A Broecker Brief

Origin of the Atlantic's glacial age lower deep water

Today's deep Atlantic shows no hint of nutrient stratification (see Figure 1). By contrast, during the last glacial maximum (LGM), the deep Atlantic was strongly nutrient stratified. The waters deeper than about 2.5 km were depleted in both ^{13}C and in carbonate ion relative to today's. By contrast, the waters shallower than 2.5 km were enriched in these properties relative to today. As shown in Figure 2, this was also the case for marine isotope stages 4 and 6. The frequently quoted explanation for this is that the depth range occupied by Antarctic Bottom Water (AABW) was much larger than today during these cold epochs. In my view the situation is more complicated. In this "brief" I make the case that the lower deep water in the LGM Atlantic was a mixture consisting of roughly one third AABW and two thirds deep water formed in the northern Atlantic. In addition, in order to explain the magnitude of the $\delta^{13}C$ and $CO_3^{=}$ changes, the mixture had in addition an enhanced inventory of respiration products.

Before discussing the origin of these cold epoch water masses, a few words about AABW are needed. As shown in Figure 3, the phosphate content of the deep Southern Ocean deep water currently feeding the abyssal Pacific is the same as in that for AABW. The various contributors to today's deep Southern Ocean are thoroughly mixed in a single pass around the Antarctic continent (see Figure 4). As the situation was very likely the same during the LGM, Southern Ocean waters entering the abyssal Atlantic had the same nutrient composition as that entering the abyssal Pacific.

My case is based on four water mass proxies: the ^{13}C to ^{12}C ratio in benthic forams (see Figure 3), the ^{14}C to C ratios in coexisting planktic and benthic forams (see Tables 1 and 2), carbonate ion concentrations reconstructed from the boron to calcium ratio in benthic *Cibicides*, and the neodymium isotope ratio for coatings on benthic entities. As summarized in Table 3, each of these properties suggests that no more than one third of the LGM lower deep water was supplied by AABW.

If the above analysis is correct, the other two thirds of the glacial age lower must be produced by sinking in the northern Atlantic. The fact that the neodymium isotope composition of LGM lower Atlantic deep water does not match that in LGM age abyssal Pacific water requires a contribution from the north.

However, in order to explain the $\delta^{13}C$ and $CO_3^{=}$ contents of cold epoch abyssal Atlantic water requires an input of additional respiration products. Normalizing to the composition of the upper deep water, it requires a drop of 0.6‰ in ^{13}C (i.e., 0.6 μmol/liter increase in phosphate content) and a 36 μmol/liter decrease in carbonate ion concentration. . The ratio of 36 μmol $CO_3^{=}$ to 0.6 μmol PO_4 is close to what is expected if based on the Redfield ratio of 120 μmol DIC to 1 μmol PO_4. As calculated for me by Taro Takahashi, the expected ratio would be 76 instead of 60 (see Table 4).

The question then arises as to why there is a large increase in the respiration contribution to the cold epoch lower deep water and a small decrease in that to the cold epoch upper deep water. Although, I don't know, I can think of three scenarios which might contribute:

1) As the lower deep water resides about twice as long as now and the upper deep water perhaps a shorter time, hence, it stores more respiration products.
2) Unlike today when the products of respiration taking place on the sea floor can be mixed through the entire deep water column during the stratified cold epochs, they would have been trapped on the lower deep water.
3) During cold epochs the lower deep contribution from the northern Atlantic formed under winter sea ice and the upper deep water south of the sea ice front. If so, perhaps the lower deep water contributor had a higher preformed nutrient content.

One might ask, weren't there large vertical and horizontal gradients in the lower deep water? Based on what I know about the LGM records for lower deep water at temperate northern and southern latitudes, the picture is similar to that for the equatorial zone. If there are differences, they are lost in the scatter. The ^{13}C data in Figure 3 is instructive in this regard. If there are differences with depth and location, they are lost in the scatter. As the signal to noise

ratio for B to Ca measurements is much more favorable than that for $\delta^{13}C$, if a serious effort were to be made to map gradients, then carbonate ion would be a better target than carbon isotopes.

Table 1. Summary of benthic-planktic radiocarbon-age differences for samples of LGM age from the deep equatorial Atlantic Ocean. The mean of 725 years is about twice that for today's surface to deep apparent ^{14}C age difference.

Latitude	**Longitude**	**Depth km**	**Calendar Age kyrs**	**ΔB-P yrs**
		Equatorial Atlantic		
4°N	43°W	2.8		
	Broecker et al., 1990		17.1	960 ± 665
			18.3	1300 ± 290
			20.6	785 ± 450
			20.6	250 ± 665
5°N	43°W	3.5		
	Broecker et al., 1990		19.3	475 ± 185
			20.4	775 ± 190
			21.3	535 ± 215
			22.2	620 ± 260
5°N	43°W	4.0		
	Broecker et al., 1990		16.4	715 ± 325
			19.5	275 ± 230
			21.3	910 ± 230
			22.0	705 ± 280
			23.3	1165 ± 585
	Average of the 13 LGM results			**725 ± 200**

Table 2. Summary of benthic-planktic radiocarbon-age differences for samples of LGM age from the deep equatorial Pacific Ocean. The mean of 1525 years is within the uncertainty of today's deep to surface ^{14}C age difference.

Latitude	Longitude	Depth km	Calendar Age kyrs	ΔB-P yrs
		Equatorial Pacific		
1°S	146°E	1.9		
	Broecker et al., 2004		21.5	1950 ± 220
			21.9	1640 ± 250
6°N	126°E	2.1		
	Broecker et al., 2004		19.1	1325 ± 200
			18.7	1170 ± 220
			19.6	1325 ± 200
1°N	130°E	2.8		
	Broecker et al., 2008		17.9	1790 ± 170
			18.6	1510 ± 120
			19.2	1700 ± 130
2°S	140°W	4.4		
	Broecker and Clark, 2010		17.2	1550 ± 300
			22.0	1500 ± 300
			24.2	1700 ± 300
		Average of the 11 LGM results		**1575 ± 150**

Table 3. Contrast between the composition of water in the deep equatorial Pacific and in the lower deep equatorial Atlantic now and in the LGM. As can be seen, the LGM composition of deep Atlantic water shifts toward that of the deep Pacific, but it shifts only about one third of the way.

Property	**Pacific Now**	**Atlantic Now**	**ΔP-A Now**	**Pacific LGM**	**Atlantic LGM**	**ΔP-A LGM**	**ΔLGM / ΔNow**	**Percent AABW**
^{143}Nd Anomaly (εNd)	-4	-14	10	-4	-11	7	0.7	30 ± 10
Deep-Surface* ^{14}C age (yrs)	1600	300	1200	1575	775	800	0.65	35 ± 10
δ^{13}C** Deep ‰	-0.3	+1.0	1.3	-0.7	+0.3	1.0	0.75	25 ± 15
$CO_3^{=}$ μmol/kg	77	114	37	~77	~90	23	0.6	40 ± 10
							Mean	**35 ± 10**

*See Tables 1 and 2
**See Figure 5

Table 4. **Upper portion**: Listing of $\delta^{13}C$ and $CO_3^{=}$ values for the Caribbean (1.8 km) and Ceara *Rise* (3.6 km) for three major cold epochs. As can be seen, the spread is nearly the same for each of the three. **Lower portion**: As 0.4 of the 1.0‰ lowerings of $\delta^{13}C$ can be explained by the addition of AABW, the assumption is that the remainder (i.e., 0.6‰) is from excess respiration. Using the sum proportions for $CO_3^{=}$, the respiration contribution comes out to be 36 μmol/kg. Hence, the observed $\Delta\delta^{13}C$ to ΔCO_3 ratio is 66. The predicted ratio is 69 μmolkg^{-1}/‰.

	$\delta^{13}C$ 1.8 ‰	$\delta^{13}C$ 3.6 ‰	$\delta^{13}C$ 1.8-3.6 ‰	$CO_3^{=}$ 1.8 μmol/kg	$CO_3^{=}$ 3.6 μmol/kg	$\Delta CO_3^{=}$ 1.8-3.6 μmol/kg
MIS 2	1.4	0.3	1.1	150	90	60
MIS 4	1.0	0.0	1.0	130	70	60
MIS 6	1.2	0.2	1.0	150	90	60
AABW Contribution			0.4 ± 0.1			24
Respiration Contribution			0.6 ± 0.1			36

Observed in deep Atlantic

$$\left.\frac{\Delta CO_3^{=}}{\Delta\delta^{13}C}\right\}_{Obs} = \frac{36}{0.6} = 60 \pm 10$$

Expected from respiration (a la Takahashi)

$$\left.\frac{\Delta CO_3^{=}}{\Delta PO_4}\right\}_{Calc} = \frac{\Delta CO_3}{\Delta\delta^{13}C} \times \frac{\Delta\delta^{13}C}{\Delta PO_4} = 76 \times 1.0 = 76 \pm 10$$

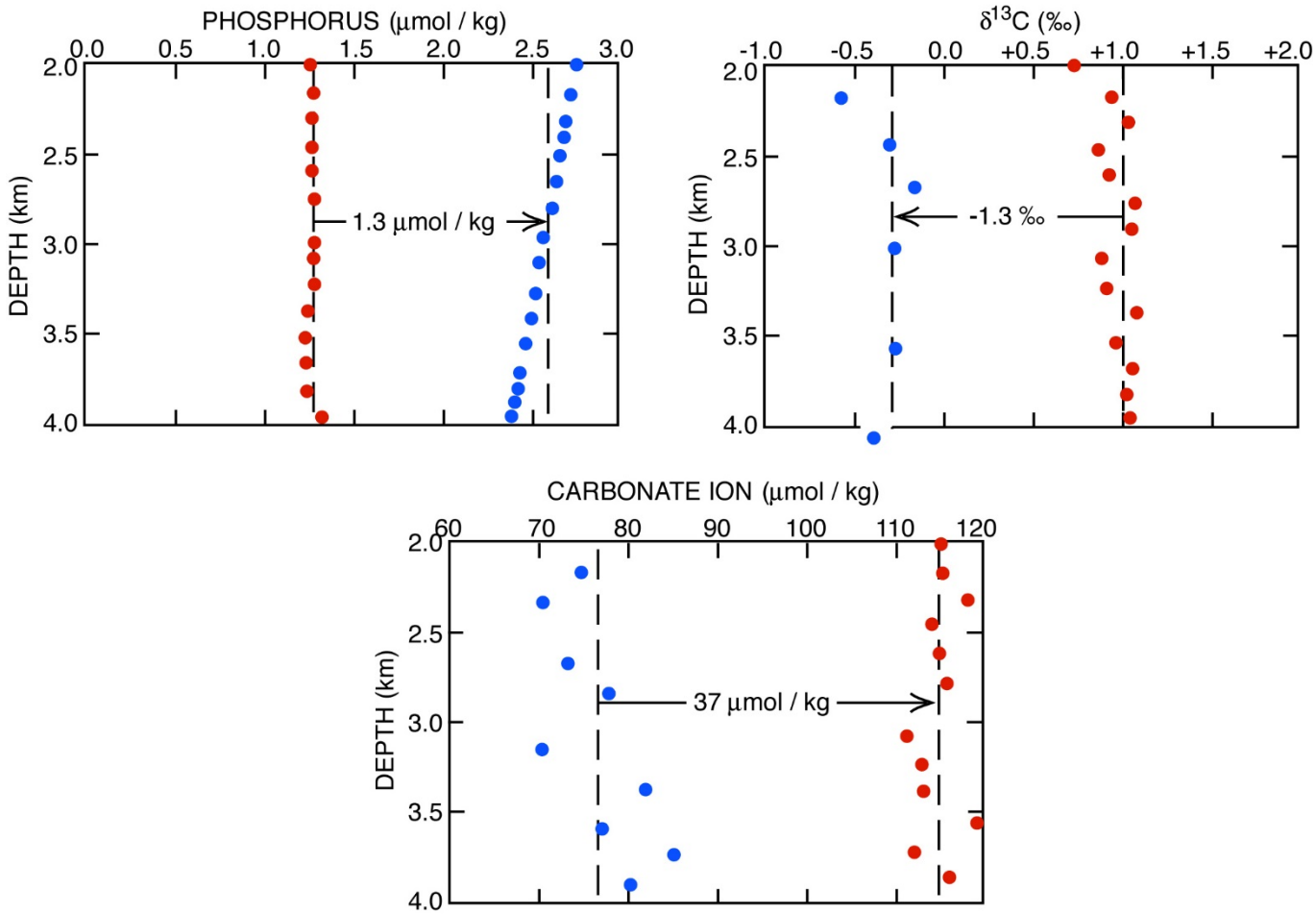

Figure 1. Plots versus water depth in the western equatorial Atlantic (red) and Pacific (blue) Oceans for PO_4, $\delta^{13}C$ and carbonate ion.

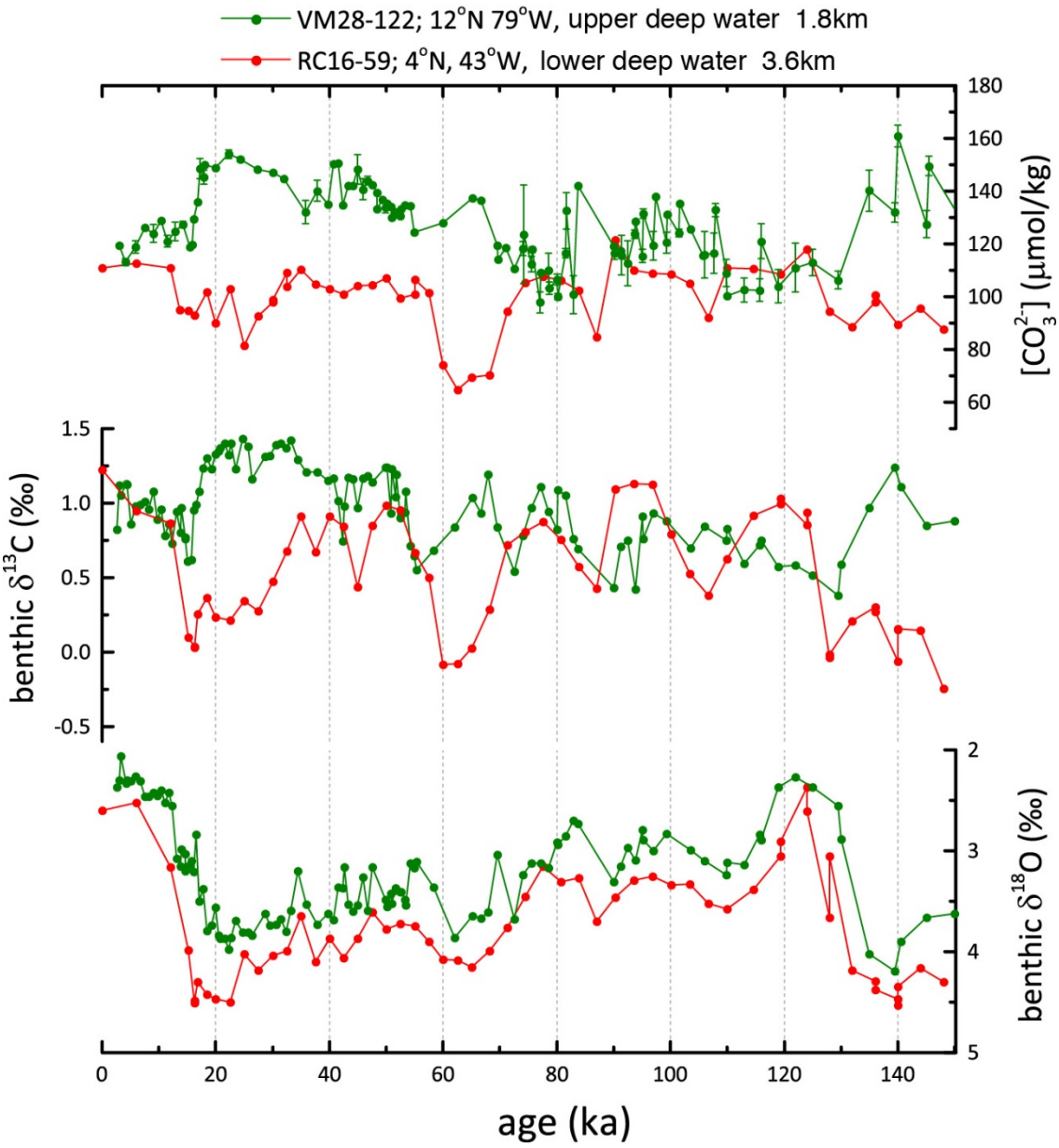

Figure 2. The carbon isotope and carbonate ion records for the last 160 kyrs in cores representing the upper and lower deep water in the Atlantic show three intervals of strong stratification, i.e., MIS 2, 4 and 6. During these cold episodes, the deep water in the Caribbean Sea (1.8 km) had a higher $\delta^{13}C$ and $CO_3^{=}$ than waters on the Ceara Rise (3.4 km). As summarized in Table 4, at each of these three times, the $\delta^{13}C$ difference was about 1‰ and the $CO_3^{=}$ about 60 µmol/liter.

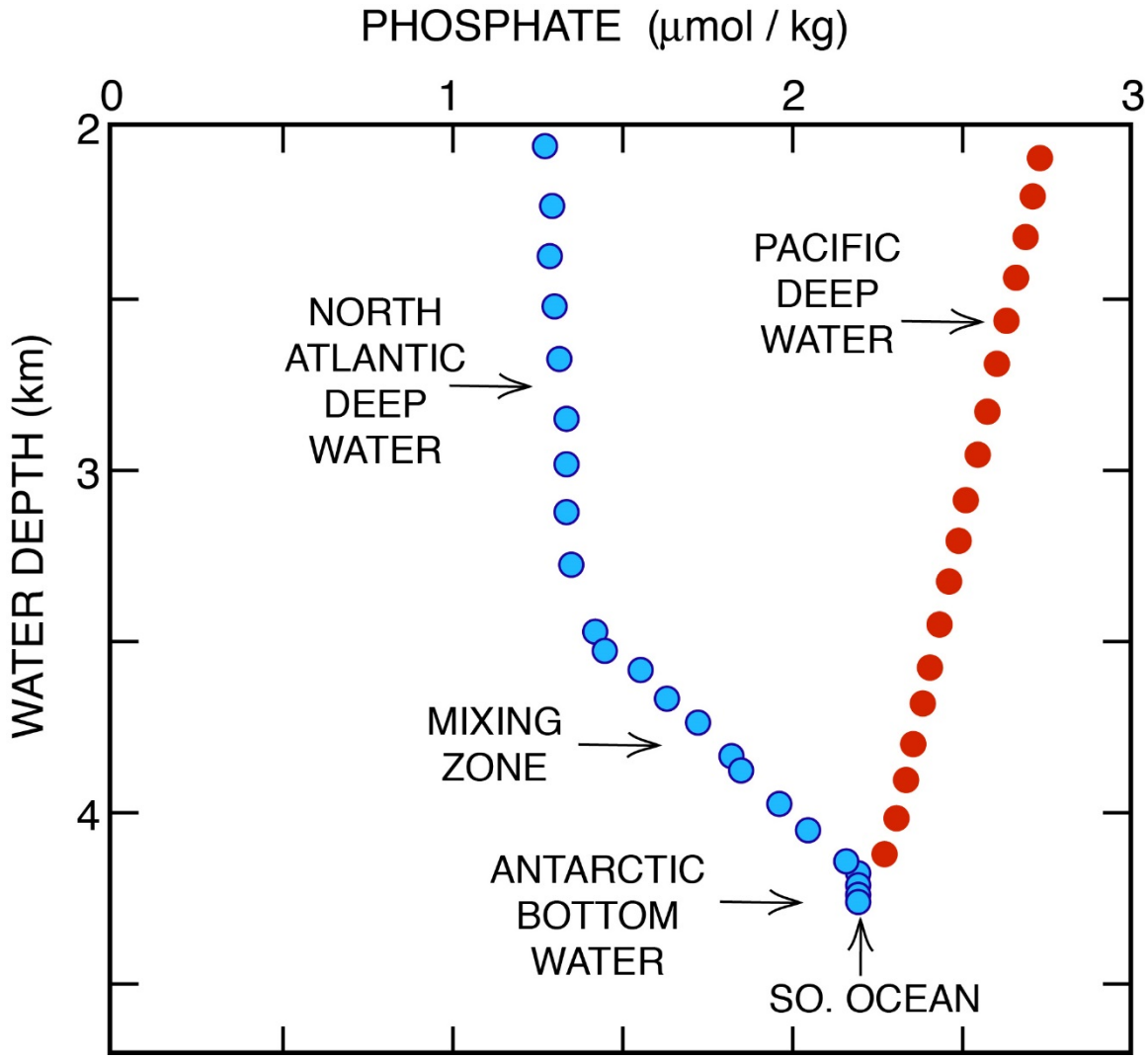

Figure 3. Plots of PO_4 versus water depth for deep waters in the deep Atlantic and deep Pacific Oceans. As can be seen, the water entering the abyssal Pacific Ocean has the same PO_4 content as Antarctic Bottom Water entering the Atlantic.

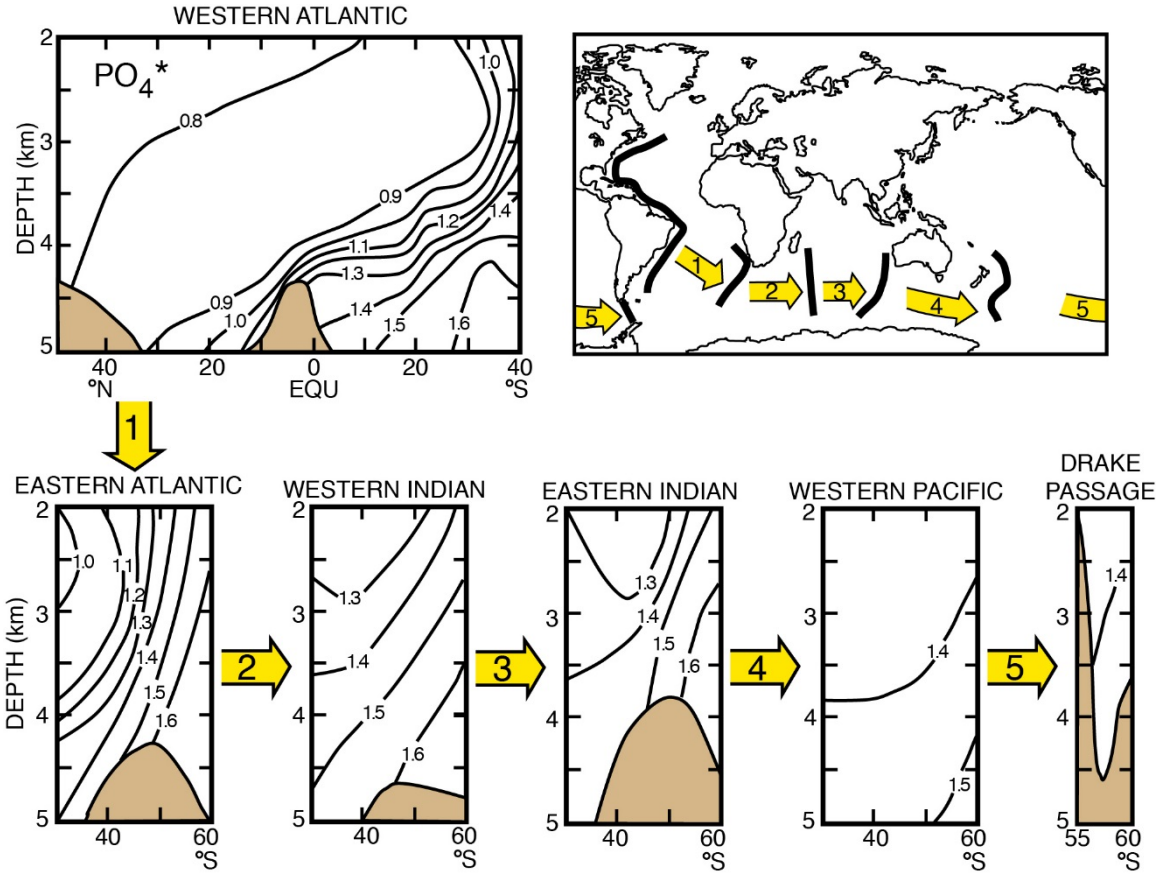

Figure 4. Sections of PO4* along N-S traverses in the Atlantic and Southern Ocean. As can be seen, the strong gradient in the eastern Atlantic section has been largely eliminated by the time the water reaches the western Pacific and Drake Passage.

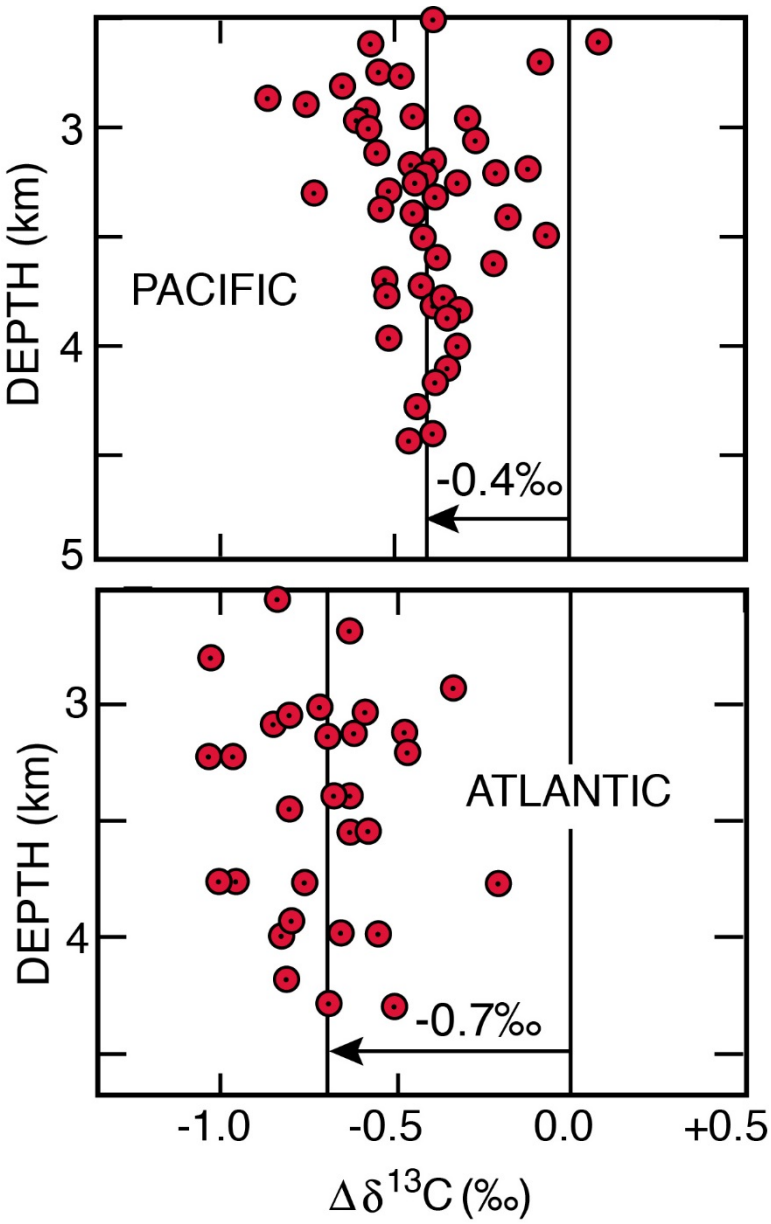

Figure 5. As recorded in benthic foraminifera, the $\delta^{13}C$ in both the deep Atlantic and the deep Pacific Oceans was lower during the LGM than during the late Holocene (presumably as a consequence of a reduction in continental biomass). If during the LGM the lower Atlantic was flooded with AABW, today's 1.3‰ $\delta^{13}C$ difference between deep Pacific and deep Atlantic would have been reduced by 1.3‰. But as it was only reduced by 0.3‰, the AABW contribution could only have been about one third. The rest was from the north.