Role of Methane Hydrates in Climate Change:
Compelling evidence and debate

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The methane hydrate reservoir has largely been ignored as a component of climate change in the Quaternary. However there is growing acceptance that changes in the methane hydrate reservoir played an important role in climate change prior to the Quaternary. The origin of several brief episodes of global warming has been linked with massive dissociation of hydrates and CH_4 transfer into the ocean/atmosphere as recorded by large, negative carbon isotope excursions.

The remarkable similarity of atmospheric methane (CH_4) and temperature variations recorded in ice cores suggests that CH_4 played an important role in late Quaternary climate change. We have proposed that the late Quaternary (last 800 kyr) was also a time of significant instability of the methane hydrate reservoir and associated episodic greenhouse climatic forcing due to transfer of CH_4 to the atmosphere (Kennett, Cannariato, Hendy and Behl, submitted).

Unlike the prevailing interpretation that continental wetlands were the principal source for the rapid atmospheric CH_4 increases during the late Quaternary, we suggest a marine sedimentary methane hydrate source. Negligible wetland ecosystems existed during the last glacial episode as a result of global aridity, low sea level, incised, well-flushed river systems and low water tables. Wetland ecosystems were insufficiently developed during the last glacial episode to account for the rapid atmospheric CH_4 increases during glacial and stadial terminations recorded in polar ice cores. The large, modern wetland ecosystems (peatlands, tropical floodplains, and coastal wetlands) developed almost exclusively during the Holocene, well after the rapid atmospheric CH_4 increases during the last glacial termination.

According to the *Clathrate Gun Hypothesis* (Kennett et al., submitted) episodic atmospheric CH_4 emissions resulting from instability of the marine sedimentary methane hydrate (clathrate) reservoir contributed significantly to the distinctive behavior of late Quaternary climate on orbital (Milankovitch) and millennial time scales. Resulting CH_4 releases to the atmosphere/ocean system provided crucial amplification to "jump-start" rapid warmings at stadial and glacial terminations that were significantly reinforced by other greenhouse gases, especially water vapor. Collectively, these changes shifted the climate system into an interglacial/interstadial state.

Late Quaternary methane hydrate instability occurred largely because of frequent, rapid upper intermediate water temperature oscillations over wide areas of the upper continental margins in the depth zone of potential hydrate instability. These temperature oscillations led to successive intervals of methane hydrate instability during the transitions and early portions of warm intervals and stability during cool intervals. Switching to sources of warm intermediate waters at stadial and glacial terminations created instability in the methane hydrate reservoir and massive release of CH_4 into the

ocean/atmosphere system due to sediment disruption that unroofed hydrates on the upper continental slopes. This led to the well-known abrupt warmings of the late Quaternary on different time scales and magnitudes and also produced the sawtooth pattern of late Quaternary climate and atmospheric CH_4 variability exhibited in the 100-kyr cycle, Bond cycles, and individual interstadials. The hypothesis predicts extensive instability of upper continental slope sediments during rapid atmospheric CH_4 increases. This instability would have been reflected by widespread development of slumps, debris flows, and pockmarks on continental slopes, and associated mass sediment transport into the ocean basins.

Many fruitful areas exist to test the hypothesis that the methane hydrate reservoir was inherently unstable during the late Quaternary and was a crucial component in climate change. These include, but are not limited to the following:

- Geochemical tests of primary CH_4 source during abrupt atmospheric increases.
- Refine models and chronology of CH_4/temperature phasing in ice cores.
- Better determine wetland evolution and variability.
- Strengthen proxies of past oceanic CH_4 emissions.
- Determine variability of major CH_4 emissions from hydrates.
- Investigate shifts in intermediate water masses and associated temperature change.
- Determine history of oceanic mass sediment wasting.
- Refine climate models to include CH_4 changes from hydrates.
- Expand global studies of abrupt millennial scale climate change.
- Compare earlier millennial/decadal scale climate behavior with the Quaternary.

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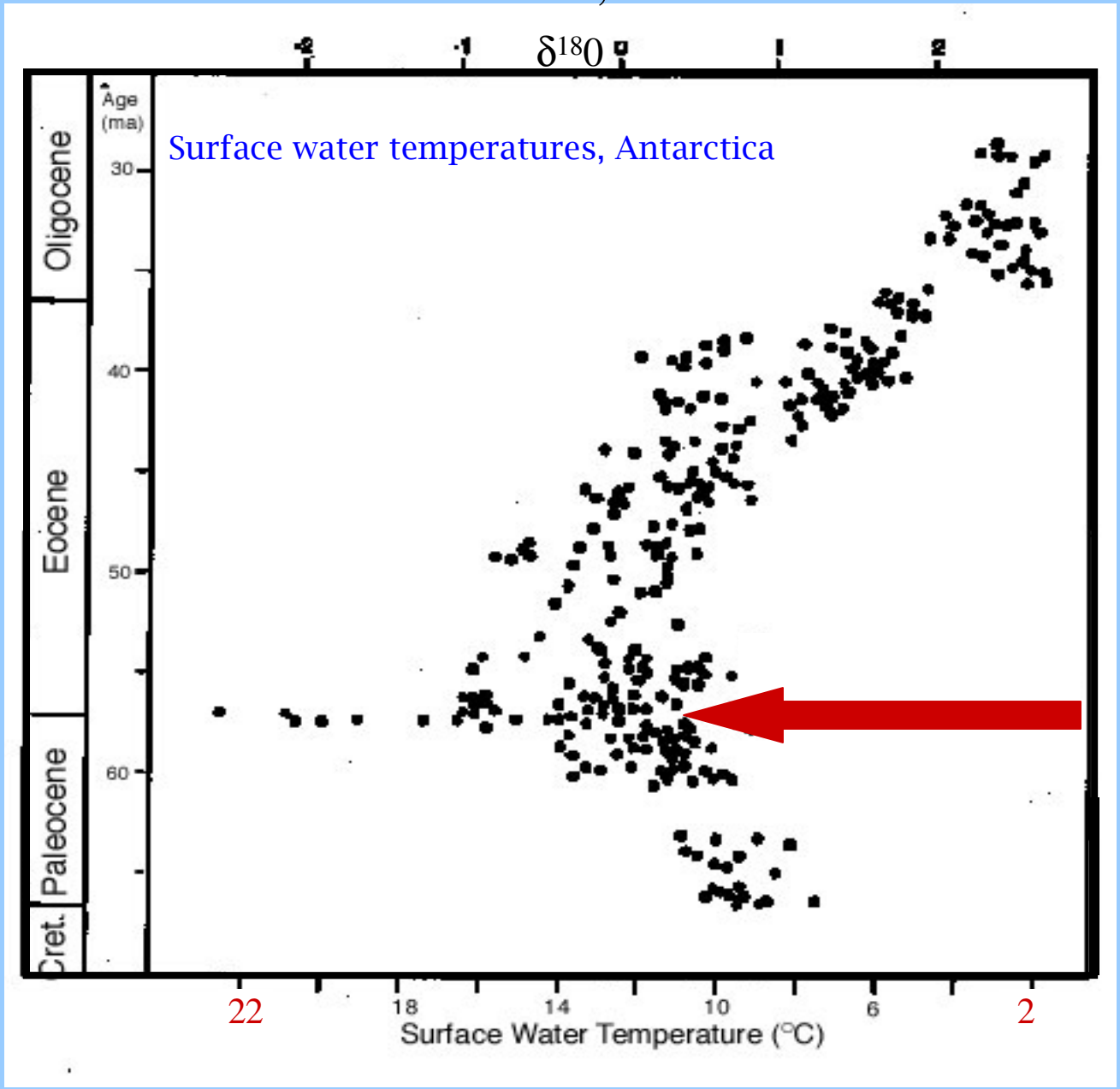
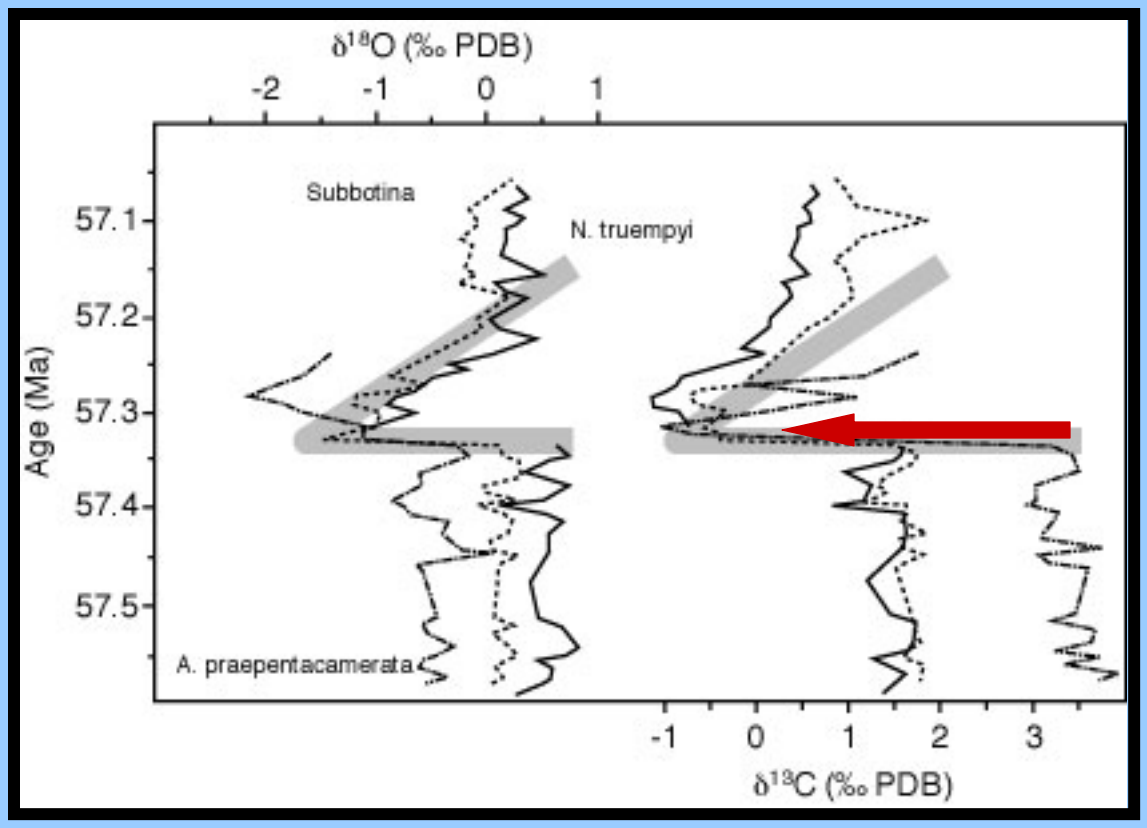
Late Paleocene Thermal Maximum (LPTM): ODP Sites 689 & 690, Antarctic Ocean



Stott et al., 1990; Kennett & Stott, 1995

Late Paleocene Thermal Maximum (LPTM)



Shows major negative carbon isotopic shift, now widely interpreted to reflect massive methane release from gas hydrates (Dickens et al.,1995).

Kennett & Stott, 1991

Vostok Ice Core

Late Quaternary Glacial/Interglacial Cycles of:

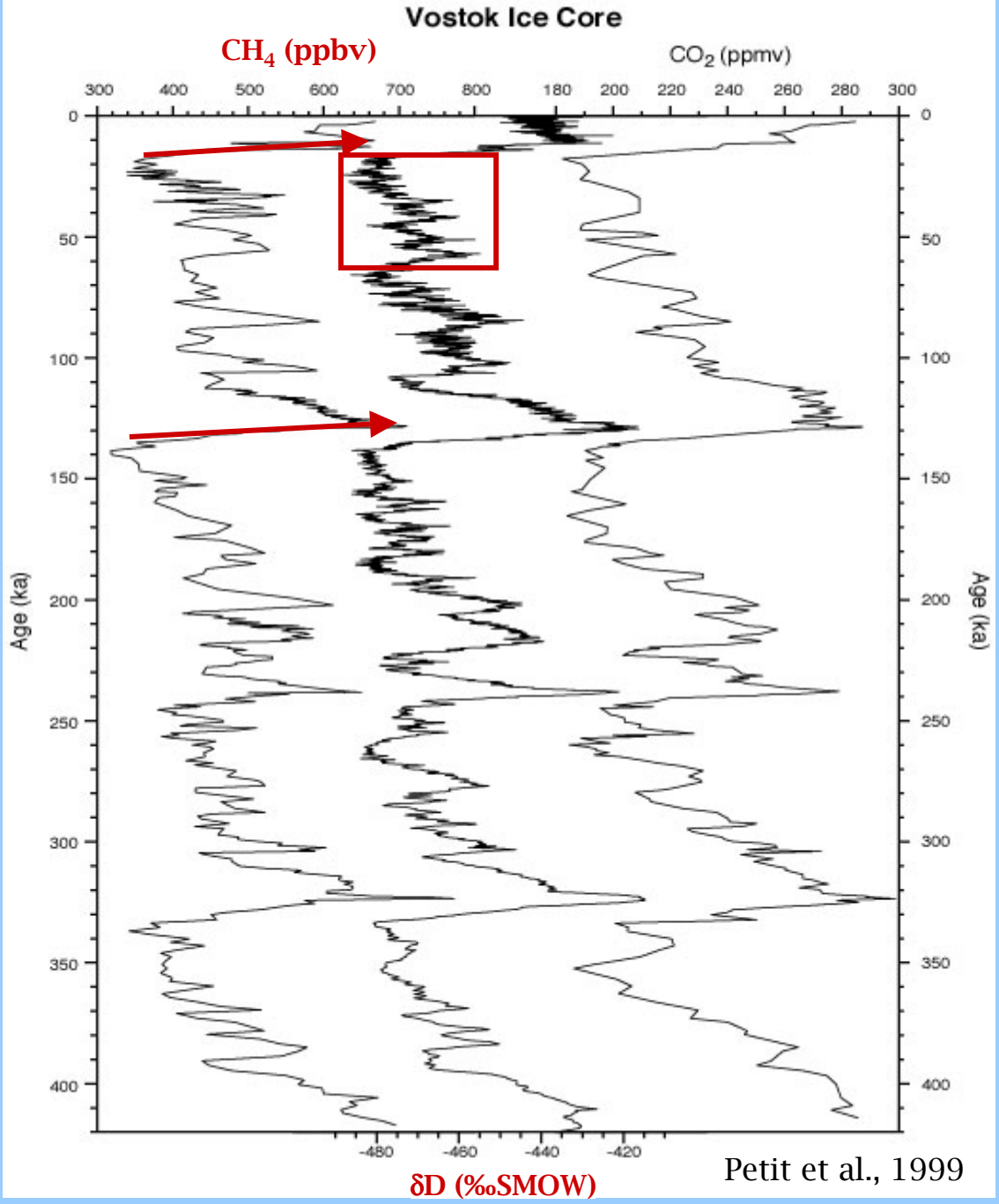
CH_4
CO_2
δD (temperature)

<u>This shows:</u>

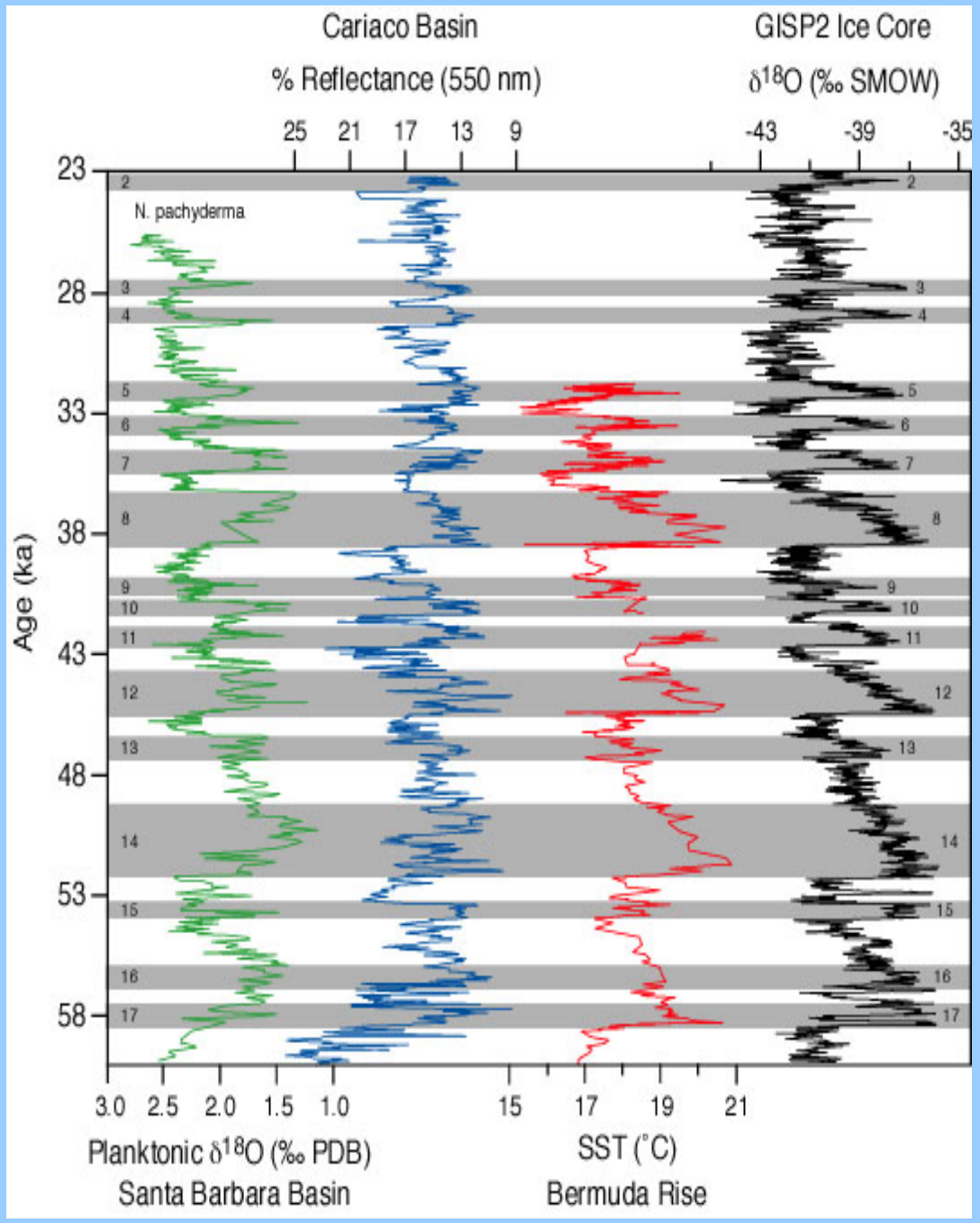
★ *cyclic behavior* in all three records

★ *abrupt warmings* associated with CH_4 and CO_2 increases at glacial terminations

★ *also note:* 100 ky sawtooth pattern



Petit et al., 1999

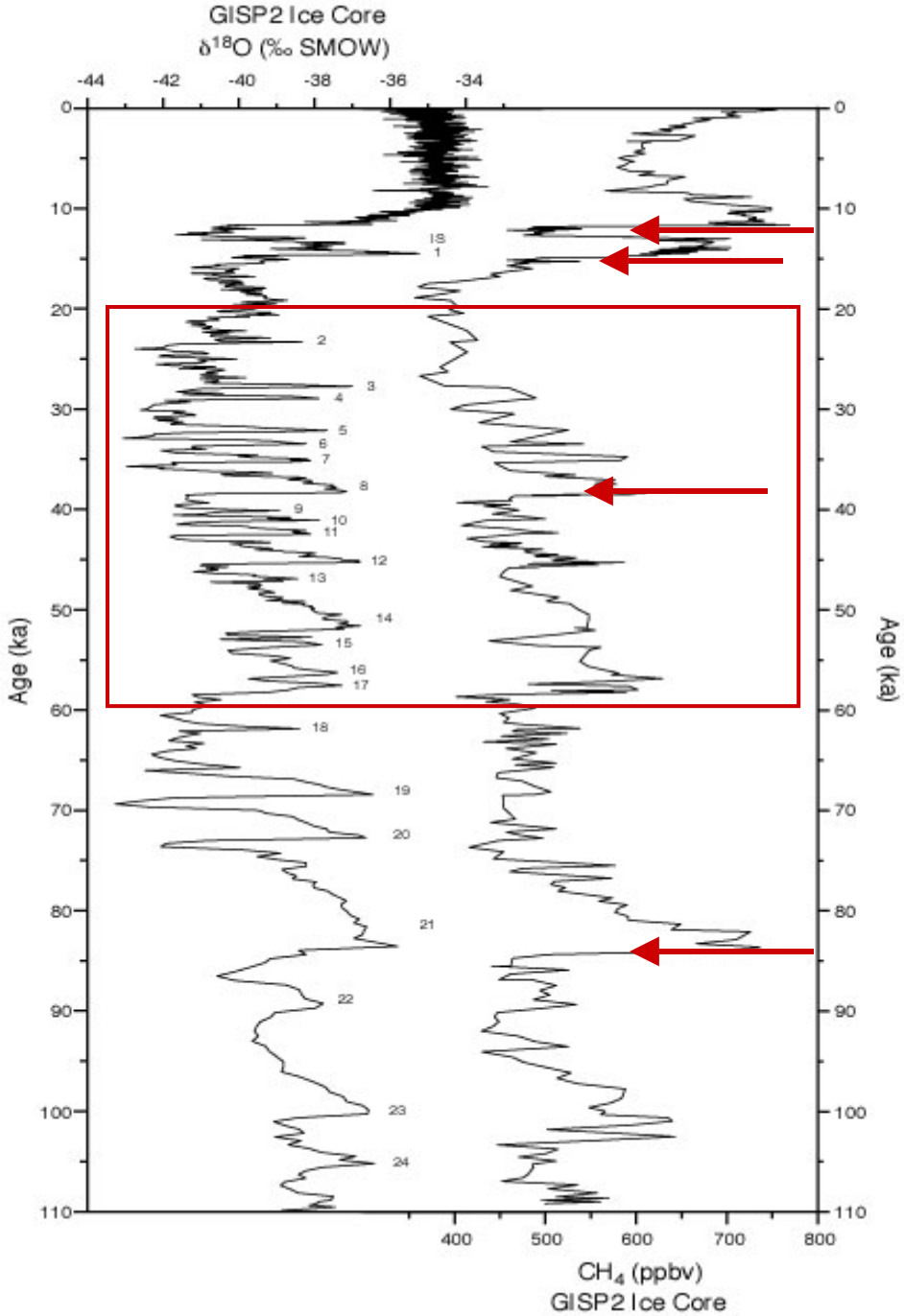


Millennial to decadal scale climate variability:

23 to 58 ka

- Demonstrates stadial/interstadial oscillations (DO cycles)
- Recorded in Northern Hemisphere oceans and Greenland
- Atmospheric telecommunication

Hendy and Kennett, 1999;
Peterson et al., 2000;
Sachs and Lehman, 1999;
Dansgaard et al., 1993 and
Stuiver and Grootes, 2000



Millennial scale climate variability

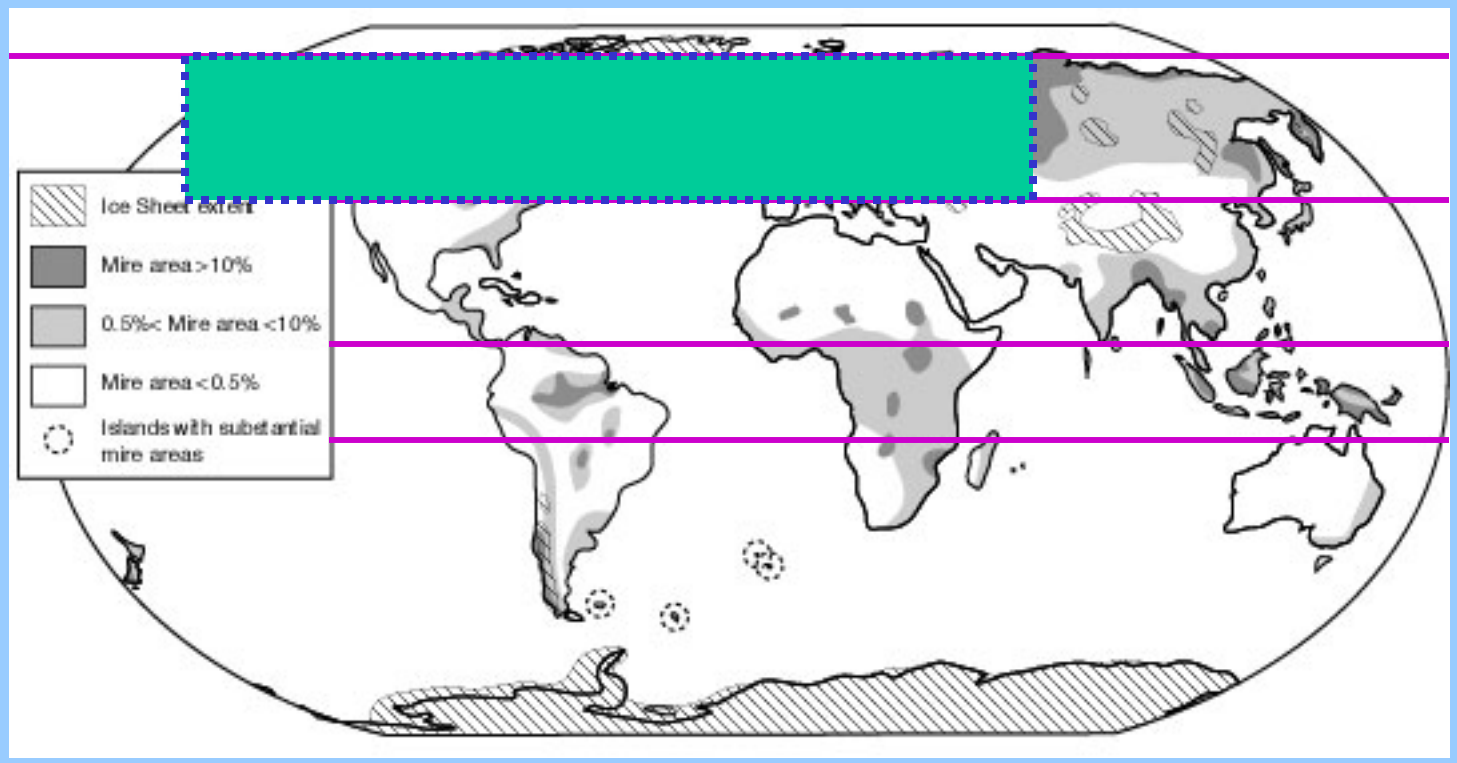
Closely associated with rapid changes in atmospheric CH_4

★*Note abrupt increases in CH_4*

Brook et al., 2000

Wetland Methane Hypothesis:
source of methane variability?

Global distribution of modern mires



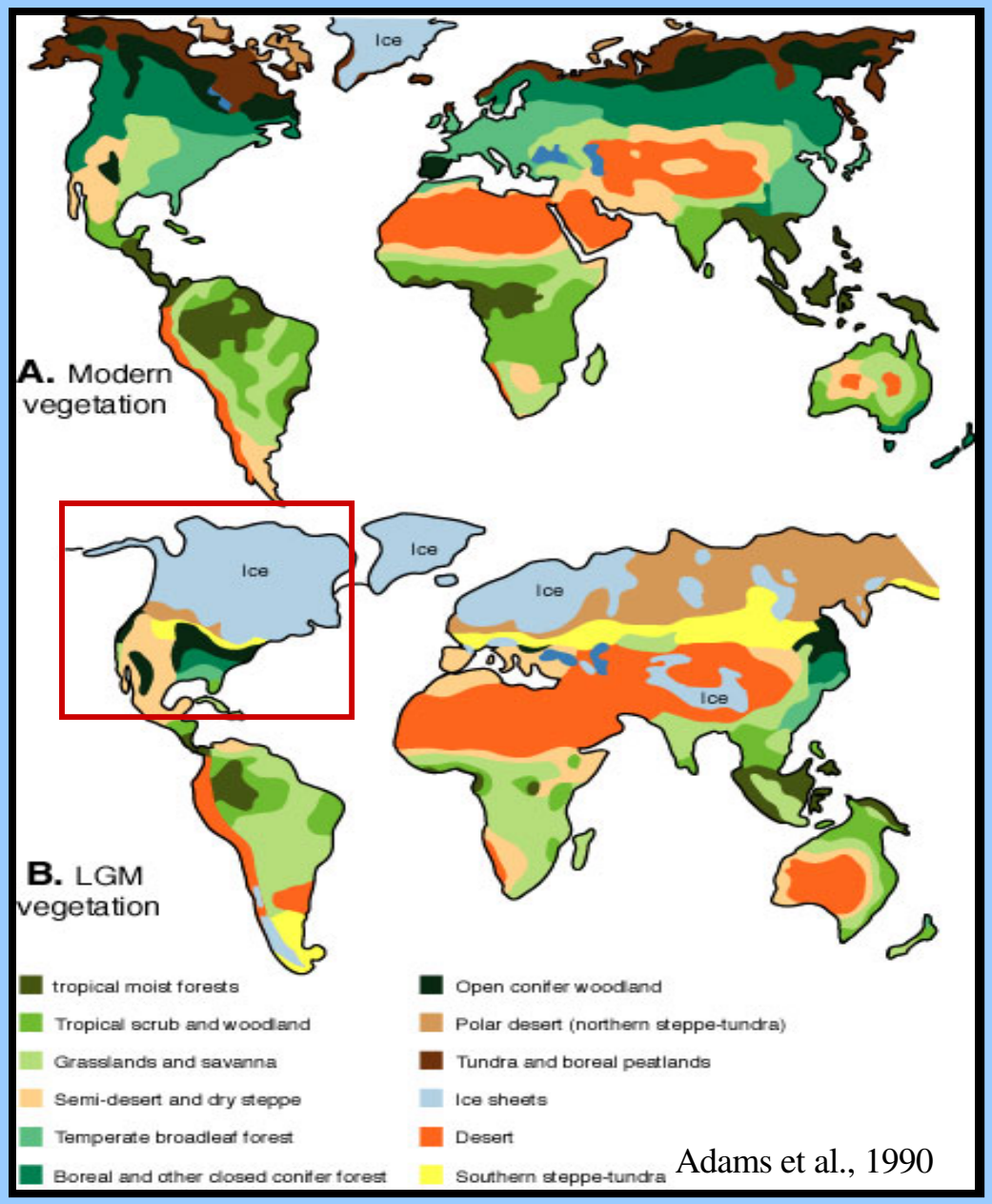
Gore, 1983

Vegetation zones:
Modern vs. Glacial

Main point:

Glacial earth dominated by dry vegetation biotopes and ice cover.

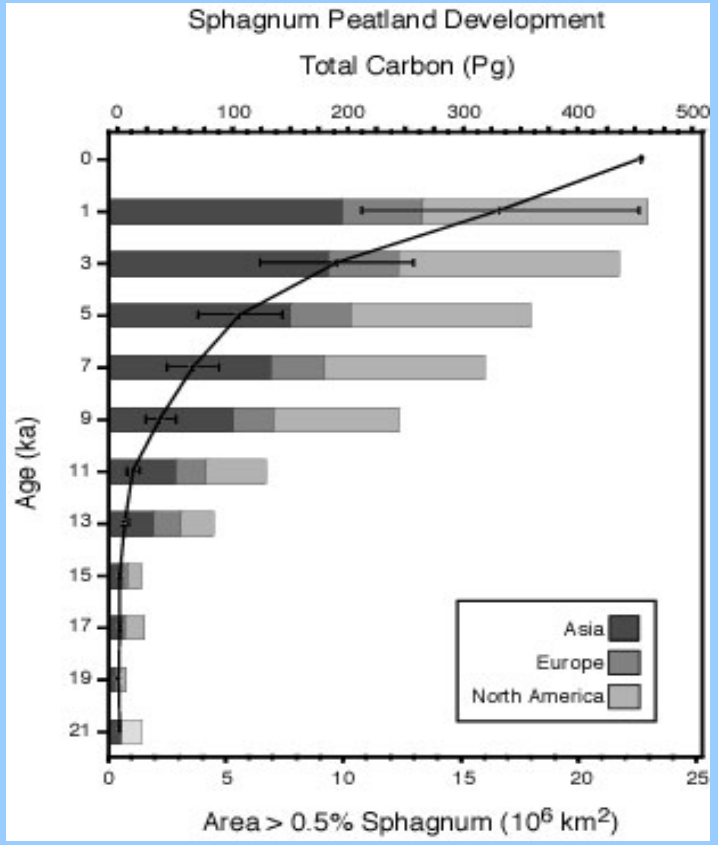
Peatland areas insignificant.

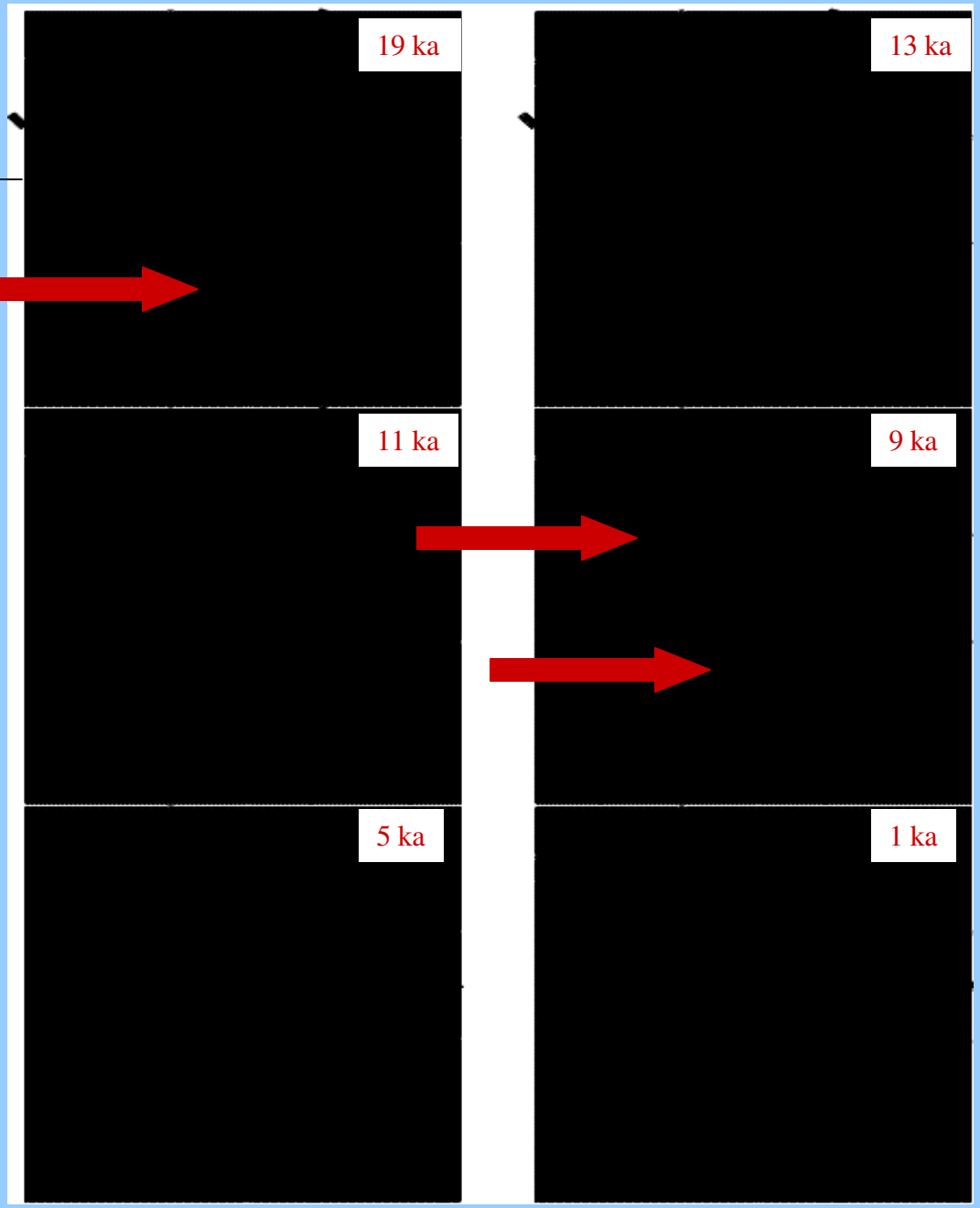


Adams et al., 1990

Changing Distribution of Peatlands (*Sphagnum* moss) on North America: Glacial to Modern

- Peatlands absent during Glacial
- Sphagnum expansion largely occurred during mid-late Holocene





Gajewski et al., 2001

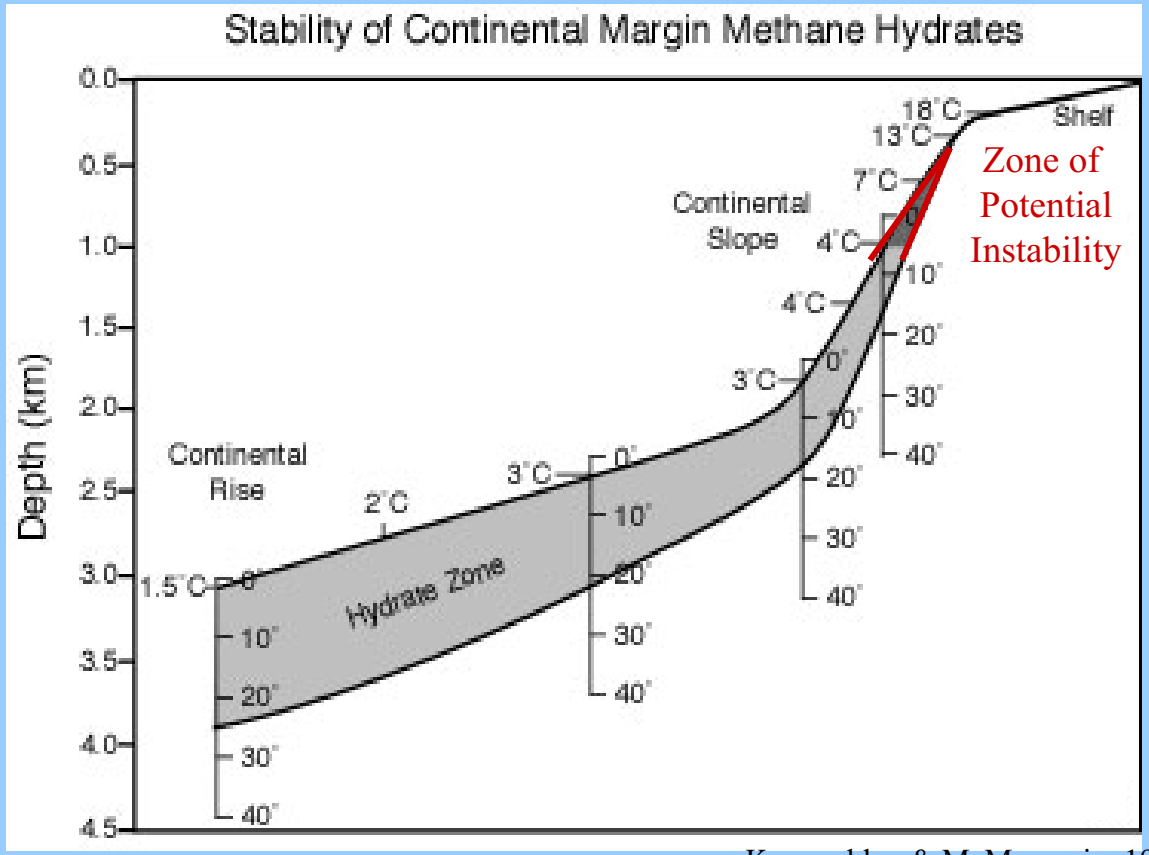
Timing of Wetland Development:

Tropical South America

AREA	AGE (ka)	CHANGE	REFERENCE
Central Brazil	< 6 < 7	Floodplains and associated wetlands. Swamp and marsh vegetation.	Turcq et al., 1997 Salgado-Labouriau et al., 1998
Rio Negro River	~ 4	White Water to Black Water transition.	Latrubesse & Franzinelli, 1998
Upper Parana River, Brazil	8 - 5	Wide Floodplains formed	Stevaux & Dos Santos, 1998
Northern Brazil	7 - 6 ~ 2.5	Low energy river system. Blocked river system; inundated forests.	Behling & Lima da Costa, 2000
Southern and Central Brazil	7 - 4	Swamp vegetation.	Ledru et al., 1998a
Western Amazonia	4.7	Poorly drained wetland development.	Behling, et al., 1999, Behling & Hooghiemstra, 1999
Central Columbia Amazon	~ 3.3	Wetland vegetation; major seasonal flooding.	Behling et al., 1999
Eastern Amazon Basin	~ 8 ~ 3	Active to passive river system. Blocked river system.	Behling et al., 2000
Columbian Llanos wetlands	< 3.3	Wetland development	Behling & Hooghiemstra, 1999
Guayan Shield	~ 8	Initial peat accumulation.	Schubert, 1998
Bolivian Amazonia	3	Savanna to rainforest	Mayle et al., 2000

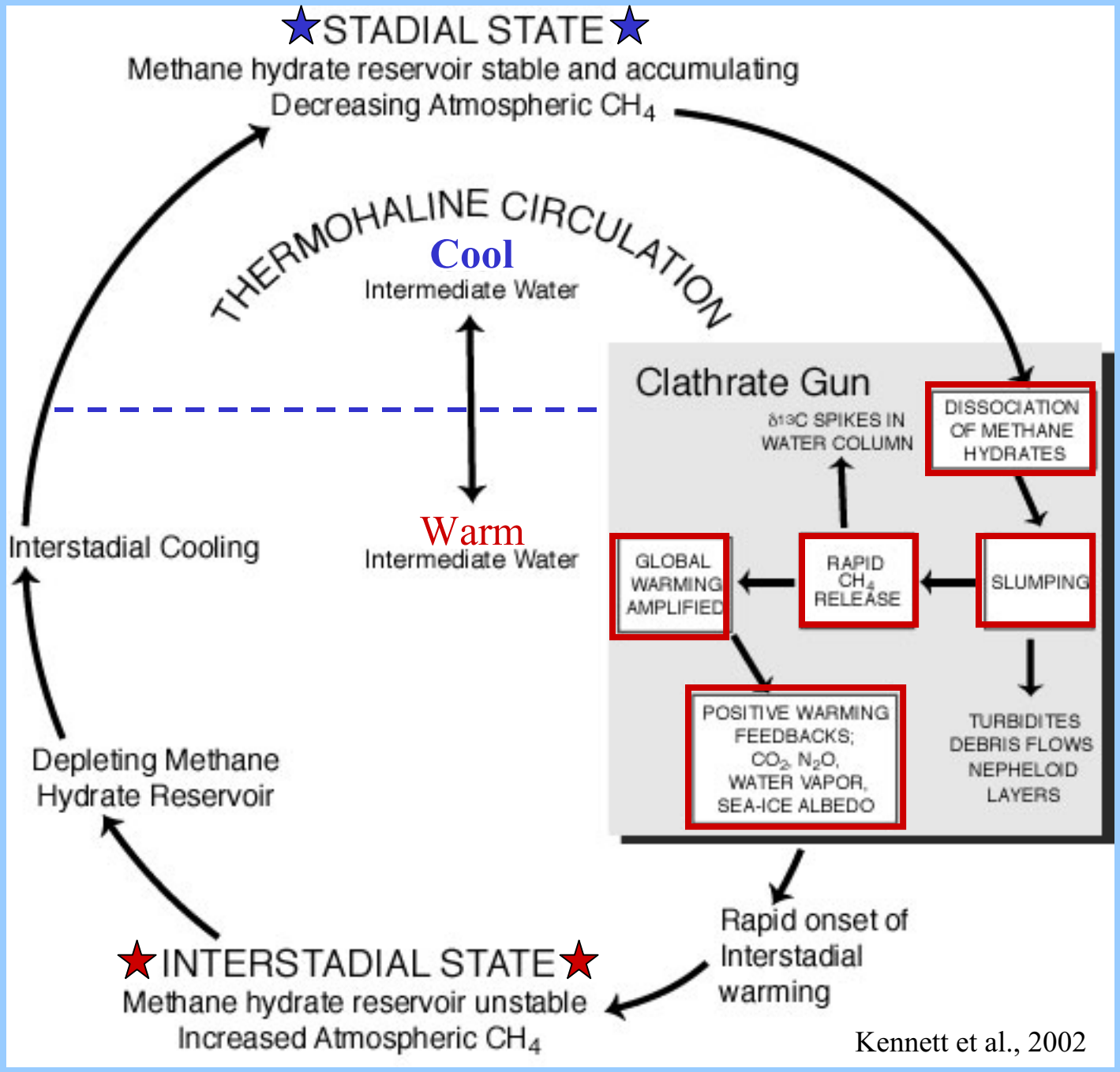
- Wetland Hypothesis for CH_4 source not supported by geological evidence

- Another source required → methane hydrates



Kvenvolden & McMenamin, 1980

Clathrate Gun Hypothesis

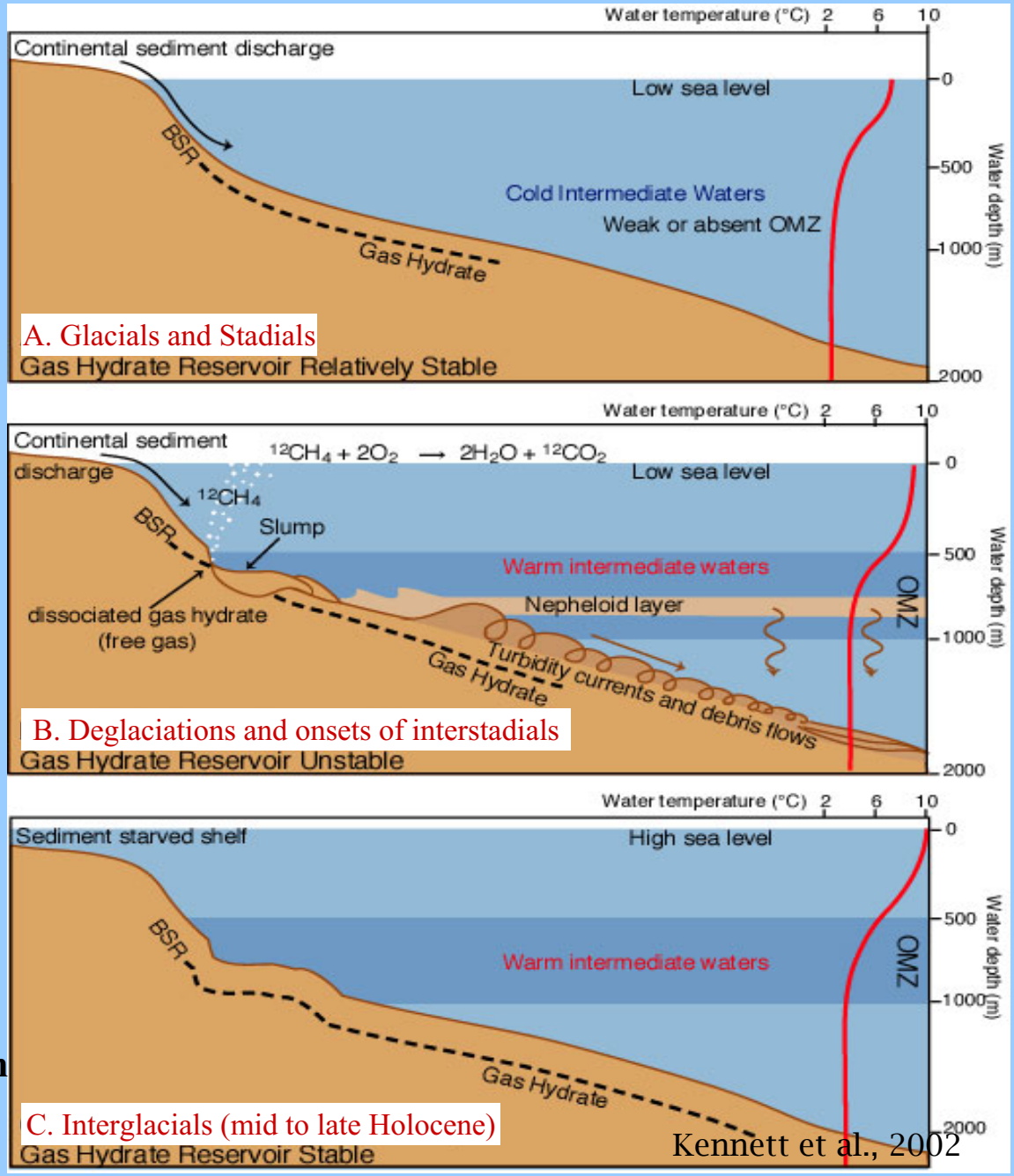


Kennett et al., 2002

Clathrate Gun Hypothesis

- gas hydrate reservoir is large
- reservoir is unstable
- destabilization due to bottom water warming when sea level low
- caused slumping, unroofing of gas hydrates
- CH_4 released into ocean/atmosphere
- recorded in ice cores
- CH_4 activates abrupt warmings at climate transitions

☆ **methane hydrates play a crucial role in Quaternary climate change** ☆



Kennett et al., 2002

Upper slope instability associated with methane hydrates: Late Quaternary

North Alaskan Slope

Nordic Seas

Barents Sea

US Atlantic Margin

Mediterranean

Gulf of Cadiz

Southern California Margin

Pacific Margin

Gulf of California

New Zealand

Southwest Africa

Evidence for instability during deglacial/early Holocene interval:

Norway, Storegga Slump

Barents Sea

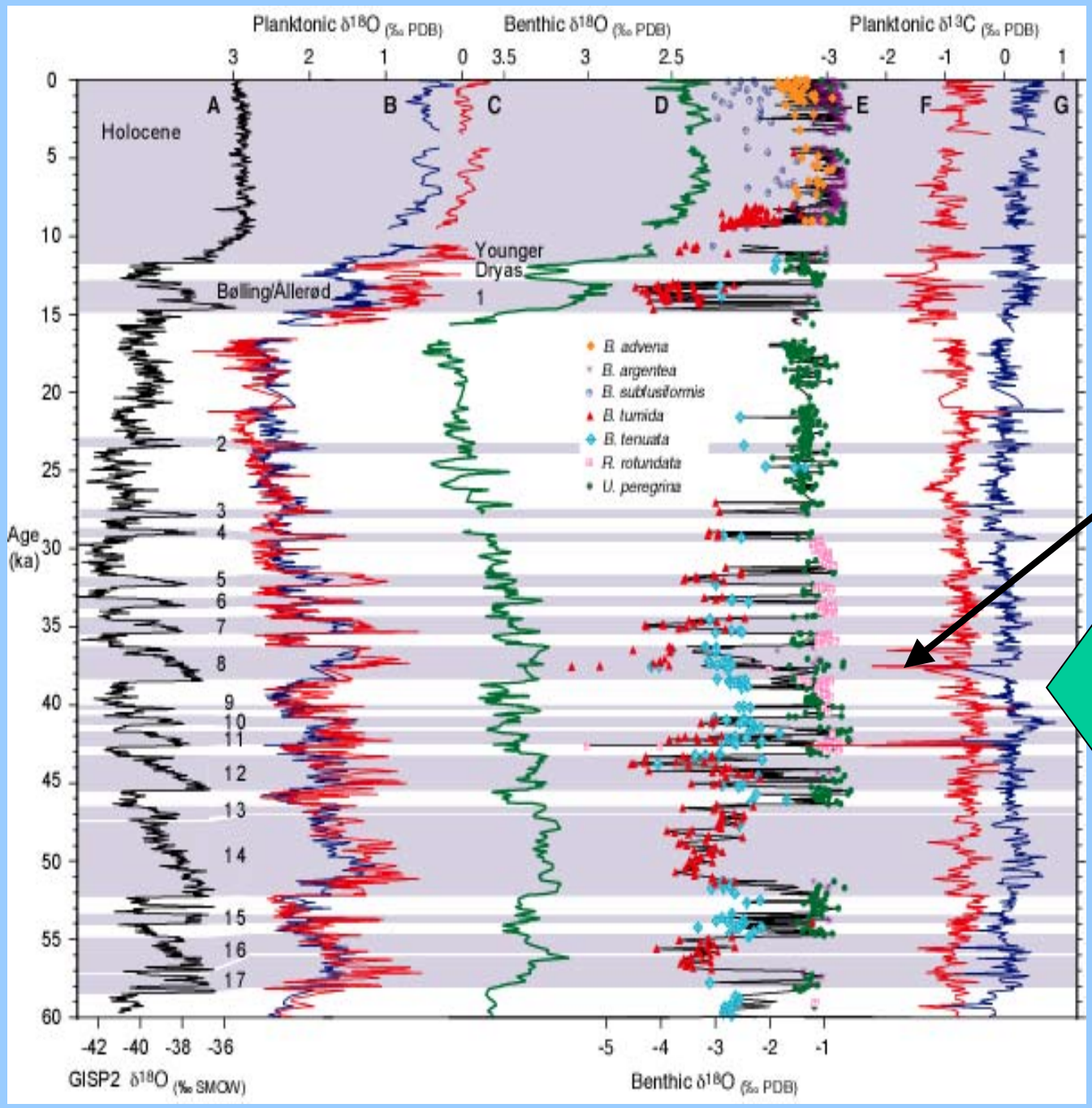
US Atlantic Margin (Cape Fear)

Labrador Slope

Amazon Fan

Northern California (Humboldt)

(various references)

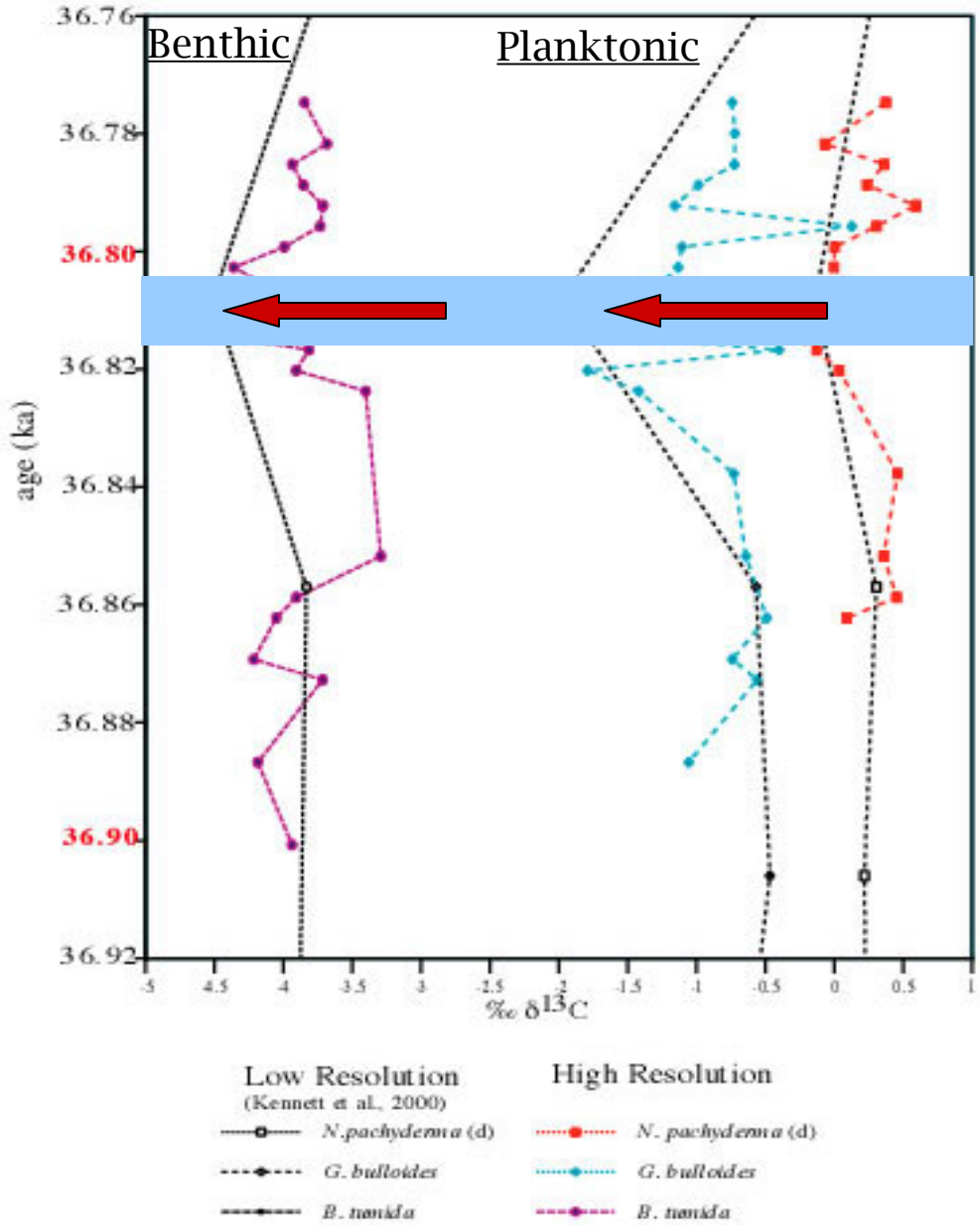


$\delta^{13}C$ Spikes in Santa Barbara Basin:

ODP Site 893

Evidence for massive CH_4 release into water column

Kennett et al., 2000



Santa Barbara Basin

Carbon Isotopic Spike: ~36.8 ka

Low resolution

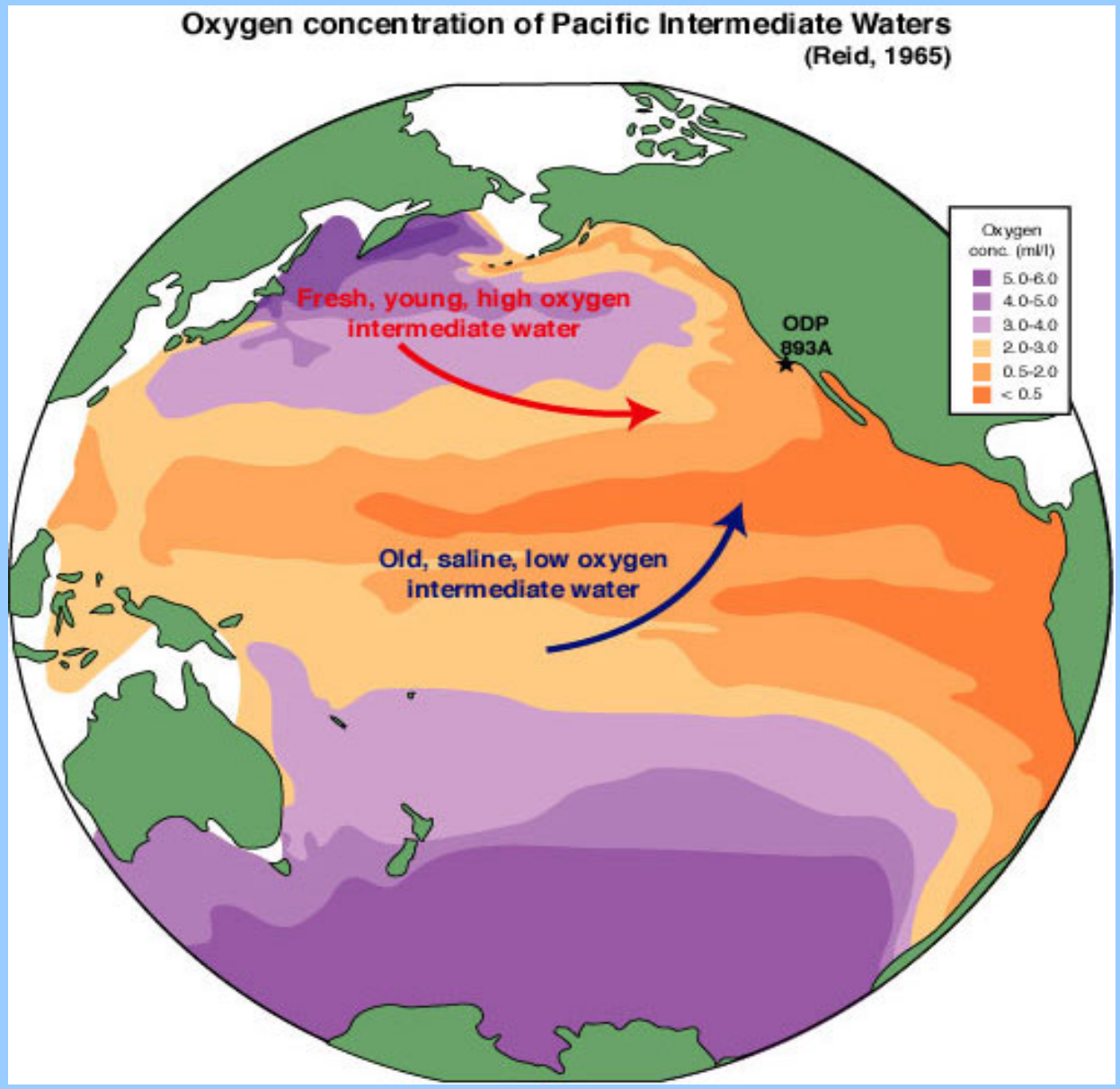
vs.

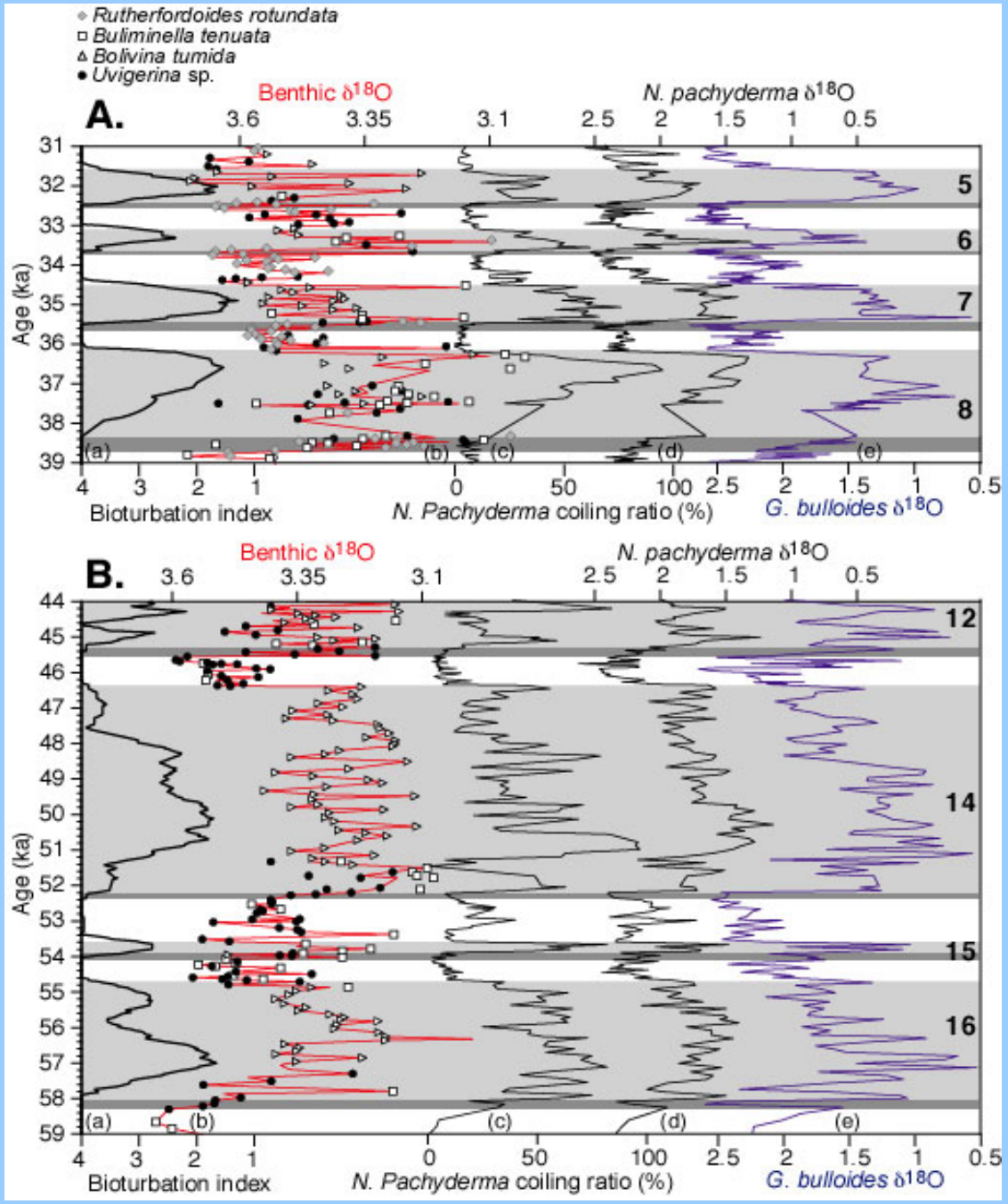
High resolution

Kennett et al., 2000
Hill and Kennett, in prep.

Causes of methane hydrate reservoir instability:

Role of upper intermediate water shifts in bottom water temperature change





Santa Barbara Basin

★Millennial scale oscillations in water masses

★Near-synchronous surface and bottom water temperature oscillations

★Benthic $\delta^{18}O$ reflects upper intermediate water temperature shifts

Hendy and Kennett, submitted

Role of Methane Hydrates in Climate Change:
Major Questions

- ★ Instability of methane hydrate reservoir during the Quaternary?
- ★ Role in ocean margin sediment instability and transport?
- ★ Atmospheric methane jumps: wetlands or *gas hydrates*?
- ★ Role of methane hydrates in late Quaternary climate change?
  - ★ major component of climate system?
  - ★ activator of abrupt warmings, or secondary reinforcement?
  - ★ relative roles of intermediate water temperature change and sea level?
- ★ Implications for modern instability of methane hydrate reservoir?

Role of Methane Hydrates in Climate Change: Proposed Tests

- Geochemical tests of CH_4 source
- Refine models & chronology of CH_4/temperature phasing in ice cores
- Wetland evolution and variability
- Strengthen proxies of past oceanic CH_4 emissions
- Determine variability of major CH_4 emissions from hydrates
- Investigations of intermediate water temperature shifts
- History of oceanic mass sediment wasting
- Refine climate models to include CH_4 changes from hydrates
- Expand global studies of abrupt millennial scale climate change
- Compare earlier climate behavior with the Quaternary