THE OCEAN CONVEYOR BELT (Part 1)

Stephen Riser, University of Washington

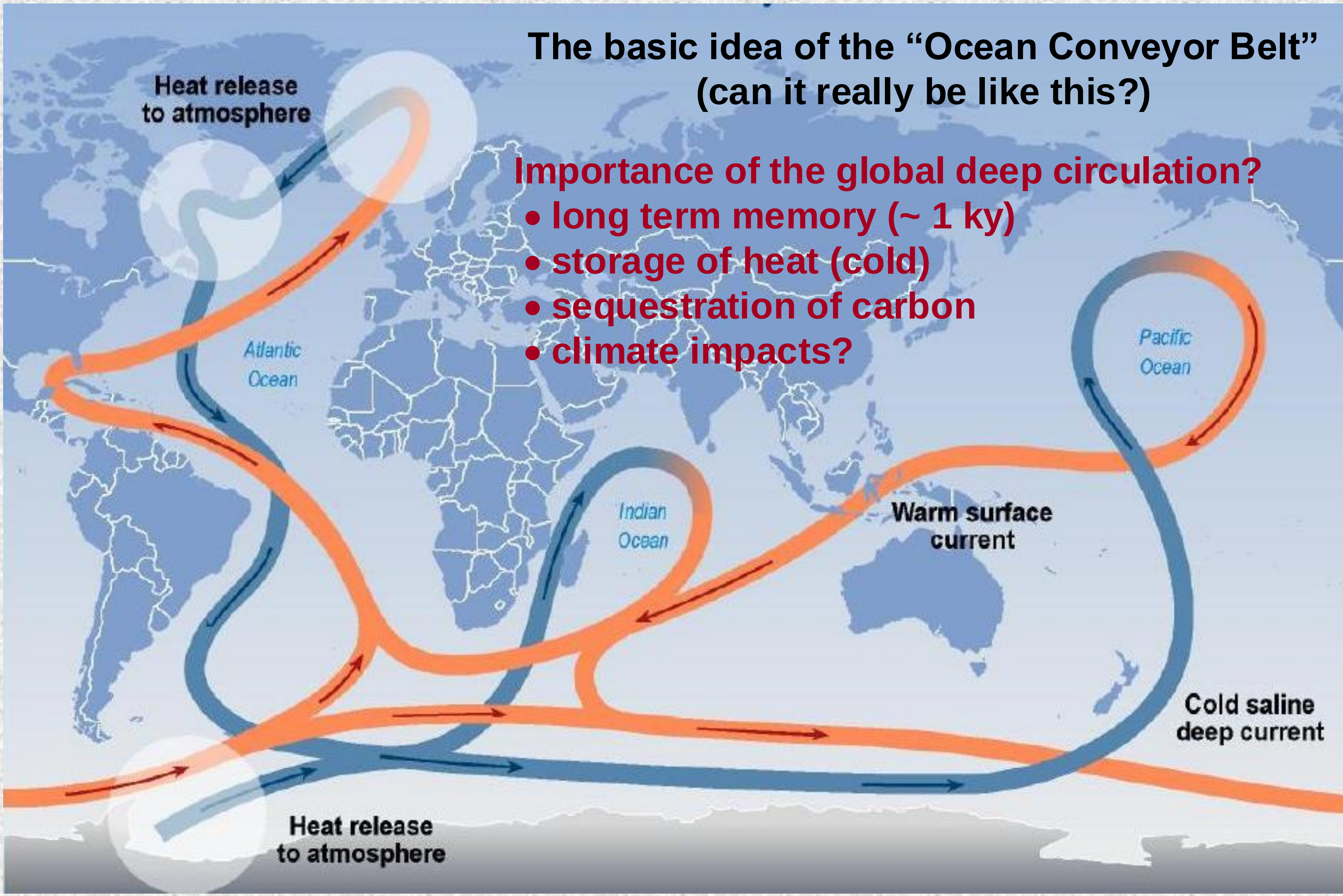
riser@uw.edu

Presented at National Institute of Oceanography, Goa

The basic idea of the "Ocean Conveyor Belt" (can it really be like this?)

Importance of the global deep circulation?

- long term memory (~ 1 ky)
- storage of heat (cold)
- sequestration of carbon
- climate impacts?



Why do our ideas about the ocean circulation have such a peculiarly dream-like quality?

or

Examples of types of observations that are badly needed to test oceanographic theories*

HENRY STOMMEL

1954

1. *How do the types of observation suggested here differ from traditional practice?*

By far the greatest part of physical oceanographic knowledge has accumulated in the following way:

(1) a grand cruise, or expedition, brings back many hydrographic stations' worth of data;

(2) extensive plots, graphs, and tabulations of the data are made and published for the benefit of future generations (e.g. *Bulletin Hydrographique*);

(3) certain of the more striking features of the data plots are noted;

(4) some plausible hypotheses are advanced to explain them.

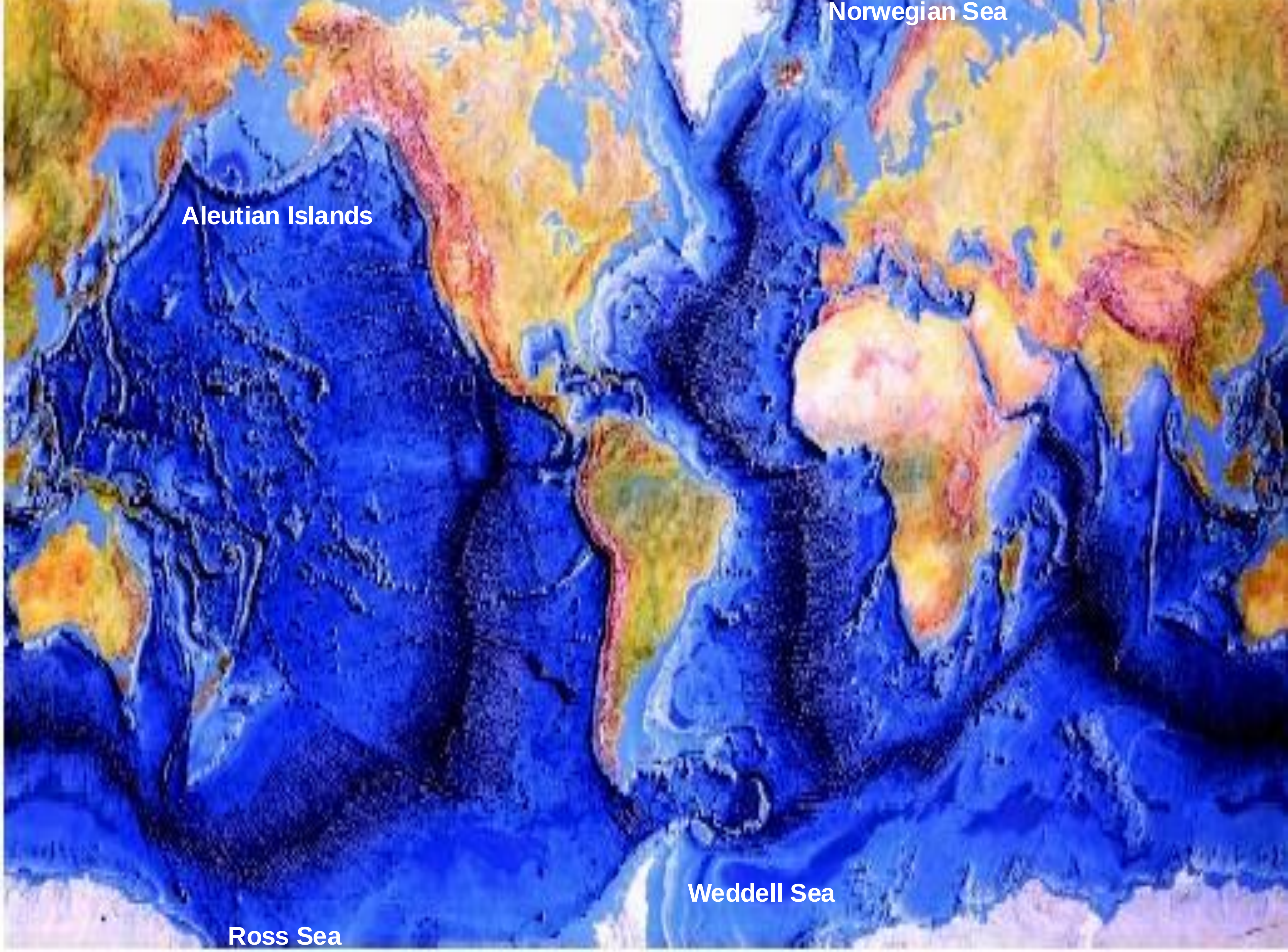
This procedure usually exhausted the energy of those involved, and almost always the funds, and the study

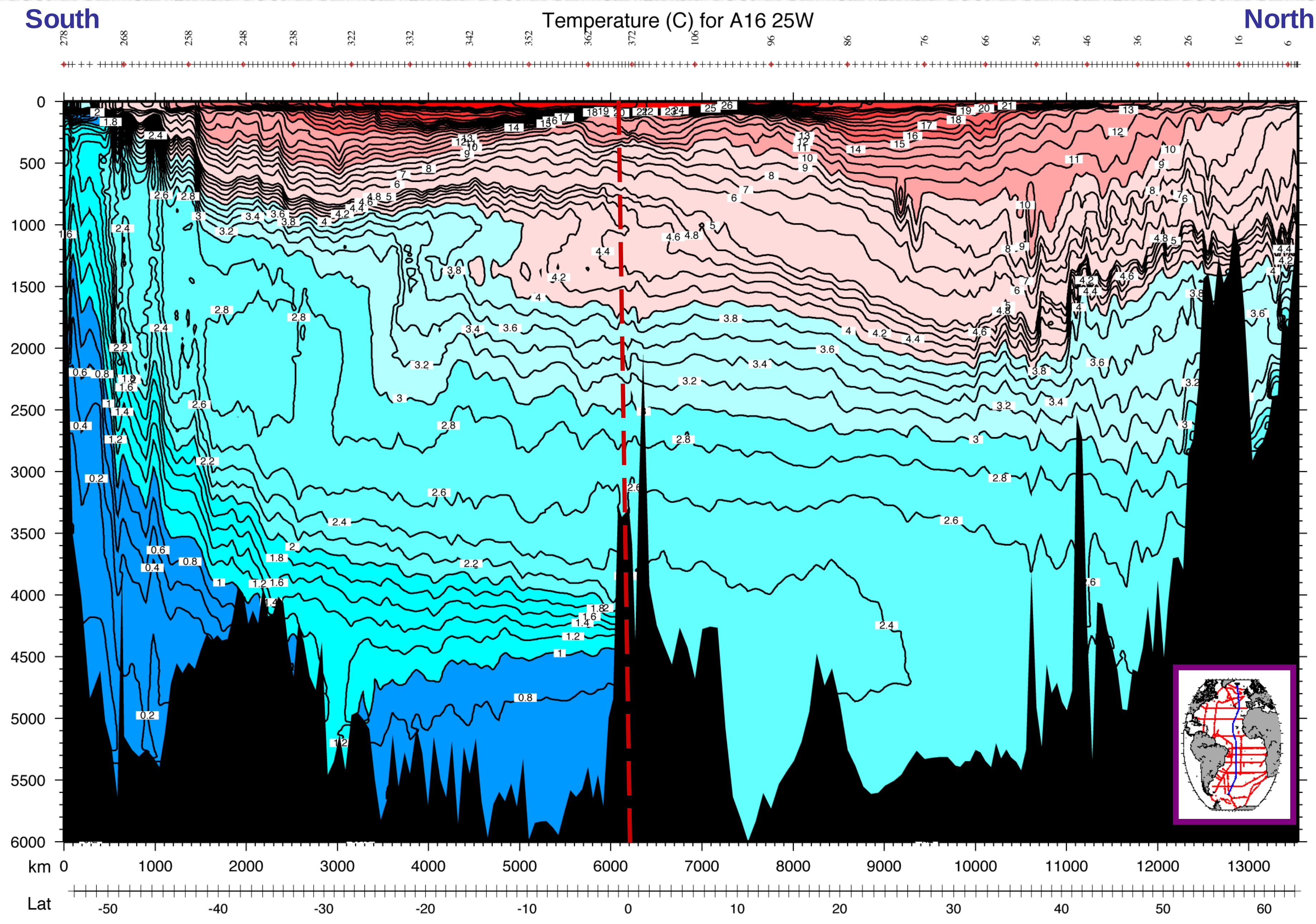
(i) attempts to detect changes in the total transport of the Stream, (ii) surveys of the shapes of meanders, (iii) determinations of the "width" of the Stream, and the transverse surface velocity profile. The plausible hypotheses are modified as needed to avoid conflict with observations. Sometimes this is very easy because a variety of different plausible hypotheses all fit the observations.

All of these steps are absolutely necessary, of course, otherwise we would know nothing at all about the ocean as it really is. But for the full development of the science there must be one additional step:

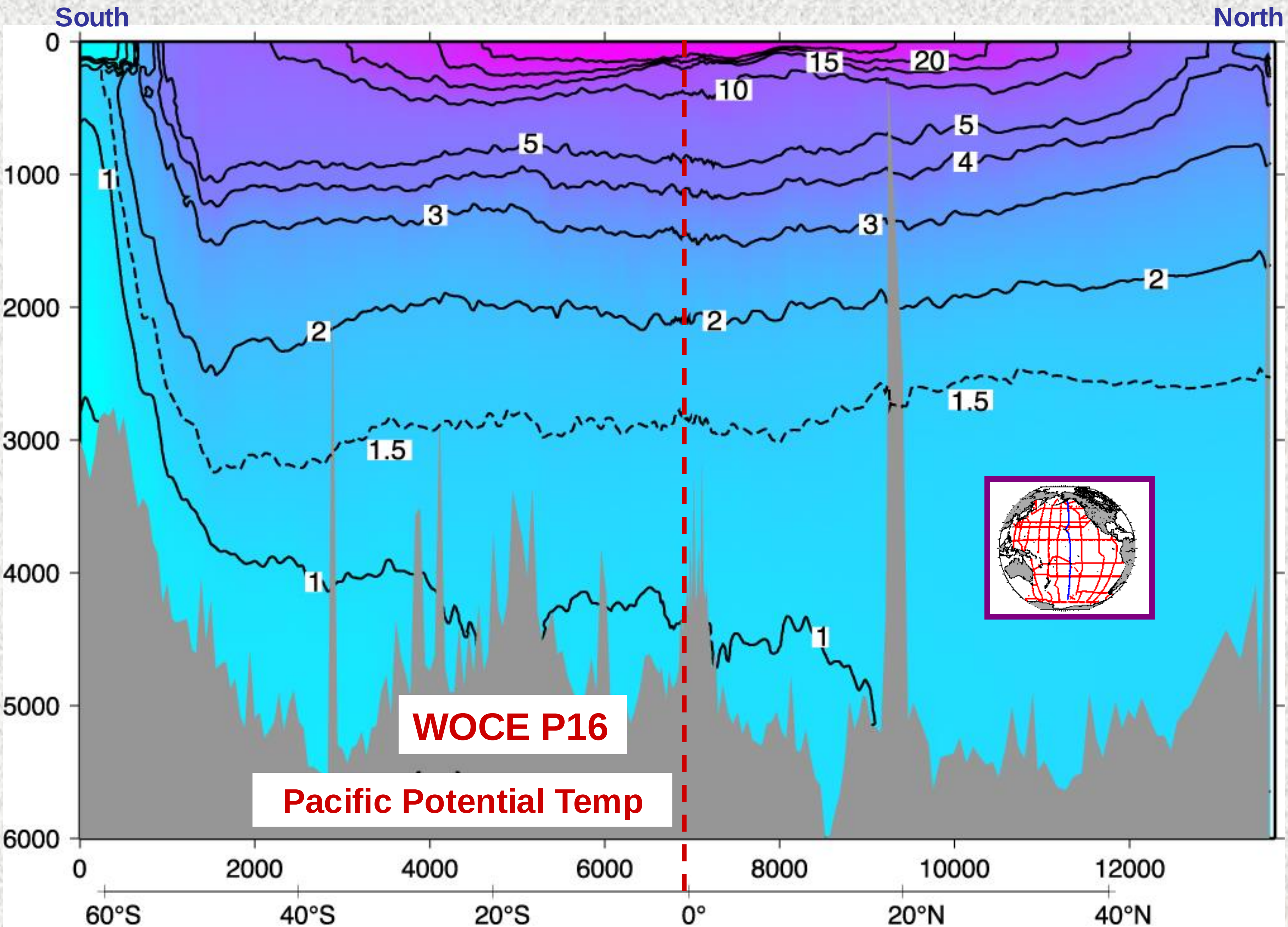
(5) The plausible hypotheses must be tested by specially designed observations. In this way theories can be rejected or accepted, or may be modified to become acceptable.

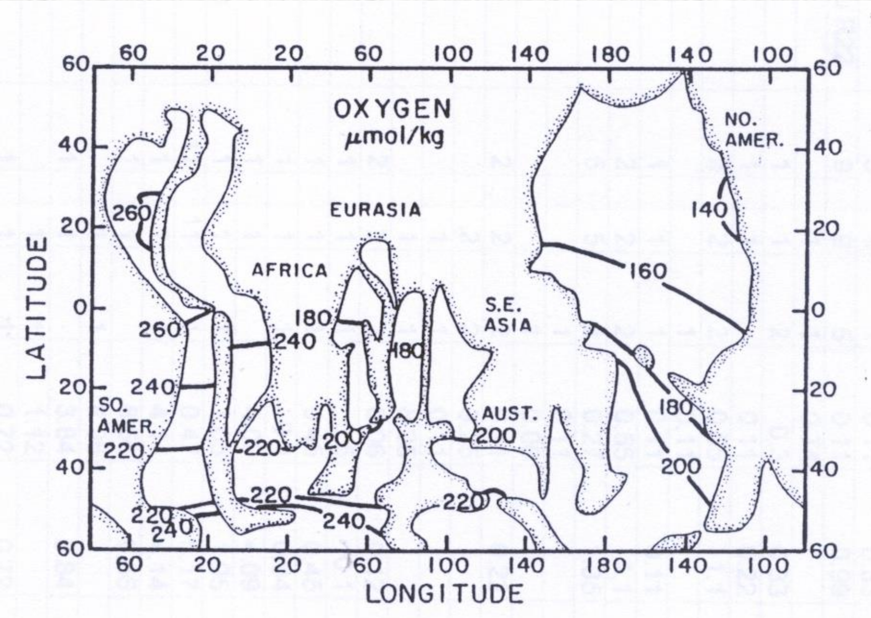
2. *Can oceanographic theories be tested?*

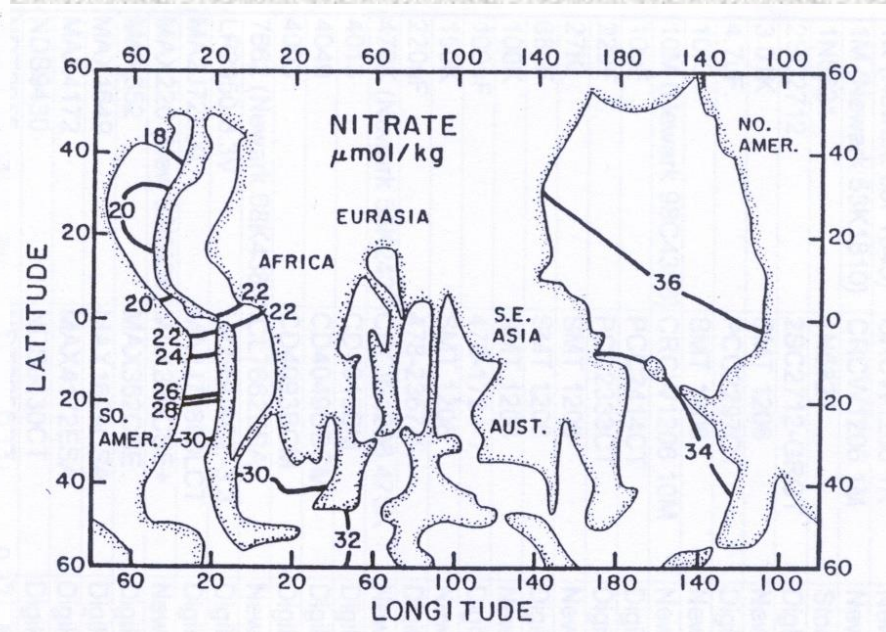

Norwegian Sea
Aleutian Islands
Weddell Sea
Ross Sea



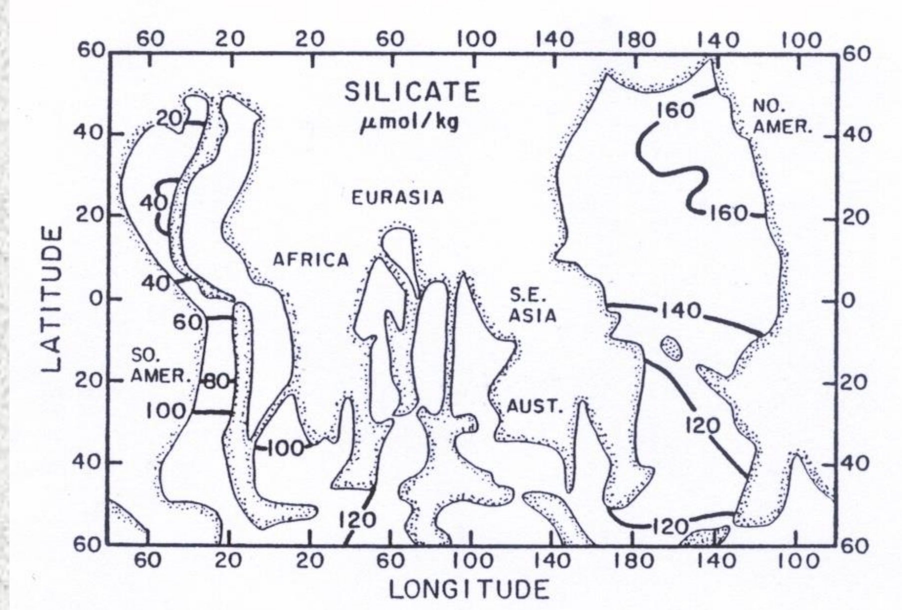
WOCE A16 Atlantic Potential Temperature


South
North
WOCE P16
Pacific Potential Temp
0
1000
2000
3000
4000
5000
6000
0
2000
4000
6000
8000
10000
12000
60°S
40°S
20°S
0°
20°N
40°N
20
15
10
5
4
3
2
1.5
1

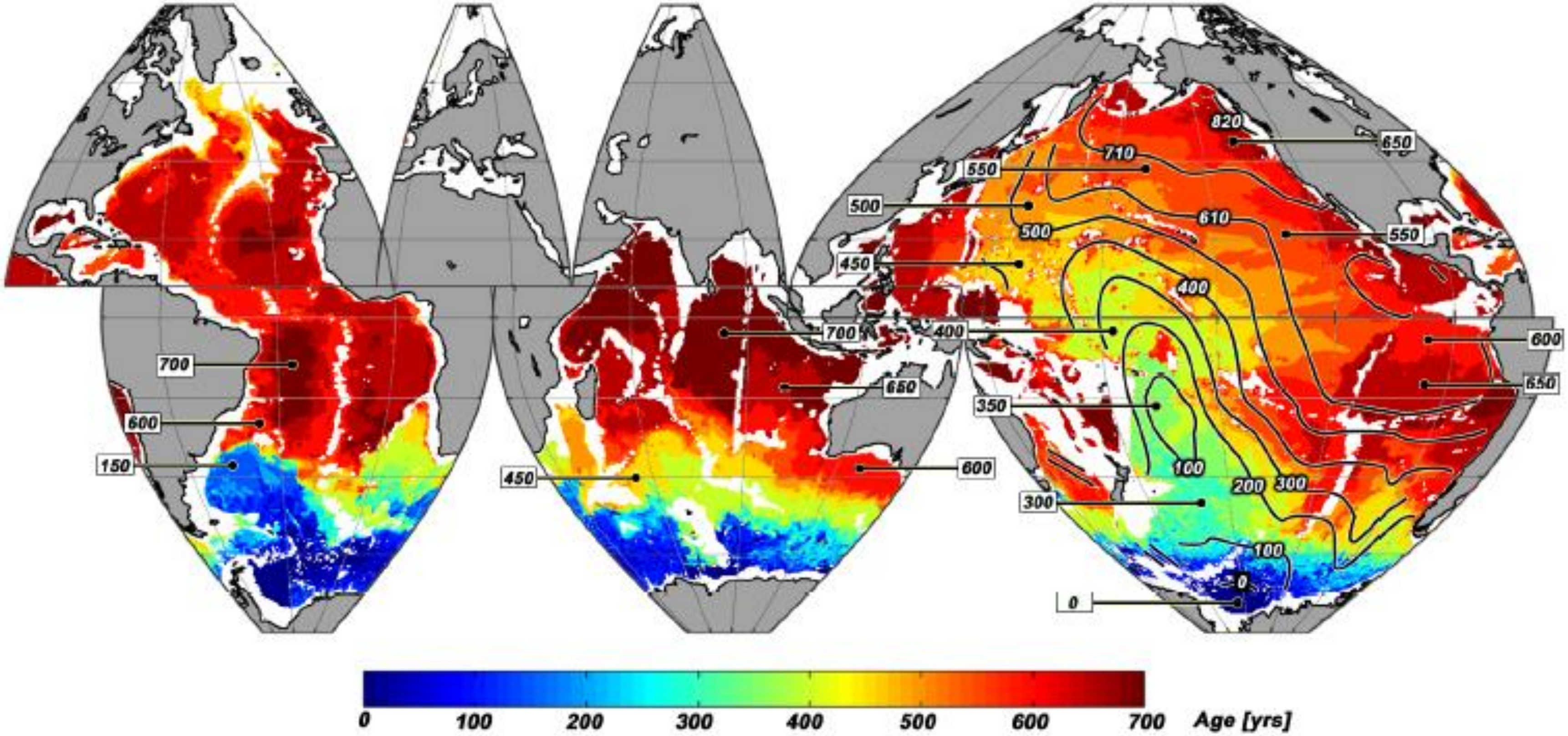




Dissolved oxygen, nitrate, and silica in the near bottom layer all show an apparent aging of deep water from the North Atlantic to the North Pacific.

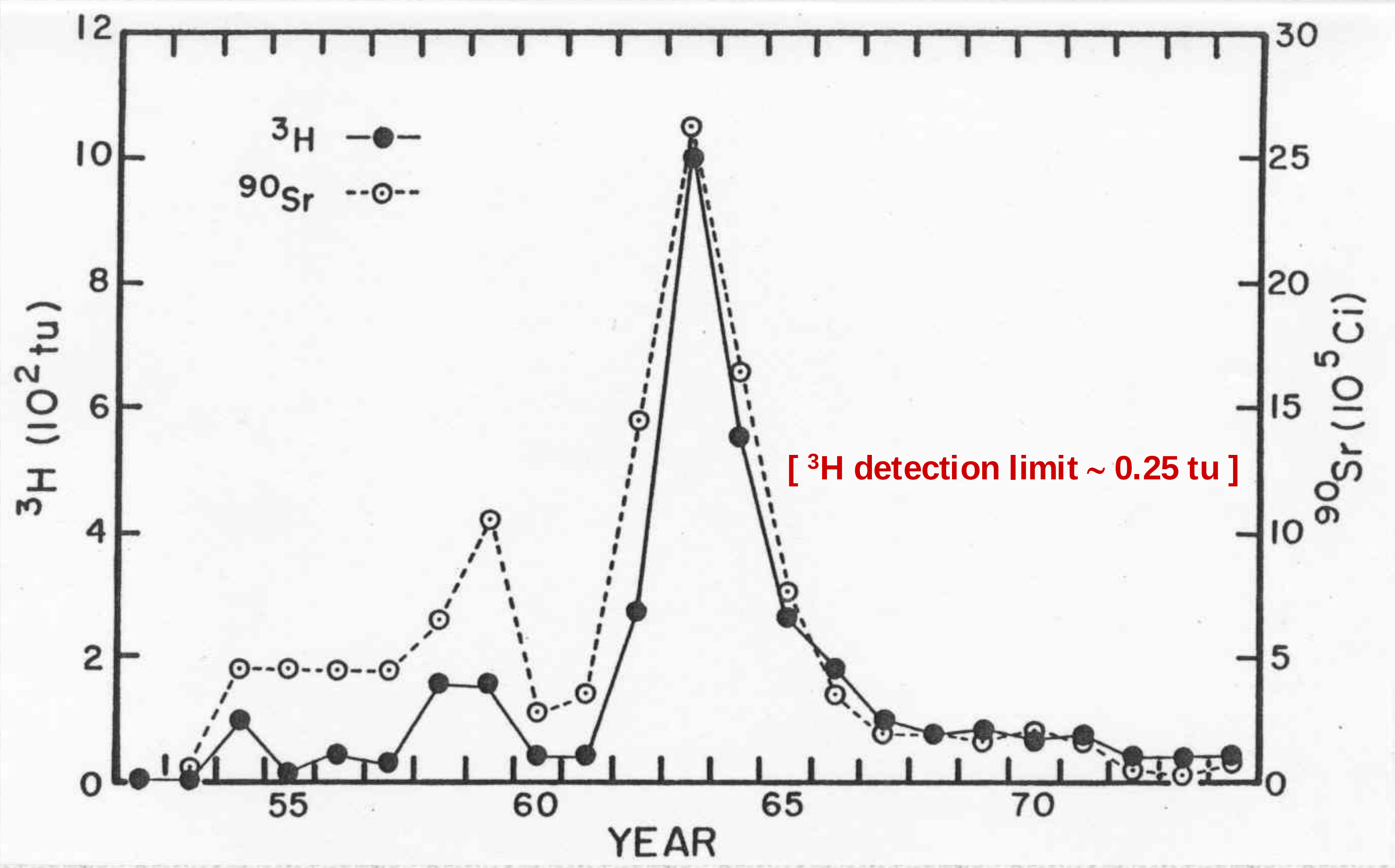


[from GEOSECS, 1970s]

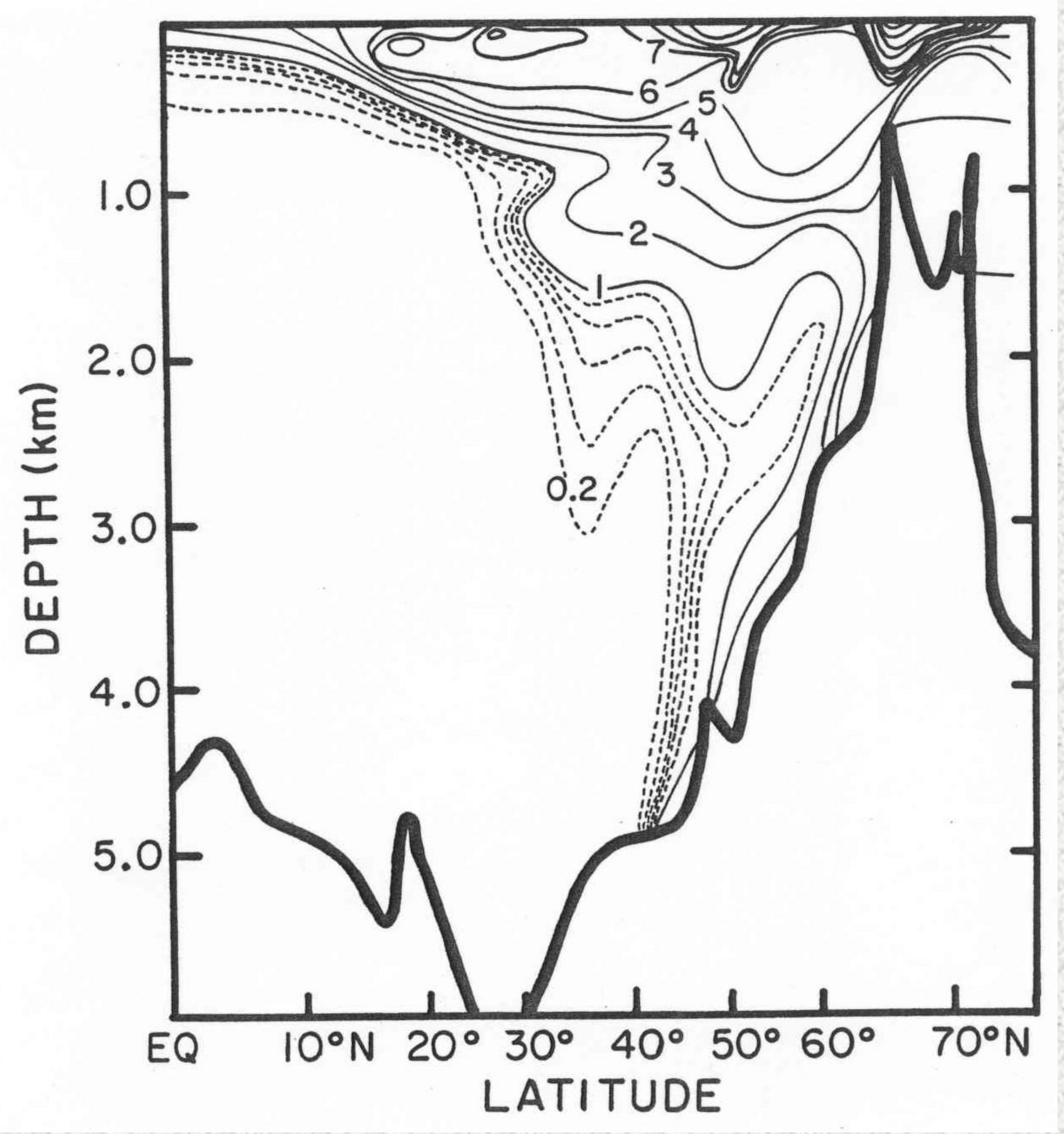


"Age", or time (in years) since deep water was in contact with the atmosphere, determined from the measured concentration of ^{14}C in the deep water.

[from GEOSECS]



Source function for tritium (HTO) input to the ocean
(tritium half-life ≈ 12.5 years)



Tritium in the western N. Atlantic, mid-1972

Tritium in the thermocline of the world ocean, 1970s.

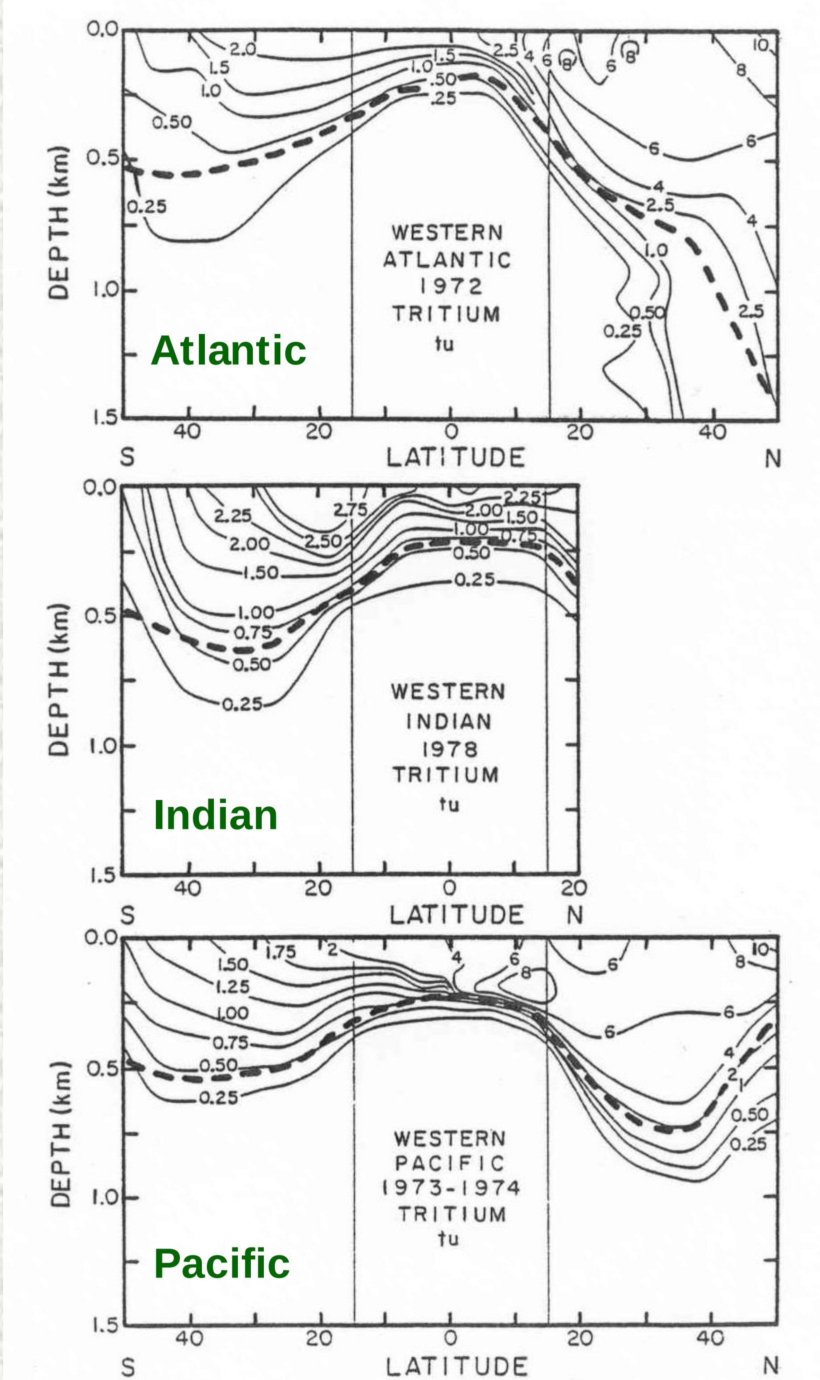
This suggests some bounds on the magnitude of vertical mixing in the ocean.

$\kappa_z \sim (\delta z)^2/\tau \sim (5\times10^4)^2/(14\times3\times10^7)$

[500 m] [14 years]

$\rightarrow \kappa_z \sim 6\ \mathrm{cm^2/sec}$

(somewhat high)



Estimates of the deep circulation….

Suppose the total amount of water that is sinking via deep convection in the world ocean is ~30 Sv (20 N. Atlantic, 10 Antarctic).

The volume of the deep ocean is ~ 10^9 km^3 .

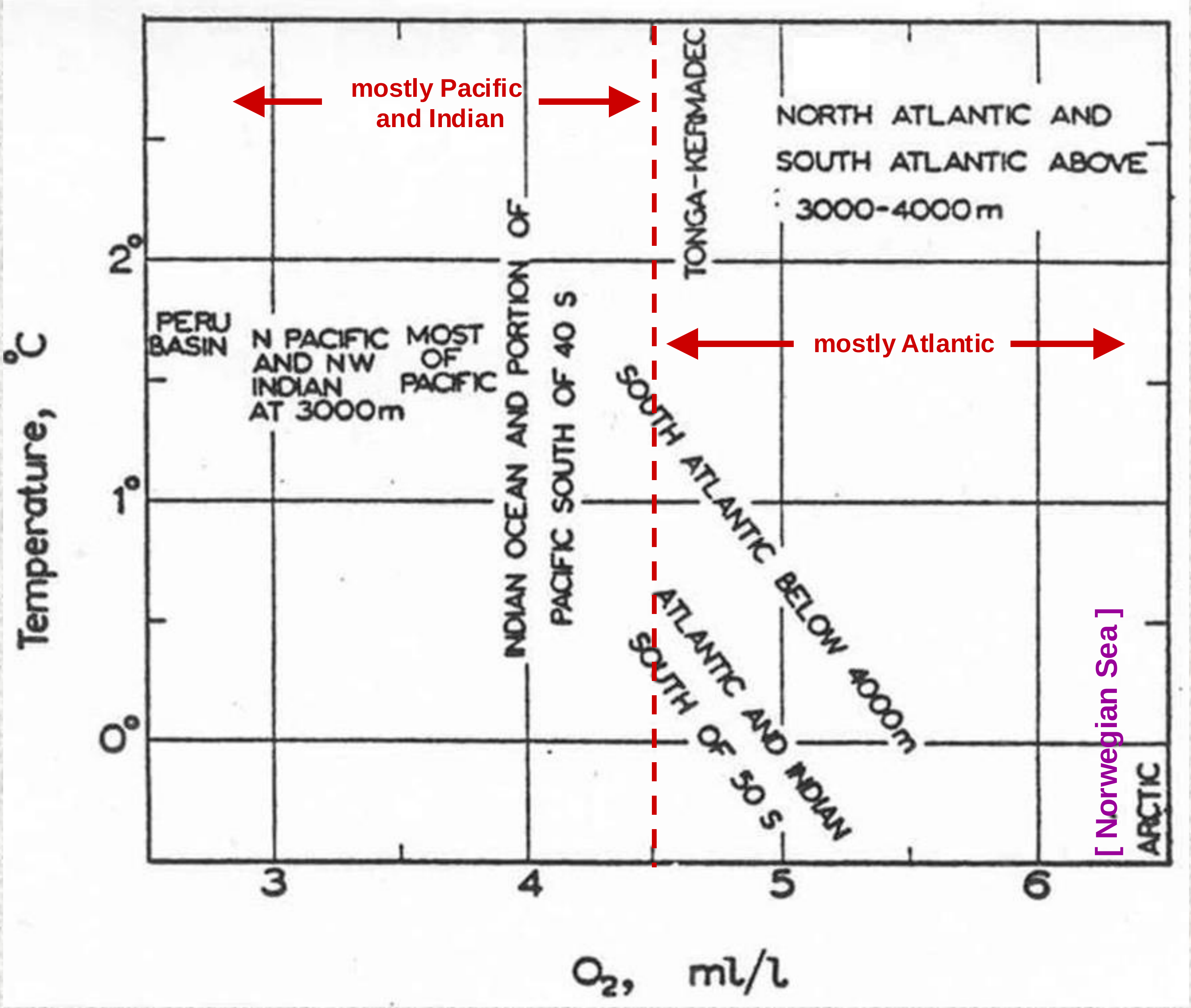
The appropriate time scale T_A for the renewal of water in the ocean by deep convection is

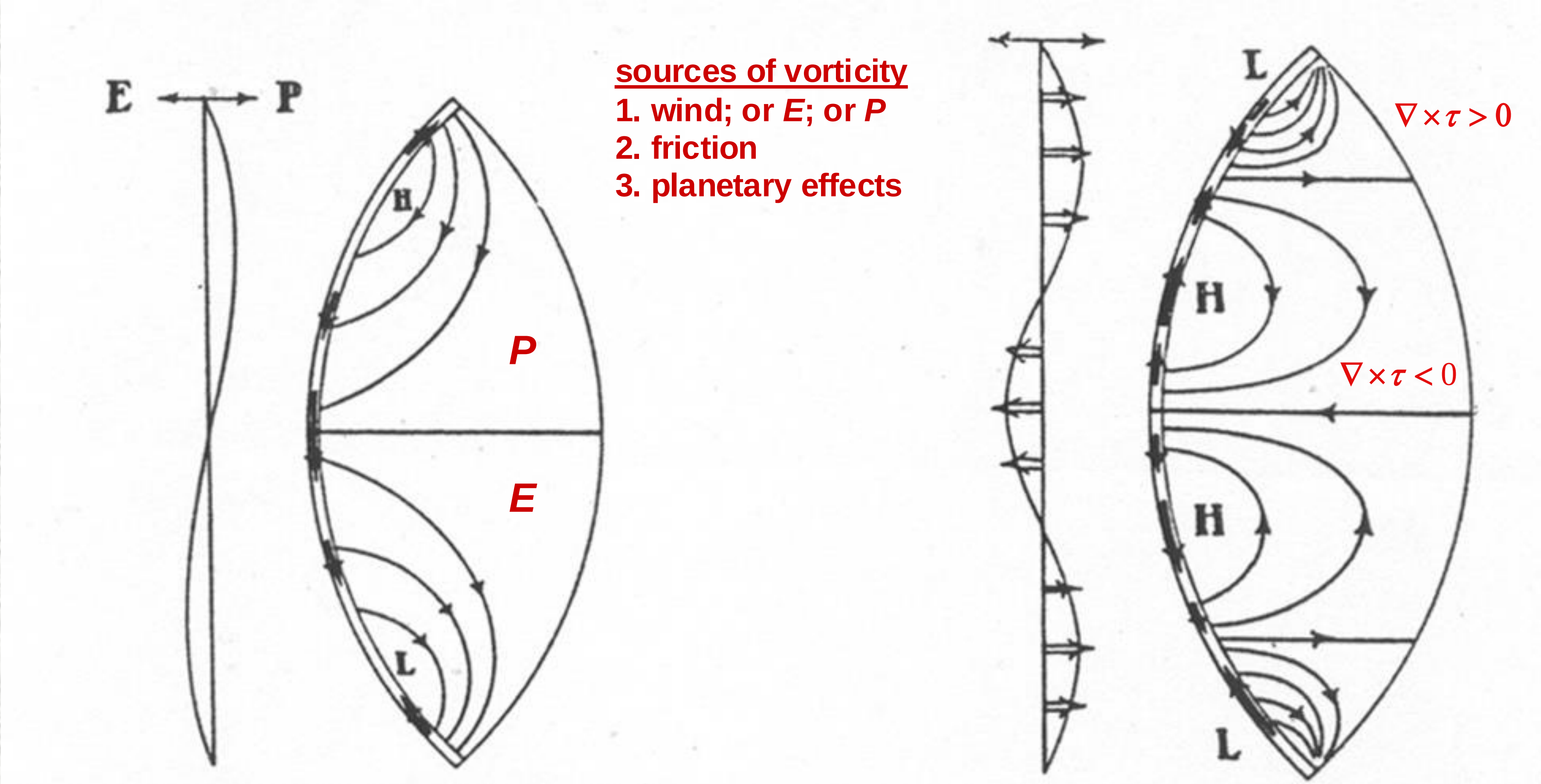
$$T_A \sim \text{(ocean volume) / (convection volume transport)}$$

$$= (10^{18}\ \text{m}^3)/(3 \times 10^7\ \text{m}^3/\text{sec}) \sim 1000\ \text{years}$$

[which seems to be consistent with the ^{14}C data]

Stommel's 1958 T-O_2 diagram, suggesting locations of deep water sources





Goldsborough's (1933) concept of ocean gyres driven by sources and sinks of mass at the sea surface (precipitation and evaporation), completely analogous to ideas of the wind-driven circulation driven by Ekman pumping or Ekman suction.

The Stommel-Arons Abyssal Circulation Model

$$\frac{\partial u}{\partial t} - 2\Omega v \cos\theta = -\frac{g}{a}\frac{\partial \eta}{\partial \theta}$$

$$\frac{\partial v}{\partial t} + 2\Omega u \cos\theta = -\frac{g}{a \sin\theta}\frac{\partial \eta}{\partial \phi}$$

$$\frac{\partial}{\partial \theta}\left(hu \sin\theta\right) + \frac{\partial}{\partial \phi}\left(hv\right) + \left(Q + \frac{\partial \eta}{\partial t}\right) a \sin\theta = 0$$

$h =$ mean ocean depth $\quad \eta =$ perturbed sea level

$\mathbf{u} = \left(u, v, w\right) \quad a =$ Earth radius $\quad Q =$ mass source

$\theta = \frac{\pi}{2} -$ latitude; $\quad \phi =$ longitude; $\quad \Omega =$ rotation rate

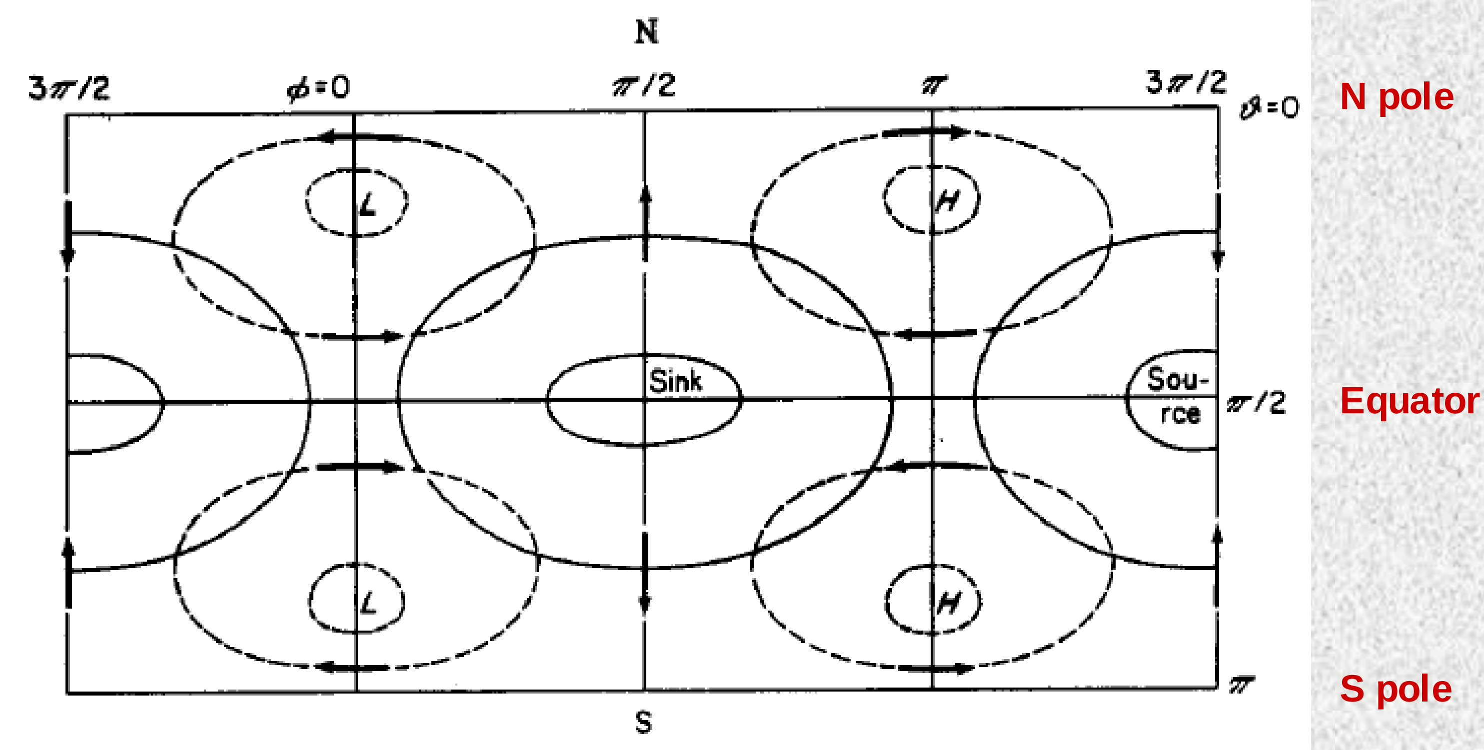
Consider only a steady circulation, so that $\frac{\partial}{\partial t} = 0$.

$$u = -\frac{Qa}{h}\cot\theta$$

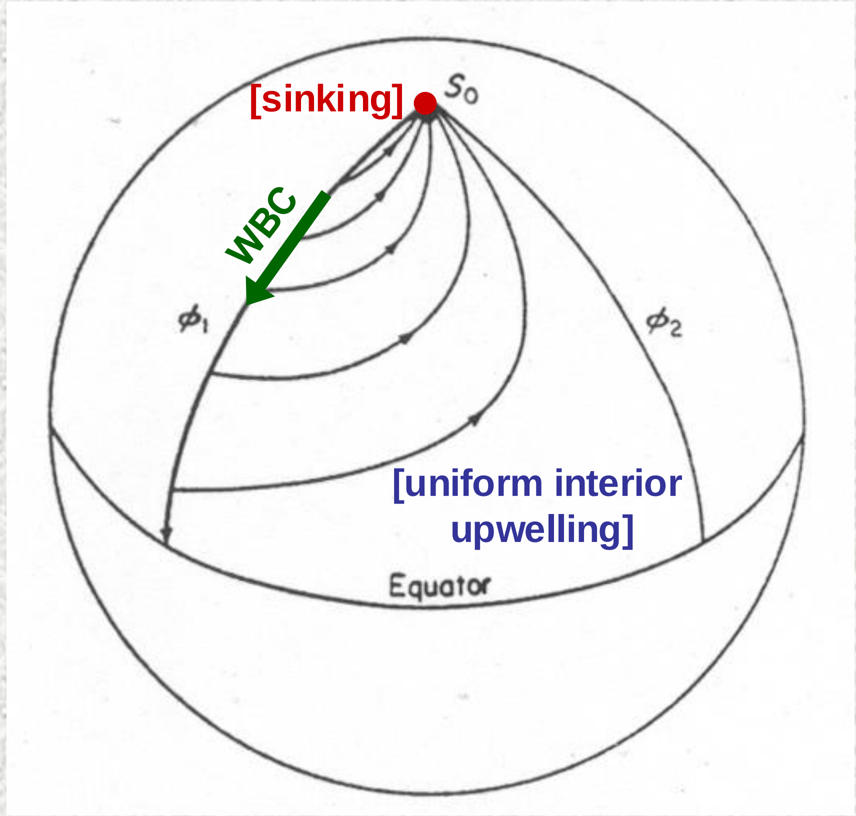
$$\frac{\partial v}{\partial \phi} = \frac{a}{h}\left[\cos\theta \frac{\partial Q}{\partial \theta} - 2Q\sin\theta\right]$$

$$\frac{\partial \eta}{\partial \phi} = 2\Omega \frac{a^2}{gh} Q\cos^2\theta$$

If $Q(\theta,\phi)$ is known, then u, v, and η can be found. This is the essence of the Stommel-Arons source-sink circulation model: specify Q and deduce the circulation by integration.



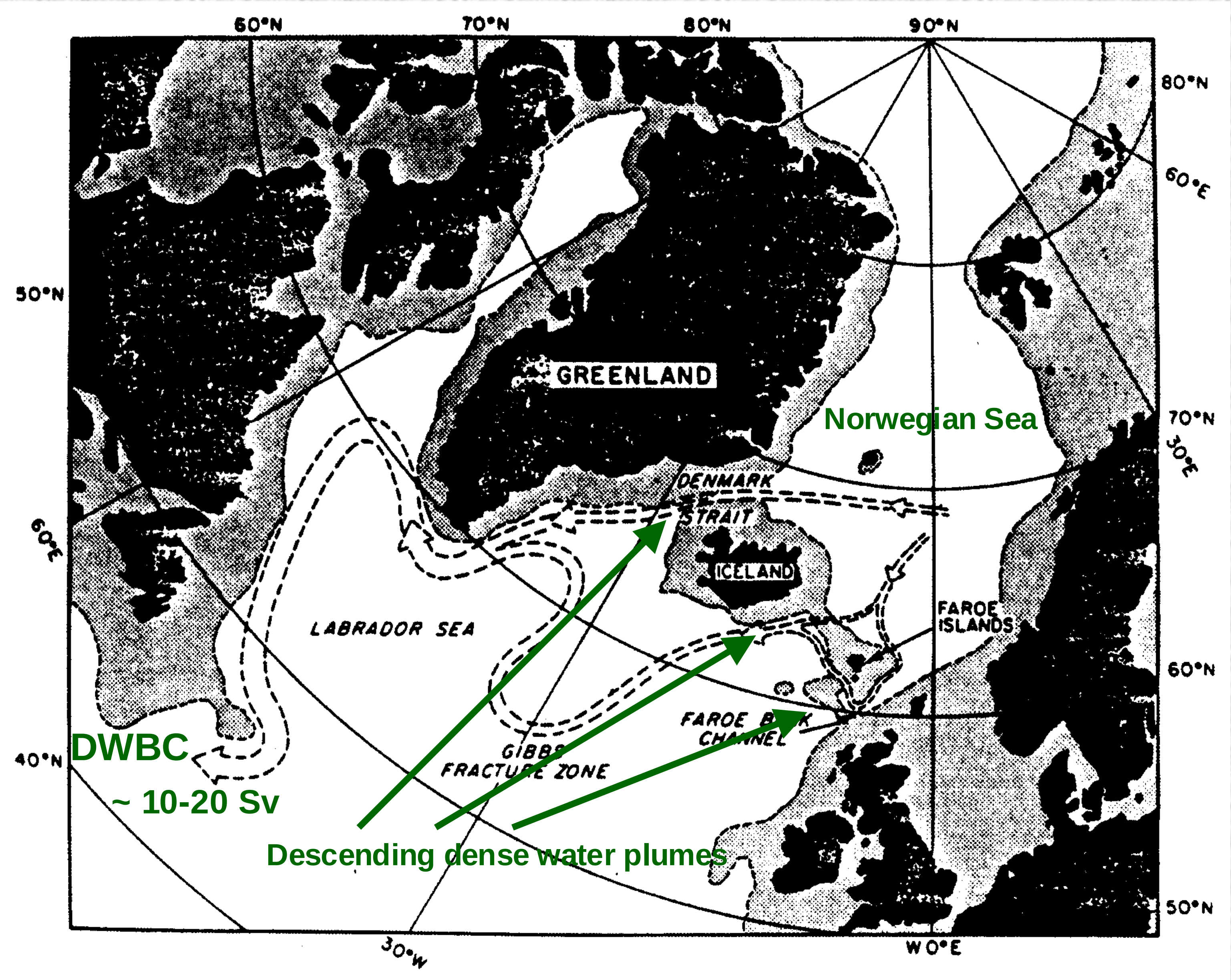
The resulting S-A source-sink circulation for $Q = Q_o \sin\phi \sin\theta$



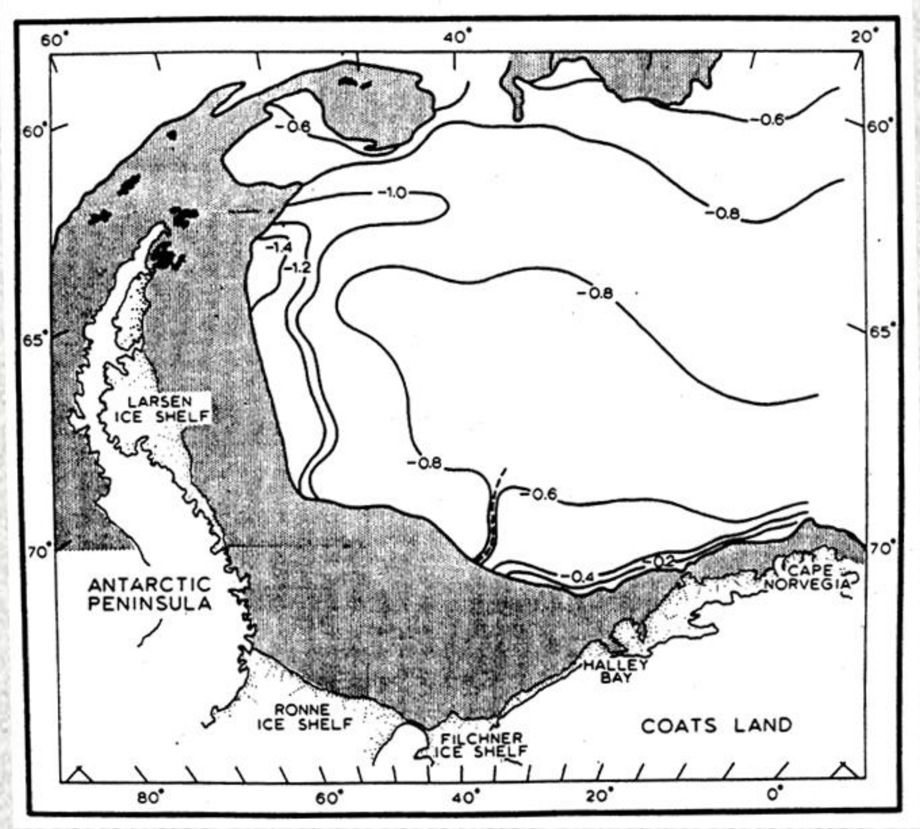
elements of the circulation
1. localized sources (sinking)
2. distributed sinks (upwelling)
3. deep w. boundary currents

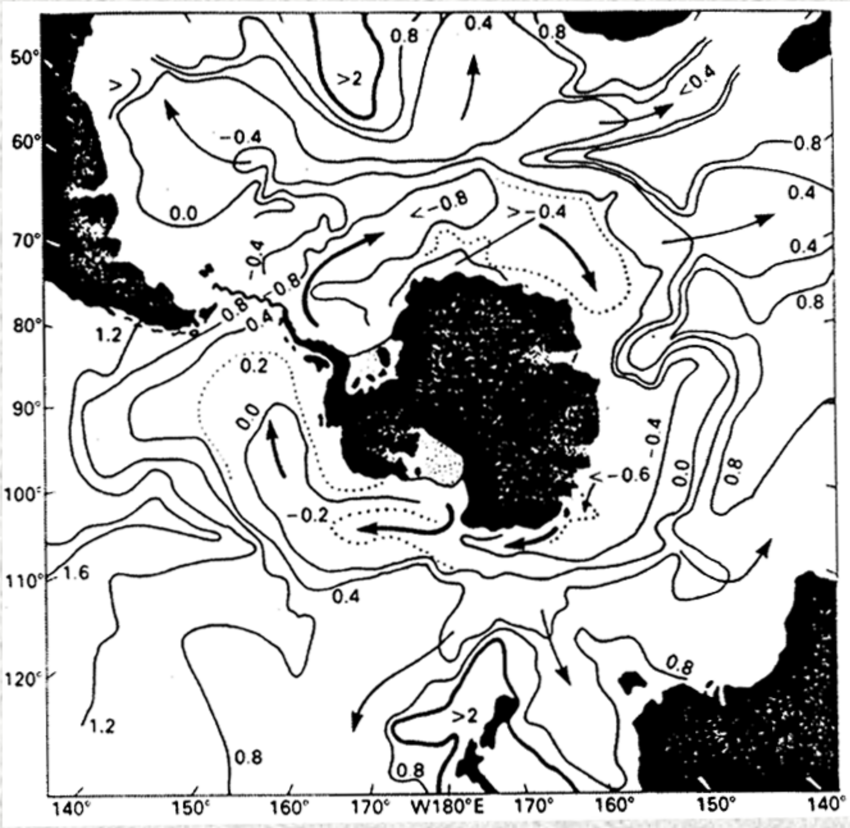
The circulation in a meridionally-bounded ocean with a source S_o at the North Pole and a uniformly distributed sink Q_o such that $S_o = Q_o a^2(\phi_2 - \phi_1)$.

From this example, the basic idea of the global abyssal circulation can be derived, with sources in the North and South Atlantic and sinks to balance everywhere else.



The northern hemisphere source of deep water: the Norwegian Sea

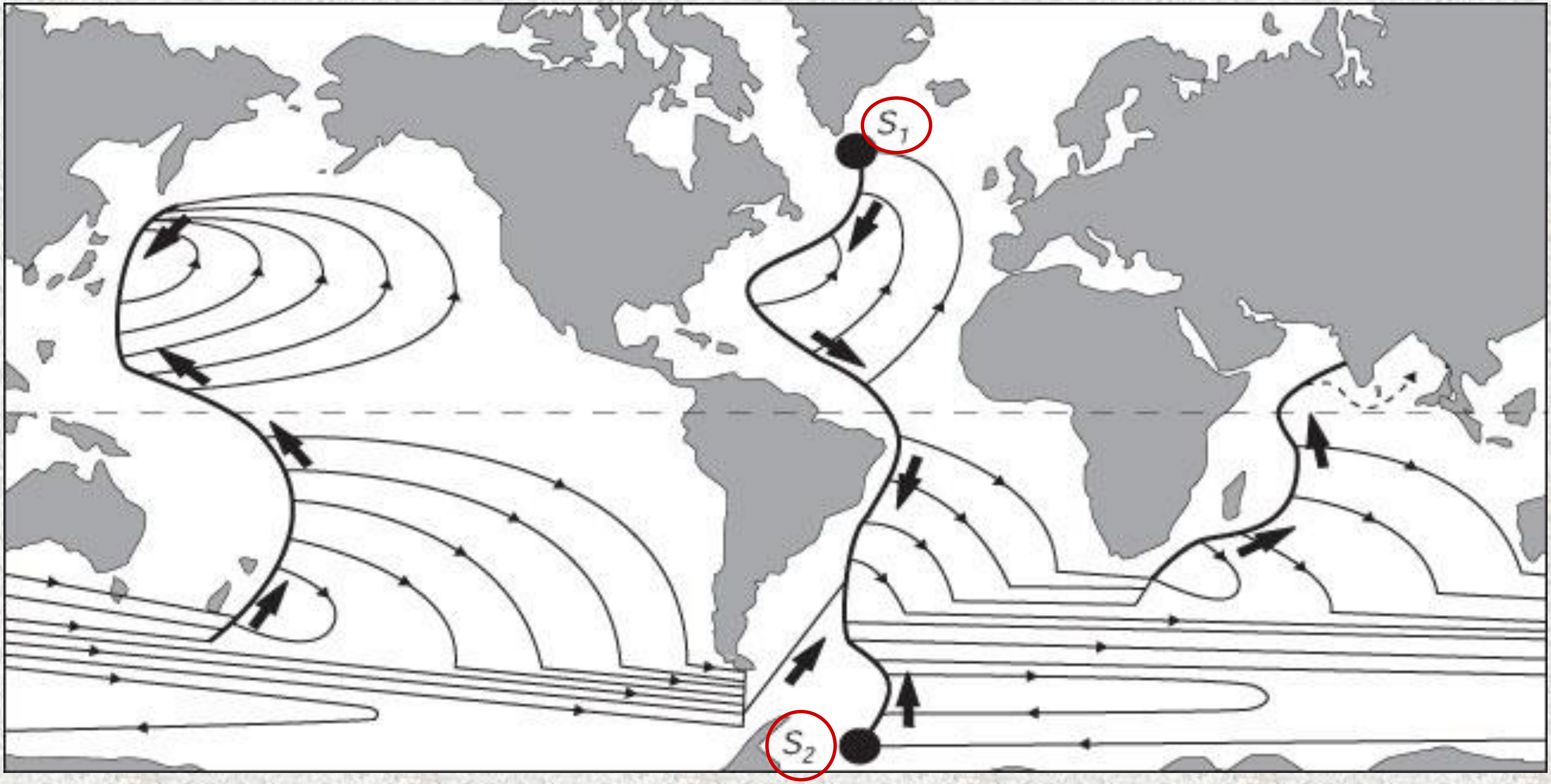




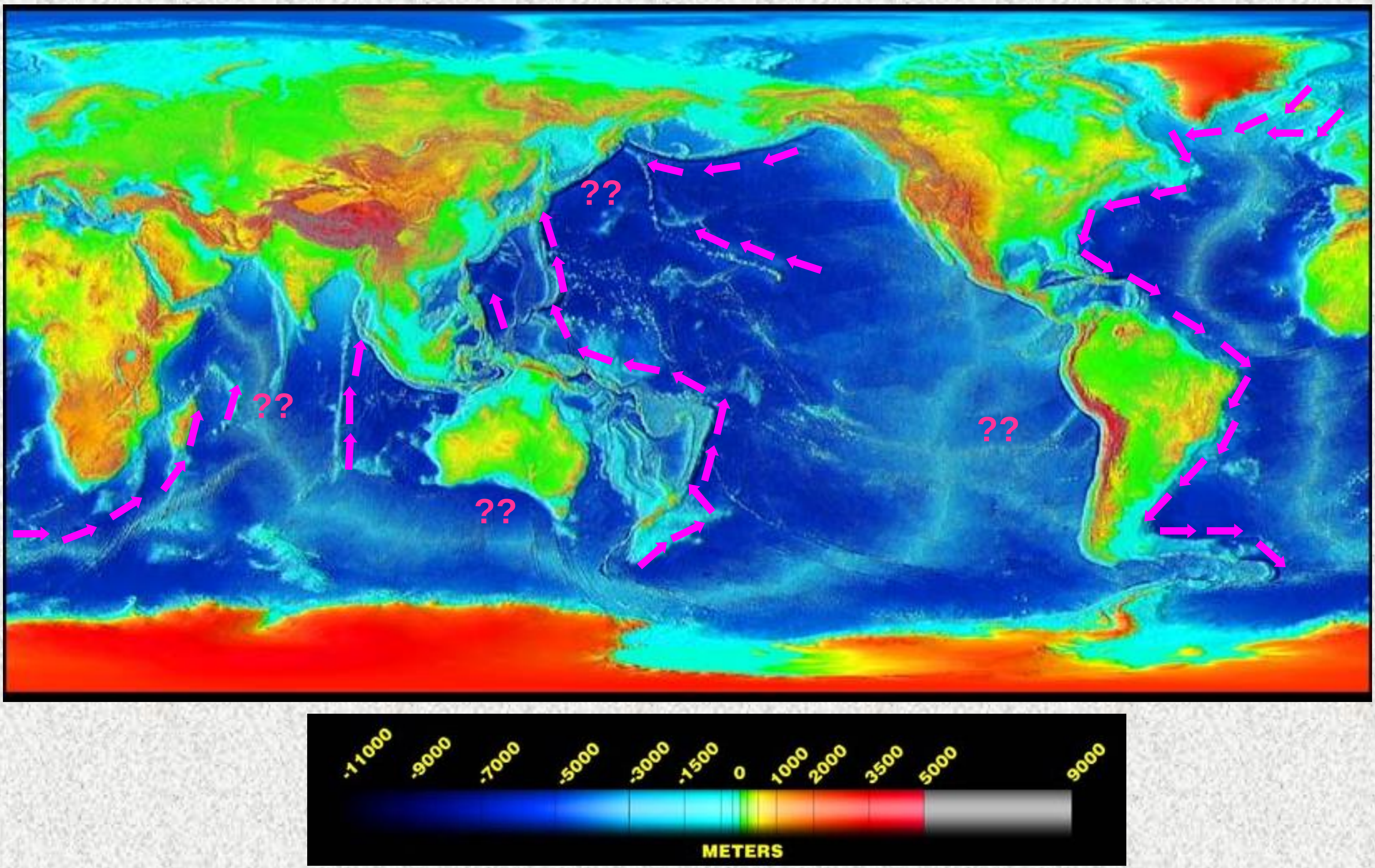
Bottom potential temperature
in the Weddell Sea

Bottom potential temperature
in the region around Antarctica

The southern hemisphere sources of deep water: the Weddell and Ross Seas



An estimate of the S-A global abyssal circulation driven by mass sources in the North and South Atlantic and uniform upwelling everywhere else. The interior flows are supplied by deep western boundary currents. Note the conceptual similarity to the contemporary "conveyor belt".



Observed deep western boundary currents of the world ocean

Estimates of the deep circulation….

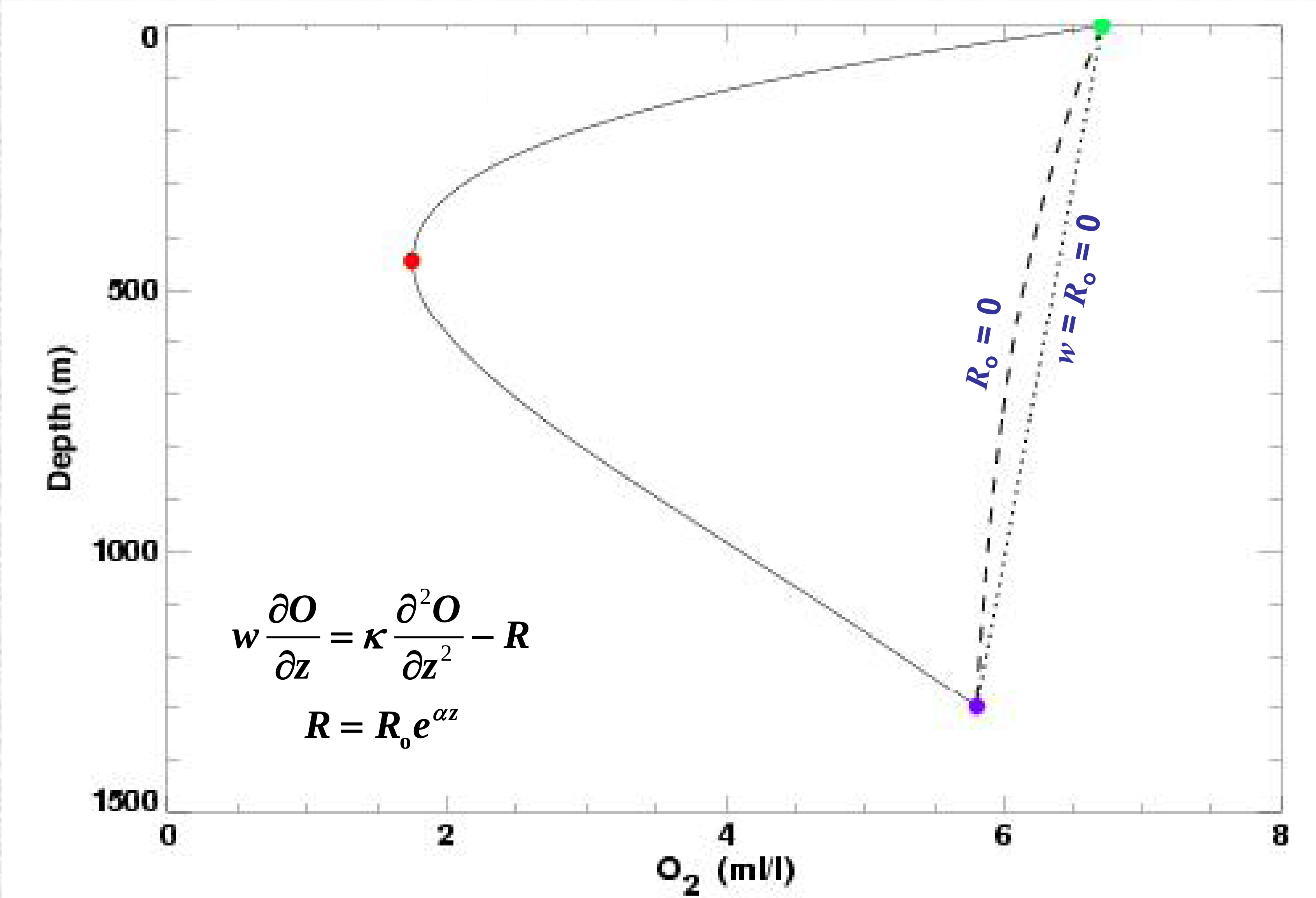
There must be a deep upwelling velocity over most of the world ocean in order to balance the downward motion in convection regions. The magnitude of this upwelling velocity can be estimated from

$$w_d A_d = -w_u A_u \rightarrow w_u = -w_d (A_d / A_u)$$

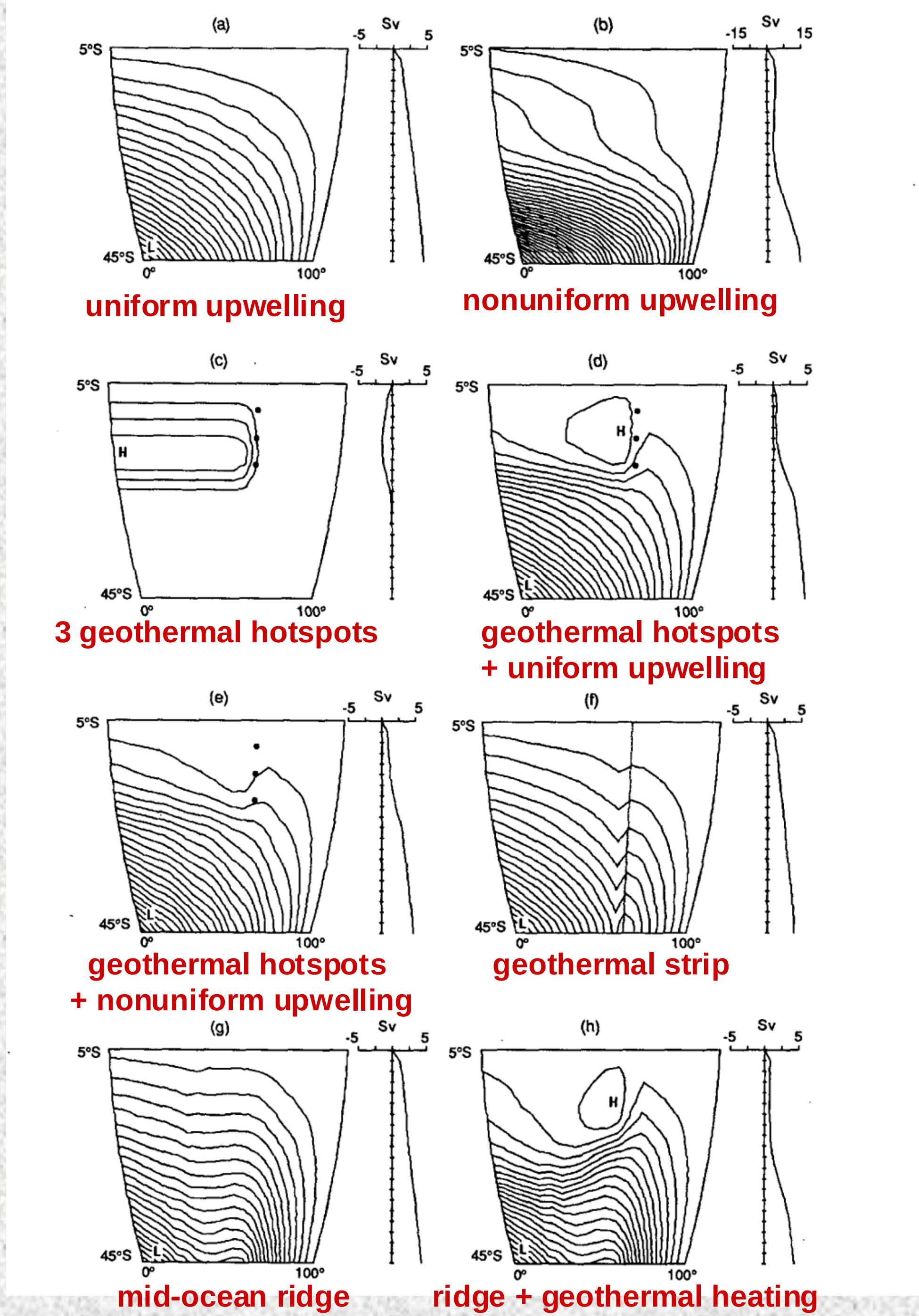
Putting in some numerical values (w_u is unknown but some measurements suggest that w_d can perhaps be as large as 1 cm/sec), it is found that

$$w_u \sim 10^{-5}, 10^{-6} \text{ cm/sec}$$

or about 30-300 meters/year [far too small to measure].

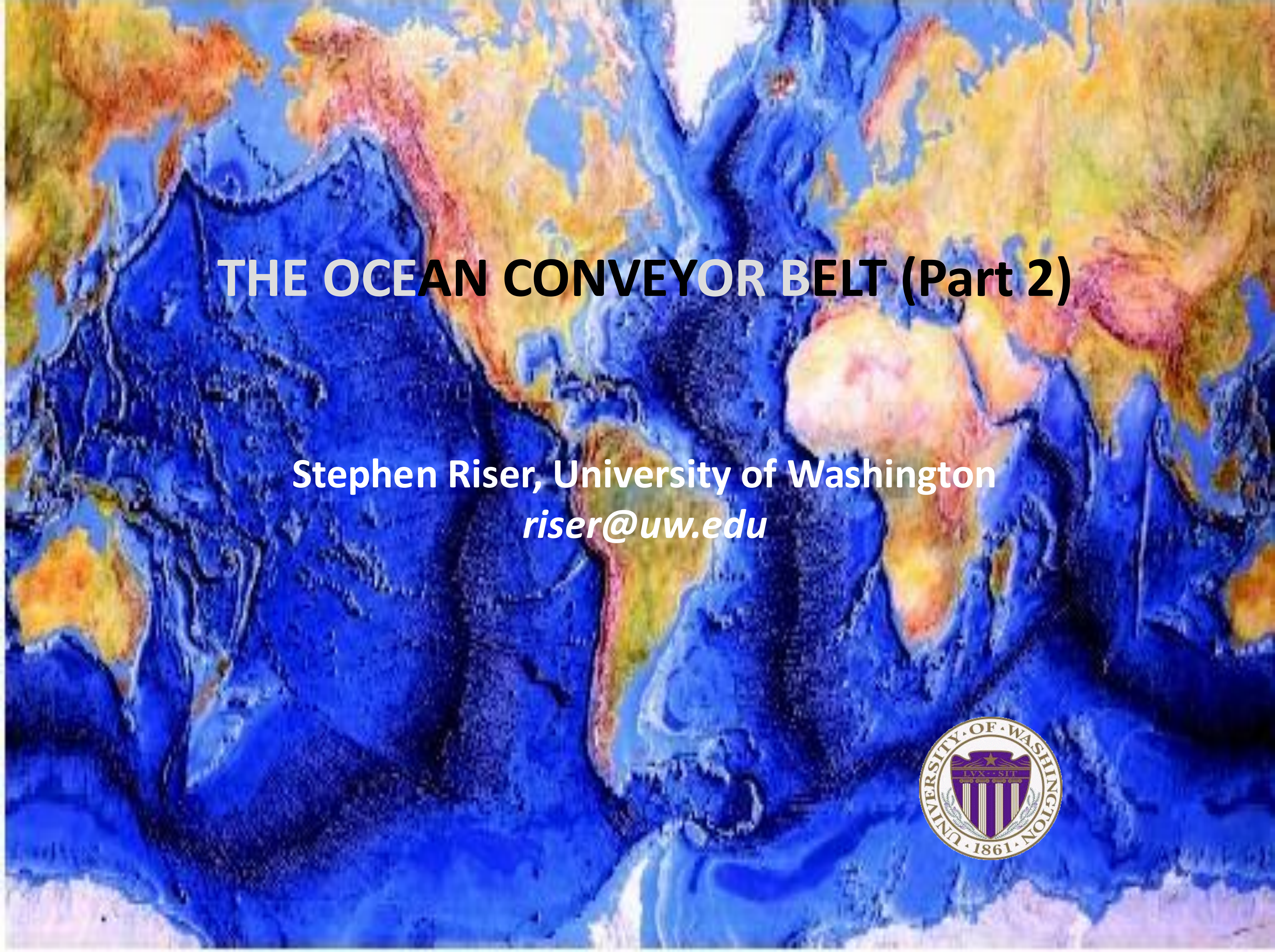


A simple one-dimensional advection-diffusion model of the dissolved oxygen distribution, showing the O_2 minimum and the effect of removing uniform upwelling (see Munk, 1966).



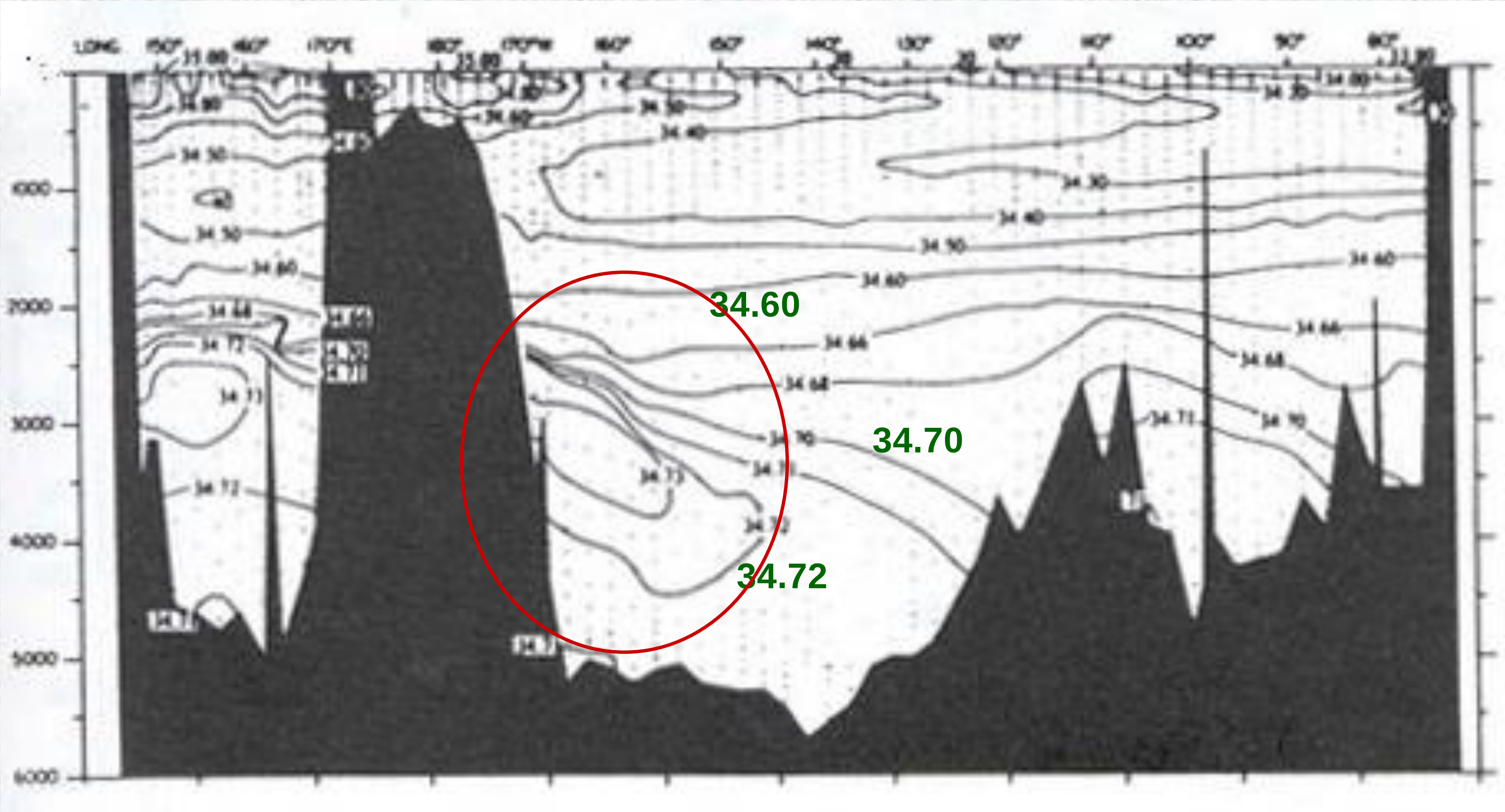
S-A model circulation for the South Pacific, showing effects of mid-ocean ridges and large-scale hydrothermal venting.

[Hautala and Riser, 1989]

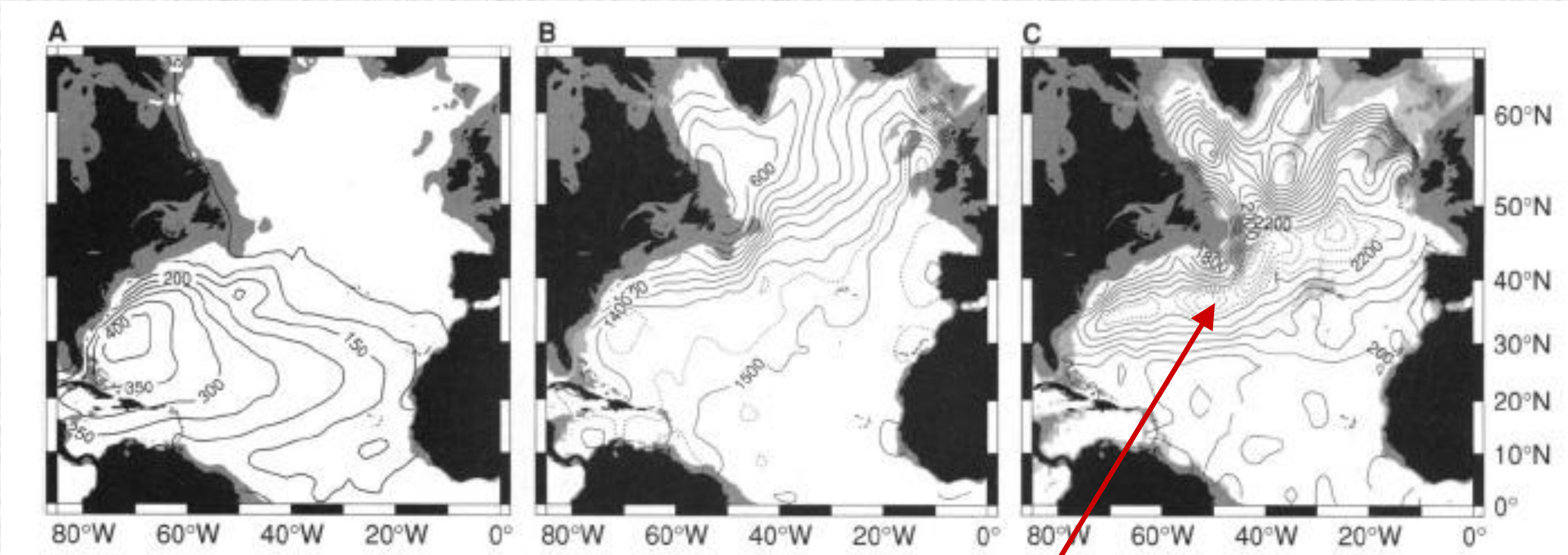


THE OCEAN CONVEYOR BELT (Part 2)

Stephen Riser, University of Washington
riser@uw.edu



This section of *S* along 43° S in the S. Pacific shows that there is considerable detail at signal levels ≤ 0.01 PSU, along with the DWBC.

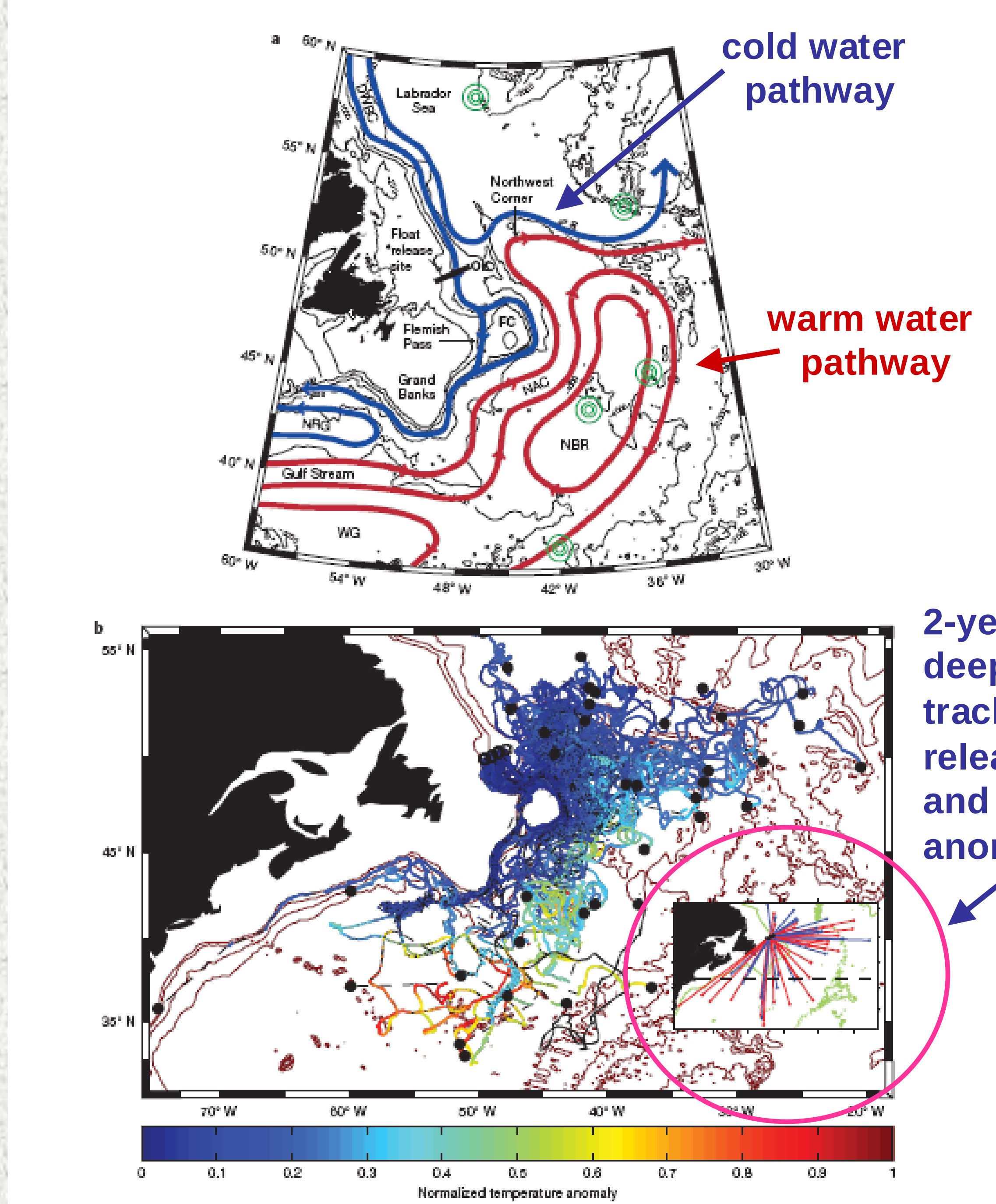


p , $\sigma_0 = 26.5$ p , $\sigma_{1.5} = 34.60$ p , $\sigma_2 = 36.95$

eddy-driven recirculation

The simple abyssal flow patterns and associated deep western boundary currents implied by the S-A model cannot be entirely correct, as the wind-driven circulation and effects of topography together produce rectified, eddy-driven mean flows that are probably stronger than the S-A flow.

[Lozier, 1997]



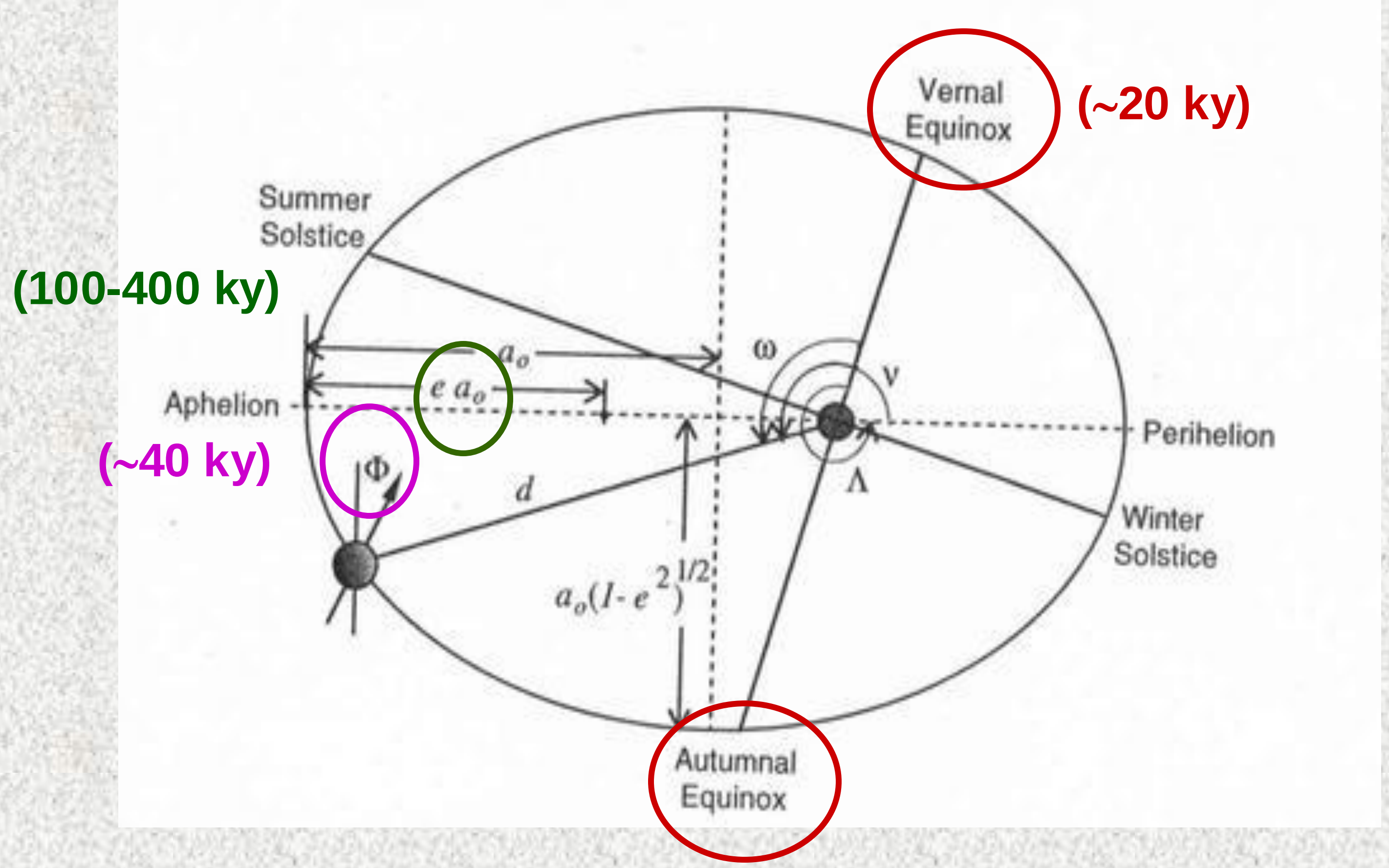
cold water pathway

warm water pathway

2-year pathways of deep acoustically-tracked floats released in the DWBC, and their temperature anomaly

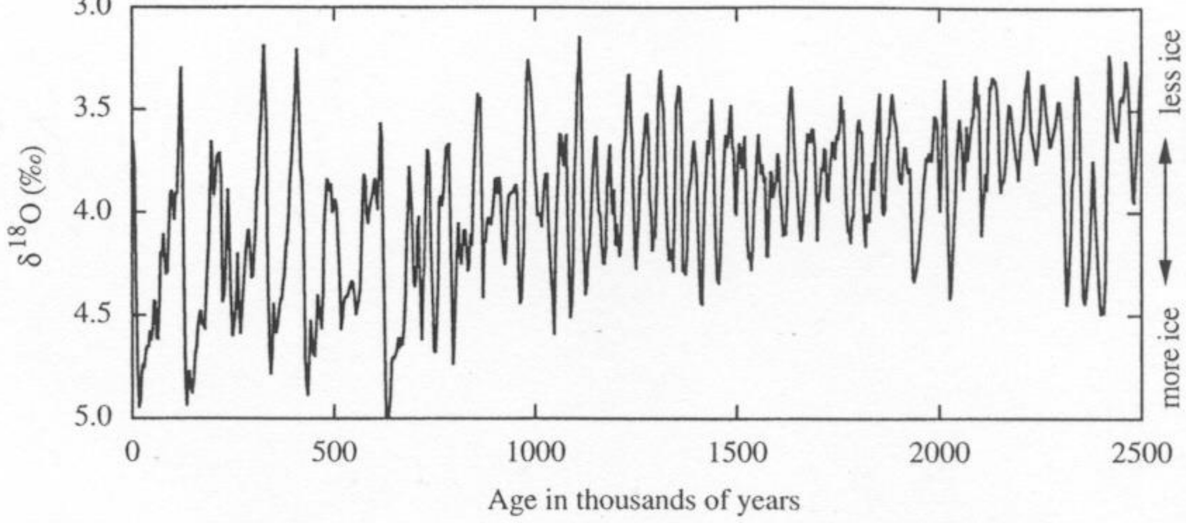
[Bower et al., 2009]

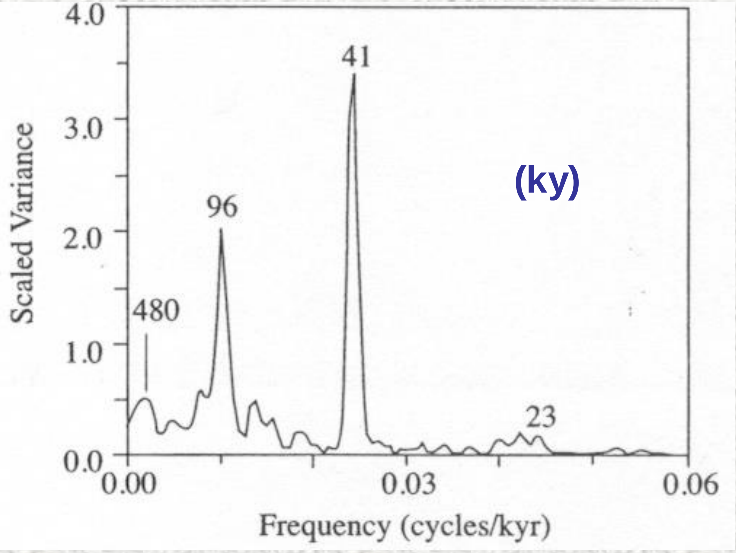
Climate variations: quasi-regular…



A schematic drawing showing the Milankovich orbital parameters.

$\delta^{18}O$ data derived from ice cores

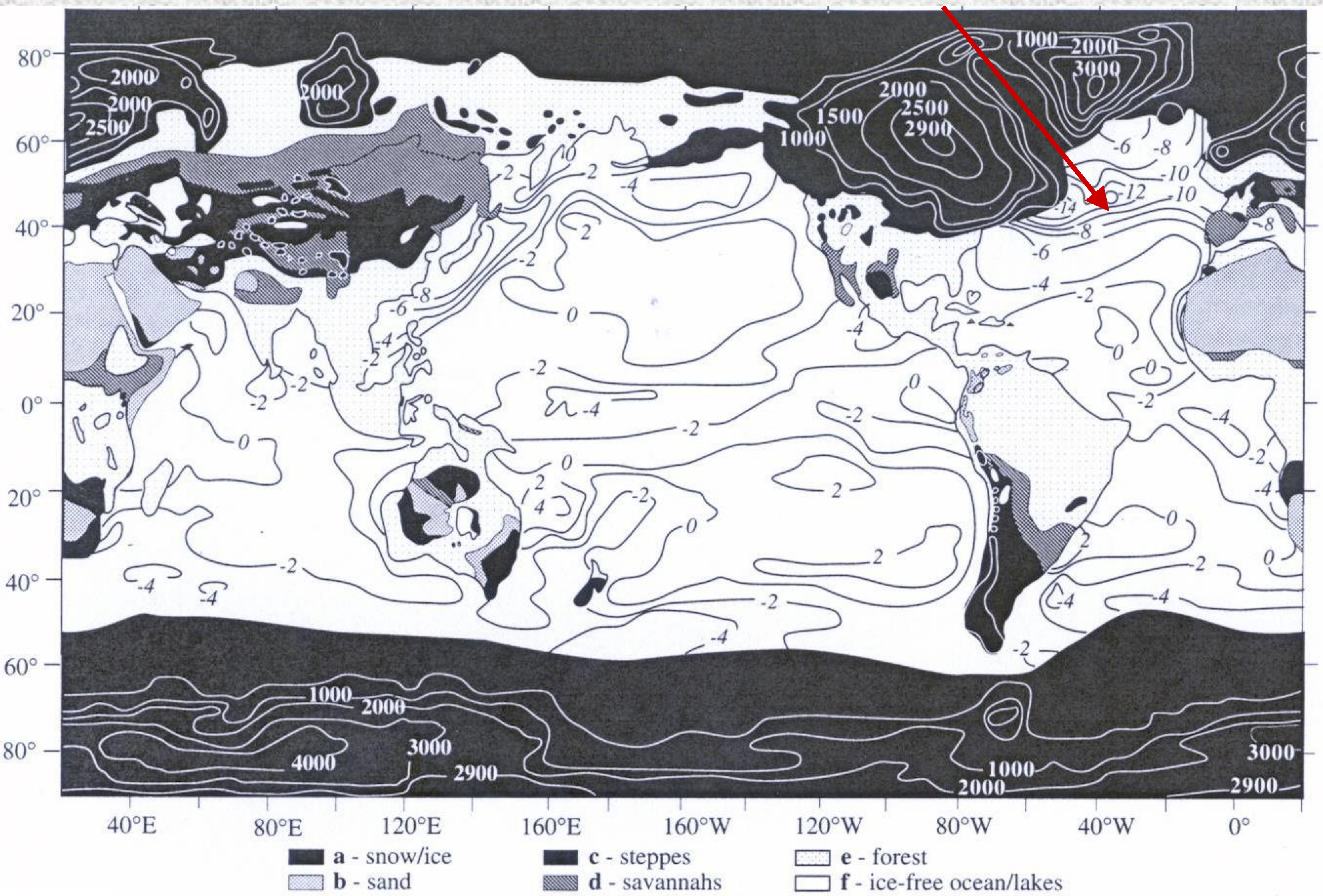




$$\delta^{18}O = \frac{\left(\frac{^{18}O}{^{16}O}\right) - \left(\frac{^{18}O}{^{16}O}\right)_{standard}}{\left(\frac{^{18}O}{^{16}O}\right)_{standard}} \times 1000$$

[from Hartmann, 1994]

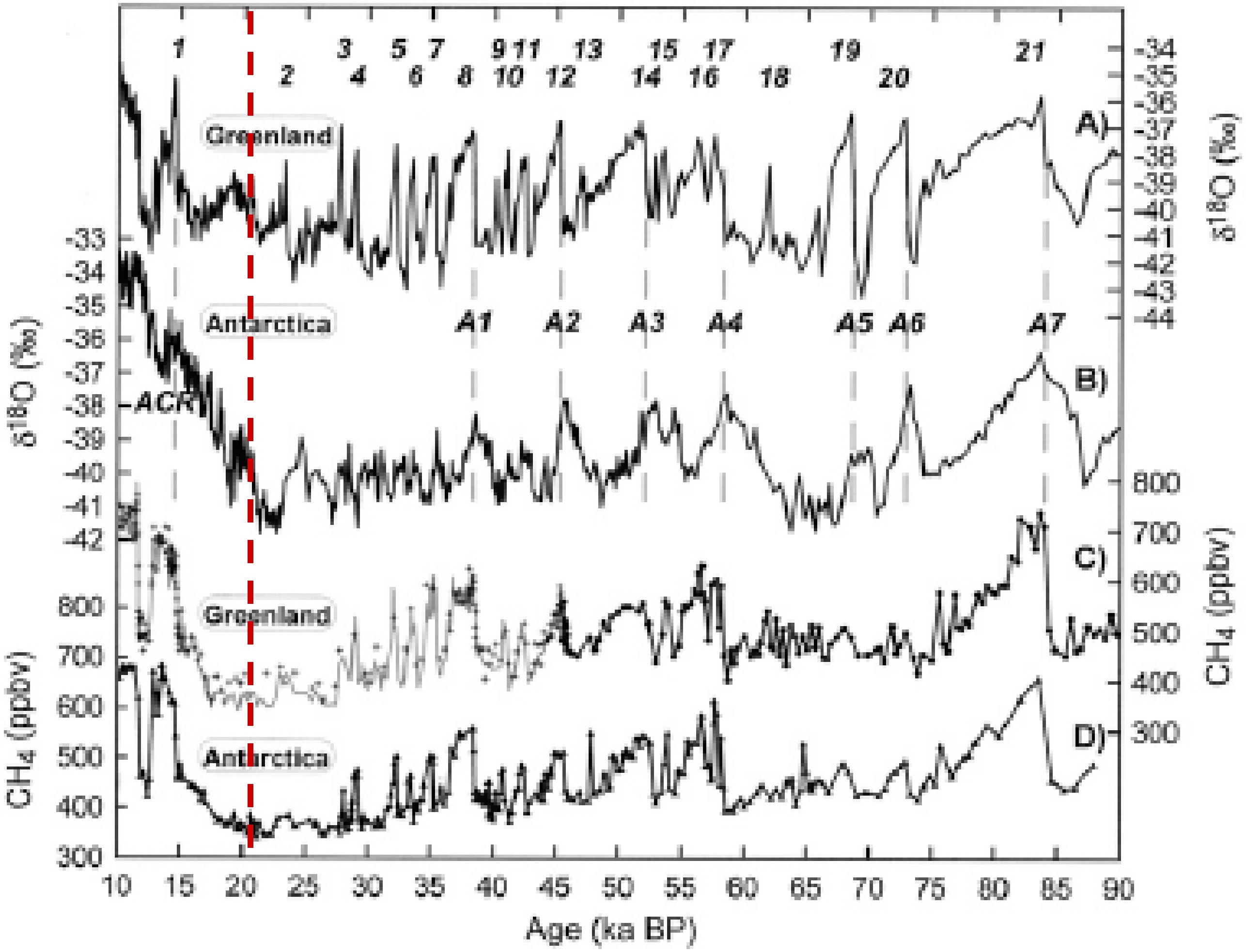
Gulf Stream/N. Atl. current



Earth's surface conditions during August 18,000 years ago. Contours in ocean areas indicate departures of SST from present values in °C. Contours in snow and ice regions indicate depth of ice in meters. [From CLIMAP Project Members (1976), © by the AAAS.]

[from Hartmann, 1994]

90,000 years of Greenland and Antarctic climate



- Rapid warmings (then cooling, then sudden cooling) in Greenland

- No such things in Antarctica

- bimodality in Greenland (Wunsch 2001)

Blunier and Brook (2001)

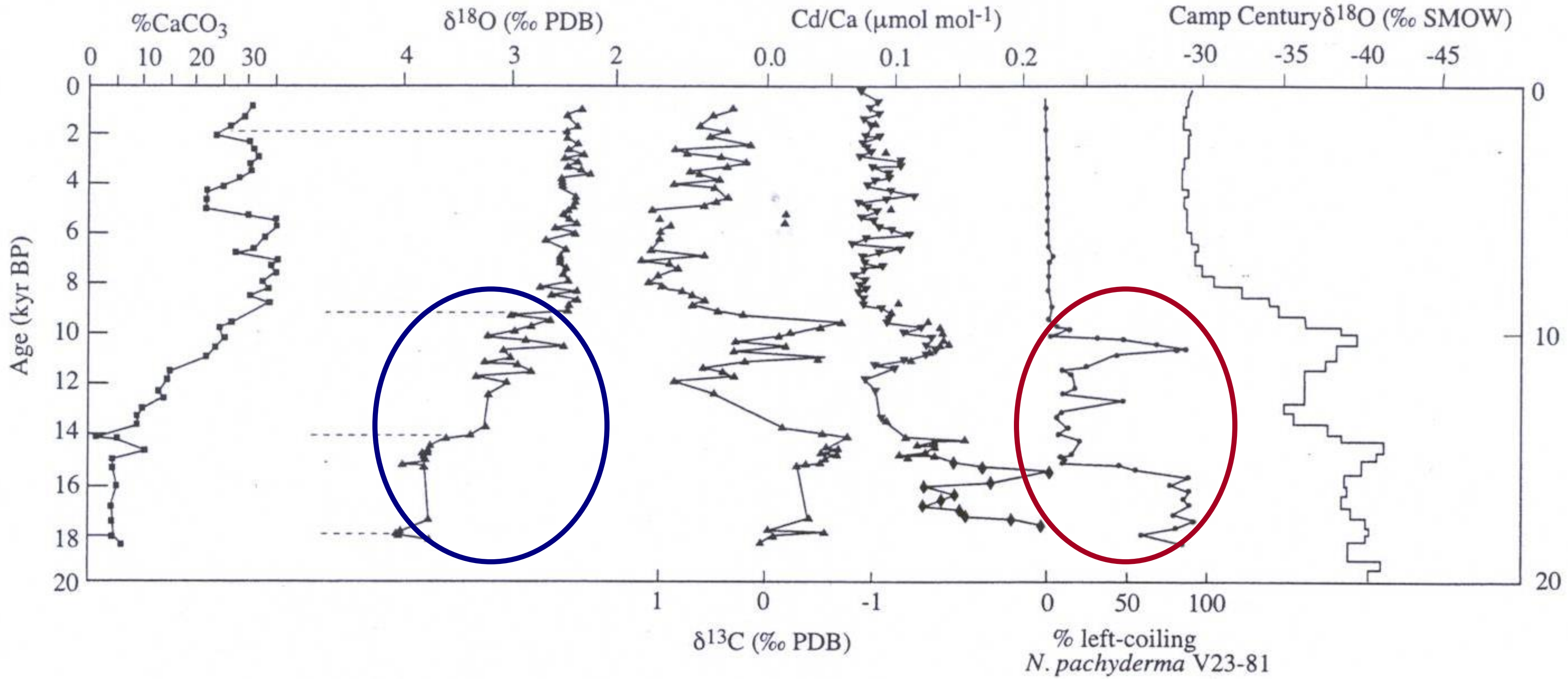


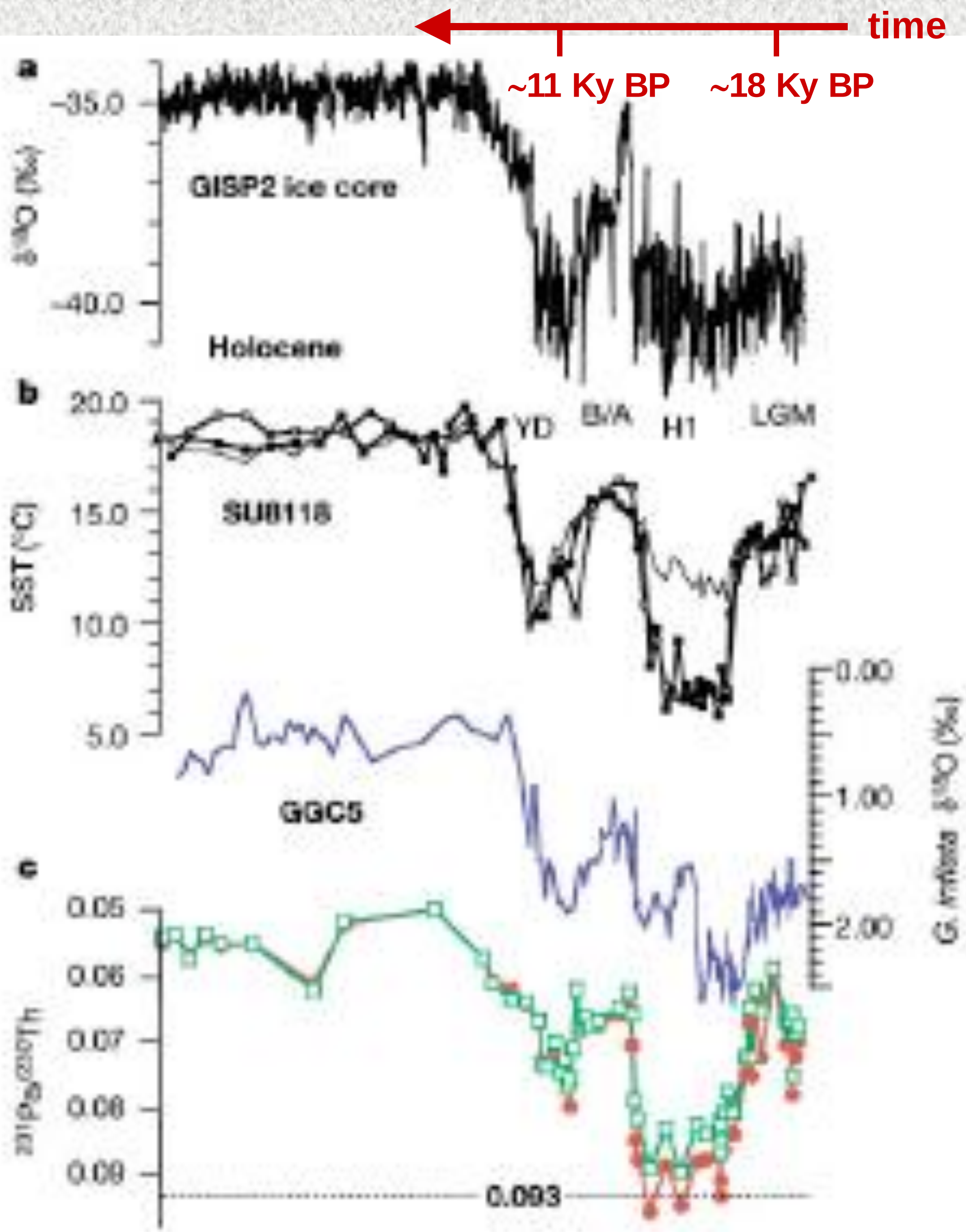
Fig. 8.11 Time histories taken from an ocean sediment core raised from 4450-m depth at 34°N, 58°W. Shown are the calcium carbonate content, ^{18}O isotope abundance, ^{13}C isotope abundance, and the cadmium/calcium ratio. Also shown are the *N. pachyderma* abundance from a north Atlantic sediment core and ^{18}O isotope fraction from a Greenland ice core (*N. pachyderma* are planktonic foraminifera that prefer cold water). Note the brief cool episode about 11,000 years ago during a period when the global ice volume was declining. [From Boyle and Keigwin (1987), © Macmillan Magazines Limited.]

[from Hartmann]

Greenland

Subpolar N Atlantic SST

overturning circulation proxy, Bermuda rise



Journal of Marine Research, 41, 327-347, 1983

Why is no deep water formed in the North Pacific?

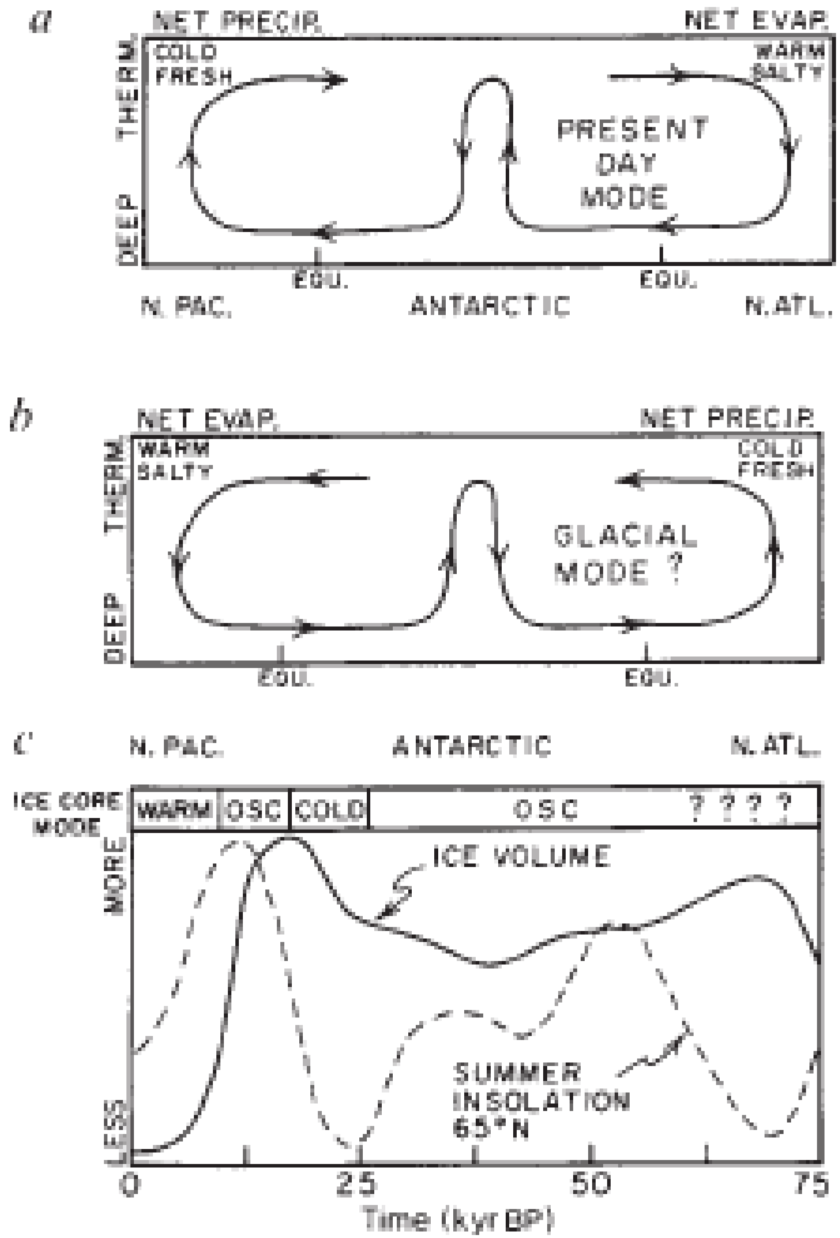
by Bruce A. Warren[1]

ABSTRACT

According to climatological data, the low salinity of near-surface water in the northern North Pacific, which reduces its density so much as to prevent sinking to great depth there, is due to the small regional evaporation rate (which allows a substantial net freshwater input to the surface layer from precipitation and runoff), in combination with the small rate of flow through the surface layer (which amplifies the effect of the freshwater flux on the salinity). The low evaporation rate is due in turn to the relatively low surface temperature (decreasing the specific humidity of the air at the air-sea interface), which seems to be caused mainly by the relatively large proportion of cold upwelling water in the inflow to the surface layer, contrasting with that in the northern North Atlantic where warm surface water to the south is the principal component of inflow. The reduction in southern inflow—and thereby in through-flow as well—results somewhat from the absence of a sink for surface water in any analogue to the Norwegian Sea, but probably in greater part from the more southerly extent of the subpolar gyre in the North Pacific than in the North Atlantic, whereby little water from the subtropical gyre passes through the northern North Pacific. The latter feature indicates a linkage between deep-water formation in the northern hemisphere and the distribution of wind-stress curl. Some aspects of this process by which lowering the temperature of seawater can reduce its density—by decreasing its salinity through diminished evaporation—are illustrated in a simple model.

cool; closed at high lat.; low net evaporation; cold upwelling

warm; higher net evaporation; NPDW??



warm; open to high lat.; high net evaporation from warm inflow; NADW

cold; ice covered; low net evaporation; no NADW formed

[Broecker et al., 1985]

Summary

- The idea of a “conveyor belt” is a greatly oversimplified (and, in Stommel’s words, *dreamlike*) conceptual model of the globally connected deep circulation.

- There is considerable evidence that deep circulation proceeds from sinking in the Atlantic on to the Indian and Pacific Oceans, with some sort of shallow return flow.

- Stommel and Arons showed how an abyssal circulation fed through a series of deep western boundary currents was not inconsistent with basic dynamics.

- Modern observations suggest that the S-A idea is a good starting point but is far to simple to include the effects of transients (eddies, etc.) on the deep circulation.

- The abyssal circulation may be connected to climate variability on century to millenial time scales; this problem is just beginning to be explored.