The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

SMR/1884-7

Conference on Milankovitch cycles over the past 5 million years

22 - 24 March 2007

The Californian Coast

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Ocean Sciences Department
1156 High Street

California and Other Coastal Upwelling Regions: Trends and Cycles of the last 5 myrs

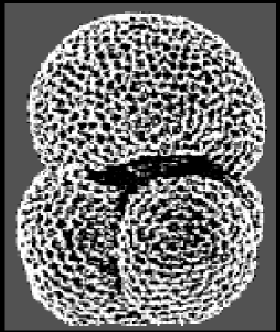
Christina Ravelo
Petra Dekens
Michael Wara
Dyke Andreasen
Andy Rothwell
University of California, Santa Cruz

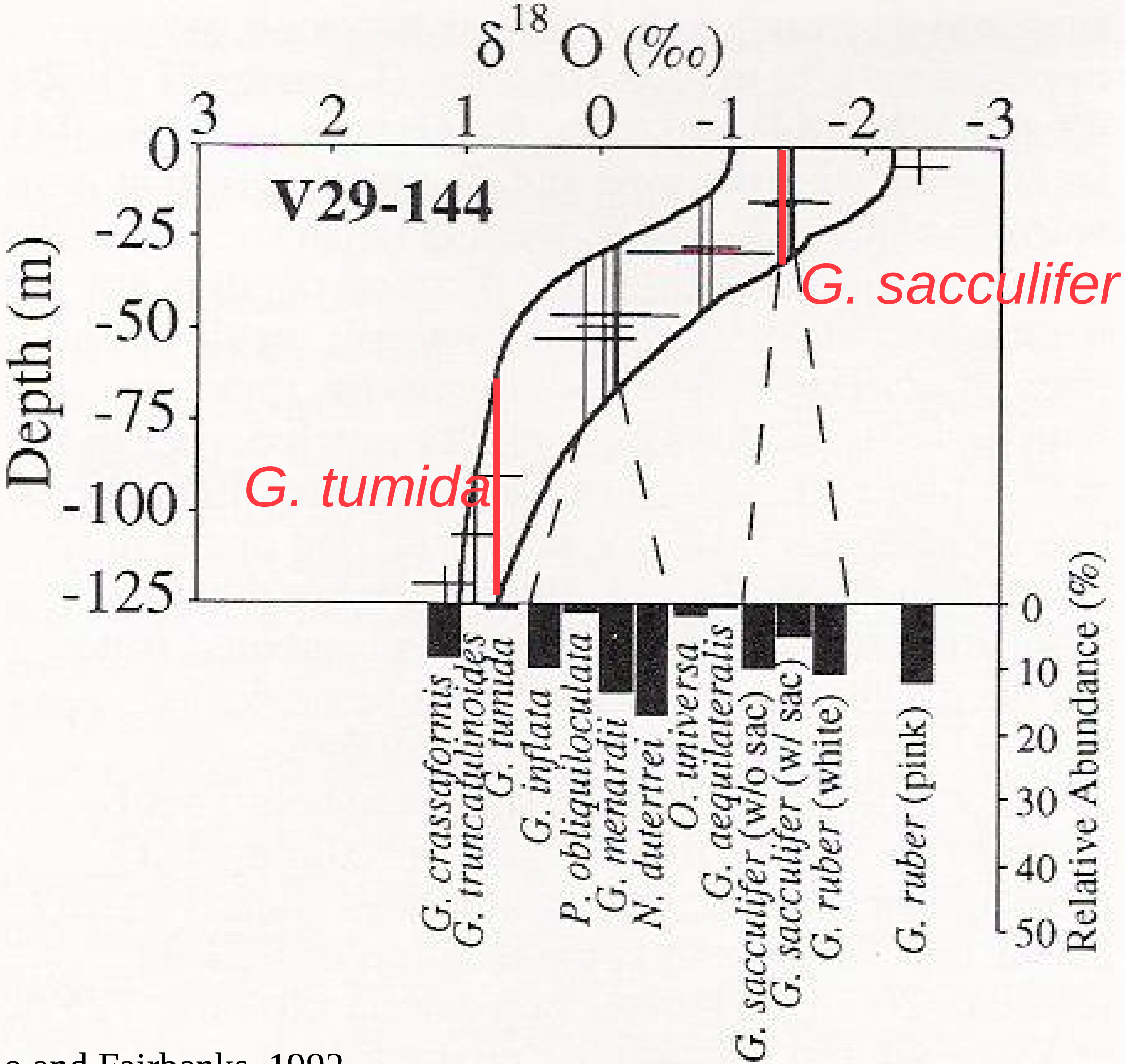
Outline

- Background
  - Early Pliocene warmth
  - La Madre conditions with some new data
- Upwelling Regions
  - Pliocene - Pleistocene trends
  - Possible mechanisms
- California Upwelling
  - Pliocene - Pleistocene Milankovitch Cycles

Deep Sea Drilling Project (1968-1983)
Ocean Drilling Program (1985-2003)
Integrated Ocean Drilling Program (2003- present)

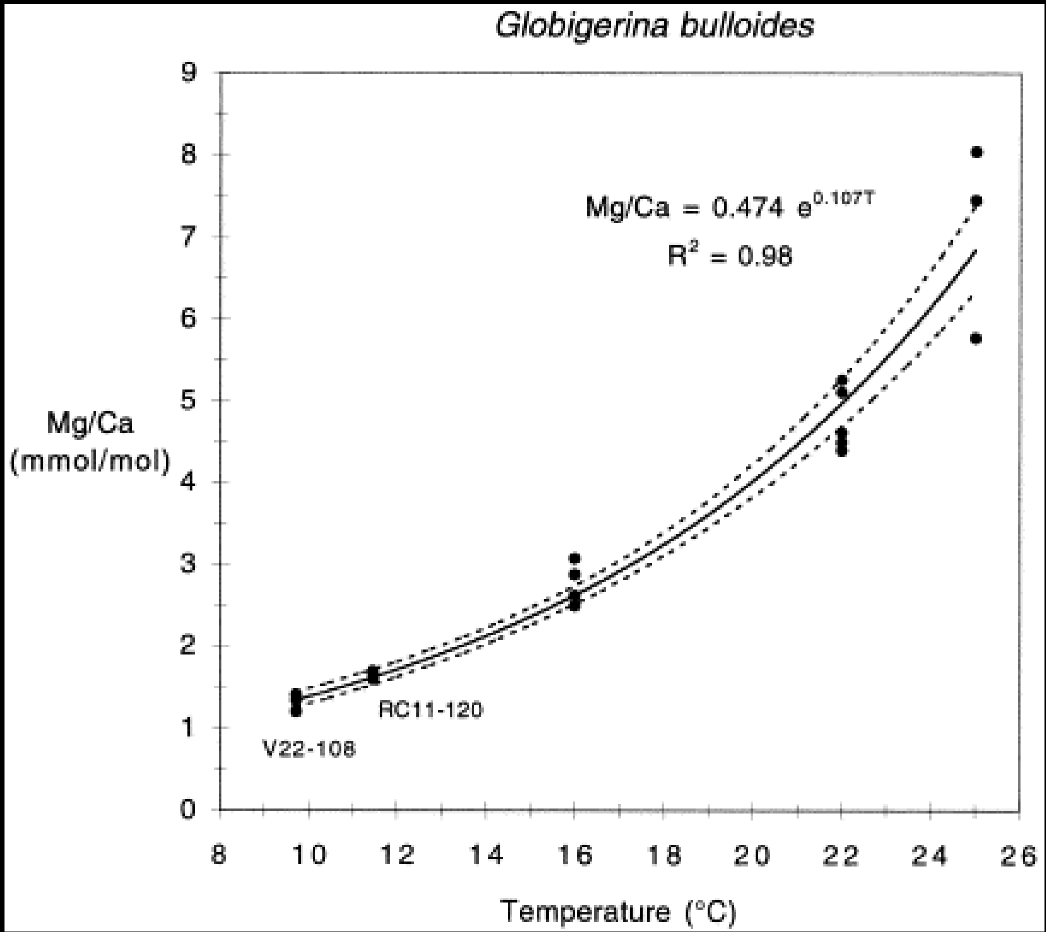
Depth Stratification of Planktonic Foramininfera





Ravelo and Fairbanks, 1992

Mg/Ca of foraminifera shells:
a function of calcification temperature



$CaCO_3$

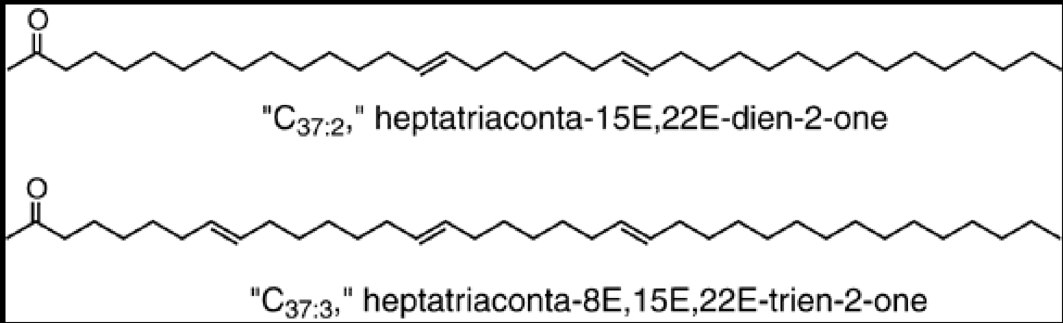
Mg^{2+} substitutes for Ca^{2+}

Thermodynamic effect, but biologically mediated

Mashiotta et al., 1999

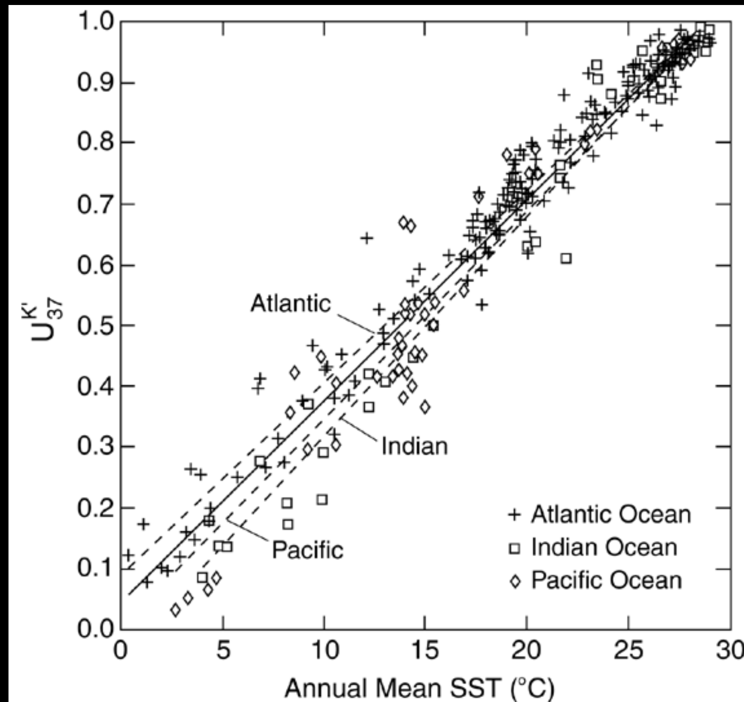
Alkenone saturation: a function of calcification temperature

Emiliania huxleyi

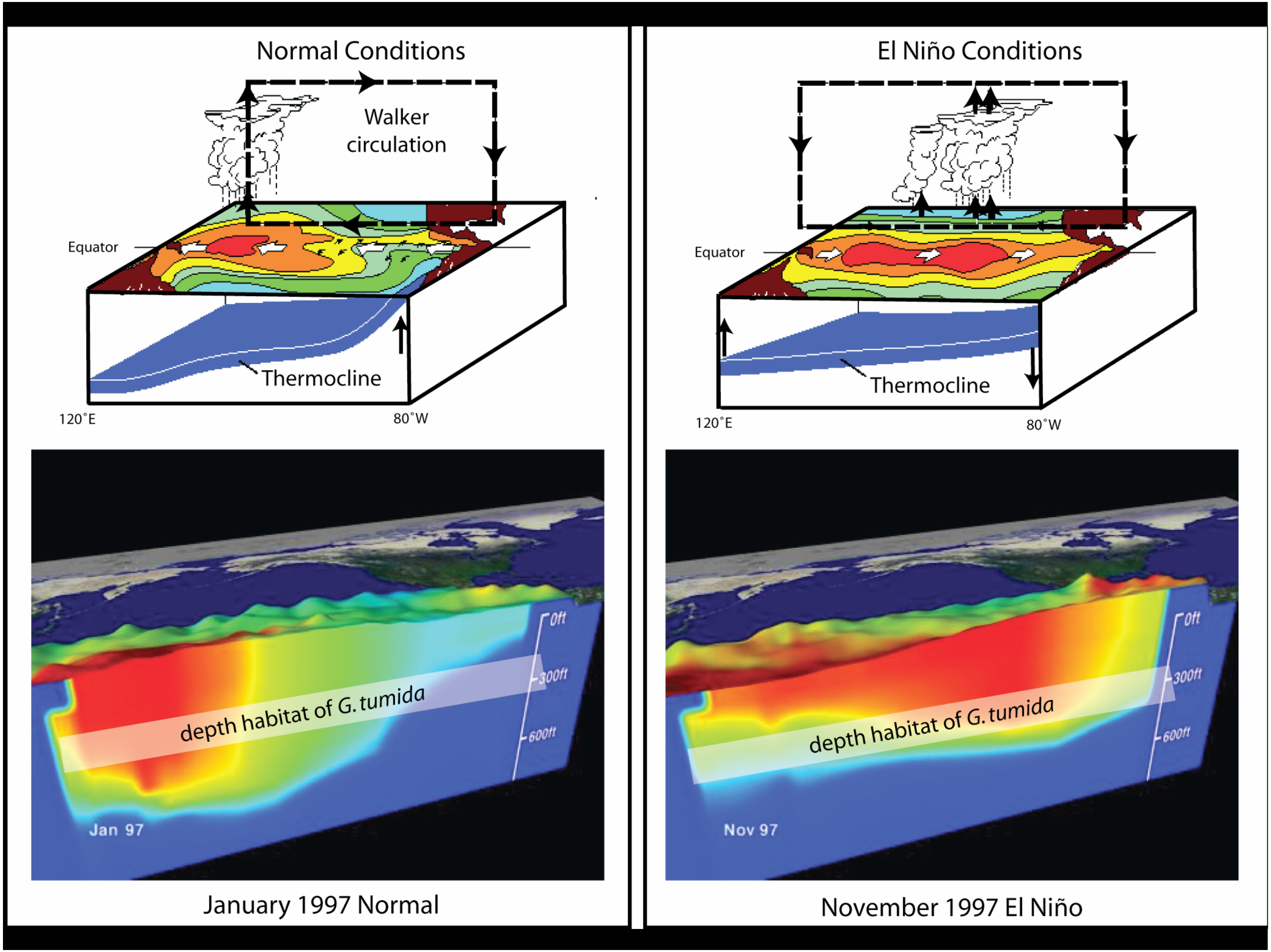


$$U^{k'}_{37} = C_{37:2}/(C_{37:2} + C_{37:3})$$

$$U^{k'}_{37} = 0.033SST + 0.044$$

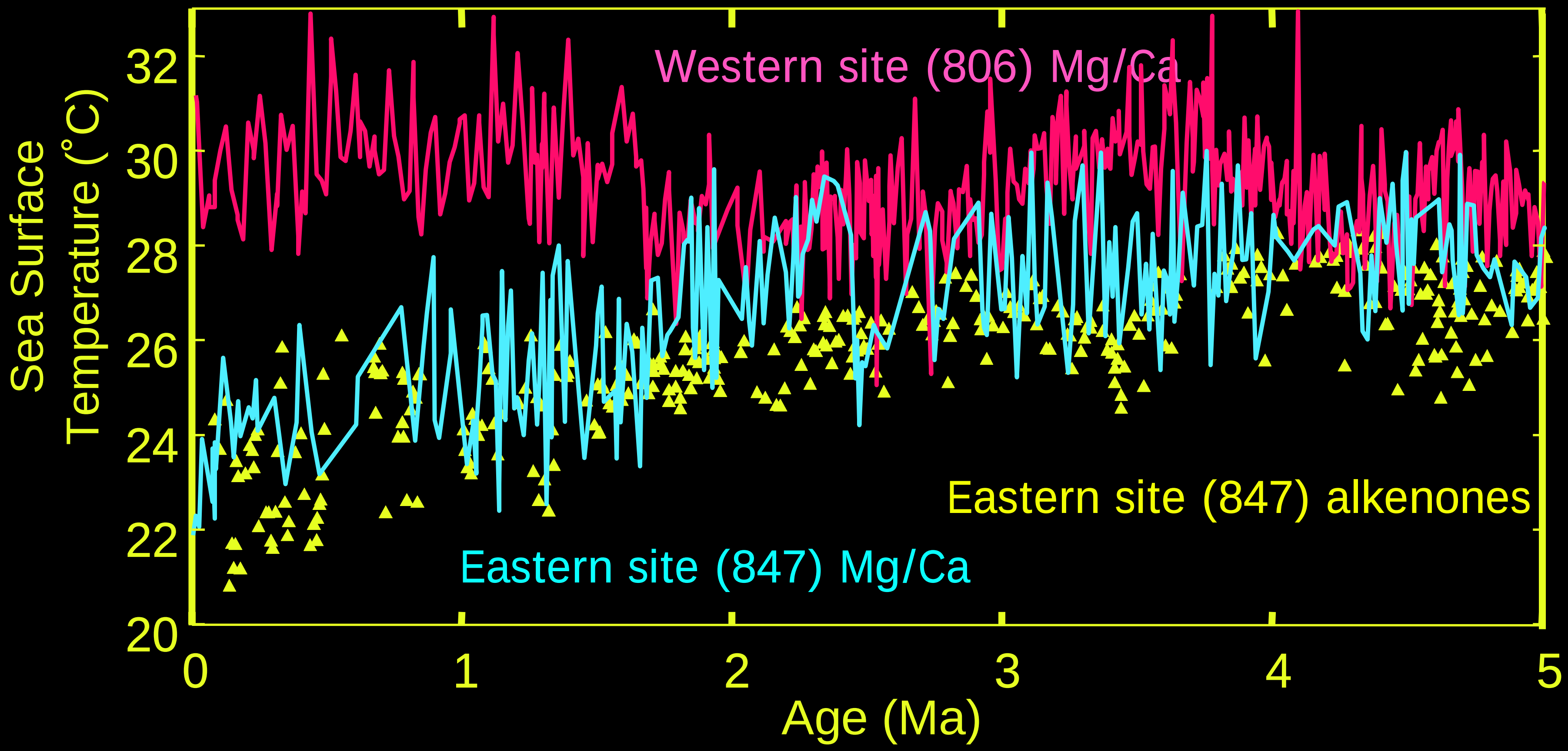


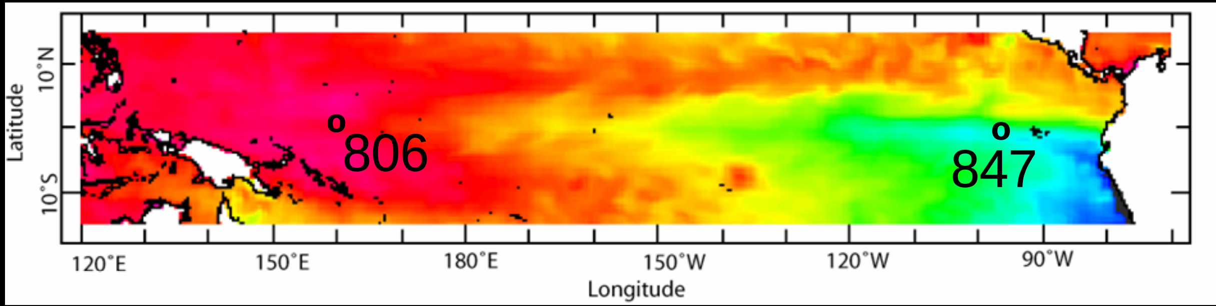
Müller et al, 1998



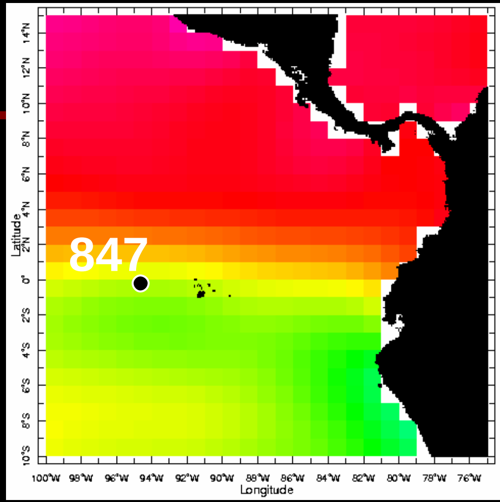
Normal Conditions
Walker circulation
Equator
Thermocline
120˚E
80˚W
0ft
300ft
600ft
depth habitat of G. tumida
Jan 97
January 1997 Normal
El Niño Conditions
Equator
Thermocline
120˚E
80˚W
0ft
300ft
600ft
depth habitat of G. tumida
Nov 97
November 1997 El Niño

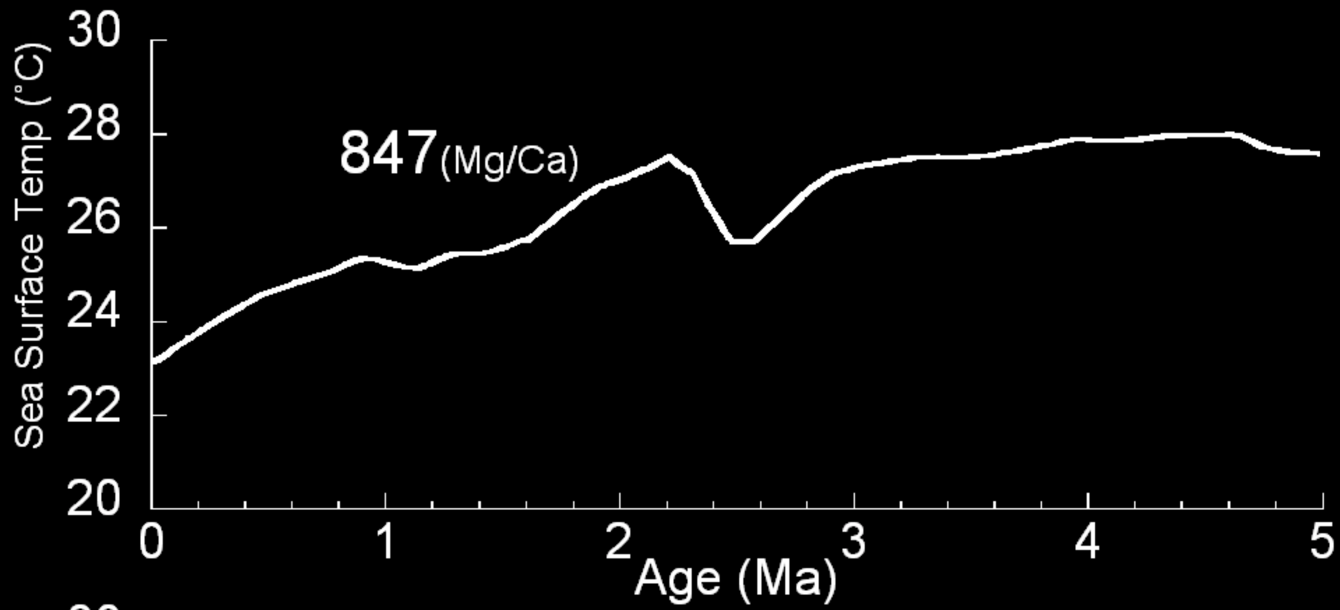
Temperature asymmetry of tropical Pacific established ~1.6 Ma

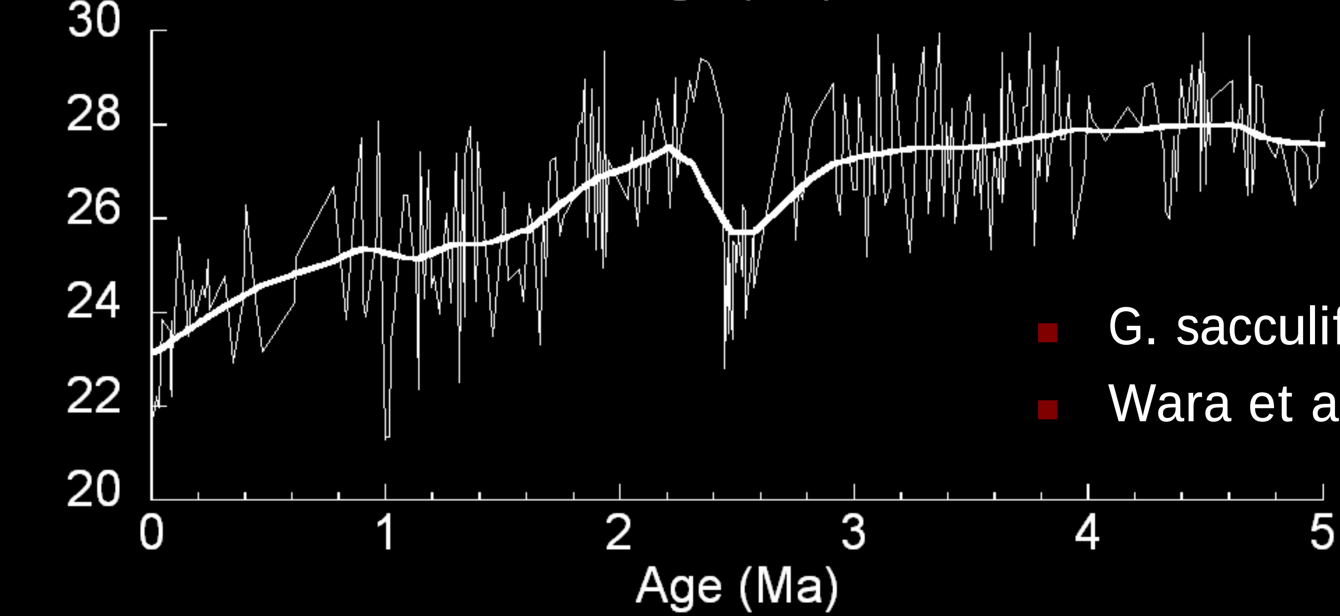




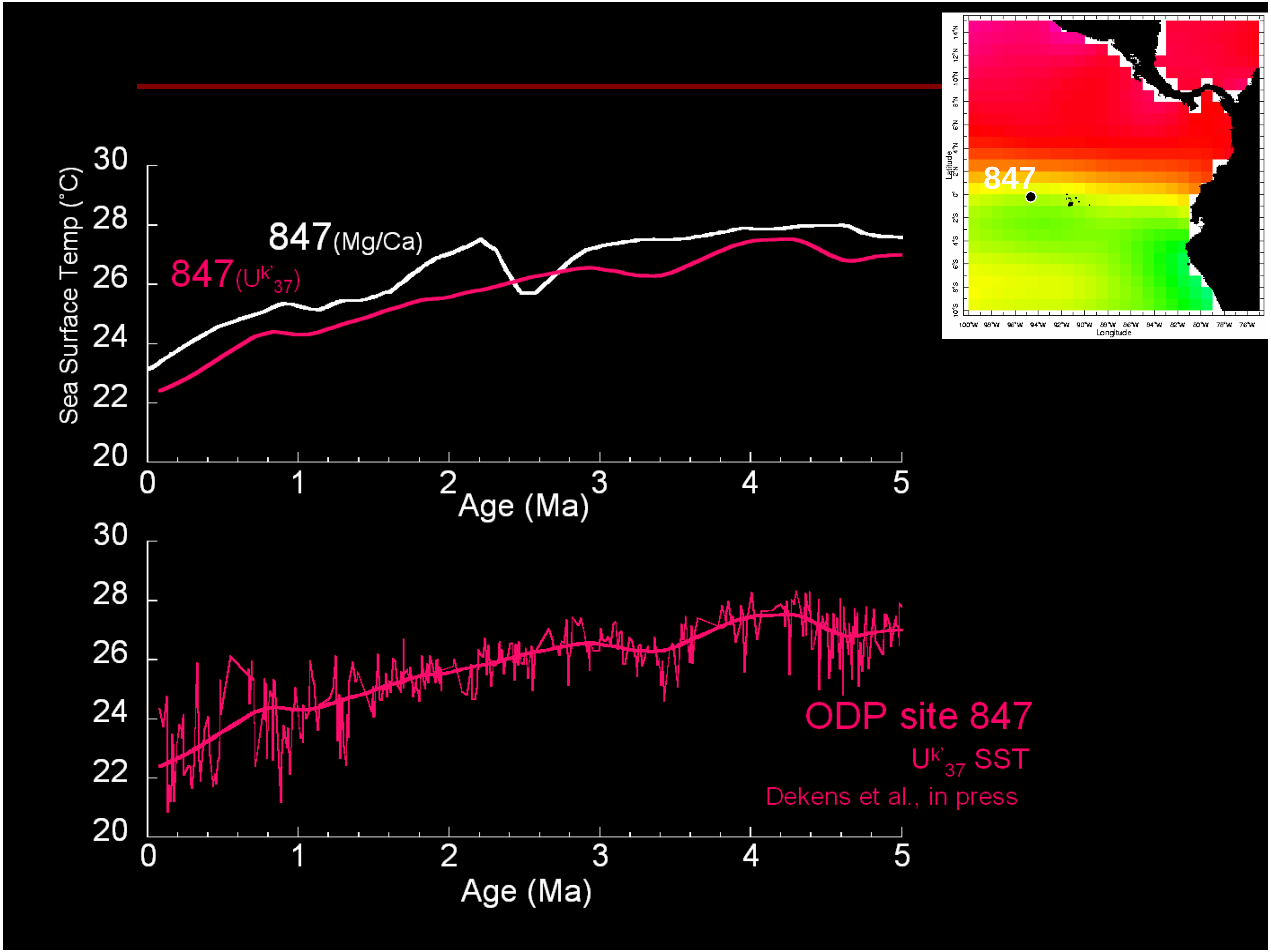
Data from: *Wara et al.*, 2005; *Dekens et al.*, in press



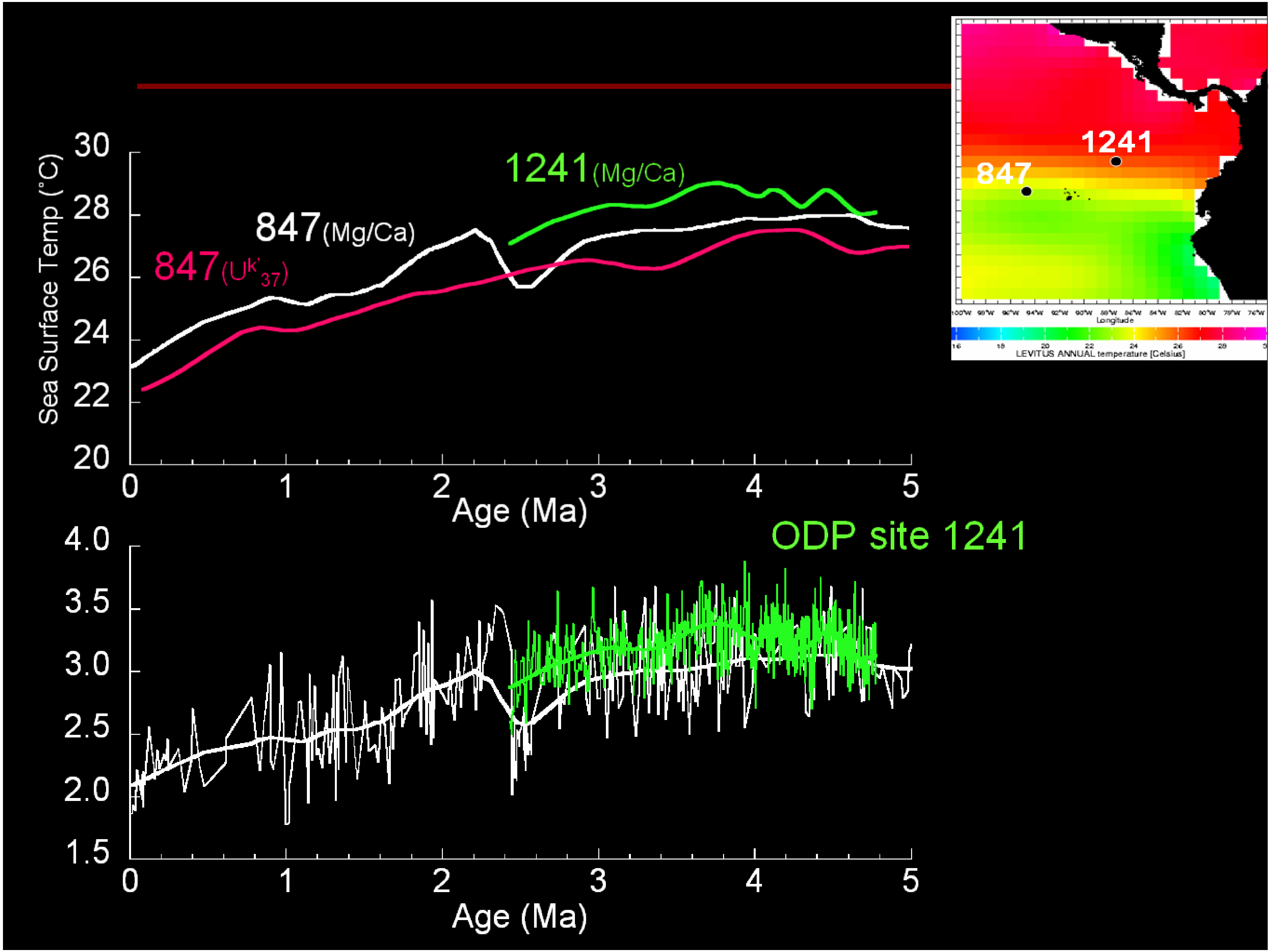




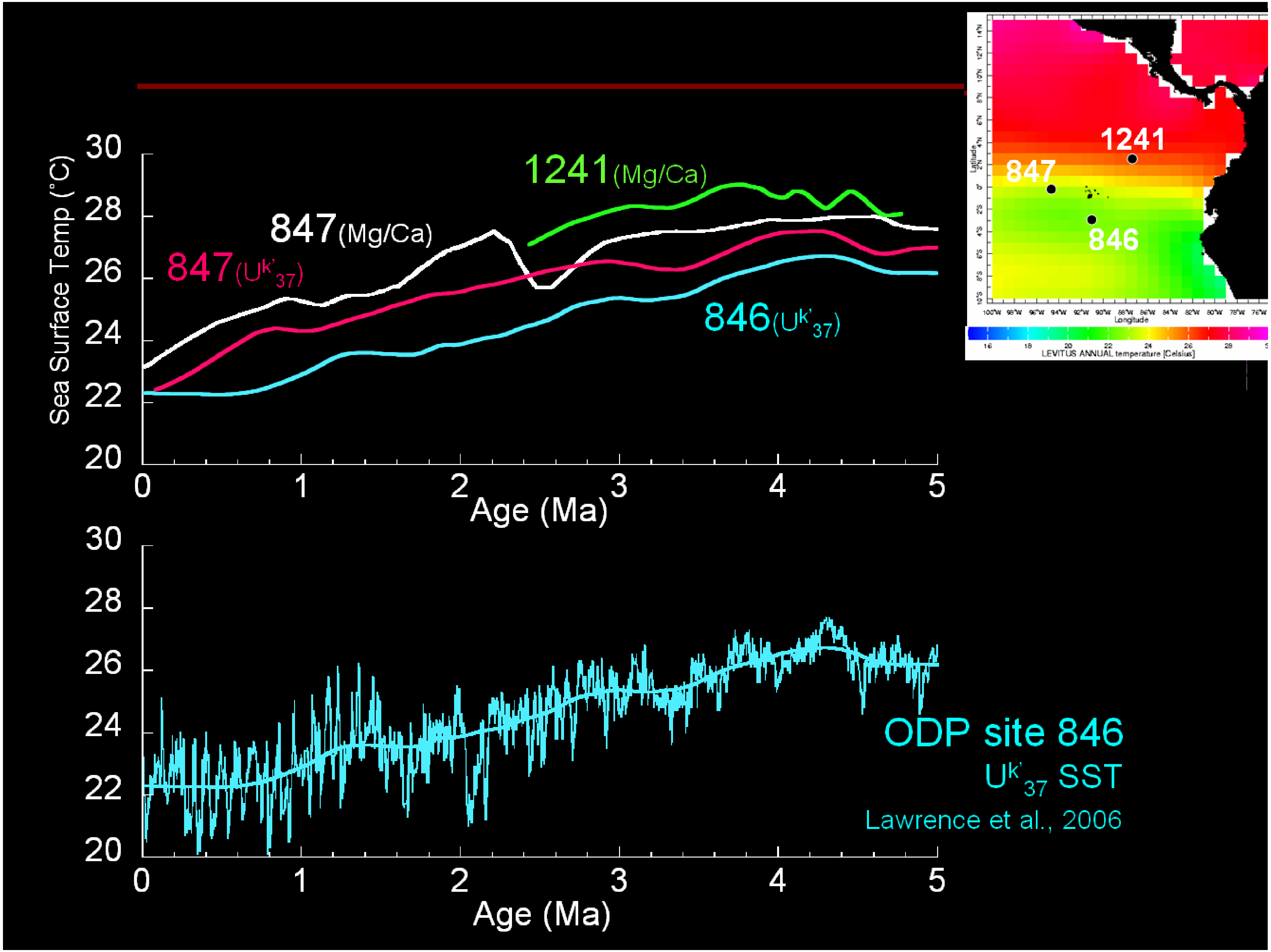
- G. sacculifer MG/Ca SST
- Wara et al., 2005



847
Latitude
Longitude
30
28
26
24
22
20
Sea Surface Temp (°C)
847(Mg/Ca)
847(Uk'37)
0
1
2
3
4
5
Age (Ma)
ODP site 847
Uk'37 SST
Dekens et al., in press



1241 (Mg/Ca)
847 (Mg/Ca)
847 (Uk'37)
Sea Surface Temp (°C)
Age (Ma)
ODP site 1241
1241
847
Longitude
LEVITUS ANNUAL temperature [Celsius]



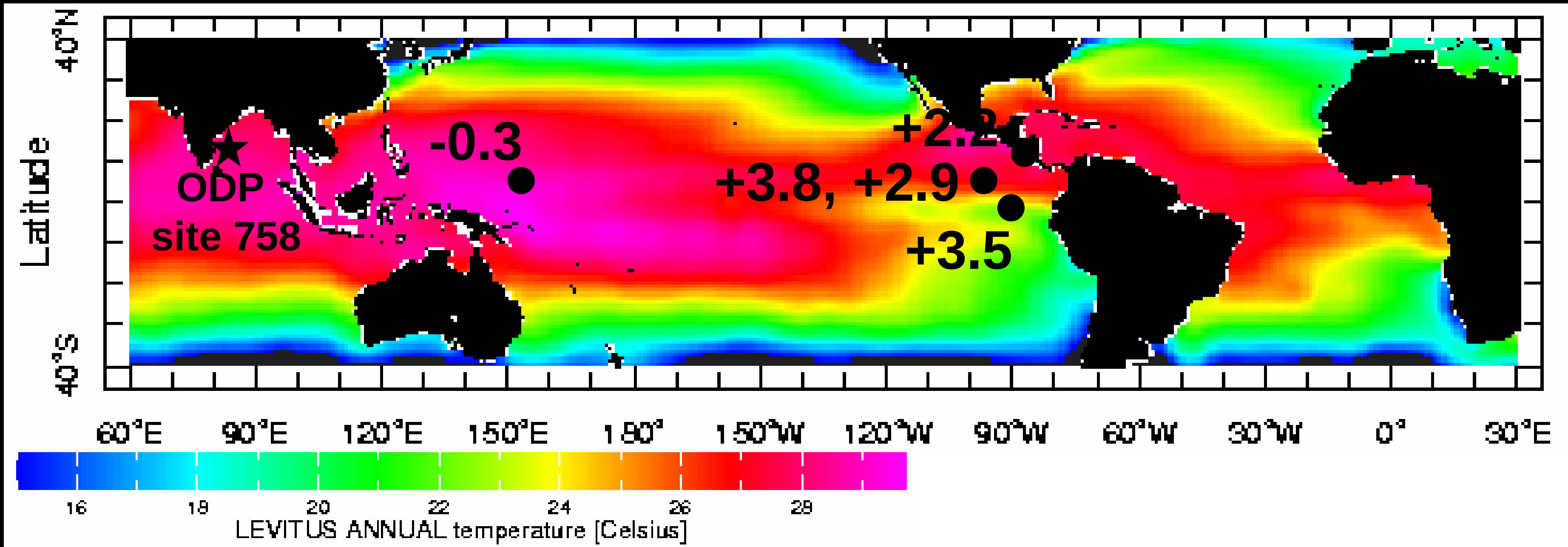
Sea Surface Temp (°C)
1241 (Mg/Ca)
847 (Mg/Ca)
847 (Uk'37)
846 (Uk'37)
Age (Ma)
1241
847
846
Latitude
Longitude
LEVITUS ANNUAL temperature [Celsius]
ODP site 846
Uk'37 SST
Lawrence et al., 2006

4 SST records, 2 proxies and 3 locations:

Eastern Equatorial Pacific was 2 – 4°C warmer than present during early Pliocene

SST difference (warm Pliocene – modern)

Warm Pliocene (3 – 4.6 Ma) average SST – modern mean annual SST



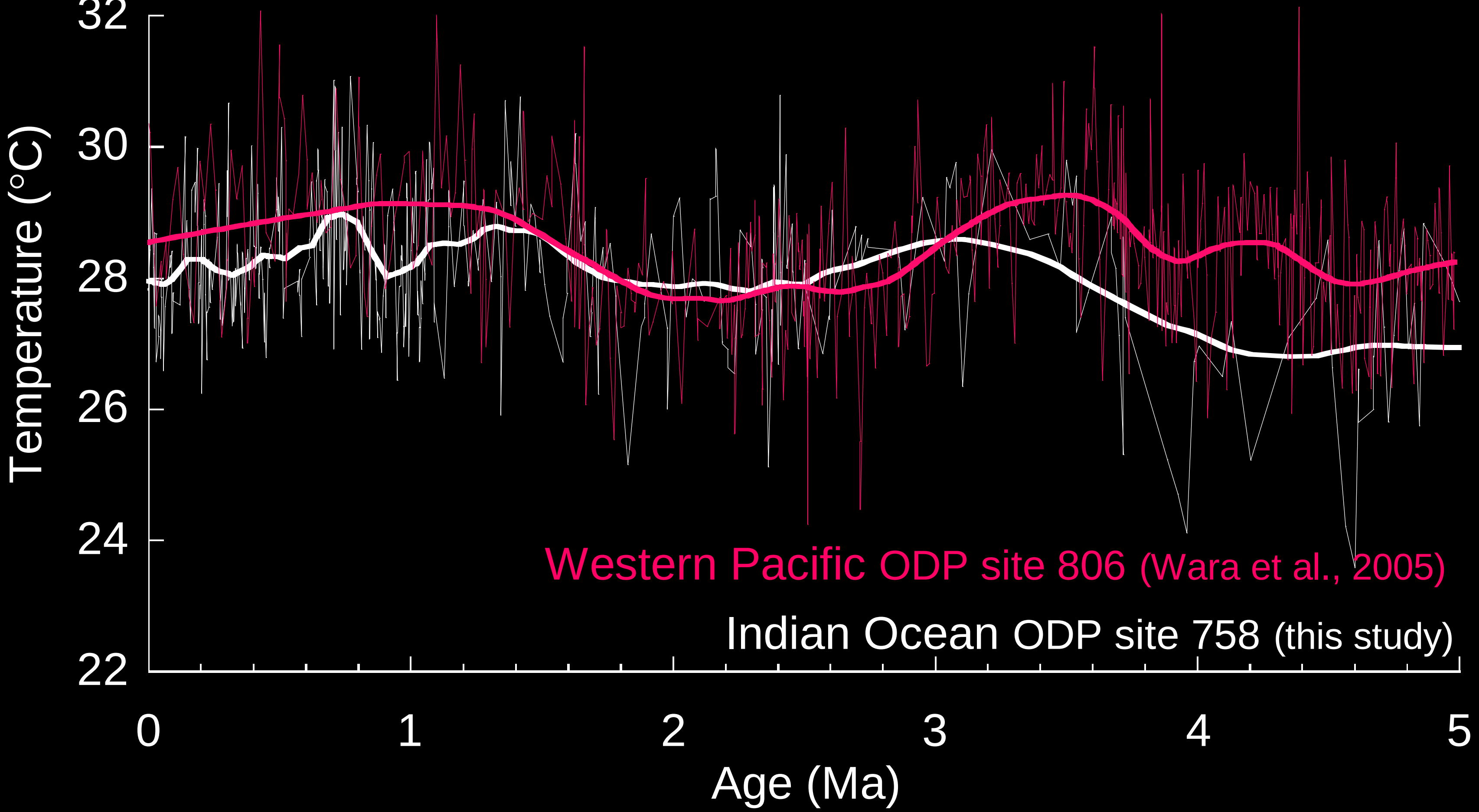
<u>ODP site 758</u>

5°23'N, 90°22'E, 2935m

Modern SST: 28.5°C

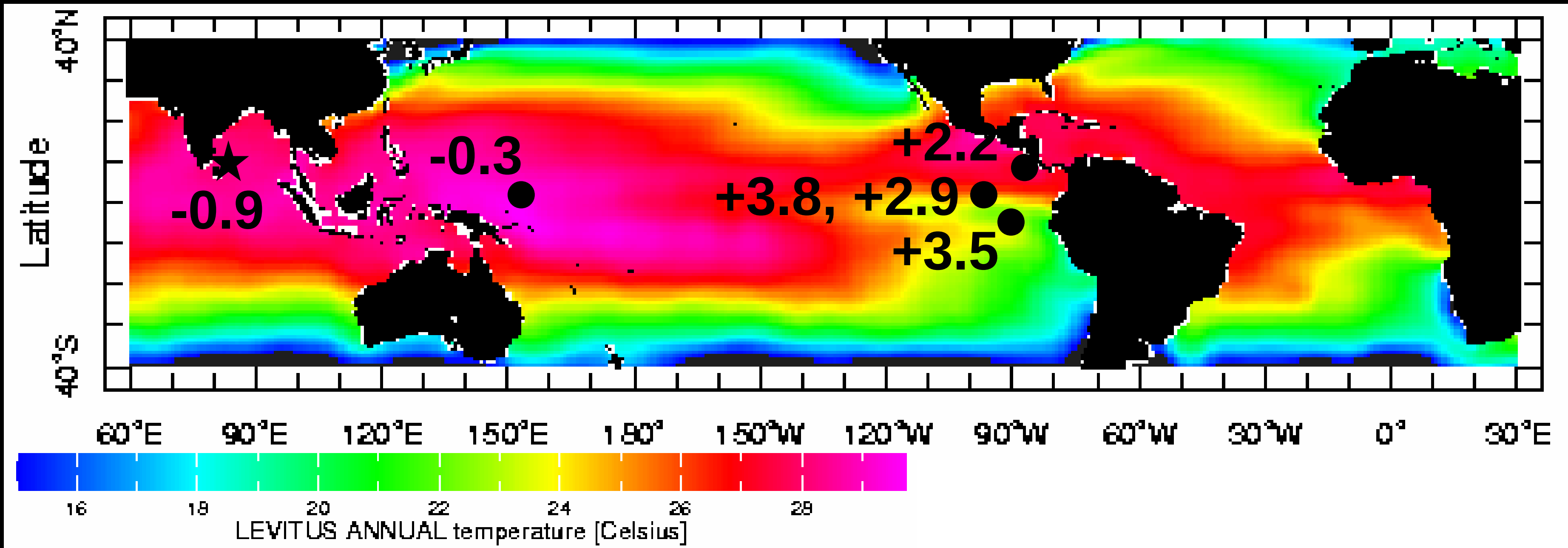
Indo-Pacific Warm Pool

G. sacculifer Mg/Ca SST Calibration: Dekens et al., 2002 ΔCO_3^{2-} correction



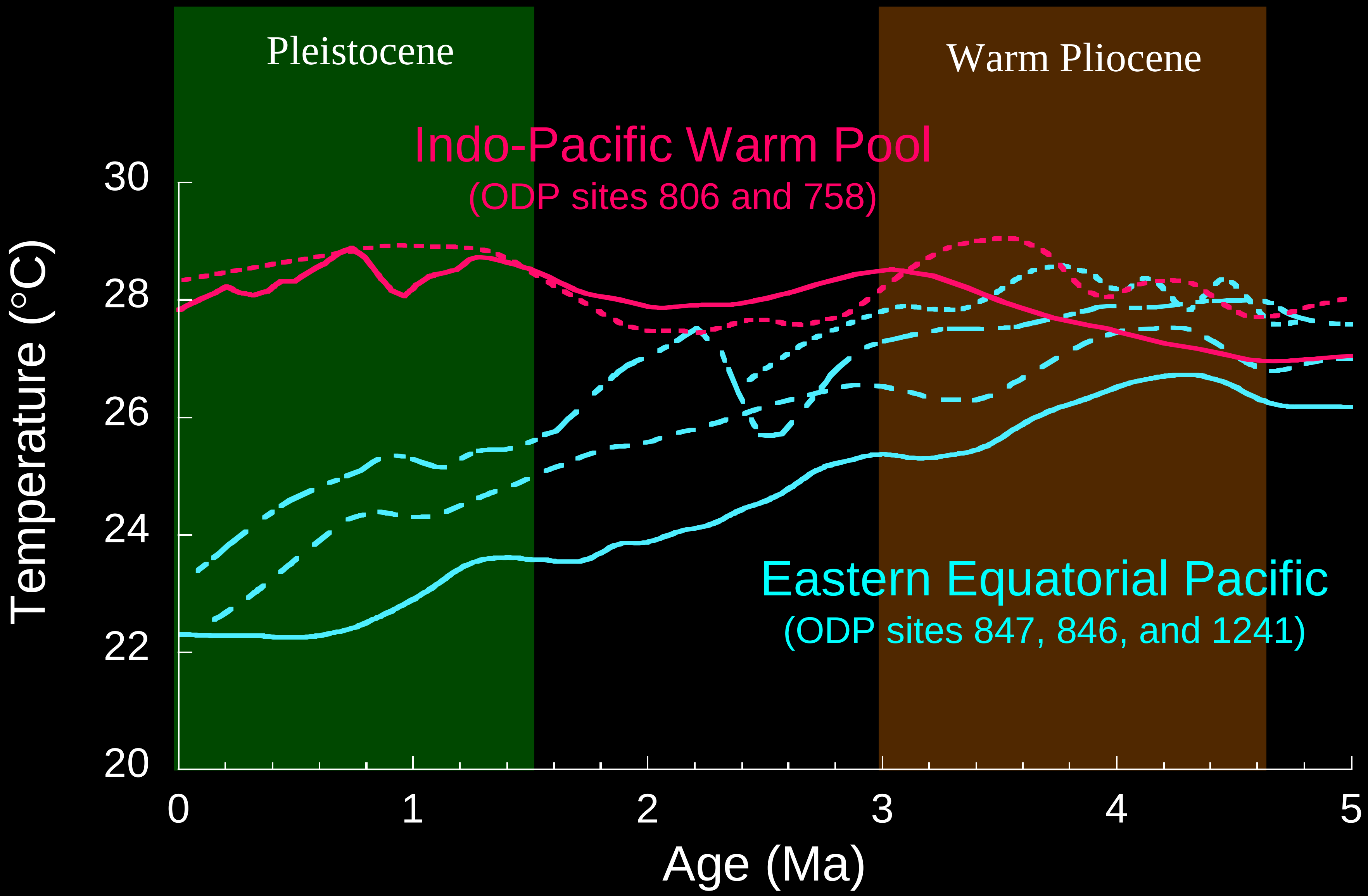
SST difference (warm Pliocene – modern)

Warm Pliocene (3 – 4.6 Ma) average SST – modern mean annual SST



Indo-Pacific warm pool was not warmer than present during early Pliocene

Indo-Pacific Warm Pool and E. Eq. Pacific



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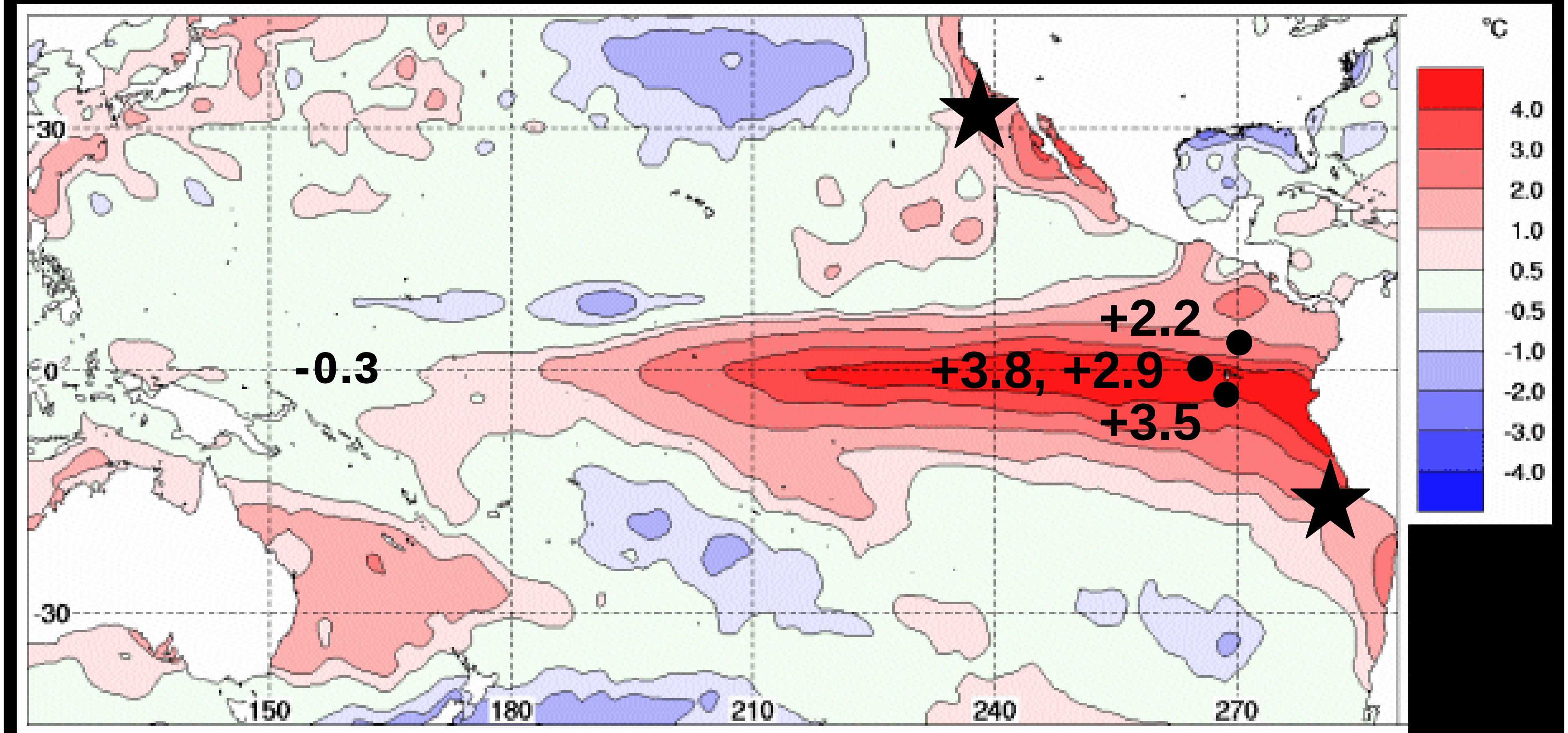
SST Anomalies during 1997 El Niño & early Pliocene



http://www.bom.gov.au/climate/enso/

Sub-tropical Upwelling Sites

California Current

ODP site 1014

32°50’N, 119°59’W

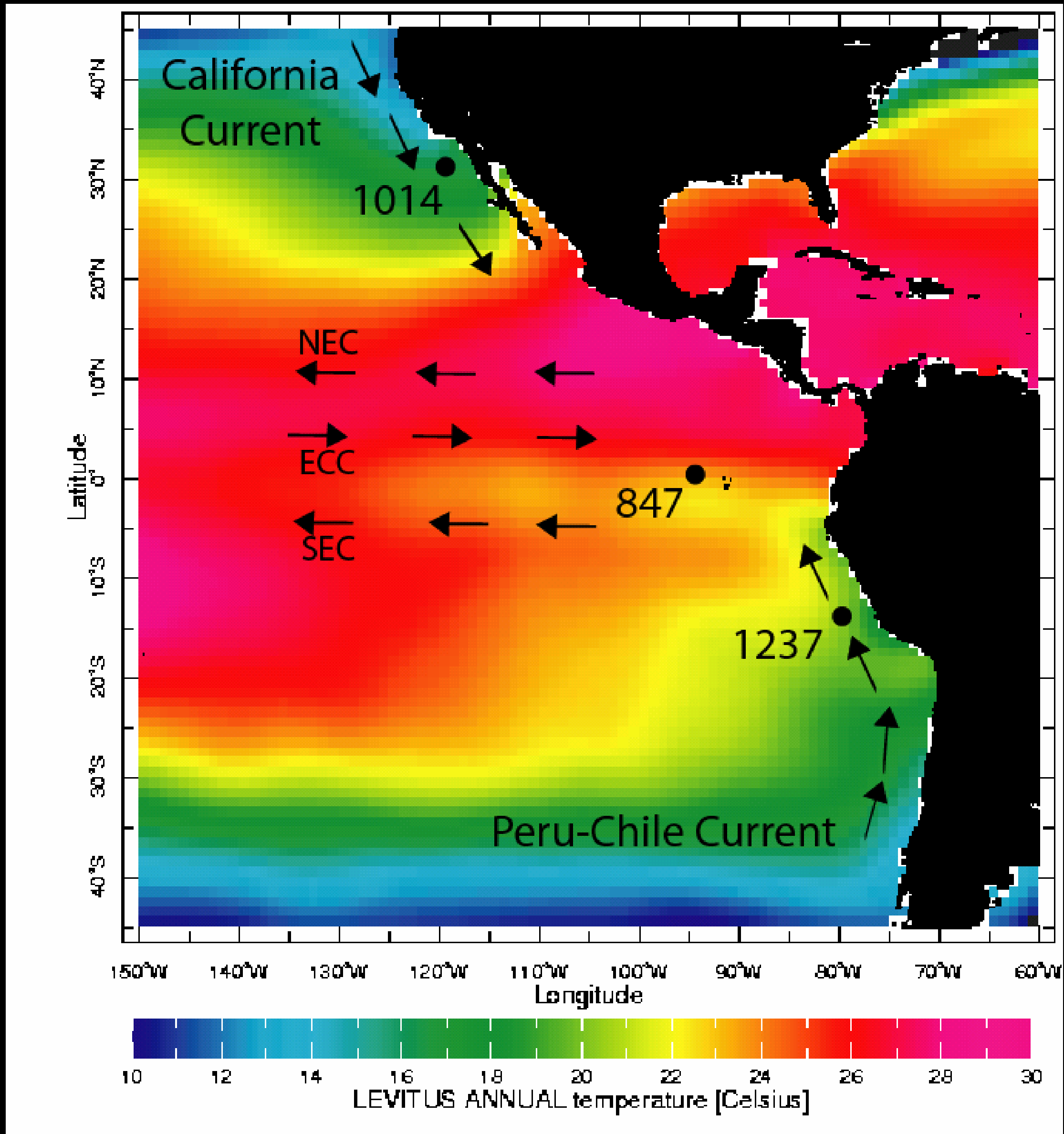
Modern SST: 15.7°C

Peru Current

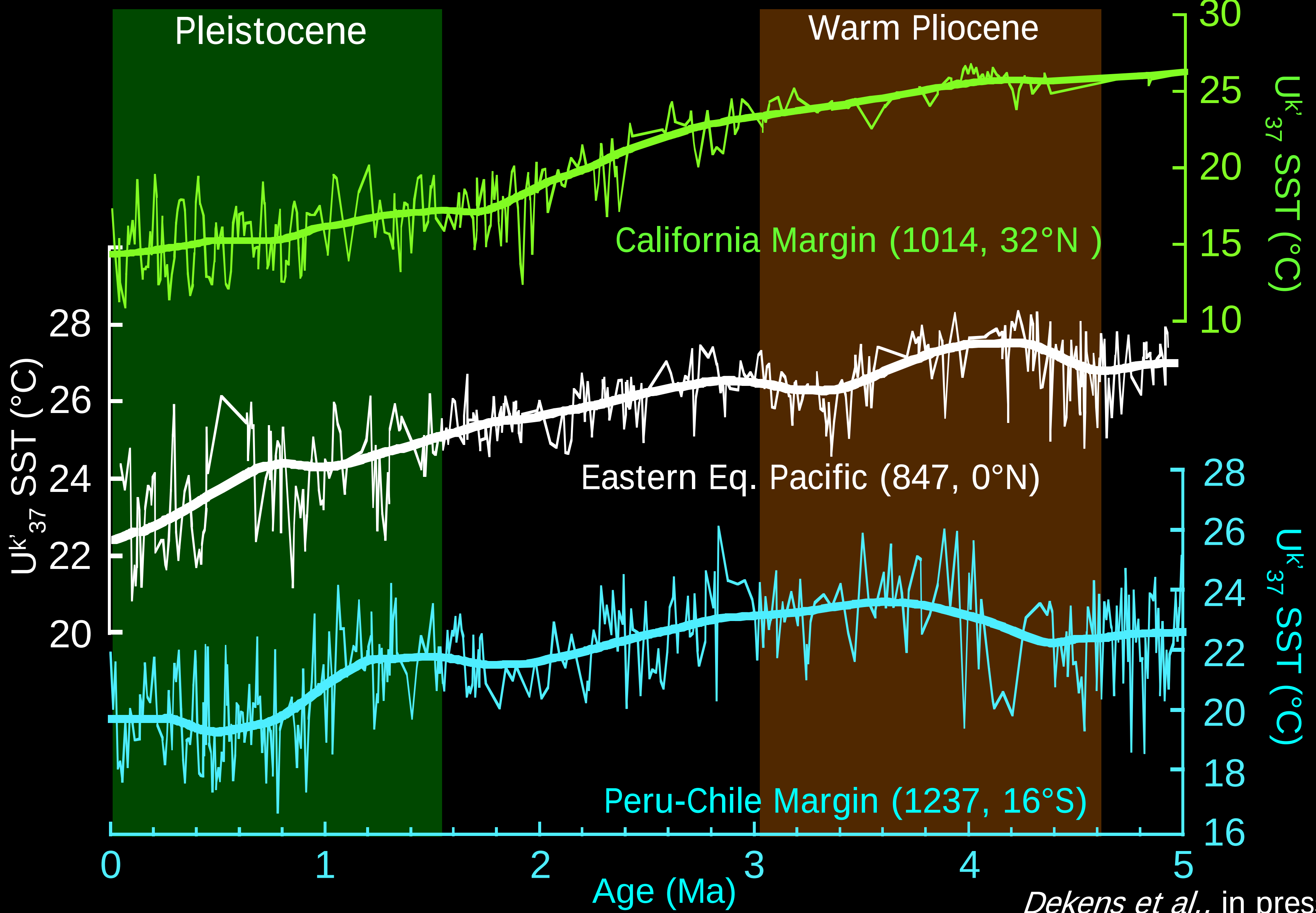
ODP site 1237

16°0’S, 76°23’W

Modern SST: 19.1°C

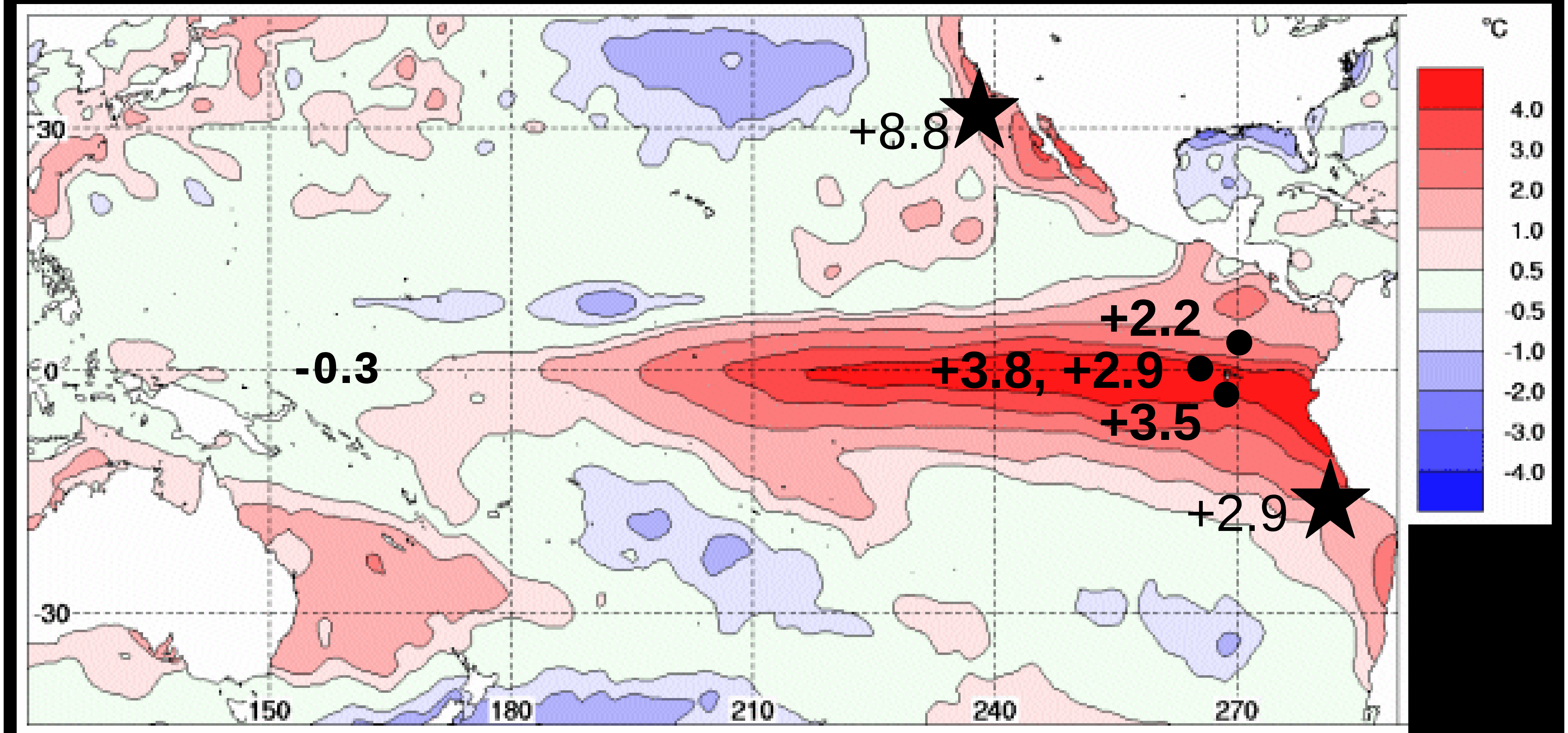


Temperature Records from Pacific Upwelling Regions

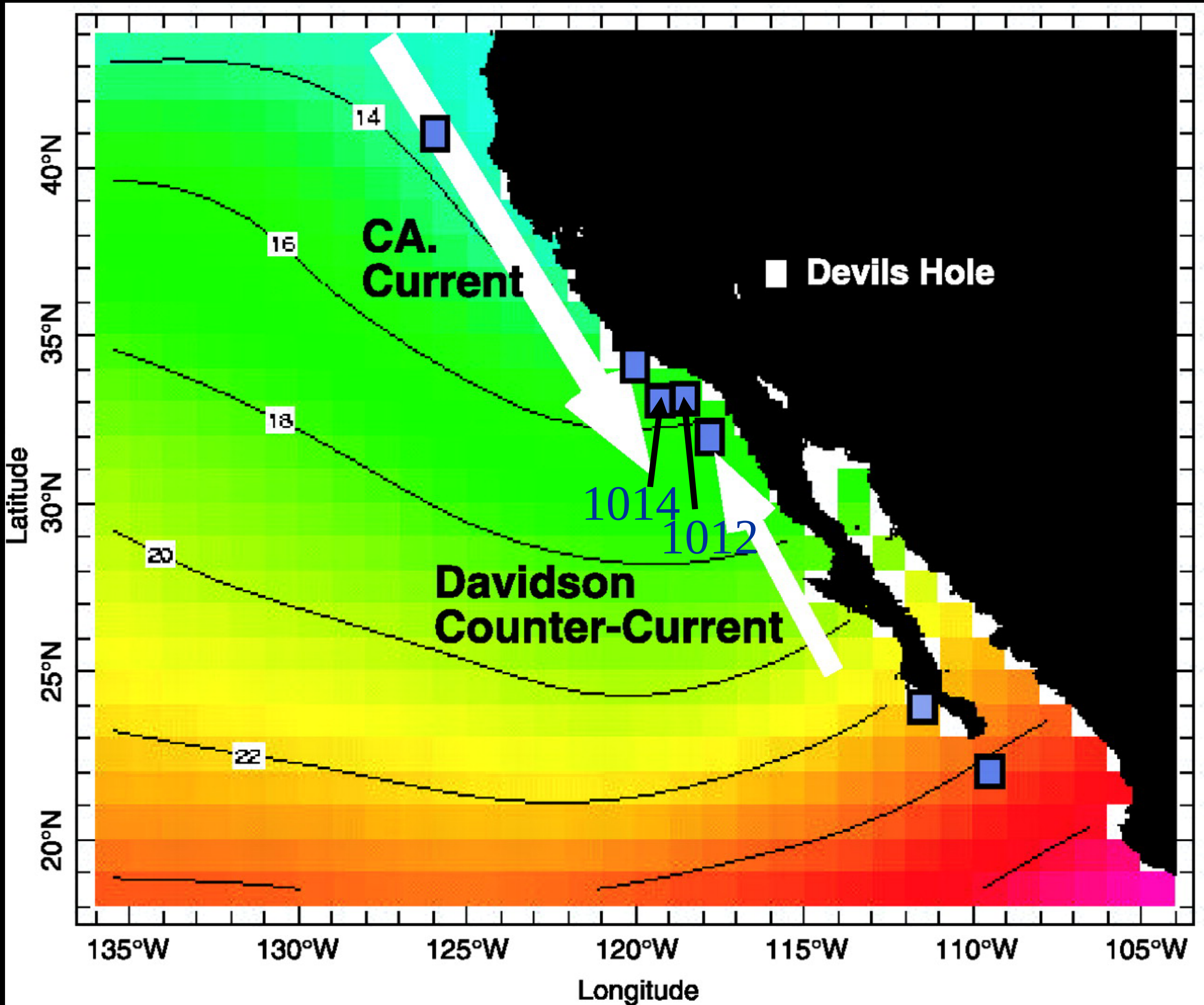


Dekens et al., in press

SST Anomalies during 1997 El Niño & early Pliocene

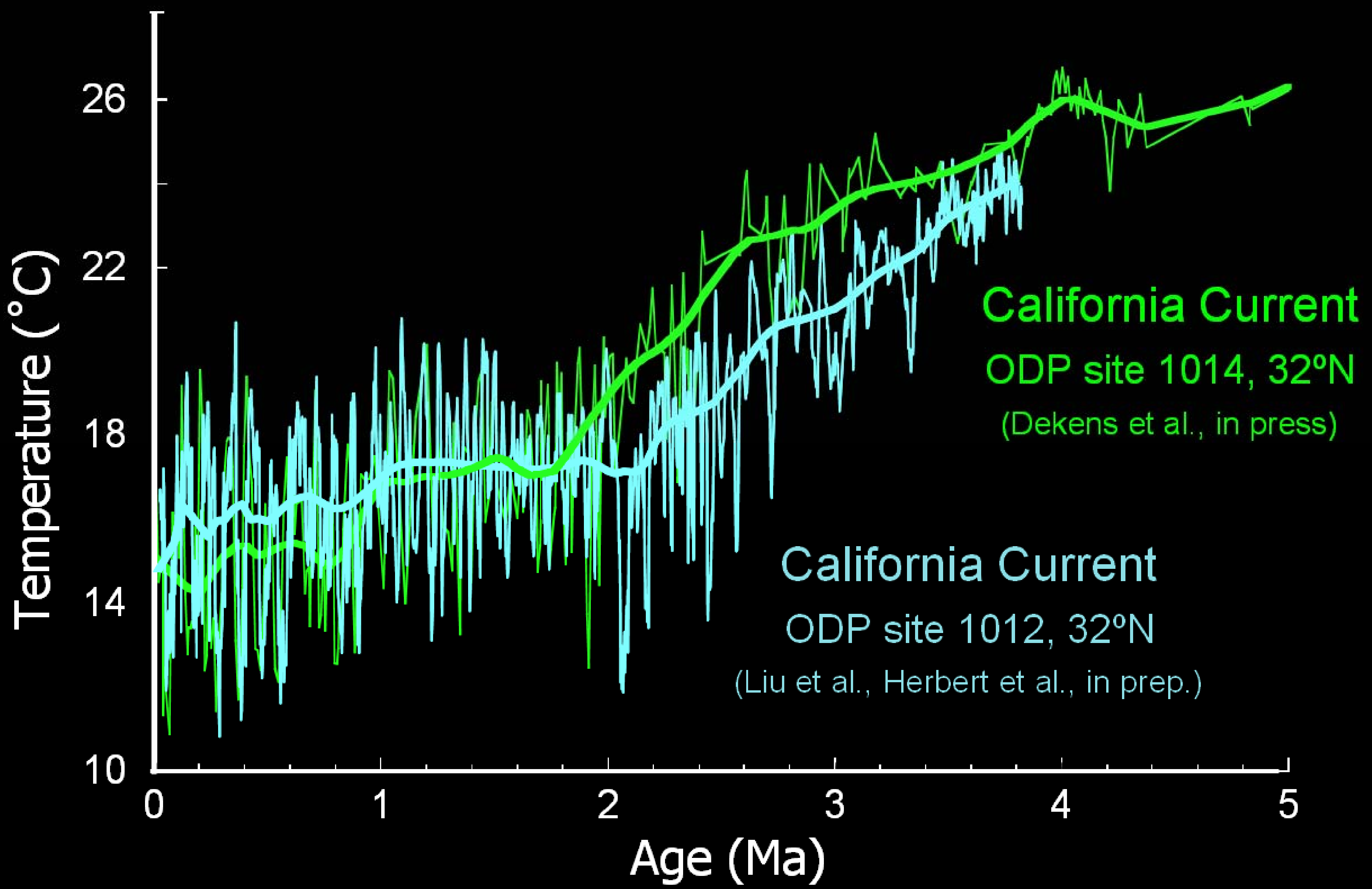


http://www.bom.gov.au/climate/enso/

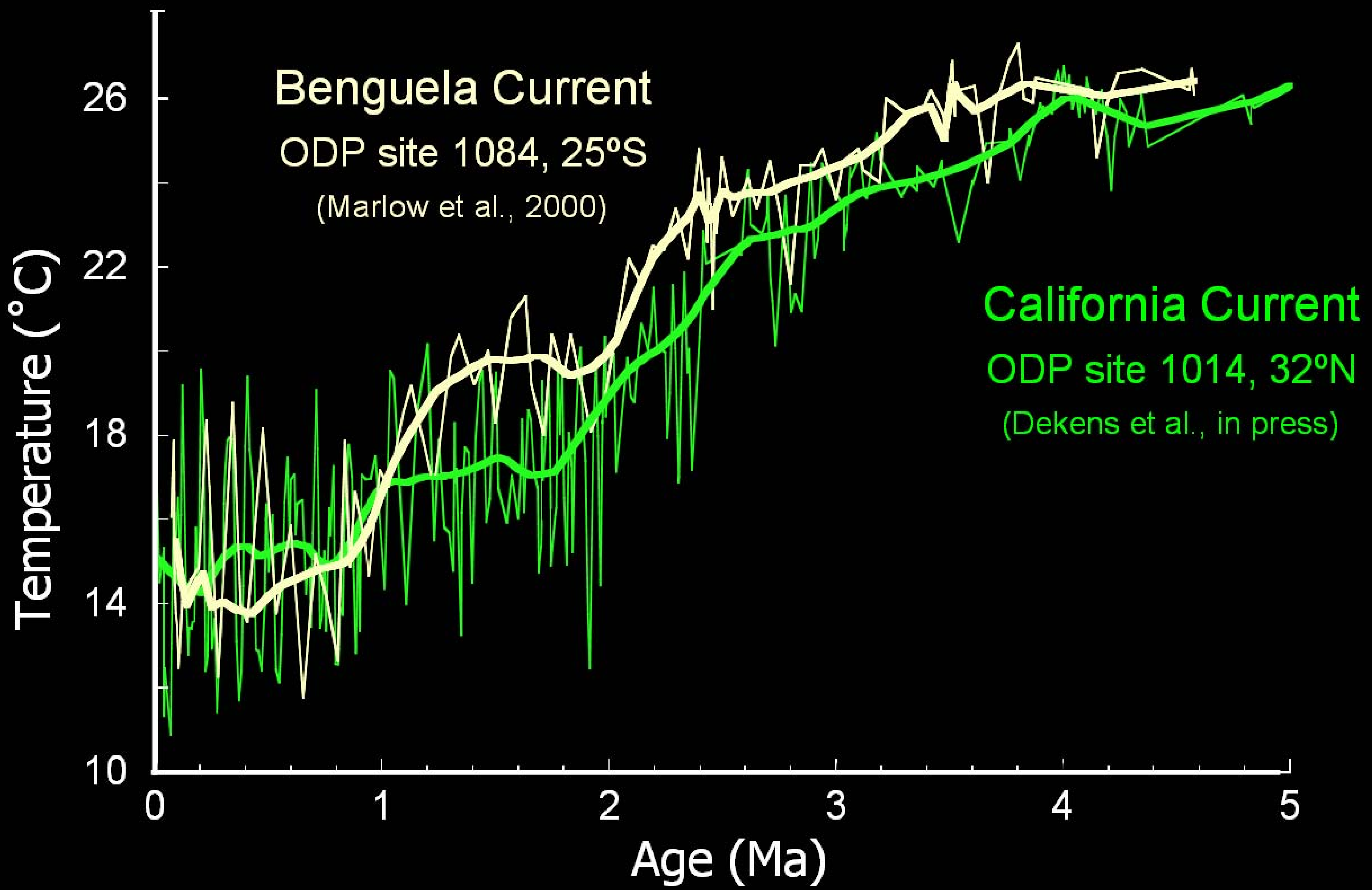


14
16
18
20
22
CA.
Current
Devils Hole
1014
1012
Davidson
Counter-Current
40°N
35°N
30°N
25°N
20°N
Latitude
135°W
130°W
125°W
120°W
115°W
110°W
105°W
Longitude

Upwelling regions: Atlantic - Pacific comparison

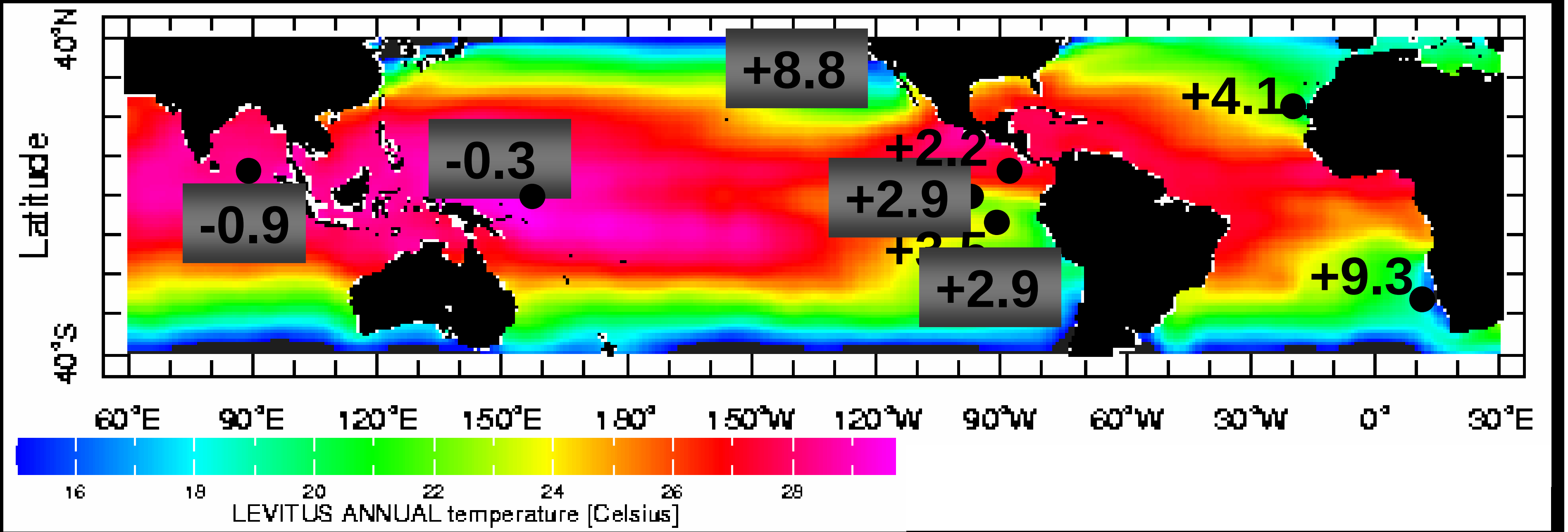


Upwelling regions: Atlantic - Pacific comparison



SST difference (warm Pliocene – modern)

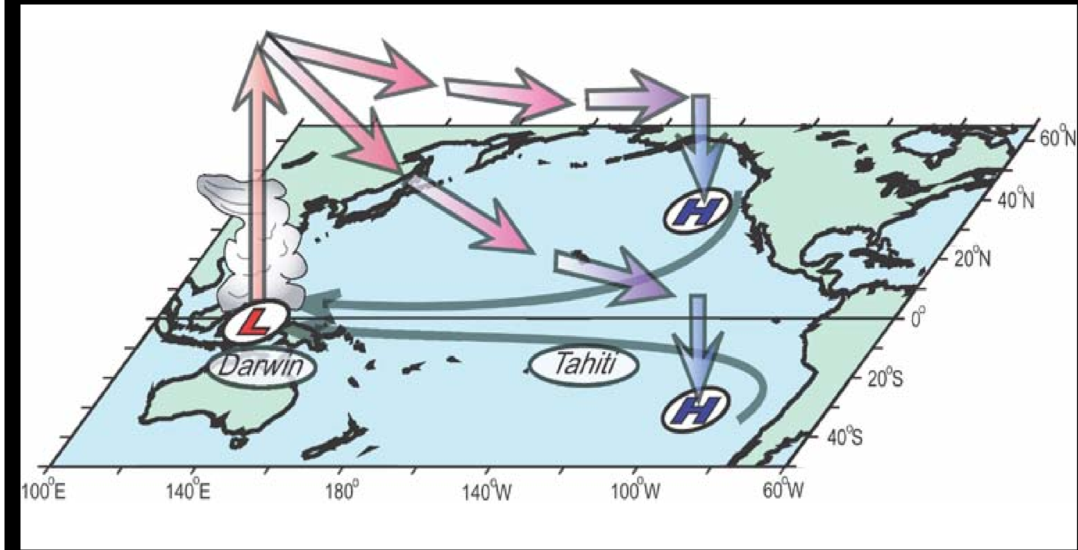
Warm Pliocene (3 – 4.6 Ma) average SST – modern mean annual SST



ODP Site	Location	Δ SST	Proxy	Reference
806	W.Eq. Pacific	-0.3	Mg/Ca	Wara et al., 2005
758	Indian Ocean	-0.9	Mg/Ca	Dekens et al., in prep
847	E. Eq Pacific	3.8	Mg/Ca	Wara et al., 2005
847	E. Eq Pacific	2.8	Uk'37	Dekens et al., in press
846	E. Eq Pacific	3.5	Uk'37	Lawrence et al., 2006
1241	E. Eq Pacific	2.2	Mg/Ca	Groeneveld et al., 2006
1014	California margin	8.8	Uk'37	Dekens et al., in press
1237	Peru margin	2.9	Uk'37	Dekens et al., in press
928	East Atlantic	4.1	Uk'37	Herbert et al., 1998
1084	Benguela current	9.3	Uk'37	Marlow et al., 2000

Pacific and Atlantic upwelling regions were all significantly warmer during the early Pliocene compared to today

Why did upwelling regions cool?



Schwing, F.B et al, 2002

Atmospheric Mechanism

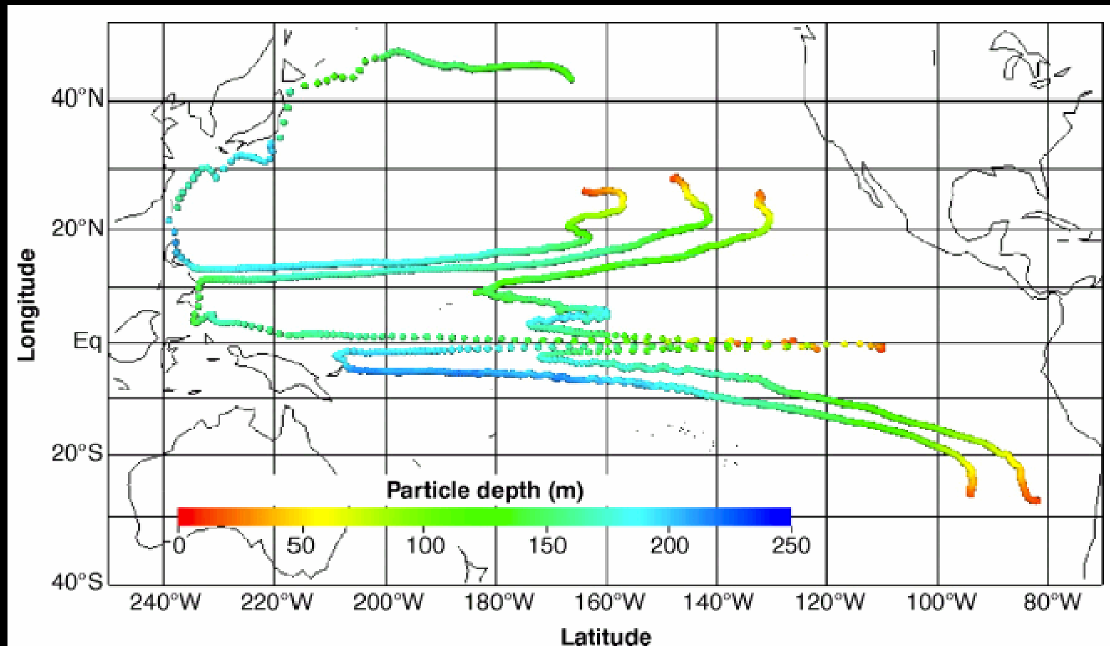
Upwelling favorable winds increased:

- because Permanent El Niño (La Madre) ended?
- because Ice Sheets grew?

Oceanic Mechanism

Subsurface source waters cooled:

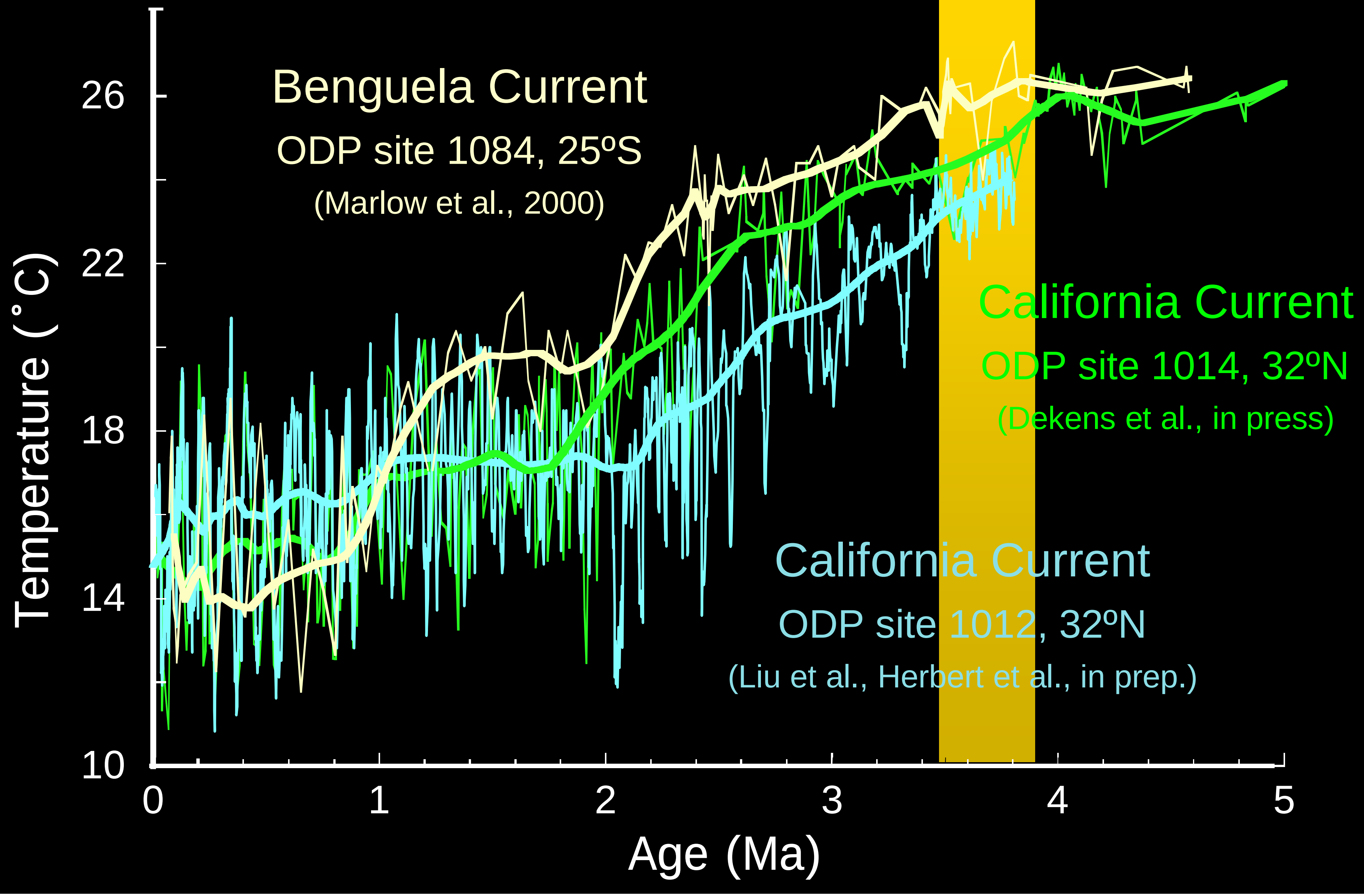
- because of changes in thermocline conditions?



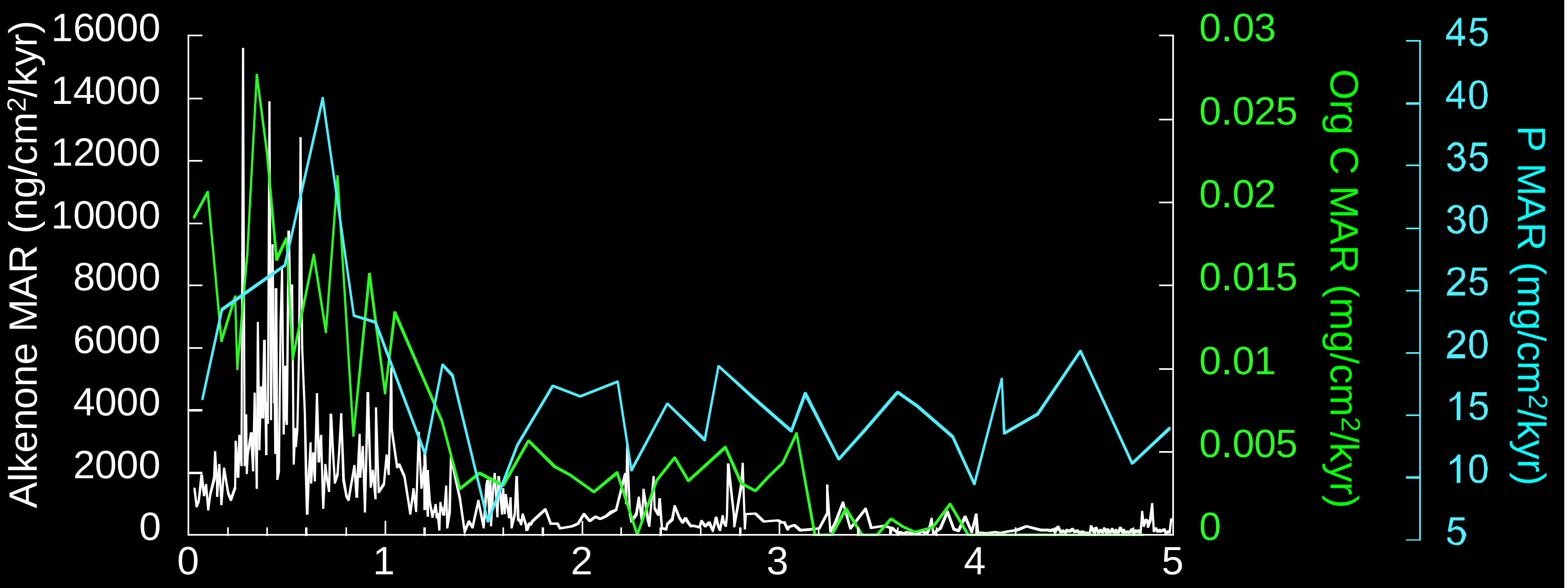
Harper, 2000

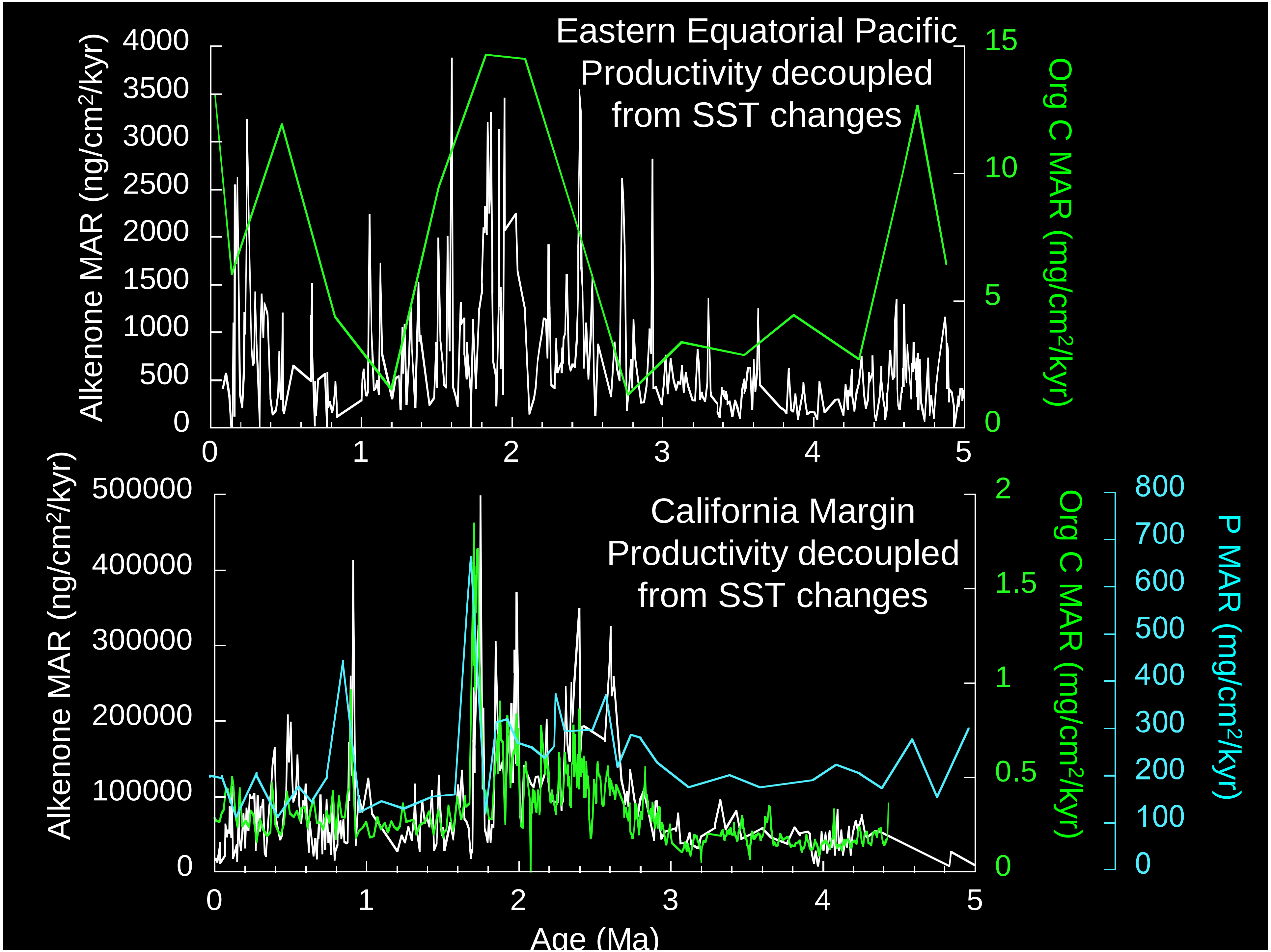
Upwelling: Cooling began by ~4.0 Ma

Not related to ice sheet growth



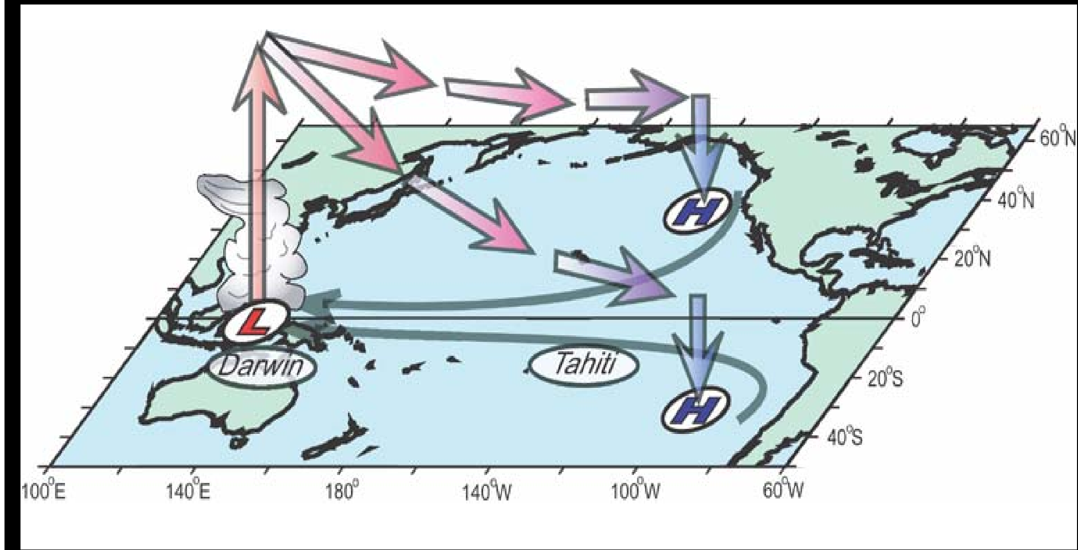
Peru Margin: Productivity increased as SST decreased





Eastern Equatorial Pacific
Productivity decoupled
from SST changes
Alkenone MAR (ng/cm²/kyr)
Org C MAR (mg/cm²/kyr)
0
500
1000
1500
2000
2500
3000
3500
4000
0
5
10
15
0
1
2
3
4
5
California Margin
Productivity decoupled
from SST changes
Alkenone MAR (ng/cm²/kyr)
Org C MAR (mg/cm²/kyr)
P MAR (mg/cm²/kyr)
0
100000
200000
300000
400000
500000
0
0.5
1
1.5
2
0
100
200
300
400
500
600
700
800
Age (Ma)

Why did upwelling regions cool?



Schwing, F.B et al, 2002

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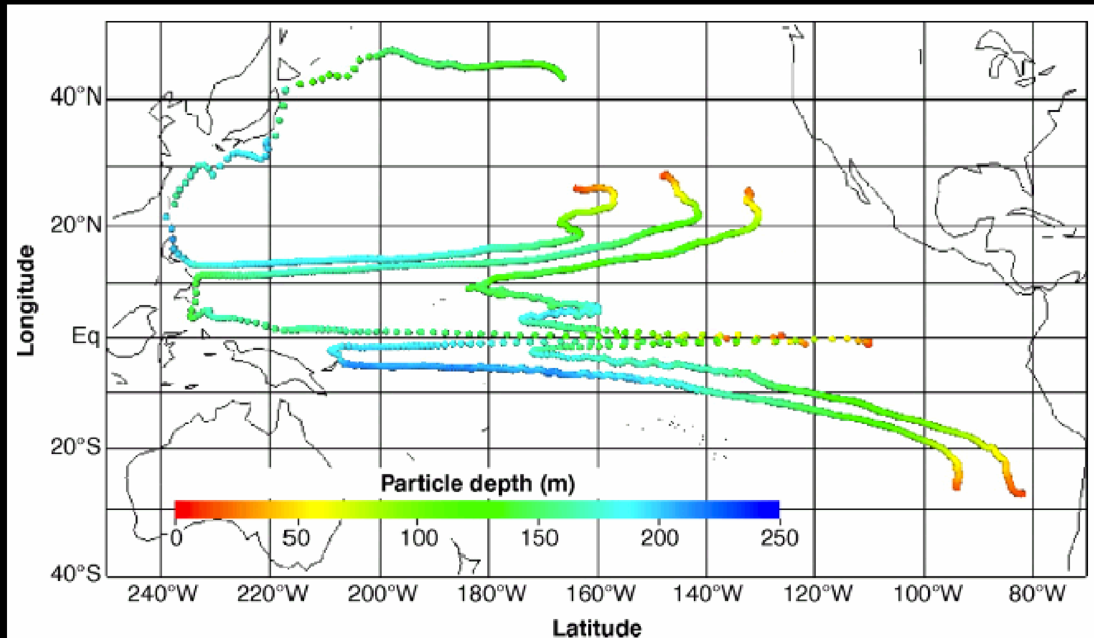
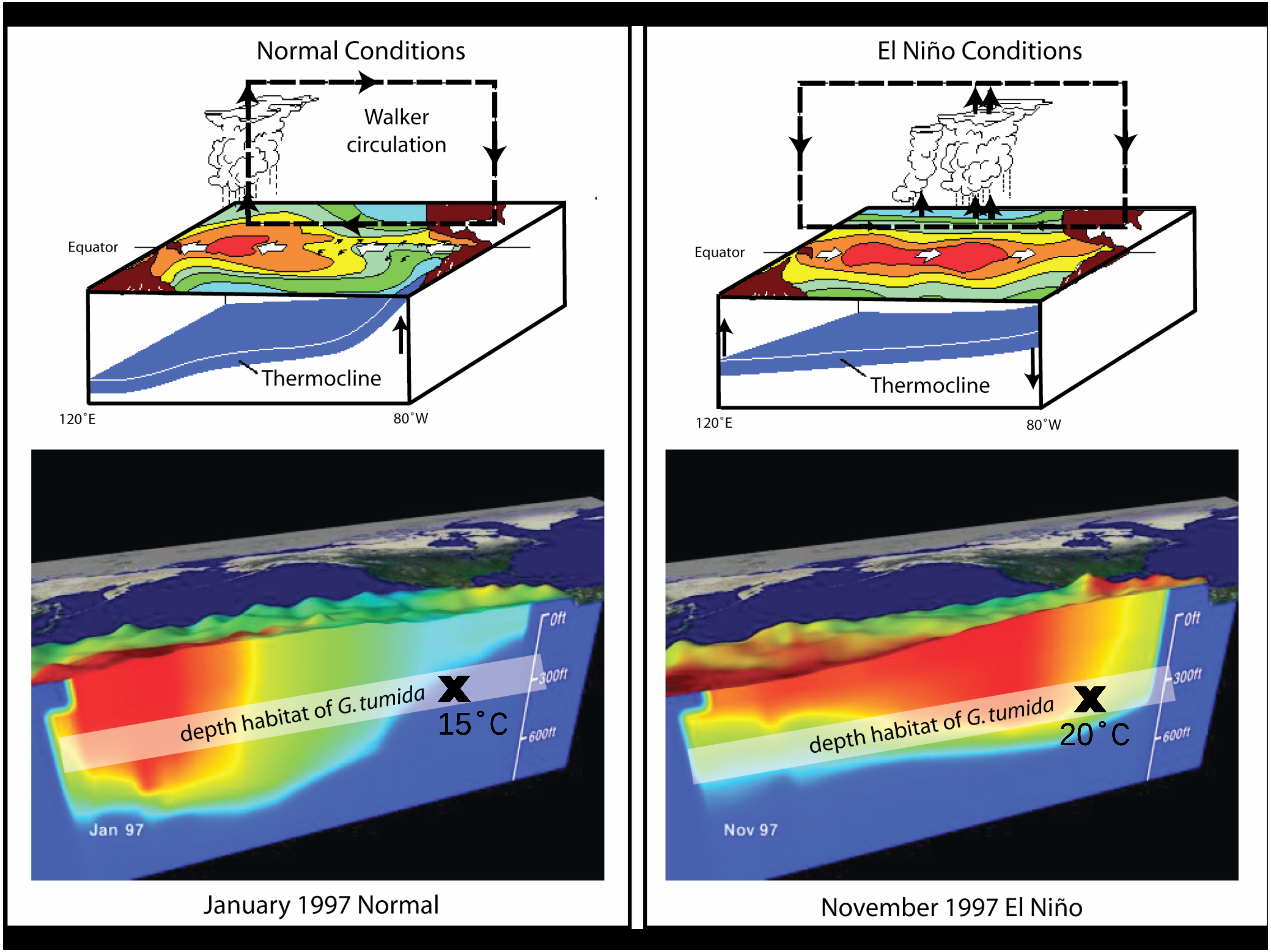
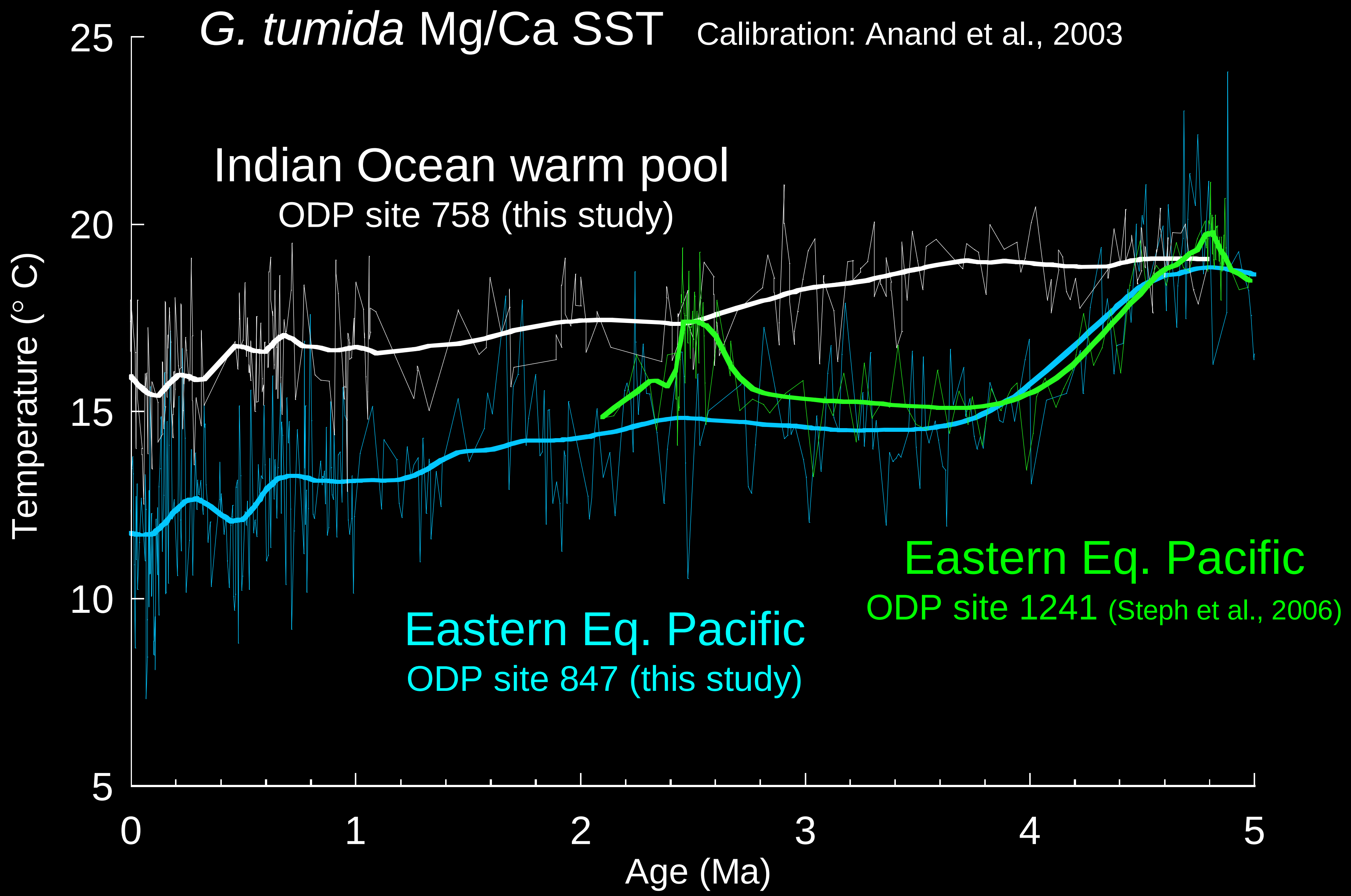


Harper, 2000

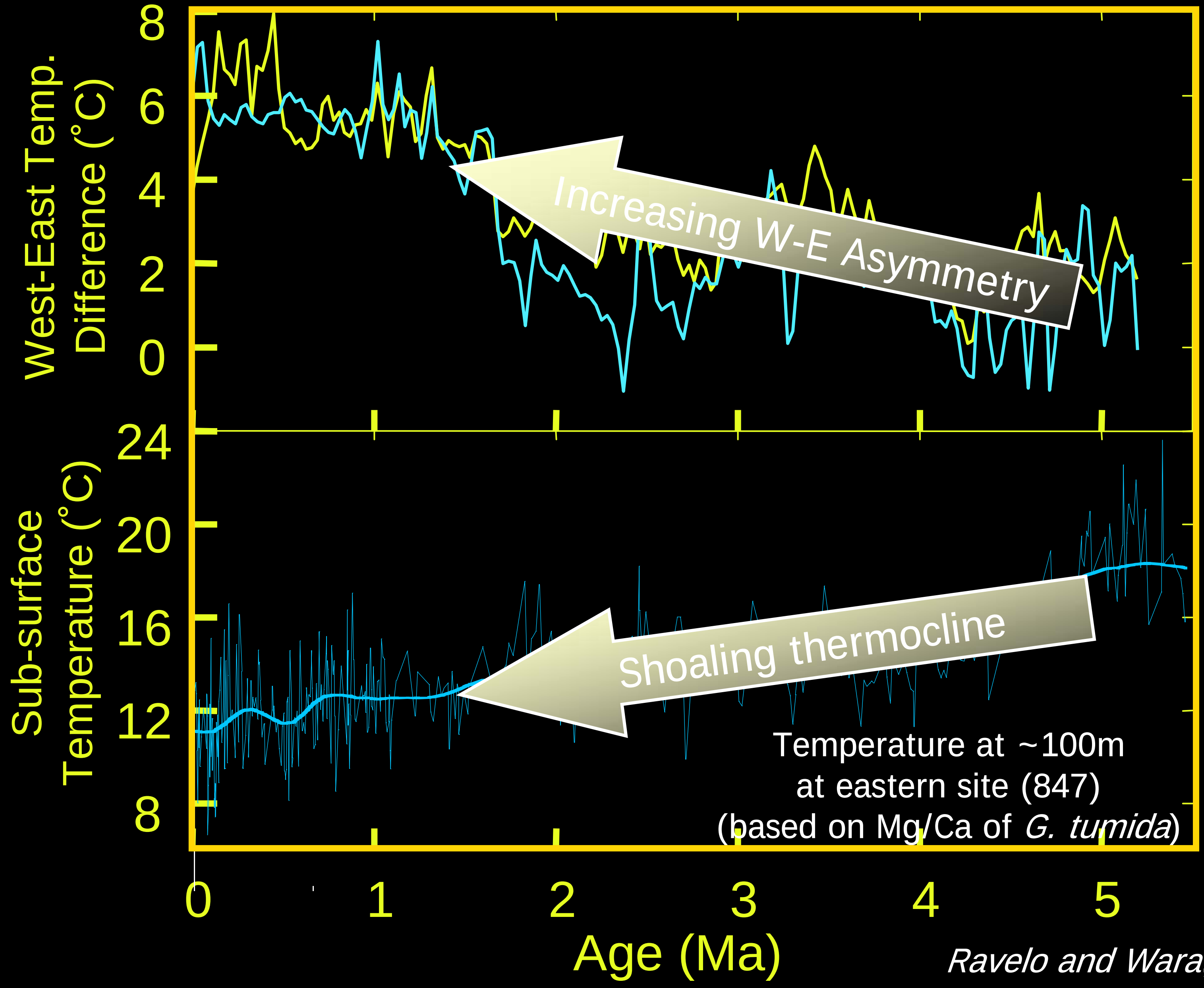


Normal Conditions
Walker circulation
Equator
Thermocline
120˚E
80˚W
depth habitat of G. tumida
15˚C
0ft
300ft
600ft
Jan 97
January 1997 Normal
El Niño Conditions
Equator
Thermocline
120˚E
80˚W
depth habitat of G. tumida
20˚C
0ft
300ft
600ft
Nov 97
November 1997 El Niño

Subsurface records (~100m)

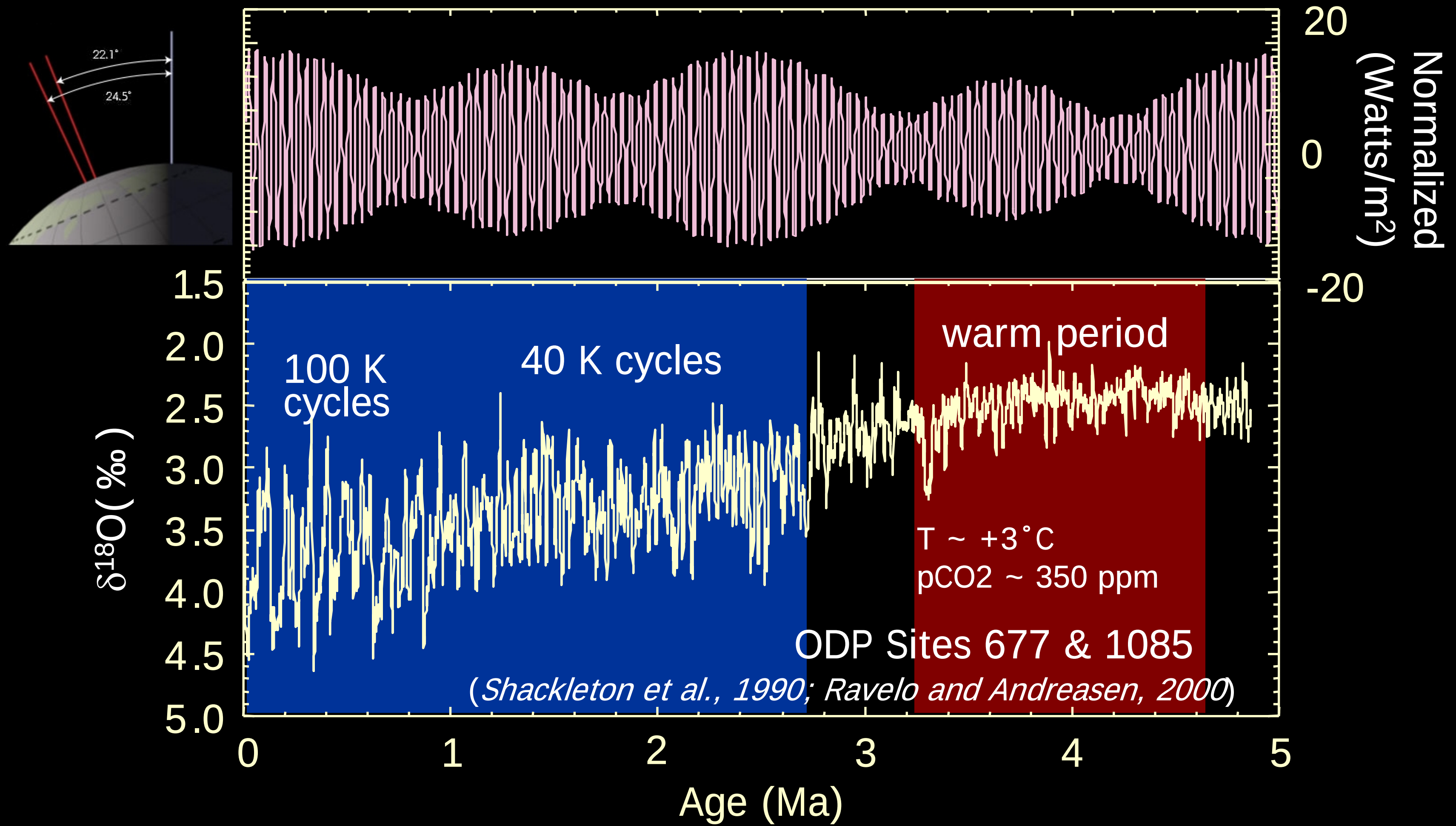


Role of the Thermocline in Development of West-East Asymmetry



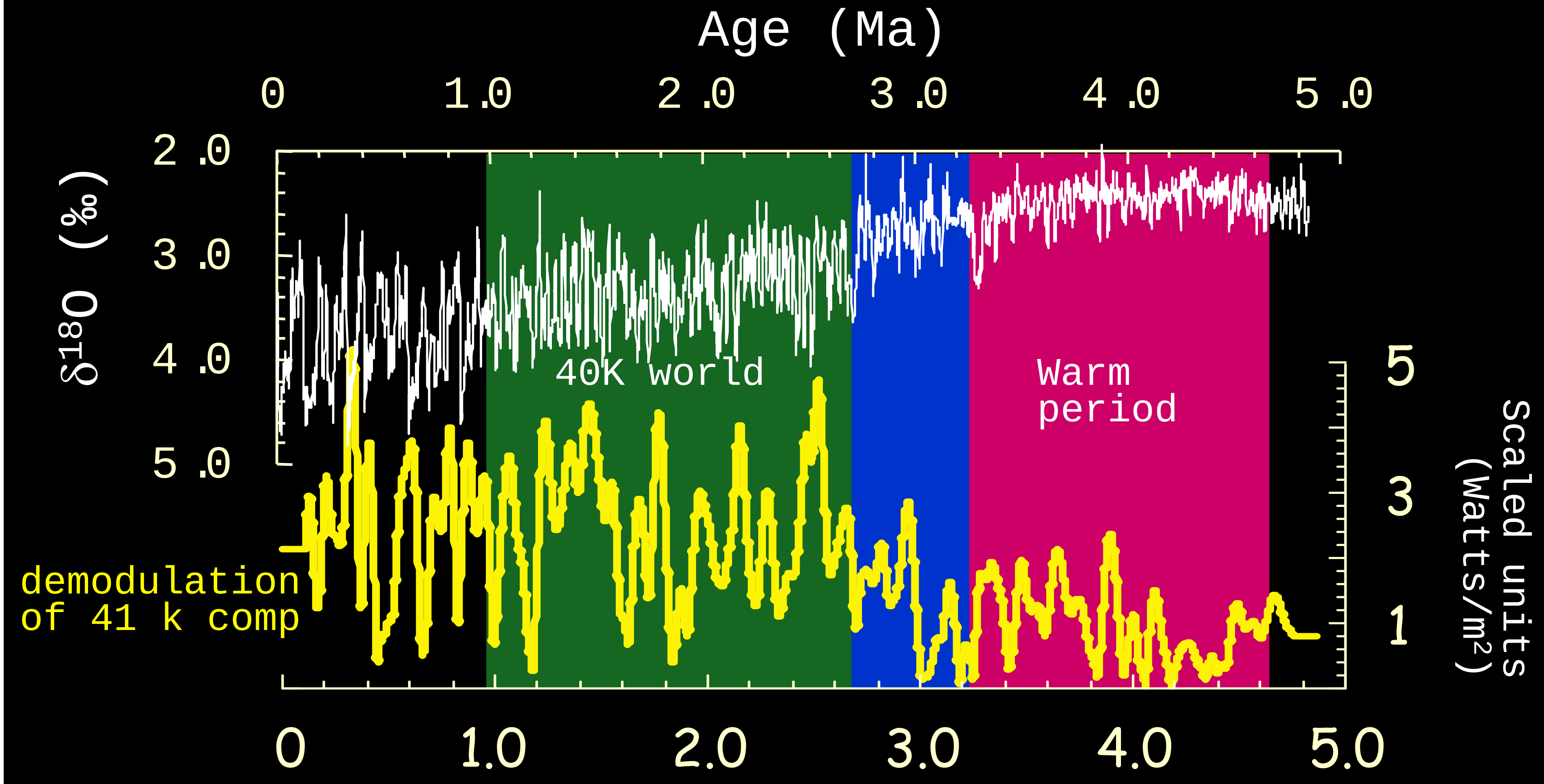
Ravelo and Wara, unpubl.

Increasing sensitivity of ice sheets

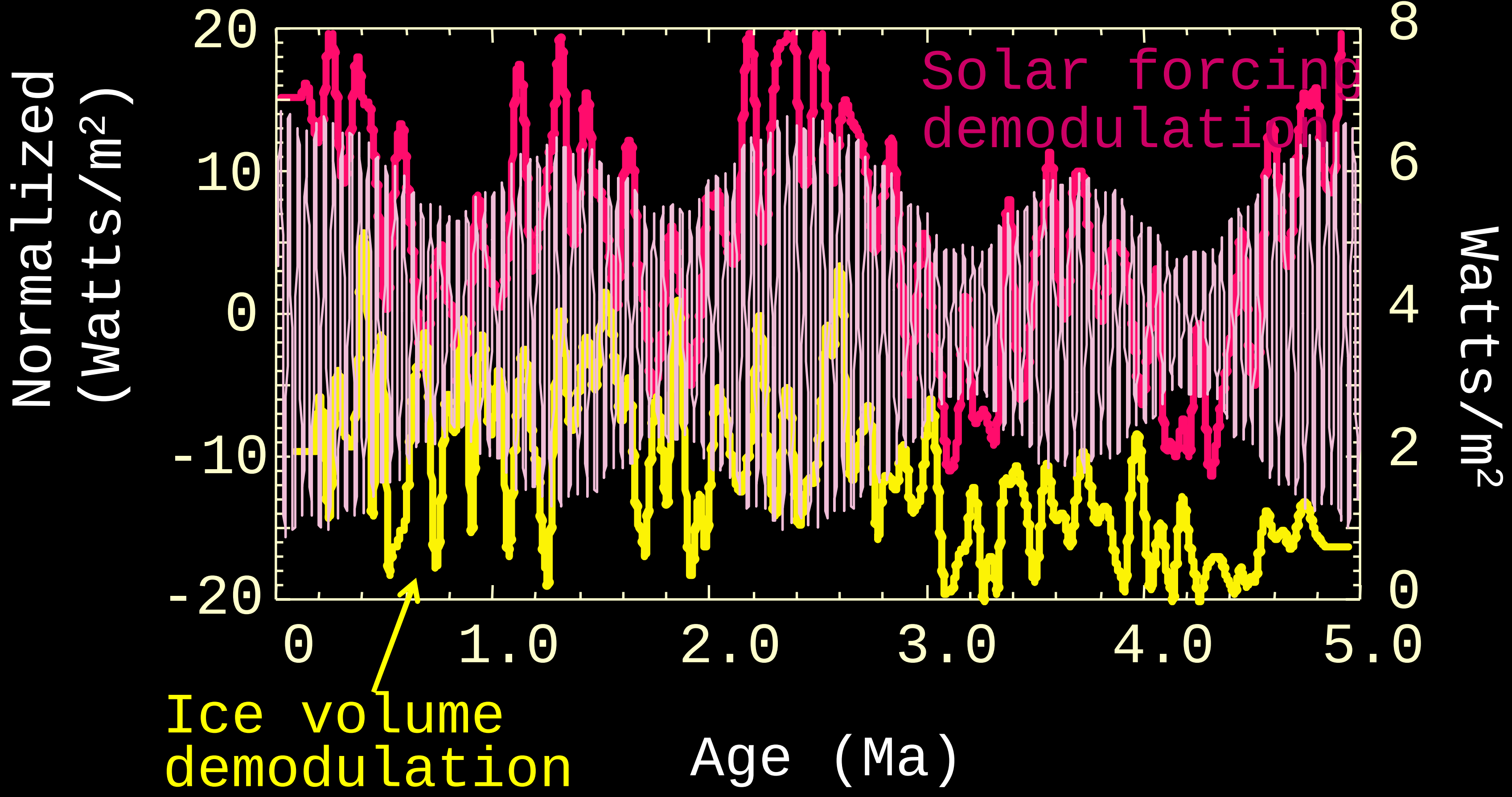


Prior to 1.0 Ma:
12% of variance in precession band
43% of variance in obliquity

Evolution of High Latitude Climate Sensitivity

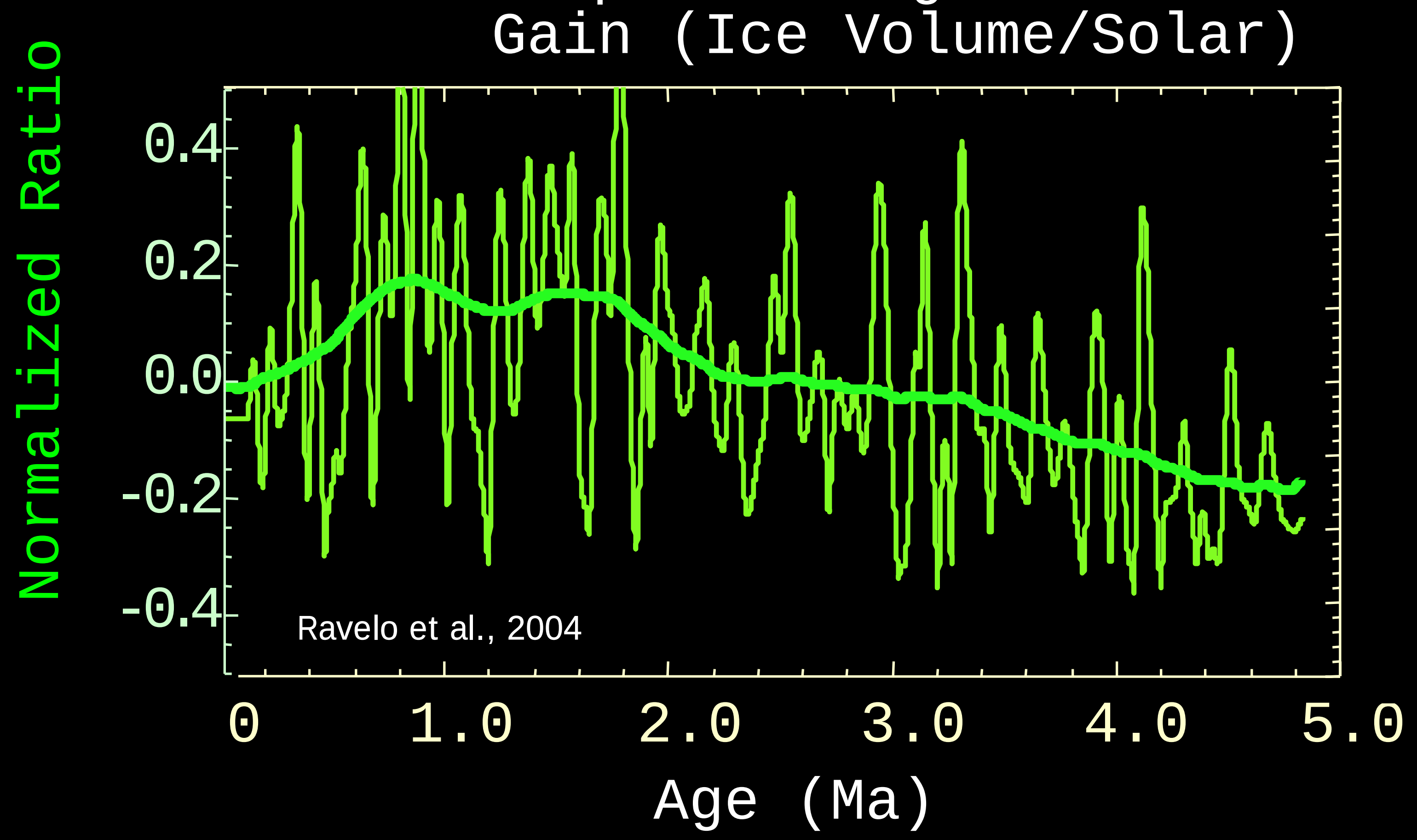


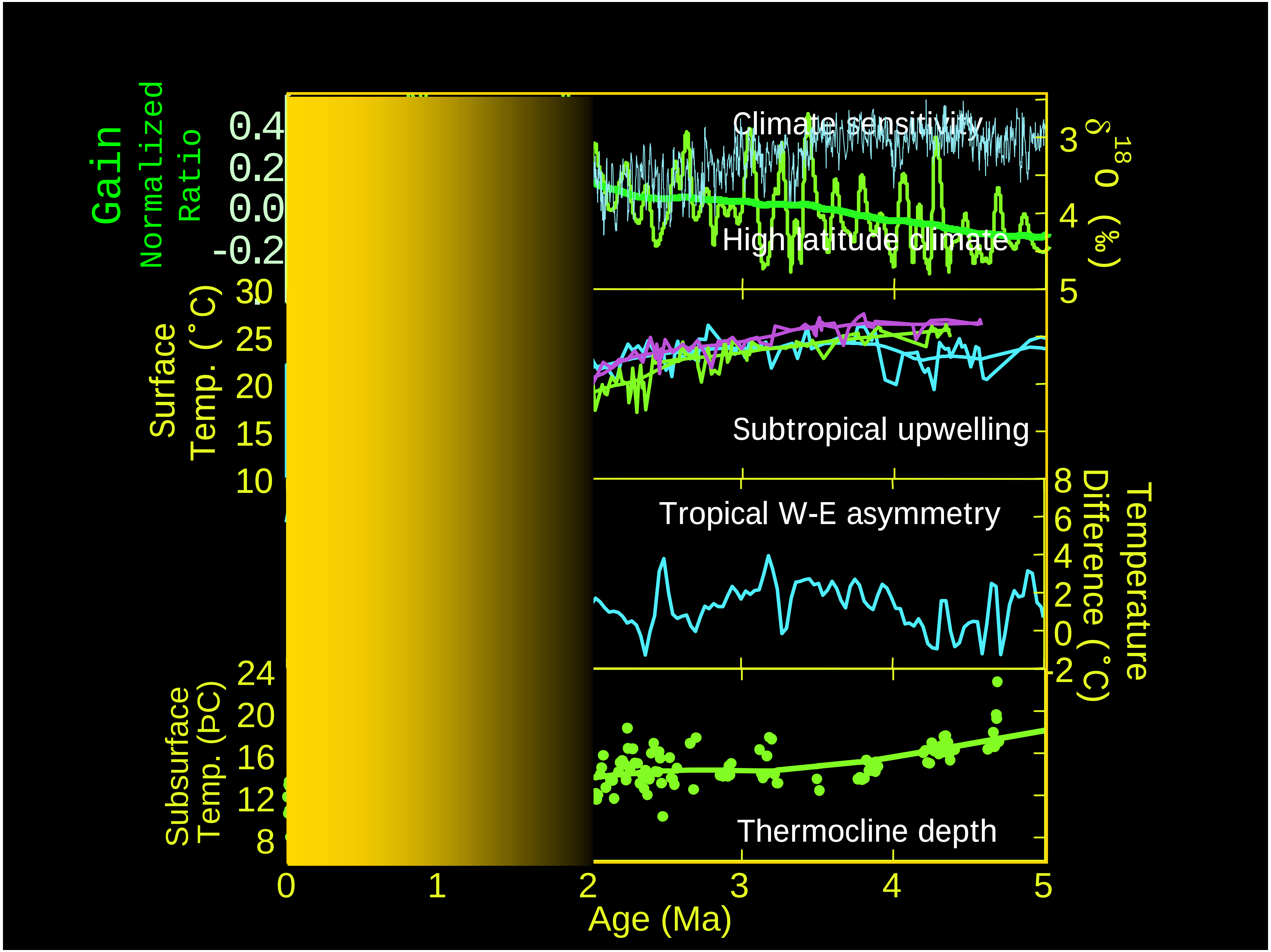
Solar Forcing (Obliquity)



Revised Look at High Lat. Climate Change
Highest sensitivity after ~ 2.0 Ma

Possibly due to development of strong air-sea interactions (Walker circulation) and strong zonal temperature gradients.





Gain
Normalized Ratio
0.4
0.2
0.0
-0.2
Climate sensitivity
High latitude climate
3
4
5
δ18O (‰)
Surface Temp. (°C)
30
25
20
15
10
Subtropical upwelling
Tropical W-E asymmetry
Temperature Difference (°C)
8
6
4
2
0
-2
Subsurface Temp. (ÞC)
24
20
16
12
8
Thermocline depth
0
1
2
3
4
5
Age (Ma)

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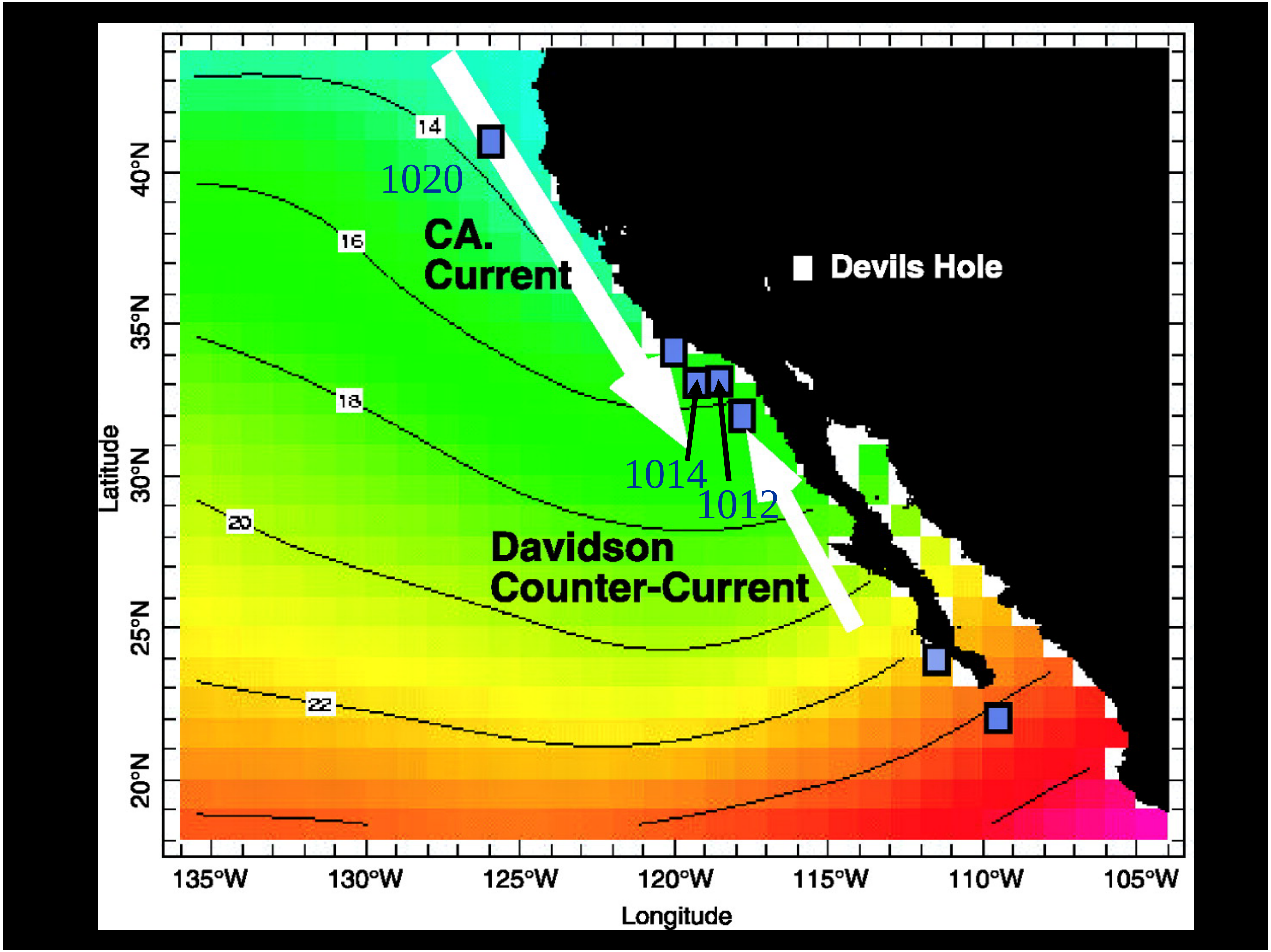
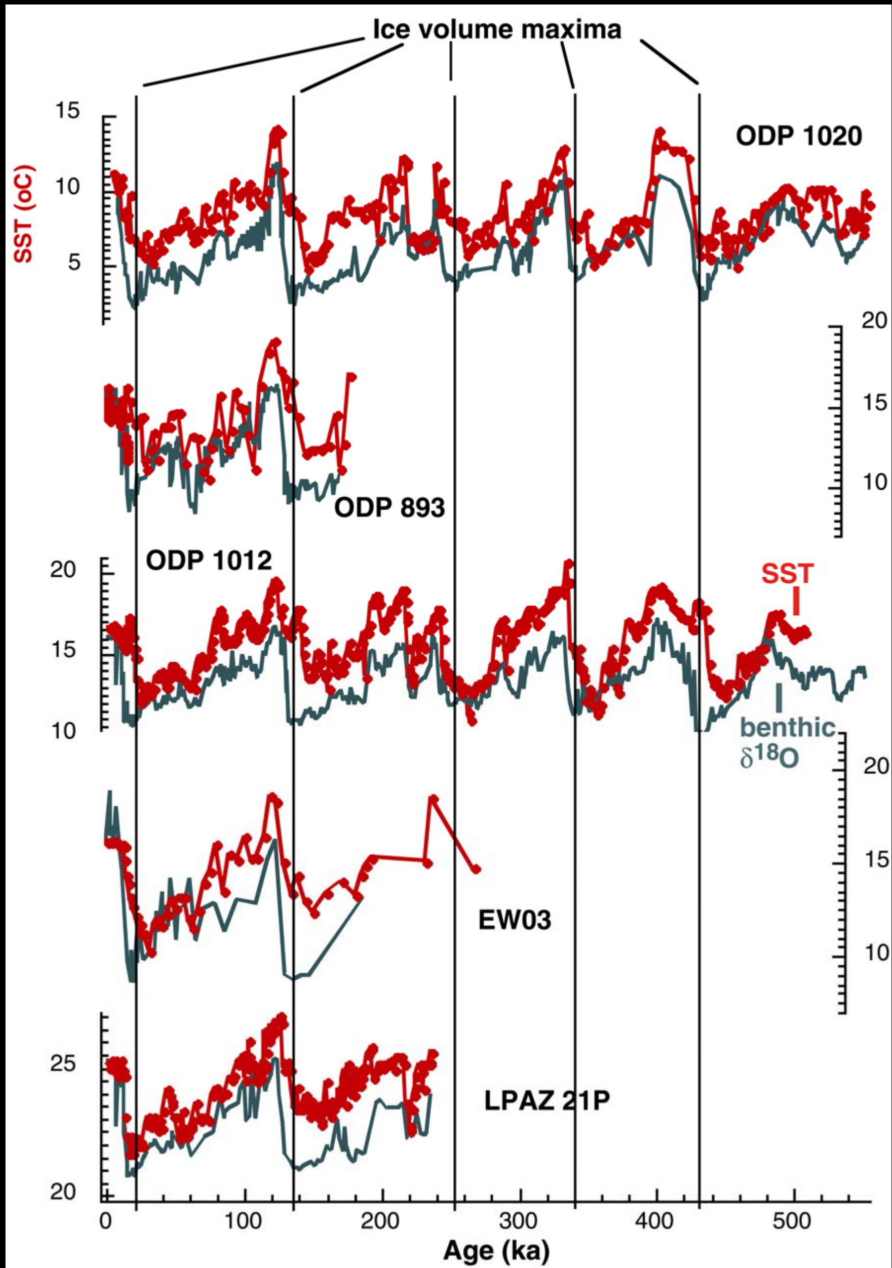


1020
CA.
Current
Devils Hole
1014
1012
Davidson
Counter-Current
14
16
18
20
22
40°N
35°N
30°N
25°N
20°N
Latitude
135°W
130°W
125°W
120°W
115°W
110°W
105°W
Longitude

California margin

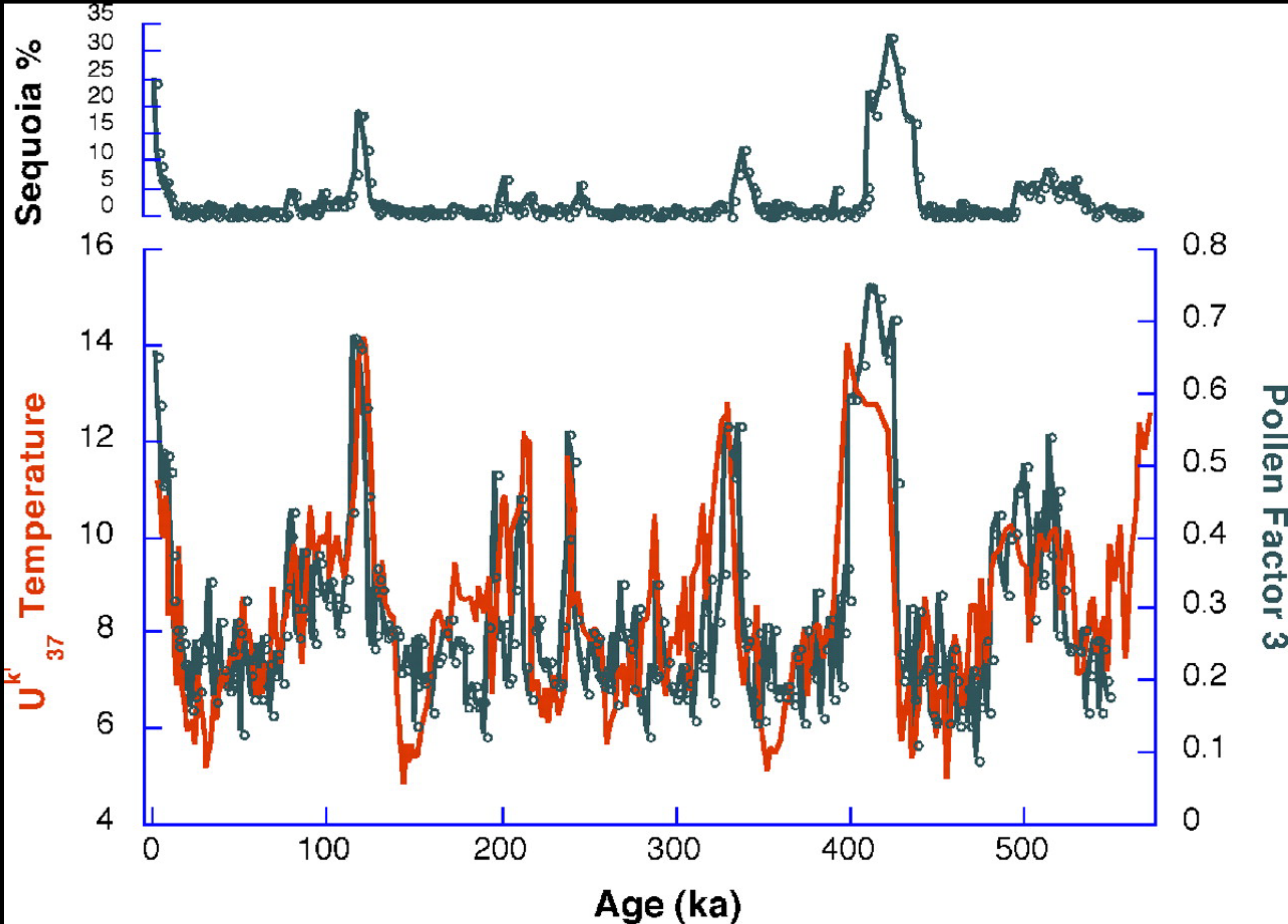


SST changes lead Ice Volume changes

Does thermocline play a role?

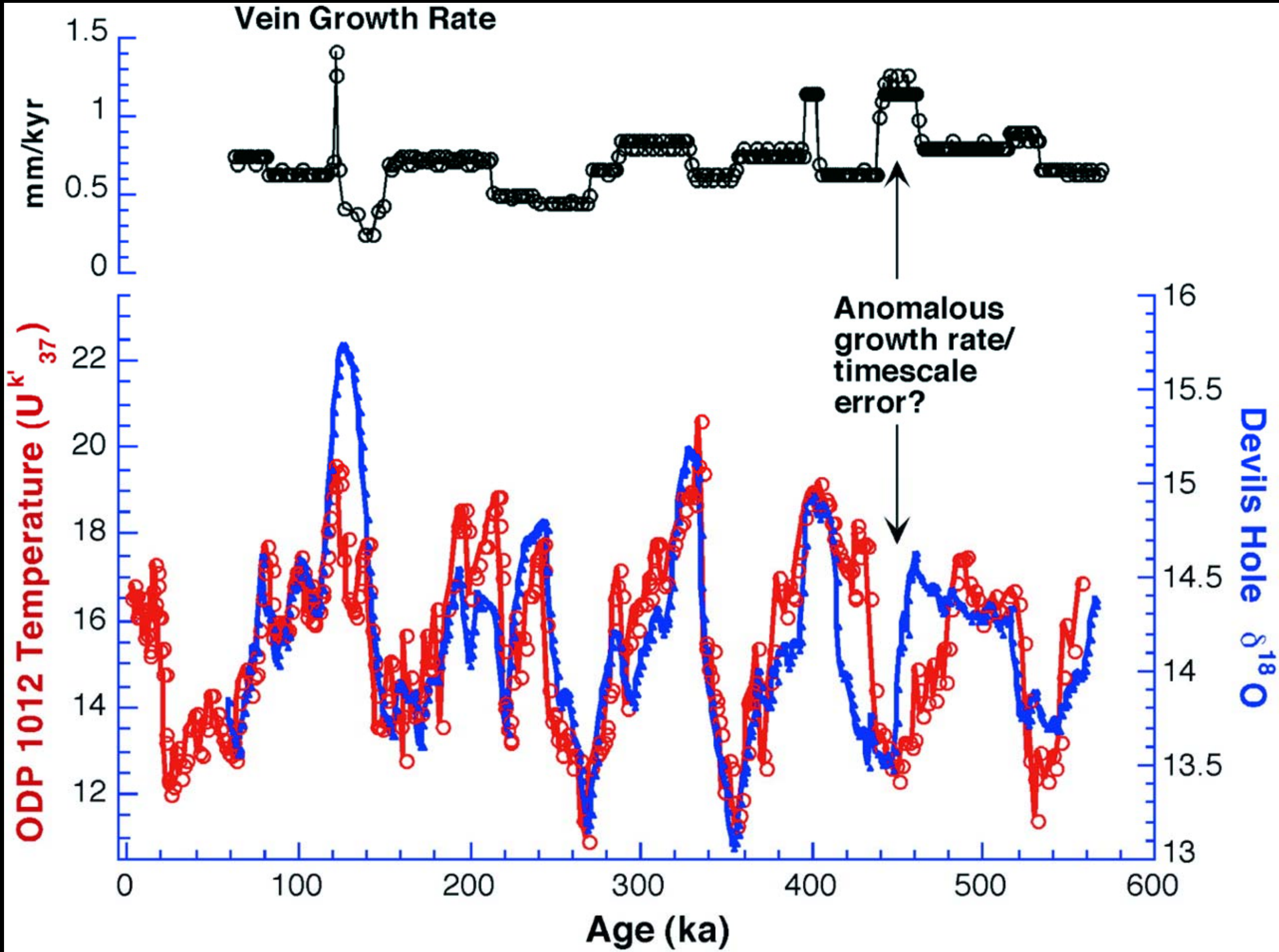
Herbert et al., 2001

California SST (ODP 1020) & Pollen

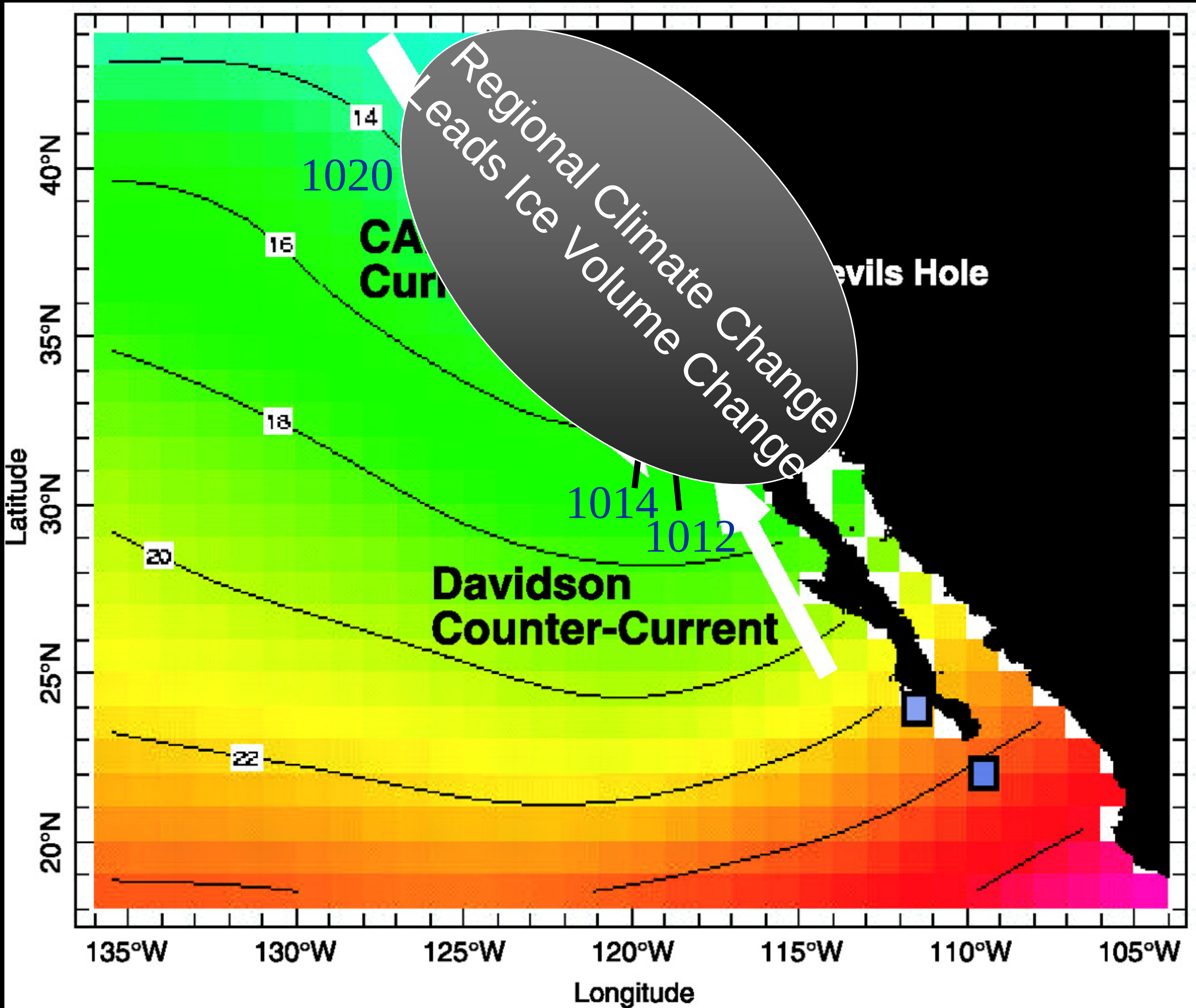


Herbert et al., 2001

California SST (ODP 1012) & Devil's Hole

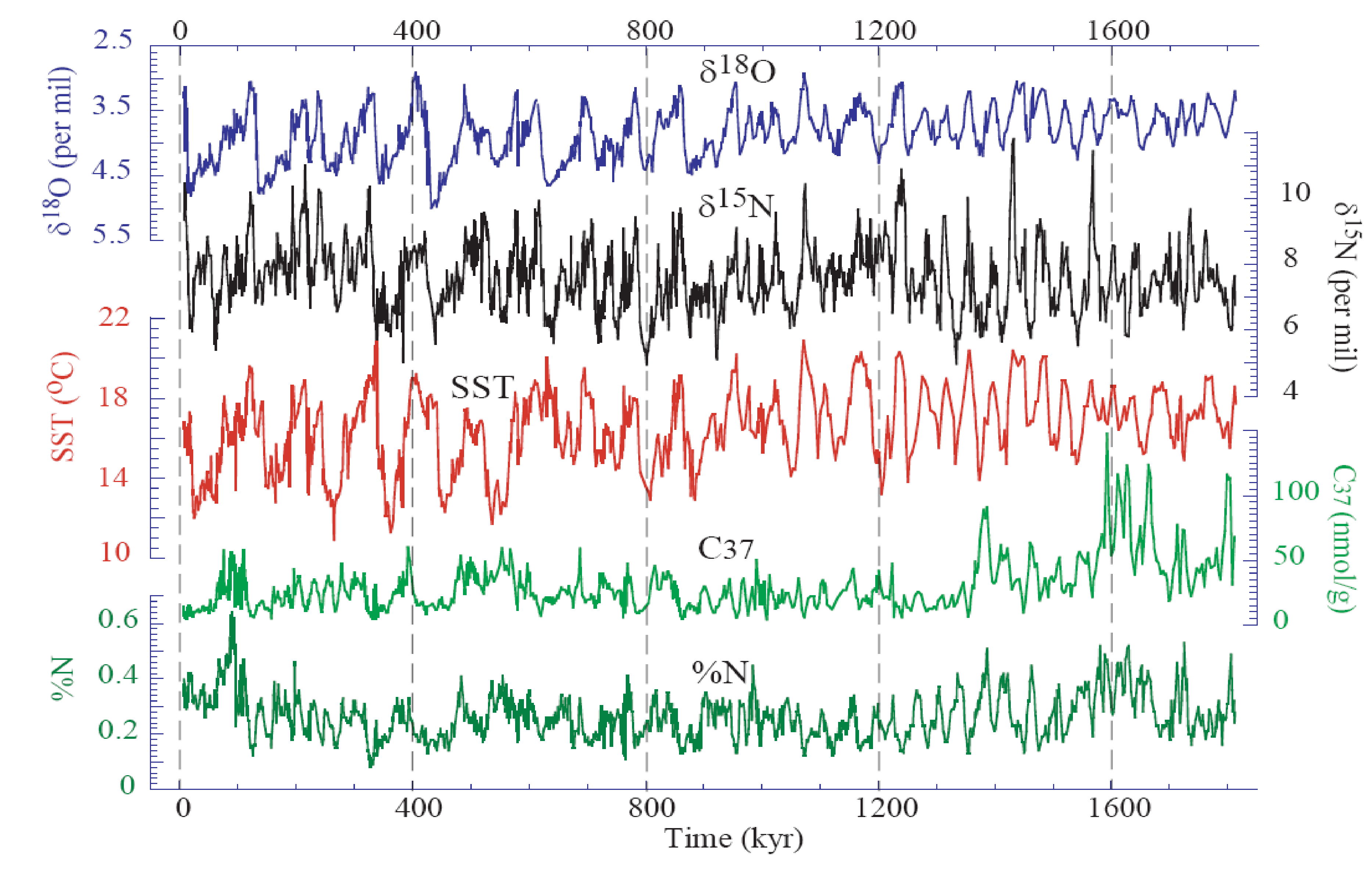


Herbert et al., 2001



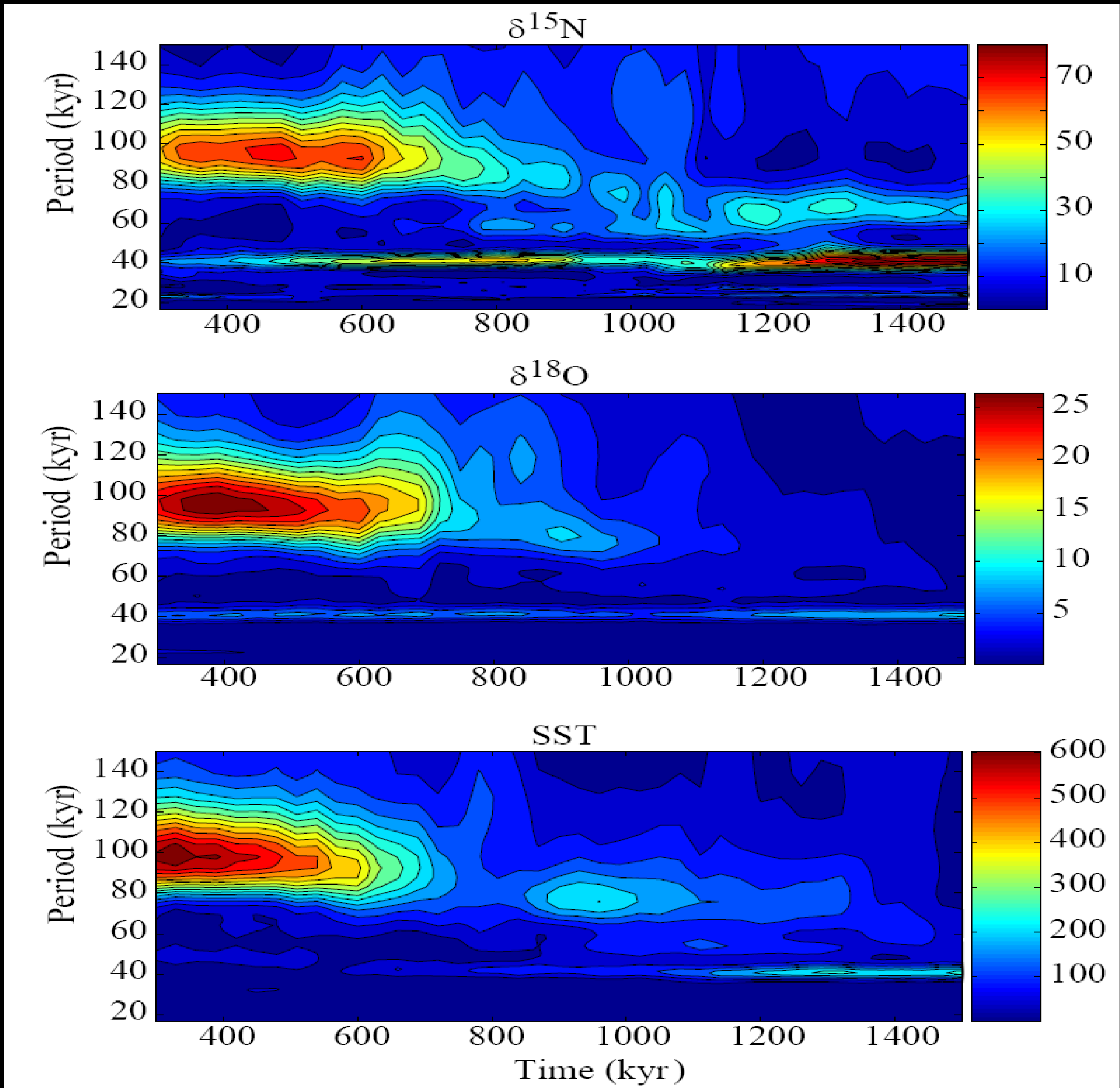
Regional Climate Change
Leads Ice Volume Change
1020
1014
1012
14
16
18
20
22
evils Hole
Davidson
Counter-Current
40°N
35°N
30°N
25°N
20°N
Latitude
135°W
130°W
125°W
120°W
115°W
110°W
105°W
Longitude

California margin (ODP Site 1012)



Liu et al., 2005

California margin (ODP Site 1012)



Liu et al., 2005

California margin (ODP Site 1012)

$\delta^{15}N$ of surface water

==> f ($\delta^{15}N$ of subsurface water, productivity)

Other productivity indicators suggest $\delta^{15}N$ is NOT related to productivity changes

$\delta^{15}N$ of subsurface water => f (oxygenation)

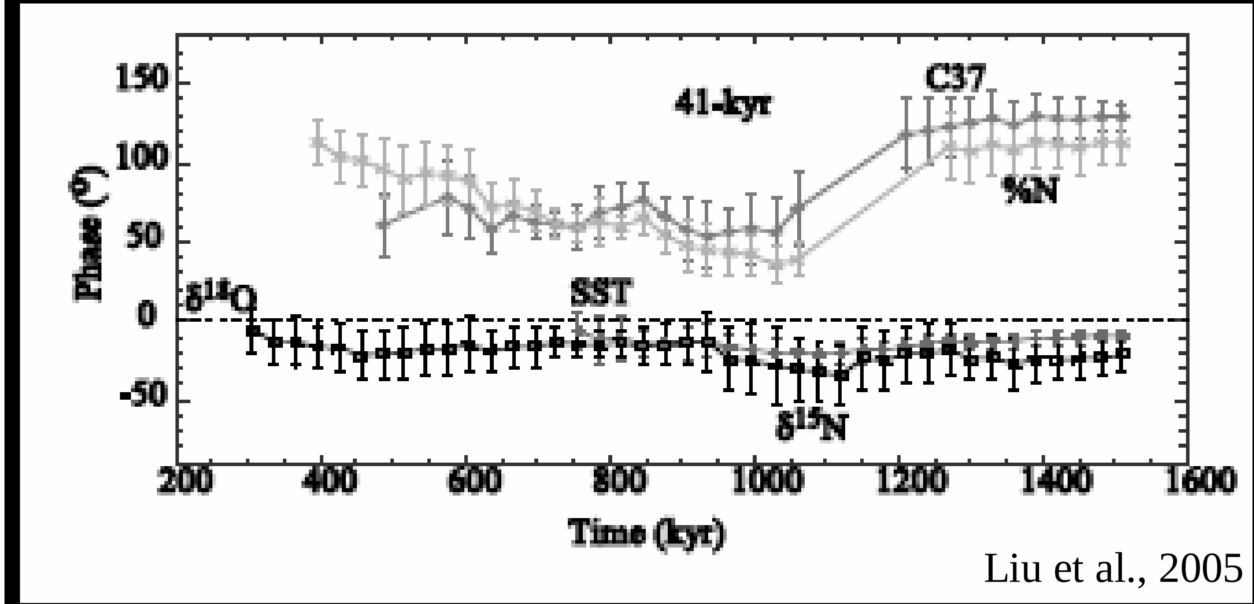
Subsurface $\delta^{15}N$ has mixture of sources from:

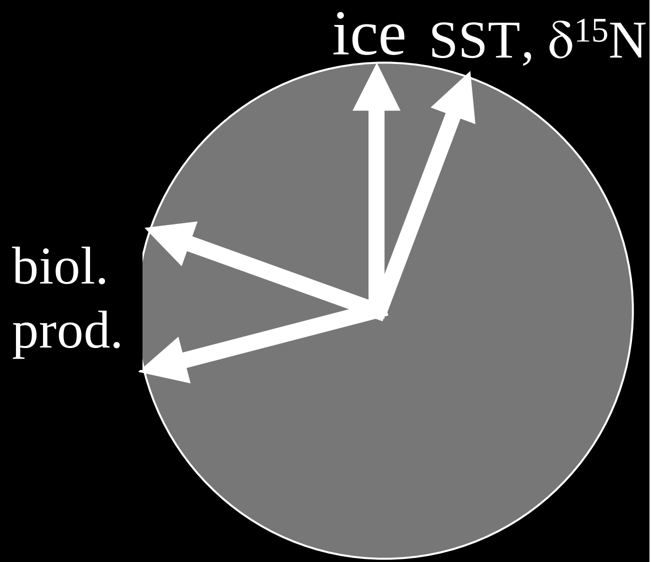
- S Pacific (intense oxygen depletion under zones of high productivity)
- N Pacific (more oxygenated)

Productivity exports ^{14}N preferentially over ^{15}N

High productivity leaves surface water rich in ^{15}N

California margin (ODP Site 1012)



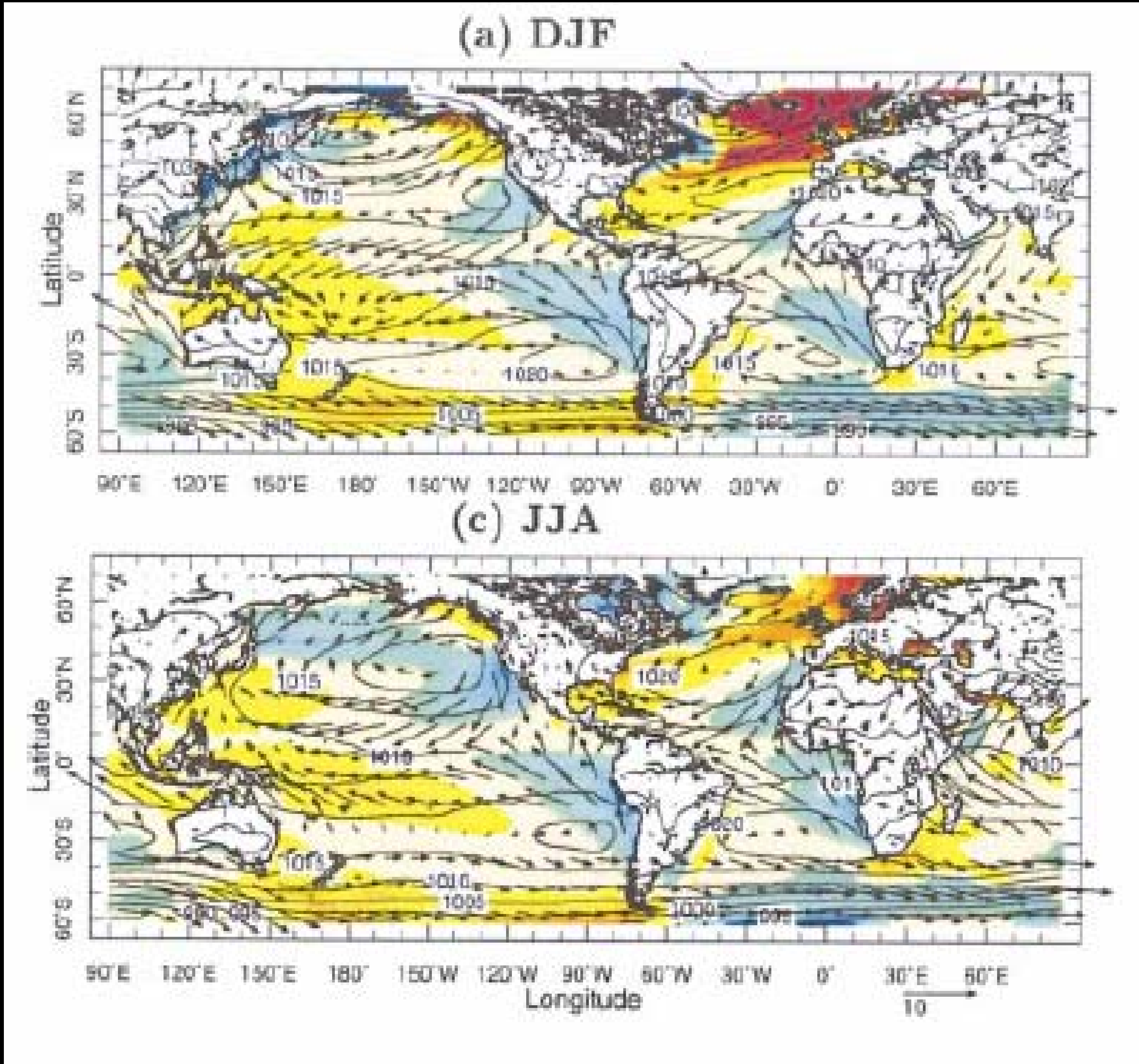


SST and $\delta^{15}N$ are in phase with each other, but lead productivity indicators

- both are tied to subsurface source water (not productivity)

SST and $\delta^{15}N$ lead $\delta^{18}O$ (ice volume) by ~2 kyrs

- subsurface source water changes before ice volume changes



Hawaii is a "dynamical" reference point - needed to put margin and equatorial data into a broader context.

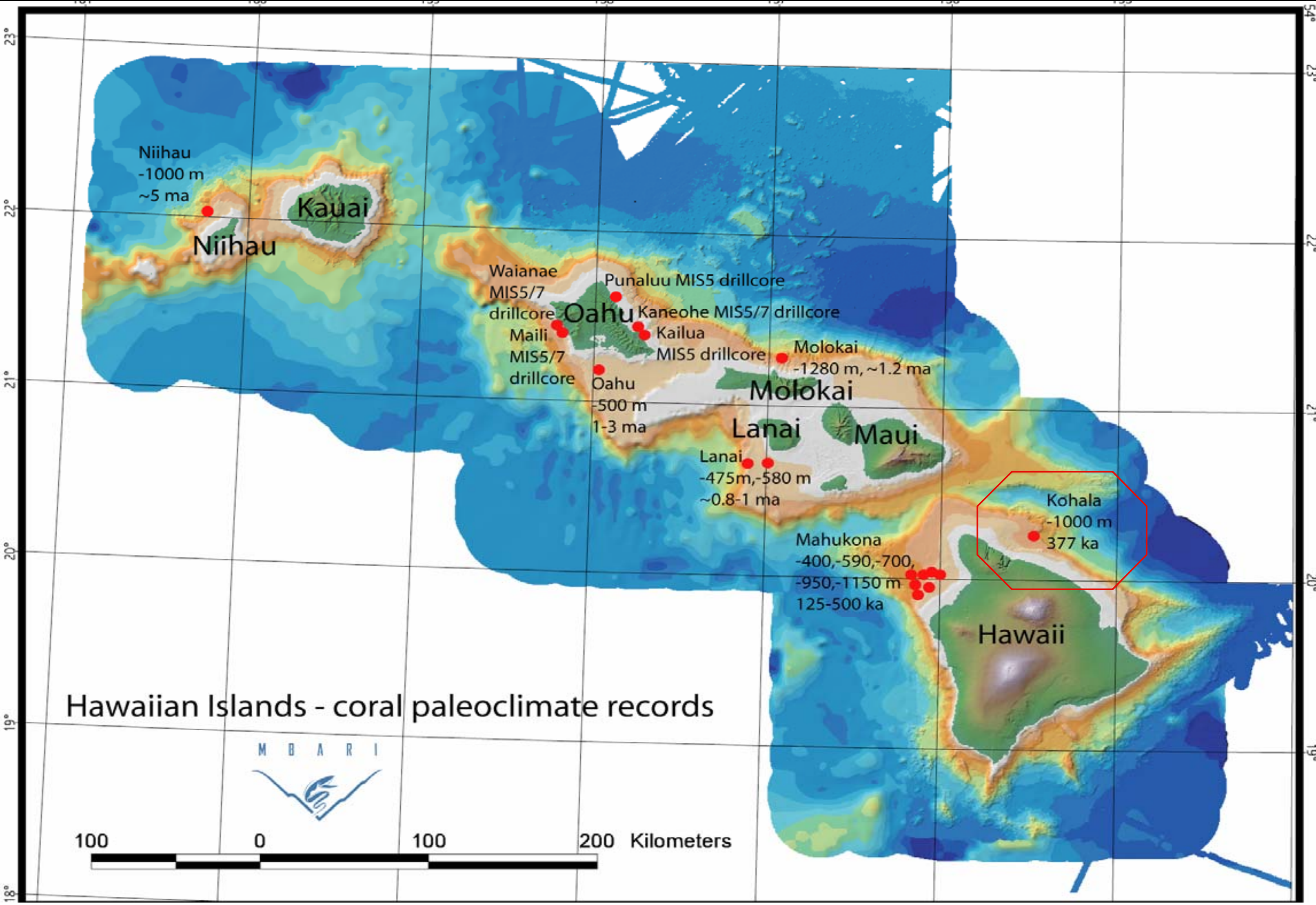
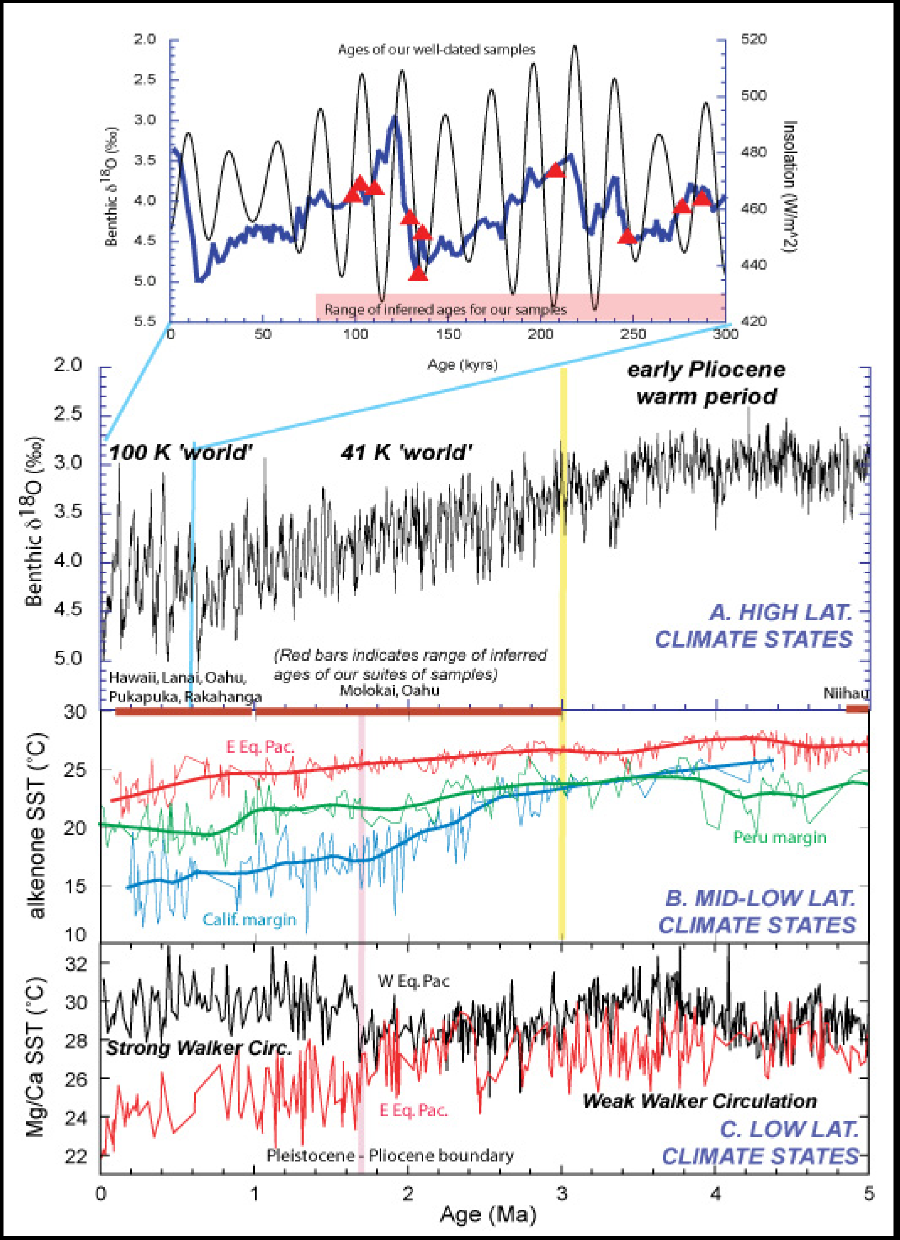
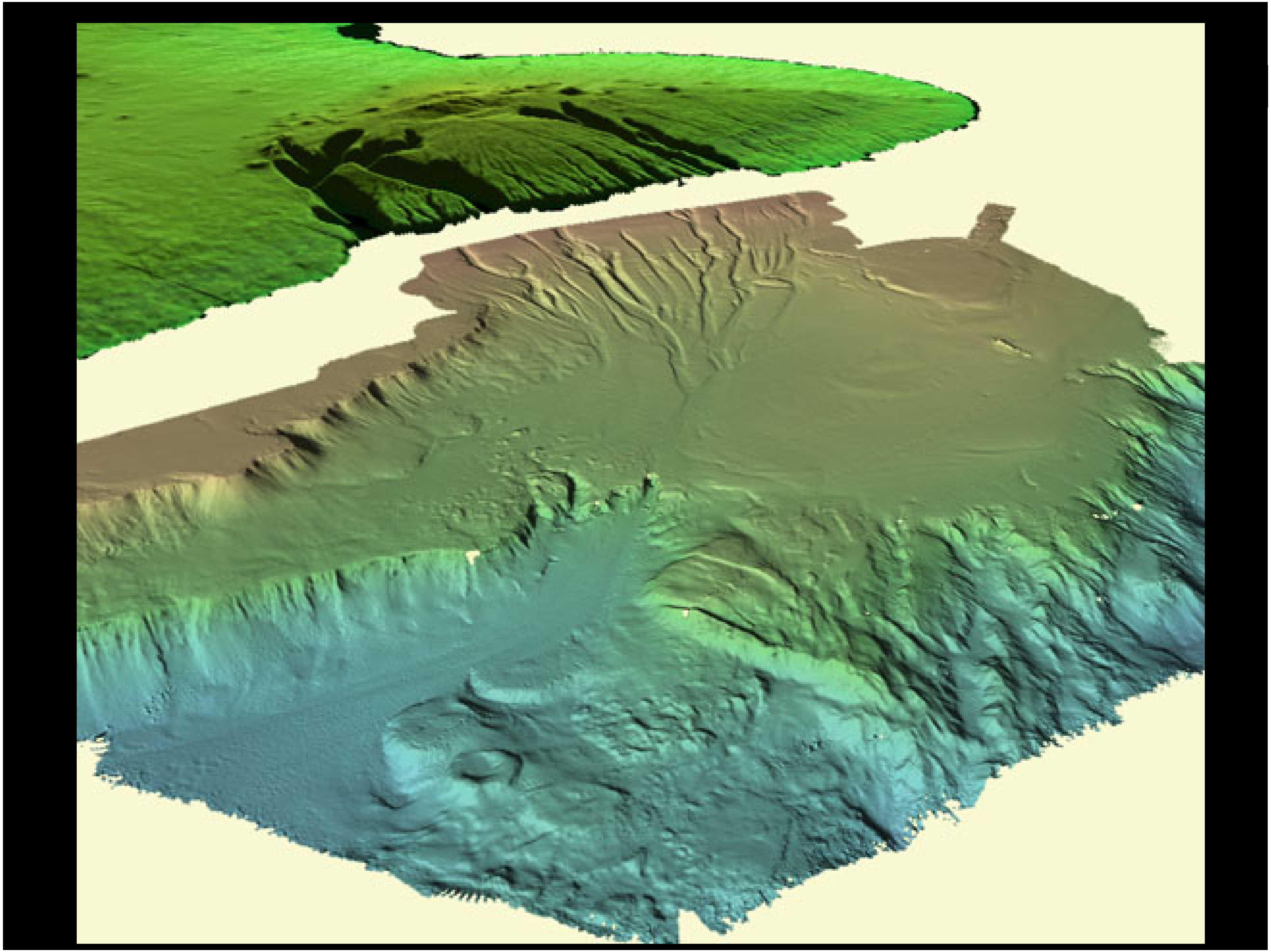


Fig. 4. Location of MHI samples displaying annual banding. A suite of samples is available from each location. Preliminary data is from Kohala -1000m reef on the Big Island. See text and Table 1 for details.


Ages of our well-dated samples
Benthic δ18O (‰)
Insolation (W/m^2)
Range of inferred ages for our samples
Age (kyrs)
early Pliocene
warm period
100 K 'world'
41 K 'world'
Benthic δ18O (‰)
A. HIGH LAT.
CLIMATE STATES
(Red bars indicates range of inferred
ages of our suites of samples)
Hawaii, Lanai, Oahu,
Pukapuka, Rakahanga
Molokai, Oahu
Niihau
alkenone SST (°C)
E Eq. Pac.
Peru margin
Calif. margin
B. MID-LOW LAT.
CLIMATE STATES
Mg/Ca SST (°C)
W Eq. Pac
Strong Walker Circ.
E Eq. Pac.
Weak Walker Circulation
C. LOW LAT.
CLIMATE STATES
Pleistocene - Pliocene boundary
Age (Ma)



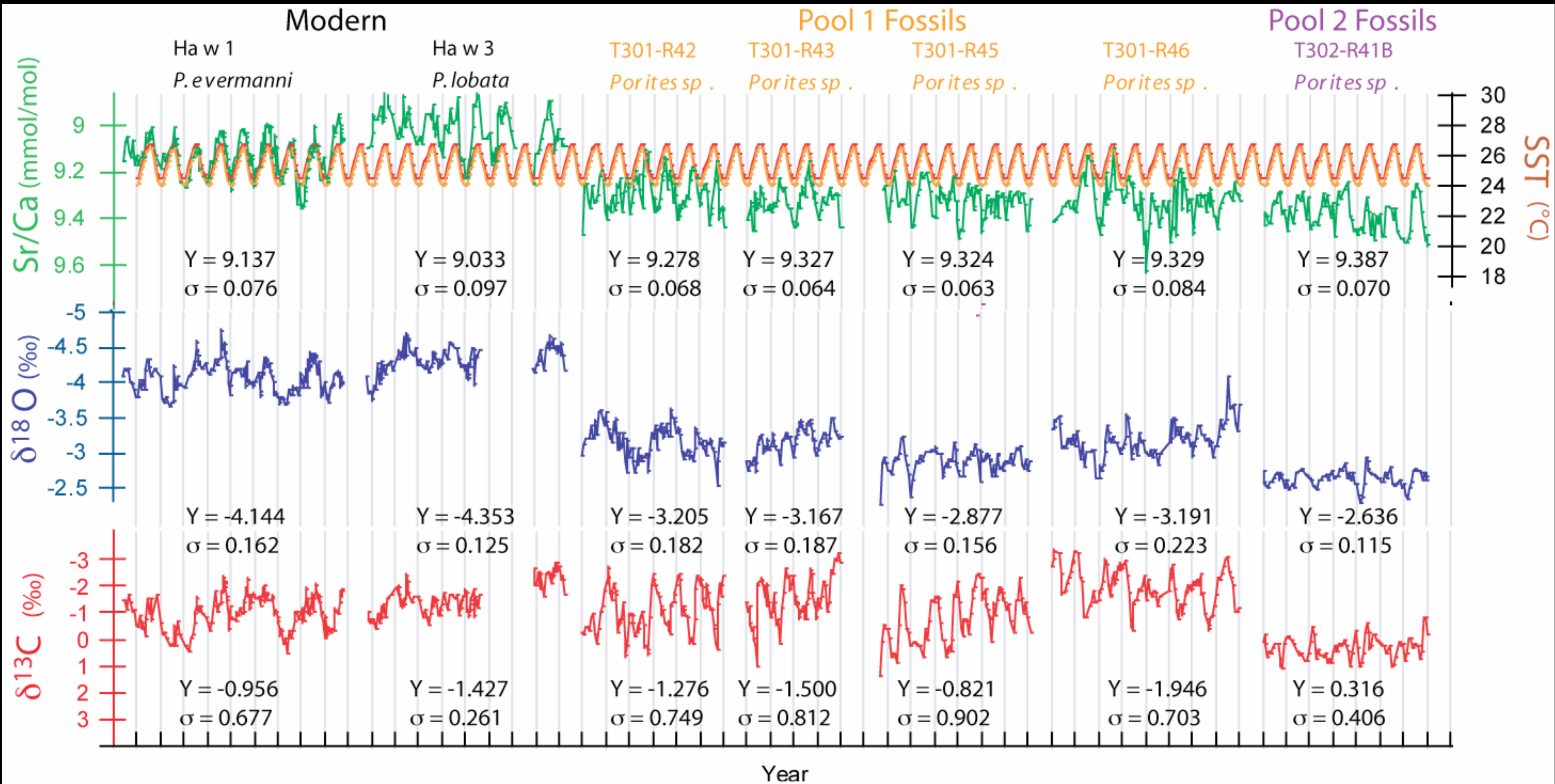


Fig. 7. Bulk measurements of modern and MIS11 corals. Pool 1 corals are from adjacent colonies, and Pool 2 is at a different location on the same reef (and could be of a different age within MIS11). Sr/Ca records (green) are plotted on top of the modern annual SST signal repeated many times (red and gold), so that the Sr/Ca record of the modern *P. evermanni* coral overlaps with modern SST. $\delta^{18}O$ (blue) and Sr/Ca records show an offset between modern and fossil samples. Note that the seasonal cycle is harder to resolve in the $\delta^{18}O$ compared to the Sr/Ca record because of the SSS/$\delta^{18}Osw$ effects on $\delta^{18}O$ of the corals. $\delta^{13}C$ records (red) show that the averages for fossil corals are not significantly different than for modern corals, but that the amplitude of the variability was different. See Fig. 10 for some preliminary evidence that cloudiness/rainfall variability is embedded in the $\delta^{18}O$ and $\delta^{13}C$ records.

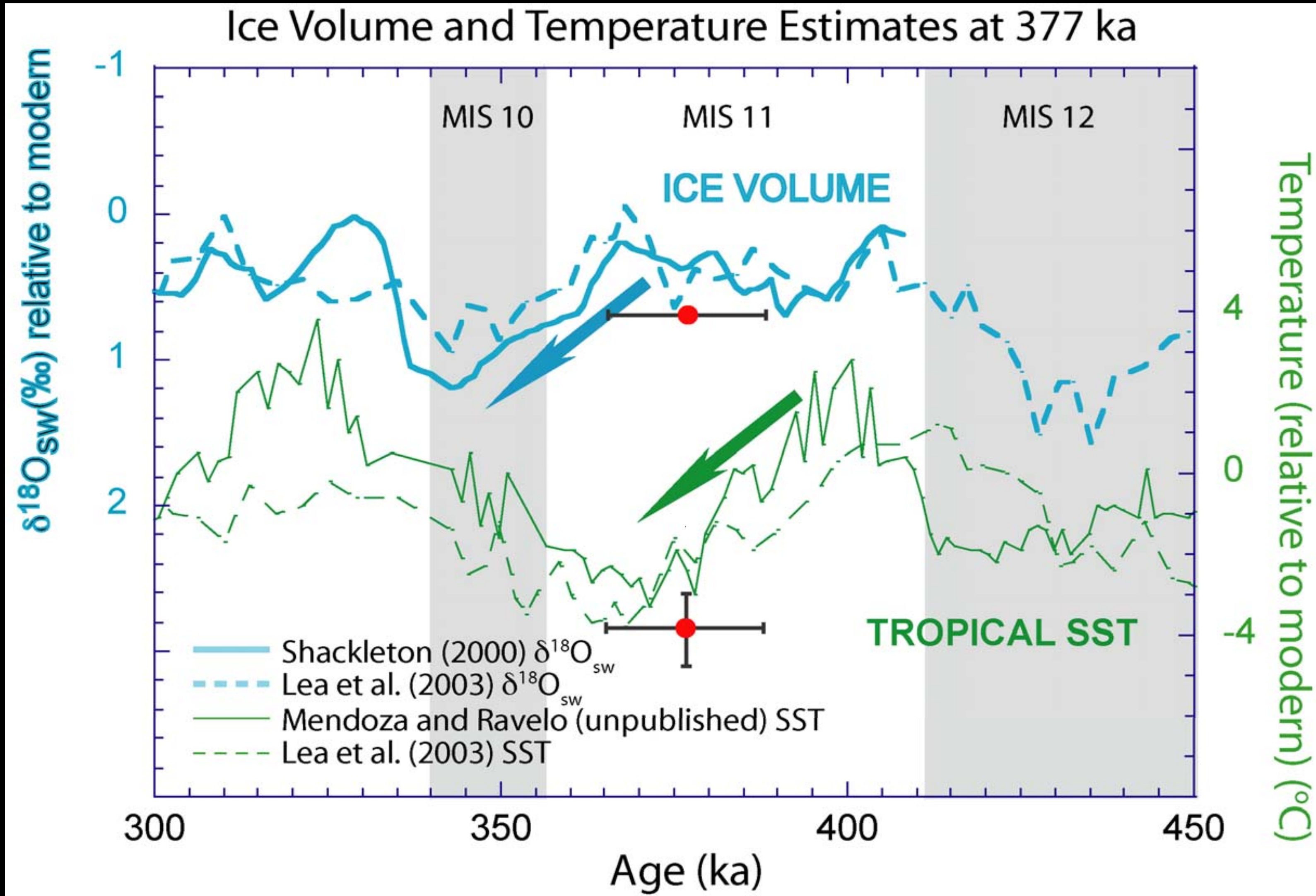


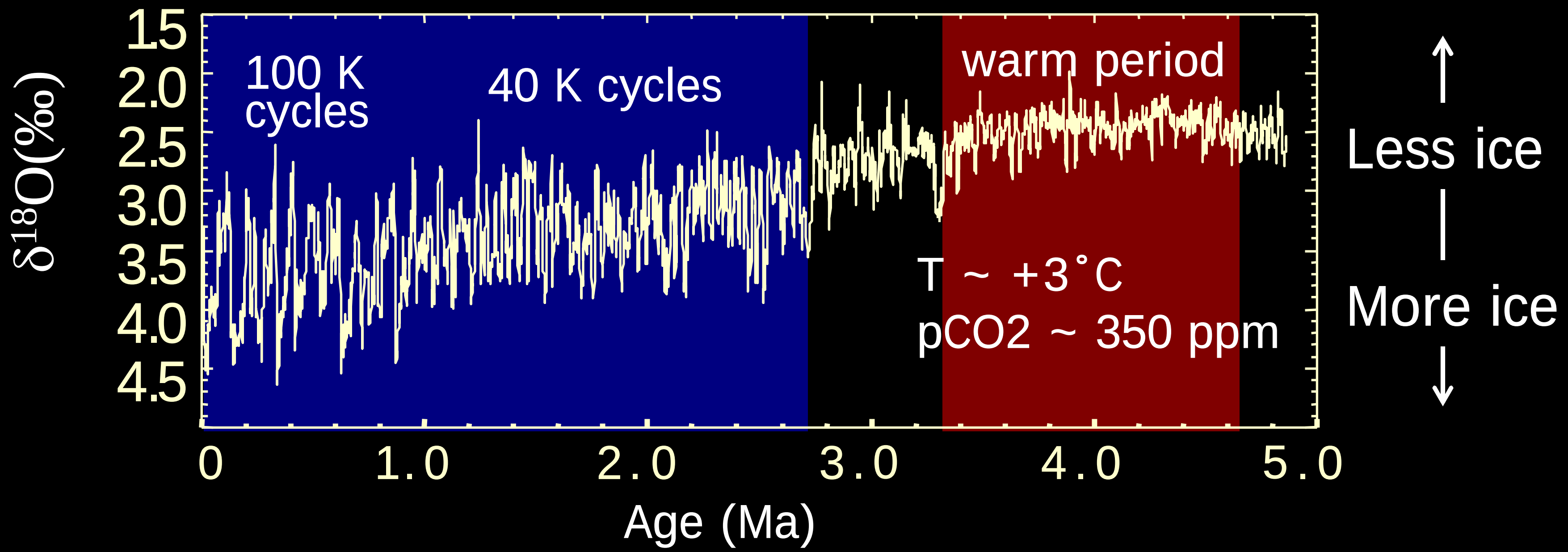
Fig. 9. Ice volume, reflected by the $\delta^{18}O_{sw}$ records (solid light blue curve from *Shackleton*, 2000, dashed light blue curve from *Lea et al*. 2003), and SST from the western eq. Pacific (dashed green curve is Mg/Ca derived SST at ODP Site 806 at 0˚, 150˚E *Lea et al*. 2003) and from the eastern eq. Pacific (solid green curve is unpublished alkenone-derived SST from ODP Site 847 at 0˚, 95˚W generated at UCSC). The red dots are the SST and $\delta^{18}Osw$ at Hawaii, reconstructed from Sr/Ca on our 377 ka fossil corals (horizontal error bars are error on age, and vertical bars are the range of SST and $\delta^{18}Osw$ estimates, from Fig. 8).

Summary (Trends of last 5 Ma)

- TRENDS OF LAST 5 MYRS
  - Increasing W-E Pacific SST asymmetry
    - La Madre ended and Walker Circulation intensified?
  - Decreasing SST in upwelling regions
    - Distant upwelling regions are linked mechanistically?
  - Cooling subsurface temperature
    - Shoaling or cooling thermocline could link distant upwelling regions?
  - Increasing ice volume amplitude relative to solar forcing
    - Climate sensitivity enhanced due to development of strong zonal gradients and air-sea feedbacks?
  - Tropical and sub-tropical climate changes began before NH glaciation
    - Global cooling was NOT driven by ice sheets themselves?
- MILANKOVITCH CYCLES
  - SST cycles and $\delta^{15}N$ cycles are synchronized and lead ice volume cycles
    - Changes in sub-surface conditions drove SST changes?
- Lots of QUESTIONS such as:
  - Can state-of-the-art models reproduce these changes?
  - What controls the depth of the thermocline?
  - Is La Madre the ‘normal’ state during warm global climates?
  - Does La Madre cause ‘feedbacks’ that enhance global warming?

Climate of the Last 5 Ma

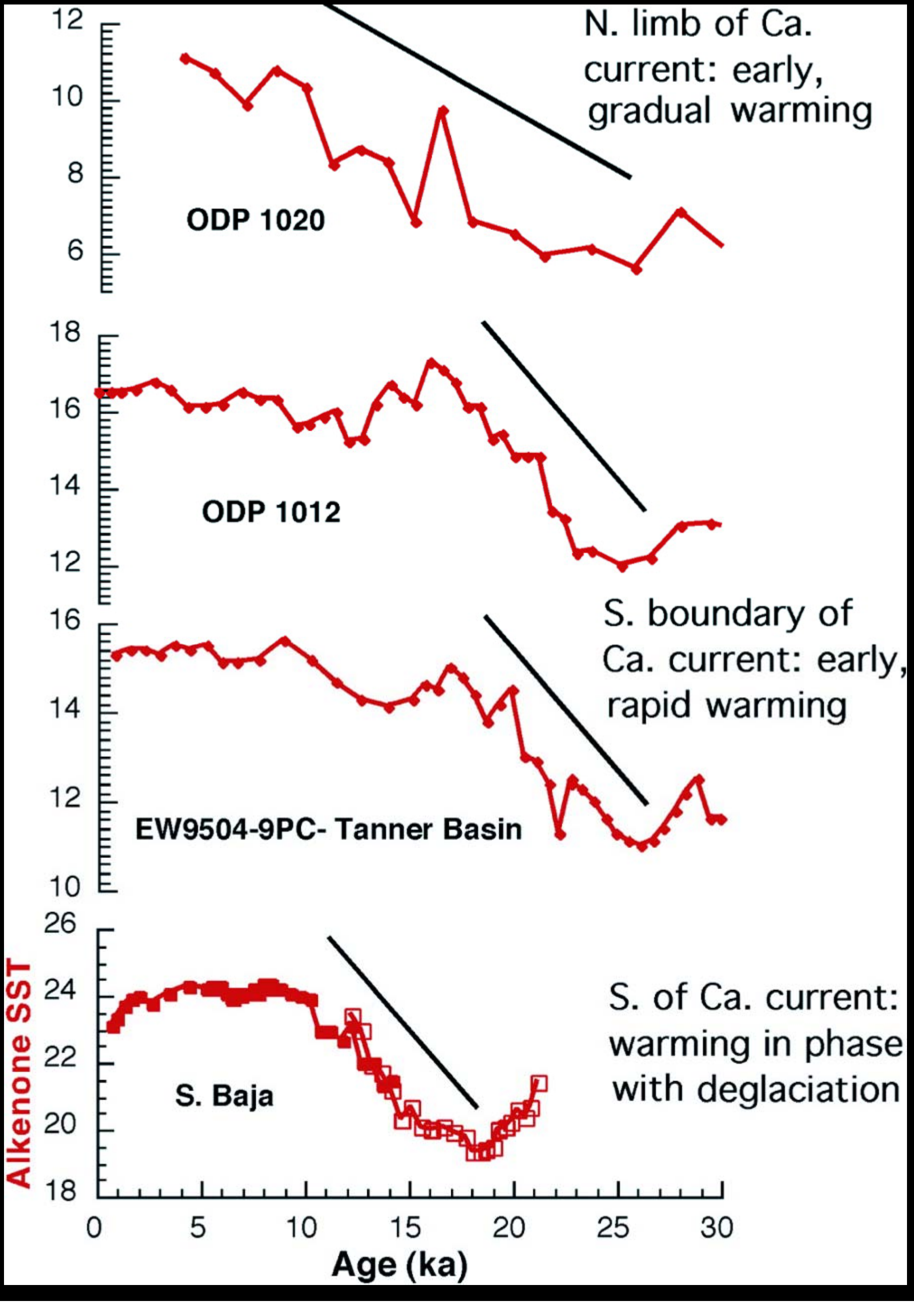
Benthic Oxygen Isotope Record => high lat. record



Pliocene: Implies a much higher climate sensitivity than predicted by models.

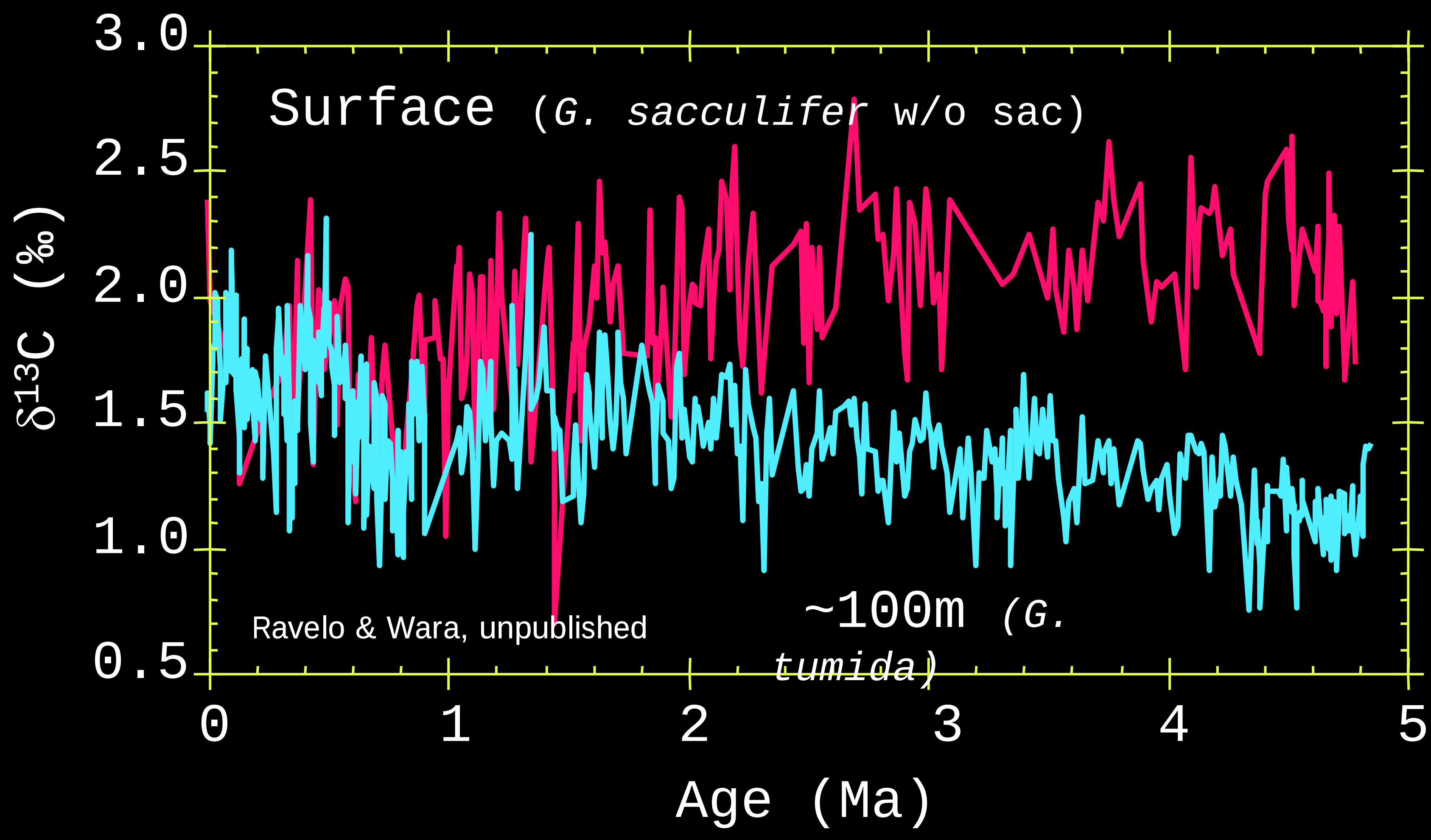
- What happened at lower latitudes?
- Why was Earth warmer before 3 Ma? What feedbacks were involved?
- Why did the Earth's sensitivity to solar forcing change?

California margin



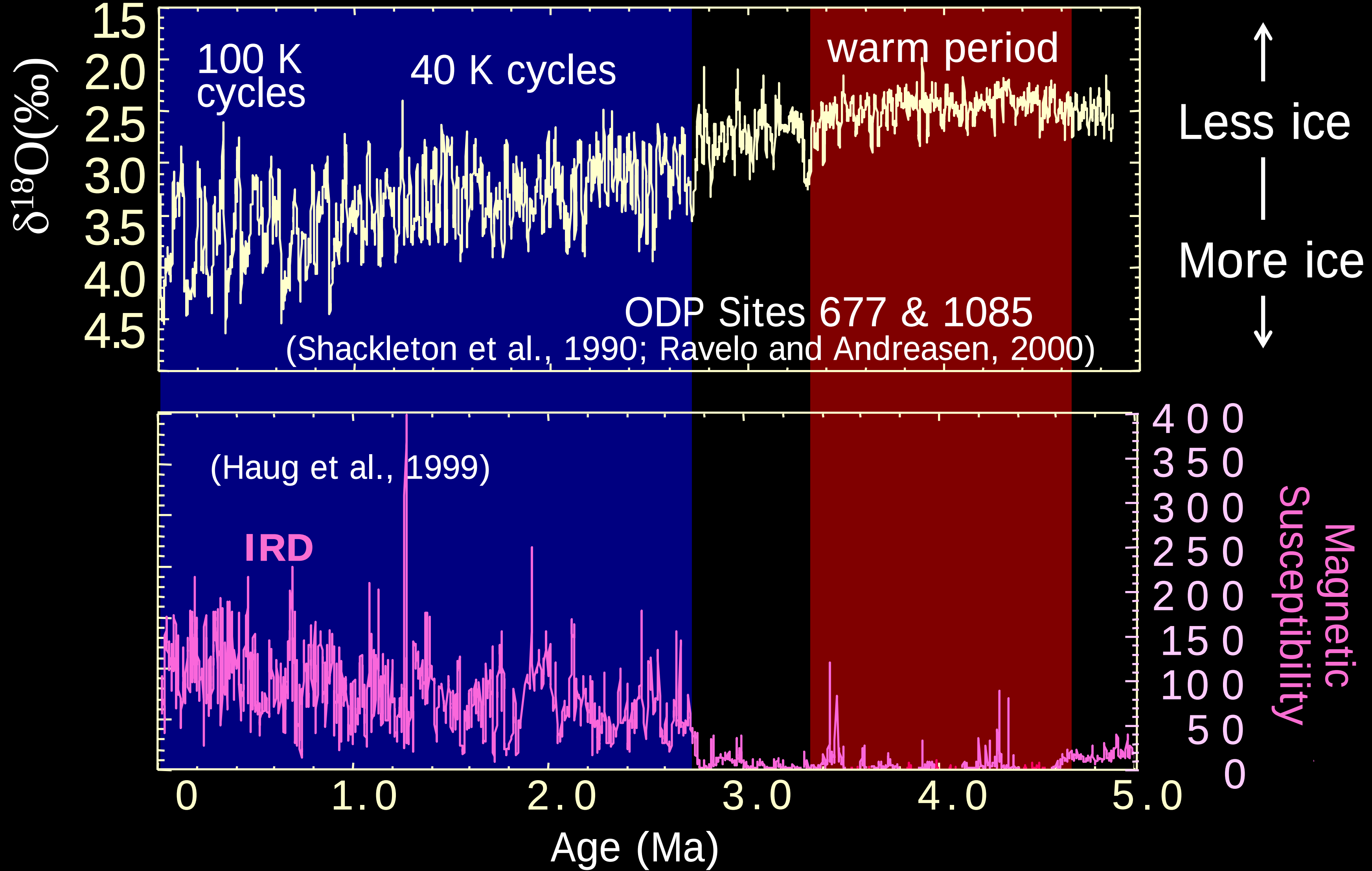
Herbert et al., 2001

Gradual evolution of thermocline nutrient composition (EEP, 847)



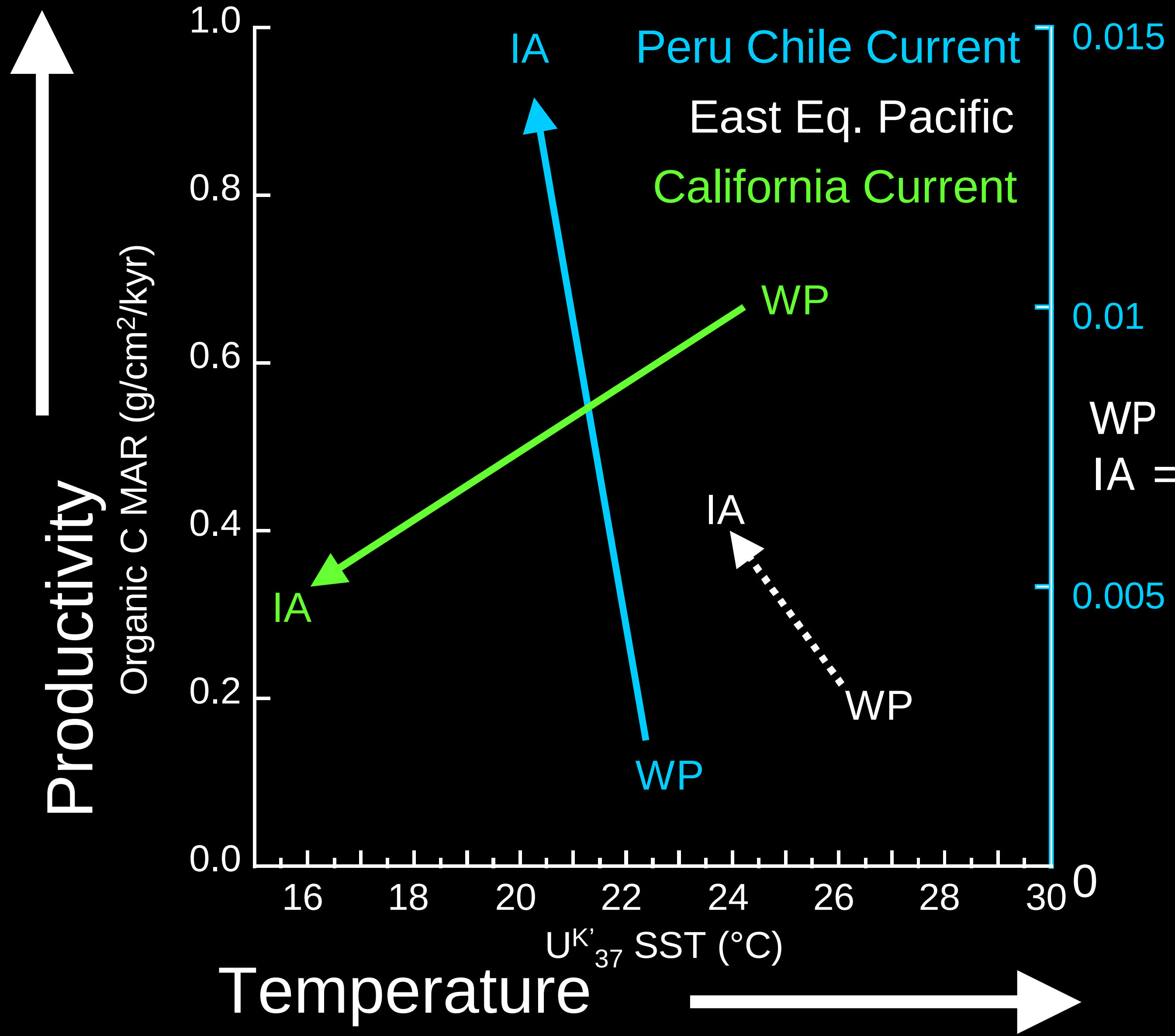
Climate of the Last 5 Ma

Onset of ICE AGES at ~2.75 Ma



Temperature and biological ecosystems are NOT simply coupled:

Character of sub-surface water (source of upwelling water) must have changed.



Dekens et al., in review

WP = Warm Pliocene

IA = Ice Ages