Early diagenesis in sediments, sediment-water fluxes and benthic-pelagic coupling in coastal seas

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Askö Summerschool 2015

Black Sea, 39 m depth, March 2008 POS 363-CO1
Photo: Tim Stevens (Kongsberg Simrad 14-208 camera)

Structure of the lecture

1. Introduction
2. Early diagenetic processes in sediments
3. Methods and instrumentation for measurements of sediment-water fluxes
4. Application of benthic flux estimates
5. Sedimentary archives
6. Approaches to benthic-pelagic coupling in models
7. Further reading

1. Introduction

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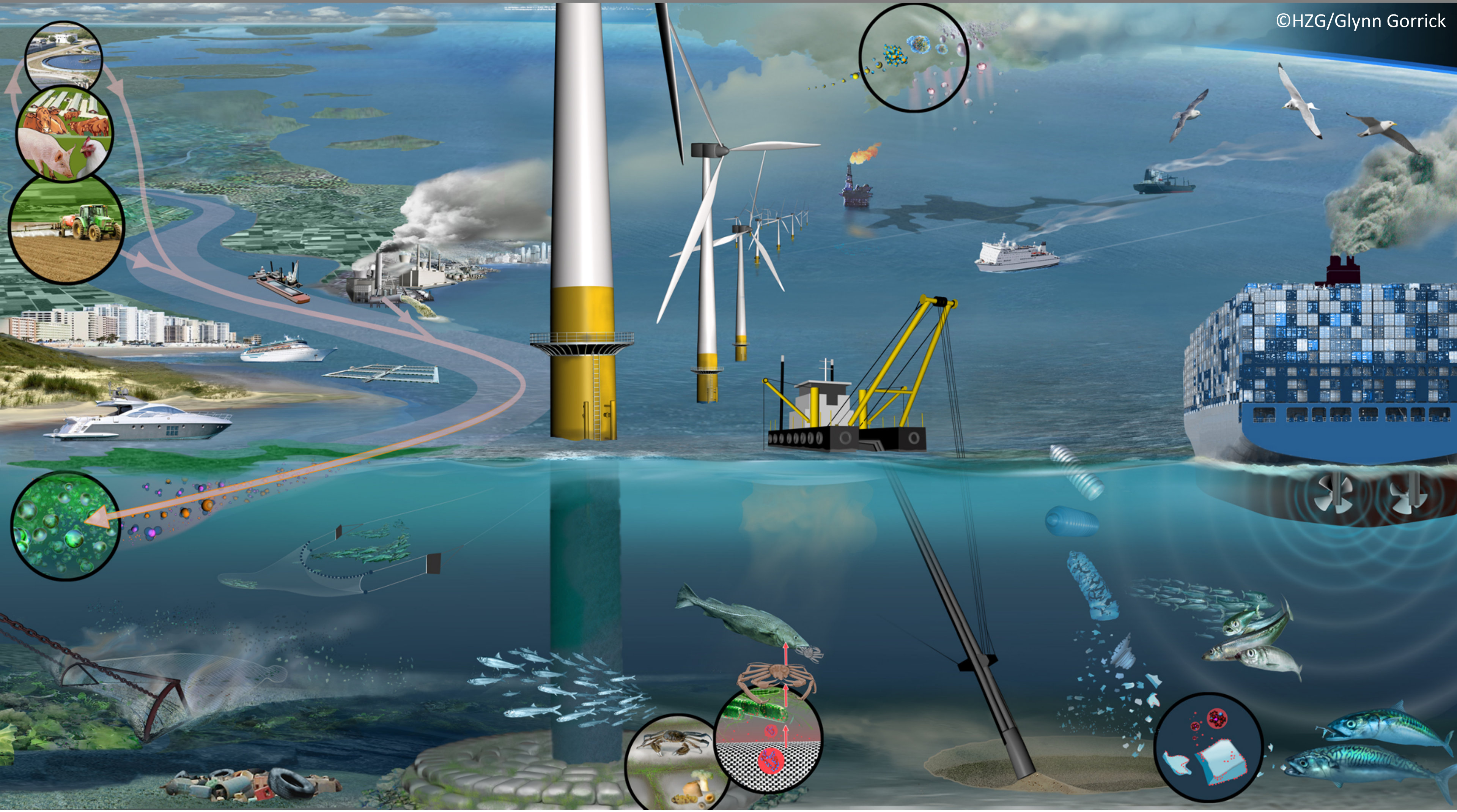

Continental shelf sediments (< 65 m) are covered mainly by

- 47% sands
- 37% muds
- 6% gravel/rocks
- 6% corals
- 4% shell debris

(Eisma 1998, Hayes 1967)

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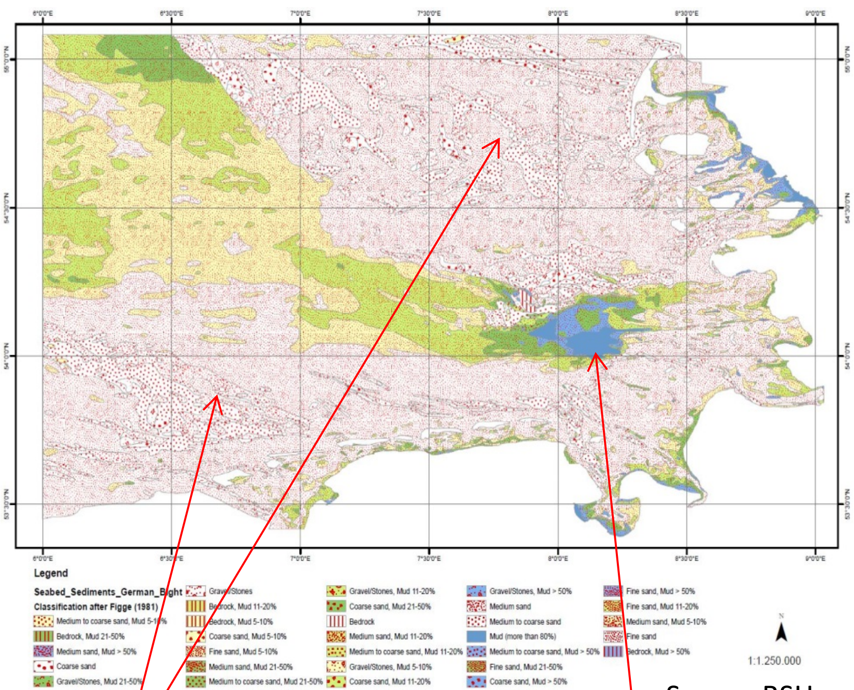
Examples:

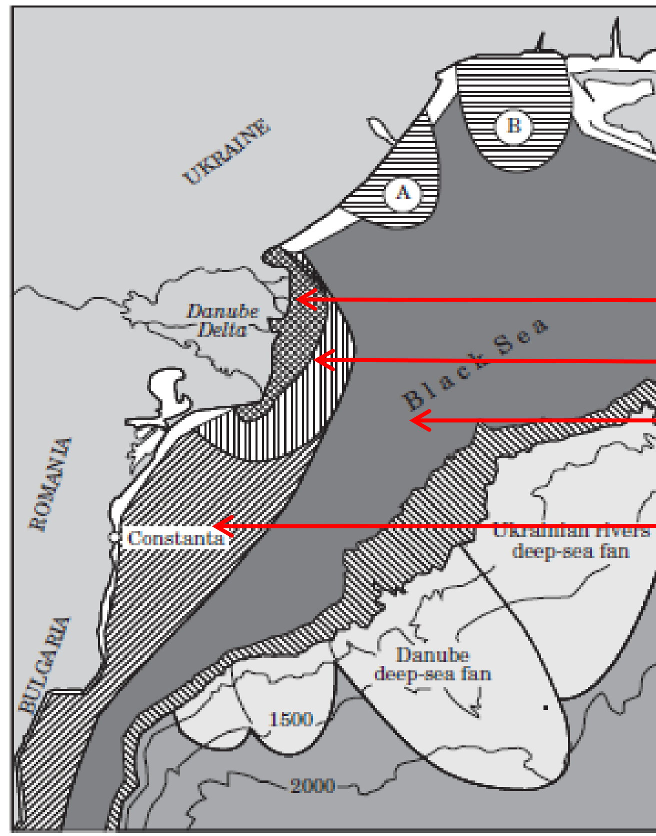
Sediments in the German Bight/North Sea



Source BSH

mostly fine to coarse sands mud

Western Black Sea shelf



coarse sands & mud

mud

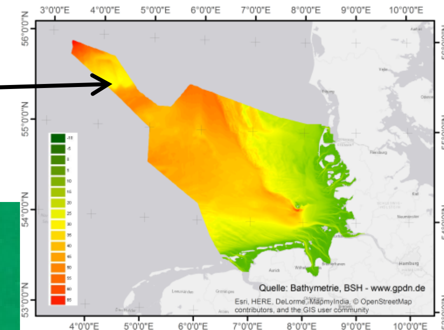
starved sediments, shell debris

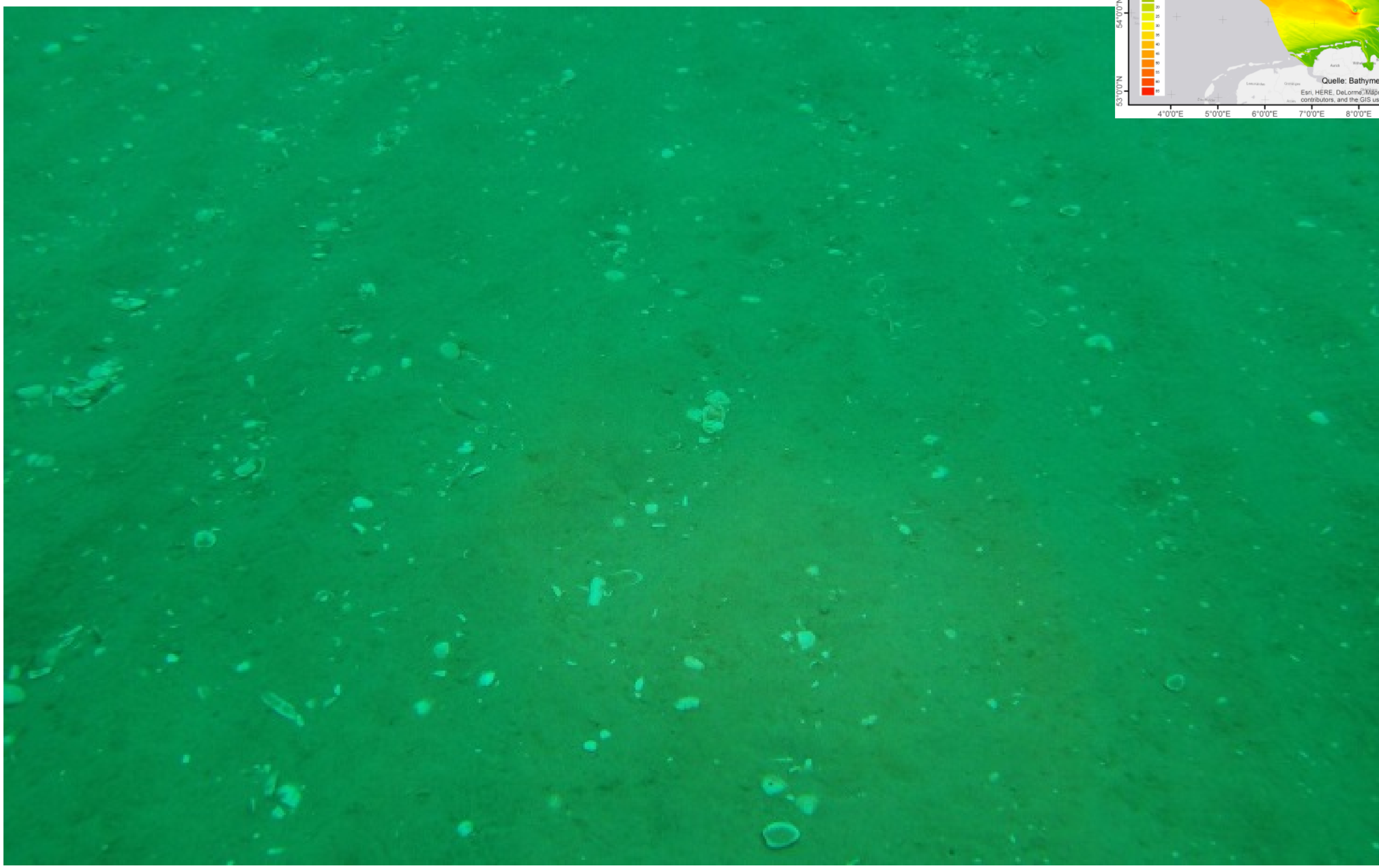
river originated sediment drift

Panin & Jipa (2002)

mostly muddy sediments and “starved” sediments and shell debris

sandy sediment
Dogger Bank/North Sea , 29m
daylight, June 2015, HE447





photo
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mud & fine sand, 39m
June 2015, HE447

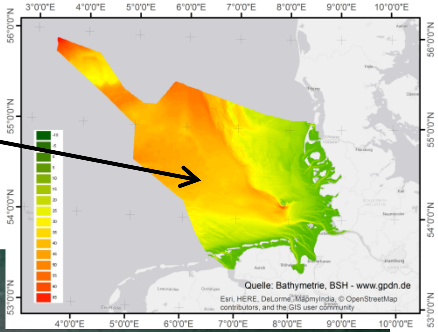

photo
J. Friedrich


Black Sea, 22m, March 2008 POS 363-Phy2
Photo: Tim Stevens (Kongsberg Simrad 14-208 camera)

Black Sea, 46 m water depth, March 2008 POS 363-DN10
Photo: Tim Stevens (Kongsberg Simrad 14-208 camera)

1. Introduction
1.1 Sediment types

healthy benthic ecosystem with epifauna (filter feeders)

degraded benthic ecosystem due to eutrophication and hypoxia

Black Sea
Photos: Tim Stevens,

J. Friedrich, HZG
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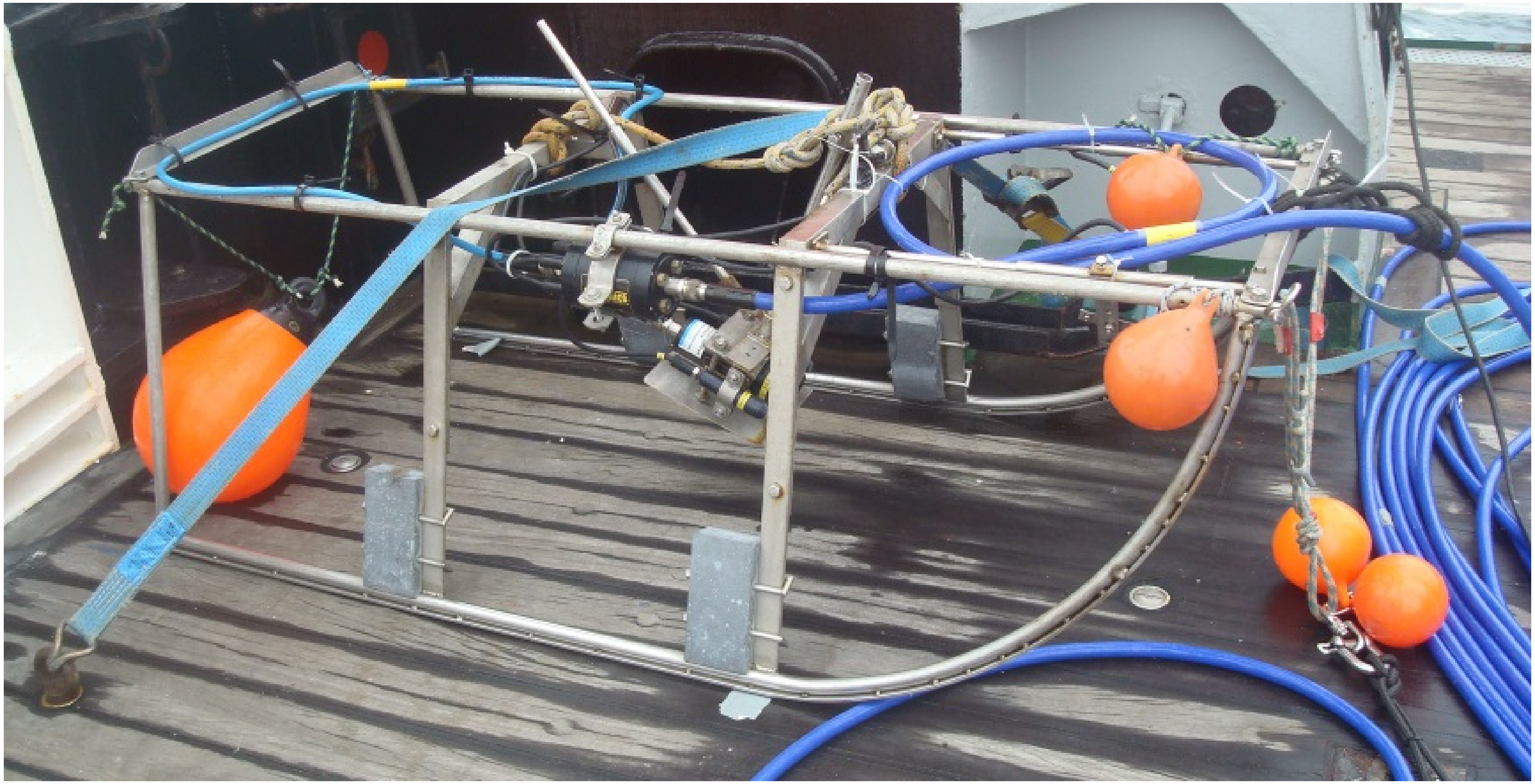
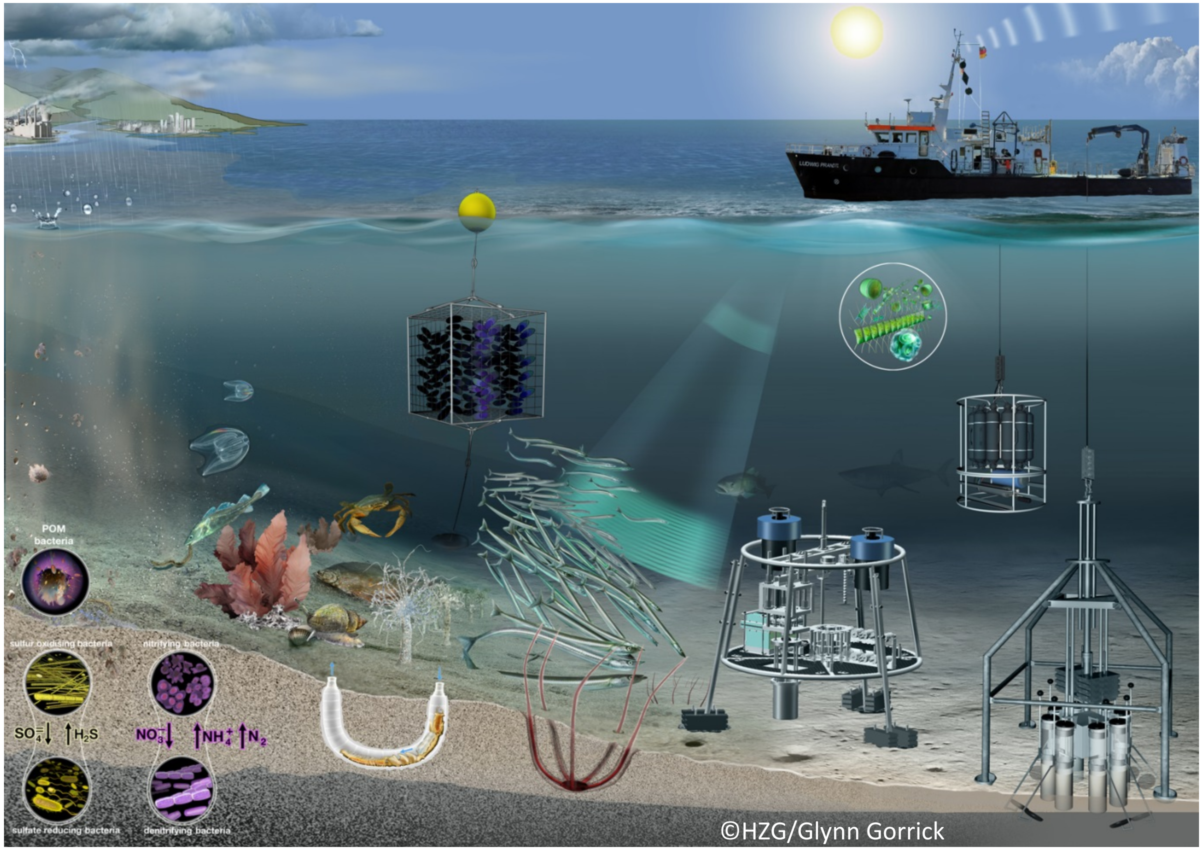
Video-imaging of seafloor

benthic sled with C-Vision (C-Technics) system & HERO 4 Black GoPro or Kongsberg Simrad 14-208 camera
geo-referenced video clips, & stills for benthic image analysis

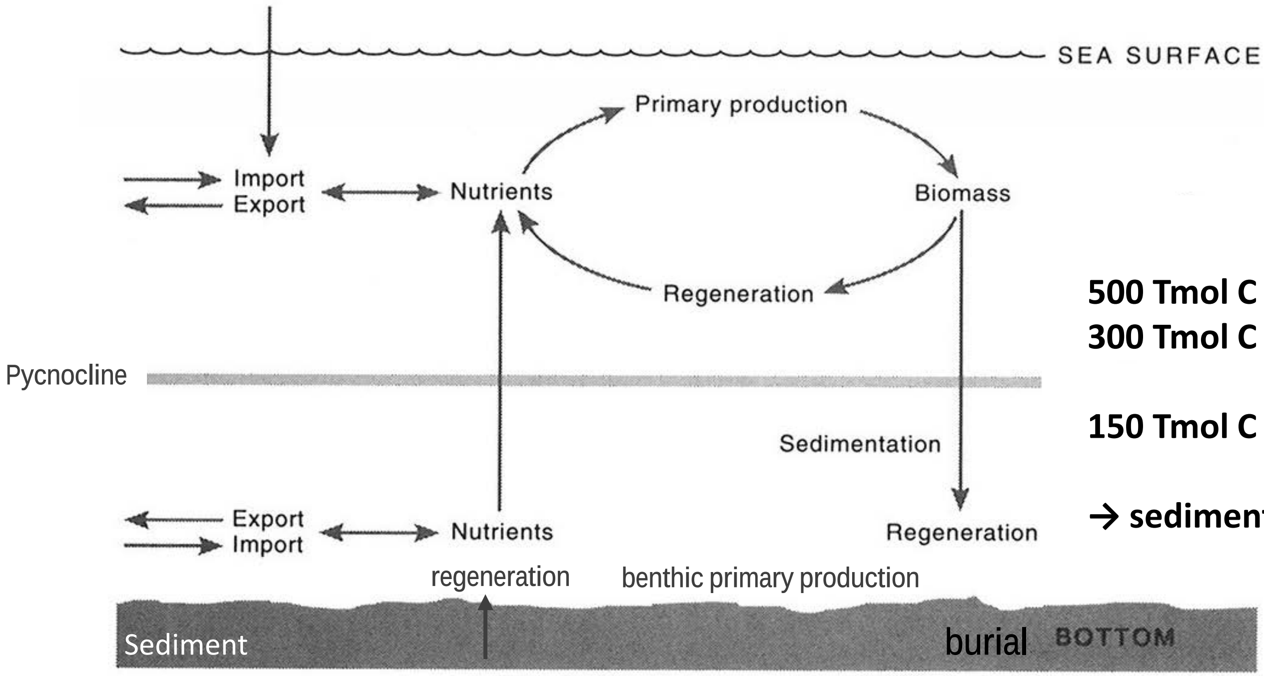


1. Introduction
1.2 Benthic-pelagic coupling

Benthic and pelagic compartments are in close contact and in two-way interaction:



Pelagic system influences ecology and biogeochemical functioning of benthic system and vice versa direct or indirect, at tidal or interannual timescales



Habitat for microorganisms, infauna, epifauna, -flora, demersal fishes, receive the legacy of anthropogenic perturbations

500 Tmol C yr^{-1} global shelf production
300 Tmol C yr^{-1} global shelf respiration

150 Tmol C yr^{-1} global shelf sediment respiration

→ sediments account for ½ of shelf respiration!

(Wollast 1998)

Proportion of benthic to total respiration depends primarily on water depth
Benthic contribution varies from 40% in shallow depths to few % at 100m

(Heip et al. 1995)

Shelf sediments are "the memory" of the pelagic system!

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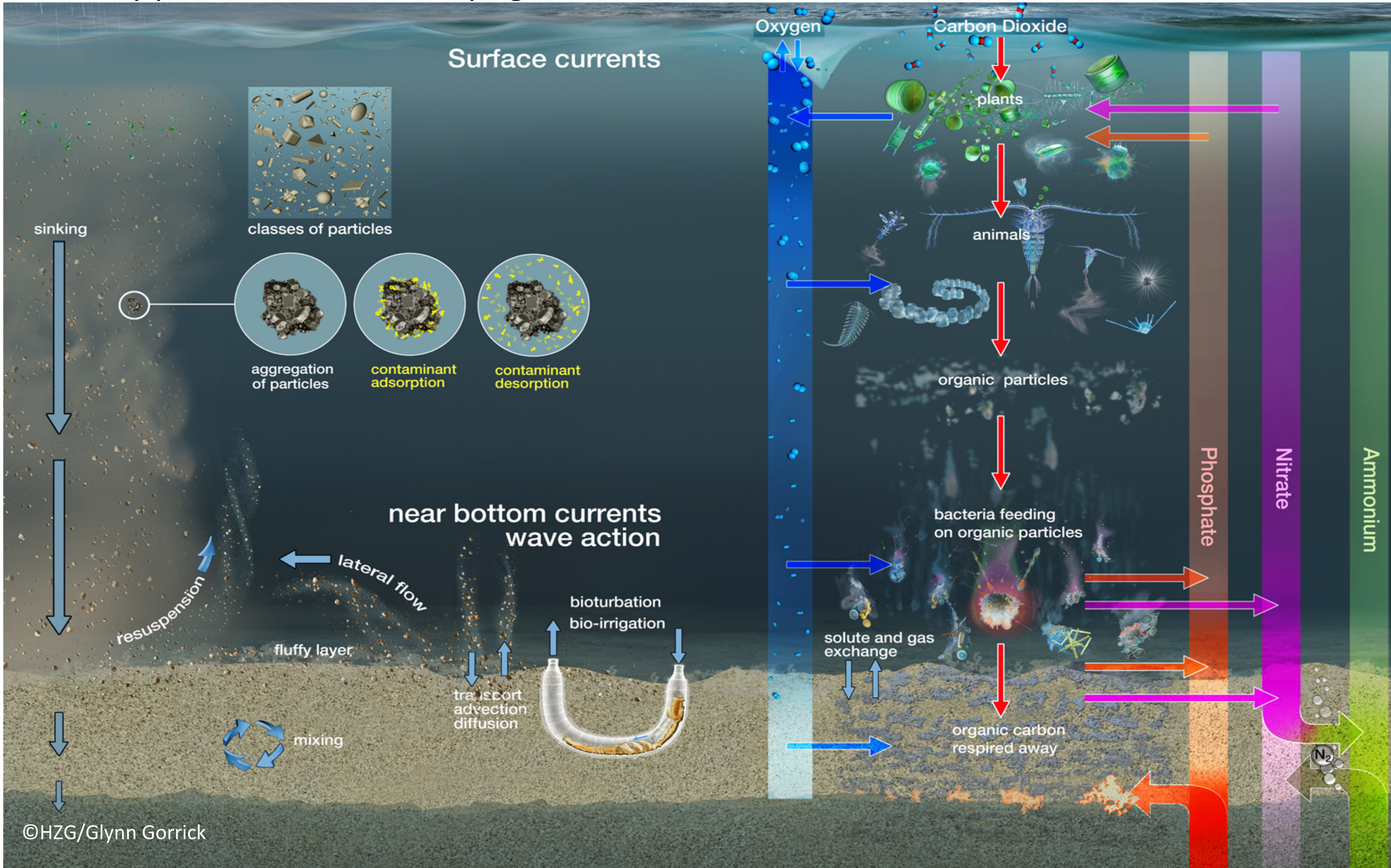
Hydrodynamic conditions and transport mechanisms into and out of the sediment determine the linkage of sedimentary processes to the overlying water.

In shallow seas, sediment is the most important site for accumulation, storage and biogeochemical transormation of organic matter and contanimants



Most important benthic transport processes

- gravitational settling
- bioturbation
- burrow irrigation (bioirrigation)
- molecular diffusion
- porewater advection
- burial due to lateral sediment transport

strongly affected by boundary layer flows causing

- water currents,
- surface gravity waves
- turbulence

control benthic-pelagic coupling

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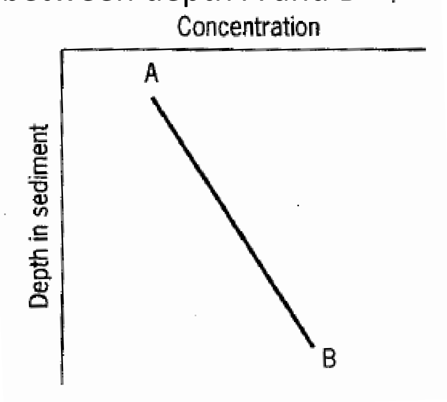
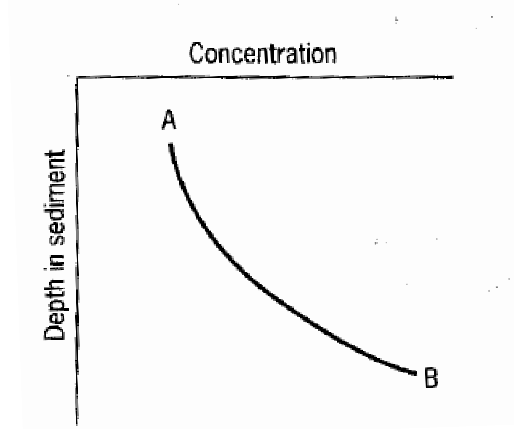
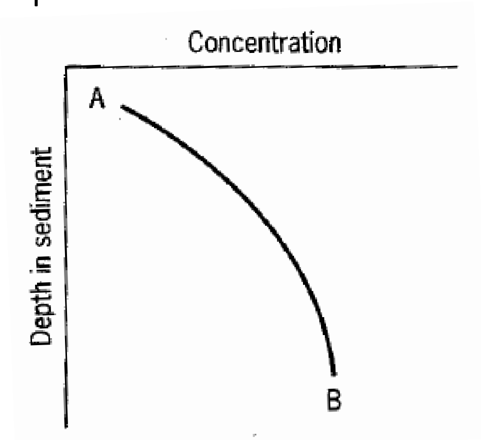
Linear gradient
solute concentration is controlled by diffusion from source at B to sink at A , no advection and reaction between depth A and B



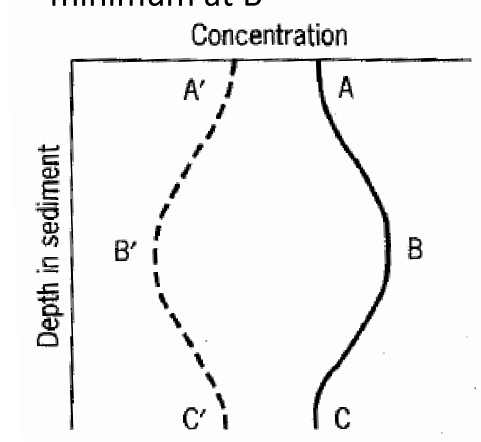
Convex gradient
removal or downward flux of solute from A to B



Concave gradient
production or upward advection of a solute in porewater from B to A



Curved gradient
if concentrations at A and C are equal, production generates maximum at B, consumption results in minimum at B'



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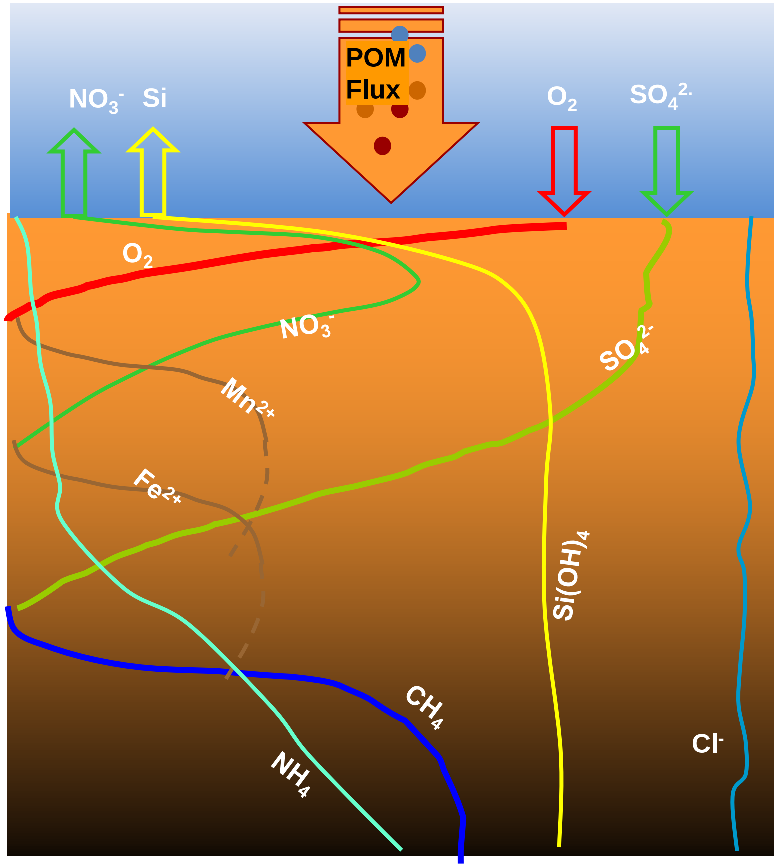
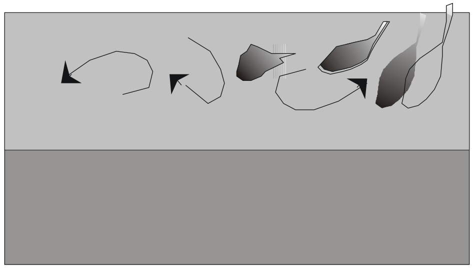
Sediment porewater profiles in a perfect biogeochemist's world…



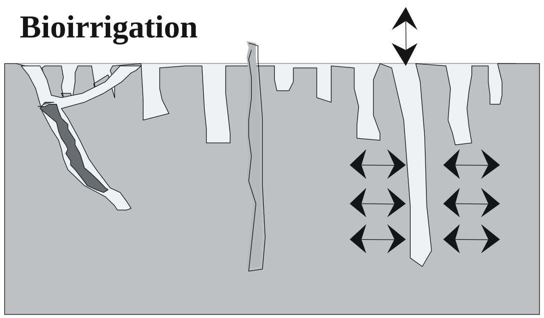
Impact of epi- and infauna

Bioturbation



Mixing of sediment particles (with/without effect on the porositiy)

Bioirrigation



Exchange and of bottom water and porewater

2. Early diagenetic processes in sediments
2.1 Transport processes

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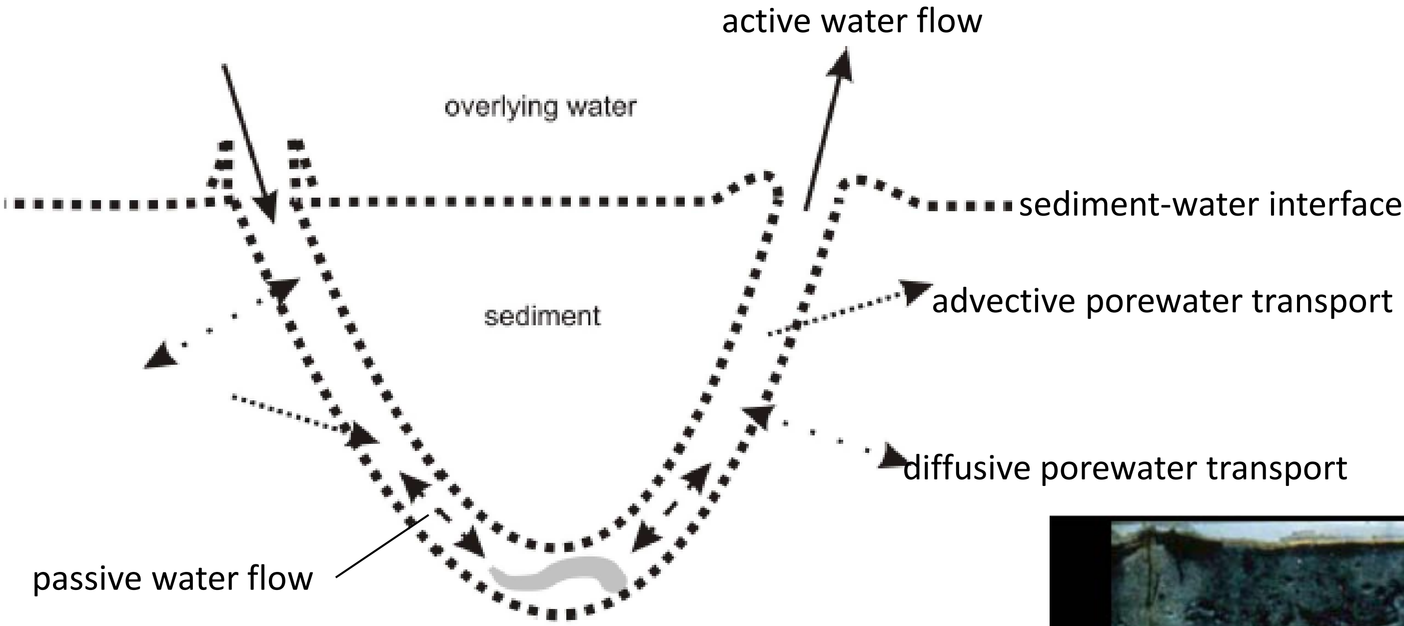
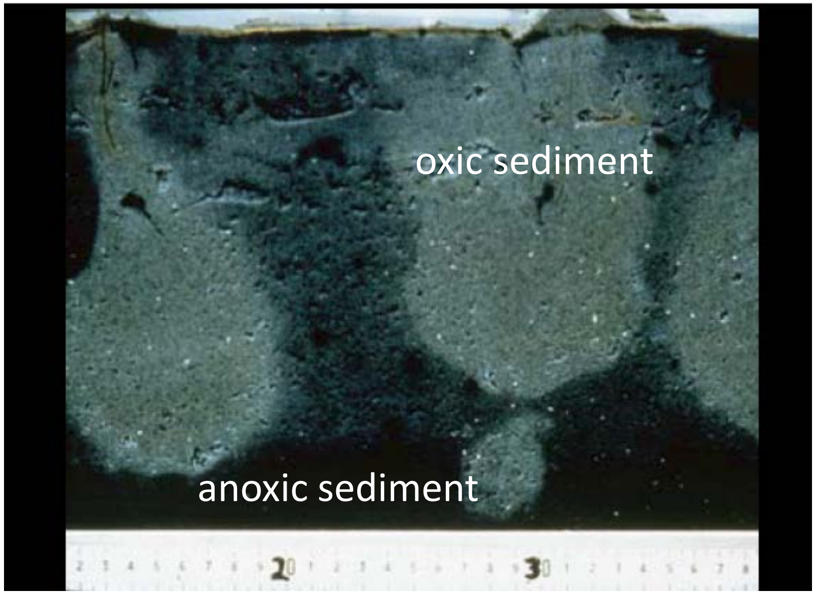
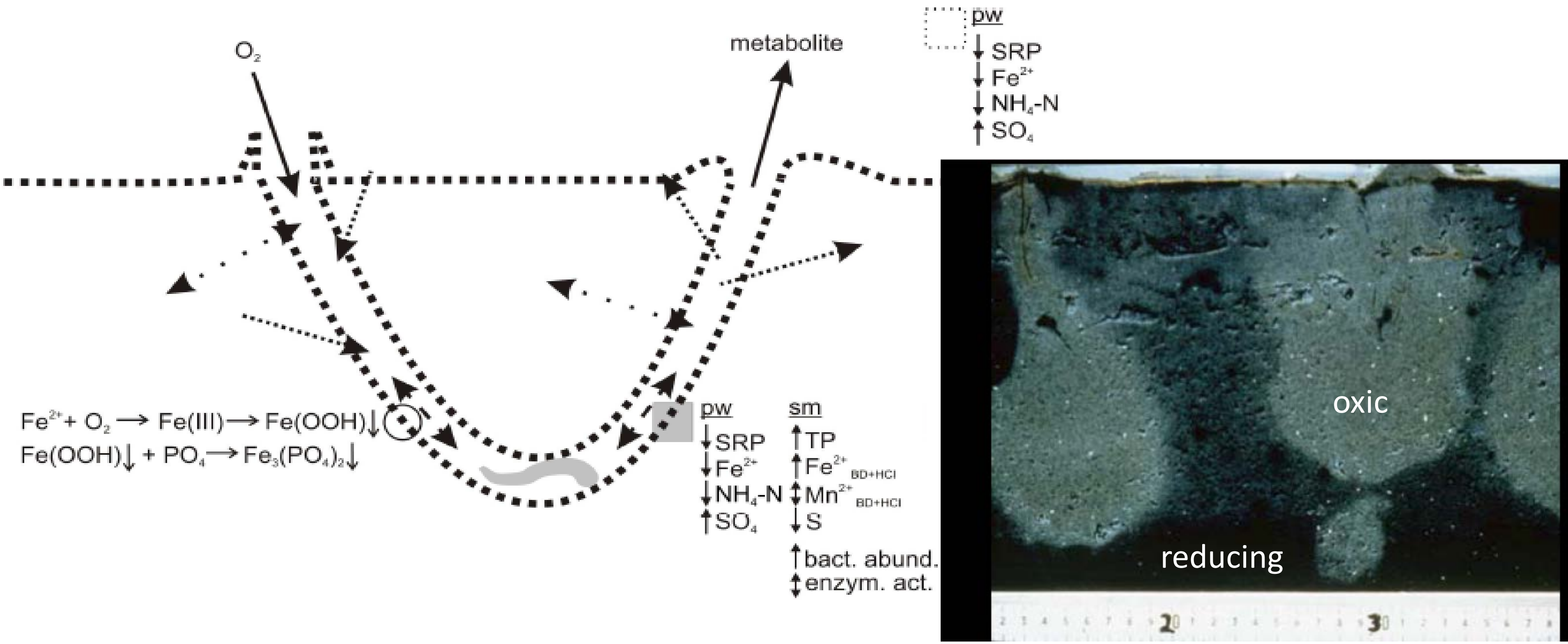
Transport processes inside a burrow caused by bioirrigating macrozoobenthos





Roskosch et al. 2011

Consequences of bioirrigation:
– ventilation of sediment and change in sediment-water chemistry



Roskosch et al. 2011

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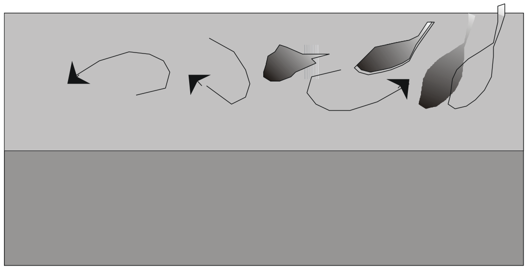
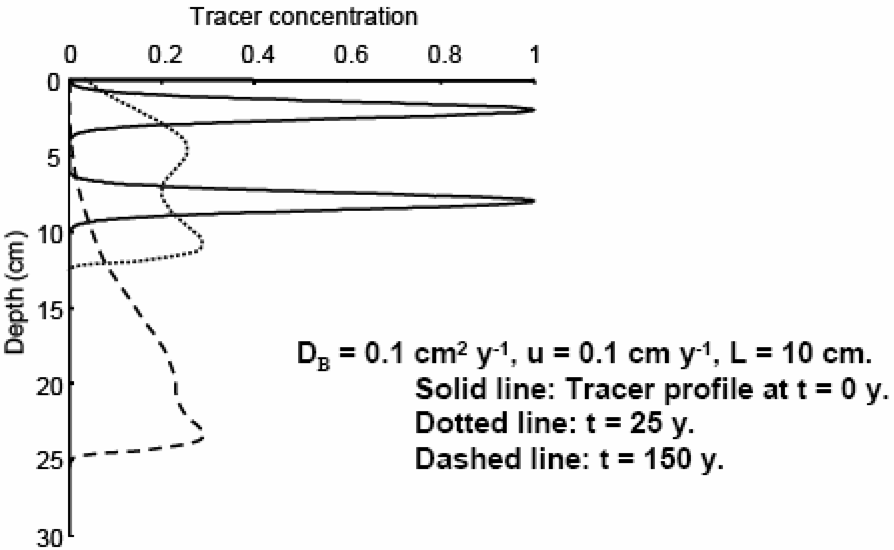
Bioturbation

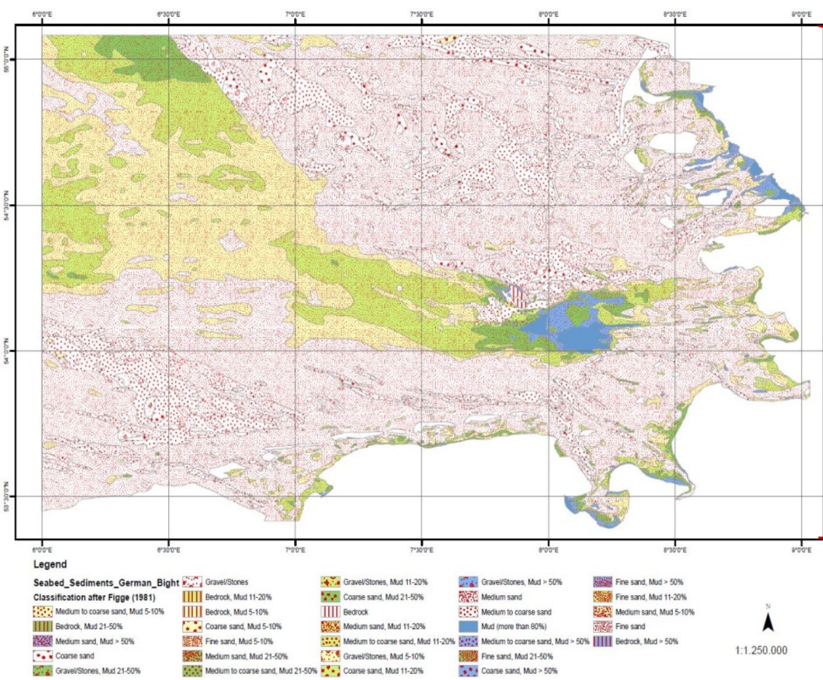


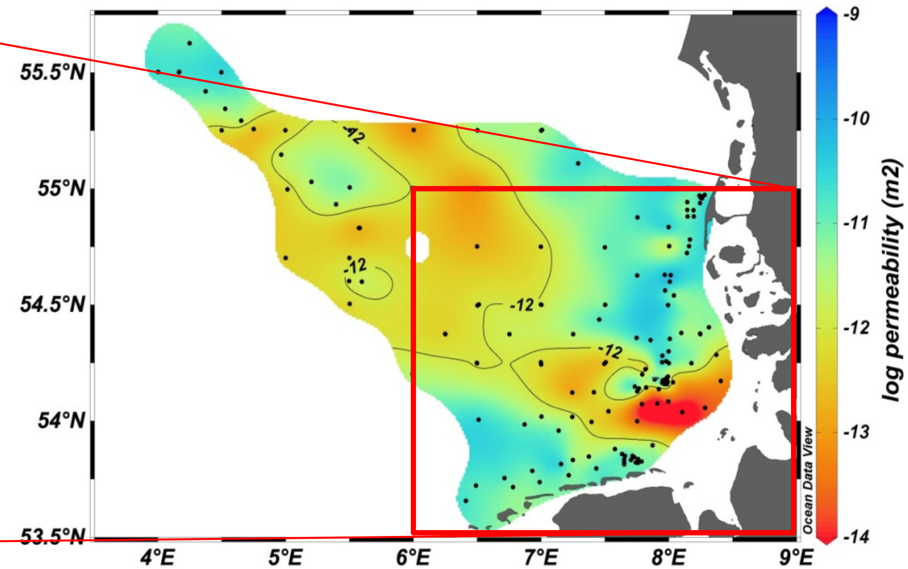
Consequences of bioturbation



mixing of substances

Gravitational settling – sediment permeability





Neumann et al. EGU2015-1296

Higher permeability in coarse-grained, sandy sediments

2. Early diagenetic processes in sediments
2.1 Transport processes

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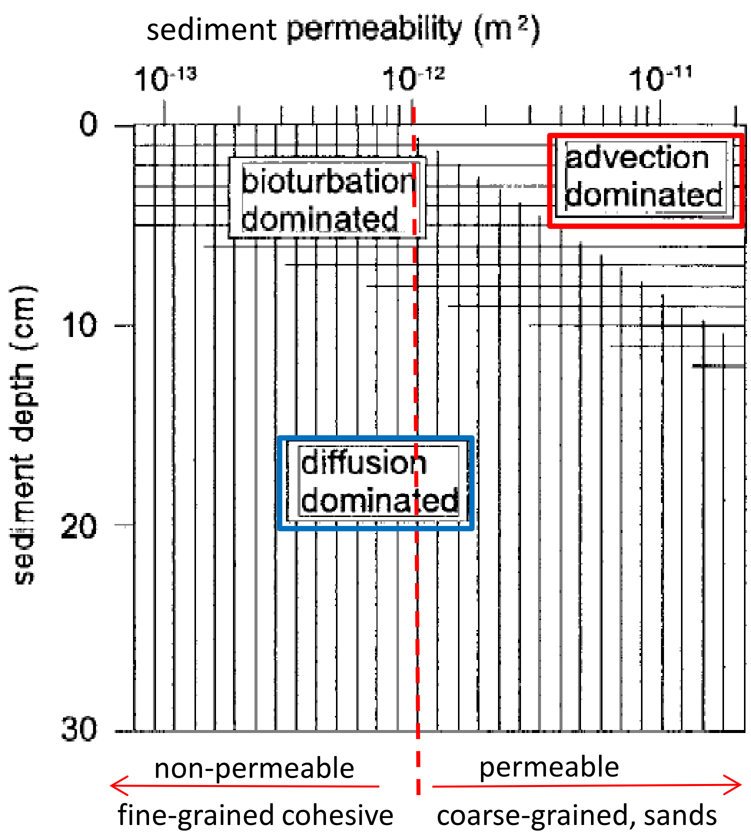
Diffusion and advection



Sediment-water exchange of matter dominated by
diffusion advection

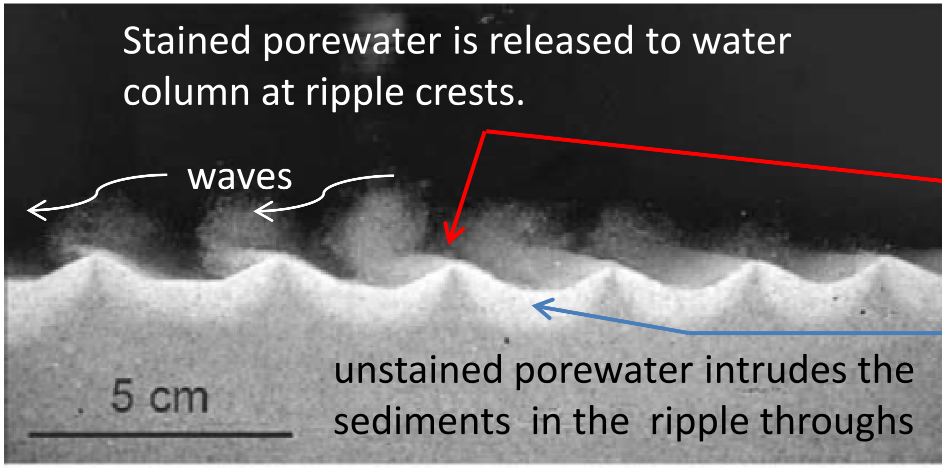
after Huettel et al., 2003

Boundary flow conditions and sediment permeability determine whether advection or diffusion dominates the sediment water fluxes.

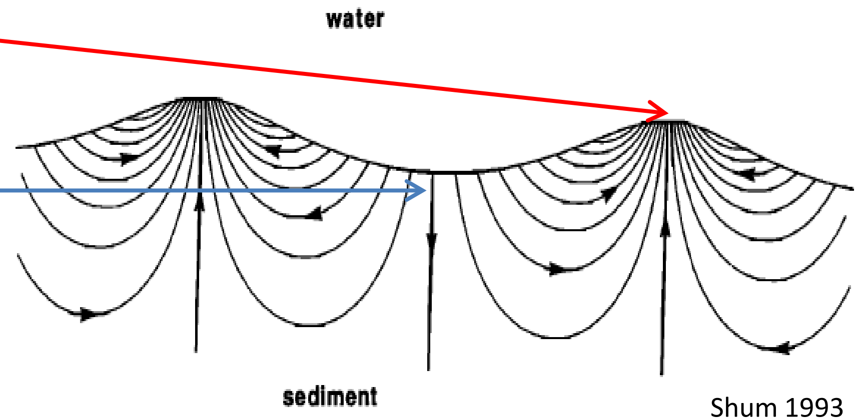
Meio- and macrofauna enhance transport of solutes and particles by bioturbation and bioirrigation.

In coastal permable sediments biological transport can be as efficient as advective exchange.

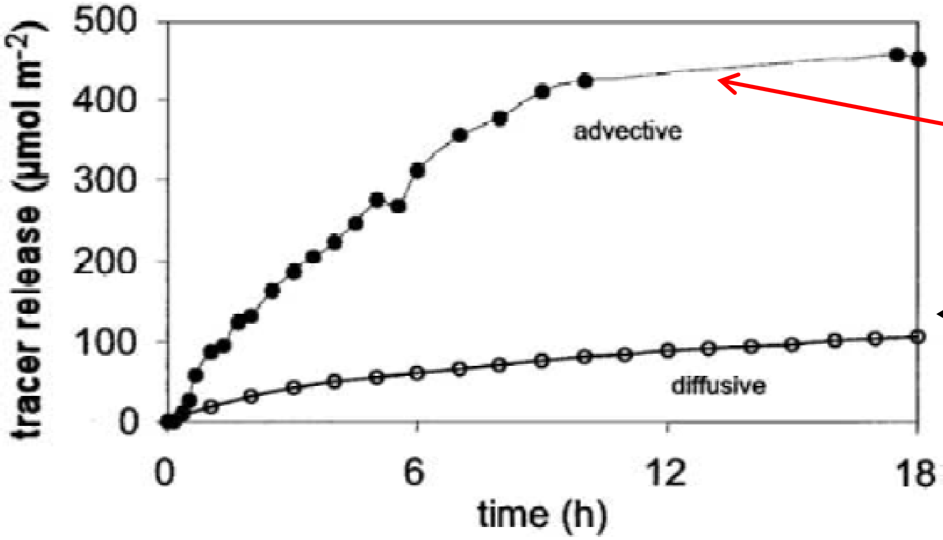
Advective porewater exchange due to boundary currents



(a)



Shum 1993



(b)

Huettel et al., 2003

tracer release when sediment exposed to waves

tracer release under stagnant conditions

advective release of solutes is higher than diffusive release

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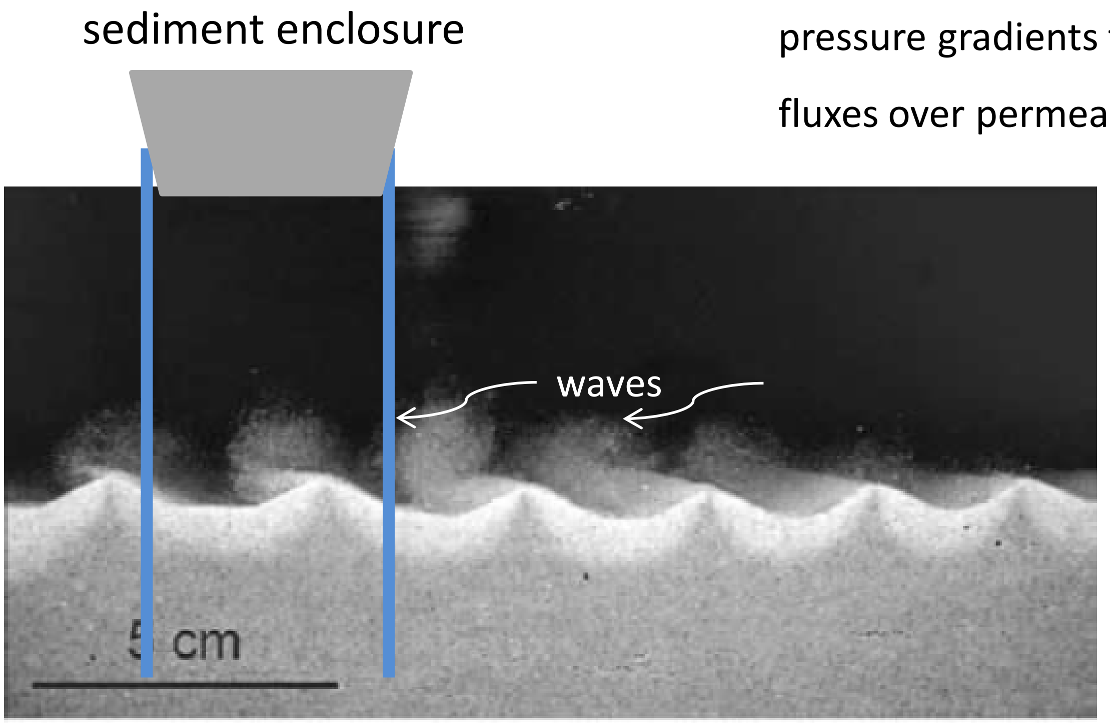
Why does it matter?

Currents due to tidal forcing and wave motion create pressure gradients that may enhance sediment-water fluxes over permeable sediments.



flow regime changes to stagnant conditions

- shift from advective to diffusive transport
- release of solutes from sediment changes

For measuring benthic fluxes, proper simulation of the flow regime is crucial for realistic results!

2. Early diagenetic processes in sediments
2.2 Transformation of organic matter in BBL and in sediments

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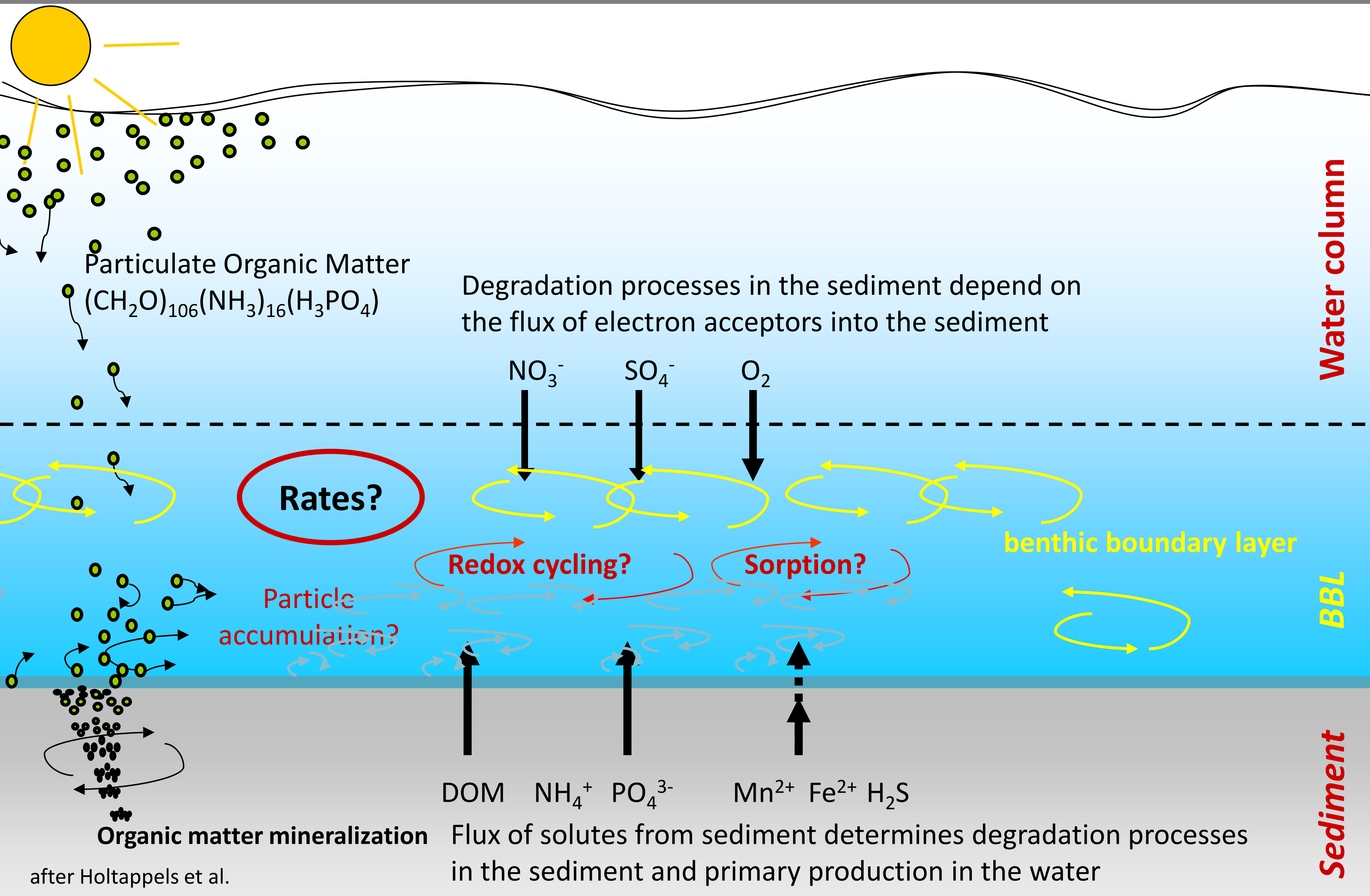

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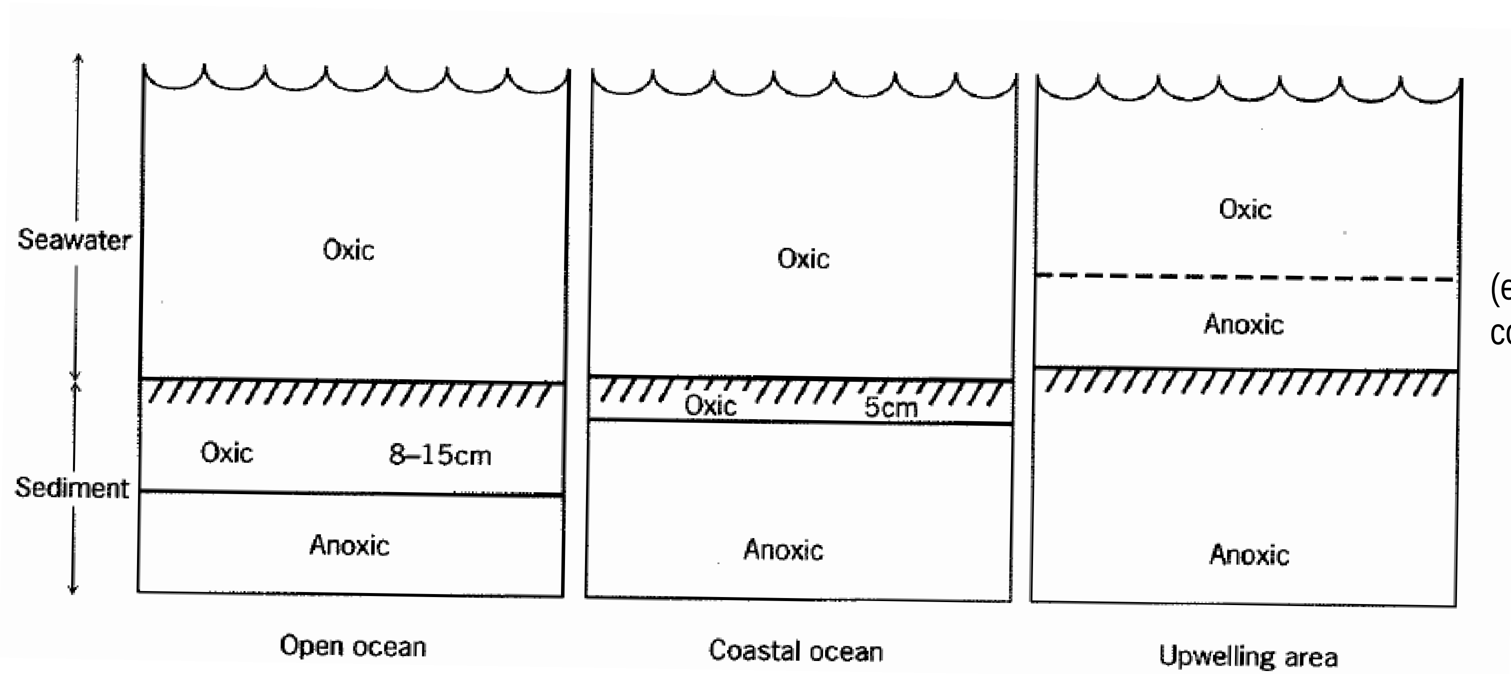
Redox regimes in sediments

controlled by

- supplies of organic matter, O_2, NO_3^-, SO_4^{2-} (electron acceptors)
- bottom water ventilation and near-bottom currents
- sediment permeability
- bioturbation/bioirrigation



(euxinic, if water contains H_2S)

stratified basins

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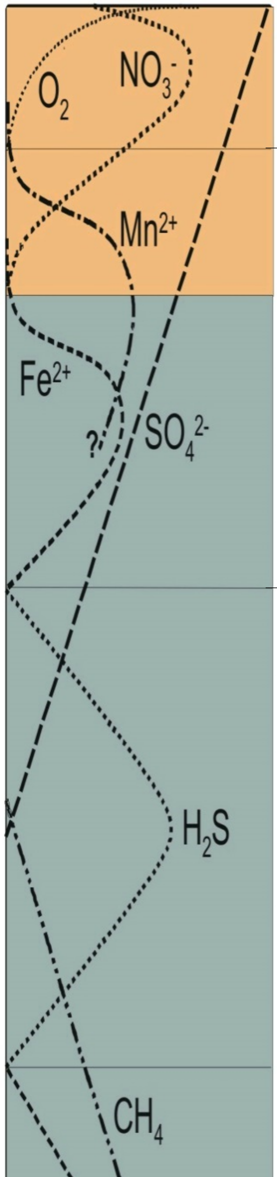
porewater profile | **pathways** | **microbial reactions (temperature and substrate dependent)**

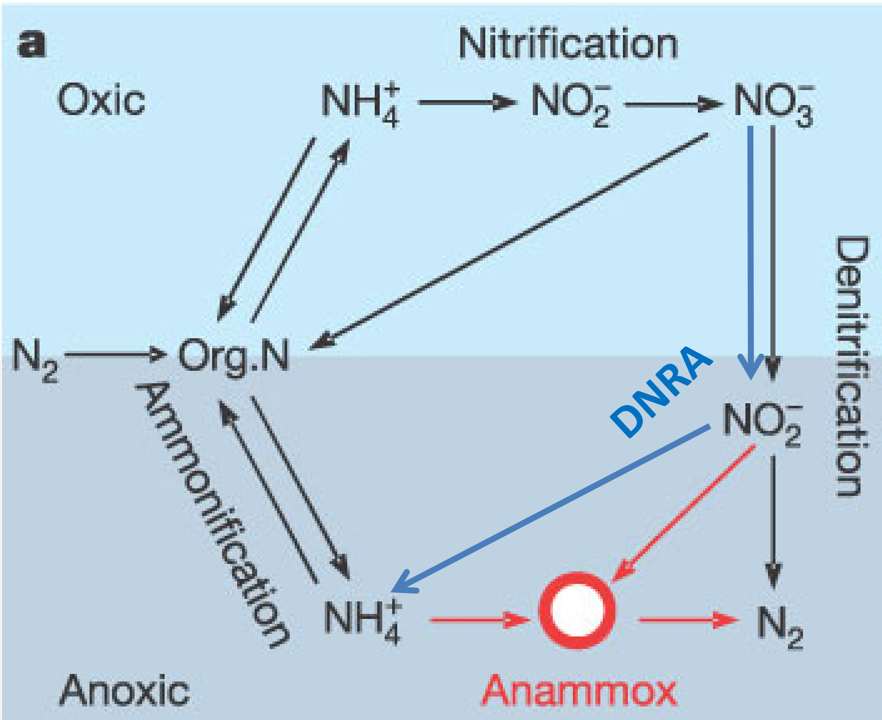


	pathways	microbial reactions
OXIC	aerobic respiration	$(CH_2O)_x(NH_3)_y(H_3PO_4)_z + (x+2y)O_2 \longrightarrow xCO_2 + yNHO_3 + zH_3PO_4 + (x+y)H_2O$
	nitrification	$NH_3 + 2O_2 \longrightarrow HNO_3 + H_2O$ (Nitrosomonas & Nitrobacter)
SUBOXIC	nitrate reduction	$(CH_2O)_{106}(NH_3)_{16} + 53HNO_3 \longrightarrow 106CO_2 + 69NH_3 + 53H_2O$ (DNRA) (e.g., Pseudomonas, nitrate storing bacteria)
	denitrification	$(CH_2O)_{106}(NH_3)_{16} + 94.4HNO_3 \longrightarrow 106CO_2 + 55.2N_2 + 177.2H_2O$ (e.g., Pseudomonas)
	Mn(IV) reduction	$(CH_2O)_x(NH_3)_y(H_3PO_4)_z + 2xMnO_2 \longrightarrow xCO_2 + 2xMn^{2+} + yNH_3 + zH_3PO_4 + 2xH_2O$
	Fe(III) reduction	$(CH_2O)_x(NH_3)_y(H_3PO_4)_z + 4xFe(OH)_3 \longrightarrow xCO_2 + 4xFe^{2+} + yNH_3 + zH_3PO_4 + 3xH_2O$ (Thiobacillus, Gallionella)
	sulfide oxidation	$HS^- + 2O_2 \rightarrow SO_2^{2-} + H^+$ (e.g., Thiobactilus, Beggiatoa, Thioploca)
ANOXIC	anammox	$NH_4^+ + NO_2^- \longrightarrow N_2 + 2H_2O$
	SO_4^{2-} reduction	$2(CH_2O)_x(NH_3)_y(H_3PO_4)_z + xSO_4^{2-} \longrightarrow 2xHCO3- + xH_2S + yNH_3 + 2zH_3PO_4$ (Desulvovibrio, archaea)
	methanogenesis	$2(CH_2O)_x(NH_3)_y(H_3PO_4)_z \longrightarrow xCO_2 + xCH_4 + 2yNH_3 + 2zH_3PO_4$ (archaea)

Stoichiometries x=106, y=16 and z=1 (Redfield 1934)
electron acceptor

(after Aller 1982, Dalsgaard et al. 2003)

Close up of nitrogen cycle



after Kuypers et al. (Nature 2003)

Denitrification (= „ecosystem service“)

$$(CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 94.4\ NO_3^- + 94.4H^+ \rightarrow$$

$$106CO_2 + 16NH_4 + 16NO_2^- + 39.2N_2 + 145.2H_2O + H_3PO_4$$

anaerobic ammonium oxidation

Anammox $16NH_4^+ + 16NO_2^- \rightarrow 16N_2 + 32H_2O$

competing nitrate reduction process:

DNRA – dissimilatory nitrate reduction to ammonium

= conserves N within the ecosystem!

$$(CH_2O)_{106}(NH_3)_{16} + 53HNO_3 \rightarrow 106CO_2 + 69NH_3 + 53H_2O$$

DNRA = major N reduction pathway in coastal ecosytems

DNRA is favored over denitrification at increased C loads (high C_{org}/NO_3 ratios), increased sulfate reduction rates, increased temperatures

Eutrophication & climate warming support DNRA

→ of critical importance for predicting eutrophication trajectories!

3. Methods and instrumentation for measurements of sediment-water fluxes

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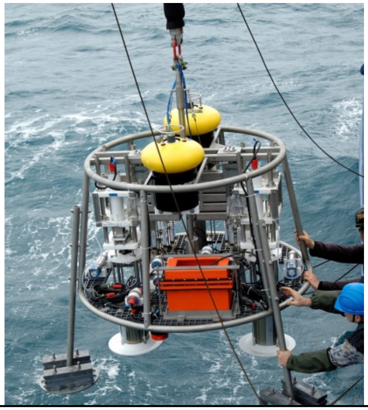
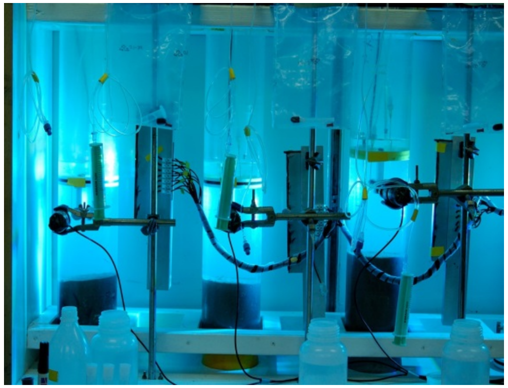
in-situ



ex-situ



non-invasive

- eddy correlation (benthic O_2 uptake)
- laser scanner (microtopography)
- HD camera (bedform migration, fauna analysis)
- ADCP (bottom currents)

invasive

- benthic chamber lander (nutrient &O_2 uptake)
- microsensor profilers (HR porewater profiles)

sediment cores or slurries

- light & dark incubations (benthic primary production & respiration, nutrient fluxes, isotope tracer experiments /N-cycle)
- microsensor profiles (O_2 penetration depth)
- rhizones (sediment porewater extraction)

3. Methods and instrumentation
3.1 Ex-situ: Sediment sampling – surface sediments (slurries)

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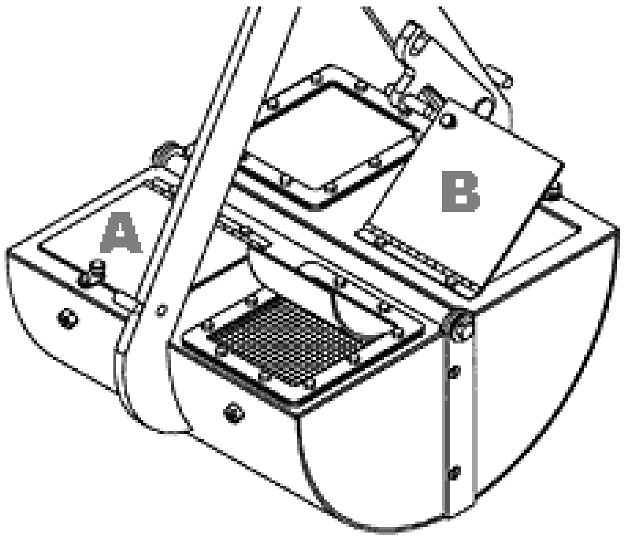
Van-Veen grab



e.g.
fauna analysis
grain-size analysis
permeability
volumetric oxygen consumption
slurry incubations

3.1 Ex-situ: Sediment sampling – surface sediments 0-40 cm

Box corer

e.g.
fauna analysis
grain-size analysis
permeability
core subsampling

3.1 Ex-situ: Sediment sampling – surface sediments 0-40 cm

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Multicorer (MUC)

photo
J. Friedrich

3.2 Ex-situ: Incubation of sediment cores in ship‘s cool lab

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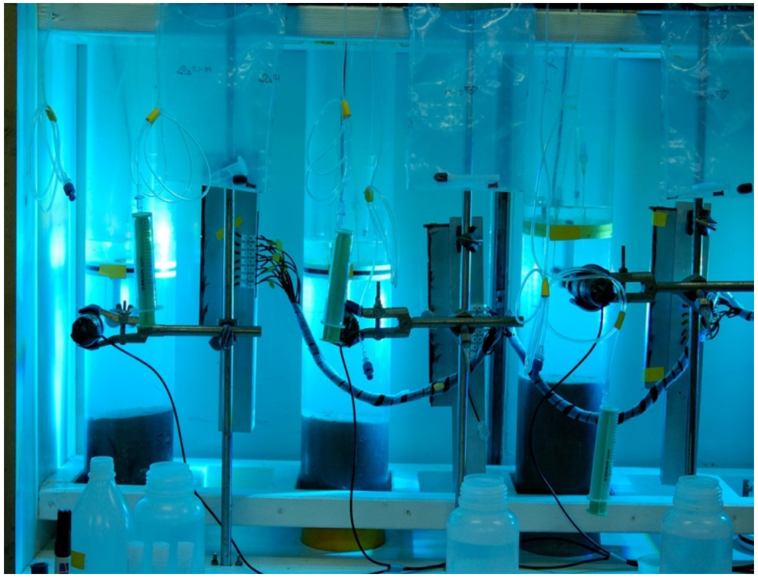
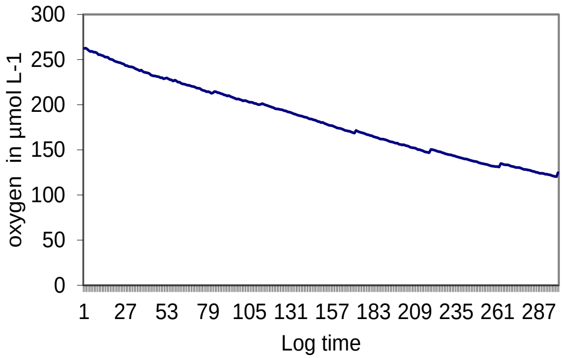
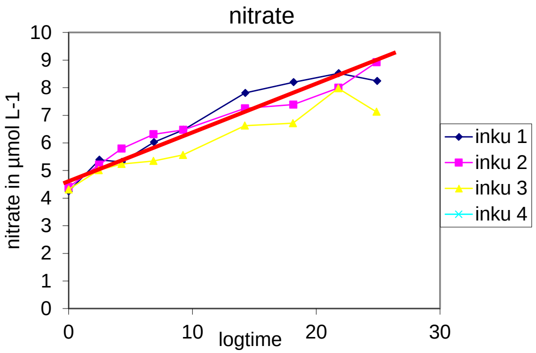
Oxygen uptake and nutrient release from sediment under laboratory conditions

$$F = h\frac{d[C]}{dt}$$



Benthic primary production from changes in oxygen concentrations in the sediment overlaying water





German Bight, HE432, Neumann et al. EGU2015-1296

h - height (m) of the water column in the enclosure

d[C]/d*t* - accumulation rate ($mmol\ m^{-3}\ d^{-1}$)

F – flux at sediment water interface ($mmol\ m^{-2}\ day^{-1}$)

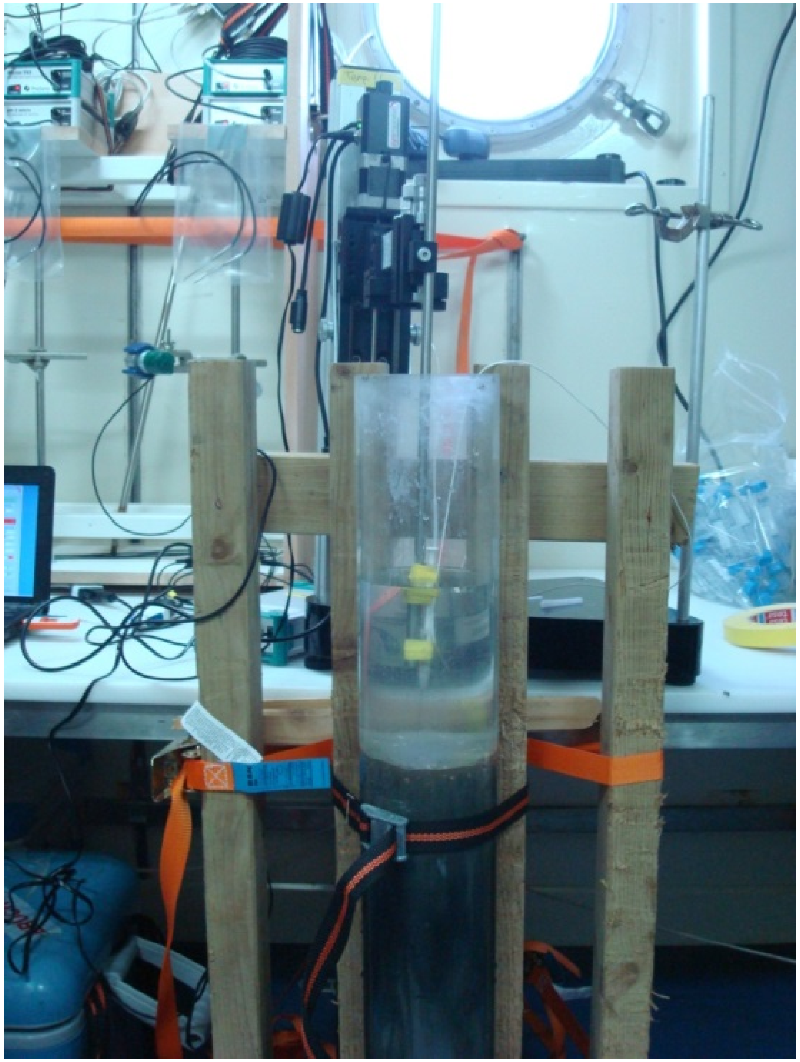
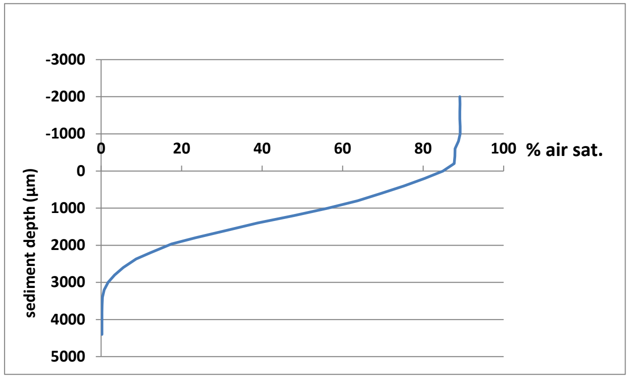


photo
J. Friedrich

Example:

High-resolution O_2 profiles at water-sediment interface

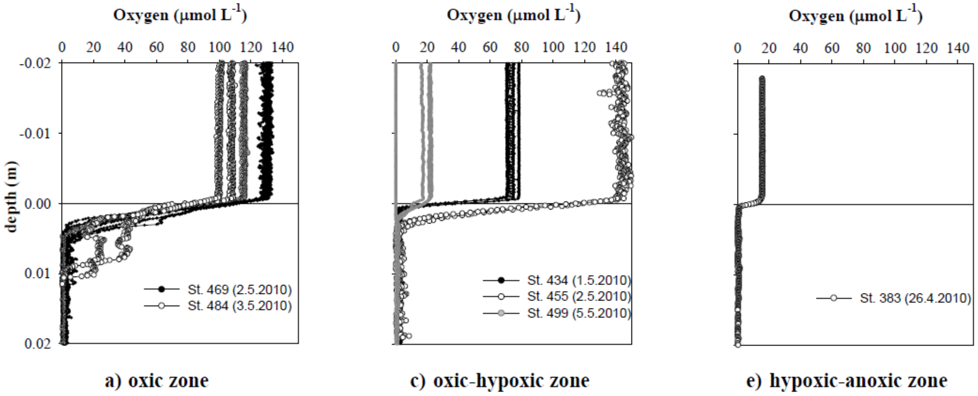
O_2 penetration depth into sediment



German Bight, sandy sediment

Janssen & Friedrich, HE383

O_2 profiles under different oxygen regimes



Crimean Shelf, Black Sea (Lichtschlag et al., submitted)

Fick´s First Law

Diffusive benthic fluxes across the (sediment-water) interface is proportional to the concentration gradient and the diffusion coefficient

$$J = -\phi D_s \frac{dC}{dx}$$

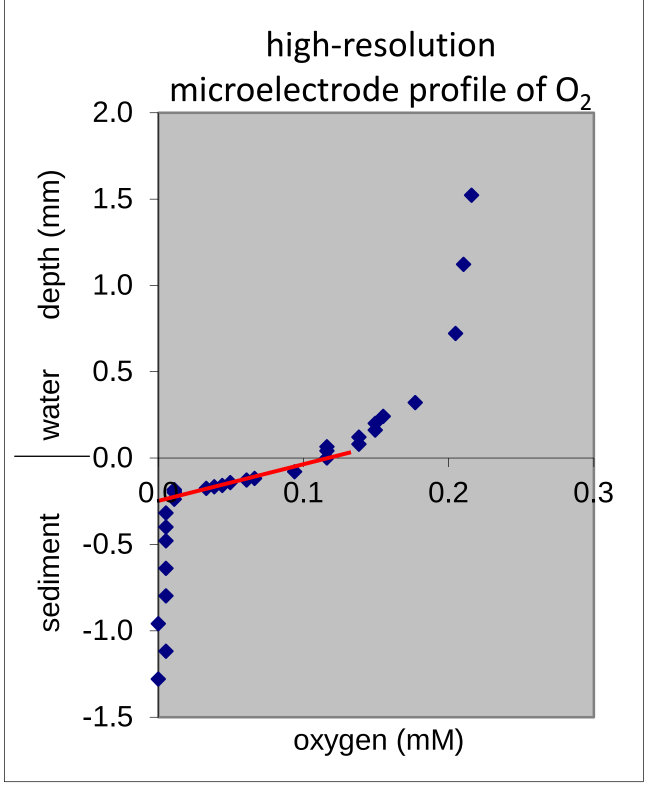
J - flux (mmol m^{-2} day^{-1})
ϕ - porosity (ml cm^{-3})

$$D_s = \frac{D}{\phi F}$$

Ds - effective diffusion coefficient in the sediments
D - molecular diffusion coefficient in seawater at 5°C (Furrer and Wehrli, 1996)

F - sediment resistivity (Berner, 1980); (Christensen et al., 1987) and is given by an empirical relationship to ϕ (Manheim, 1970)

$$F = \frac{1}{\phi^m}$$



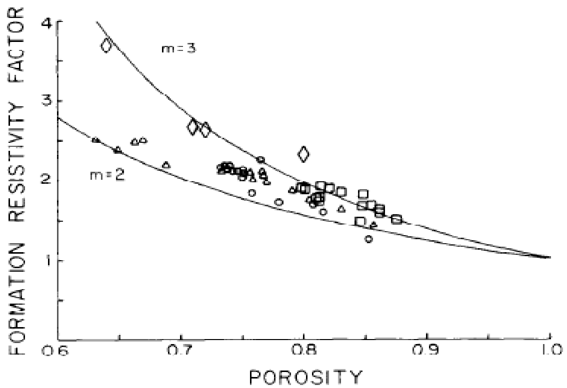


Fig. 3. Relationship between *F* and *ϕ*; □—Mud Bay, station 5; ○—Long Island Sound, station NWC; △—Florida Bay, Captain Key Bank; ◇—from

Ullman & Aller 1982

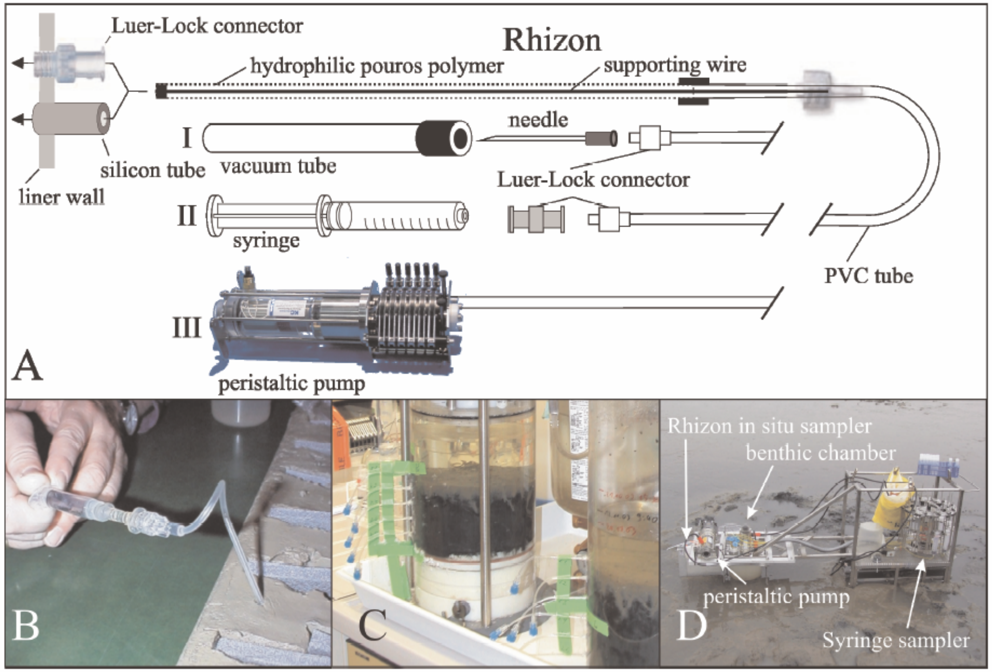
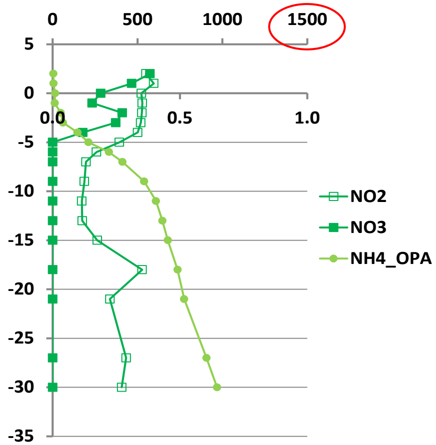


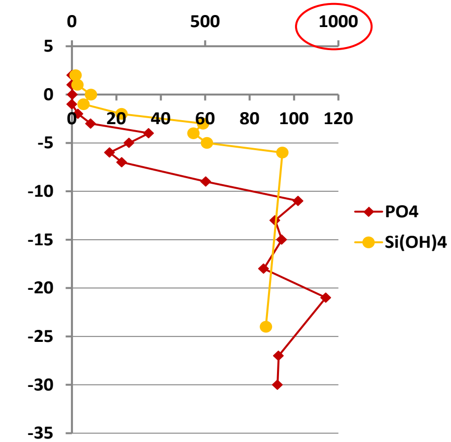
Fig. 1. (A) Schematic diagram of a Rhizon (length 5 and 10 cm, respectively, outer diameter 2.5 mm, dead volume 0.5 mL, pore size 0.1 µm) and the devices used for porewater extraction (vacuum tubes, syringes, and peristaltic pumps, I-III). Modes of application are (B) sampling of porewater with a Rhizon and a syringe from an open sediment core, (C) insertion of Rhizons through predrilled holes in a liner used for sediment sampling or for microcosm experiments, and (D) combined flux and porewater studies using a benthic chamber and an array of Rhizons inserted into the sediment. Typically, 2 mL porewater was sampled from sediments.

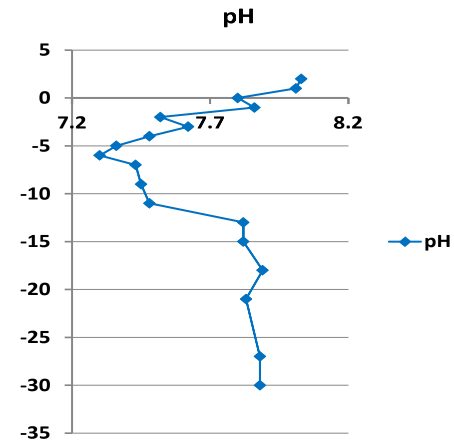
Seeberg-Elverfeldt et al. 2005

Porewater concentrations and gradients differ depending on sediment composition

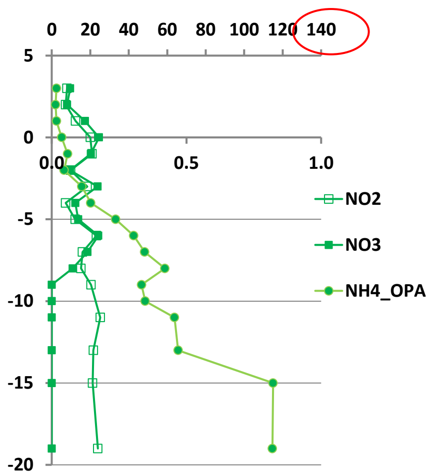
Helgoland mud area (HE432) (porewater concentrations in µmol L^{-1})

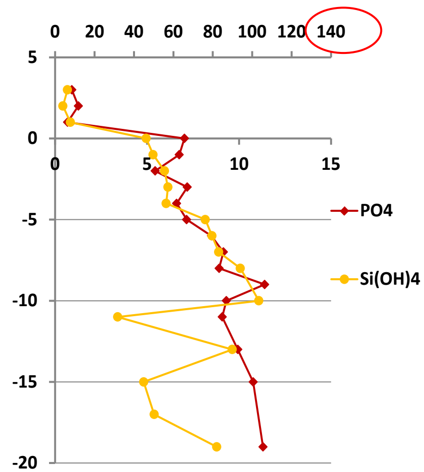


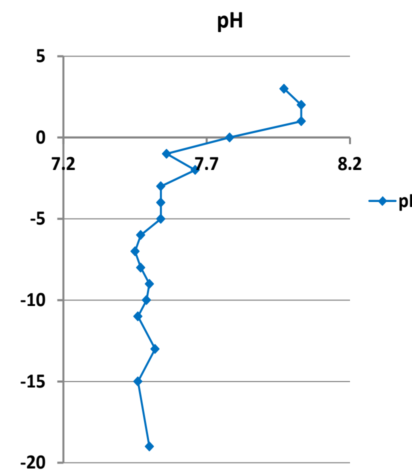




Helgoland starved dunes



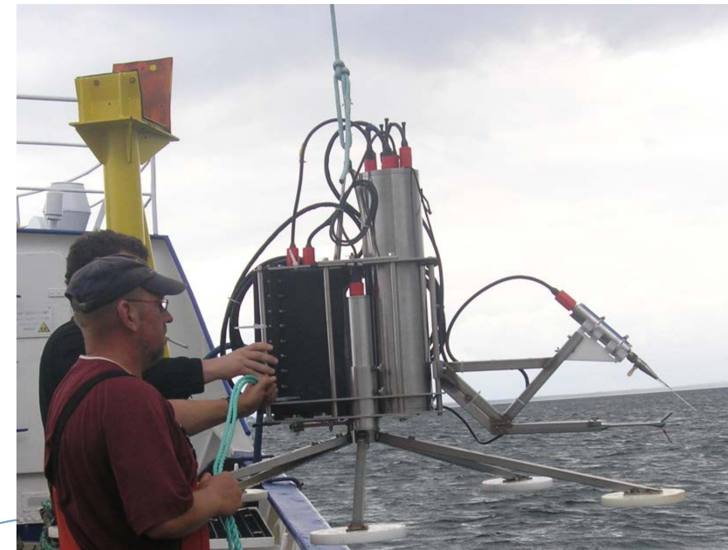


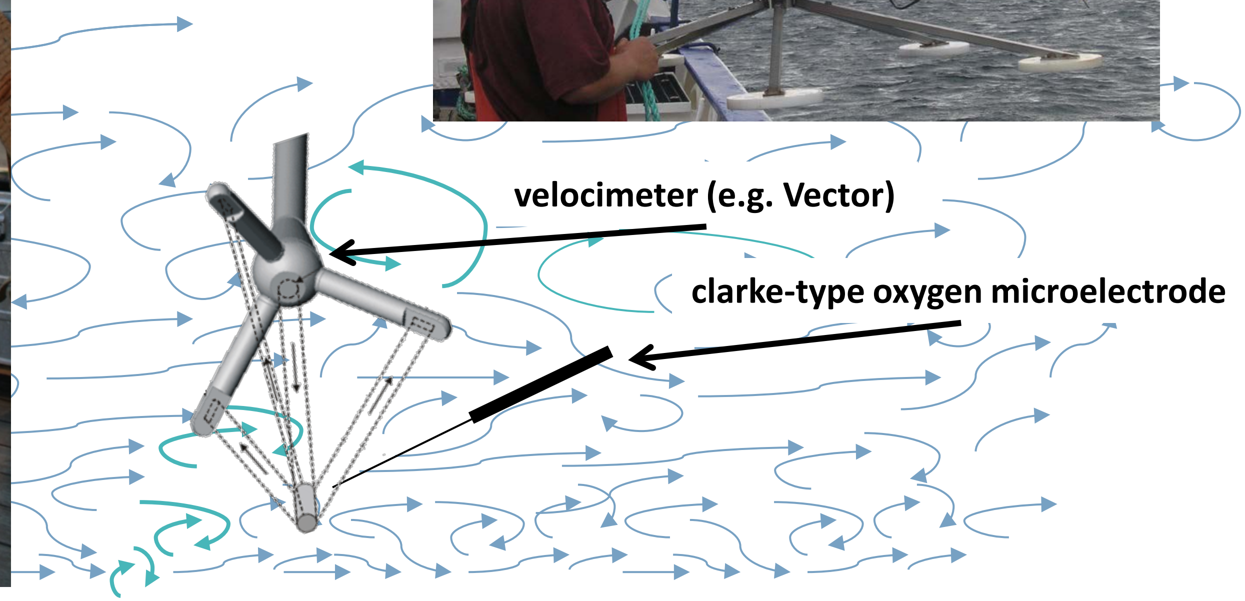


Friedrich et al., EGU2015-9199

Benthic oxygen uptake

$$J = u_i * C$$





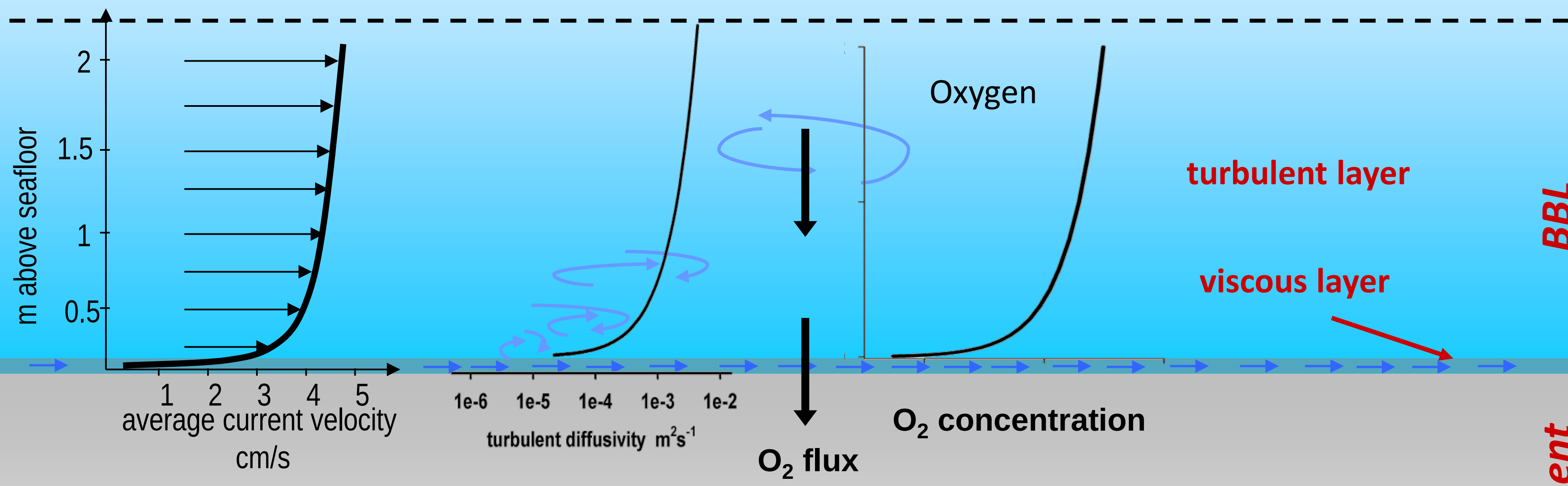
after Holtappels et al. 2013, Berg et al., 2003
MPI Bremen

J. Friedrich, HZG
Askö Summerschool 2015

Solute flux measurements in the BBL:

- **are non invasive**
- **integrate a large surface area that contributes to the flux**
- **consider diffusive and advective transport across the sediment-water interface (e.g. sandy sediment)**

Water column



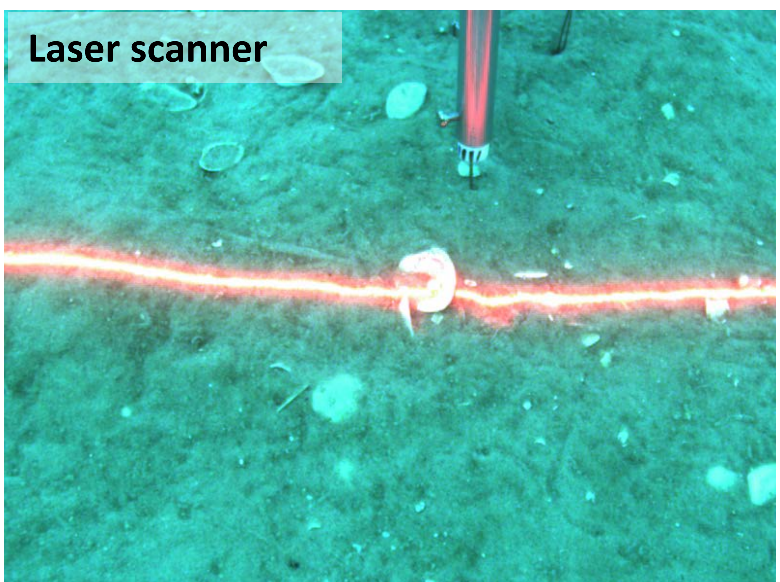
Sediment

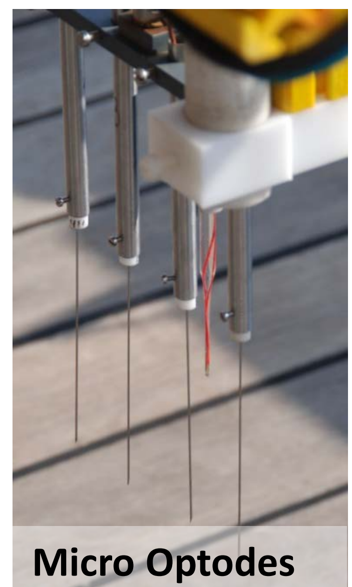
Holtappels et al. 2013

3. Methods and instrumentation
3.5 In-situ techniques: microprofiler lander and laser scanner

Measurements

- Current velocity
- Topography
- Bedform migration
- O_2 depth profiles
- O_2 flux dynamics in the field





Ahmerkamp et al. in prep.

3.6 In-situ techniques: Benthic flux chamber lander

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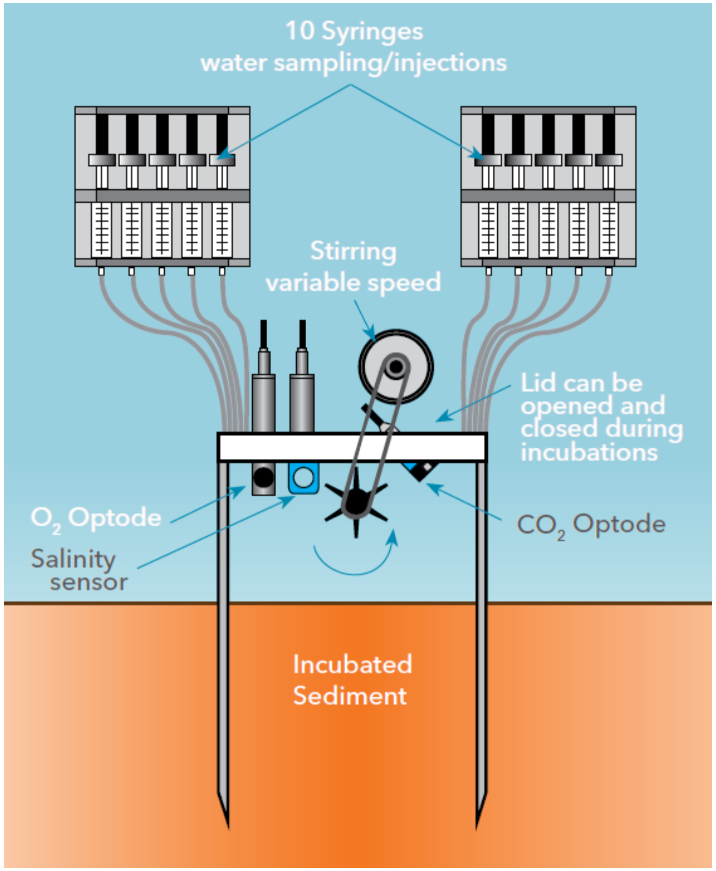
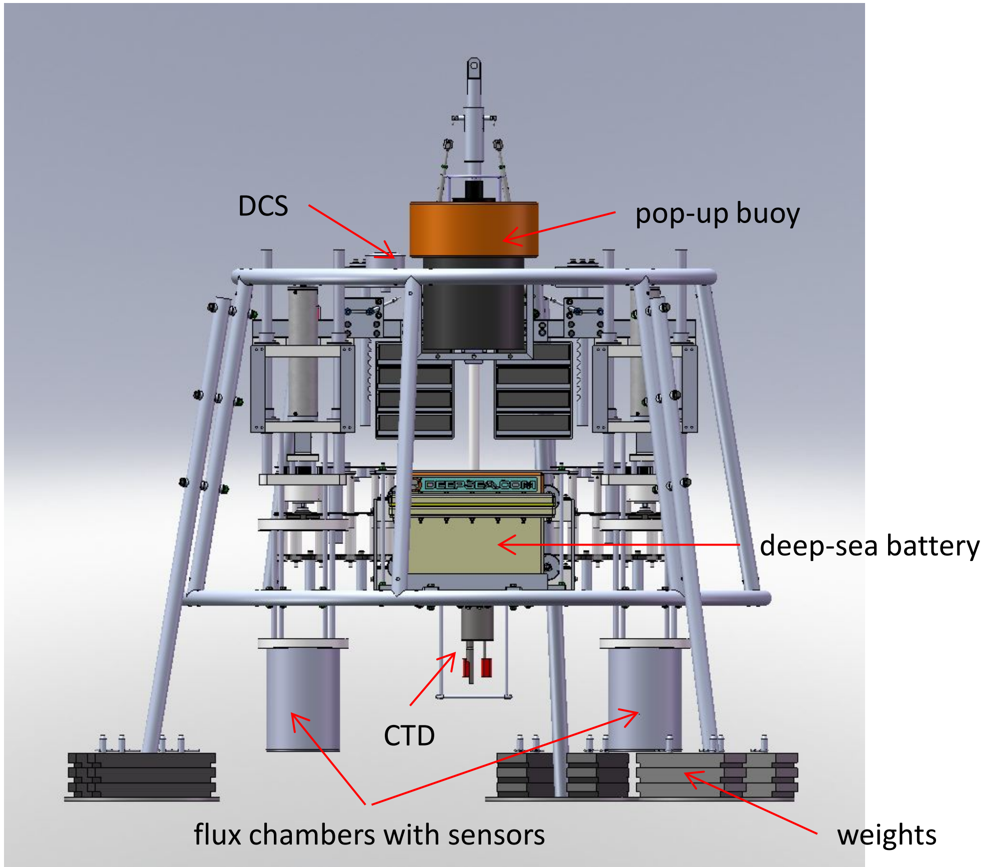
Measurement of solute fluxes across the sediment-water interface

Principle

sediment-bottom water enclosure





UGOT lander, Univ. Gothenburg

FLUXSO lander, HZG

3.6 In-situ techniques: Benthic flux chamber lander

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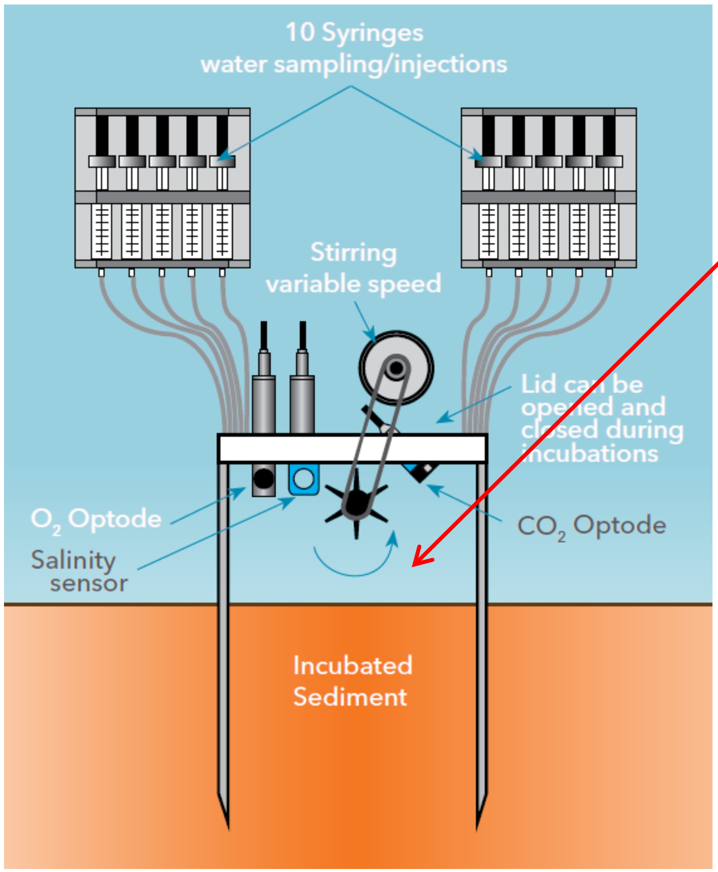
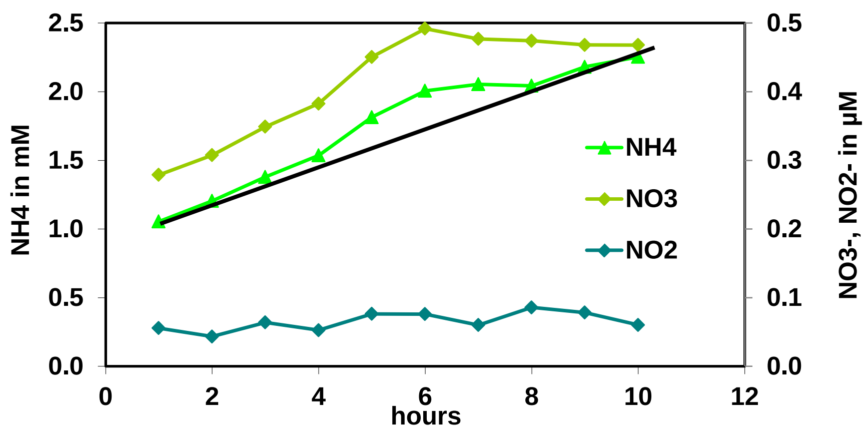
Calculation of benthic fluxes across the sediment-water interface

change in solute concentration in chamber over time



UGOT lander, Univ. Gothenburg



linear regression to the change in concentration over time in the flux chambers/microcosms

$$F = h\frac{d[C]}{dt}$$

h - height (m) of the water column in the enclosure

d[C]/d*t* - accumulation rate ($mmol\ m^{-3}\ d^{-1}$)

F – flux at sediment water interface ($mmol\ m^{-2}\ day^{-1}$)

0.66 mmol $NH_4^+\ m^{-2}\ day^{-1}$
0.11 mmol $NO_3^-\ m^{-2}\ day^{-1}$

NOAH-E Sep 2014
fine sand, epi- /infauna

Friedrich et al., EGU2015-9199

3.6 In-situ techniques: Benthic flux chamber lander

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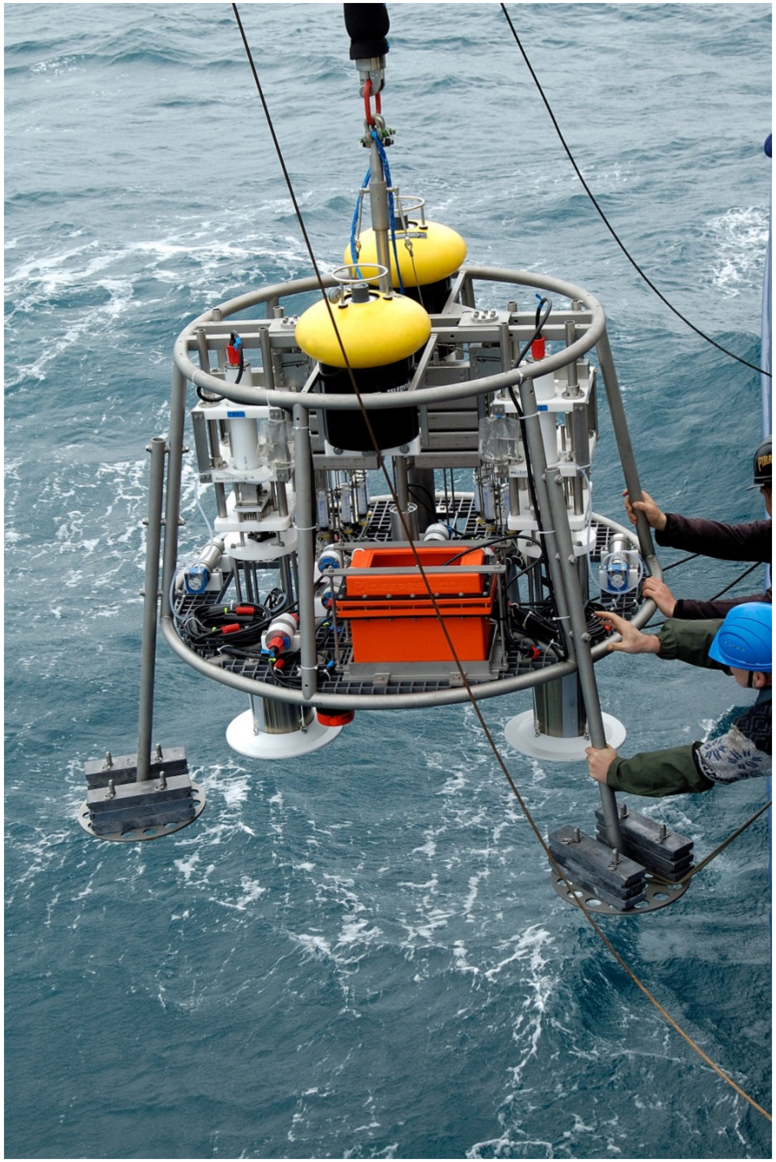
Example: HZG Chamber lander „FLUXSO“ – **Flux**es on **S**ands **O**bservatory



2 chambers, equipped with:

stirrer disk (variable speeds)
oxygen optode
CO_2 optode
pH sensor Hamilton
conductivity sensor
syringe sampler for tracer injection and sampling from chamber

outside chamber:

CTD with fluorescence & turbidity sensors, PAR, oxygen optode, pH sensor Hamilton
z-pulse doppler current sensor

3.6 In-situ techniques: Benthic flux chamber lander

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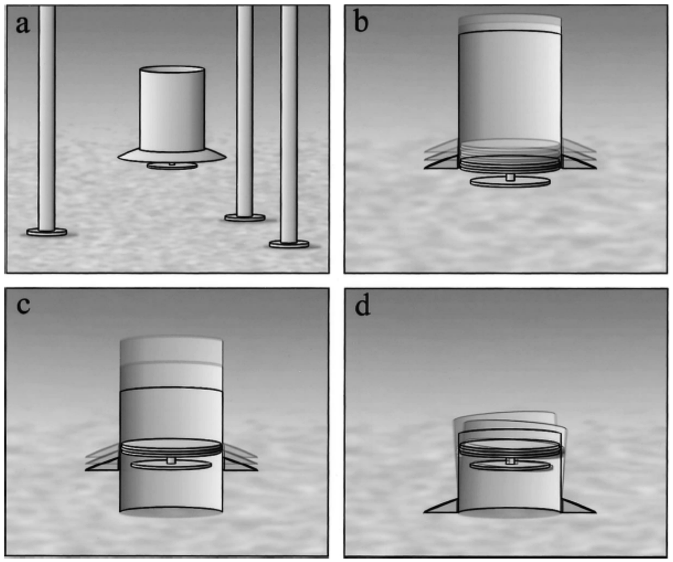
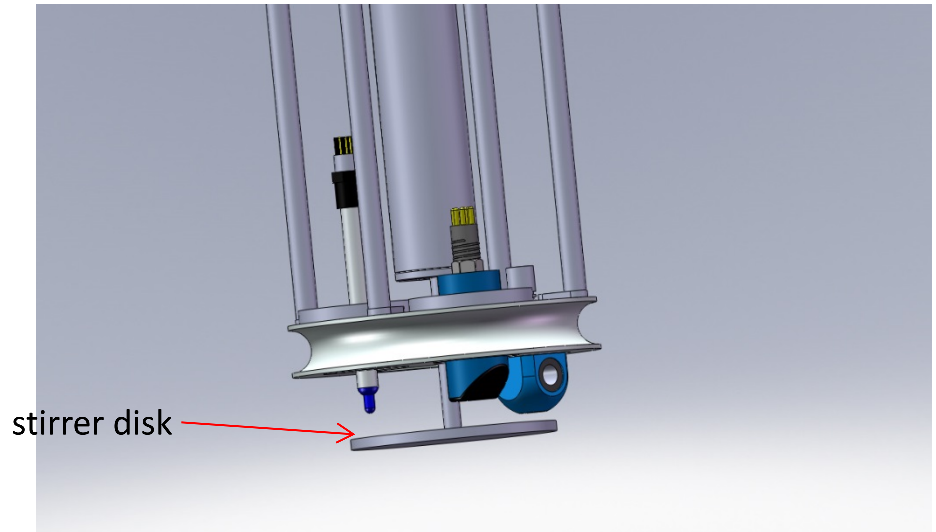
Wiggling chamber for sandy and consolidated sediments

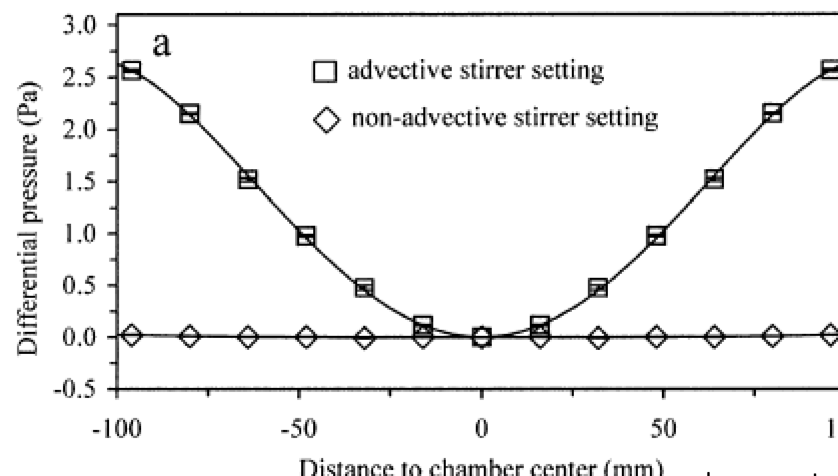


Janssen et al. 2005

Chamber lid with sensors and stirrer disk



Appropriate simulation of hydrodynamic regime is crucial for reliable measurement of fluxes on permeable sediments!

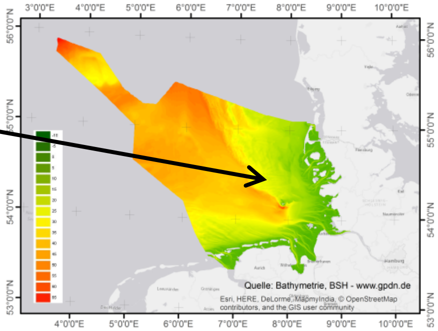


Janssen et al. 2005

3.6 In-situ techniques: Benthic flux chamber lander

FLUXSO on fine sand

North Sea, 27 m water depth



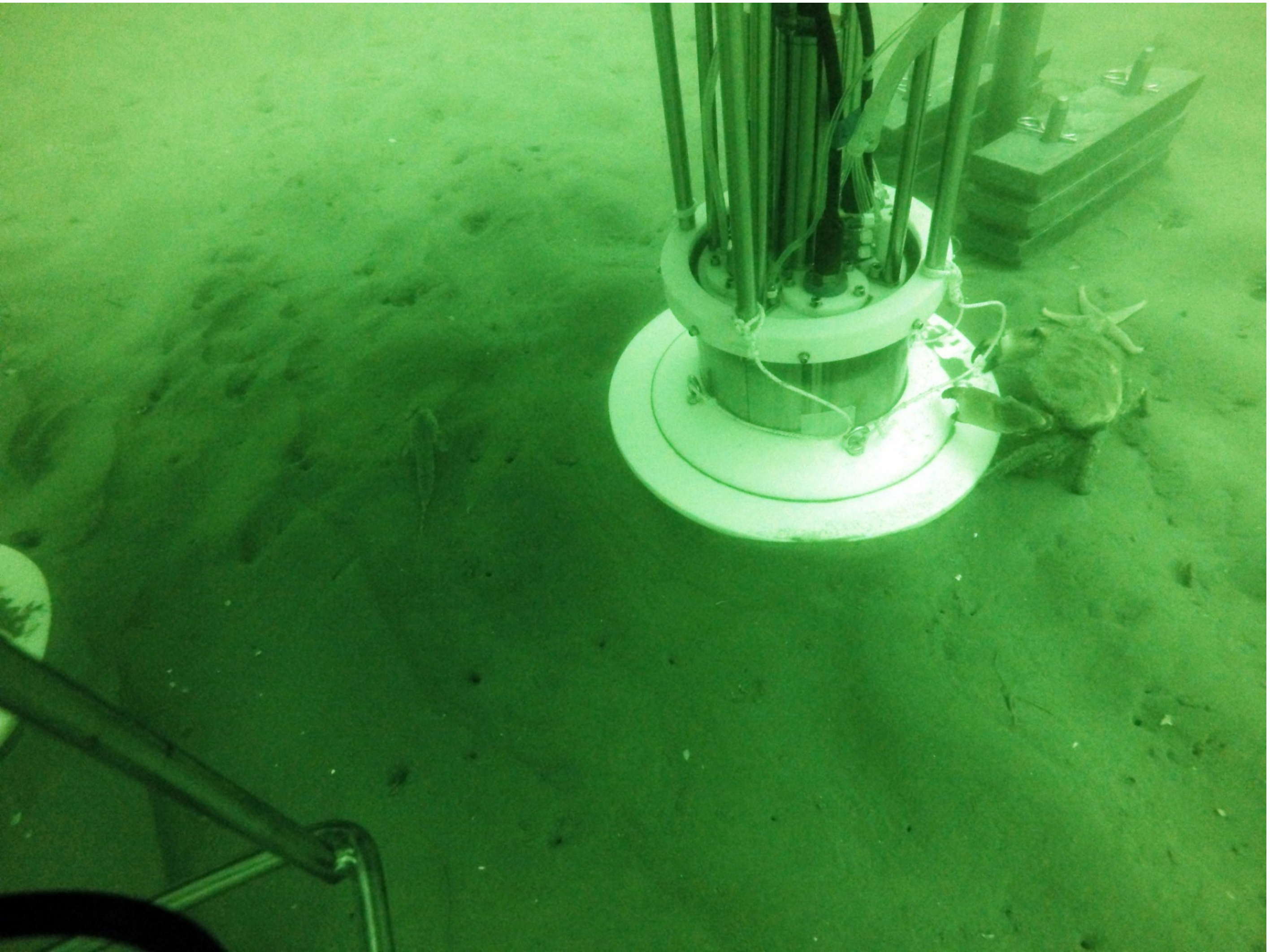


photo
J.Friedrich

3.6 In-situ techniques: Benthic flux chamber lander

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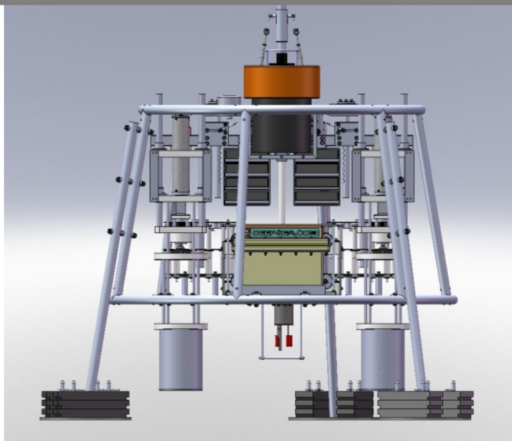
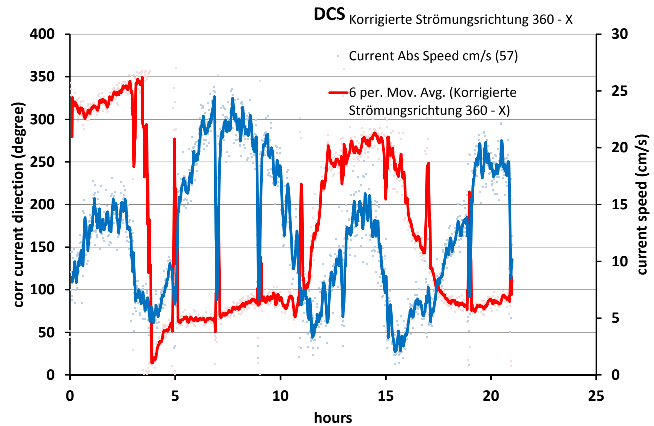


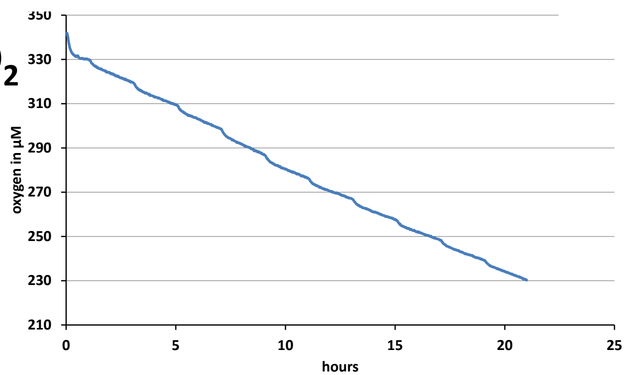
Example: FLUXSO on the Dogger Bank, June 2015



current speed (cm/s) & direction

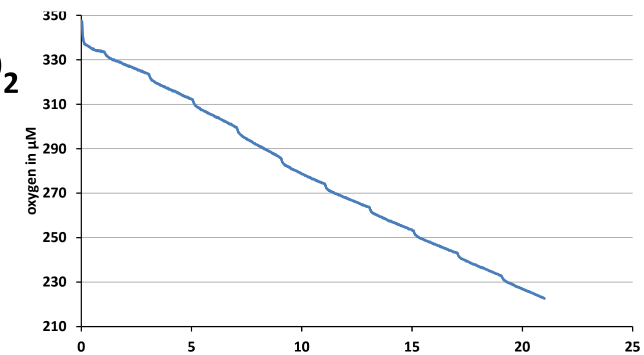
chamber 1

O_2



chamber 2

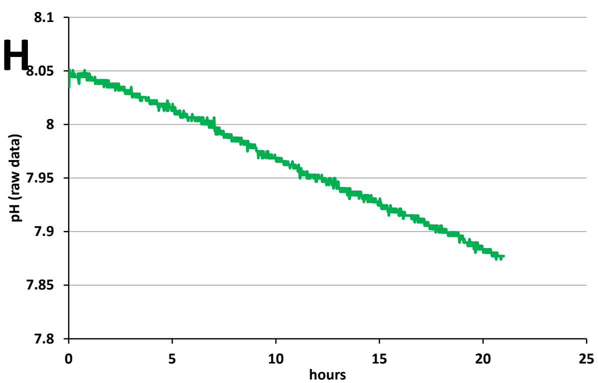
O_2



O_2 (µM)

-16.4 mmol m^{-2} day^{-1}

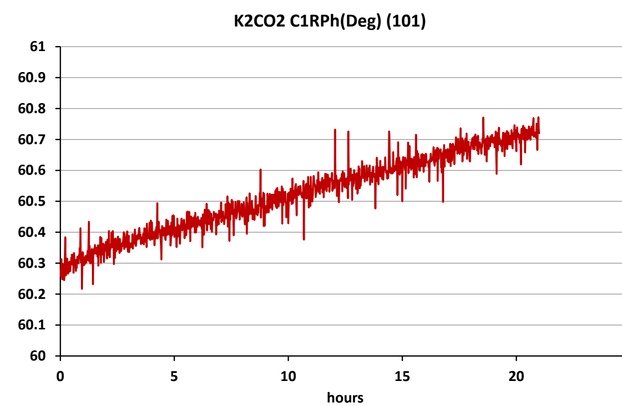
pH



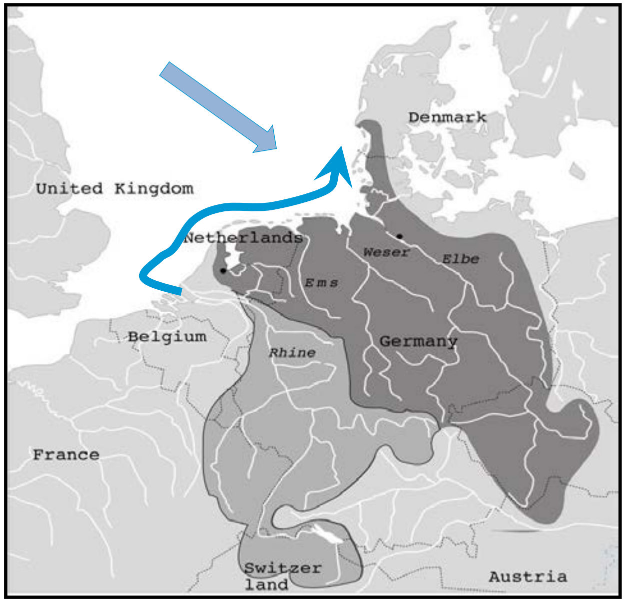
pH CO_2

(raw data)

CO_2

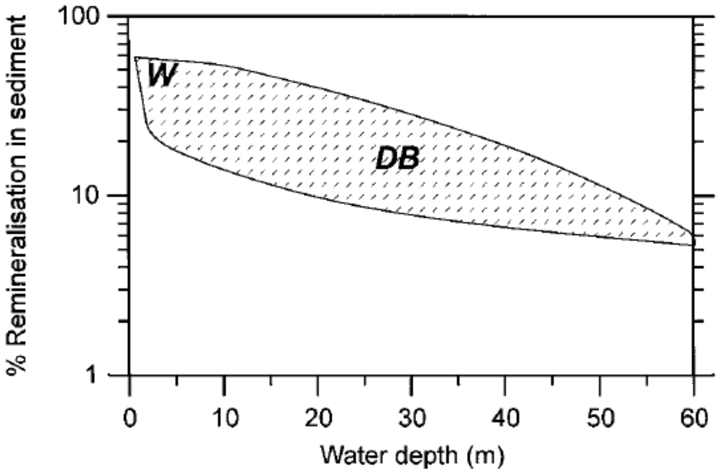


Friedrich et al., unpublished data



Influences on North Sea

- Atlantic (North Atlantic / Fair Isle current Channel)
- Rivers (Rhine, Maas, Elbe & Weser etc)
- anti-clockwise circulation driven by semi-diurnal tides & wind

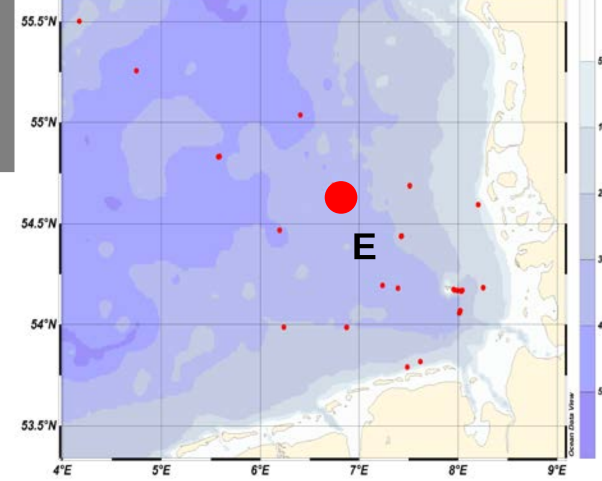


Hypothesis

In the German Bight (DB), 10-30% of total remineralisation occurs in sediments, depending on water depth

(after Heip et al.1995)

4.1 Comparison of benthic and pelagic fluxes in the North Sea



Comparison of benthic and pelagic respiration

German Bight (27 m):
weakly permeable sand with infauna & epifauna

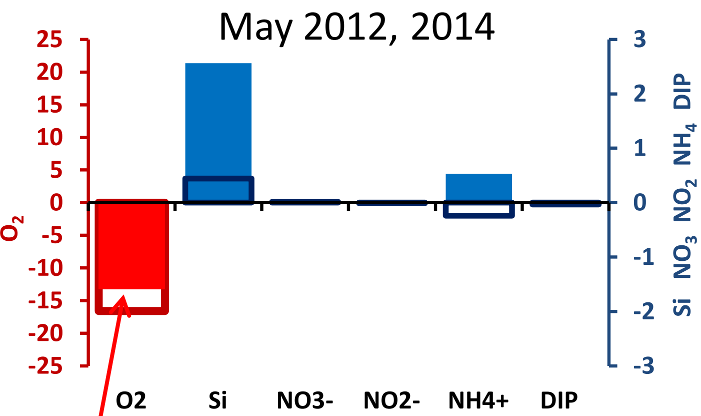
Integrated pelagic O_2 respiration

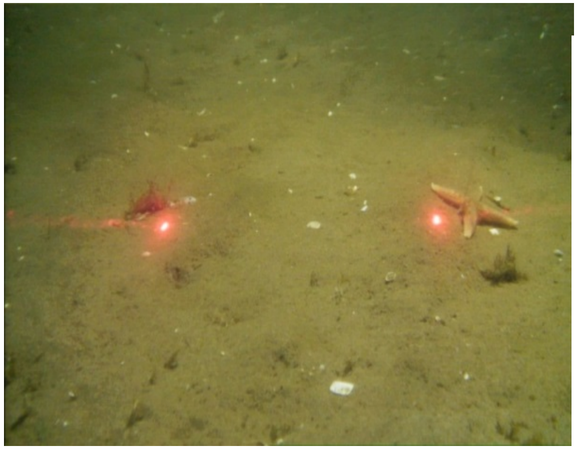
May 84 mmol m^{-2} day^{-1}

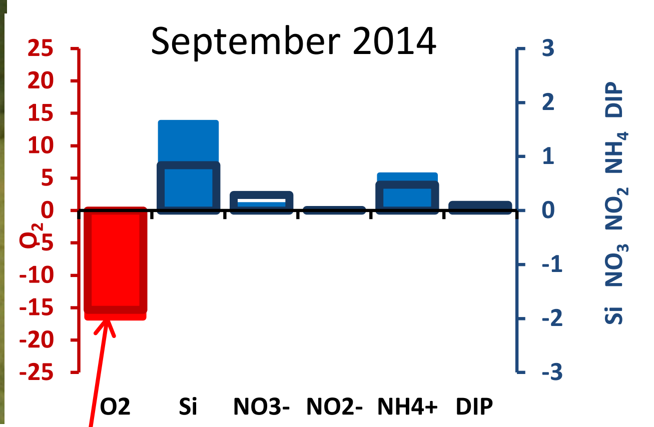
Integrated pelagic O_2 respiration

September 324 mmol m^{-2} day^{-1}

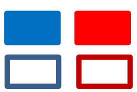
Benthic fluxes (mmol m^{-2} day^{-1})







- ca 20% of pelagic respiration in May



in-situ (Lander Sandy)
ex-situ (Inkubation Andy)

- ca 5 % of pelagic respiration in Sep.

Friedrich et al., EGU2015-9199

4.2 Sediments contain the legacy of eutrophication

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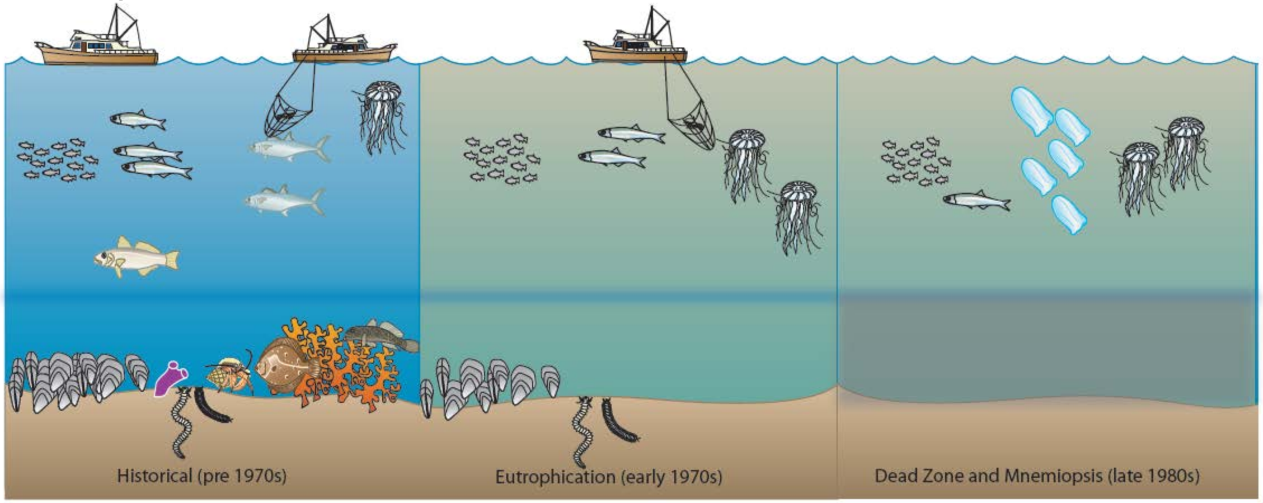
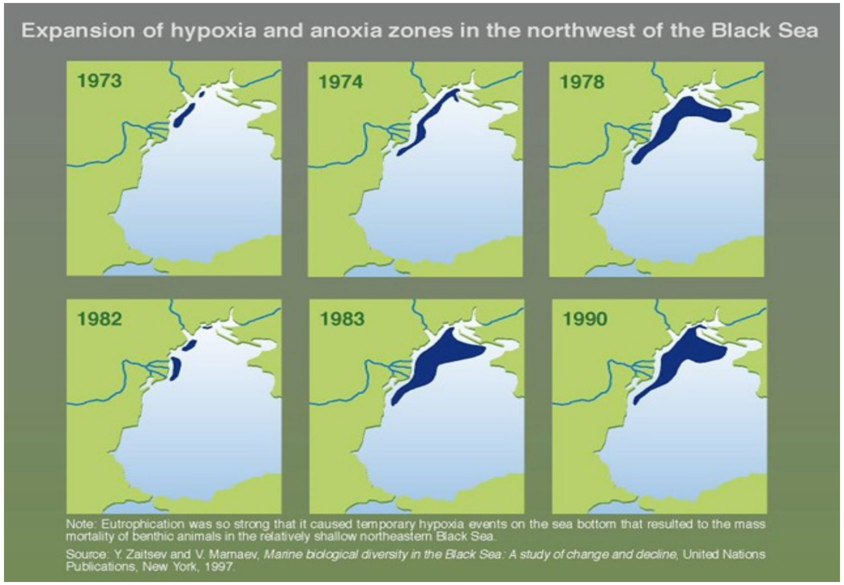
Example from the Black Sea western shelf

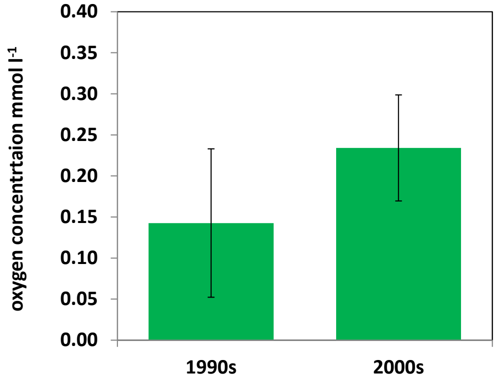


Mee 2005



Borysova et al. 2005

Bottom water oxygen in western Black Sea shelf



Friedrich et al. 2010

4.2 Sediments contain the legacy of eutrophication

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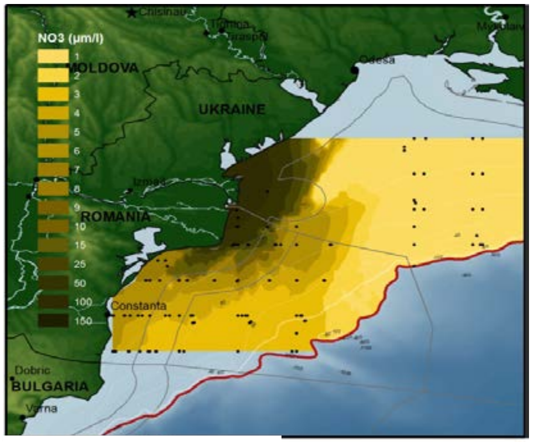
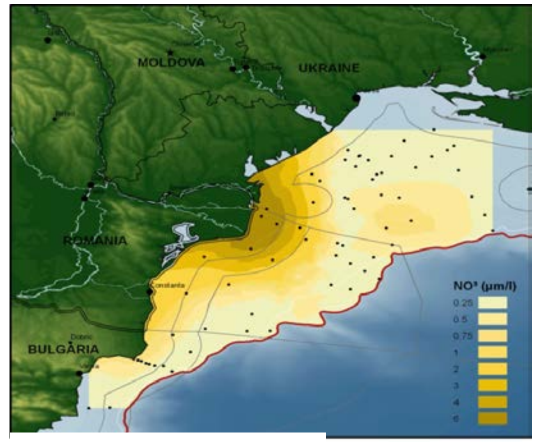
Askö Summerschool 2015

Changes in nitrate in the surface water of the western Black Sea shelf in the 1990s and 2000s



Winter 1990-1995



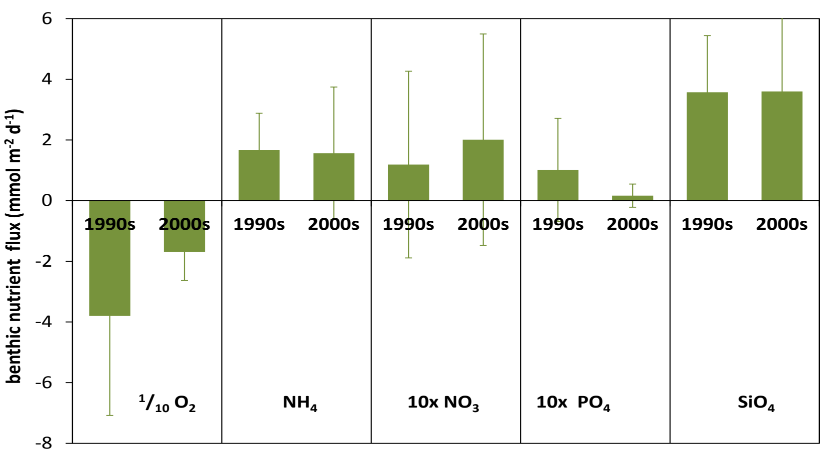
Winter 2005-2010

1990s = eutrophication
2000s = recovery from eutrophication

data from Black Sea database http://sfp1.ims.metu.edu.tr/ODBMSDB/)
2006 and 2008 data from Friedrich et al. P363 cruise report.

Changes in sediment-water nutrient fluxes in the 1990s and 2000s

1990s = 1995, 1997, 1998
2000s = 2006, 2008, 2010



Friedrich et al., 2010

Sediment nutrient release is an internal source for productivity.

Despite decrease in eutrophication, sediment nutrient release continues for longer than the legislation period of politicians!

Shelf sediments contain legacy of eutrophication!

Dating the last 100 years with ^{210}Pb and ^{137}Cs

^{137}Cs half life 30 years
nuclear fission product

^{210}Pb half life 22.3 years
by decay of natural ^{238}U

Radioisotopes provide physical „clocks“

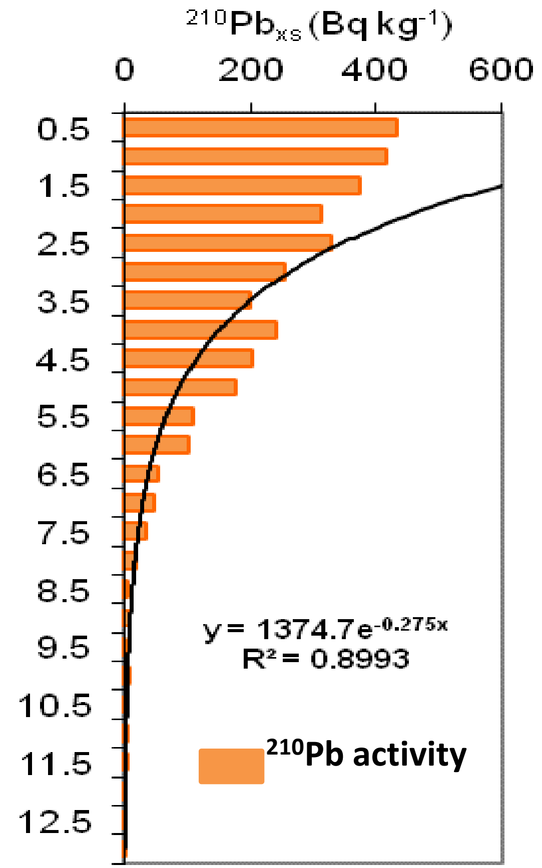
$$A(t) = A(t=0)\,e^{-\frac{\ln(2)\,t}{T_{1/2}}}$$

Age range and resolution depend on half-life

$$0 \leq t \leq 5\,T_{1/2}$$

^{210}Pb and its gaseous precursors , ^{137}Cs, ^{241}Am = gamma emitters

➢ gamma spectrometry



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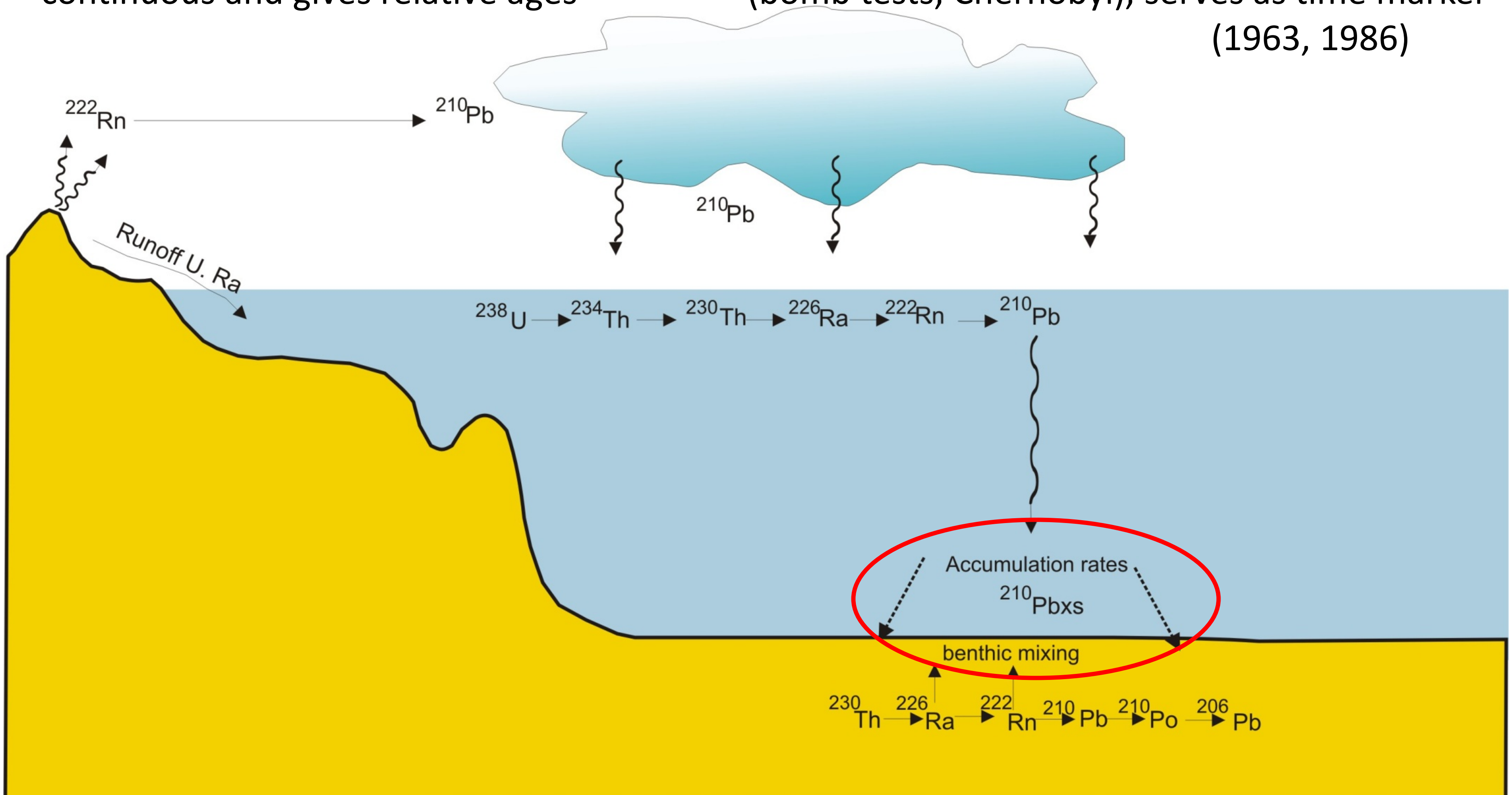
^{210}Pb and ^{137}Cs pathways to sediments

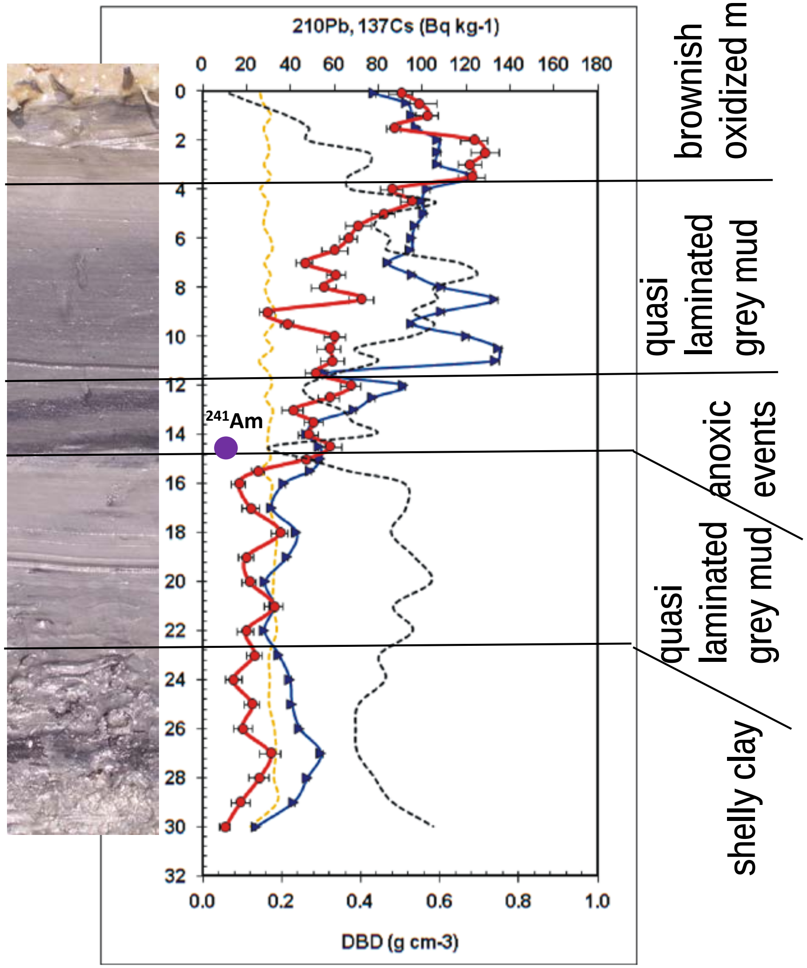
^{210}Pb production/deposition is continuous and gives relative ages

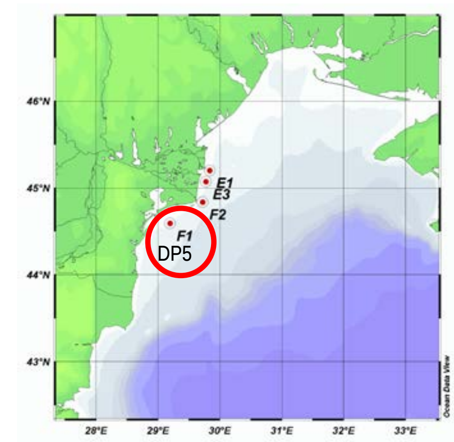
^{137}Cs, ^{241}Am is deposited discontinuously (bomb tests, Chernobyl), serves as time marker (1963, 1986)



5.1 Example from thewestern Black Sea shelf

Example: Core from the western Black Sea shelf (F1)





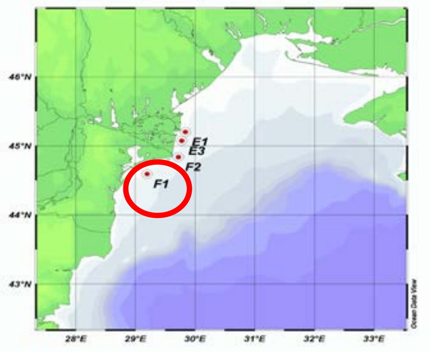
^{241}Am – independend time marker for 1963

high ^{137}Cs peaks mark Chernobyl event and floods

- $^{210}Pb_{xs}$
- ^{137}Cs
- DBD
- $^{210}Pb_{s}$

Friedrich & Laptev EGU2010-15234

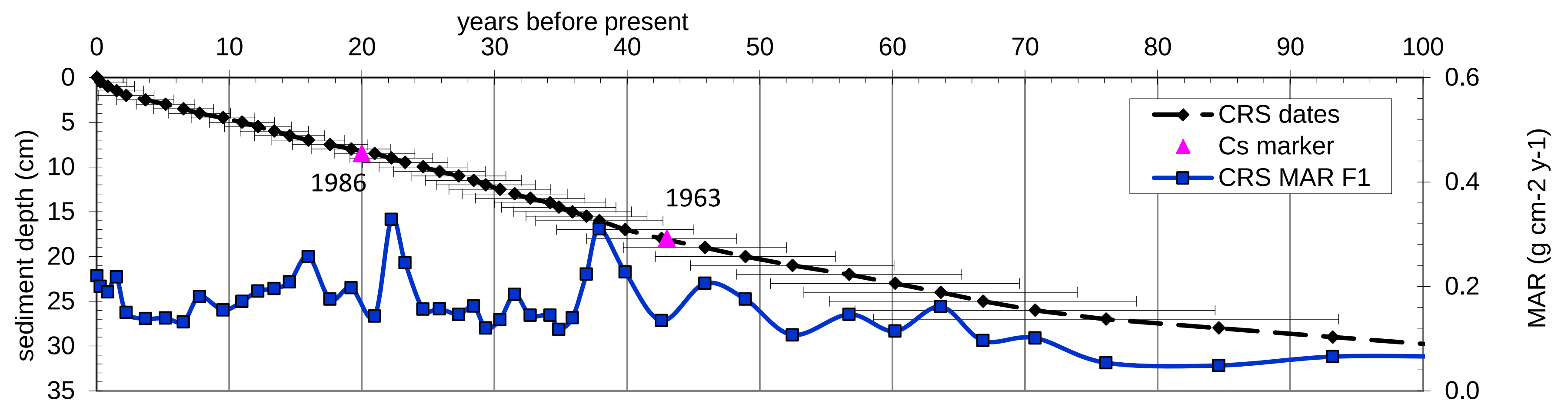
5.1 Example from thewestern Black Sea shelf

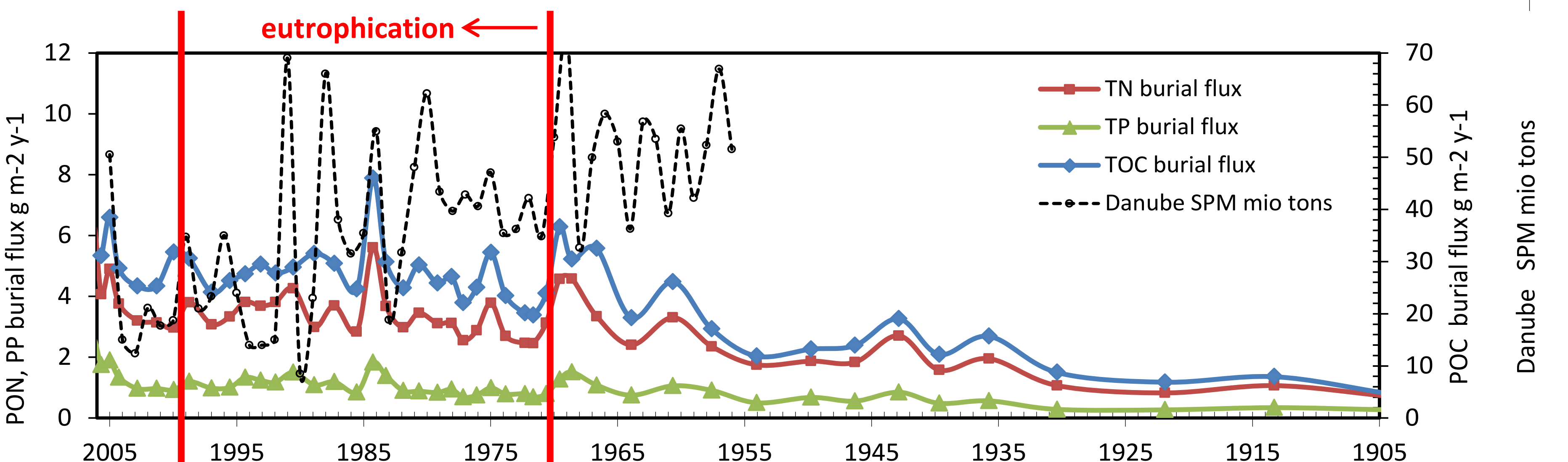


Example: dated sediment core from the western Black Sea shelf (F1)

CRS model - Constant Rate of Supply (Appleby 2008)

Mass accumulation rates (MAR) = 0.1 - 1.2 g cm^{-2} $year^{-1}$





Friedrich & Laptev EGU2010-15234

Coupling sediment and water column dynamics…

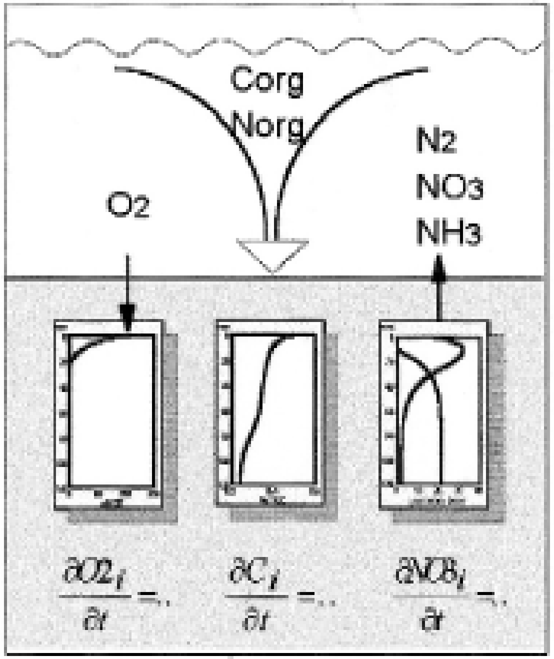
Earth-Science Reviews 51 (2000) 173–201

On the coupling of benthic and pelagic biogeochemical models

Karline Soetaert *, Jack J. Middelburg, Peter M.J. Herman, Kerst Buis
Netherlands Institute of Ecology, Centre for Estuarine and Coastal Ecology, PB 140, Yerseke 4400 AC, Netherlands

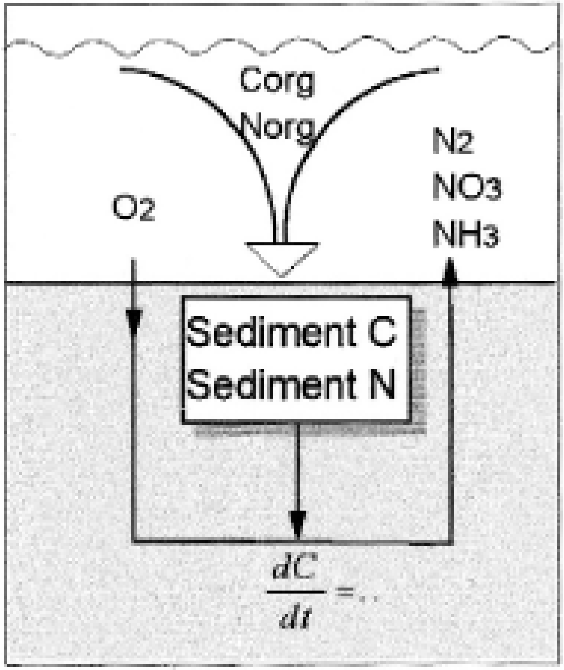
Received 17 February 1999; accepted 7 December 1999

Level (4): vertically resolved



- dynamic, **vertically resolved**, biogeochemical model of the sediment coupled with a vertically resolved dynamic model of the water column
- Particles sinking is incorporated into the sediment by burial and bioturbation
- Solute exchange via molecular diffusion /advection near the sediment–water interface
- considers faunal irrigation
- considers distinct layers of the sediment
- e.g., C, O and N cycle at a shelf-break site Soetaert et al., 2000)

Level (3): vertically integrated



- dynamic **vertically integrated** model for the sediments coupled with a water column model

- Particles settling to the seafloor are added to sediment layer

- exchange of dissolved constituents is described as a function of the particulate transformation rate

- e.g., C incorporated in a thin sediment layer and C-mineralisation is translated in corresponding O_2 demand (global ocean carbon cycle model of Maier-Reimer 1993)

(Soetaert et al. 2000)

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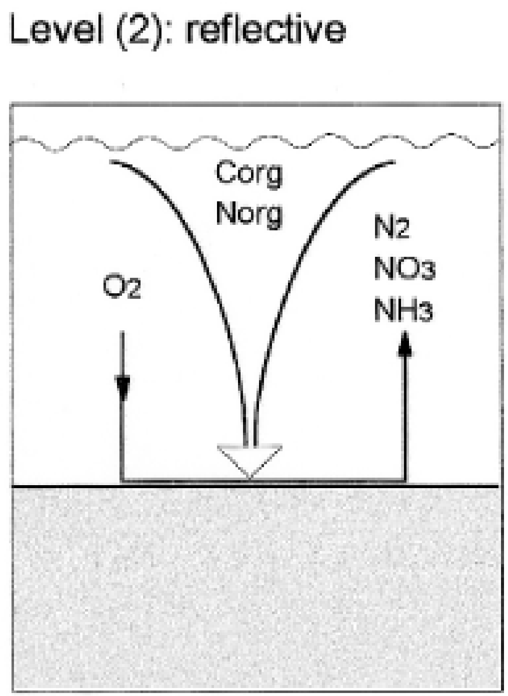


- the sediment interface is represented as a **reflective boundary**

- particles arriving at the sediment surface are instantaneously transformed into nutrients and CO_2

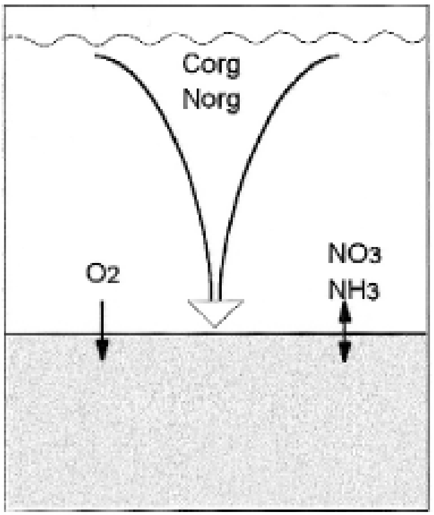
- Partitioning of the return flux is parameterised but may be calculated based on steady-state diagenetic modelling (Lancelot and Billen, 1985)

- most often used in global ocean biogeochemical models because of its computational efficiency

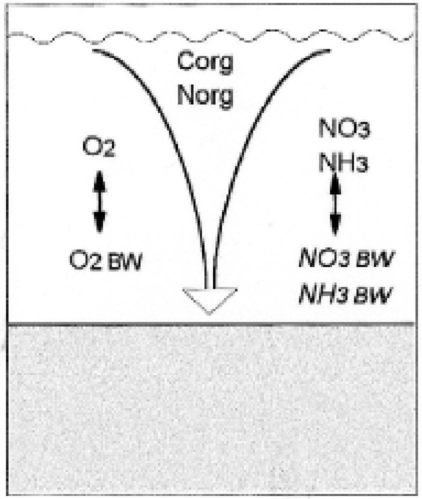
(Soetaert et al. 2000)

6. Approaches to benthic-pelagic coupling in models

Level (1 a): Flux imposed



Level (1 b): BW conc imposed



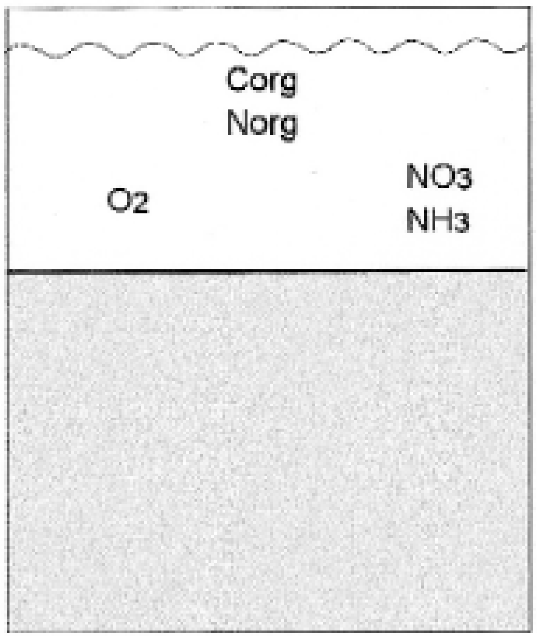
- either the sediment–water exchange rate (e.g., Chapelle et al., 1994) or the bottom-water concentration of dissolved substances (e.g., Sharples and Tett) is imposed, usually based on data

- includes lower boundary conditions where solute flux, or the gradient at the lower boundary, equals 0 (e.g., Kühn and Radach, 1997)

- widely used and akin to the specifications commonly imposed at open boundaries in water column models

(Soetaert et al. 2000)

Level (0): no bottom



- no particulate material arrives at the sediments

- reactive material just accumulates in the lowermost water layer or is exported along the lateral boundaries

(Soetaert et al. 2000)

6. Approaches to benthic-pelagic coupling in models

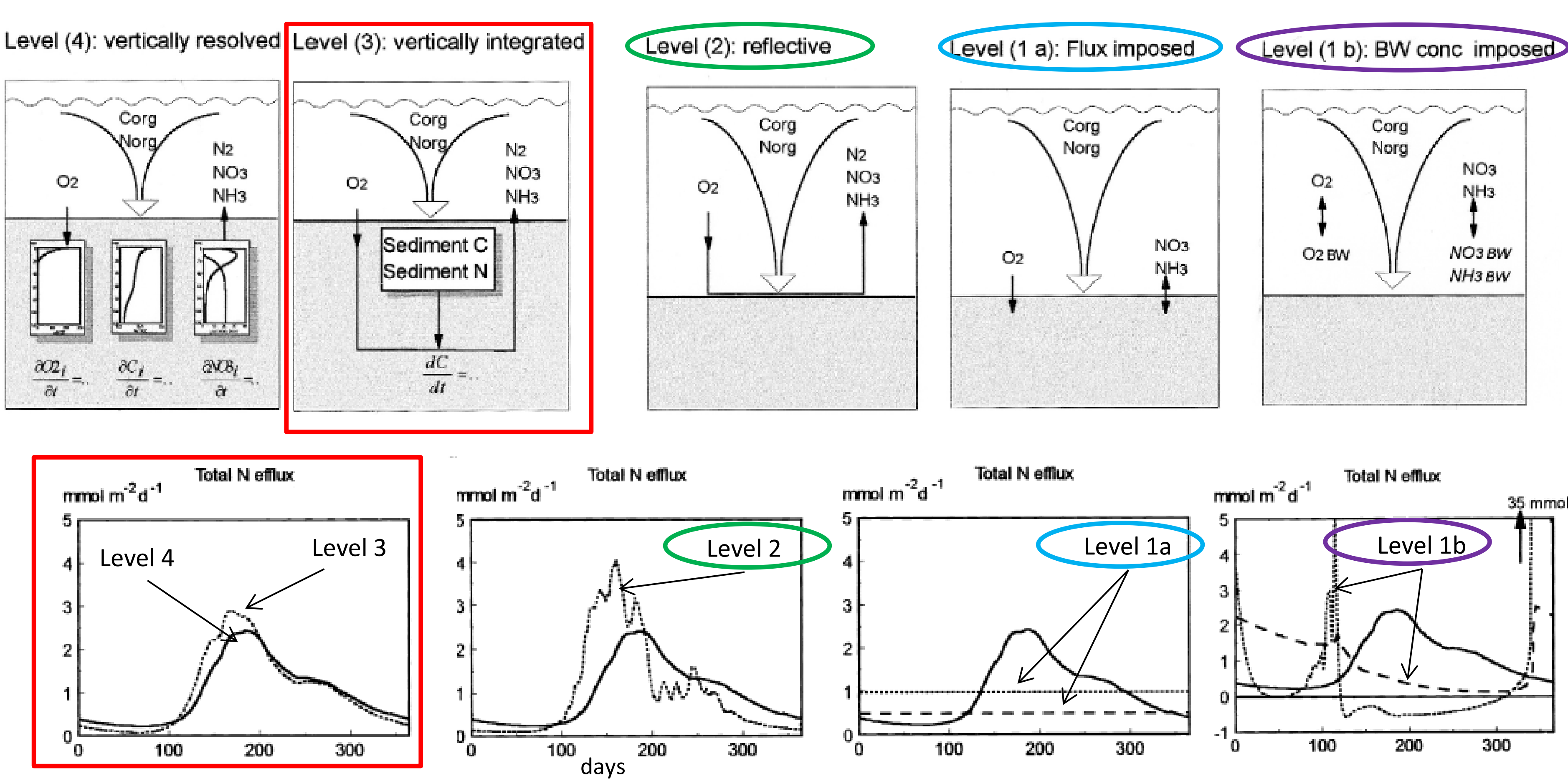
J. Friedrich, HZG
Askö Summerschool 2015

Summary of model characteristics for the various levels of sediment–water exchange parameterisation
(+) Accounted for; (−) not accounted for or not appropriate; (±) partially accounted for, depending on the exact formulation.

Level	Mass conser-vation	Retention capacity	Speciation characteristics of efflux	Short- and medium-term response	Long-term effects	Initialisation of sediment	Parameter requirements	Calibration and validation data	Computational demand
4 — Fully coupled diagenetic model	+	+	+	+	+	Special attention for slow-reacting components	Bioturbation, irrigation, advection rate	Vertical profiles; in situ fluxes	High
3 — Vertically integrated model	+	+	±	±	+	Special attention for slow-reacting components	Speciation characteristics of return flux	In situ fluxes	Low
2 — Reflective boundary	+	+	±	−	−	−	Speciation characteristics of return flux	Long-term averaged fluxes	Insignificant
1 — Solute flux or BW concentration imposed	−	+	−	−	−	−	Bottom water concentrations or sediment fluxes	−	Insignificant
0 — Sediment ignored	+	−	−	−	−	−	None	−	None

(Soetaert et al. 2000)

Effect of different levels of sediment–water exchange formulations on the total sediment DIN efflux (DIN+N_2)



- computationally inexpensive
- only integrated concentration of 2 fractions of sedimentary solid substances is described prognostically
- offers the possibility to reproduce sediment response on both short- and long-term scales

(Soetaert et al. 2000)

Why coupled benthic-pelagic models?

Understanding of biogeochemical processes

Modeling benthic–pelagic nutrient exchange processes and porewater distributions in a seasonally hypoxic sediment: evidence for massive phosphate release by *Beggiatoa*?

A. W. Dale, V. J. Bertics, T. Treude, S. Sommer, and K. Wallmann

Understanding the role of ecosystem components for assessments of ecosystem functioning

Modeling eutrophication and oligotrophication of shallow-water marine systems: the importance of sediments under stratified and well-mixed conditions

Karline Soetaert · Jack J. Middelburg

Extrapolation of point measurements for budget estimates

Nitrogen budget of the northwestern Black Sea shelf inferred from modeling studies and *in situ* benthic measurements

M. Grégoire[1,3,*], J. Friedrich[2,4]

Assessment of ecosystem state drivers and forecasts scenarios for decision making

Drivers, mechanisms and long-term variability of seasonal hypoxia on the Black Sea northwestern shelf – is there any recovery after eutrophication?

A. Capet[1,2], J.-M. Beckers[1], and M. Grégoire[2]

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7. Further reading

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