What can we learn from the paleo record about past changes in ocean productivity and controls of atmospheric CO_2?

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Bob Anderson, Gisela Winckler, Martin Fleisher

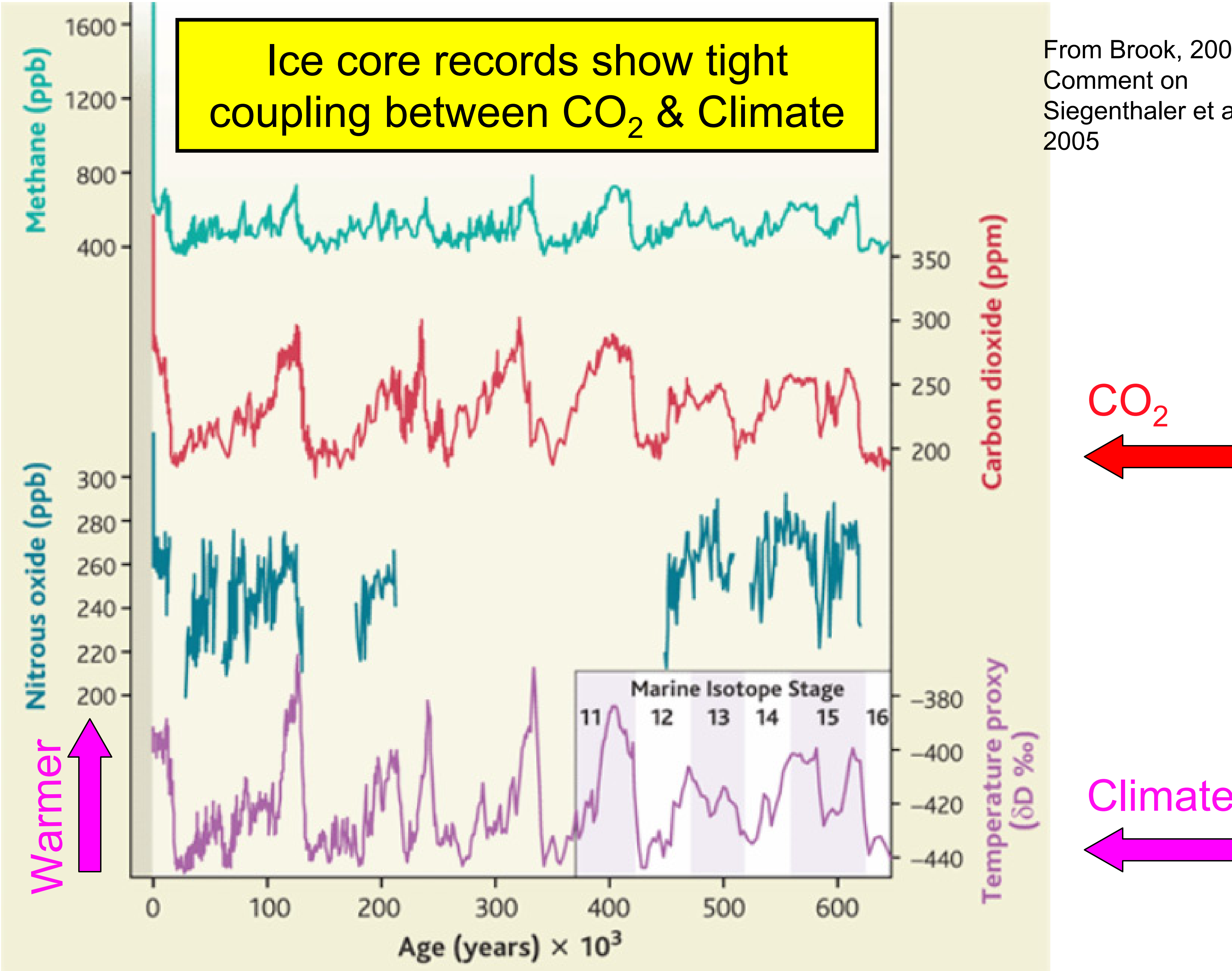
Lamont-Doherty Earth Observatory

Columbia University

Exploring Ocean Iron Fertilization, WHOI, September, 2007

Ice core records show tight coupling between CO_2 & Climate

From Brook, 2005 Comment on Siegenthaler et al., 2005



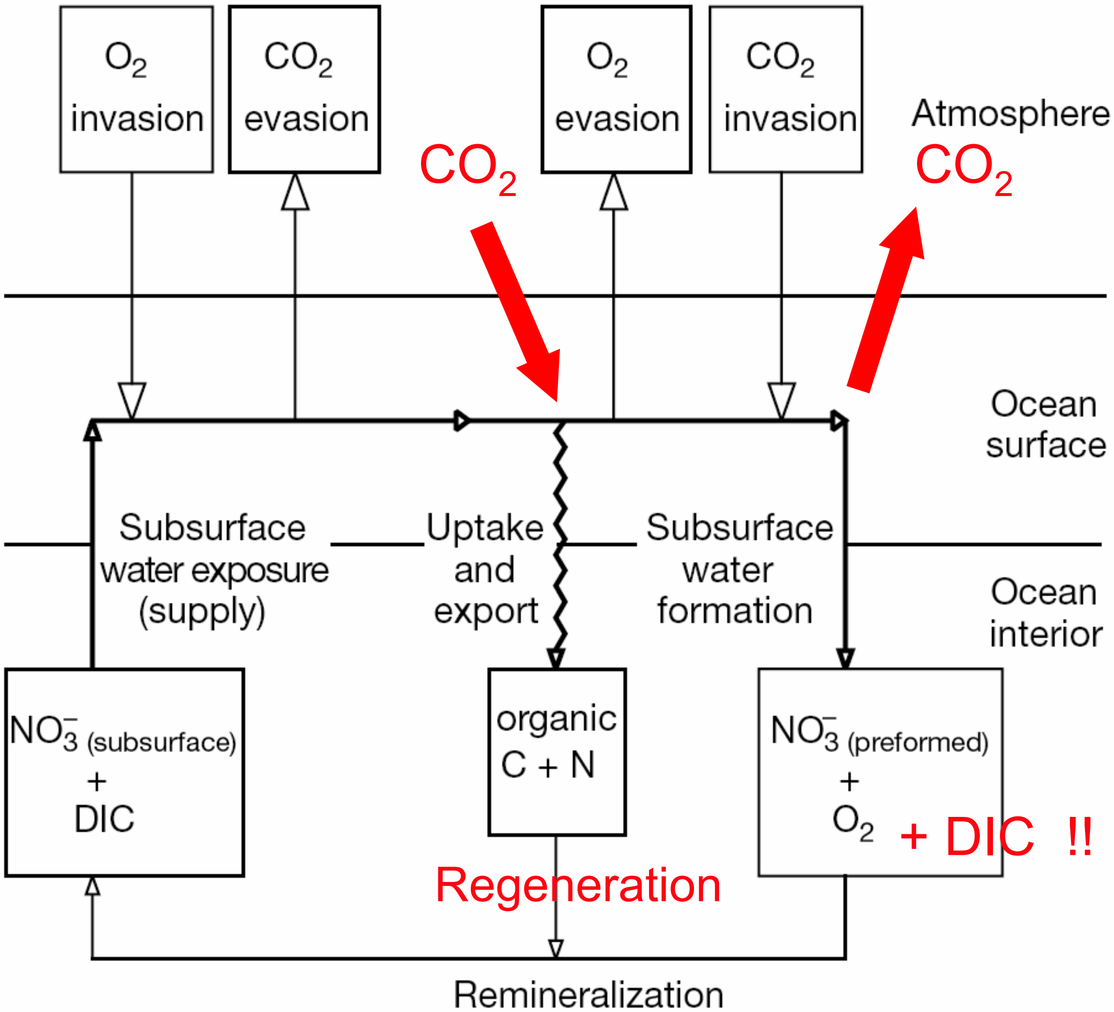
How did the ocean lower glacial atmospheric CO_2 levels?

Plausible mechanisms

1) **Increased strength of the biological pump**
   - Increase nutrient inventory (capacity)
   - Increase nutrient utilization (efficiency; today at ~50%)

2) **Increase ocean ALK/DIC ratio ($[CO_3^{2-}]$)**
   - Continental weathering
   - Shelf-basin fractionation ("Coral Reef" hypothesis)
   - C-org/$CaCO_3$ ratios ("Rain Ratio" hypothesis)

Biological pump of Sigman & Boyle, 2000



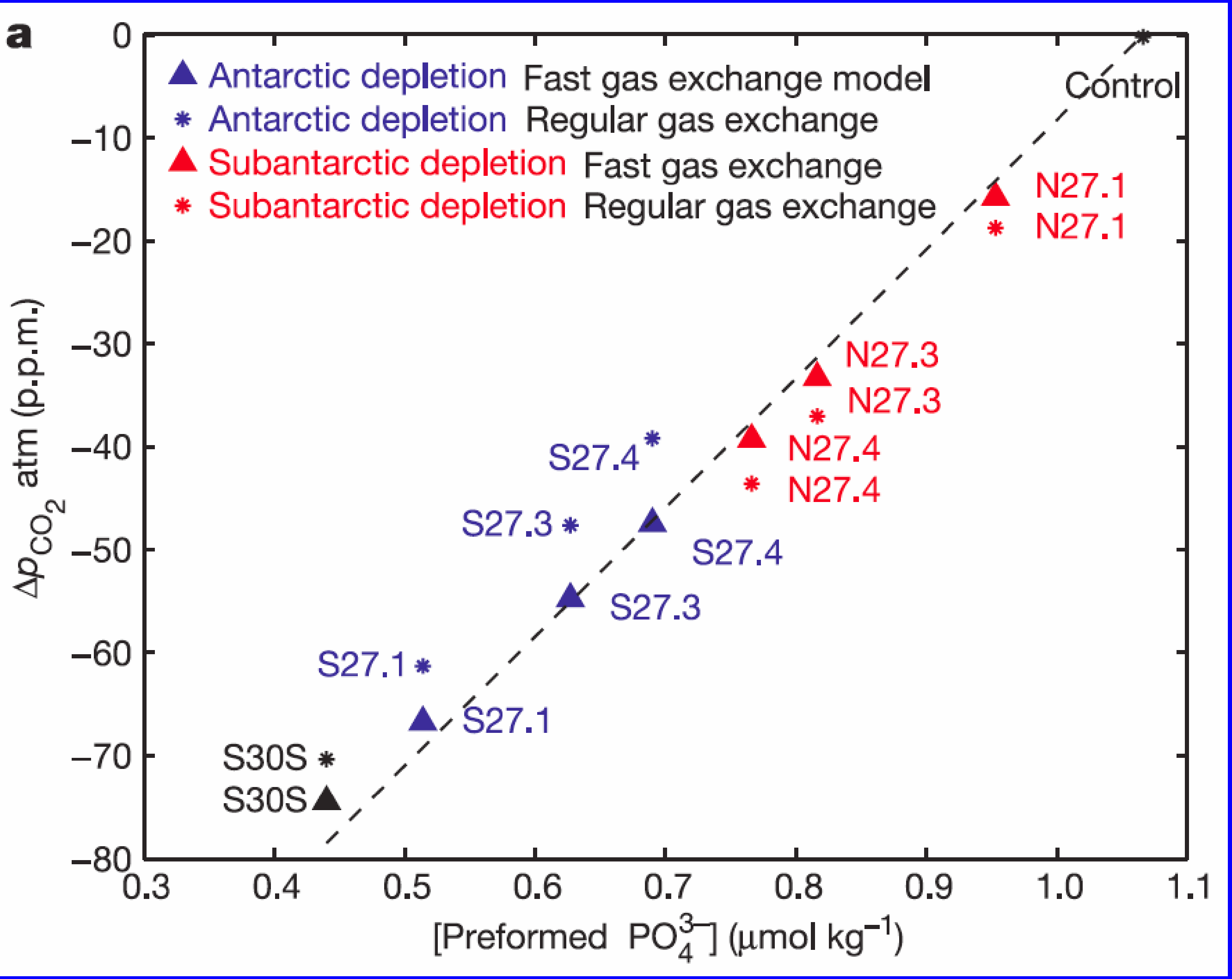
$$\text{Nutrient utilization} \equiv \frac{\text{Uptake}}{\text{Supply}} = 1 - \frac{[NO_3^-]_{\text{preformed}}}{[NO_3^-]_{\text{subsurface}}} \propto \frac{CO_2 \text{ invasion}}{CO_2 \text{ evasion}}$$

What does "efficiency" of the biological pump mean?

It is the fraction of upwelled nutrients that are utilized and exported to depth as organic matter.

Preformed nutrients are the master variable to characterize the efficiency of the biological pump.

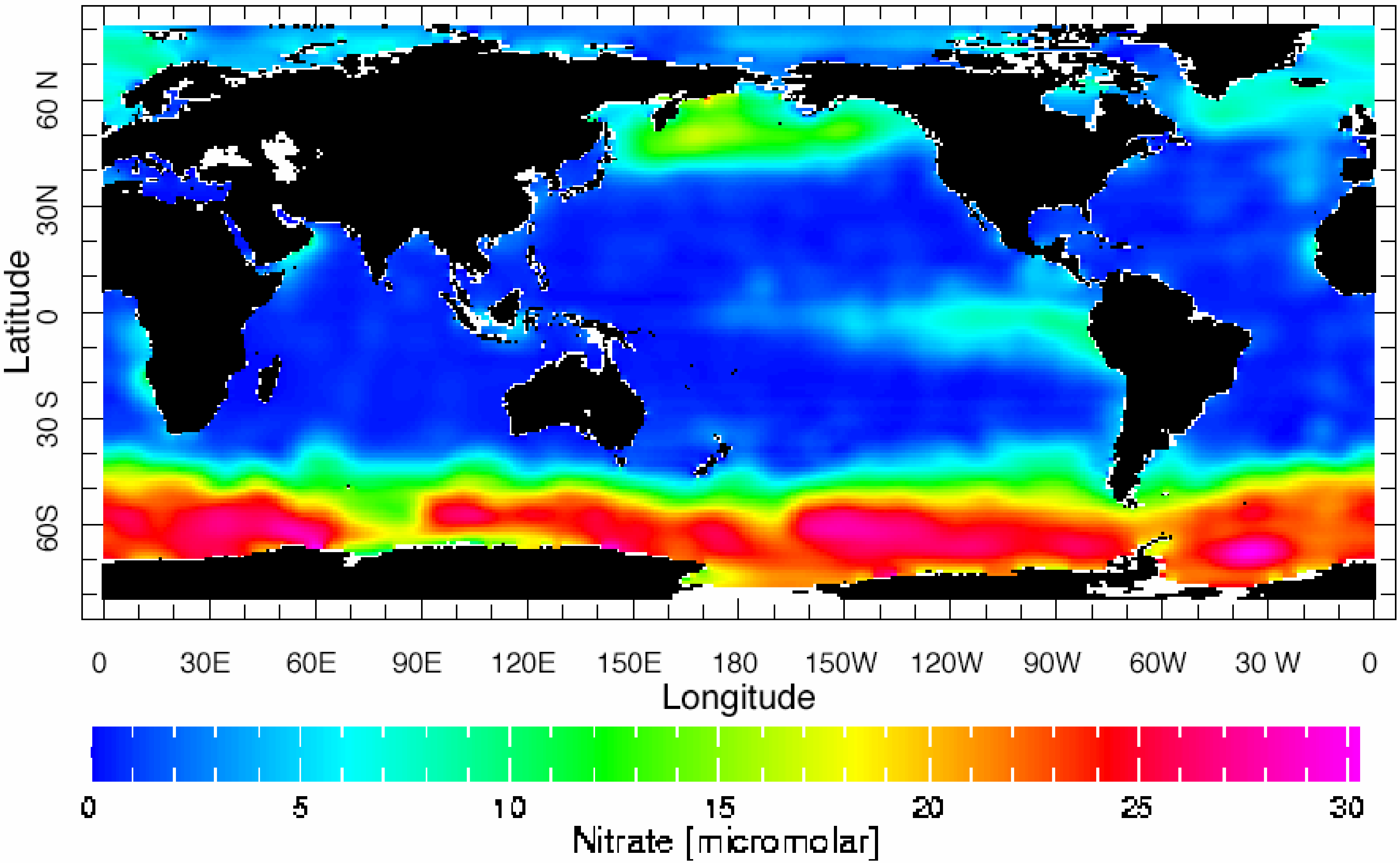
Sensitivity of CO_2 to preformed nutrients



Princeton Ocean GCM runs with different nutrient utilization scenarios.
Constant ocean nutrient inventory

Marinov et al., Nature, 2006

Annual average Nitrate Concentration at 20 m



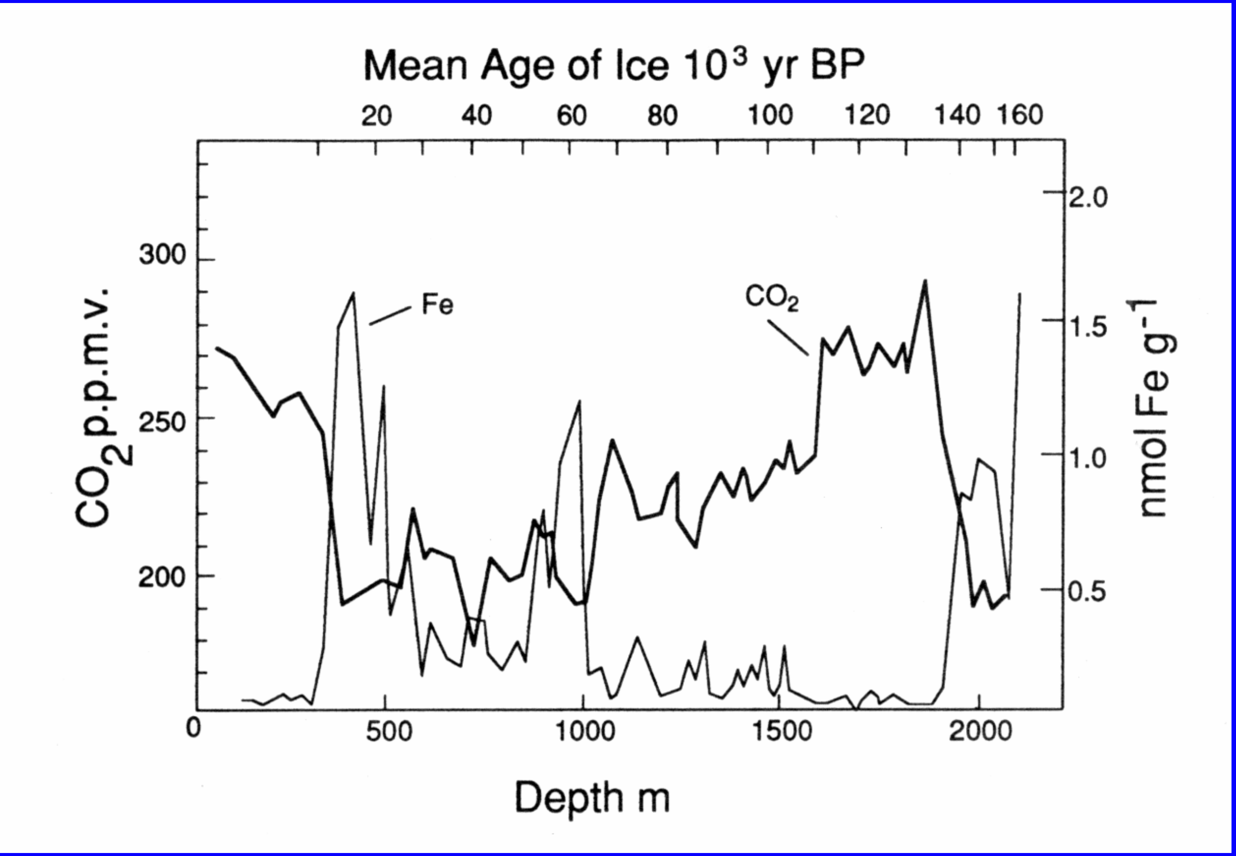
Only about half of the upwelled nitrate is used by phytoplankton.

Efficiency of the Biological Pump today is low. Potential to alter CO_2 is high.

From: iridl.ldeo.columbia.edu/SOURCES/.LEVITUS94

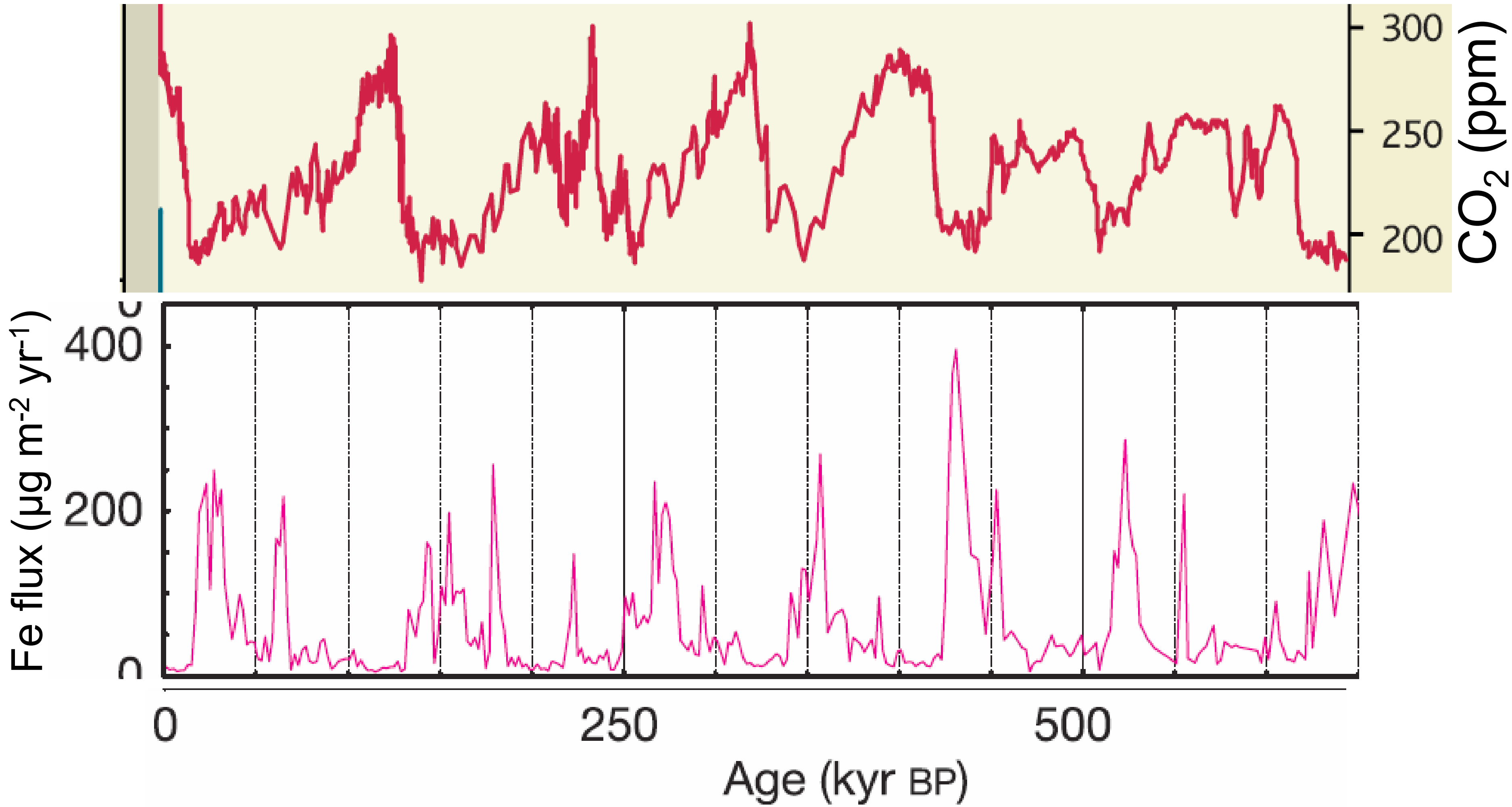
Martin's "Iron Hypothesis"

Dust is inversely correlated with CO_2 in Antarctic ice core records -- is there a causal relationship?



Martin (1990) reasoned that increased dust fluxes relaxed Fe limitation in the glacial Southern Ocean, allowing increased efficiency of the biological pump to draw down atmospheric CO_2

Antarctic Ice Core
Dust (Fe) - CO_2 (anti)correlation



Fe flux from Wolff et al., Nature 2006; CO_2 from Brook, Science 2005

Questions to ask of the paleo record:

1) **Did dust affect Productivity in HNLC regions?**

2) **Did other sources of Fe have a significant impact on productivity?**

3) **What caused glacial CO_2 to be 80-100 ppm lower?**

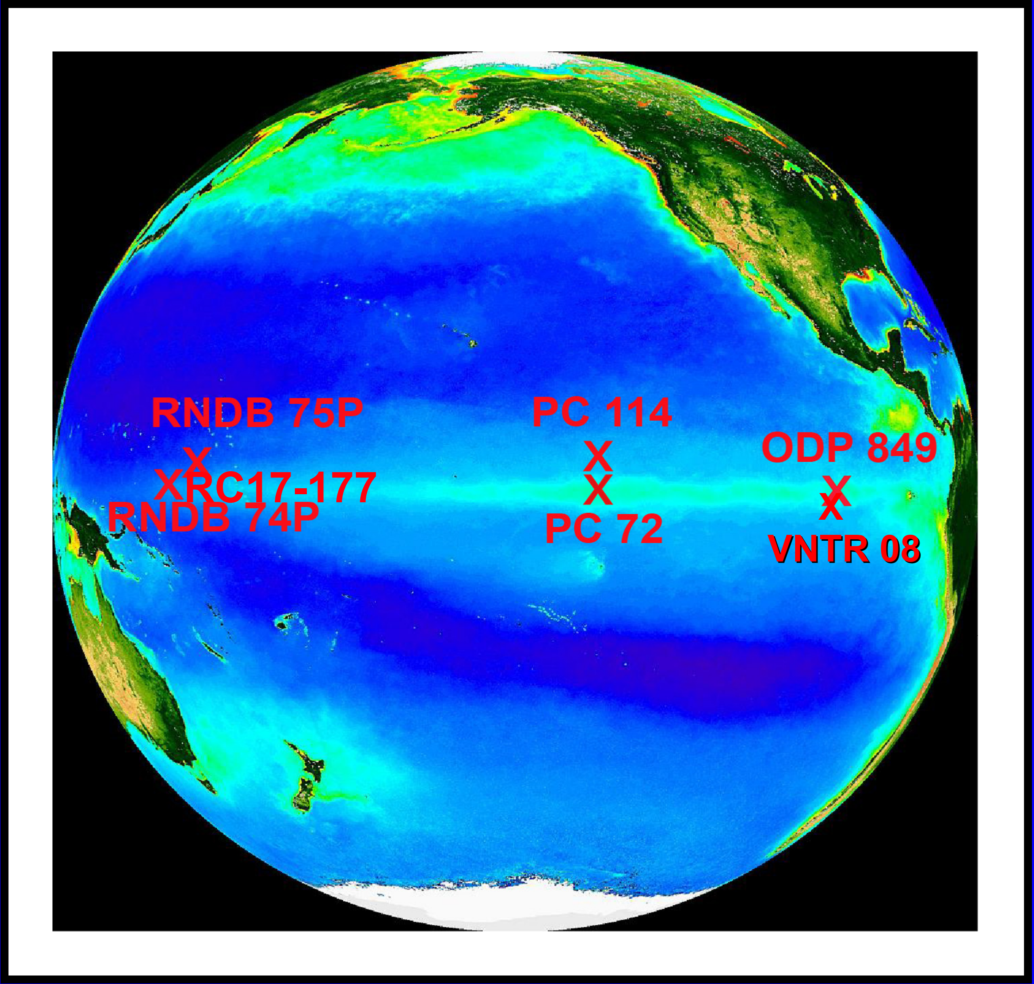
Questions to ask of the paleo record:

1) **Did dust affect Productivity in HNLC regions? (No)**

2) **Did other sources of Fe have a significant impact on productivity? (I think so)**

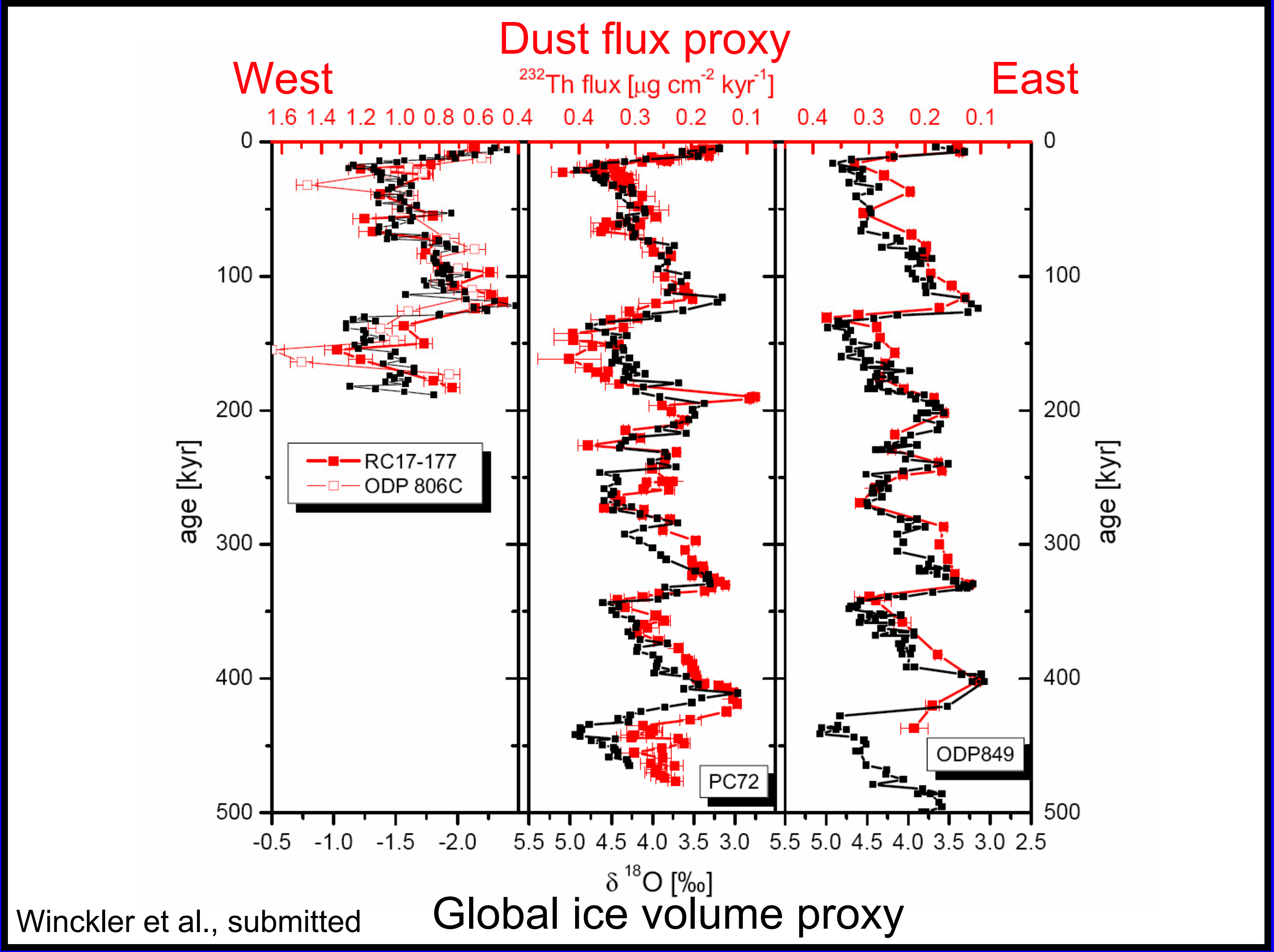
3) **What caused glacial CO_2 to be 80-100 ppm lower? (**

Equatorial Pacific



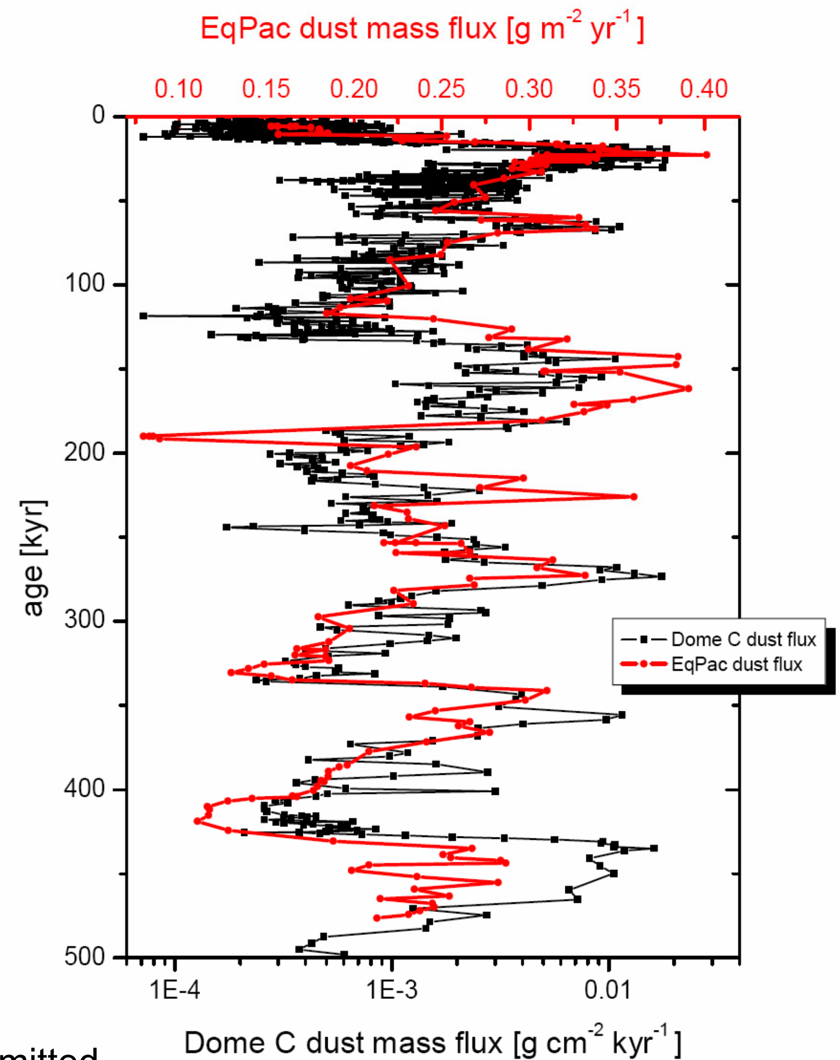
Search for evidence of dust influence in regions with paired records of dust flux and paleoproductivity.

Equatorial Pacific Dust-Climate Correlation



- Dust flux proxy is tightly correlated with climate
- Glacial-interglacial amplitude ~2.5X at all sites

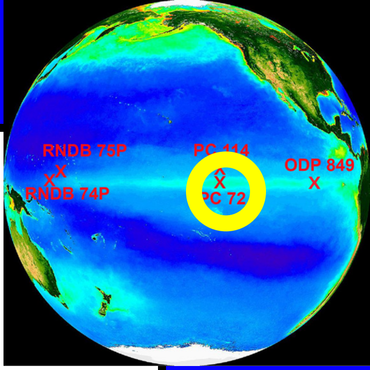
Equatorial Pacific - Antarctica Correlation

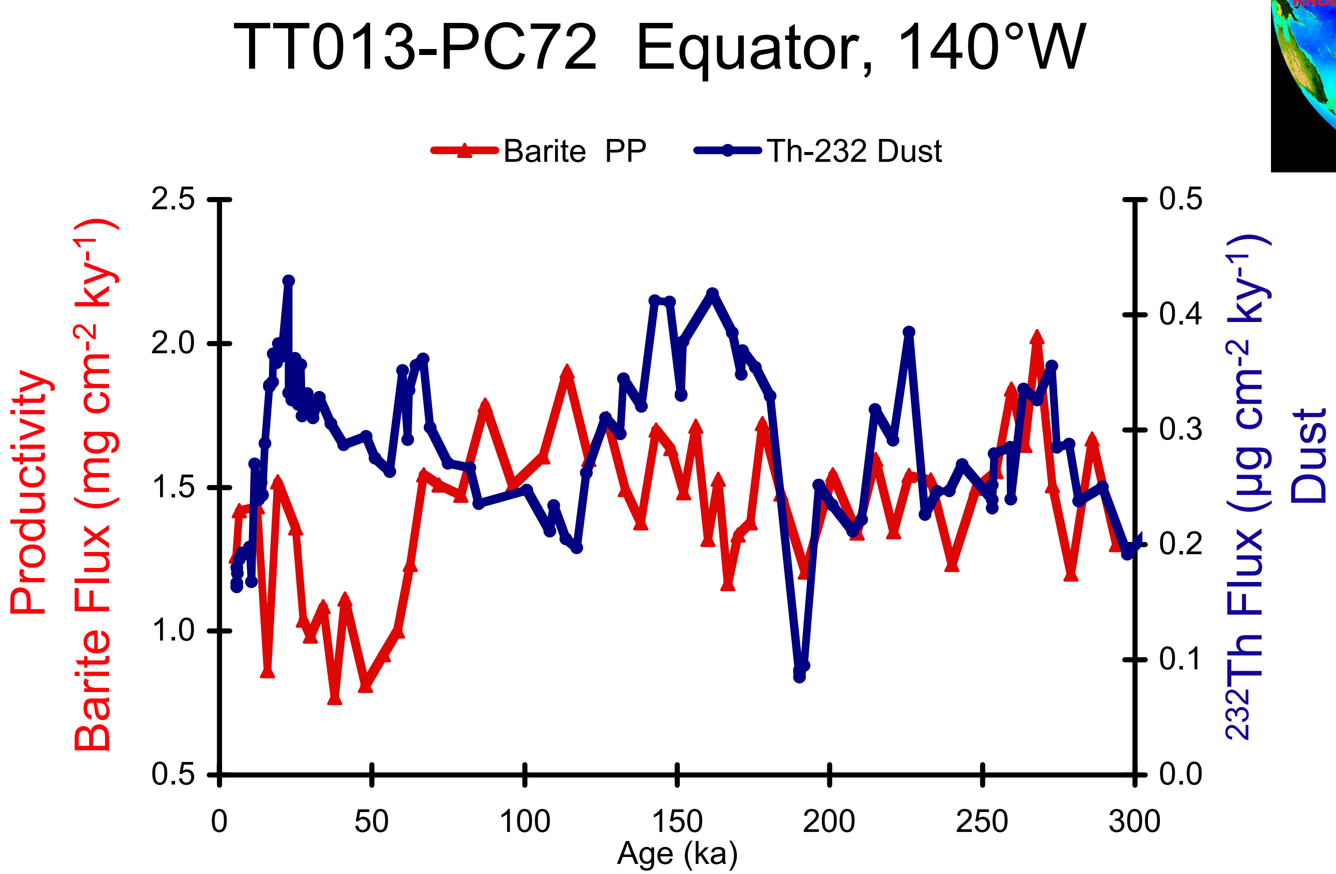


Winckler et al., submitted

Internally-consistent change in dust flux from at least 3 sources suggests control by global hydrological cycle

CEP - No Productivity Response

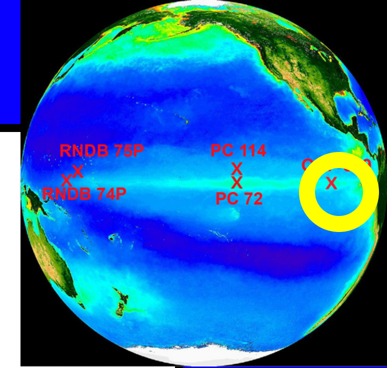




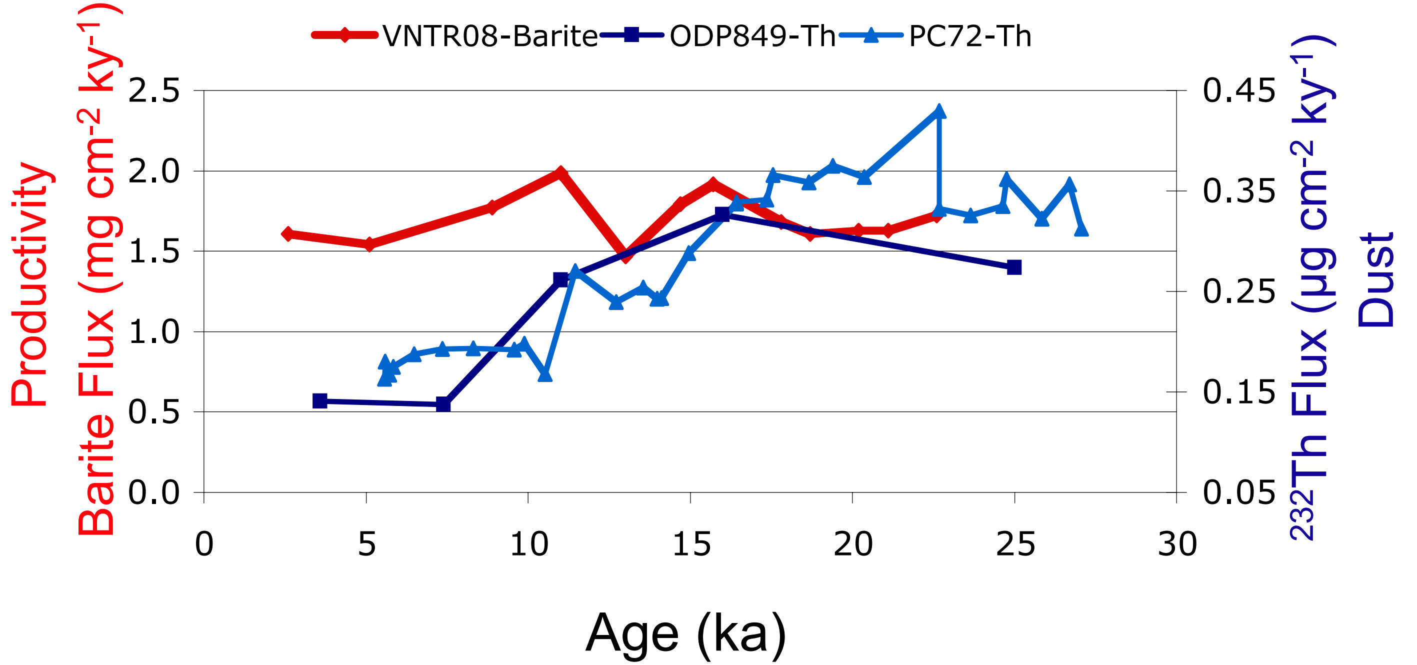
^{232}Th flux (Dust proxy) - Winckler et al., submitted
Barite concentration - Paytan, 1995
Barite flux (PP proxy) - Anderson et al., in press

Proxy records for paleoproductivity and dust flux are uncorrelated over the last 3 glacial cycles

EEP - No Productivity Response



TT013-PC72 Equator, 140°W
VNTR08 & ODP 849, Eq., 110°W



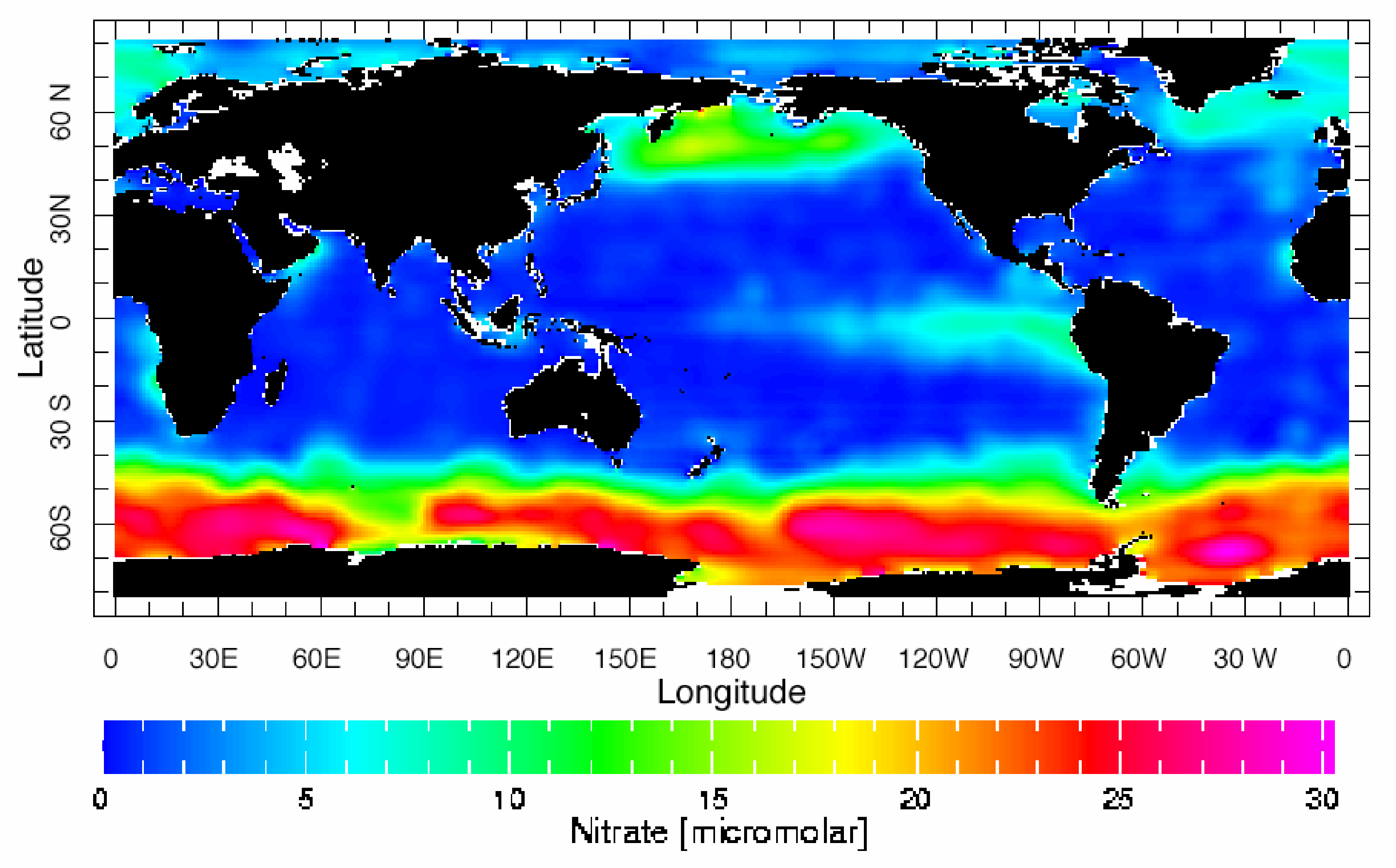
^{232}Th flux (Dust proxy) - PC72, Anderson et al., 2006; ODP849, Winckler et al., sub.
VNTR08 Barite Flux (PP proxy) - Barite conc. Paytan, 1995
Sediment flux - Pichat et al., 2004

Productivity shows no response to a 2-fold drop in dust flux over the last deglaciation

Equatorial Pacific:

Increased glacial dust fluxes had no detectable effect on export production.

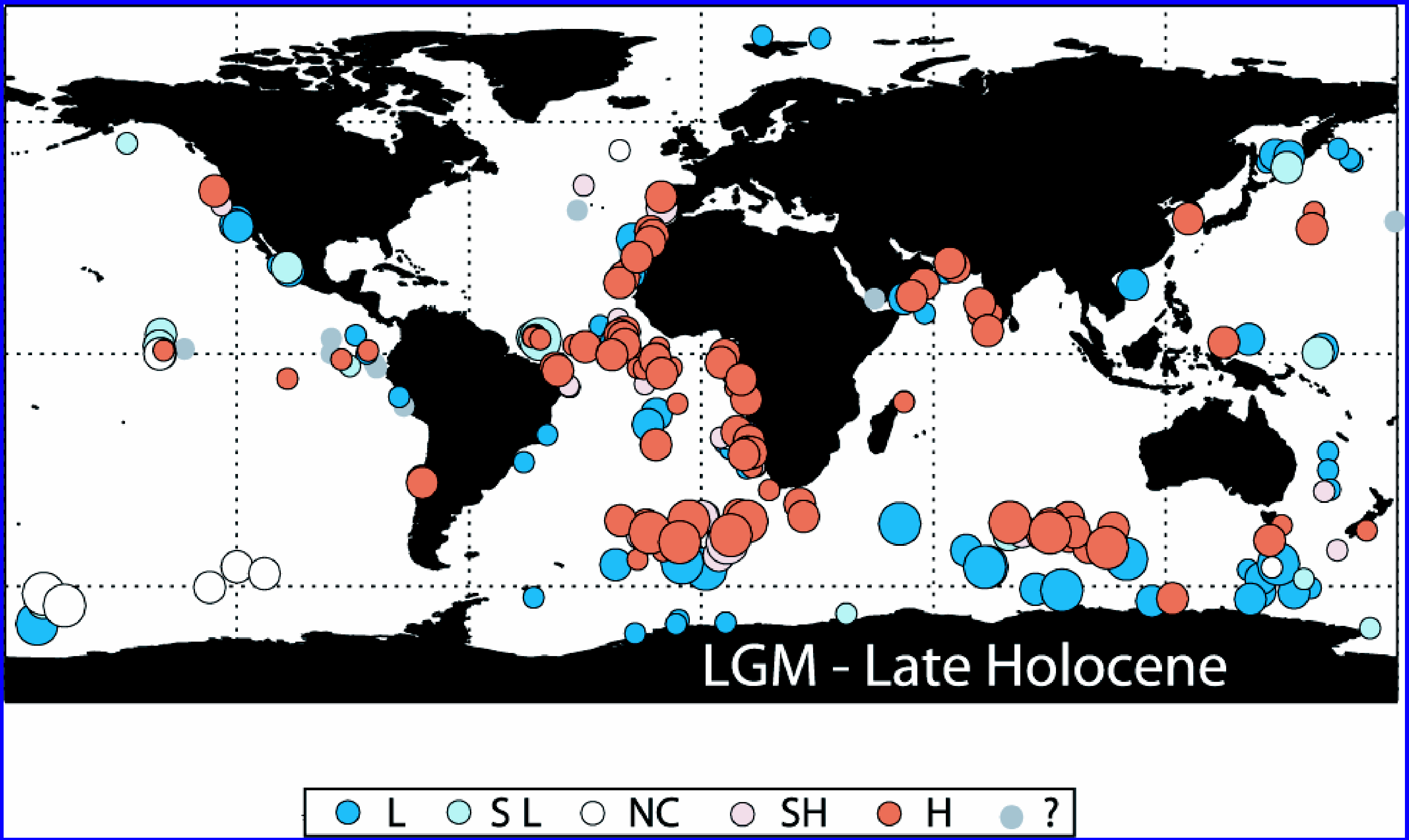
What about the Southern Ocean?



Here, increased nutrient utilization south of the Antarctic Polar Front has the greatest potential to affect atmospheric CO_2.

From: iridl.ldeo.columbia.edu/SOURCES/.LEVITUS94

LGM minus Modern Export Production (synthesis of published data; all proxies)

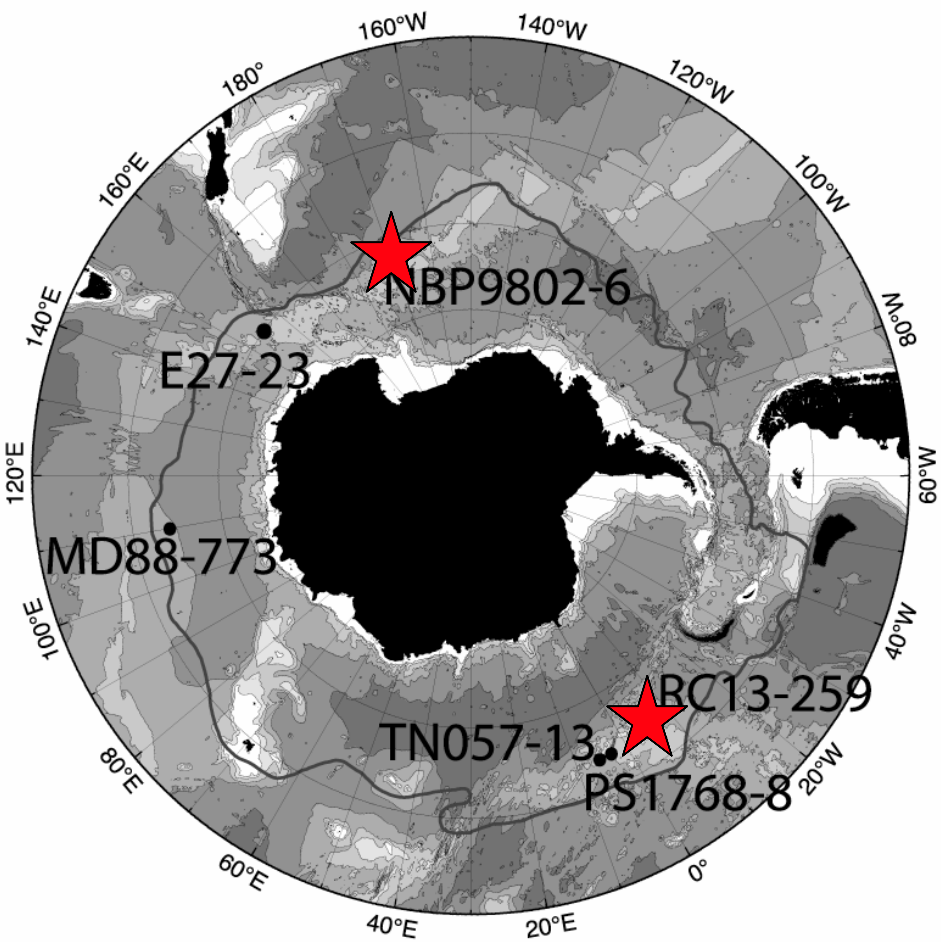


High glacial productivity is restricted to the Subantarctic zone

<u>Iron fertilization was not pervasive throughout the Southern Ocean</u>

Kohfeld, LeQuéré, Harrison and Anderson, Science, 2005

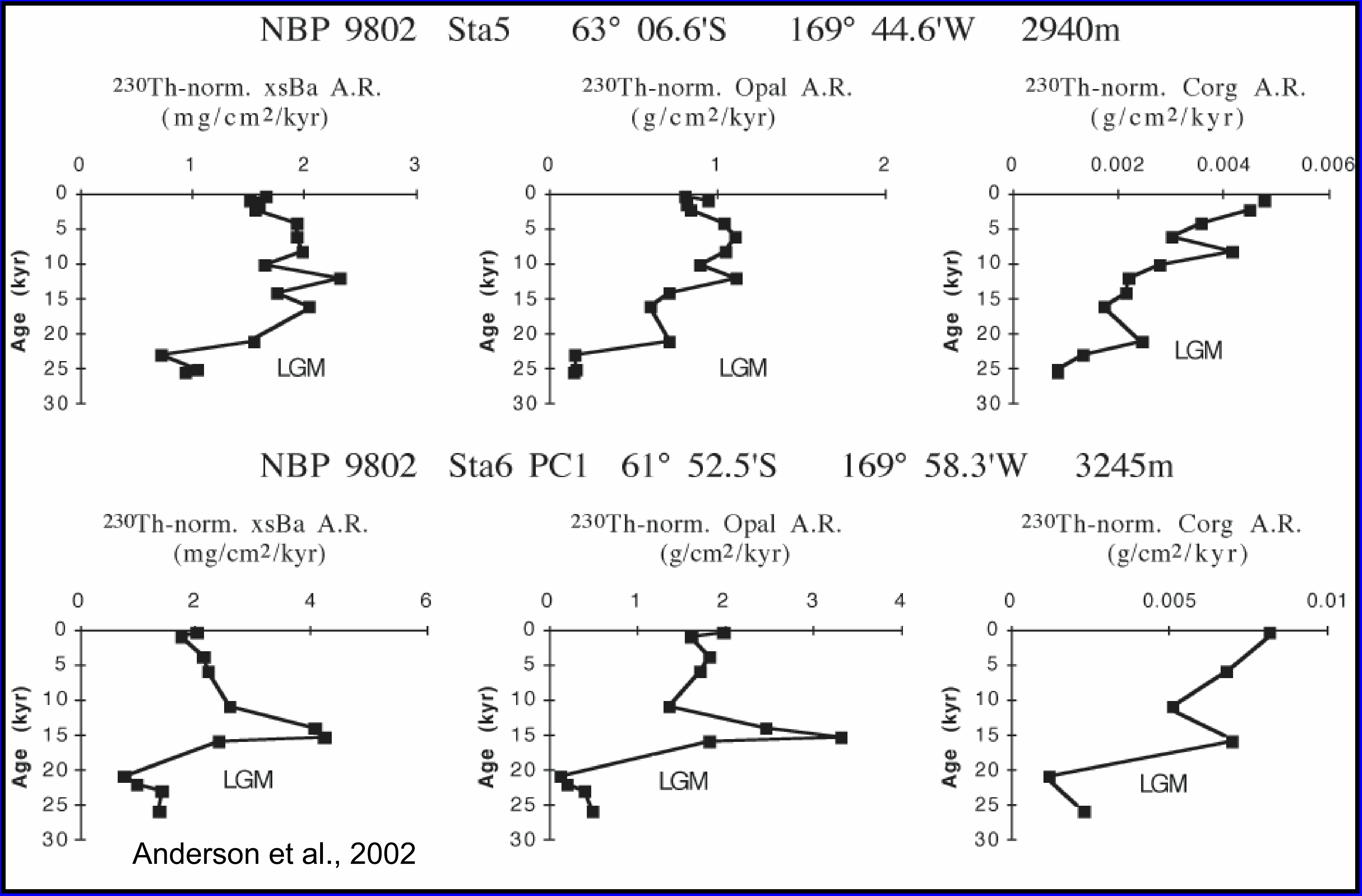
Sites around the Southern Ocean with detailed records showing glacial productivity < interglacial



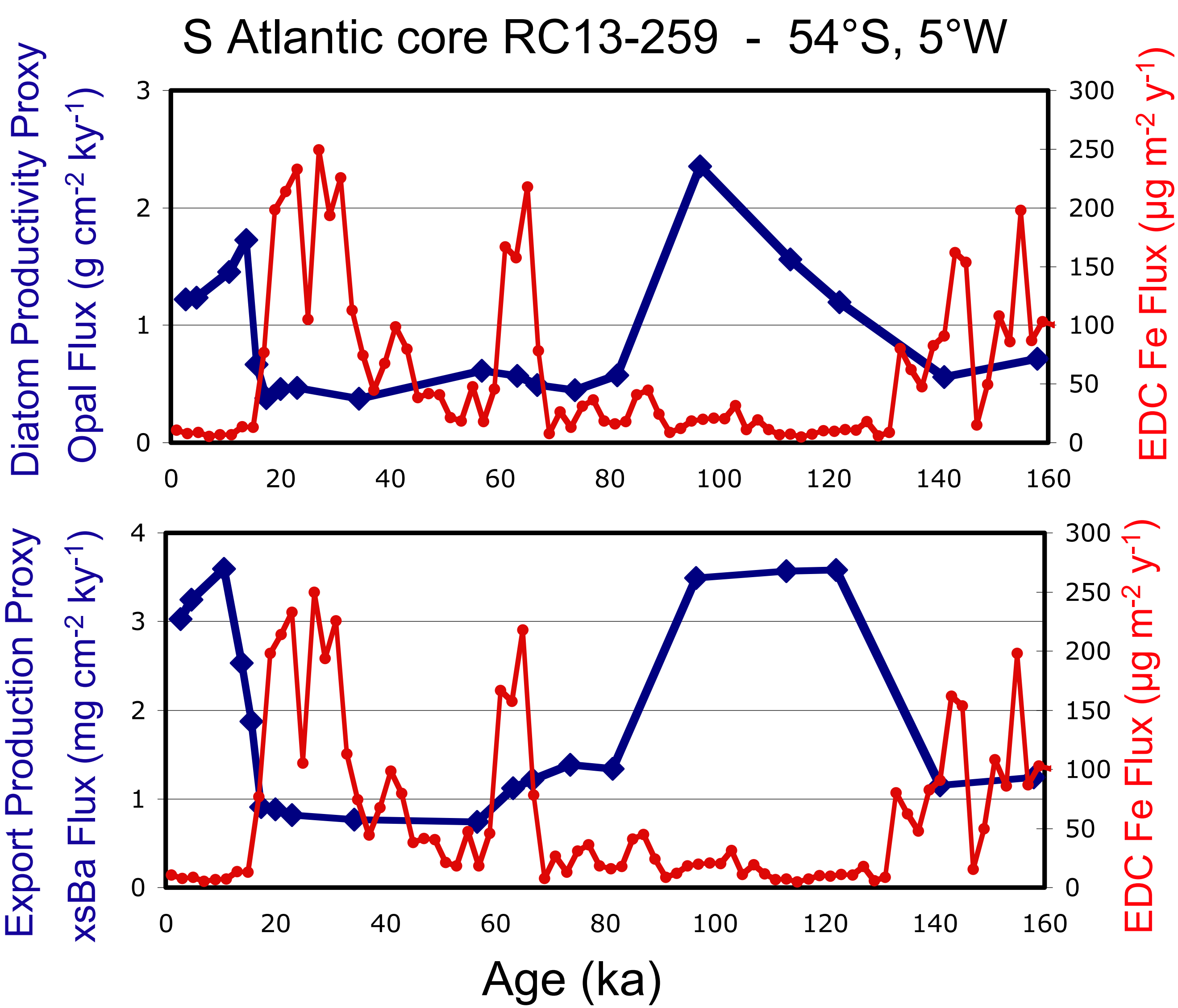
Nutrient utilization south of the APF has the greatest potential to impact global inventory of preformed nutrients.

Marinov et al., (2006)

SW Pacific - Two Cores & Three Proxies Consistently show glacial productivity < Holocene

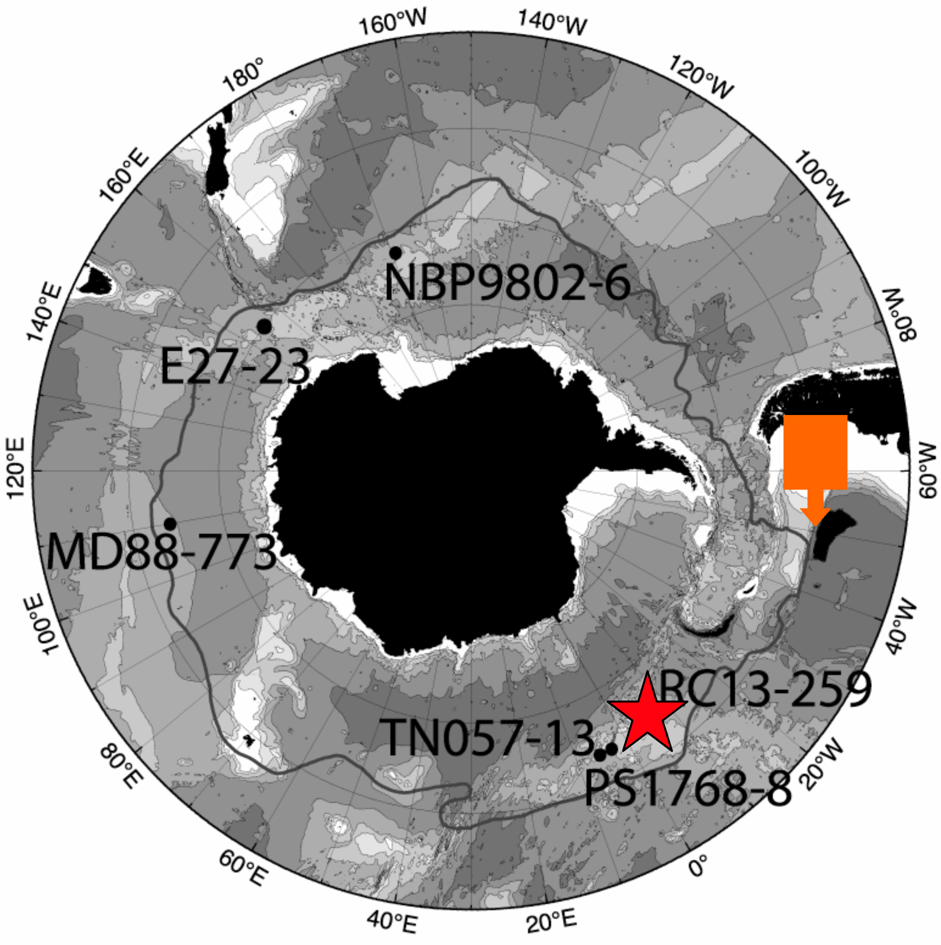


S Atlantic Productivity anti-correlated with dust



Opal & Ba fluxes: Anderson et al., 2002 - EPICA Dome C Fe flux: Wolff et al., 2006

Site is downwind of the Patagonian dust source



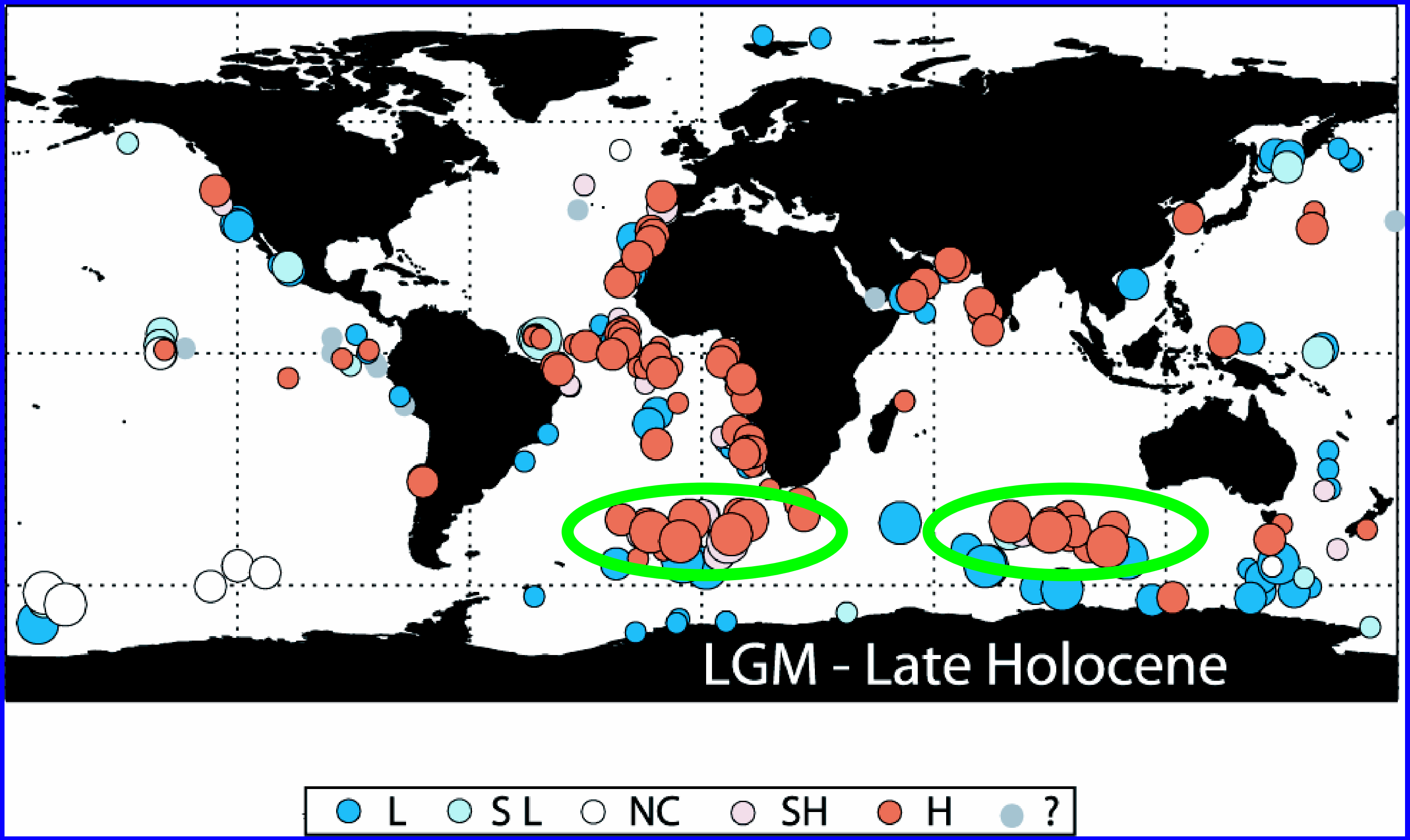
If dust-borne Fe stimulated nutrient utilization in the glacial Southern Ocean, then it should have been evident here.

Southern Ocean (South of APF):

Any iron fertilization by increased glacial dust fluxes was more than offset by other factors that reduced export production.

Did Fe have any impact on glacial productivity in the Southern Ocean?

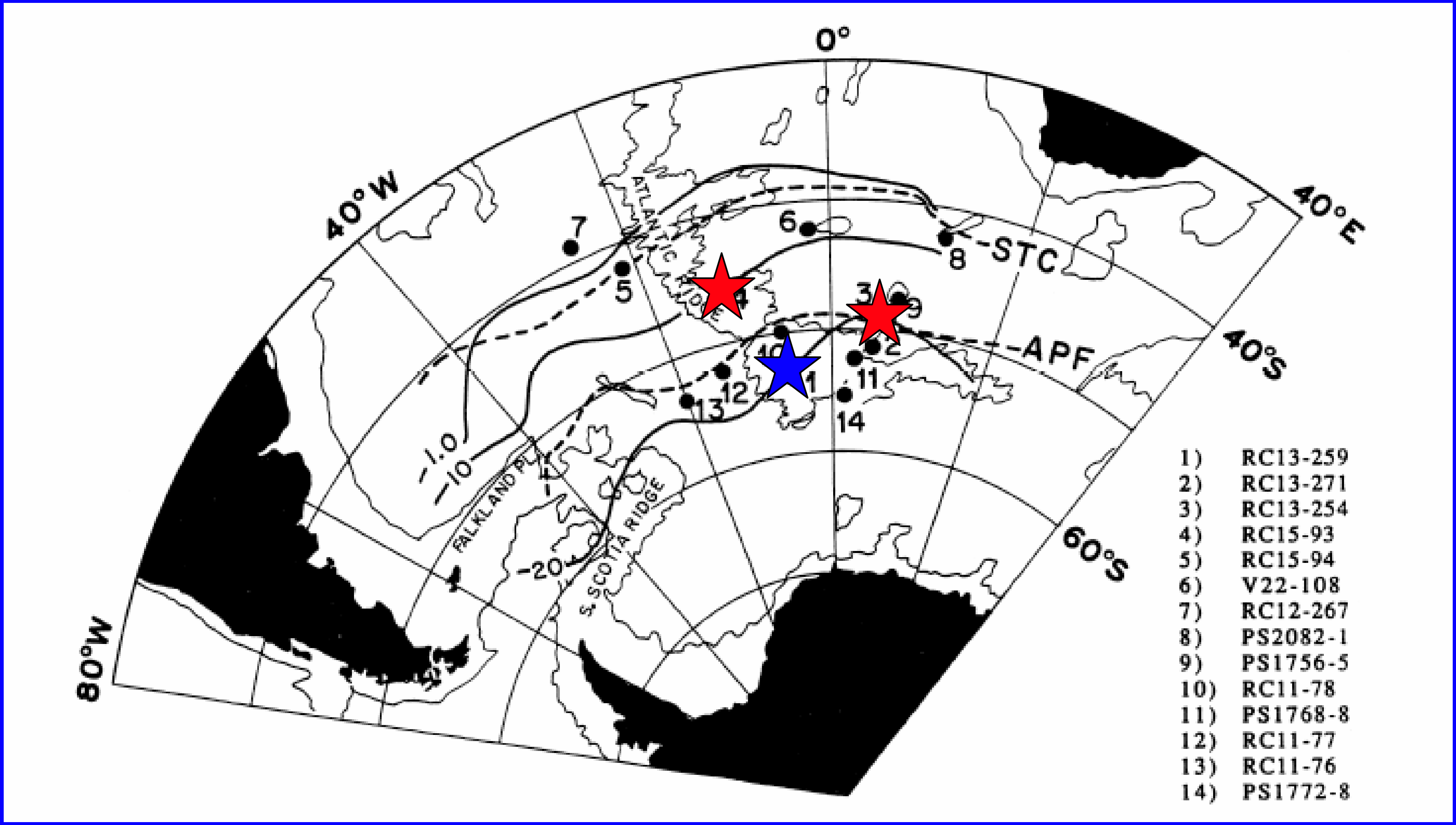
LGM minus Modern Export Production (synthesis of published data; all proxies)



"Hot Spots" - Subantarctic Sites Experienced High Productivity

Kohfeld, LeQuéré, Harrison and Anderson, Science, 2005

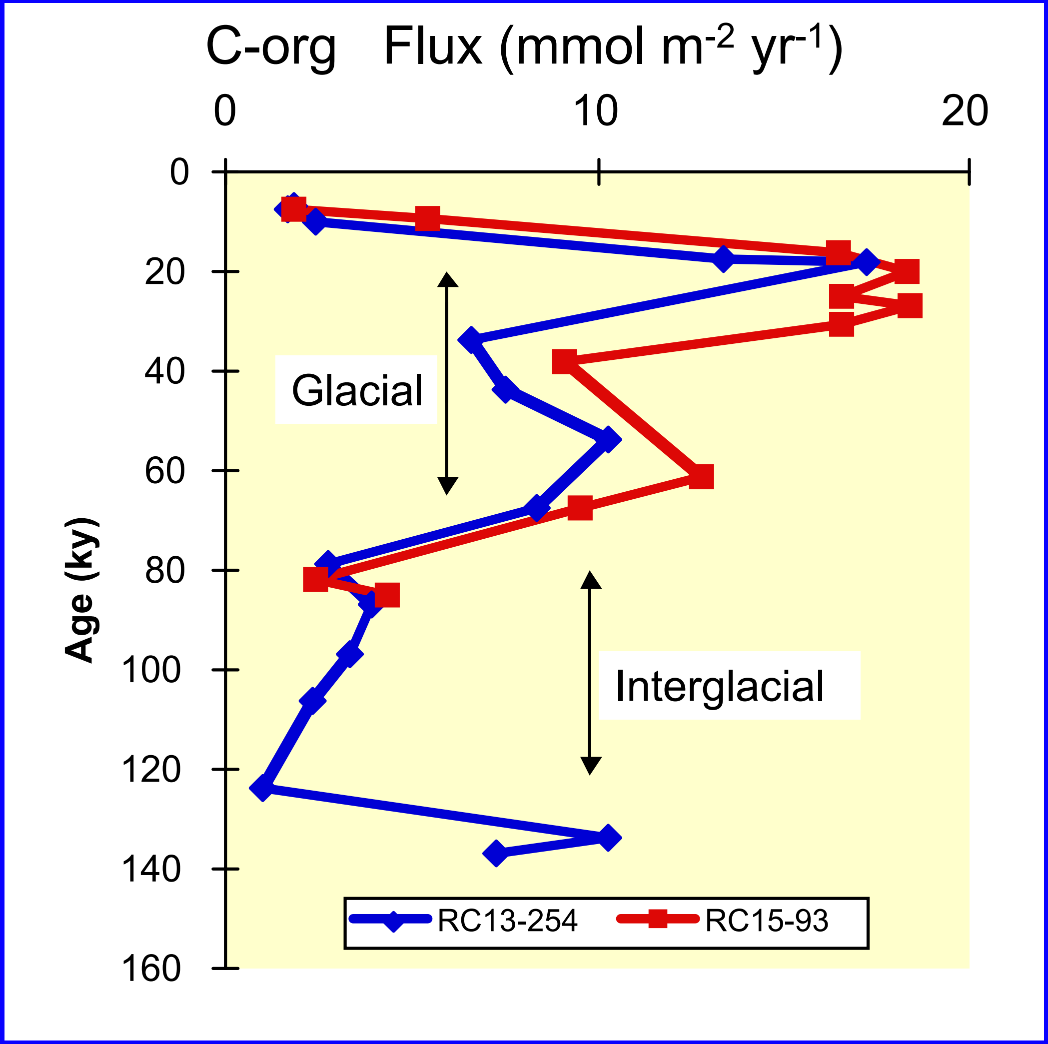
Examples from Subantarctic “Hot Spot”



Higher Subantarctic Productivity in LGM supported by order of magnitude greater C-org burial

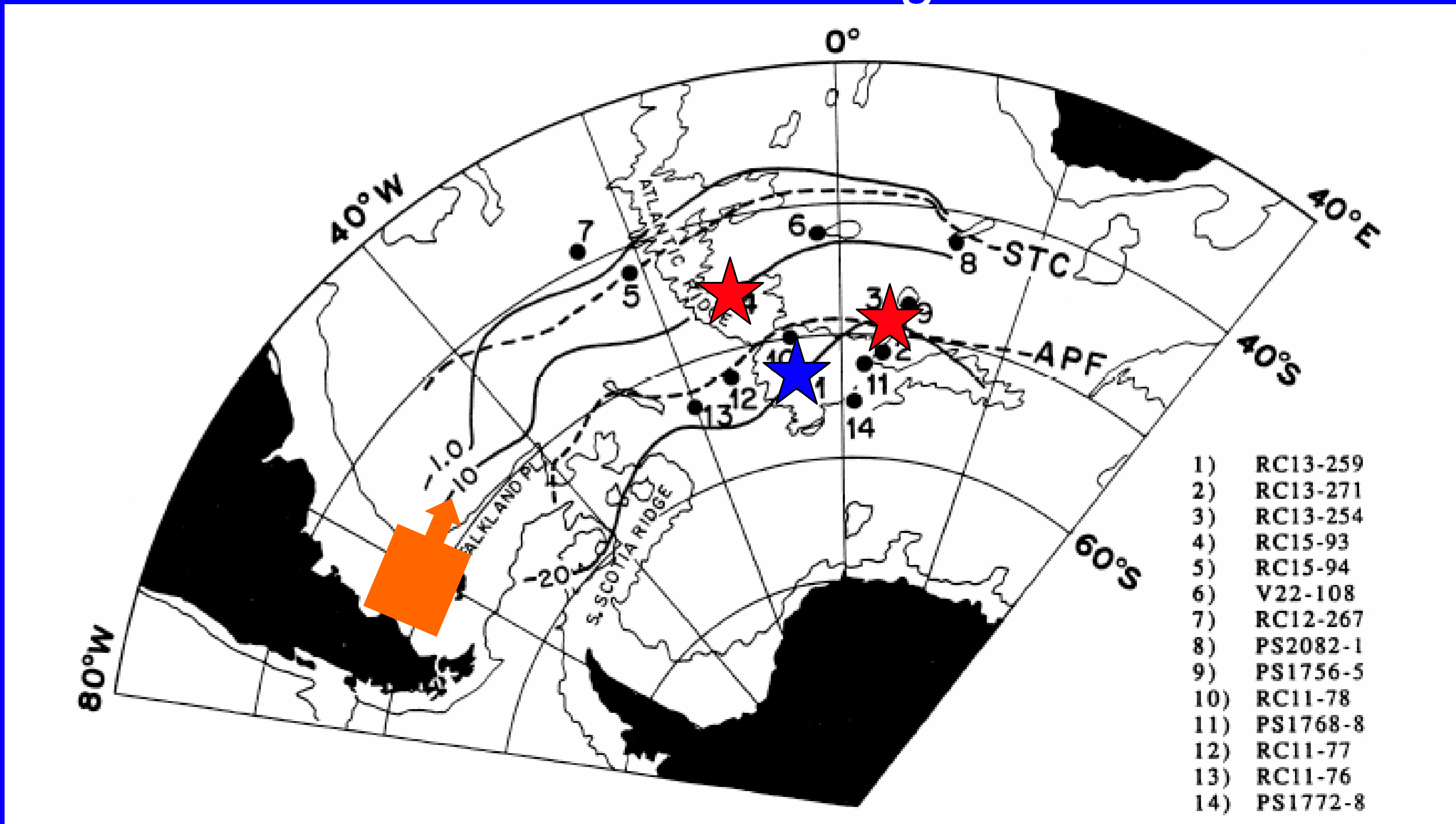
Patterns reproduced in two cores

Changes were BIG!



Anderson et al., 1998, 2002

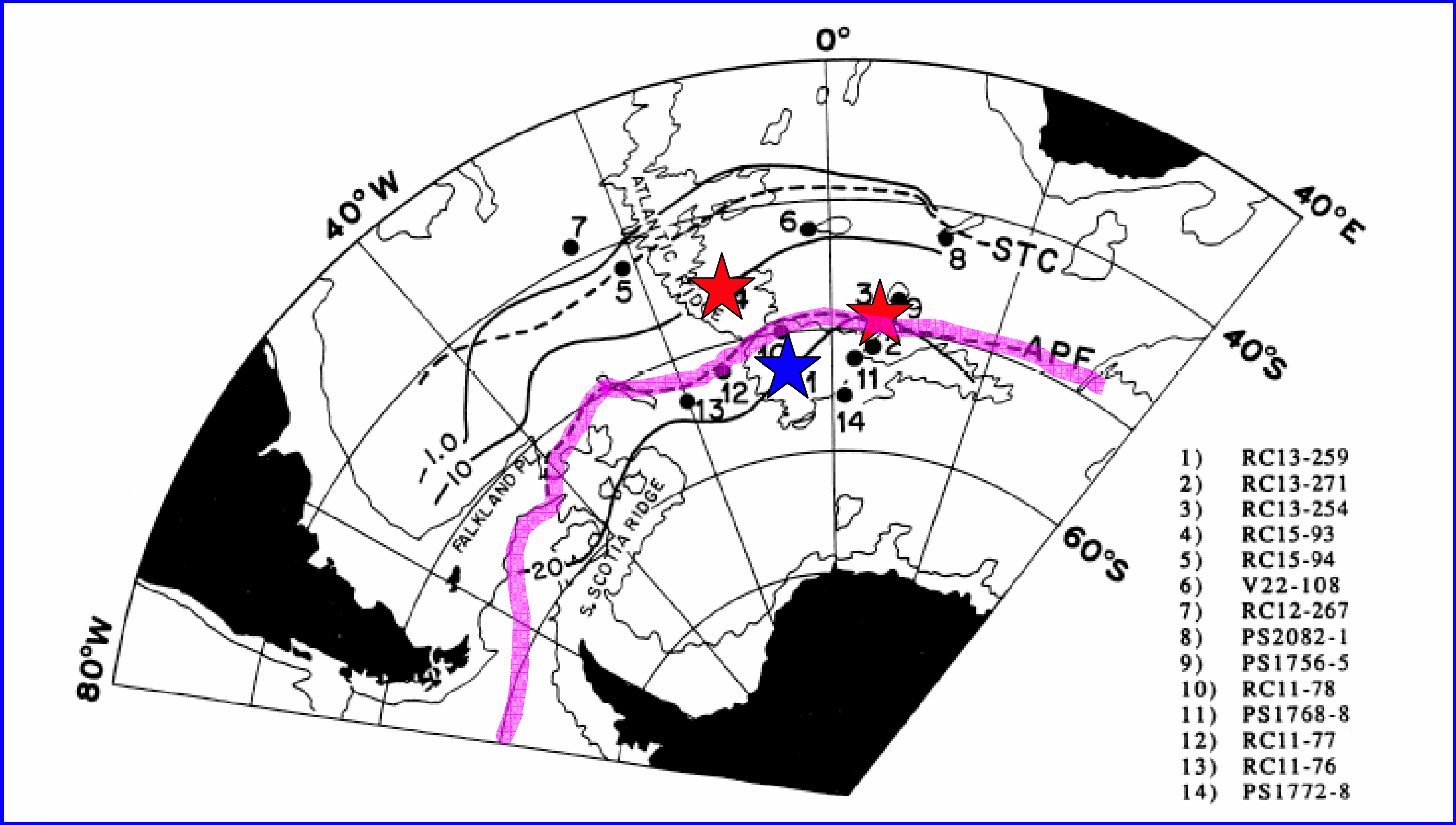
Why such different behavior among cores downwind of Patagonia?



Blue = Lower glacial productivity; Red = Higher glacial productivity

Contours = Summer Nitrate μM; ample nutrients N of APF

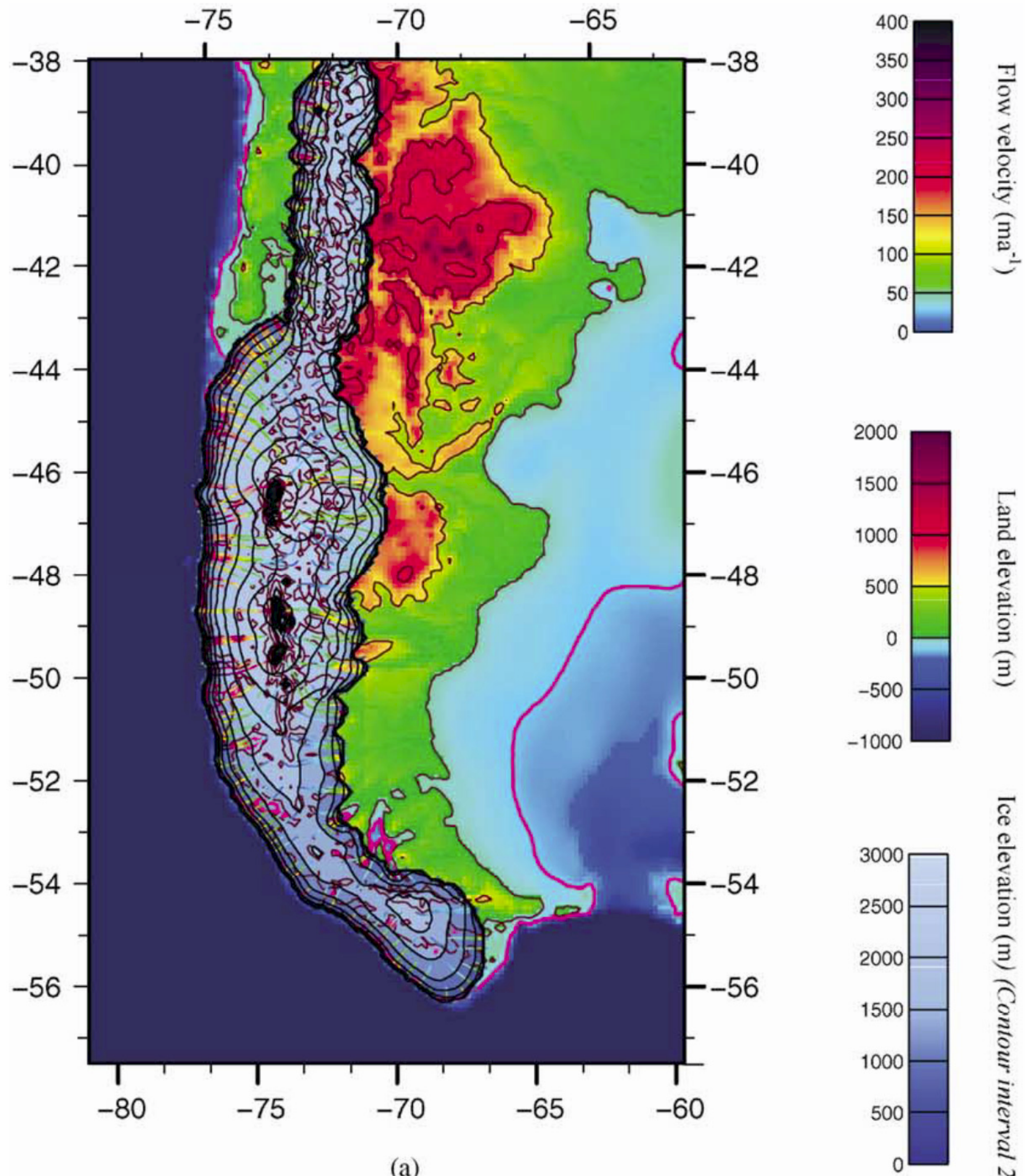
Why such different behavior among cores?



Is the APF (convergence) a barrier to supply of essential factor?

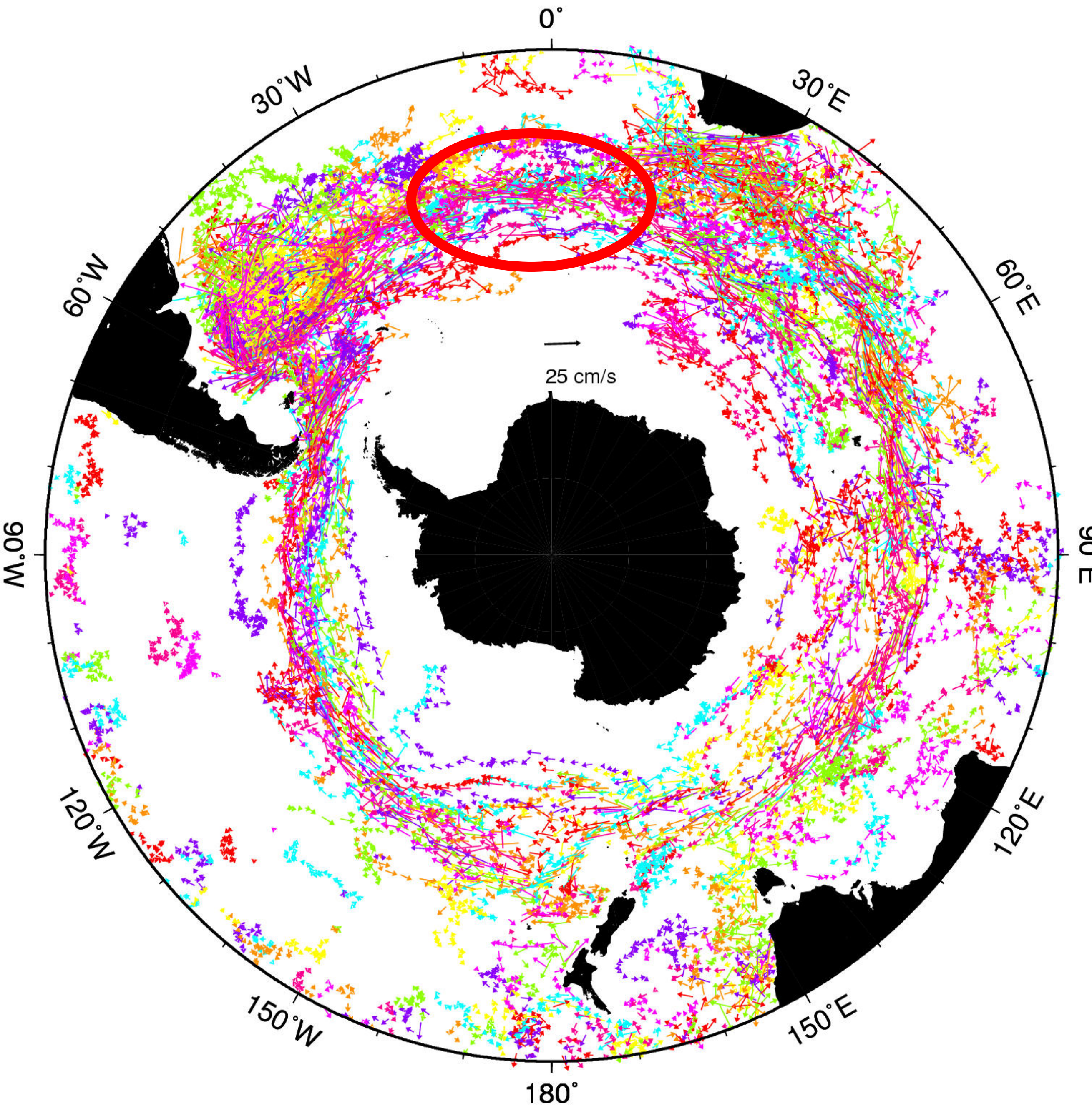
Patagonian ice sheet during glacial times delivered Ice-Rafted Debris (IRD) to the Southern Ocean

N.R.J. Hulton et al. / Quaternary Science Reviews 21 (2002) 233–241



(a)

Modern ALACE float tracks show that currents would have carried Patagonian IRD into the S Atlantic



Courtesy of
S. Gille, SIO

Icebergs as a source of Fe - location matters!

Subpolar

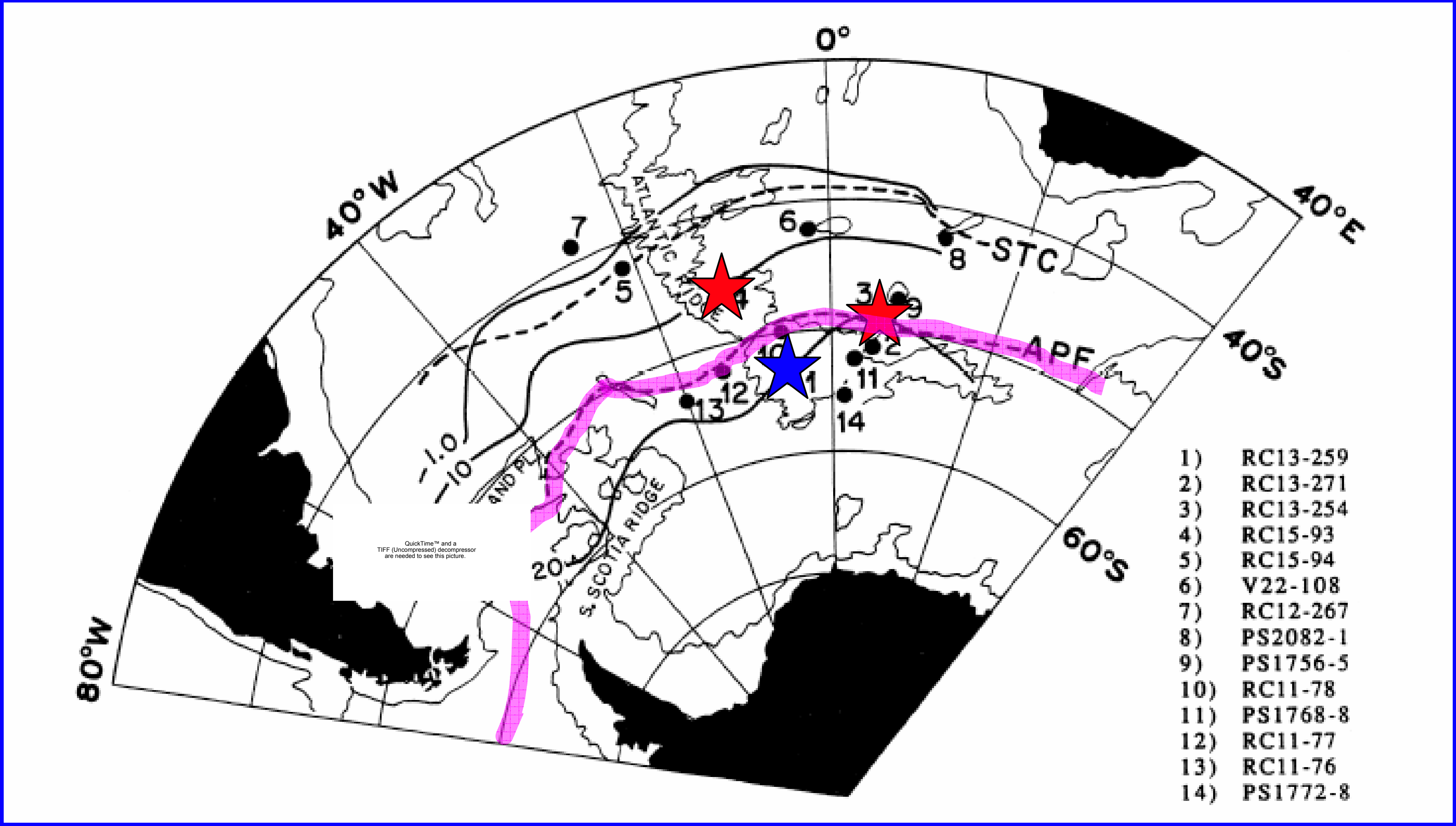
Antarctic

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

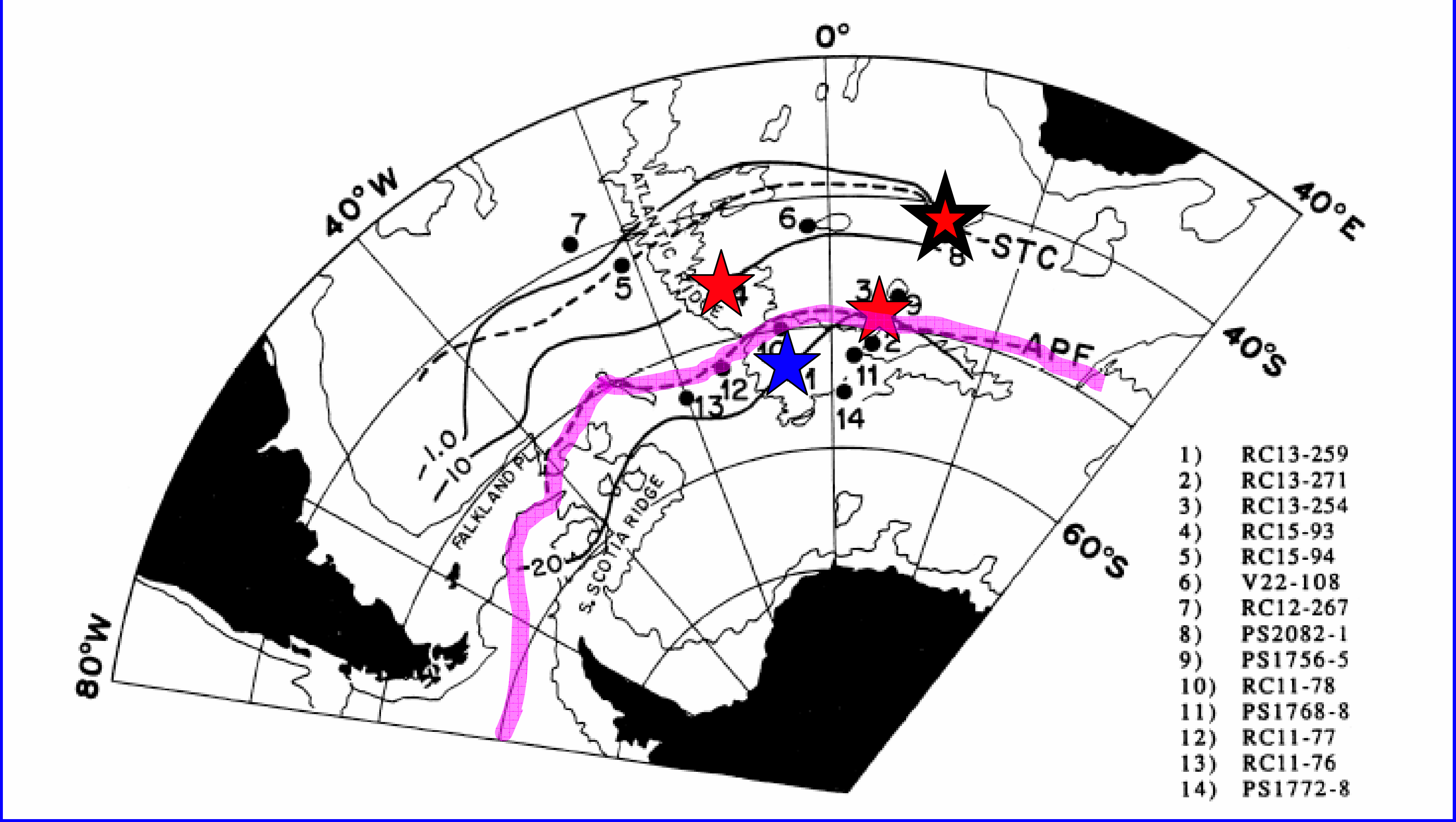
Alaskan photos from John Crusius

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

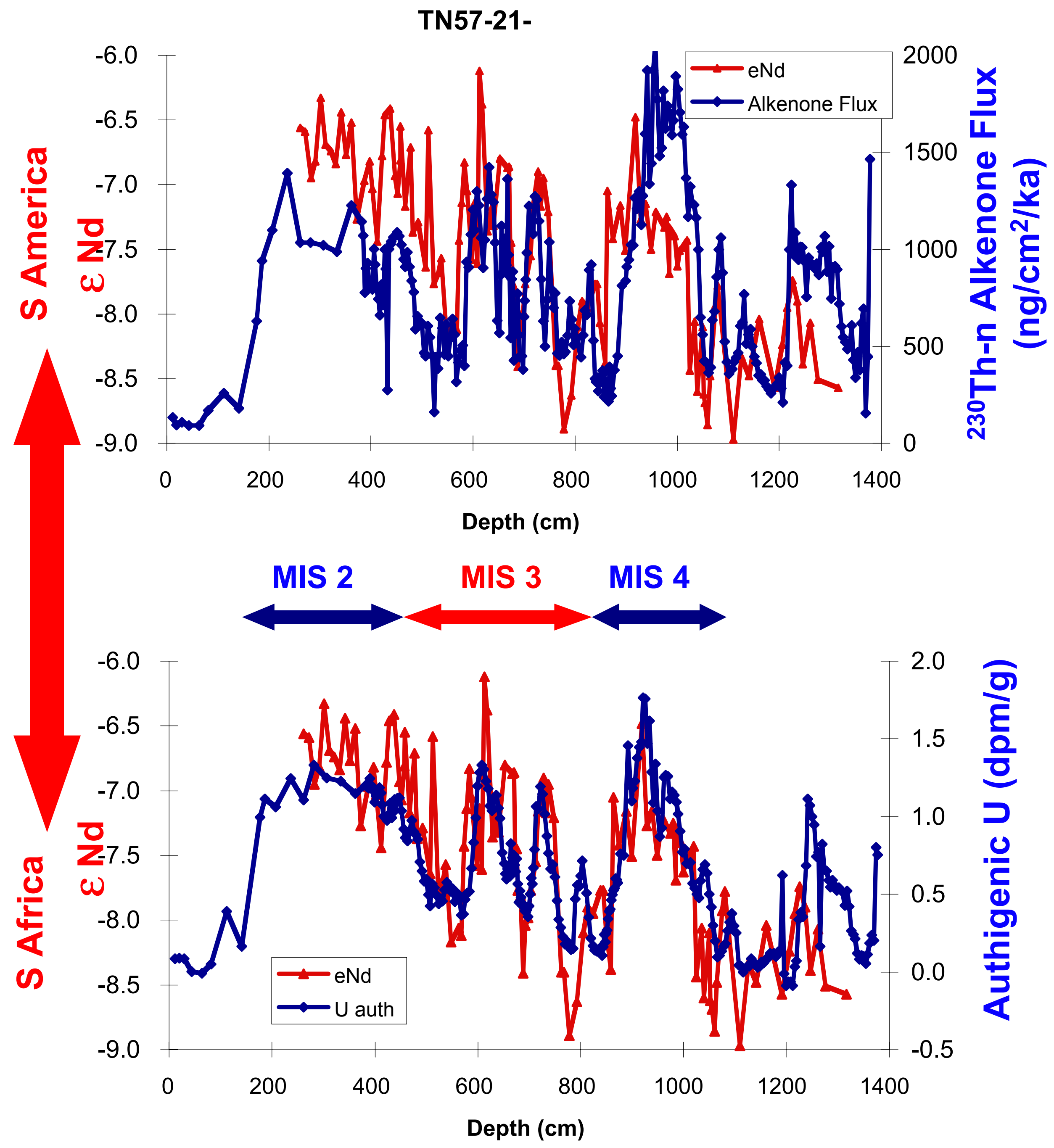
APF would have been a barrier to icebergs, IRD, and any Fe released from IRD



Evidence for Patagonian Fe fertilization?



1) YES - Isotopic and mineralogical data; Diekmann, Walter, Kuhn, & others at AWI;
2) Nd isotopes in Cape Basin (highlighted star)



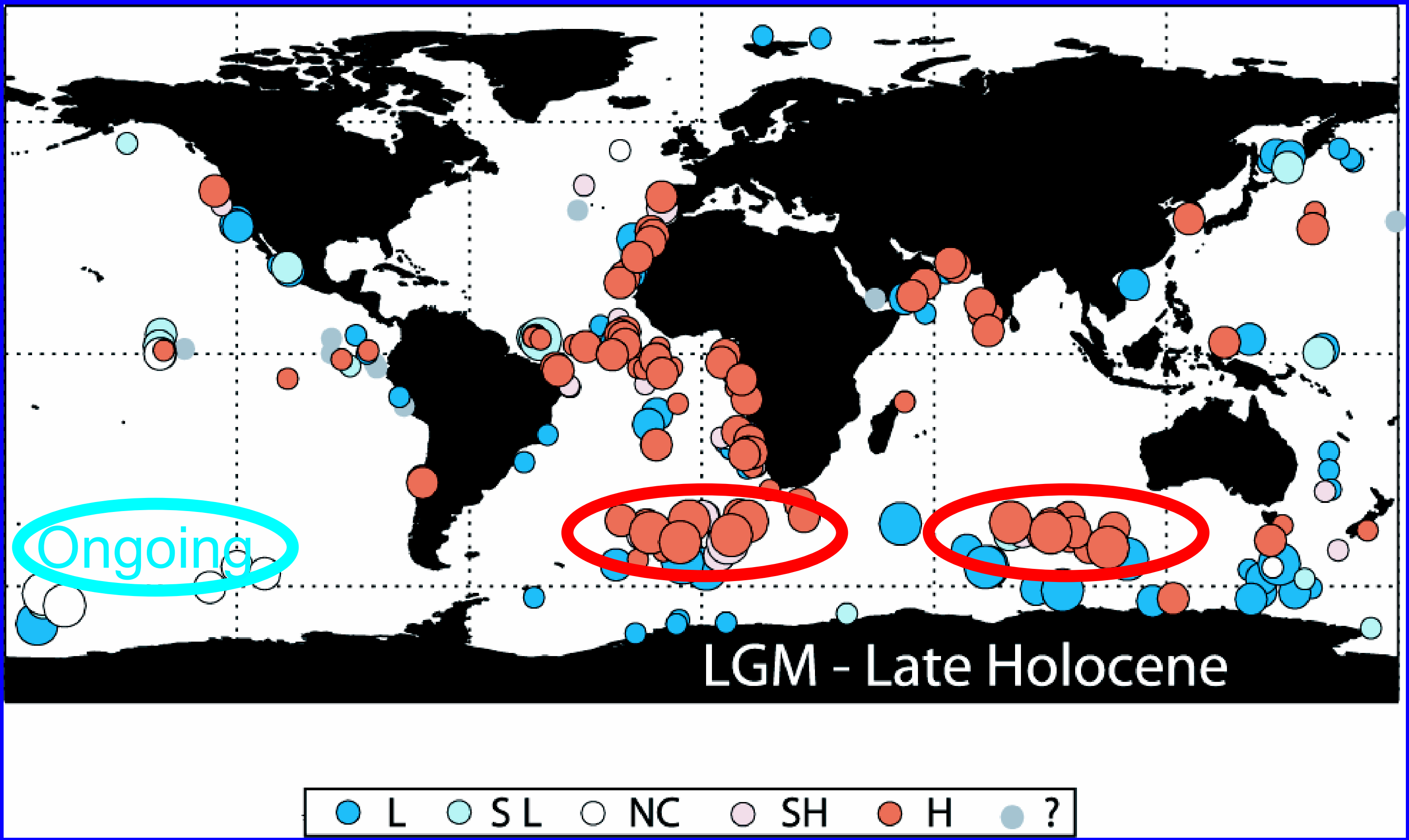
Cape Basin: Nd isotopes correlate with productivity proxies… May reflect Fe supply.

Alkenone Flux
Sachs & Anderson, 2003

Uranium
Sachs & Anderson, 2005

εNd
Piotrowski et al., 2005

LGM minus Modern Export Production (synthesis of published data; all proxies)



Hypothesis- “Hot Spots” reflect Fe from Patagonia & Kerguelan

Current work on S Pacific shows no hot spots; supports local Fe fertilization

Kohfeld, LeQuéré, Harrison and Anderson, Science, 2005

Summary:

No evidence for Fe fertilization of HNLC regions (EqPac & So. Ocean) by increased glacial dust fluxes.

Subantarctic: Hot spots of high productivity may have been fertilized by local sources of Fe; not dust, maybe icebergs.

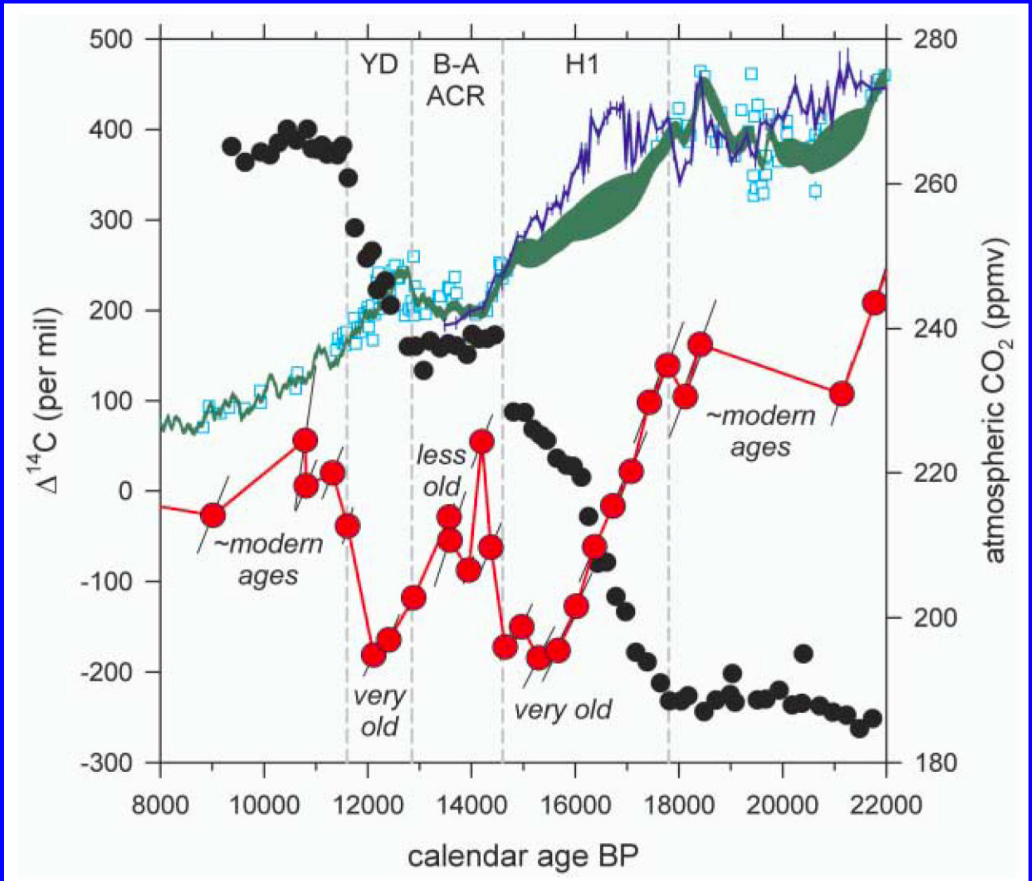
Impact of Subantarctic on CO_2 minor because disconnected from main inventory of preformed nutrients.

Increased ocean stratification, with feedbacks from $CaCO_3$ compensation, lowered glacial atm. CO_2

(Marchitto et al., Science, 2007)

What caused lower glacial CO_2?

Increased ocean stratification was a primary factor.



Marchitto et al, Science, 2007

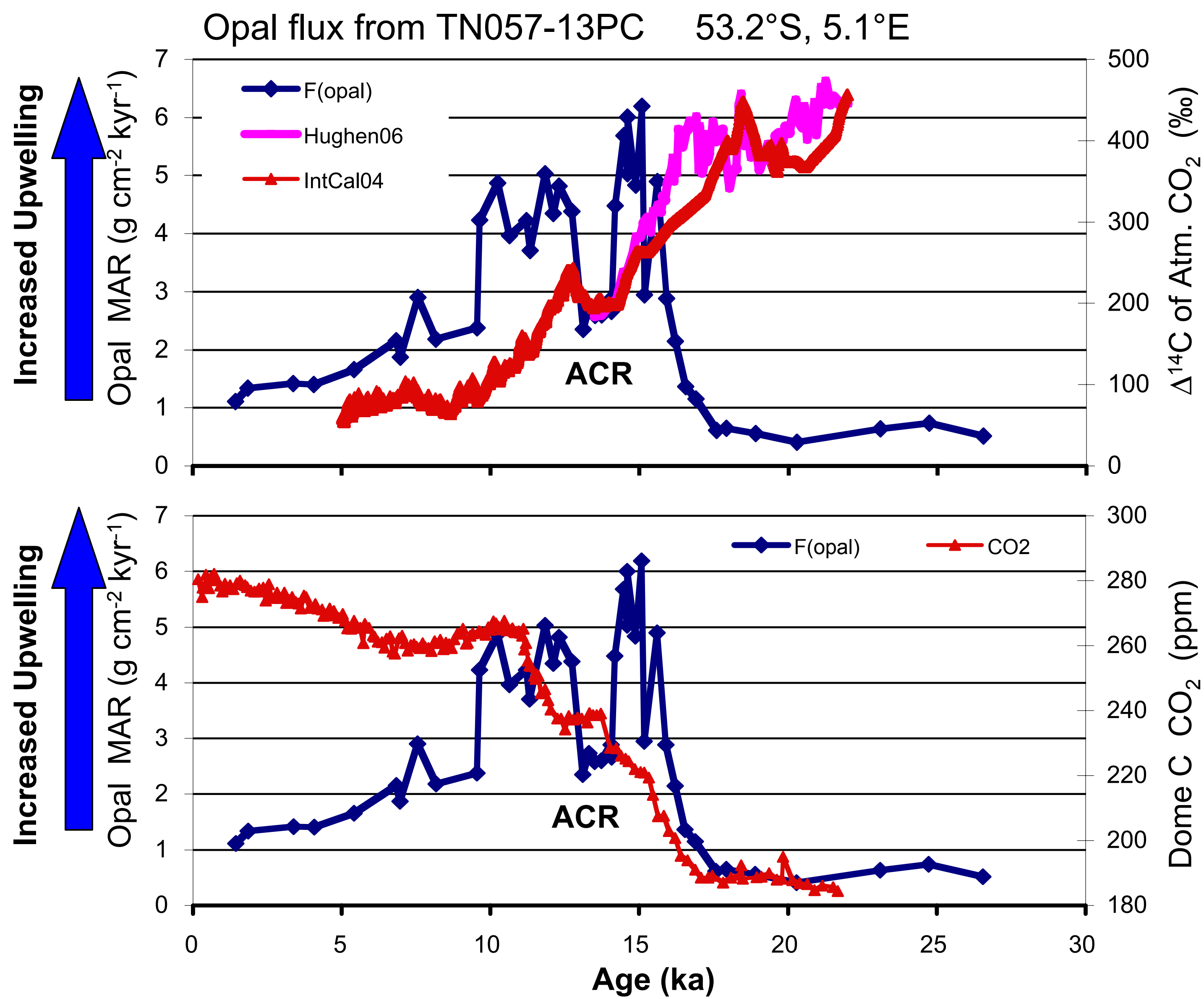
Indirect evidence from ^{14}C of benthic forams at 700m in N Pacific. Accelerated overturning of deep waters brought CO_2 to the atm., and ^{14}C-depleted DIC, both to intermediate depths and to the atm.

More direct evidence: Deglacial increase in So Ocean upwelling coincided with rise in CO_2 and drop in $\Delta^{14}C$ of Atm. CO_2

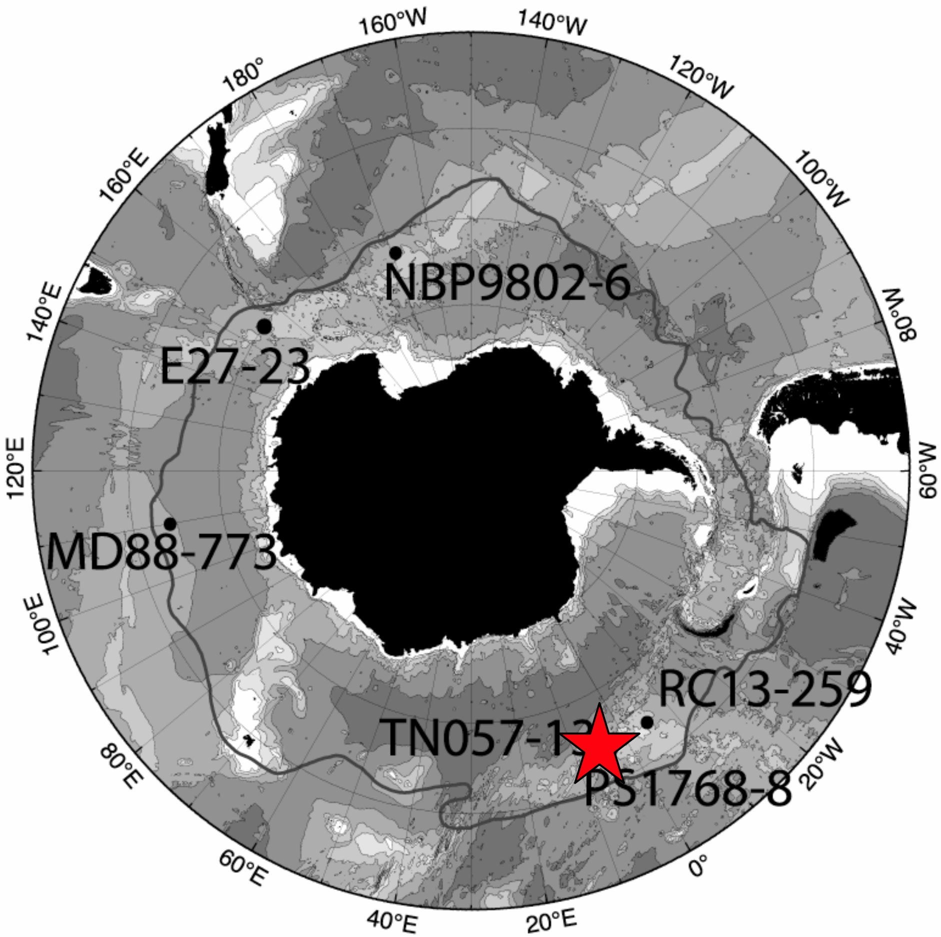
IntCal Atm. ^{14}C from Reimer et al., 2004

Hughen Atm. ^{14}C from Cariaco Basin. Hughen et al., 2006

CO_2 from Monnin et al., EPSL, 2004



Deglacial increase in upwelling is evident at sites all around the Southern Ocean



Red star = TN057-13