Benthic oxygen demand = sediment respiration = benthic metabolism

Aerobic demand measured as O_2 consumption in cores or in situ

Oxygen is the most efficient electron acceptor
highest ΔG; The other acceptors are vertically structured
Electrons are transferred as H^+ ions
$(1/2\ H_2 \rightarrow H^+ + e^-)$

Total metabolism measured as CO_2 production

CO_2/O_2 rates = respiratory quotient (RQ)
= 0.8 - 1.2 for aerobic respiration
> when anaerobiosis is present

Convert O_2 to CO_2 with RQ, subtract from total CO_2 production to partition aerobic vs anaerobic

Sulfate reduction (primary anoxic respiration) measured with ^{35}S incorporation into sulfides

Bacterial carbon transformations in sediments

CHO = organic compound $\leq C_6$

<u>Respiration</u>

aerobic: $CHO + O_2 \longrightarrow CO_2 + H_2O$

nitrate red: $CHO + NO_3 \longrightarrow CO_2 + NH_3$

$\longrightarrow N_2$ (denitrification)

sulfate red: $CHO + SO_4 \longrightarrow CO_2 + H_2S$

methanogenesis: $CHO + CO_2 \longrightarrow CO_2 + CH_4$

fermentation: $\underset{\text{ethanol}}{C_2H_3O_2} + \underset{\text{acetate donor}}{C_2H_6O} \longrightarrow \underset{\text{butyrate}}{C_4H_7O_2} + H_2O$

<u>Autotrophy</u>

photo- $CO_2 + H_2O \xrightarrow{\text{light}} CHO + O_2$ (oxygenic)

photo - $CO_2 + H_2S \xrightarrow{\text{light}} CHO + S^{\circ}$ (anoxygenic)

chemo - $H_2S + O_2 \longrightarrow H_2O + S$ + energy

nitrification $NH_3 + O_2 \longrightarrow H_2O + NO_3$ + energy

methylotrophy $CH_4 + O_2 \longrightarrow H_2O + CO_2$ + energy

All chemo: $CO_2 + \xrightarrow{\text{energy}} CHO$

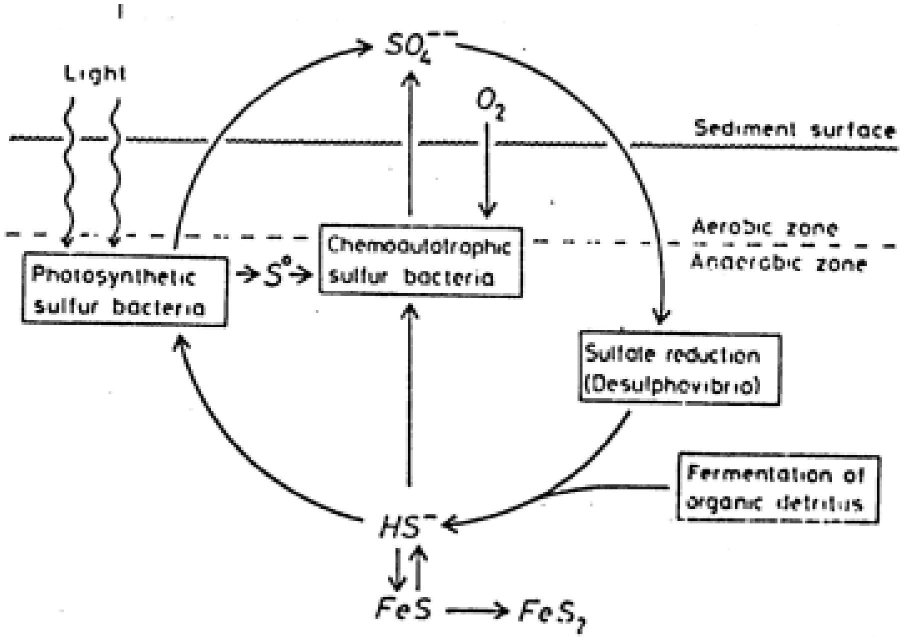
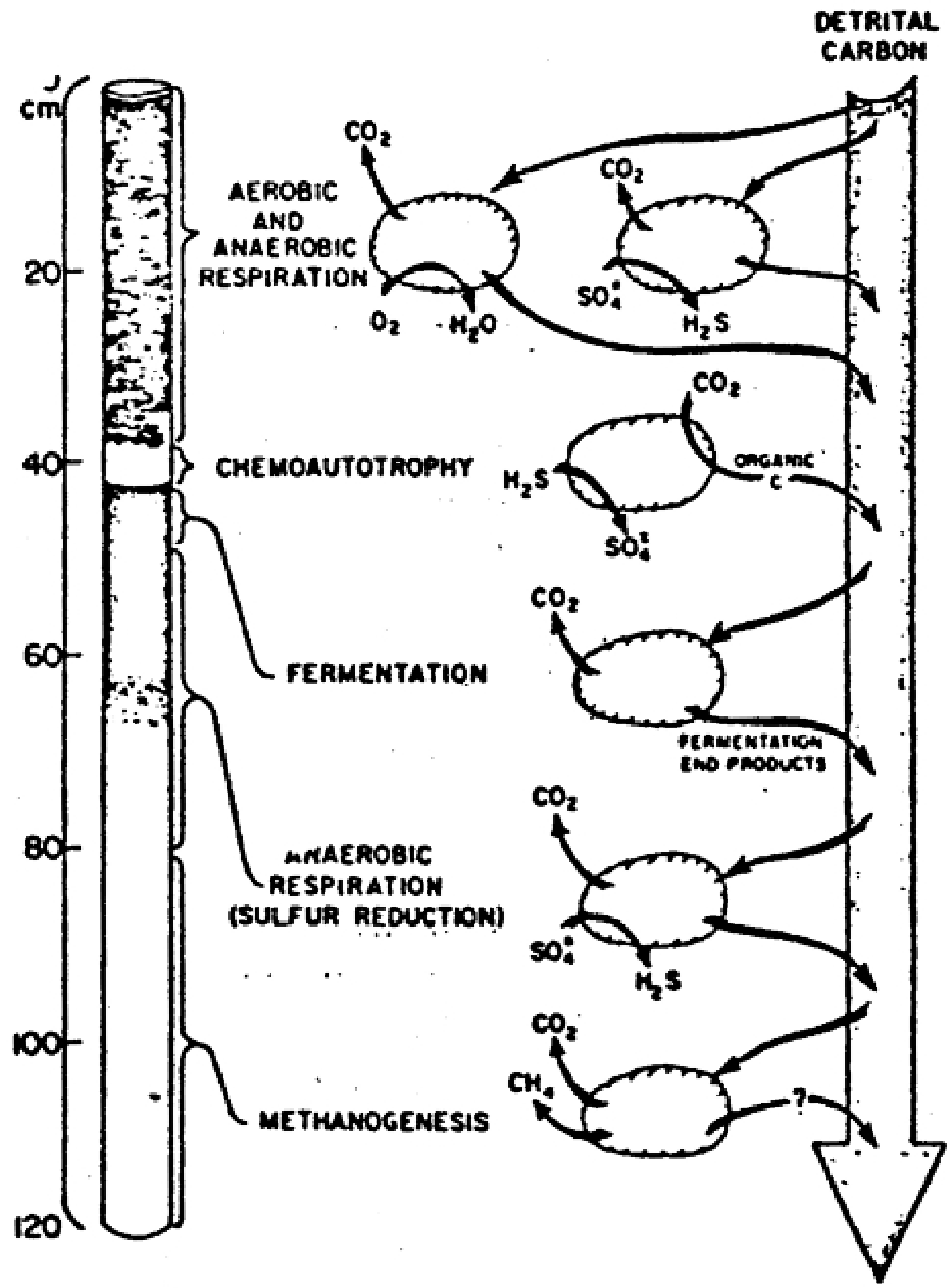


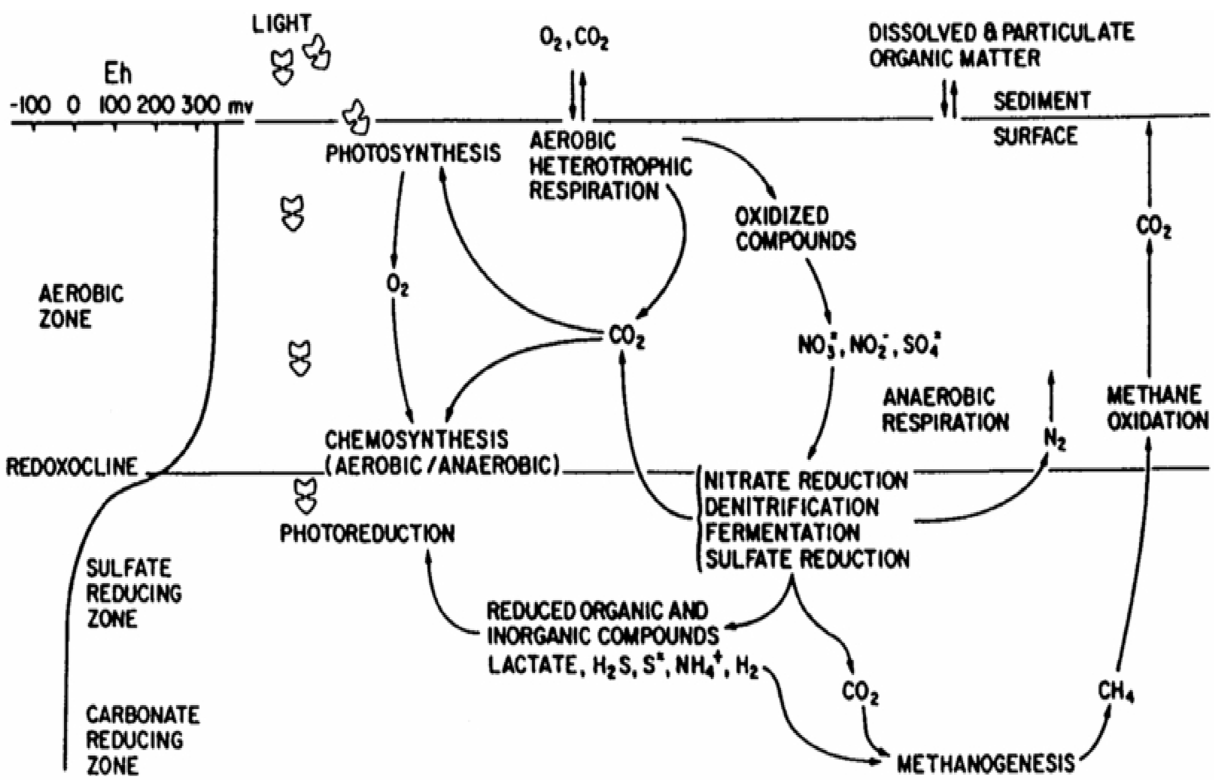
Fig. 21. The microbial sulfur cycle.

Vertical structure of electron acceptors



Schematic diagram of microbial metabolism and carbon flow in Halifax Harbor sediments. Only the predominant type of metabolism is listed for the various horizons. This does not imply that they are exclusive or nonoverlapping

A summary of biogeochemical processes in marine sediments



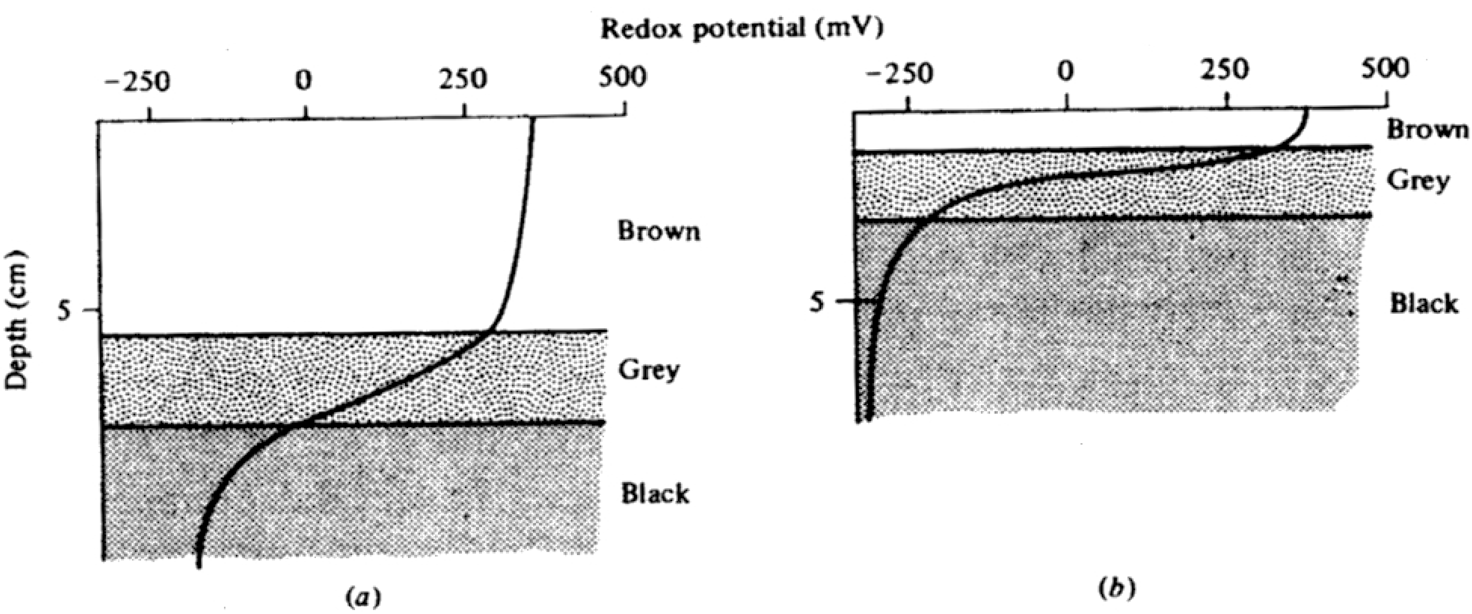
Inter-relationships between photosynthetic, heterotrophic, and chemosynthetic processes in sediments. Photosynthesis and photoreduction only occur in the presence of light. *Aerobic metabolic processes:* heterotrophic respiration (oxidation of simple reduced organic compounds with possible reduction of CO_2); photosynthesis (reduction of CO_2 to carbohydrates using H_2O and light); aerobic respiration (reduction of oxygen to water with organic compounds as electron donors); aerobic chemosynthesis (oxidation of CH_4, H_2S, NH_3, Fe^{++}, H_2 to form organic carbon compounds by fixation of CO_2). *Anaerobic metabolic processes:* anaerobic respiration (oxidized inorganic end products of aerobic decomposition used as hydrogen acceptors for the oxidation of organic matter); fermentation (organic compounds used as hydrogen acceptors to produce CO_2, H_2O and reduced organic compounds such as lactate, glycollic acid, H_2S, NH_3); photoreduction (reduced compounds used to reduce CO_2 to carbohydrates in the presence of light with H_2S, SO_3, S, H_2 or reduced organic compounds serving as hydrogen donors); anaerobic chemosynthesis (oxidize inorganic compounds H_2, H_2S, Fe^{++} $NO_2^=$ and use energy to reduce CO_2 to carbohydrates) (redrawn from Fenchel, 1969, with modifications).

Sediment redox reactions

Shortage of electron acceptors leads to negative electrical potential in 'reducing' sediments measured with an electrode in mV.

Zero mV is the redox potential discontinuity
Generally means anoxic sediments, but is not a measure of oxygen

Typical redox potential profiles for two intertidal sediments: (*a*) medium sand, (*b*) fine sand.

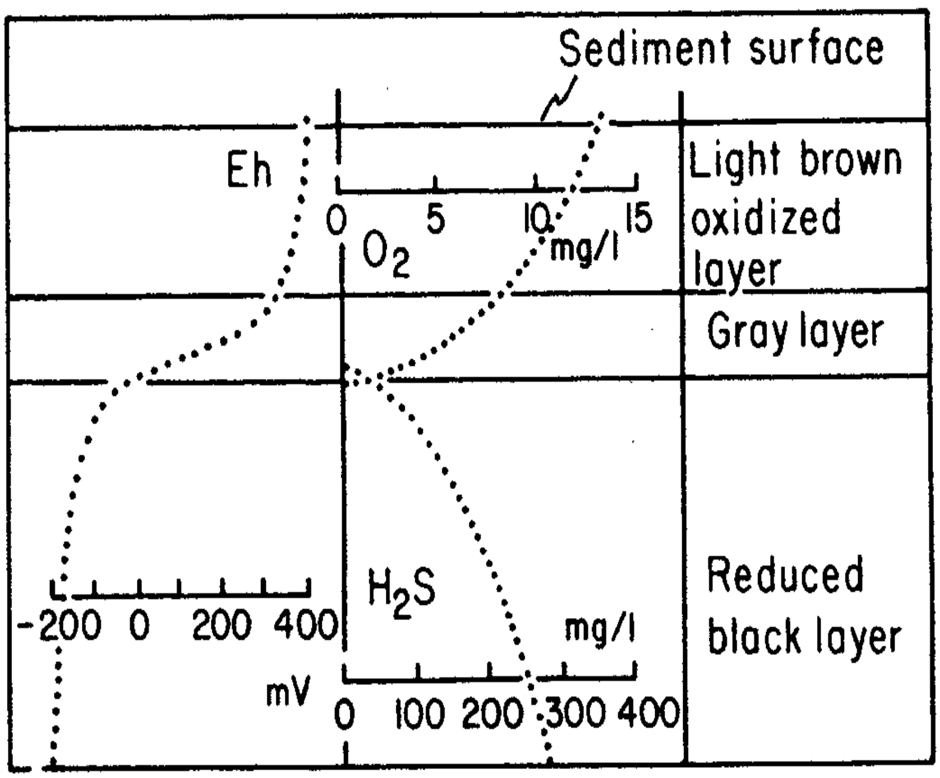


Oxygen in sediments

Diffusion limited relative to consumption

Organic loading = excessive consumption = zero oxygen (e.g. hypereutrophication)

Vertical structure



Schematic representation of the vertical distribution of some chemical properties of a typical marine bottom mud. (Modified after Fenchel and Riedl, 1970, from *Marine Biology*, vol. 7)

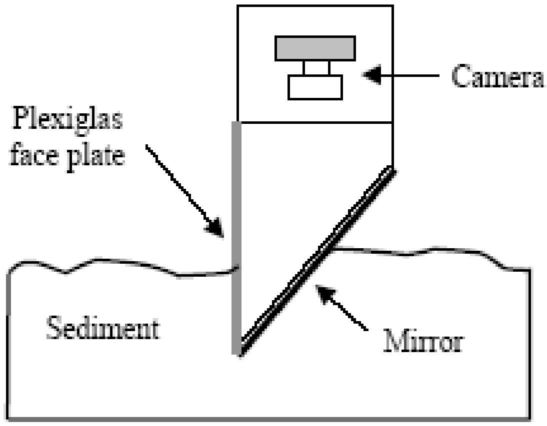
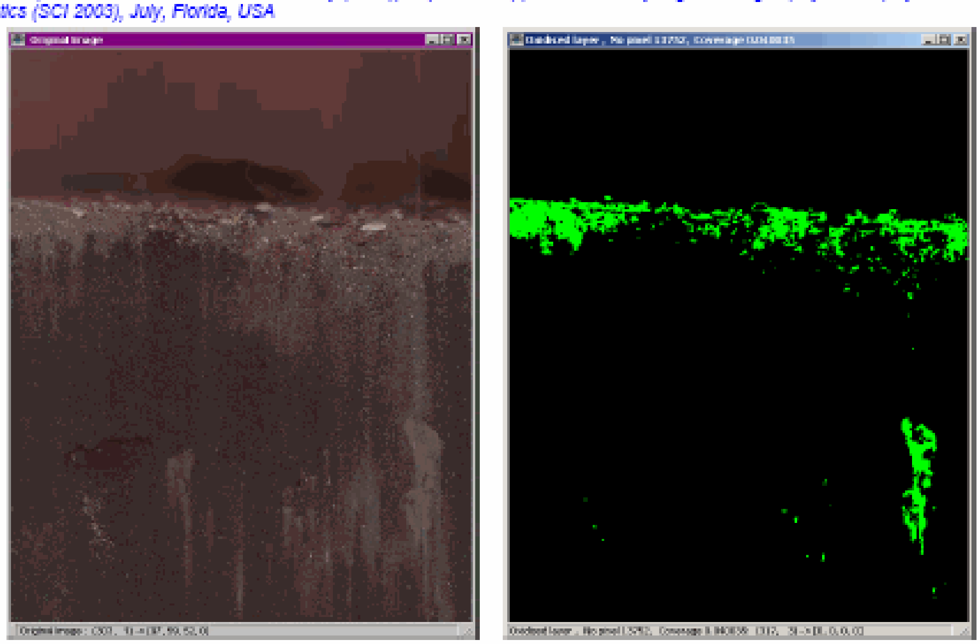


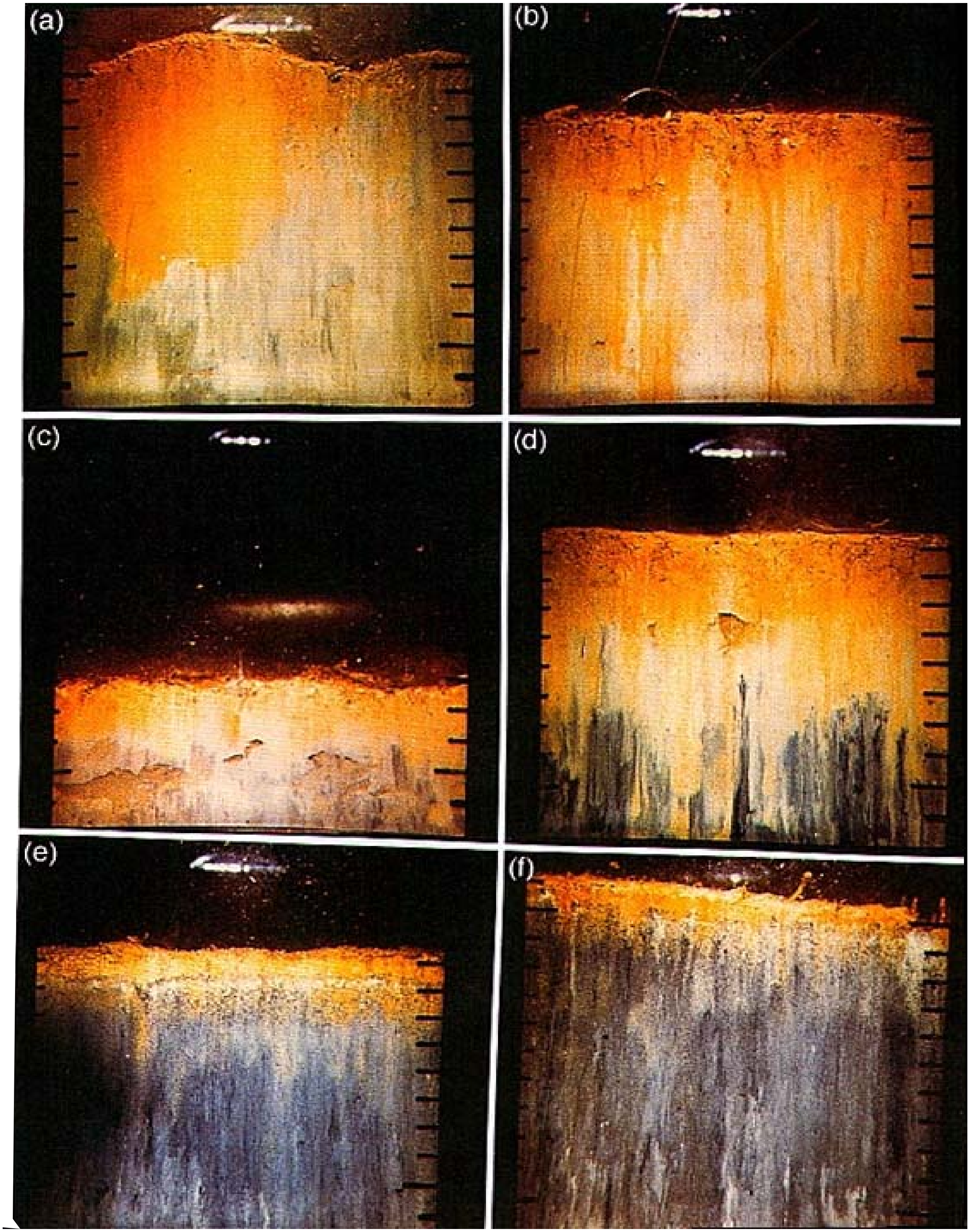
Figure 1. Diagram of the SPI camera.

Ovidiu Ghita, Paul F Whelan and Robert Kennedy (2003), "A practical approach for analysing SPI images", Systemics, Cybernetics and Informatics (SCI 2003), July, Florida, USA



(a) (b)

Figure 4. Detection of the oxidised layer. (a) Original image (sample Scangbds8-3).
(b) Oxidised layer.



Reducing sediments and the RPD

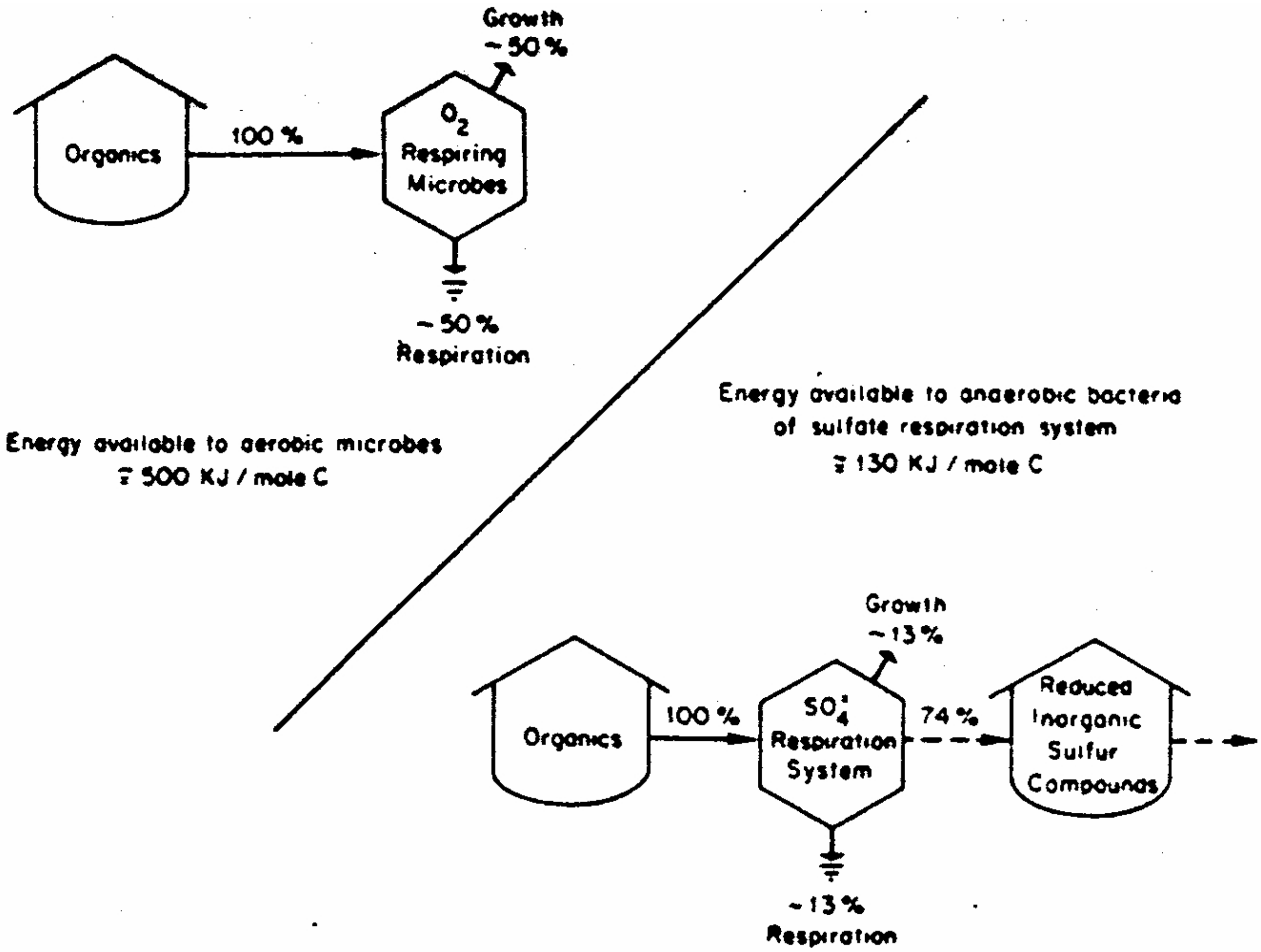
The sulfur cycle

Primary form of anaerobic metabolism
due to availability of sulfate

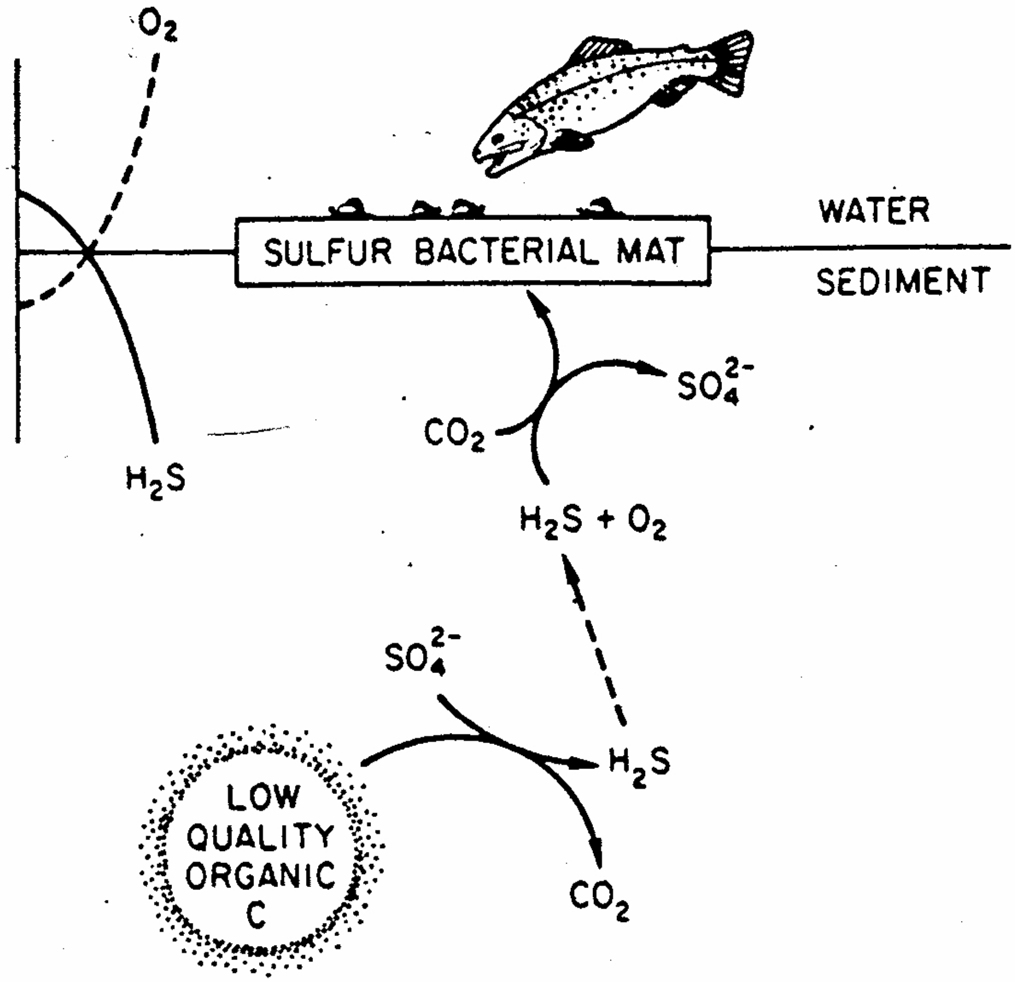
Sulfate reducing bacteria cannot use glucose;
only low chain C compounds like acetate -
important coupling to fermenters

Reduced product (sulfide) is toxic and
oxidized by O_2 and by chemoautotrophs

Reduced product is also stored as minerals
(e.g. pyrite)



Comparisons of oxygen respiration with sulfate reduction. During sulfate reduction and associated fermentation reactions, there is a decoupling of energy flow from carbon cycling. See text.



Schematic diagram illustrating the ecological importance of the sulfur cycle in concentrating high-quality food near the sediment-water interface.

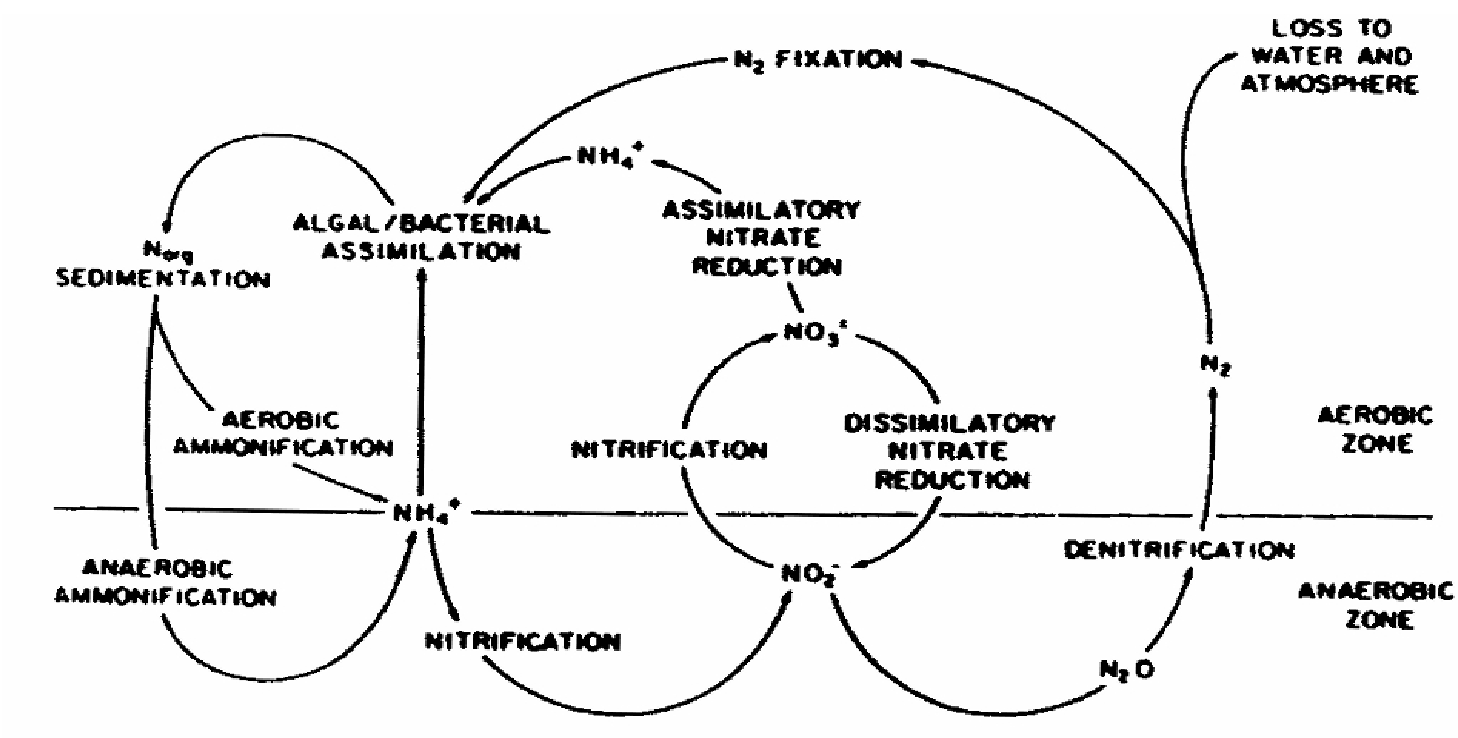
The Nitrogen Cycle

All POM decomposition and animal excretion yields ammonia from protein

Ammonia is nitrified to nitrate (chemoautotrophs)

Nitrate is denitrified to ammonia or nitrogen gas (anaerobic heterotrophs)

N_2 pathway is a net loss to marine systems



Processes in the cycling of nitrogen through marine sediments (redrawn from Wiebe, 1979).

Methods

Fluxes of oxygen and other solutes are measured directly, either influxes or effluxes at the sediment-water interface

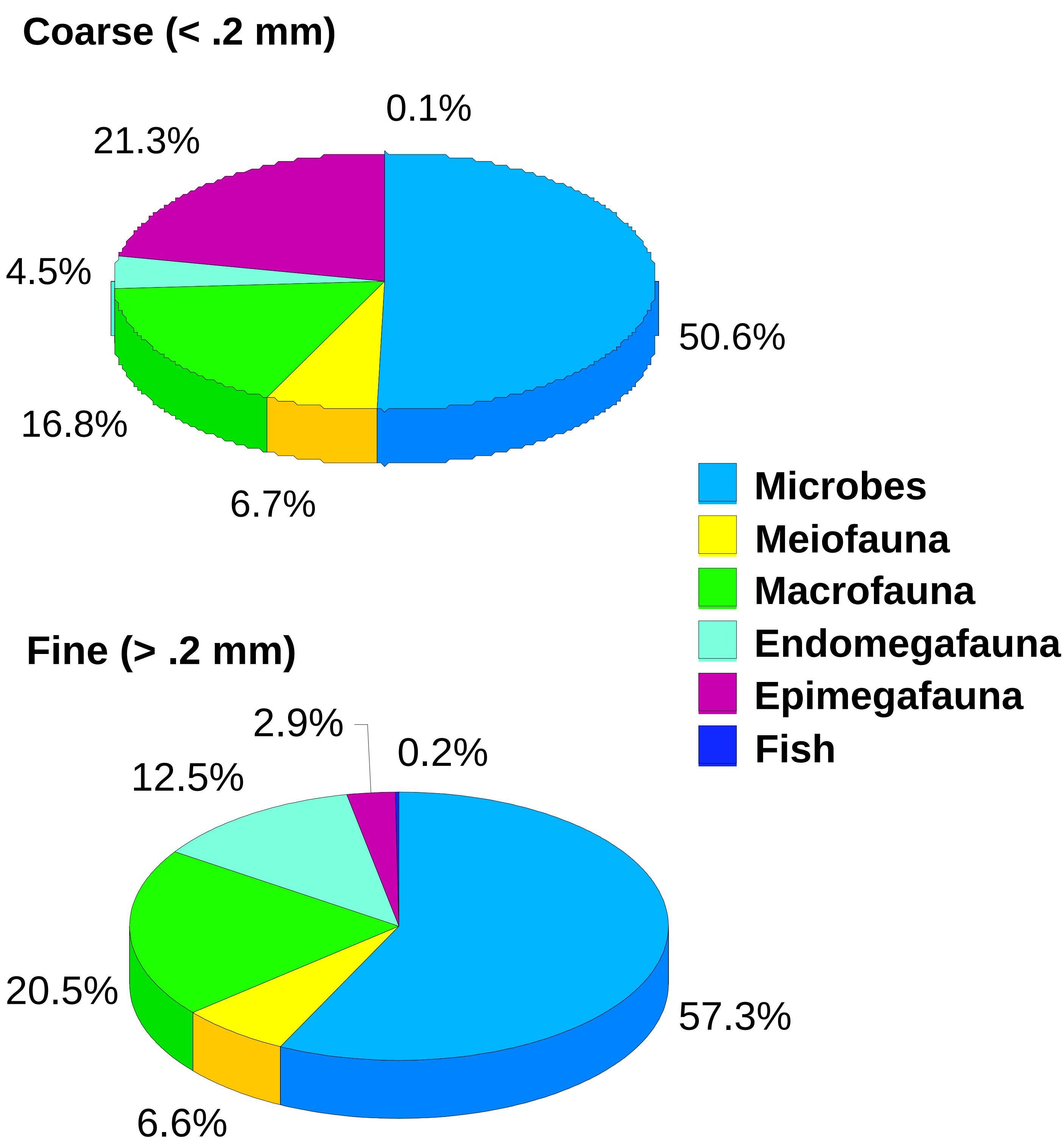
Closeup of incubation core
Note stir bar and burrows

Cores in water bath with stirring motors and sampling ports

Who is respiring?

Partitioning of benthic metabolism - Barents Sea

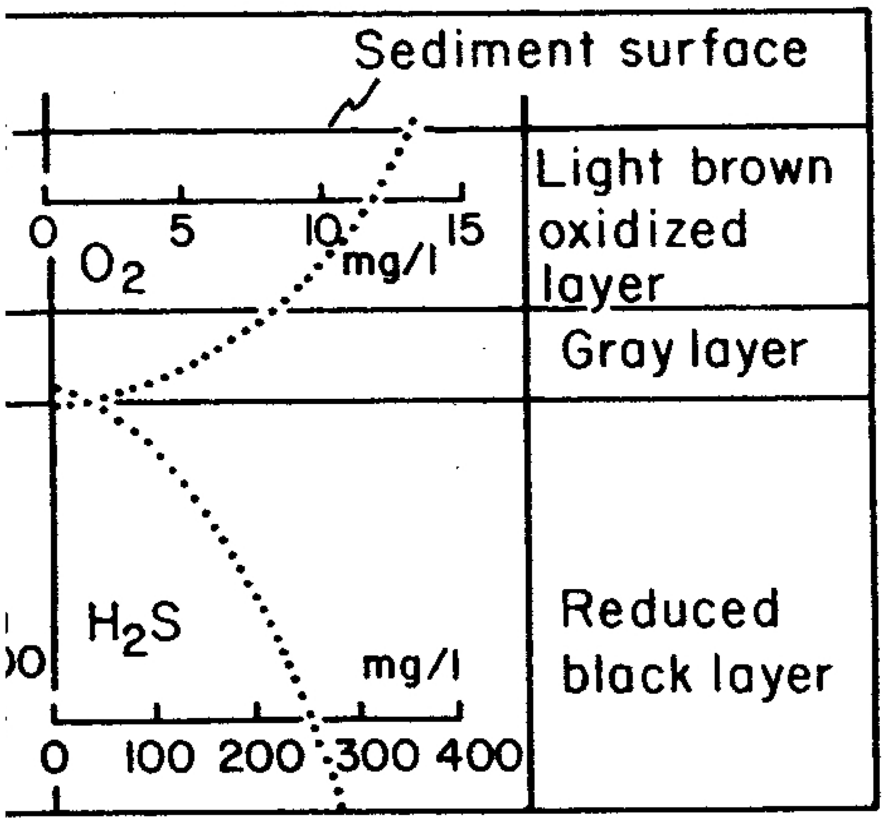
(Piepenburg et al. 1995 Mar. Ecol. Prog. Ser. 118)



Vertical gradients in oxygen

Profiles are the balance between consumption and diffusion; these shapes may thus be used to calculate consumption rates.

<u>but,</u> bioturbation disrupts the profiles
e.g. straightens them and leads to more complex models



Flux J = D (dC/dz) where
D is diffusion coefficient, and dC/dz is the solute gradient

Bioturbation has a variety of impacts on the sediment surface and subsurface

Surface structure and rougness (tubes, burrows, mounds)

De-compacted sediment surface and increased porosity

Increased erodibility

Changes in grain size through feeding and pelletization

Deepening of oxygen penetration and the RPD

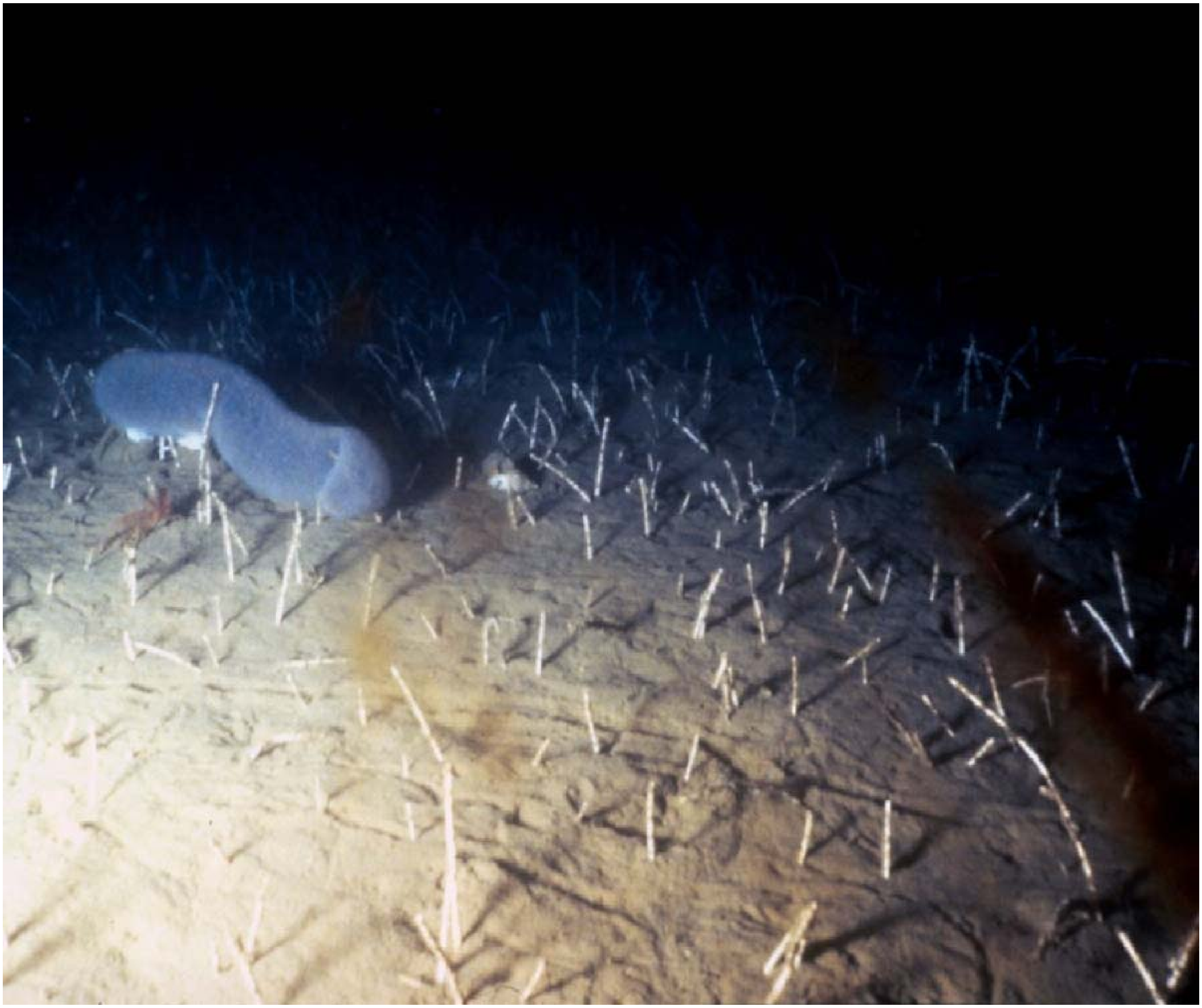
Changes in solute fluxes

Fauna have a huge influence on the sedimentary environment via **bioturbation**, including sediment texture and its interaction with the sediment column and BBL. These interactions are known as animal-sediment relations.

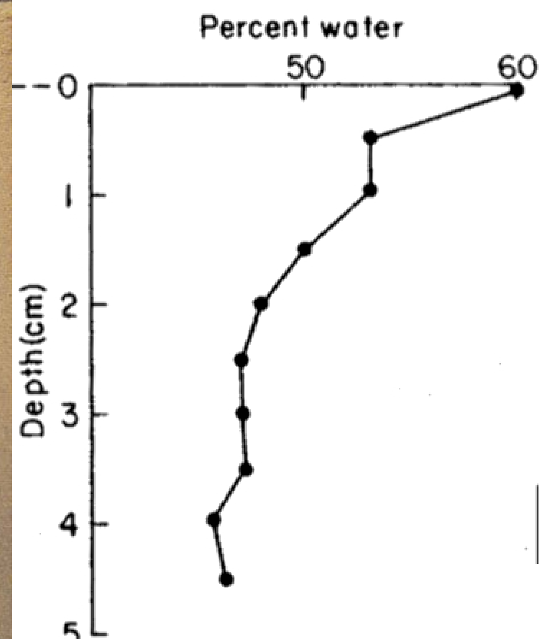
FUNCTIONAL GROUPS OF INFAUNA AND TYPES OF INTERACTIONS•

Function group	Ingests or disturbs by its feeding activities surface or near-surface larvae	Filters larvae from water	Alters sediment	Larval type at settlement	Predicted dense co-occurring forms
Deposit-feeding bivalve	yes	no	destabilizes	surface or burrowing	burrowing polychaetes
Suspension-feeding bivalve	no	yes	much less than deposit feeders	surface	none
Tube-building forms	yes	depends on feeding type	stabilizes by attracting algal mat; destabilizes by increasing near-bottom turbulence; reduces space below surface, increases settling surface due to tubes	surface	epifaunal bivalves and tube epifauna

Tubes and tracks in the deep sea

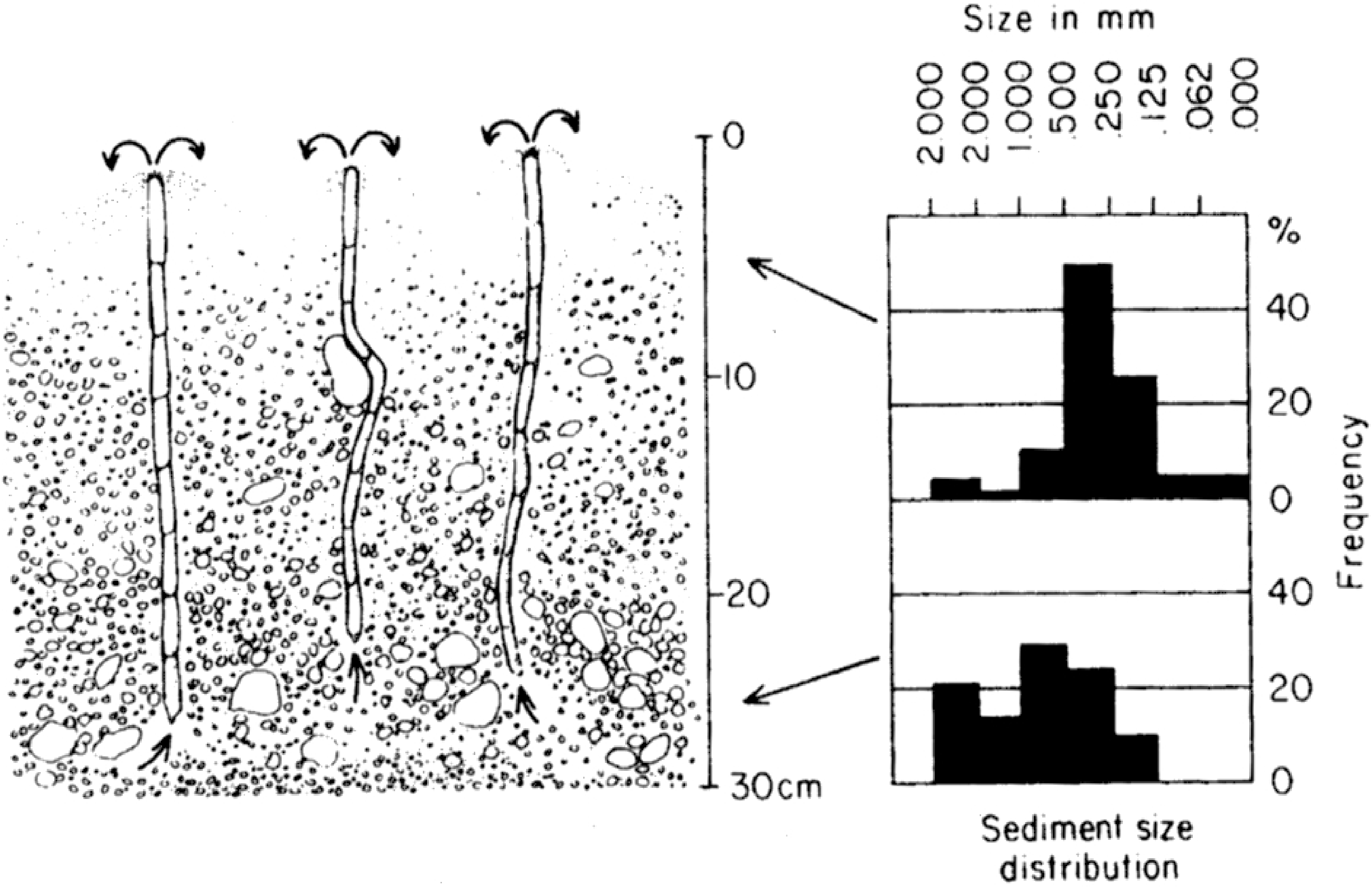


Surface porosity effects - note easily resuspended surface



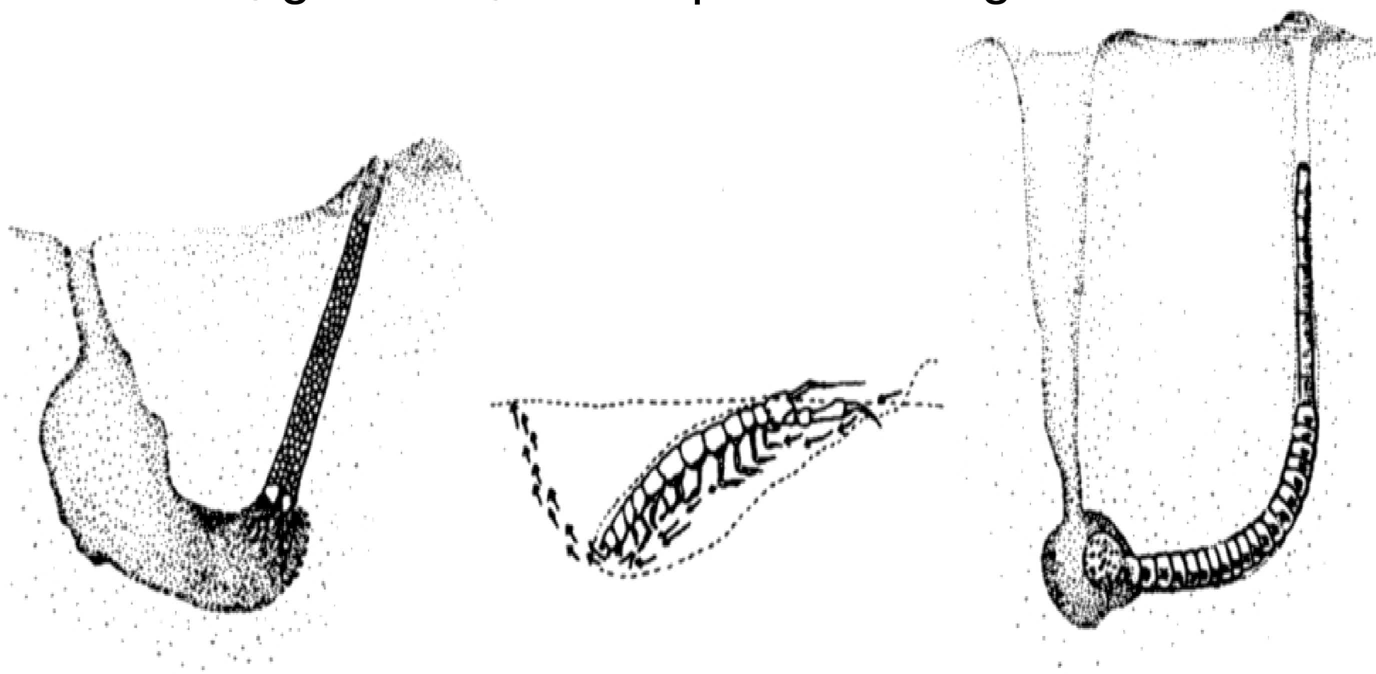
A sediment–water interface photograph of a typical shallow-water marine mud. The percent water content as a function of depth below the sediment–water interface is shown to the right. Note the thin layer of pelletized sediment near the interface. (Compiled from Levinton, 1977)

Sediment sorting by deposit feeders - feeding and fecal pellets alter grain size

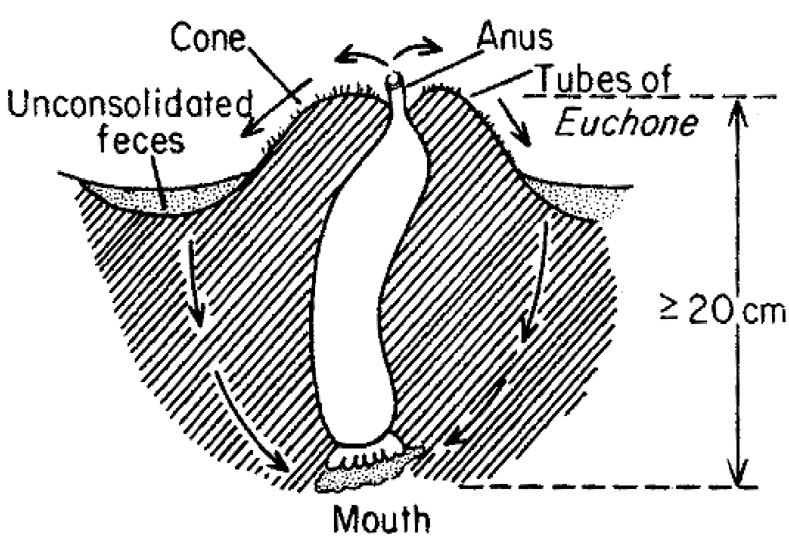


(a) Vertical reworking of intertidal sediments by the tubeworm, *Clymenella torquata*. (b) Change in the vertical distribution of particle sizes as a result of vertical reworking of the sediment by the tubeworm. (After Rhoads, 1967, with permission from the *Journal of Geology* and the University of Chicago Press)

Burrows, galleries, and deposit-feeding



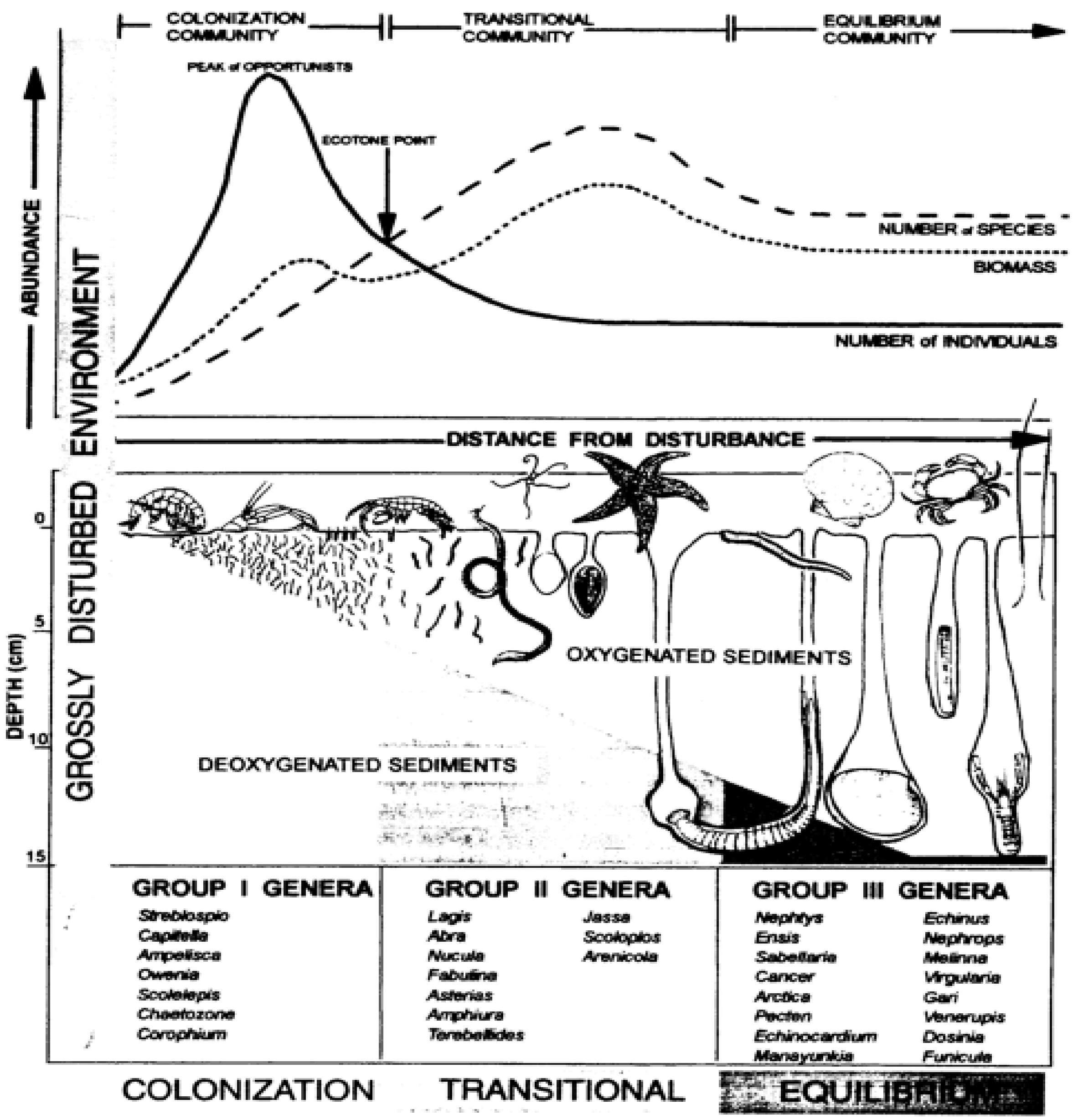
Living positions of some burrowing invertebrates. (a) The burrowing polychaete, *Pectinaria;* (b) the amphipod, *Corophium;* (c) the polychaete, *Abarenicola*.



Cross section of the sediment showing the feeding position, surface cone, and overall microtopography generated by the burrowing sea cucumber, *Molpadia oolitica,* in Cape Cod Bay, Massachusetts. (From Young and Rhoads, 1971, reprinted from *Marine Biology,* volume 11)

Animal-sediment relations in the context of disturbance and succession (originated by Pearson/ Rosenberg/Rhoads

R. C. NEWELL, L. J. SEIDERER AND D. R. HITCHCOCK



Pictorial diagram showing the ecological succession that characterizes benthic communities through a gradient of environmental disturbance. Note that in highly disrupted environments (on the left side of the diagram) few organisms may be capable of survival. In polluted or semi-liquid muds the sediments are colonized by few (resistant) species but which can attain very high population densities. As the stability of the environment increases, these opportunistic *r*-selected species are replaced by increased species variety, including slower-growing *K*-selected species. Finally in environments of high stability the community is dominated by equilibrium species with complex biological interactions between members of the community. (Based on Pearson & Rosenberg 1978, Rhoads et al. 1978).

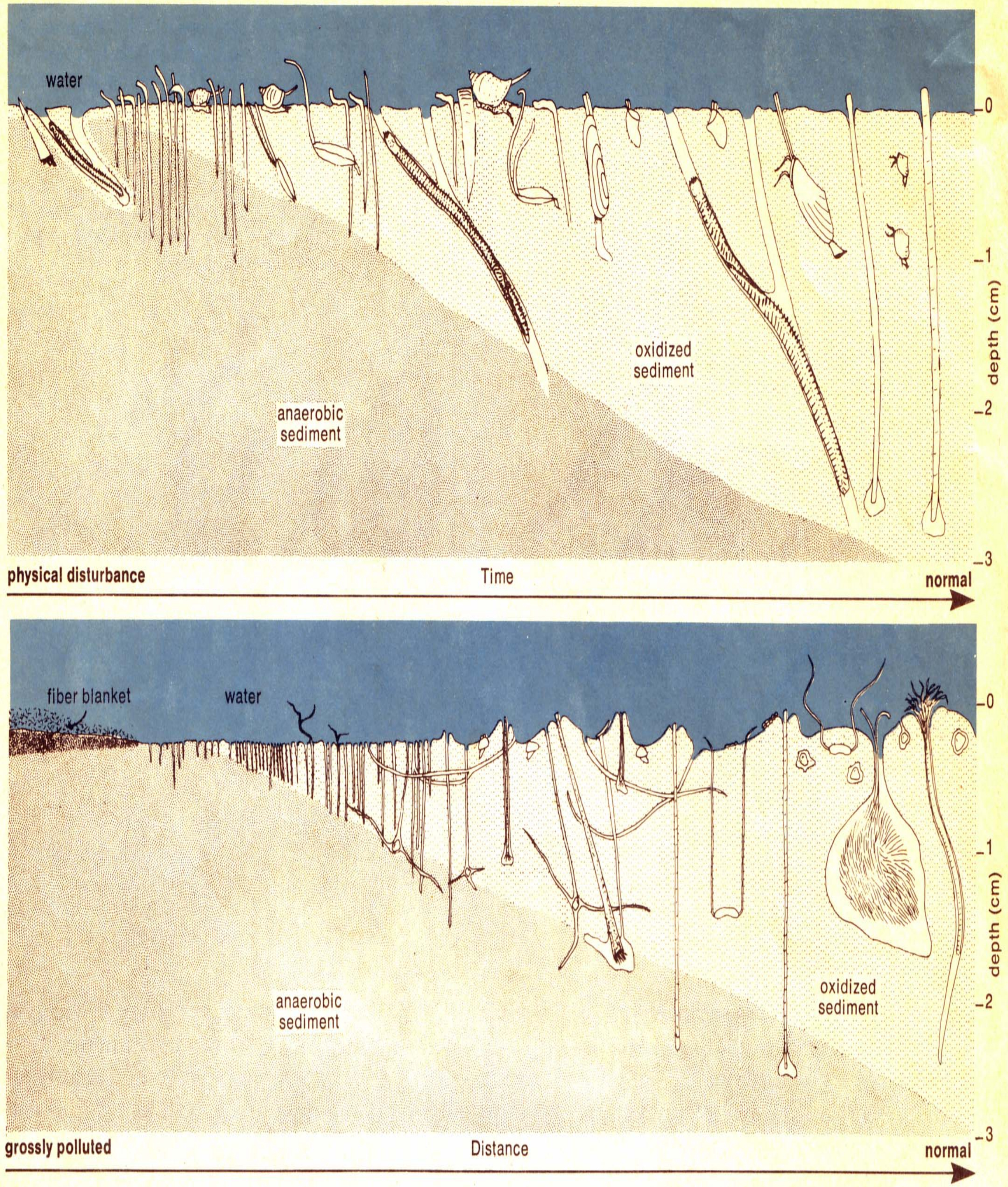
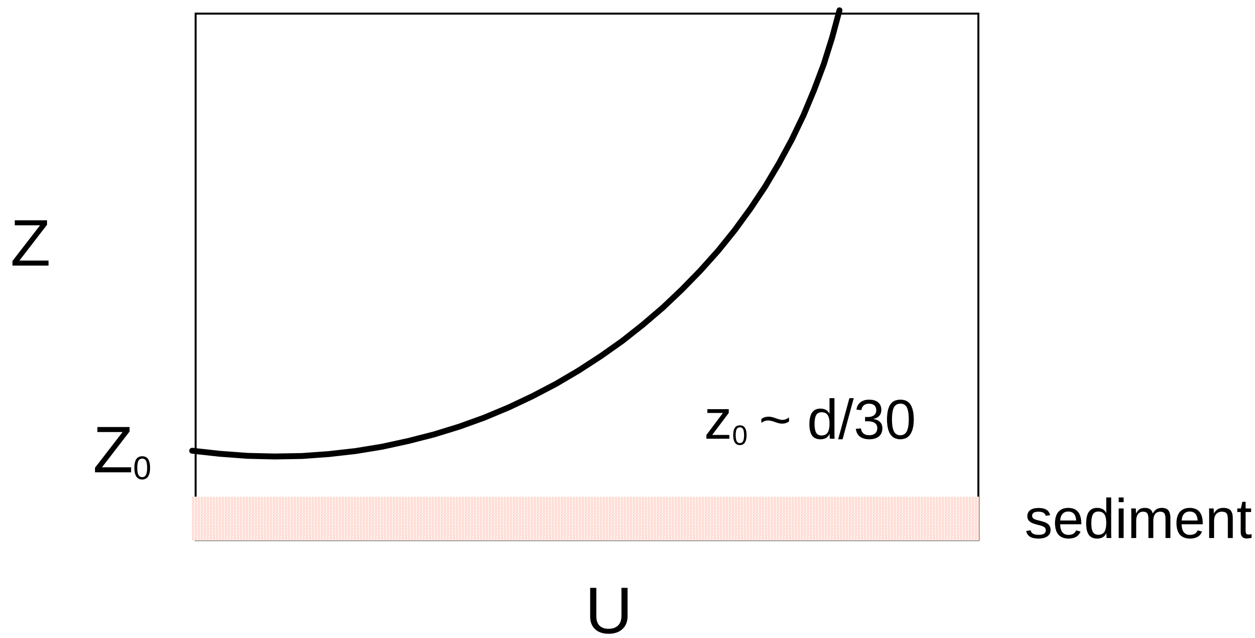


Figure 5. An interesting parallel is found between change in faunal composition over time after a singular physical disturbance, such as the dumping of dredge spoil, and that over distance from a chronic pollutant effluent such as the blanket of fiber from a cellulose factory. Immediately after disturbance or close to the source of pollution, a few species of abundant and productive polychaete worms are found. These are followed—in time or space—by suspension-feeding or surface-deposit-feeding molluscs, which are in turn replaced by less productive species that live deeper in the mud, feeding on buried detritus and oxygenating the sediment. Pioneering species at or near the surface may be more available as prey for foraging fish and crustaceans than deeply buried species of the mature stage. (Diagram of faunal changes over distance from pollutant effluent after Pearson and Rosenberg 1976).

The Benthic Boundary Layer (BBL)

Bottom friction causes shear in the lower water column and a log decrease in velocity
Friction is a function of grain size (roughness)



shear stress τ = μ (dU/dz)

i.e. the velocity gradient scaled by dynamic viscosity
units of $M\ L^{-1}\ T^{-2}$
It is thus force per unit area as follows:

$F = \rho\ C_D\ \text{Area}\ U^2$

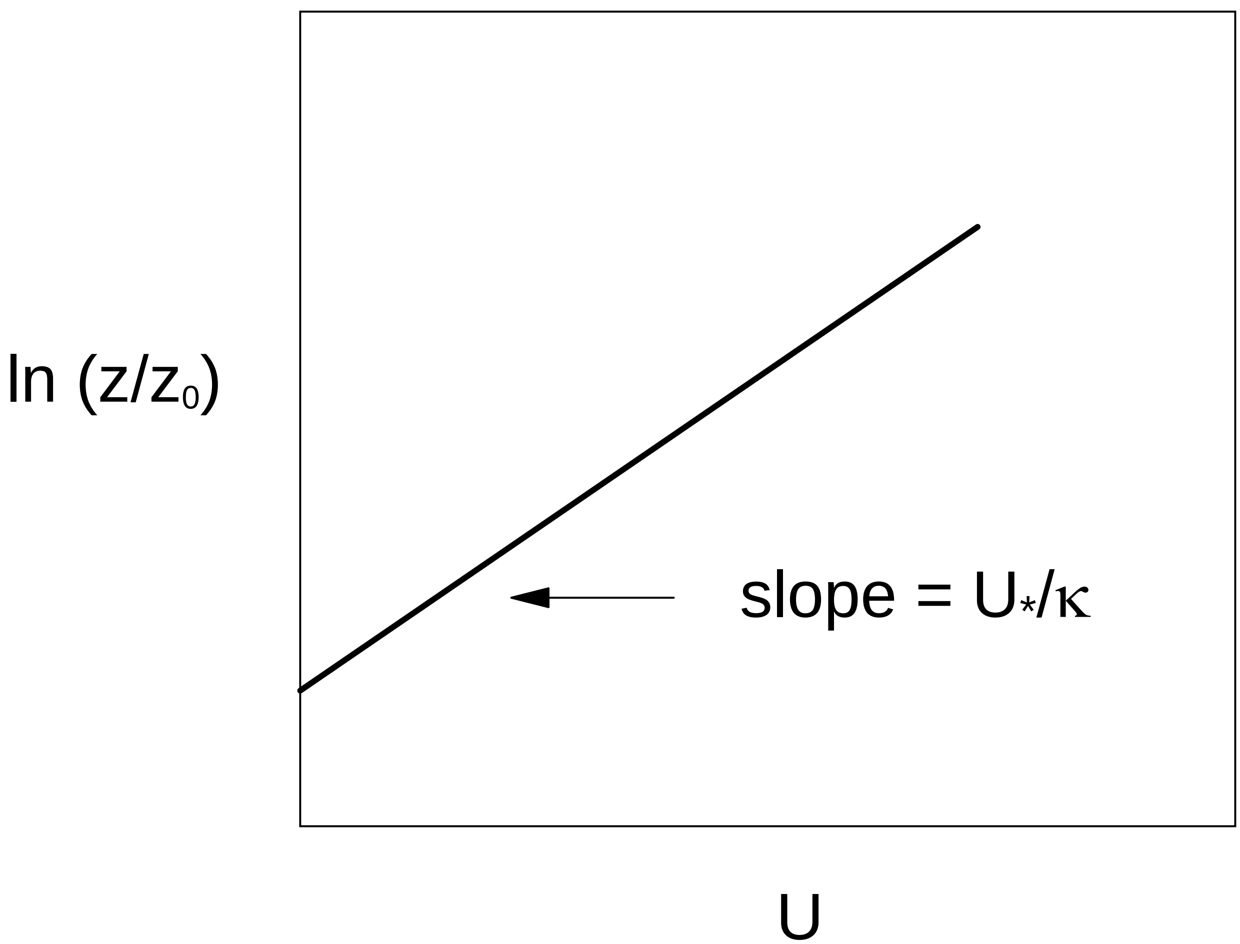
where ρ is density, C_D is drag coefficient, A is area, U is velocity
$F/A = \tau = \rho\ C_D\ U^2$
Define friction velocity $U_* = (\tau/\rho)^{1/2}$
$U_*^2 = C_D\ U^2$

The 'Law of the wall'

Velocity gradient as a function of roughness

$$U_z = U_*/\kappa\ [\ln (z/z_0)]$$

where κ is von Karman's constant



The BBL affects:

solute exchange
particulate deposition and resuspension
renewal of food for benthos
suspension feeding rates
larval dispersal and settling
and interacts with bioturbation

An example with oxygen profiles and flow

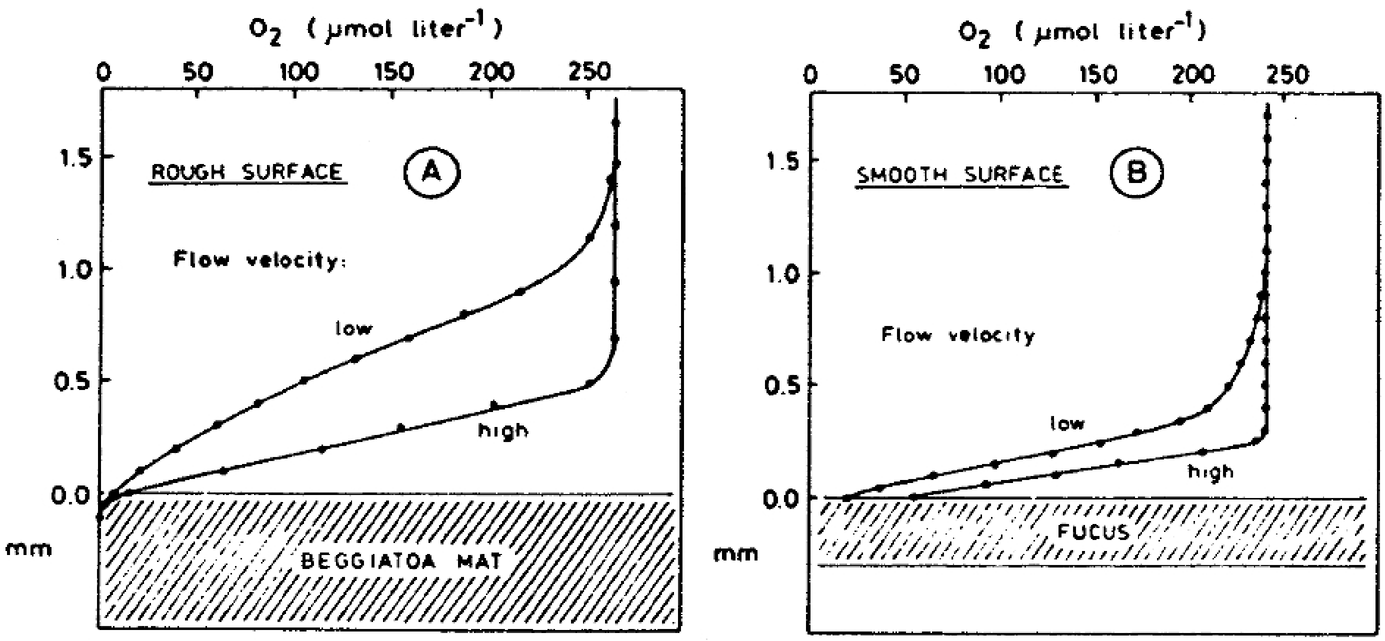


Fig. 3. Oxygen microprofiles at low and high flow velocities. A. Over a *Beggiatoa* mat lying on top of an organic-rich sediment. B. Over a decomposing fragment of *Fucus serratus* coated by bacteria.

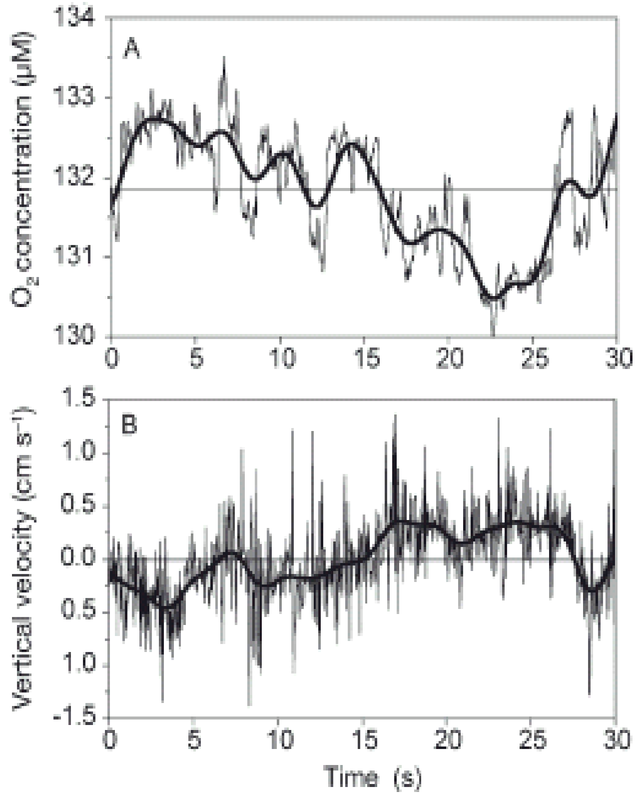


Fig. 2. Time series of (A) fluctuating O_2 concentration (thin line) and (B) associated vertical velocity (thin line). Positive velocity values indicate flow up and away from sediment surface. Data were measured 15 cm above a sediment surface at a frequency of 25 Hz. Mean values for time series are also shown (horizontal lines), as are the smoothed O_2 concentration and the smoothed vertical velocity (thick lines) (Aarhus Bay, Denmark)

Berg et al. 2003. MEPS 261: 75-83