Ocean Sediments

OCN 401

7 Nov 2017

Outline

Significance & terms

Origin & distribution of major types of marine sediments

Delivery - dissolution – destruction

mid-ocean ridges

Significance of ocean sediments

Continents are sites of erosion. Ocean is site of deposition.

b. Therefore oceans retain a more complete and organized record of Earth history.

c. Law of superposition

Superposition

sedimentary layers are deposited in a time sequence, the oldest at the bottom and the youngest at the top;

in the case of a strata, layers on top conform to the shape of the lower layers

Categories of Marine Sediments

- Classification according to the origin of the components:
- Authigenic - formed in situ by precipitation or submarine alteration
- Terrigenous - detritus from continental erosion and explosive vulcanism
- Biogenic - shells or skeletons of organisms that sink to the sea floor after the organisms death; made of silicate or carbonate

The Origin of Marine Sediments

- Volcanogenic particles are derived from volcanic eruptions, range from boulders to dust
- Lithogenous particles are derived from pre-existing rocks by weathering (disruption of rocks by wind, temperature, water), deposited by wind or rivers
- Glacially derived particles are ground from rock beds by moving glaciers
- Biogenic particles are shells or skeletons of organisms that sink to the sea floor after the organisms death; made of silicate or carbonate

What Controls the Distribution of Various Kinds of Seafloor Sediments?

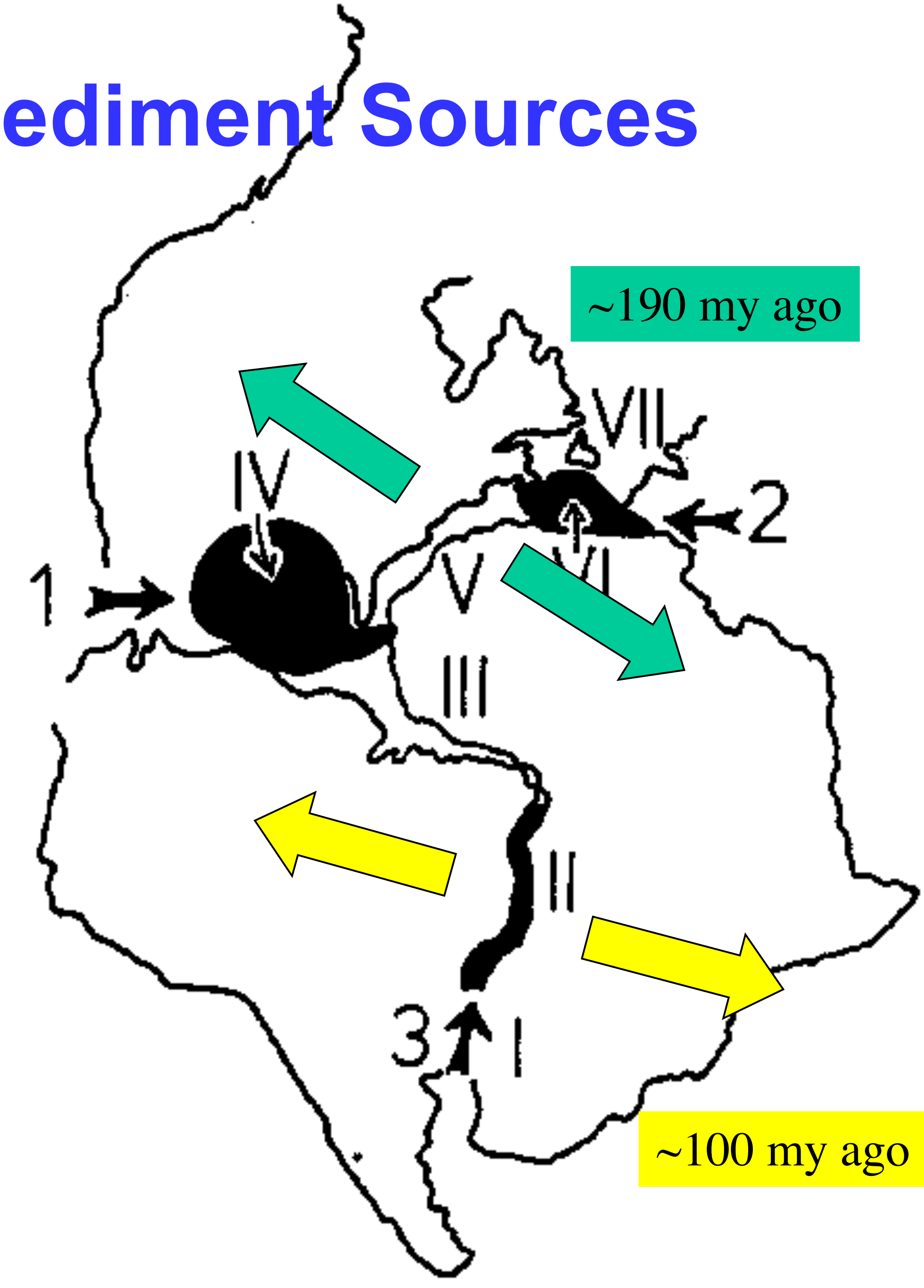
The answer is "the 3 D's":

1) Delivery: Without delivery of sediments into the ocean, they will of course never be found there.
2) Dilution: Many different types of sediment particles reach the seafloor. If too much of one type reaches a given place, or the rate of dilution is very high, the other types will become unimportant.
3) Destruction: Certain chemical, physical, and biological processes destroy sedimentary particles, removing them from the seafloor sediment.

Authigenic Sediment Sources

I. Evaporites:

- form when flux of freshwater out of a body of water exceeds flux of freshwater in;
- Require unusual geological circumstances;
- Examples: (a) Mediterranean isolation from Atlantic ~6mya, (b) breakup of Gondwanaland
- As rift valleys form, their floors lie below adjacent oceans



Authigenic Sediment Sources

II. Phosphorites:

- Sediments or sedimentary rocks rich in phosphate;
- Typically concentrated in coastal areas with:
  - (a) intensive upwelling,
  - (b) little or no terrigenous input

>20% phosphate content vs. <0.2% of typical sedimentary rock

Authigenic Sediment Sources - phosphorites

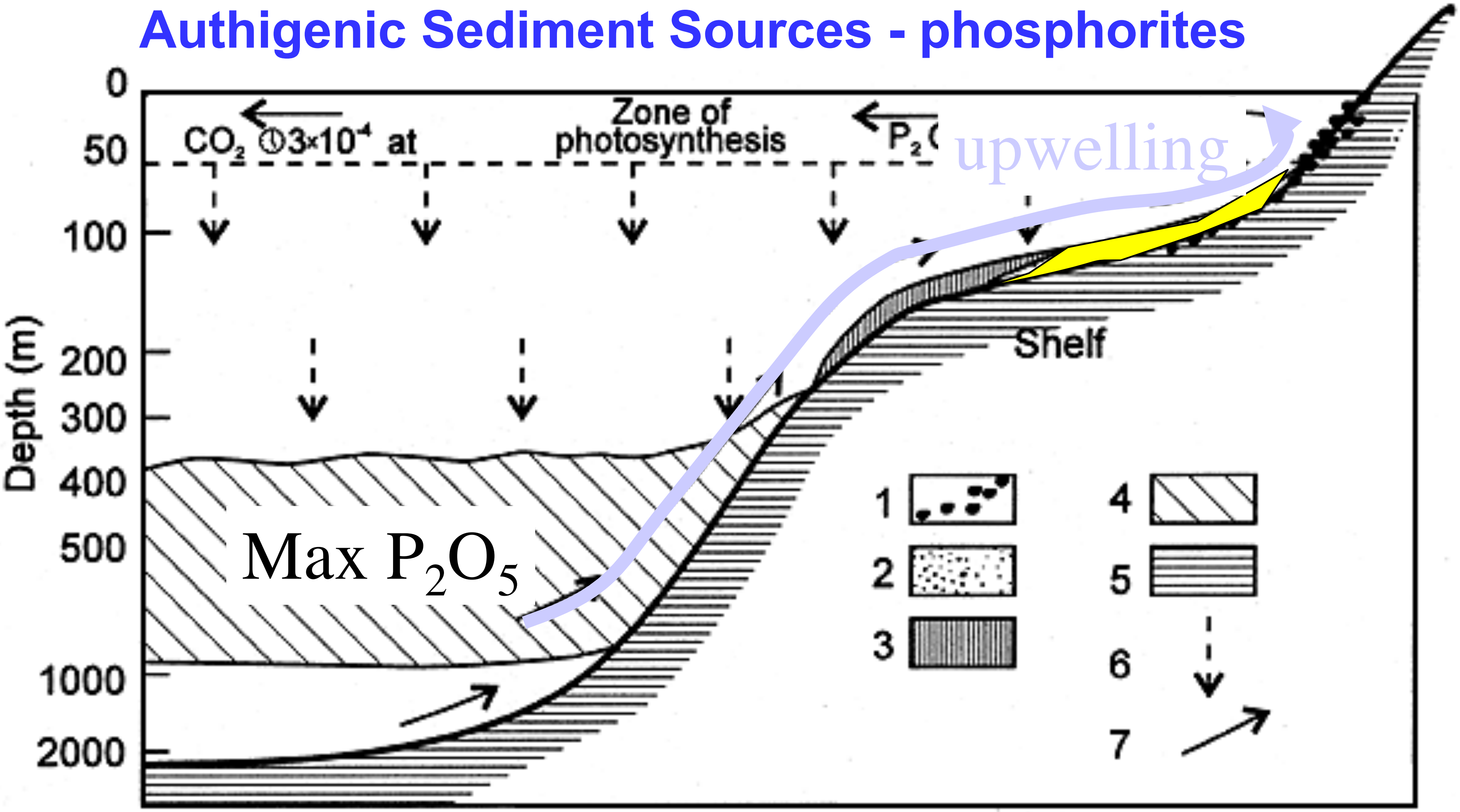


Figure 7.17. Diagram showing the formation of phosphorites (after Kazakov in Strakhov 1962). 1, facies of littoral gravel and sand; 2, phosphate facies; 3, facies of calcareous sediments; 4, zone of maximum CO_2 and organic P_2O_5 content (partial pressure of CO_2 up to 12×10^{-4} atm, P_2O_5 concentration 300-600 mg/m^3); 5, landmass; 6, sedimentation of plankton remains; 7, current directions.

Source: Holland, Heinrich D. and Ulrich Petersen (1995) Living Dangerously: The Earth, Its Resources, and the Environment. New Jersey: Princeton University Press.

Authigenic Sediment Sources - phosphorites

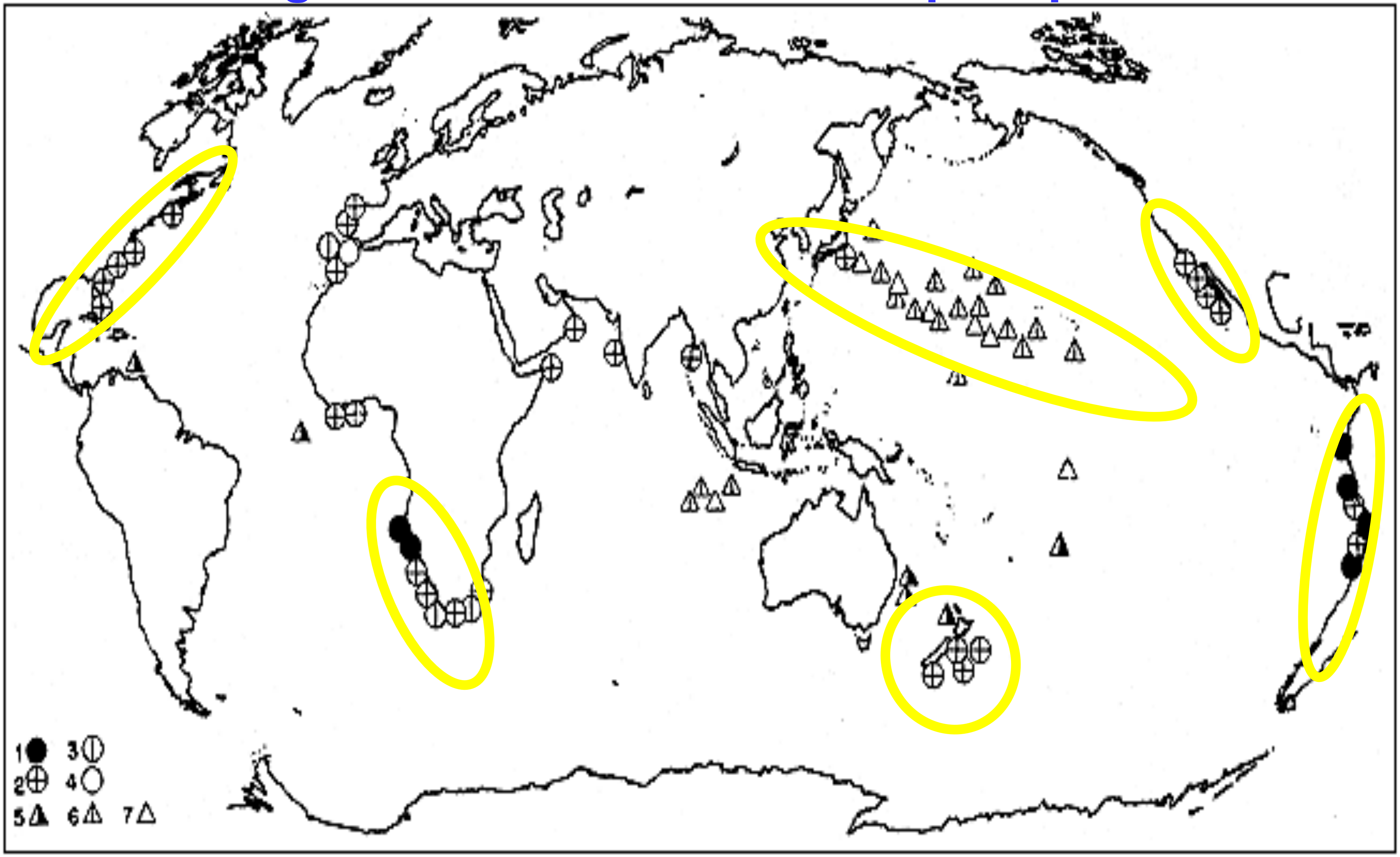


Figure 7.16. Location of phosphorites on the seafloor. 1-4, phosphorites on continental margins; 5-7, phosphorites on submerged mountains. Geological age: 1, Holocene; 2, 5, Neogene; 3, 6, Paleogene; 4, 7, Cretaceous. (From Bezrukov and Baturin 1979)

Source: Holland, Heinrich D. and Ulrich Petersen (1995) Living Dangerously: The Earth, Its Resources, and the Environment. New Jersey: Princeton University Press.

Terrigenous Sediment Sources

I. To the continental margins:

- Most clastics are left either along the margins of continents or are delivered to the abyssal plains.
- Transport of large sediment grains requires high energy (i.e., fast moving water).
- Very thick deposits - up to 10km beneath continental shelves.
- Sediments are funneled across continental margins through submarine canyons to deep sea fans.
- Sedimentation rate on deep sea fan: up to 1 km/my.

Terrigenous Sediment Sources - continental margins

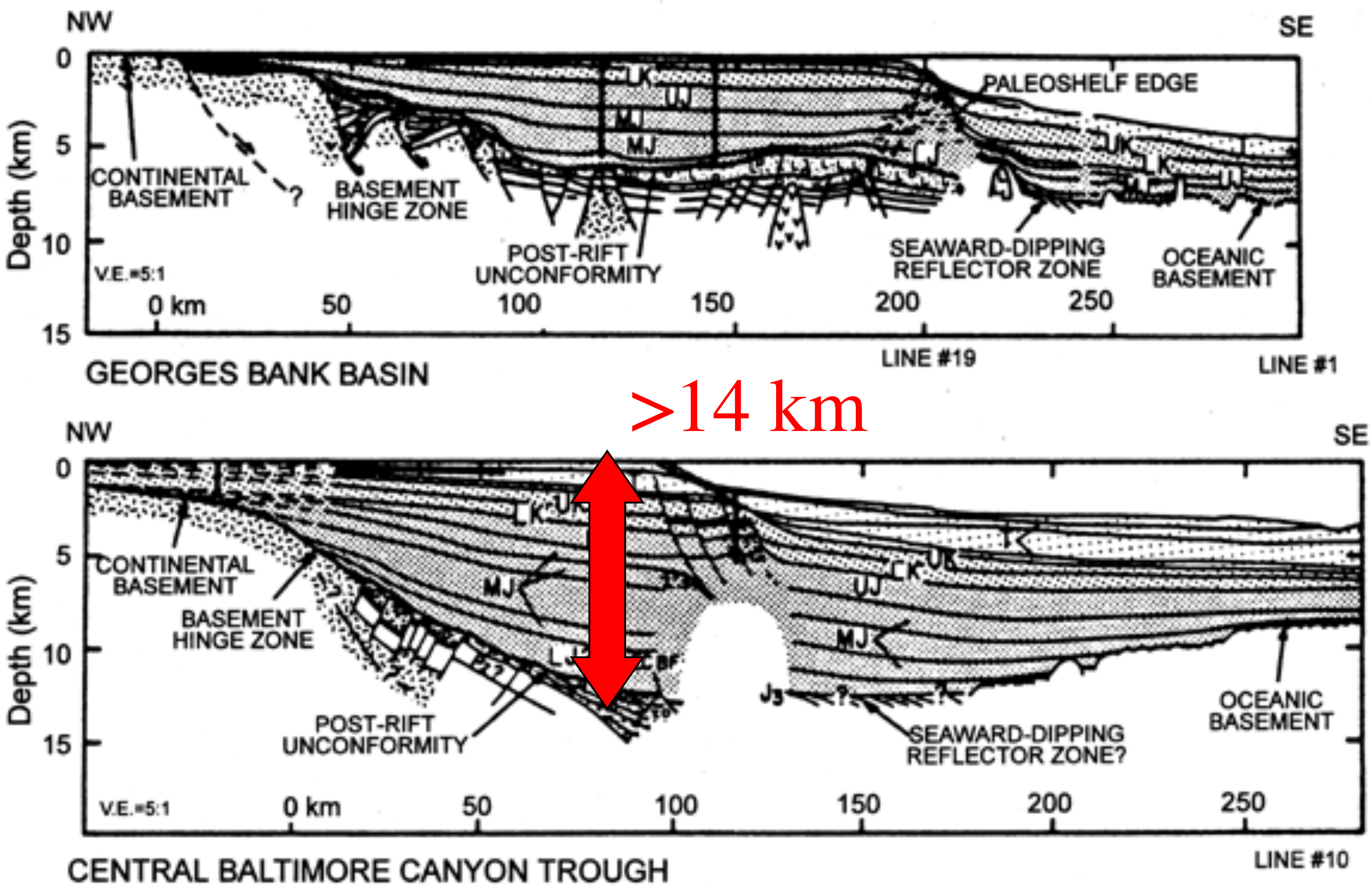
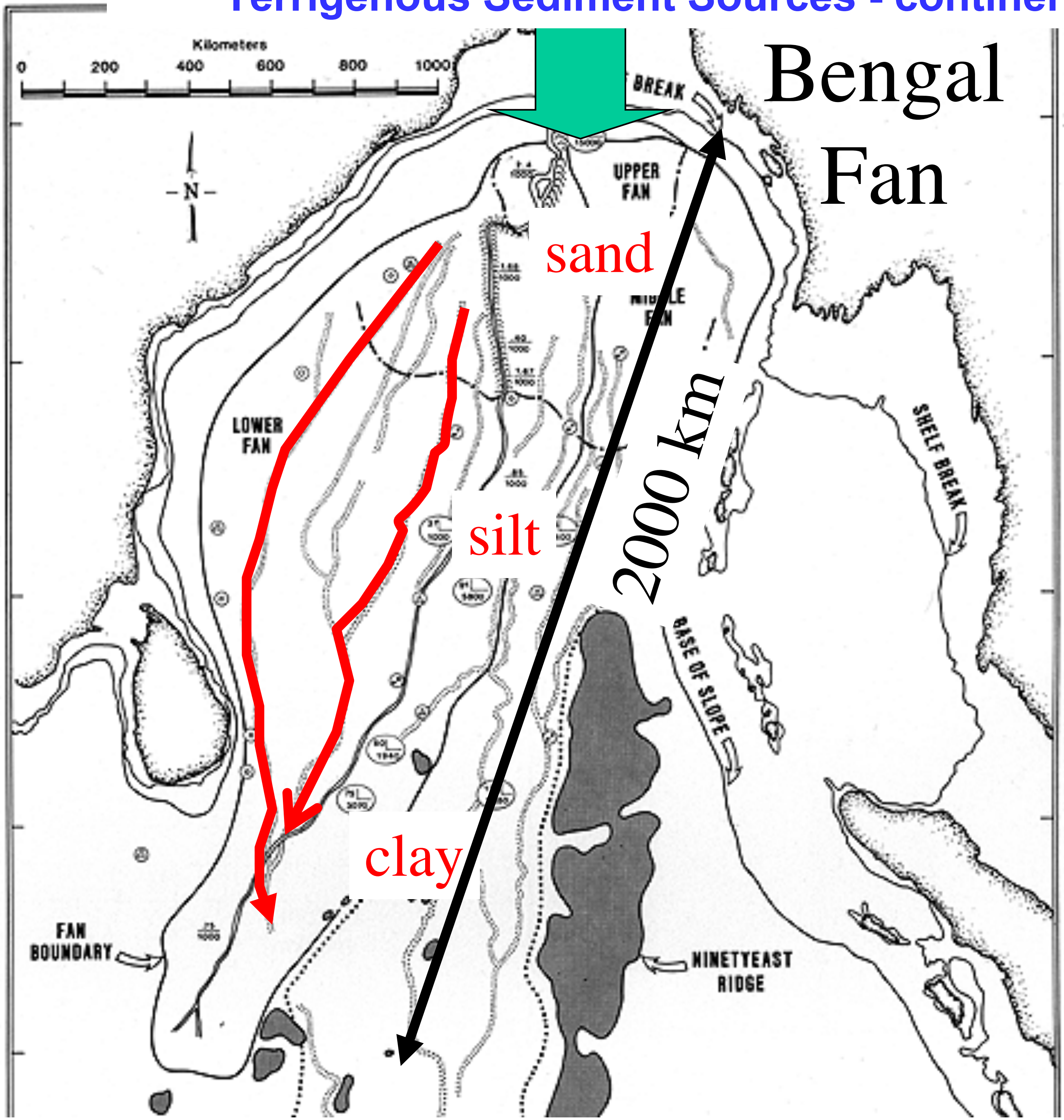


Figure 7.6. Cross sections across the Georges Bank Basin (upper) and the central Baltimore Canyon Trough (lower) (from Klitgord and Hutchinson 1985; Klitgord et al. 1988). ECBF = East Coast Boundary Fault; J3 = deepest Atlantic continental rise reflection (Sheridan 1989). T = Tertiary; UK = Upper Cretaceous; LK = Lower Cretaceous; UJ = Upper Jurassic; MJ = Middle Jurassic; LJ = Lower Jurassic.

Source: Holland, Heinrich D. and Ulrich Petersen (1995) Living Dangerously: The Earth, Its Resources, and the Environment. New Jersey: Princeton University Press.

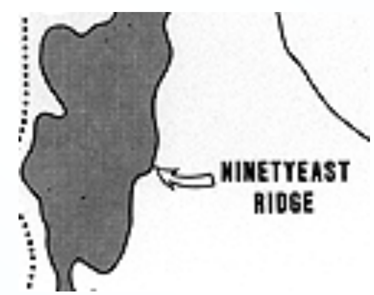
Terrigenous Sediment Sources - continental margins



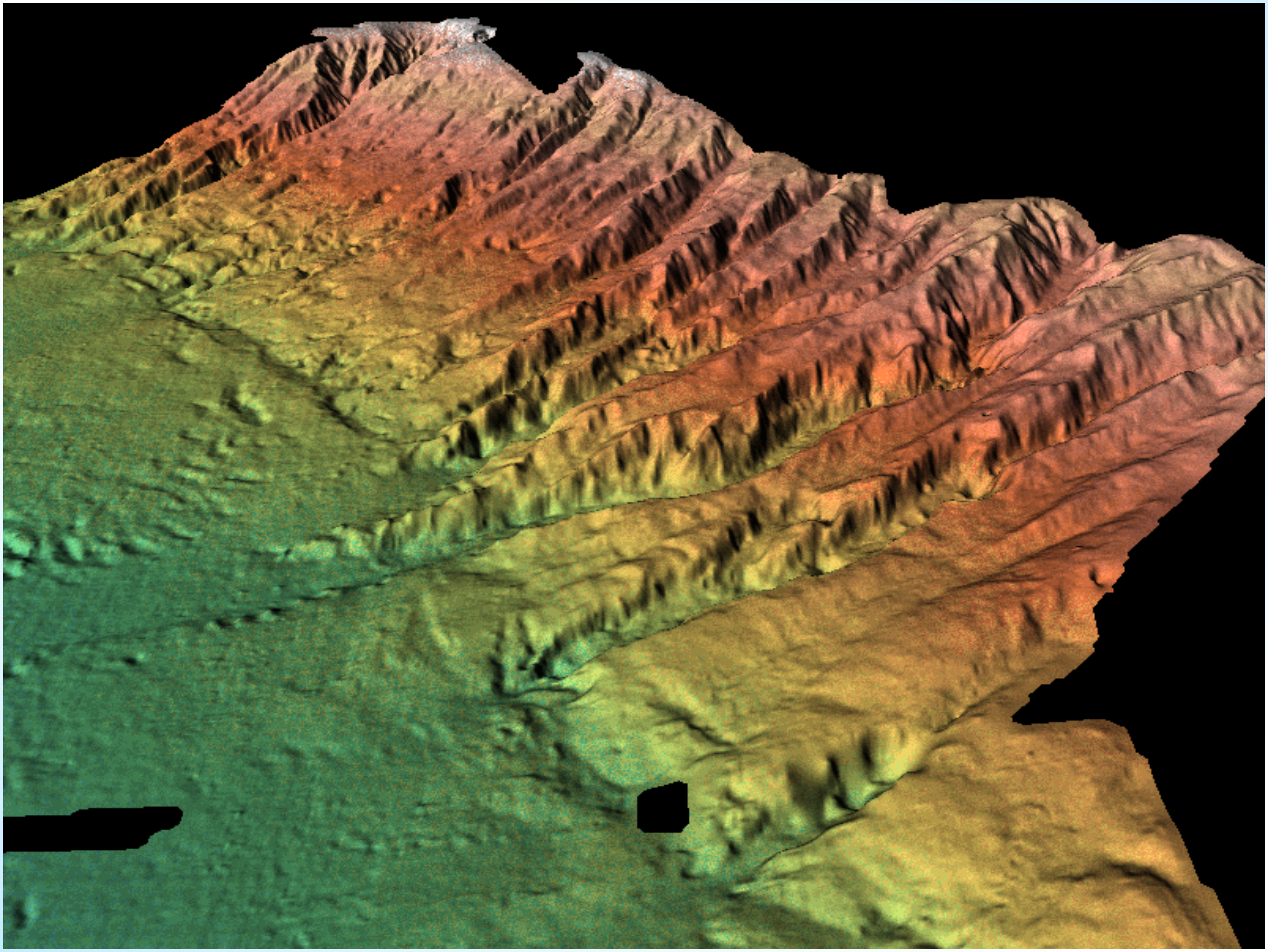
channels

source

topographic highs



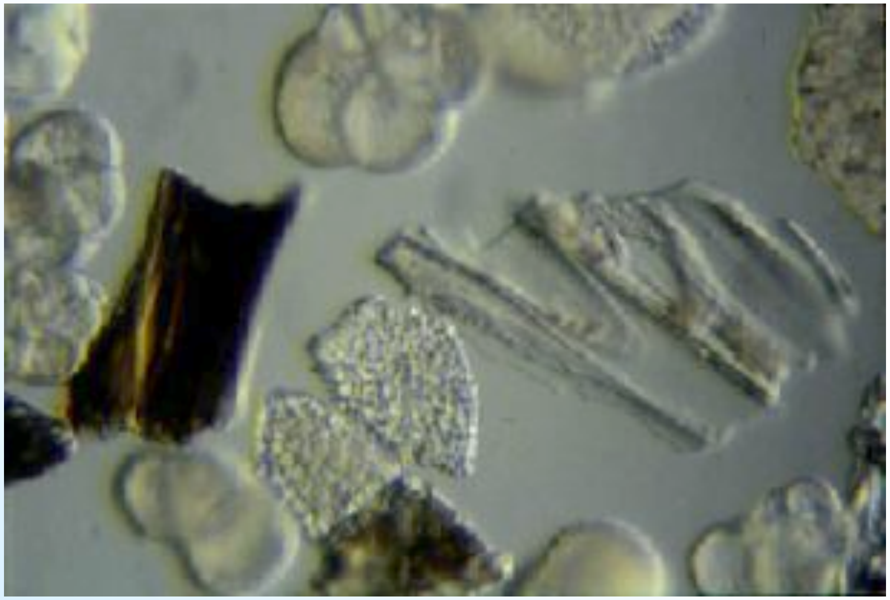
Terrigenous Sediment Sources - continental margins

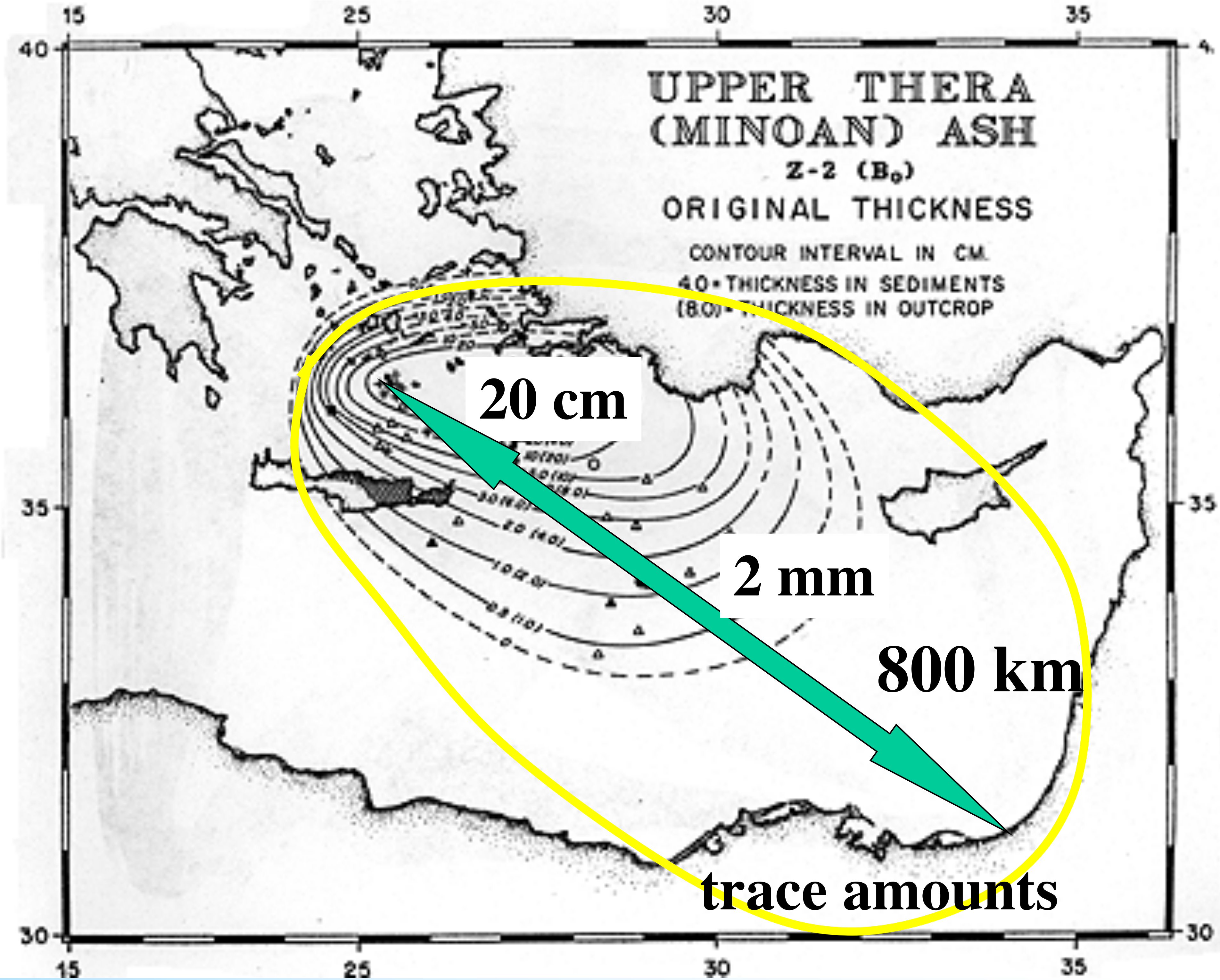


Terrigenous Sediment Sources

II. To the deep sea:

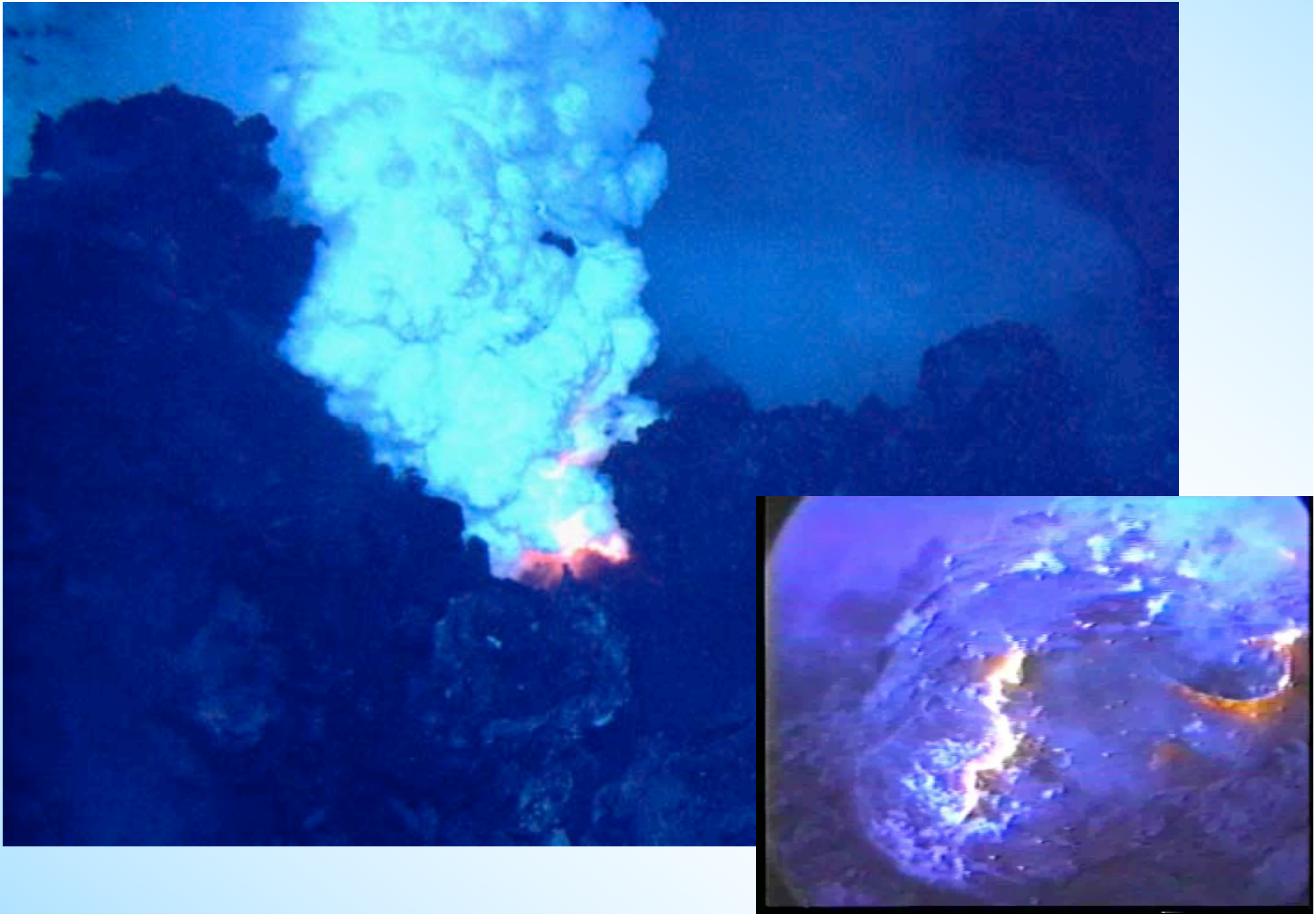
- Volcanic ash, tephra
- Sand to silt sized fragments of glass exploded into the atmosphere and transported by wind
- Useful as a stratigraphic marker
- Useful for regional volcanic history





UPPER THERA
(MINOAN) ASH
Z-2 (B₀)
ORIGINAL THICKNESS
CONTOUR INTERVAL IN CM.
4.0 • THICKNESS IN SEDIMENTS
(8.0) • THICKNESS IN OUTCROP
20 cm
2 mm
800 km
trace amounts
15
25
30
35
40
30

Subseafloor eruptions

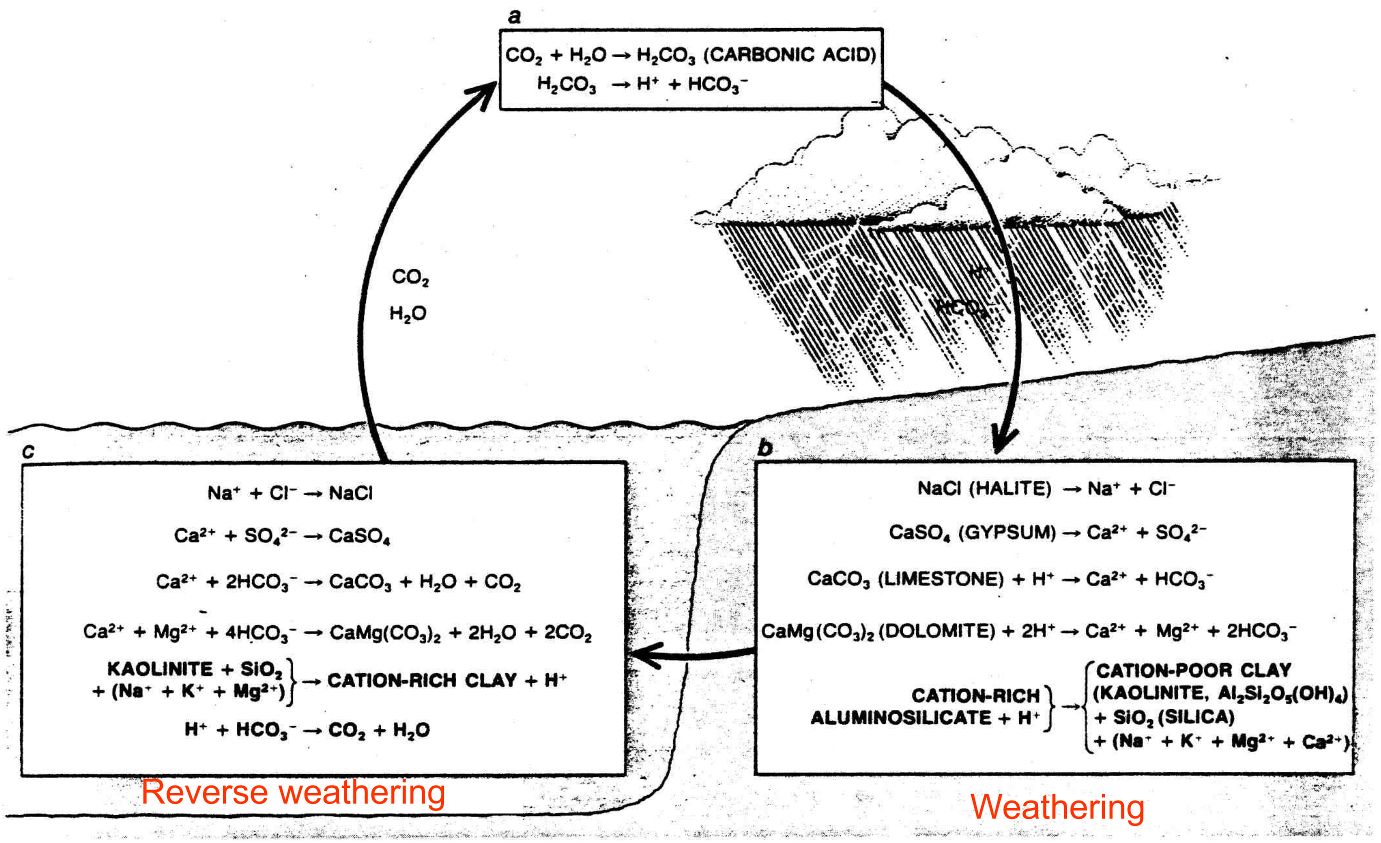


Terrigenous Sediment Sources

II. To the deep sea (continued):

- Eolian (wind-borne dust); useful for paleo-wind direction and paleo-desert location;
- Glacial marine; dropped from icebergs, useful for paleo-ice-extent;
- Deep sea clays accumulate at very slow rates (meters per millions of years)

Review of reverse weathering



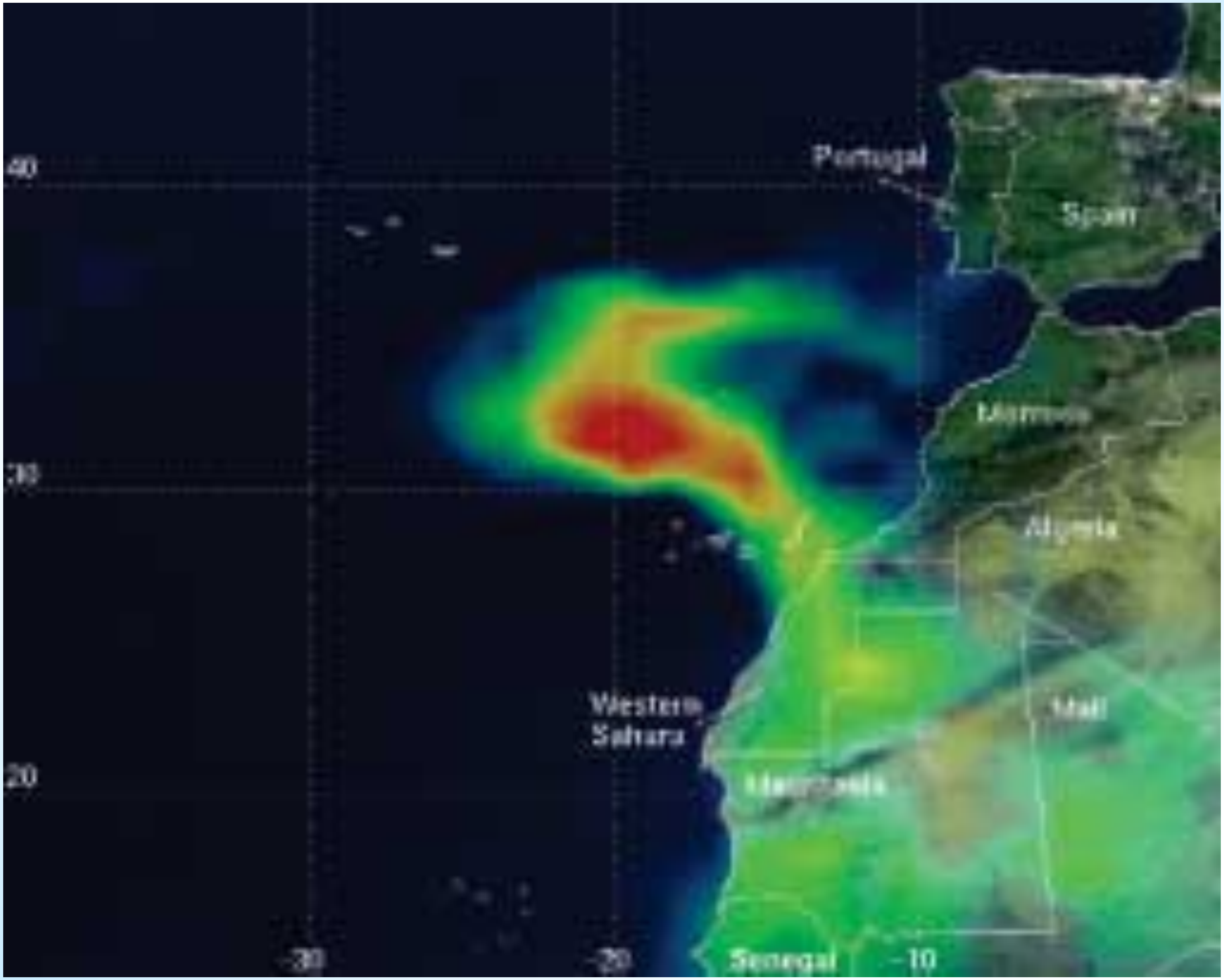
CHEMICAL BALANCE between the atmosphere, the continents and the oceans was hypothesized in the 1950's by Lars Gunnar Sillén of the Royal Institute of Technology in Stockholm and worked out in detail by Frederick T. Mackenzie and Robert M. Garrels of Northwestern University. In the atmosphere (*a*) carbon dioxide is dissolved in water vapor as carbonic acid. The water rains or snows on the continents (*b*), where hydrogen ions from the acid solution leach cations (positive ions) such as calcium, magnesium, sodium and potassium out of the continental rocks. Rivers carry the results of the continental weathering to the oceans (*c*). In the oceans, which are poor in hydrogen ions, the reactions reverse, creating sedimentary rock rich in cations and restoring carbon dioxide to the atmosphere.

Silica + degraded aluminous clays + iron oxide + organic carbon + soluble cations + bicarbonate

↓

New clay material + Carbon dioxide + water

Western Sahara Dust



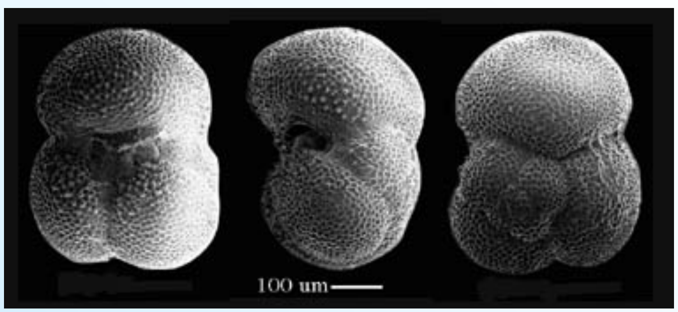
Biogenic Sediment Sources

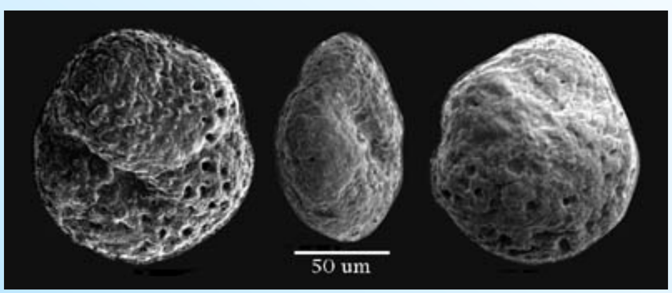
Biogenic sediments

a. Organisms (marine plants and animals) use dissolved materials delivered from rivers (flux in), especially calcium carbonate and silica

b. Organisms remove these dissolved products from seawater (flux out) to build shells and skeletons.
   - Calcium carbonate - mollusks, corals, foraminifera, coccoliths, some algae.
   - Hydrated silica - diatoms, radiolaria.

Biogenic Sediment Sources

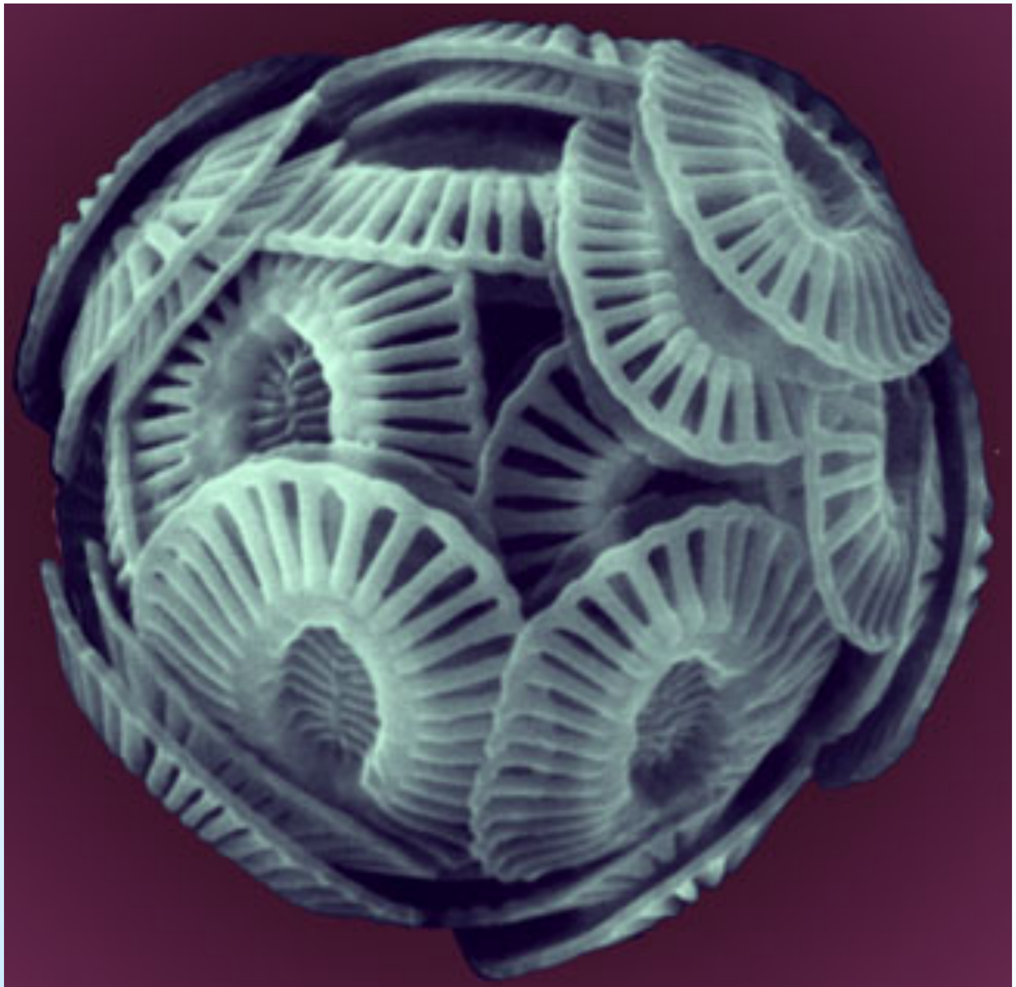


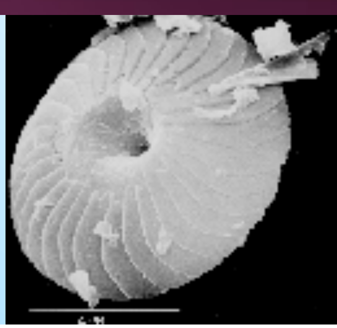


Foraminifera: relatives of amoeba with calcite shell, which is composed of a series of chambers; 30 µm to 2 mm (most are 50-400 µm); bacteriovores; most abundant 40° N – 40° S

plaza.ufl.edu/ mrosenme/Forams.htm

Biogenic Sediment Sources

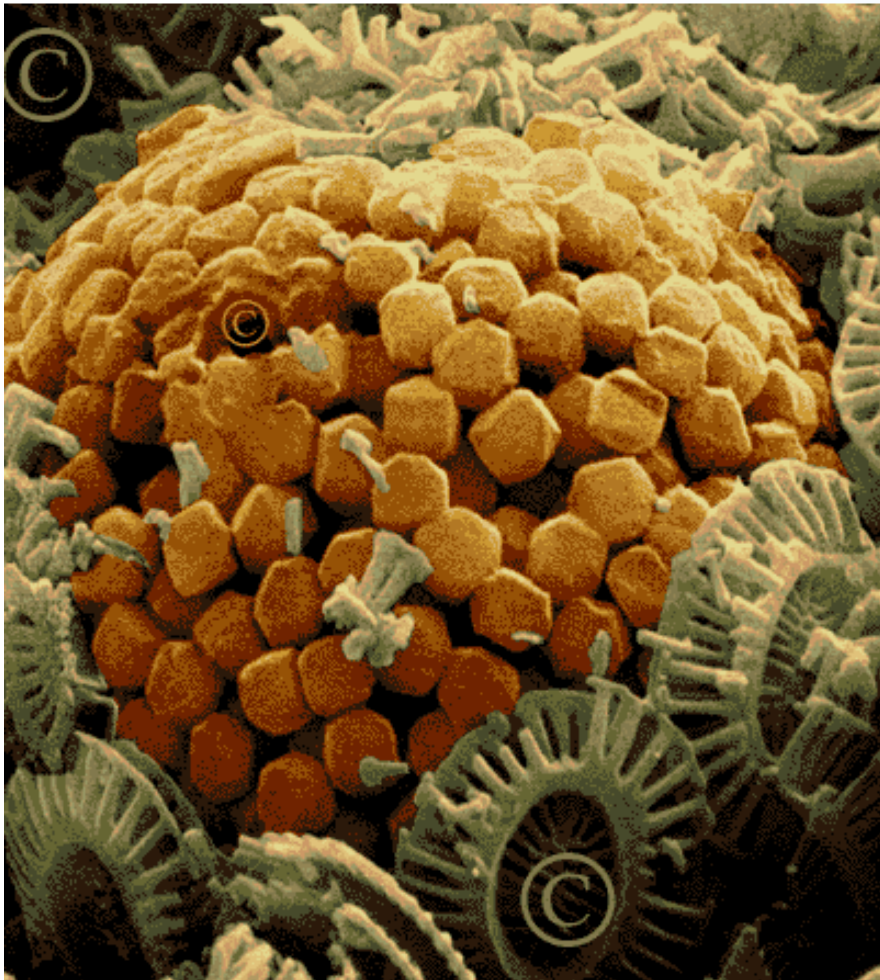




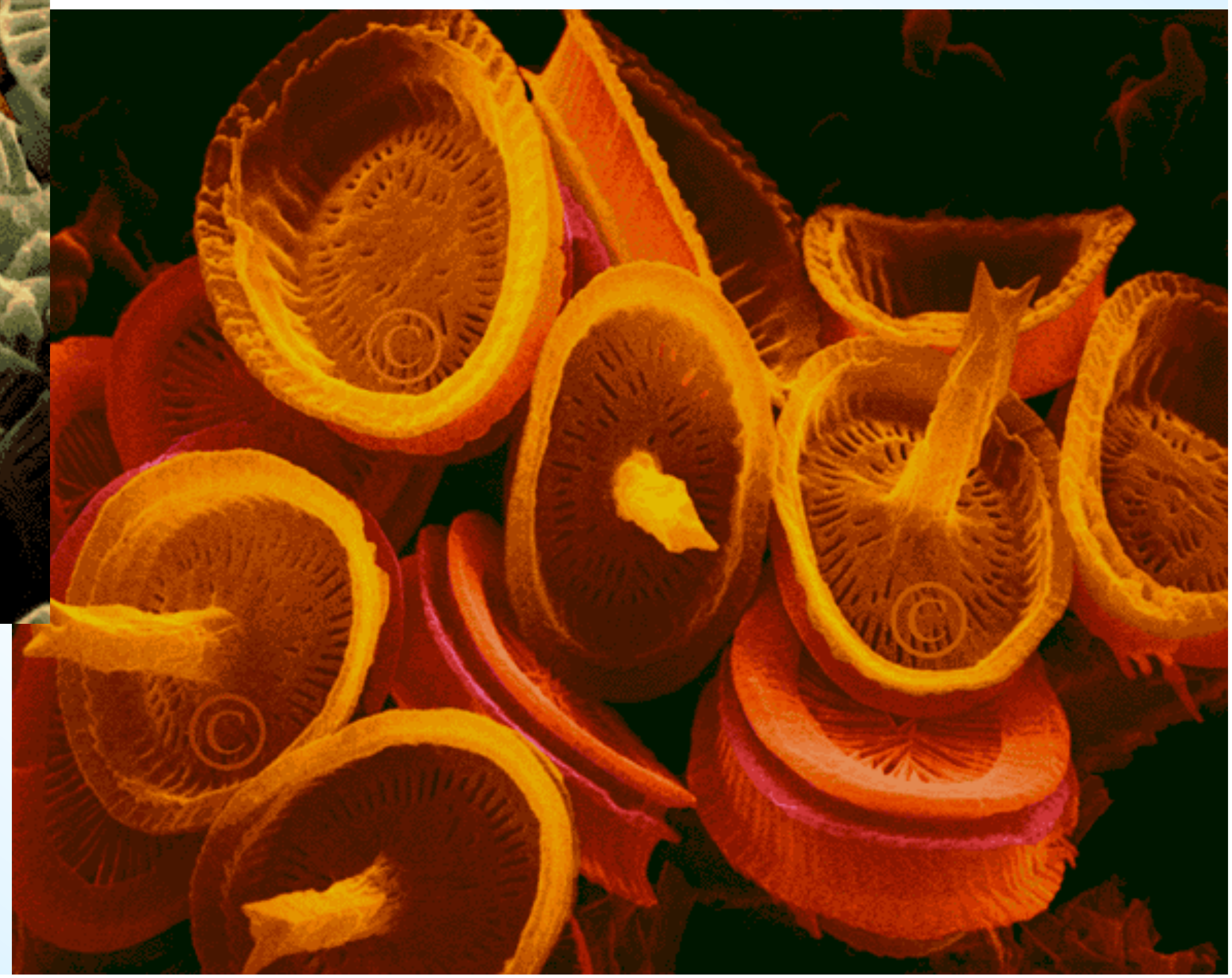
www.unf.edu/~gmead/ocbasins/marseds.htm

Coccolithophorids: single-celled flagellated algae, produce platelets called "coccoliths" that cover the cell for reasons that are poorly understood; very small (2-50 µm)

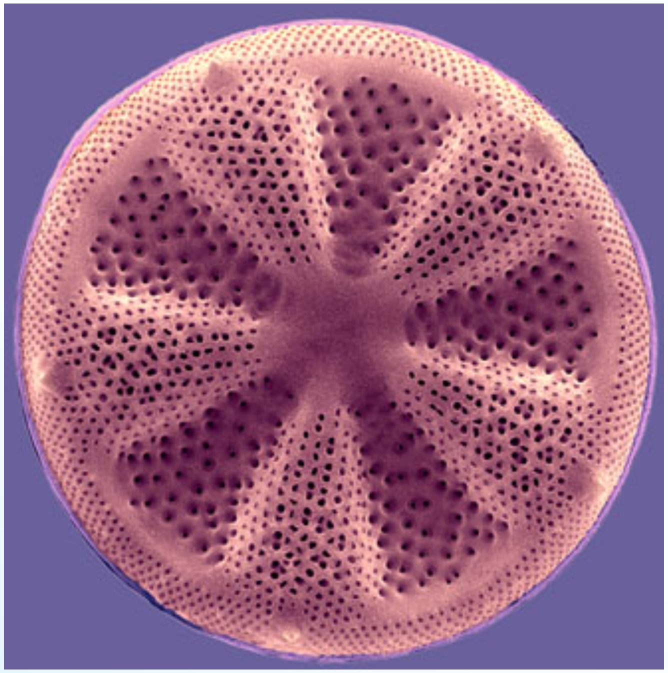
Biogenic Sediment Sources



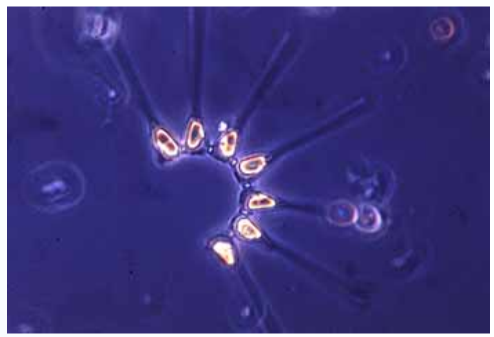
More coccolithophorids:
crunchy, FeS centers?!

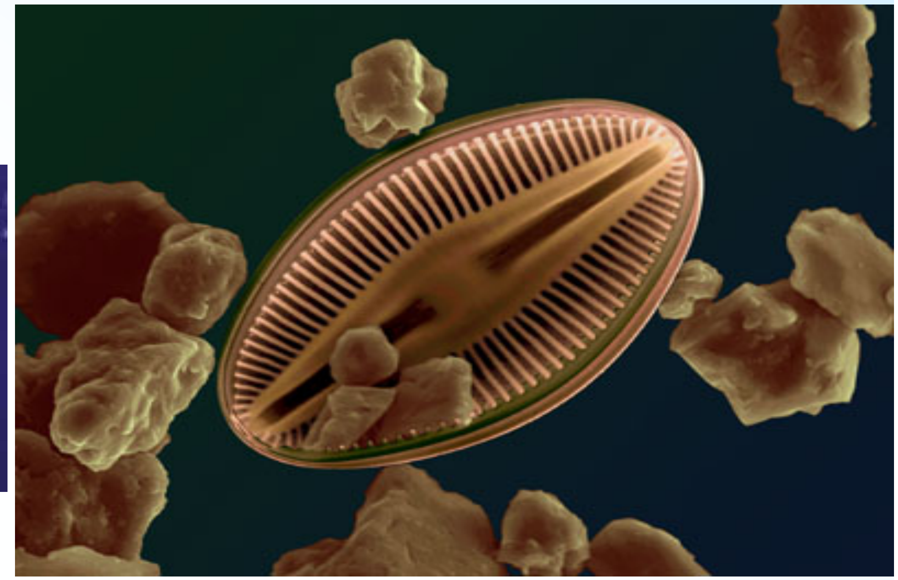


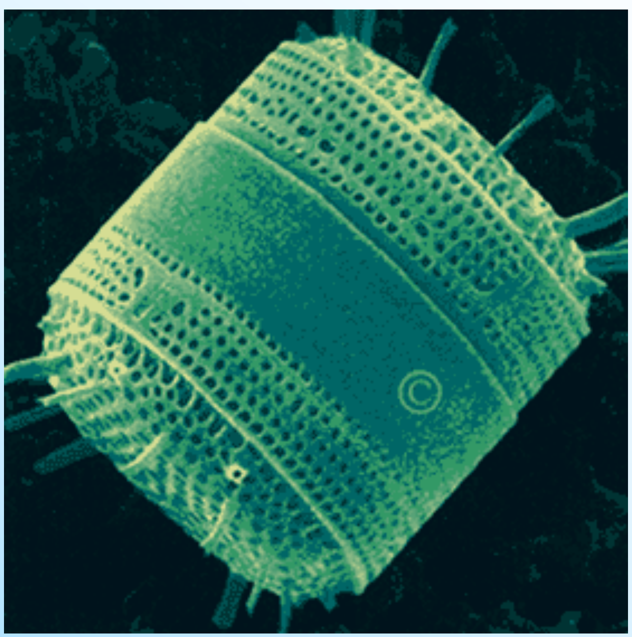
Biogenic Sediment Sources

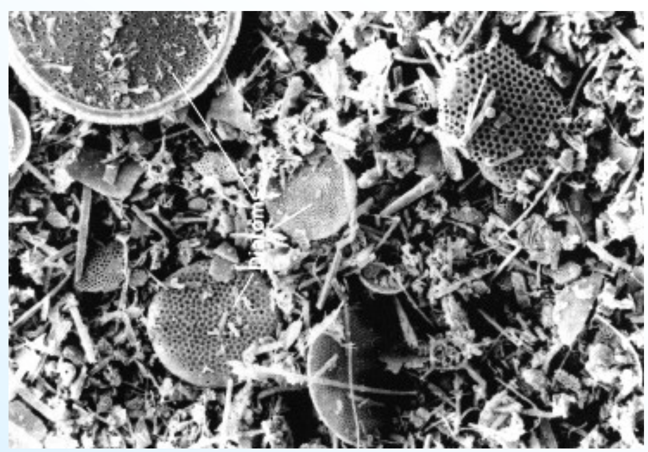


Diatoms: unicellular microalgae
with cell walls made of silica;
2 μm to 2 mm







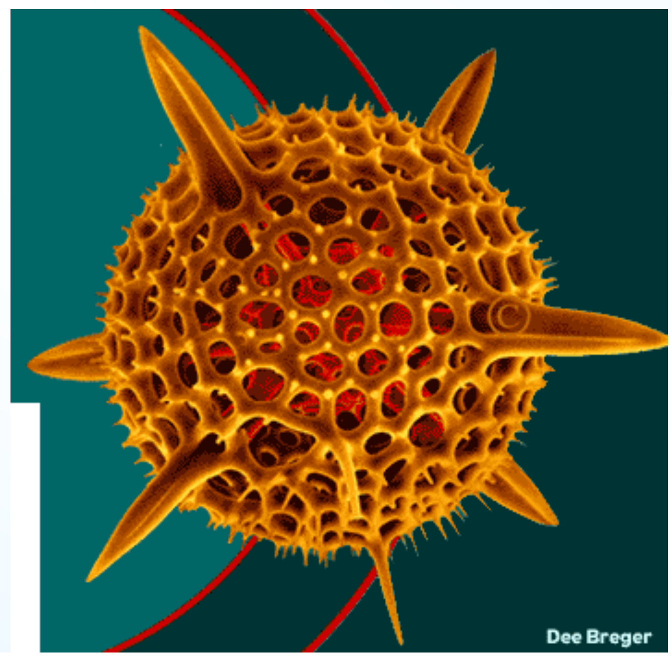


Biogenic Sediment Sources

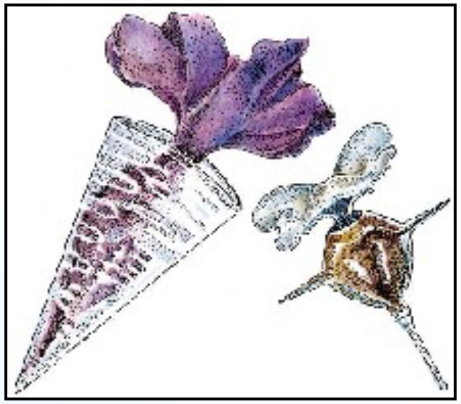
www.microscopy-uk.org.uk

1 mm

Radiolaria: spherical, protozoans with silica capsule; 50 µm to several mm; feed on bacteria, small phyto- and zooplankton; cold water and deep-sea



Biogenic Sediment Sources



www.jochemnet.de/fiu/OCB3043_24.html

www.clipart.com

Pteropods: pelagic mollusk, suspension feeder; produce large mucous nets to capture prey; carbonate shells produce pteropod ooze on sea floor; generally 300 μm to 10 mm

www.oceans.gov.au/norfanz/Creature_feature2.htm

Biogenic Sediment Sources

Biogenic sediments (continued)

c. Conditions limiting sedimentation include biological productivity and dissolution

Surface waters are supersaturated in bicarbonate, but deeper water is undersaturated due to increasing pressure and acidity below 3.4 - 4.4km

Calcium carbonate dissolves below this depth, so no calcareous sediments can be deposited.

Distribution of Siliceous Sediments....

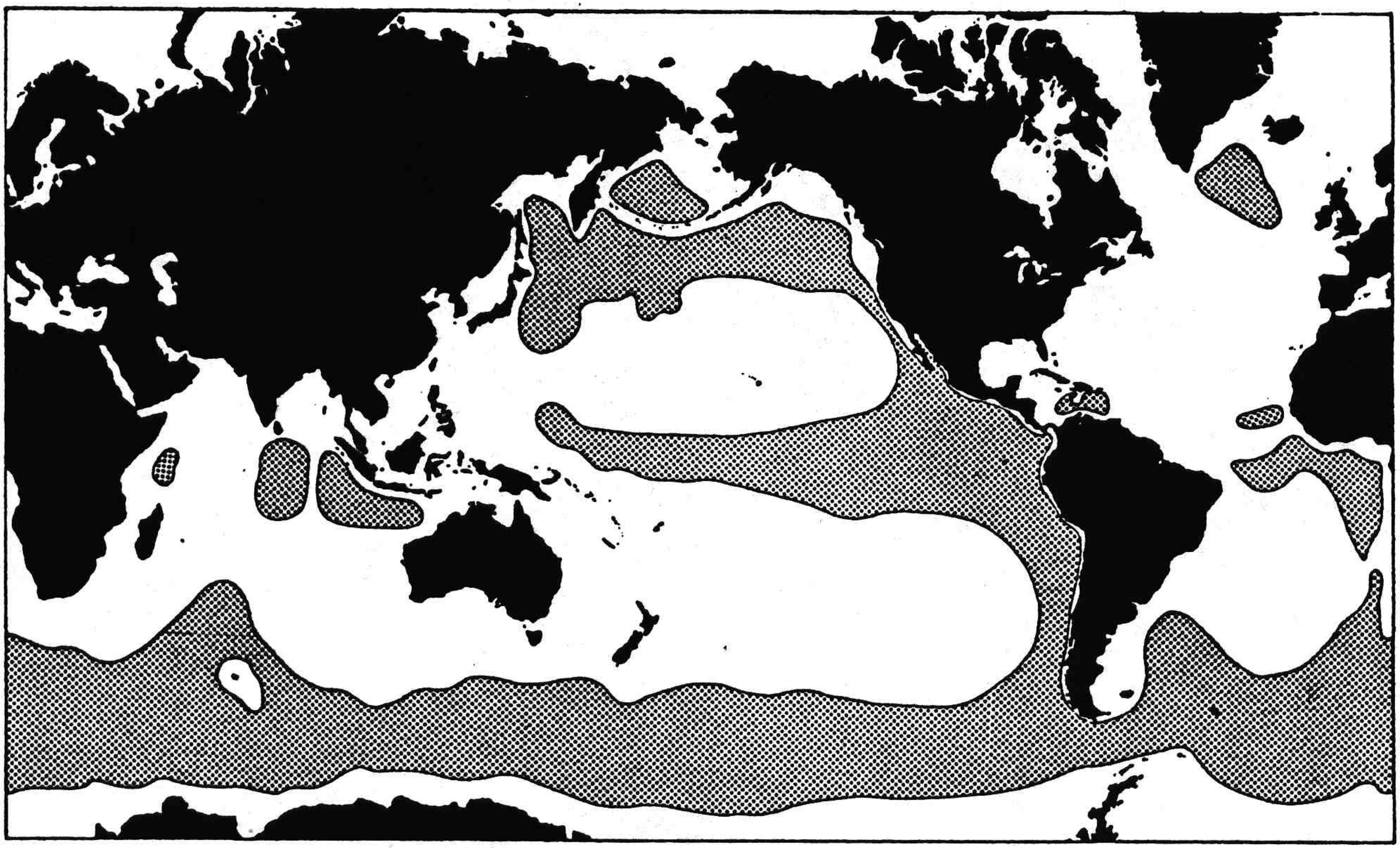


FIG. 24.5. Distribution of siliceous fossils (stippled) in ocean sediments. (Based largely on Berger, 1974, and Luyendyk and Davies, 1974).

Davis & Gorsline, 1976

....is *Largely* Controlled by Delivery

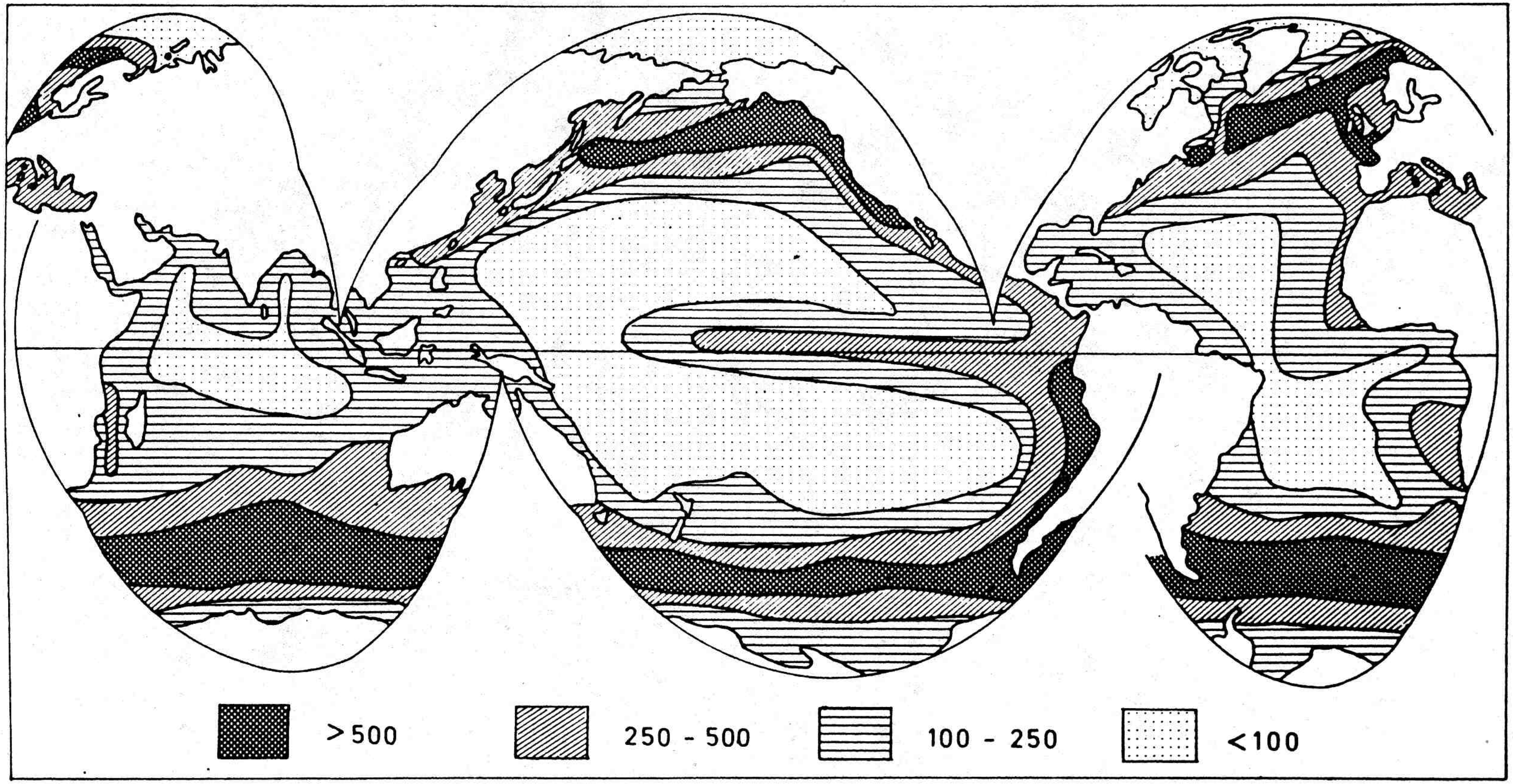
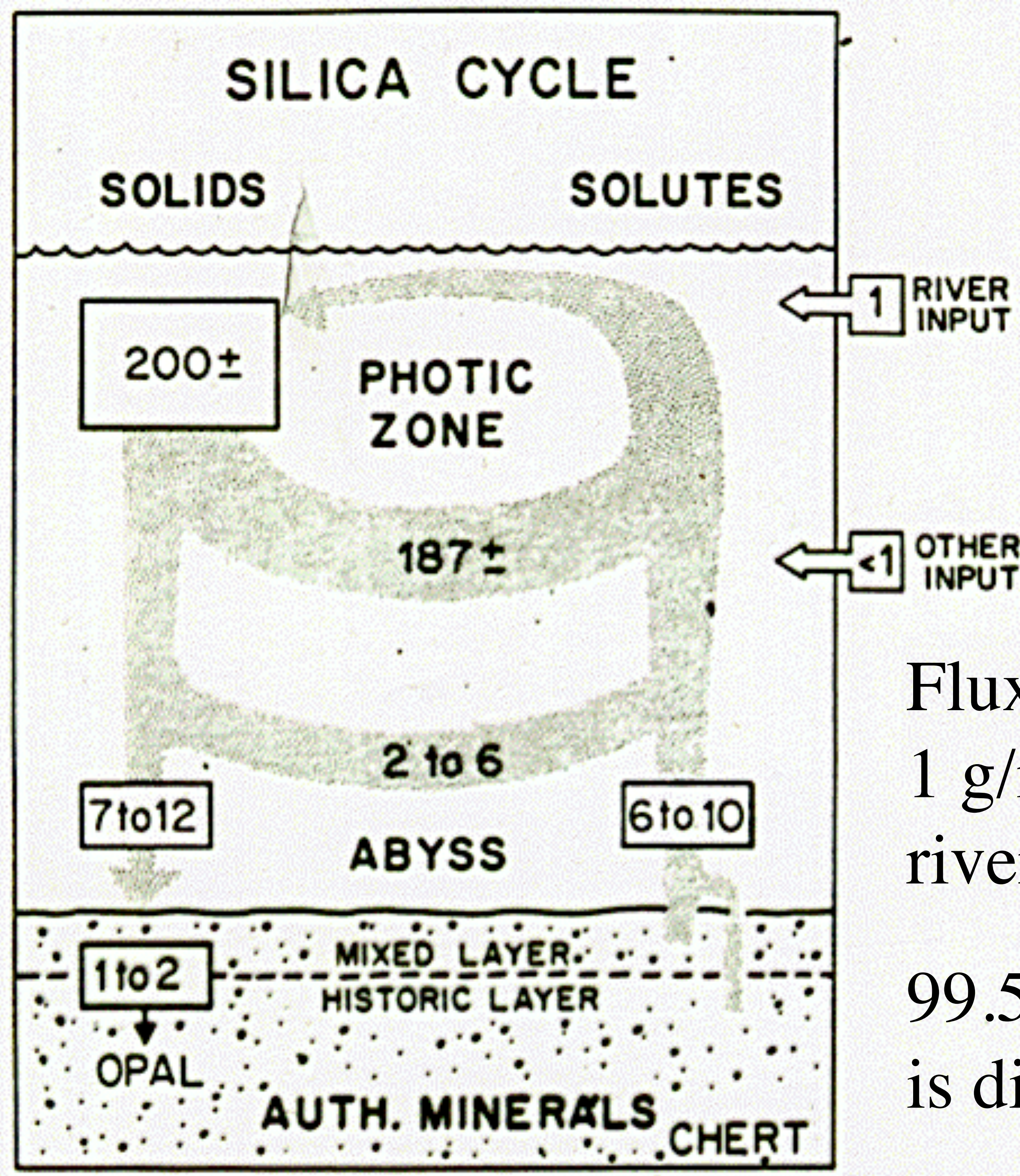


Fig. 2. Regional variation in the rate of extraction of dissolved silicon (g SiO_2 m^{-2} year $^{-1}$) by phytoplankton in near-surface waters. Modified from Lisitzin *et al.* (1967).



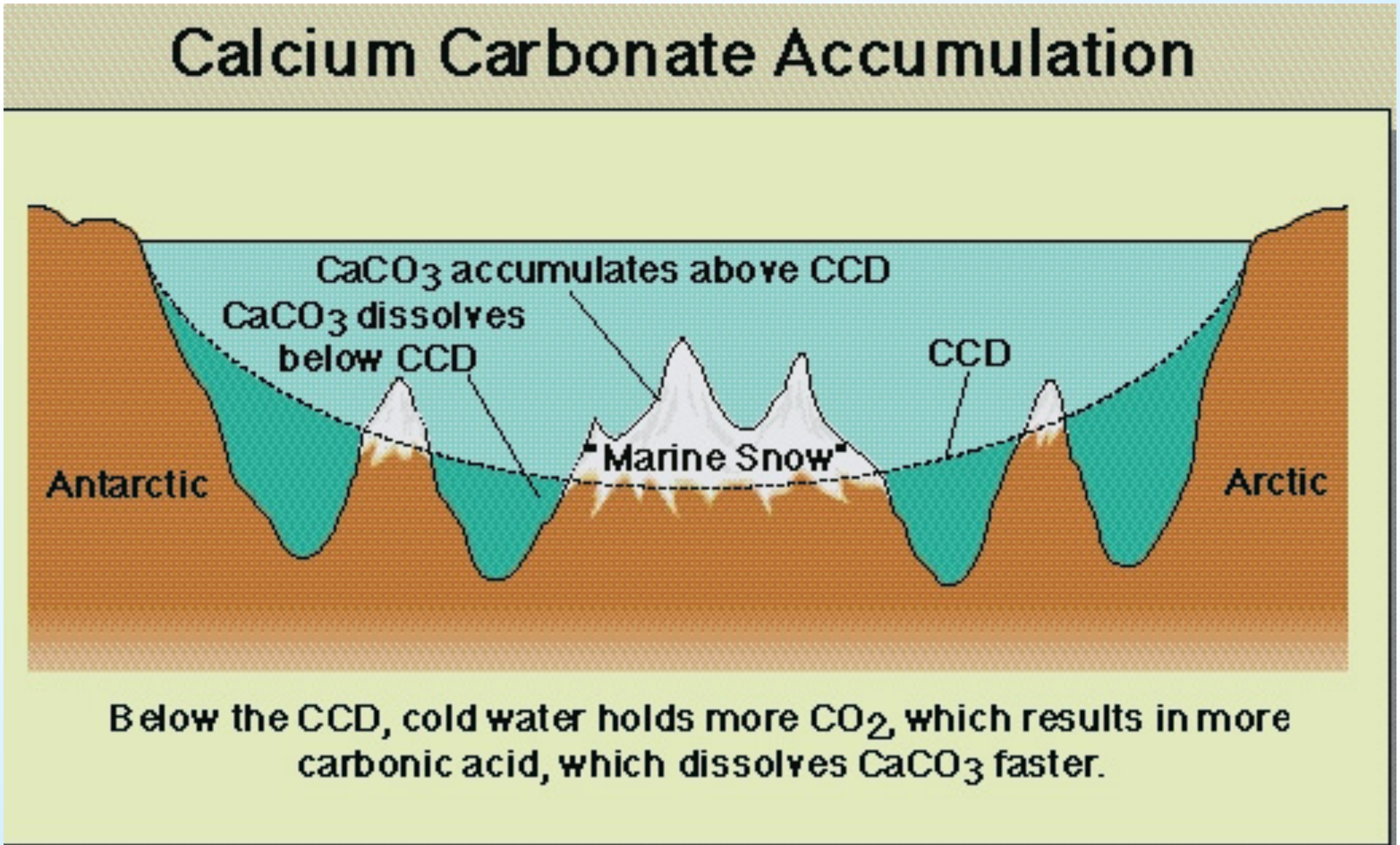
River input is 4×10^{14}g/yr

Production is 200 $g/m^2/yr$

Flux into sediment is 1 $g/m^2/yr$ to balance river input

99.5% of production is dissolved

In Contrast, Carbonate Sediments are Generally Controlled by Sediment Depth



faculty.uvi.edu/users/sratchf/SSEA_ocean/files/origins/origins20.htm

CCD = Carbonate Compensation Depth, the depth at which there is an abrupt decrease in the sediment carbonate content

First, a review of the CO_2 system…

Why is it important to understand the CO_2 system?

- CO_2 is the raw material used to build organic matter
- CO_2 controls the pH of the oceans
- CO_2 controls the fraction of inbound radiation that remains trapped in the atmosphere (greenhouse effect), which controls planetary climate
- Distribution of CO_2 species affects preservation of $CaCO_3$ deposited on the sea floor

CO_2 Speciation

- CO_2(g) reacts extensively upon contact with H_2O
- Major dissolved forms:
  - $CO_{2(aq)}$ (*aqueous carbon dioxide*)
  - HCO_3^- (*bicarbonate ion*)
  - CO_3^{-2} (*carbonate ion*)
- Species interconvert readily
- Changes to one part of CO_2 system lead to redistribution of all CO_2 species
- Reactions not always intuitive!

Equations for CO_2 Speciation

The equilibrium of gaseous and aqueous carbon dioxide:

$$CO_{2(g)} \leftrightarrow CO_{2(aq)}$$

Subsequent hydration and dissociation reactions:

$$CO_{2(aq)} + H_2O \leftrightarrow HCO_3^- + H^+$$

$$HCO_3^- \leftrightarrow CO_3^{-2} + H^+$$

Hint: when pH is between 7.5 and 8.5:

$$CO_{2(aq)} + CO_3^{-2} + H_2O \leftrightarrow 2HCO_3^-$$

$$CO_{2(g)} \leftrightarrow CO_{2(aq)}$$

$$CO_{2(aq)} + H_2O \leftrightarrow HCO_3^- + H^+$$

$$HCO_3^- \leftrightarrow CO_3^{-2} + H^+$$

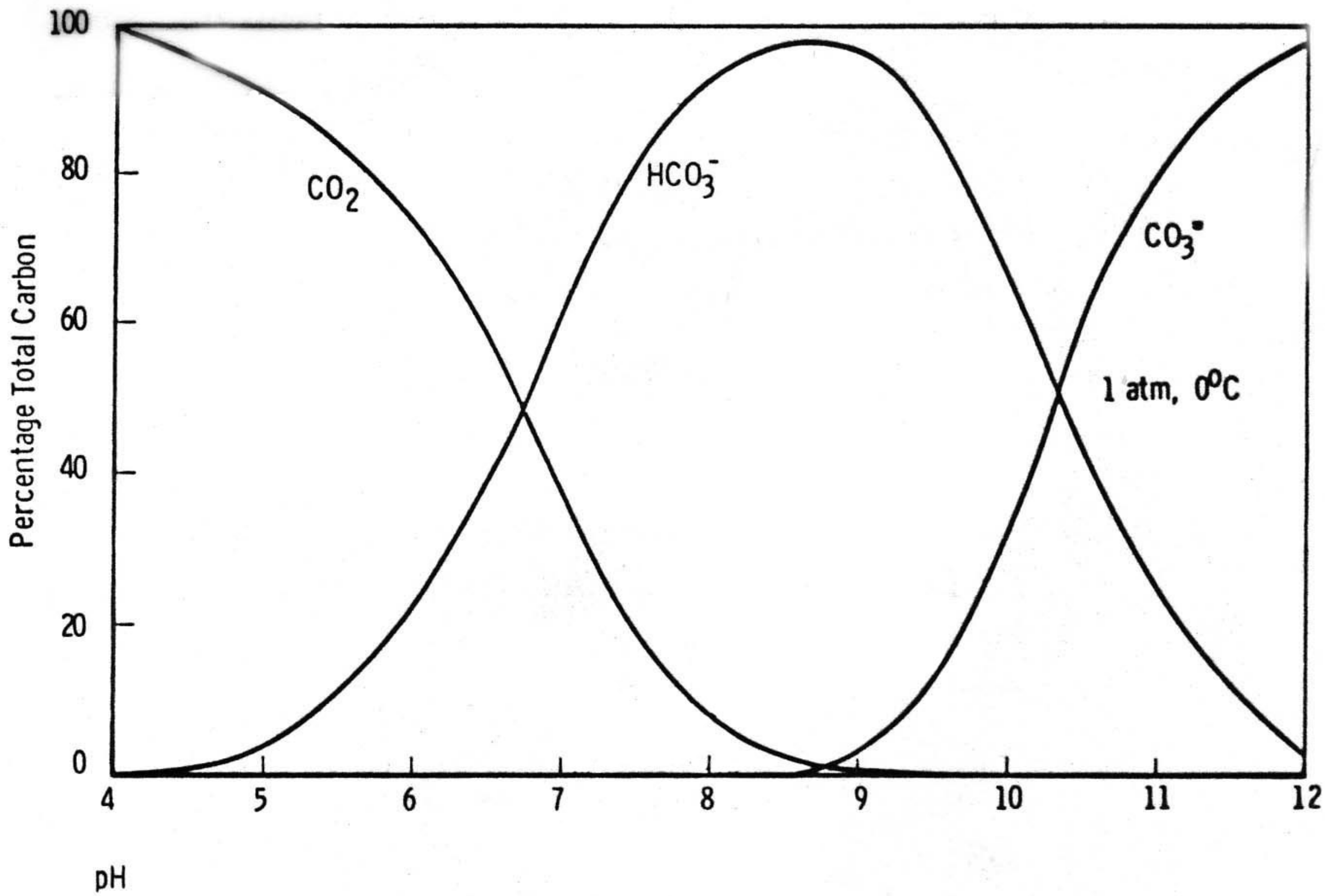


Figure 7.12 Distribution of the CO_2-HCO_3-CO_3^{2-} System in Pure Water at 1 atm, as a Function of pH.

SW curves are offset to the left by ~1 pH unit

(mostly HCO_3^- with some CO_3^{2-})

Total CO_2 (ΣCO_2)

$$\textit{Total } CO_2 = [CO_{2(aq)}] + [H_2CO_3] + [HCO_3^-] + [CO_3^{-2}]$$

- At seawater pH, >99% of CO_2 species are HCO_3^- and CO_3^{-2}, so we can simplify:

$$\textbf{\textit{Total } } \boldsymbol{CO_2 = [HCO_3^-] + [CO_3^{-2}]}$$

- This is also known as ***dissolved inorganic carbon (DIC)*** or ***total inorganic carbon (TIC)***

Vertical ΣCO_2 Profiles

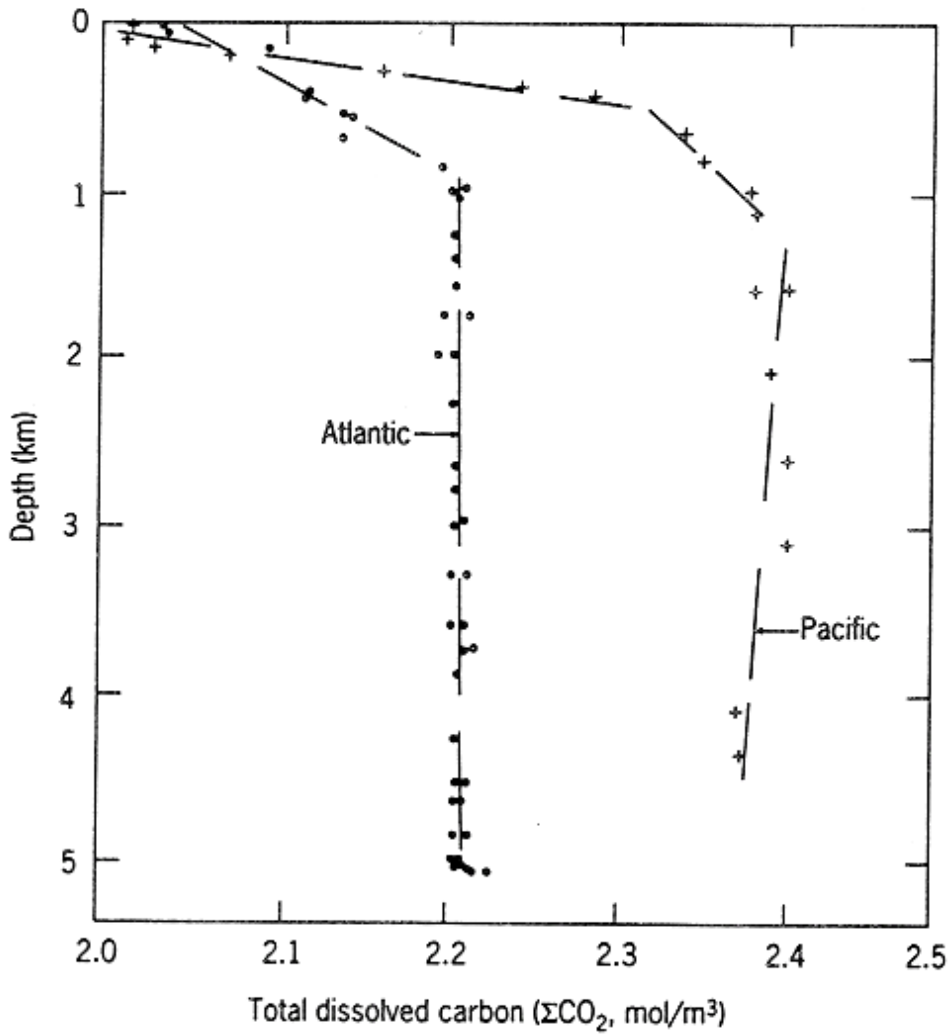


FIGURE 15.4. Variation of total dissolved inorganic carbon concentrations with depth in the Atlantic (36°N 68°W) and in the Pacific (28°N 122°W). *Source:* From *Chemical Oceanography*, W. S. Broecker, copyright © 1974 by Harcourt, Brace and Jovanovich, Publishers, Orlando, FL, p. 39. Data from Dr. R. Weiss, Scripps Institute of Oceanography, La Jolla, CA. Reprinted by permission.

Oceanic CO_2 and Biogenic Particle Production

- Surface ocean often under- or over-saturated wrt atmospheric CO_2 due to primary production and mixing
- Primary production removes atmospheric CO_2 via organic C to deep waters -- most is remineralized in water column
- Sedimentary $CaCO_3$ sink is 4x greater than organic carbon sink

Calcite Dissolution

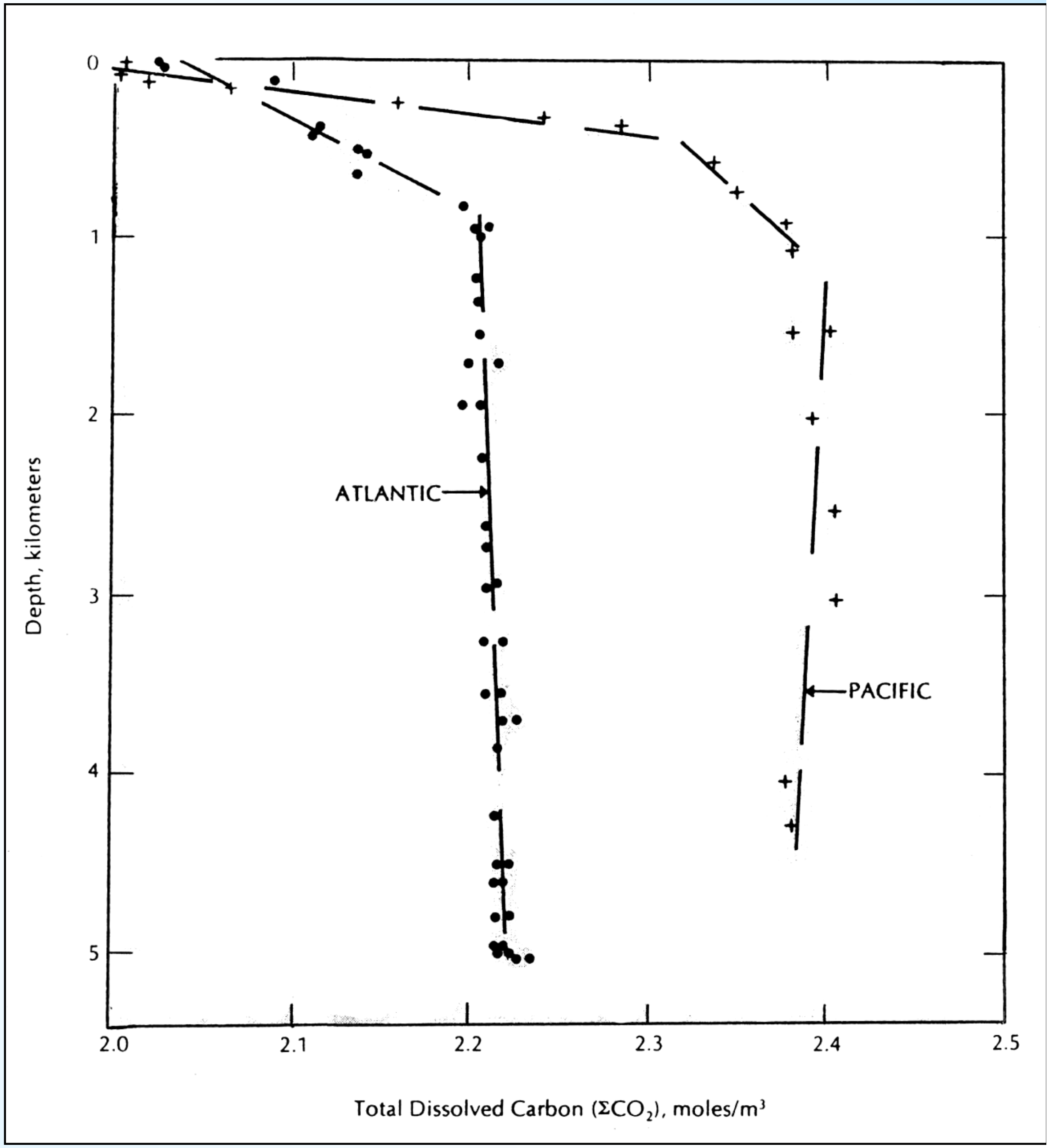
- Remineralization of organic matter in the water column produces CO_2 that reacts with CO_3^{-2}

$$CH_2O + O_2 \rightarrow CO_2 + H_2O$$

$$CO_2 + CO_3^{-2} + H_2O \rightarrow 2HCO_3^-$$

- Higher ΣCO_2 at depth
- Lower CO_3^{-2} at depth

- In the deep ocean, the decrease in $[CO_3^{-2}]$ from this reaction has a big effect on $CaCO_3$ solubility



Saturation State of SW

$$CaCO_3 \rightarrow Ca^{2+} + CO_3^{2-}$$

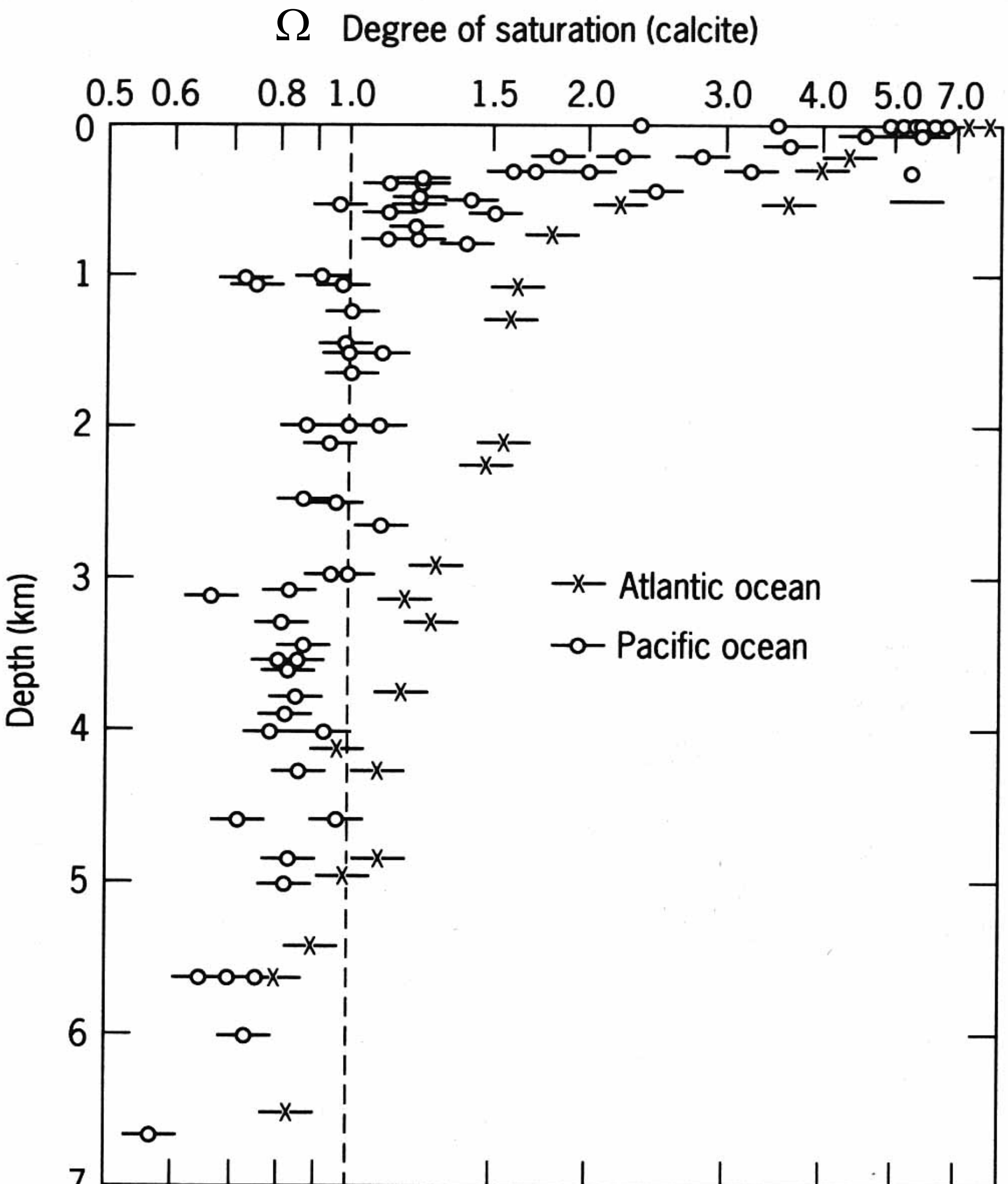
- The saturation state of SW with respect to calcium carbonate (calcite, aragonite, etc.) determines whether these phases will dissolve or not
- Define the *saturation state of SW with respect to calcite* ($CaCO_3$) as:

$$\Omega = \frac{[Ca^{2+}][CO_3^{2-}]_{\text{Seawater}}}{[Ca^{2+}][CO_3^{2-}]_{\text{Calcite-saturated seawater}}}$$

- Ca^{2+} concentrations don't vary much in the ocean
- Depth at which $\Omega = 1$ is called the ***saturation horizon***

Interpretation of Ω Values

Ω	Description	$CaCO_3$ Transformations
<1	Undersaturated	Net dissolution
1	Saturated	Equilibrium
>1	Supersaturated	Net precipitation



- The upper ocean is supersaturated wrt calcite
- Saturation horizon is shallower in Pacific than in Atlantic – because of higher ΣCO_2 and lower CO_3^{2-}

Carbonate Compensation Depth

Factors affecting CCD:

-Temperature

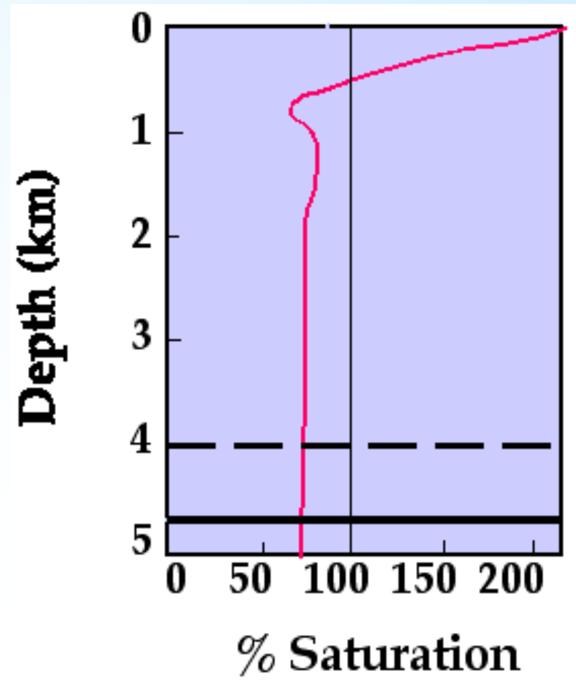
-Depth

-[CO_2]

-pH

-Carbonate supply

-Terrigenous supply



Depth of the lysocline (dotted line) and the CCD (solid line) in the Equatorial Pacific, along with amount of water column carbonate saturation

The Shallower CCD in the Pacific Has a Dramatic Effect on Sediment Distribution….

TABLE 29.4.

*Relative areas of World Ocean covered by pelagic sediments (in percent)**

	Atlantic	Pacific	Indian	Total extent
Foram ooze	65·1	36·2	54·3	47·1
Pteropod ooze	2·4	0·14	—	0·6
Diatom ooze	6·7	10·1	19·9	11·6
Radiolarian ooze	—	4·6	0·5	2·6
Oxypelite ("red clay")	25·8	49·1	25·3	38·1
Relative size of ocean (%)	23·0	53·4	23·6	100·0

* Data from Sverdrup *et al.* (1942). Pacific pteropod ooze area from Bezrukov (1970). Area of deep sea floor = 268·1 × 10^6 km^2.

Berger, 1976

Effects on Sediment

- ***Saturation Horizon*** is where "Ω" = 1
- ***Lysocline*** is where dissolution effects first appear in carbonate grains
  - Since degree of saturation decreases with depth, dissolution rates should increase with depth
- ***Carbonate Compensation Depth (CCD)*** is where the deposition rate of carbonate is equal to the dissolution rate (*i.e.*, no net accumulation of carbonates on the seafloor)

Kinetic Considerations

- $CaCO_3$ should not be preserved in sediments below the saturation horizon
- Yet, calcareous shells do persist… Why?
- Main factors: slow dissolution rates relative to rates of sinking (in water) and burial (in sediment)
  - Likelihood of dissolution of a shell depends on factors that control sinking rate and dissolution rate
  - Both influenced by the size, density and shape of a shell
- Dissolution is also controlled by organic coatings and effects of trace ions on shell surfaces

$CaCO_3$ Precipitation

A tricky subject when discussing "CO_2"
(or, more properly, p_{CO2})

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$$

Does this reduce the CO_2 (p_{CO2}) level of the seawater?

No! Lost CO_3^{2-} will be replaced:

$$HCO_3^- \rightarrow CO_3^{2-} + H^+$$

But this H^+ release causes:

$$HCO_3^- + H^+ \rightarrow CO_2 + H_2O$$

$CO_{2(g)} \leftrightarrow CO_{2(aq)}$
$CO_{2(aq)} + H_2O \leftrightarrow HCO_3^- + H^+$
$HCO_3^- \leftrightarrow CO_3^{-2} + H^+$

Thus, $CaCO_3$ precipitation causes a decrease in Total CO_2, but an <u>increase</u> in p_{CO2}

Hint: when pH is between 7.5 and 8.5:
$CO_{2(aq)} + CO_3^{-2} + H_2O \leftrightarrow 2HCO_3^-$

….Which is Reflected in the Distribution of the Principal Types of Sediment on the Seafloor

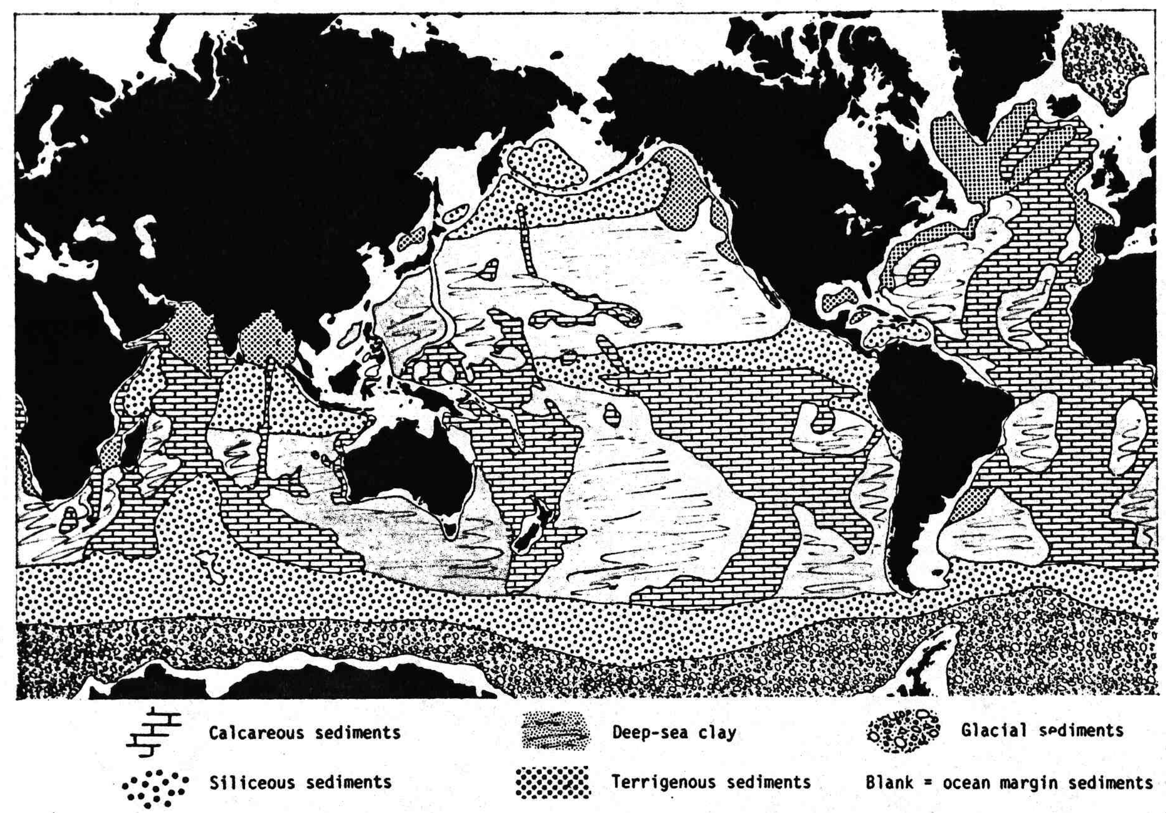
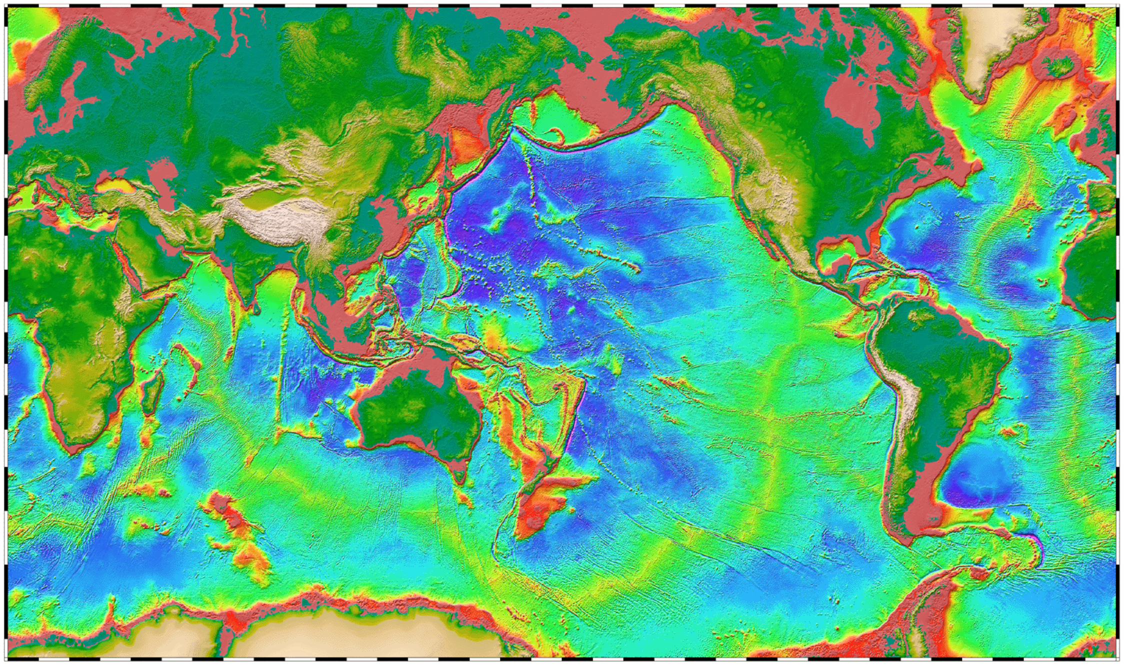


FIG. 24.7. Distribution of the principal types of sediment on the floors of the oceans. (Based on data from many sources.)



Comparison of Silica *vs.* Calcite Dissolution in the Ocean

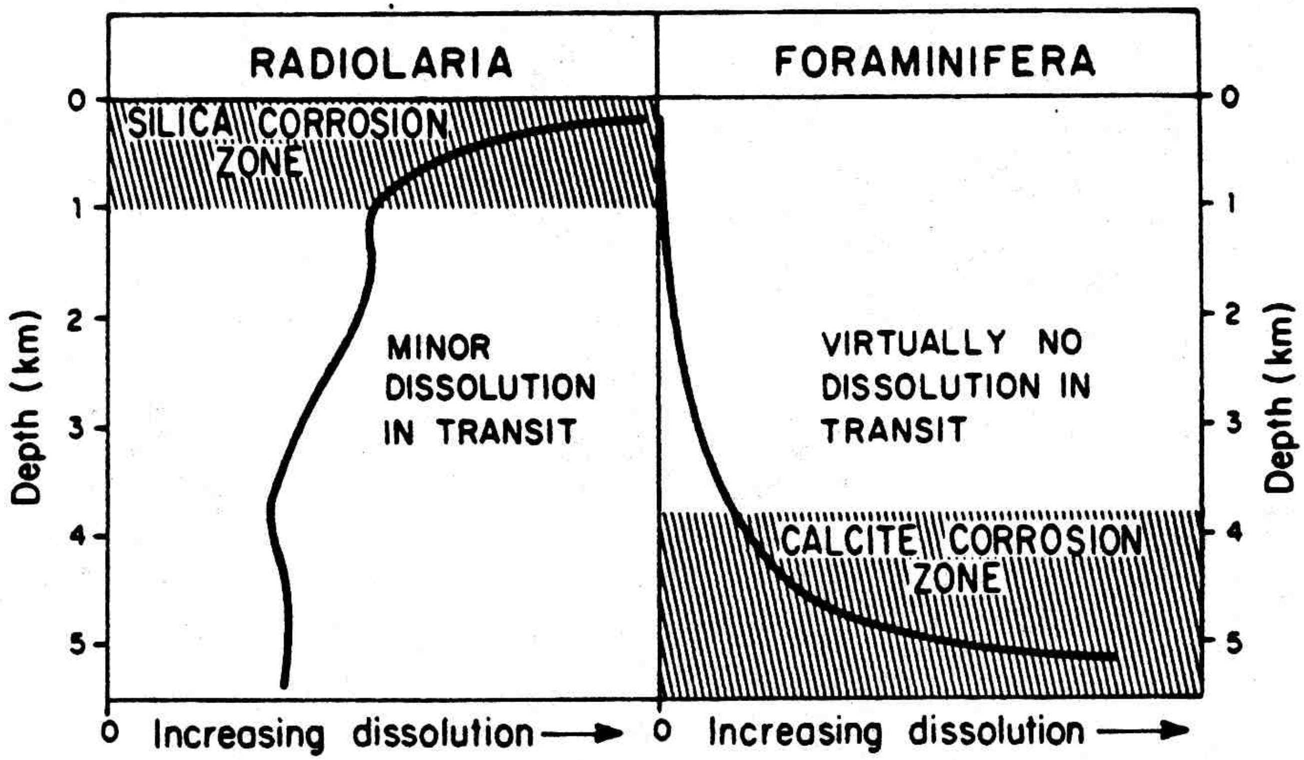


FIG. 29.17. Corrosion zones for siliceous and calcareous particles, based on field experiments in the North Pacific near 19° N, 169° W (Berger, 1967, 1968b). Boundaries have been drawn at depth of maximum rate change, they are not the same as facies boundaries in the ocean.

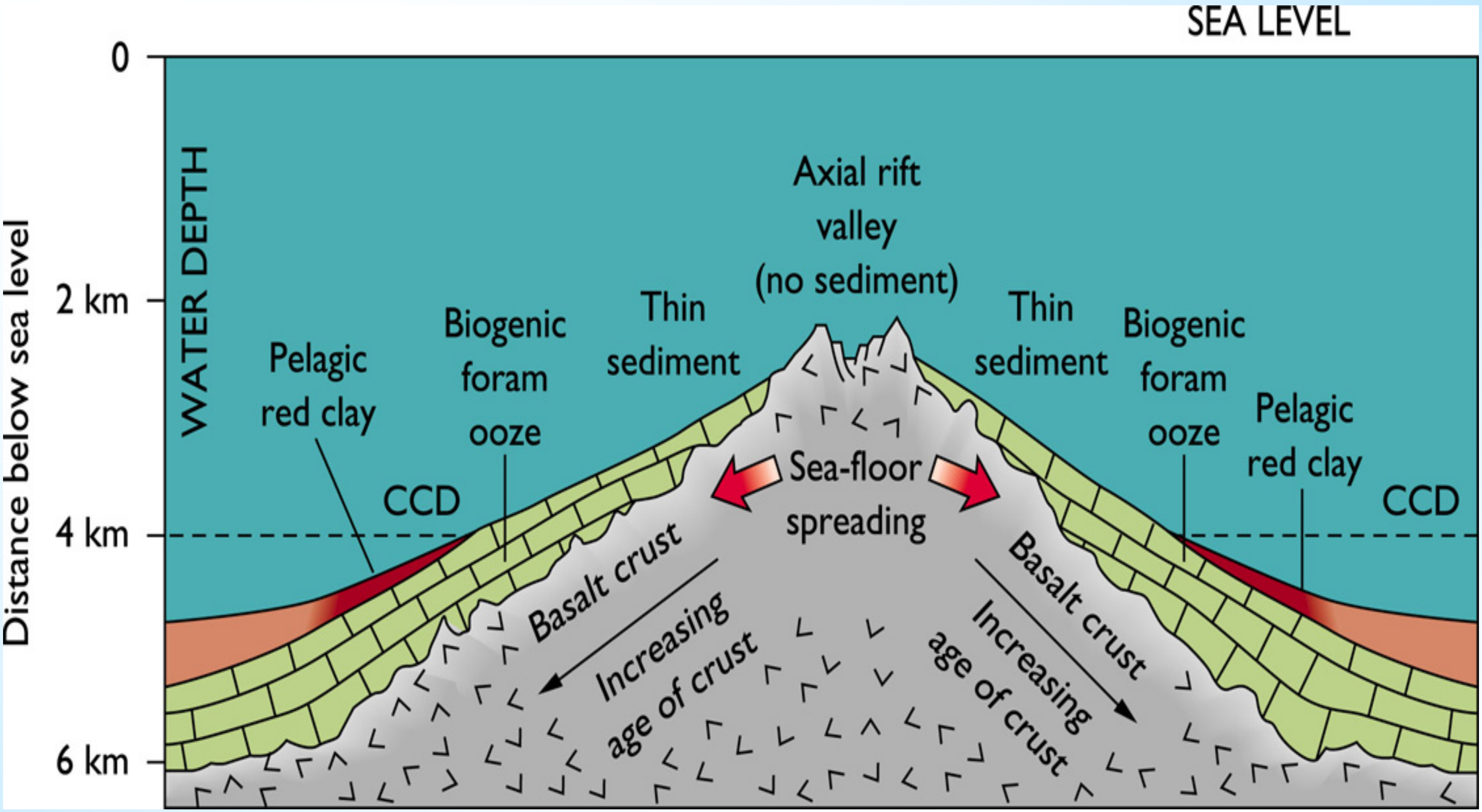
Berger, 1976

Calcite = $CaCO_3$

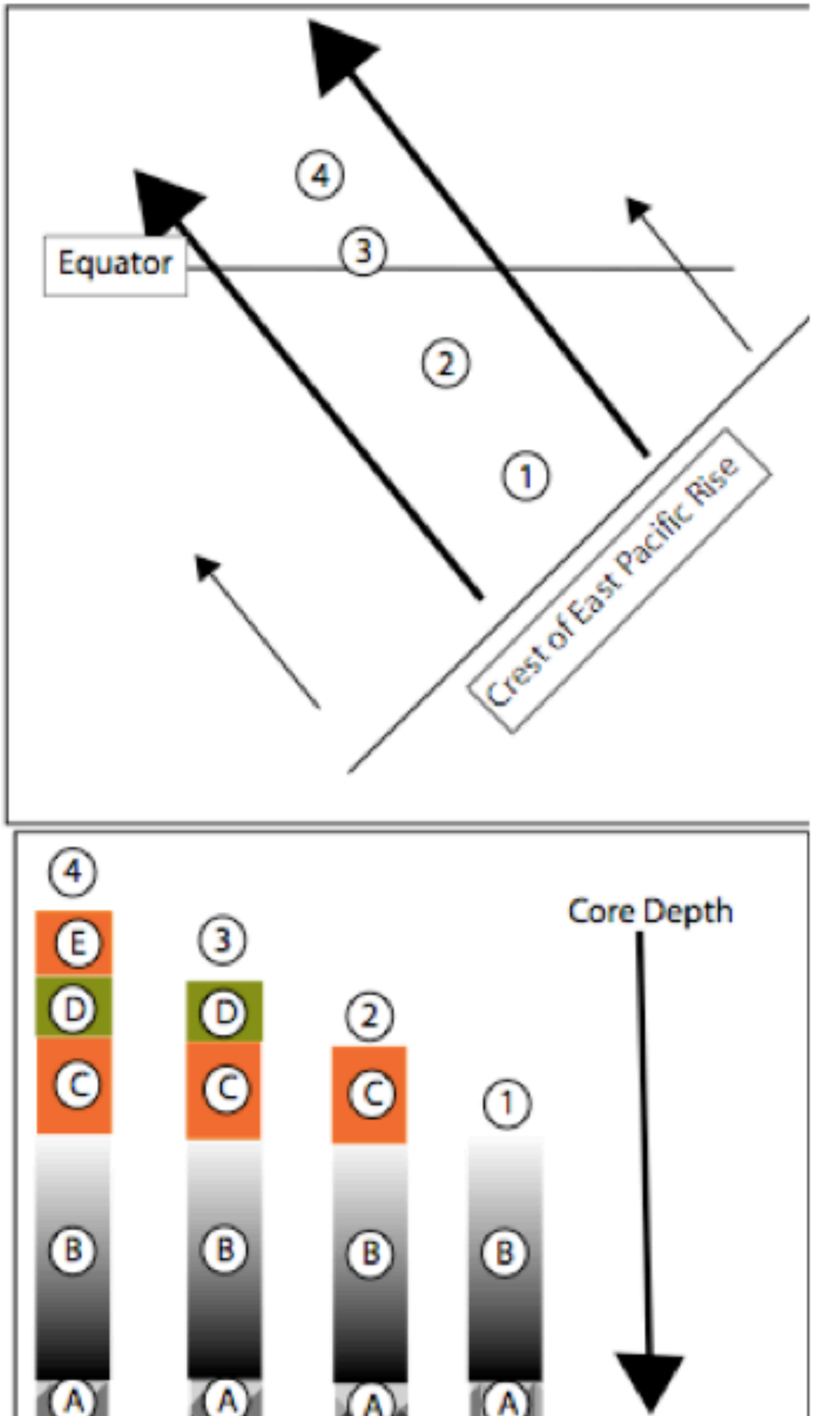
To recap some definitions…

- ***Saturation Horizon*** is where "Ω" = 1
- ***Lysocline*** is where dissolution effects first appear in carbonate grains
  - Since degree of saturation decreases with depth, dissolution rates should increase with depth… (Libes has this wrong)
- ***Carbonate Compensation Depth (CCD)*** is where the depositional rate of carbonate is equal to the dissolution rate (i.e., no net accumulation)
- The lysocline occurs above the CCD, but is at or below the saturation horizon because of
  - Kinetic effects
  - Protection by organic matter on particulates
  - Inhibitory effect of dissolved species like phosphate which have mid-depth maxima

Sediment Distributions are Related to Mid-Ocean Spreading



Compare with figures: "Sediment Deposition Rates"
"Deep-Sea Sediment Distribution"



Note: 'core depth' does not equal 'water depth'.

Distribution Summary of the Principal Types of Sediment on the Seafloor

Thick terrigenous layers in aprons around continents;

Biogenic in equatorial band & along western continental boundaries…WHY?

Authigenic and eolian sediments across vast areas of deep ocean floor covered by sediments of ~100s meters

Volcanic tephra within 1000km of islands arcs and volcanic belts

Thin sediment at active spreading centers

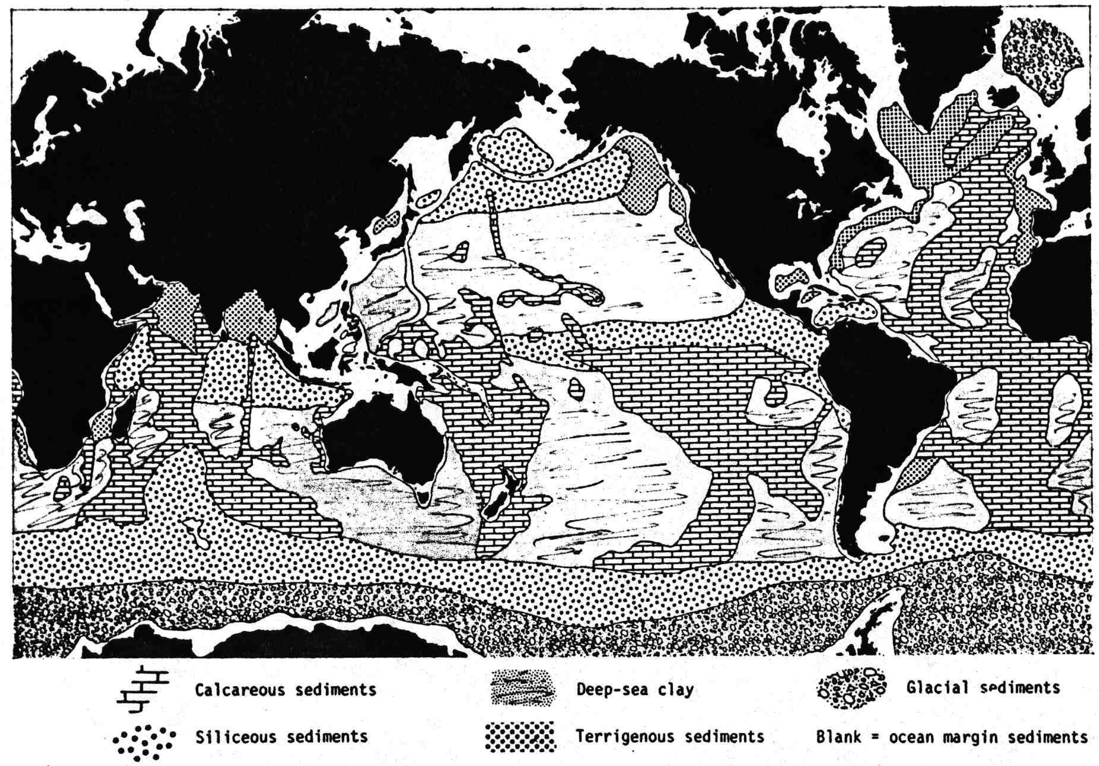


FIG. 24.7. Distribution of the principal types of sediment on the floors of the oceans. (Based on data from many sources.)

Davis & Gorsline, 1976