Marine Biogeochemistry: Interaction with Physical Oceanography 2008

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Subdivisions of Oceanography

- **Biological Oceanography:** Marine Botany, Marine Zoology, Marine Microbiology and Fisheries Oceanography
- **Chemical Oceanography:** natural chemistry of inorganic and organic compounds, Marine Biogeochemistry, Marine Pollution
- **Geological Oceanography:** Marine Geology, Sedimentology and Marine Geophysics
- **Physical Oceanography:** Tides and other waves, Currents, Marine Meteorology
- **Engineering Oceanography:** Coastal Engineering, Ship Design, some Marine Engineering

What is Biogeochemistry?

"***The ocean is a place where biological, physical, geological and chemical processes interact; the study of marine chemistry is very interdisciplinary …this field is…marine biogeochemistry***"

(Susan Libes' textbook, "Marine Biogeochemistry" 1992, John Wiley, 734pp)

Photosynthesis: almost certainly the single, most important, chemical reaction on Earth

Ocean Photosynthetic Production: by **phytoplankton** (plant plankton, 'ϕ') & **microbes**; a highly simplified equation-incompletely balanced (Chester 1990):

$106\ CO_2(g) + 122\ H_2O(l) + H_3PO_4(aq) + 16\ HNO_3(aq)$
$[+\ nSiO_4^{4-}(aq)$ (if siliceous)$] + m\{Ca^{2+}(aq) + H_2O(l) +$
$CO_2\ (g)$ (if calcareous)$\}$ + (light energy) $\Rightarrow$

$(CH_2O)_{106}(NH_3)_{16}\ H_3PO_4.nSiO_2.mCaCO_3(s) + 138\ O_2(g)$

1 mole "biomass" (microbial or phytoplankton)

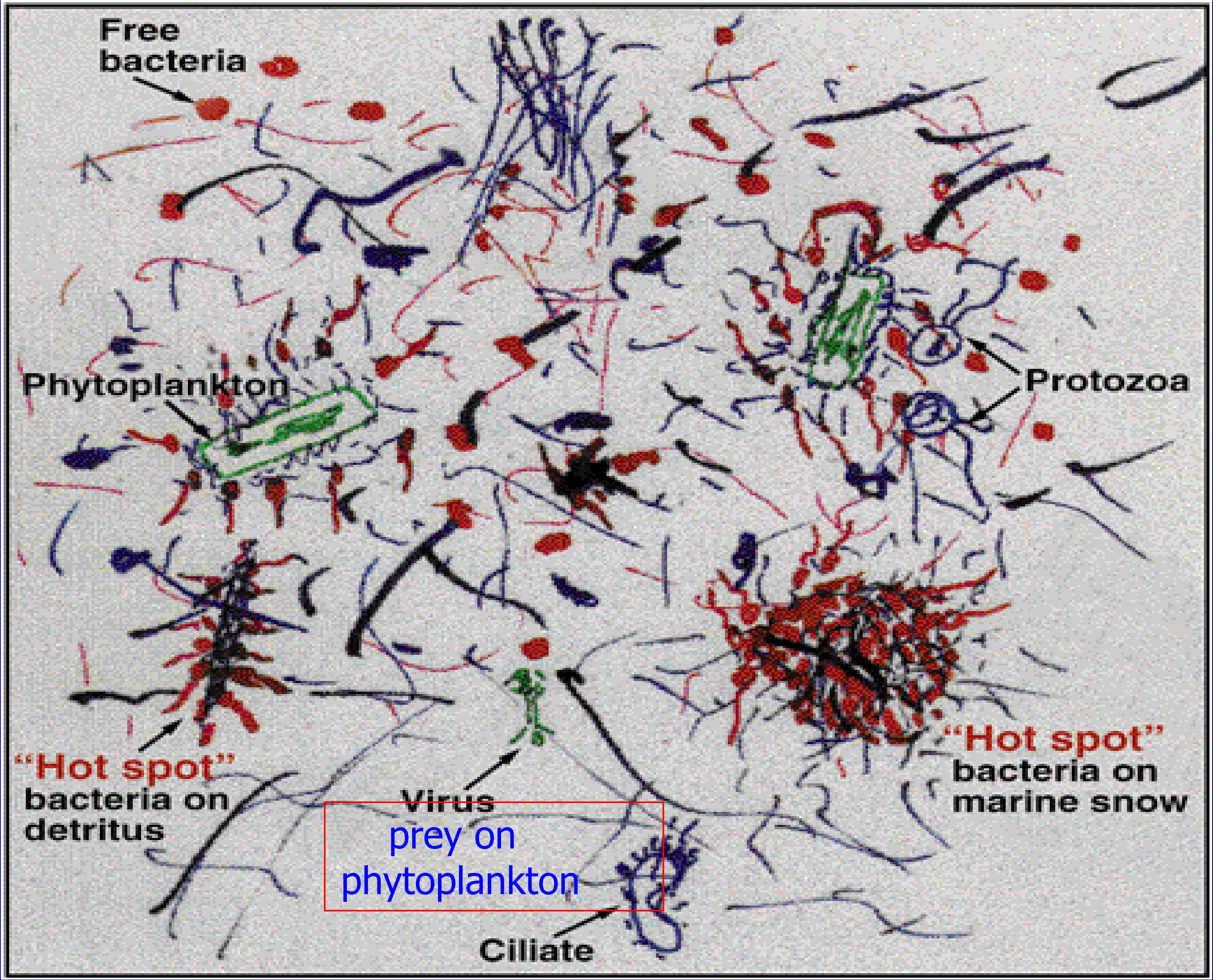
Free O_2 damages cells

in the presence of **light**, **chlorophyll** and essential **micro-nutrients,** such as **iron, copper, manganese** and **vitamins**

1kg cleanest seawater contains ~ 10^9 microbes*

* bacteria, viruses, protists

photosynthetic bacteria carry out ~ 50% **all** oceanic photosynthesis (Pomeroy *et al*., 2007)



The microbial loop: impressionist version

A bacteria-eye view of the ocean's euphotic layer   Bacteria (red) acting on marine snow (black)   from Azam, F. 1998 *Science* **280** (5364) 694-696

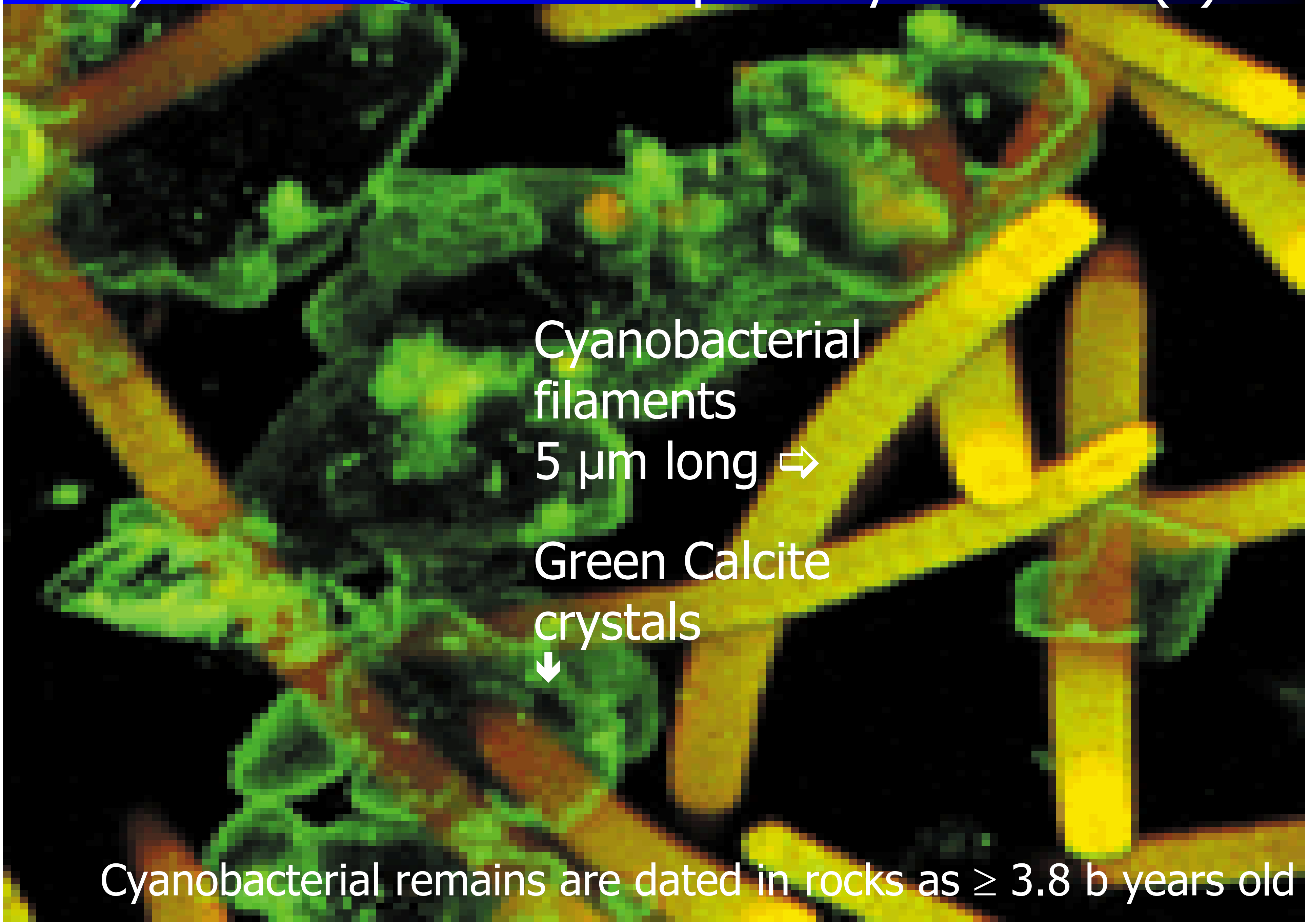
Photosynthesis, an ancient marine reaction active for at least 3.8 billion years, has:

- provided virtually all the oxygen (O_2) we, and all other higher animals, breathe (a minute amount comes from solar UV dissociation of water*)
- removed most carbon dioxide (CO_2) from the original atmosphere, depositing huge masses of marine carbonate minerals, much now on land
- overwhelmingly provided the major food source for **all** creatures in the ocean

$$* \quad 2H_2O(g) \xrightarrow{UV} 2H_2(g) + O_2(g)$$

lost to space

Cyanobacteria-the first photosynthesisers(?)



Cyanobacterial remains are dated in rocks as ≥ 3.8 b years old

Photosynthesis only occurs where sunlight penetrates-the Euphotic Zone, lying in the thin surface skin of the 3800m (mean) deep ocean

Summary:

to grow, organisms require **light** and **nutrients**:

- **carbon dioxide and water-supplies C, H and O**
- **nitrate** and **phosphate** (**N** and **P**, in micromole (µmole) amounts) (also sulphur, chlorine, sodium, potassium, iodine, barium, strontium)
- **silicate** (**Si,** µmole) for their SiO_2 'skeletons' (frustules)
- **calcium** (**Ca,** mmole), together with more CO_2 to make structural $CaCO_3$
- **iron** (**Fe**, nanomole) for enzymatic processes plus manganese, magnesium, copper, selenium, boron, zinc, Vitamin B_{12} and some others-all essential in **minute** amounts

These substances, present in the surrounding sea water in milli- to pico mole amounts, are very efficiently extracted during photosynthesis

Growing blooms (massed phytoplankton), often of a **single species**, are at maximum between 5-8 m depth, may extend to 30-40m

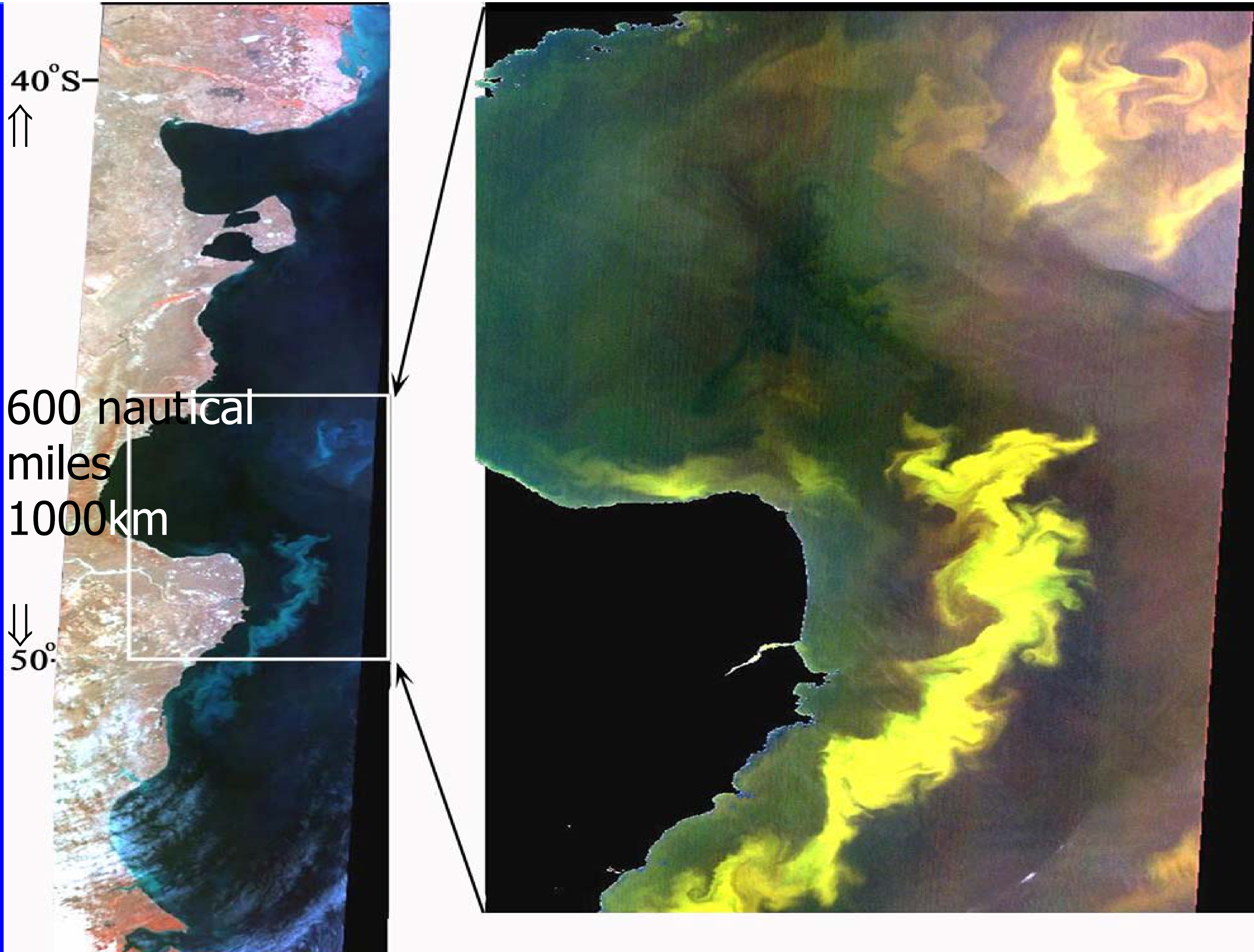
"shading" reduces growth further down

photosynthetic production approaches zero as light intensity declines to ca. 1% surface light intensity (set at 100%); the bottom of the Euphotic Zone

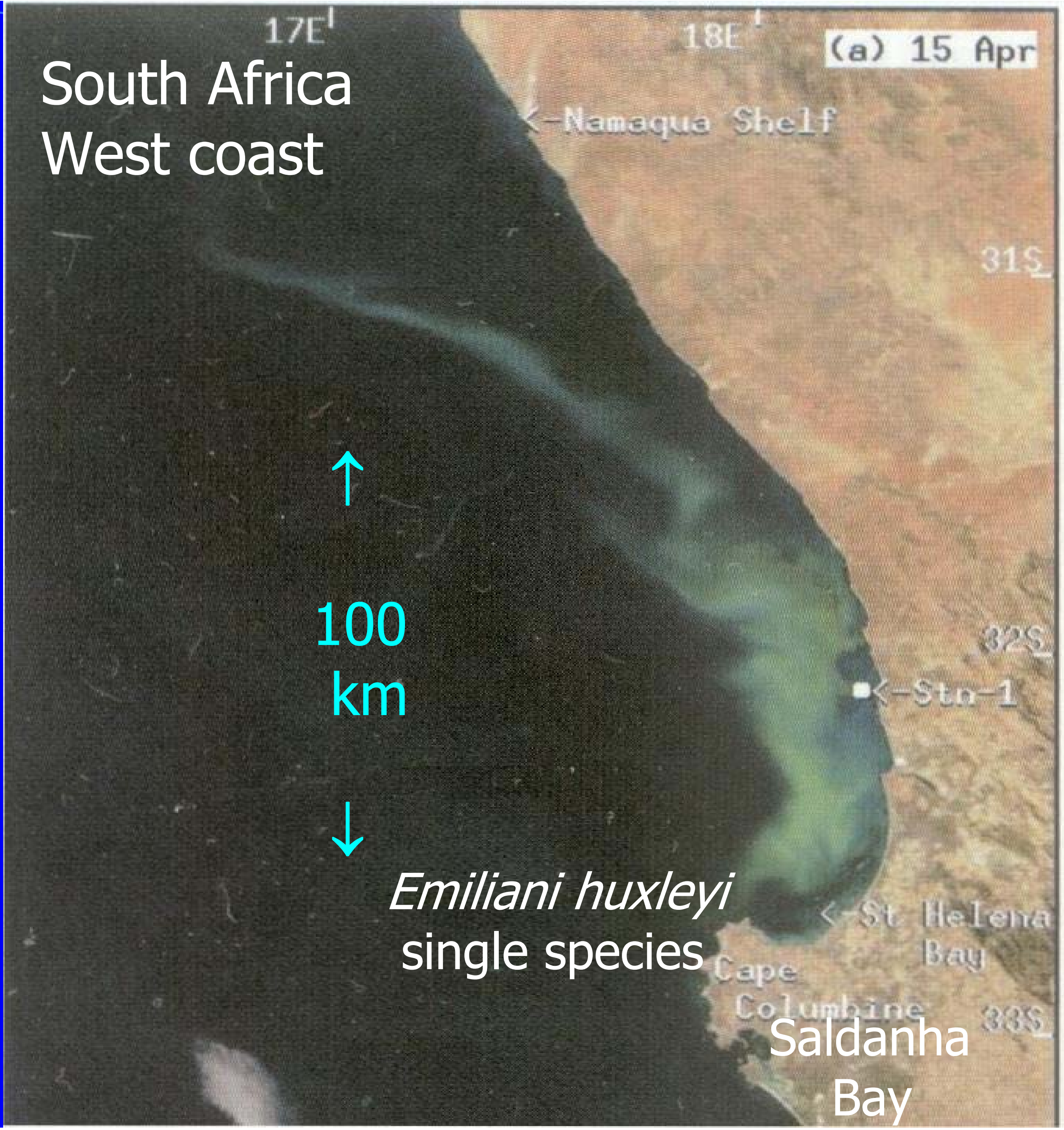
Phytoplankton synthesise a **very** large number of complex molecules for their own use, including:

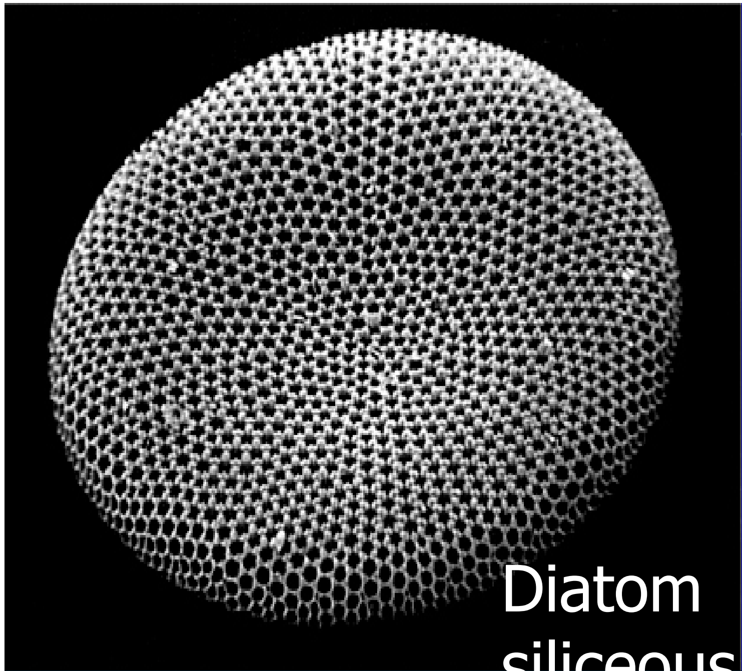
- carbohydrates-energy, energy storage (“CHO” compounds, cellulose, starch)
- chlorophyll-converts solar photon flux to electron flow, and other **pigments** (carotenoids)
- lipids (“oils”)-buoyancy control to optimise light intensity
- terpenes-essential oils
- proteins-for nucleus, ‘templates’ for frustules and shells
- DNA-nucleus, reproduction
- ATP, NADPH-transporters of cellular energy
- enzymes, very many-run chemistry efficiently
- antibiotics-ward off invading microbes
- fluorescing molecules-”phosphorescence”
- very powerful toxins-to deter predators (?)
- DMS (dimethyl sulphide)-converts to atmospheric sulphate, reflecting solar energy; and others

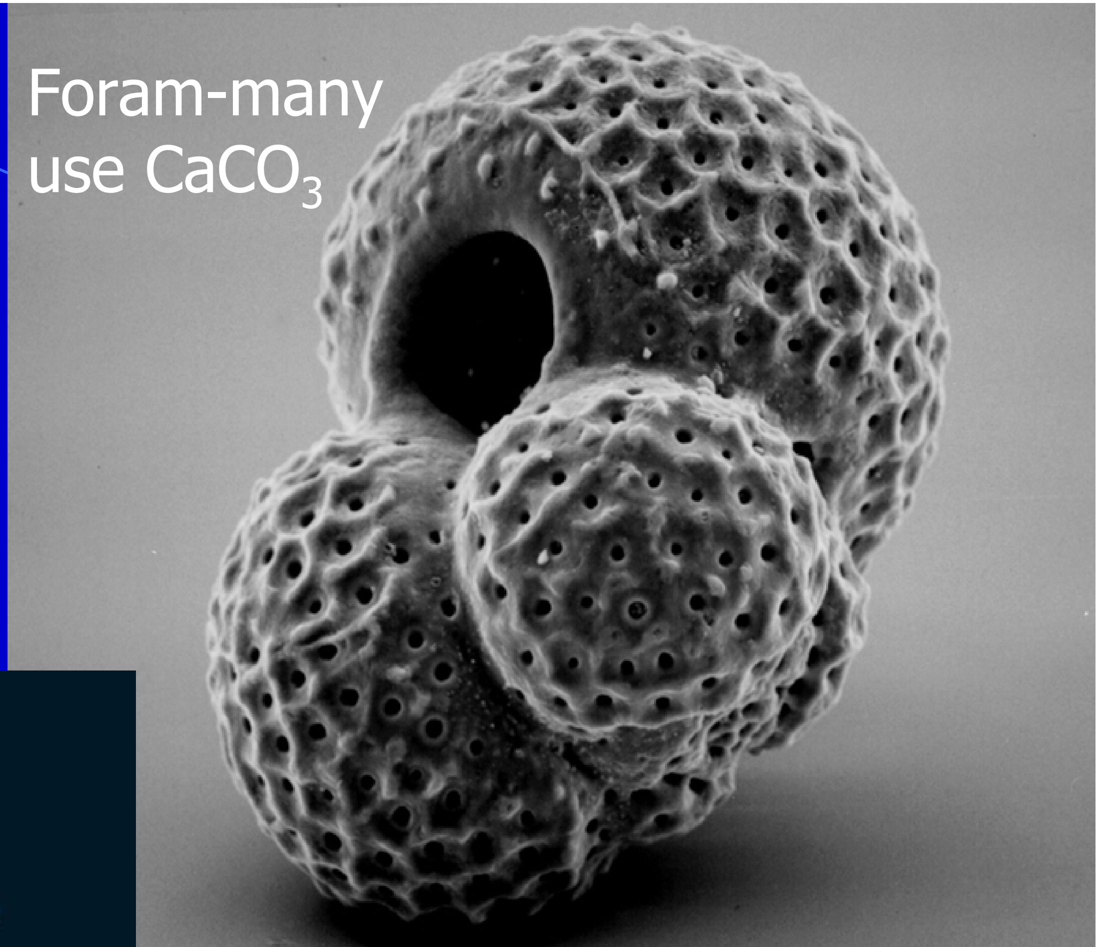
Enormous phytoplankton blooms occur when conditions are suitable

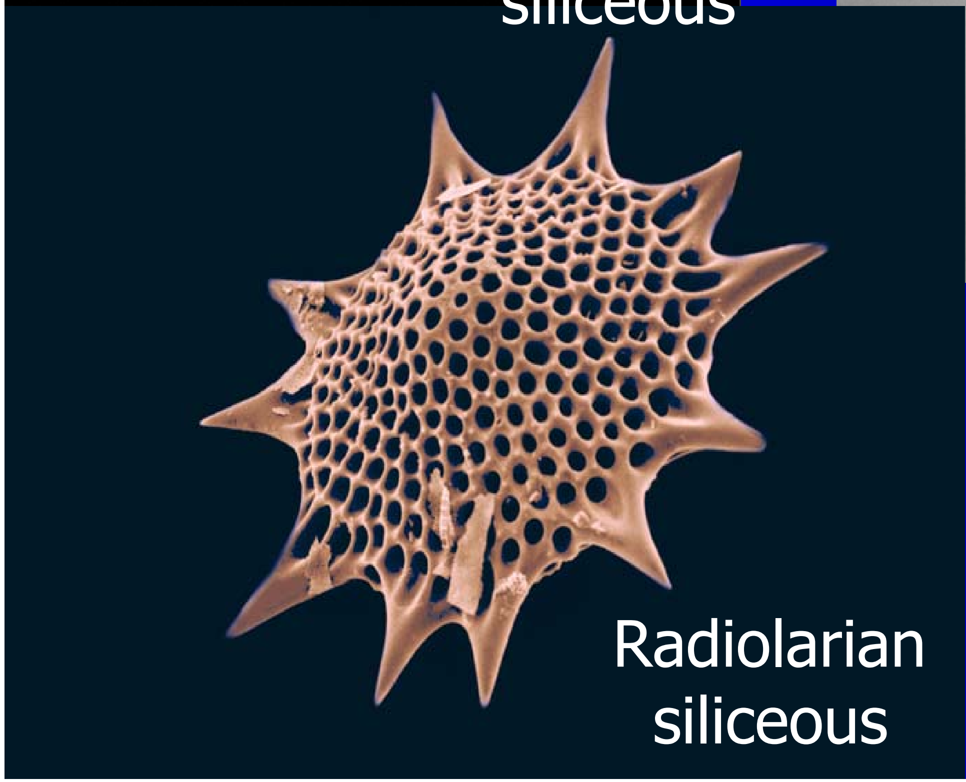


Bloom off Patagonia


South Africa
West coast
17E
18E
(a) 15 Apr
<-Namaqua Shelf
31S
100
km
32S
<-Stn-1
Emiliani huxleyi
single species
<-St Helena
Bay
Cape
Columbine
33S
Saldanha
Bay







Exquisite symmetry, created by protein templates

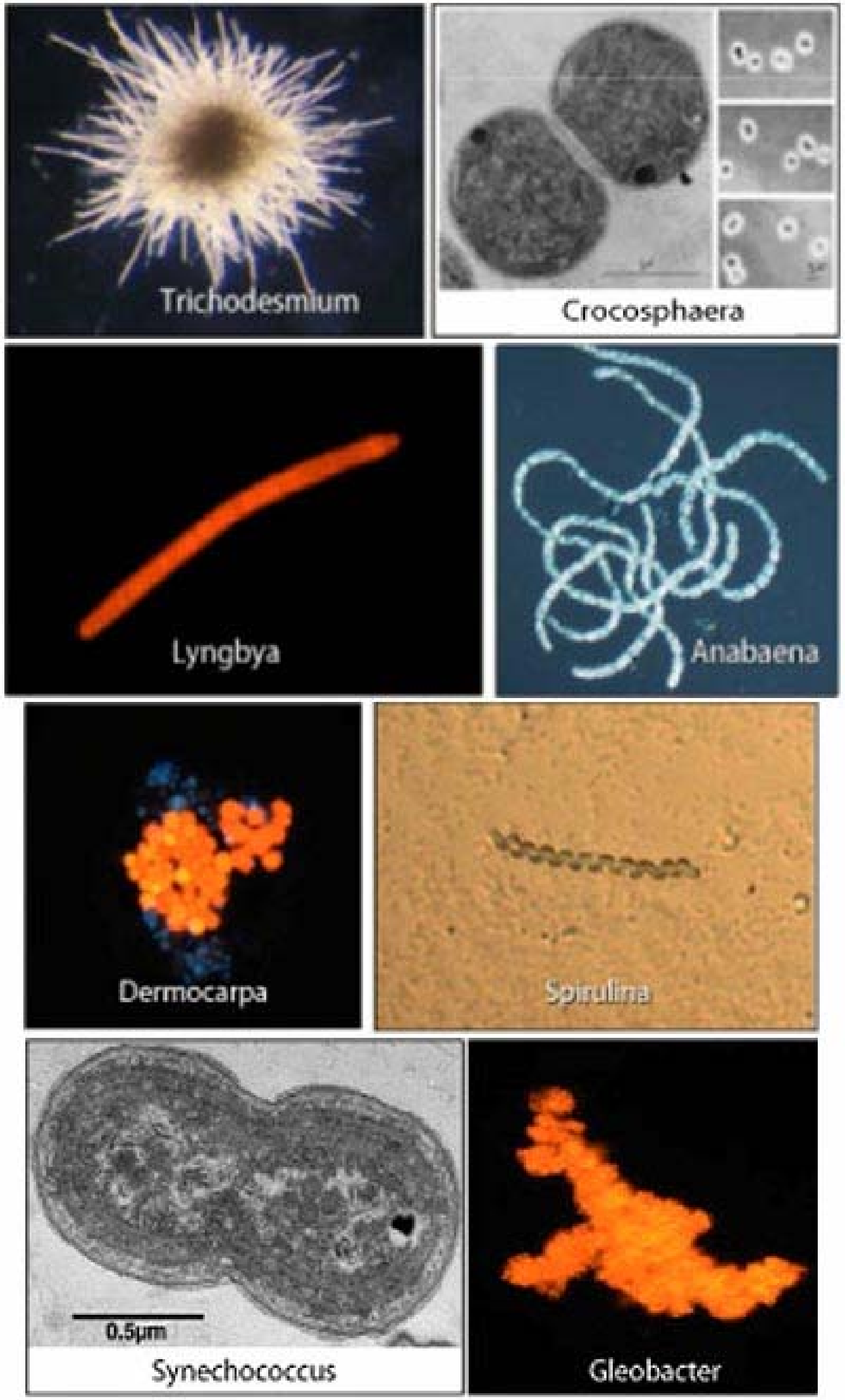
Making solid silica from the minute amounts in seawater is chemically <u>very</u> difficult

Cyanobacteria spp.

Trichodesmium **"fixes" N**, i.e., converts stable nitrogen gas into soluble ammonium ion available for photosynthetic uptake
(as NH_4^+ or NO_3^-)

This **very** endothermic reaction is catalysed by molybdenum under strictly anaerobic (no O_2) conditions inside the cell
($N\equiv N \sim 945$ kJ mol^{-1})

Very important in nitrate-deficient ocean areas



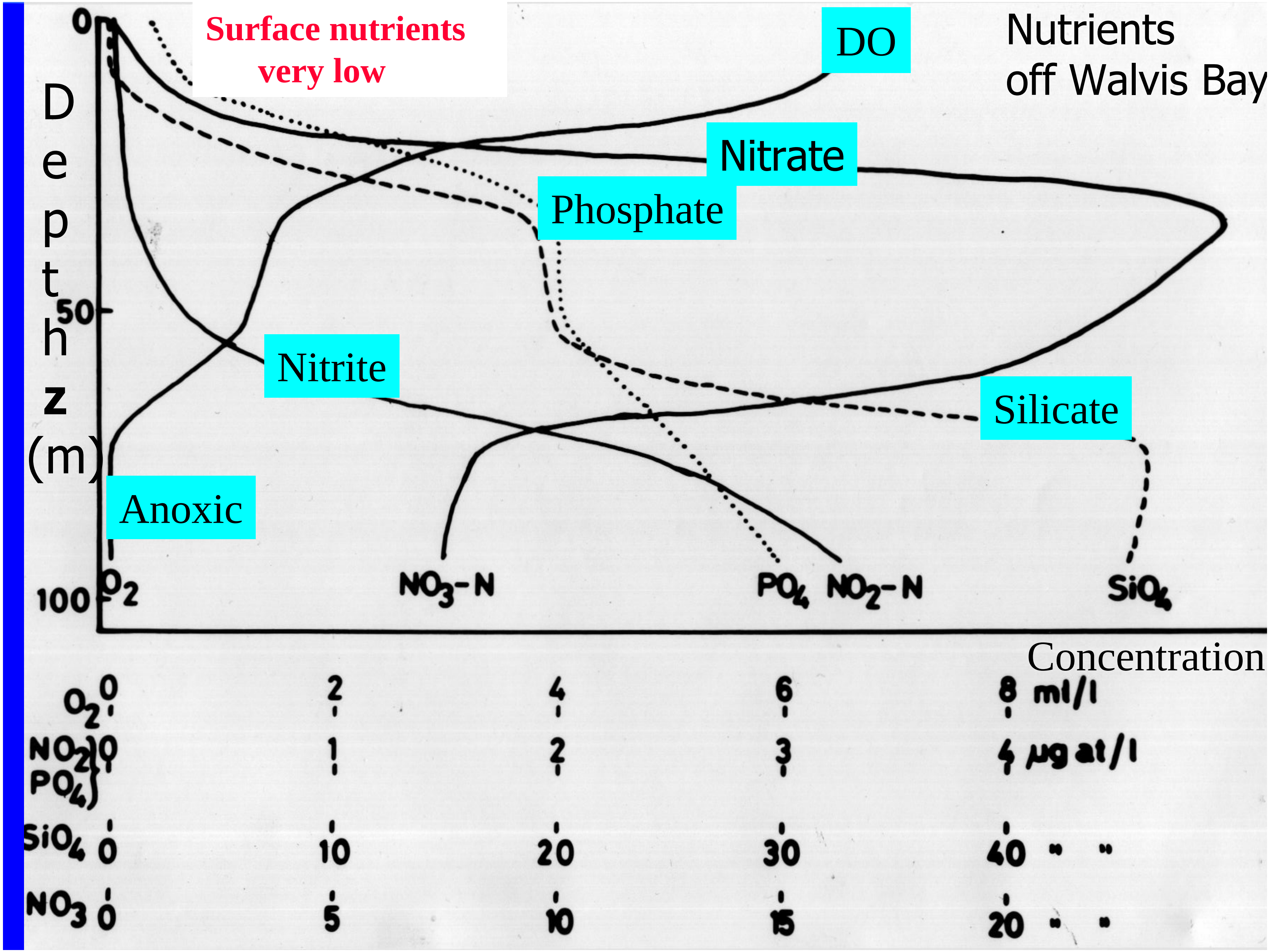
When one critical nutrient is used up, usually **nitrate**, next silicate, very rarely phosphate growth slows, then stops

Large ocean areas (HNLC*) with moderate to high nutrients have no growth-this is mainly due to lack of iron

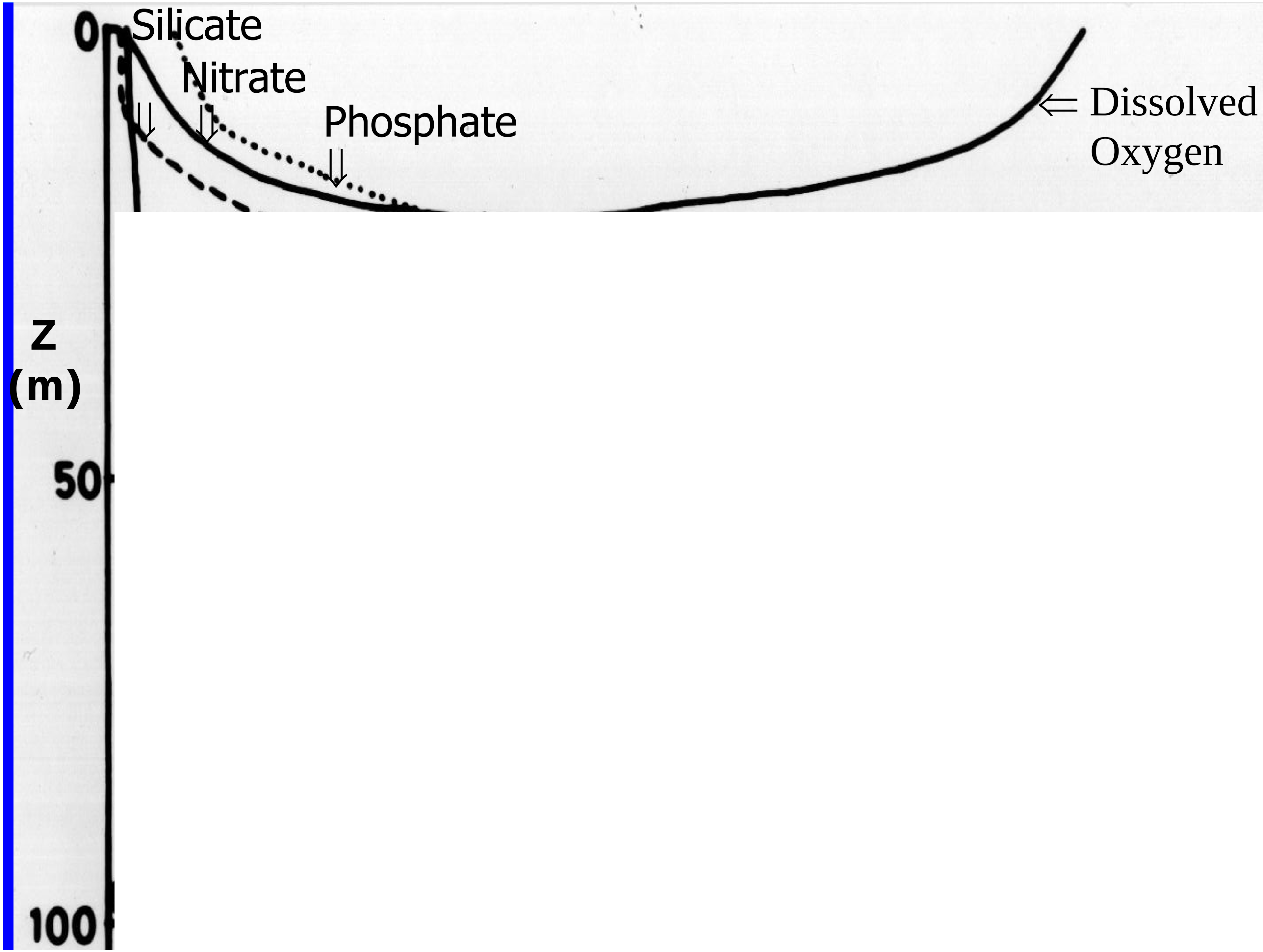
* High nutrients/low chlorophyll

Removal of nutrients:

Very active photosynthesis (>12 million diatom cells/litre) counted



Nutrients off Walvis Bay
Surface nutrients very low
DO
Nitrate
Phosphate
Nitrite
Silicate
Anoxic
Depth z (m)
0
50
100
O_2
NO_3-N
PO_4
NO_2-N
SiO_4
Concentration
O_2 0 2 4 6 8 ml/l
NO_2 PO_4 0 1 2 3 4 µg at/l
SiO_4 0 10 20 30 40 " "
NO_3 0 5 10 15 20 " "



Silicate
Nitrate
Phosphate
⇐ Dissolved Oxygen
Z (m)
0
50
100

Huge masses of organic matter sink when plankton and microbial biomass 'die' carrying the load of **detritus** below the Surface Water

Less dense surface water is separated by a significant pycnocline, (density increasing rapidly with depth) from denser deeper water

Detritus falls easily, but slowly, through the pycnocline, decay begins

Aerobic Decay (simplified)(Chester 1990)

$$5\{(CH_2O)_{106}(NH_3)_{16}\ H_3PO_4(s)\} + 690\ O_2(g) \xrightarrow[\text{microbes}]{\text{aerobic}}$$

5 moles "detritus" needs 690 mole O_2

$$530\ CO_2(g) + 80\ HNO_3(aq) + 5\ H_3PO_4\ (aq) + 610\ H_2O\ (l)$$

produces 530 mole CO_2

Regeneration to simple nutrients 99% complete by time detritus has sunk to 1000m

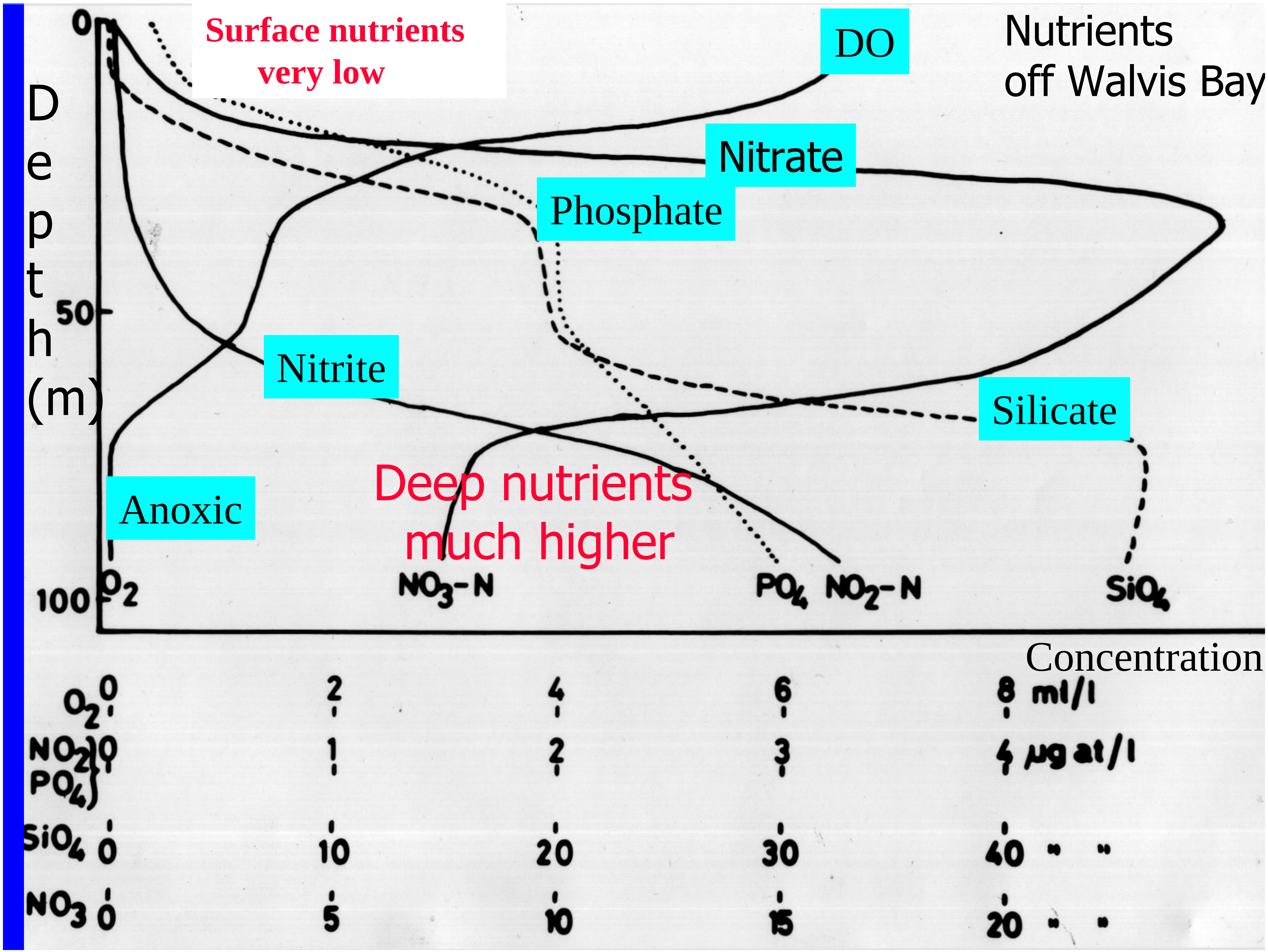
Were conditions <u>static</u>, the pycnocline would prevent upward turbulent mixing of deeper waters; molecular diffusion is orders of magnitude slower

Considerable energy is required to break down an intense pycnocline (stability proportional to $d\sigma_T/dz$, $z < 100m$)

There would be **no** mechanism to provide the Euphotic Zone with the nutrients depleted by photosynthesis, and the entire process would **stall:**

- **no life** in the sea,
- **no atmospheric O_2,**
- **excessive CO_2** in the air,
- a stinking, **stagnant mess** at all lower depths

How to re-supply Surface Water with the essential nutrients, now stored beneath: the lower half of the vertical section?


Nutrients off Walvis Bay
Surface nutrients very low
DO
Nitrate
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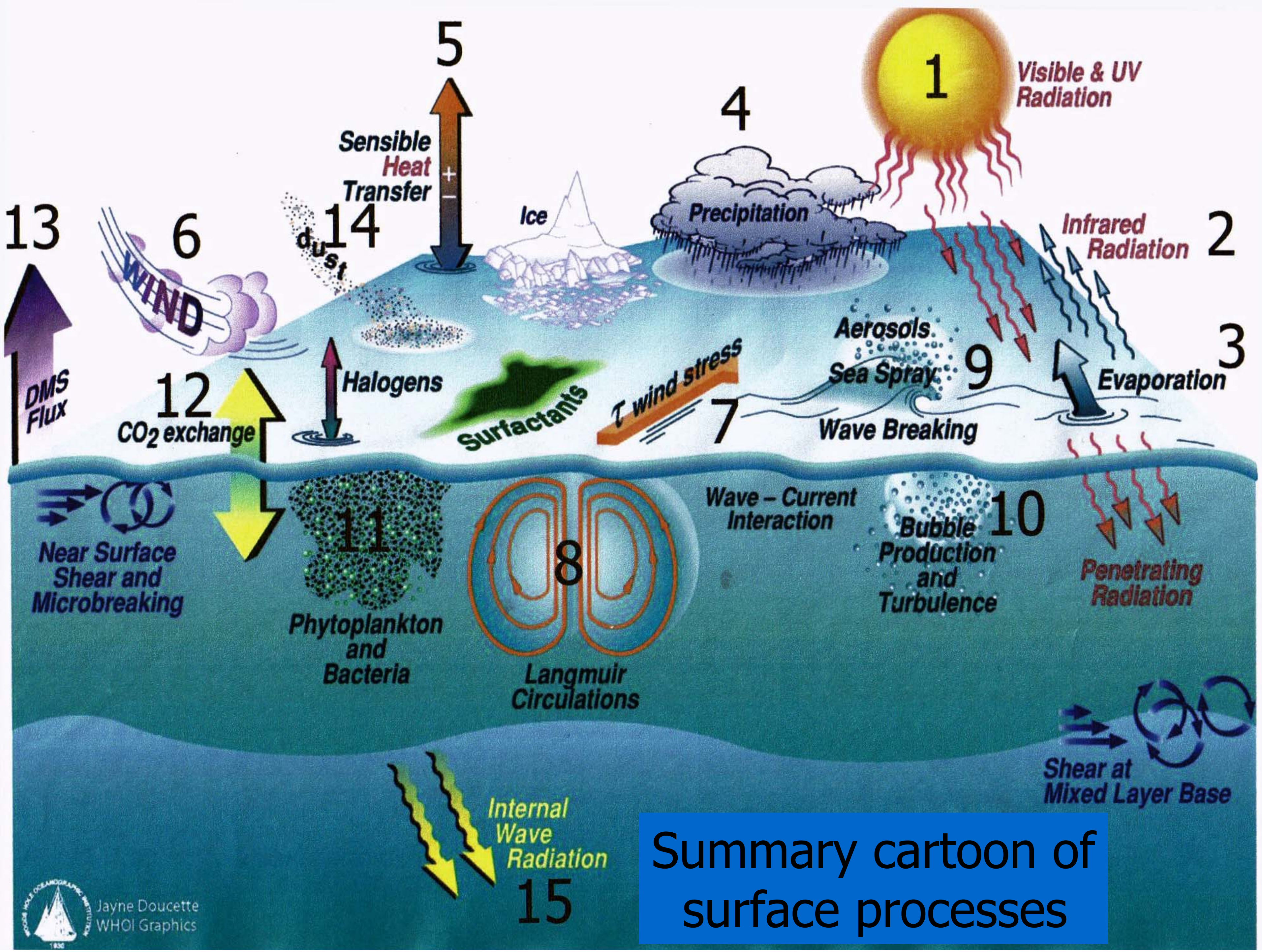
Nitrite
Silicate
Anoxic
Deep nutrients much higher
Depth (m)
0
50
100
O2
NO3-N
PO4
NO2-N
SiO4
Concentration
O2 0 2 4 6 8 ml/l
NO2 } PO4 0 1 2 3 4 µg at/l
SiO4 0 10 20 30 40 " "
NO3 0 5 10 15 20 " "

The global ocean on a rotating Earth is <u>never</u> static, and

physical processes which induce vertical mixing come to the rescue

There are many



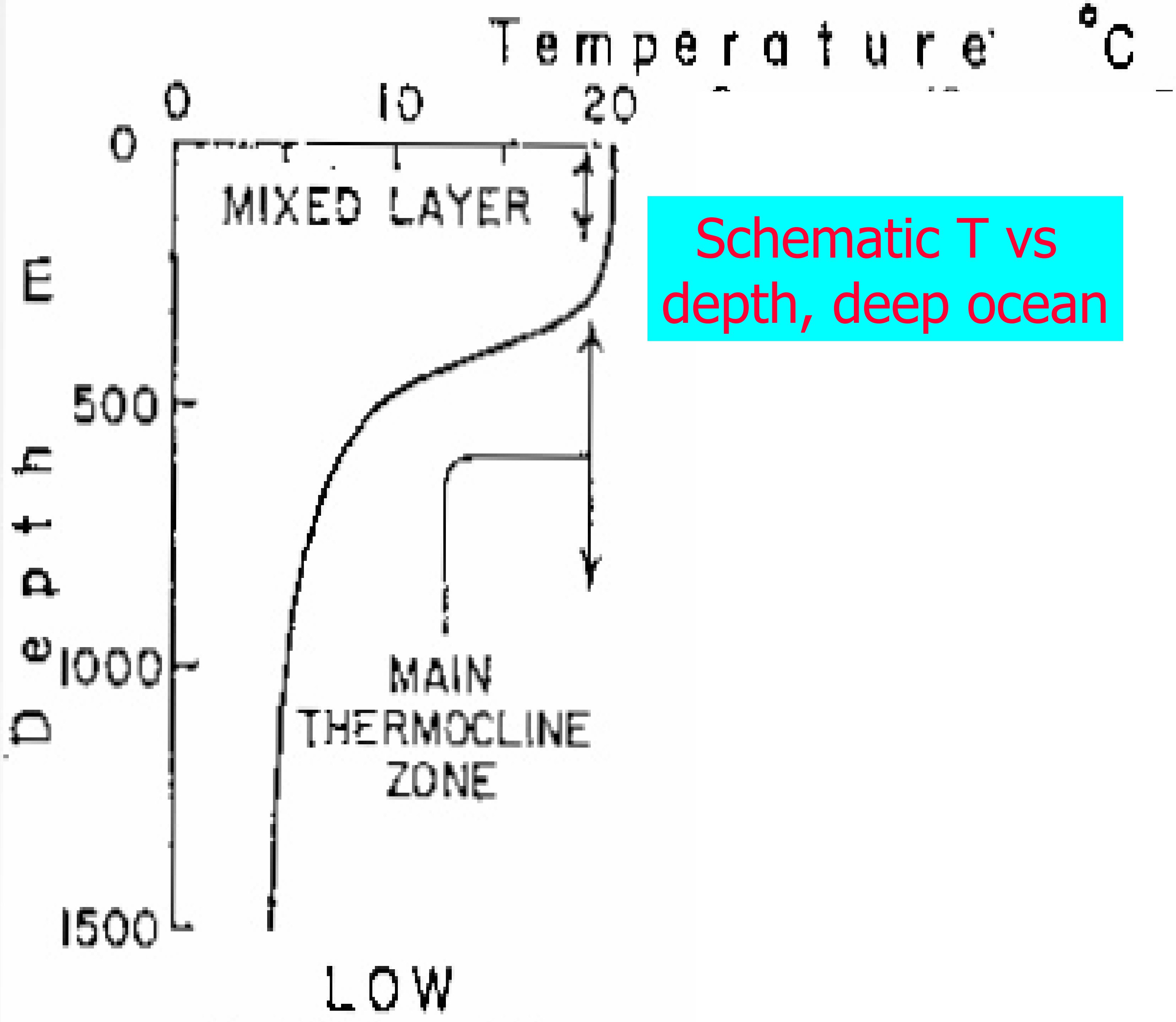
Summary cartoon of surface processes

Wave-induced mixing:

Wind-driven surface gravity waves mix deeper waters, typically from 20 to 60m depth, up to the Surface Water in the deep ocean, less in calmer coastal waters

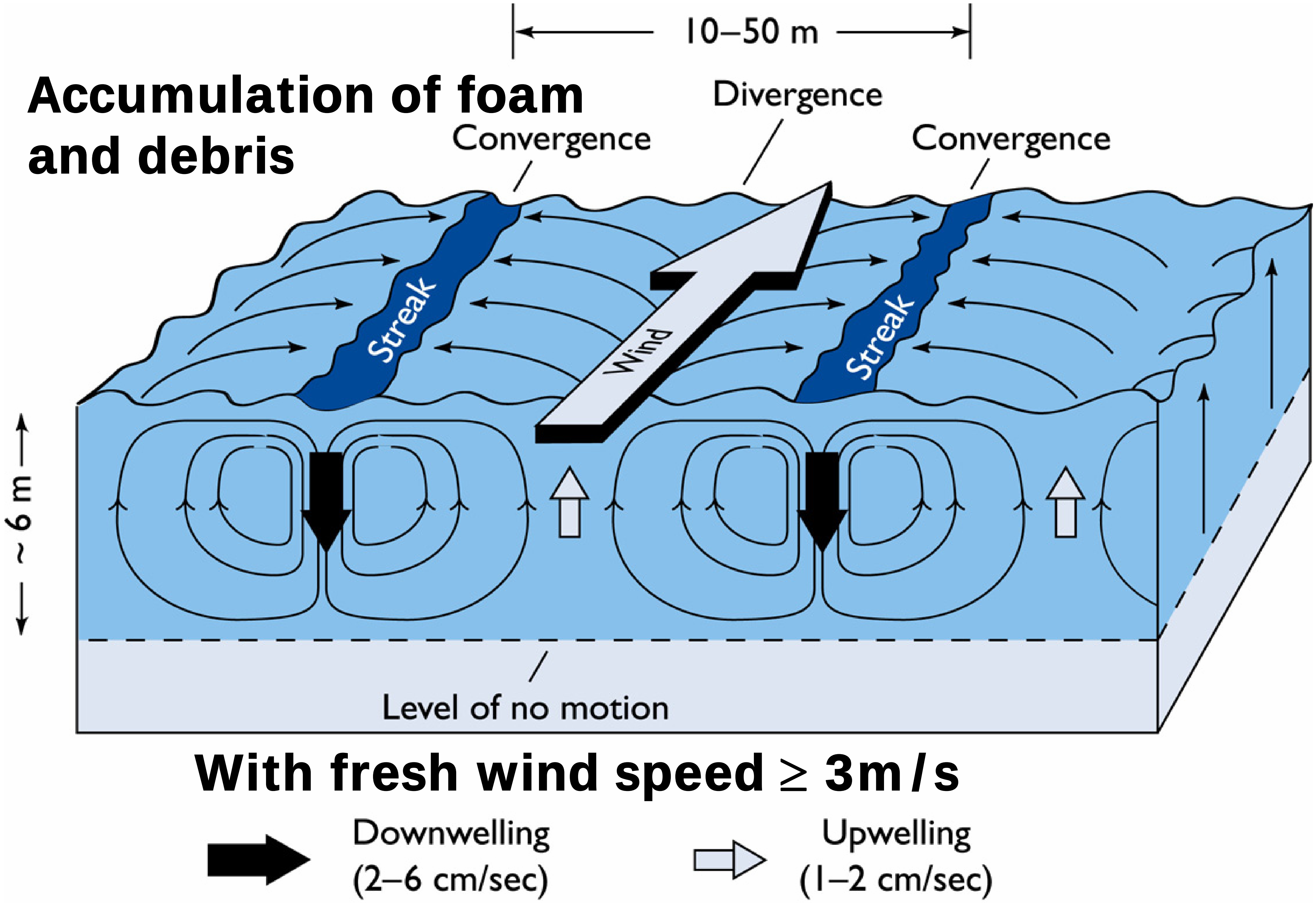
The almost ever-present waves keep Surface Water vertically well-mixed and almost homogeneous

½ way



Schematic T vs depth, deep ocean

Within the wave -mixed zone, localised Langmuir circulation strongly mixes nutrients when winds exceed about 3m s^{-1}, supplying nutrients more efficiently to growing blooms



(a) LANGMUIR CELLS

Water immediately surrounding growing cells is greatly depleted by strong gradient diffusion of nutrients into cell membrane

small-scale turbulent mixing considerably enhances the kinetics both of nutrient supply, and of oxygen removal

Slight, near-surface density inversions are maintained by strong Langmuir circulation (by about $\sigma_T \sim 0.02$ to 0.05)

[σ_T a density unit of seawater used by oceanographers, is Density-1000 kg/m^3 when pressure is 0 but the S and T are as *in situ;* σ_T for density of 1026 kg/ m^3 is thus 26.0]

Tidal current mixing:

If tidal range is large, e.g., North Sea, Severn estuary, strong tidal currents mix water from $\leq$ 70m to the surface

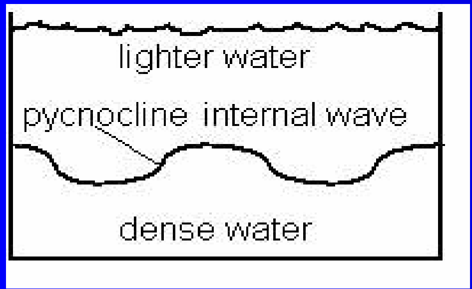
Resuspended fine sediment makes the water very turbid, and despite accompanying nutrient enrichment, light reduction decreases photosynthesis

Internal waves may be set up by current shear, tides, atmospheric disturbances, or even by ships (below)*, and propagate along the interface between water masses

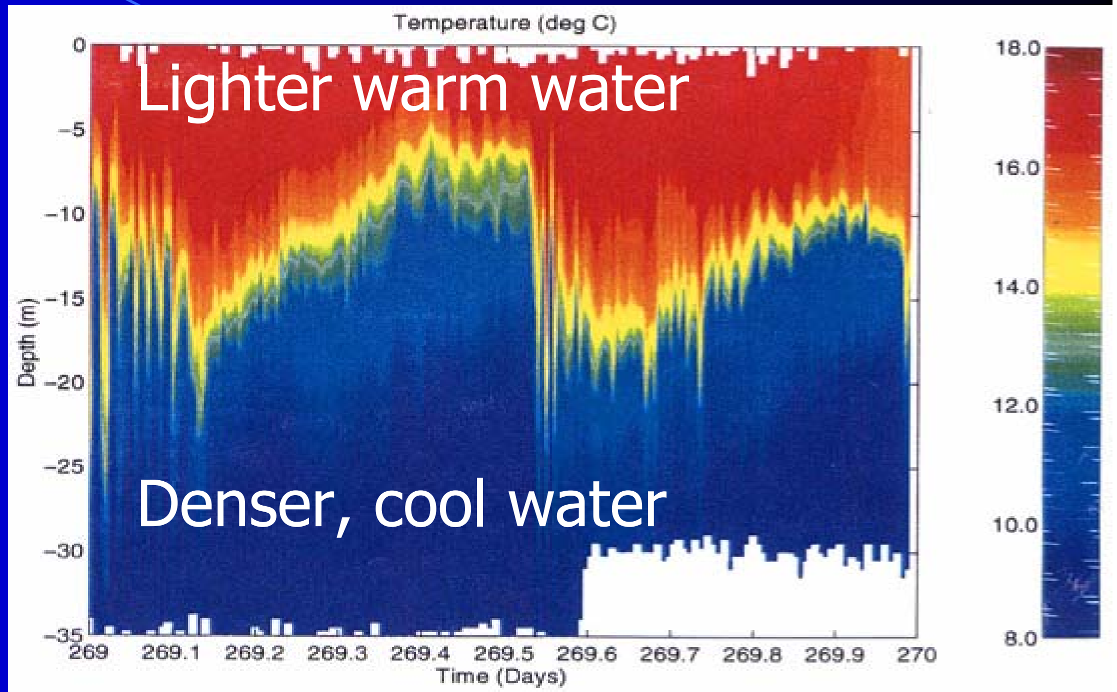
Internal wave breaking induces mixing from 50-100m or deeper to near surface

Breaking is enhanced in submarine canyons, shoaling waters or over rough topography

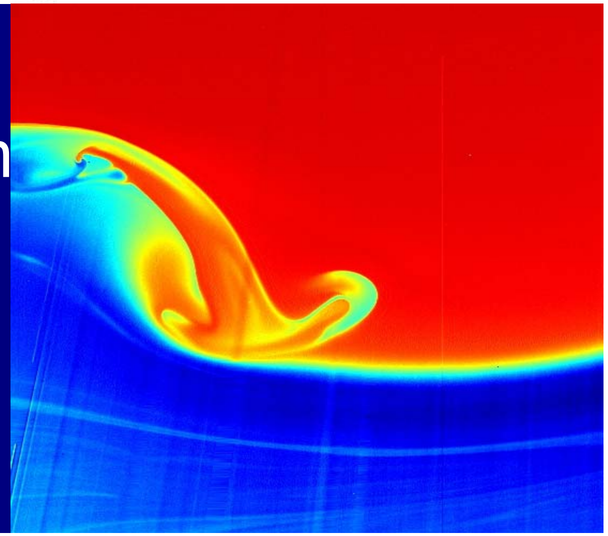
Internal waves occur along the boundaries of two fluids of different densities, e.g., water masses of different densities



Manifestation of internal waves at surface



Height may be quite large-say 10m and length 100m



Internal wave 'breaking' (model); intense mixing

* The '**dead water**' phenomenon

The forward momentum of a ship straddling an interface sets up internal waves and the energy loss for the ship almost stops it 'dead', despite increasing engine power

Puzzling for master mariners, even today!

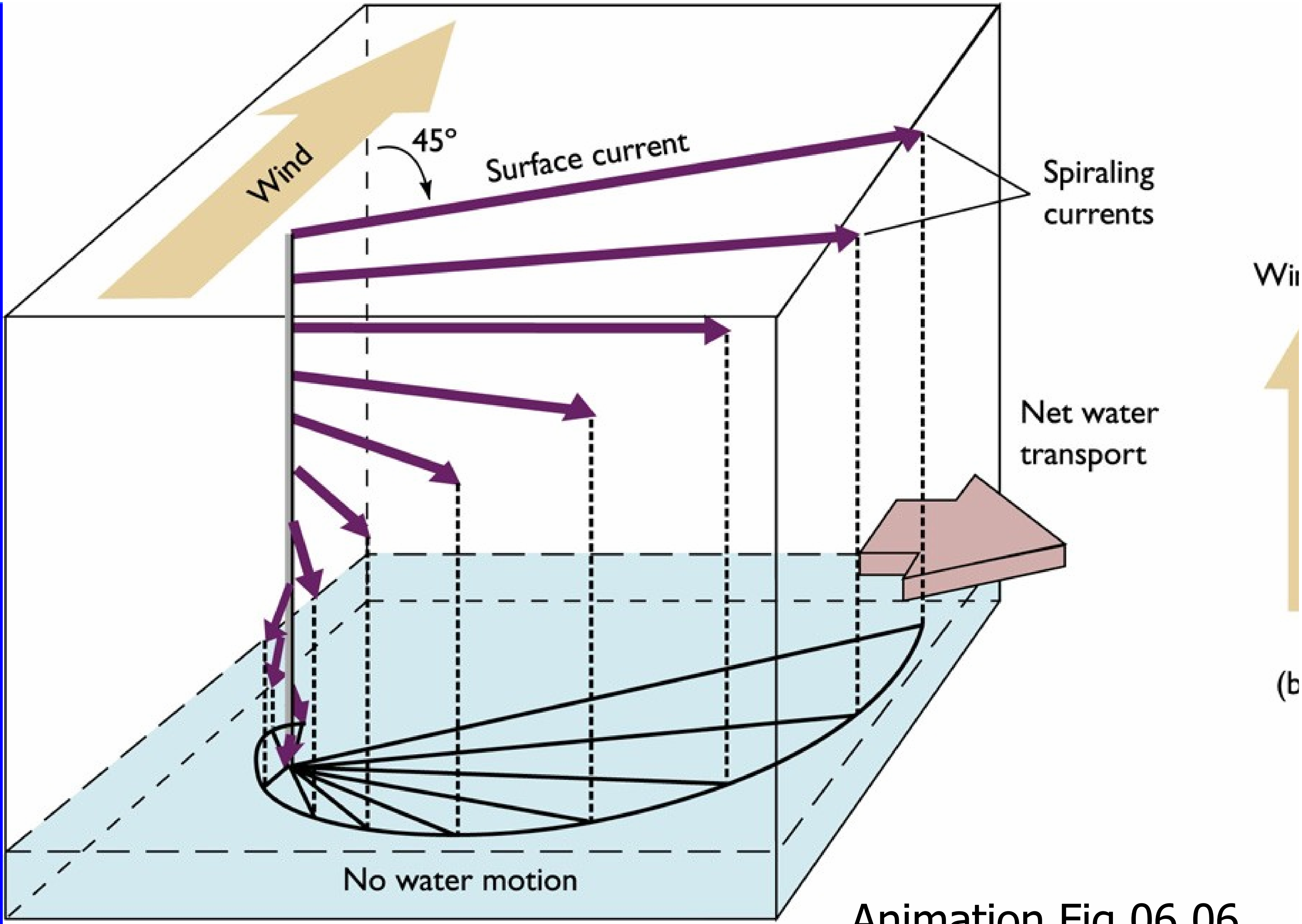
Observed by Fridtjof Nansen (1893-1896) in Arctic where fresher ice melt water lies over denser saline water; often observed in the Kiel Canal, Kattegat, Baltic and the Dardanelles

Upwelling:

the major process for bringing deep, nutrient-rich water to the euphotic zone

With appropriate winds, Ekman transport brings water from as deep as several 100’s metres to near surface, enhanced by topography such as canyons and headlands

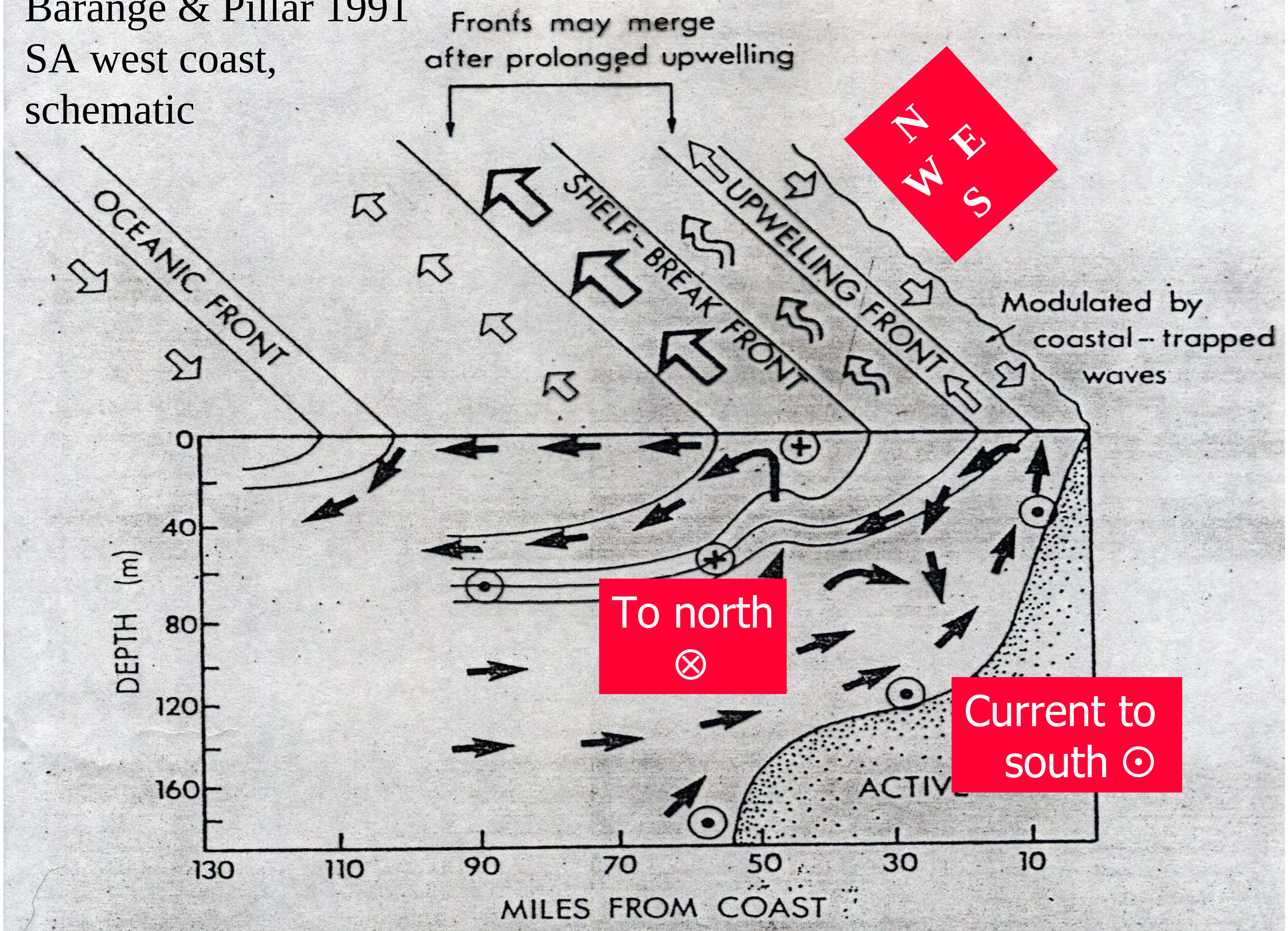
Photosynthesis is greatly enhanced and shoals of commercial fish flourish



(a) EKMAN SPIRAL IN THE NORTHERN HEMISPHERE

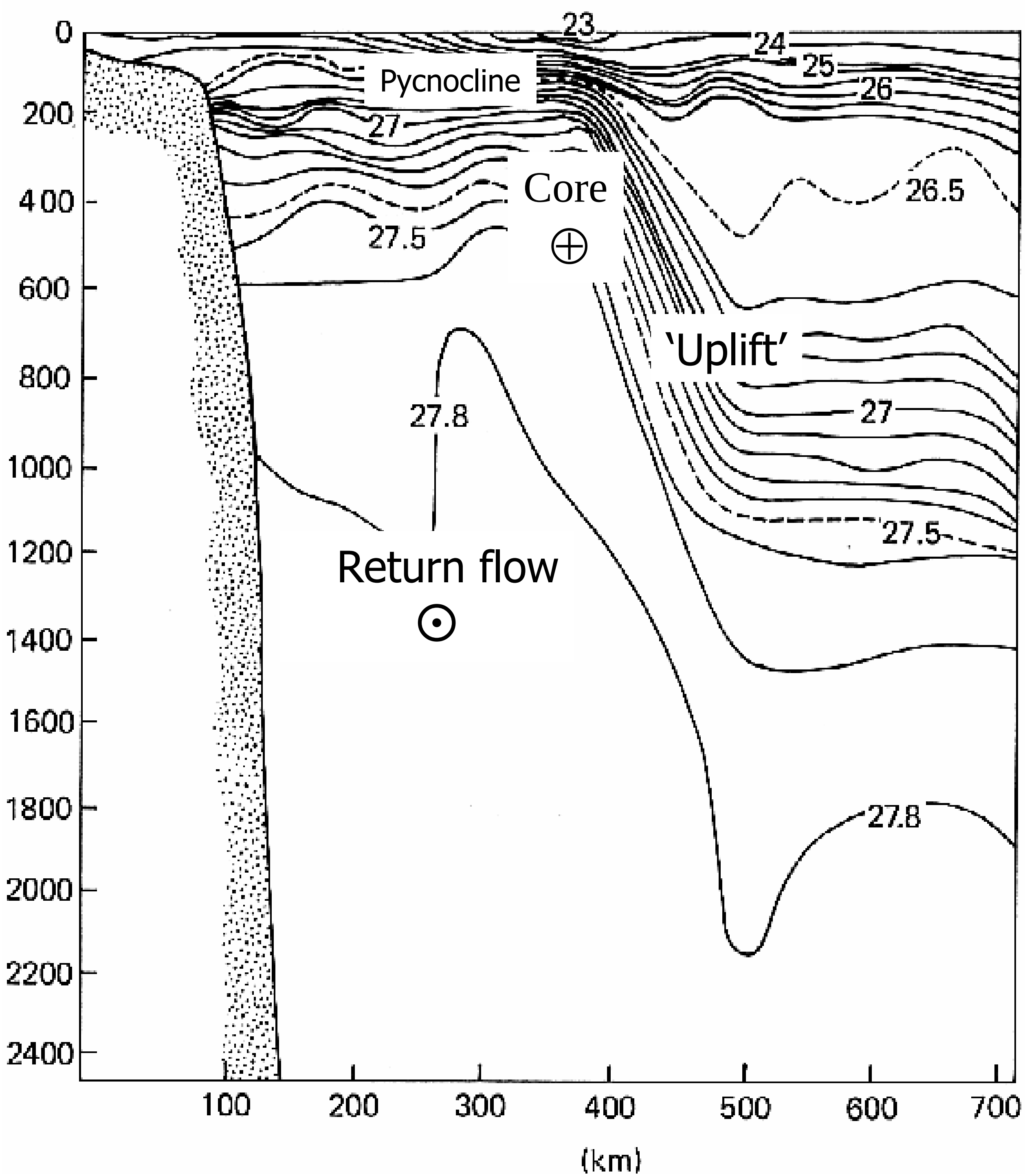
Animation Fig 06 06

Barange & Pillar 1991
SA west coast,
schematic



In large momentum currents (N. Hemisphere) lighter water lies offshore, the isopycnals are tilted up towards the Continental Shelf, e.g., North Atlantic Drift, (Gulf Stream), Agulhas Current (South Africa)

This causes uplift of deeper water when the current is close to the shelf-a kind of “dynamic upwelling”



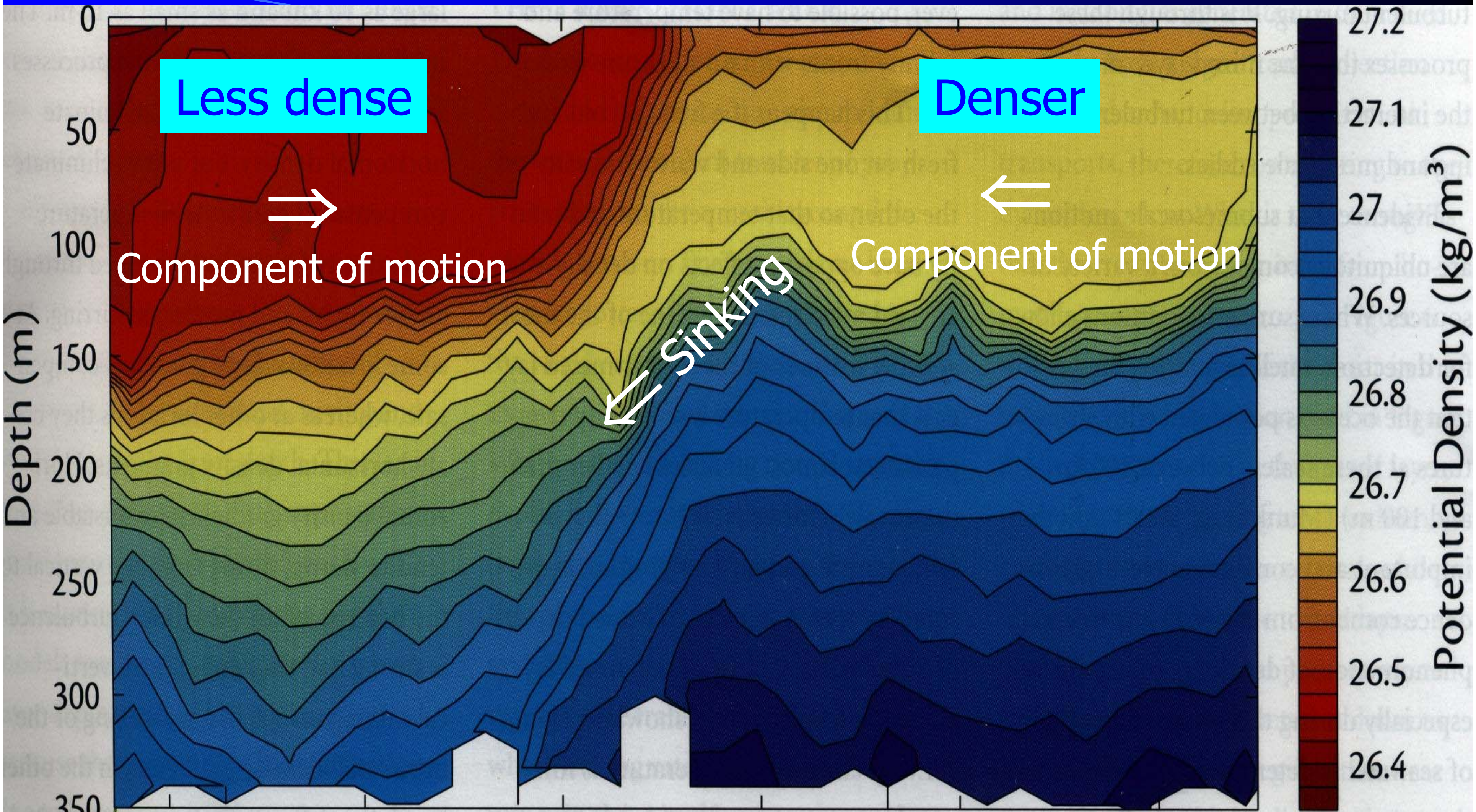
Isopycnals section, Gulf Stream, σ_T vs depth

Current is flowing into the plane of the diagram ⊕; return current out ⊙

Uplifted, nutrient-rich water spreads laterally across the shelf under the pycnocline and is mixed upwards by local upwelling, storm waves, or internal waves

Internal waves propagate along the interface between cool, uplifted water and warmer water, ‘breaking’ in shallow water or over rough topography

Mixing occurs across deep-sea fronts when warm, less dense surface water converges with cold, dense surface water



Similar density ‘Front’ to that at the Polar Front and Subtropical Convergence with warmer water (red) abutting cooler water of higher density (yellow). Cooler, denser water sinks and spreads when it reaches the same density level

Meandering causes vertical motion

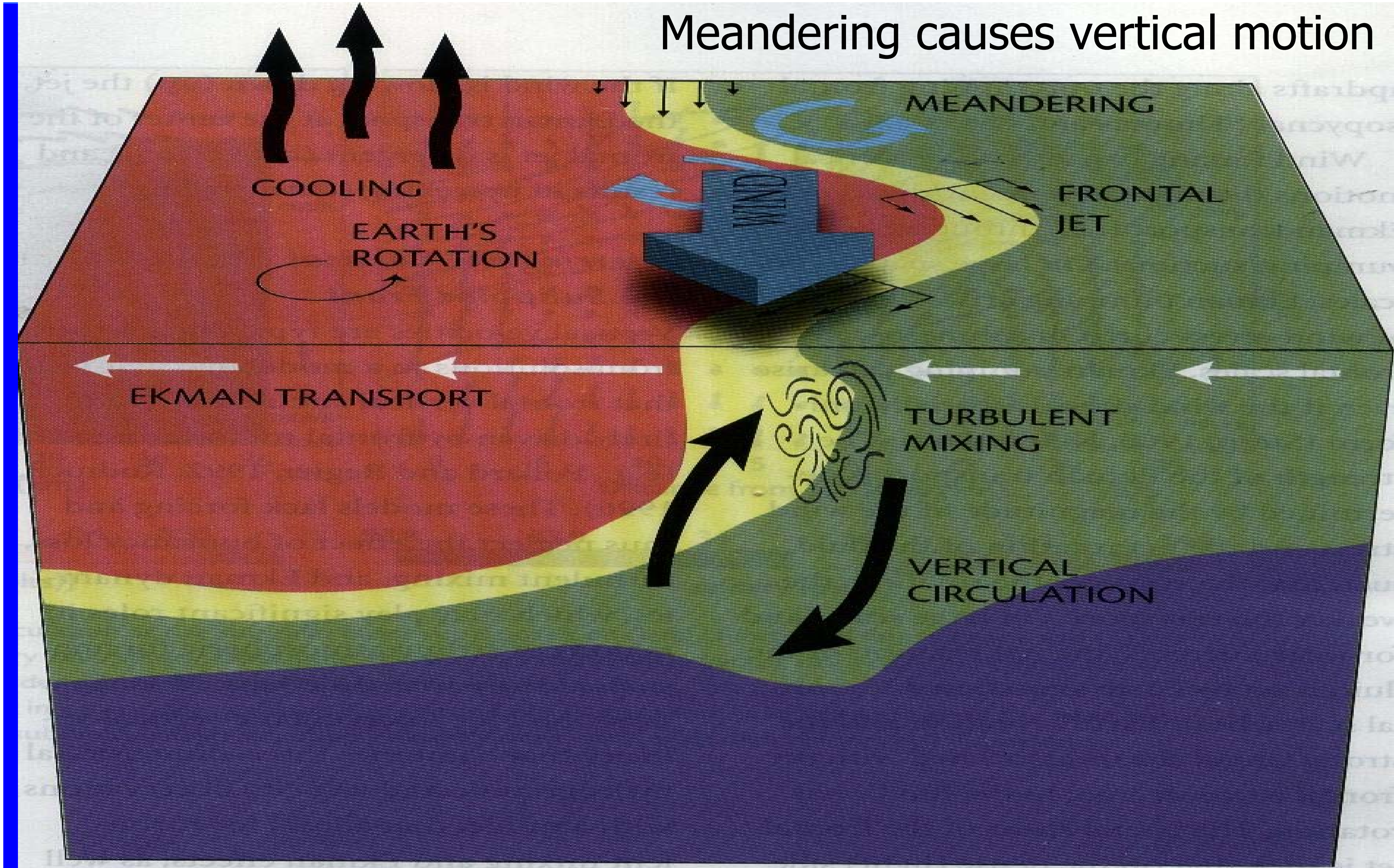
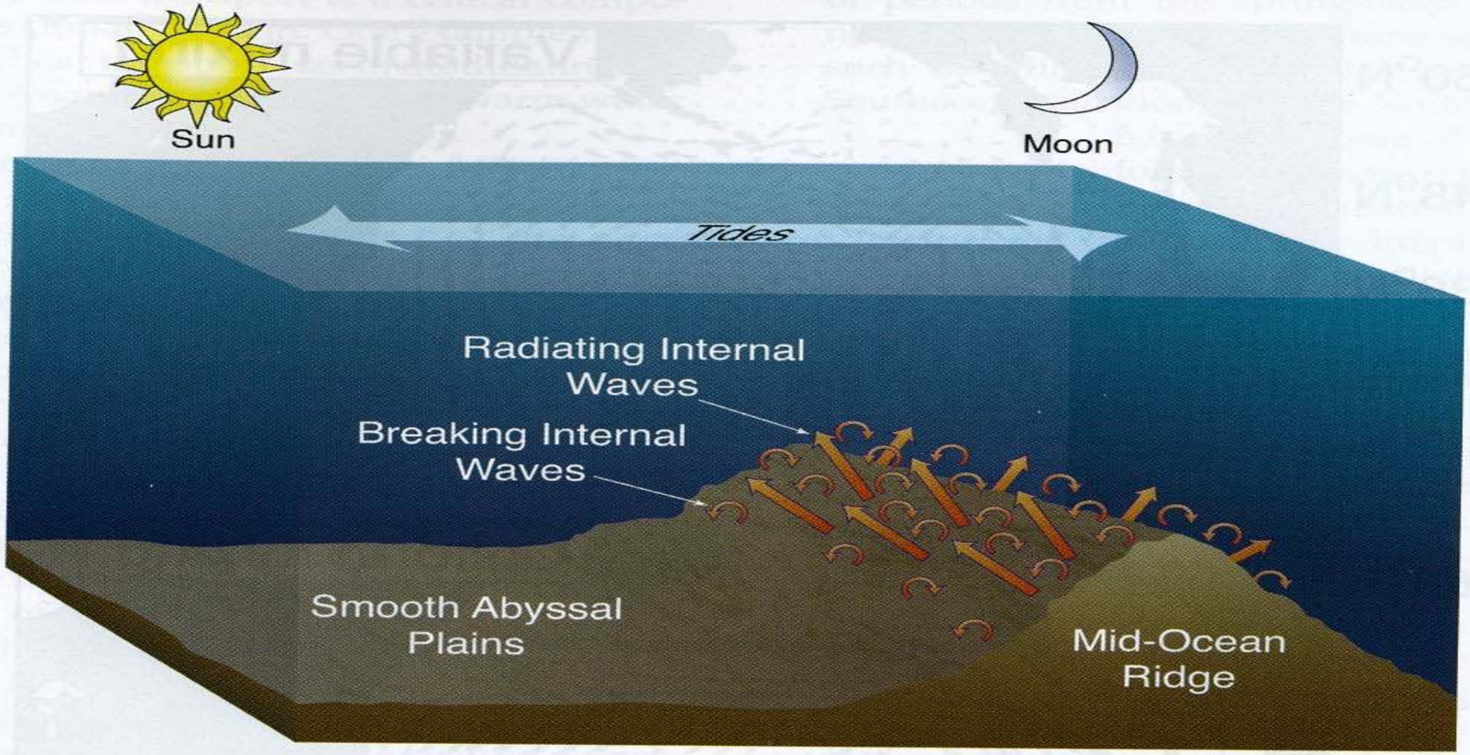


Figure 8. Schematic illustrating the various processes that can generate vertical circulation at a front. Frontal meandering can induce vertical motion irrespective of atmospheric forcing. Forcing by wind stress and/or surface cooling can drive turbulent mixing due to destabilizing buoyancy loss and, for along-front wind forcing, advection of denser water over light by Ekman flow. Lateral shear associated with the frontal jet can impart cross-front variability in Ekman transport, generating convergent/divergent flows. These processes break the geostrophic balance of the frontal jet and drive greatly enhanced vertical circulation.

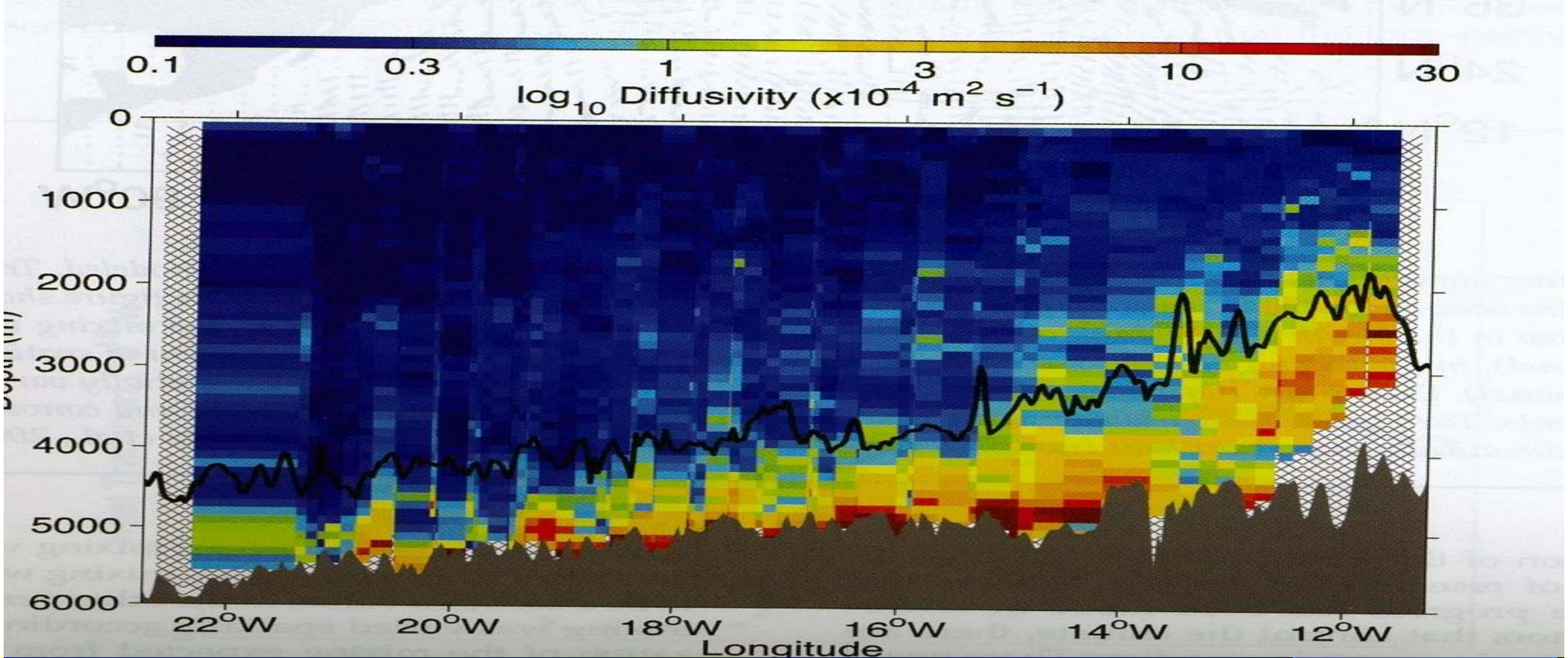
A long-standing problem in oceanography-how does deeper water mix back up to the upper layers?

Tidal currents passing over deep ridges or rough topography set up internal waves which radiate away and break, causing turbulent mixing

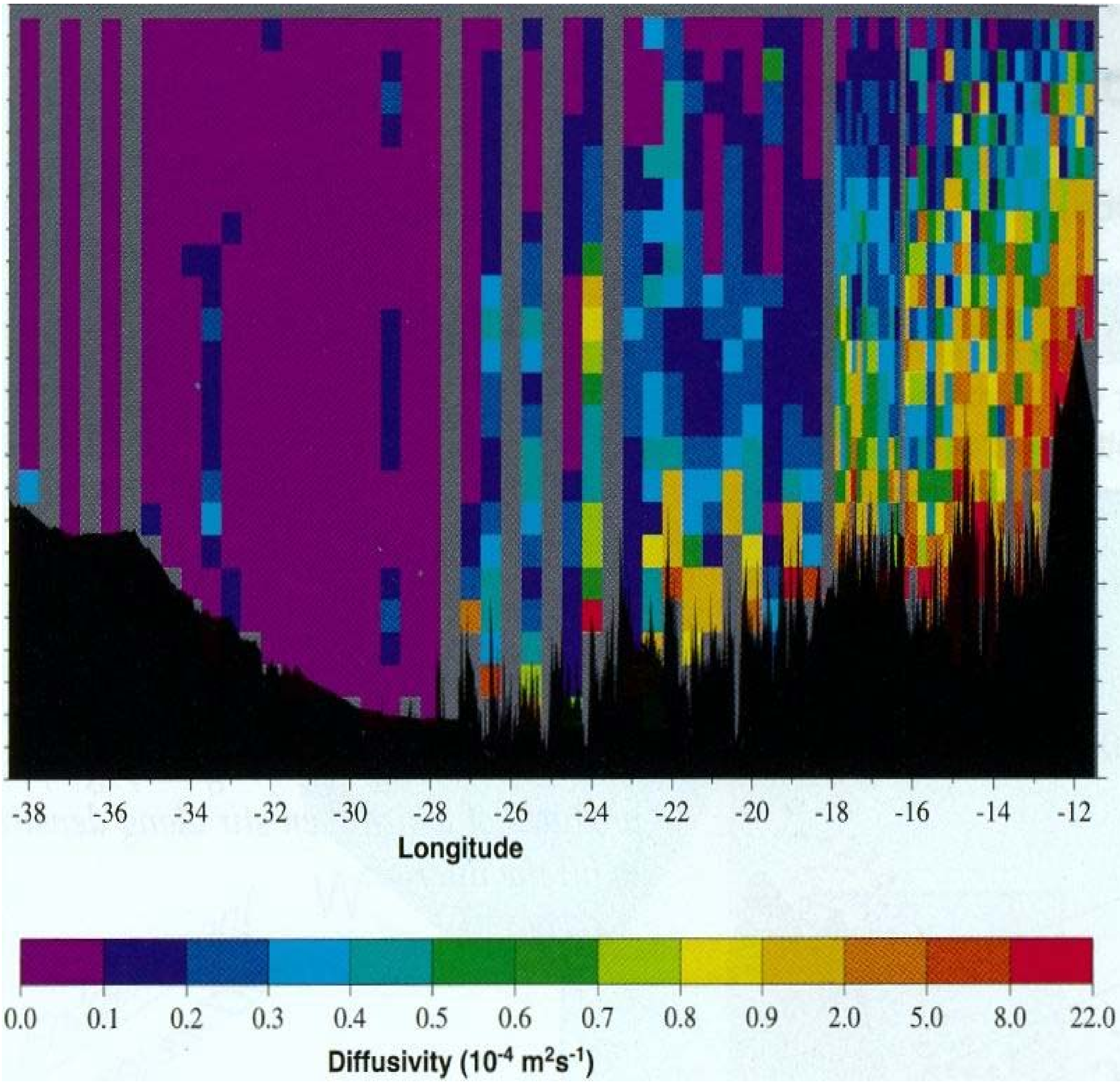


Internal tidal currents passing over a ridge create internal waves which greatly increase mixing:schematic

Such waves reach 80m (peak to peak) over the Kerguelen Plateau (Park *et al.*, *Deep-Sea Research Part II* **55 (5-7)** 582-593, April 2008)



Diffusivity as measure of **mixing intensity**, increasing as topography roughens


-38 -36 -34 -32 -30 -28 -26 -24 -22 -20 -18 -16 -14 -12
Longitude
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 2.0 5.0 8.0 22.0
Diffusivity (10^{-4} m^2s^{-1})

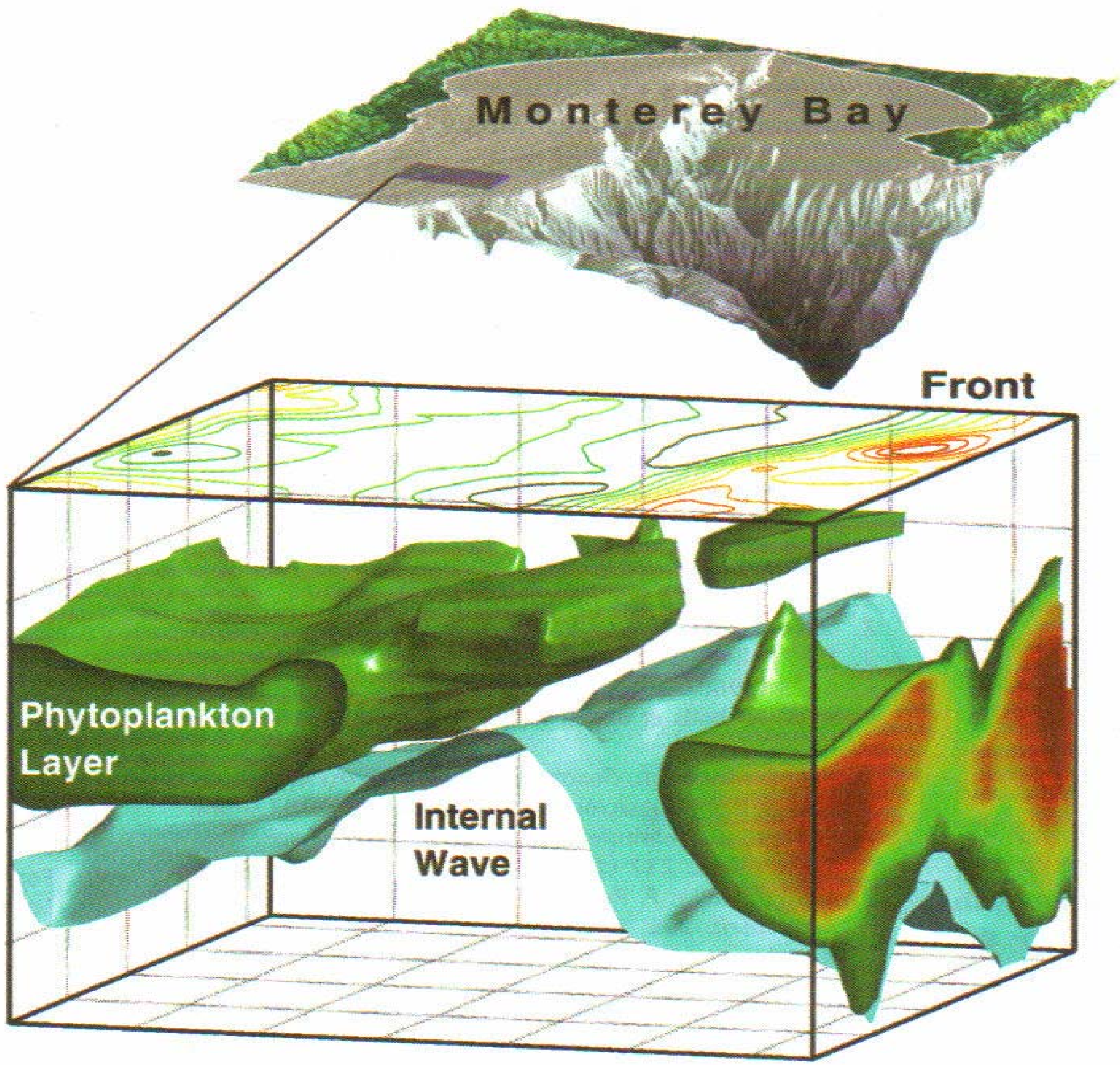


Fig. 3. A three-dimensional image of the interaction of physical and biological processes, as mapped by an Odyssey AUV off the coast of California (*52*). The green volumes show a phytoplankton layer, detected by its chlorophyll fluorescence. The underlying cyan surface shows deflection of the constant-density surface by an internal wave, interrupting the phytoplankton layer. To accomplish this survey, the AUV moved in a sawtooth pattern across the survey area while profiling vertically. The volume shown is 6.5 by 2.5 km in horizontal extent and 23 m in depth.

Real-life mapping of interaction of physical and biological processes by submersible (AUV), Monterey Bay, CA, USA

Life both in the oceans and that of all higher animals clearly depends on marine photosynthesis and on physical mixing processes-are these in equilibrium?

CO_2 dissolves, is utilised, ϕ producing O_2

Microbial decay: 99% detritus releases CO_2, taking up O_2 in upper 1000m

~1% detritus reaches bottom sediments-were this not so, **all** O_2 produced would be used in microbial decay **none** would enter the atmosphere!

Atmospheric free oxygen first appeared 2.2 billion years years ago-

% composition has varied little for **millions of years**

A finely balanced set of very complex biogeochemical processes-until man introduced extra fossil fuel burning and excess CO_2

"Oceanic productivity, fishery yields and the net marine sequestration of atmospheric greenhouse gases are all controlled by the structure and function of planktonic communities"

Karl *et al.*, 2001

"The sea is as important as the atmosphere in controlling the planet's weather"

(Webster & Curry, 1998)

53 times total amount of $CO_{2(atmosphere)}$ today is dissolved in the global ocean

which is absorbing about 10^6 tonnes an hour, and

has absorbed about 48% of all man-made CO_2, totalling 118 billion tonnes

Uptake now reduced to ~ 37±7% (because of Global Climate Change)

Southern Ocean wind speed increase:
has reduced CO_2 uptake there (15% global CO_2 sink is in Southern Ocean)

Extra CO_2 has made seas more acid (pH decrease) hampering growth of many microscopic creatures and shellfish which use calcium carbonate for structures

Uptake is less efficient in more acidic water, reducing food supply for fish

Photosynthesis **slows** as water warms hence less CO_2 is absorbed, also CO_2 is slightly less soluble in warmer water

These now warmer sea surfaces are less productive: less photosynthesis, less marine life, less oxygen

"Ocean deserts", the vast subtropical gyres with little life, have increased in area by **15%** from 1998 to 2007 (NOAA, 2008)

Sea level is sneakily creeping up on us by 2 mm a year; **all** low-lying coastal areas are increasingly threatened with severe flooding during storm surges at high spring tides

The ocean has been man's friend for a long time but its capacity to cope with our excesses is declining

These results are derived from from quality scientific research, let us continue to extend this so as to still better understand our global ocean/atmosphere system

The End