Università di Trieste

LAUREA MAGISTRALE IN GEOSCIENZE SM62A

Percorso Esplorazione Geologica

Anno accademico 2026 - 2027

Geologia Marina 953SM

Modulo 1.2 evoluzione degli oceani e tipi di depositi sedimentari

Laura De Santis

Erikson, J., 2003. Marine Geology. Exploring the new frontiers of the Ocean. Facts on File publisher ebook available from the Univ. TS library

"….With a further drop in atmospheric temperatures, water vapor condensed into heavy clouds that shrouded the planet.
They completely blocked out the Sun and plunged the surface into total darkness. As the atmosphere continued to cool, sheets of rain fell from the sky.

Around 4 billion years ago, when the rains ceased and the skies finally cleared, Earth emerged as a giant blue orb covered by a global ocean nearly 2 miles deep dotted with numerous volcanic islands.

Some volcanoes poked through the sea surface to emerge as scattered islands, yet no continents graced Earth's watery face."

The earliest organisms were likely sulfur-metabolizing bacteria without oxygen
Thermophilic (heat-loving) bacteria found today in hot-water environment



Perhaps the only safe place for life to evolve was on the deep ocean floor hydrothermal vents

environment capable of generating an immense number of organic reactions and providing the ingredients and energy necessary to create the planet's first life

TABLE 1 THE GEOLOGIC TIME SCALE

Era	Period	Epoch	Age (millions of years)	First Life-forms	Geology
		Holocene	0.01		
	Quaternary				
		Pleistocene	3	Humans	Ice age
Cenozoic		Pliocene	11	Mastodons	Cascades
		Neogene			
		Miocene	26	Saber-toothed tigers	Alps
	Tertiary	Oligocene	37		
		Paleogene			
		Eocene	54	Whales	
		Paleocene	65	Horses, Alligators	Rockies
	Cretaceous		135		
				Birds	Sierra Nevada
Mesozoic	Jurassic		210	Mammals	Atlantic
				Dinosaurs	
	Triassic		250		
	Permian		280	Reptiles	Appalachians
	Pennsylvanian		310		Ice age
				Trees	
	Carboniferous				
Paleozoic	Mississippian		345	Amphibians	Pangaea
				Insects	
	Devonian		400	Sharks	
	Silurian		435	Land plants	Laursia
	Ordovician		500	Fish	
	Cambrian		570	Sea plants	Gondwana
				Shelled animals	
			700	Invertebrates	
Proterozoic			2500	Metazoans	
			3500	Earliest life	
Archean			4000		Oldest rocks
			4600		Meteorites

Large volumes of water flooded Earth's surface.

Most of the crust was deeply submerged during the Archean

chert deposited (precipitated from silica-rich water in deep oceans, leached out from volcanic rocks) more than 2.5 billion years old.

Modern seawater is deficient in silica because organisms (e.g. diatoms) extract it to build ornate skeletons. Massive deposits of diatomaceous earth, or diatomite, during the last 600 million years

Seawater probably began salty due to the volcanic outgassing of chlorine and sodium.

TABLE 2 RADIATION AND EXTINCTION OF SPECIES

Organism	Radiation	Extinction
Mammals	Paleocene	Pleistocene
Reptiles	Permian	Upper Cretaceous
Amphibians	Pennsylvanian	Permian-Triassic
Insects	Upper Paleozoic	
Land plants	Devonian	Permian
Fish	Devonian	Pennsylvanian
Crinoids	Ordovician	Upper Permian
Trilobites	Cambrian	Carboniferous & Permian
Ammonoids	Devonian	Upper Cretaceous
Nautiloids	Ordovician	Mississippian
Brachiopods	Ordovician	Devonian & Carboniferous
Graptolites	Ordovician	Silurian & Devonian
Foraminiferans	Silurian	Permian & Triassic
Marine invertebrates	Lower Paleozoic	Permian

The ocean did not contain its present concentration of salts until about 500 million years ago.

Major changes in
- Seawater chemistry,
- oxygen,
- CO_2

often correlate with biologic extinction

The oxygen level jumped significantly between 2.2 and 2 billion years ago

TABLE 3 EVOLUTION OF THE BIOSPHERE

	Billions of Years Ago	Percent Oxygen	Biologic Effects	Event Results
Full oxygen conditions	0.4	100	Fish, land plants, and animals	Approach present biologic environs
Appearance of shell-covered animals	0.6	10	Cambrian fauna	Burrowing habitats
Metazoans appear	0.7	7	Ediacaran fauna	First metazoan fossils and tracks
Eukaryotic cells appear	1.4	>1	Larger cells with a nucleus	Redbeds, multicellular organisms
Blue-green algae	2.0	1	Algal filaments	Oxygen metabolism
Algal precursors	2.8	<1	Stromatolite mounds	Initial photosynthesis
Origin of life	4.0	0	Light carbon	Evolution of the biosphere

Before 2.2 billion years Oxygen levels remained low because of gases emitted from submarine hydrothermal vents and because of the oxidation of dissolved metals in seawater (world's great iron ore reserves)

Global tectonics' role in driving ice ages

TABLE 4 THE MAJOR ICE AGES

Number of years ago	Event
10,000–present	Present interglacial
15,000–10,000	Melting of ice sheets
20,000–18,000	Last glacial maximum
100,000	Most recent glacial episode
1 million	First major interglacial
3 million	First glacial episode in Northern Hemisphere
4 million	Ice covers Greenland and the Arctic Ocean
15 million	Second major glacial episode in Antarctica
30 million	First major glacial episode in Antarctica
65 million	Climate deteriorates, poles become much colder
250–65 million	Interval of warm and relatively uniform climate
250 million	The great Permian ice age
700 million	The great Precambrian ice age
2.4 billion	First major ice age

Global tectonics, featuring extensive volcanic activity and seafloor spreading, might have triggered the ice ages **by drawing down the level of oxygen in the ocean and atmosphere**

A drop in global temperatures initiated the first known glaciation about 2.4 billion years ago: massive ice sheets nearly over entire landmass.



700 million years ago, all landmasses assembled into the supercontinent **Rodinia** centered over the equator

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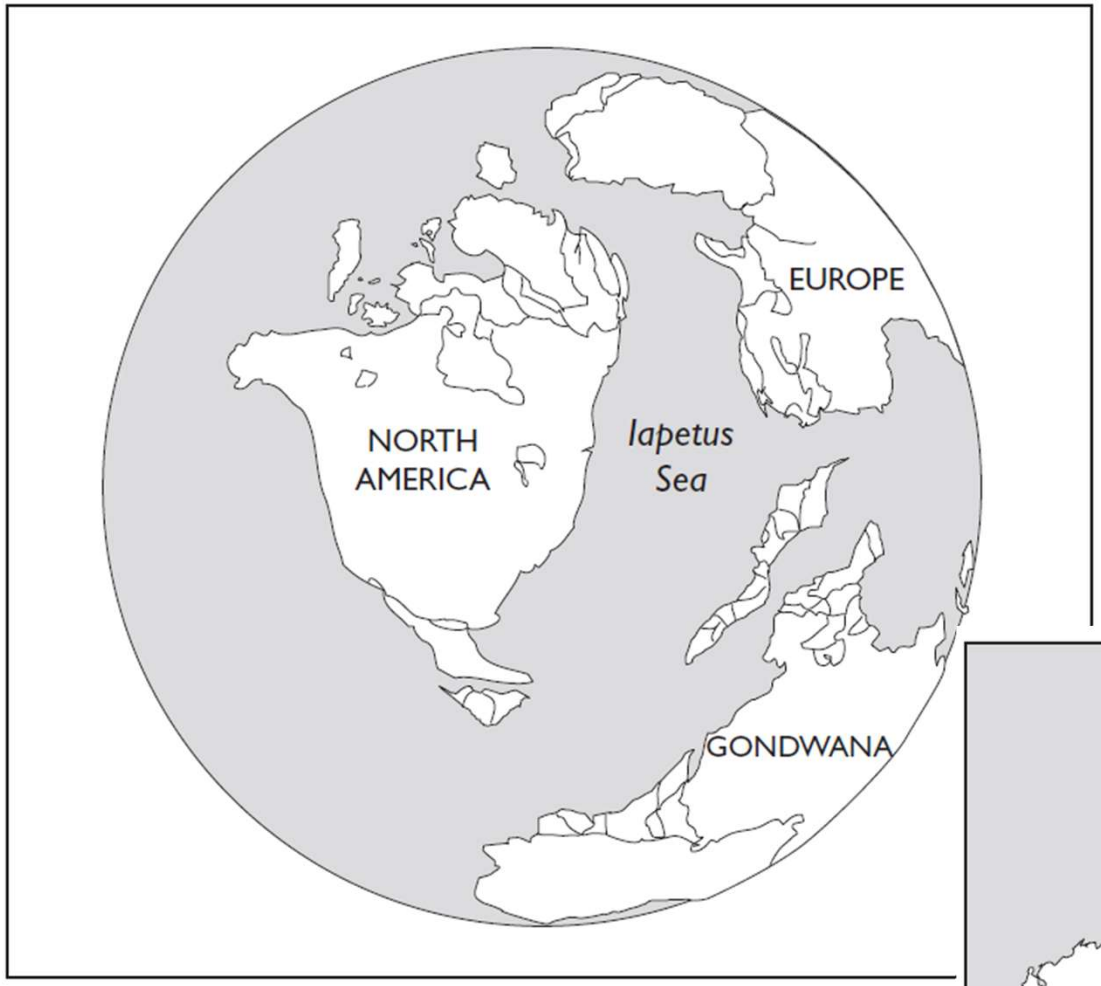
diversification of multicellular life

even the Tropics froze
"snowball Earth."
Major extinction

Plate tectonics - volcanic activity caused the loss of oxygen => preservation of more organic carbon in the marine sediments

850-580 Ma burial of carbon in Earth's crust => cooling

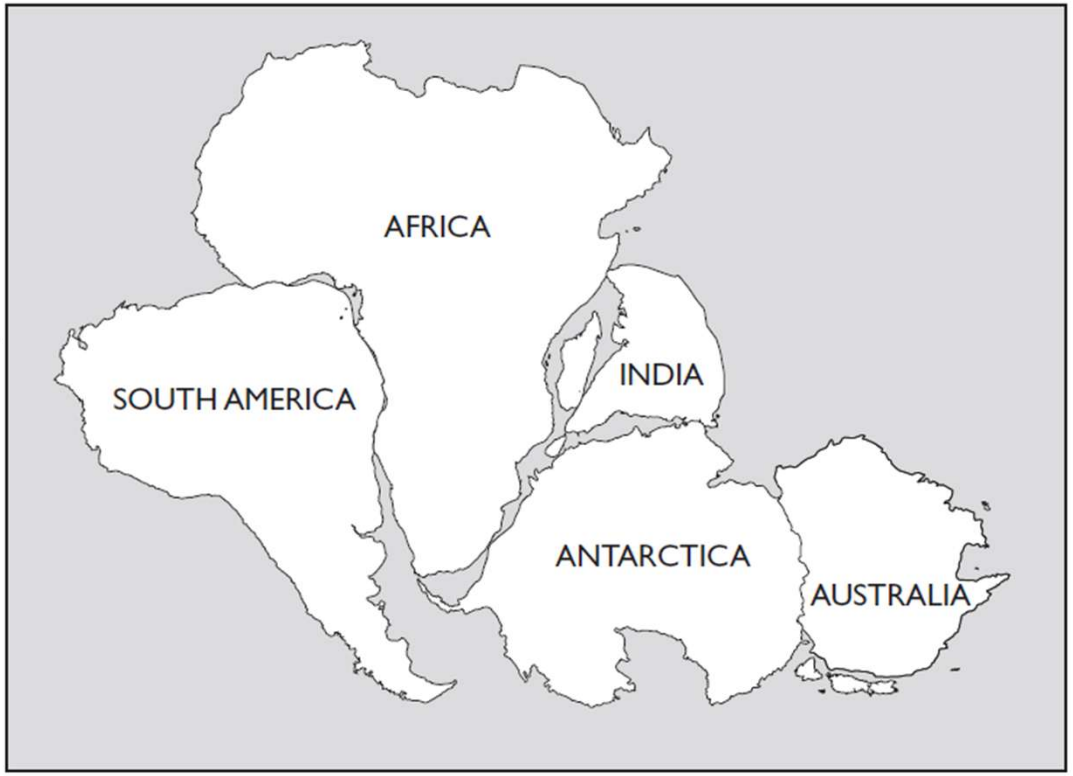
When lands reached the colder latitudes, glacial ice built up.



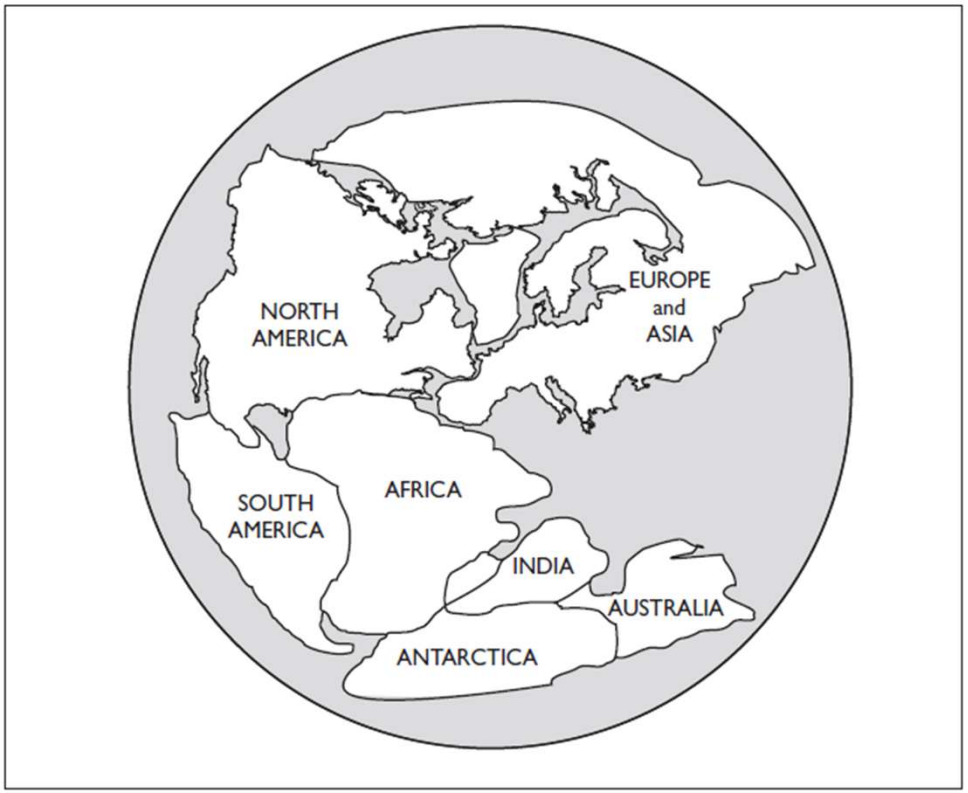
Between 630 and 560 million years ago, the supercontinent rifted apart.

The continental breakup caused sea levels to rise and to flood large portions of the land at the beginning of the Cambrian

the supercontinent Gondwana persisted



oceans have repeatedly opened and closed in the vicinity of the Atlantic basin, a single ocean has existed continuously at the site of the Pacific basin



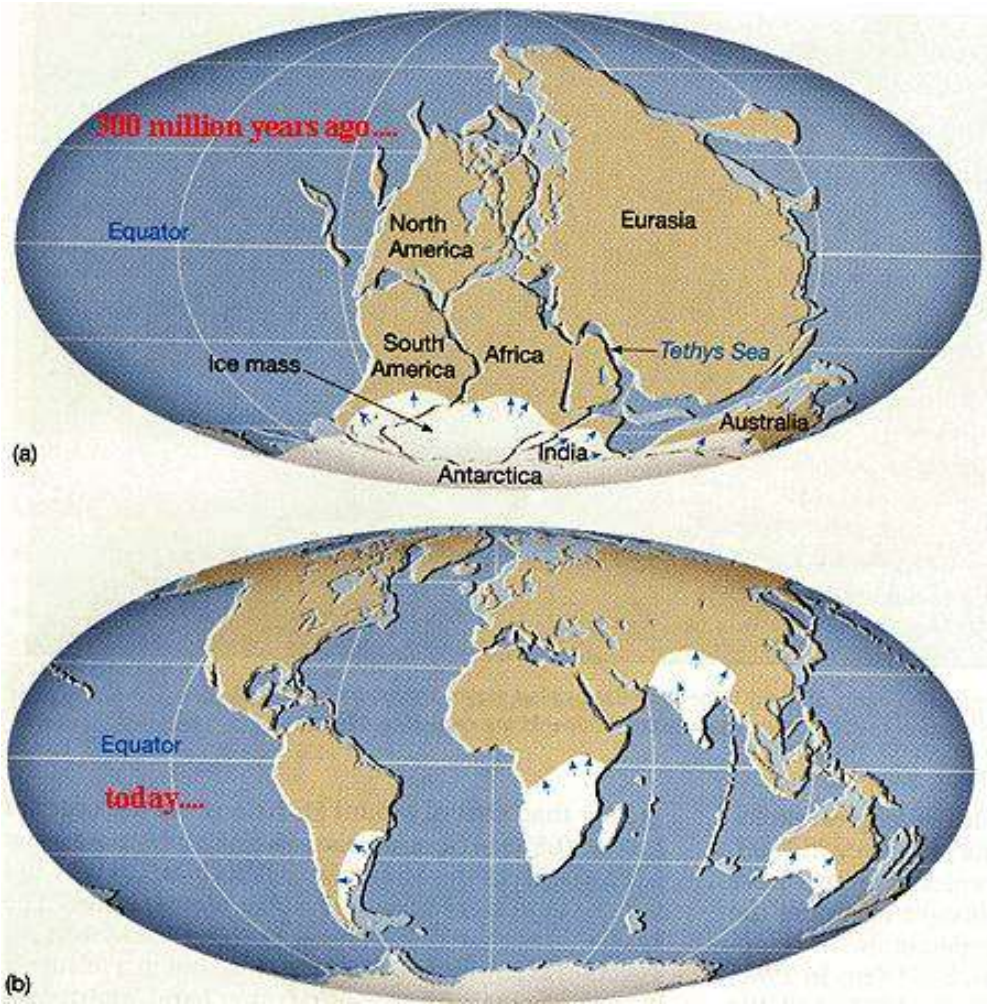
From 360 million to 270 million years ago, Gondwana and Laurasia converged into **Pangaea**, extended almost from pole to pole.

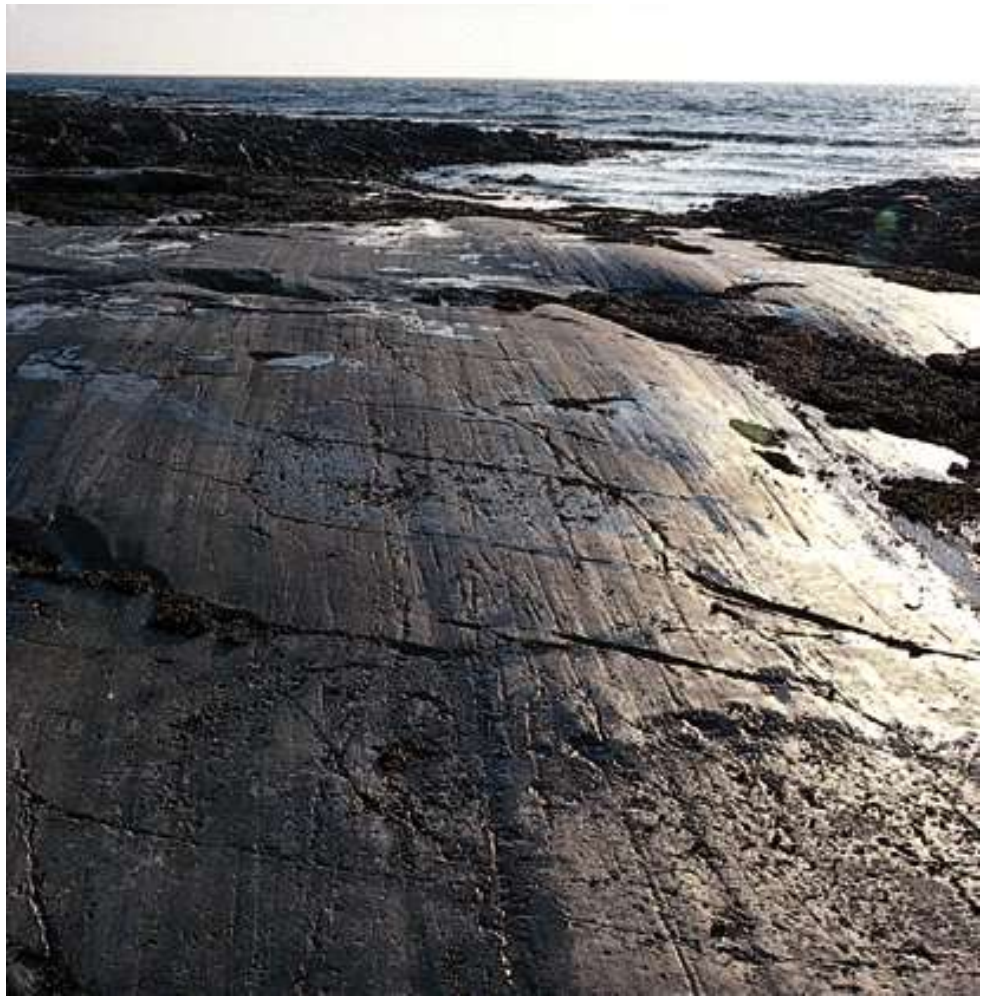
More than one-third of the landmass was covered with water

The continental margins were less extensive and narrower than they are today due to a drop in sea level (Permian ice age) as much as 170 m ca. => habitat areas for shallow water marine organisms were limited, resulting in low species diversity

Evidence of Continental Drift

- **Stratigraphic Evidence**: Orientation of glacial markings on all continents suggest they were linked





The Permo-Carboniferous glaciation led to the development of an ice sheet that left traces in Antarctica, Australia, India, South Africa, and South America

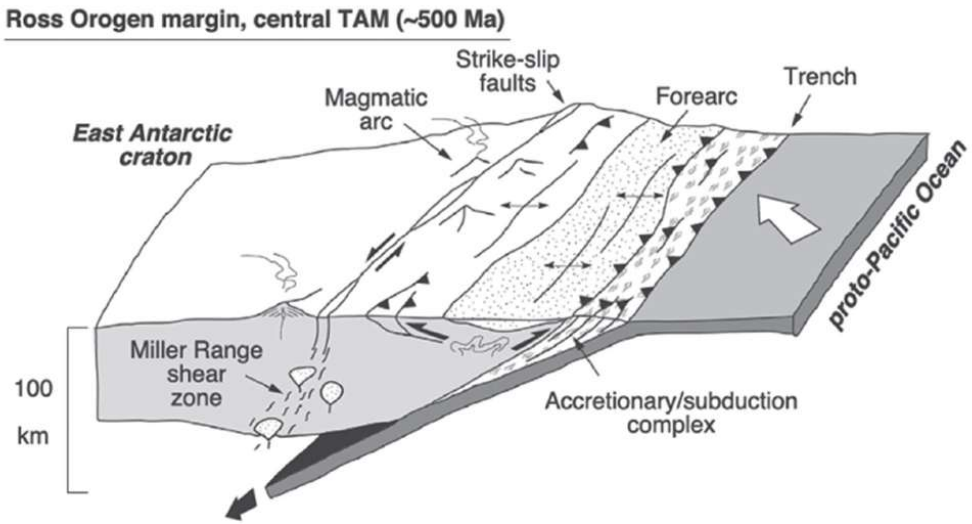


FIGURE 6.10 Schematic diagram of Transantarctic Mountains plate-boundary regime at ~500 Ma (after Goodge, 2020).

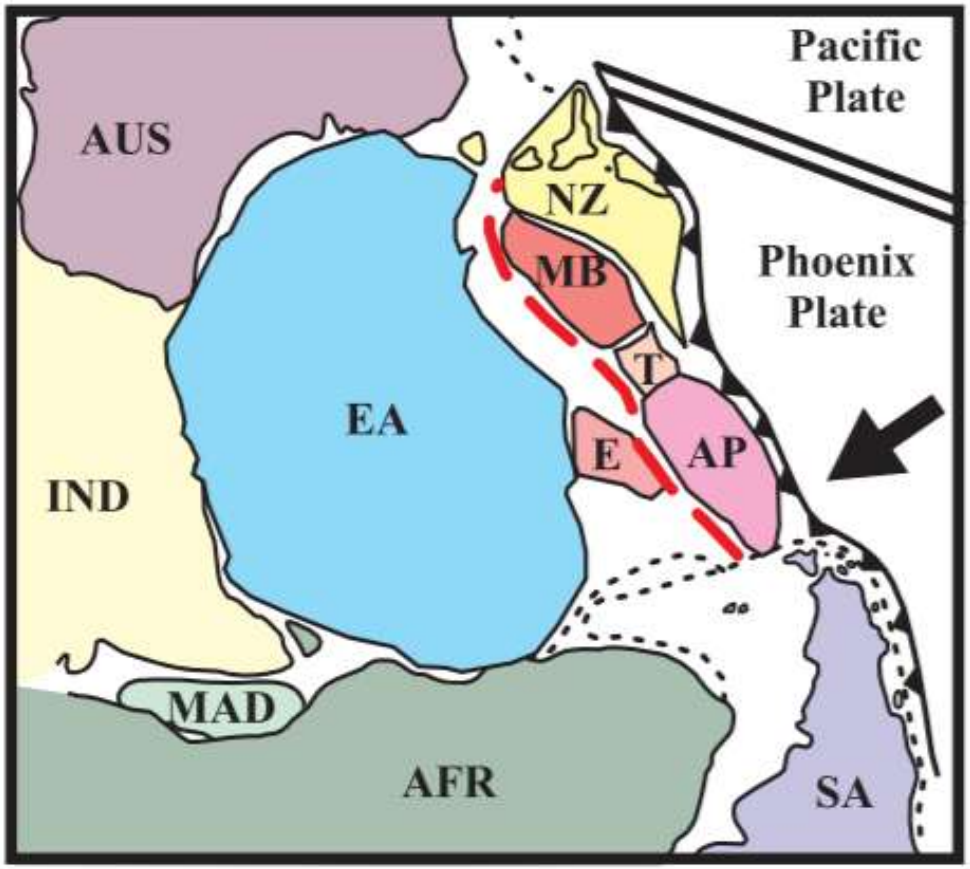


Figure 2. Paleogeographic map of the East Gondwana Pacific margin during the Late Cretaceous. The onset of extension in the WARS coincided with subduction of the Pacific-Phoenix spreading ridge beneath the East Gondwana margin and with separation of Zealandia from West Antarctica. Red dashed line indicates trend of incipient WARS. AUS, Australia; IND, India; EA, East Antarctica; MAD, Madagascar; AFR, Africa; SA, South America; NZ, New Zealand; MB, Marie Byrd Land; T, Thurston Island block; E, Ellsworth Island block; AP, Antarctic Peninsula block. Modified from Fitzgerald (2002) and Torsvik et al. (2007).

Triassic magmatic rocks testify to the presence of an active Andean-style continental magmatic arc all along the Antarctic margin to the Patagonian belts

Wenman, et al. (2020).

Late Permian: Gondwana migrates towards intermediate latitudes (mild climate)

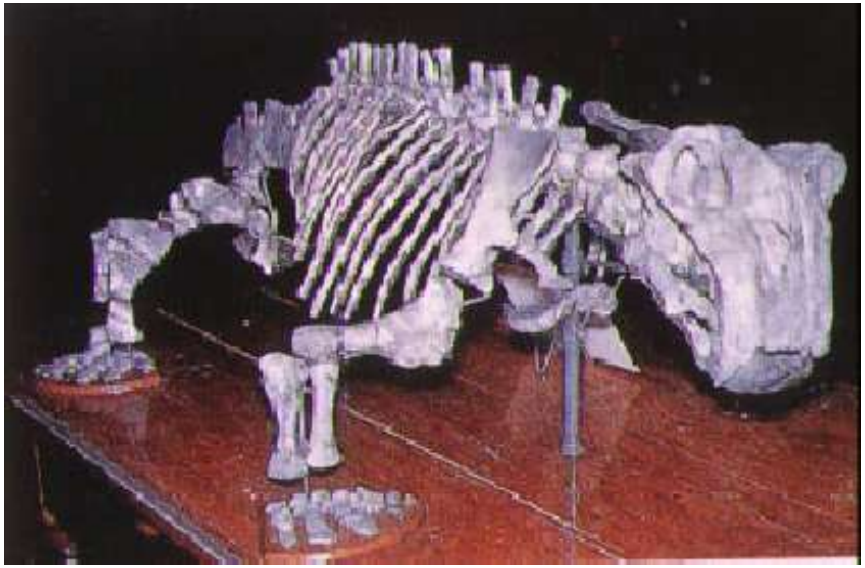


Fossil leaf of Glossopteris

photo: P. Barrett.



Fossilized Glossopteris trunk in the Beacon Sandstones of northern Victoria Land (Permo-Triassic age) => conifer forests. Photo: C. A. Ricci.

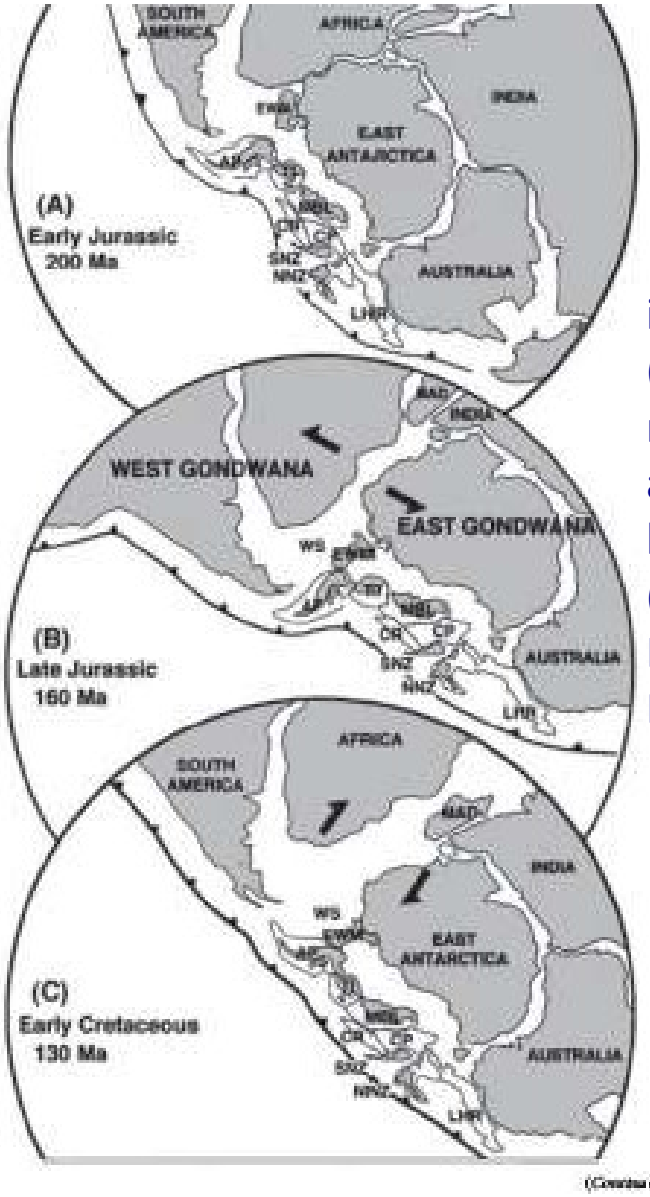


Reconstruction of the skeleton of Lystrosaurus, a herbivorous reptile—about one meter tall and nearly two meters long—that lived in various regions of the supercontinent Gondwana during the Triassic period and had limited swimming ability. Photo: P. Barrett.

Catena Transantartica

Doleriti del Ferrar (lave giurassiche)

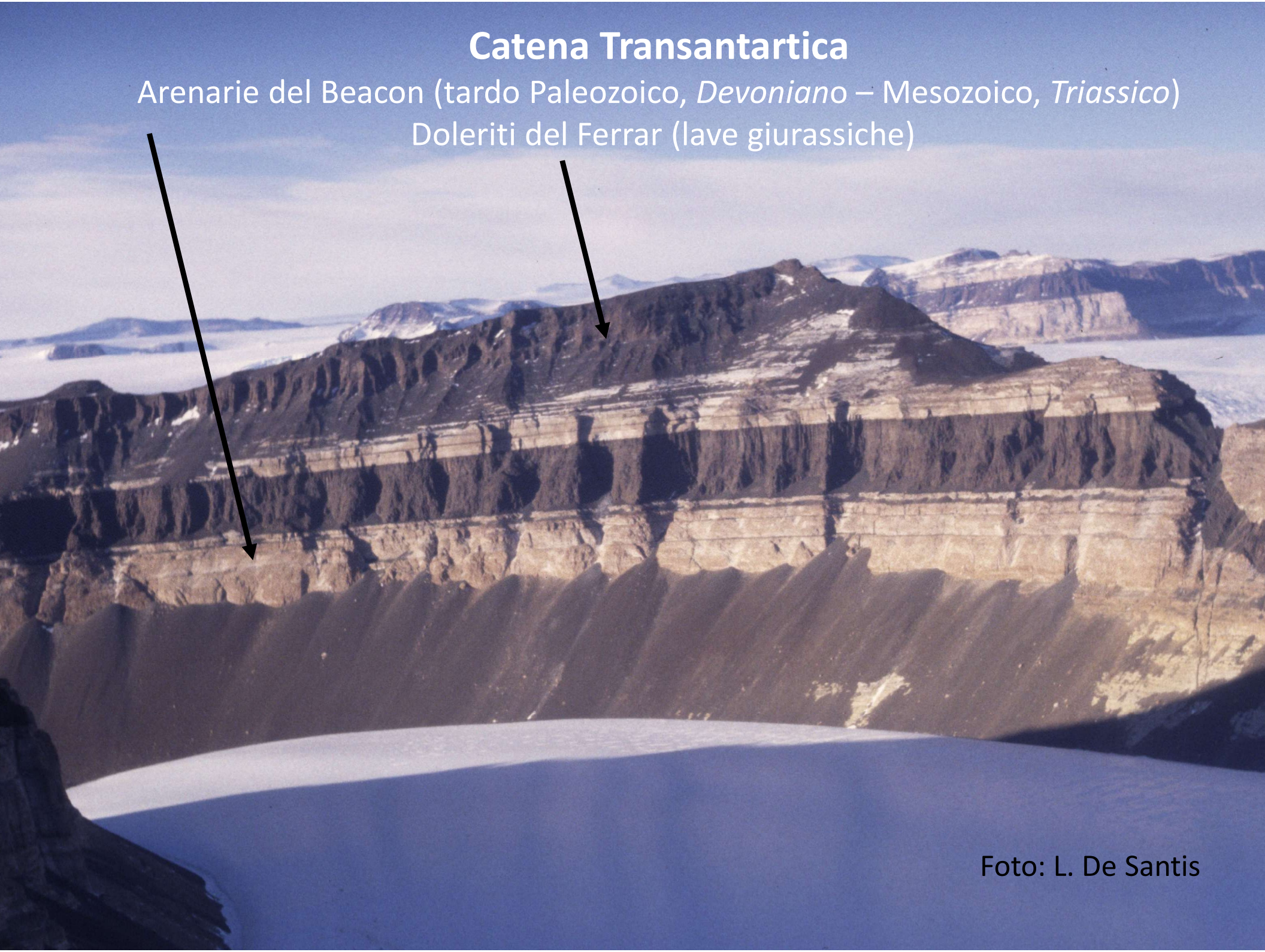
Arenarie del Beacon (tardo Paleozoico, *Devoniano* – Mesozoico, *Triassico*)



initial (transtension) rifting phase as a back-arc basin (FerrarLarge Igneous Province)



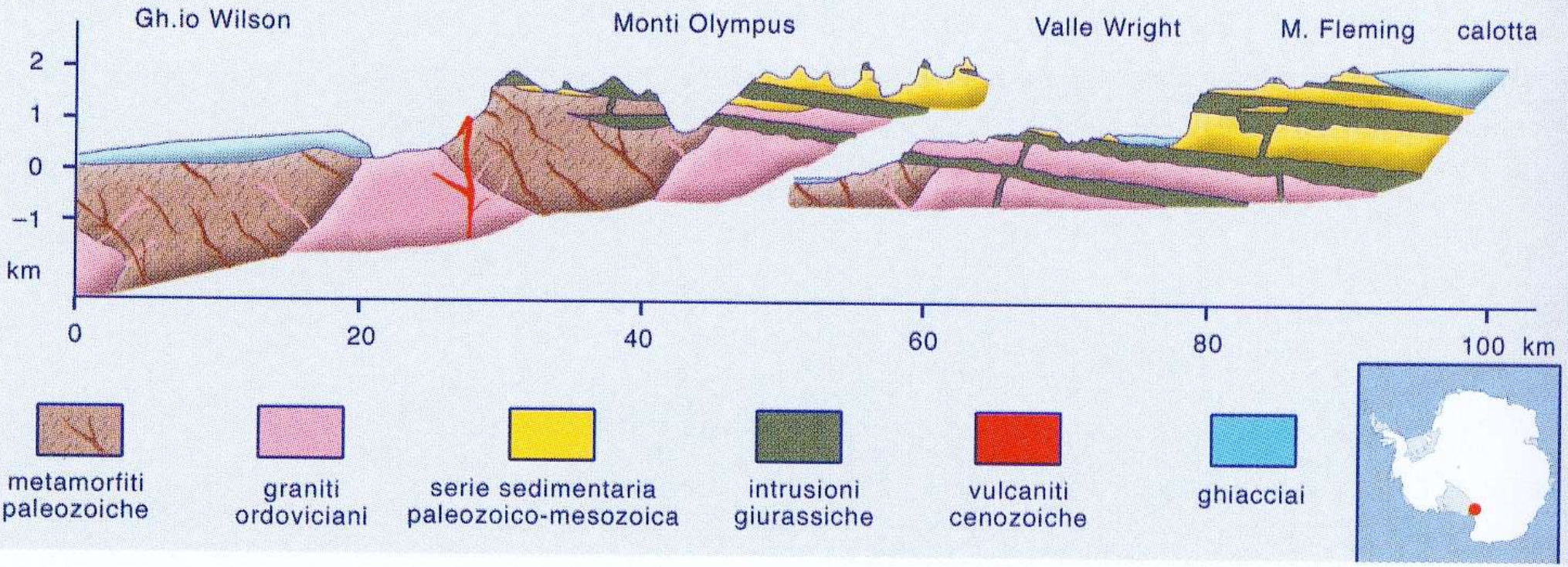
Foto: L. De Santis

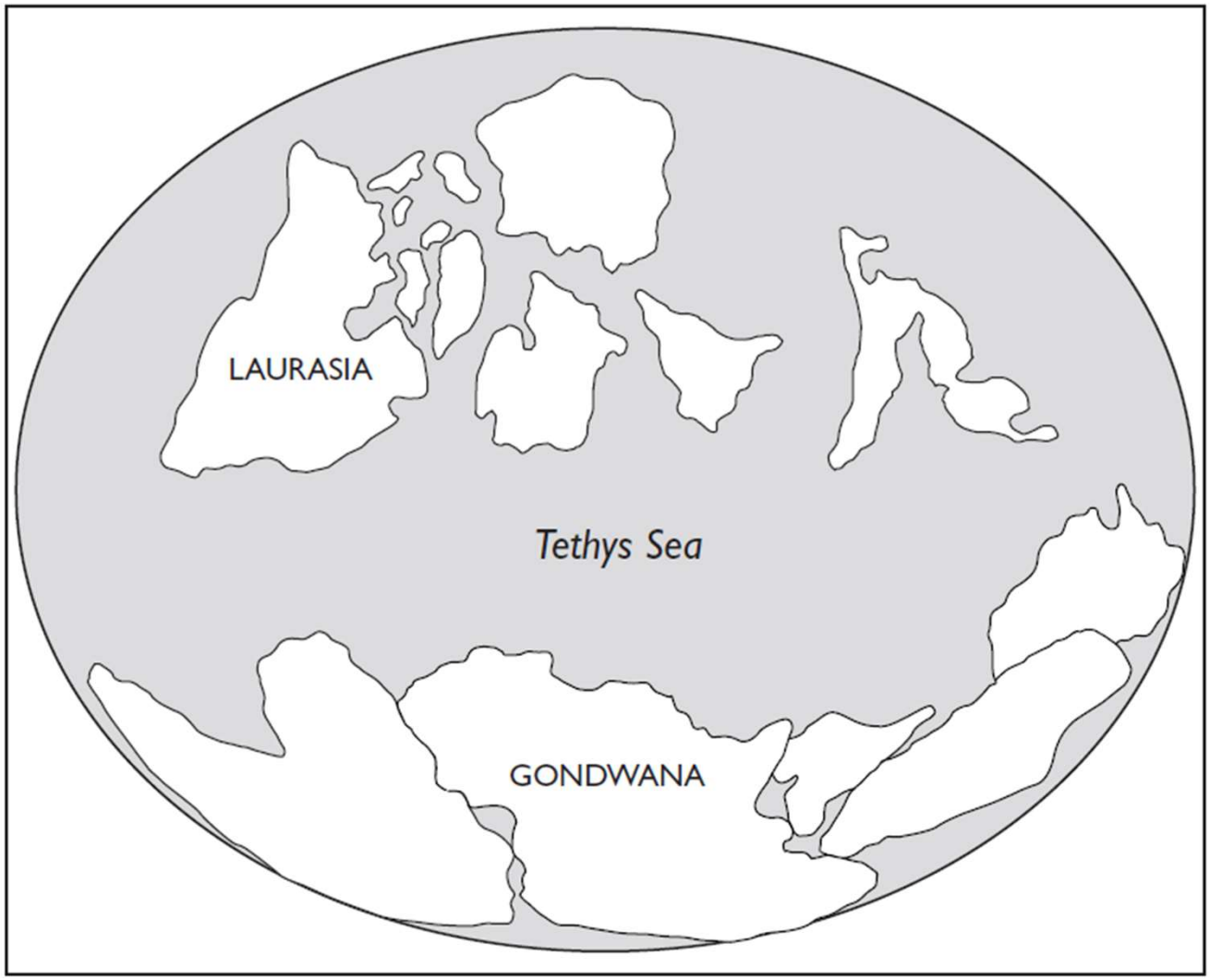

Catena Transantartica
Arenarie del Beacon (tardo Paleozoico, *Devoniano* – Mesozoico, *Triassico*)
Doleriti del Ferrar (lave giurassiche)
Foto: L. De Santis





sezione geologica attraverso le Valli Secche di McMurdo

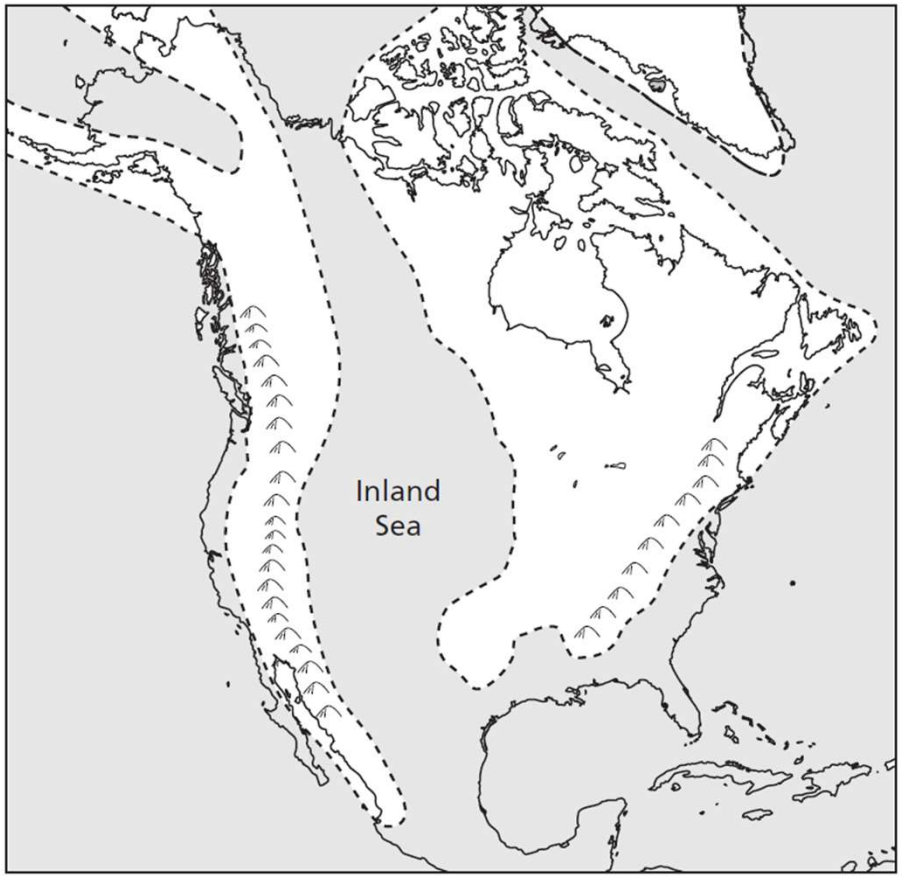




The Tethys was a broad tropical seaway extending from western Europe to southeast Asia that harbored diverse and abundant shallow-water marine life.

Reef building in the Tethys Sea was intense, forming thick deposits of limestone and dolomite laid down by prolific lime-secreting organisms.

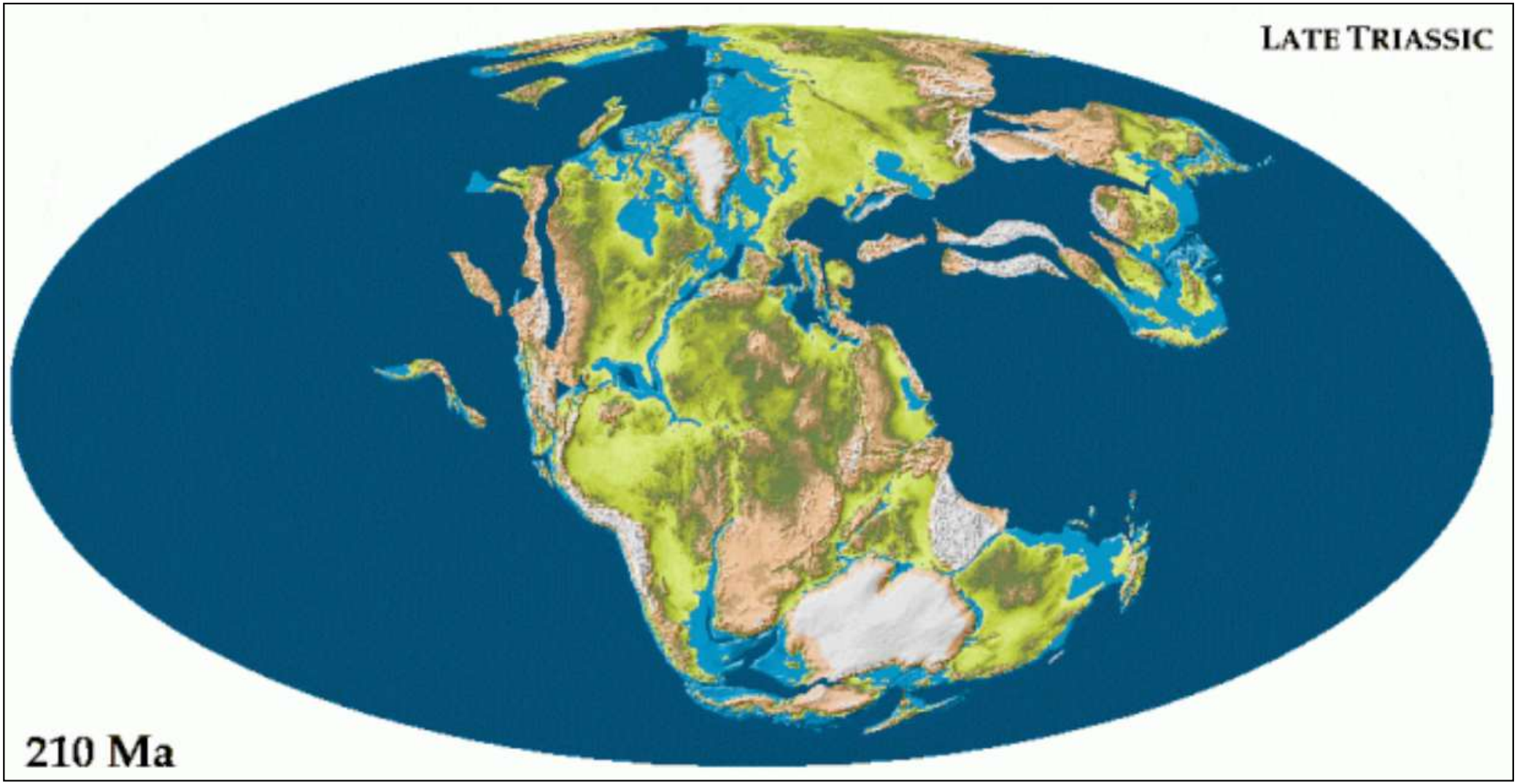
The broad shallow seas at the tropics served as an evolutionary cradle

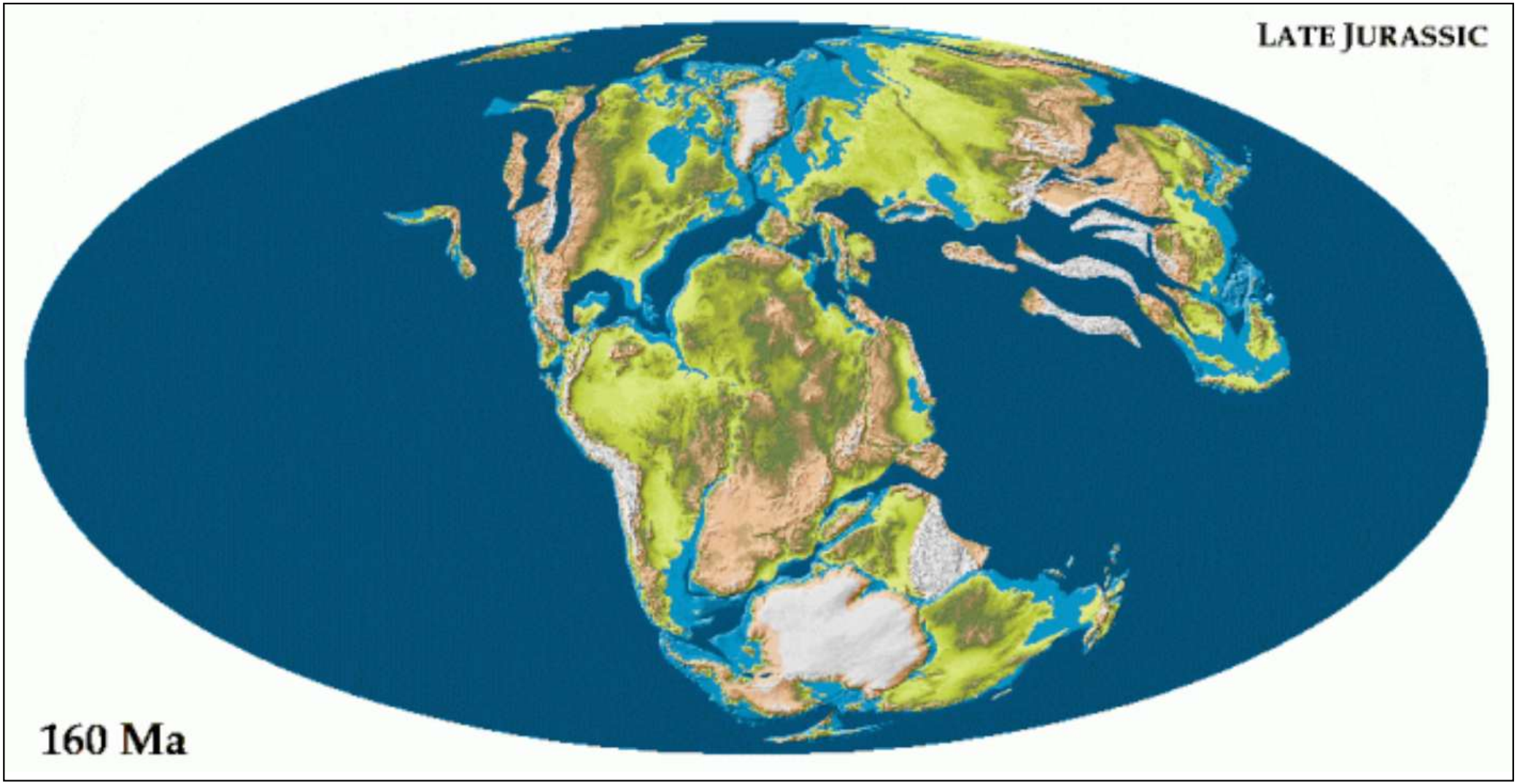


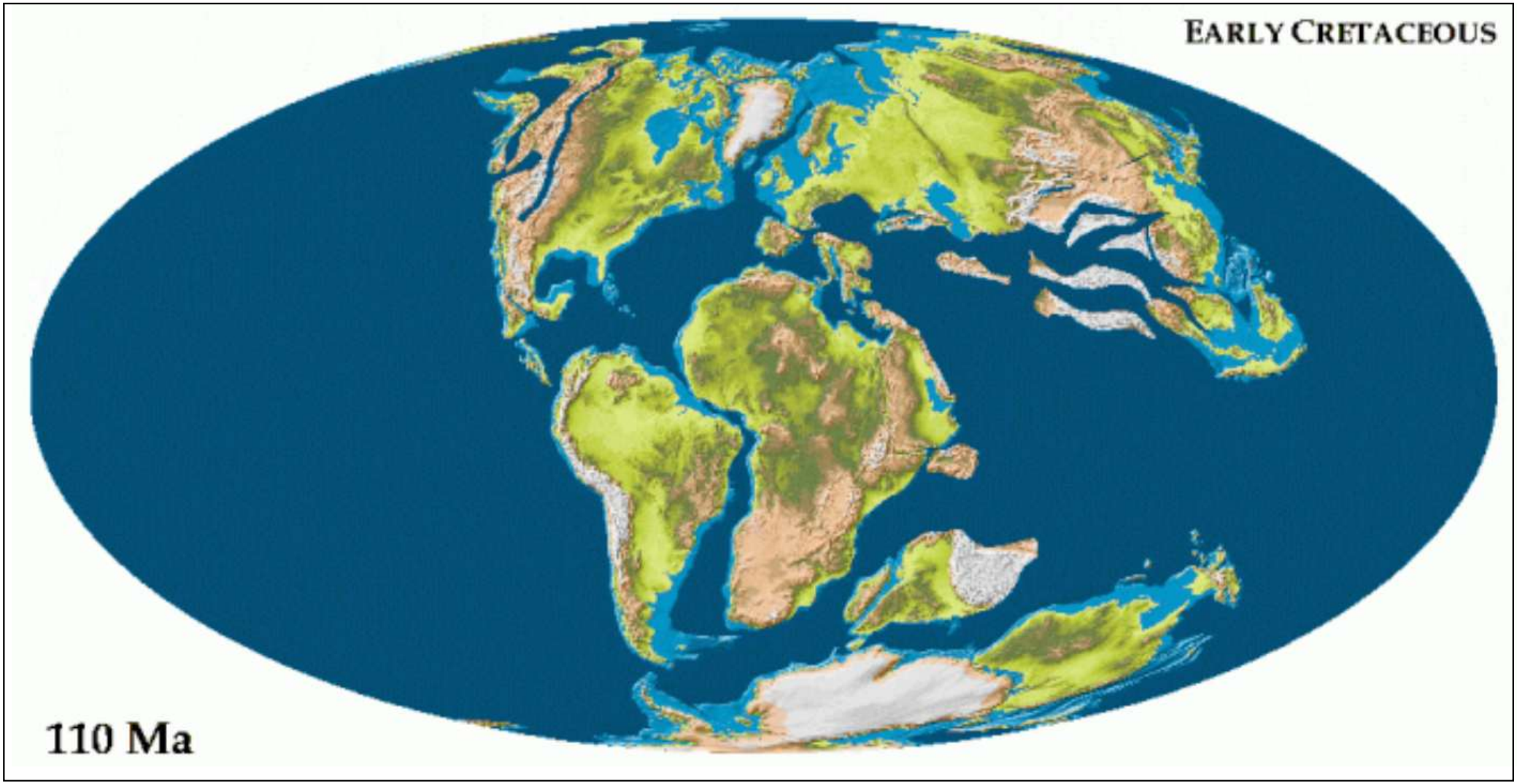
During the Mesozoic era shallow seas flowed into the west-central portions of North America, and also South America, Africa, Asia, Australia, the area between Australia and Antarctica.

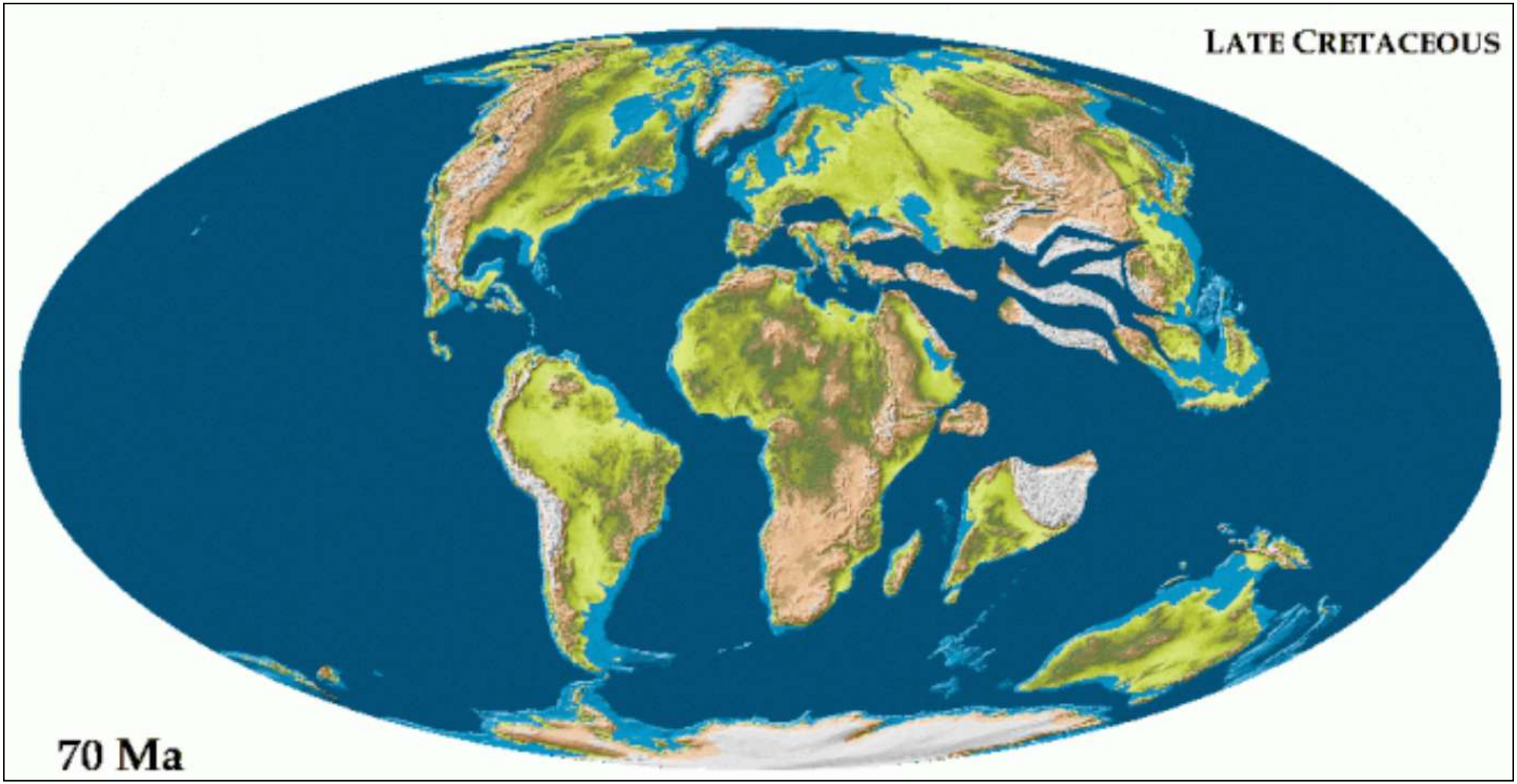
The continents were flatter, mountain ranges were lower, and sea levels were higher than at present.

Thick beds of limestone and dolomite were deposited in the interior seas of Europe and Asia. These rocks later uplifted to form the Alps and Himalayas.


LATE TRIASSIC
210 Ma

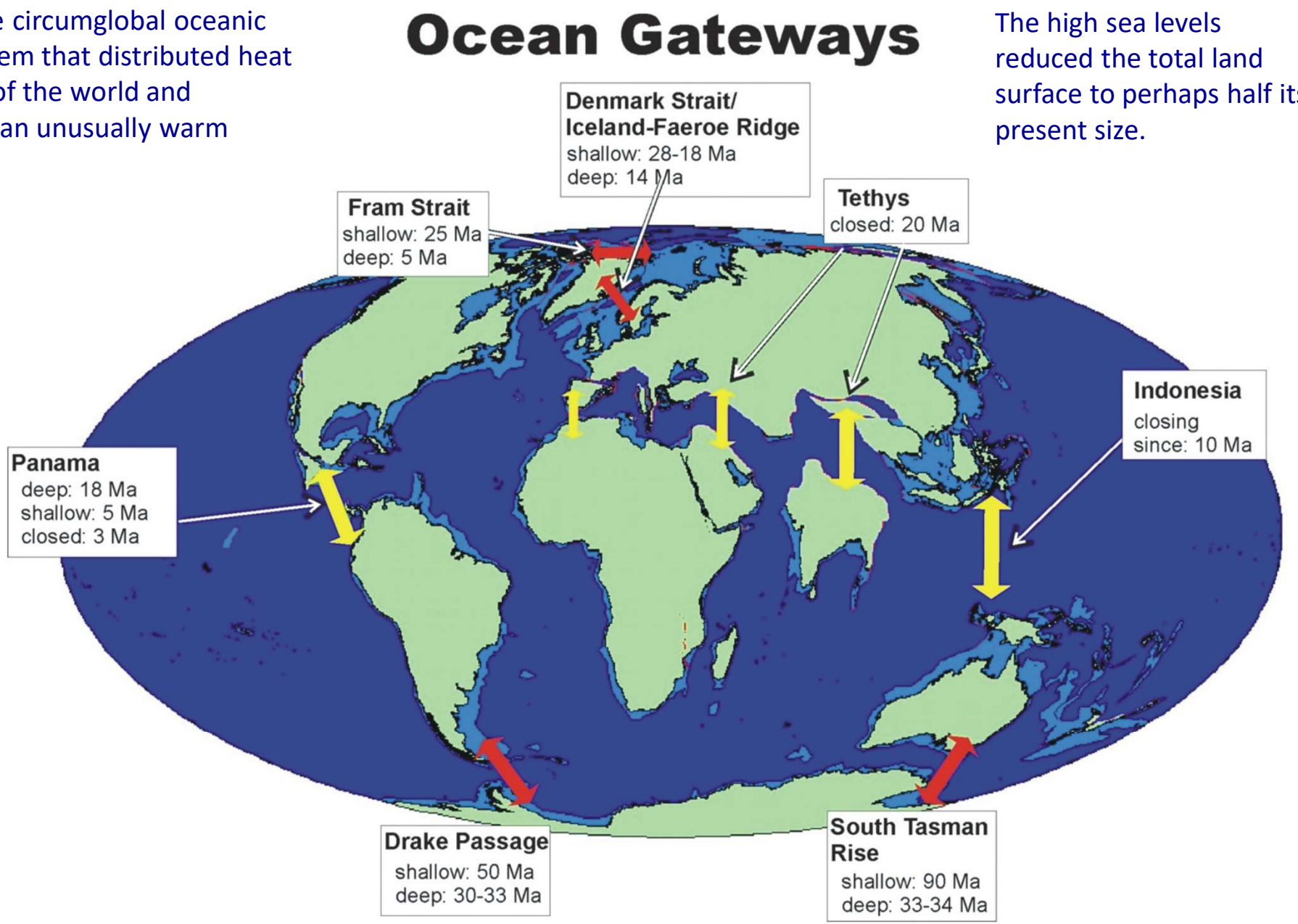

LATE JURASSIC
160 Ma


EARLY CRETACEOUS
110 Ma

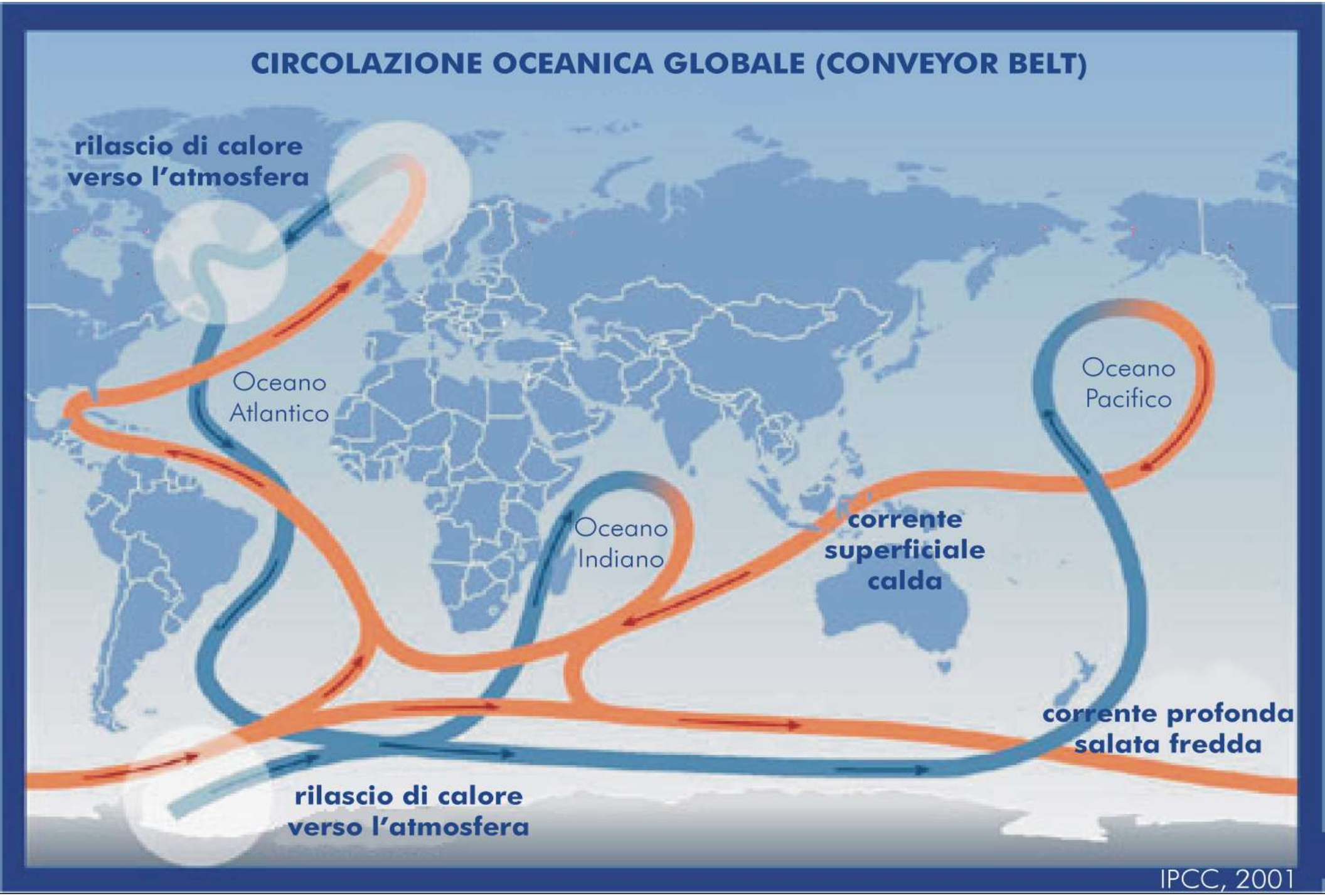

LATE CRETACEOUS
70 Ma

The oceans were interconnected in the equatorial regions by the Tethys and Central American seaways

Low latitude circumglobal oceanic current system that distributed heat to all parts of the world and maintained an unusually warm climate.



The high sea levels reduced the total land surface to perhaps half its present size.


CIRCOLAZIONE OCEANICA GLOBALE (CONVEYOR BELT)
rilascio di calore verso l'atmosfera
Oceano Atlantico
Oceano Indiano
Oceano Pacifico
corrente superficiale calda
corrente profonda salata fredda
rilascio di calore verso l'atmosfera
IPCC, 2001

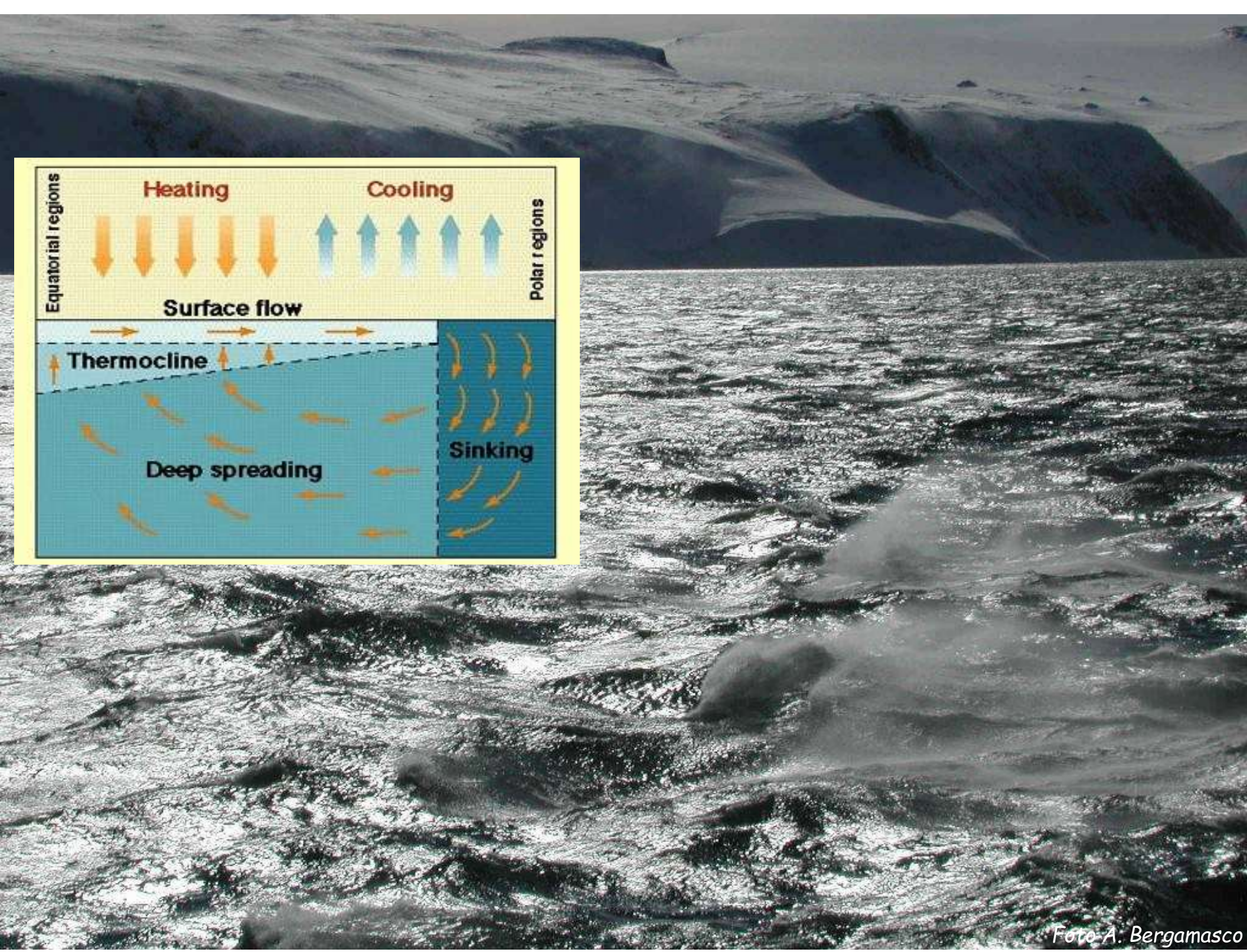
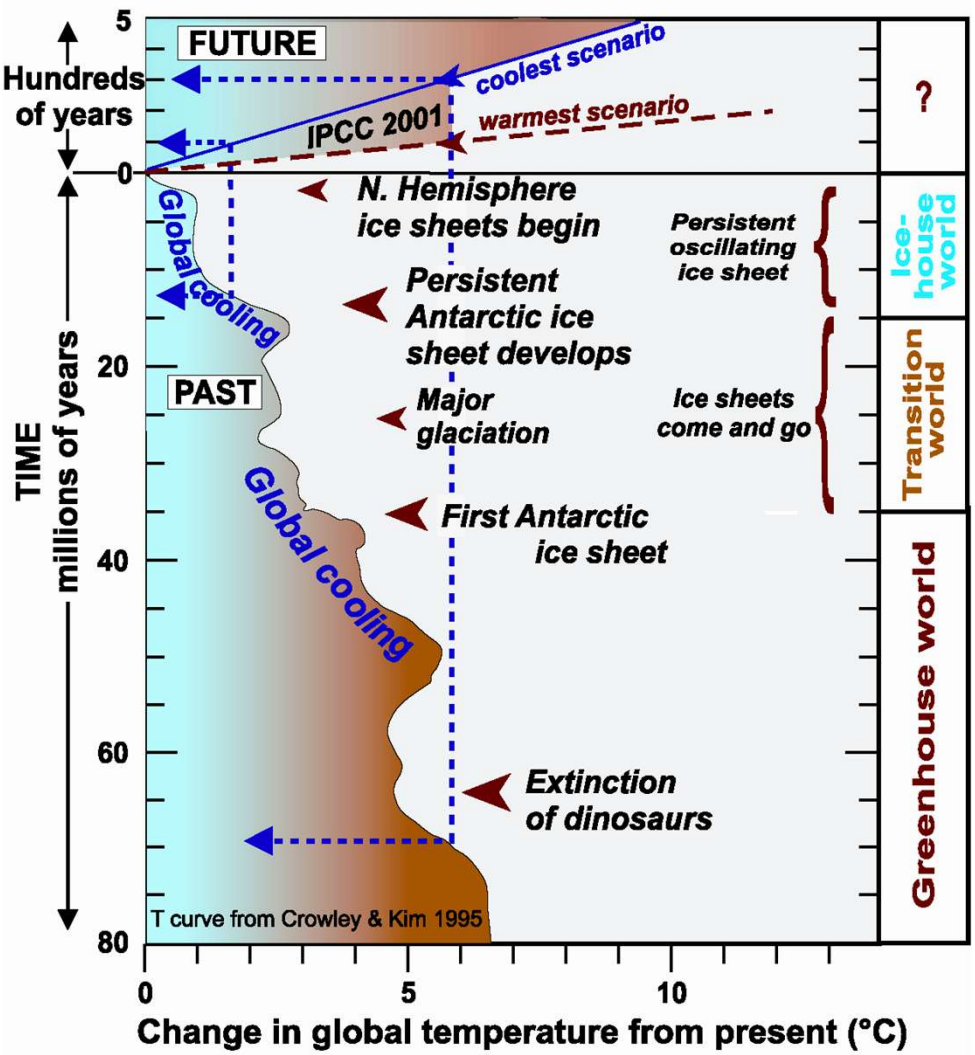


Foto A. Bergamasco



During the Cretaceous period, plants and animals were especially prolific and ranged practically from pole to pole.

The deep ocean waters, which are now near freezing, were about 15 degrees Celsius during the Cretaceous.

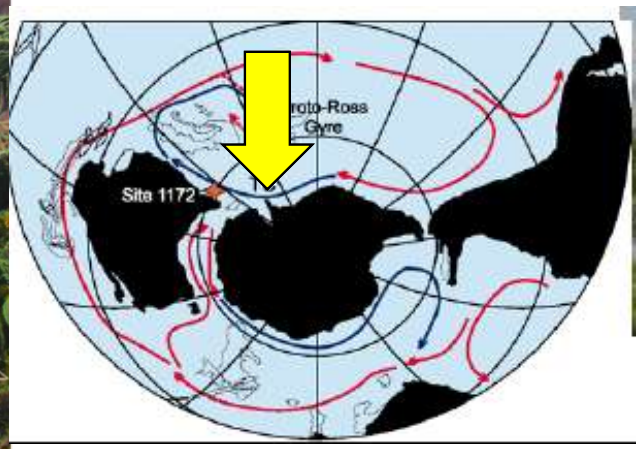
The average global surface temperature was warmer than at present.

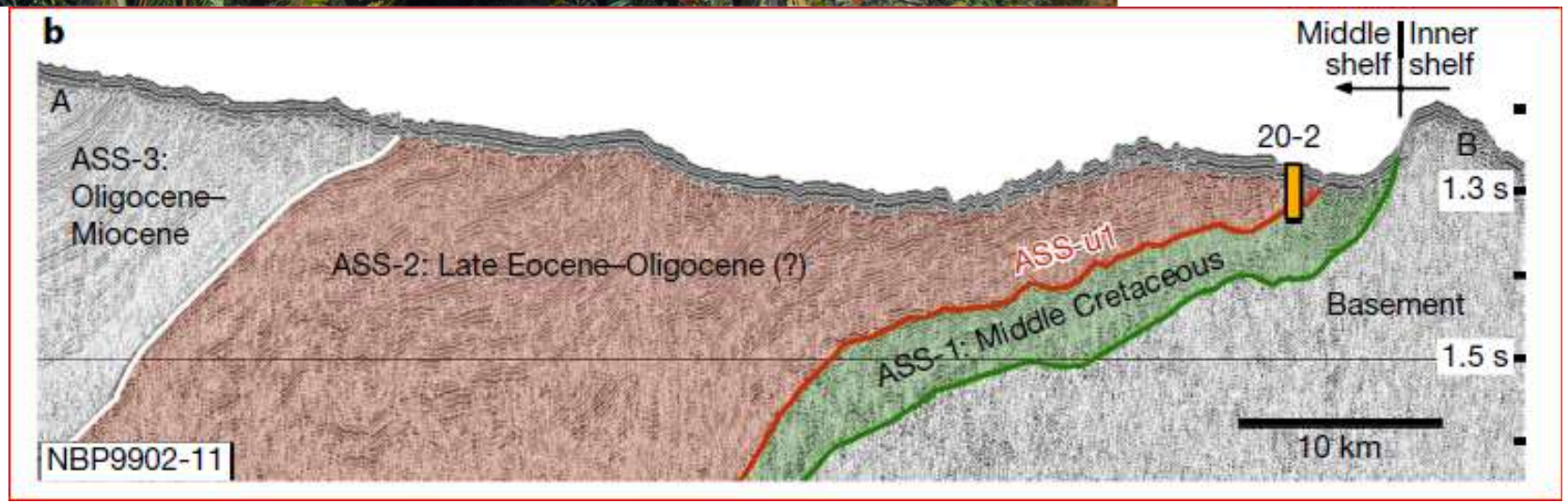
Conditions were also much warmer in the polar regions. The temperature difference between the poles and the equator was about half that of today.

82° S Turonian–Santonian age (92 to 83 million years ago)



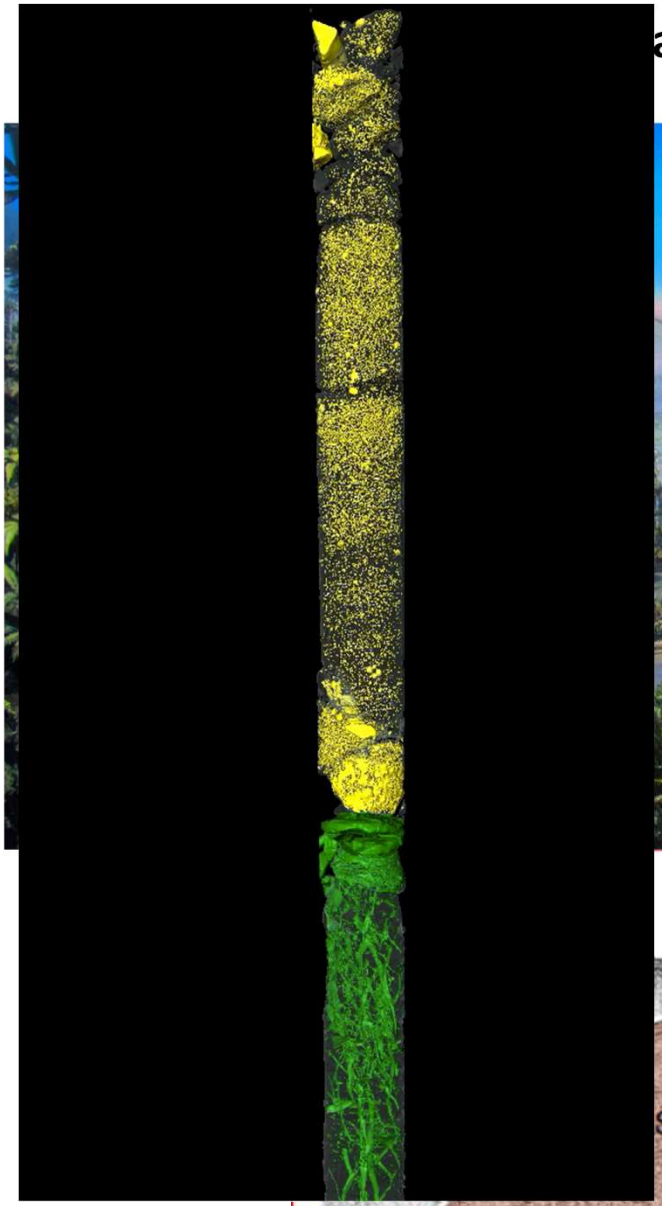
- mean annual temperature +13 °C
- precipitation of 1,120 mm yr−1
- 4 months fully dark
- CO2 1,120–1,680 ppm
- No ice





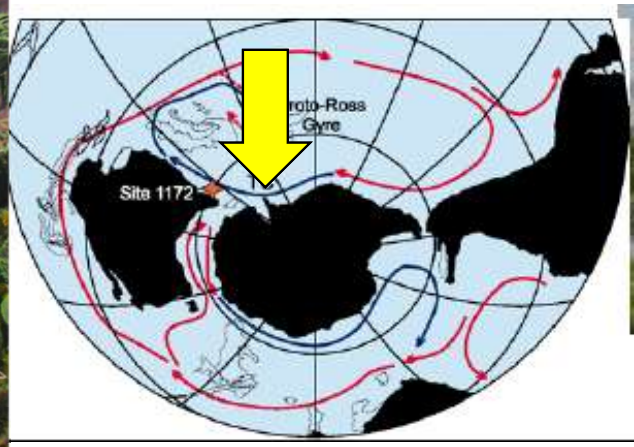
Klages et al., 2020

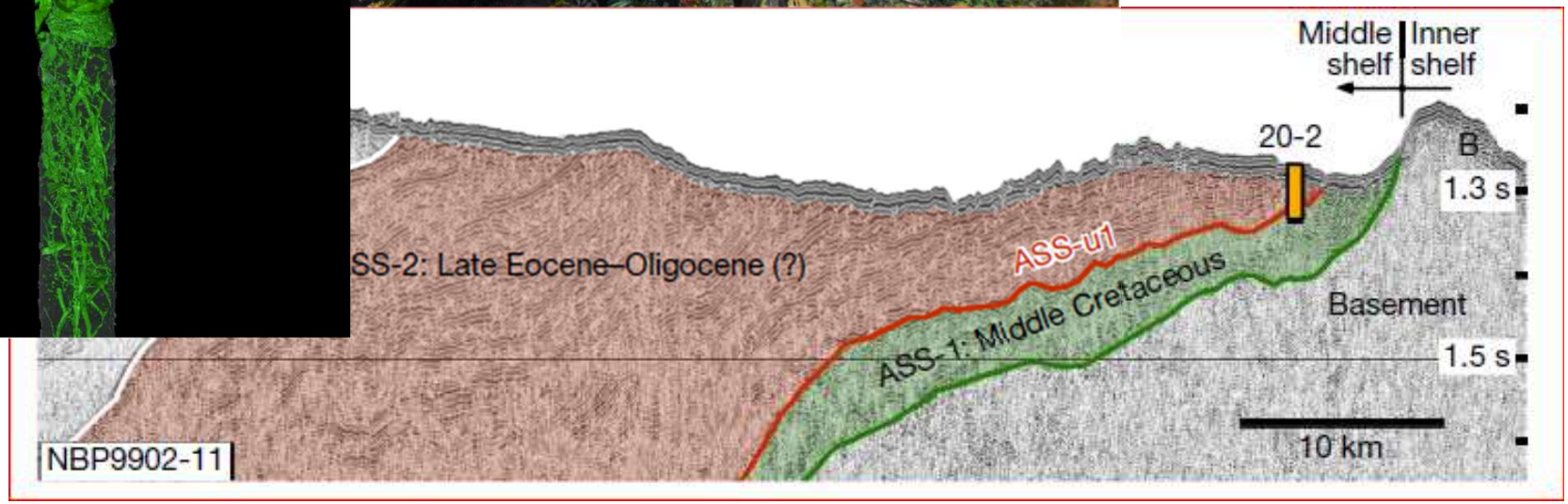
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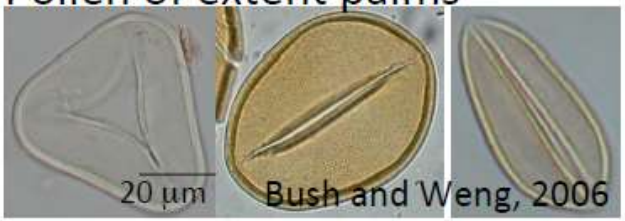




Pollen from the e. Eocene peak greenhouse conditions
Wilkes Land IODP Site 1356



Pollen of extent palms

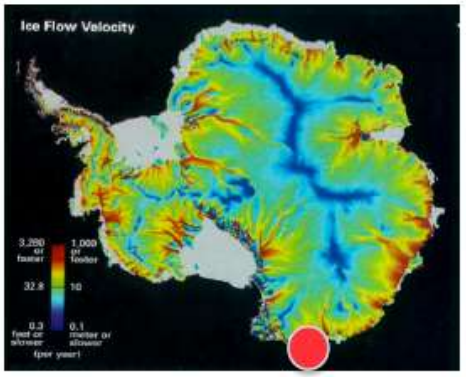


Pollen from Wilkes Land



despite polar winter darkness

Mean Annual T: >13.3 °C
Cold Month mean T: >5°C + 3°C
Warm Month mean T: >22.8 °C





Pollen of extent Bombacaceae plants



Pollen from Wilkes Land



Mean Annual T: >16.8 ºC
Cold Month mean T: >10.6 °C + 3°C
Warm Month mean T: >21.5 °C

Pross et al., Nature, 2012
Contreras et al., 2013

Eocene records of Antarctic vegetation and landscape history (e.g. Lewis et al., 2007, Hambrey et al., 2007, Wilson et al., 2011).

The Eocene/Oligocene boundary unconformity was crossed by exp. 318, and sub-tropical vegetation was found at 53.6–51.9 Ma in the early Eocene (Pross et al., 2012).

IODP Exp. 318 (2010)

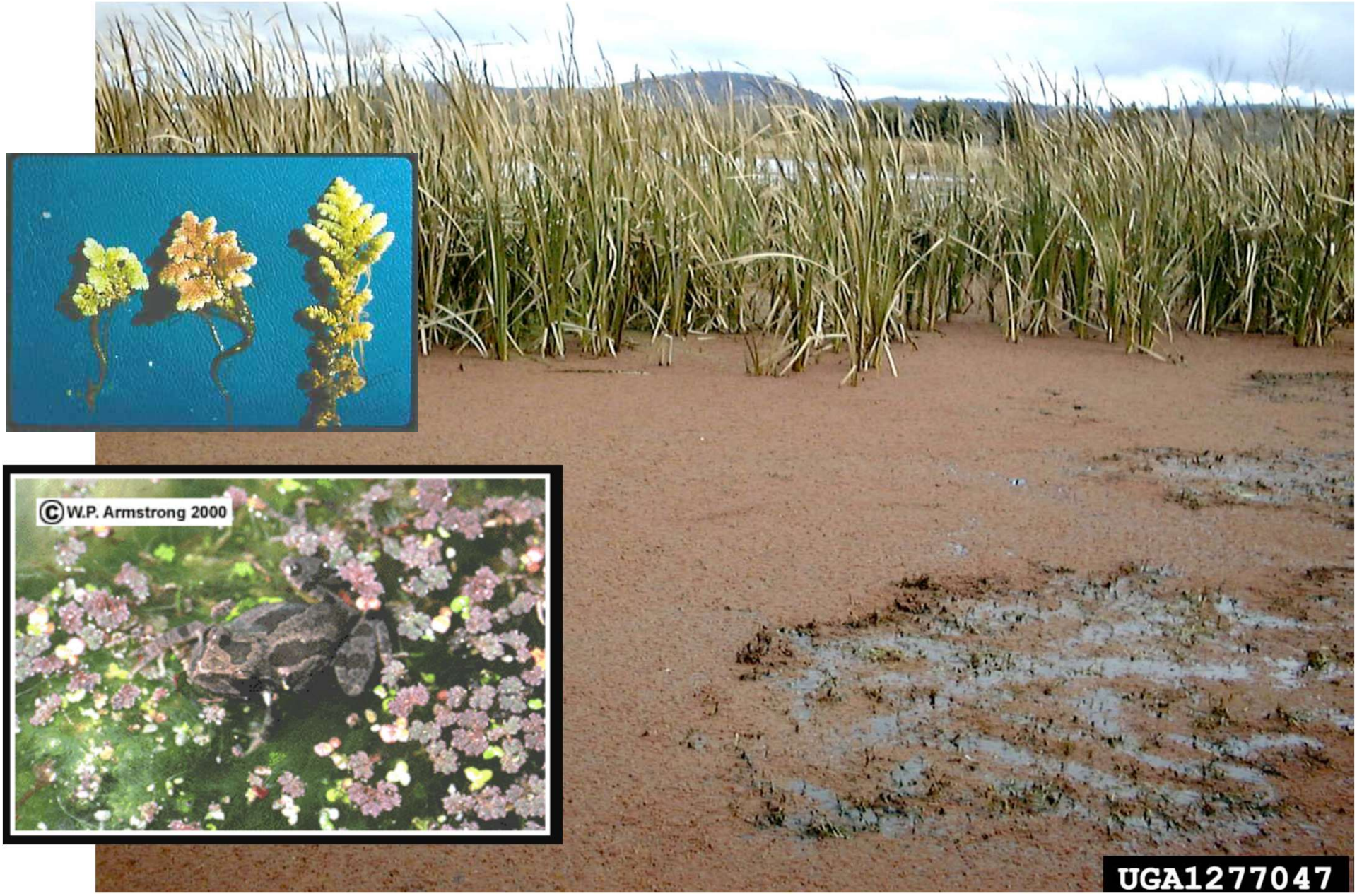
LETTER

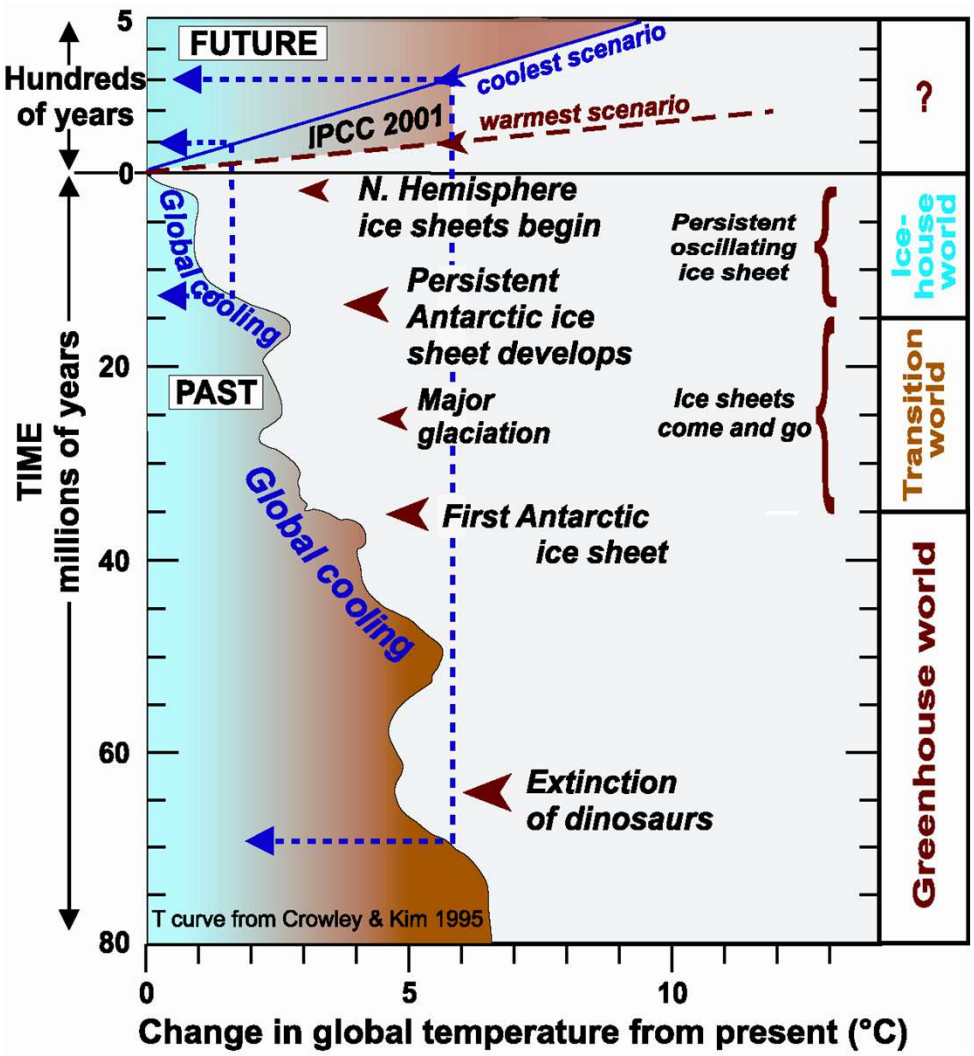
doi:10.1038/nature11300

Persistent near-tropical warmth on the Antarctic continent during the early Eocene epoch

Jörg Pross[1,2], Lineth Contreras[1], Peter K. Bijl[3], David R. Greenwood[4], Steven M. Bohaty[5], Stefan Schouten[6], James A. Bendle[7], Ursula Röhl[8], Lisa Tauxe[9], J. Ian Raine[10], Claire E. Huck[11], Tina van de Flierdt[11], Stewart S. R. Jamieson[12], Catherine E. Stickley[13], Bas van de Schootbrugge[1], Carlota Escutia[14], Henk Brinkhuis[3] & Integrated Ocean Drilling Program Expedition 318 Scientists*

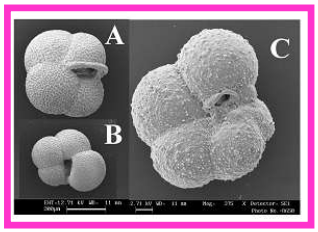
Environmental conditions typical of modern tropical regimes 55 million years ago—featuring poor ventilation, fresh water, and anoxic conditions (Arctic pond)—and around 48.5 million years ago (hydrocarbon source rocks).





Ar 35 Ma the climate cooled
The seas withdrew from the land as the ocean dropped to perhaps its lowest level since the last several hundred million years and remained depressed for the next 5 million years

Deep Sea Oxygen isotope record from Foraminifera (carbonatic Benthic and Planktonic Protozoans)



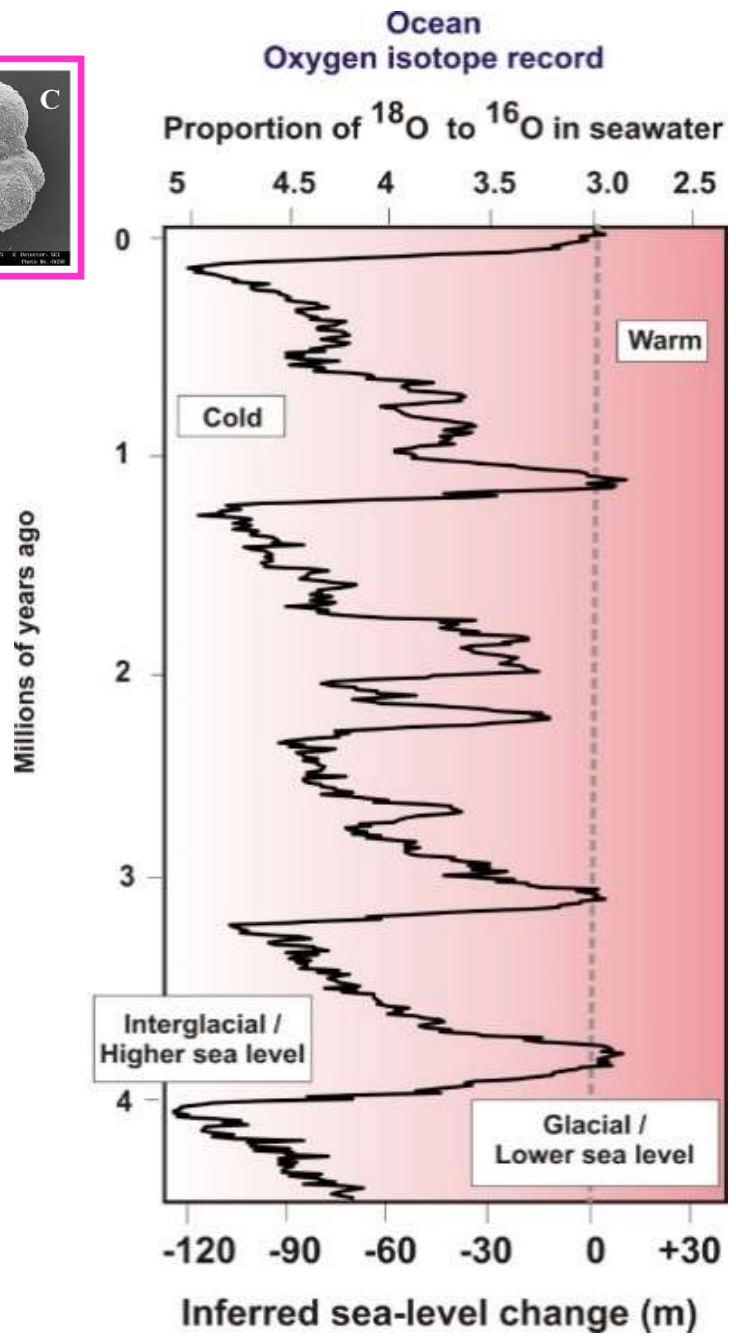
Ice ages (glacials) – light oxygen ^{16}O is removed from the ocean through photosynthesis and evaporation and accumulates in ice sheet

Warm periods (interglacials) – light oxygen ^{16}O is returned to the ocean by ice melting

Translated in term of ice volume through empirical relationships:

$\delta^{18}O = 0.11‰ \longrightarrow$ 10 m SLE

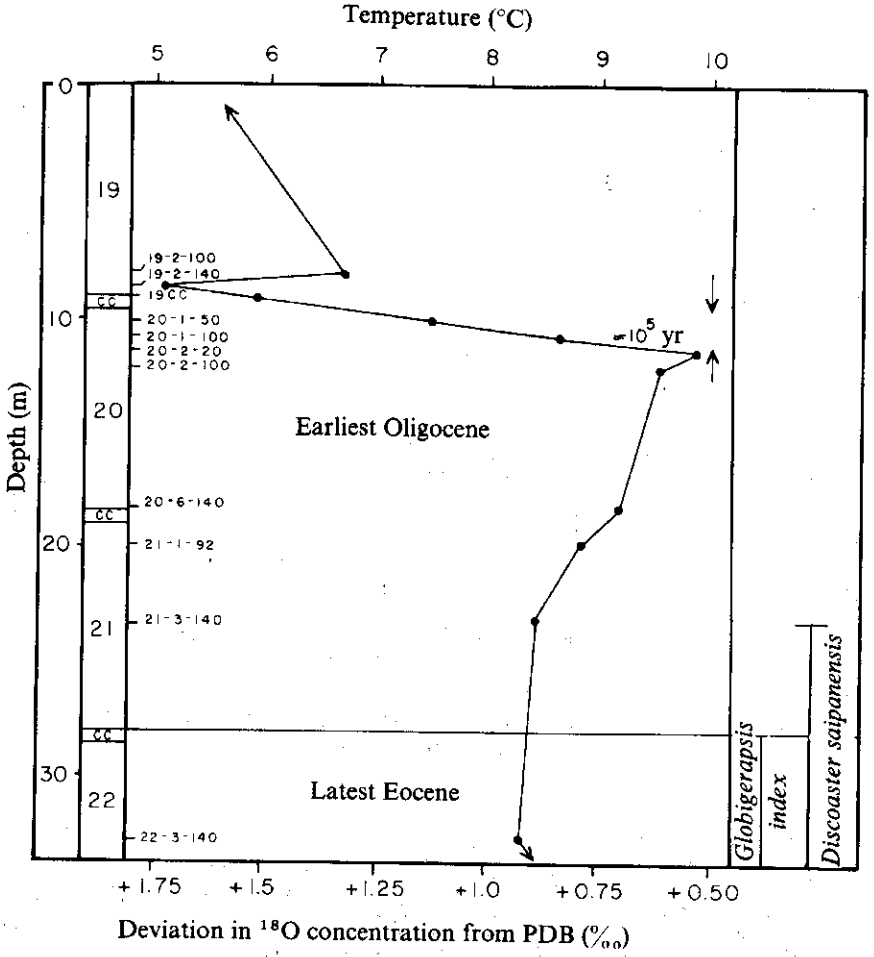
For the LGM: $\delta^{18}O$ change ~1.5‰ $\longrightarrow$ ~ 136 m SLE



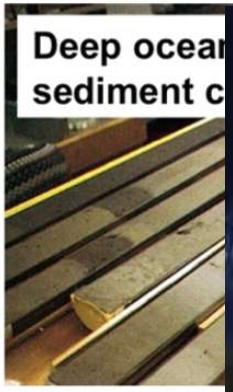
DSDP Leg 29 Ocean Deep sea Geochemical evidence for the onset of Antarctic glaciations at c. 34 Ma

Campbell Plateau, SW Pacific Ocean

mean annual temperatures at these latitudes were ca. freezing => Antarctic glaciers would develop

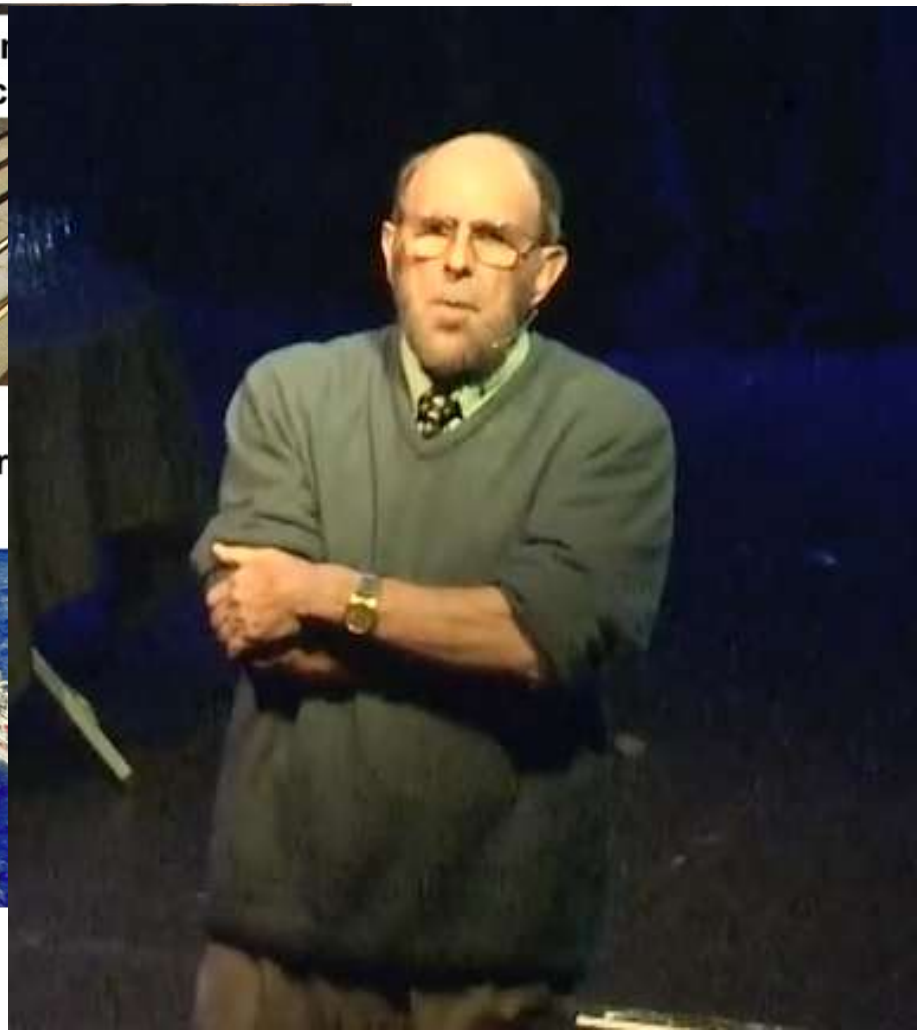


Kennett and Shackleton (1976), *Nature, DSDP Site 277*



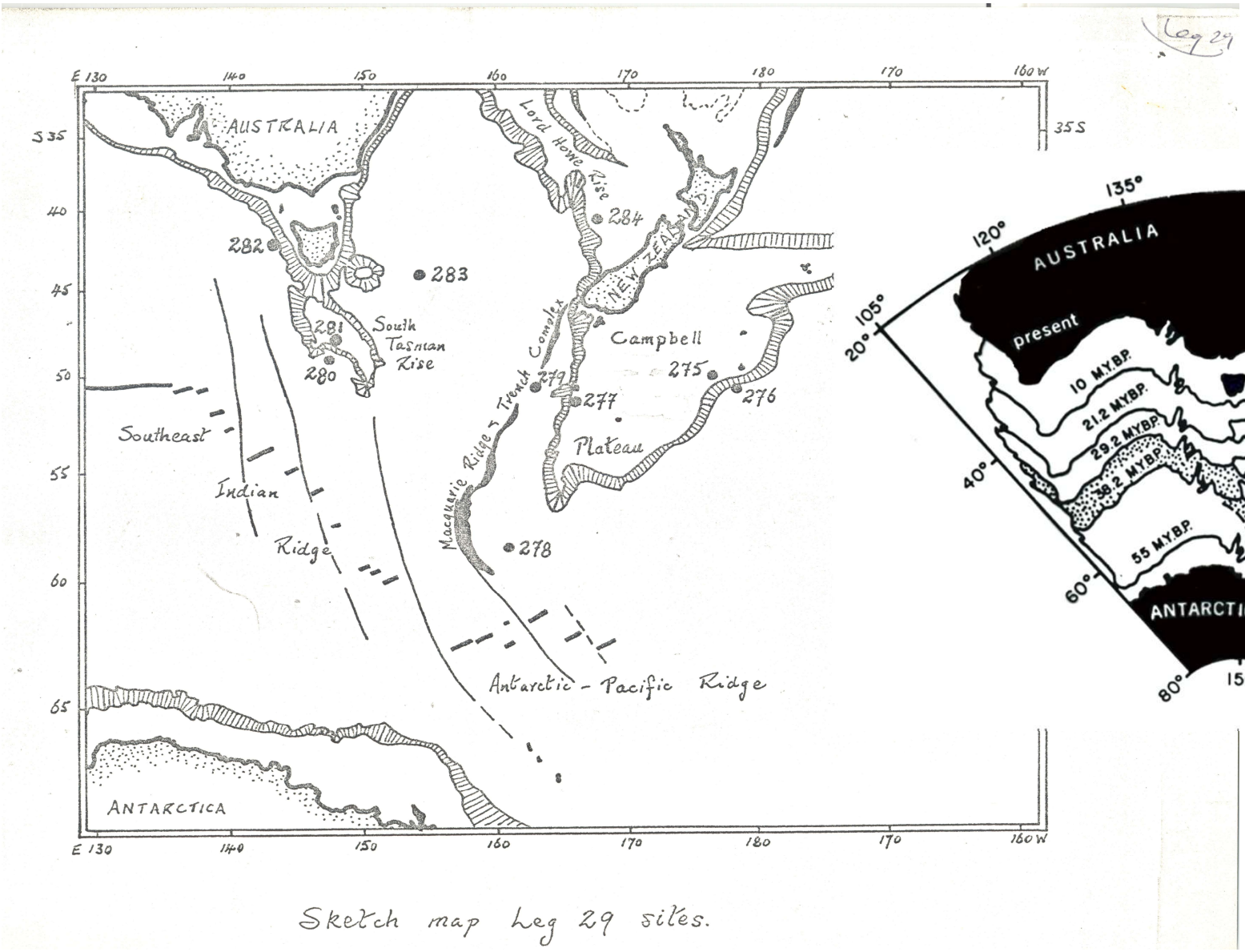
Foraminifer

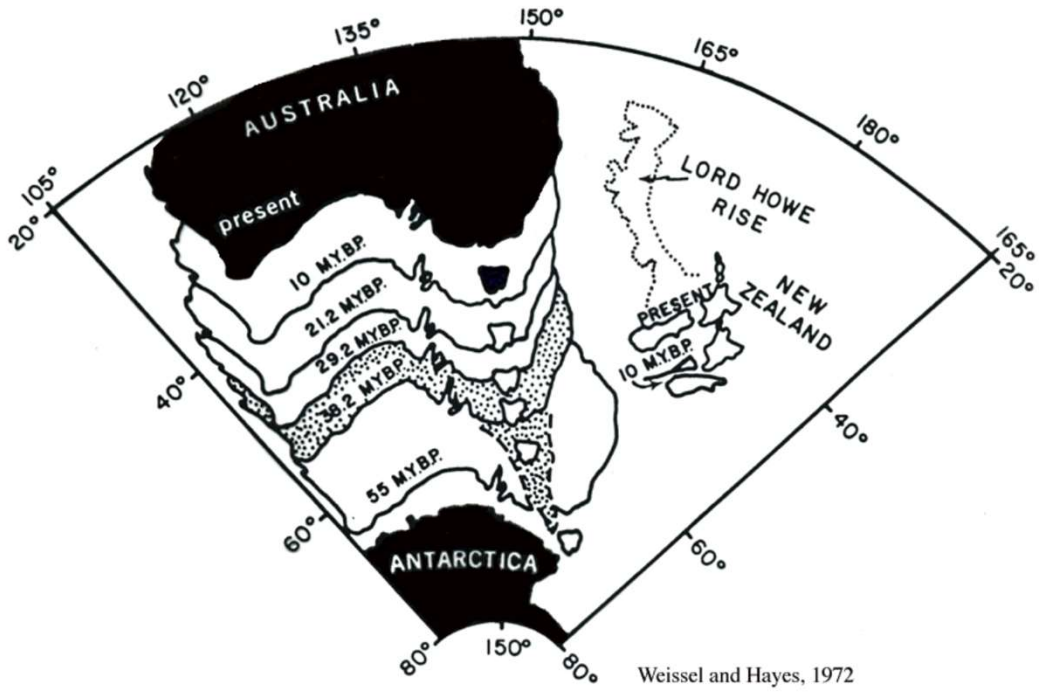




Talk by Jim Kenneth (Univ. California) March 8th 2018

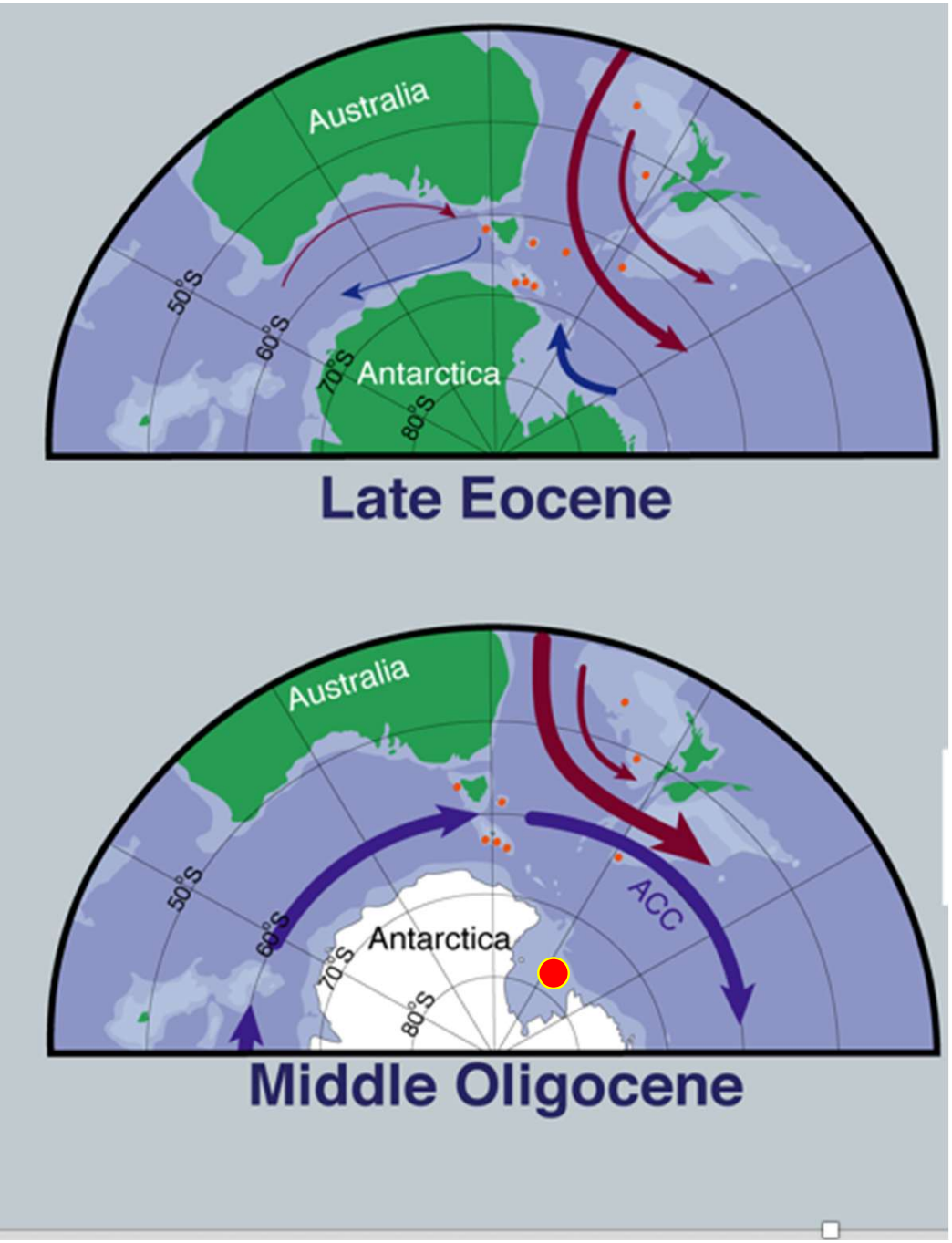
https://www.scar-instant.org/pais/index.php/insights/video





GEOTIMES July 1973

Thermal isolation of Antarctic ~35 Ma when ocean gateways opened – *James Kennett's hypothesis*



Ocean Gateway Hypothesis

Warm Eocene
Ice free continent (greenhouse world)

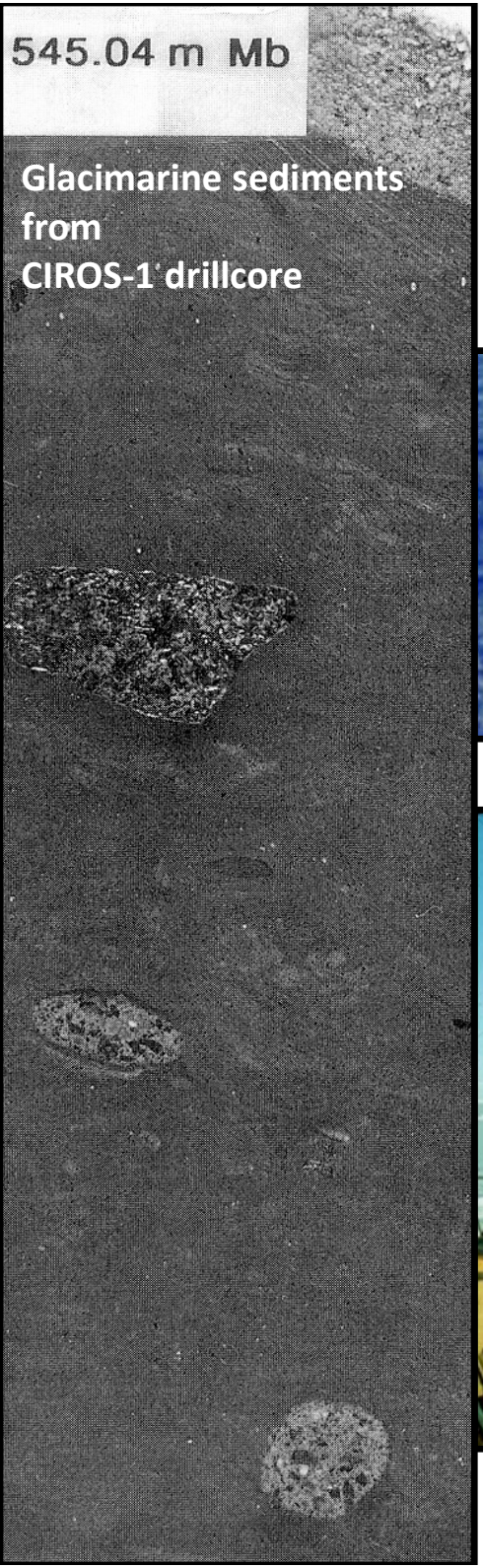
Opening of the Tasmanian Gateway during the Eocene/Oligocene transition

Initiation of Circum Antarctic Current (ACC)

Thermal isolation of Antarctica And Glacial Expansion

First evidence of grounding ice dated 25 Ma DSDP leg 28 (Hayes and Frakes, 1973)

ice albedo feedback amplified cooling => icehouse world



Proximal sedimentary evidence for earliest Oligocene Antarctic glaciation (33-35 Ma)

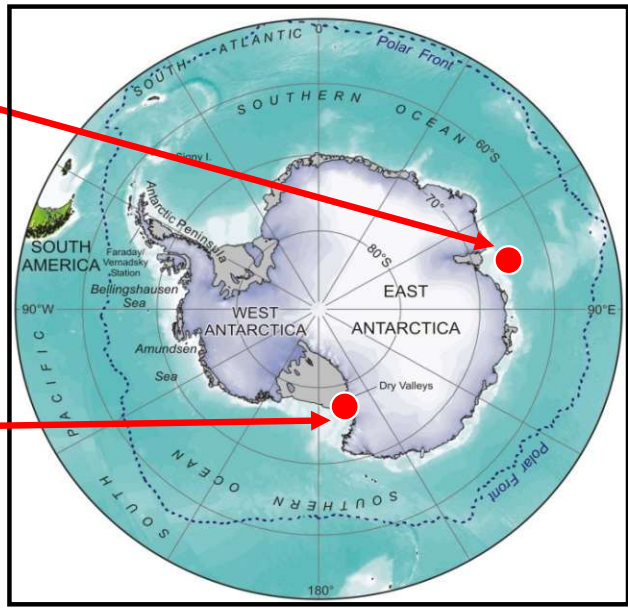
Hambrey et al (1991), ODP Leg 119, Prydz Bay
O'Brien, Cooper et al. (2004), ODP Leg 188



Barrett et al. 1989



Iceberg rafted debris



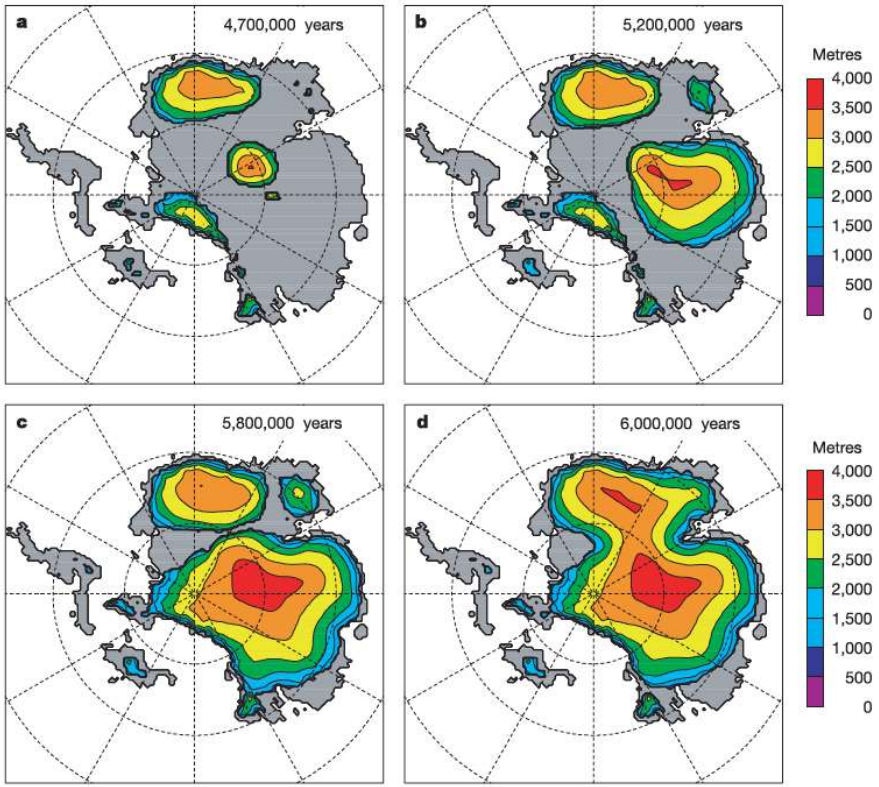
Atmopsheric carbon dioxide caused Antarctic glaciation
- *DeConto & Pollard's hypothesis*

letters to nature

Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2

Robert M. DeConto* & David Pollard†

** Department of Geosciences, University of Massachusetts, Amherst, Massachusetts 01003, USA*
† EMS Environment Institute, The Pennsylvania State University, University Park, Pennsylvania 16802, USA

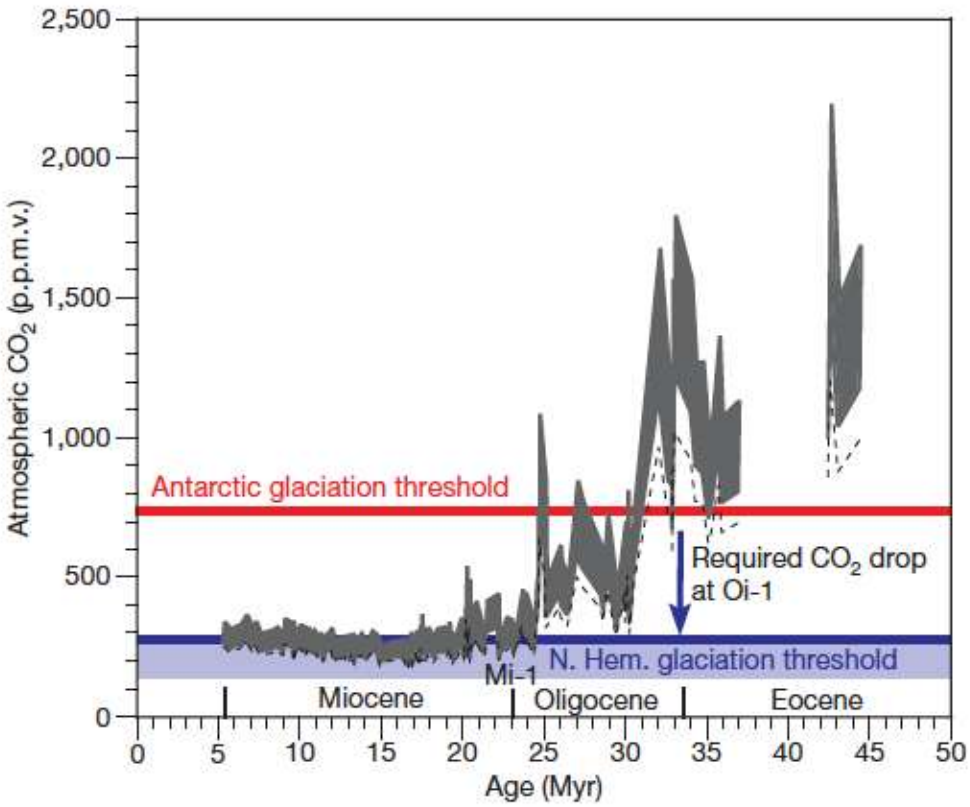


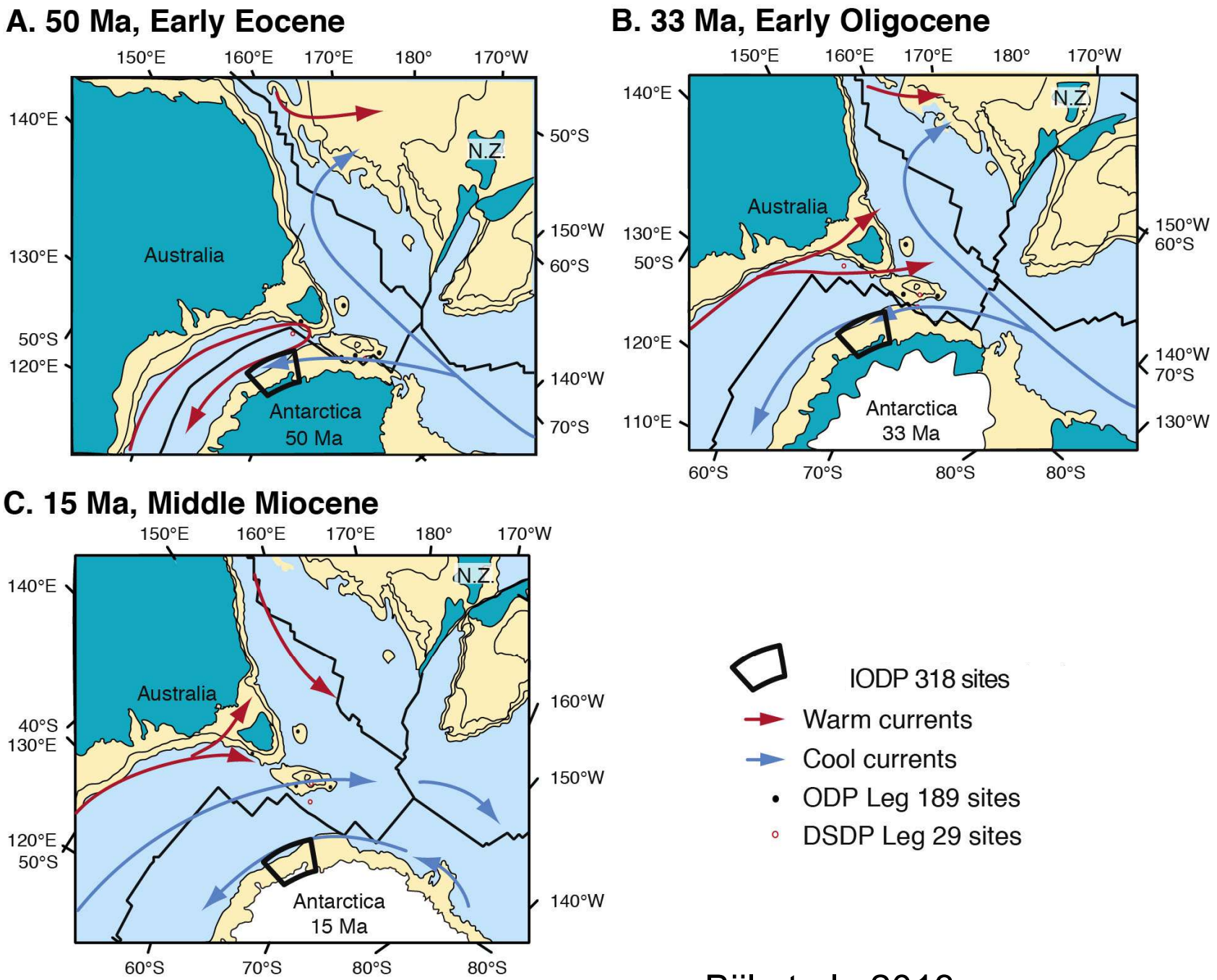
nature Vol 455|2 October 2008|doi:10.1038/nature07337

LETTERS

Thresholds for Cenozoic bipolar glaciation

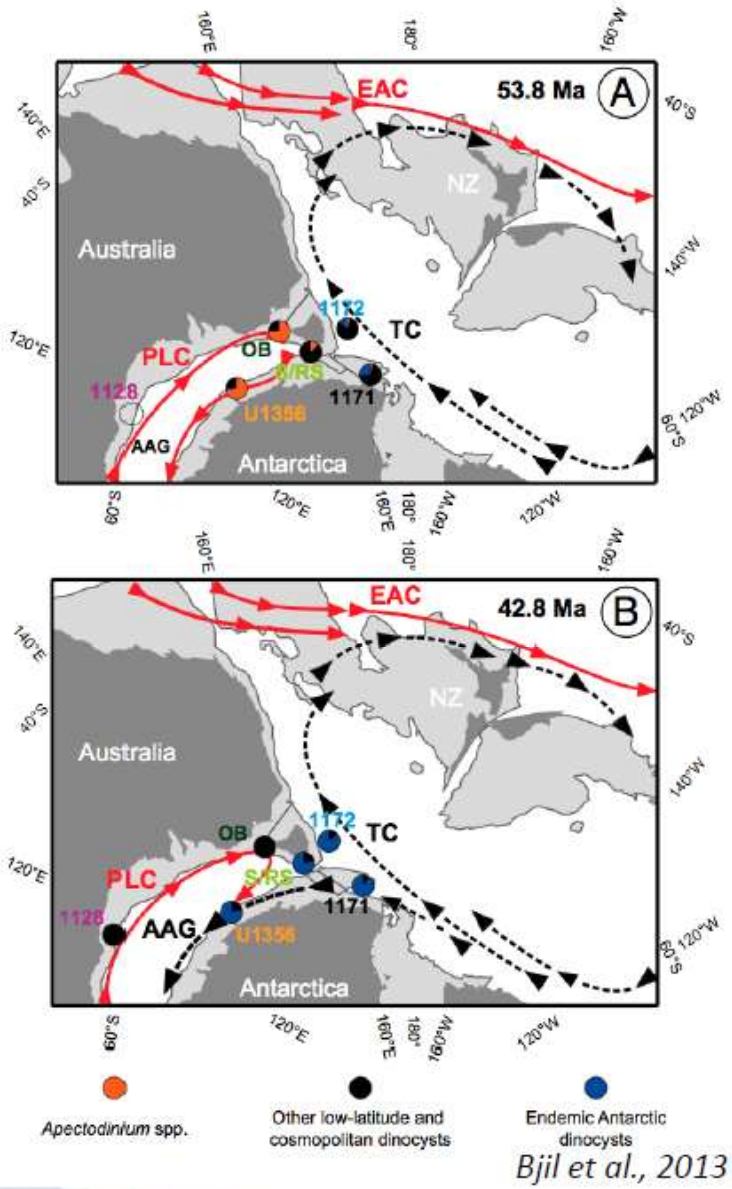
Robert M. DeConto[1], David Pollard[2], Paul A. Wilson[3], Heiko Pälike[3], Caroline H. Lear[4] & Mark Pagani[5]





Bjil et al., 2013

Eocene paleogeographic, paleoceanographic and paleotopographic reconstructions



Bijl et al., 2013

Dinocyst assemblage and organic biomarker paleothermometry data from Site U1356

Cooling coincided with cold waters from the Ross Sea Gyre flowing through the incipient opening of the southern Tasman Gateway, following the Early Eocene Climatic Optimum

although atmospheric CO2 forcing alone might provide uniform middle Eocene cooling, the early opening of the Tasman Gateway is more consistent with Southern Ocean surface water and global deep ocean cooling in the apparent absence of (sub-) equatorial cooling

Proto-Leeuwin Current (PLC)
Tasman Current
Australo-Antarctic Gulf (AAG)





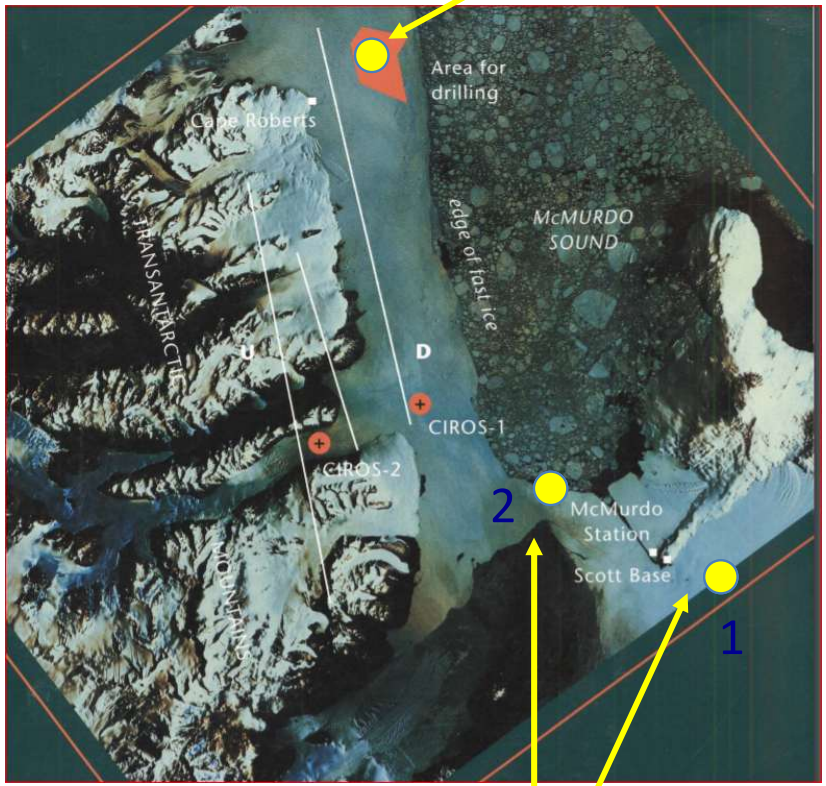
OGS Istituto Nazionale di Oceanografia e di Geofisica Sperimentale

Cape Roberts project
1997-99

(1500 m) 34-17 Ma

98% recovery In the continental shelf!
from cool temperate to subpolar to polar climate


Photo L. De Santis

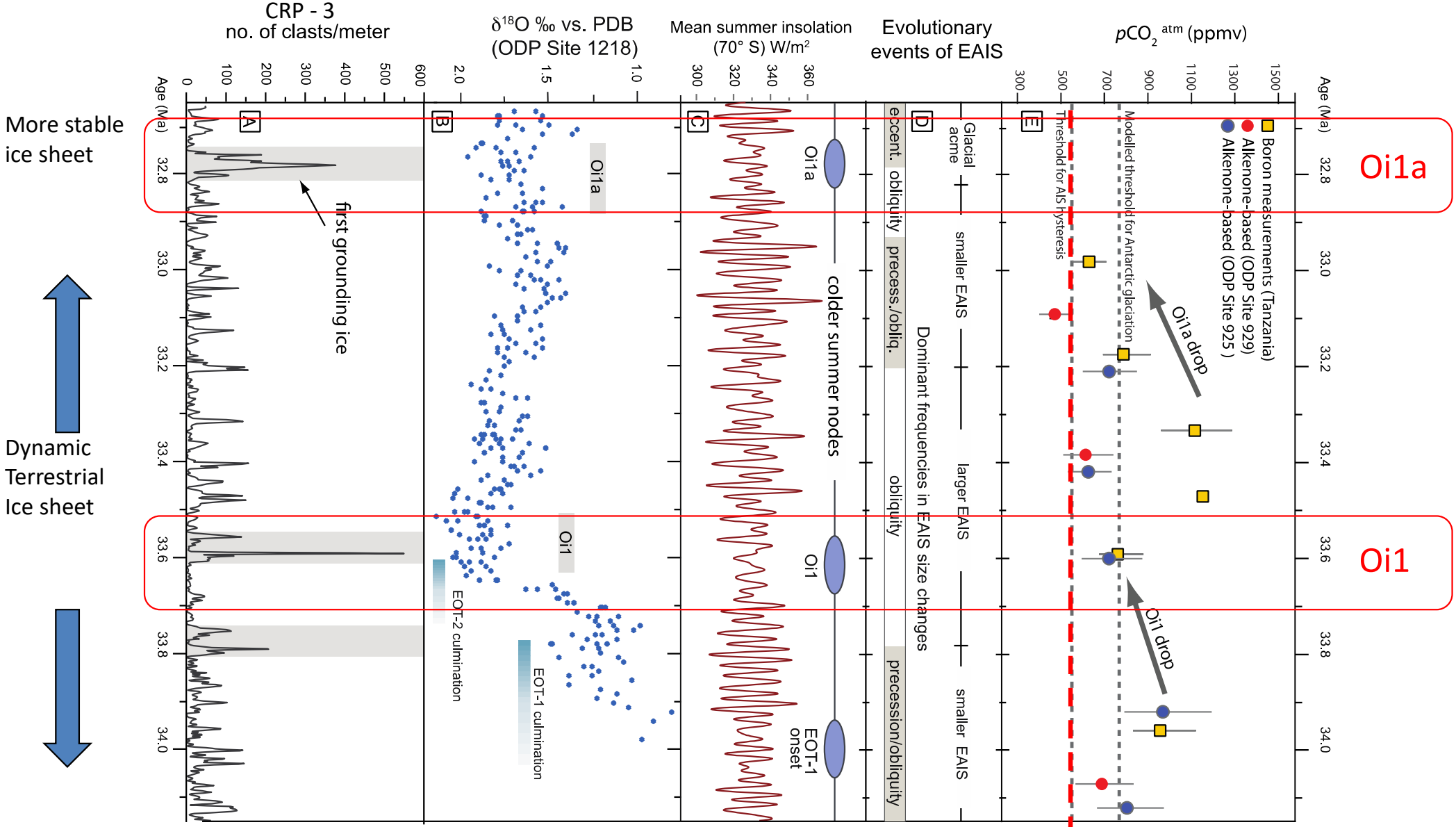


ANDRILL (**AN**tarctic **DRILL**ing Project
2006-07-08

(2500 m) last 17 Ma

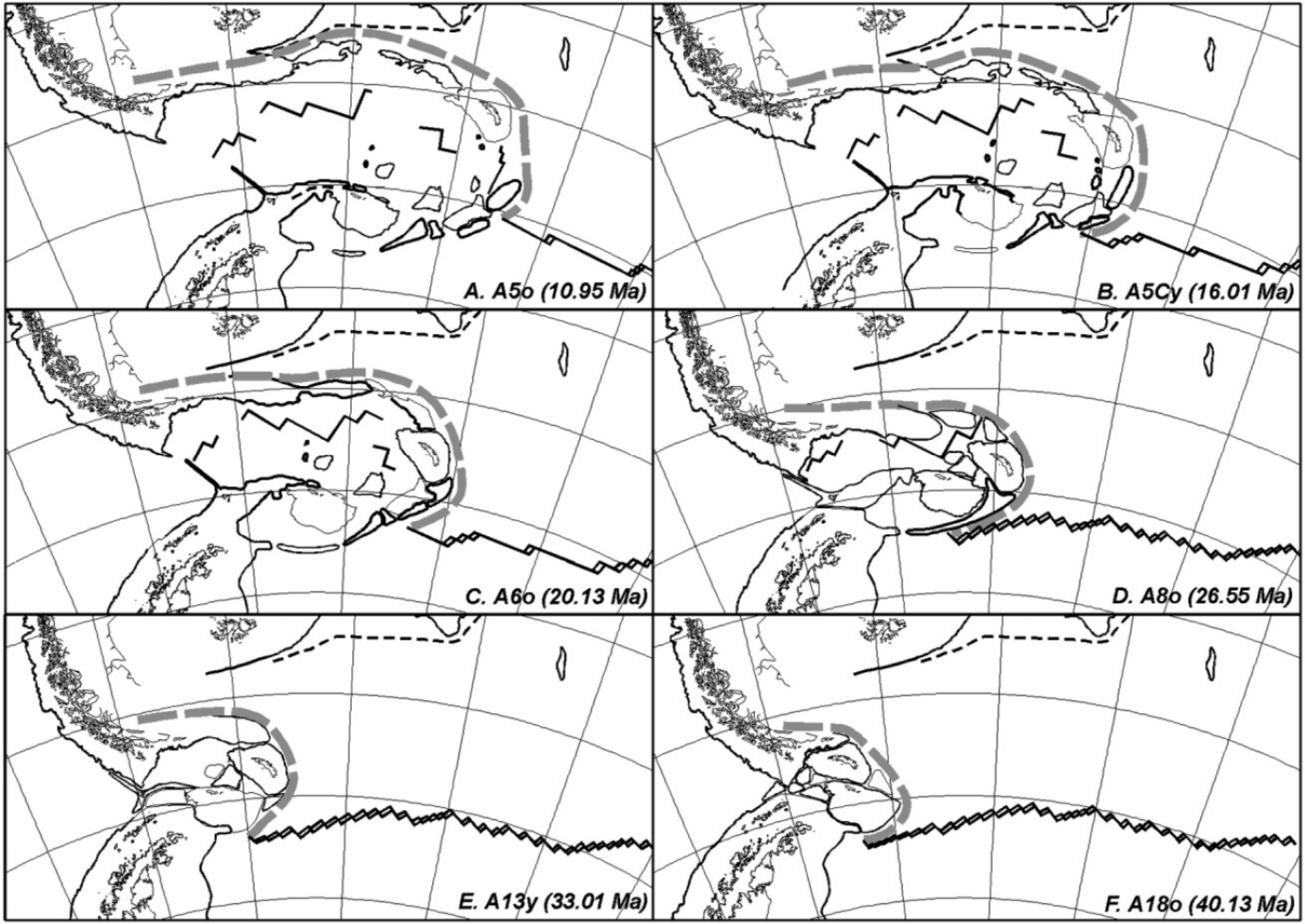
CO_2 threshold delays continental scale glaciation until Oi1a

Is this a CO2 threshold across which no ice will exist in the future?

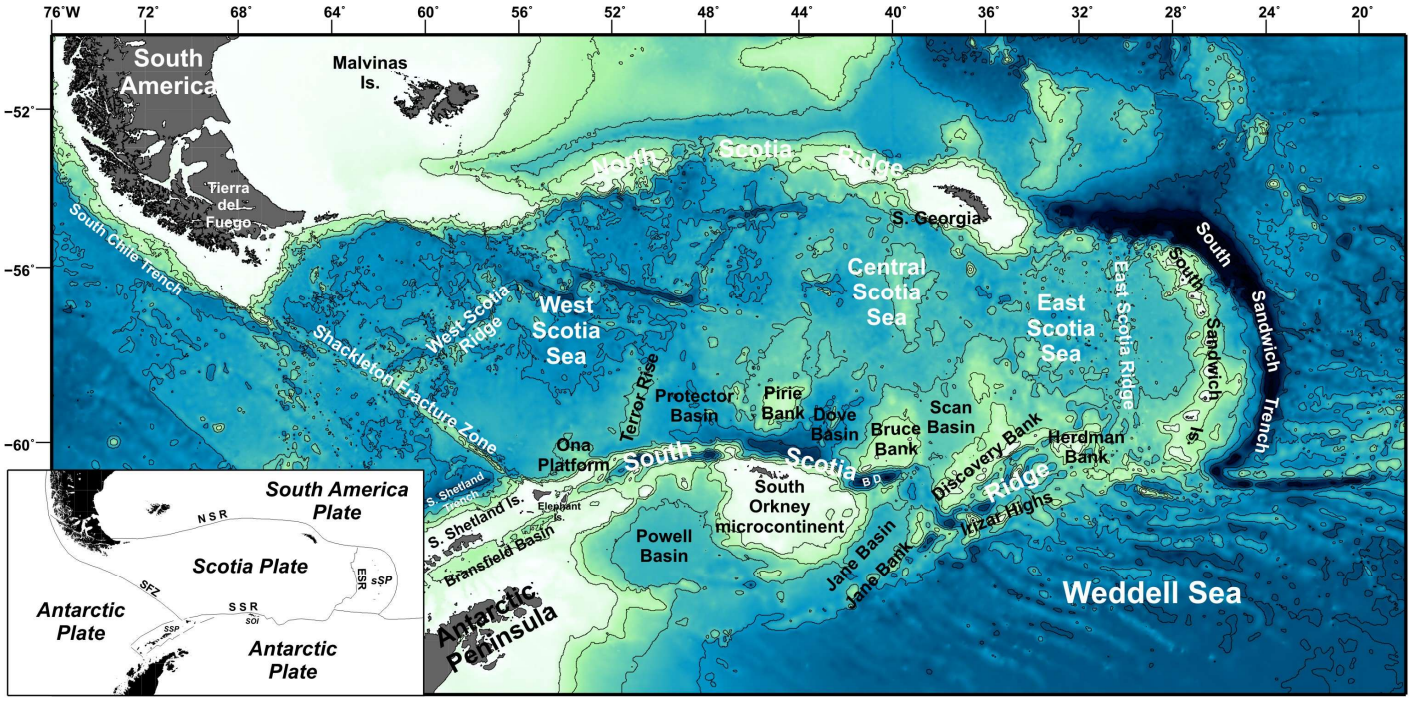


Galleoti, DeConto, Naish, Stocchi et al. (2016, Science)

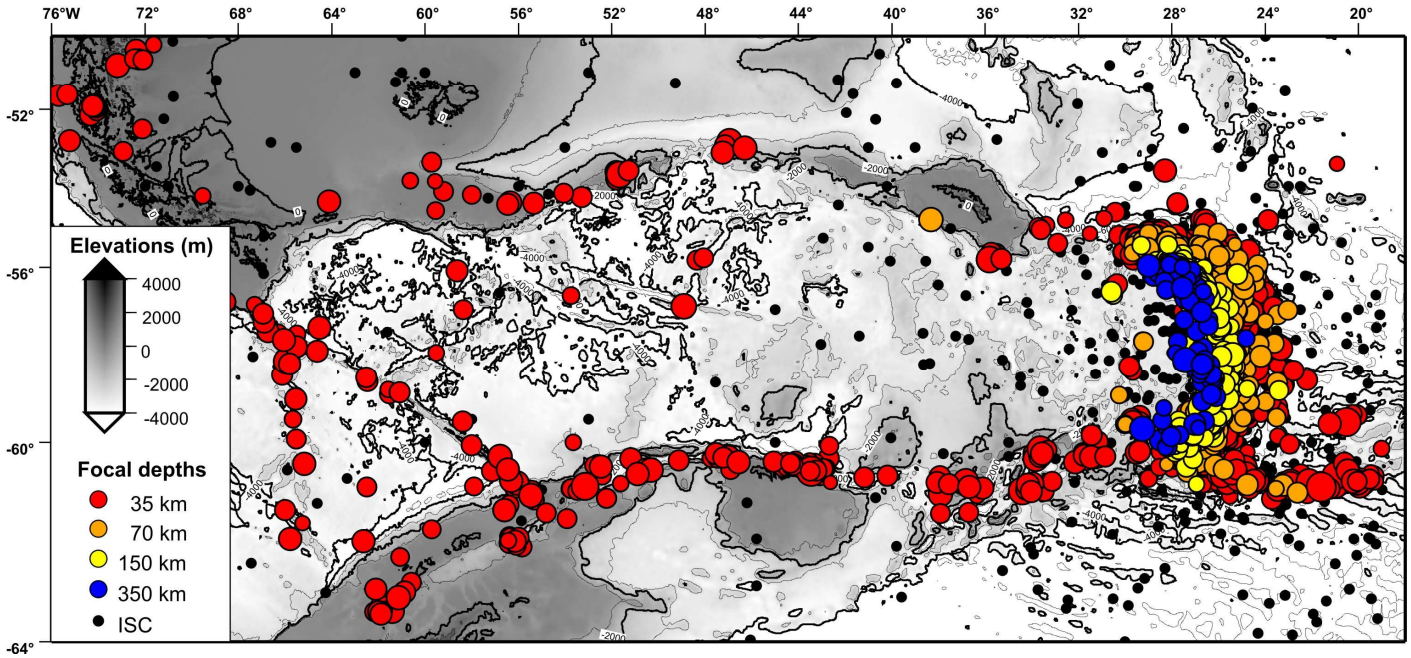
600ppm CO_2 threshold not permanently crossed until Oi1a



Barker, 2001, Earth Sciences Review



Principali elementi morfo-strutturali della placca di Scozia (sopra) e distribuzione degli eventi sismici (sotto)



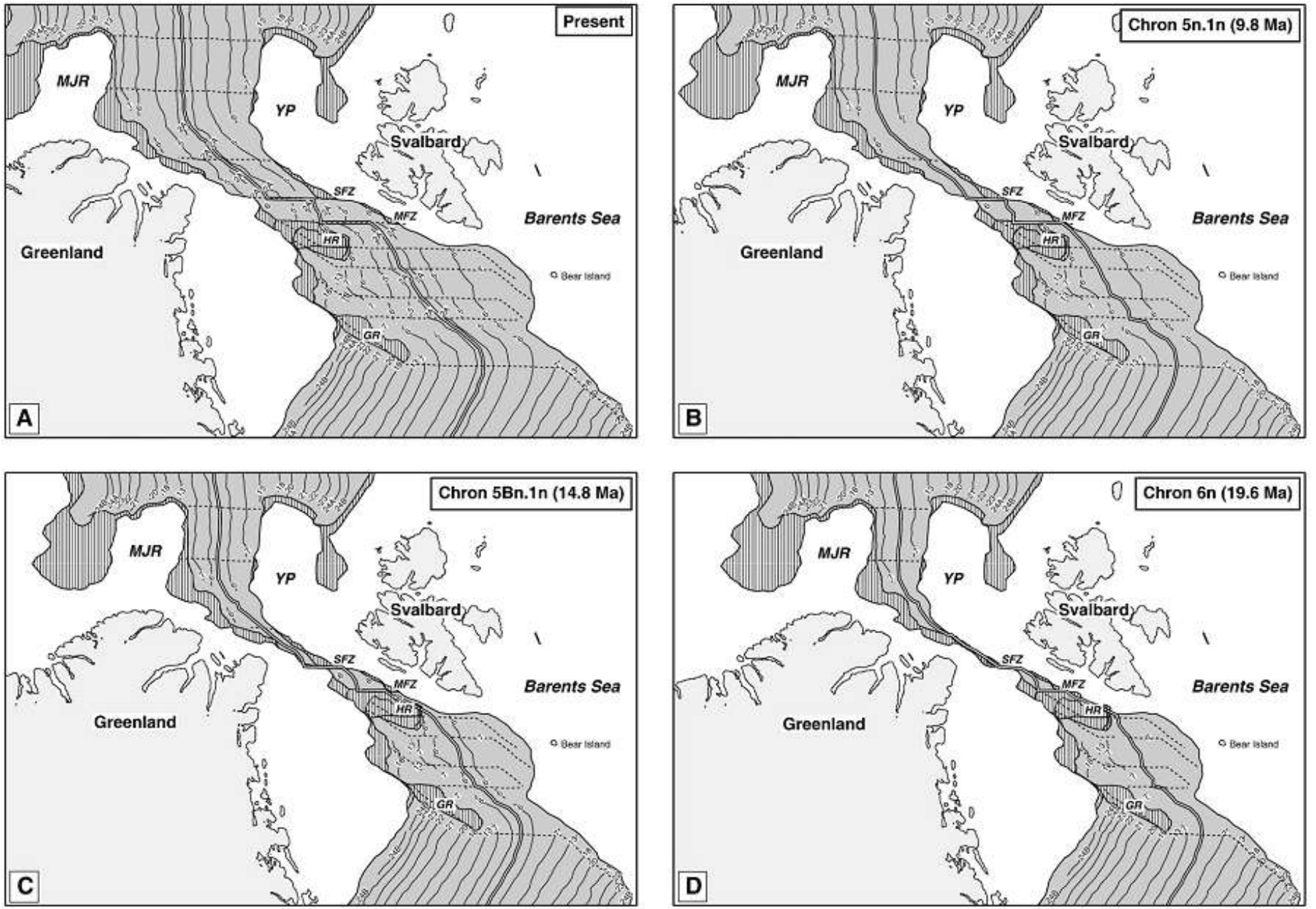


Fig. 12. Plate tectonic reconstruction of the Fram Strait gateway. Eurasia is kept fixed and Greenland and North America rotated using the poles in Table 1. Oceanic crust is shaded and magnetic seafloor spreading anomalies shown as annotated bold lines. COT and uncertain crustal provinces hachured as in Fig. 2. Flowlines of relative plate motion shown by dashed lines. Reconstructions indicate (A) present-day Lena Trough; (B) Development of first well developed seafloor spreading anomalies during late Miocene times (~10 Ma); (C) Formation of an initial, narrow oceanic corridor during early Miocene times (20–15 Ma); and (D) closure between Svalbard and NE Greenland prior to early Miocene times (~20 Ma).





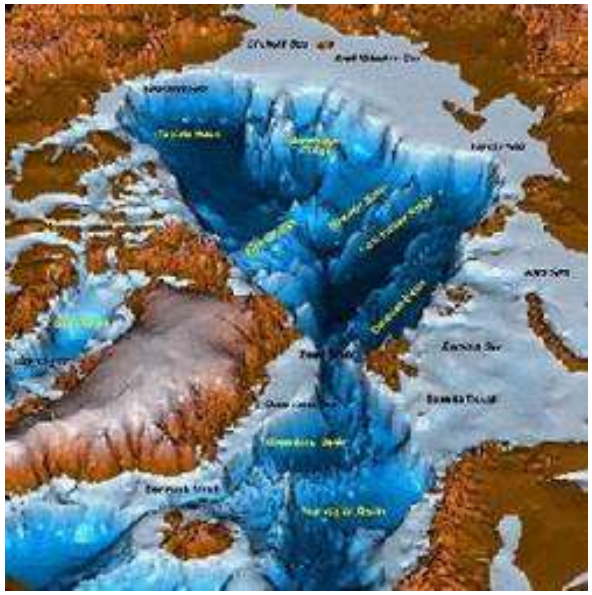
The main currents in the Arctic



Outflow from the Arctic Ocean

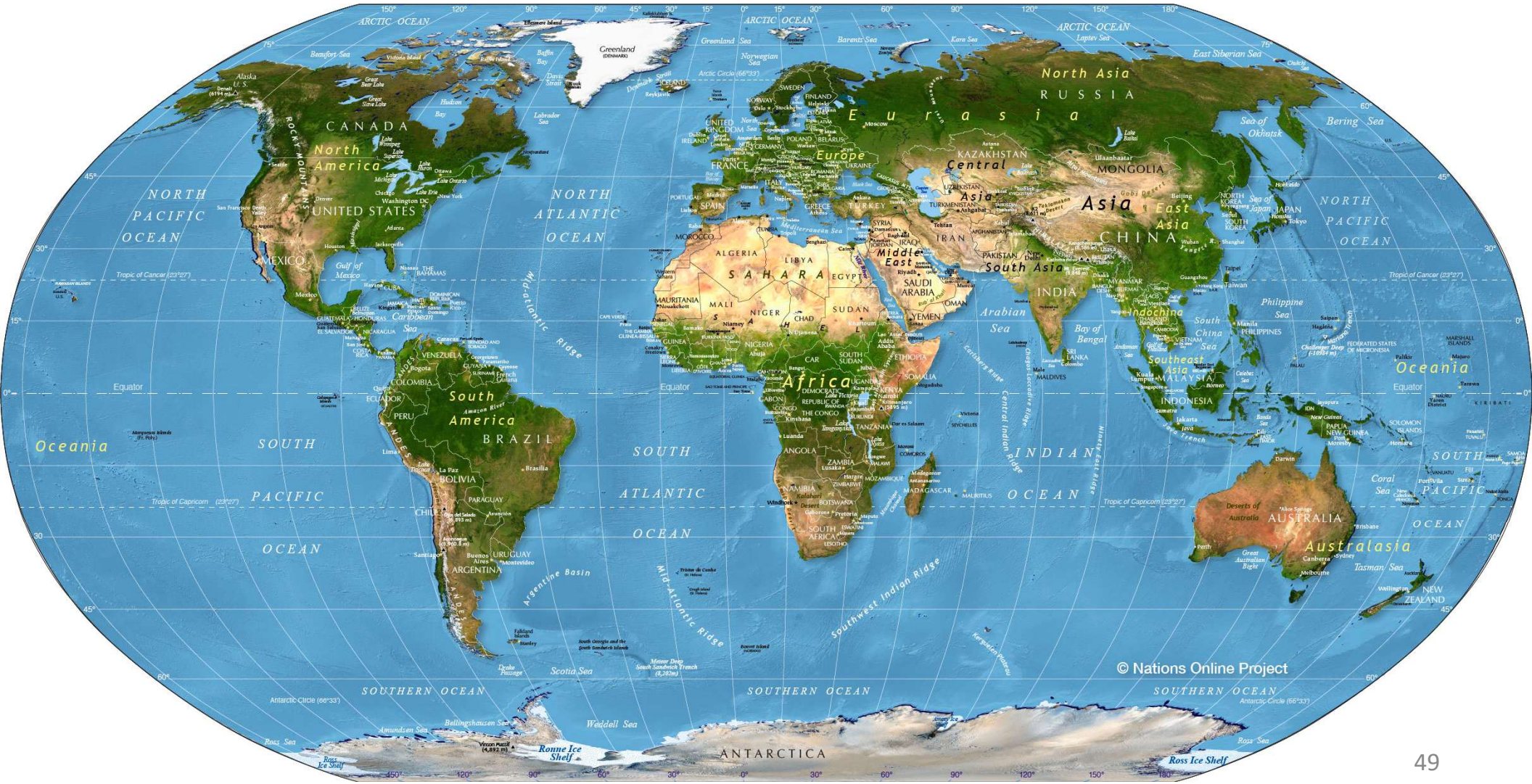


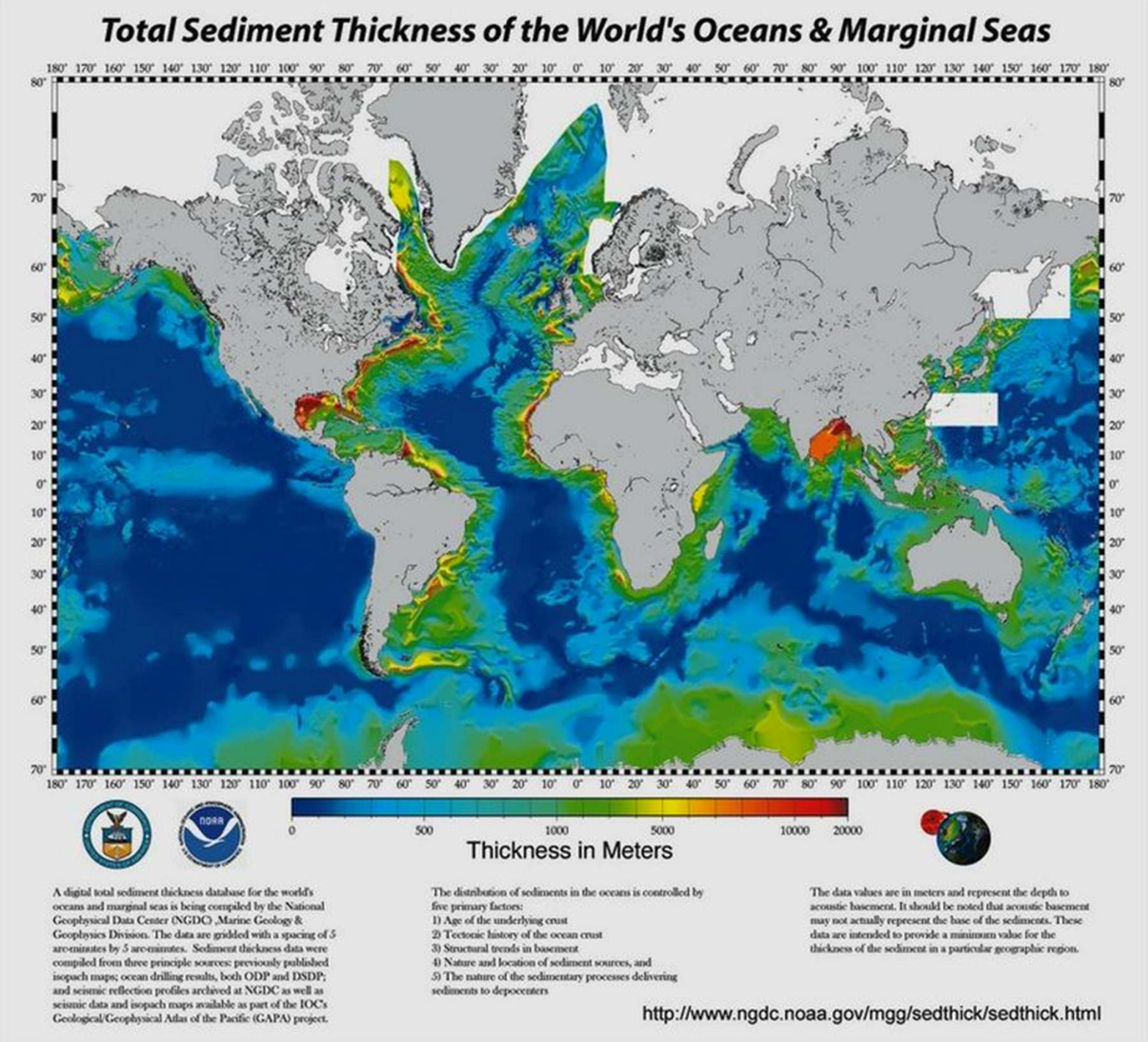
Areas of inflow for the Arctic Ocean

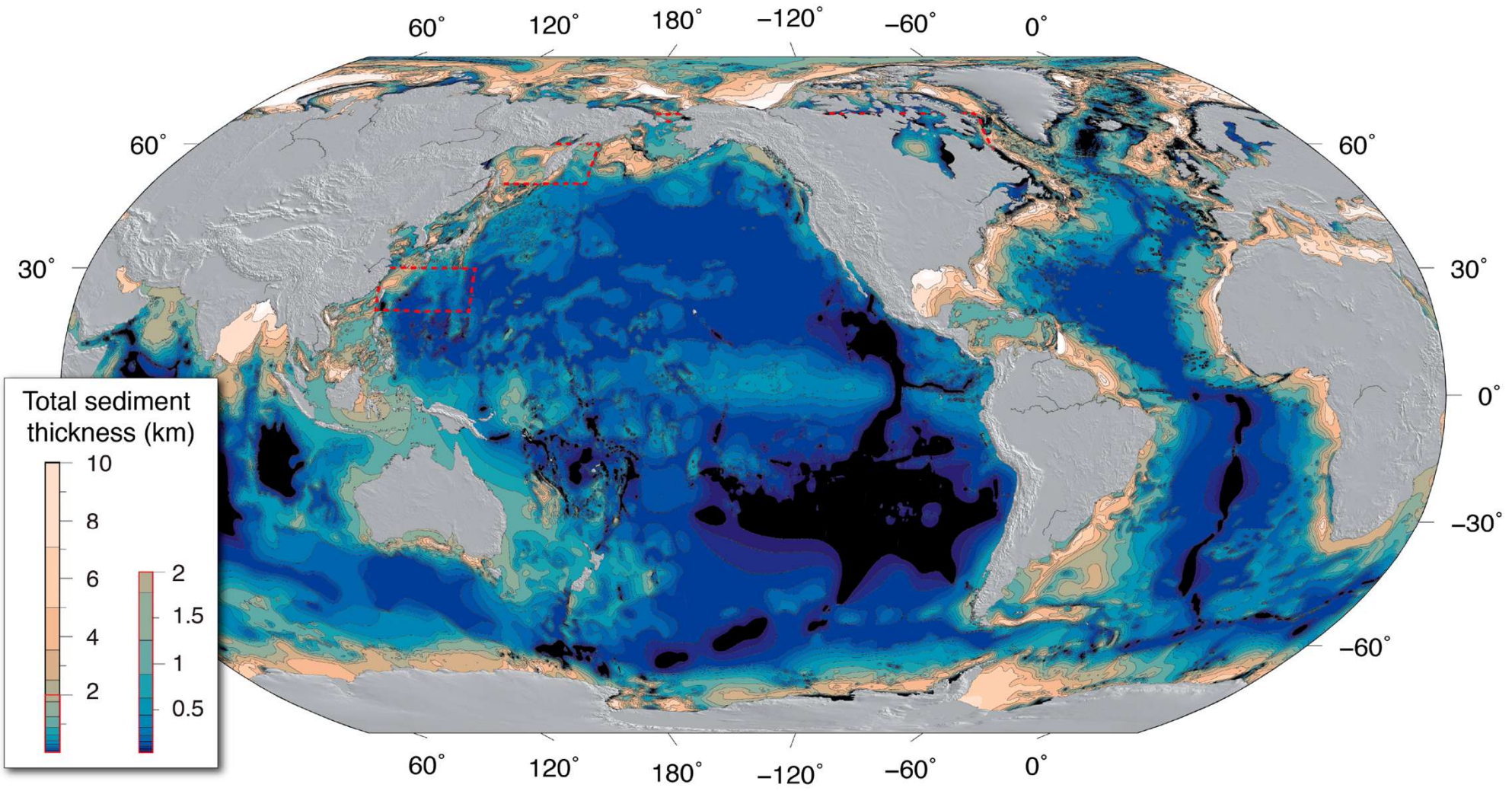


Oceans and Seas:

Global sinks of sediments eroded on continents



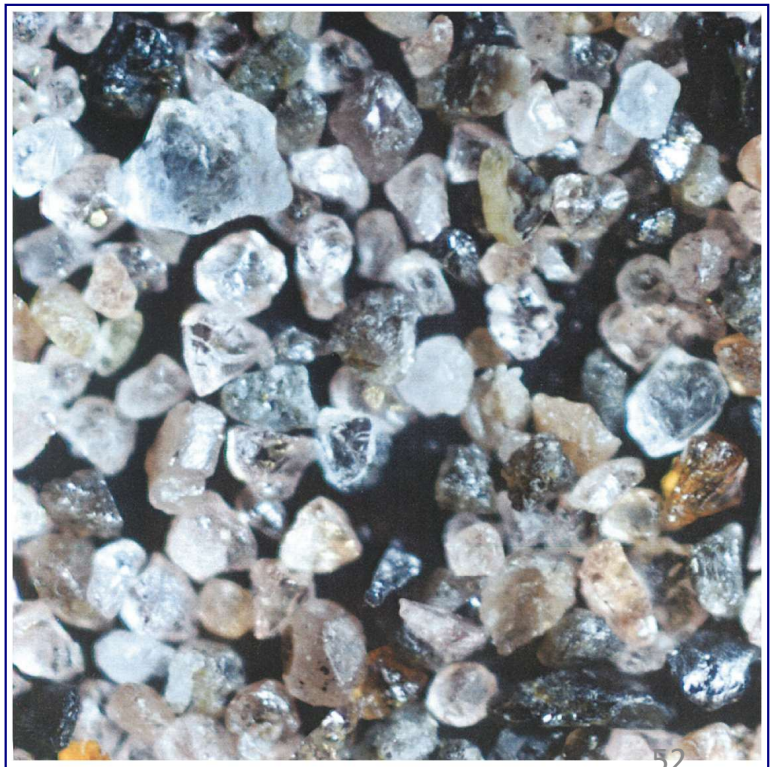

Total Sediment Thickness of the World's Oceans & Marginal Seas
180° 170° 160° 150° 140° 130° 120° 110° 100° 90° 80° 70° 60° 50° 40° 30° 20° 10° 0° 10° 20° 30° 40° 50° 60° 70° 80° 90° 100° 110° 120° 130° 140° 150° 160° 170° 180°
80° 70° 60° 50° 40° 30° 20° 10° 0° 10° 20° 30° 40° 50° 60° 70°
0 500 1000 5000 10000 20000
Thickness in Meters
A digital total sediment thickness database for the world's oceans and marginal seas is being compiled by the National Geophysical Data Center (NGDC) „Marine Geology & Geophysics Division. The data are gridded with a spacing of 5 arc-minutes by 5 arc-minutes. Sediment thickness data were compiled from three principle sources: previously published isopach maps; ocean drilling results, both ODP and DSDP; and seismic reflection profiles archived at NGDC as well as seismic data and isopach maps available as part of the IOC's Geological/Geophysical Atlas of the Pacific (GAPA) project.
The distribution of sediments in the oceans is controlled by five primary factors:
1) Age of the underlying crust
2) Tectonic history of the ocean crust
3) Structural trends in basement
4) Nature and location of sediment sources, and
5) The nature of the sedimentary processes delivering sediments to depocenters
The data values are in meters and represent the depth to acoustic basement. It should be noted that acoustic basement may not actually represent the base of the sediments. These data are intended to provide a minimum value for the thickness of the sediment in a particular geographic region.
http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html



Straume et al., 2020. Geochemistry, Geophysics, Geosystems, 20, . DOI: 10.1029/2018GC008115

Terrigenous Sediments (also: *lithogenous*)

- Eroded rock fragments from land
- Transported from land to the sea by:
  - Water (e.g., river-transported sediment)
  - Wind (e.g., windblown dust) - *aeolian transport*
  - Ice (e.g., ice-rafted rocks)
  - Gravity (e.g., turbidity currents)


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Terrigenous Sediments (also: *lithogenous*)

SILTS and SANDS

Silts (2 - 63 µm)

Sands (>63 µm)

Mainly transported by turbidity currents, debris flows, icebergs

Reflect composition of surrounding land masses

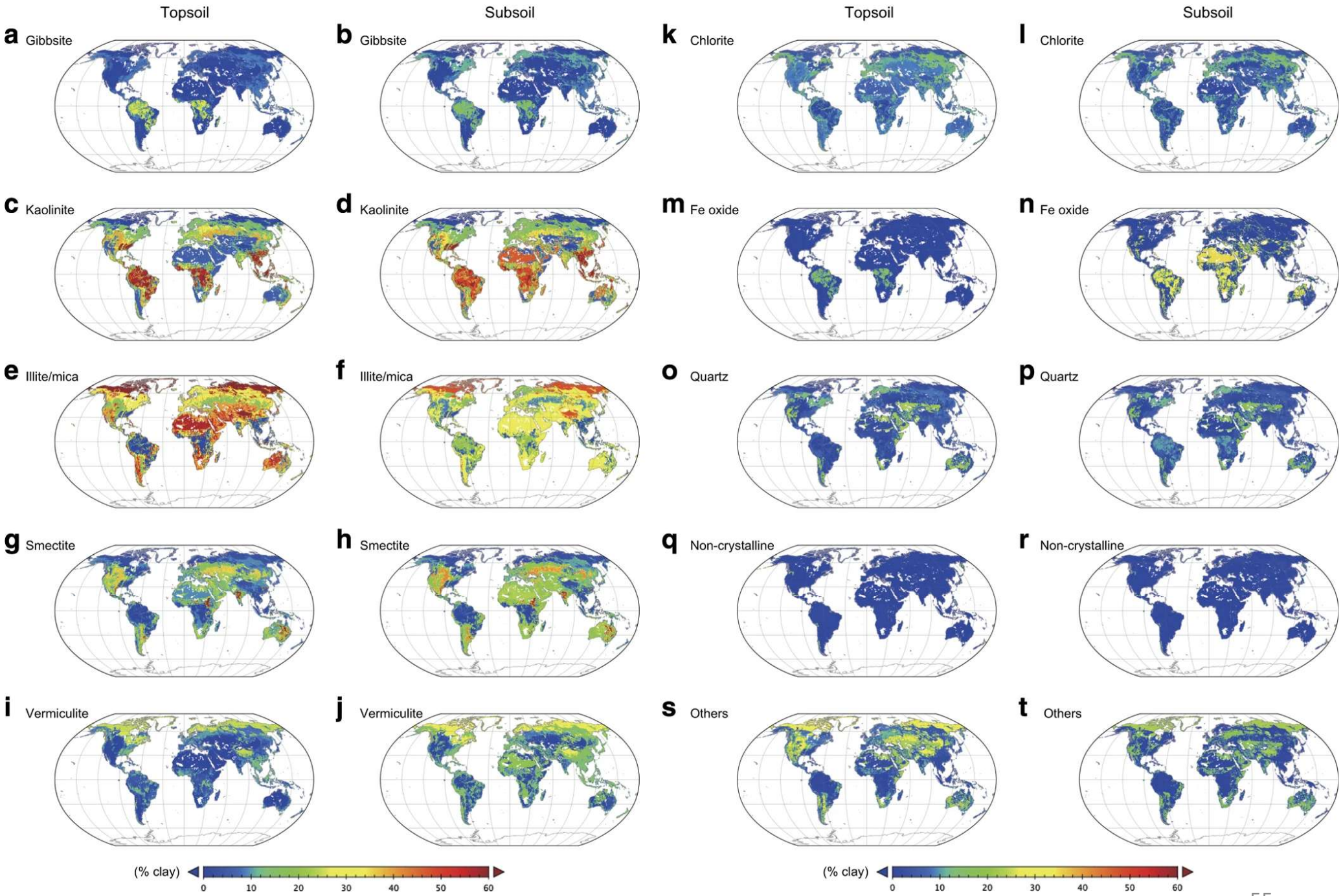
Terrigenous Sediments (also: *lithogenous*)

CLAYS (hydrates alumosilicate mineral)

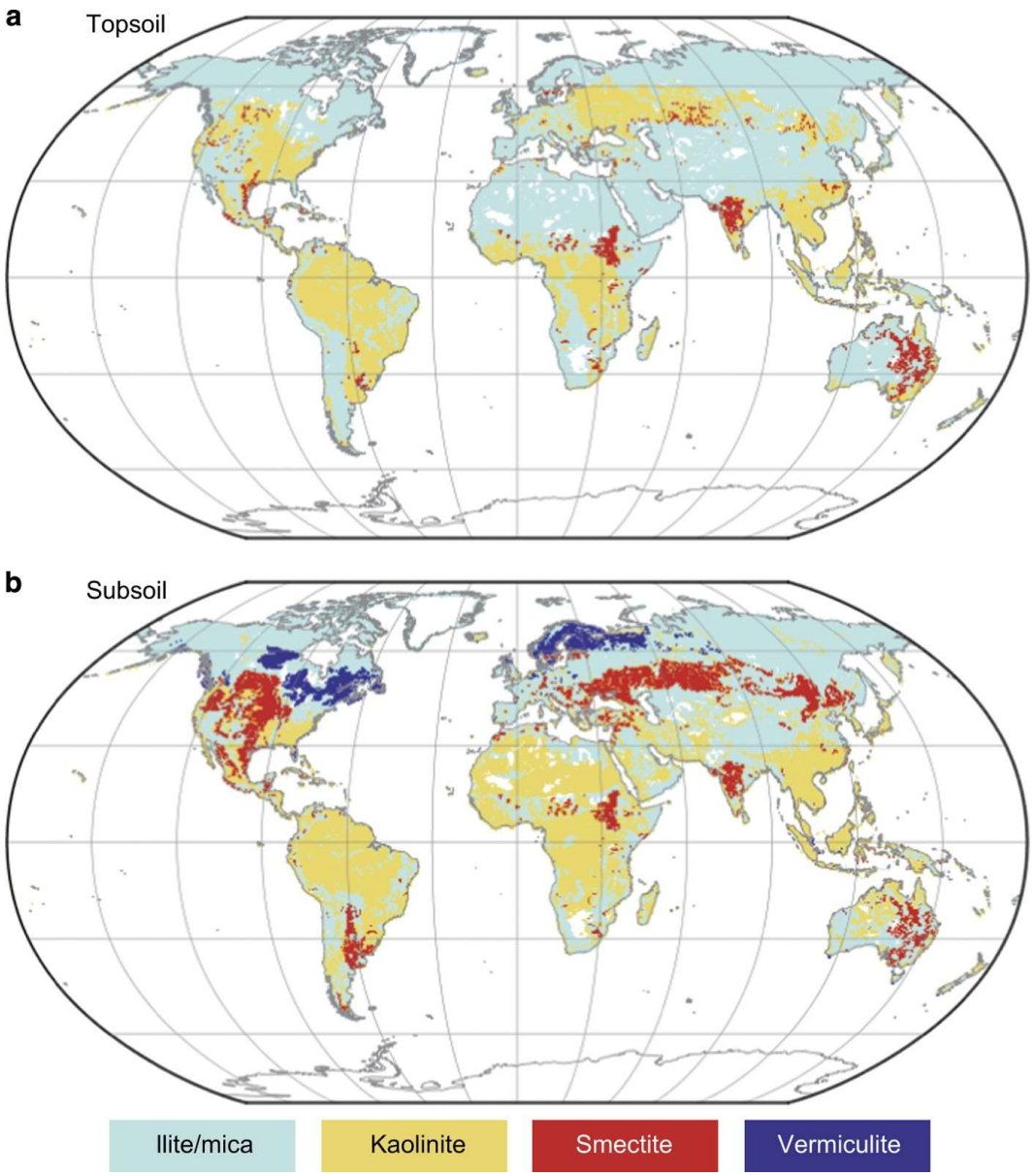
- Particles are generally < 2 µm
- may form aggregates and flocs
- sheet or fiber-shaped
- Absorb water

=> high buoyancy => are widely dispersed by marine currents

- Illite
- Smectite
- Kaolinite
- Chlorite
- Montmorillonite, vermiculite, sepiolite, talc, pyrophyllite, etc.



Ito, A., Wagai, R. Global distribution of clay-size minerals on land surface for biogeochemical and climatological studies. *Sci Data* **4**, 170103 (2017). https://doi.org/10.1038/sdata.2017.103



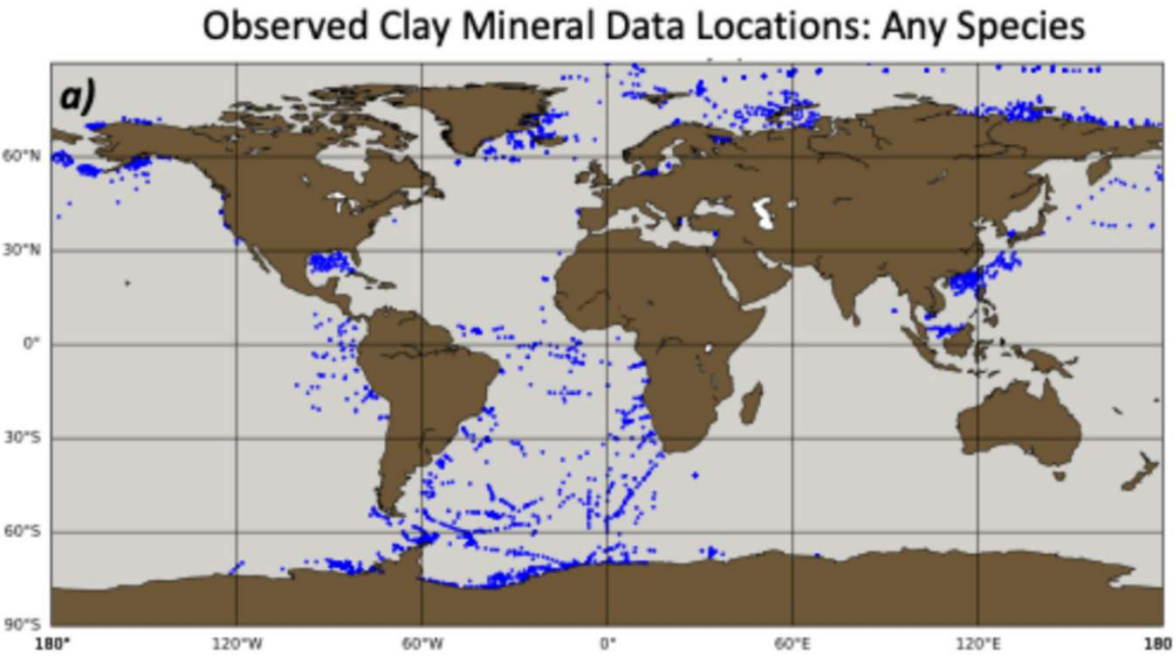
Illite and chlorite mainly derive from physical weathering of sedimentary rocks by river, glaciers, wind => cold high latitude regions or tectonic uplift (e.g. Indus and Gange rivers drainage system of the Himalayan chain)

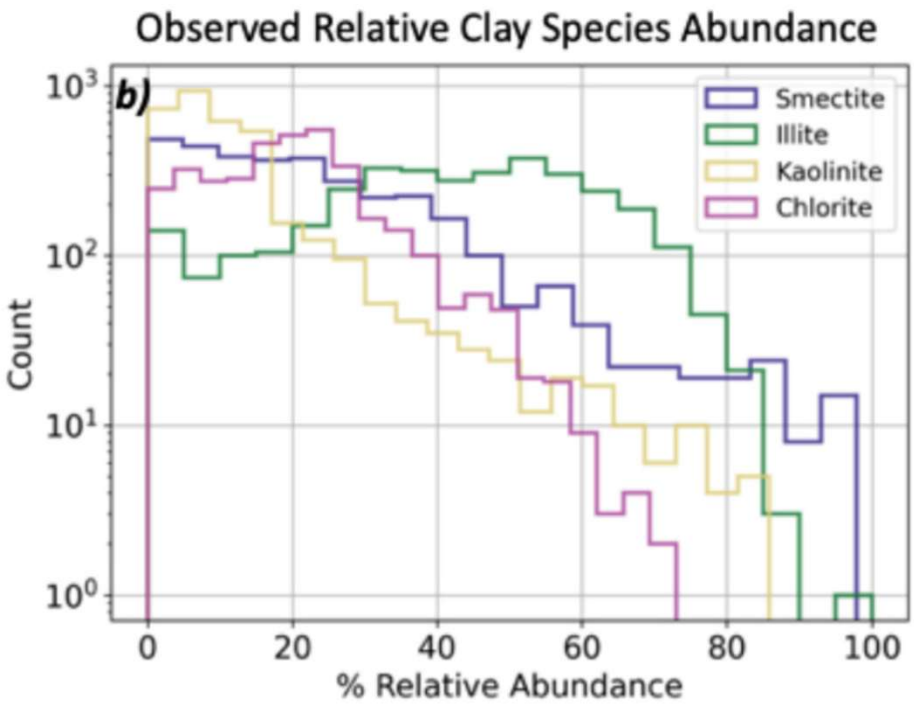
Kaolinite mostly forms chemically under warm, humid soil conditions (intertropical marine deposits)

Kaolinite/Chlorite in marine clay deposits is index of chemical versus mechanical processes => climatic variations of the clay's source (land) environment

Smectite: volcanic input, temperate, degradation of chlorite and illite

Ito, A., Wagai, R. Global distribution of clay-size minerals on land surface for biogeochemical and climatological studies. *Sci Data* **4**, 170103 (2017). https://doi.org/10.1038/sdata.2017.103



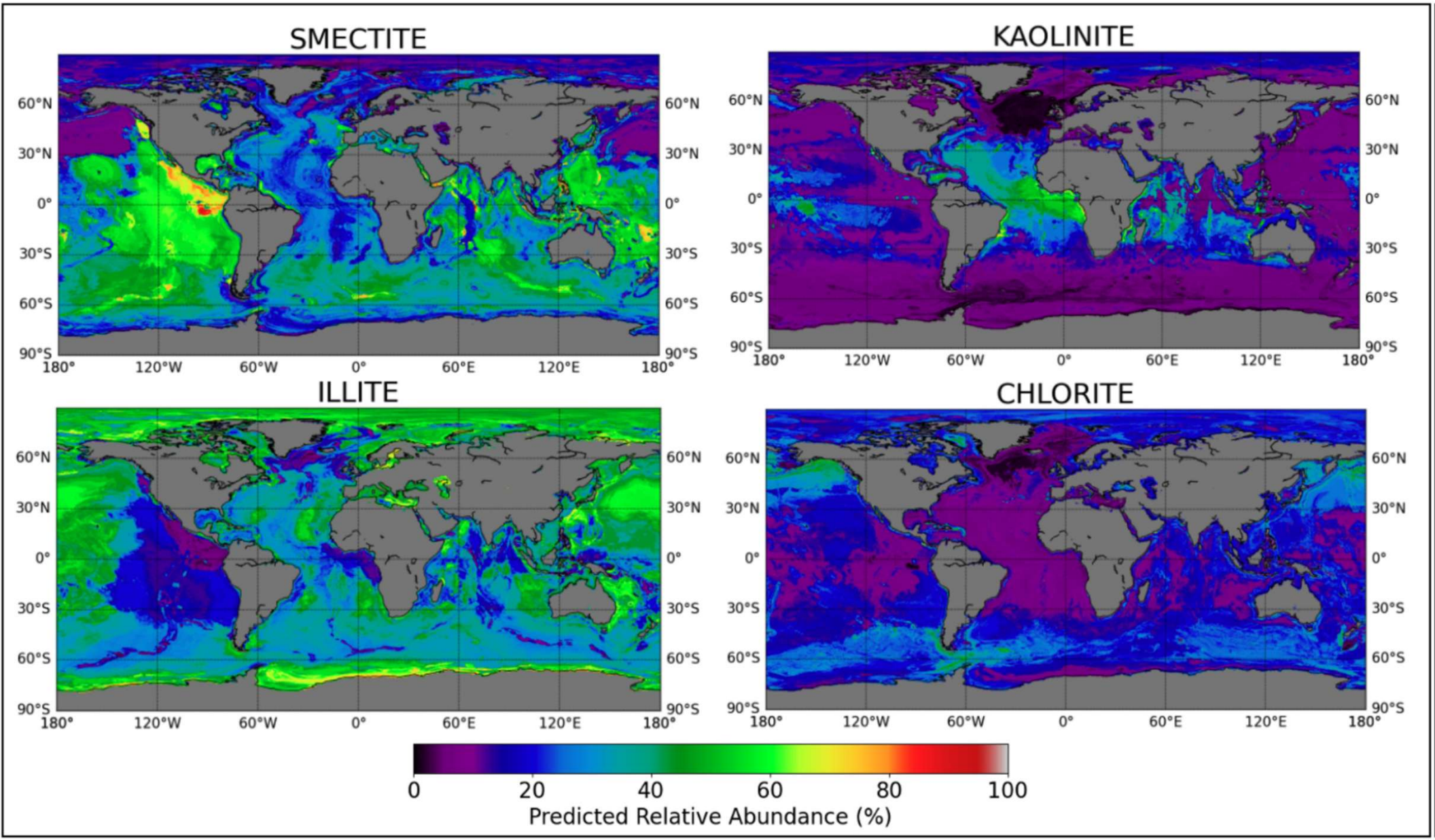


a) Global surficial (<1 m below seafloor) seafloor distribution of locations where a raw mineral abundance was reported (from x-ray diffraction data of the <2 µm grain size). Most of these locations have coincident measurements of all clay species type - chlorite, smectite, illite, and kaolinite.

b) Histograms (raw, unbinned) of the four different mineral species relative abundances. Values are binned at 5 % intervals and Y-axis is in log scale.

Lee et al., 2026. The updated distribution of clay minerals in the World Ocean https://doi.org/10.1016/j.margeo.2025.107695

Geospatial machine learning predictions of dominant clay minerals (from the <2 μ grain size fraction) in surficial (< 1 m) seafloor sediments



Lee et al., 2026. The updated distribution of clay minerals in the World Ocean https://doi.org/10.1016/j.margeo.2025.107695

Clays forming from basalts alteration (e.g. Mg-Smectite and Fe-smectite) are confined to the volcanic areas (expecially explosive centers). The composition depends on fluid temperature, oxydation-reduction processes, fluid/rock ratio

The hydrogenous formation of clay at sea water-sea bed interface in deep water (>4000 m, e.g. central Pacific) originates the reddish-brown oozes rich in Fe and Mn oxides (e.g**. deep sea red clay**) – Smectite : long time interaction, low temperature, biogenic silica input

Glauconite is a specific clay mineral rich in Fe and K that forms in shallow marine water (150-300 m) in temperate-warm regions, with low sediment rate

Change of Chlorite crystalline status can be caused by living organism ingestion and digestions processes (e.g. crustaceans).

The abundance of the different clay types and christalline status does not depend on the organic matter content. But in sapropel, high content of organic matter may have influenced the degradation of detrital clay minerals

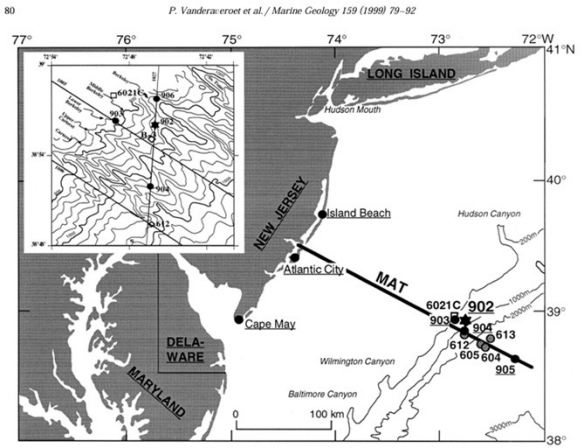


Fig. 1. Location of ODP Hole 902D (Leg 150) in the northwestern Atlantic Ocean, and detailed bathymetric map of the studied area. MAT: Mid-Atlantic Transect, *Site*: sites drilled during ODP Legs 150 and 150X, 6021C: site AMCOR.

Paleoceanographic importance

Vanderaveroet et al. 1999. A record of glacial/interglacial alternations in Pleistocene sediments off New Jersey expressed by clay mineral, grain-size and magnetic susceptibility data

ODP Site 902

Kaolinite/Chlorite

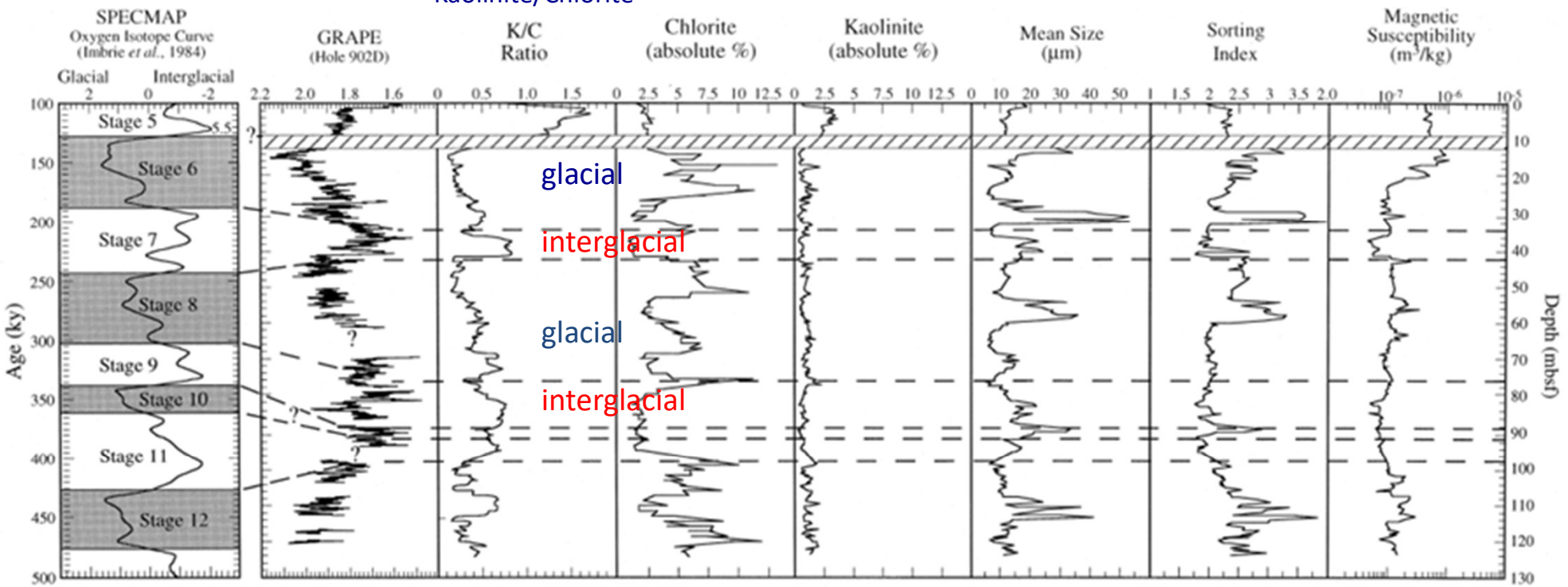


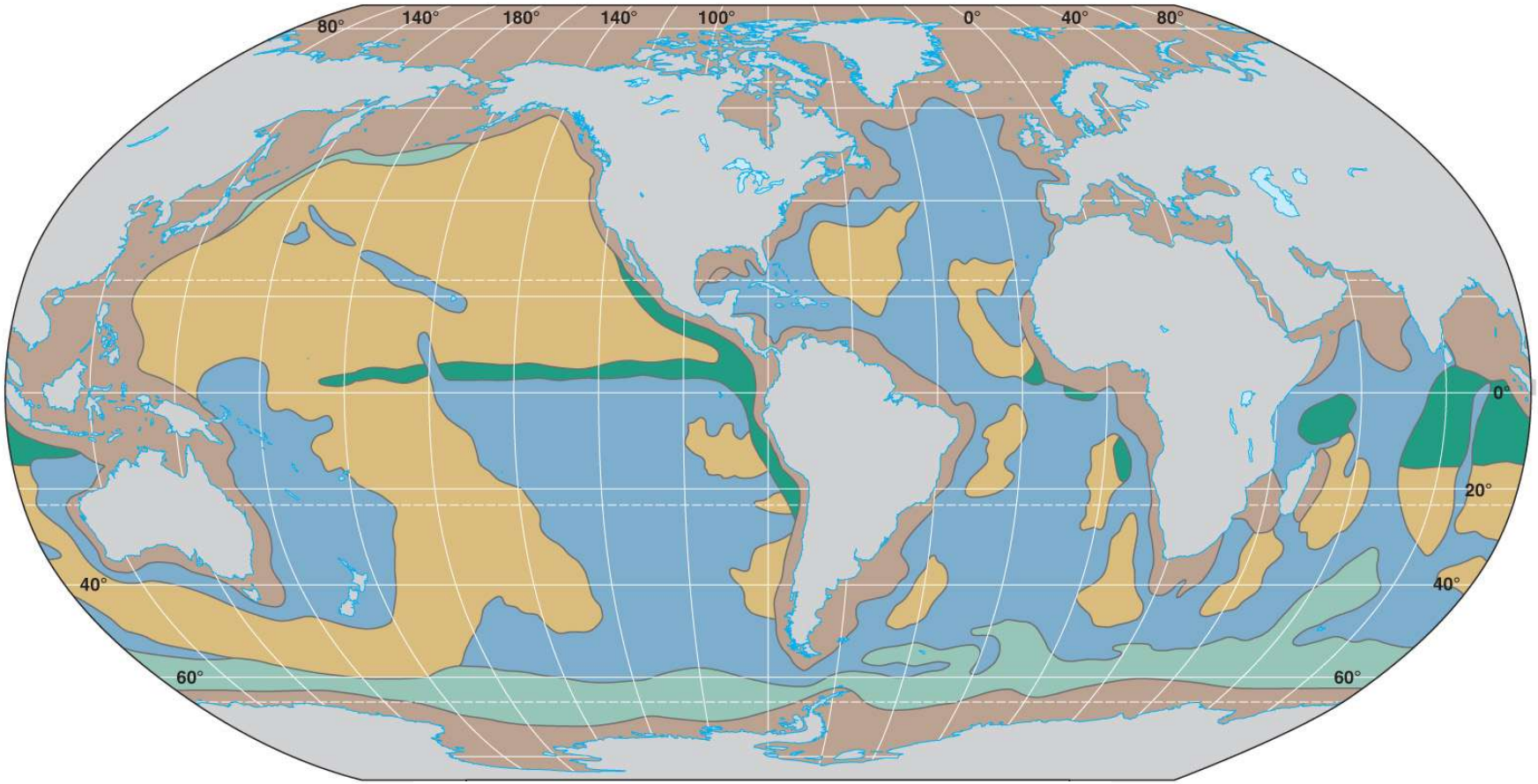
Fig. 3. Correlation between SPECMAP curve and GRAPE data (after the work of Christensen et al. (1996), modified), and comparison with kaolinite/chlorite (K/C) ratio, proportions of chlorite and kaolinite, grain-size parameters (mean size and sorting index), and magnetic susceptibility of Pleistocene sediments.

Clay minerals helped to identify the passage from a non-glacial world (dominated by chemical weathering, smectite, Kaolinite) to a glacial world (dominated by physical weathering, Illite, Chlorite) at ca. 40 Ma.

Clay minerals can also help to identify paleo-curculation pathways as currents can entrain and strapsort clay minerals for long distance e.g. The North Atlantic Deep Water is enriched of Kaolinite supplied by the rivers draining the tropical south america continent. The Antarctic northward flowing carries smectite and chrlorite from Argentina and Antarctica.

Clay may also be used to reconstruct tectonic activity changes: e.g. hymalyan chain fast and constant re-juveneation and erosion produce abundant detrital clay, preventing pedogenetic processes when clay minerals tend to be in equilibrium with climate condition => abundant illite in the equatorial Indian ocean

Clay helps indentifying change of source area due to tectonic and geomorphologic processes



Neritic **Oceanic** Abyssal clay Calcareous Ooze Siliceous Ooze

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Biogenic Sediments (also: *biogenous*)

Hard remains of dead organisms

- Macroscopic
  - Shells, bones, teeth
- Microscopic
  - Tiny shells or tests settle through water column
  - Mainly algae and protozoans
  - Biogenic ooze (30% or more tests)

- Calcium carbonate ($CaCO_3$)
- Silica (SiO_2 or $SiO_2 \cdot nH_2O$)

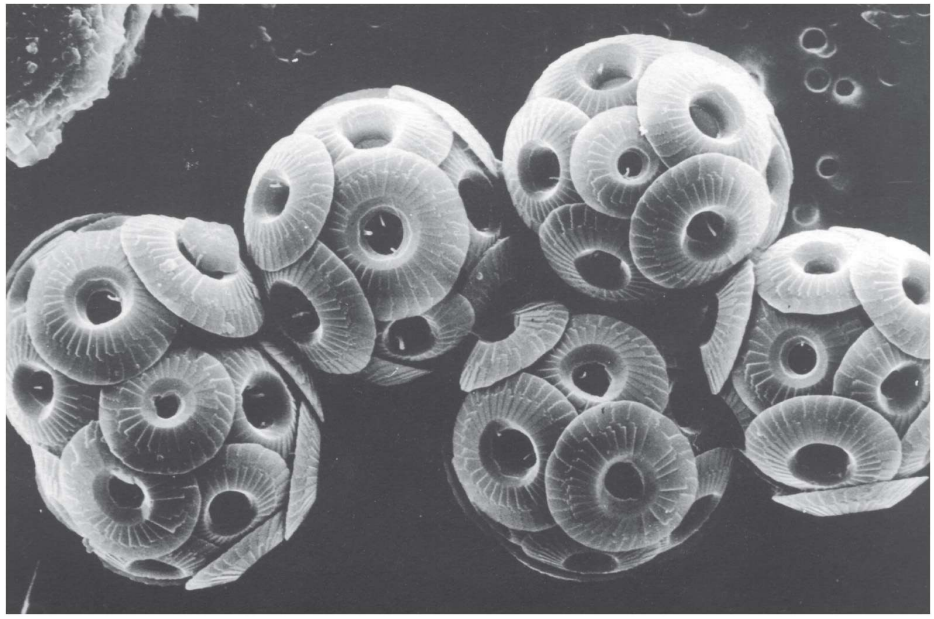
Biogenic Sediments (also: *biogenous*) continued

Calcium carbonate in biogenous sediments

Coccolithophores (unicellular algae)

- Photosynthetic
- Coccoliths (nano-plankton)

2-25µm



(a)

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Habitat: Only marine mainly tropical water. Only planktonic (upper few meters of water depth)
First appearance: earliest Jurassic
Importance:

- The most abundant of phytoplancton groups (10% of global phytoplancton biomass).
- 50% of total vertical CaCO3 flux in open ocean waters (inorganic carbon pump)
- Producer of Dimethylsoniopropionate => increase cloud cover
- Scatter light toward the atmosphere (albedo)

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Biogenic Sediments (also: *biogenous*) continued

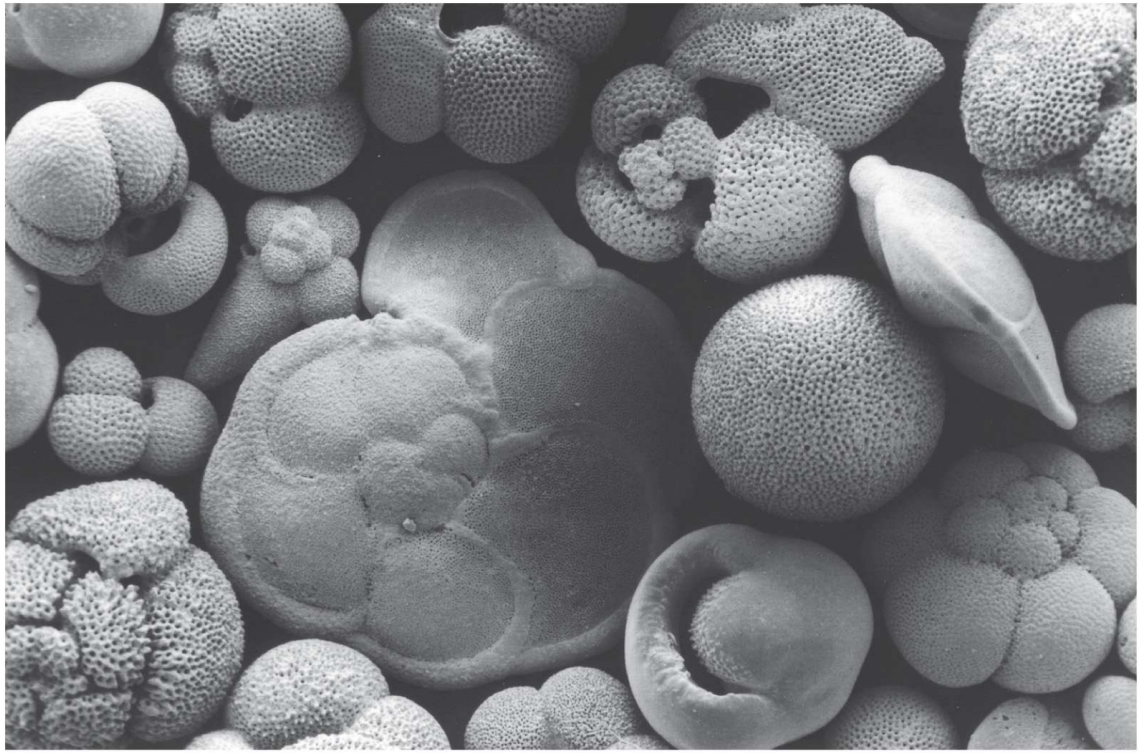
Calcium carbonate in biogenous sediments

Foraminifera

(Benthic and Planktonic unicellular Protozoans)

Calcite

30µm - 1 mm



(c)

Copyright © 2008 Pearson Prentice Hall, Inc.

First appearance: middle Jurassic

=> Since then the deep Ocean have become enormous sinks for carbonate deposition

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Biogenic Sediments (also: *biogenous*) continued

Pteropods
(planktonic gastropods molluscs)
Several mm, fragile shell

Aragonite
(a variety of calcite, more soluble)

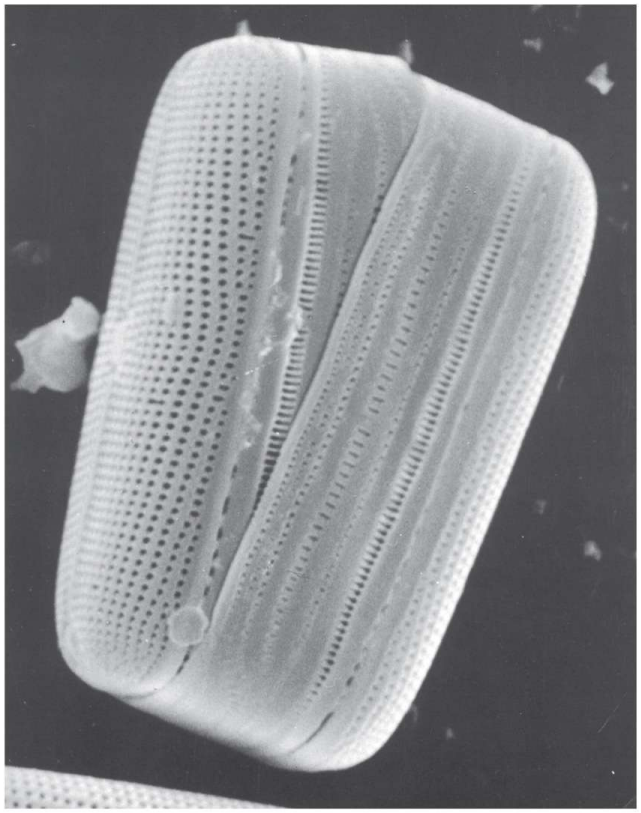




Biogenic Sediments (also: *biogenous*) continued

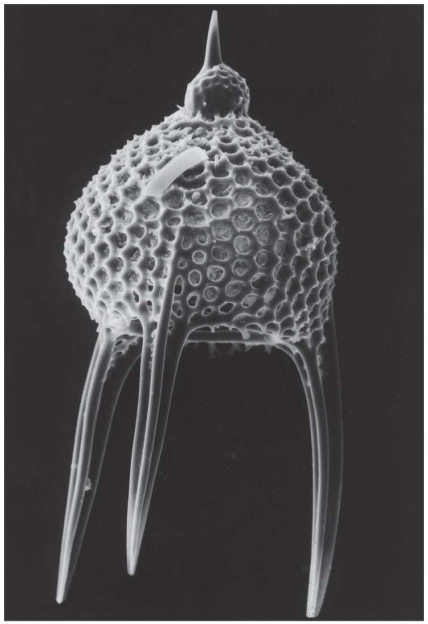
Silica in biogenic sediments

Diatoms (algae unicellular, with frustule composed of two valves) < 200 µ m.
Ubiquitous, most common in high latitudes
Radiolarians (protozoans) 50-300 µm



(a)

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(b)

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(a)

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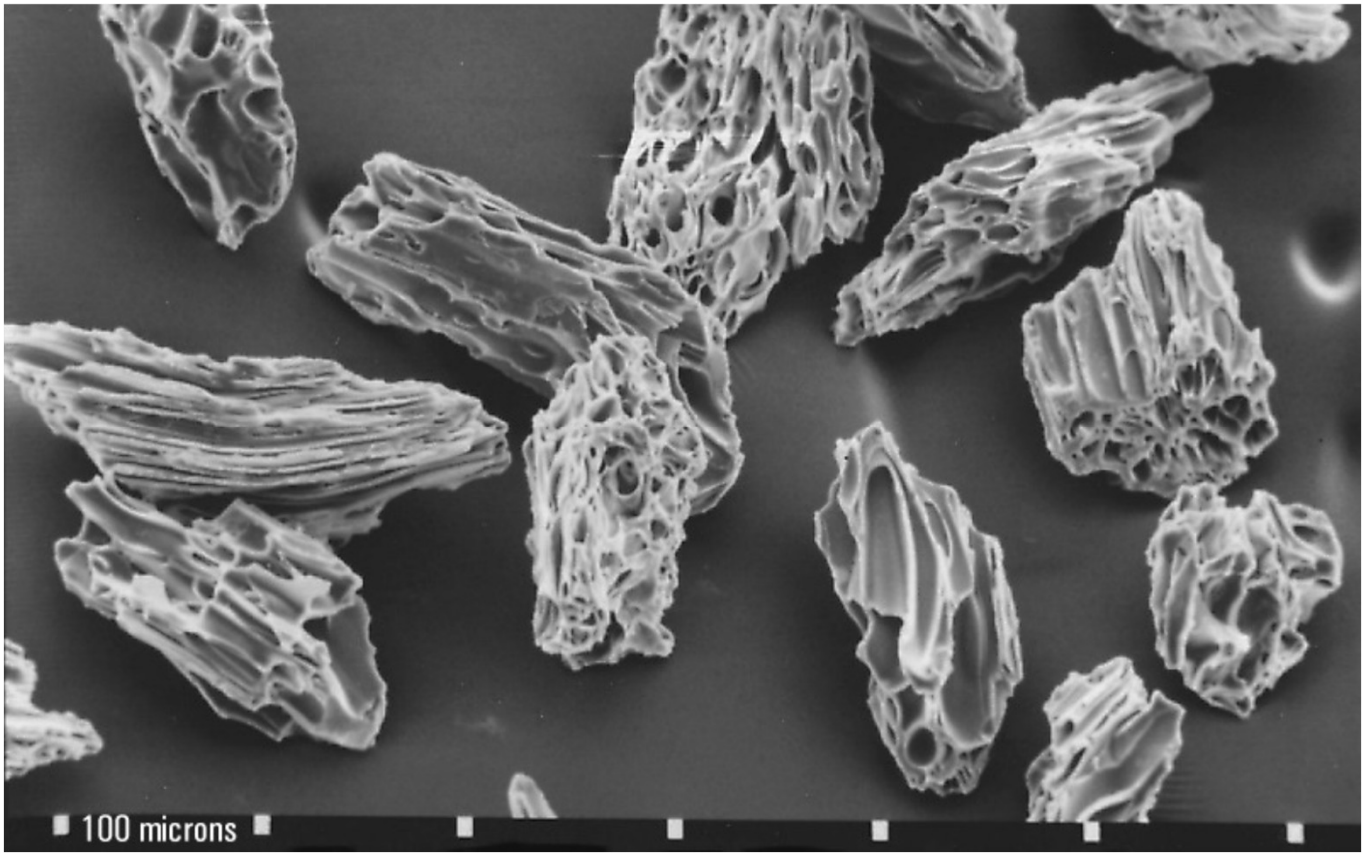
Authigenic Sediments (also: *Hydrogenous*)

- Minerals precipitate directly from seawater
  - Manganese nodules
  - Phosphates (beneath areas in surface ocean high biological productivity)
  - Carbonates (Aragonite and calcite)
  - Metal sulfides (Associated with hydrothermal vents)
  - Evaporites (Minerals that form when seawater evaporates)

- Small proportion of marine sediments

Volcanogenic Sediments (also: *Hydrogenous*)

- Ash layers
- Lava basalts
- Tephra layers



Glass shards

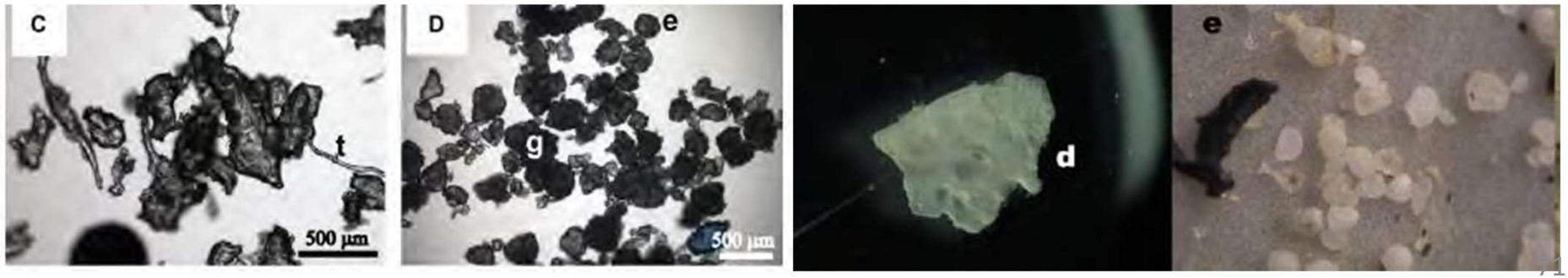
Cosmogenous Sediments

- Macroscopic meteor debris
- Microscopic iron-nickel and silicate spherules
- Tektites
- Space dust
- Overall, insignificant proportion of marine sediments

Microplastics

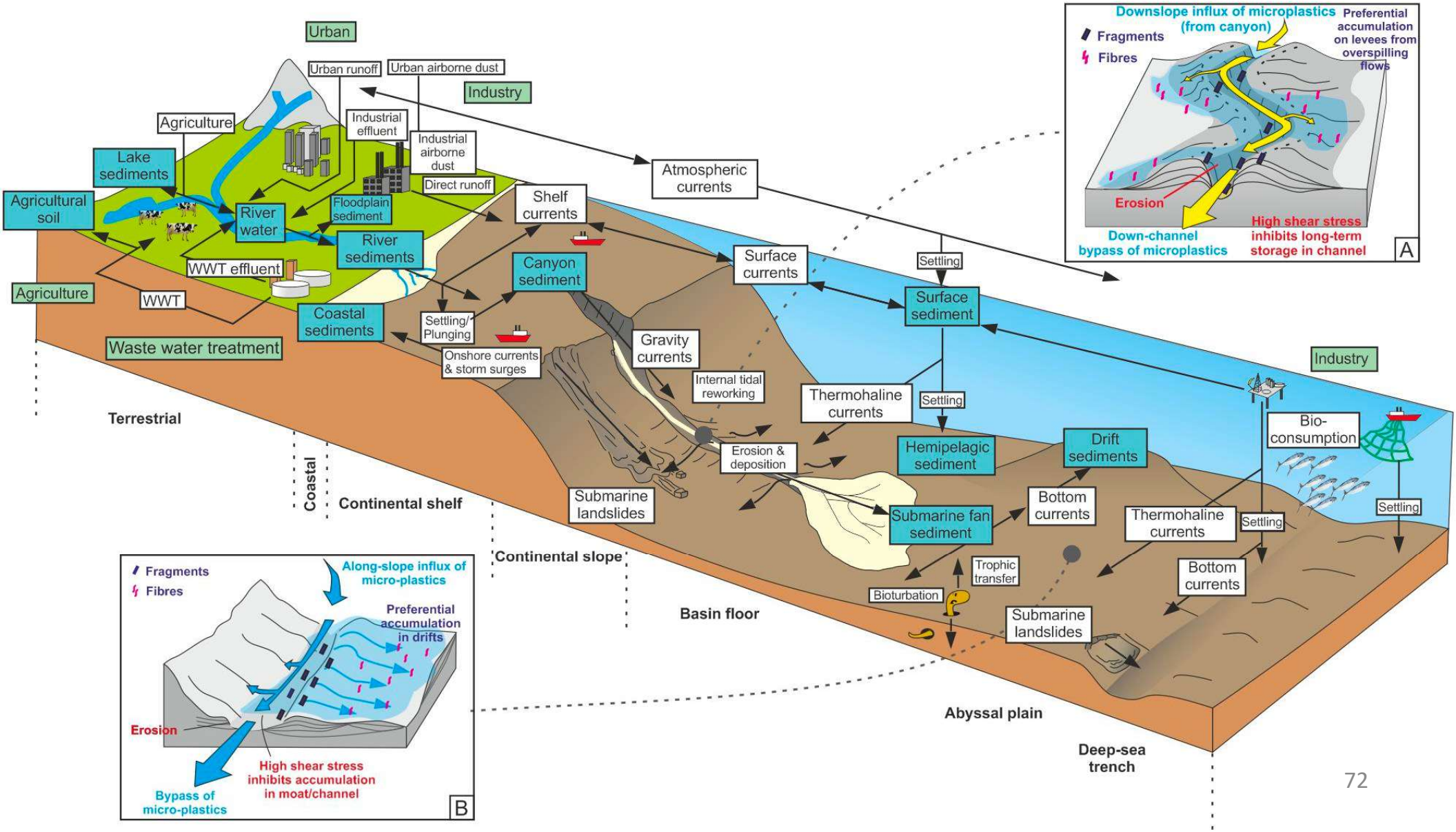
- "New and emerging issue" – GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) is an advisory body, established in 1969, that advises the United Nations (UN) system on the scientific aspects of marine environmental protection.

- Plastic particles < 5mm
- Primary microplastics are deliberately manufactured
- Secondary microplastics are break-down products of larger debris
- Most plastic derives from land-based sources
  - Household and industrial waste + wastewater
  - Fishing, aquaculture, shipping, tourism, etc.



Front. Earth Sci., 30 April 2019 | https://doi.org/10.3389/feart.2019.00080

Dispersion, Accumulation, and the Ultimate Fate of Microplastics in Deep-Marine Environments: A Review and Future Directions



MARINE SEDIMENTS

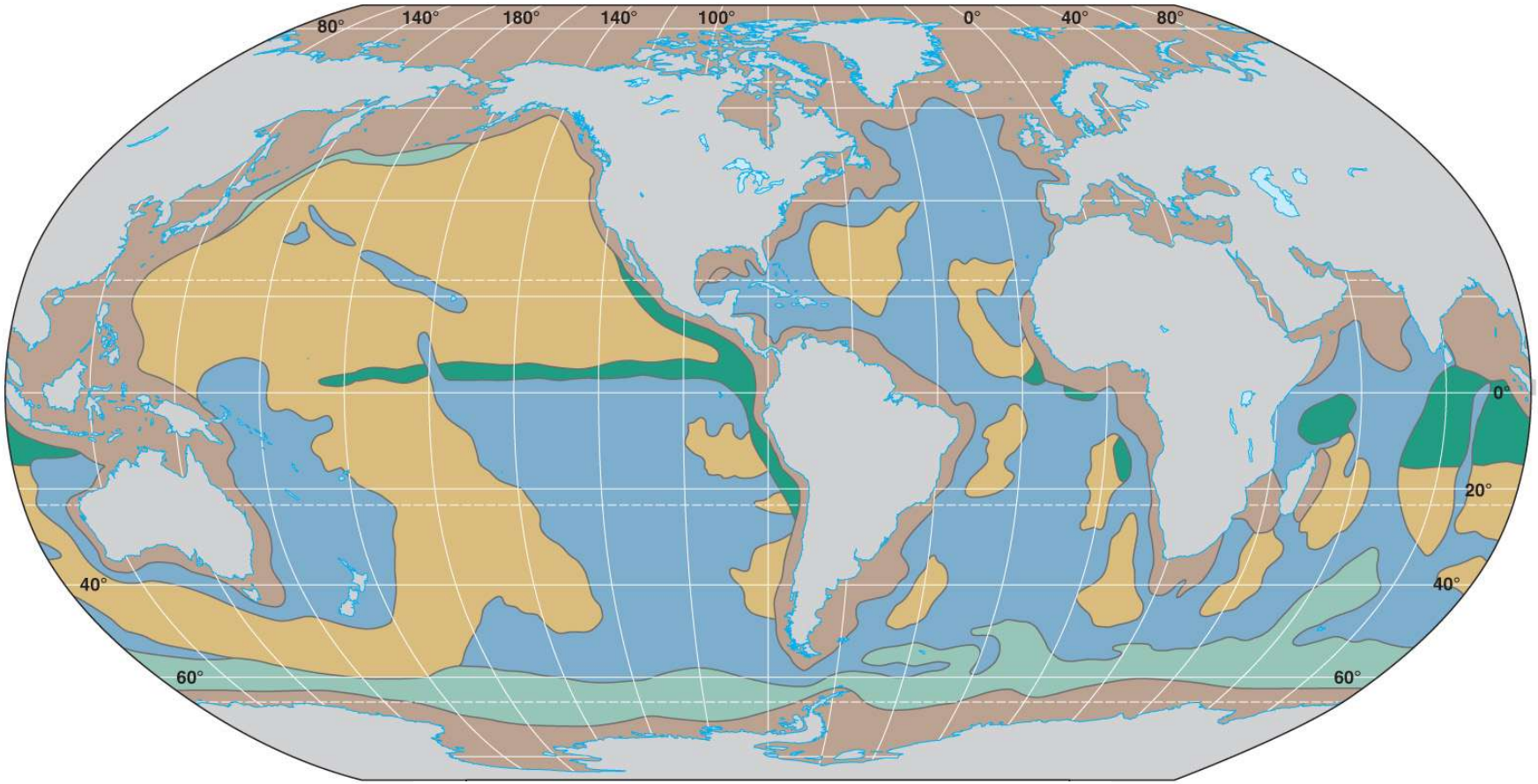
Distribution

Neritic

- Shallow water deposits
- Close to land
- Dominantly lithogenous
- Typically deposited quickly

Pelagic (Also Oceanic)

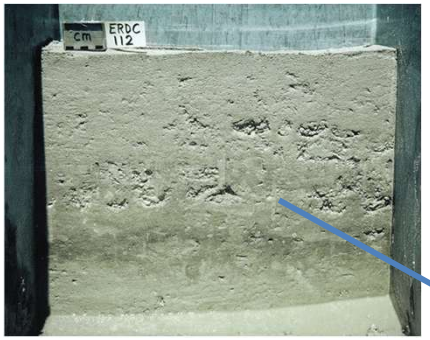
- Deeper water deposits
- Finer-grained sediments
- Deposited slowly

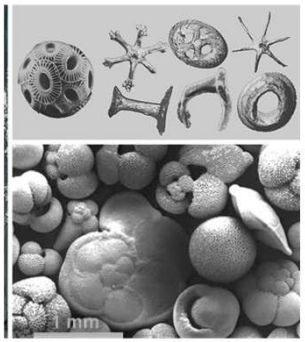


Neritic **Oceanic** Abyssal clay Calcareous Ooze Siliceous Ooze

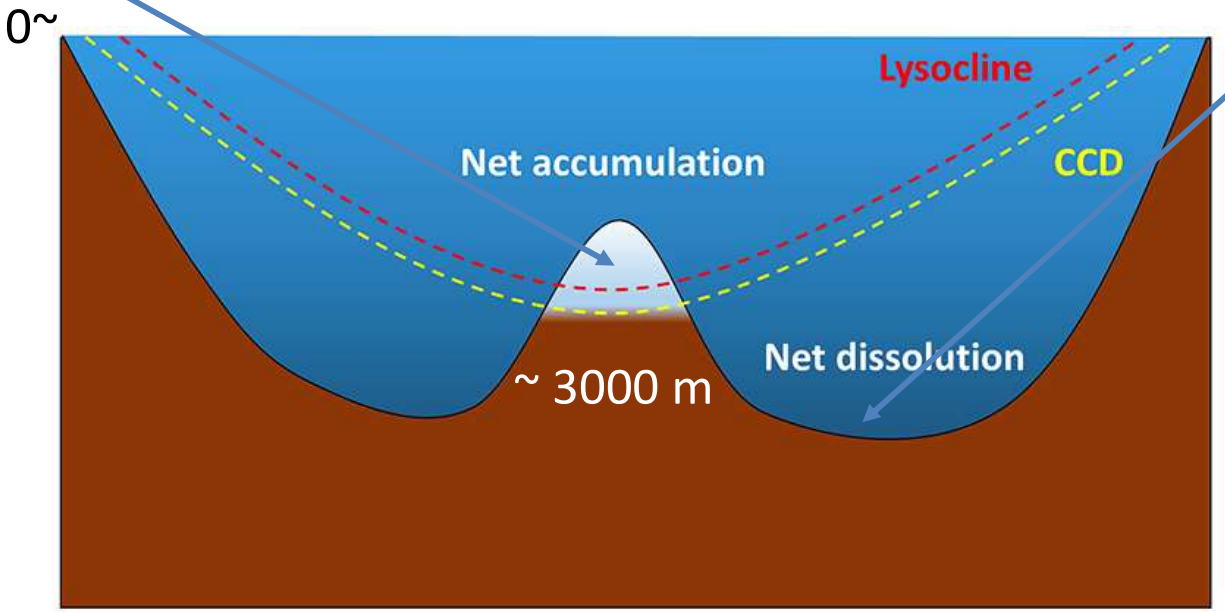
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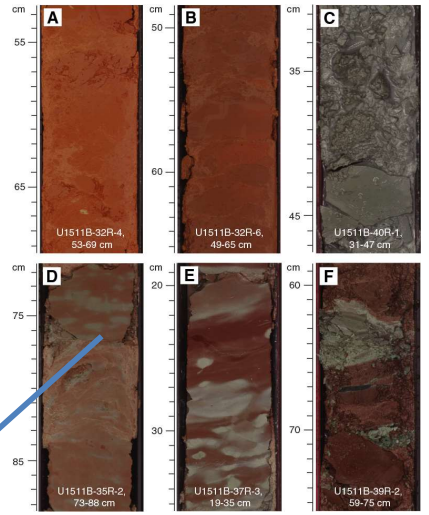
Carbonate compensation depth (similar to snow-line on land)





Calcareous ooze (Nannofossils, forminifera) Above the CCD





Abyssal clays
Red clays
Below CCD

Southern high latitudes equator Northern high latitudes

Calcareous sediment can only accumulate in depths shallower than the calcium carbonate compensation depth (CCD). Below the CCD, calcareous sediments dissolve and will not accumulate. The **lysocline** represents the depths where the rate of dissolution increases dramatically.
https://commons.wikimedia.org/wiki/File:Calcareous_sediment_in_the_ocean.png

Within the water column the calcium carbonate saturation state (CSS) is controlled by concentration of carbonate ions (CO_3^{2-}), pH , water pressure (increases with water pressure), temperature (decreases with temperature)

=> Calcium carbonate is more soluble in deep sea than at the surface

- In the Pacific Ocean the CCD is typically found at 3500-4000 m (old water CO2 enriched)
- In the Atlantic Ocean is at 5000 m (ventilated by newly sourced pole water CO2 depleted)

Close to the continental margin the CCD tends to shoal (also due to terrigenous dilution).

Carbonate dissolution is confined within 10 cm below the sea floor bioturbated layer

Foraminifera, coccolith, pteropod lysoclines differ because of varying resistance to dissolution.

Taxa living in:

- tropical warm (low density) water have thin shells => easier to be dissolved
- Cold water have heavily calcified thick shells => more resistant
- Larger foraminifera sink faster after death (2 km/day) => less dissolution comparing to small foraminifera (150m/day) or coccolith (0.3m/day)

$\Rightarrow$ Bias in water paleo-temperature, paleo-depth and paleo-productivity reconstructions

North Atlantic (3547 m water depth)

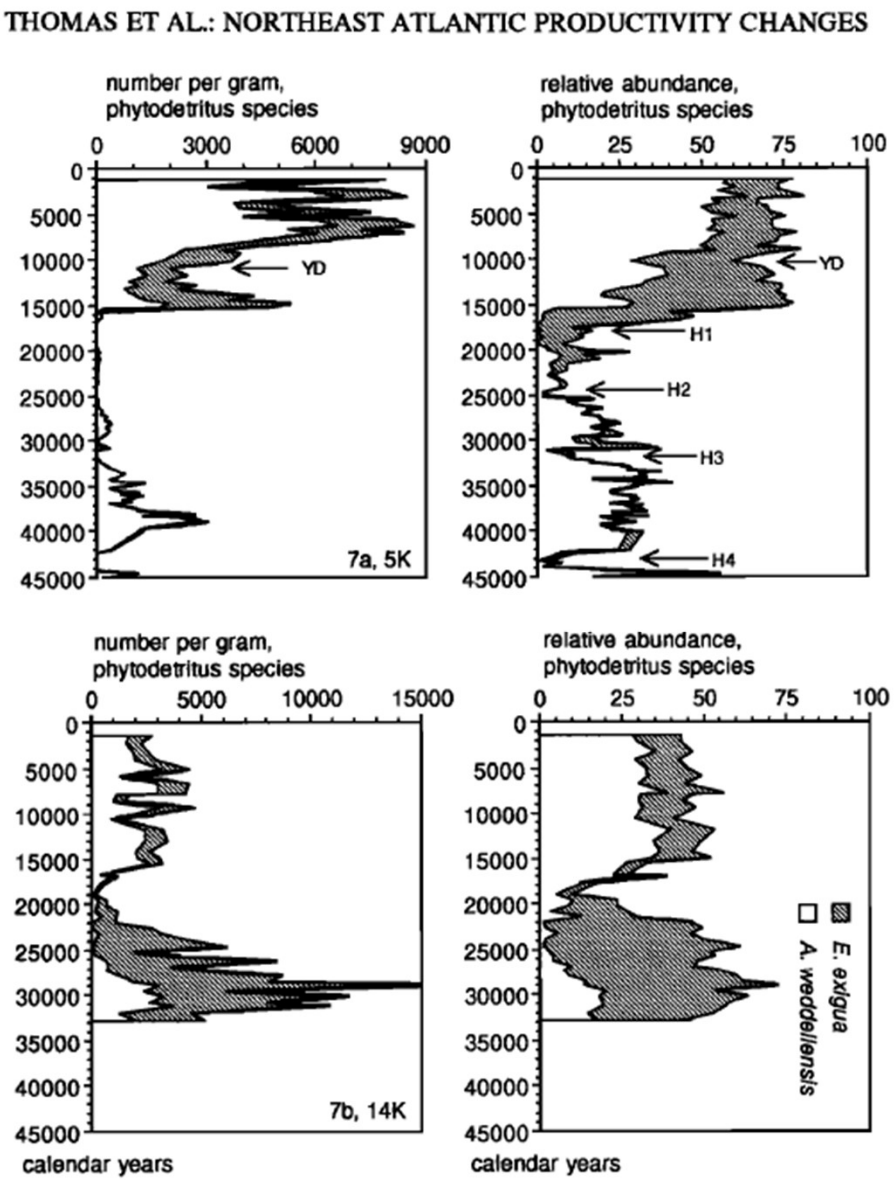


Figure 7. Relative and absolute abundances of *E. exigua* and *A. weddellensis*, the "phytodetritus species"; (a) 5K; (b) 14K

Increase in abundance at 15,000 years of benthic foraminifera species proxy of surface productivity

15,000 years correspond to the age of main Northern Hemisphere deglaciation and retreat of the Polar front. **More productive water were characterised by strong spring phytoplancton bloom**=> food source for opportunistic benthic species which became more abundant

Short period of climatic fluctuations (YD=Younger Dryas; H1-4=Henrich events, periods of meltwater large production), are also evident in the record of these two species

Thomas et al., 1995. PALEOCEANOGRAPHY, VOL. 10, NO. 3, PAGES 545-562

Coccoliths and foraminifera are influenced by the chemistry of the sea water that they are synthesized from => they are used for past reconstructions

- Elemental ratios Sr/Ca and Mg/Ca are used to infer past seawater chemistry, ocean productivity and temperatures
- The isotopic composition of the calcium carbonate is used to infer past carbon cycling, temperature, ice volume
- Eutrophic and oligotrophic species assemblages are used to infer productivity
- The age of sediments
- Alkenones (some organic constituents) survive degradation in sediments => are used to reconstruct paleotemperature

Within the water column, calcium (Ca^{2+}) content varies little, hence the calcium carbonate saturation state (CSS) is controlled by concentration of carbonate ions (CO_3^{2-}), pH , water pressure, temperature, salinity

$CSS = (Ca^{2+}) \times (CO_3^{2-}) \div K'sp$

whereas K'sp is the equilibrium solubility product for the mineral phase of calcite or aragonite, respectively.

CSS: supersaturated > 1
saturated = 1
undersaturated < 1

with carbonate ions.

Position and thickness of the saturation horizon in the water column can be defined as the difference ΔCO_3^{2-} between the concentration of carbonate ions in situ and the concentration of saturated carbonate ion for the respective mineral phase.

https://www.encyclopedia.com/science-and-technology/astronomy-and-space-exploration/astronomy-general/ccd

Carbonate ooze in the deep Ocean serve as a major reservoir of calcium and carbon dioxide on the Earth's surface

Their spatial and temporal accumulation patterns in the marine stratigraphic record are critical information about:

- past Ocean circulation
- Carbonate Chemistry
- Global geochemical cycle of CO2

The technique of transfer functions applied to biogenic assemblages could be used to determinate quantitative paleo sea surface parameter such as the sea ice or SST (Sea Surface Temperature).

The transfers functions require three databases:

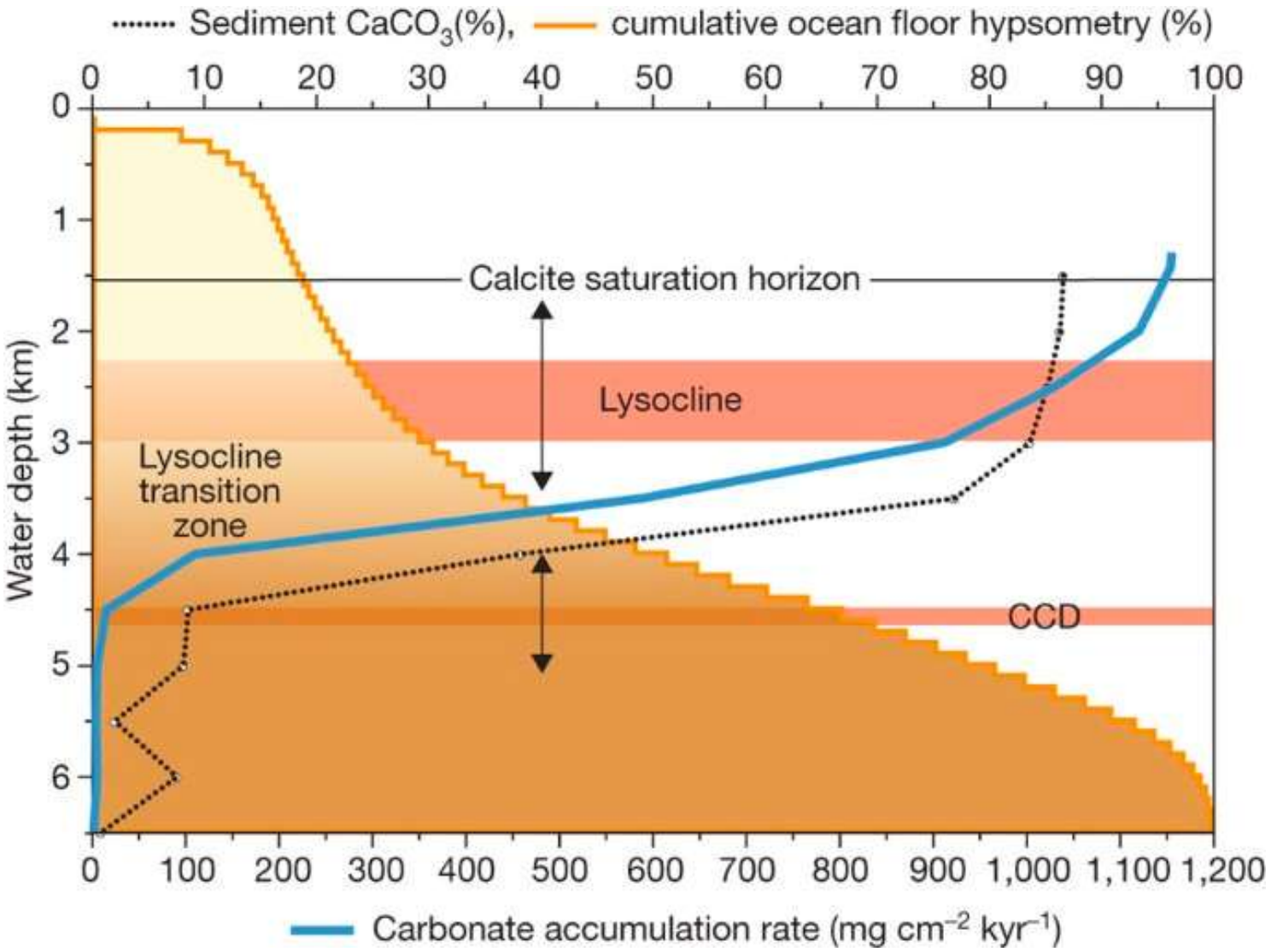
- modern species database that displays the species present in surface sediments,
- modern parameter that gives quantitative values of surface properties extracted from in situ measurements
- the fossil assemblages

Polar oceans have lower calcium carbonate saturation states ($\Omega=[CO^{2-}_3] \times [Ca^{2+}]/K^*_{sp}$) due in part to the higher stoichiometric solubility product (K^*_{sp}) **as a function of lower temperature** (e.g., Azetsu-Scott et al., 2010).

Low foraminiferal abundances and frequent barren samples in the diatom-rich intervals may be a consequence of **carbonate dissolution due to a high flux of organic matter** associated with generally **open marine conditions** during deposition of diatom-rich sediments.

Alternatively, **dissolution of calcareous foraminifera** may be due to the **production of corrosive High Saline Shelf Water (HSSW) associated with sea ice formation and brine rejection**

Another hypothesis is **dilution by high sedimentation rates**



Pälike et al., 2012, Nature

Distribution of pelagic sediment

Dominant component	Composition	Atlantic	Pacific	Indian	Total %
Foraminiferal and nannofossil ooze	Calcium carbonate	65	36	54	47
Pteropod ooze	Calcium carbonate	2	0.1	-	0.5
Diatom ooze	Silica (opal)	7	10	20	12
Radiolarian ooze	Silica (opal)	-	5	0.5	3
Red (actually brown) clay K, Fe	Al silicate	26	49	25	38

Source P.Pinet Invitation to Oceanography, 2000 2nd Edition, Jones and Barlett Publishers, Massachusetts

Take-home messages

Marine sediments are very heterogeneous material, whose solid component is made by a mixture of particles with different composition, shape and size

All of the inorganic solid components of marine sediments undergo some kind of chemical alteration through time essentially in consequence of the exposure to salt water