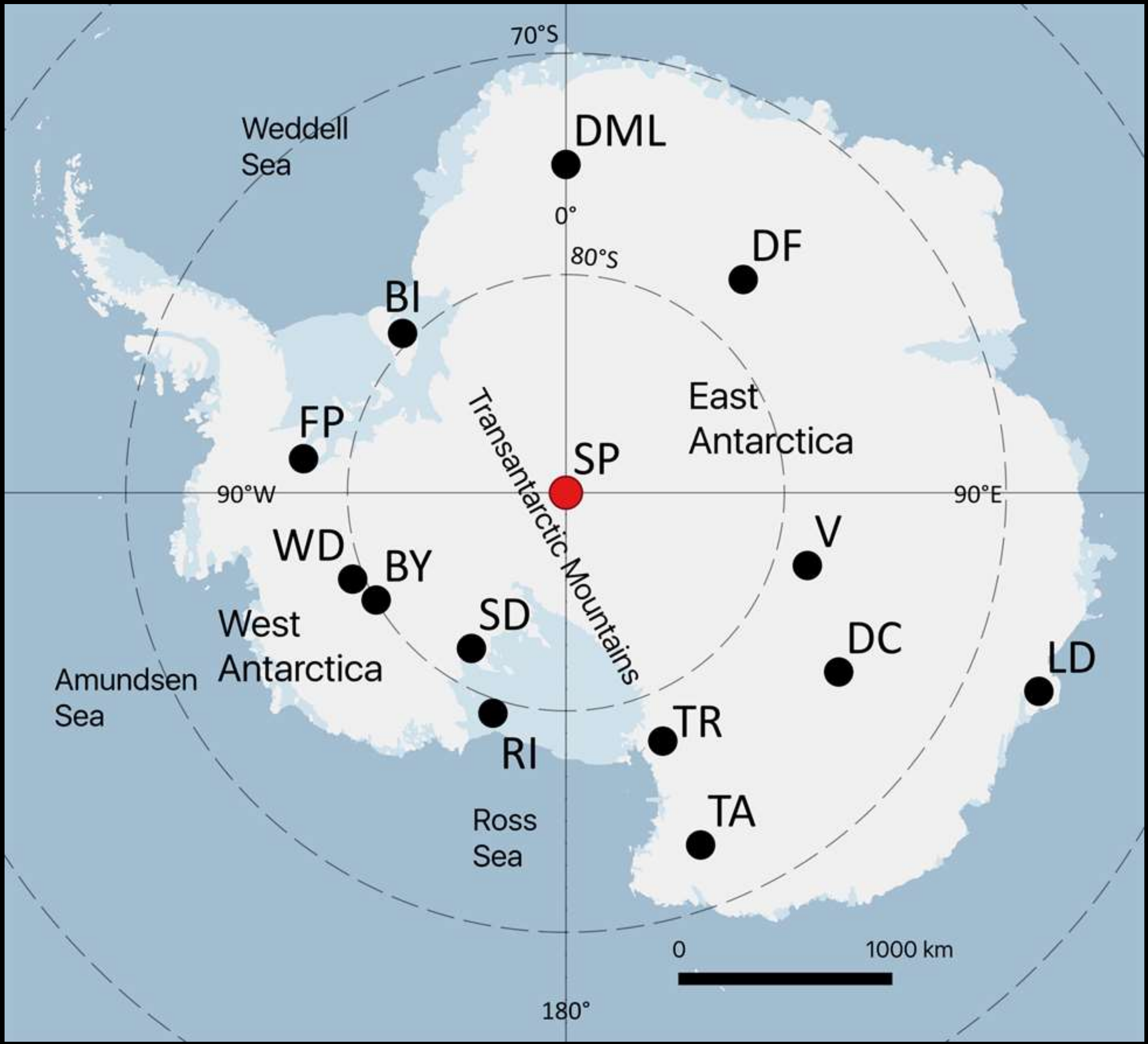
**GISP2**, 3053 m deep, year 1993

**NGRIP**, 2931 m deep, year 2000

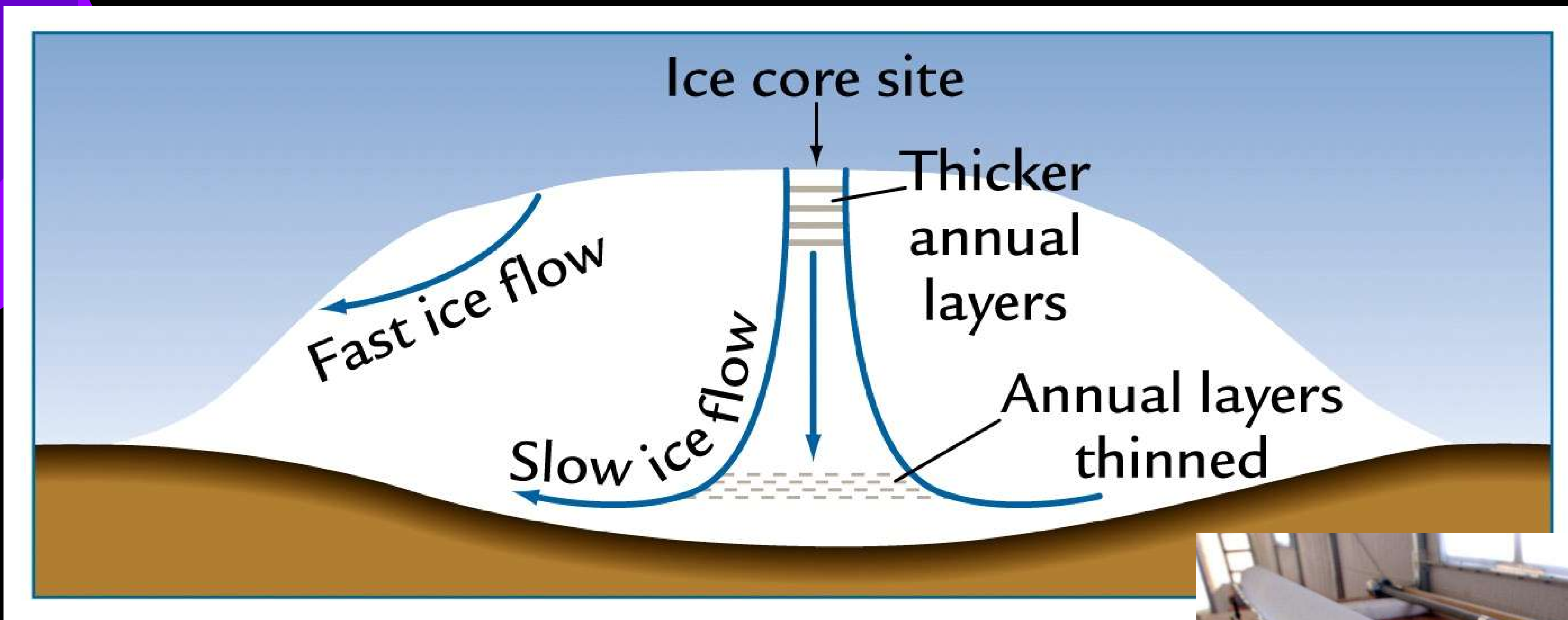
**NEEM**, 2540 m deep, year 2012

# Deep ice core drilling sites ANTARCTICA

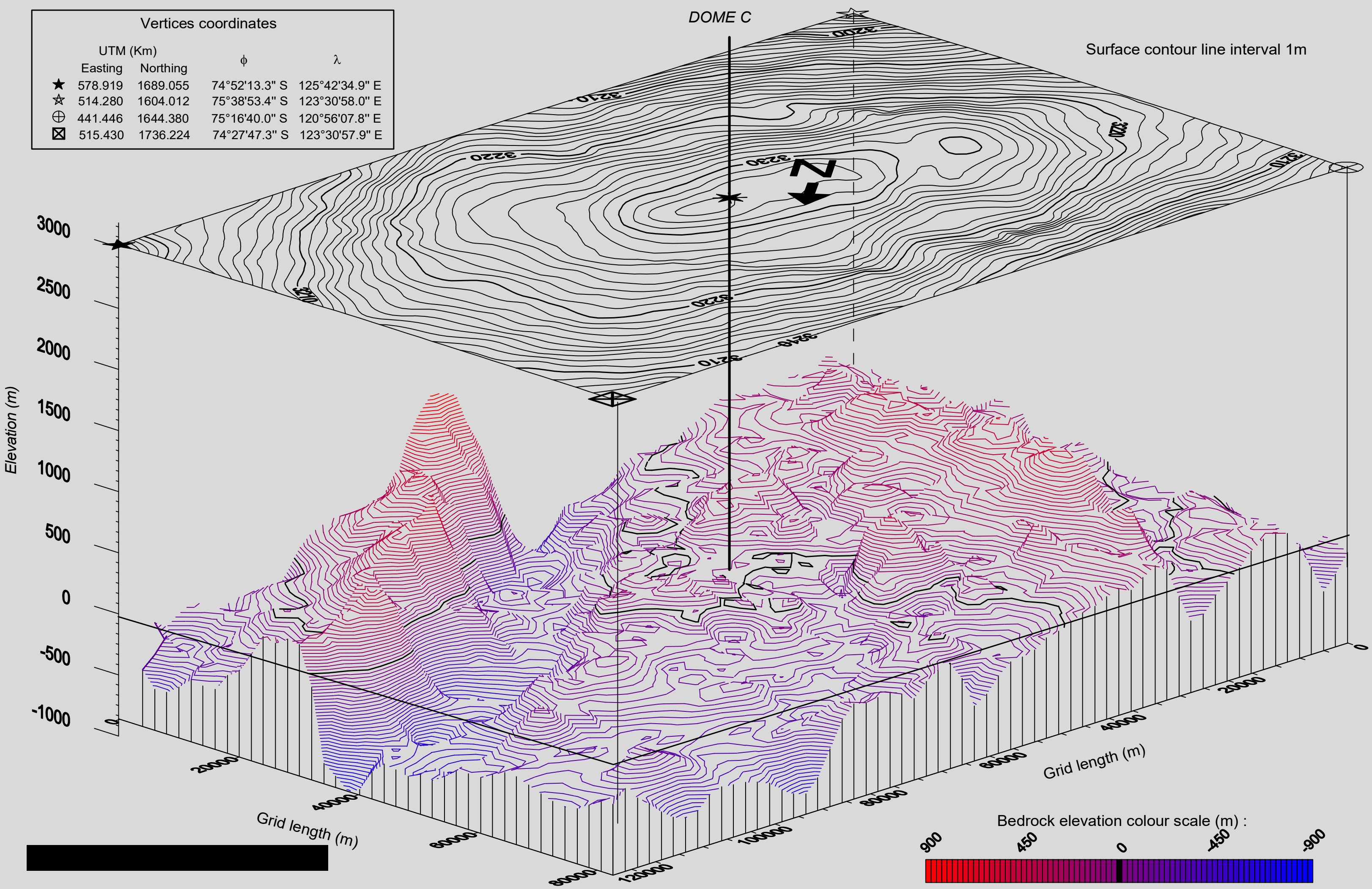
There are logistical constraints related to the access to remote sites and difficulties linked to the drilling technology itself



*The best conditions for ice core drilling are topographic culminations of polar ice sheets, where the horizontal Surface velocity is very small (few mm/yr) and the subglacial bedrock has flat or smooth topography.*




# Dome C
# ice sheet surface and bedrock topography

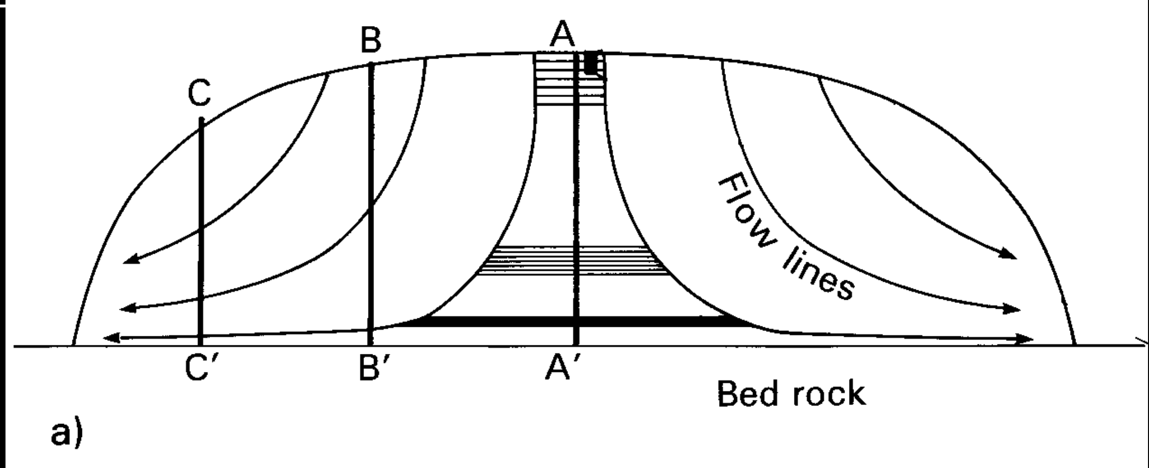



*Tabacco et al., 1998*

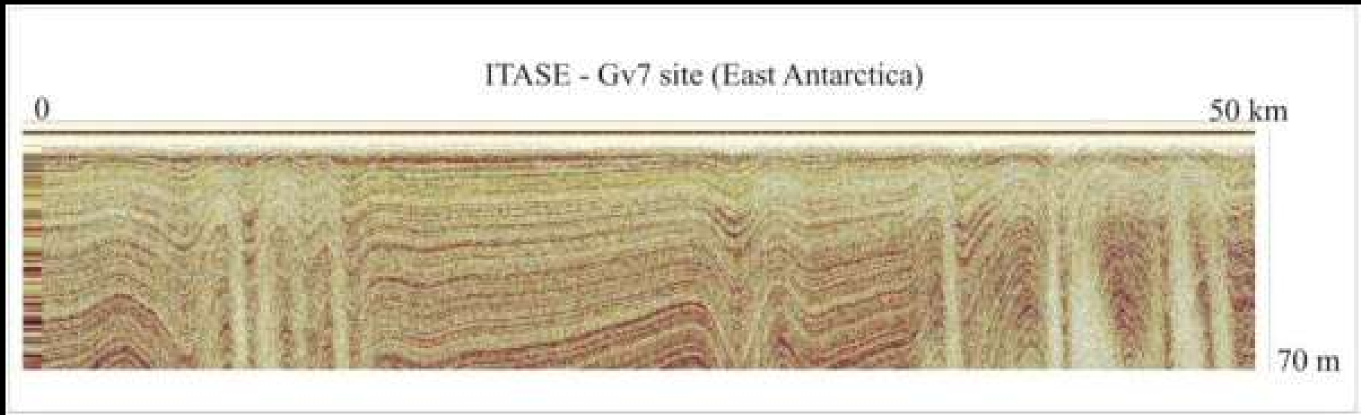
# Schematic ice sheet considered frozen to a horizontal bedrock

Flow lines diverge from the interior to the periphery. Cores B and C will cross ice formed more and more inland of the drilling site. At A, near the divide, the ice moves downward, thinning with depth but preserving the original horizontal layering.

*(Modified after Bradley, 1992)*



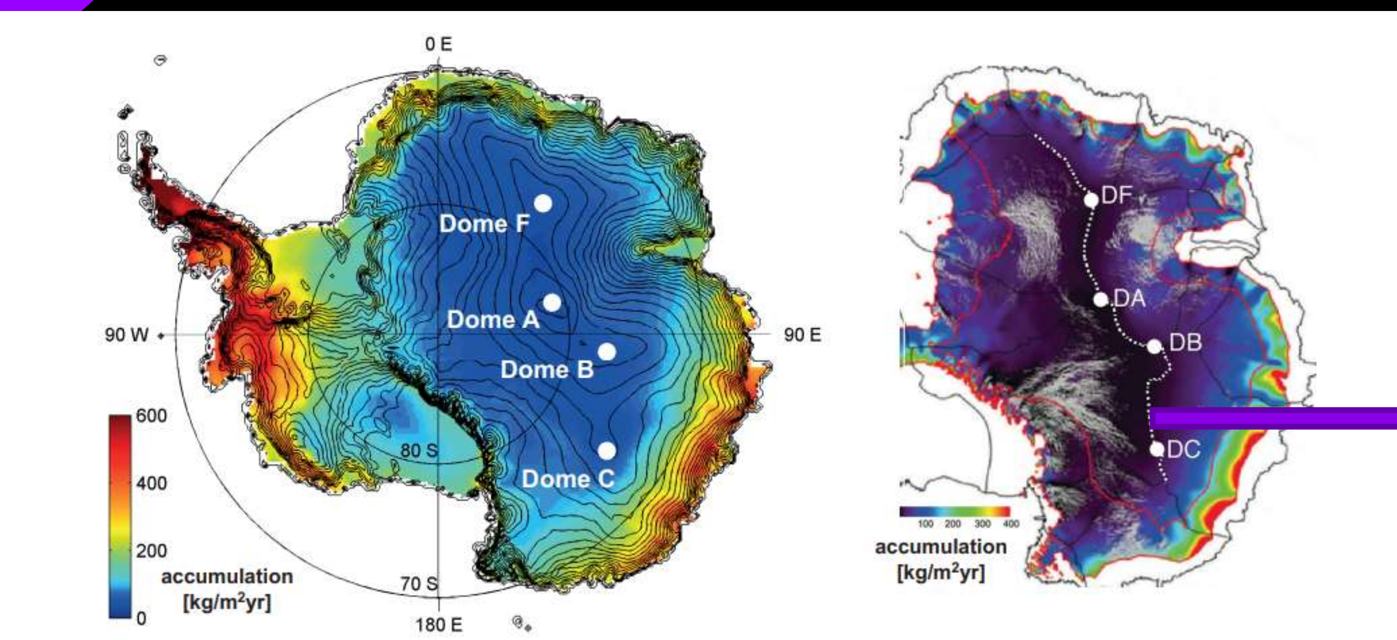

Deep penetrating radar surveys reveal many subparallel reflectors due to discontinuities of electrical properties, which are considered isochronous and coinciding with depositional surfaces.

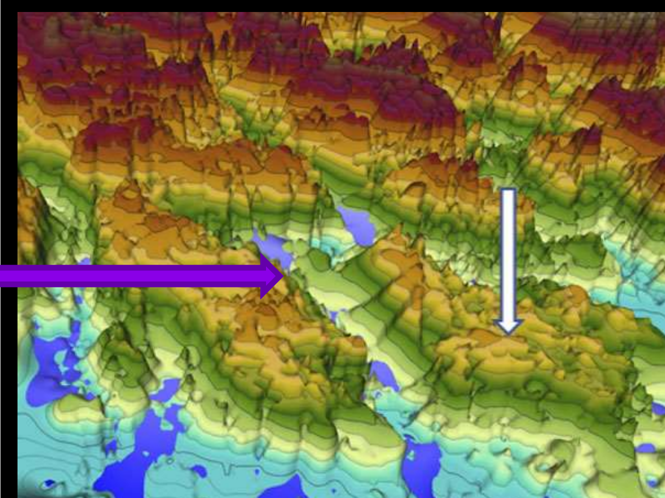


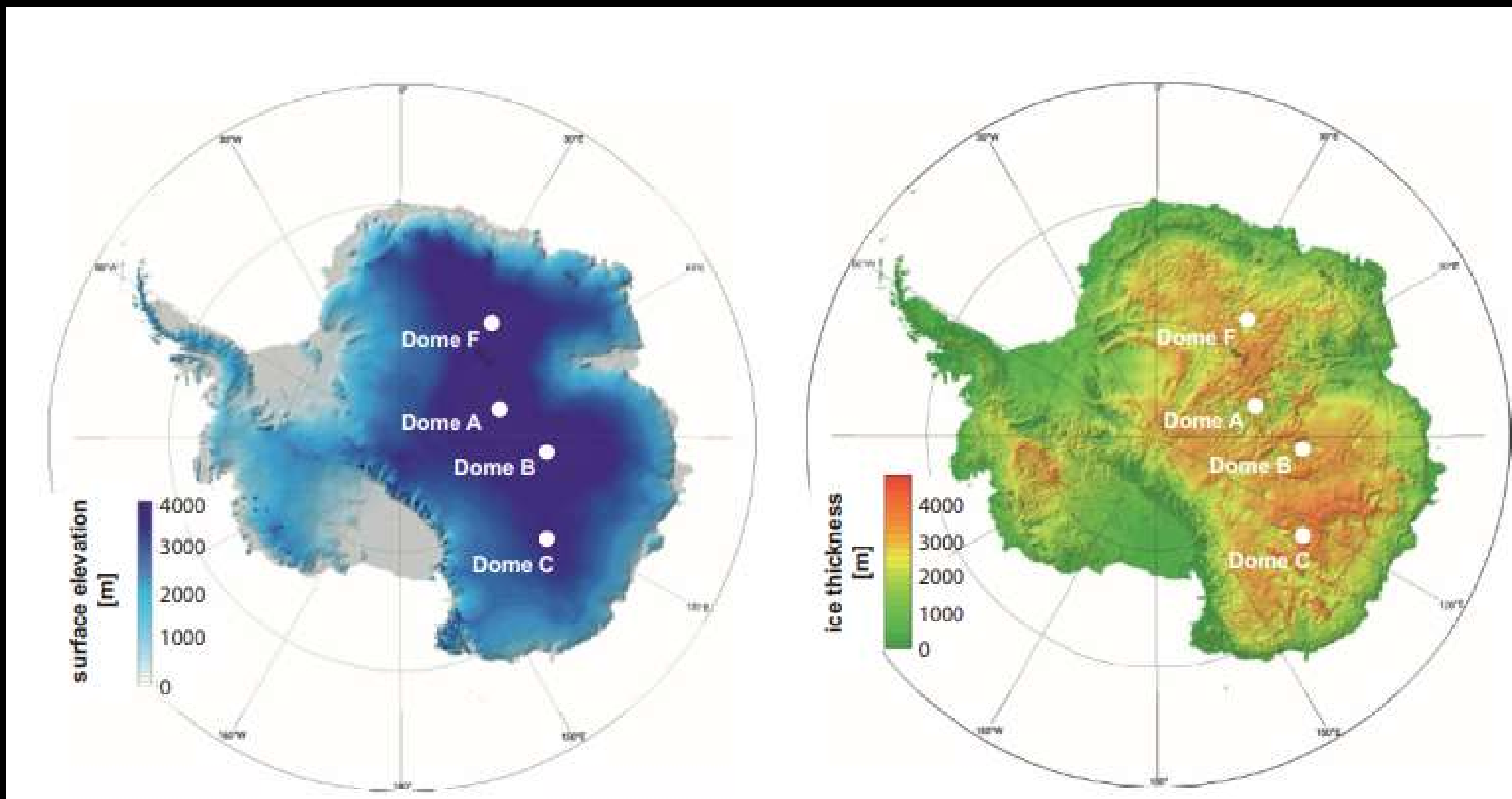

(*Zirizzotti et al., 2010)*

# Where can we find the oldest ice core?

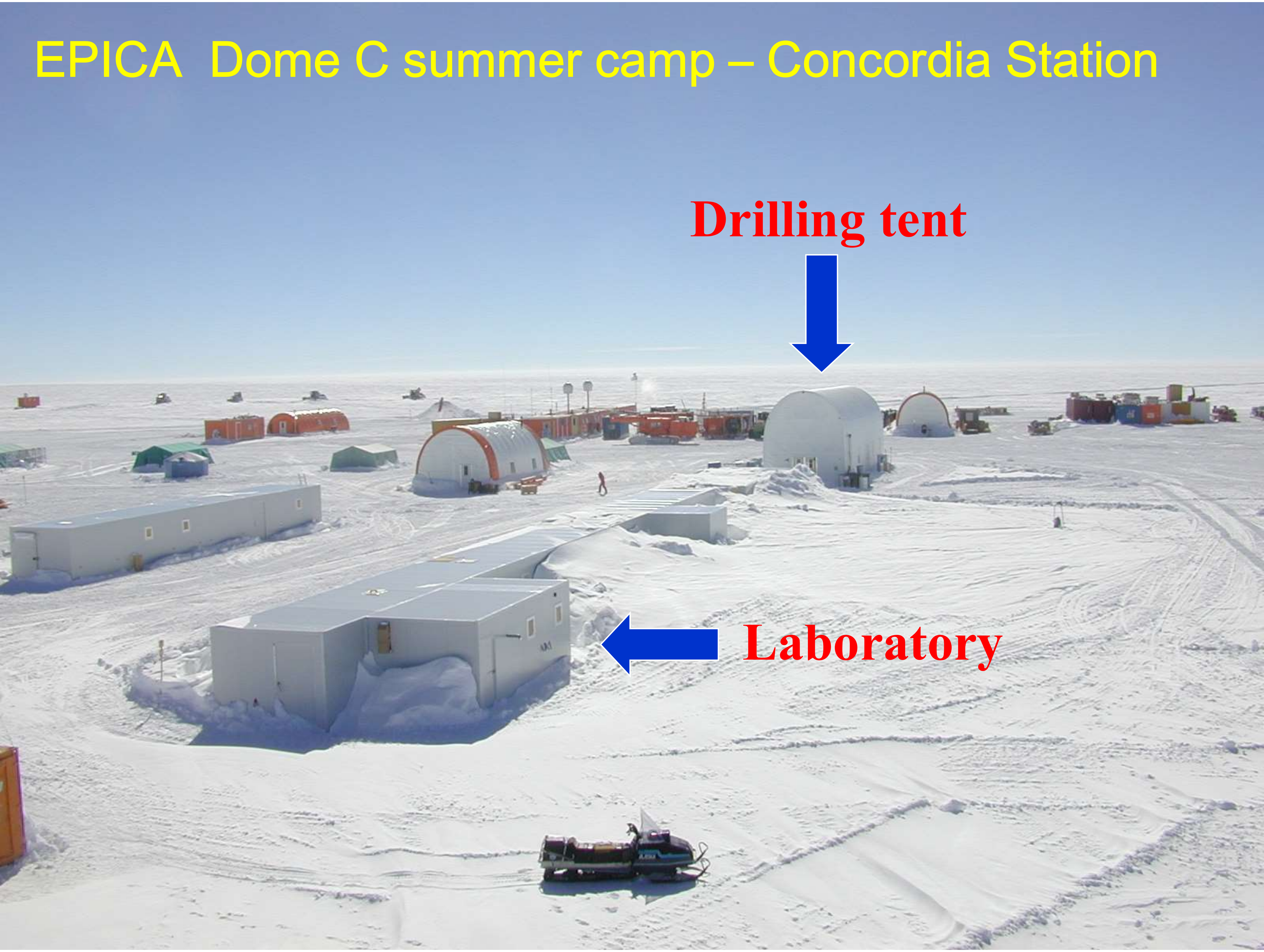
- Constraints are provided by (1) accumulation, (2) ice thickness, (3) geothermal heat flux



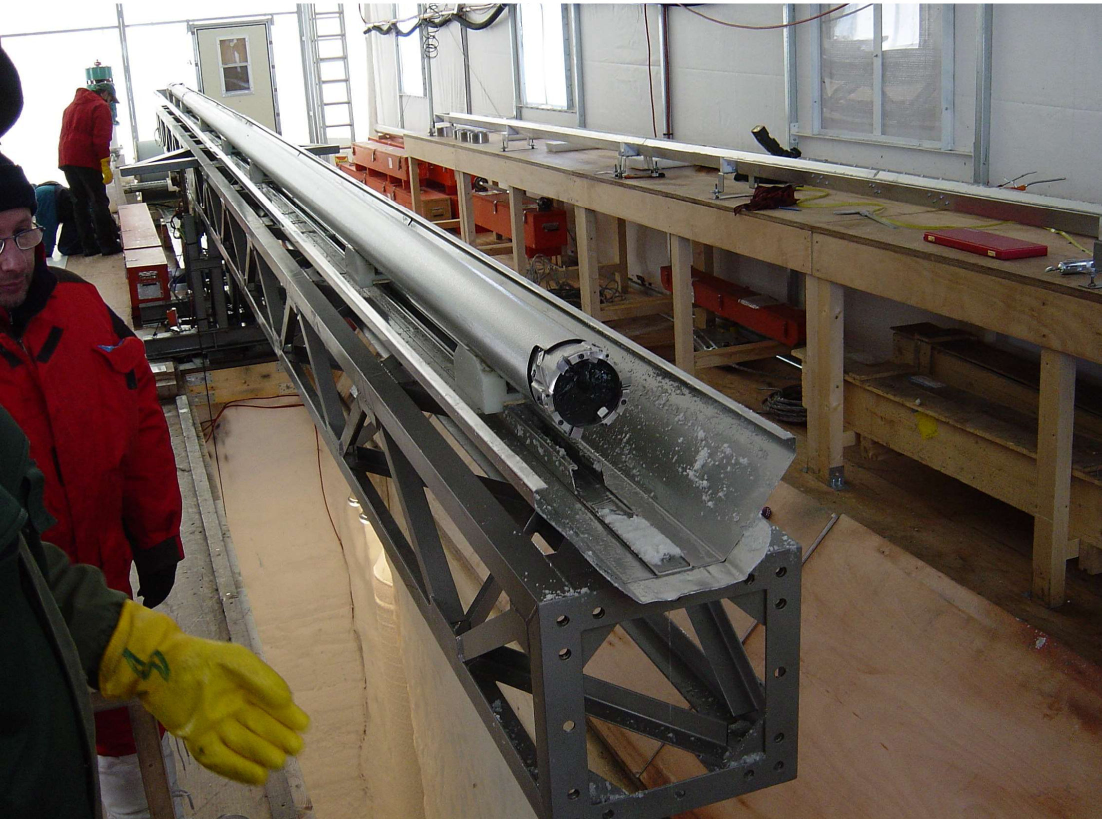




Dome F
Dome A
Dome B
Dome C
surface elevation [m]
4000
3000
2000
1000
0
Dome F
Dome A
Dome B
Dome C
ice thickness [m]
4000
3000
2000
1000
0

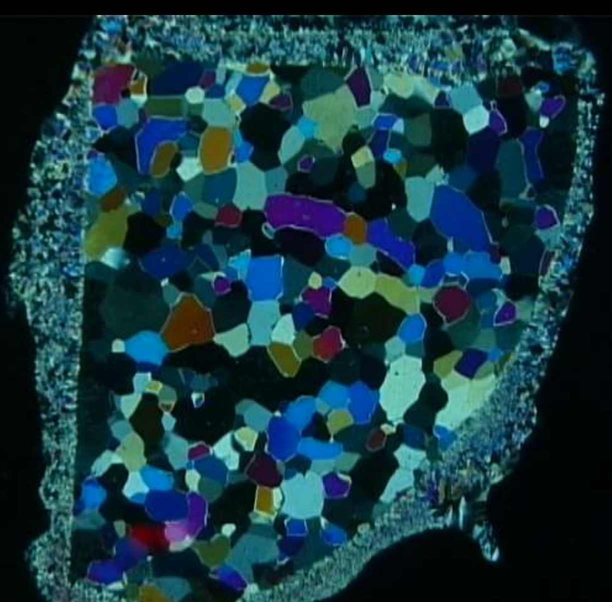

CATERPILLAR


EPICA Dome C summer camp – Concordia Station
Drilling tent
Laboratory

# Drilling activities

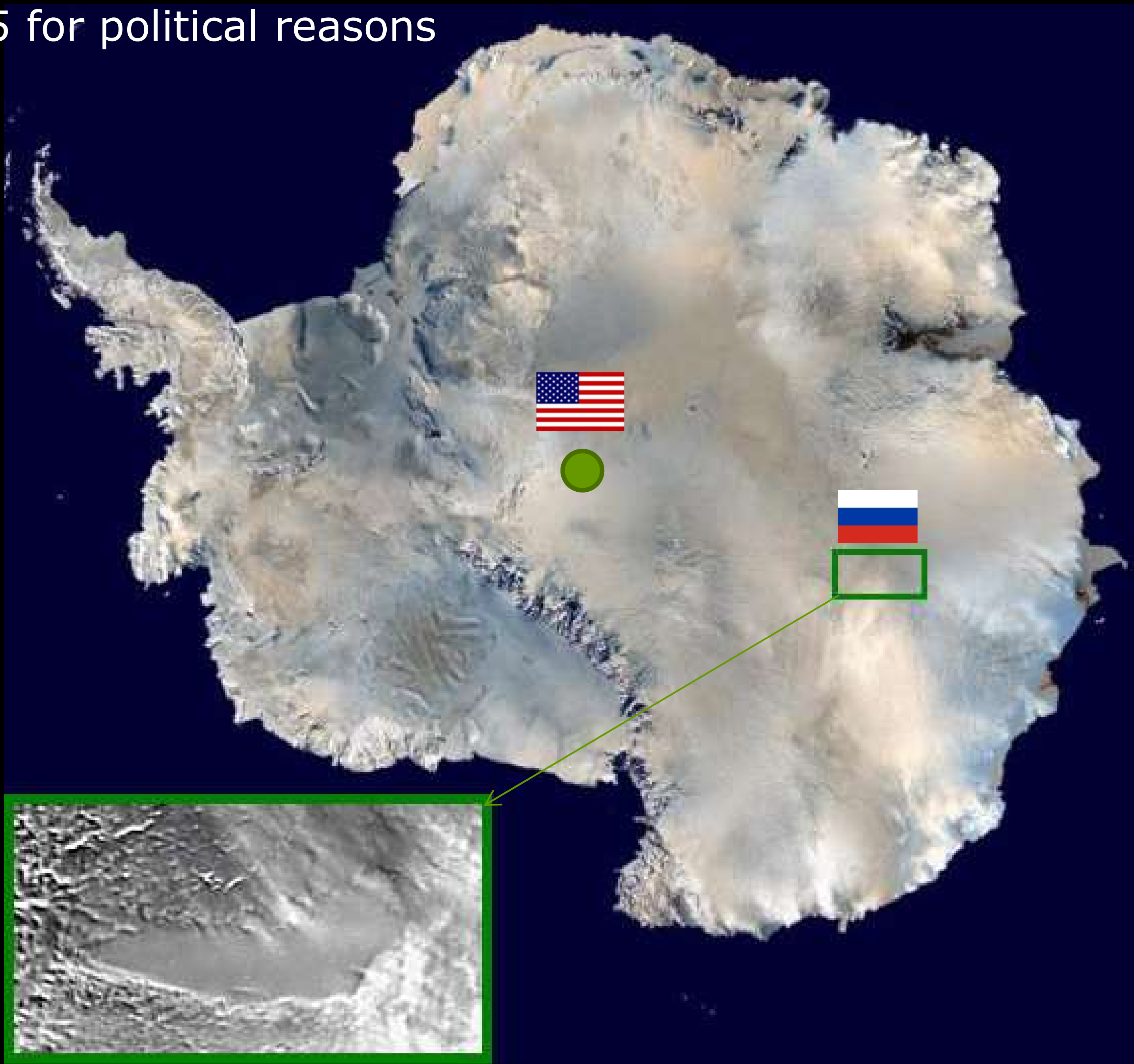


# Core processing in situ



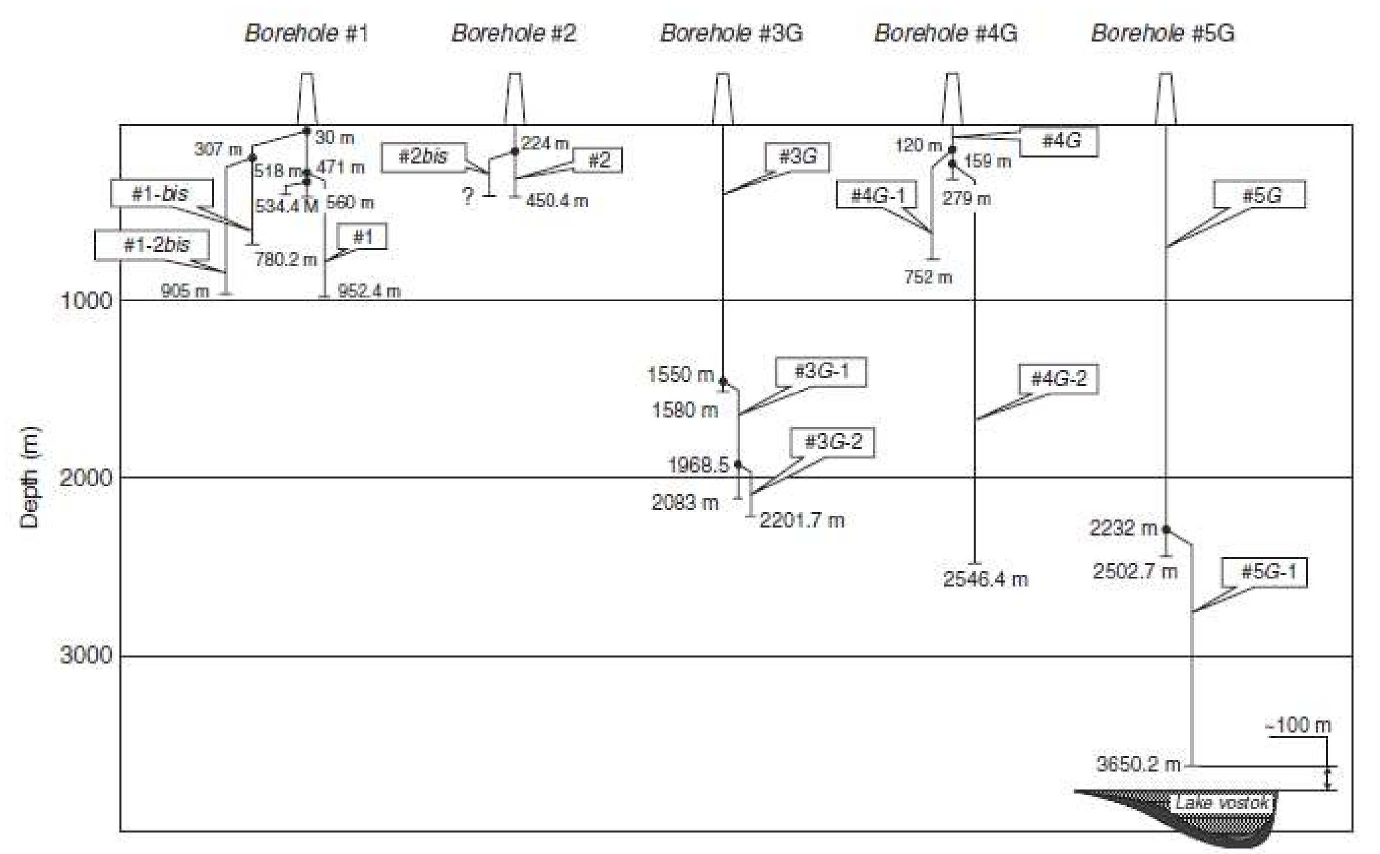
# Two important exceptions: South Pole & Vostok

..selected in 1955 for political reasons

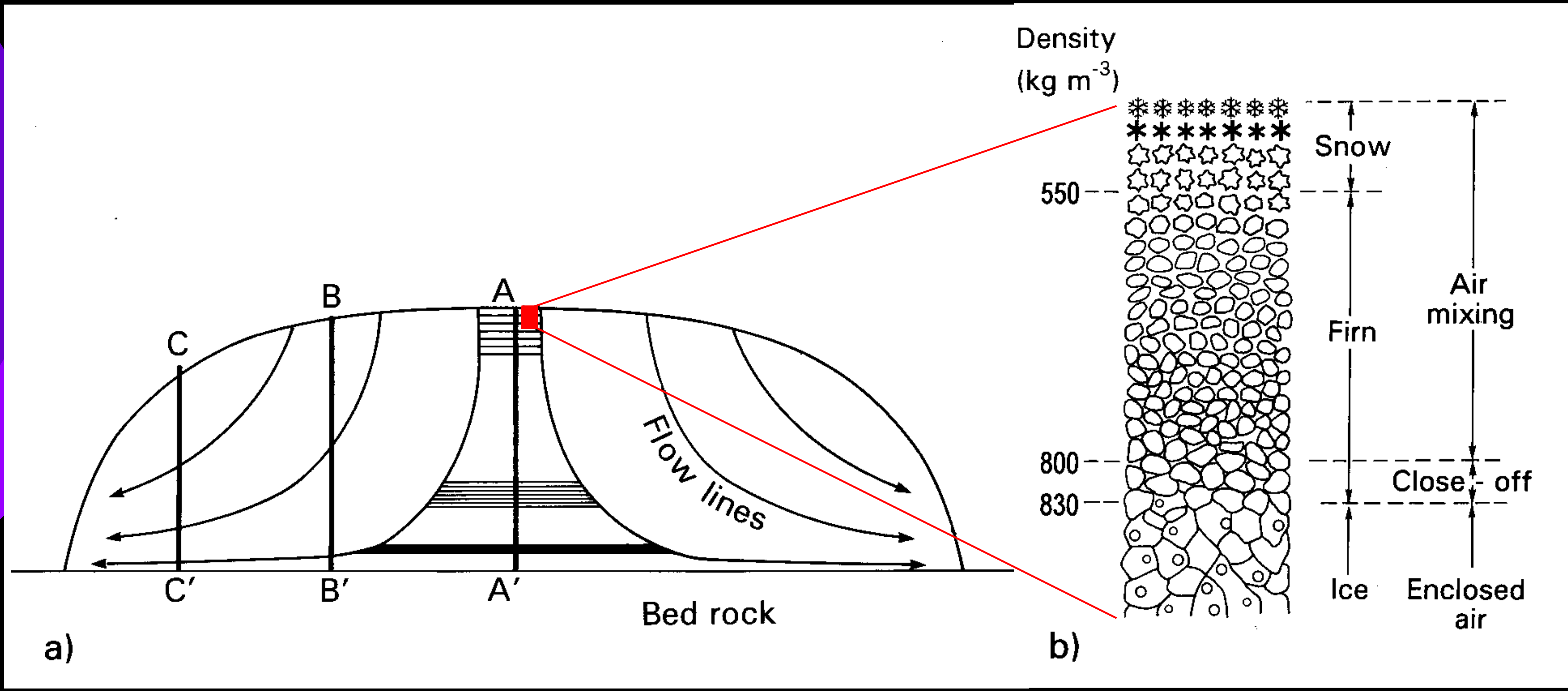


The former Leningrad Mining Institute (St. Petersburg State Mining Institute since 1991) started in 1970 a series of ice core drilling project in Vostok.

Borehole # 1 - 952 m (deepest dry drilling, ended in 1972);
Borehole #2 - 450.4 m;
Borehole #3G (3G-1, 3G-2) - 2201.7 m;
Borehole # 4G (4G-1, 4G-2) - 2546.4 m;
Borehole # 5G (5G-1) -3650.2 m



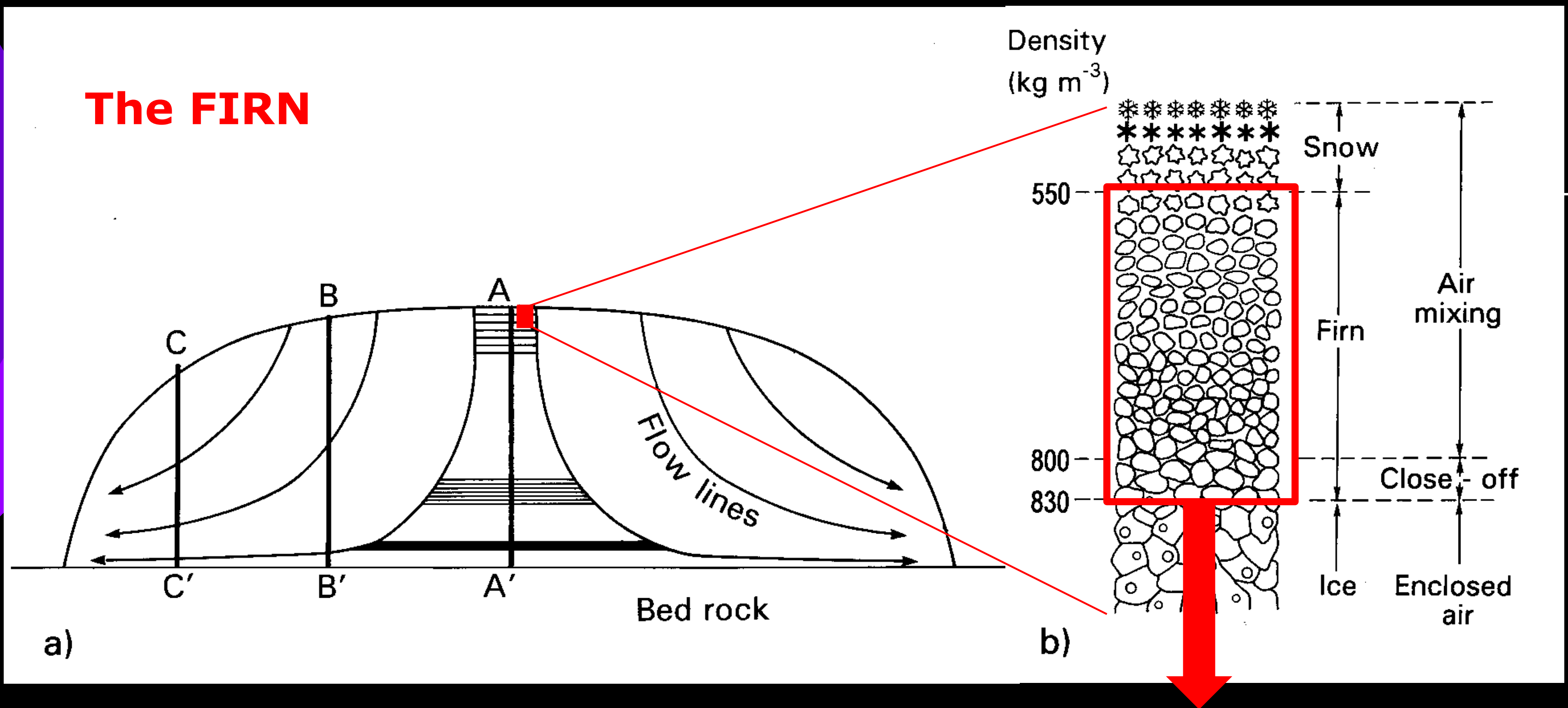

*(Modified after Bradley, 1992 and after Legrand at al., 1995)*




Snow transforms into firn and glacier ice, with increase in density and reduction of open voids.

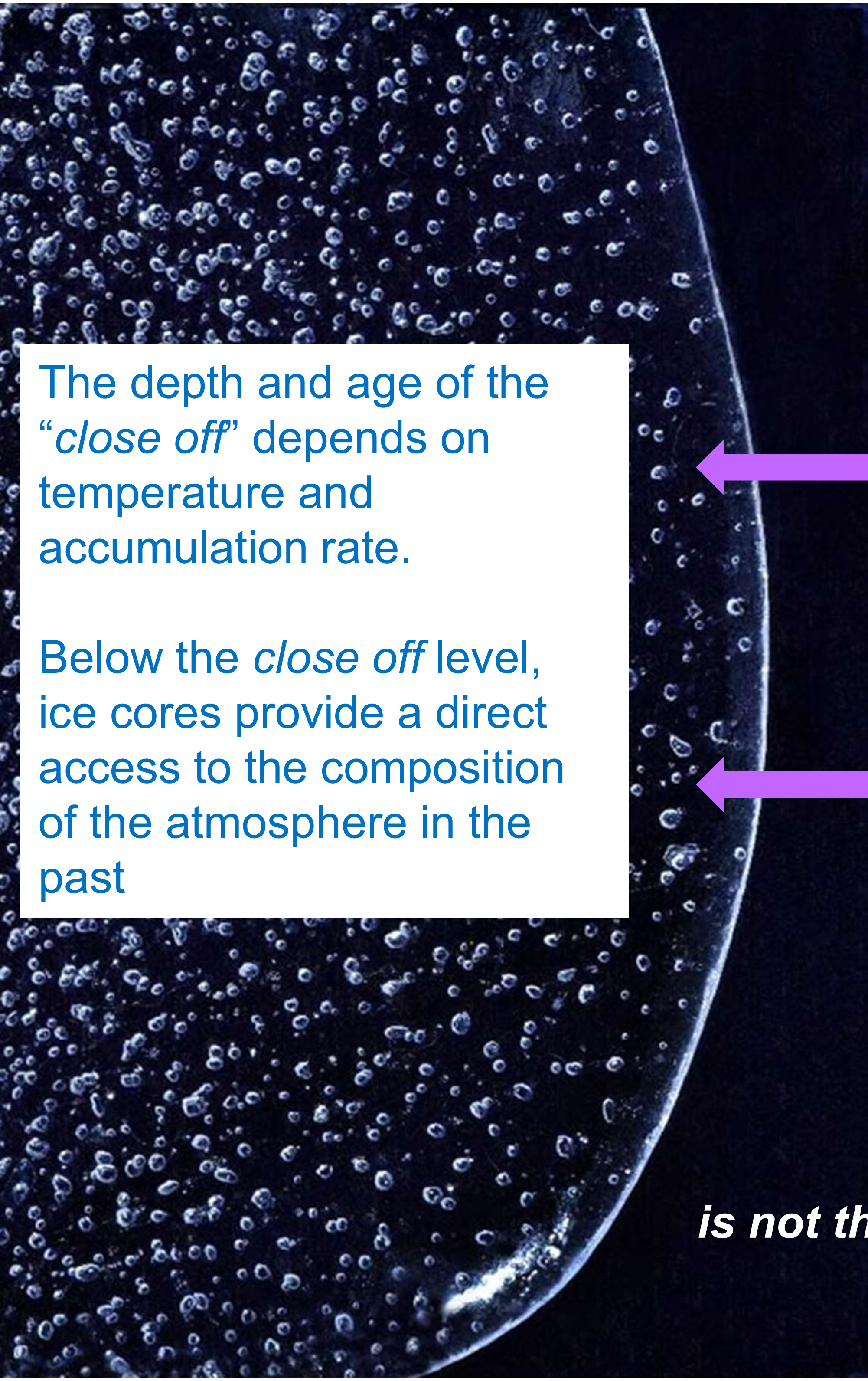
At the firn/ice transition depth, the pores are sealed and air entrapped. Therefore, not only snow/firn and ice preserve climate and environmental information but also “fossil air”.

*(Modified after Bradley, 1992 and after Legrand at al., 1995)*



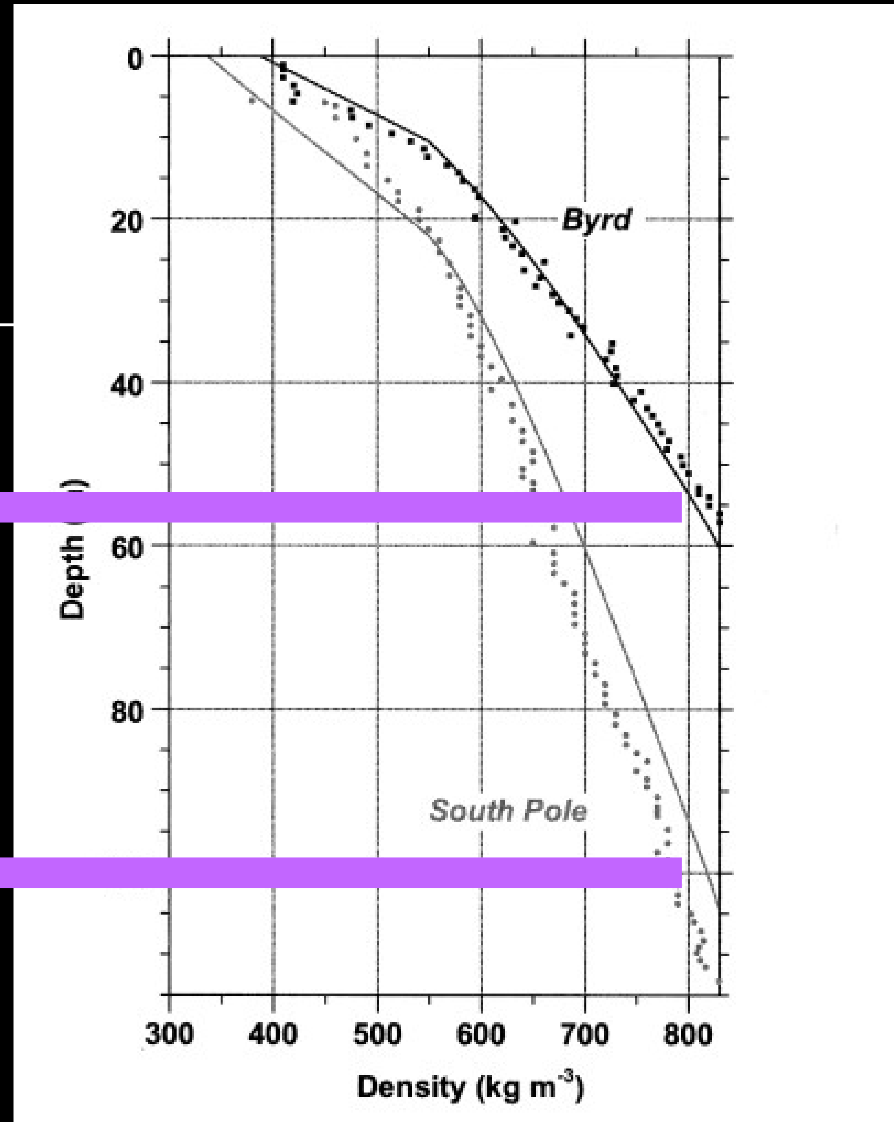

Firn can be divided into 3 three sections in terms of gas flows (Sowers et al., 1992, Severinghaus and Battle, 2006):

1-**CONVECTIVE ZONE** where gases are freely mixed with the atmosphere by wind pumping (Colbeck, 1989, Kawamura et al., 2006); from 0 to 2 m in Greenland. No gas fractionation.
2-**DIFFUSIVE ZONE** in which gases are nearly in diffusive equilibrium. In this section, gas movements are governed primarily by molecular diffusion, and gas fractionation occurs. 65–70 m thick in Greenland (Schwander et al., 1993).
3-**LOCK-IN ZONE** (~10 m), where the vertical mixing of the gas is inhibited by sealing of dense layers, but horizontal mixing still occurs in less-dense layers. All the bubbles are closed at the bottom of the lock-in zone.



The depth and age of the "*close off*" depends on temperature and accumulation rate.

Below the *close off* level, ice cores provide a direct access to the composition of the atmosphere in the past

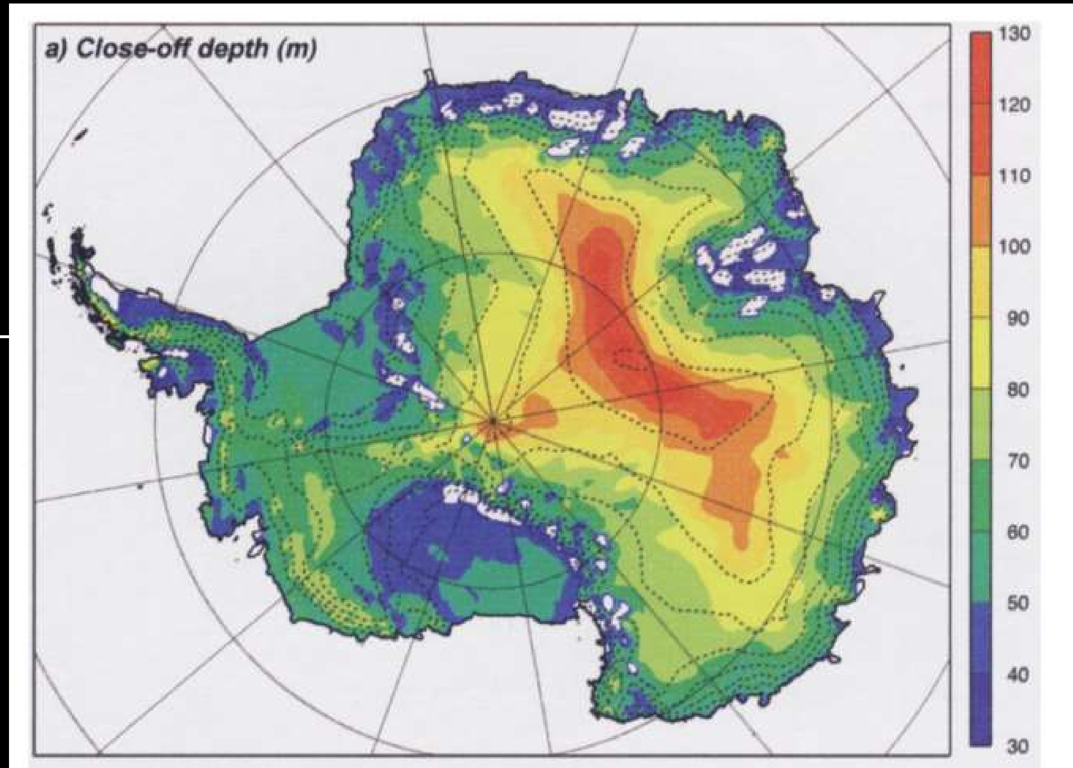


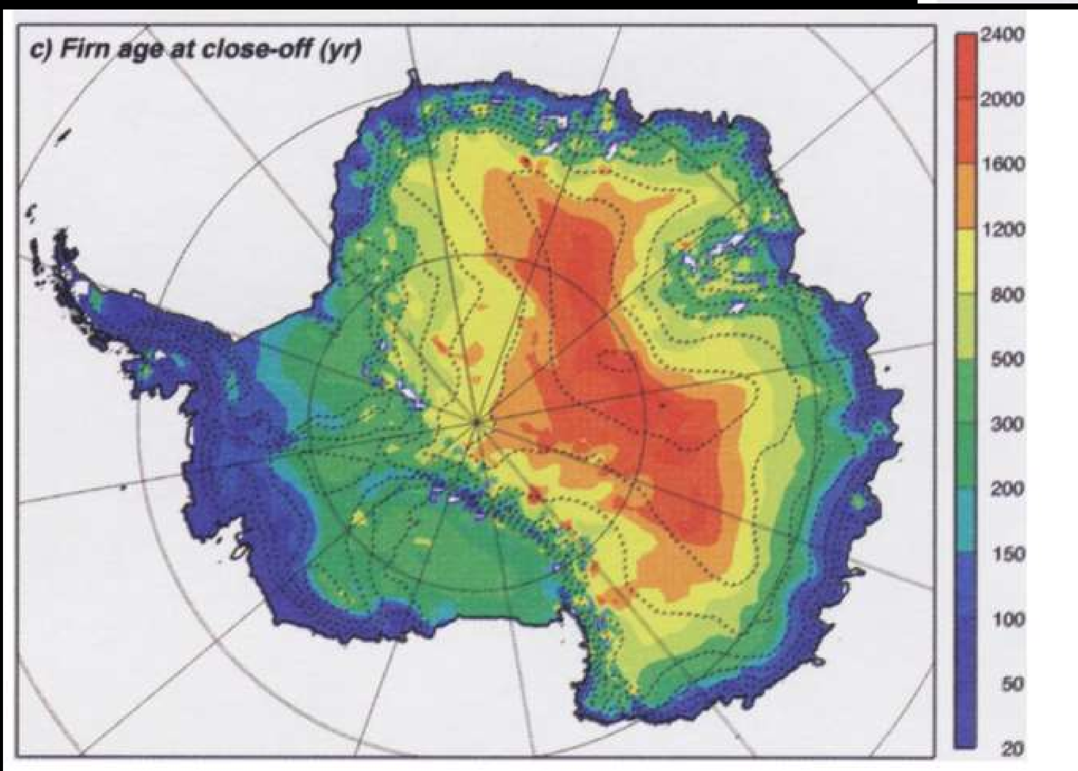

***…but the age of the gas is not the same of that of the surrounding ice!***

*Arctic, Antarctic, and Alpine Research, Vol. 40, No. 2, 2008, pp. 432–438*

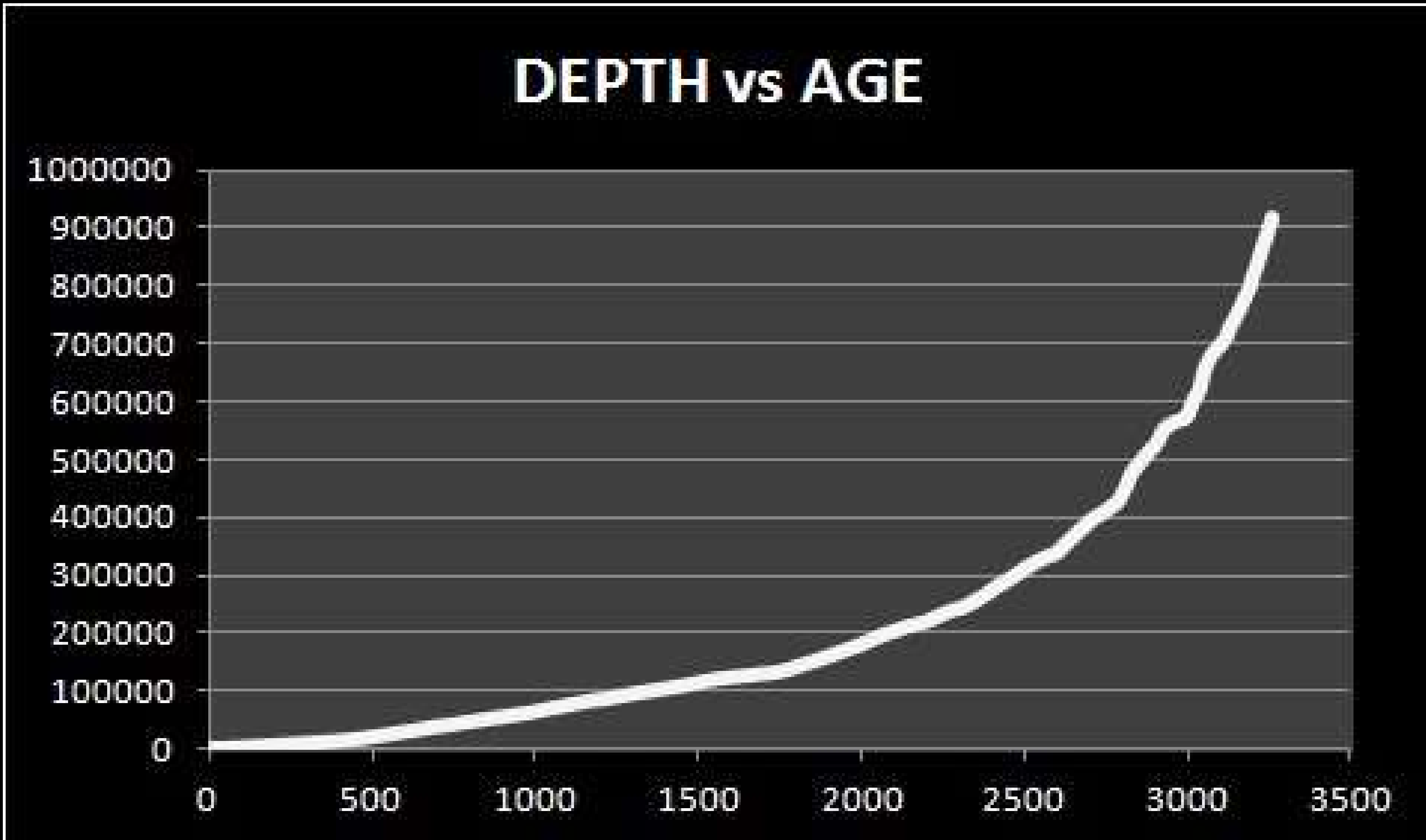
# Depth and Density of the Antarctic Firn Layer

*Michiel van den Broeke*



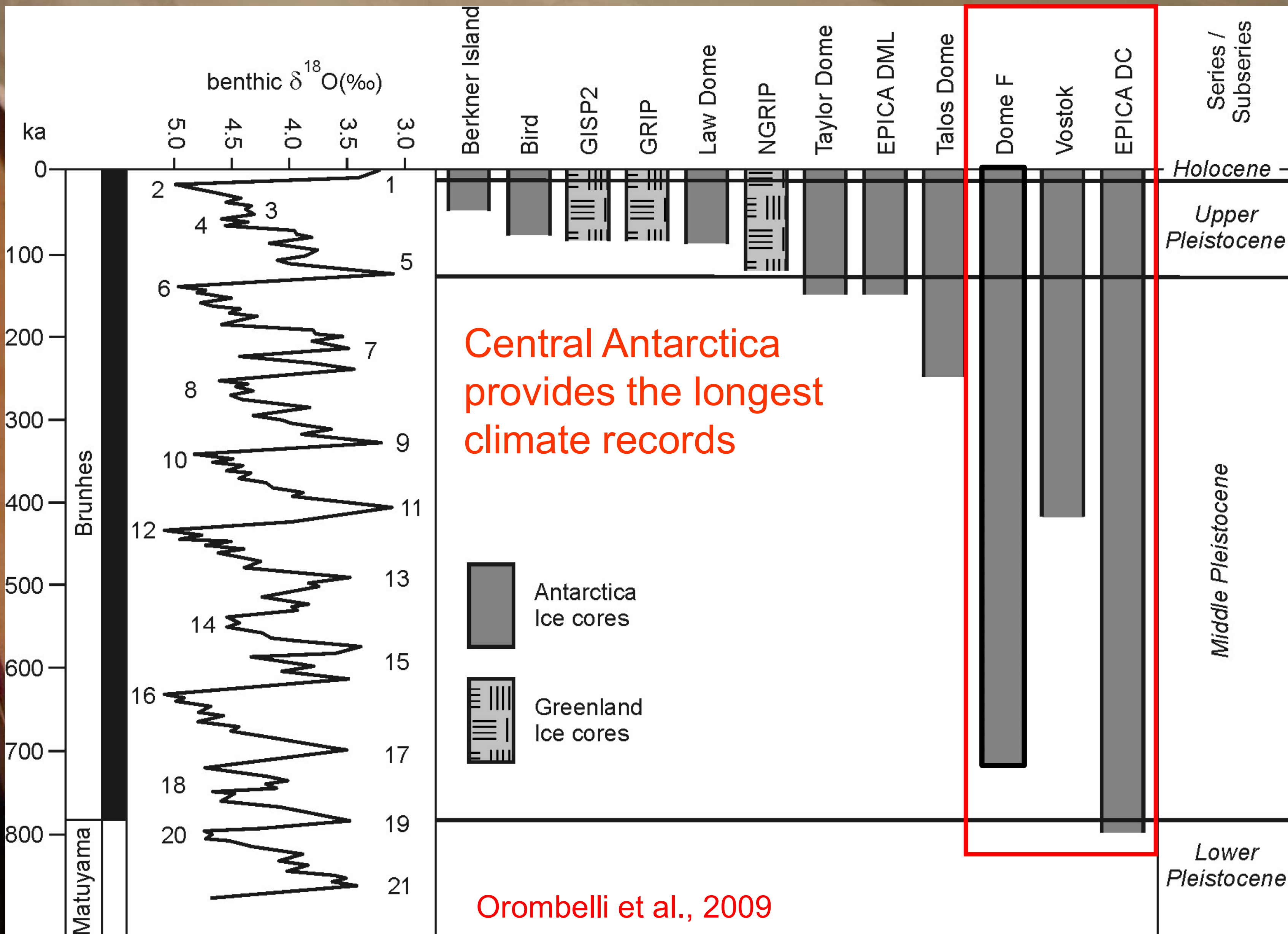



ice is ductile, therefore ice layers are squeezed and thinned with increasing depth and ice load; consequently, time resolution decreases downcore almost systematically

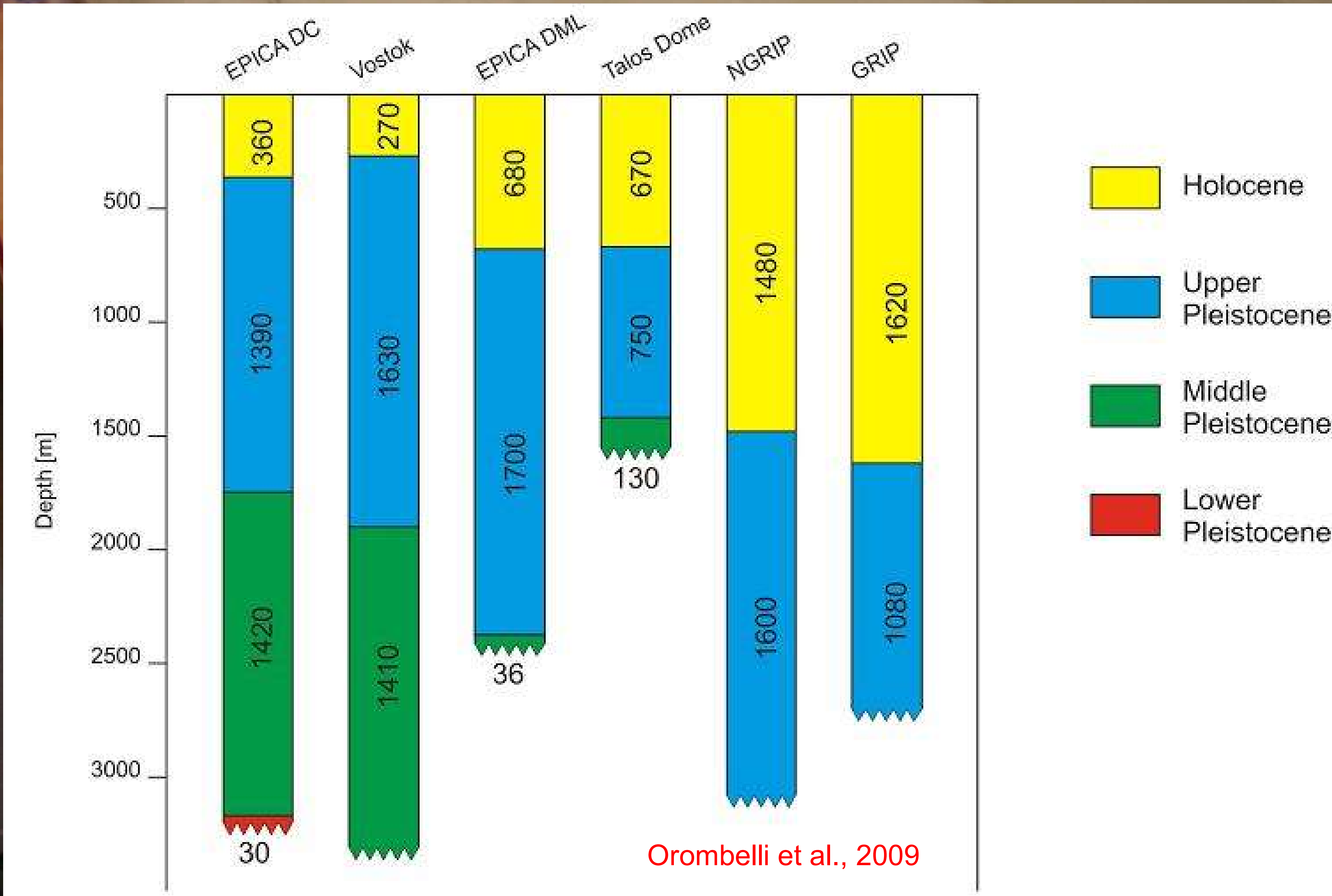



EPICA-dome C depth versus age (Lemieux-Dudon et al., 2010)

# Time and chronostratigraphic extent of ice cores



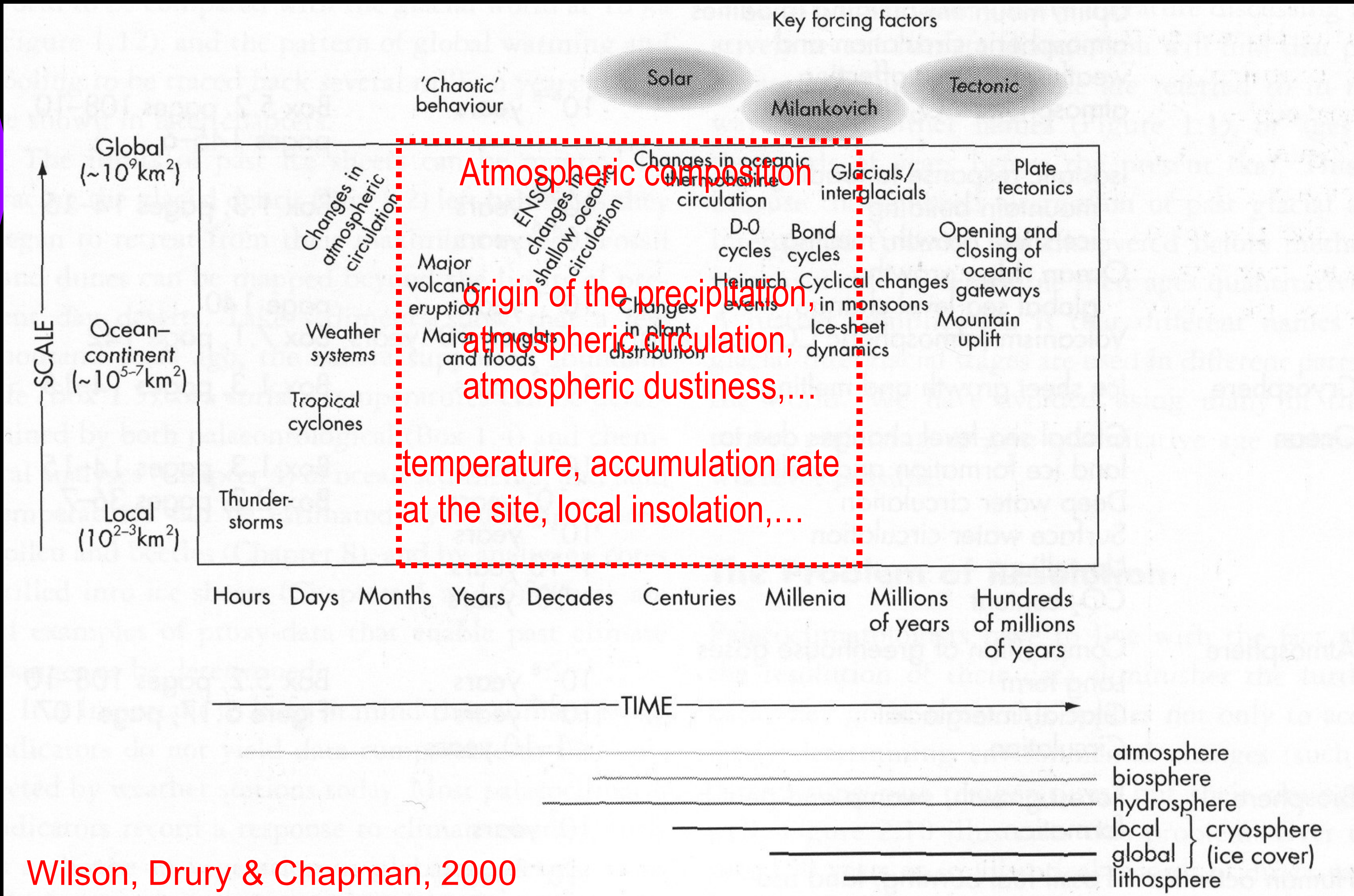
But the different thickness of chronostratigraphic units makes Greenland and peripheral Antarctic ice cores highly detailed.



# Frozen climate parameters

| PARAMETER | PROXY |
|---|---|
| **Paleo-Temperature** | δD, $\delta^{18}O$, $^{15}N$ – $^{40}Ar$ correction for seasonality |
| **Accumulation rate** | Chemical stratigraphy, δD, reference horizons, .. |
| **Origin of precipitation** | Deuterium excess, $^{17}O$-excess |
| **Local summer insolation** | Total air content, $O_2/N_2$ |
| **Atmospheric composition** | $CO_2$, $CH_4$, $N_2O$, |
| **Natural aerosol** | Mineral dust , volcanic ash, Al, $Ca^{2+}$, $Na^{+}$, $SO_4^{2-}$ , $NO_3^{-}$, acidity peaks,.. |
| **Anthropogenic compounds** | Trace metals, Pb, radioactive fallout, $SO_4^{2-}$, organic compounds, .. |
| **climate-independent natural forcing** | Volcanic eruptions, solar activity ($^{10}Be$) |

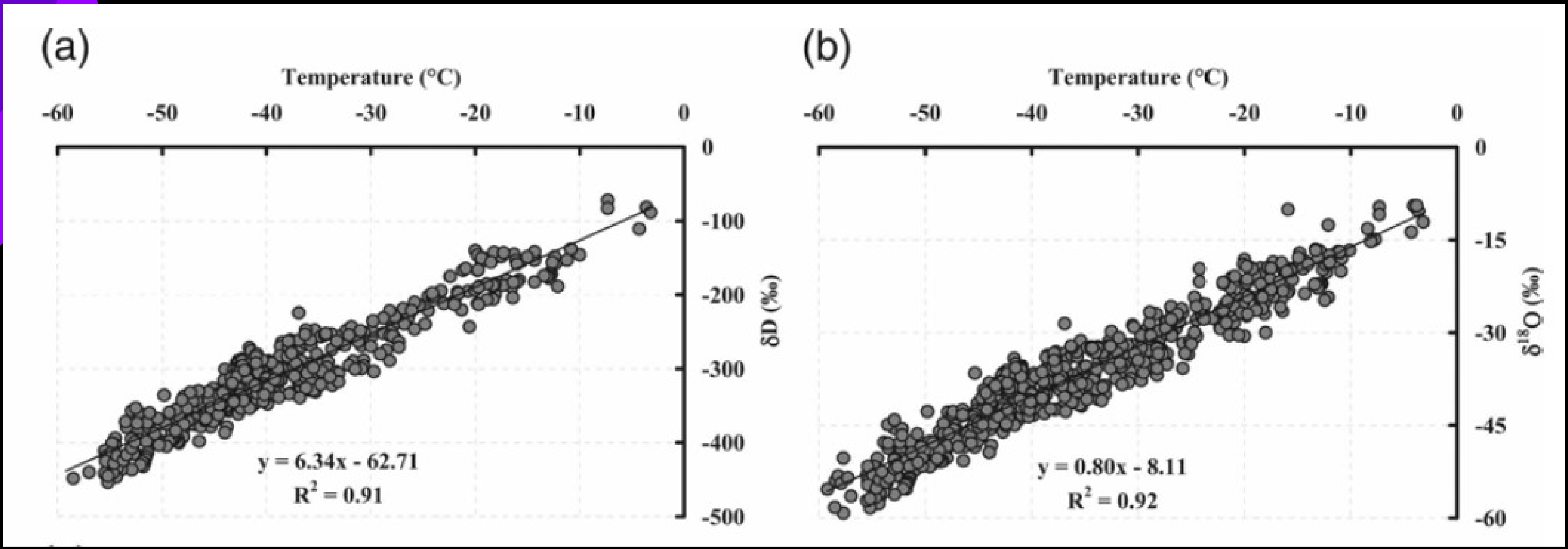
- Wide range of timescales - from decades to hundreds of millennia
- Resolution of the climate signal sometimes is very high (seasonal)




Wilson, Drury & Chapman, 2000

# 1: PALEO-TEMPERATURE

***"isotopic paleothermometer"*** : well-obeyed linear relationship between isotopic composition ($\delta$D or $\delta$18O) of snowfall and the temperature of the site.




Masson-Delmotte et al., 2008

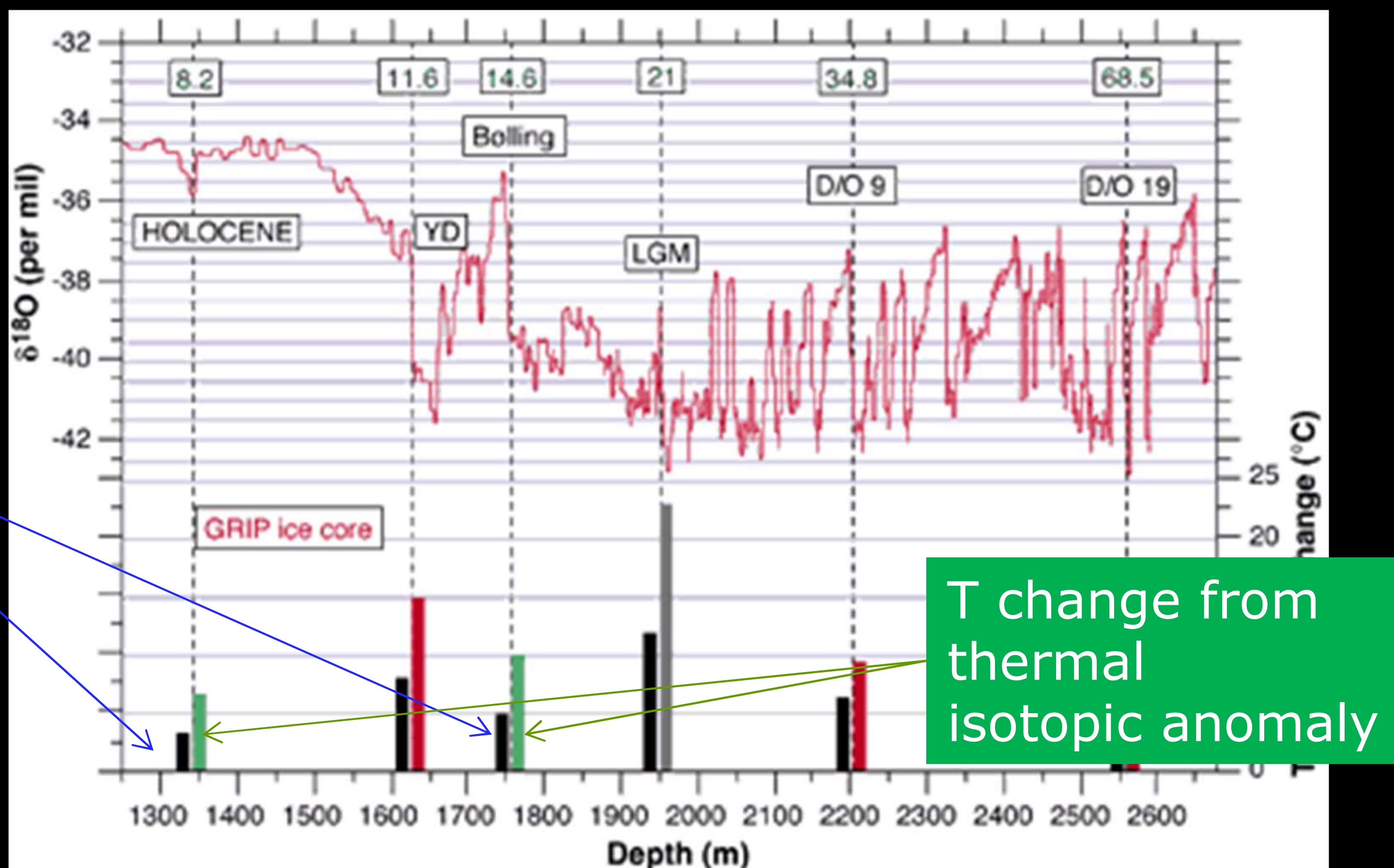
The isotopic paleo-thermometer assumes that the seasonality of precipitation remains unchanged between different climates, which is not at all guaranteed!

In the **DIFFUSIVE ZONE** of firn, the gases undergo a (1) gravitational and (2) thermal fractionation.

(1) Gravitational fractionation: governed by the depth of the diffusive column and the mass difference of gases (Craig et al., 1988; Schwander, 1989).

(2) Thermal fractionation: caused by a temperature gradient between top and bottom of the diffusive column (Severinghaus et al., 1998).

Coupling $^{40}Ar$ and $^{15}N$ measurements with firn modeling new estimates of past T changes during abrupt climate changes have been provided.




paleothermometer

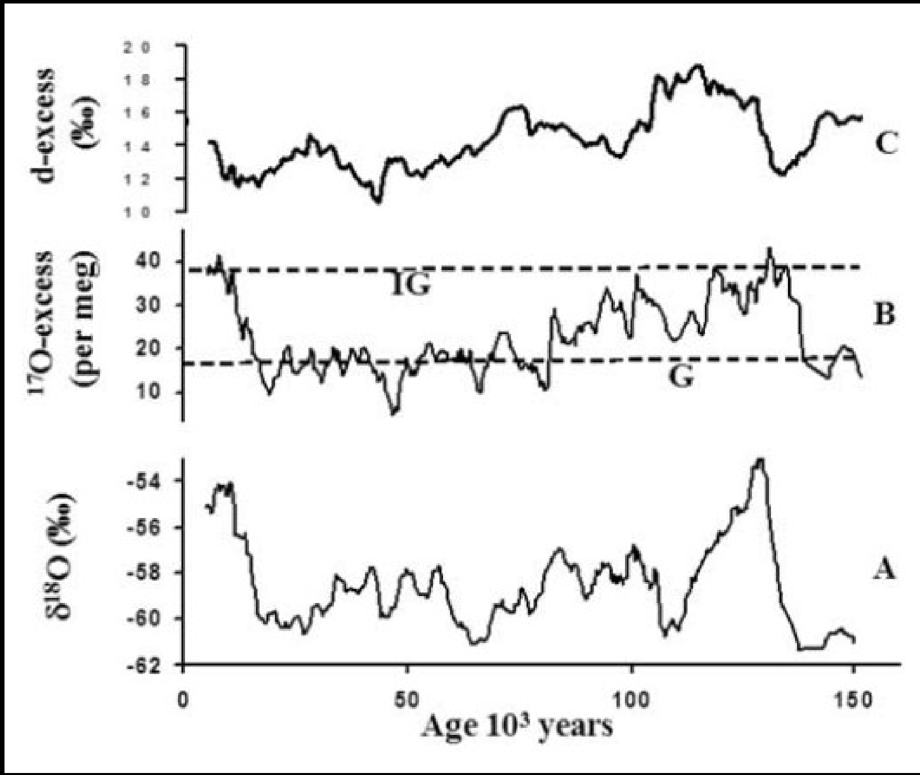
## *2: Origin of precipitation: deuterium excess and $^{17}O$-excess*

**Deuterium-excess** "d" parameter

d = δD-8*δ$^{18}$O  (*Craig,1961; Dansgaard, 1964*)

depends essentially on (1) relative humidity of the oceanic source region, (2) sea surface T and (3) polar temperature.

Decoupling of these signals is possible by using $^{17}$O-excess, that is a robust indicator of diffusive fractionation over the ocean and does not depend on temperature at the deposition site (*Landais et al., 2008*).

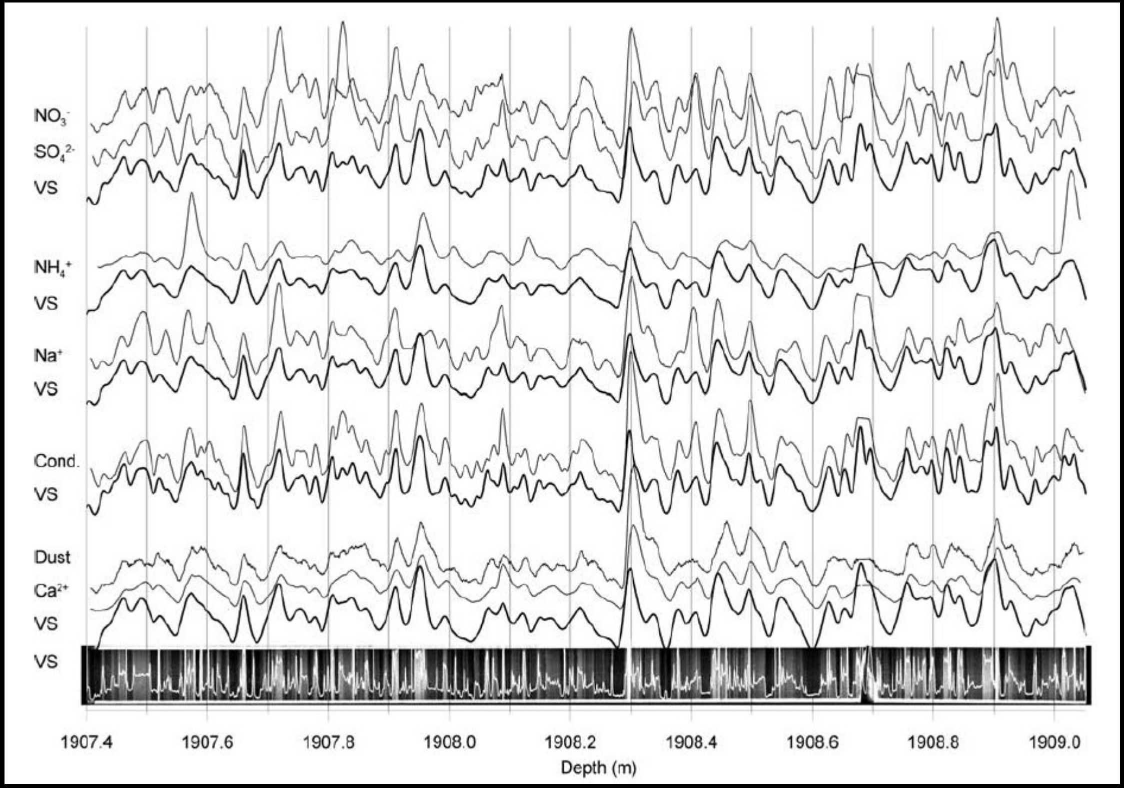


## *3: Accumulation rate*

In “***high accumulation sites***” (Greenland, peripheral Antarctica) the identification of successive annual layers is possible by visual inspection of isotopic and chemical records

⇒some signals are rapidly smoothed out (e.g., water isotopes)
⇒annual layer thickness has to be corrected for thinning

In Greenland this approach has been applied back to 60.000 yrs BP (*Svensson et al., 2008*)



## *3: Accumulation rate*

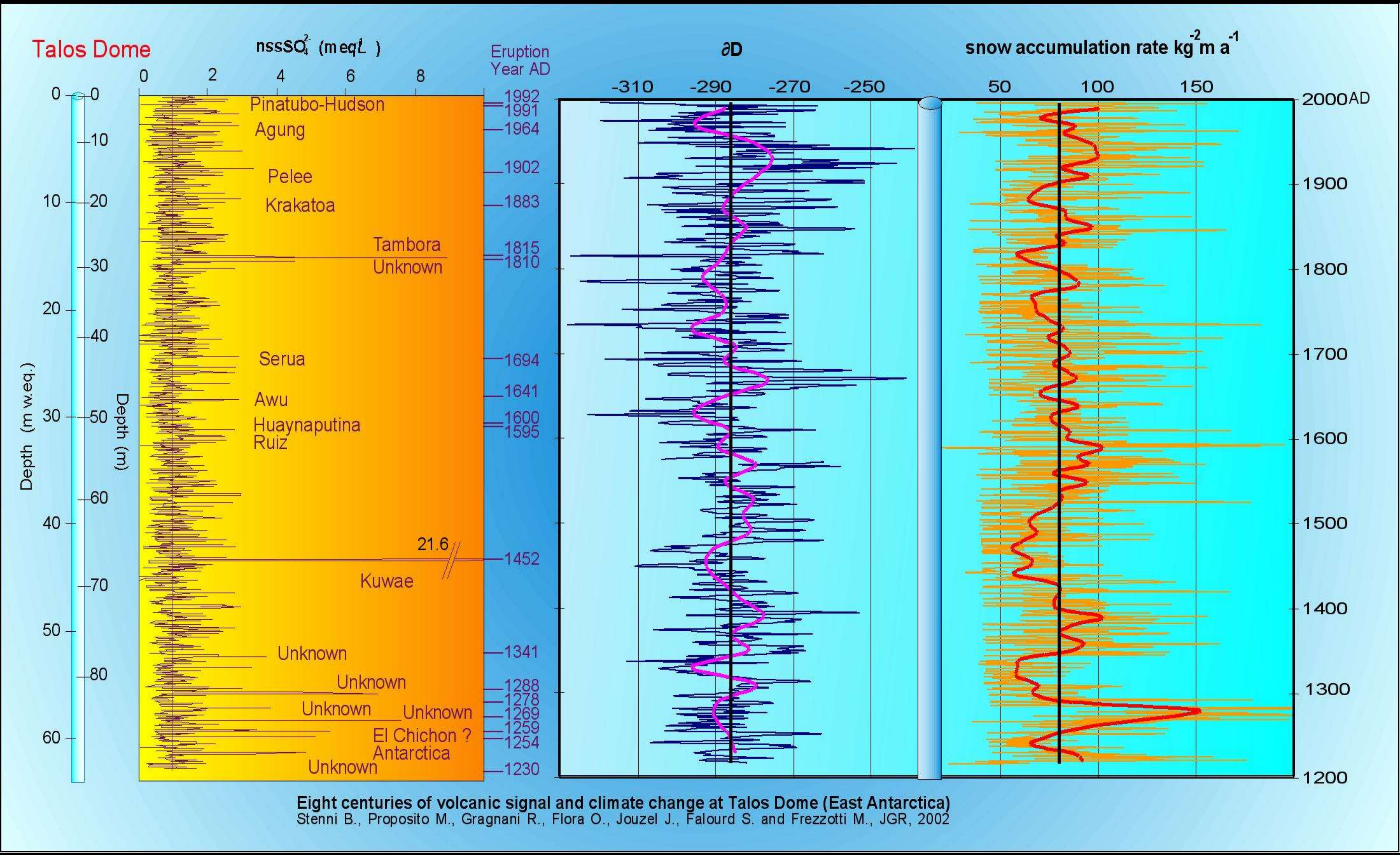
In "***low accumulation sites"*** (central Antarctica) the identification of successive annual layers is not possible.

⇒ thermodynamical relationship between local air temperature (derived from stable isotopes) and accumulation rate (e.g. Parrenin et al., 2001)

$$A_{\mathrm{H}}/Acc = \exp[-\eta\beta(\delta D - \delta D_{\mathrm{H}})]$$

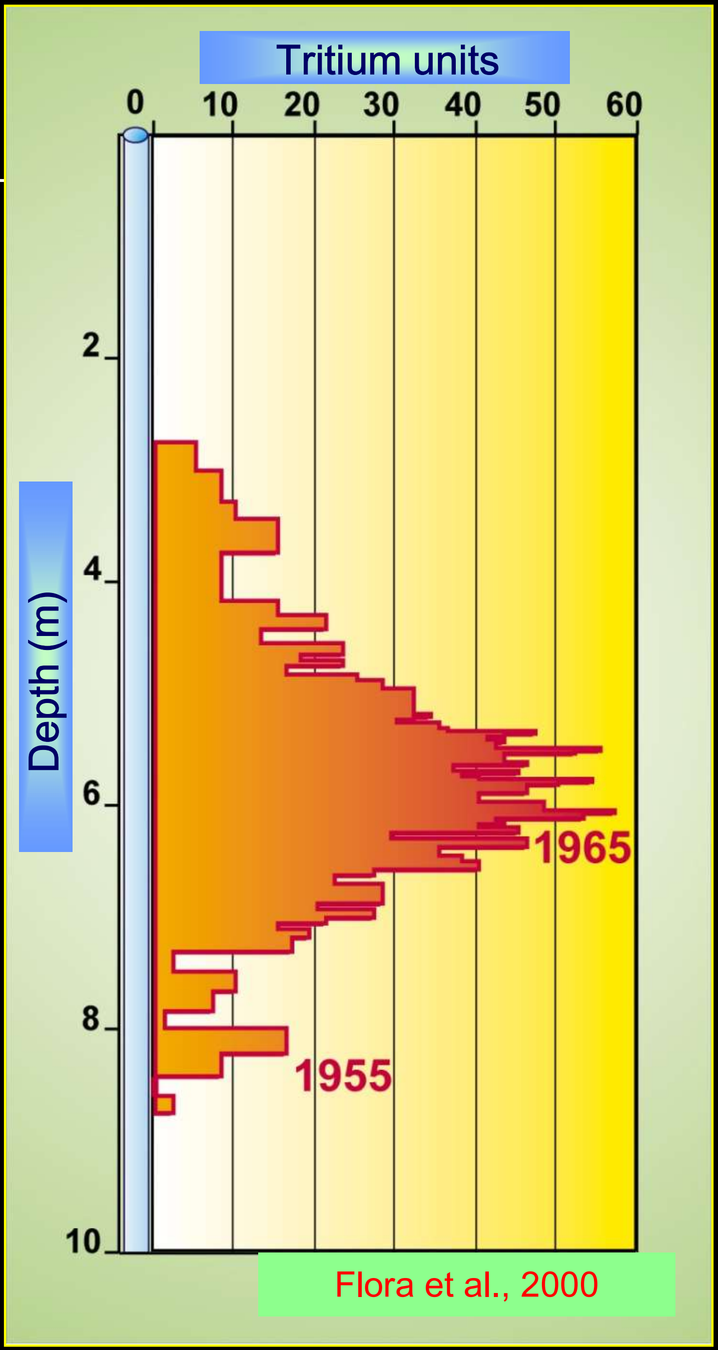
⇒independent contraints on the chronology

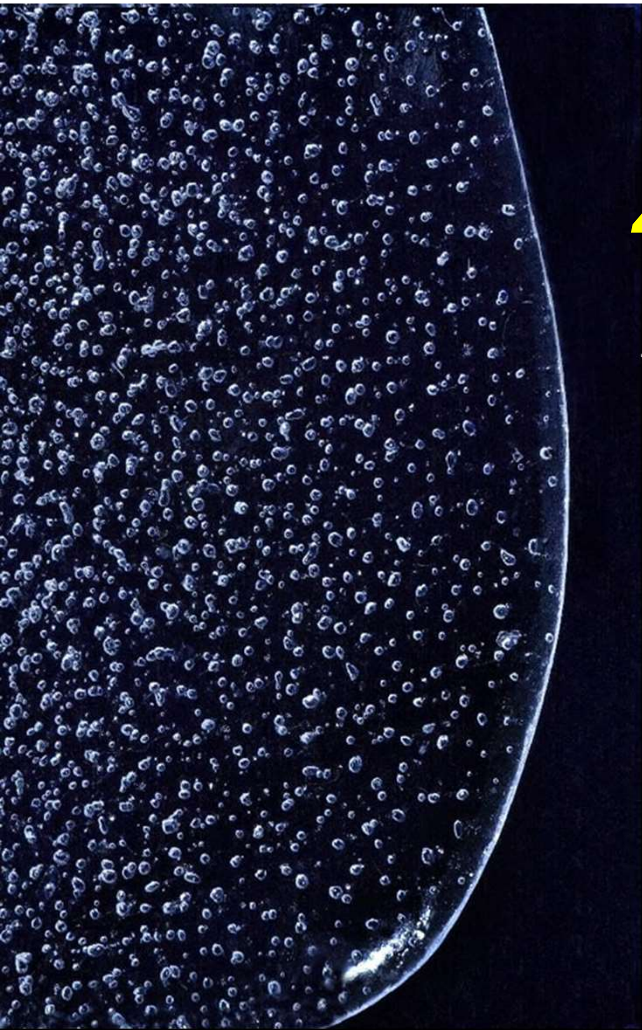
(e.g. distance between two known volcanic horizons)




Stenni et al., 2002

# Atmospheric Tritium concentration





# 4: Local summer insolation

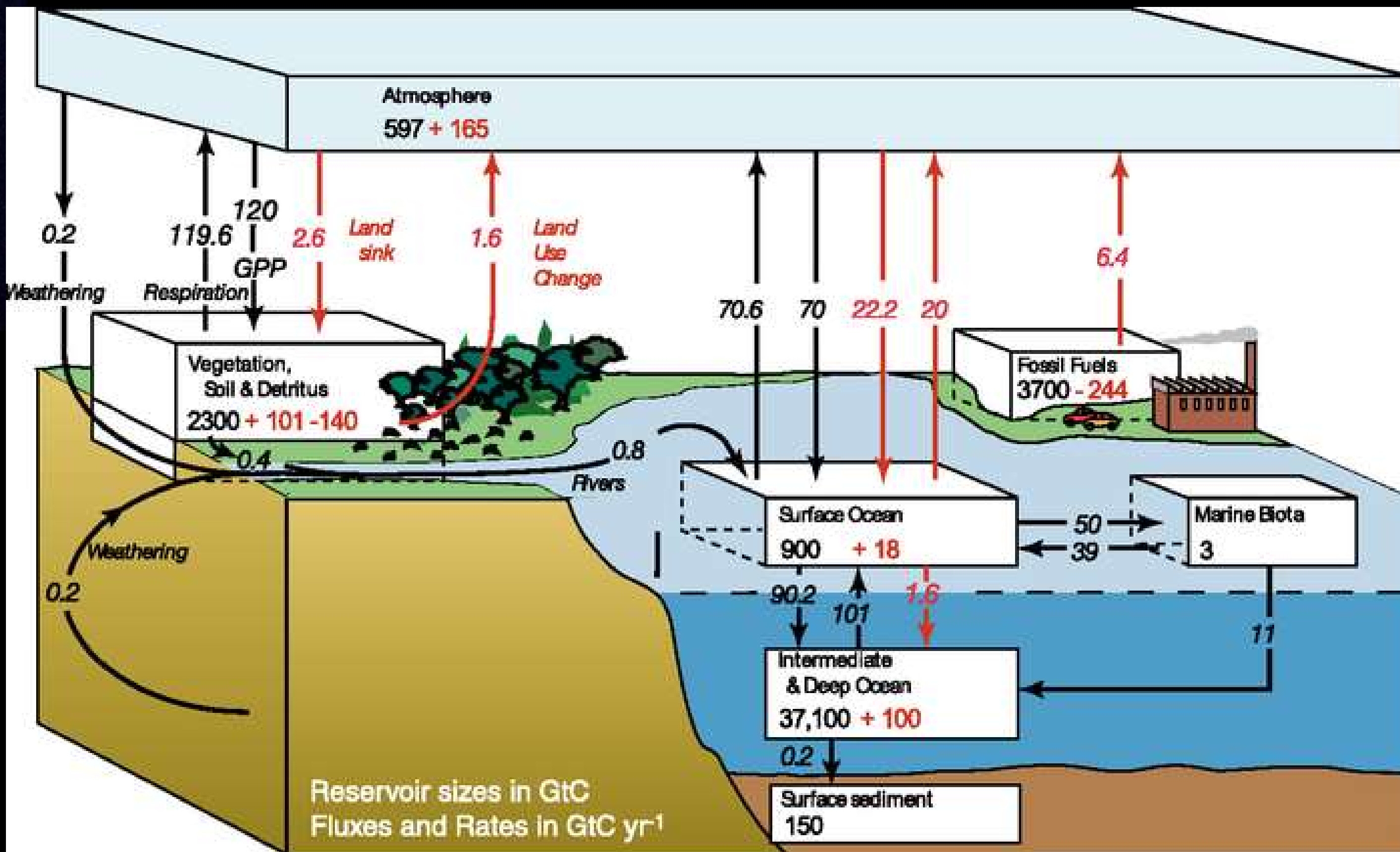
Information about the local insolation can be obtained from:

TOTAL AIR CONTENT of ice (Raynaud et al., 2007); *the solar radiation modifies the snow structure in the first upper meters of firn and in turn the porosity at the close off layer.*

$O_2/N_2$ (Severinghaus and Battle, 2006): This ratio is depleted relative to the atmospheric ratio during air-bubble formation at the close-off depth, and the magnitude of this depletion is controlled by the magnitude of snow metamorphism, driven by local summer insolation when the layer was originally at the surface (Bender et al., 2002; Kawamura et al., 2007).

# 5: Atmospheric composition

**$CO_2$:** Antarctic (but not Greenland!) ice cores offer the possibility to study atmospheric $CO_2$ variability before the human intervention to alter the global carbon cycle



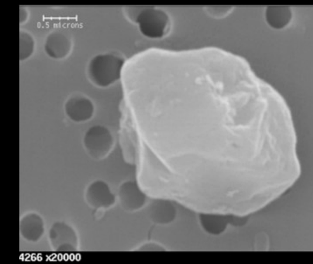

IPCC 2007

# *5: Atmospheric composition and biogeochemical cycles*

**$CH_4$:** Variations in the concentration of globally well-mixed atmospheric $CH_4$ are attributed to variations in the extent and productivity of natural wetlands, the main natural sources.
$\delta D(CH_4)$ and $\delta^{13}C$ $(CH_4)$ allow assessing the magnitude of past individual methane emission sources and the atmospheric lifetime of methane.
(Fischer et al., 2008).

**$N_2O$**: variations in atmospheric $N_2O$ burden are thought to be dominated by variations in the global source strength. About two-thirds of the total pre-anthropogenic $N_2O$ sources are terrestrial soils, and one-third are nitrification and denitrification processes in the ocean.

# *6: Natural aerosol: mineral dust*

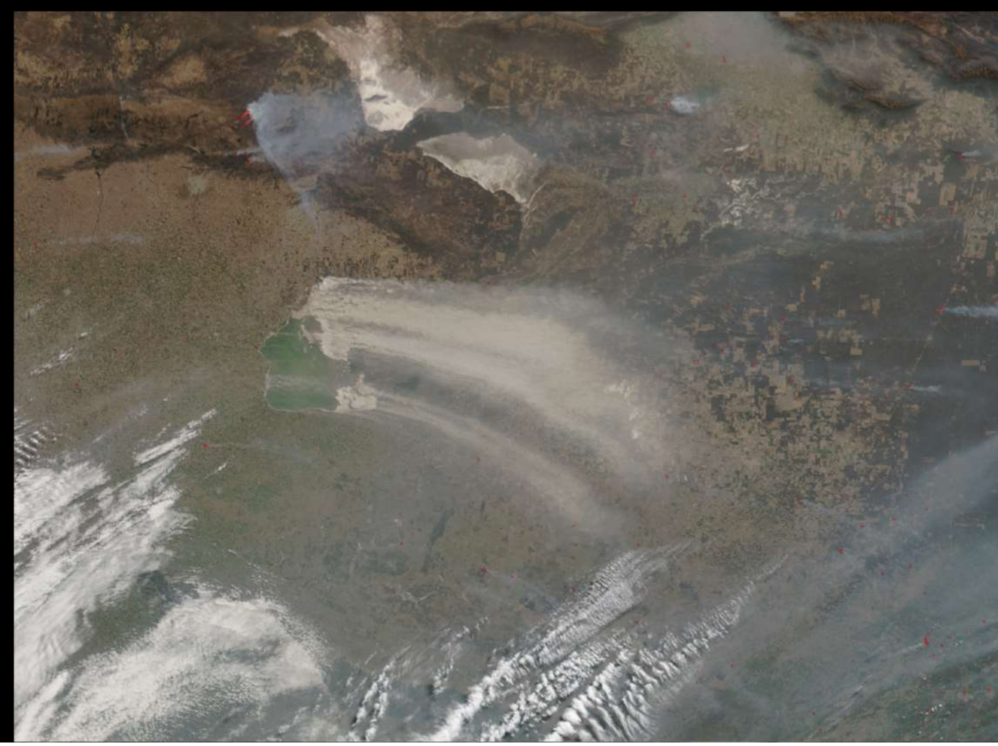



Mineral dust originating from arid regions can be transported long distance to polar latitudes.

Dust flux variability in time provides constraintes on paleo-aridity and atmospheric transpor patterns.

Dust influences climate through its radiative forcing, heterogeneous atmospheric reactions, fertilization of the oceans and $CO_2$ uptake, etc…

In turn, climate influences dust production, emission and atmospheric transport.



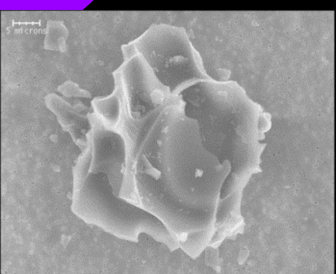
# *7: Natural and anthropogenic aerosols*

Human activities modified the chemical composition of the natural atmosphere even polar areas.

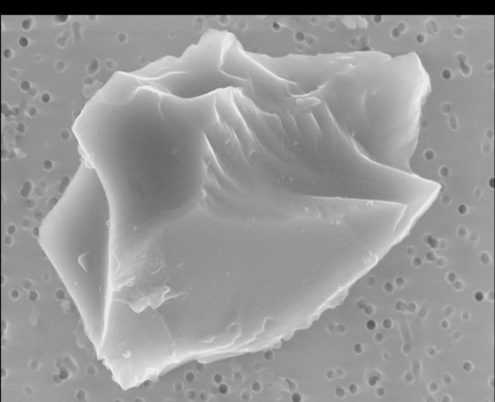
Glaciochemistry of ice cores provides a unique tool for obtaining information on the composition of the preindustrial atmosphere and its natural variability over the past.

| *Species* | *Formula* |
|---|---|
| Proton | $H^+$ |
| Ammonium | $NH_4^+$ |
| Potassium | $K^+$ |
| Magnesium | $Mg^{++}$ |
| Calcium | $Ca^{++}$ |
| Sodium | $Na^+$ |
| Fluoride | $F^-$ |
| Formate | $HCOO^-$ |
| Acetate | $CH_3COO^-$ |
| Oxalate | $C_2O_4^{--}$ |
| Methanesulfonate (MSA) | $CH_3SO_3^-$ |
| Chloride | $Cl^-$ |
| Nitrate | $NO_3^-$ |
| Sulfate | $SO_4^{--}$ |
| Formaldehyde | $HCHO$ |
| Hydrogen peroxide | $H_2O_2$ |

# *6: Natural aerosol: volcanic ash*

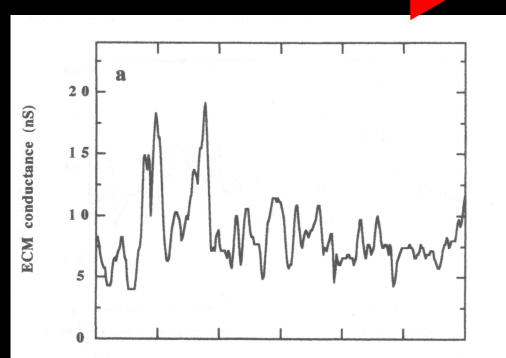


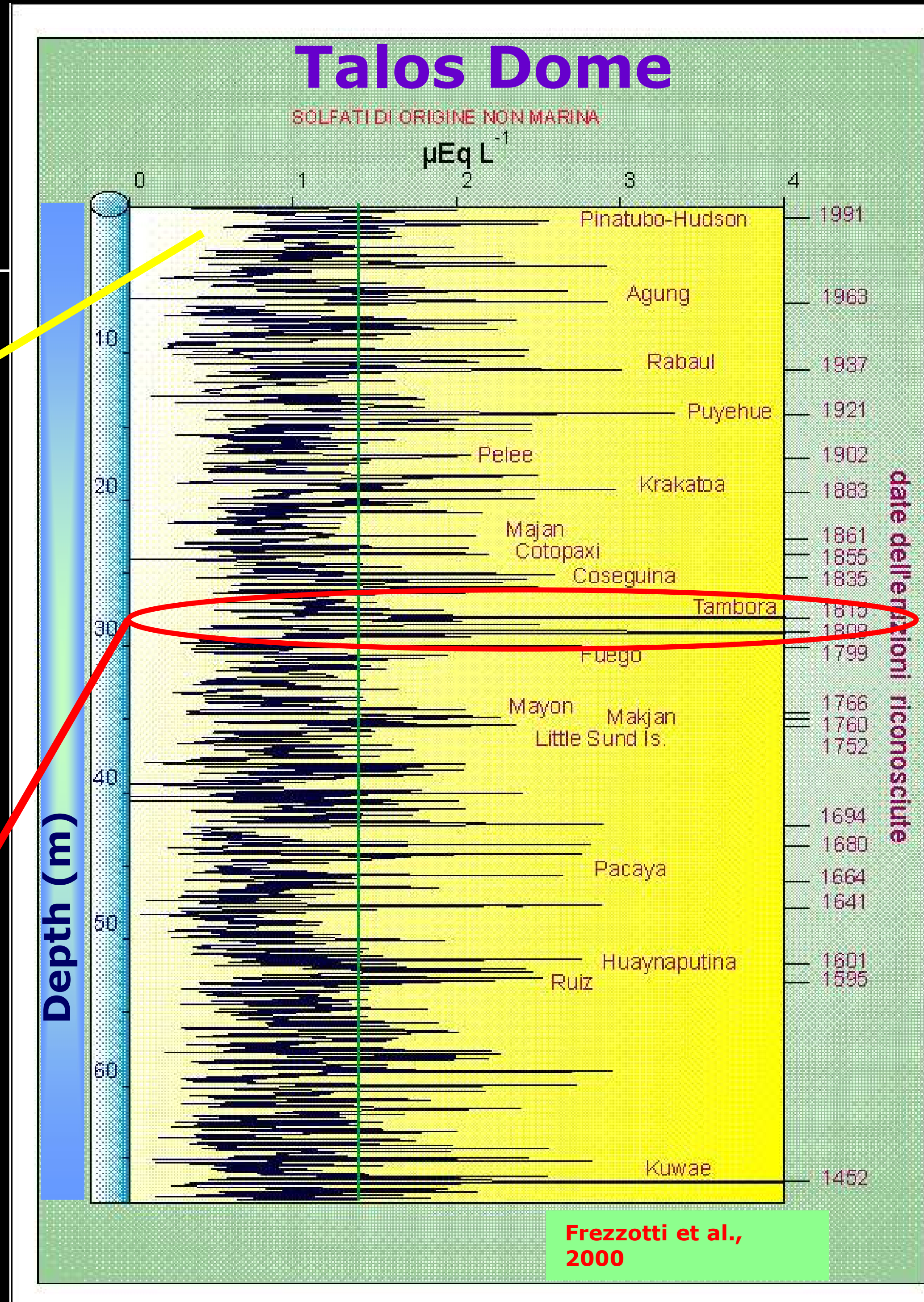
618-11 x1500



5070 x5000

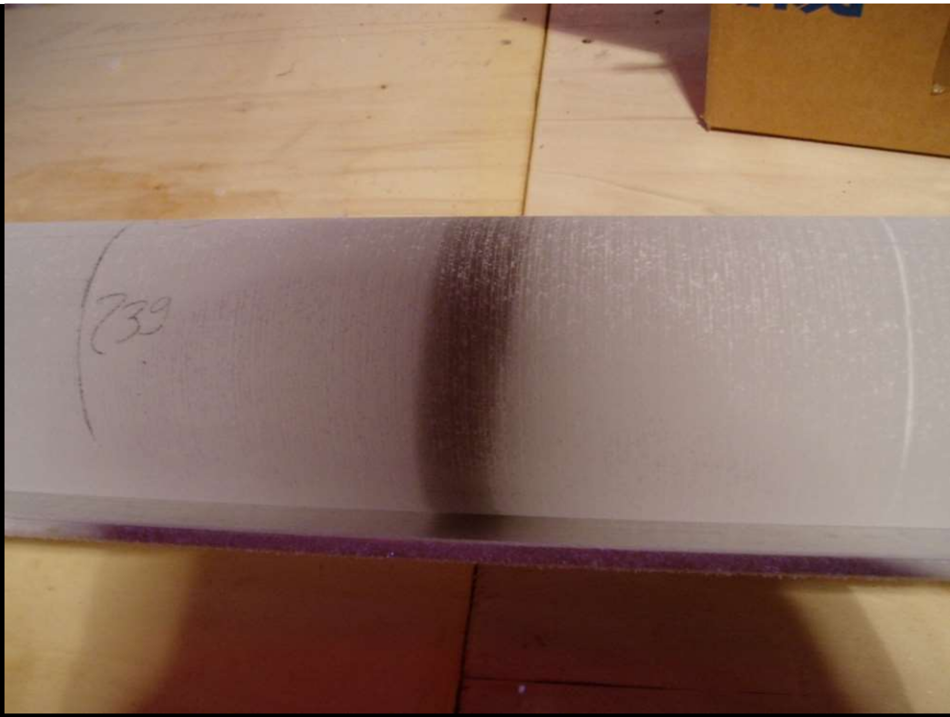
Tambora *signature*

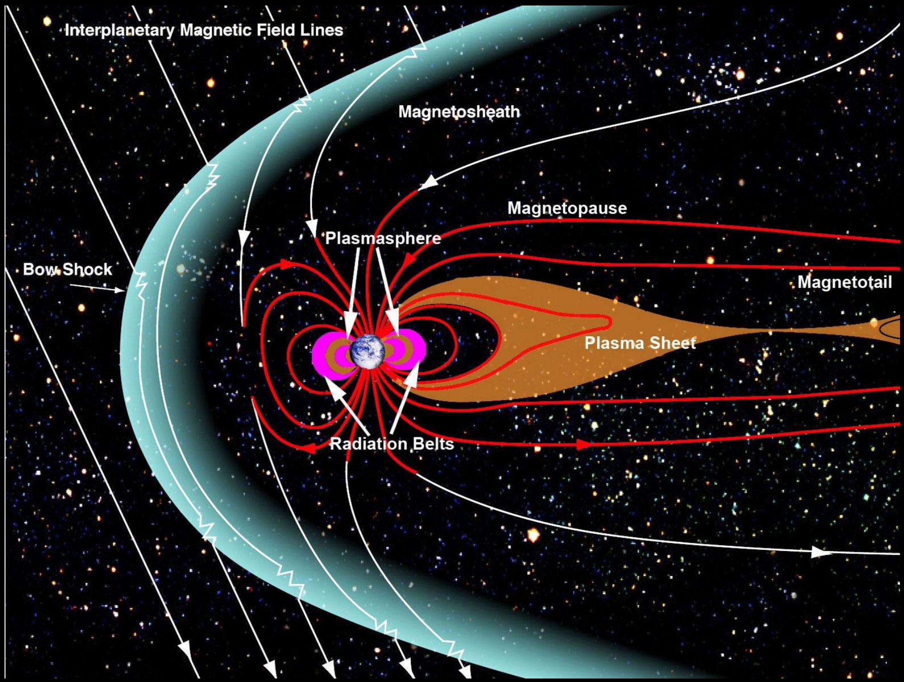


# 8: Climate – independent forcing factors

- volcanic activity
- solar forcing




Enhanced solar wind deflects the primary flux of charged cosmic particles which reduces cosmogenic nuclide production in the Earth's atmosphere, and vice versa.
It has been shown that solar activity modulates the $^{10}Be$ production recorded in polar ice cores.

# Take home messages

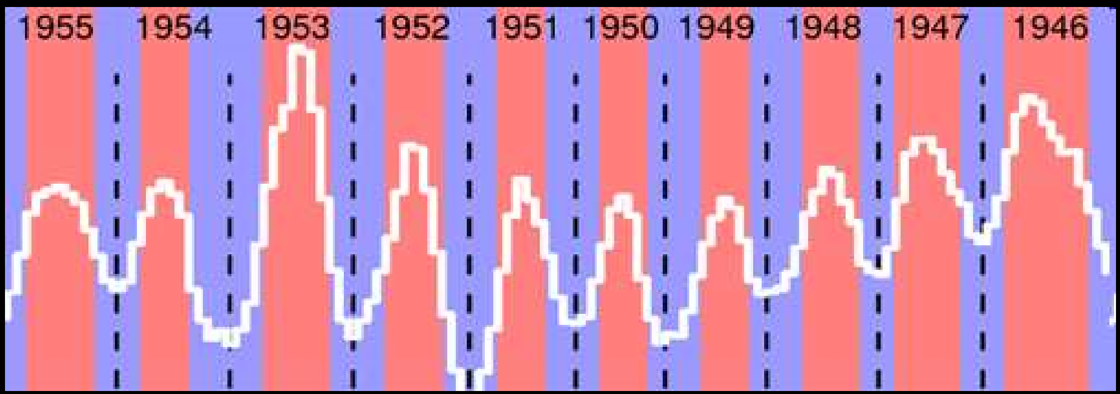
- *Ice is not just frozen water*
- Ice cores drilled in suitable glaciological settings are unique climate archives although big logistic efforst are needed.
- Atmospheric parameters such as paleotemperature, accumulation rate, precipitation origin, insolation, atmospheric composition (gas, aerosol) can be measured.
- Ice cores allow separating the natural forcing (volcanic, solar, natural aerosol and greenhouse gas forcing) from anthropogenic forcing related to alteration of atmospheric composition.

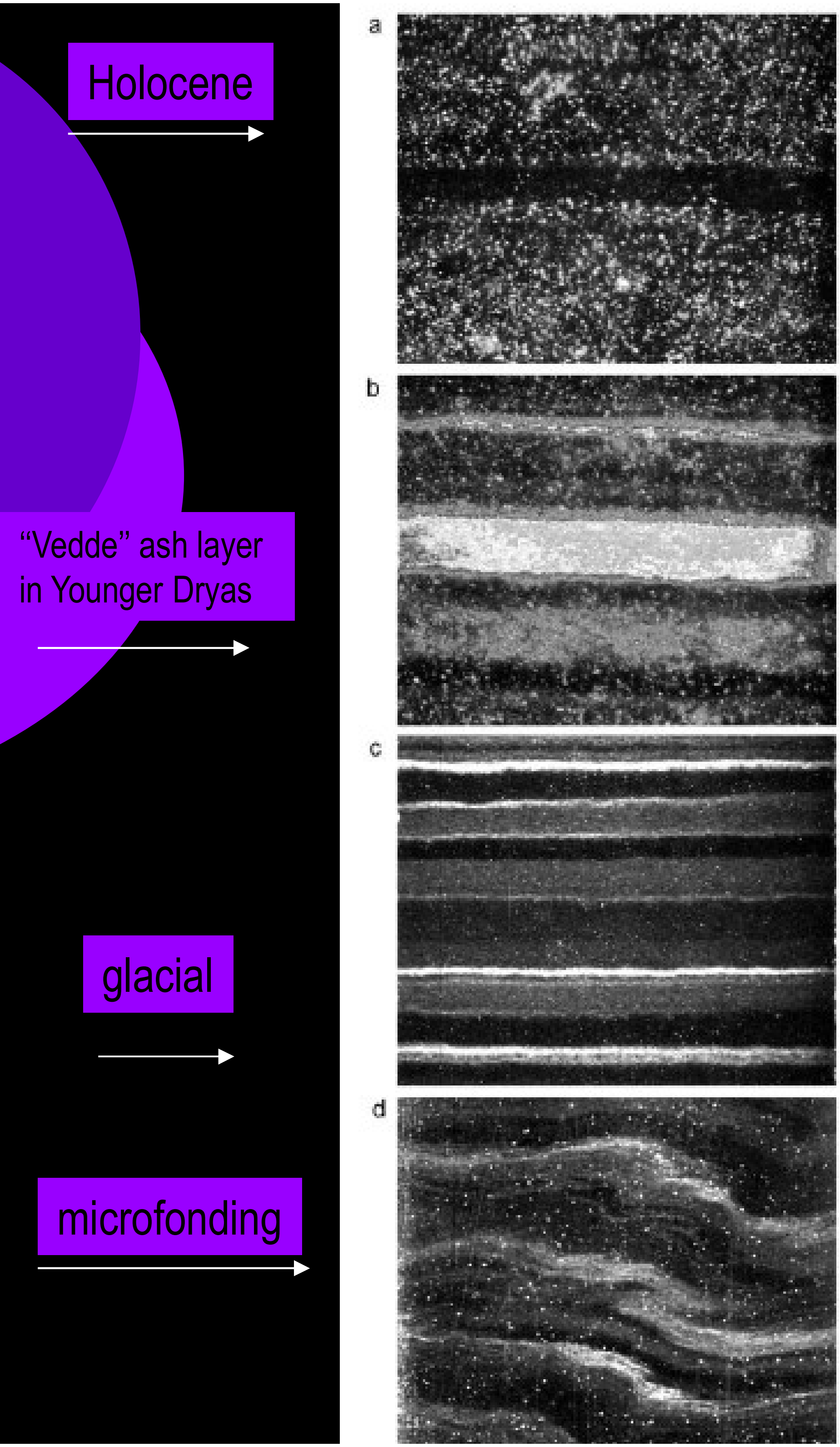
# Ice core dating

*Tricky process,*
*before and after drilling*

# Dating strategies

- (1) layer counting (e.g. in Greenland)
- (2) glaciological modeling (*forward* and inverse *modelling)*
- (3) stratigraphic markers (tephras, abrupt events, $^{10}Be$ peaks, etc.)
- (4) correlation ("*wiggle matching*") with other dated time series (even non-glaciological, such as speleothems)
- (5) Orbital tuning (insolation changes)






# GREENLAND ICE CORES VISUAL STRATIGRAPHY

Ice core stratigraphy clearly visible throughout the glacial period with the most frequent and brightest visible layers appearing during the coldest events.

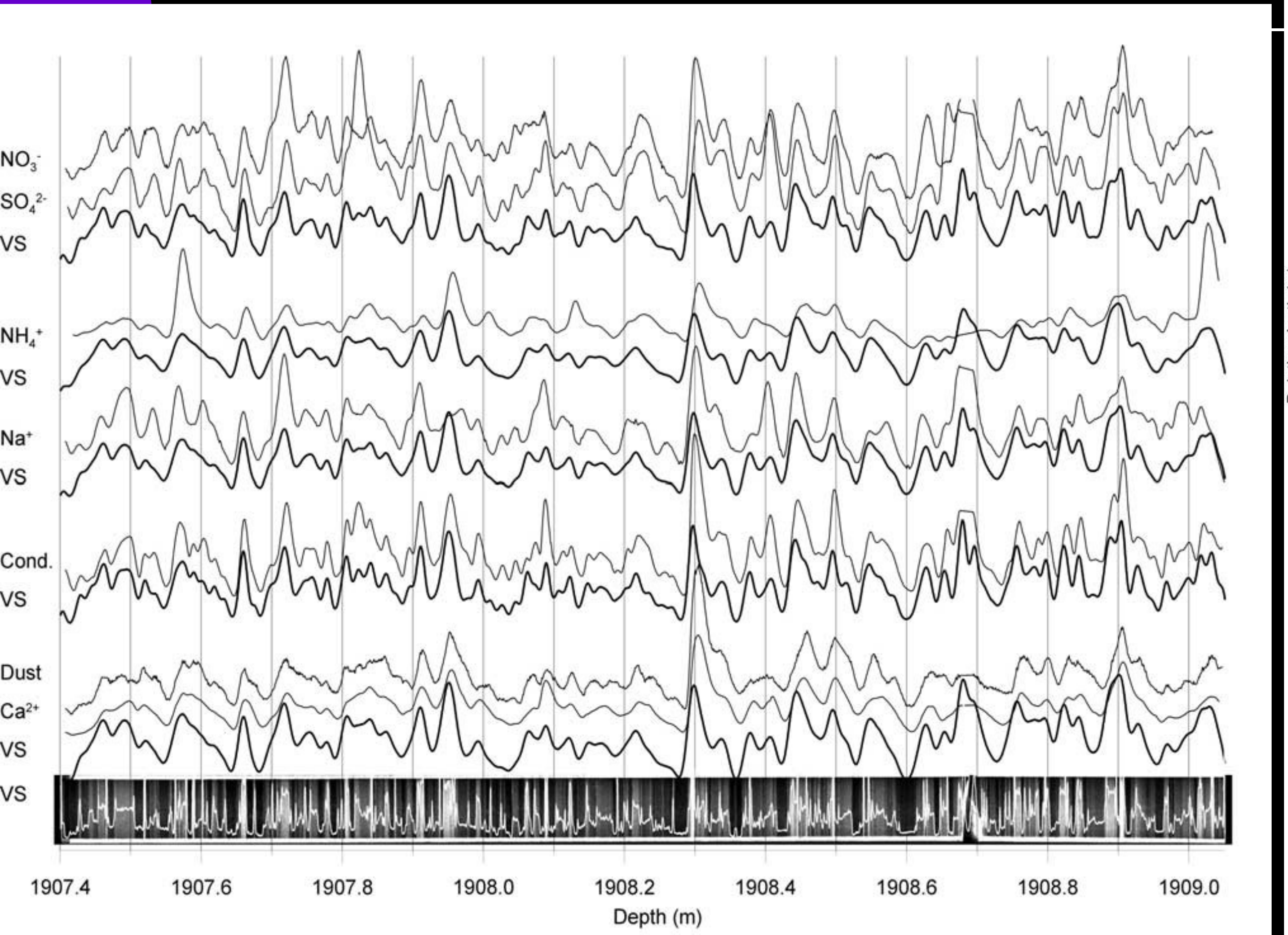
**NGRIP allowed using a new approach for automatic determination of annual layer thicknesses from the visual stratigraphy record**

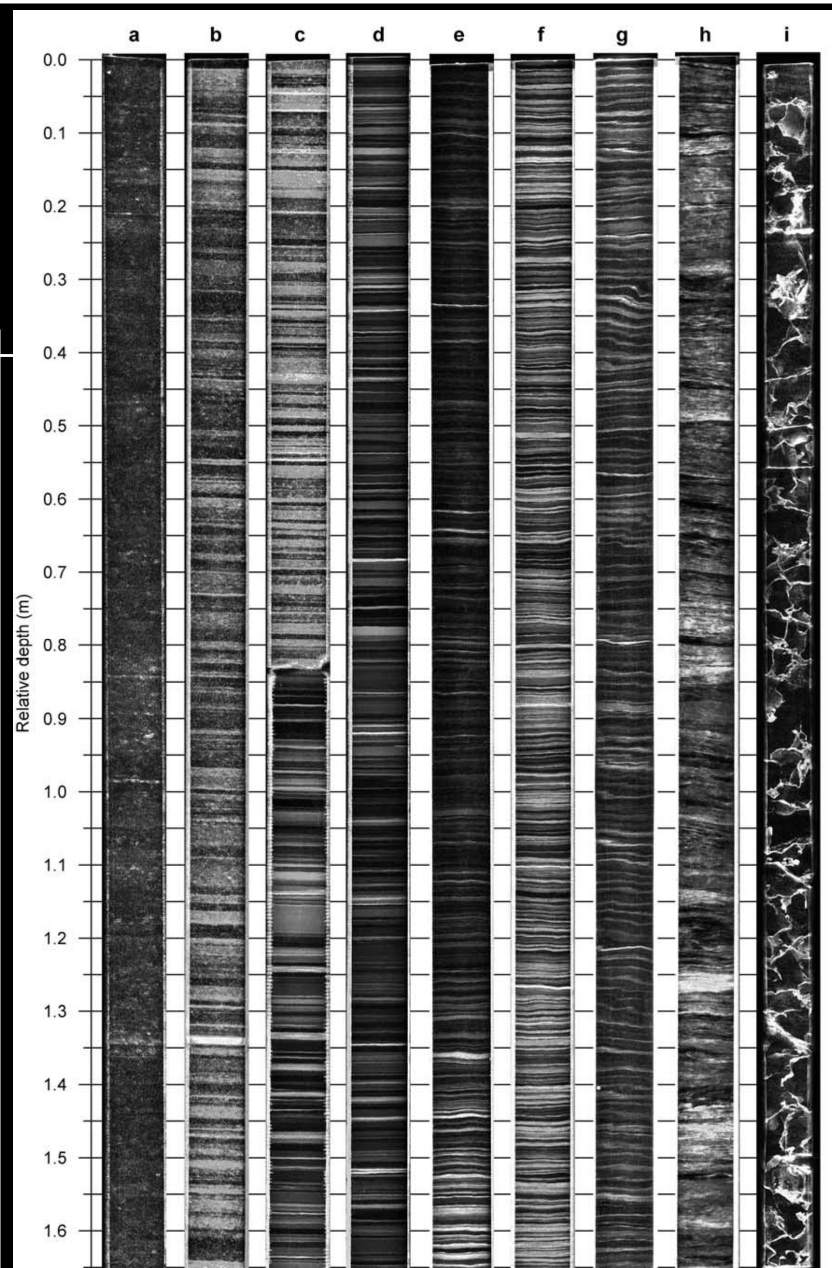
NGRIP:
Down to a depth of 2600 m the horizontal layering is very regular; below, small irregularities in the layering start to appear.

Below 2800 m the visual stratigraphy becomes more uncertain, perhaps because of penetration into climatically warmer ice (Eemian).

Svensson et al., 2005

# Greenland: Annual layer counting



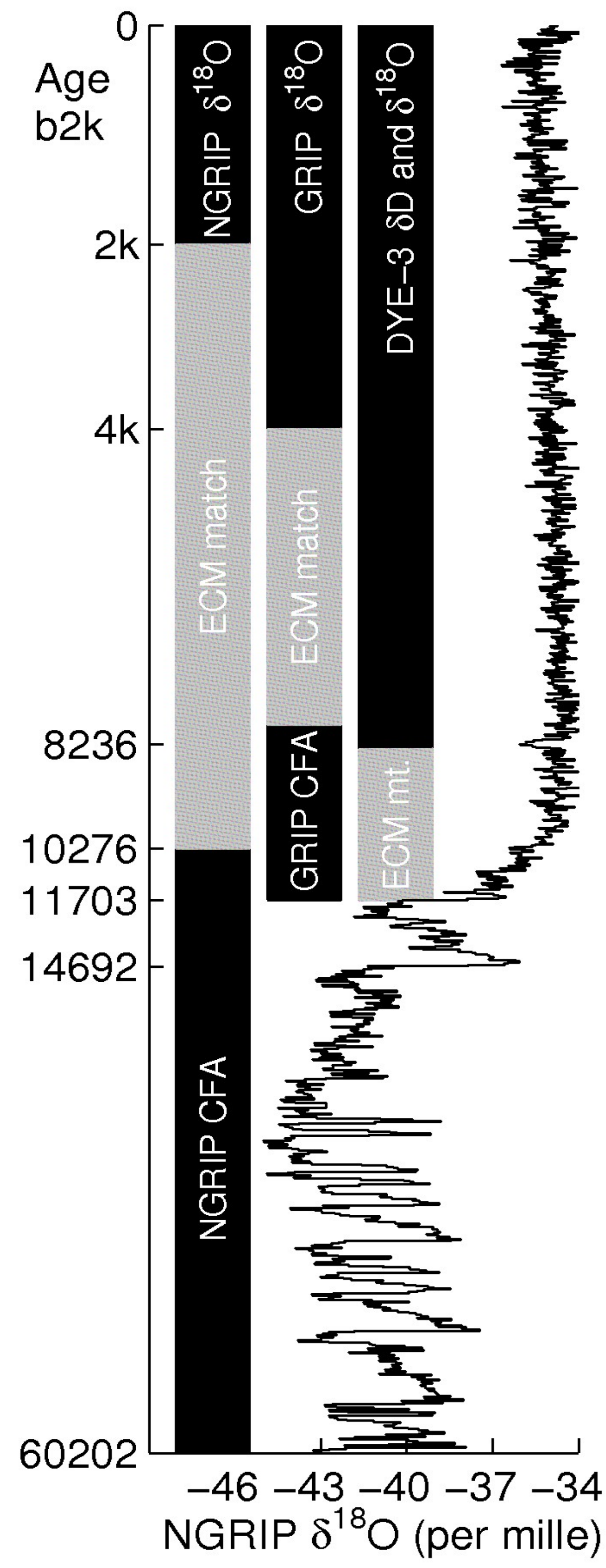

back to **60,202** b2k (*before A.D. 2000) !*

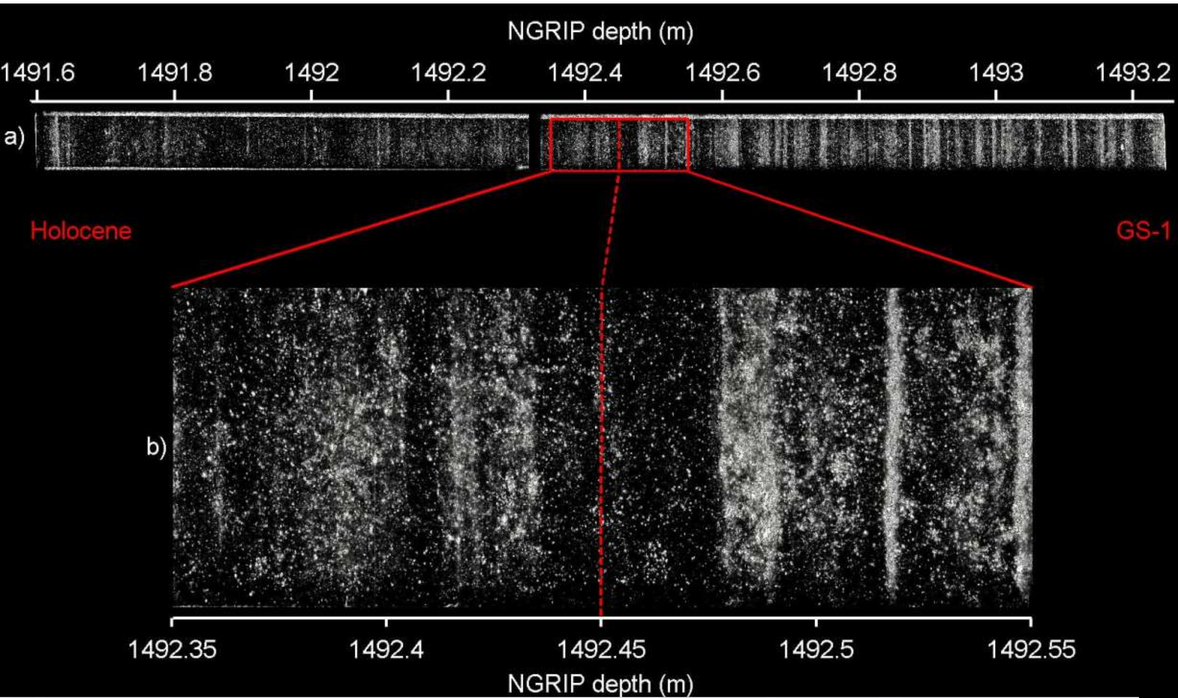
# Greenland Ice Core Chronology 2005 (GICC05)

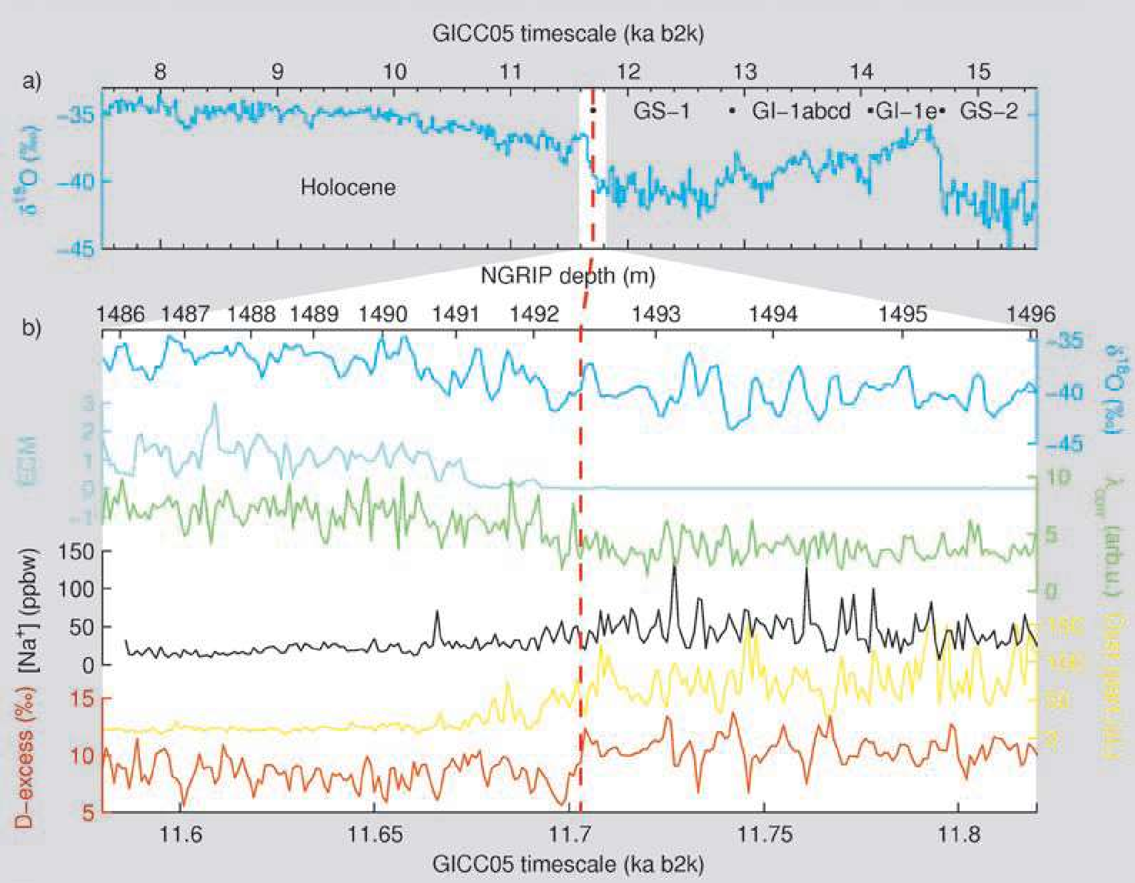
Back to 7,900 b2k:
DYE-3 stable isotope data set is the main basis.

From 7,900 to 10,276 b2k:
GRIP impurity data represent the best available data for annual layer identification.

At 10,276 b2k:
NGRIP CFA data set starts. Together with measurements of the ice conductivity and visual stratigraphy, the CFA data set provides an impressive data set of up to 9 parallel data series with a strong annual signal.






**THE BASE OF THE HOLOCENE has been established on the NGRIP ice core (**1492.45 m) (Pleistocene-Holocene **GSSP)**

*The boundary is located in correspondence to a sharp decline in the d-excess curve, that is accompanied by slower changes in dust, sea salt and temperature.*

*Walker et al,2008*

# Antarctica: glaciological modelling and more (EDC3)

*Antarctic ice core dating is evolving continuously*

A good ice core chronology :

1- **accurate in absolute terms:** to allow examining the phasing of different paleoclimatic records

2 – **accurate in relative terms:** to allow investigating the phasing of climate changes (e.g. Antarctic temperature and CO2)

3 **– accurate with respect to the duration** of climate events

(Parrenin et al., 2007)

# Antarctica: glaciological modelling and more (EDC3)

Example : **EDC3** (Parrenin et al., 2007)
Setup in 3 steps

step1» direct modelling approach
(snow accumulation +mechanical flow model)

1) The initial annual layer thickness (i.e. the accumulation rate) is evaluated from the deuterium content of the ice.
2) The vertical compression of the layers, or total thinning ratio, is evaluated with a mechanical model.

The age at a depth z is then given by:

$$\text{age}(z) = \int_0^z \frac{1}{T(z')\,a(z')} dz'.$$

*Compression factor*

*Initial annual layer thickness*

*This ice flow model contains several poorly known parameters*

# Antarctica: glaciological modelling and more (EDC3)

step2» the preliminary age scale obtained is constrained with age markers  and sinchronized with GICC05.

Markers are:

1) the dated volcanoes of the last millenium;
2) the two $^{10}$Be age markers in the last 6 kyr;
3) one methane age marker during the last deglaciation;
4) the Laschamp age marker  at 41.2 kyr BP;
5) The Mt. Berlin ash layer dated 92.5±2 kyr BP by Ar/Ar method on ash material collected close to the volcano.
6) Timing of Termination II  - found by comparison to U-Th speleothem records (Israel, China) assuming that these transitions are synchronous.
7) Air content  0-440 kyr BP
8) $^{18}O_{atm}$ for 300-800 kyr BP
9) The Brunhes – Matuyama reversal localized in the core through $^{10}$Be record

# Antarctica: glaciological modelling and more (EDC3)

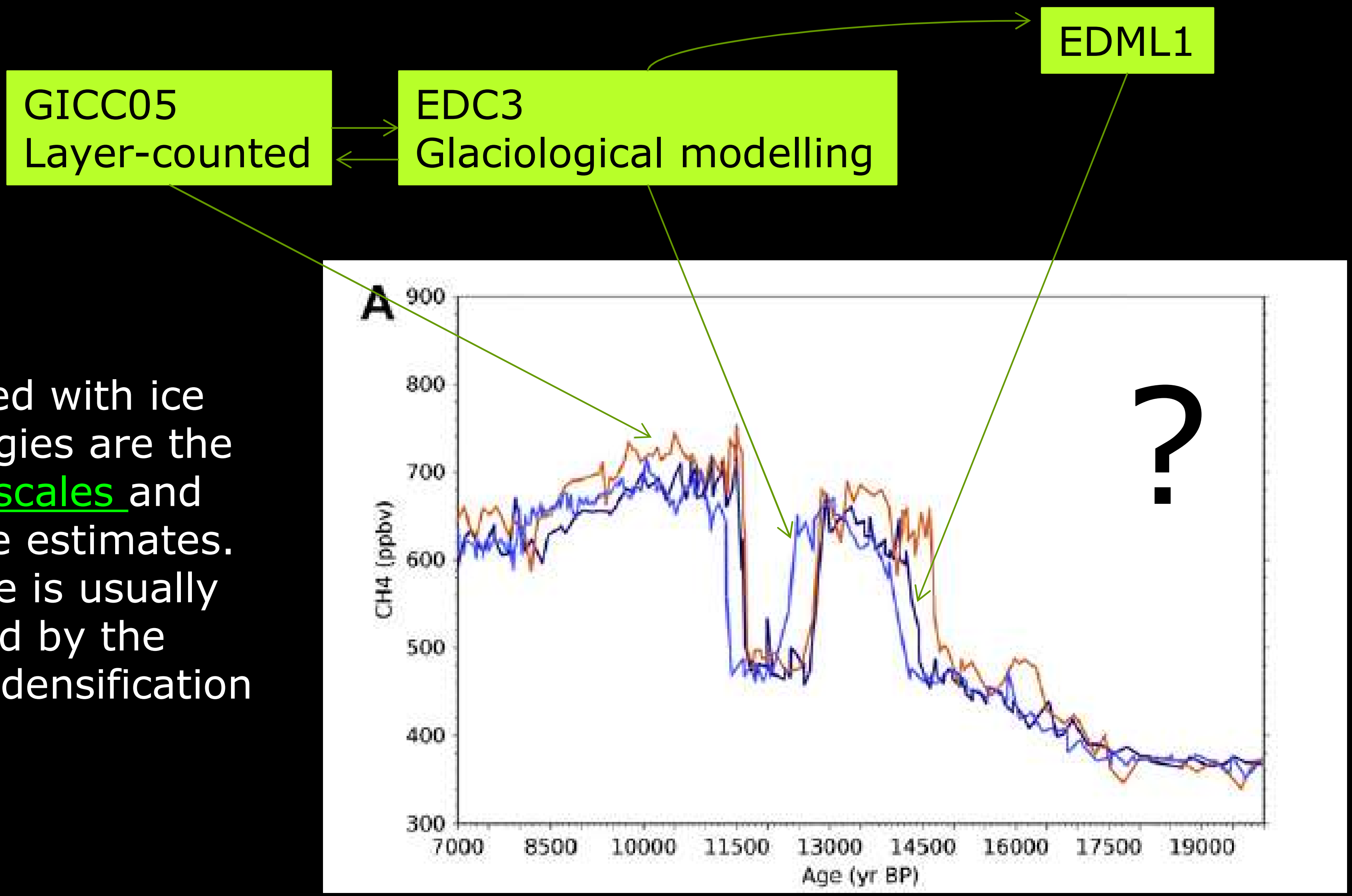
step3 » correction of the modelled thinning function in the bottom 500m of the core (beyond MIS11, 400 kyr BP), where the ice flow model is unable to fit the $^{18}O_{atm}$ age markers (Dreyfus et al., 2007).

*Accuracy of **EDC3 dating**:*

*100 yr at 2000 yr BP and stays stable back to 6000 yr BP.*
*400 yr at 14 kyr BP (roughly the error on the CH4 markers)*
*1 kyr at 18 kyr (Last Glacial Maximum)*
*1.5 kyr at 40 kyr, and finally*
*3 kyr at 100 kyr BP*
*6 kyr at 130 kyr and stable down to the bottom*

*Accuracy in the duration of events: 20% to 40% (bottom part of core)*

# EDC3 chronology has been transferred on other antarctic ice cores




Associated with ice chronologies are the gas age scales and delta-age estimates. Delta-age is usually calculated by the mean of densification models.

# Alternative dating methods

Probabilistic approaches based on inverse techniques *(Lemieux-Dudon et al., 2010)*

Approach: “best compromise” between model-based dating scenarios and chronological information from data.
Stratigraphic markers are related to the gas or ice phases. This enables to cross-constrain different chronologies.

These methods can be applied to several cores at the same, potentially covering the full depth intervals of the cores.

The probabilistic formulation provides the means to estimate confidence intervals of the new dating scenarios.

# Orbital tuning – deep part of cores

Comparison of paleoclimatic records to insolation variations (orbital tuning) is generally applicable to a whole ice core, as long as the stratigraphy is preserved but:

(1) the accuracy in terms of event durations is poor;
(2) the accuracy in terms of absolute ages is limited by the hypothesis of a constant phasing between the climatic record used for the orbital tuning procedure and the insolation variations

The advantage is that the achieved accuracy does not decrease with depth.

It is currently the most precise method to date the bottom of deep ice cores.

*Tuning is performed using proxies of local summer insolation which can impact firn physics such as total air content and* $O_2/N_2$ *ratios.*

# Towards absolute dating?

Promising absolute dating methods arise from:

- absolute Ar/Ar dating of Antarctic tephra (*Dunbar et al., 2008*)

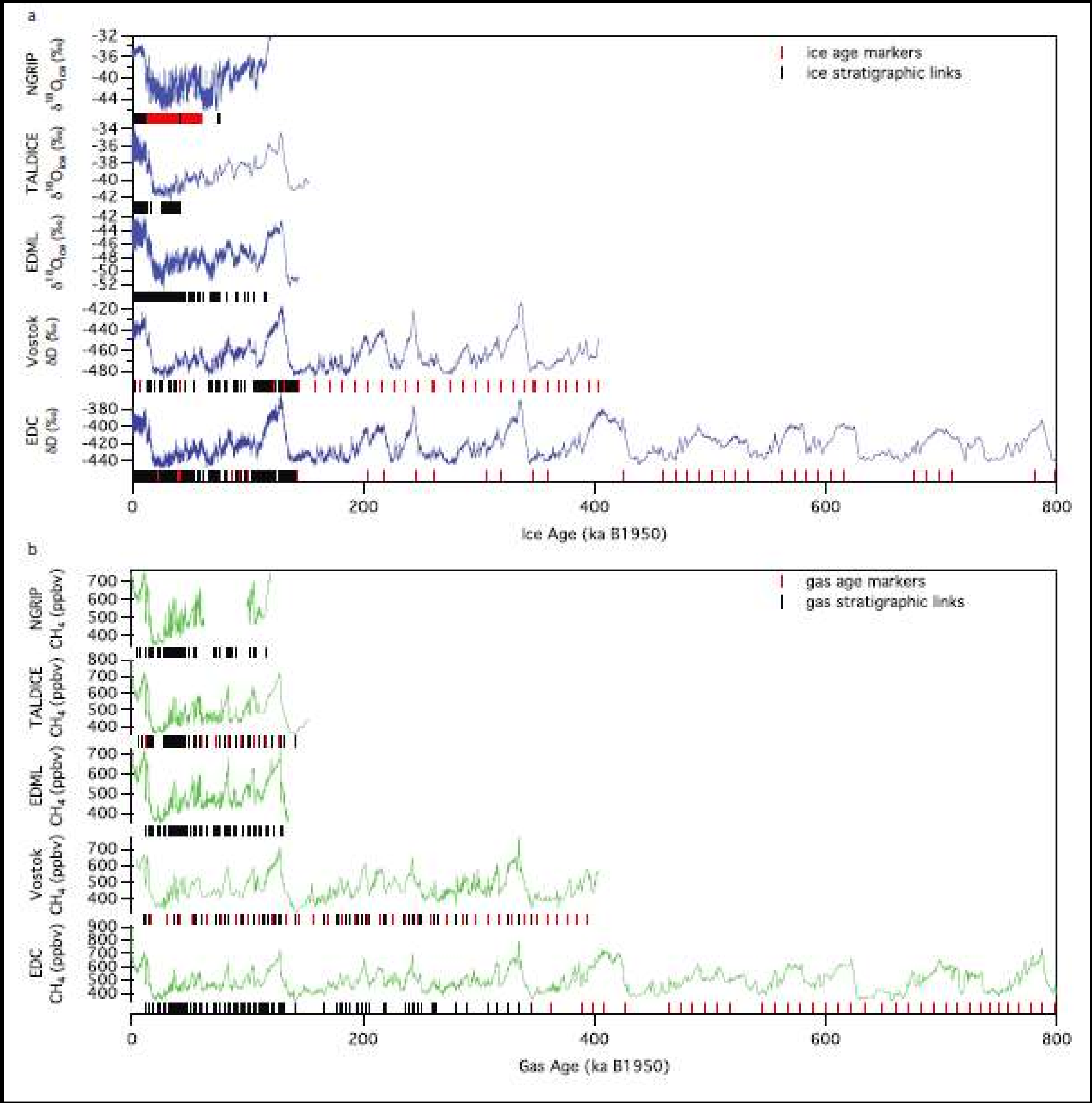
- U-series recoil ages (*S.Aciego et al, 2009*)

# AICC 2012

Coherent timescale developed for four Antarctic ice cores (Vostok, EPICA Dome C, EPICA Dronning Maud Land, TALDICE, alongside the Greenlandic NGRIP record, constructed using an improved version of the Bayesian Datice (Lemieux-Dudon et al., 2010)

*What's new in AICC2012?*

-New stratigraphic markers
-Improved calculation of the lock-in depth based on $^{15}N$ data
- New orbital gas age constraints : $\delta^{18}O_{atm}$ over MIS 11–12 on EDC and a complete $\delta^{18}O_{atm}$ record of the TALDICE ice core.




*Stable isotopes and $CH_4$ from different ice cores on AICC2012 timescale with indication of the stratigraphic links and age markers under each core*