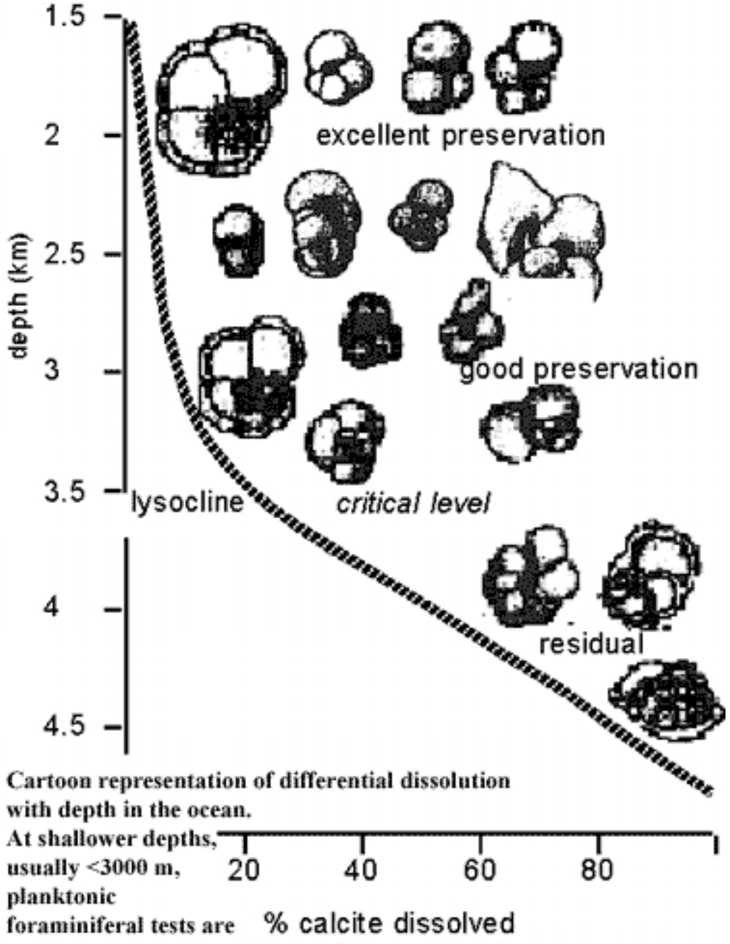
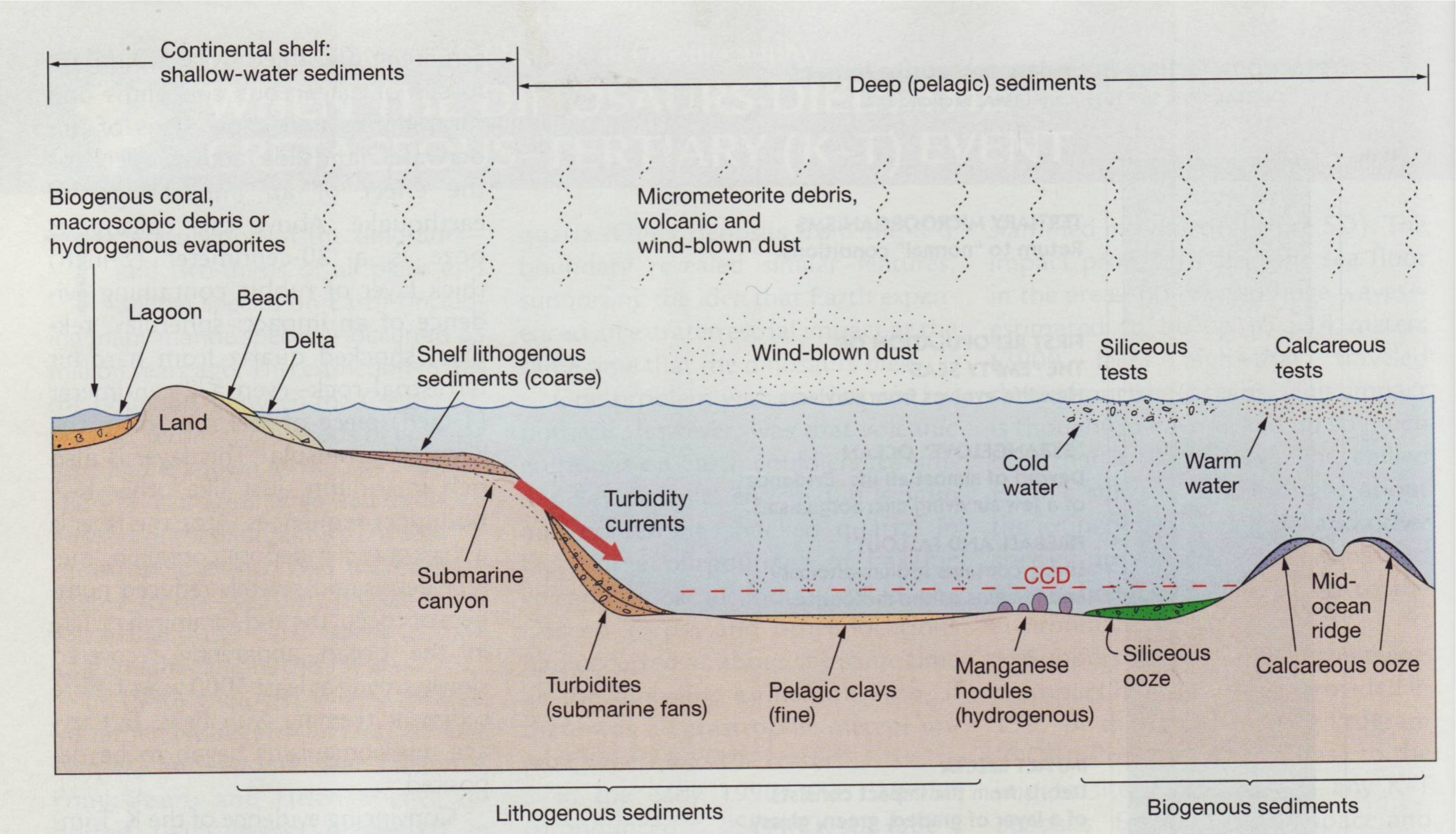
# Oceanic Sediments

# CCD

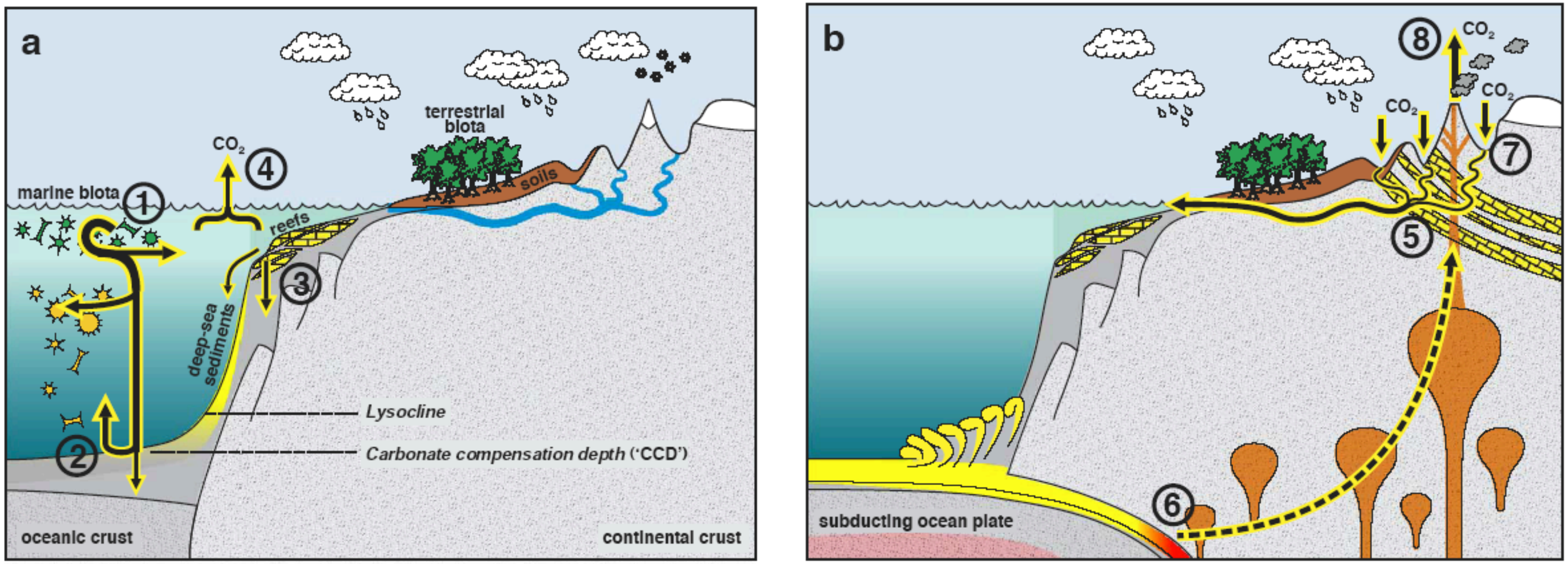
- Cold pressurized water can hold more $CO_2$ in solution than warm water.
- Consequently, deep ocean water has more $CO_2$ in solution.
- This recombines to form carbonic acid.
- Hence, below a certain depth (typically around 3.5 km.) carbonates dissolve.
- If you find calcite in deep ocean sediments, you know that they were deposited above the CCD.



Cartoon representation of differential dissolution with depth in the ocean. At shallower depths, usually <3000 m, planktonic foraminiferal tests are well preserved in the sediment. Below the lysocline, preservation rapidly deteriorates with depth. Below the CCD, tests are not preserved.

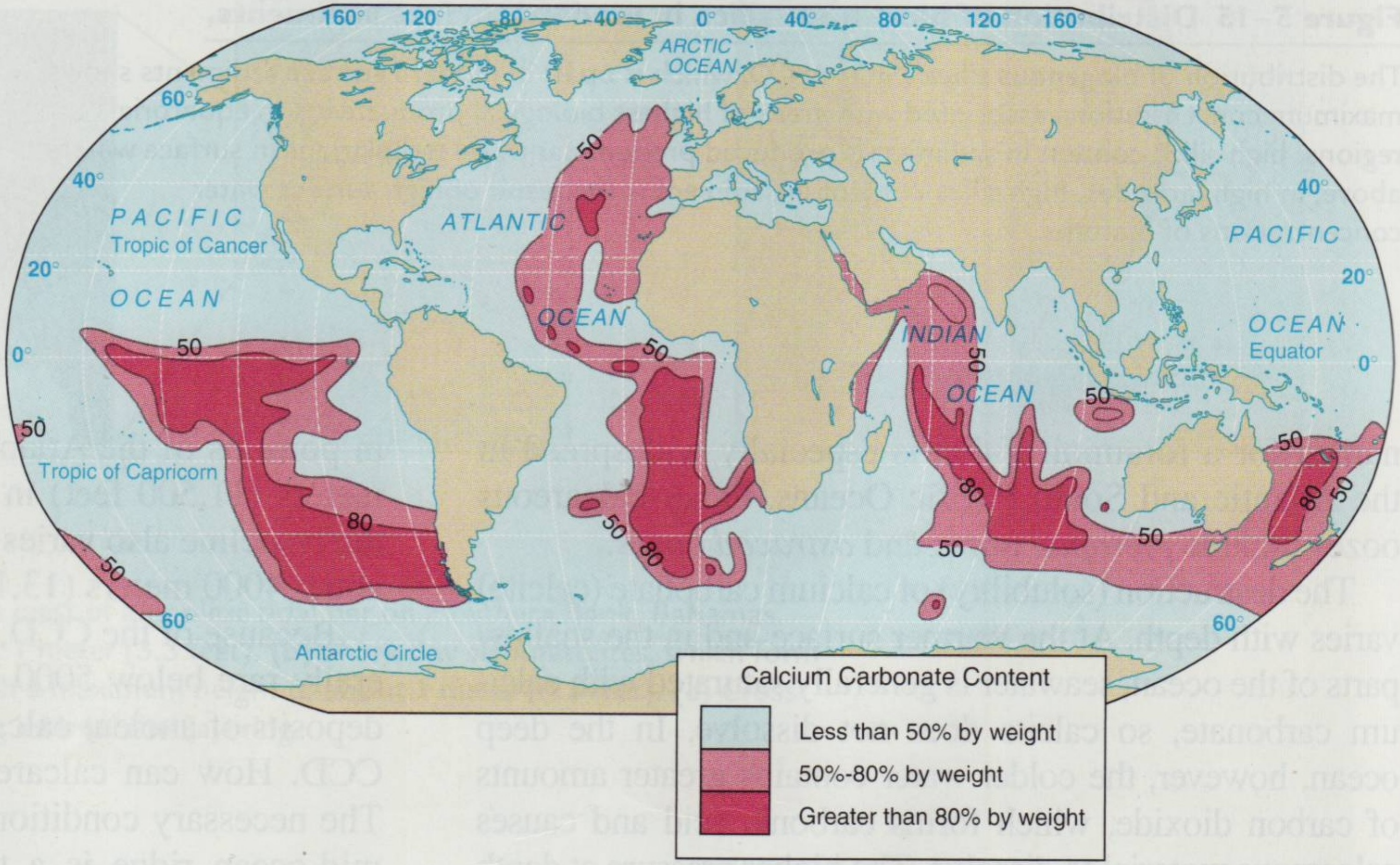

Continental shelf:
shallow-water sediments
Deep (pelagic) sediments
Biogenous coral,
macroscopic debris or
hydrogenous evaporites
Micrometeorite debris,
volcanic and
wind-blown dust
Lagoon
Beach
Delta
Shelf lithogenous
sediments (coarse)
Wind-blown dust
Siliceous
tests
Calcareous
tests
Land
Cold
water
Warm
water
Turbidity
currents
Submarine
canyon
CCD
Mid-
ocean
ridge
Turbidites
(submarine fans)
Pelagic clays
(fine)
Manganese
nodules
(hydrogenous)
Siliceous
ooze
Calcareous ooze
Lithogenous sediments
Biogenous sediments

# Global cycling of calcium carbonate

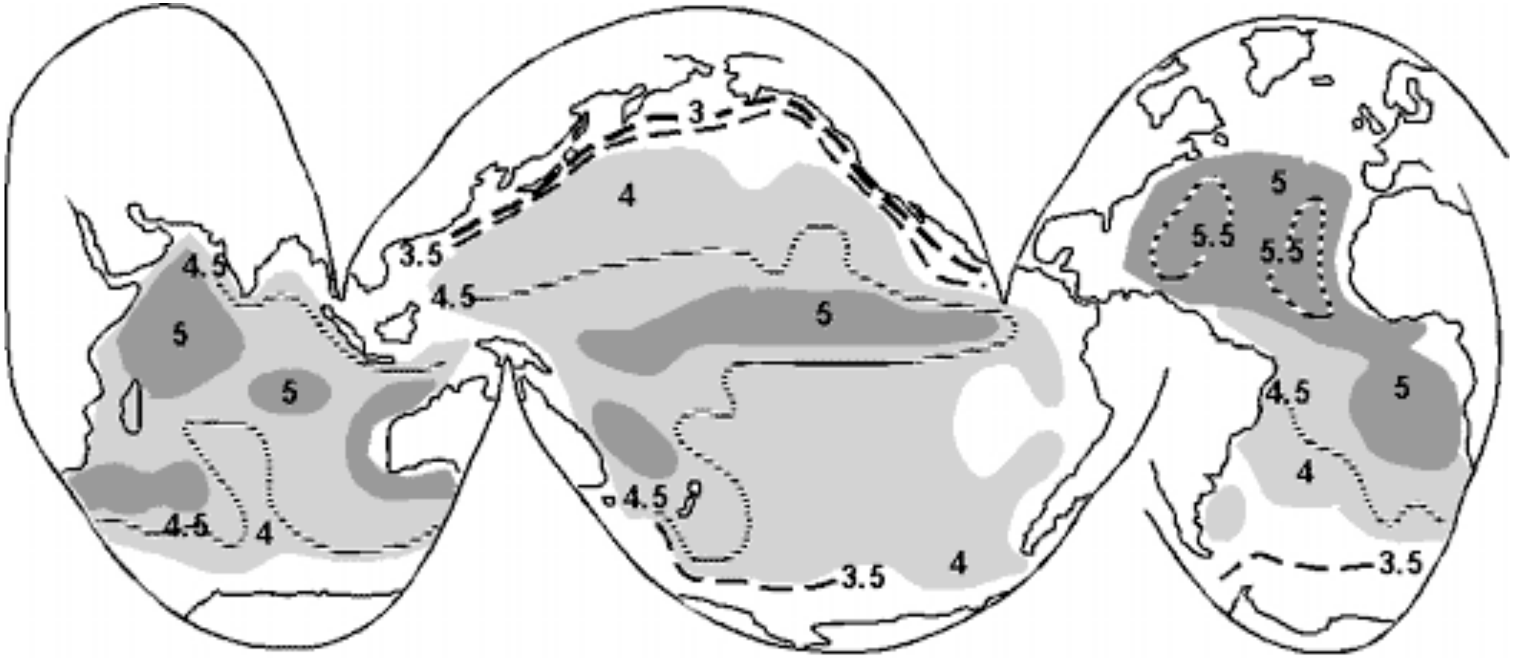


From Ridgewell and Zeebe (2005)

# Calcium carbonate distribution



# Topography of the CCD

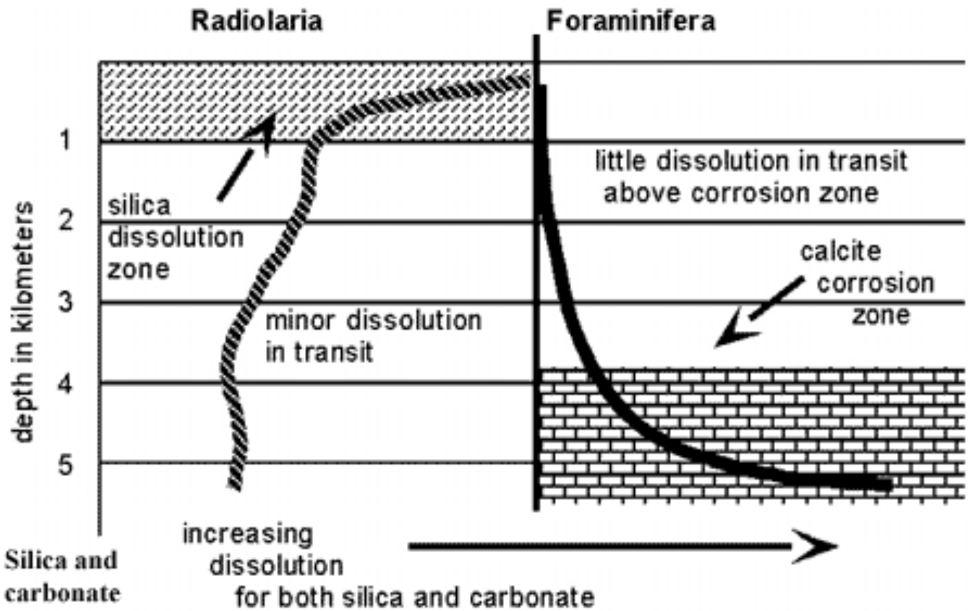


Topography of the calcium carbonate compensation depth (CCD), i.e., the depth in kilometers below which little or no CaCO3 accumulates

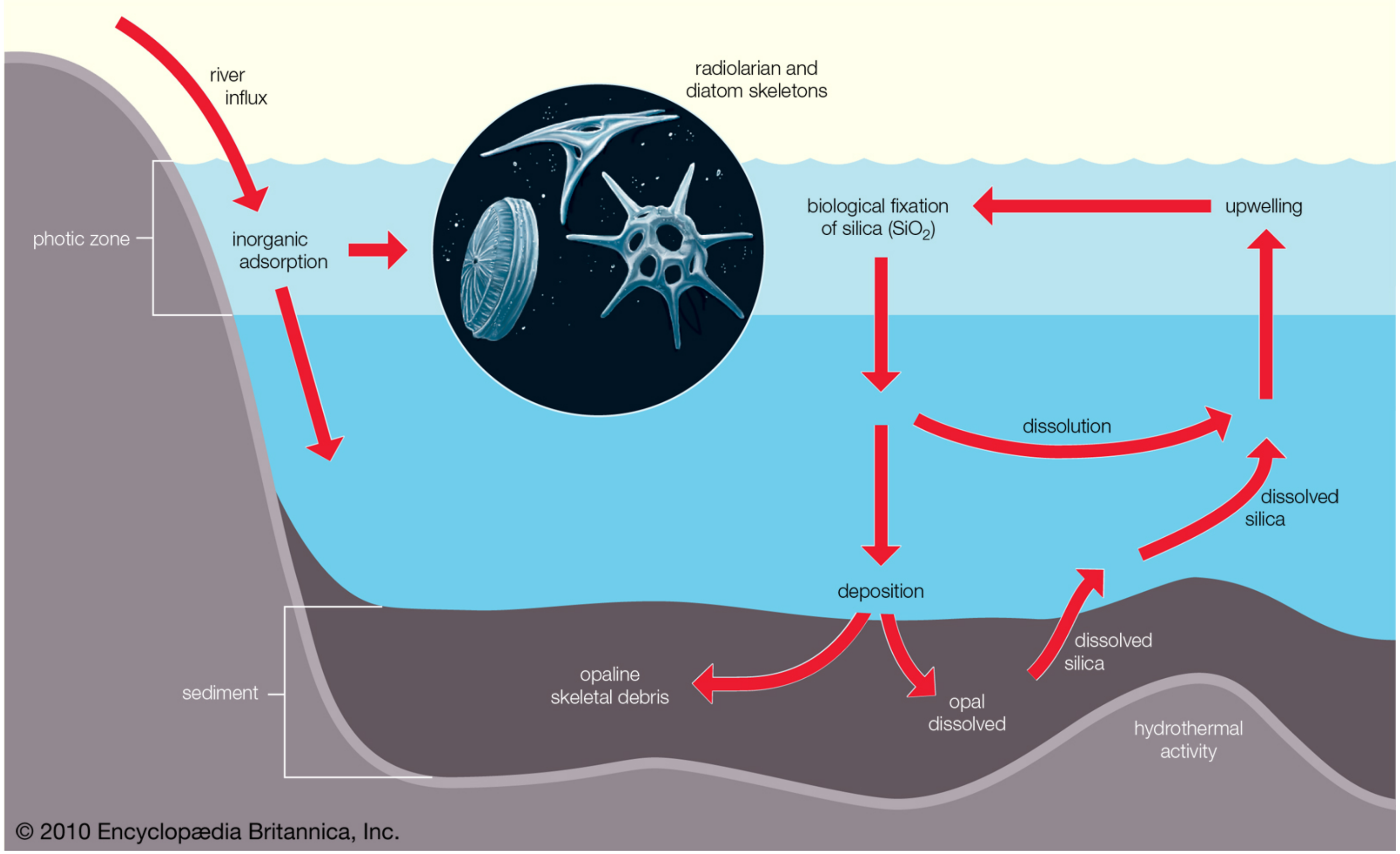
- High production of carbonate means lower/deeper CCD
- Low production of carbonate means higher/shallower CCD
- Deep sea sediments associated with equatorial upwelling will still contain biogenic carbonate and silica compared to other regions

# Silica

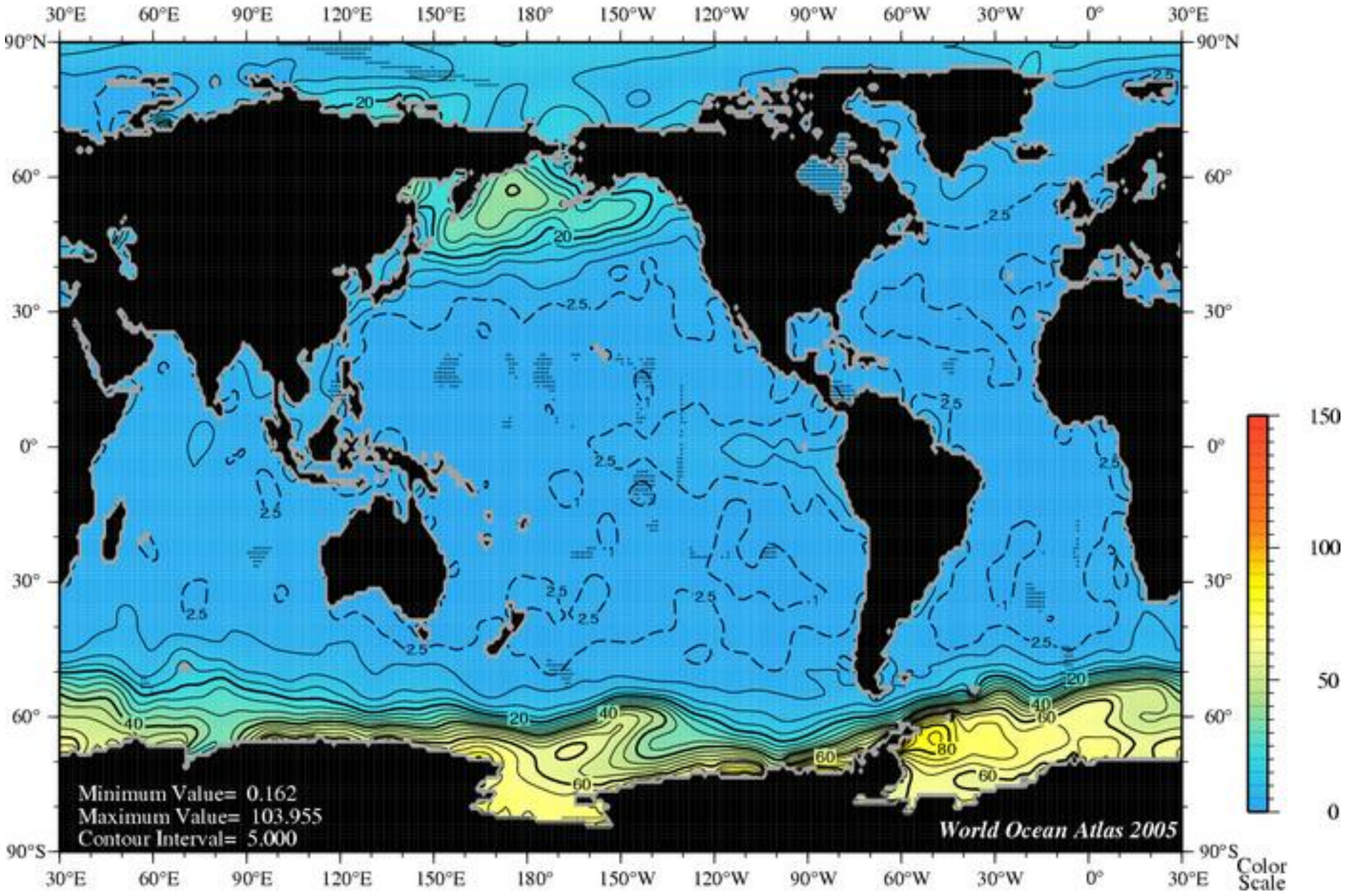
- Diatoms, radiolarians, silicoflagellates, sponges
- Most oceans undersaturated wrt silica (esp. surface water)
- Higher concentrations in old deep seawater, volcanic islands and island arcs
- Silica solubility increases with decreasing P and increasing T
- Preservation enhanced by rapid burial
- Some ooze will dissolve and reprecipitate as chert



Silica and carbonate solubility curves in sea water. In contrast to the increasing solubility of carbonate with temperature decrease and pressure increase (increasing depth) silica solubility decreases with depth.

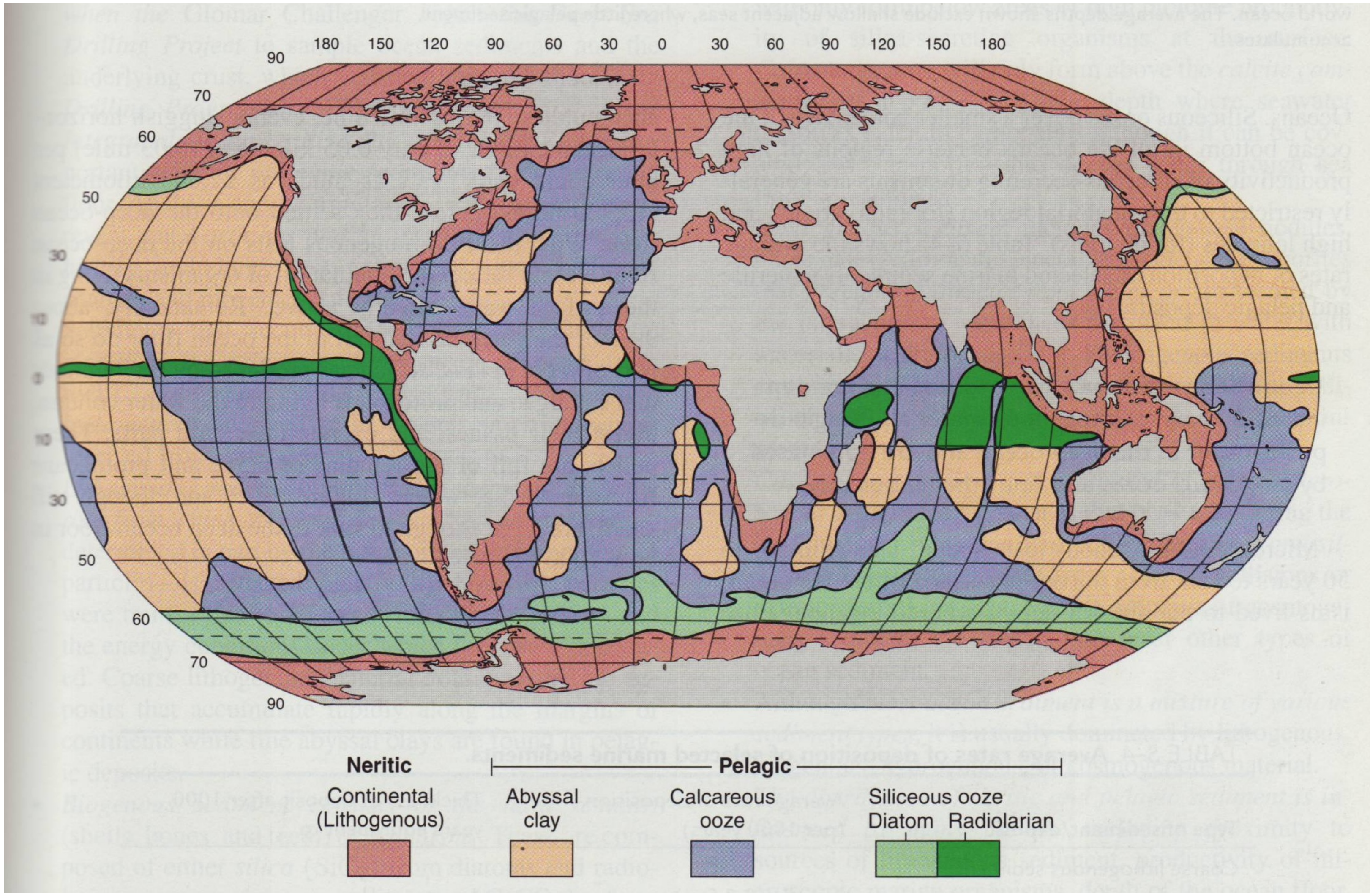
river influx
radiolarian and diatom skeletons
photic zone
inorganic adsorption
biological fixation of silica ($SiO_2$)
upwelling
dissolution
dissolved silica
deposition
sediment
opaline skeletal debris
opal dissolved
dissolved silica
hydrothermal activity

# Silica distribution – ocean surface



Annual silicate [umol/l] at the surface.

# Silica Distribution



# Siliceous ooze

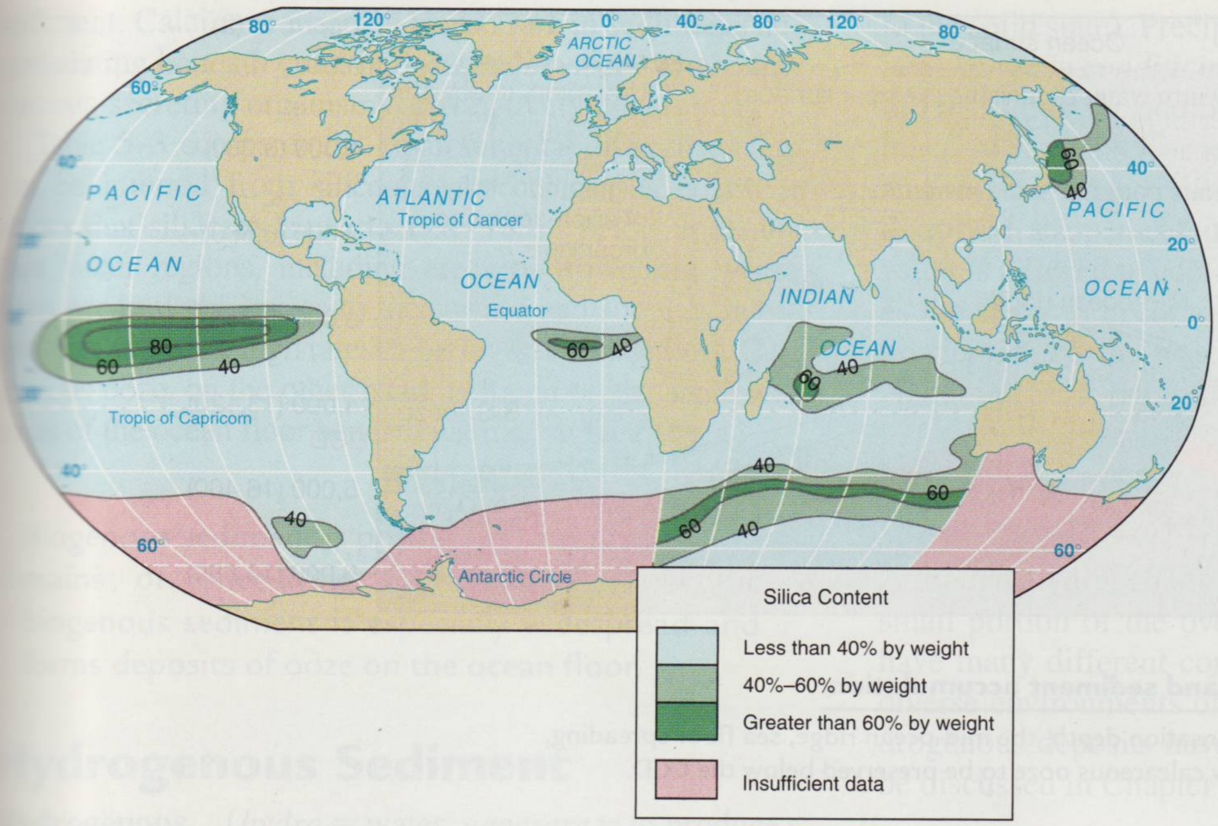
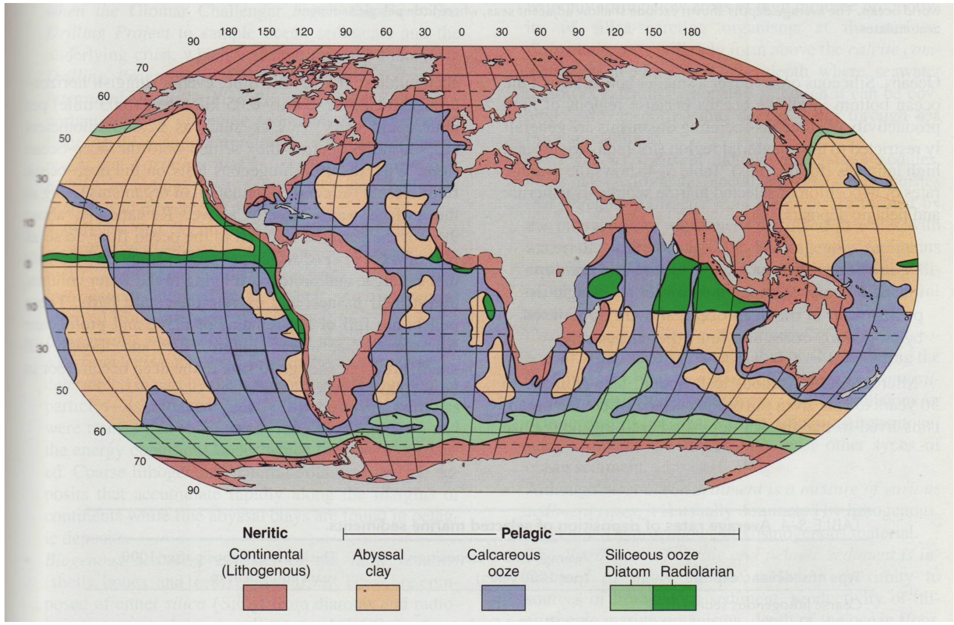


**Figure 5–15 Distribution of biogenous silica in modern surface sediments.**

The distribution of biogenous silica ($SiO_2 \cdot nH_2O$, which is opal) in modern surface sediments shows maximum concentrations associated with areas of highest biological productivity. In equatorial regions, high silica content in sediment is produced predominantly by radiolarians in surface waters above; in high latitudes, high silica content in sediment is the result of high surface water concentrations of diatoms.

# High concentrations of opaline silica

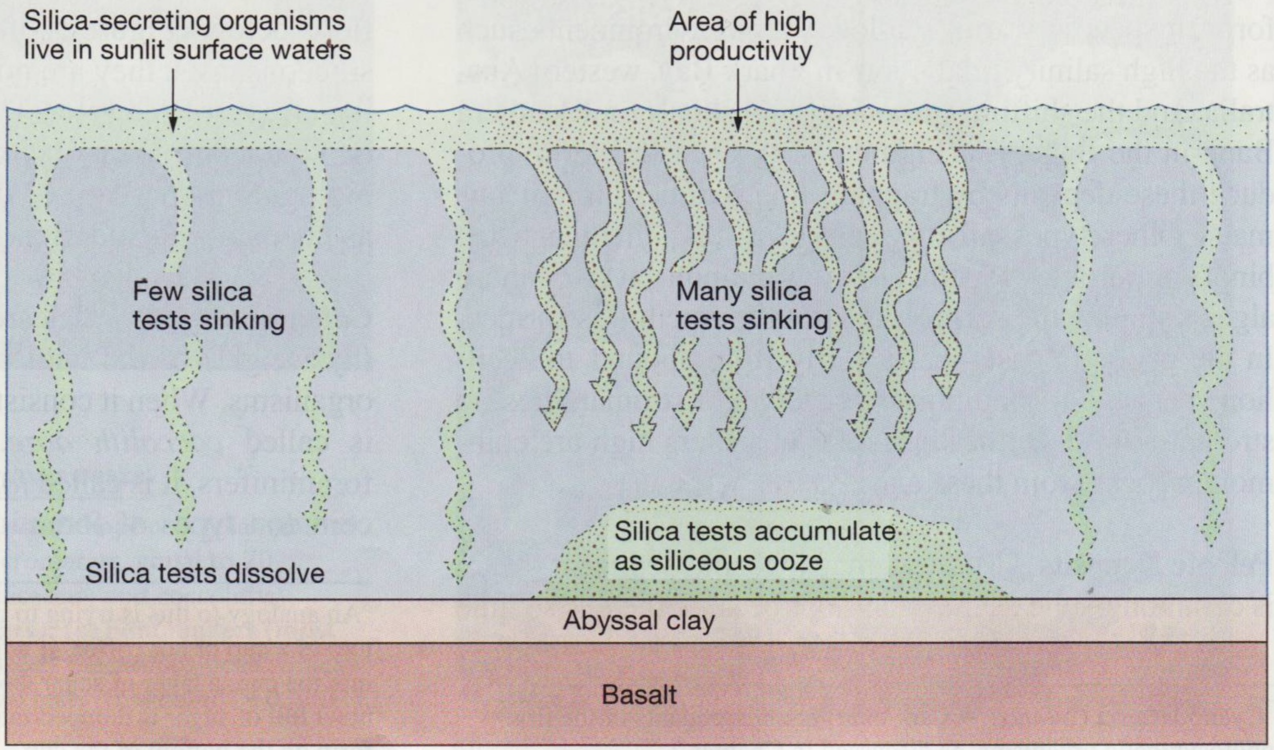
- High primary productivity (e.g., upwelling)
- Low terrigeneous input (dilution effect)
- Low carbonate production
- And/or high CCD and lysocline



# Silica ooze accumulation

**Figure 5–14** **Accumulation of siliceous ooze.**

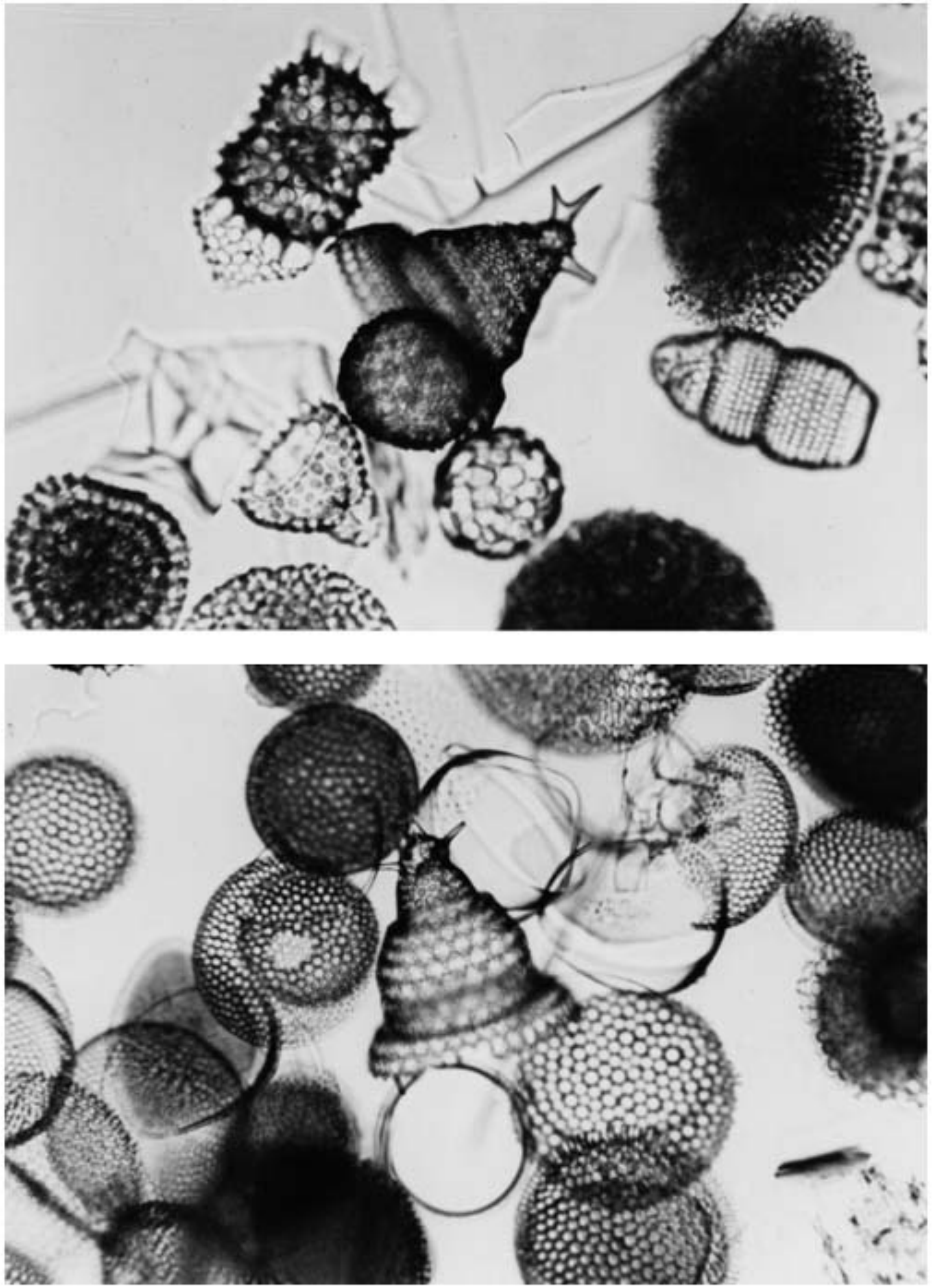
Siliceous ooze accumulates on the ocean floor beneath areas of high productivity, where the rate of accumulation of siliceous tests is greater than the rate at which silica is being dissolved.



# Chert

Some microorganisms secrete *silica* shells.

When these pile up on the deep ocean floor, they lithify to become a micro-crystalline quartz rock called *chert* (the same stuff as the substance flint).



diatoms and radiolaria

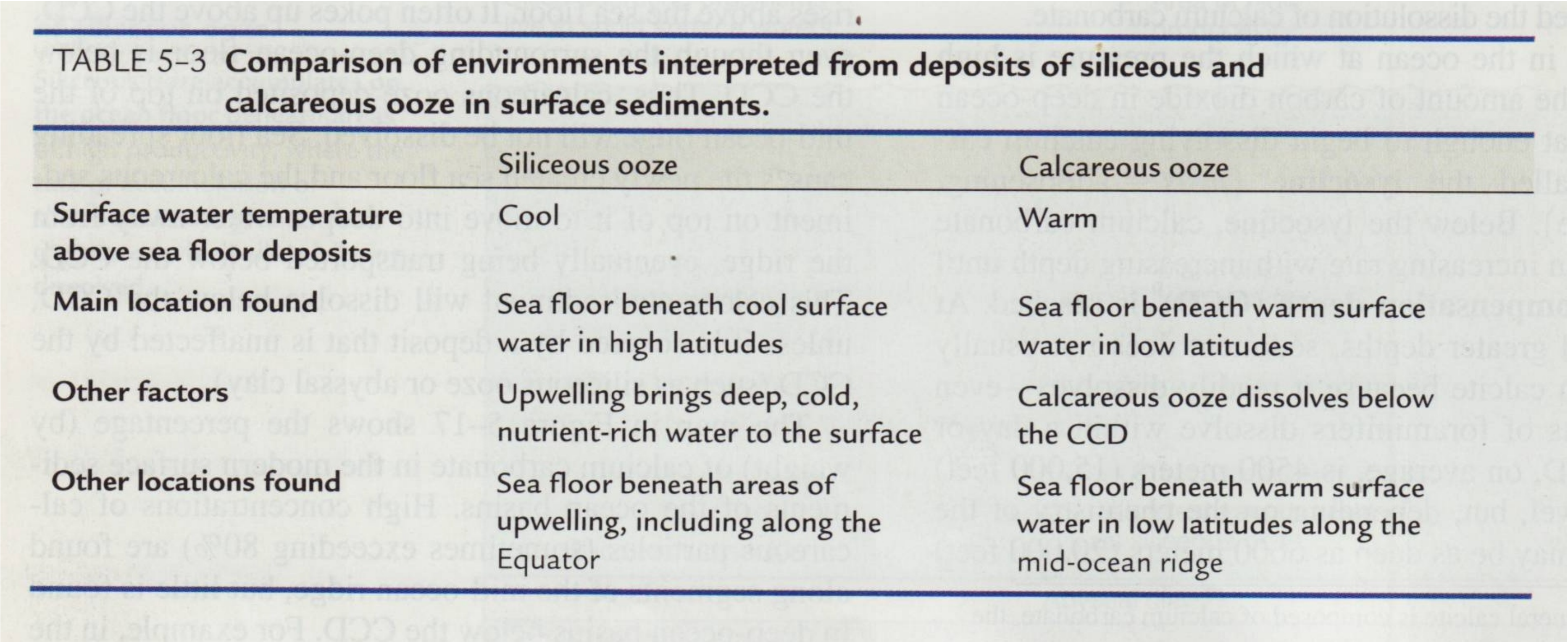
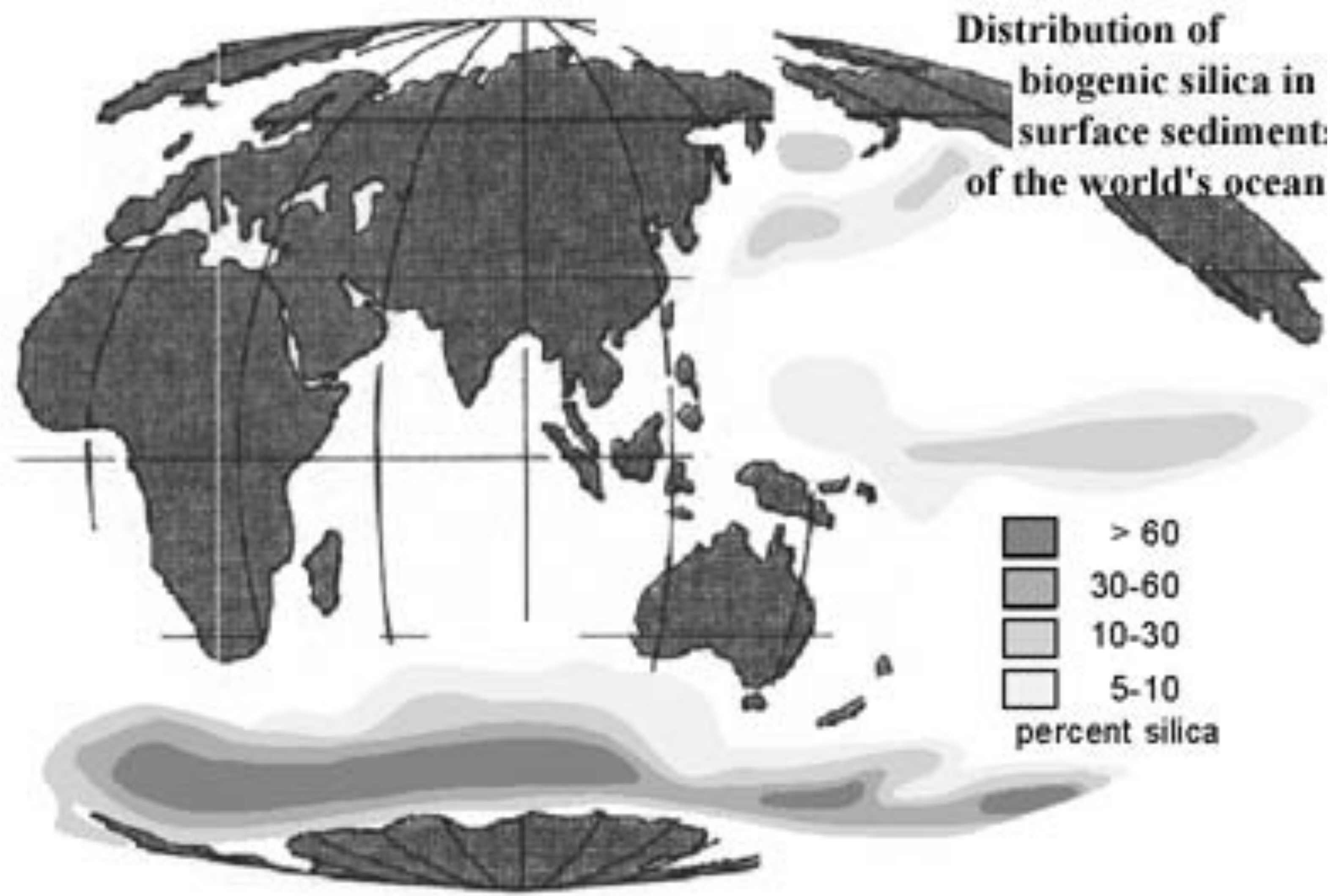


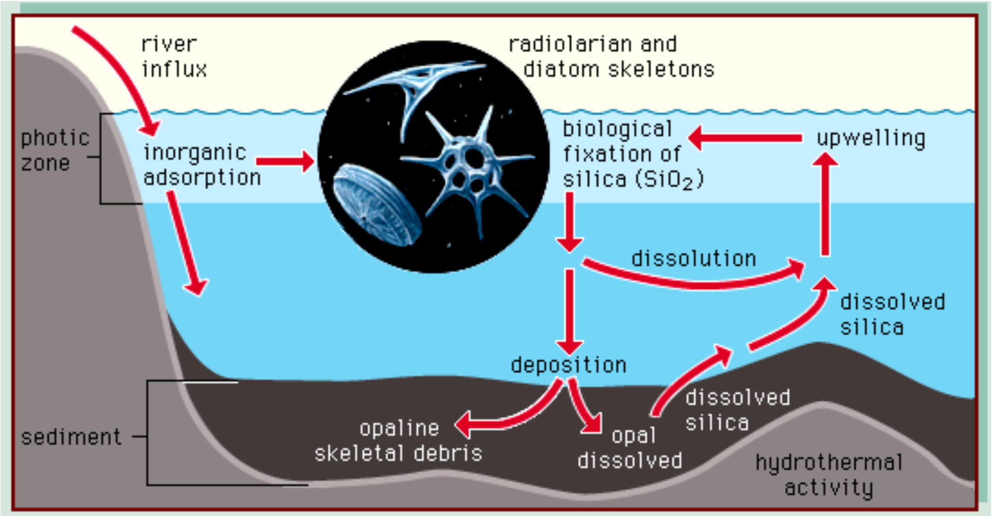
TABLE 5–3 **Comparison of environments interpreted from deposits of siliceous and calcareous ooze in surface sediments.**

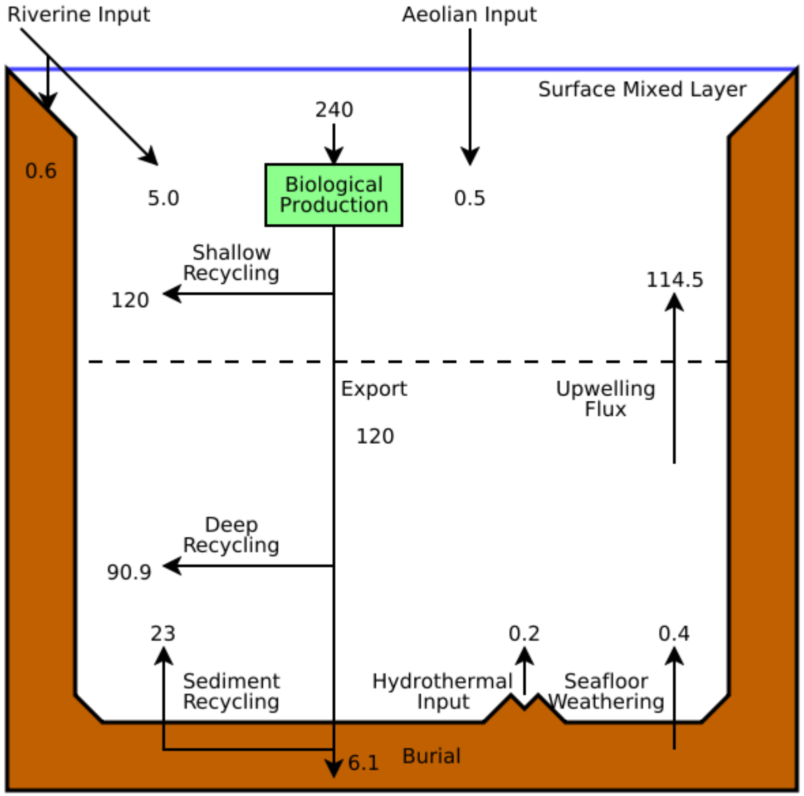
| | Siliceous ooze | Calcareous ooze |
|---|---|---|
| **Surface water temperature above sea floor deposits** | Cool | Warm |
| **Main location found** | Sea floor beneath cool surface water in high latitudes | Sea floor beneath warm surface water in low latitudes |
| **Other factors** | Upwelling brings deep, cold, nutrient-rich water to the surface | Calcareous ooze dissolves below the CCD |
| **Other locations found** | Sea floor beneath areas of upwelling, including along the Equator | Sea floor beneath warm surface water in low latitudes along the mid-ocean ridge |



Distribution of biogenic silica in surface sediments of the world's ocean

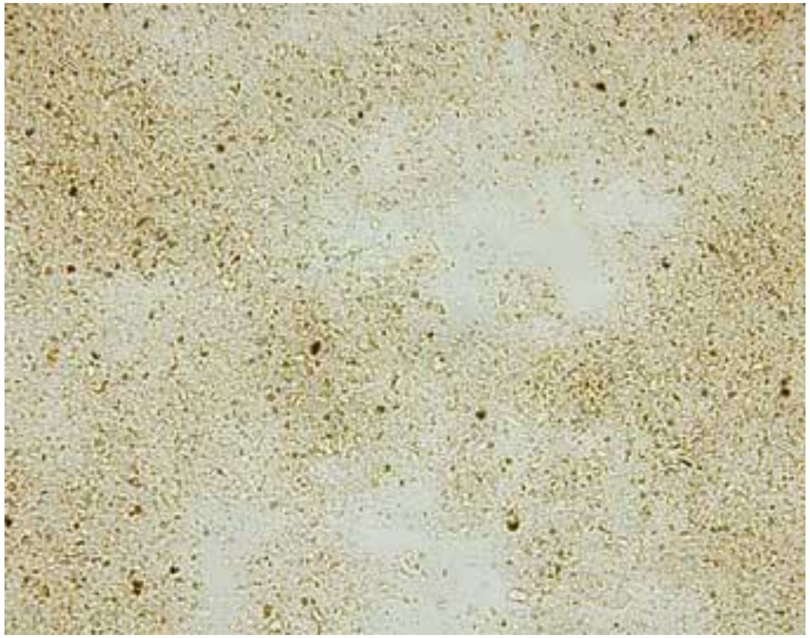
# Ocean Silica Budget



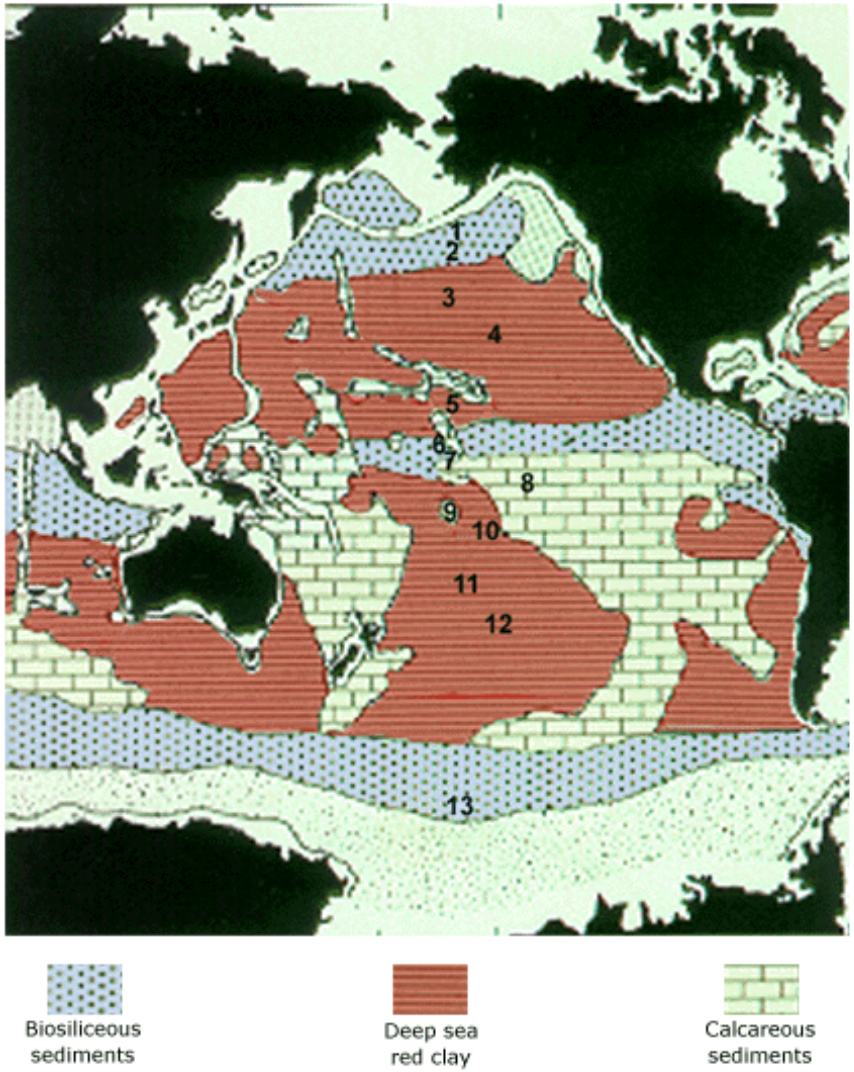


The modern ocean's silicon cycle budget,
fluxes in Tmol Si y-1. Adapted from Treguer et al. (1995).

# Deep Sea Red Clay (central ocean basins)



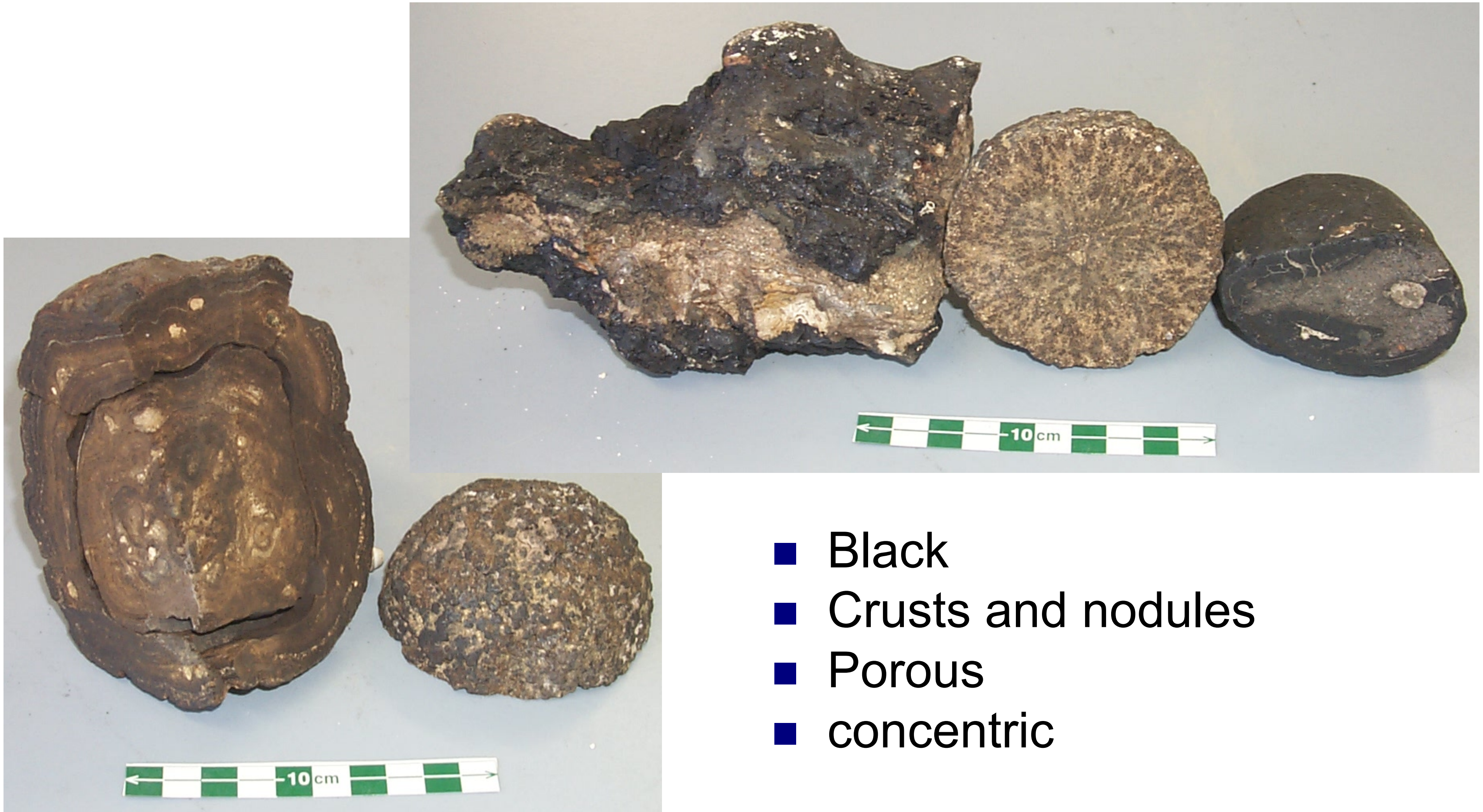
- Planktonic productivity low
- CCD tends to rise
- Little terrigenous input
- Water well oxygenated
- Unique to deep ocean (> 4 km depth)
- <1-2 mm/1,000 years



**From: http://www.flickr.com/photos/bringingfriendstogether/3945480461/**

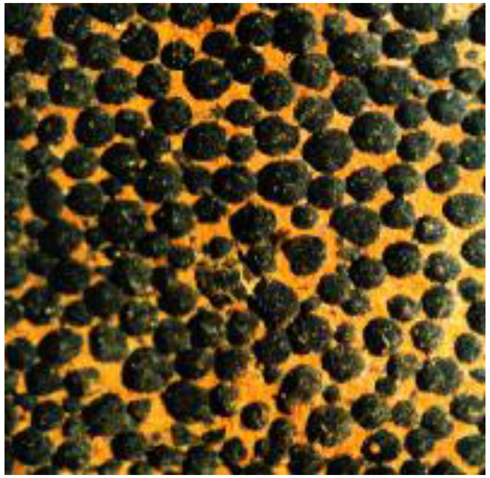
# (Ferro)Manganese nodules

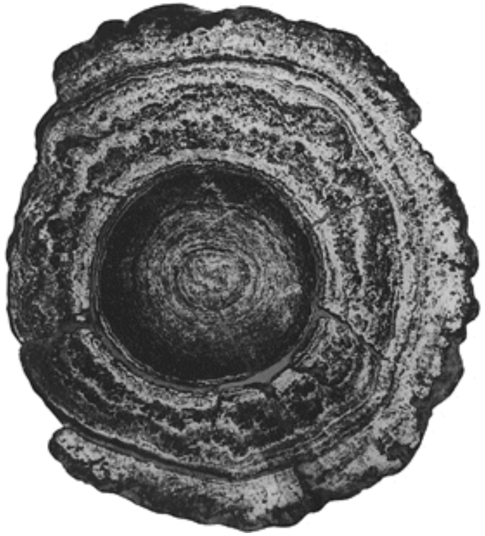
- Slow accretion rates (1-200mm / million yrs)



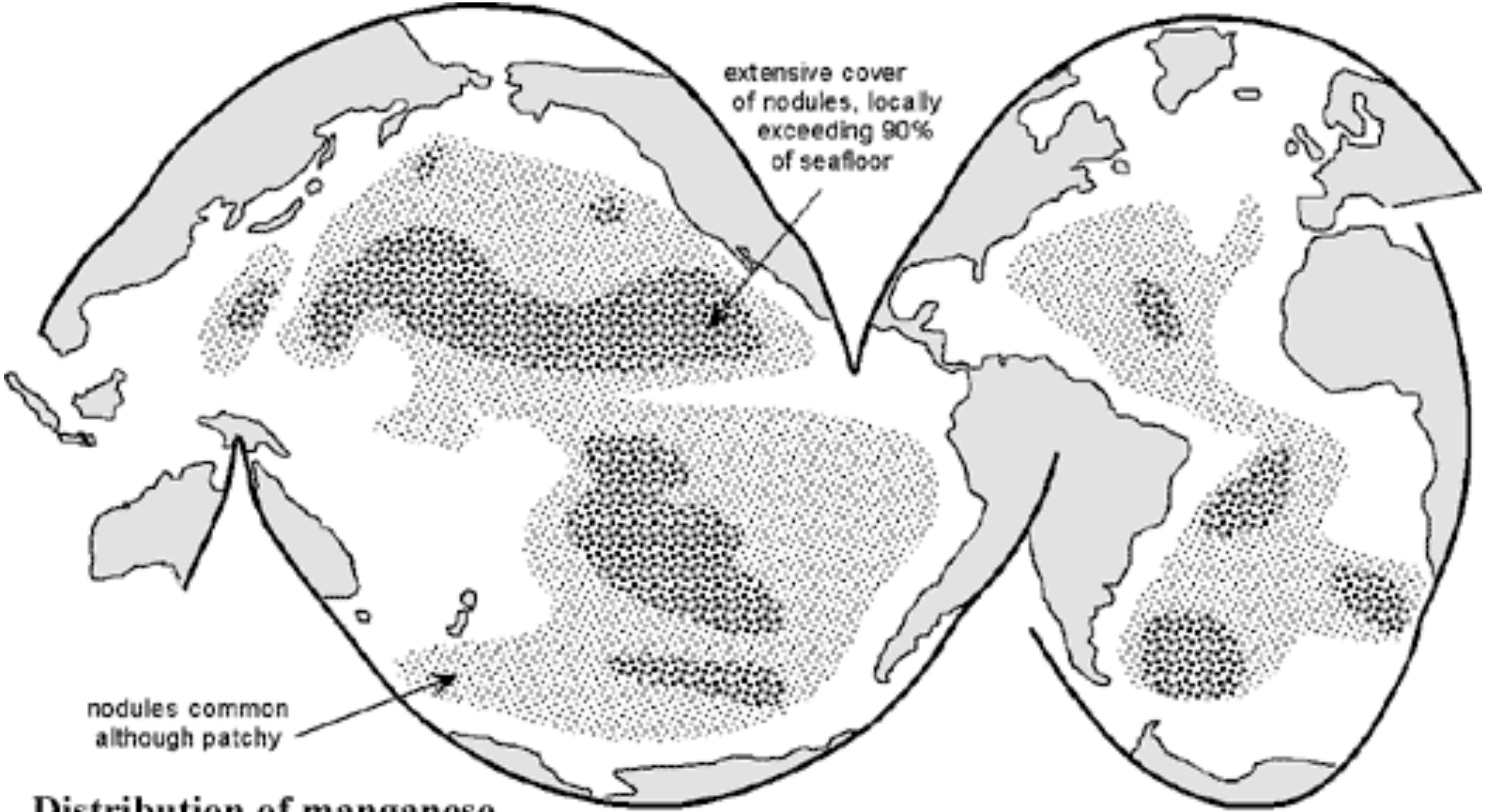
- Black
- Crusts and nodules
- Porous
- concentric

# Manganese Nodules





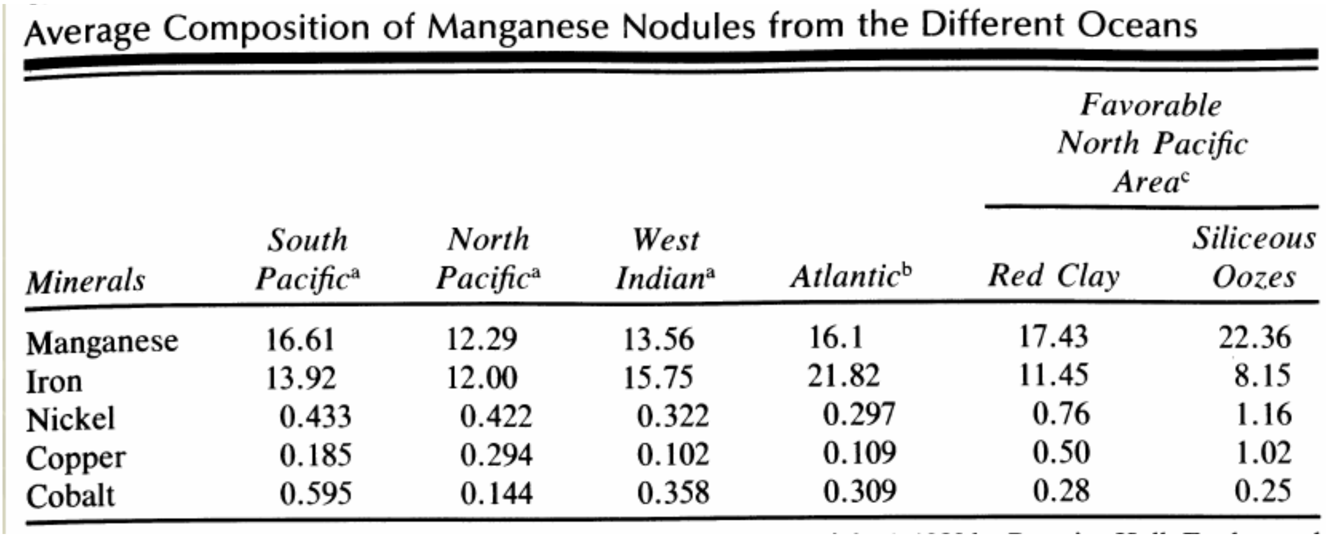
- Very slow process
- Several processes may be involved
    - Precipitation of metals from seawater
    - Remobilisation of managanese in the water column
    - Decomposition of basaltic debris
    - Precipitation of metal hydroxides through biological activity



Distribution of manganese nodules in the Pacific and Atlantic Oceans

# Ferromanganese nodules

- Ferromanganese nodules are small (typically pea to golf ball sized) deposits that exist in the deep ocean.
- They contain a relatively high percentage of the metals manganese, iron, nickel, copper, and cobalt.
- Nodules are formed in situ from metals and other minerals that have accumulated around a core.



Average Composition of Manganese Nodules from the Different Oceans

| | | | | | Favorable North Pacific Area[c] | |
|---|---|---|---|---|---|---|
| *Minerals* | *South Pacific*[a] | *North Pacific*[a] | *West Indian*[a] | *Atlantic*[b] | *Red Clay* | *Siliceous Oozes* |
| Manganese | 16.61 | 12.29 | 13.56 | 16.1 | 17.43 | 22.36 |
| Iron | 13.92 | 12.00 | 15.75 | 21.82 | 11.45 | 8.15 |
| Nickel | 0.433 | 0.422 | 0.322 | 0.297 | 0.76 | 1.16 |
| Copper | 0.185 | 0.294 | 0.102 | 0.109 | 0.50 | 1.02 |
| Cobalt | 0.595 | 0.144 | 0.358 | 0.309 | 0.28 | 0.25 |

# General trends

- Exist in most oceanic basins.
- They are most abundant in oceanic abundant in oceanic regions where sedimentation rates are slow.
- They are more abundant where non-biogenic sediments dominate (red clay).
- Concentrated on the sea floor, becoming sparse below the surface.
- Form where sedimentation rates are low
- Nodules carpets are strongly associated with bottom currents.
- Not found at the sea floor below OMZ (oxygen minimum zone)

# Vampire Squid

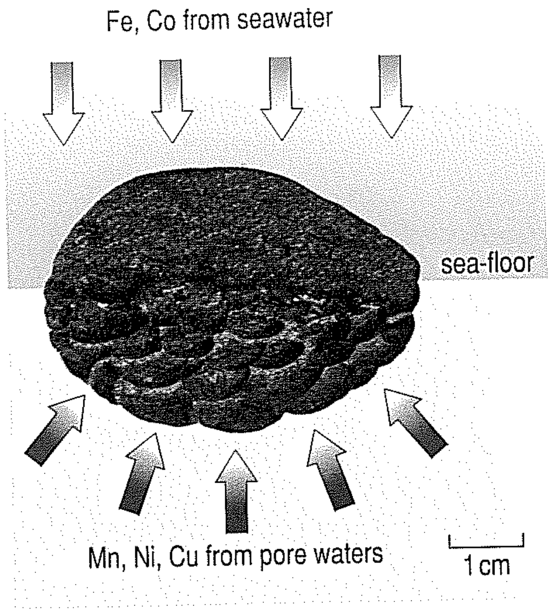
- Box corer shows high density of ferromanganese nodules

# Ferromanganese nodule “conundrum”

- Managanese nodules grow at extremely slow rates (1-200 mm/ million years)
- Average sedimentation in abyssal plains is approximately 1 mm per thousand years
  - Sediment Accumulation rates > Nodule Growth Rates
- Why do the nodules exist at all?
  - They should be buried before they reach typical sizes observed in the ocean
  - Manganese nodules are rarely found below surface sediments (>4 cm) in some areas – Why?
  - Metal Composition can be highly variable – Why?

# Nodule formation

- Three end-members
  - Direct precipitation of metal oxides from seawater
    - Manganese crusts
  - Oxic diagenesis
    - Release of transition elements (eg. Mn, Co, Ni) into pore waters
  - Suboxic diagenetic processes involve recycling of elements

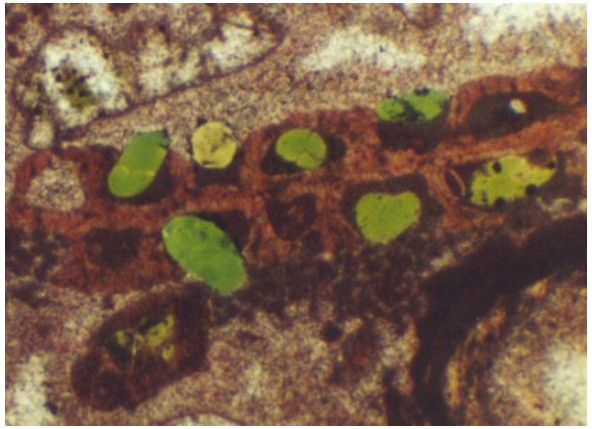


- Hydrogenous nodules have a smooth surface texture.
- Diagenetic nodules botryoidal to rough surface texture.

# Glauconite

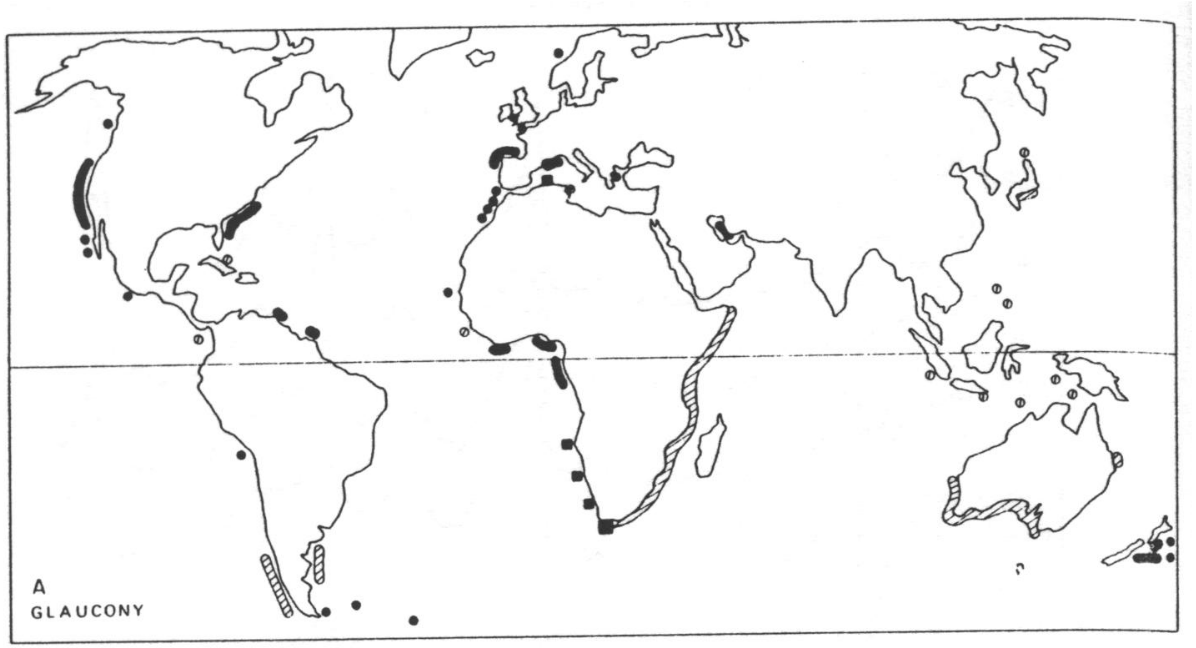
- Hydrous clay mineral

  potassium-magnesium-iron-alumino-silicate (K-Mg-Fe-Al silicate)
- Sand to pebble sized green particles
- Surface coating on particles and hardgrounds
- Continental shelf marine environments with slow rates of accumulation and reducing conditions
- Diagenetic alteration



# Glauconite

- Widespread on continental shelves
- Open-marine setting, low sedimentation
- Typically linked to transgressive intervals



# Glauconization

- Replacement of clay mineral (particularly in faecal pellets) by authigenic minerals (smectite).
- Cold waters, in environments of slow discontinuous deposition.
- Sediment should contain mica and develop slightly reducing conditions.
- Formation of glauconite is controlled by availability of iron and potassium.
- Increased inclusion of potassium reflects maturity and prolonged exposure to sea-water.
    - ~$10^3$-$10^4$yrs to $10^5$-$10^6$yrs

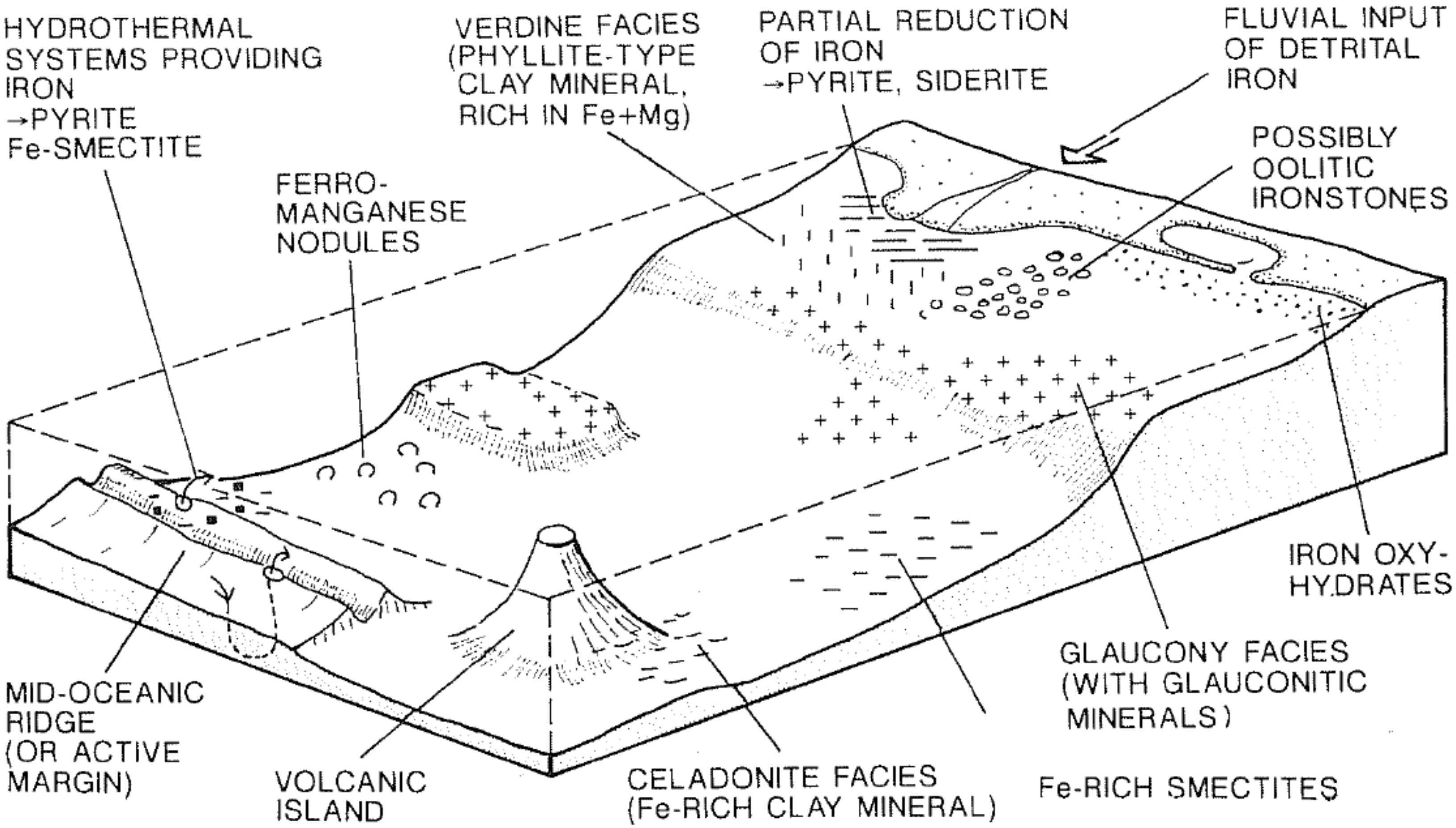


**Fig. 6.1.** Generalized model demonstrating source and distribution of iron-rich marine sediments, mostly green clays. Note that iron is provided either by fluvial input or by volcanic activity, including submarine leaching of basaltic rocks. See text for explanation of the various facies types. (After Odin 1988)

# Phosphorites

- Contain > 20% $P_2O_5$
- Preferentially forms on continental shelves and shelf-breaks, and seamounts and guyots.
- Often associated with coastal upwelling and transgressions, P can be from continental sources.
- Giant sulphur bacteria (explanation for massive deposits?)

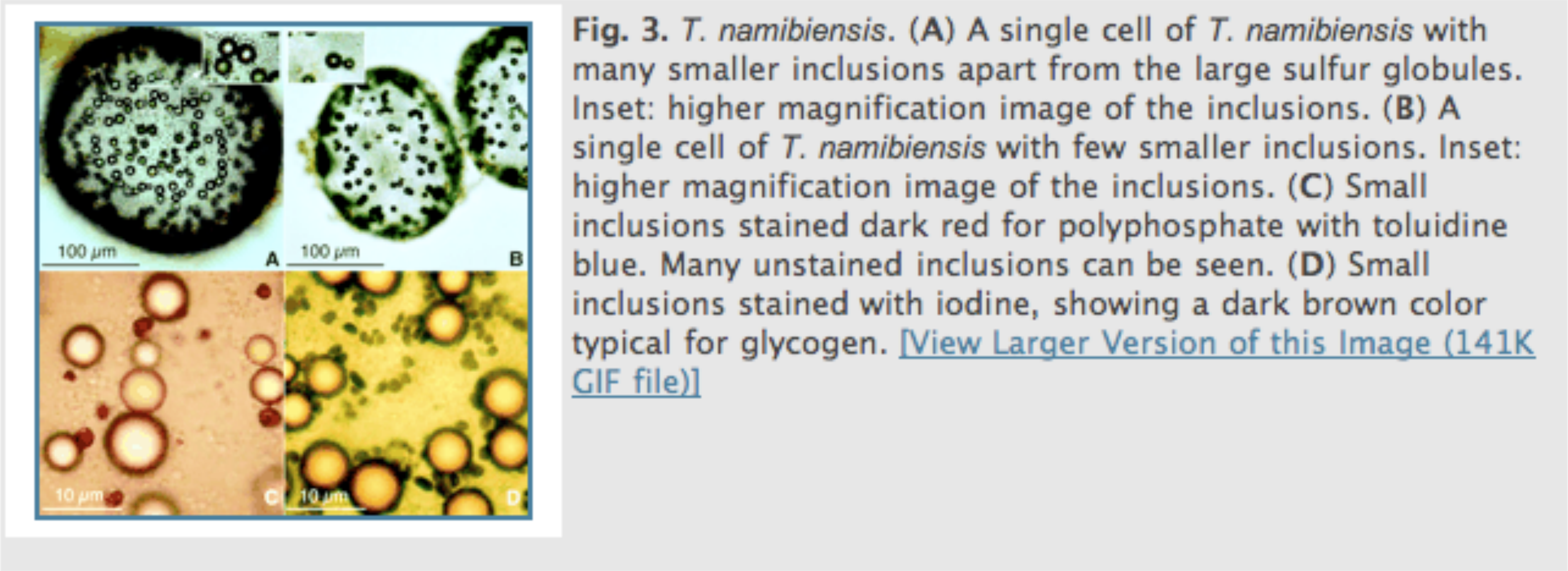
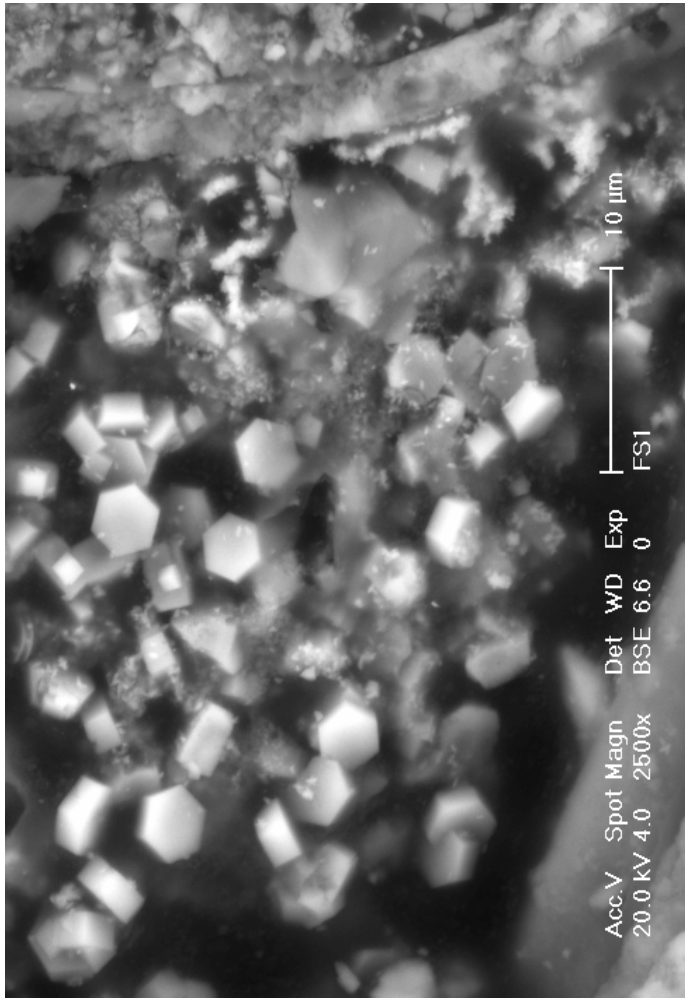


**Fig. 3.** *T. namibiensis*. (**A**) A single cell of *T. namibiensis* with many smaller inclusions apart from the large sulfur globules. Inset: higher magnification image of the inclusions. (**B**) A single cell of *T. namibiensis* with few smaller inclusions. Inset: higher magnification image of the inclusions. (**C**) Small inclusions stained dark red for polyphosphate with toluidine blue. Many unstained inclusions can be seen. (**D**) Small inclusions stained with iodine, showing a dark brown color typical for glycogen. [View Larger Version of this Image (141K GIF file)]

Guano Island, Peru

# Phosphorites



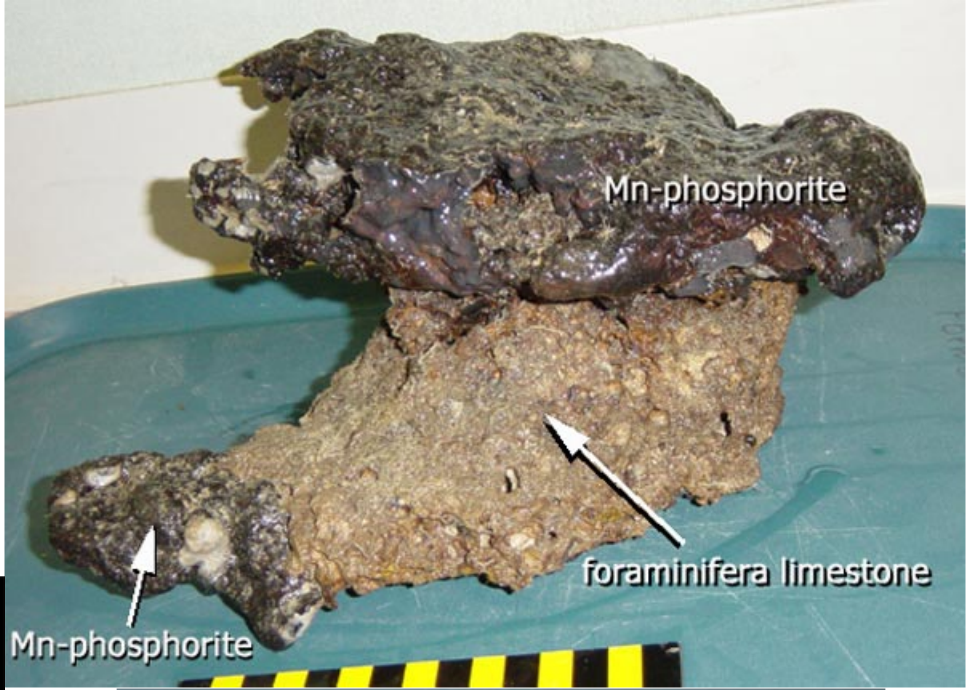
- Phosphorites are sediments that include significant proportions of authigenic and biogenic phosphate minerals
  > 18% $P_2O_5$
- Francolite the most common sedimentary phosphate mineral
- Precipitated within the uppermost layer of organic-rich sediment during early diagenesis

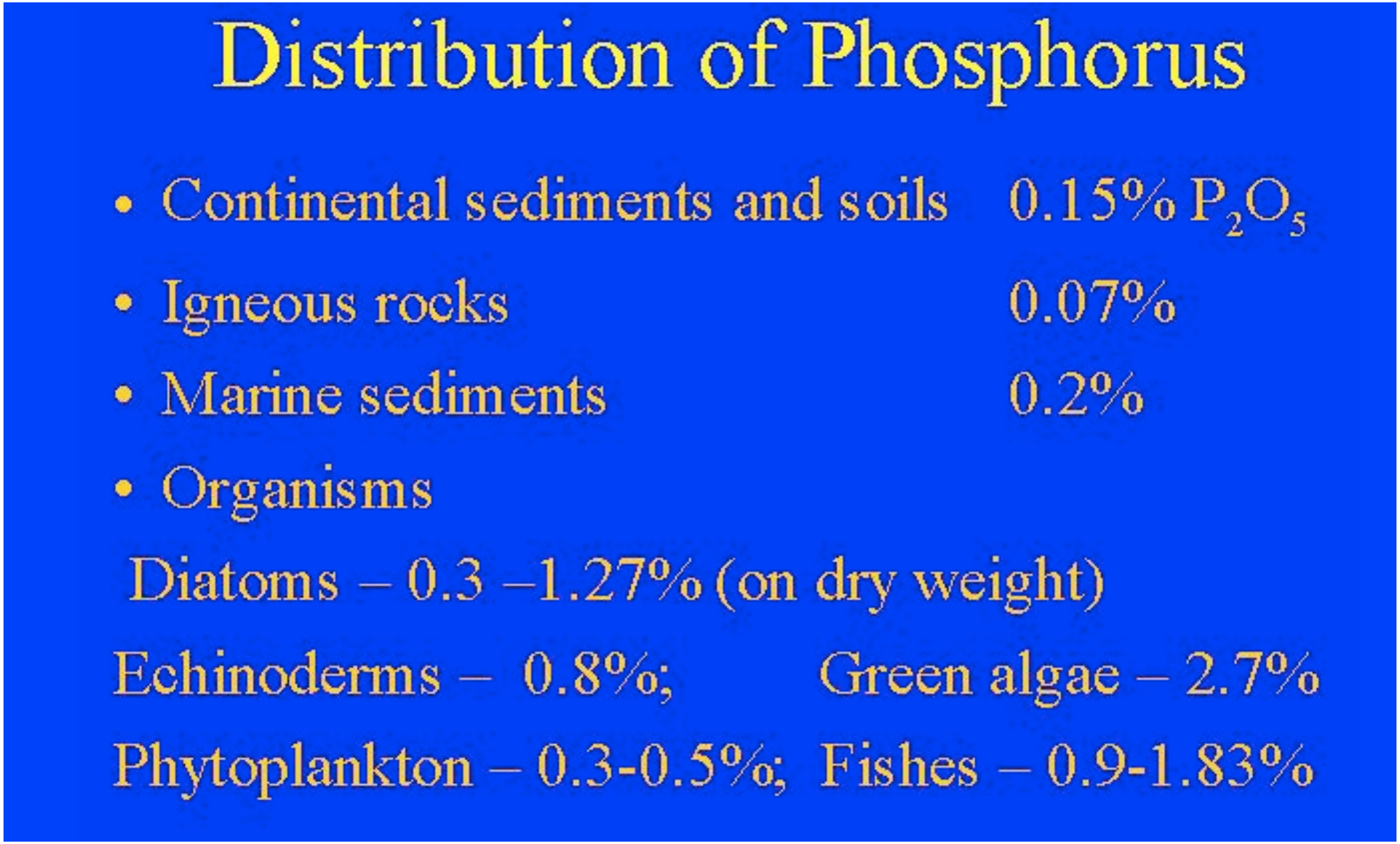
= Carbonate fluorapatite

$$Ca_{10-a-b}Na_aMg_b(PO_4)_{6-x}(CO_3)_{x-y-z}(CO_3.F)_y(SO_4)_zF_2$$

# Phosphorites

- Forms ooid-like pellets, nodules, crusts and coatings on other materials, esp. on the surface of carbonates and calcareous shells, which can be replaced by phosphate over time





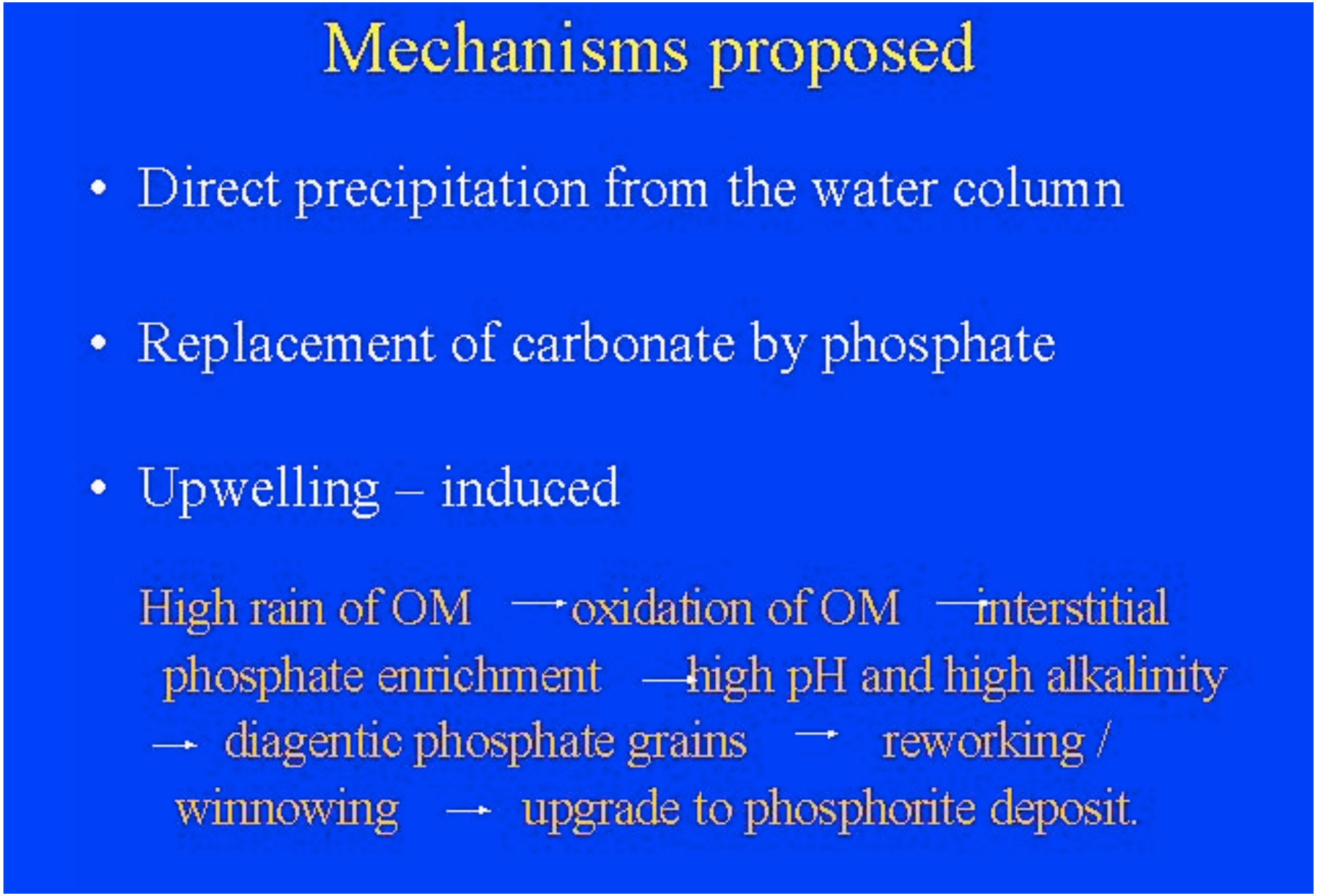
# Distribution of Phosphorus

- Continental sediments and soils 0.15% $P_2O_5$
- Igneous rocks 0.07%
- Marine sediments 0.2%
- Organisms

Diatoms – 0.3 –1.27% (on dry weight)

Echinoderms – 0.8%; Green algae – 2.7%

Phytoplankton – 0.3-0.5%; Fishes – 0.9-1.83%



# Mechanisms proposed

- Direct precipitation from the water column
- Replacement of carbonate by phosphate
- Upwelling – induced

High rain of OM → oxidation of OM → interstitial
phosphate enrichment → high pH and high alkalinity
→ diagentic phosphate grains → reworking /
winnowing → upgrade to phosphorite deposit.

# Phosphorite occurrences

- Condensed beds on top of drowning shallow-water carbonate platforms, followed by pelagic sediments
- At the top of shallowing, coarsening upwards sequences, overlain by sediments of deeper water
- In condensed intervals, rich in organic matter, topped by siliceous sediments indicating an increase in coastal upwelling
- In transgressive-regressive sequences, in shallow marine envs, where organic-rich sediments (with P) deposited during the transgression are partially or entirely reworked during the subsequent regression

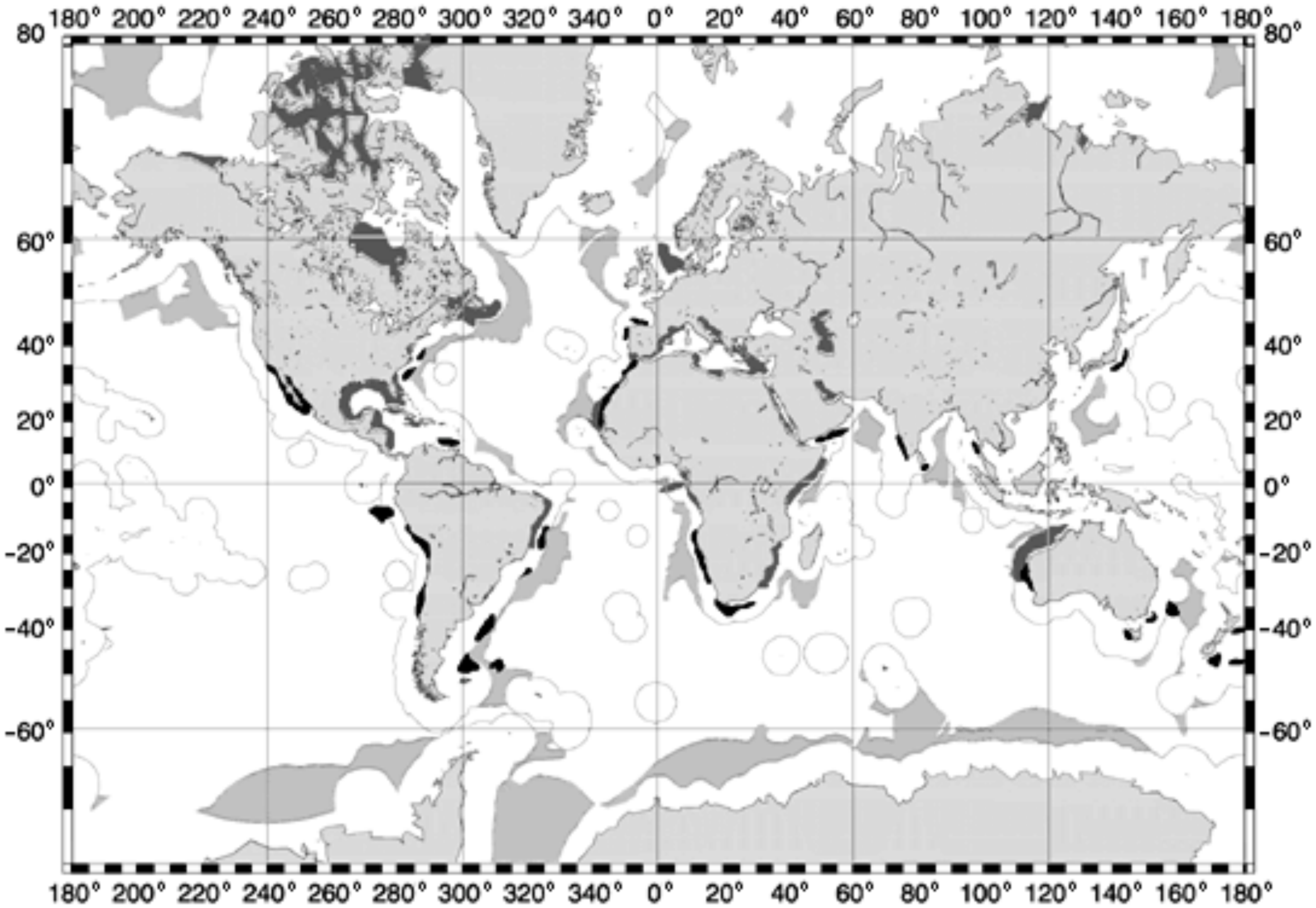
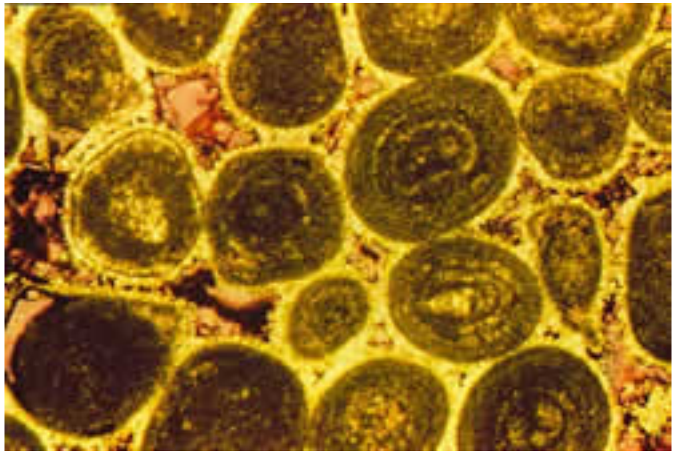


Figure 1. Location of known marine phosphorite deposits (in light black - after Baturin and Savenko, 1985; Baturin 1998; Rao and Nair, 1991; Earney, 1990) and evaporite deposits (in dark grey - after Cronan, 1980; Earney, 1990; Warren, 1999; Teleki *et al.*, 1987 and others cited in the text) with reference to the ELCS regions (in pale grey) and EEZ areas (outlined by thin curved grey lines) – modified after Prescott, 1985.

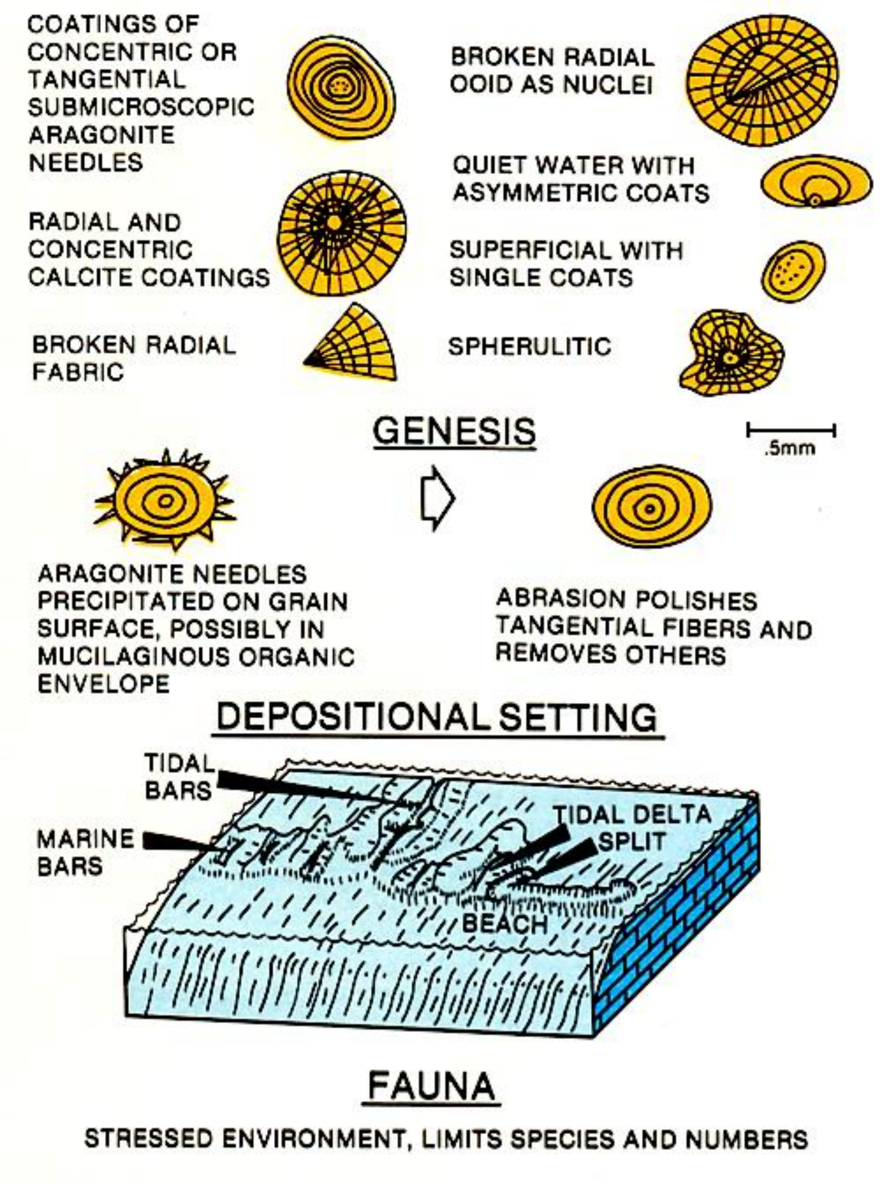
# Ooids



- Coated grains include oolites, pisolites, oncoids, and oncolites.
- Formed by a series of concentric layers surrounding a nucleus.

# Ooid Formation

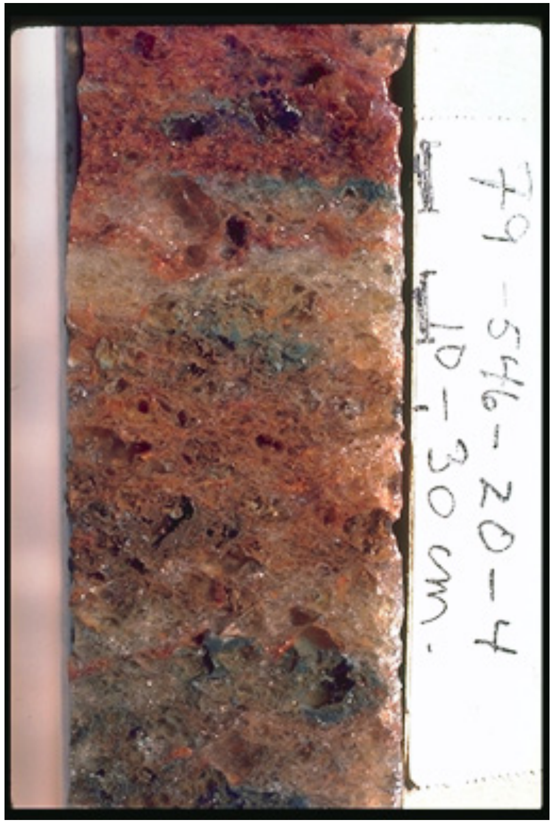
- Agitated marine environment (tidal sand bars, tidal deltas, barrier sands)



# Marine Evaporites

# Marine evaporites

- Evaporites-form when sea water evaporates; often at divergent margins as the process is just changing from continental rifting to seafloor spreading.
- Only form in climates where evaporation > precipitation



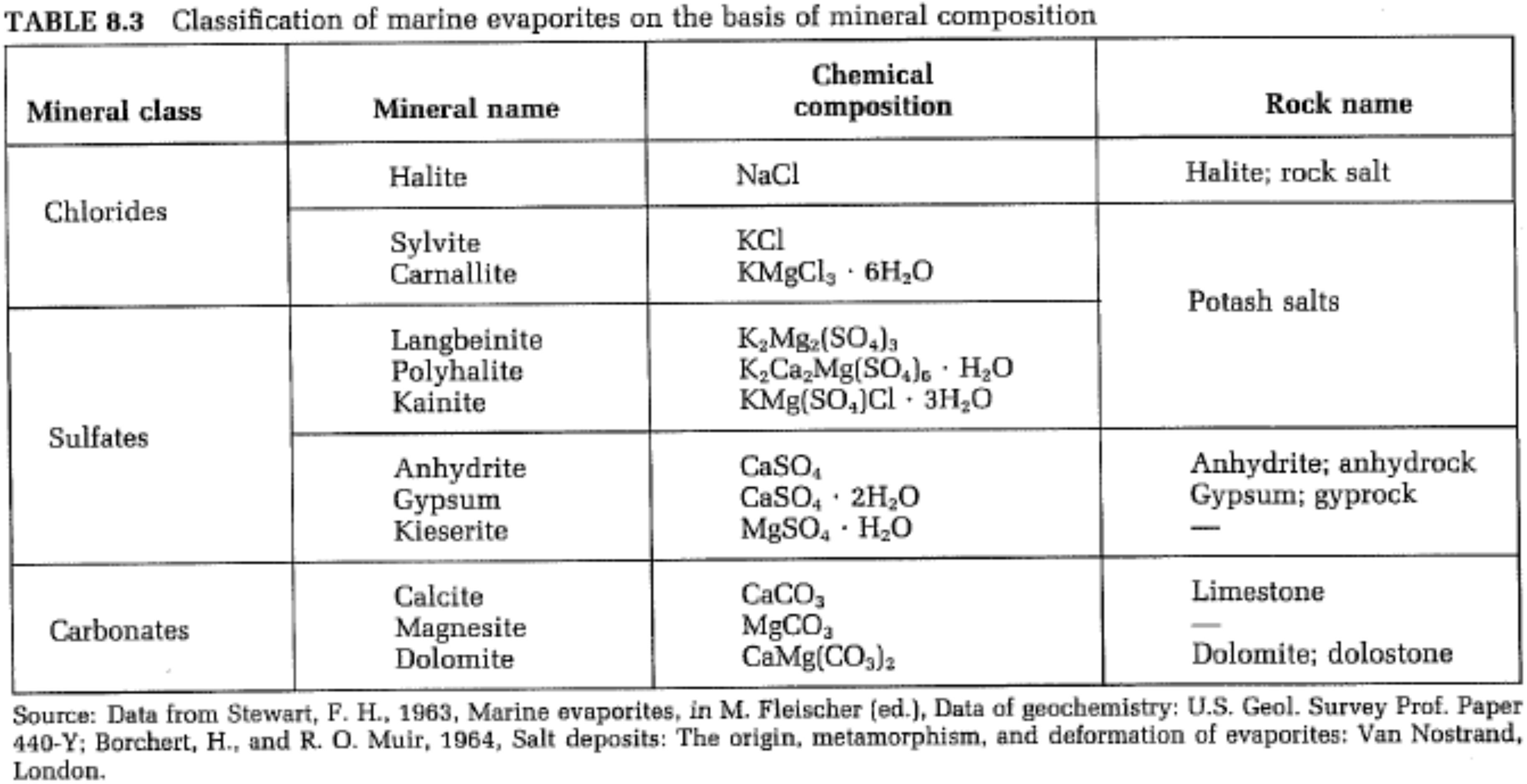


**TABLE 8.3** Classification of marine evaporites on the basis of mineral composition

| Mineral class | Mineral name | Chemical composition | Rock name |
|---|---|---|---|
| Chlorides | Halite | $NaCl$ | Halite; rock salt |
| | Sylvite<br>Carnallite | $KCl$<br>$KMgCl_3 \cdot 6H_2O$ | Potash salts |
| Sulfates | Langbeinite<br>Polyhalite<br>Kainite | $K_2Mg_2(SO_4)_3$<br>$K_2Ca_2Mg(SO_4)_6 \cdot H_2O$<br>$KMg(SO_4)Cl \cdot 3H_2O$ | |
| | Anhydrite<br>Gypsum<br>Kieserite | $CaSO_4$<br>$CaSO_4 \cdot 2H_2O$<br>$MgSO_4 \cdot H_2O$ | Anhydrite; anhydrock<br>Gypsum; gyprock<br>— |
| Carbonates | Calcite<br>Magnesite<br>Dolomite | $CaCO_3$<br>$MgCO_3$<br>$CaMg(CO_3)_2$ | Limestone<br>—<br>Dolomite; dolostone |

Source: Data from Stewart, F. H., 1963, Marine evaporites, *in* M. Fleischer (ed.), Data of geochemistry: U.S. Geol. Survey Prof. Paper 440-Y; Borchert, H., and R. O. Muir, 1964, Salt deposits: The origin, metamorphism, and deformation of evaporites: Van Nostrand, London.

# Where & when do thick evaporites accumulate?

**Lacustrine and Marine settings adjacent to continental plate margins during:-**

- Break up of continental plates
- Collision & compression of continental plates
- Generation of structural & depositional barriers

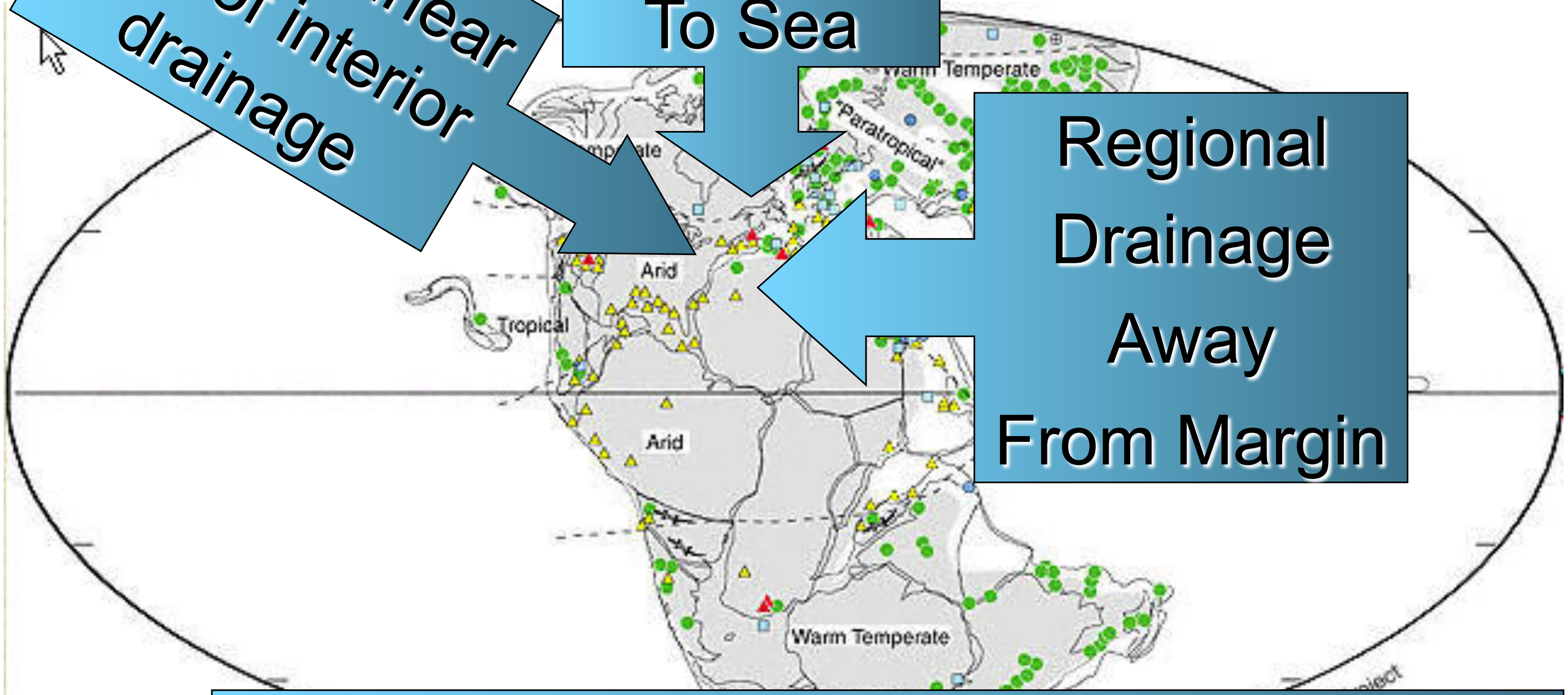
**Commonly within Air System of Arid Tropics**

# Arid Climates Common in Earth History

- Evaporites of Mesozoic to Tertiary of Middle East; Paleozoic & Mesozoic the USA, Europe & Middle East
- Salt Flat Evaporites
- Arid Coastline Evaporites
- Isolated Marine & Lacustrine Evaporite Basins
- Aeolian sediments

# Evaporite generation during break up of continental plates

- Isolated linear belts of interior drainage.
- Linear belts connected by restricted entrance to the sea.
- Regional drainage tends to flow away from break up margin
- Air system of the arid tropics
- Wide envelope of surrounding continents.
- Mesozoic of North Atlantic



Isolated linear Belt of interior drainage

Restricted Entrances To Sea

Regional Drainage Away From Margin

Wide Envelope of surrounding continents

Arid Tropics Air System