# PHY392S
# Physics of Climate

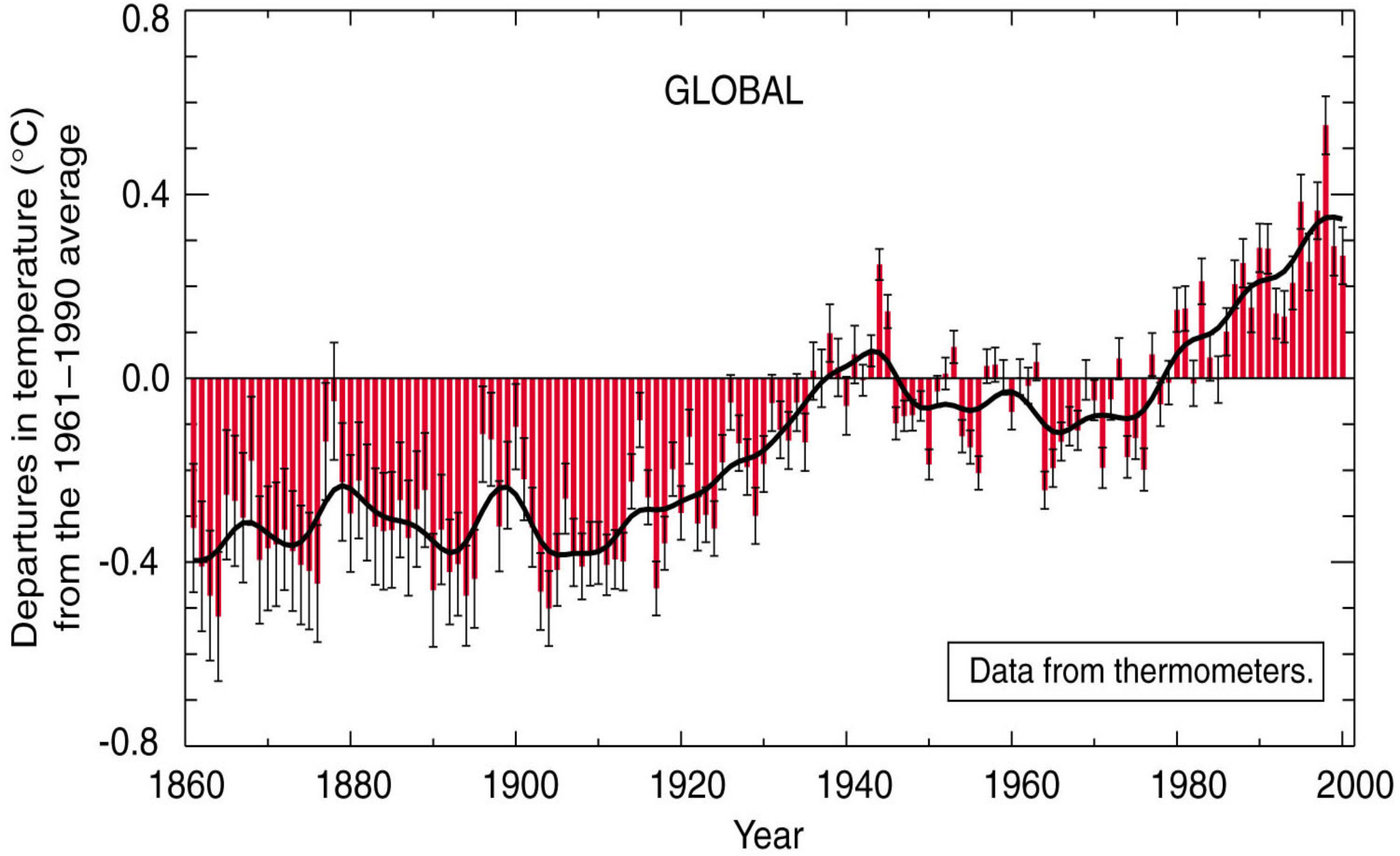
## Lecture 2

# Geologic Time Scale

| Eon | Era | Period | Epoch | Millions of Years Ago |
|---|---|---|---|---|
| Phanerozoic | Cenozoic | (Quaternary) | Holocene | |
| | | | | 0.011 |
| | | | Pleistocene | |
| | | | | 1.6 |
| | | (Tertiary) | Pliocene | |
| | | | | 5.1 |
| | | | Miocene | |
| | | | | 24 |
| | | | Oligocene | |
| | | | | 38 |
| | | | Eocene | |
| | | | | 55 |
| | | | Paleocene | |
| | | | | 65 |
| | Mesozoic | Cretaceous | | |
| | | | | 144 |
| | | Jurassic | | |
| | | | | 200 |
| | | Triassic | | |
| | | | | 250 |
| | Paleozoic | Permian | | |
| | | | | 285 |
| | | Carboniferous Pennsylvanian | | |
| | | | | 320 |
| | | Mississippian | | |
| | | | | 360 |
| | | Devonian | | |
| | | | | 410 |
| | | Silurian | | |
| | | | | 440 |
| | | Ordovician | | |
| | | | | 505 |
| | | Cambrian | | |
| | | | | 550 |
| Proterozoic | | | | |
| | | | | 2500 |
| Archean | | Oldest Rock | | 4000 |
| | | Age of the Solar System | | 4550 |

[From Turekian, 1996]

# Global surface temperature change over the Last 150 years




[Jones et al 2001, Folland et al. 2001]

# NH Temperatures during the Hypsithermal (8-5k years ago) were warmer than present

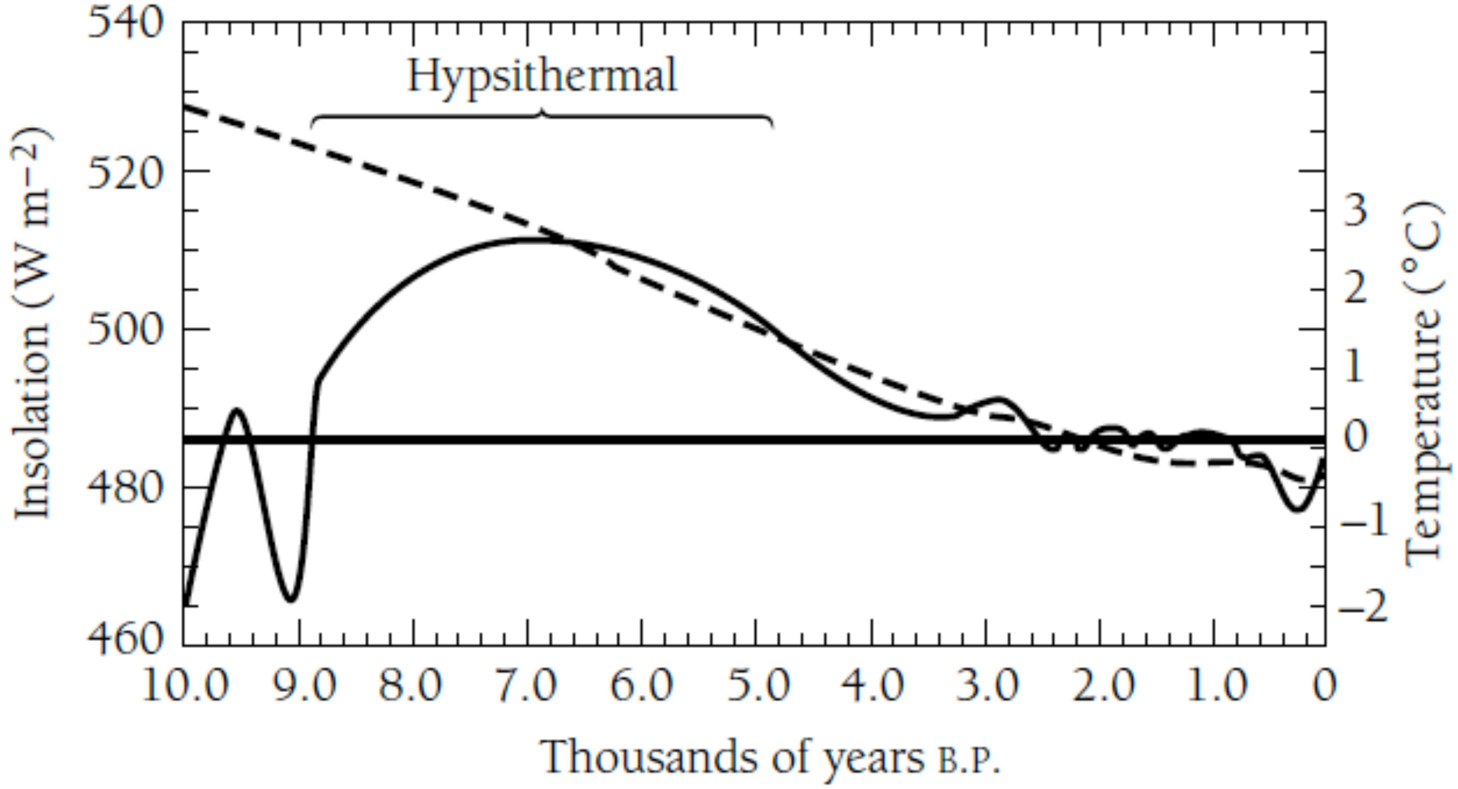



*Figure 10.18 Variation of temperature (solid curve) and daily insolation at 60°N for summer solstice in the Jostedalsbreen region of Norway (62°N, 7°E), based on a variety of lithostatigraphic and paleobotanical techniques. Source: McElroy 1994.*

[From McElroy, 2002]

# Glacial fluctuations in Europe during the last 10 kyr

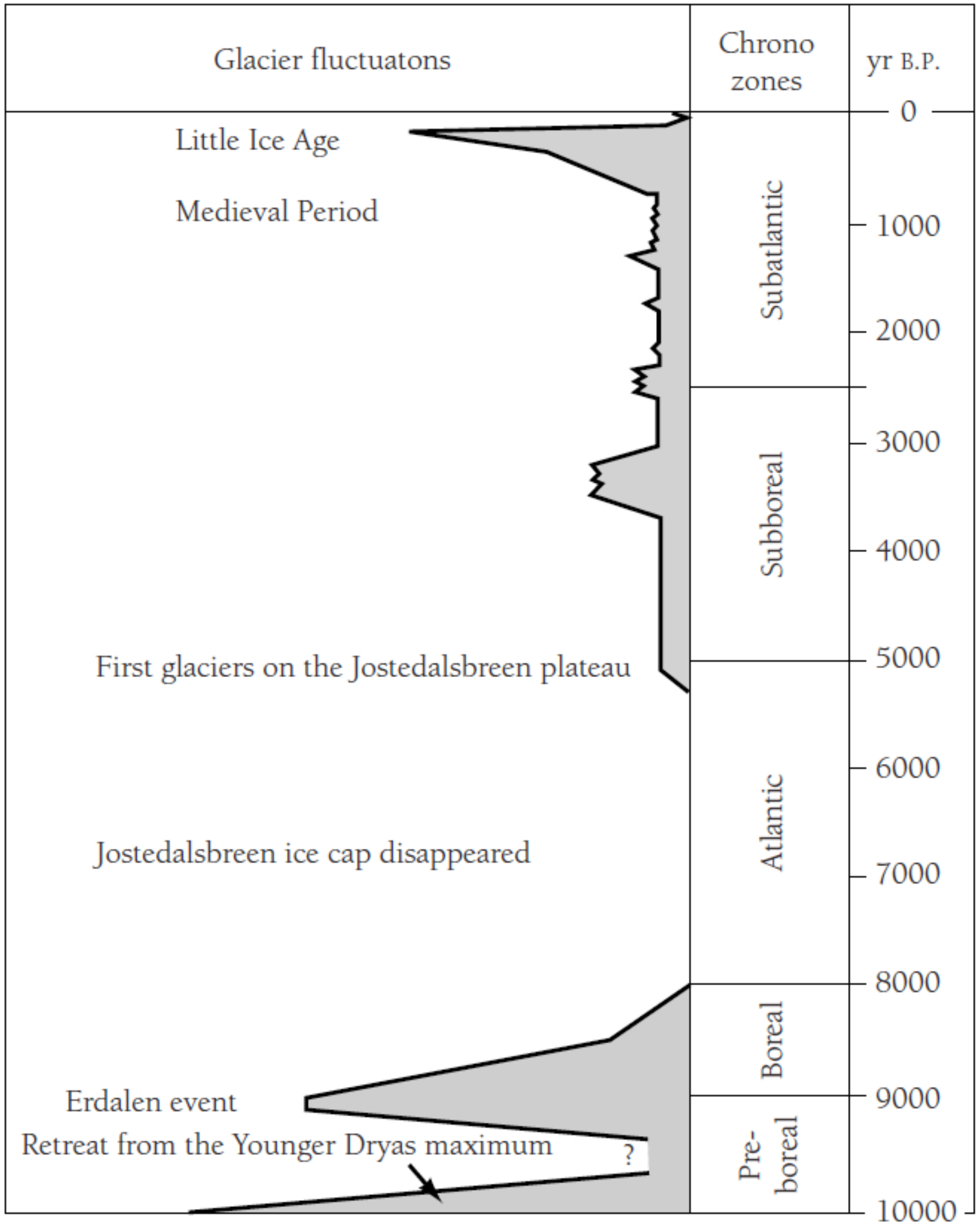



*Figure 10.19 The fluctuation of glaciers over the past 10,000 years in the Jostedalsbreen region of Norway (62°N, 7°E), based on a variety of lithostatigraphic and paleobotanical techniques. Source: Nesje and Kwamme 1991.*

The Jostedalsbreen ice cap disappeared during the hypsithermal

[From McElroy, 2002]

# Precipitation fluctuations over Peru during the last 1.5 kyr

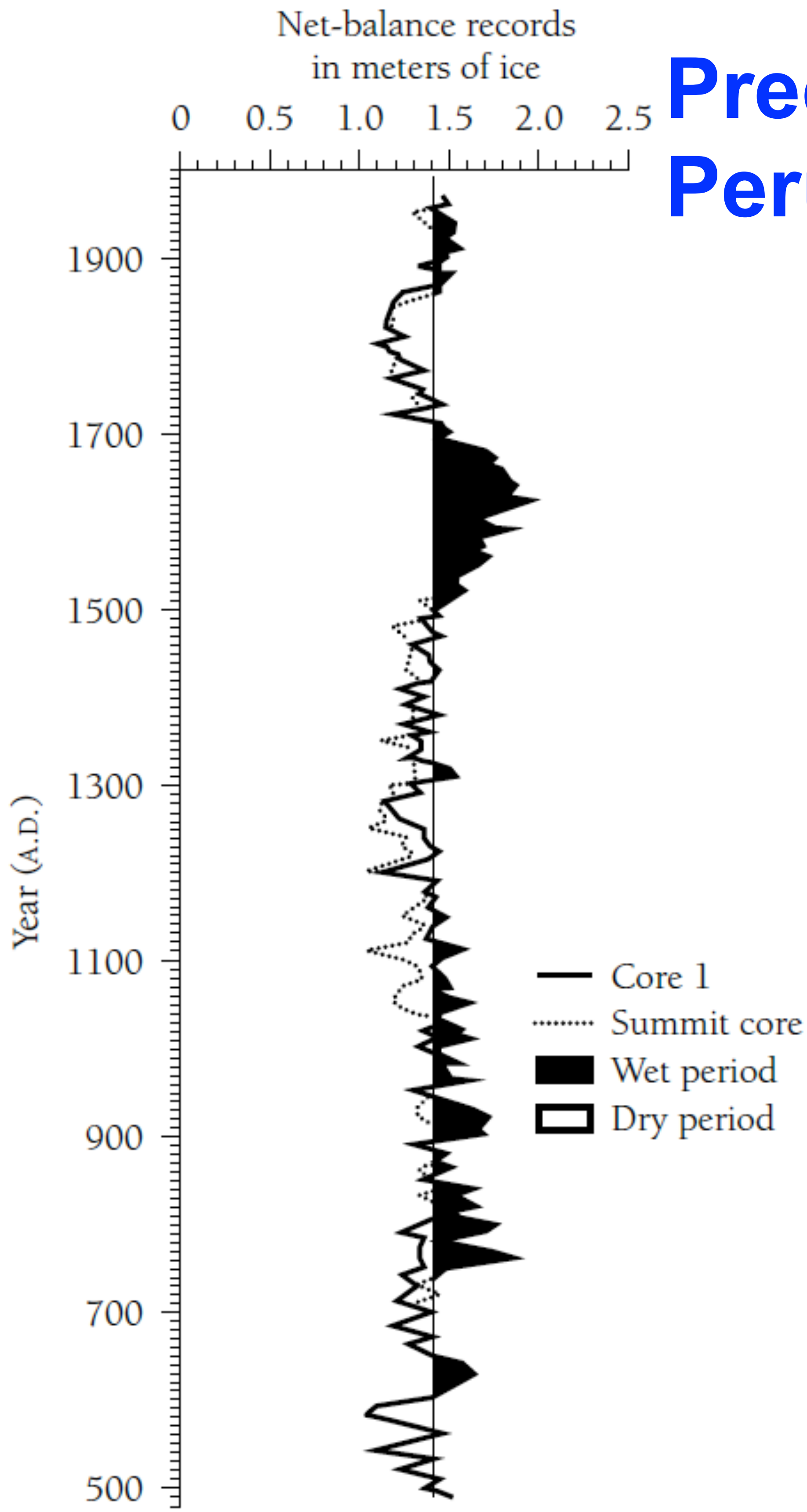
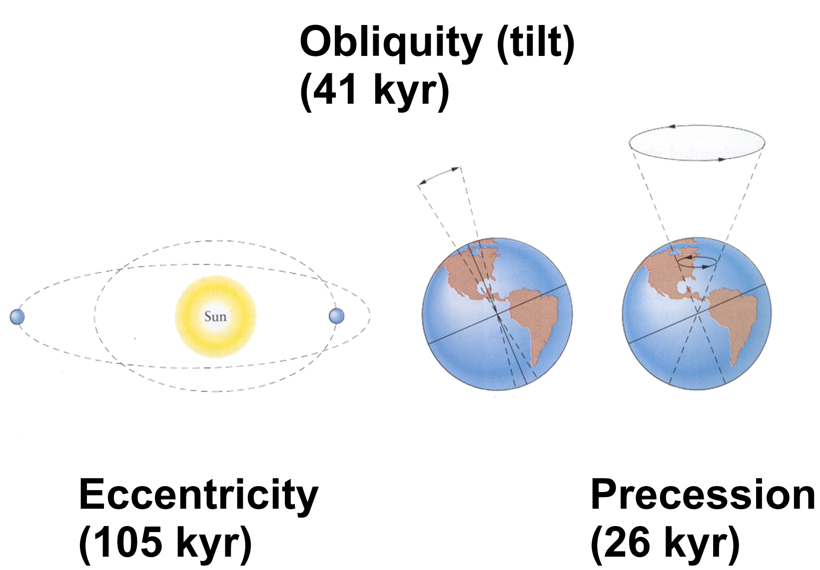
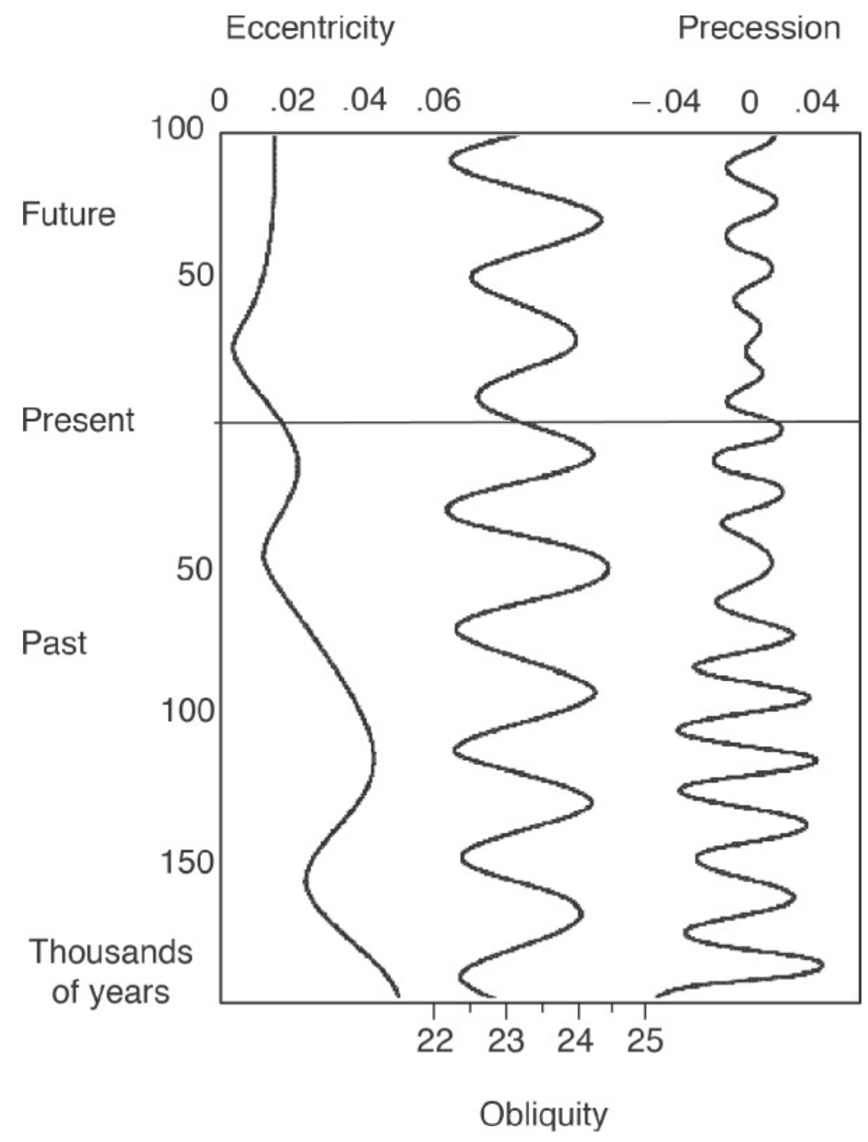



*Figure 10.20 Reconstructed rate of precipitation, based on annual accumulation rates, for two ice cores in the Quelccaya ice cap (14°S, 71°W, 5160 m elevation). Extended periods of aridity and moistness are indicated. Source: Thompson et al. 1985.*

[From McElroy, 2002]

**<u>Milankovitch</u> cycles: periodic changes in the flux of solar radiation received by Earth driven by changes in Earth's orbit**




[Marshall and Plumb]

# Milankovitch Cycles

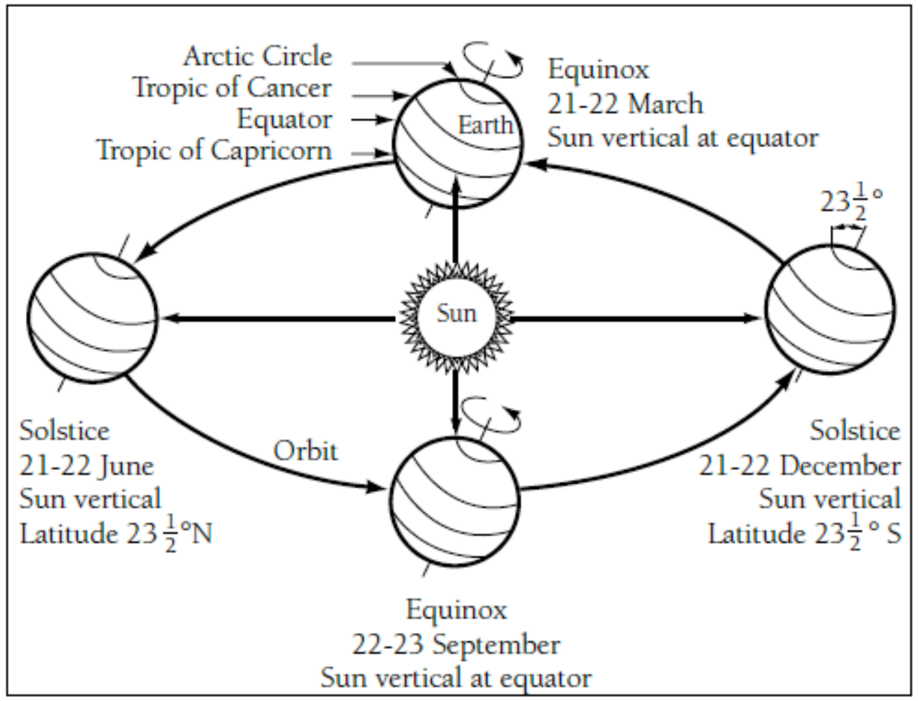



*Figure 10.8 Seasons. Source: Anthes.*

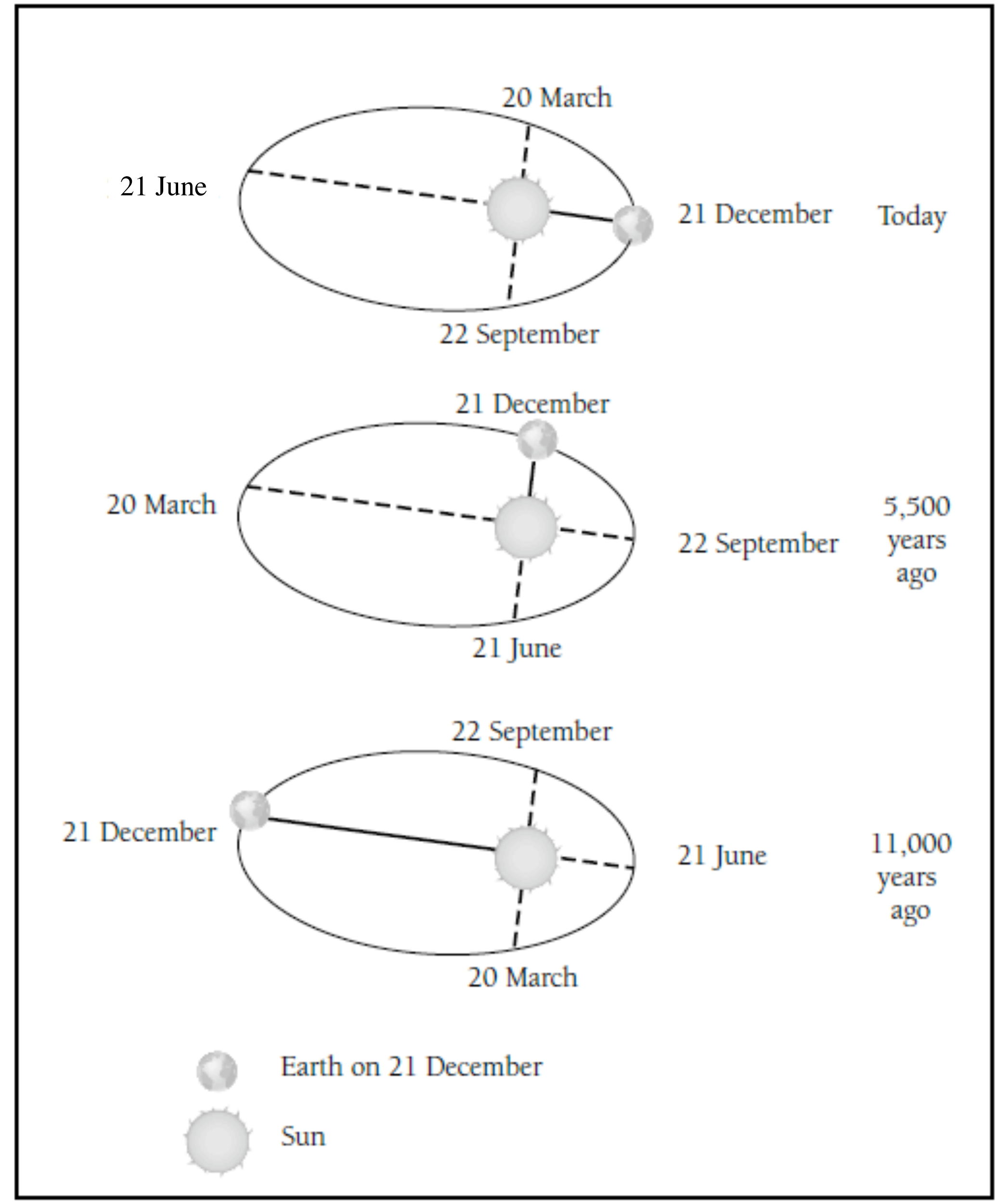



*Figure 10.9 Precession of the equinoxes. Source: Imbrie and Imbrie 1978.*

[From McElroy, 2002]

# Changes in solar insolation at the top of the atmosphere over the last 100,000 years

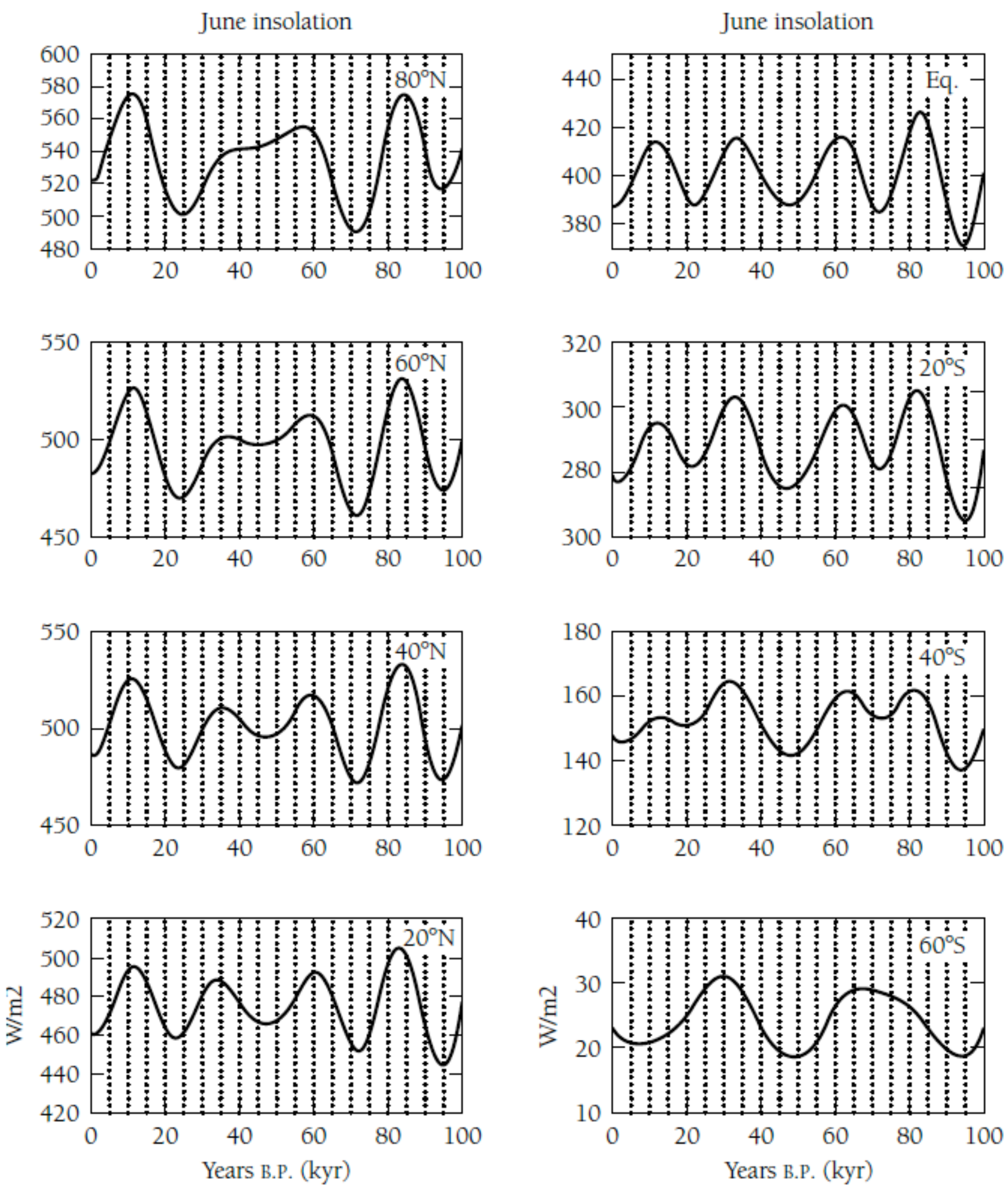



*Figure 10.11* *Insolation in June during the last 100 kyr.*

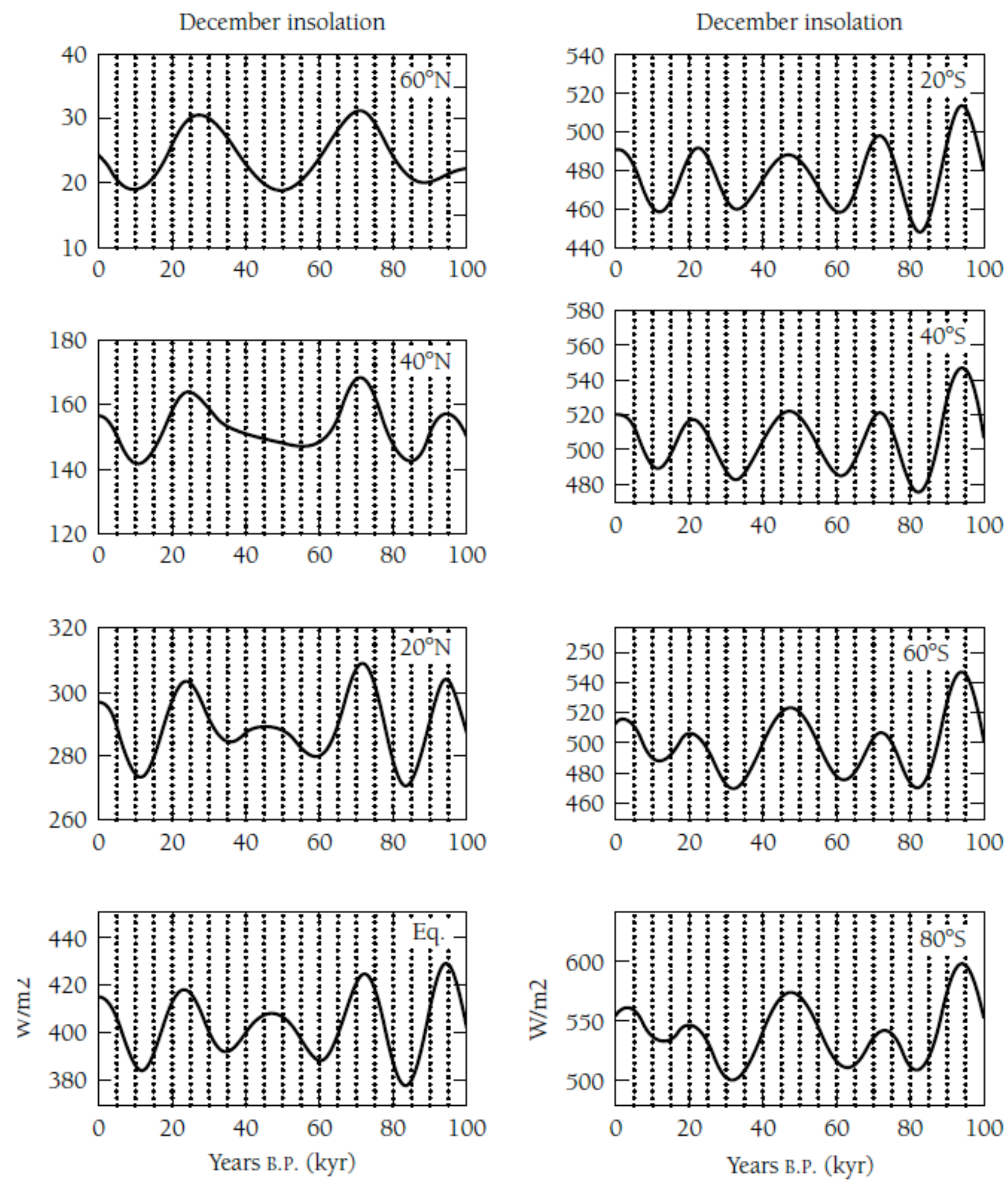
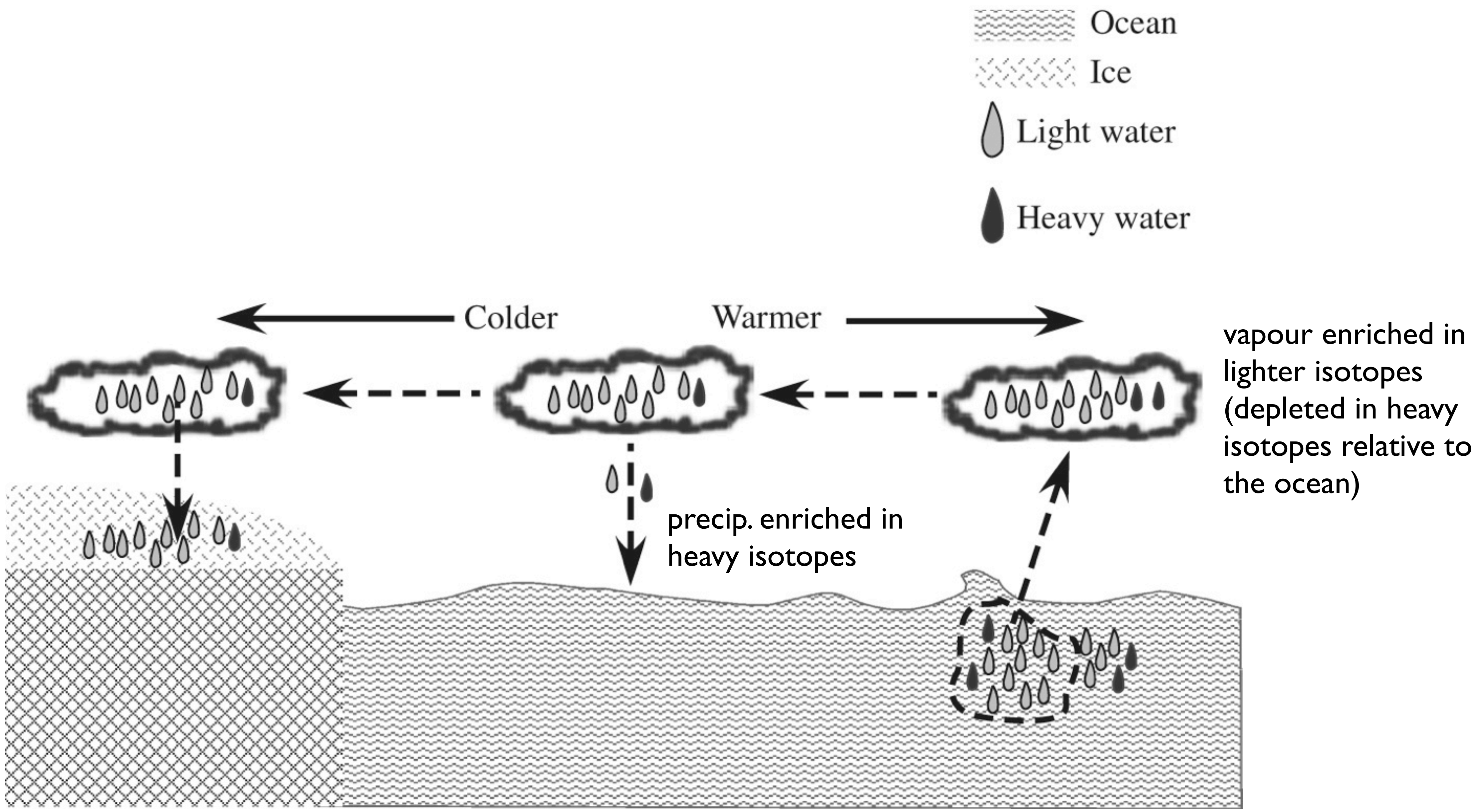



*Figure 10.13* *Insolation in December during the last 100 kyr.*

[From McElroy, 2002]

# Isotopic proxies for temperature

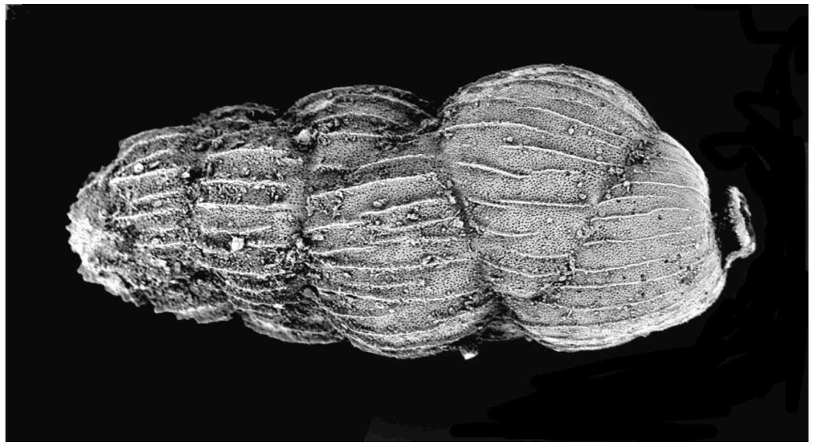



Temperature dependent fractionation of $^{16}O$ and $^{18}O$ and H and D in water during evaporation and precipitation

$$\delta^{18}O = \left[ \frac{\left({}^{18}O/{}^{16}O\right)_{\text{sample}}}{\left({}^{18}O/{}^{16}O\right)_{\text{standard}}} - 1 \right] \times 1000$$

- At 273 K, water vapour is depleted by -11.7‰ relative to the ocean
- Snow in Greenland has a $\delta^{18}O$ of about -35‰

# Isotopic proxies for temperature



Shell (test) of a benthic foraminiferan (foram)

[From Pierrehumbert, 2010]

Can use the $^{18}O/^{16}O$ ratio in $CaCO_3$ of the shells

$$\mathrm{Ca}^{++}(aq) + \mathrm{CO}_3^{=}(aq) = \mathrm{CaCO}_3(s)$$

$$\mathrm{H_2}\,{}^{18}\mathrm{O} + 1/3\,\mathrm{C}^{16}\mathrm{O}_3^{=} = \mathrm{H_2}\,{}^{16}\mathrm{O} + 1/3\,\mathrm{C}^{18}\mathrm{O}_3^{=}$$

$$K(T) = \frac{[\mathrm{H_2}\,{}^{16}\mathrm{O}][\mathrm{C}^{18}\mathrm{O}_3^{=}]^{1/3}}{[\mathrm{H_2}\,{}^{18}\mathrm{O}][\mathrm{C}^{16}\mathrm{O}_3^{=}]^{1/3}} = \frac{\left([\mathrm{C}^{18}\mathrm{O}_3^{=}]/[\mathrm{C}^{16}\mathrm{O}_3^{=}]\right)^{1/3}}{\left([\mathrm{H_2}\,{}^{18}\mathrm{O}]/[\mathrm{H_2}\,{}^{16}\mathrm{O}]\right)^{1/3}}$$

[From Turekian, 1996]

Two types of forams: planktonic (surface dwelling) and benthic (bottom dwelling). For benthic forams:

$$T(°C) = 17.96 - 4.0[\delta_c(VPDB) - \delta_w(VSMOW)]$$

$T$ = temp at which the foram grew, $\delta_c$ = $\delta^{18}O$ of the shell and $\delta_w$ = $\delta^{18}O$ of the water in which the foram grew.

# Glacial Cycles During the Past 2 Million Years

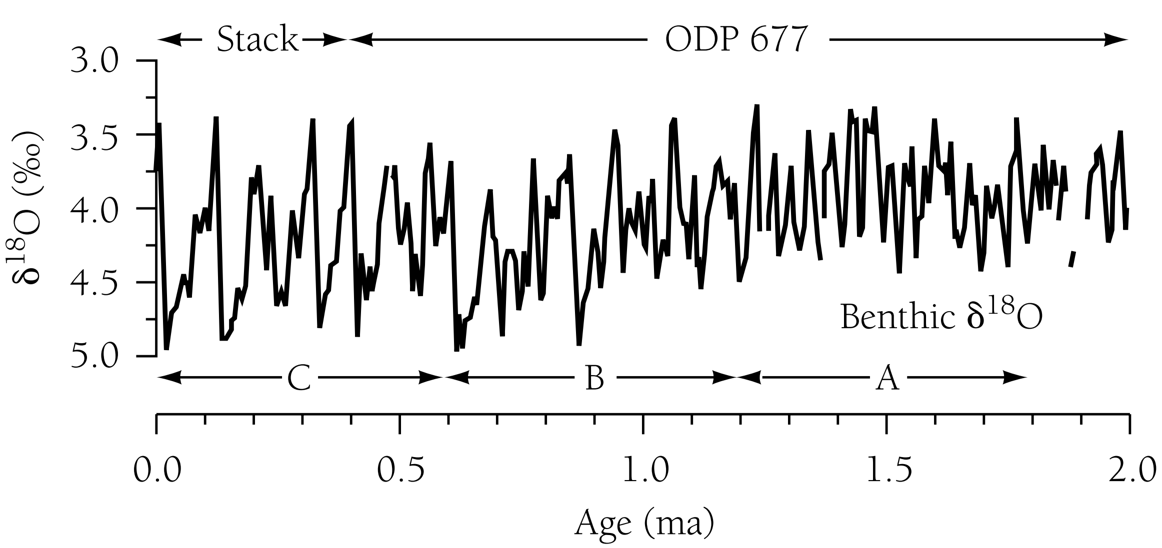



*Figure 10.22 The $\delta^{18}O$ record for the past two million years, showing glaciation cycles. The data are plotted on an inverted scale: values of $\delta^{18}O$ decrease with height on the vertical axis. We choose this form of presentation to emphasize the associated changes in climate. Small values of $\delta^{18}O$ (peaks in the Figure) reflect interglacial conditions; high values of $\delta^{18}O$ (minima in the Figure) indicate periods of maximum glaciation. Source: Imbrie et al. 1984.*

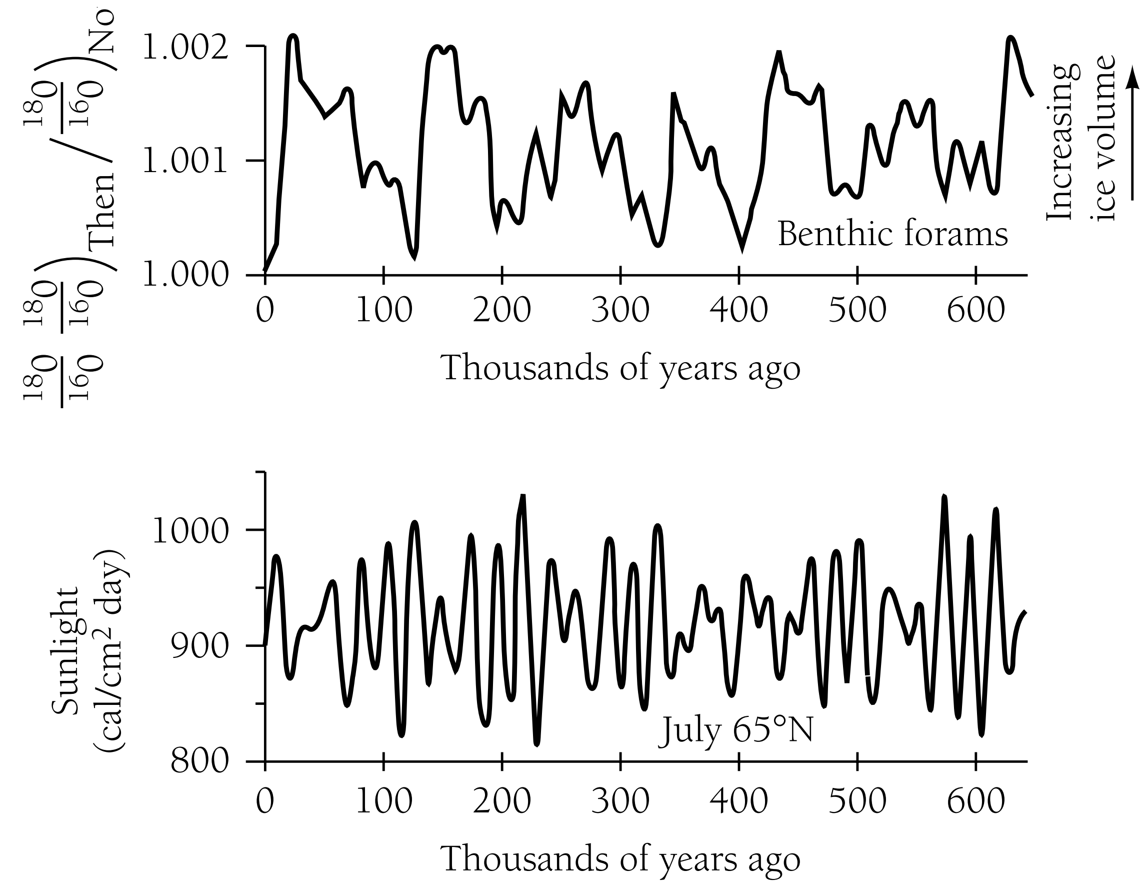



*Figure 10.23 Comparison between the ice-volume record and the July solar-radiation record for 65°N. Source: Broecker 1995.*

[From McElroy, 2002]

# The Past 130k Years

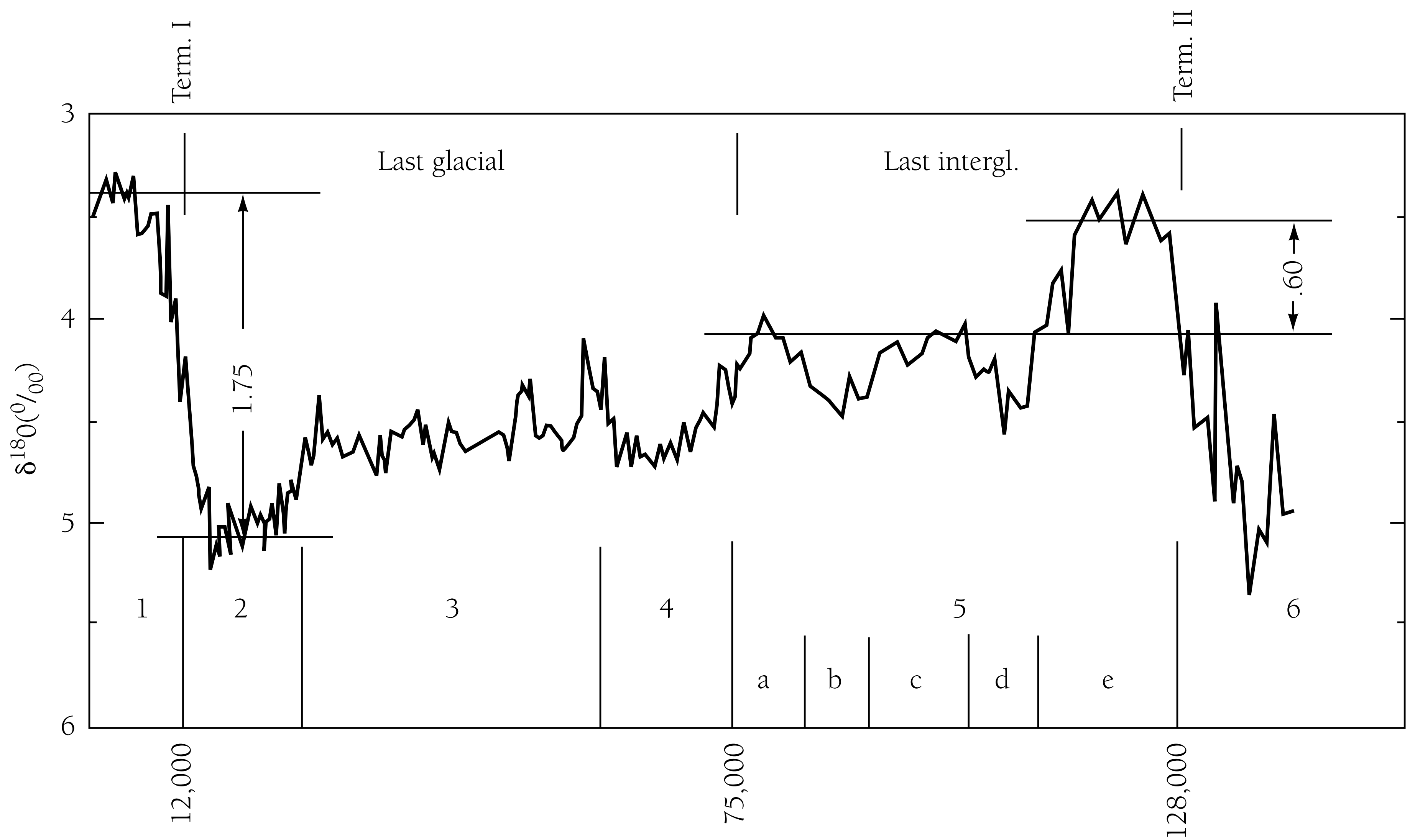



*Figure 10.24 The $\delta^{18}O$ record for benthic foraminifera from a deep-sea core from the eastern part of the equatorial Pacific, as well as isotope stage numbers and generally accepted ages for the major boundaries. Source: Broecker 1995.*

[From McElroy, 2002]

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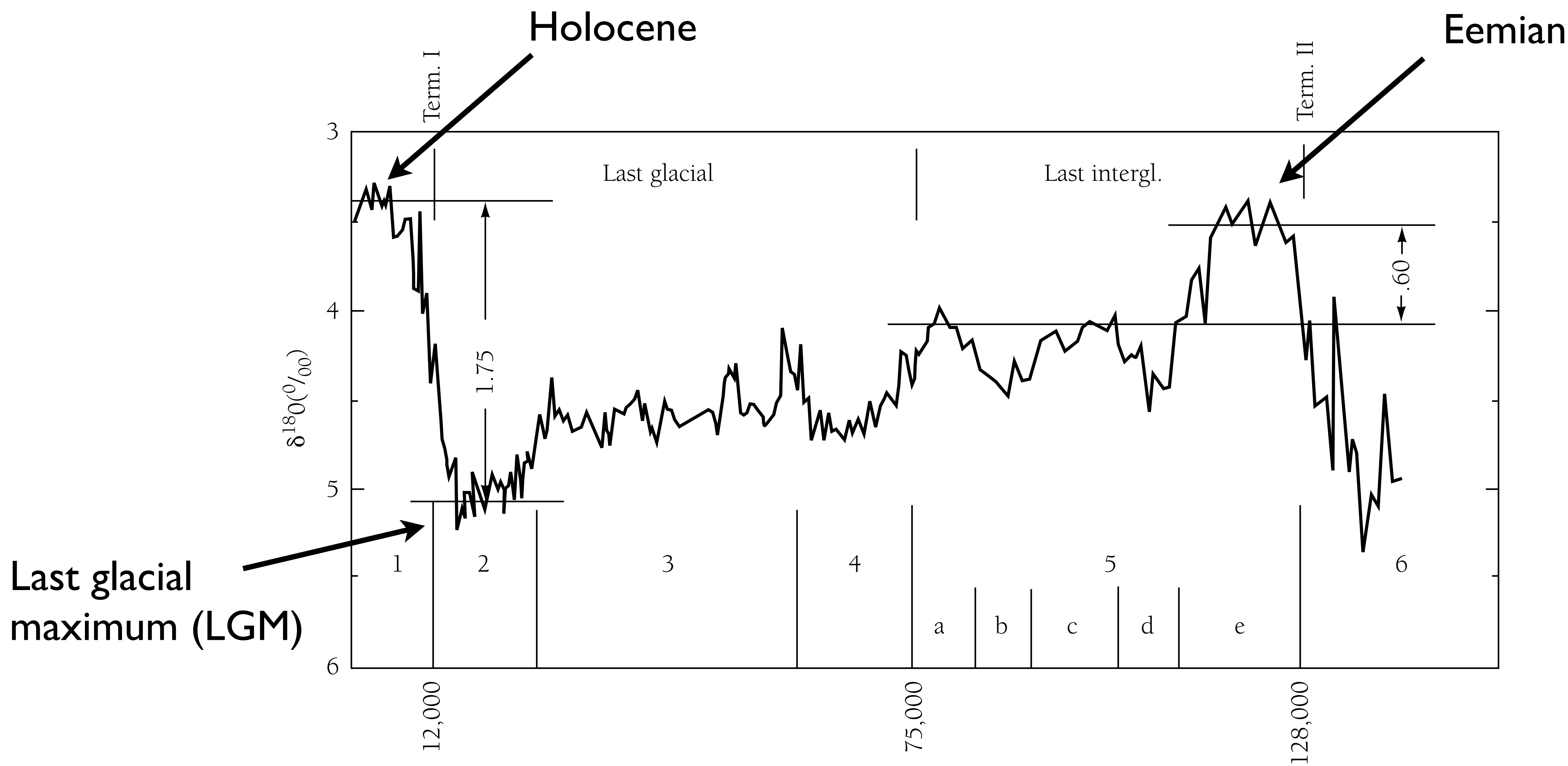


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[From McElroy, 2002]

# The Last Interglacial Transition

End of the last ice age;
beginning of the Holocene

Sea level rose by about 120 m

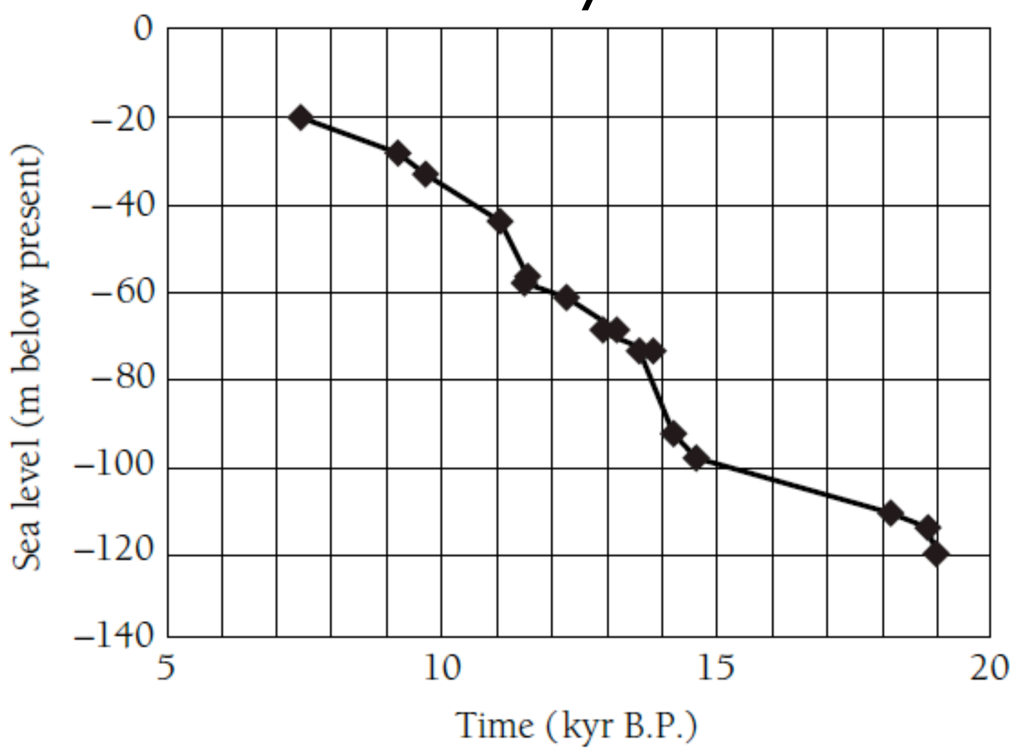


*Figure 10.6* *Rise in sea level during the last deglaciation.*

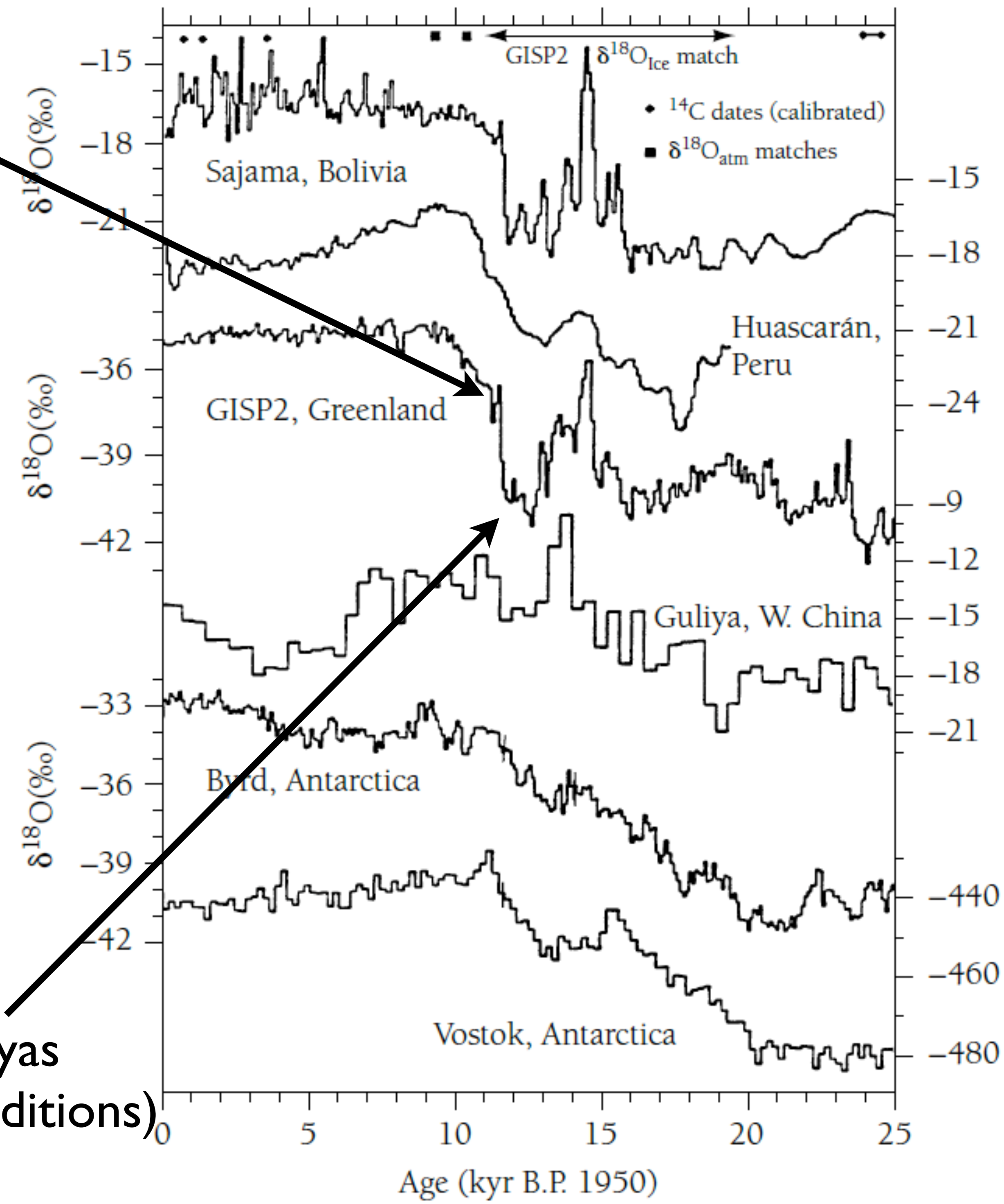


*Figure 10.7* *Interhemispheric comparison of stable isotope records from ice cores. Source: Thompson et al. 1998.*

The Younger Dryas
(return to glacial conditions)

[From McElroy, 2002]

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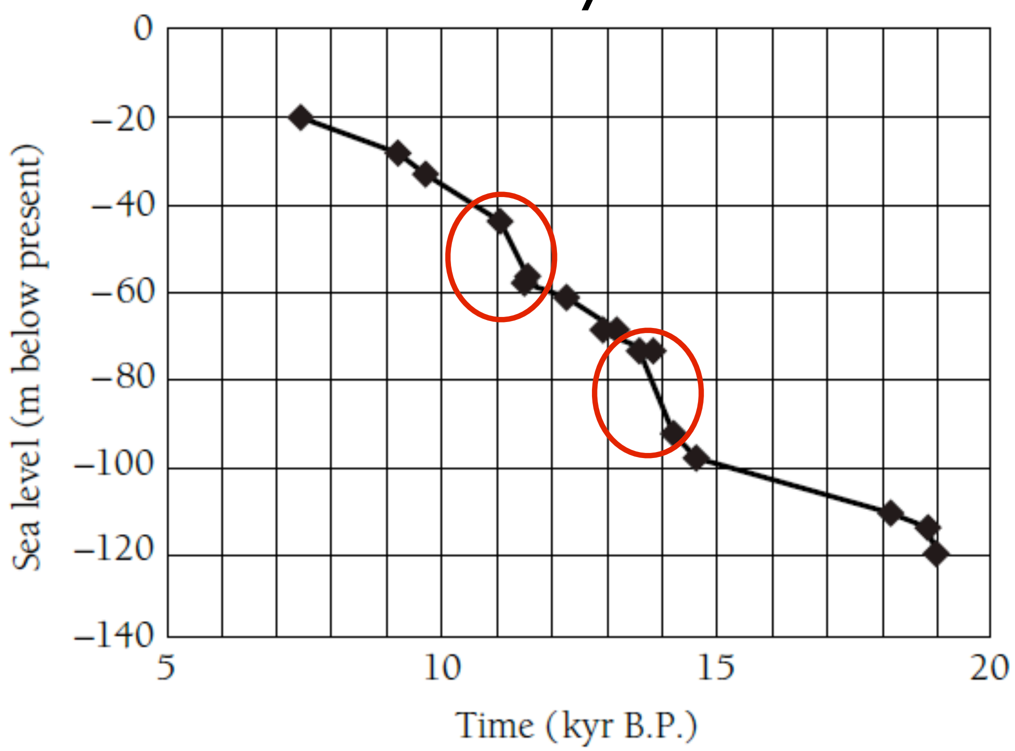



*Figure 10.6 Rise in sea level during the last deglaciation.*

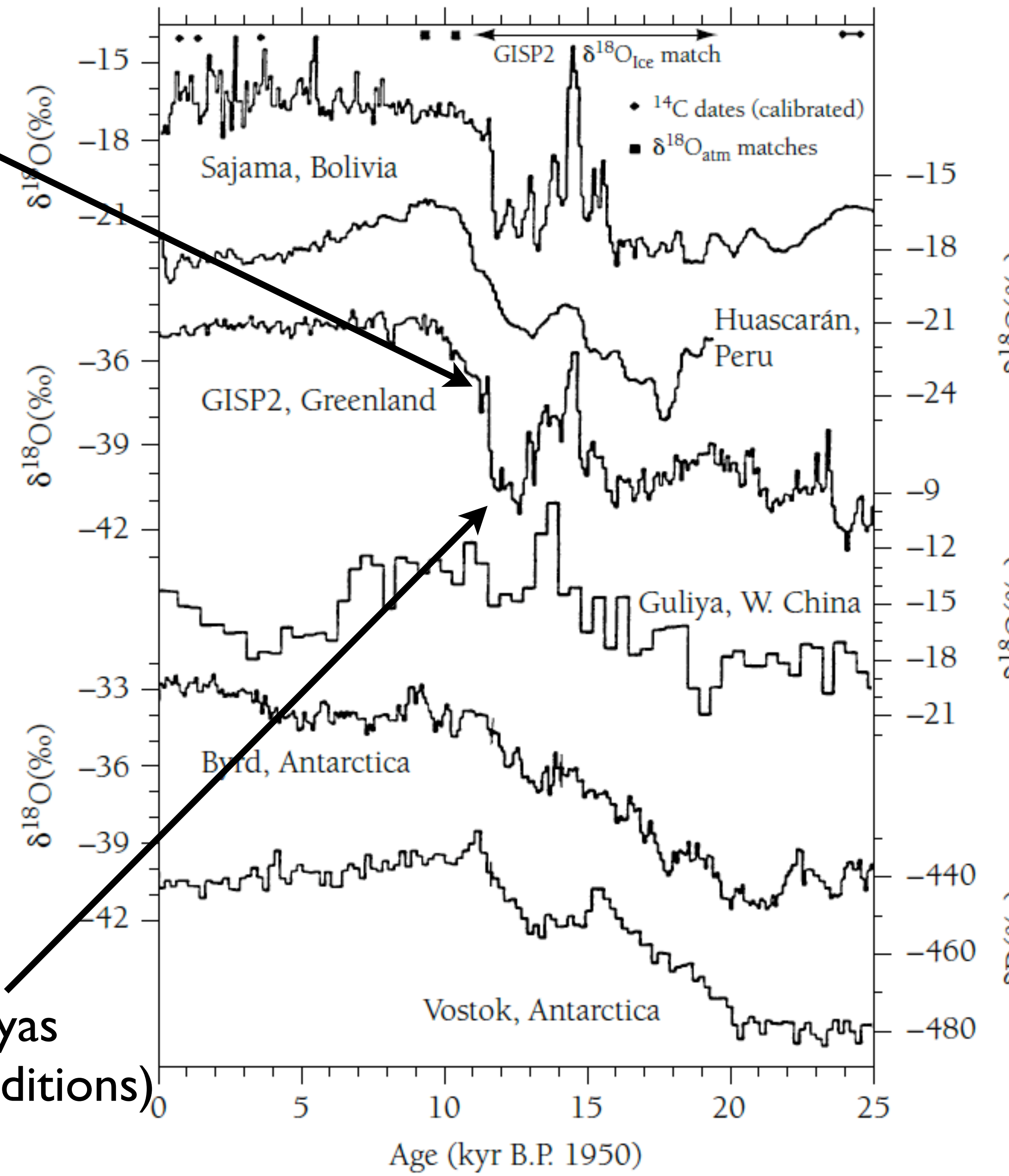
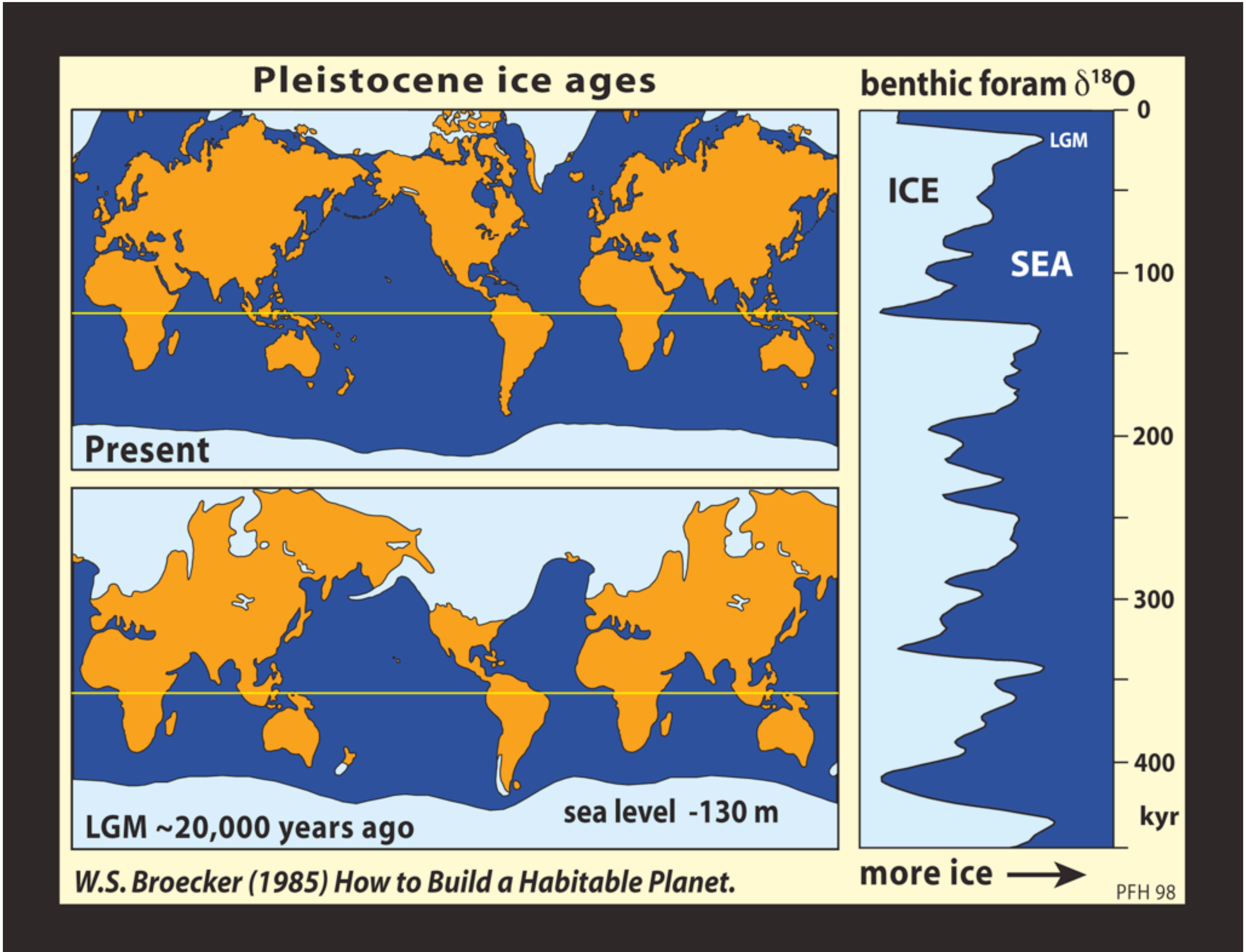



*Figure 10.7 Interhemispheric comparison of stable isotope records from ice cores. Source: Thompson et al. 1998.*

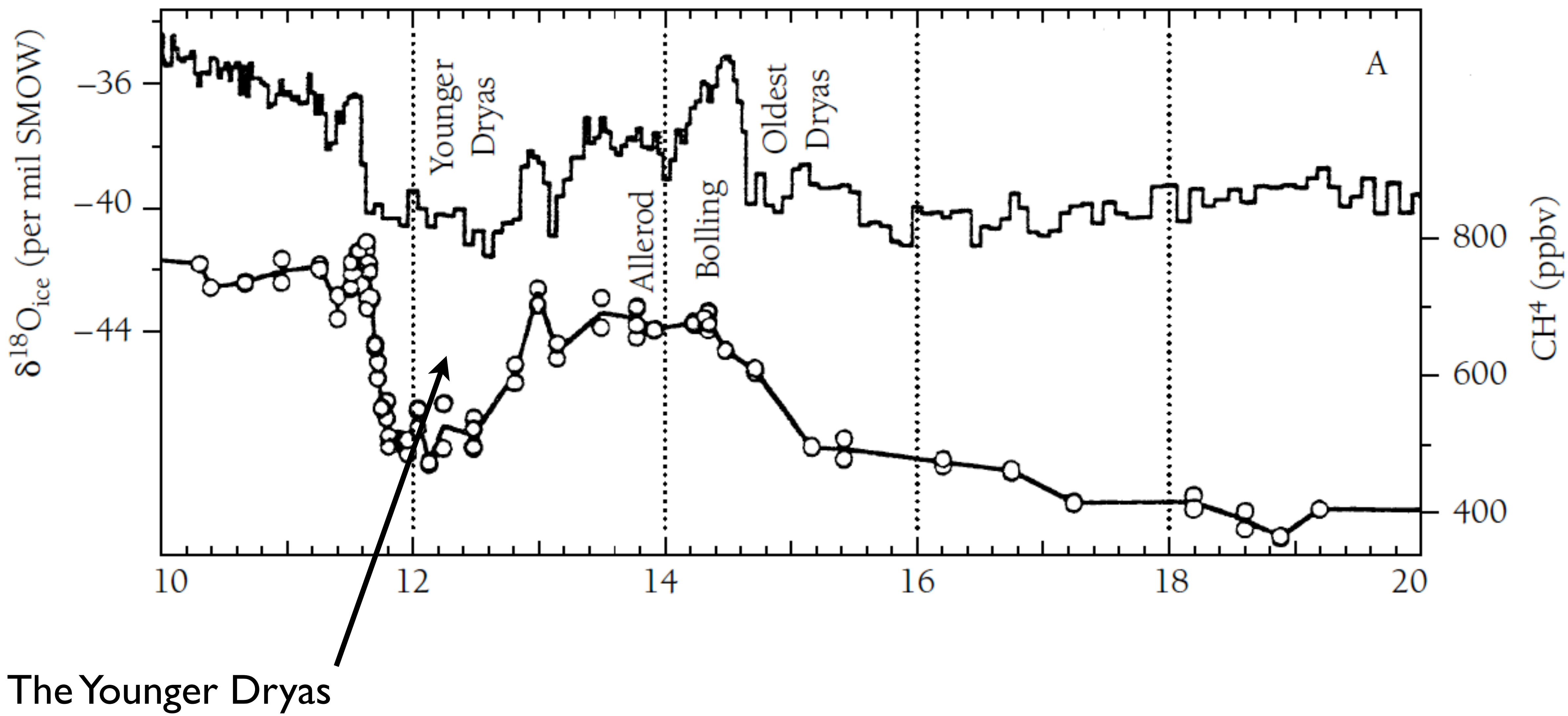
The Younger Dryas
(return to glacial conditions)

[From McElroy, 2002]




[From Snowball Earth (http://www.snowballearth.org)]

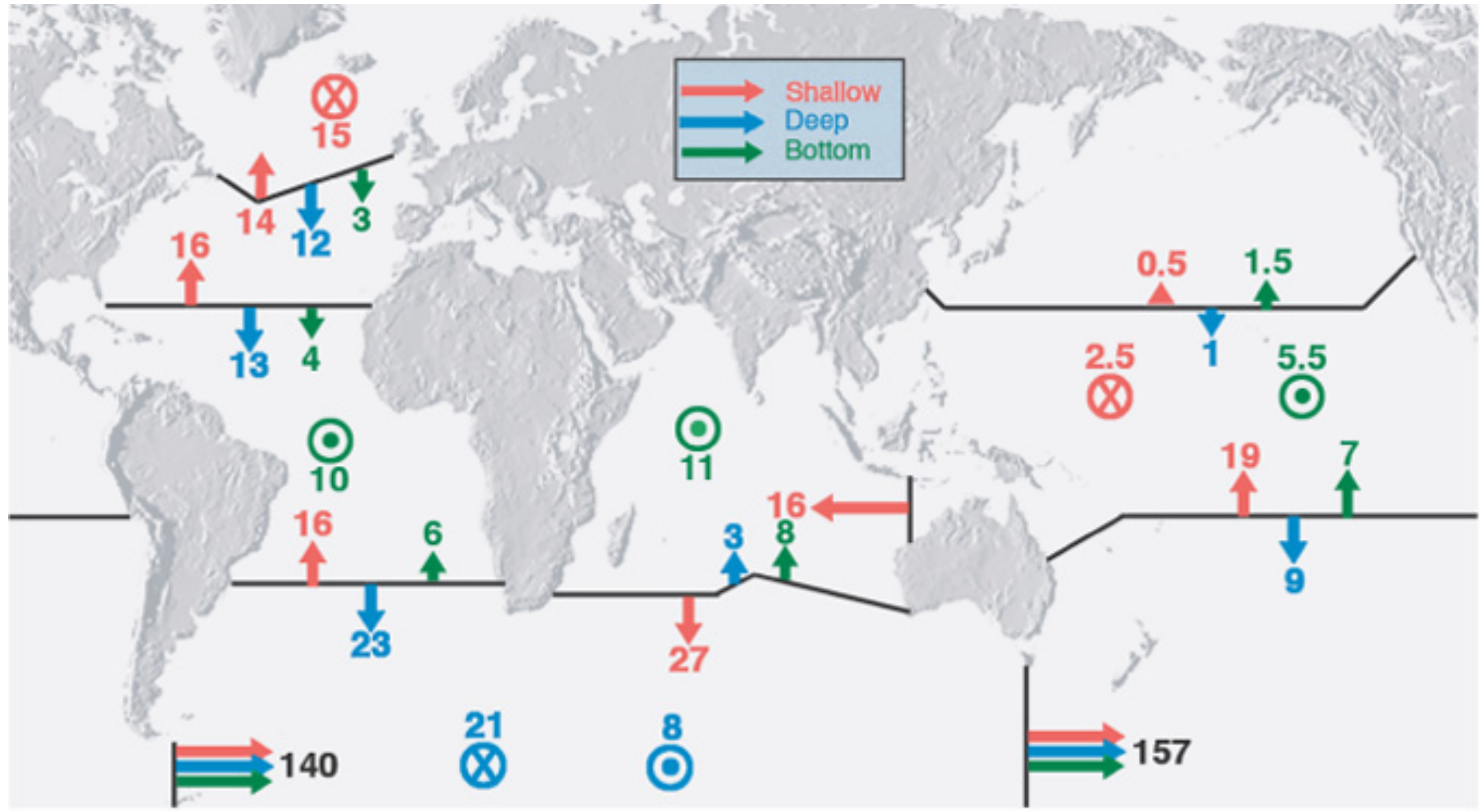
# The Younger Dryas



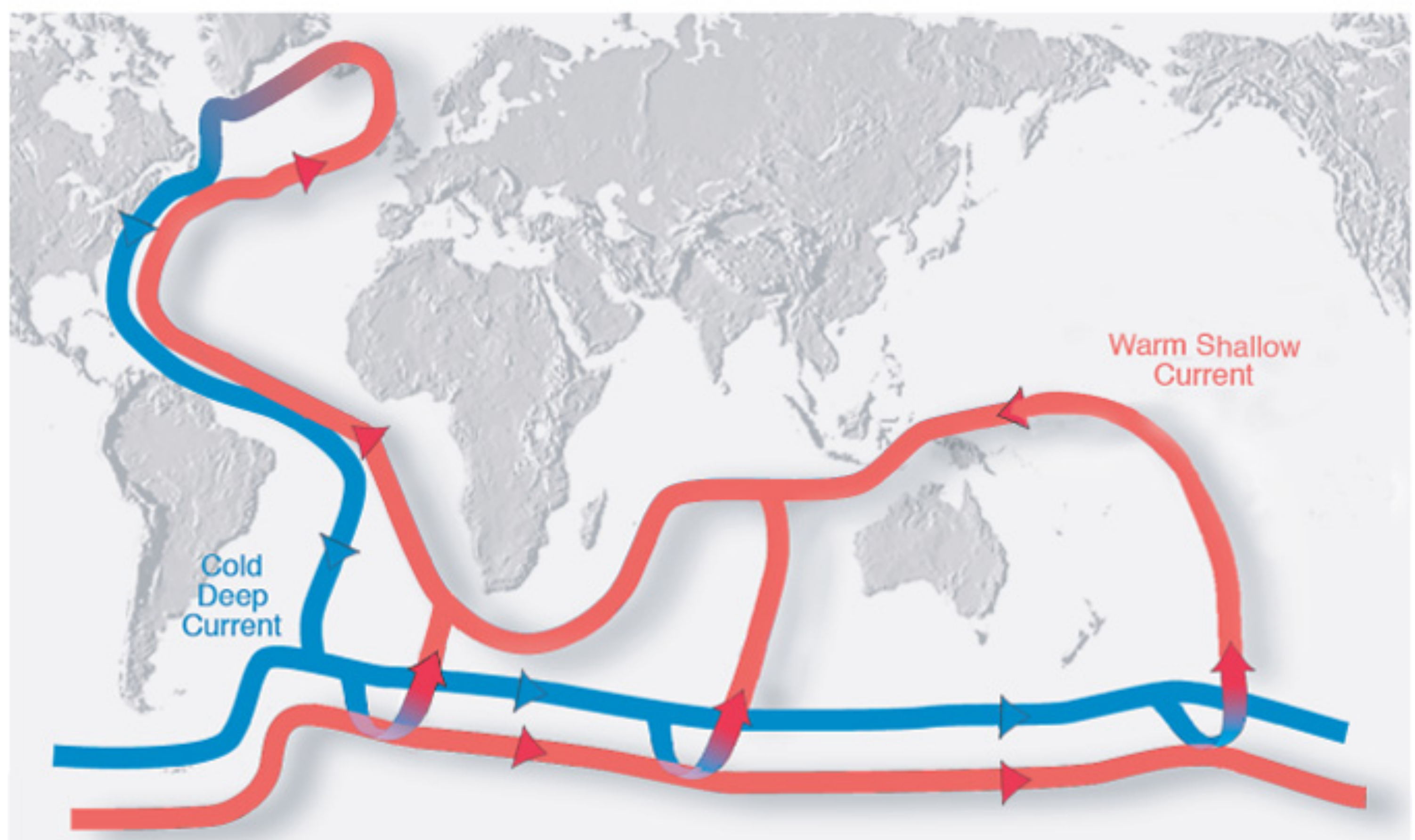

[From McElroy, 2002]

# The Thermohaline Circulation

Large-scale overturning of the ocean, driving by the sinking of cold, saline water in the North Atlantic




1 Sv = $10^6$ m$^3$/s




[Marshall and Plumb]

# Glacial/interglacial modes of the thermohaline circulation

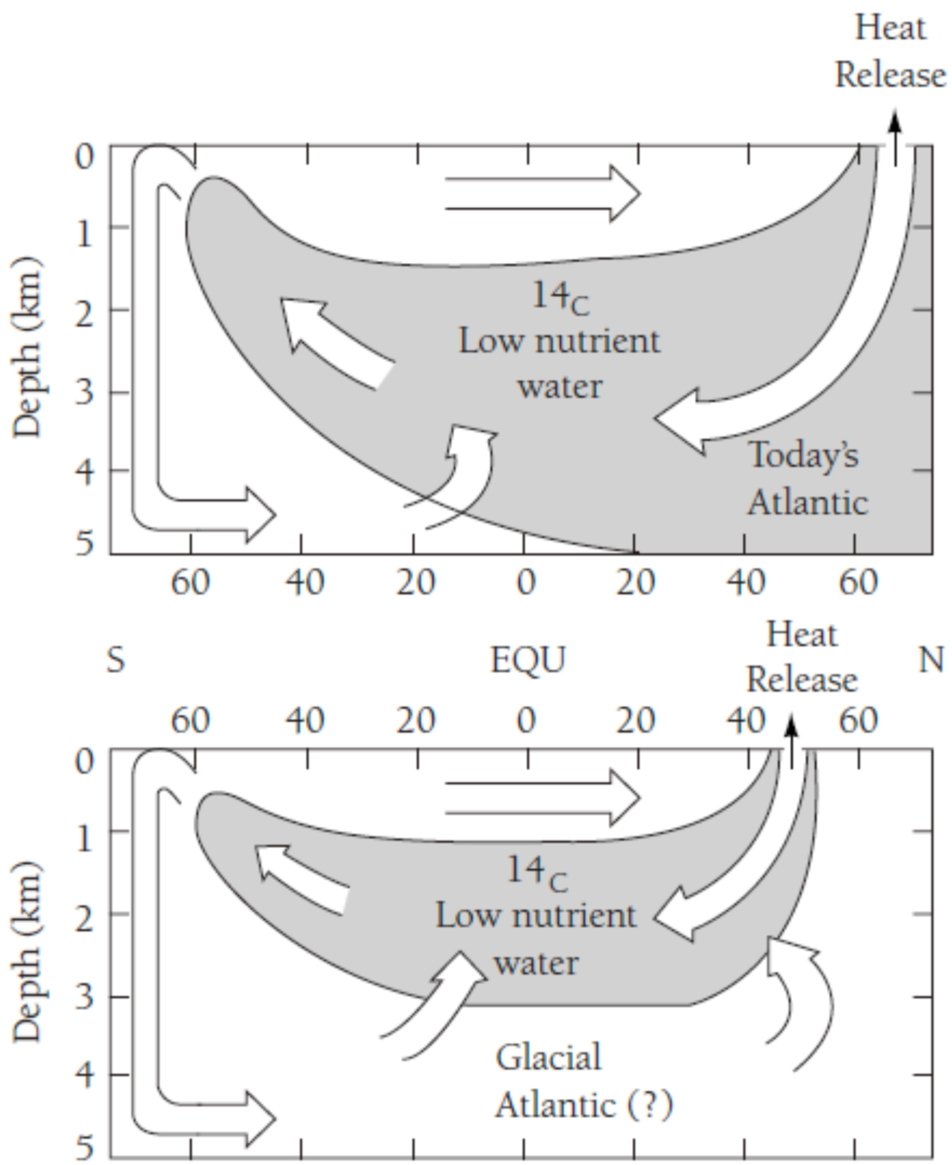



*Figure 10.17 Diagram showing the suggestion, based upon the records of cadmium kept in shells of bottom-dwelling foraminifera, that there was conveyor-like circulation in the glacial ocean but that it did not penetrate to as great a depth. Source: Broecker 1995.*

During glacial conditions North Atlantic deep water (NADW) formation shifts equatorward NADW formation is suppressed. Antarctic bottom water (AABW) instead fills the deep ocean

[From McElroy, 2002]

# $CO_2$, $CH_4$, and Temperature During the Past 600k Years

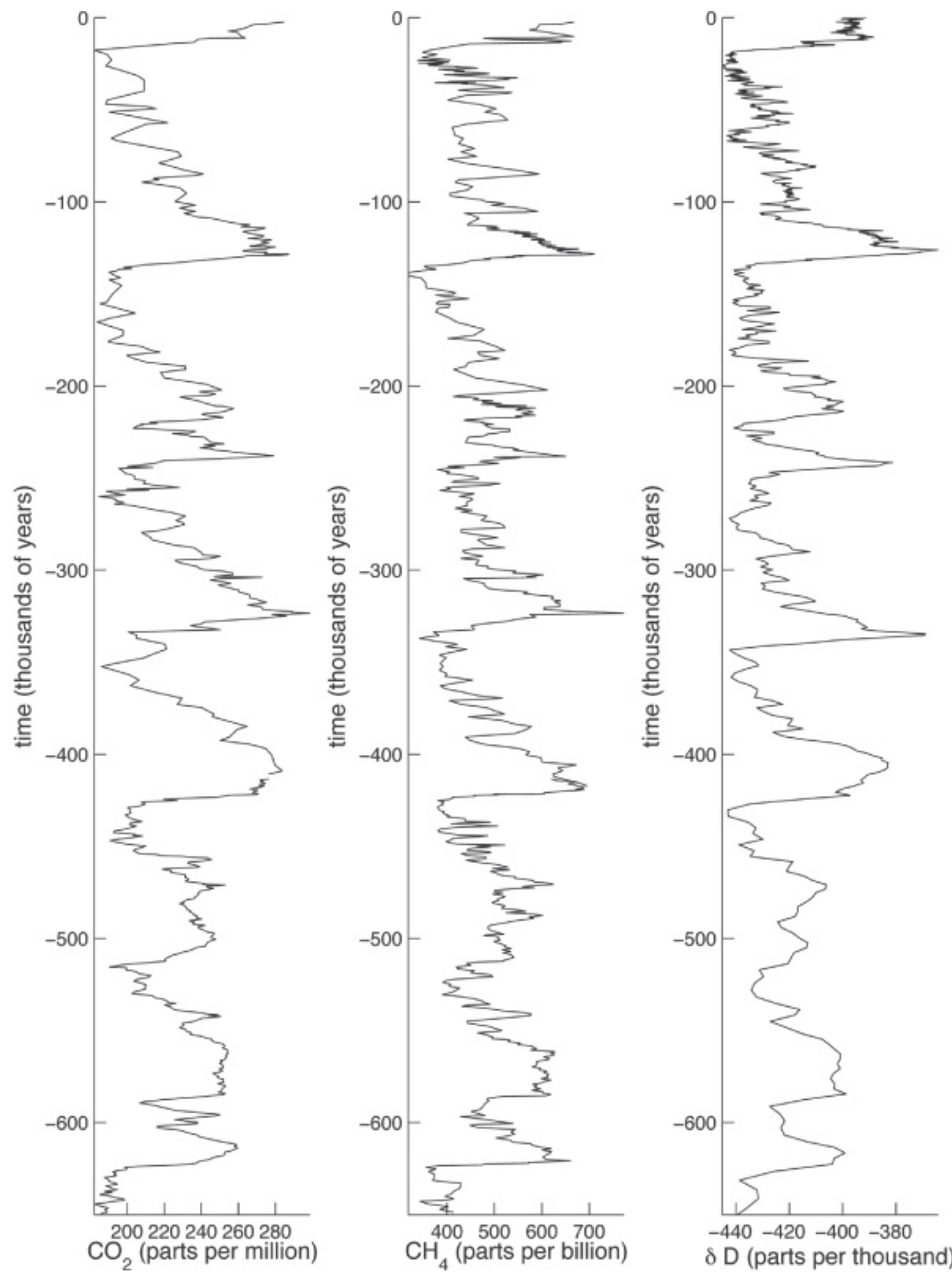





Figure 12.19

# $CO_2$ During the Past 160 Ma

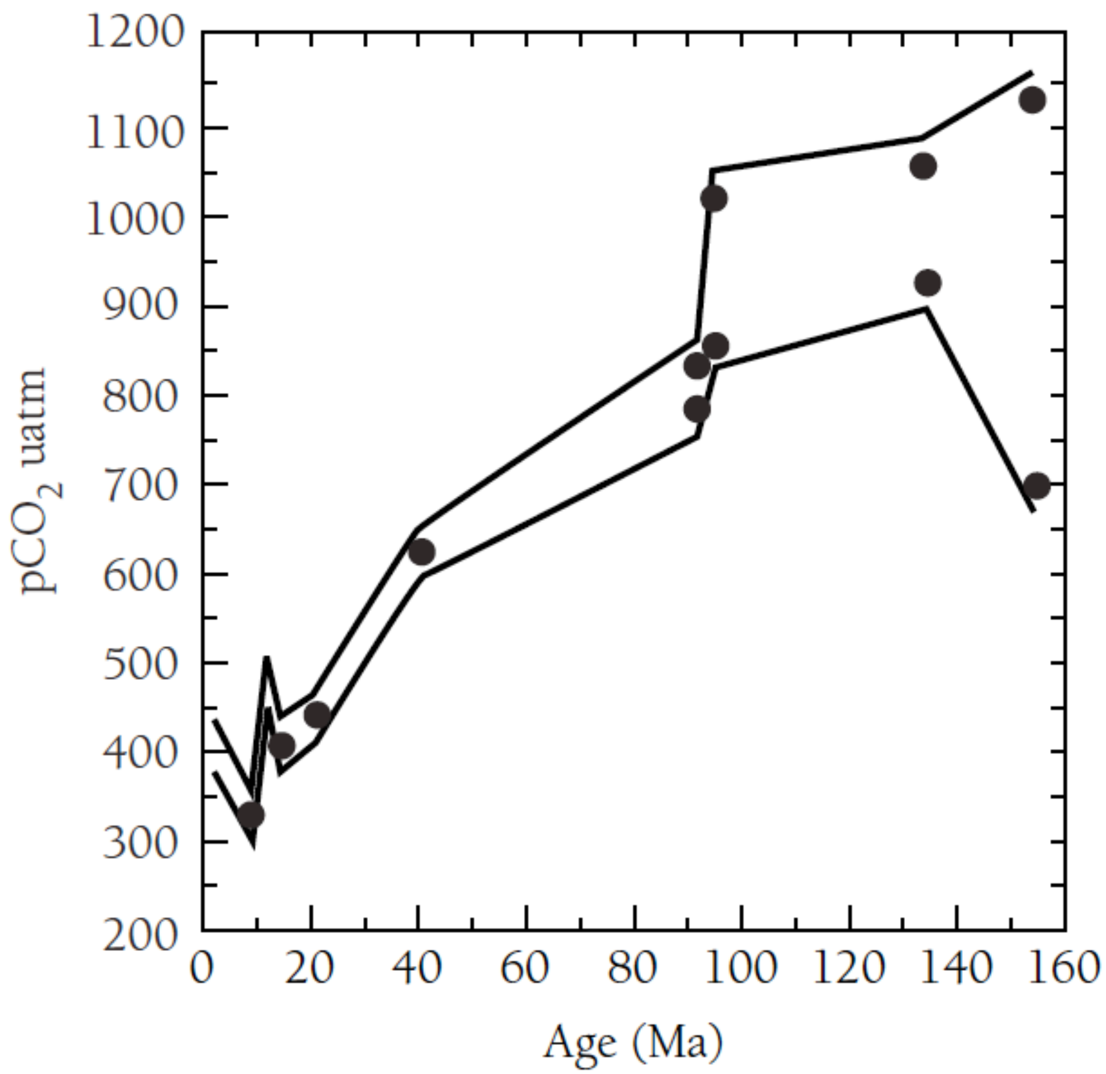



*Figure 10.30 Reconstructed $CO_2$ during the Cretaceous and Eocene. Source: Freeman and Hayes 1992.*

- Levels of $CO_2$ have decreased significantly during the past 140 million years (Ma)
- Projected levels of $CO_2$ by the end of the 21st century will be comparable to that of 50 Ma ago

[From McElroy, 2002]

# Temperatures of the deep ocean during the past 140 Ma

[From McElroy, 2002]

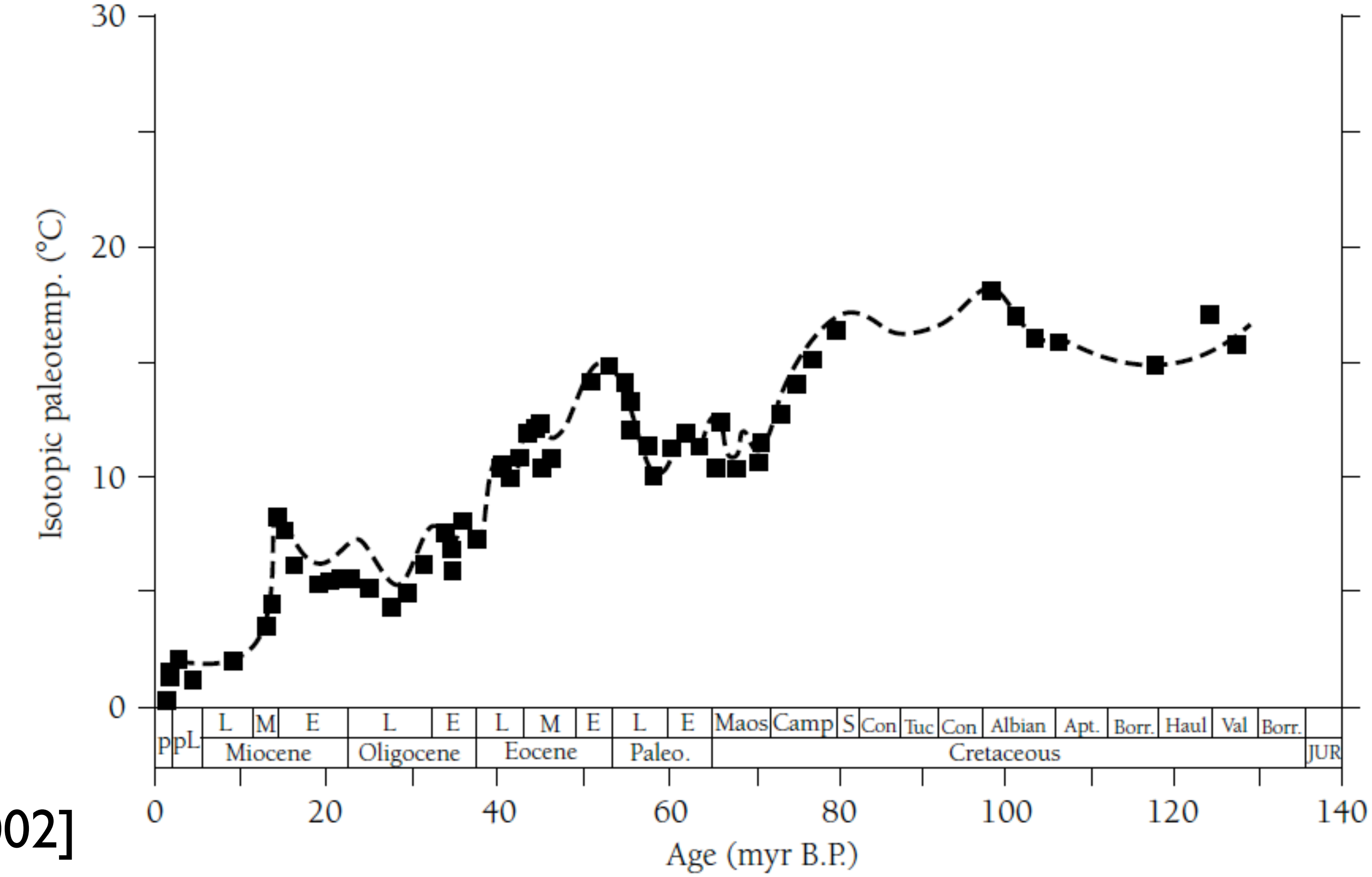
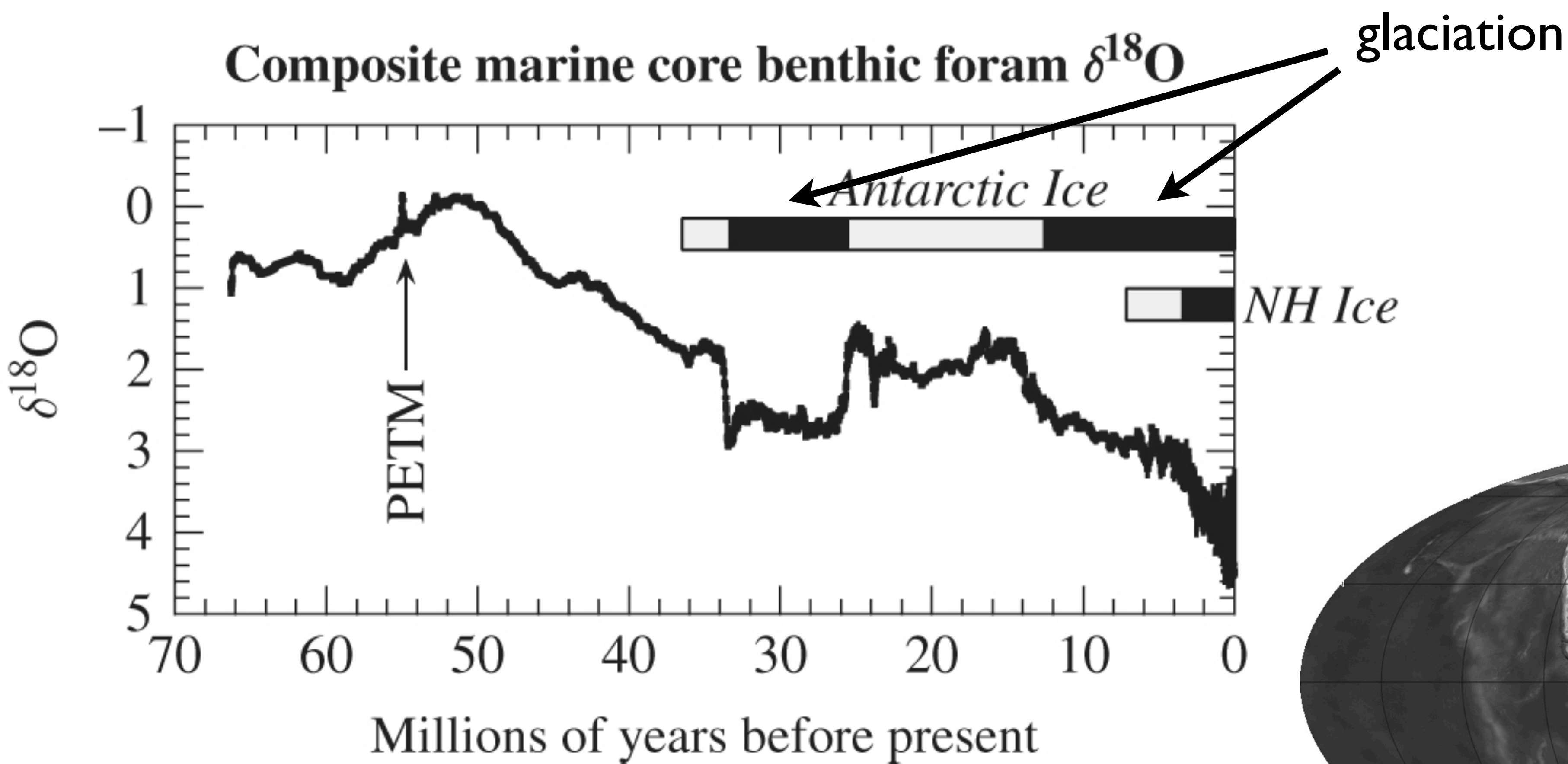


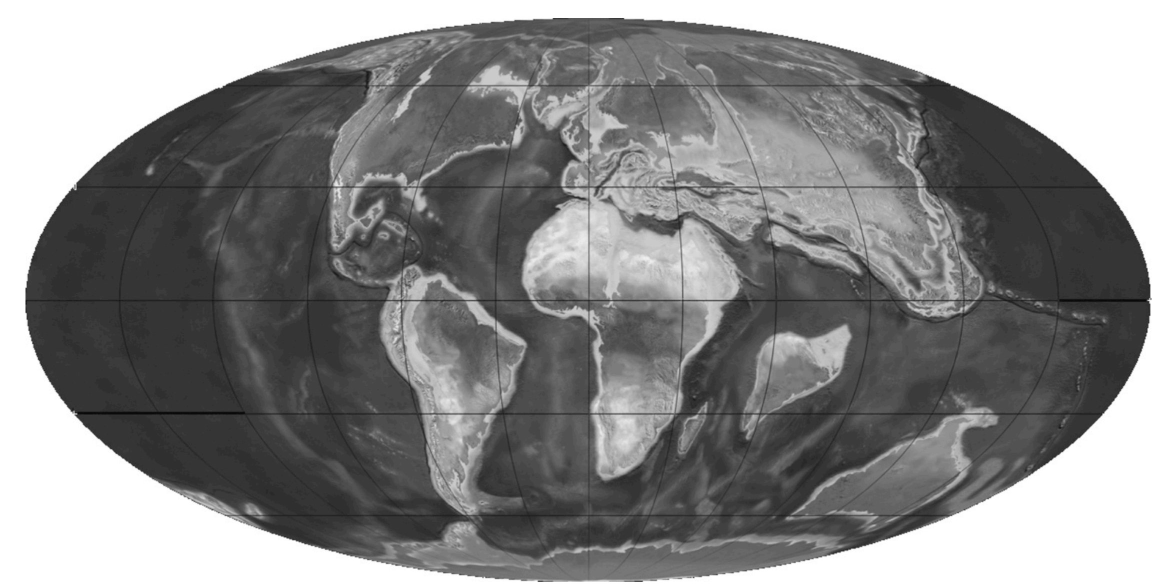

*Figure 10.29 Reconstructed temperature of the deep tropical Pacific Ocean over the past 140 myr based on the oxygen-isotopic composition of benthic foraminifera. Source: Douglas and Woodruff 1981.*

The planet has cooled gradually during the past 100 Ma

# Climate during the past 70 Ma




[From Pierrehumbert, 2010]

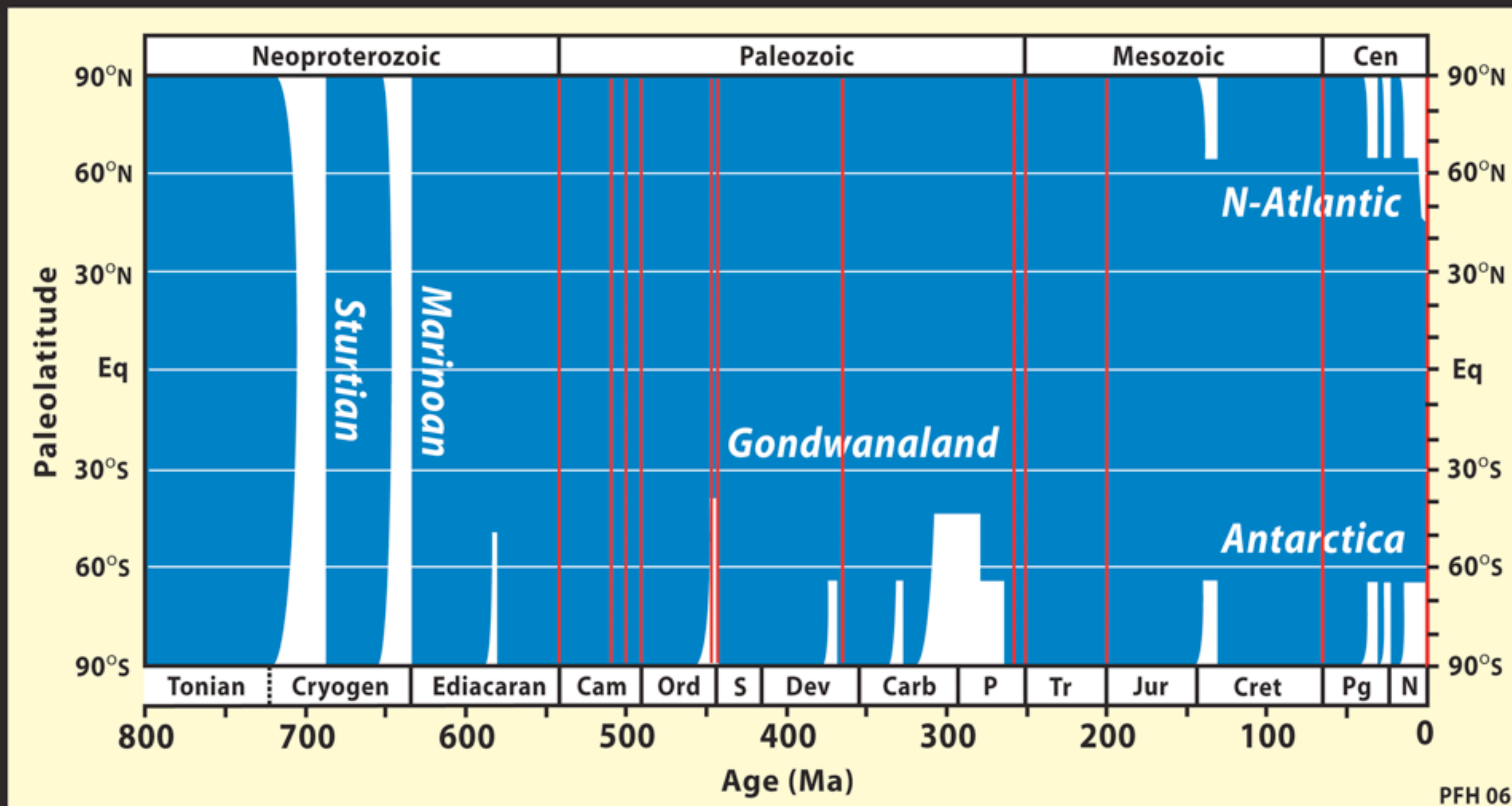


Position of the continents at the end of the Cretaceous, 65 Ma

During the Cretaceous and early Eocene, high-latitude ocean temperatures were 15-20°C

PETM (Paleocene-Eocene Thermal Maximum): a period of rapid global warming of about 4°C

# Paleogeographic extent of continental ice sheets and permanent sea ice over the last 800 Myr (red lines indicate major mass extinctions)




[From Snowball Earth (http://www.snowballearth.org)]