Harvesting of polymetallic nodules: opportunity for energy transition vs. particulate pollution

seminar to be delivered
under the auspices of
UCLouvain's *semaine de la transition*
on **21 November 2025**
at 08:30 AM in room BARB01
as part of course
LGCIV2056 (Marine hydrodynamics)



Abstract. The growing global demand for critical minerals to support the low-carbon transition has spurred increasing interest in deep-sea mining in the eastern Pacific, particularly the extraction of polymetallic nodules (PMN). The International Seabed Authority (ISA), which oversees the environmental impacts related to these activities, currently has a limited capacity to properly assess and mitigate their potential effects on deep-sea ecosystems.

We present results from a three-dimensional hydrodynamic model coupled with a Lagrangian sediment transport model aimed at simulating the dispersal of sediment plumes generated by PMN mining operations. It appears that fine particles predominantly control the spatial extent of the impacted area, while effective impact assessment and mitigation strategies show strong sensitivity to the biological threshold of unacceptable harm. A complementary analytical approach — resorting to the concepts of Green's function and residence time — allows estimating the order of magnitude of the ocean bottom surface area impacted by sediment, thereby pointing to the type of PMN collector trajectory minimising some of the aforementioned environmental impacts.

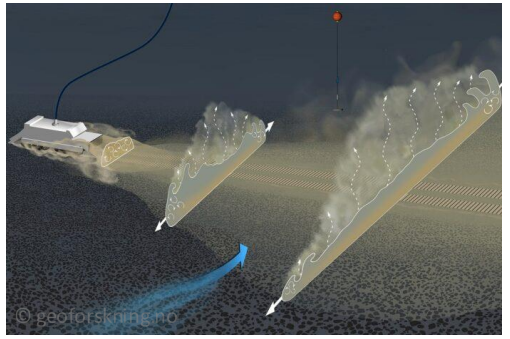
About the speakers

Théo Clotman holds a degree in Environmental Sustainability Bioengineering from UCLouvain. He is currently pursuing a PhD at the Earth and Life Institute (UCLouvain), focusing on the eco-hydrodynamics of Lakes Tanganyika and Kivu in Central Africa. During his master's thesis, Théo investigated the environmental impacts of deep-sea mining activities, with a particular focus on sediment plume dispersion resulting from polymetallic nodule extraction in the Clarion-Clipperton Zone, eastern Pacific Ocean.

Eric Deleersnijder holds a degree in electrical and mechanical engineering as well as a doctorate in applied sciences (mechanics). He has been a researcher with the F.R.S.-FNRS (www.fnrs.be) for about half of his career. He held visiting positions in France and the Netherlands. He is now a reader with the UCLouvain, where he (co-)teaches courses related to various aspects of mechanics, especially geophysical and environmental fluid dynamics (GEFD). His research interests focus on several aspects of GEFD, especially tracer and timescale methods. He is the founding father of SLIM (www.slim-ocean.be) and one of kingpins of the development of CART (www.cartdiagnoses.be). Additional pieces of information may be found on his homepage (www.ericd.be).







Harvesting of polymetallic nodules: opportunity for energy transition *vs* particulate pollution

by

Théo Clotman[1] & Eric Deleersnijder[2,1]

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- Impacted area and its minimum conditions

Théo Clotman
Master's thesis

Éric Deleersnijder

A hot topic related to climate change



Climate change



Renewable sources - Batteries

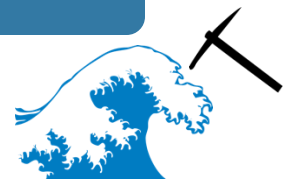


Mineral demand increase

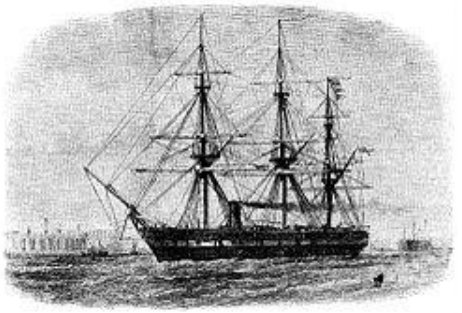


Sourcing methods

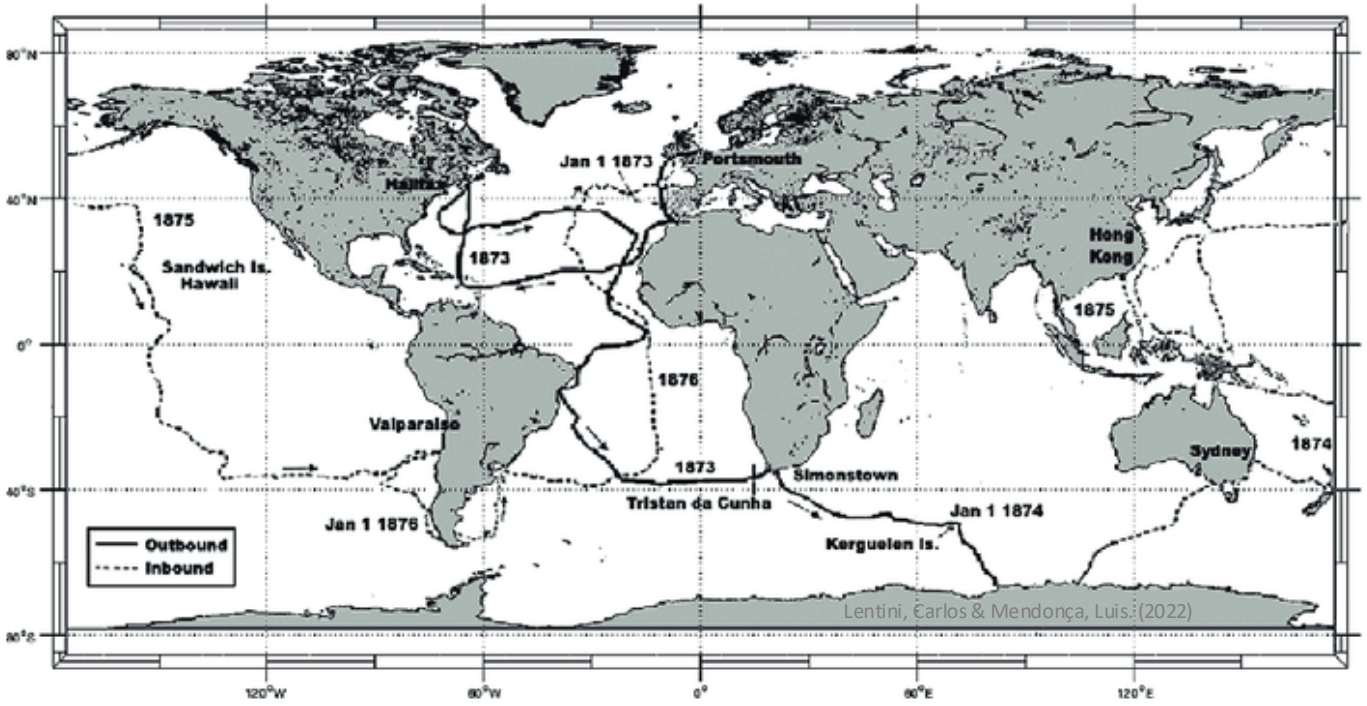
Deep-sea mining ?



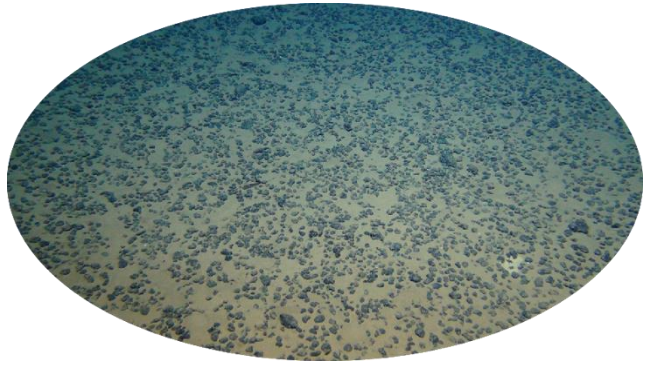
In 1870’, the Challenger expedition found a rocky treasure on Ocean’s floor



Route of the Challenger expedition







Polymetallic Nodules

Nodules as cover story for CIA during cold war

Hughes Glomar Explorer



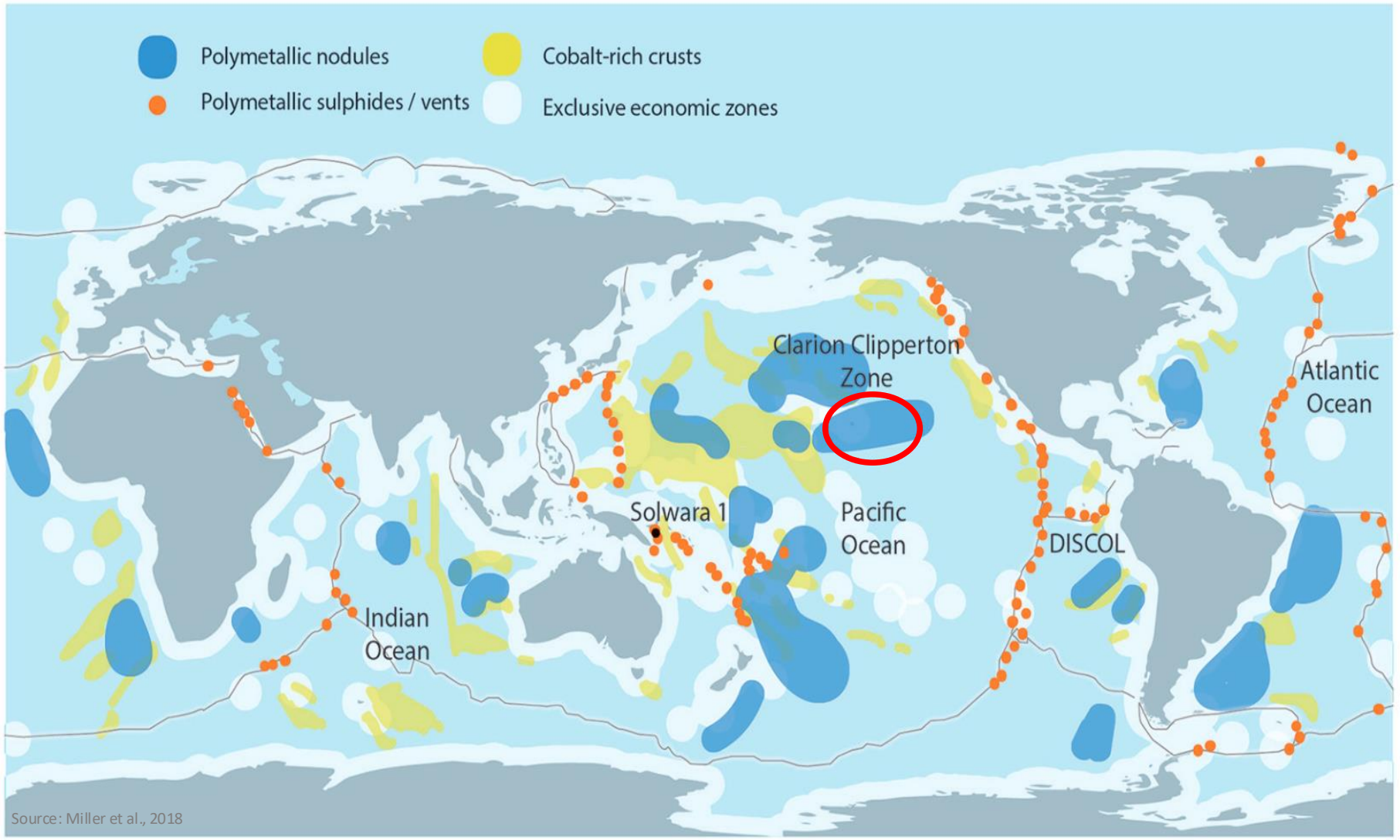



Panel Backs Glomar Explorer Conversion



K-129 submarine

A rocky treasure on the bottom of Pacific



A treasure full of valuable minerals



Manganese (28% mass):
steel, batteries



Polymetallic Nodules



Nickel (1.3% mass):
wind turbines, batteries

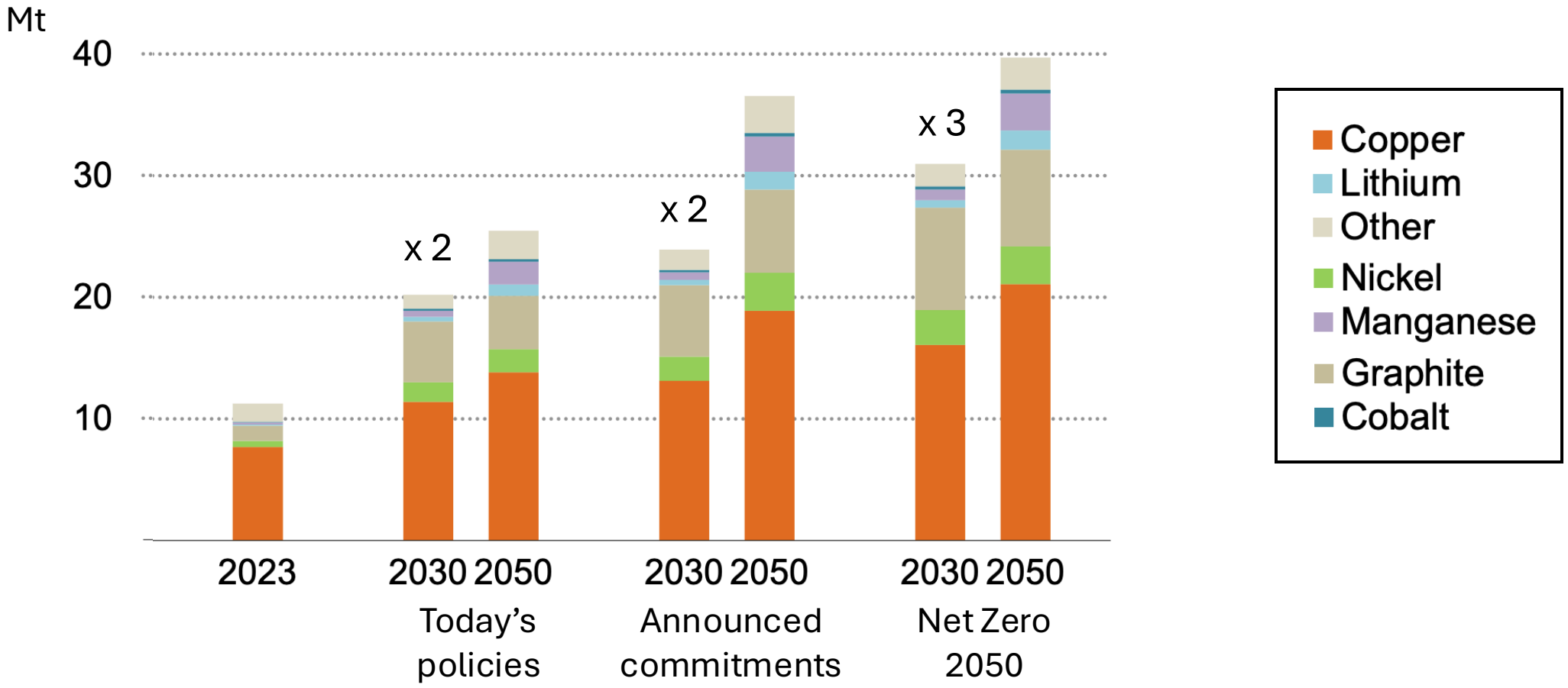


Copper (1% mass):
conductor, electronics



Cobalt (0.2% mass):
electromagnets, batteries

Mineral demand doubles to triples between 2023 and 2030



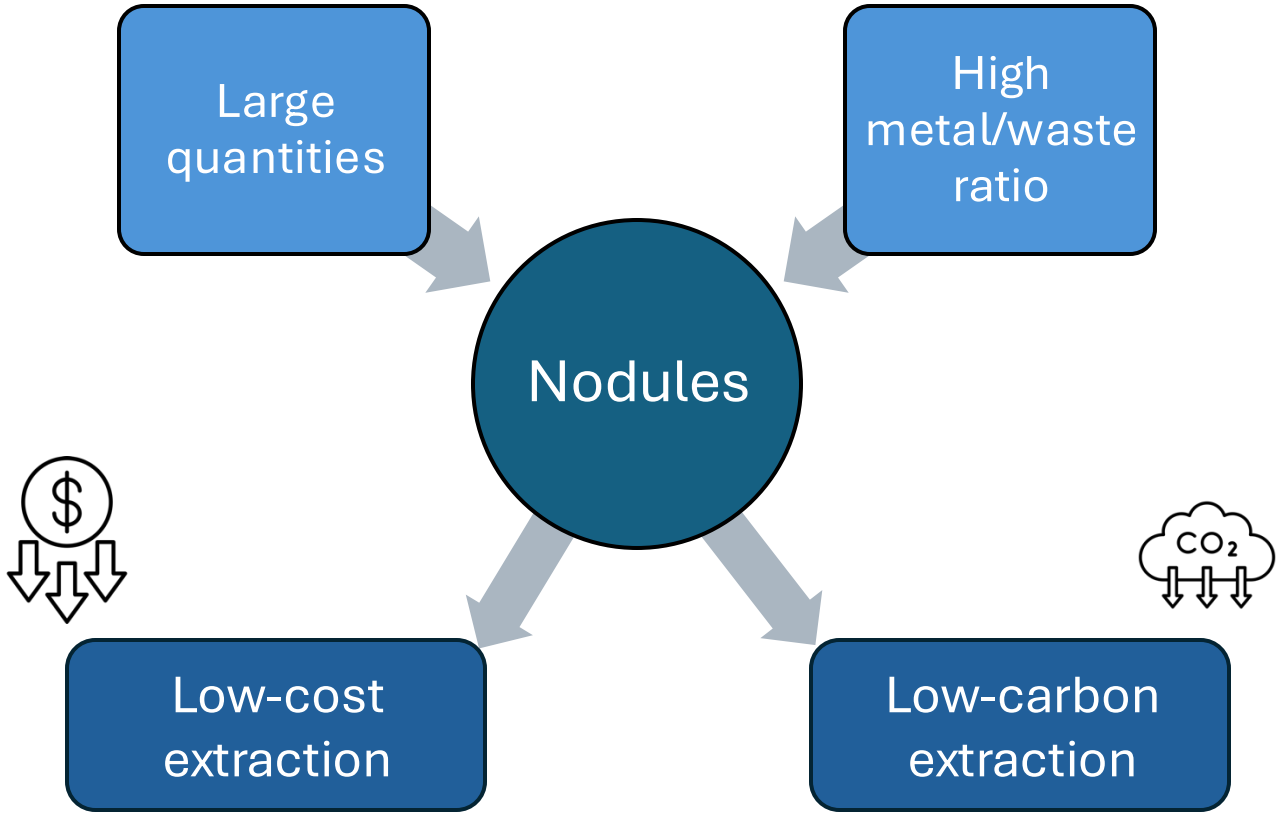
A miraculous way to source minerals ?



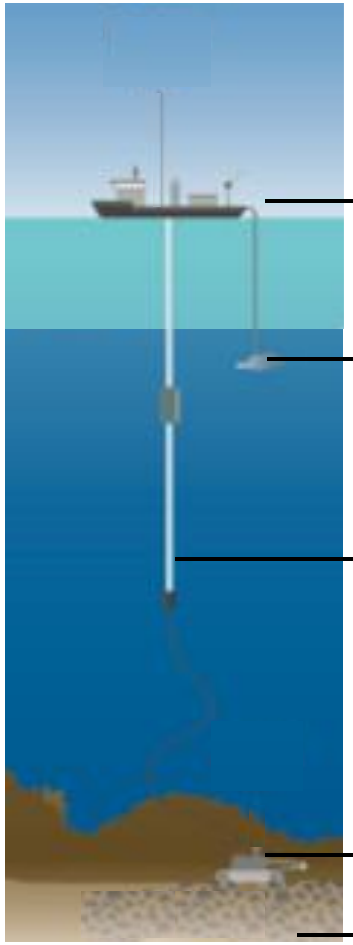


Land mining

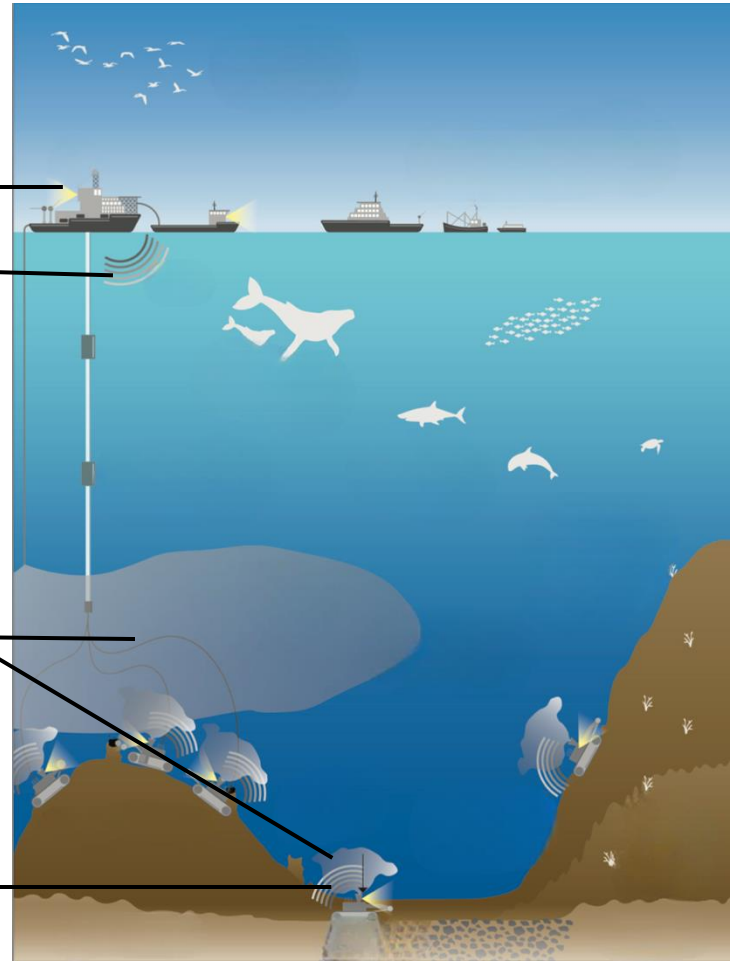
VS



Heavy extraction methods



Modified from Miller et al., 2018



Source: Miller et al., 2018

International Seabed Authority regulates deep-mining activities



In Favor

VS



Opponents

International Seabed Authority

United Nations Convention on the Law of the Sea

1) Heritage of humankind

2) Prevent pollution

3) Conserve resources and life

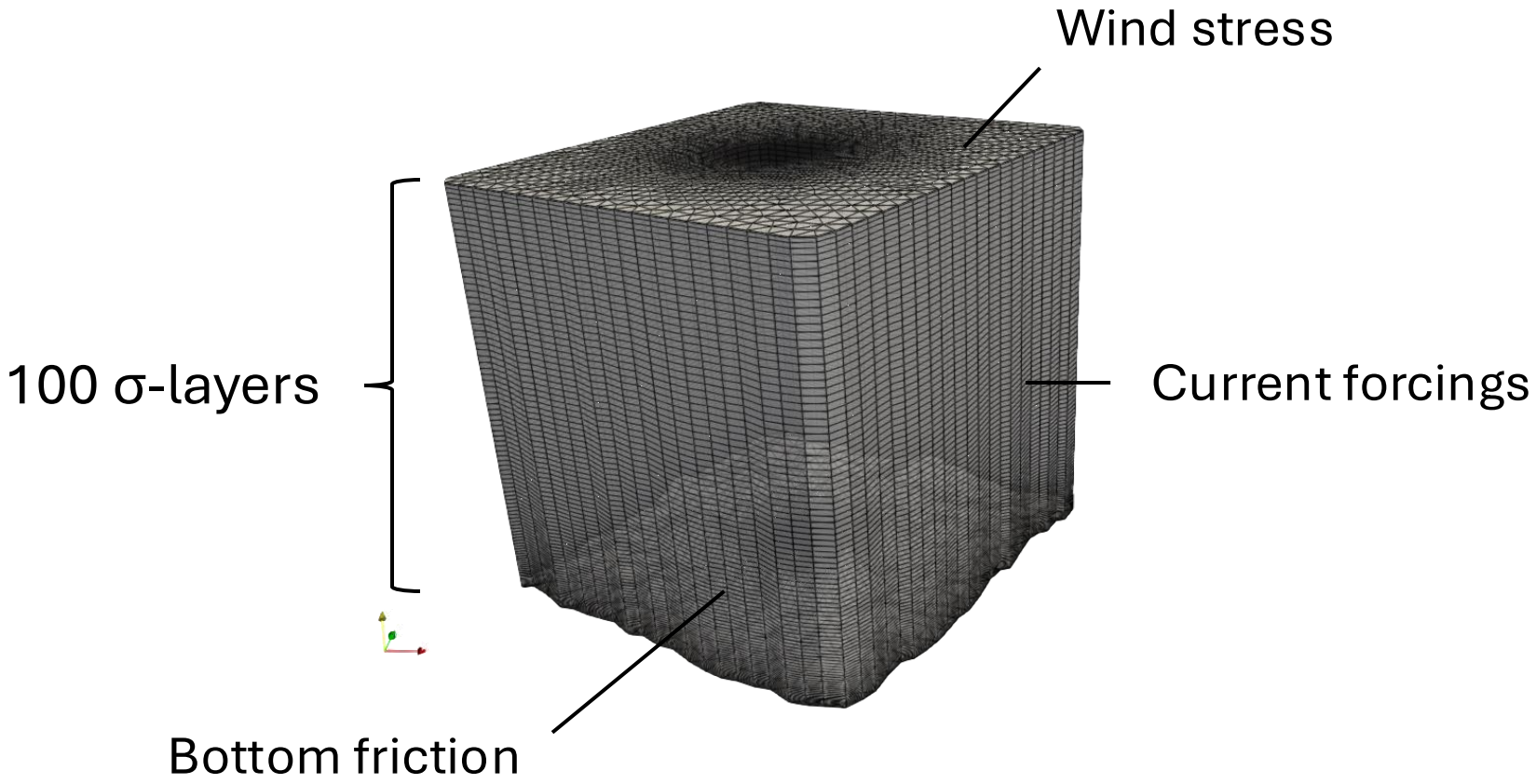
A gap in knowledge to be fullfilled

→ *How will **sediment plumes** from polymetallic nodule extraction in the Clarion-Clipperton Zone **disperse and impact** seafloor biodiversity ?*

→ *How to **mitigate this impact** ?*

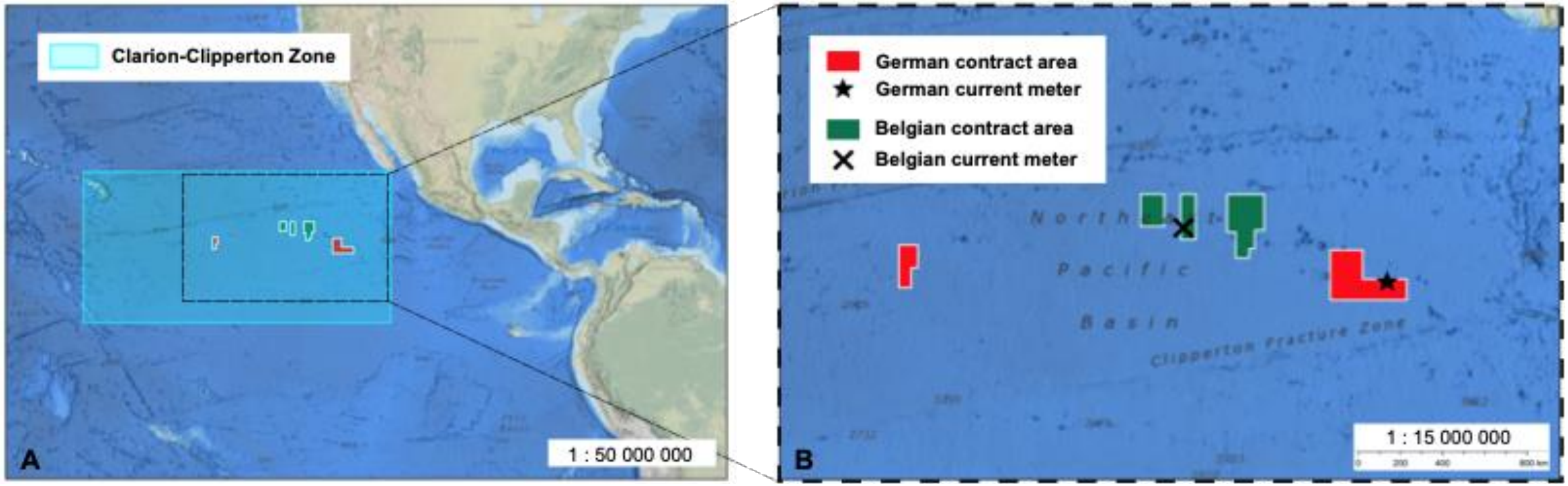


SLIM, simulating current on a 3D domain with boundary conditions

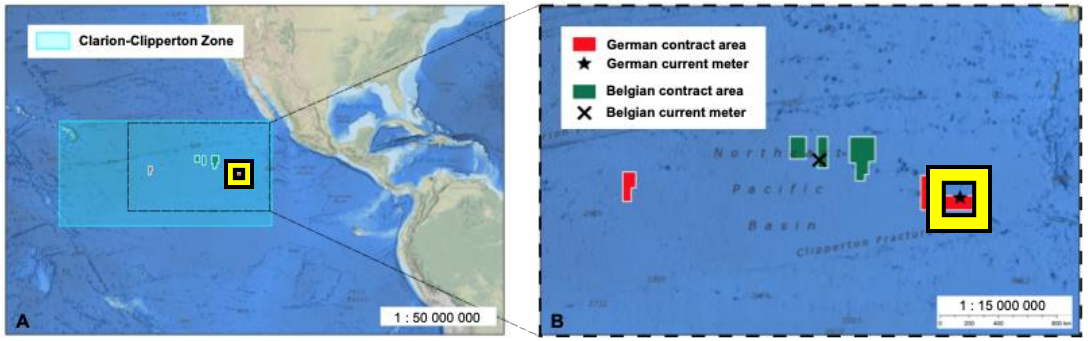


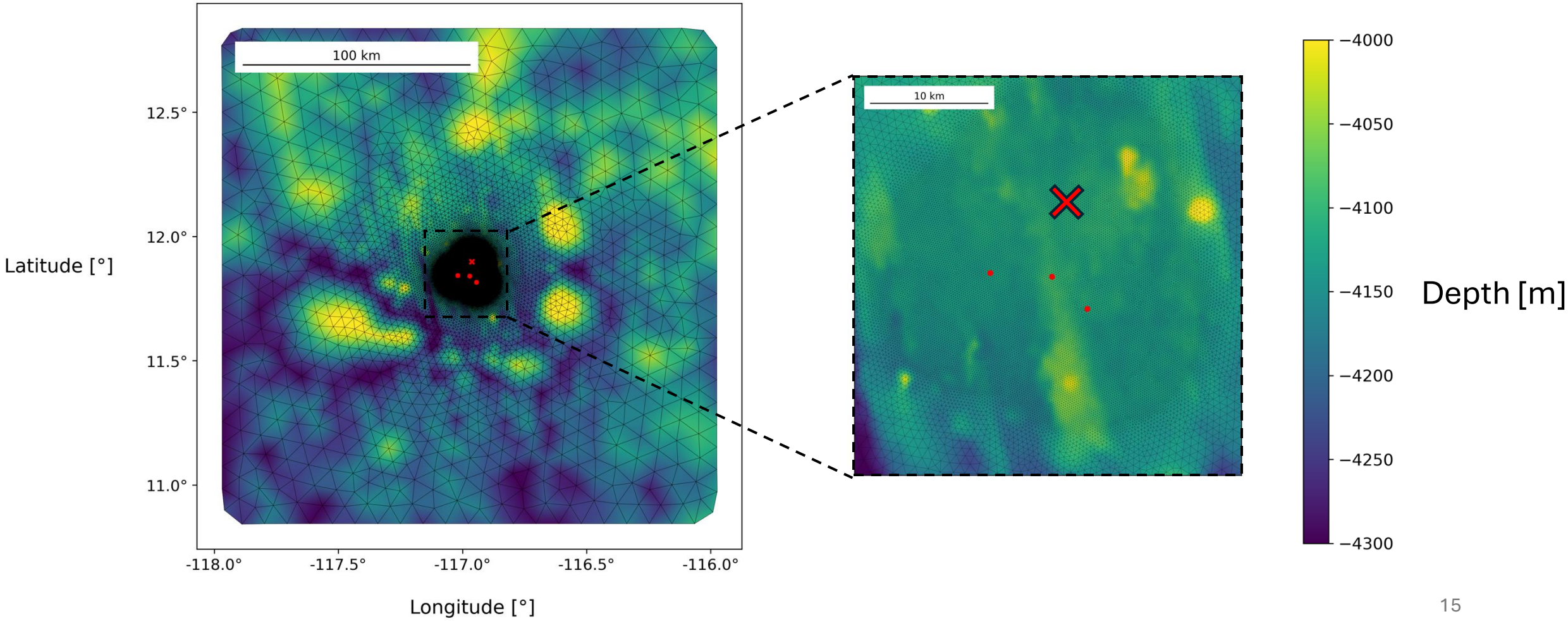
3D domain Ω

Two simulation areas, ~1000 km apart

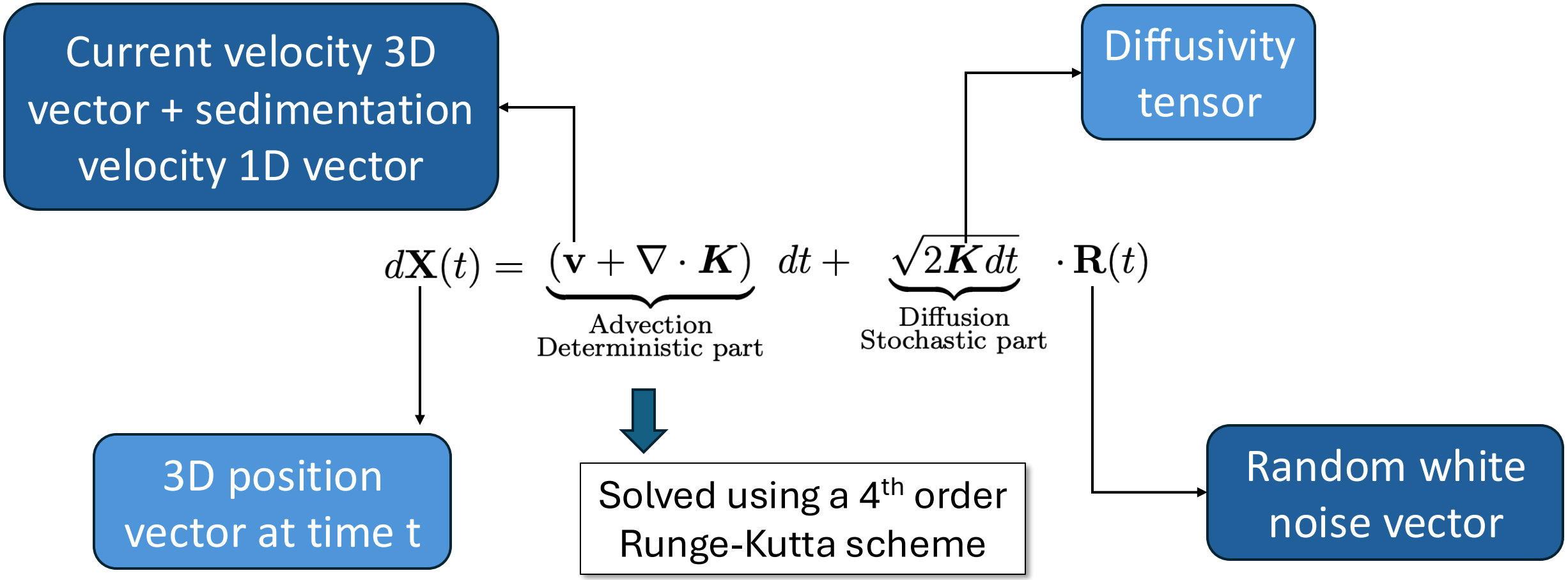


German contract area in Pacific Ocean

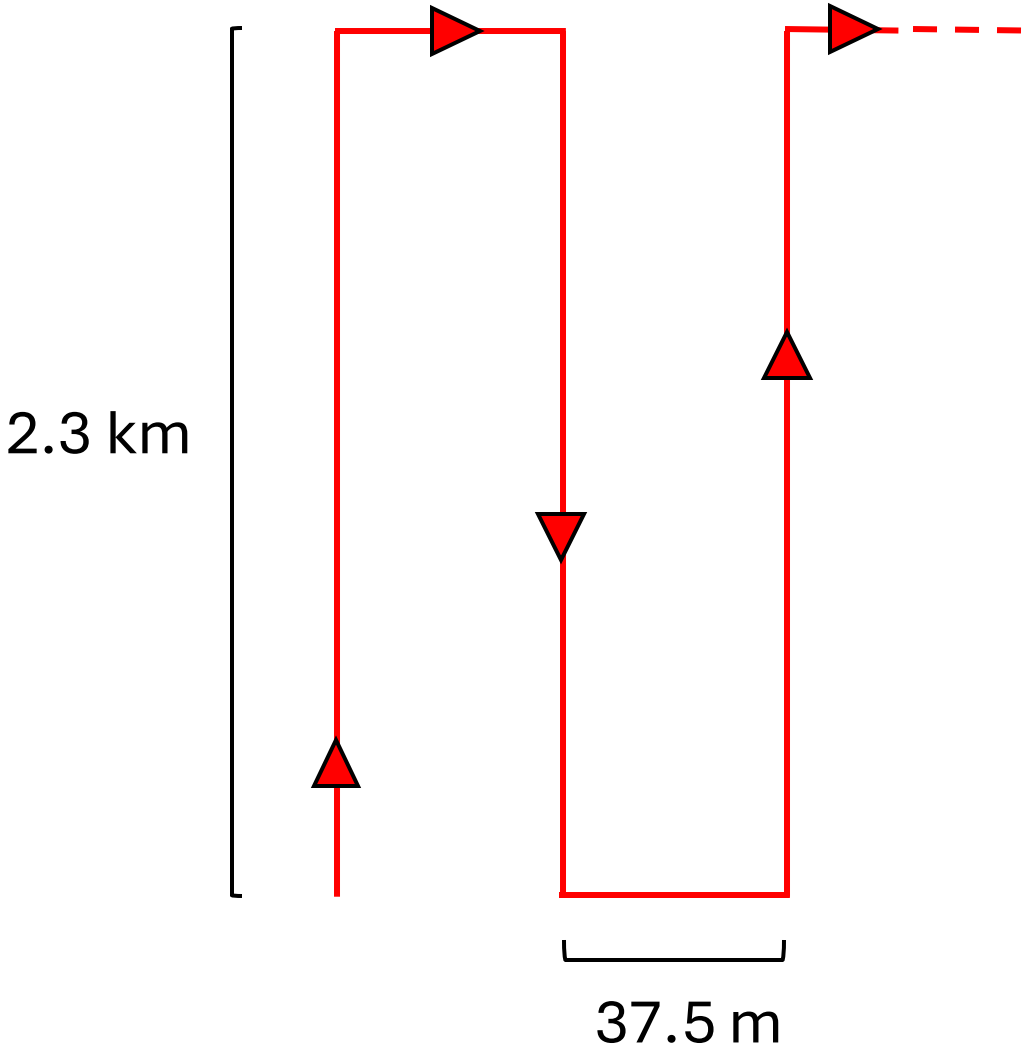




3D positioning of particles using an advection-diffusion equation in Lagrangian form

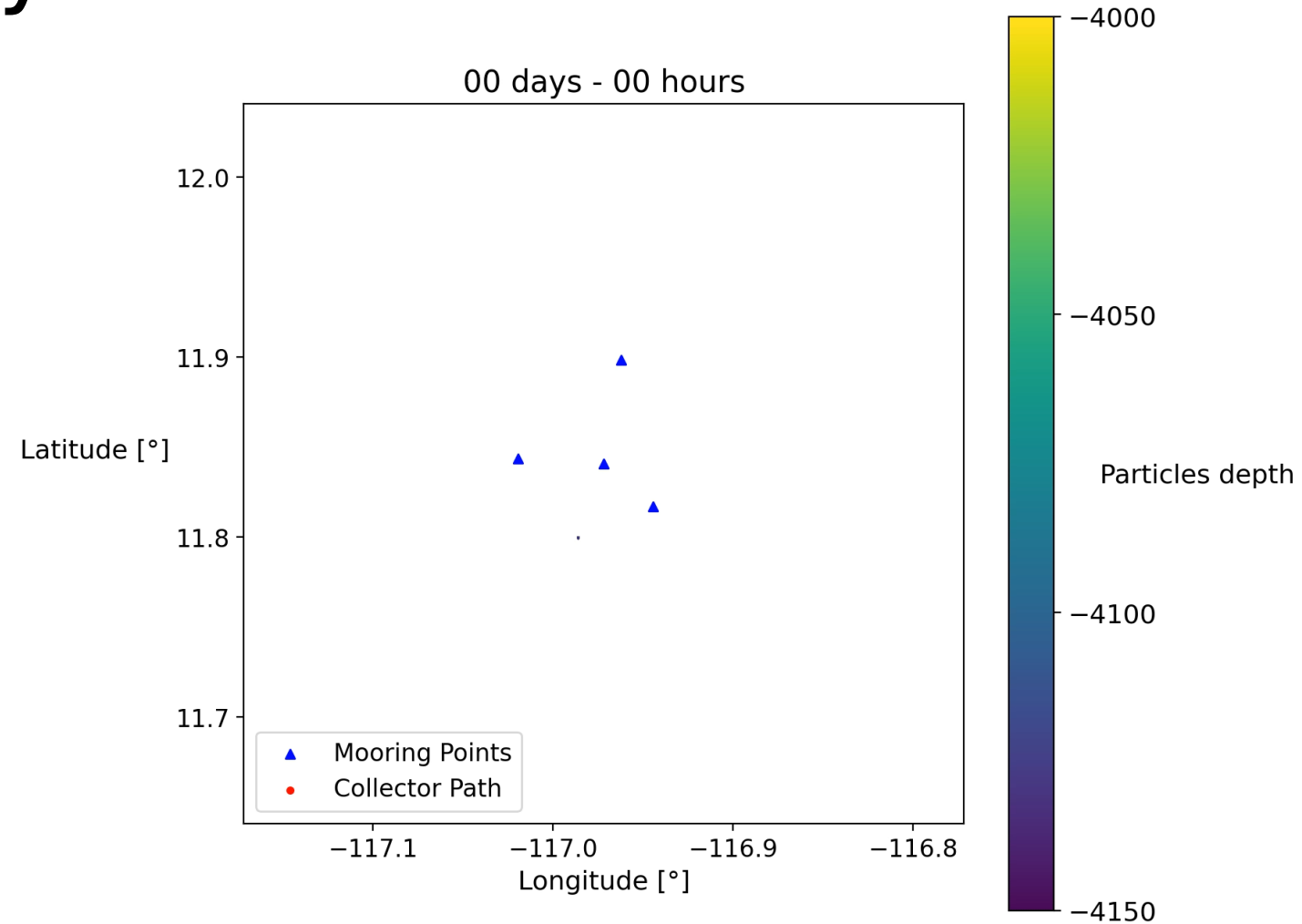


A back-and-forth collector route

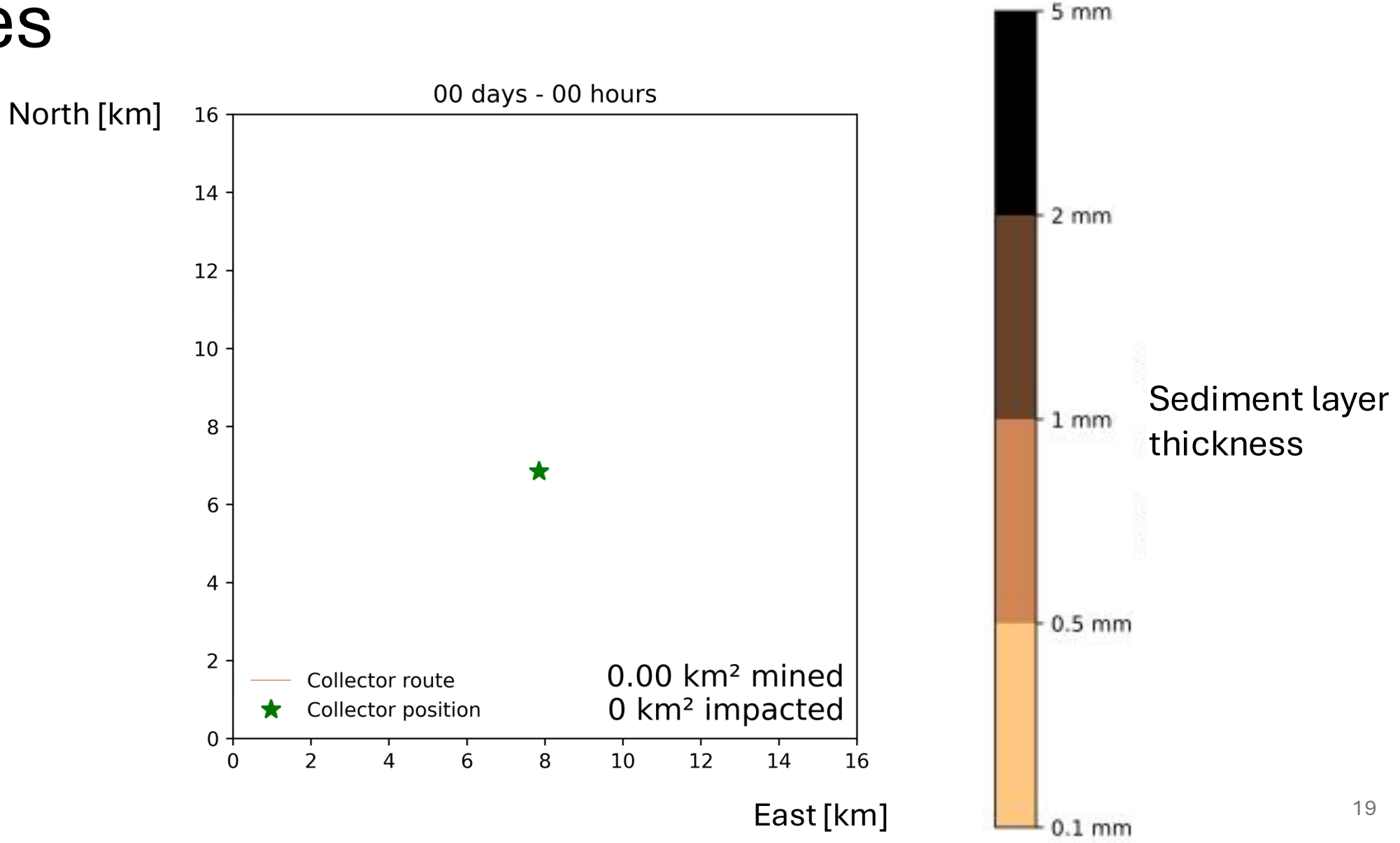


- 60 t/h discharge
- Sediments from 1 µm to 2 mm
- 6 m release height
- dt of 450 seconds (7.5 minutes)

The moving collector suspends sediments along its trajectory

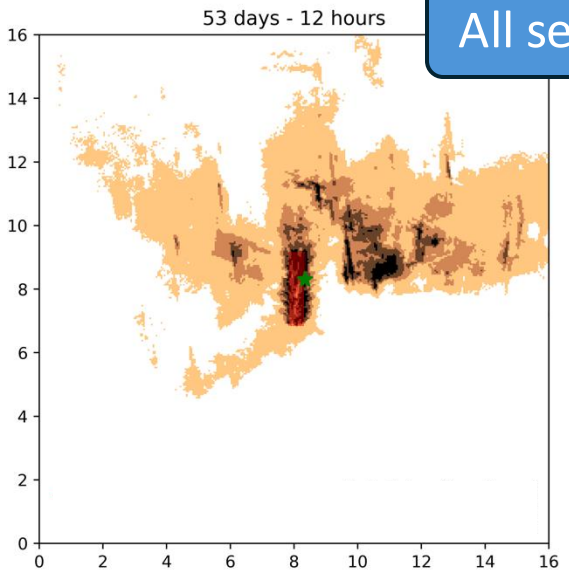


Sediments settle back as the collector collects nodules

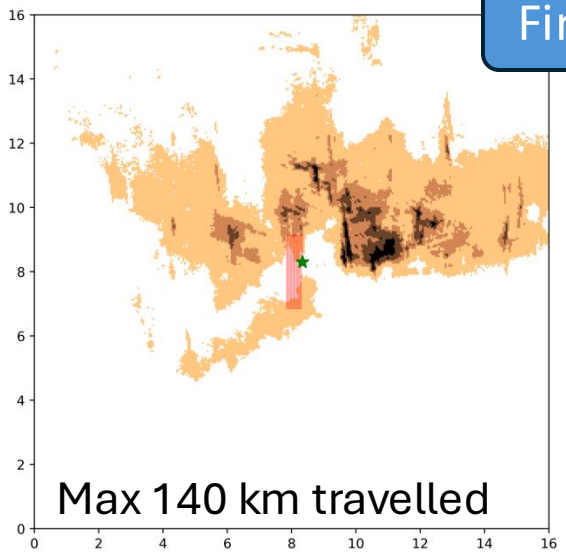


Fine sediments travel far, coarse sediments don’t

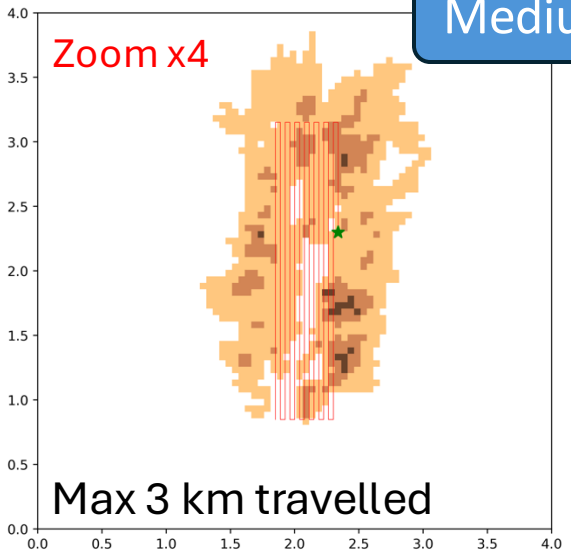
All sediments



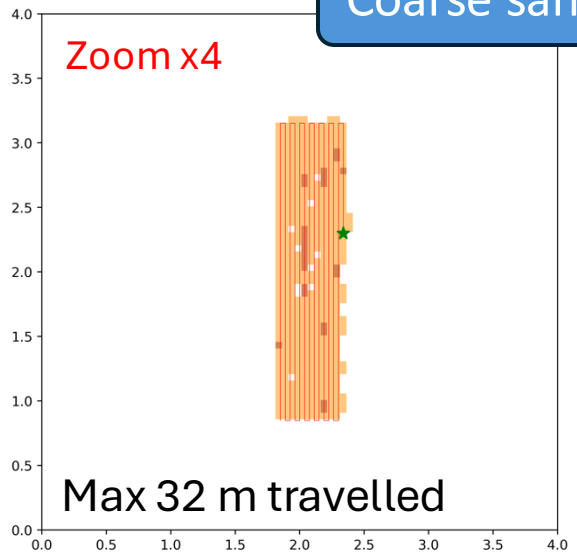
Fine silt

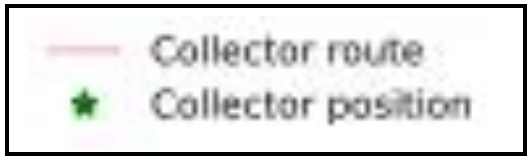


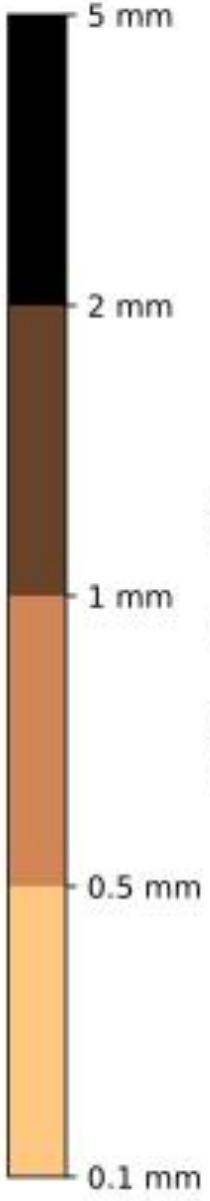
Medium silt



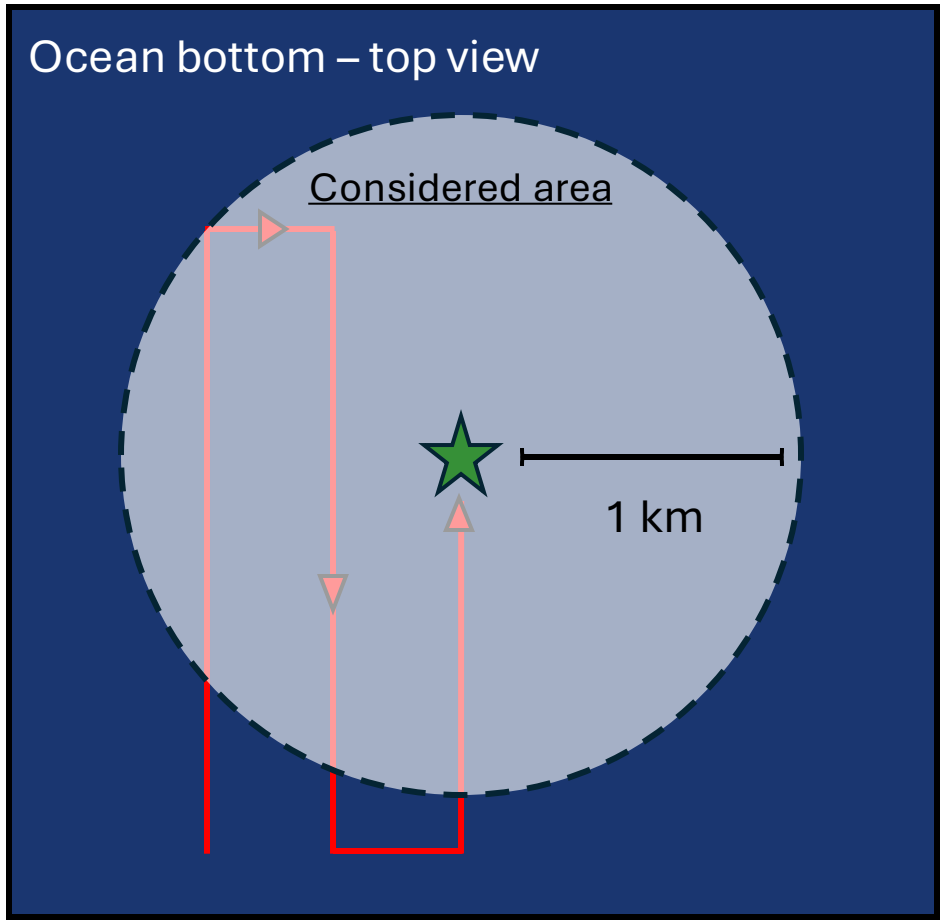
Coarse sand







Stopping the collector in strong currents to minimize environmental harm



Illustrative scheme – not to scale

Efficiency indicator:

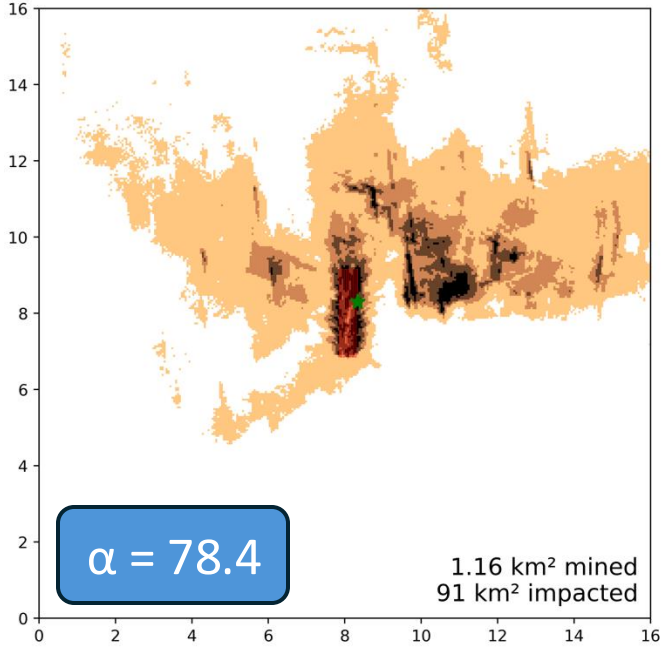
$$\alpha\,[-] = \frac{\text{Impacted area } [\text{m}^2]}{\text{Mined area } [\text{m}^2]}$$

Higher constraints induce less impact, but less nodules collected

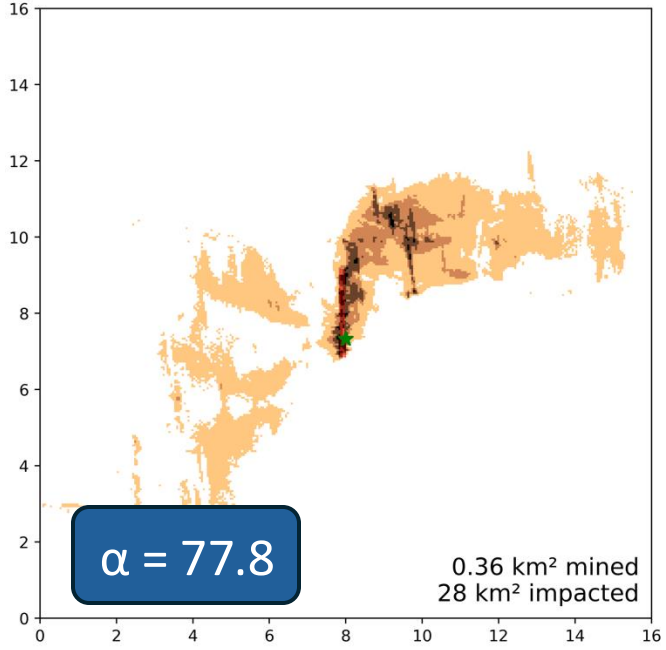
00 days - 00 hours

North [km]

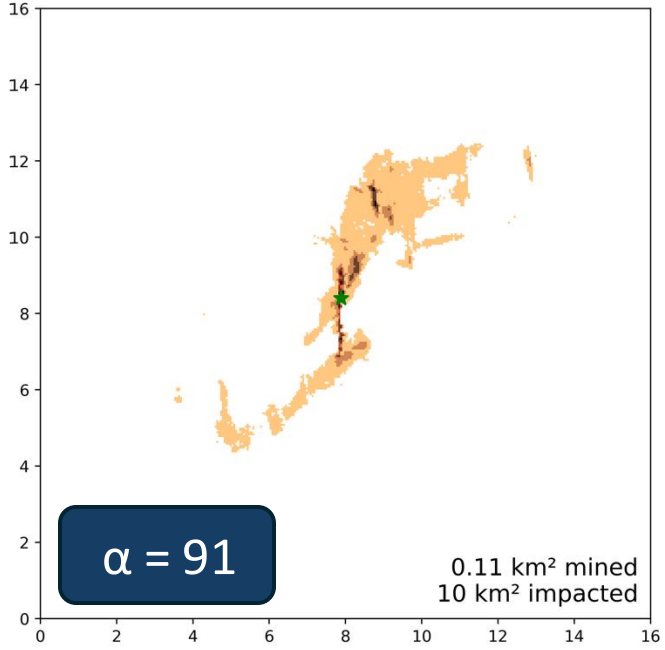
Baseline



Scenario 5 cm.s^{-1}



Scenario 3 cm.s^{-1}



East [km]

Collector route

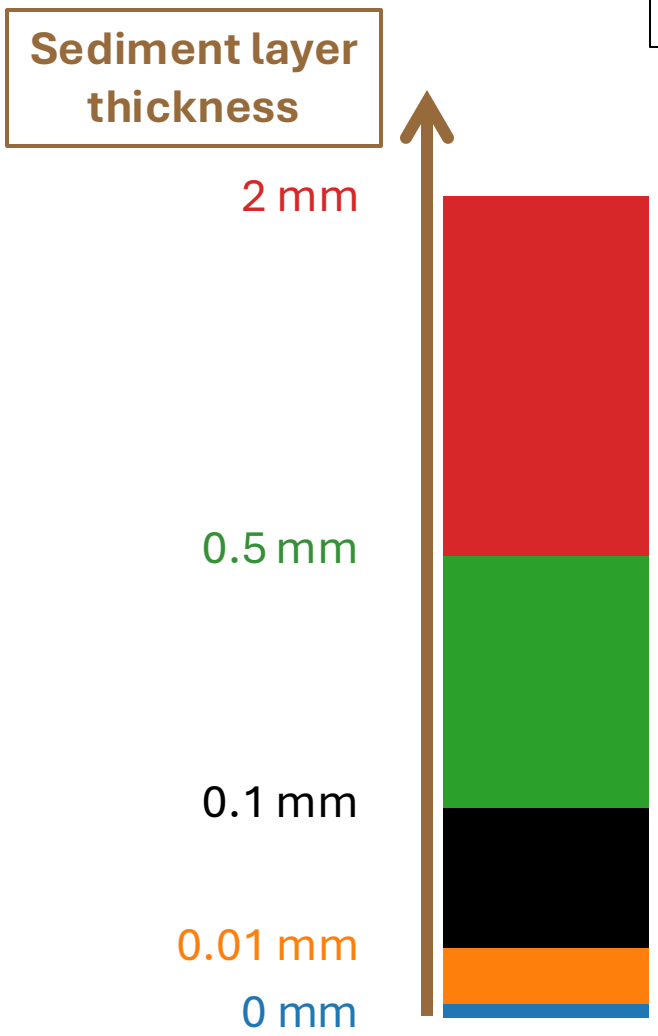
Collector position

Sediment layer thickness

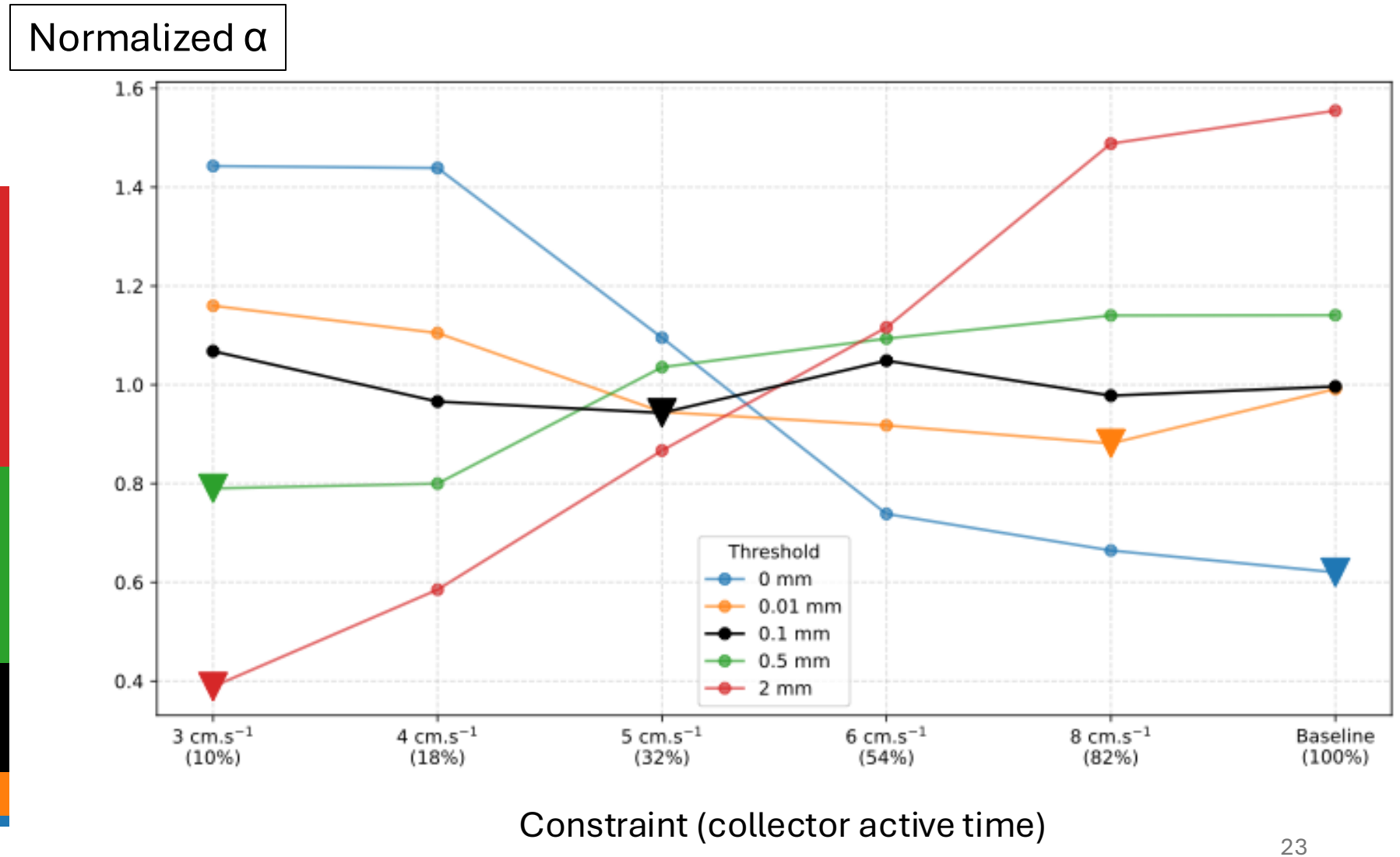


0.1 mm 0.5 mm 1 mm 2 mm 5 mm

Alpha trends highly depend on the impacted area threshold



Illustrative scheme – not to scale

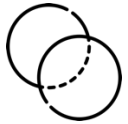


What message can we take home ?

Sensitive sediment model

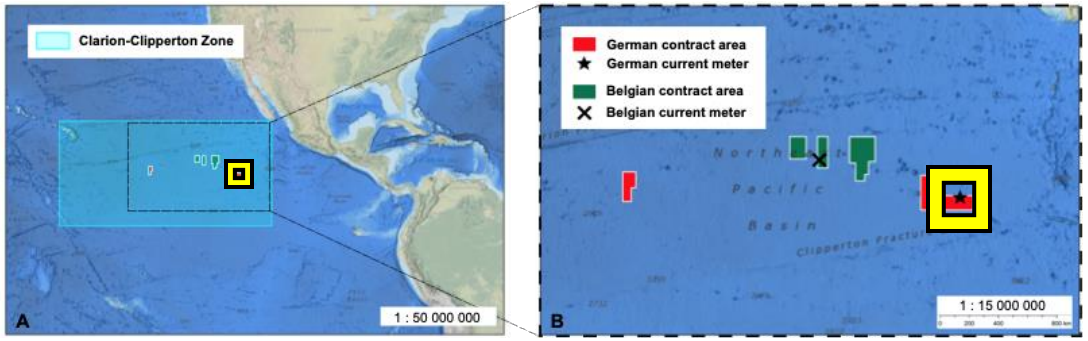
- To sediment size 
- To release height 

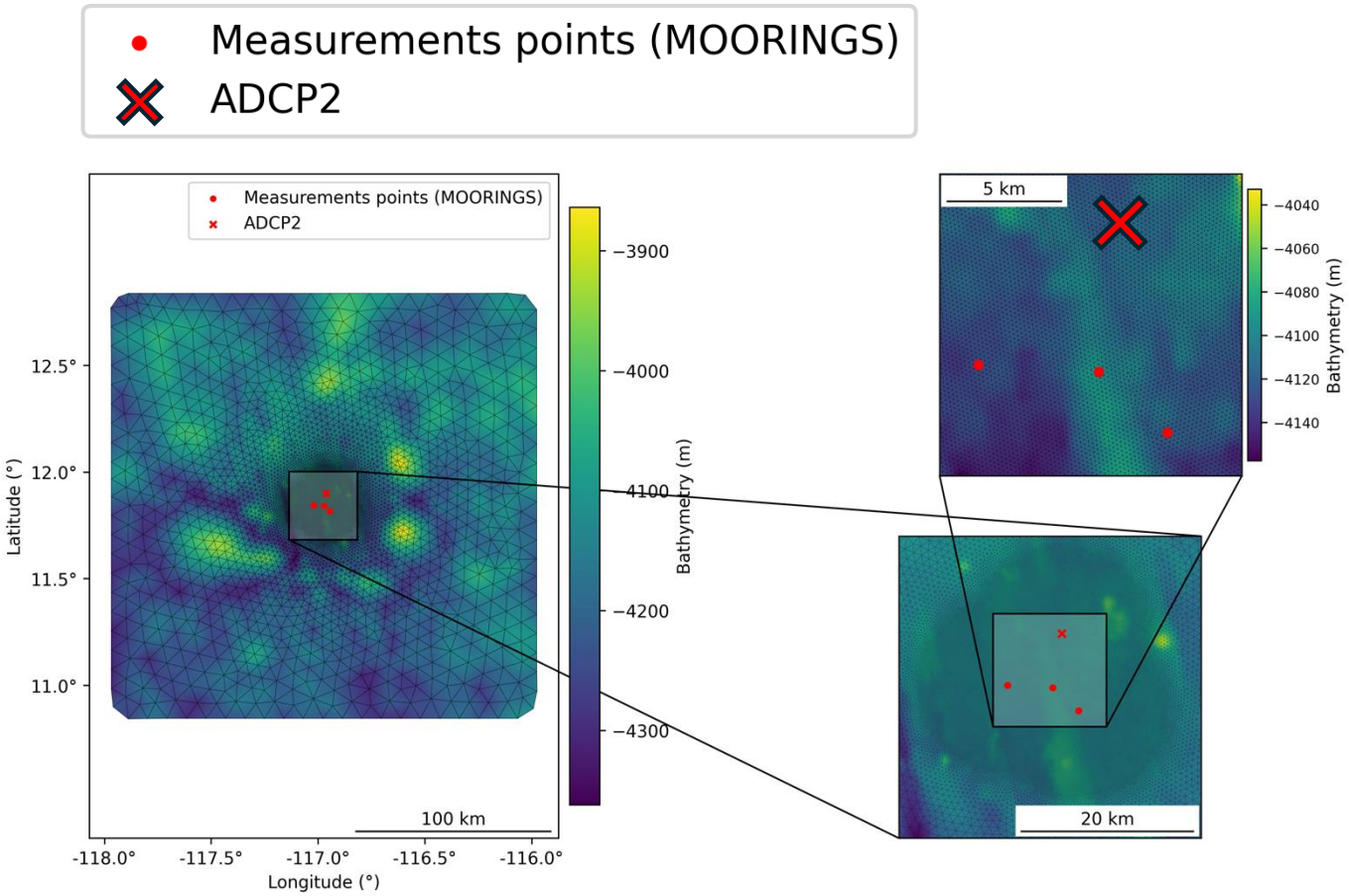
Accurate recommendation not feasible

- Unknown biological thresholds 
- Poor realism 

Backup slides

German setup: smaller domain, fine horizontal mesh





- 450 m bathymetry resolution
- 220x220 km square
- 50 000 triangles
- Triangles from 200m to 10 000m

Sediment classes

Table 3: Sediment classes ran distinctly in the particle tracker.

Sediment Class	Size Range
Baseline	0–2 mm
Clay	0–2 µm
Fine Silt	2–20 µm
Coarse Silt	20–63 µm
Fine Sand	63–200 µm
Medium Sand	0.2–0.5 mm
Coarse Sand	0.5–2 mm

Settling velocity

The first component corresponds to currents velocities $\mathbf{u}_{curr}$ and corresponds to the output of the hydrodynamic model. The second component corresponds to particle settling velocity $\mathbf{w}_s$ only in the vertical direction thus $\mathbf{w}_s = [0 \;\; 0 \;\; -w_s]$. The latter is related to sediment physical properties. Non zero component of this vector is determined using an empirical formula introduced by Soulsby and Whitehouse (1997) and adapted for extremely fine grain sizes by MacDonald et al. (2006):

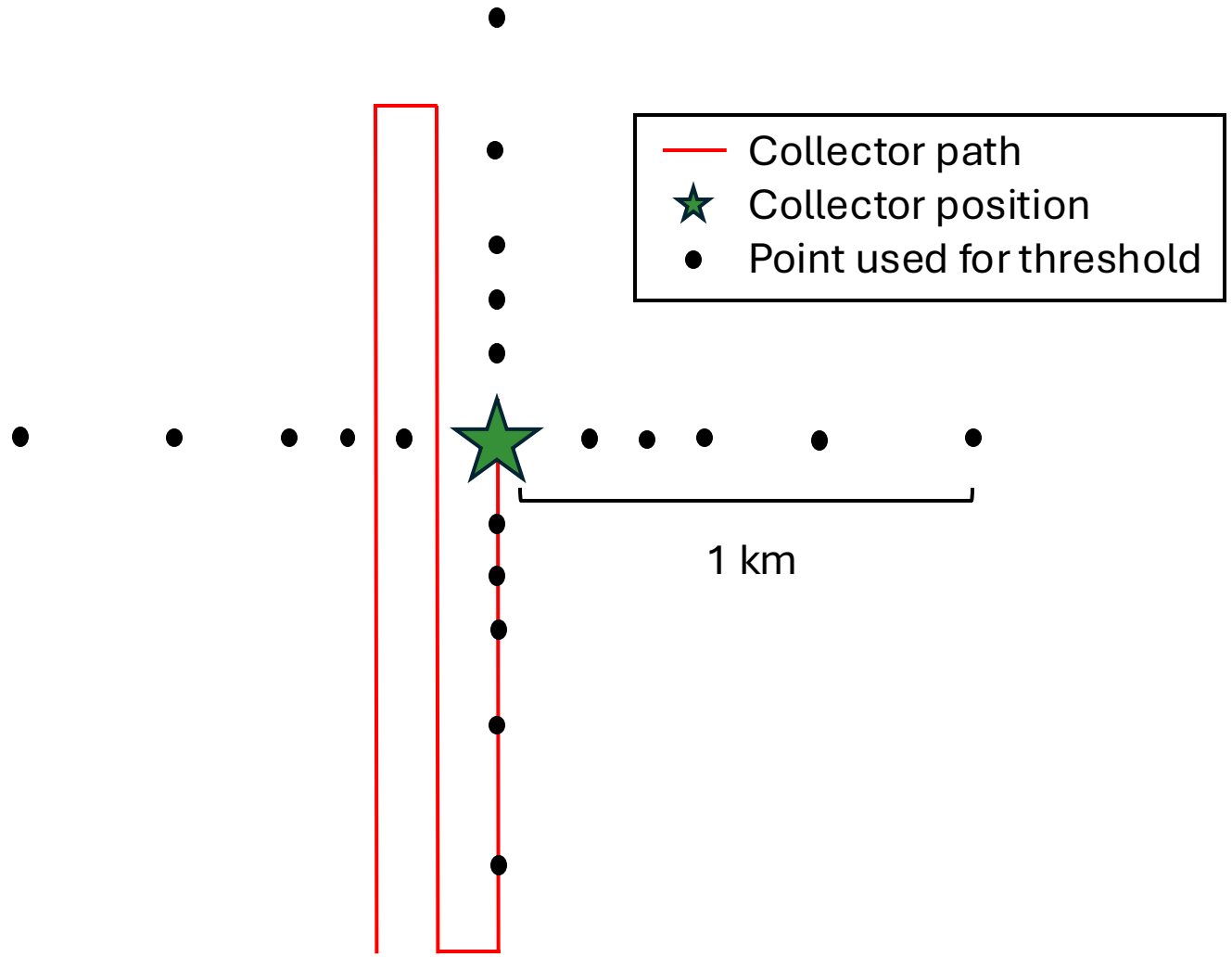
$$\frac{w_s D}{\nu} = \begin{cases} \sqrt{107.33 + 1.049 D_{gr}^2} - 10.36, & D_{gr} \geq 0.672 \\ 0.0077 D_{gr}^2, & D_{gr} < 0.672 \end{cases} \tag{31}$$

where ν is the kinematic viscosity [$\mathrm{m}^2.\mathrm{s}^{-1}$], D is the sediment grain size [m] and D_{gr} is a dimensionless sediment grain size [-] given by

$$D_{gr} = D_{50} \sqrt[3]{\frac{\left(\frac{\rho_s}{\rho} - 1\right) g}{\nu^2}} \tag{32}$$

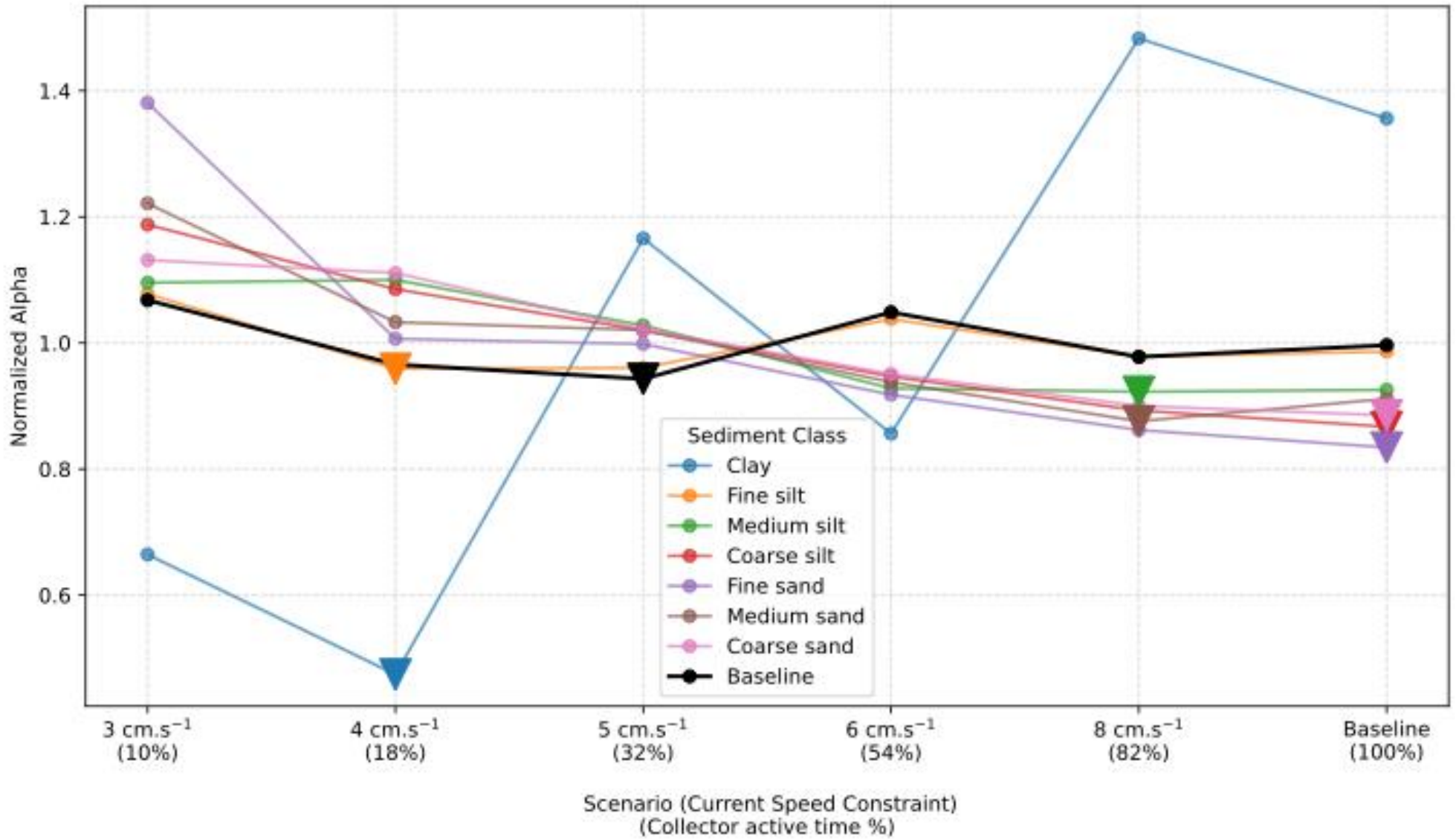
where D_{50} is the median sediment diameter, ρ is the mean seawater density [$\mathrm{kg.m}^{-3}$] and ρ_s the sediment density[$\mathrm{kg.m}^{-3}$]. The latter is computed using the relation of Hamilton and Bachman (1982).

Stopping the collector in strong currents to minimize environmental harm



Illustrative scheme – not to scale

Alpha trends depend on the sediment class



II. Minimising the impact of a sediment plume: a tentative residence time-based analytical approach

II.1. Objectives

• Evaluate analytically the **ocean floor surface area** (S) impacted by **sediment** particles released by a polymetallic nodule (PMN) collector.

• Determine the type of the PMN trajectory that **minimizes** S.

• Assess the **sensitivity** of the obtained results to the model parameters.

II.2. General solution using the Green's function

• To model sediment transport and deposition, we adopt the Eulerian framework (unlike Clotman 2025) and rely on the Boussinesq approximation. We define sediment particle concentration $C(t,\mathbf{x})$ as a

mass fraction, i.e., a dimensionless variable. Thus, the mass of sediment contained at time t and location $\mathbf{x} = (x, y, z)$ in elemental control volume δV reads

$$\delta m(t, \mathbf{x}) \sim \rho_{\bullet} C(t, \mathbf{x}) \delta V \quad , \quad \delta V \to 0 \tag{II.2.1}$$

where constant $\rho_{\bullet} \approx 1030\,\mathrm{kg\,m^{-3}}$ is the reference density of the fluid mixture (water, salt, sediment, etc.) under consideration.

• Sediment is treated as an inert tracer. Hence, its concentrations obeys

$$\frac{\partial C}{\partial t} = \frac{\sigma(t, \mathbf{x})}{\rho_{\bullet}} - \nabla \bullet (C\mathbf{v} - \mathbf{K} \bullet \nabla C) \tag{II.2.2}$$

where $\mathbf{v}(t, \mathbf{x})$ is the macroscopic velocity of sediment particles (including the settling velocity) and $\mathbf{K}(t, \mathbf{x})$ is the relevant diffusivity tensor; $\sigma(t, \mathbf{x})$ is the body sediment source ($\mathrm{kg\,m^{-3}\,s^{-1}}$). Accordingly, the elemental mass of sediment injected by the source during time interval $[t, t + \delta t]$ tends to $\sigma(t, \mathbf{x}) \delta V \, \delta t$ in the limit $\delta V, \delta t \to 0$.

• In domain of interest Ω, (II.2.2) is to be solved under initial condition

$$\left[C(t,\mathbf{x})\right]_{t=0} = C^0(\mathbf{x}) \tag{II.2.3}$$

and relevant boundary conditions (not discussed in this Section).

• If the model is linear, the sediment concentration is the sum of two convolution products:

$$C(t,\mathbf{x}) = \overbrace{\int_{\Omega} \mathcal{G}(t,\mathbf{x}\,|\,0,\mathbf{x}')C^0(\mathbf{x}')\,d\mathbf{x}'}^{\text{response to initial concentration}} + \underbrace{\frac{1}{\rho_{\bullet}}\int_0^t \int_{\Omega} \mathcal{G}(t,\mathbf{x}\,|\,t',\mathbf{x}')\sigma(t',\mathbf{x}')\,d\mathbf{x}'\,dt'}_{\text{response to the source}} \tag{II.2.4}$$

where $\mathcal{G}(t,\mathbf{x}\,|\,t',\mathbf{x}')$ is the Green's function of the problem, which is also

known as “impulse response” or “transfer function”. This concept dates back to Green (1828) and is still in use nowadays to deal with linear (ordinary or partial) differential problems (e.g., Arfken and Weber 2005, Duffy 2018), including some of those of ocean science (e.g., Haine et al. 2025).

• Notice, in passing, that the initial concentration is equivalent to the result of a source injecting abruptly the relevant amount of sediment at the initial time ($t=0$), i.e., $\sigma(t',\mathbf{x}')=\rho_{\bullet}C^0(\mathbf{x}')\delta(t'-0)$, where δ is the Dirac delta function.

• Green's function $\mathcal{G}(t,\mathbf{x}\,|\,t',\mathbf{x}')$ is the response to an impulse forcing. Accordingly, it satisfies

$$\frac{\partial \mathcal{G}}{\partial t} = \delta(t-t')\delta(\mathbf{x}-\mathbf{x}') - \nabla\bullet(\mathcal{G}\mathbf{v}-\mathbf{K}\bullet\nabla\mathcal{G}) \qquad \text{(II.2.5)}$$

$$\mathcal{G}(t,\mathbf{x}\,|\,t',\mathbf{x}') = 0\,, \quad \text{if} \quad t<t' \qquad \text{(causality principle)} \qquad \text{(II.2.6)}$$

as well as appropriate boundary conditions. In the present context, the physical dimension of $\mathcal{G}(t,\mathbf{x}\,|\,t',\mathbf{x}')$ is length^{-3}.

• The Green's function concept underpins the developments carried out hereinafter. Detailed calculations may be found in Deleersnijder and Clotman (2026).

II.3. Idealised abrupt sediment release model

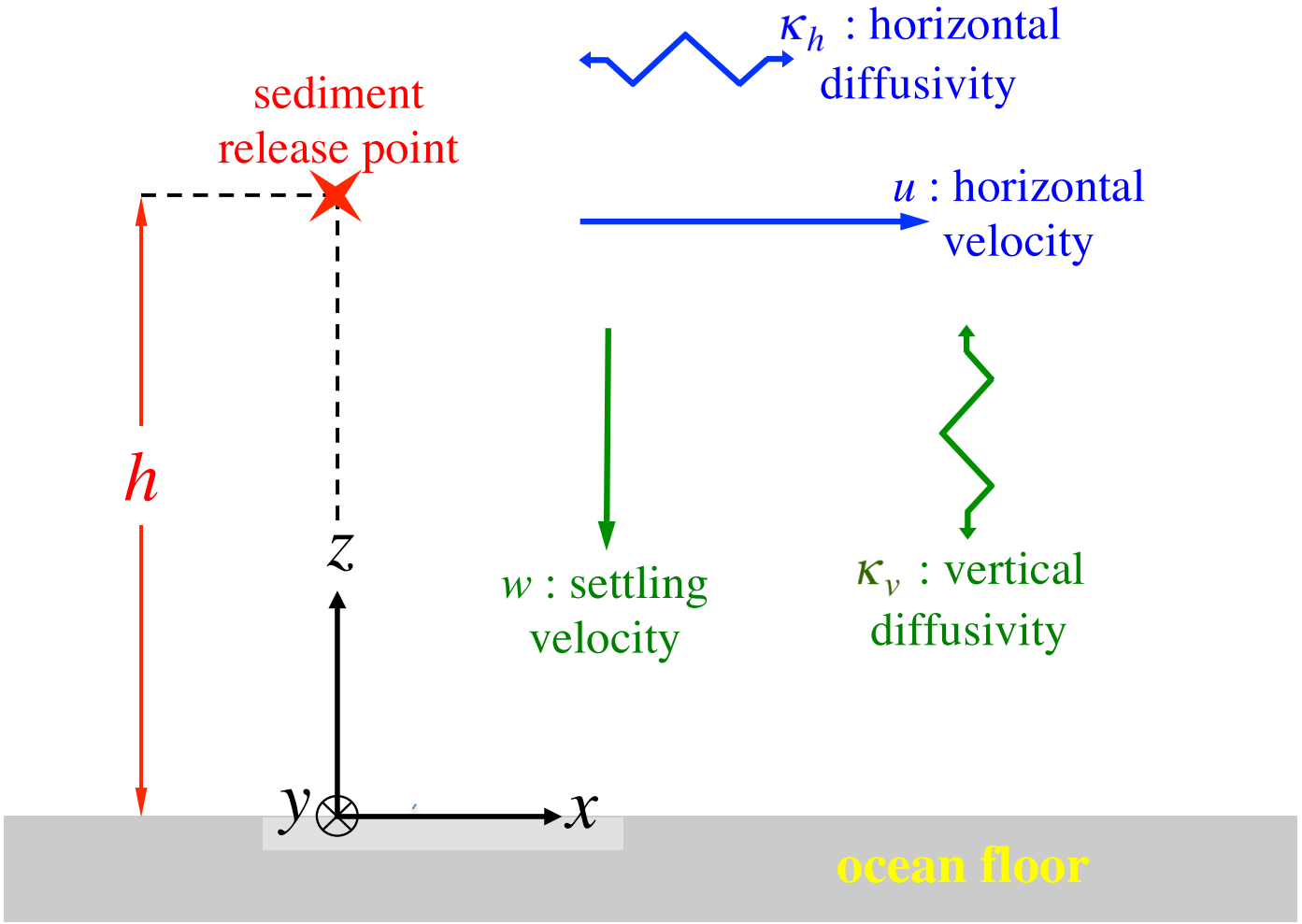
• The domain of interest (Ω) is a flat-bottomed, semi-infinite ocean defined by

$$-\infty < x < \infty \quad , \quad -\infty < y < \infty \quad , \quad 0 \leq z < \infty \tag{II.3.1}$$

where x and y are horizontal Cartesian coordinates, whilst z is the vertical coordinate pointing upwards (with $z = 0$ at the ocean bottom).

• The sediment velocity is constant $\mathbf{v}(u,0,-w)$, with $u,w > 0$. The

constant horizontal and vertical diffusivities are denoted κ_h and κ_v, respectively, with $\kappa_h, \kappa_v > 0$.



• Sediment mass M is abruptly released at $t = 0$ and point $(0,0,h)$. Then, sediment concentration $C(t,x,y,z)$ is the solution of

$$\frac{\partial C}{\partial t} = \frac{1}{\rho_{\cdot}} \overbrace{M\delta(t-0)\delta(x-0)\delta(y-0)\delta(z-h)}^{=\sigma(t,x,y,z)} - \frac{\partial}{\partial x}\left(uC - \kappa_h \frac{\partial C}{\partial x}\right) - \frac{\partial}{\partial x}\left(-\kappa_h \frac{\partial C}{\partial y}\right) - \left(-wC - \kappa_v \frac{\partial C}{\partial x}\right) \tag{II.3.2}$$

$$\underbrace{\left[C(t,x,y,z)\right]_{t=0^-} = 0}_{\text{initial condition}} , \qquad \underbrace{\left[\kappa_v \frac{\partial C}{\partial z}\right]_{z=0} = 0}_{\text{bottom boundary condition}} \tag{II.3.3}$$

The bottom boundary condition is the simplest one that can be conceived. More realistic expressions may be found in, e.g., Xiong and Chen (2022) and references therein.

• No simple analytical solution to (II.3.2)-(II.3.3) seems to exist. However, by having recourse to the Constituent-oriented Age and Residence time Theory (CART, www.cartdiagnoses.be), the average time that sediment particles spend in the water column, i.e., their (mean) **residence time** (θ), can be evaluated (without resorting to any simplifying assumption):

$$\theta \triangleq \frac{1}{M}\int_0^\infty m(t)\,dt = -\frac{1}{M}\int_0^\infty t\,\frac{dm(t)}{dt}\,dt = \frac{h}{w} + \frac{\kappa_v}{w^2} \qquad \text{(II.3.4)}$$

where

$$m(t) = \rho_s \int_{\Re^2}\int_0^\infty C(t,x,y,z)\,dz\,dy\,dx \qquad \text{(II.3.5)}$$

is the mass of sediment present in the domain of interest at time t. If κ_v

and w depend on vertical coordinate z, it is still possible to derive (by means of CART's tools) a mathematical expression of the residence time.

• The residence time is independent of the horizontal velocity and diffusivity. This is because, in the present idealised model, horizontal transport proceeds independently of settling and vertical diffusion. Accordingly, it is appropriate to introduce the "horizontal Green's function" (m^{-2})

$$G(t,x,y) = \frac{1}{4\pi\kappa_h t}\exp\left[-\frac{(x-ut)^2+y^2}{4\kappa_h t}\right] \qquad \text{(II.3.6)}$$

which obviously satisfies

$$\int_{\Re^2} G(t,x,y)\,dy\,dx = 1 \qquad \text{(II.3.7)}$$

• Herein, only the bottom settling flux, $\phi(t,x,y)$ ($\mathrm{kg\ m^{-2}\ s^{-1}}$), is needed,

i.e.,

$$\phi(t,x,y) = \rho_s w\, C(t,x,y,0) \tag{II.3.8}$$

allowing to evaluate the residence time as follows

$$\theta \triangleq \frac{1}{M}\int_0^t \int_{\Re^2} t\,\phi(t,x,y)\,dy\,dx\,dt \tag{II.3.9}$$

• Based on the considerations above as well as Deleersnijder et al. (2006) and de Brauwere and Deleersnijder (2010), it is suggested that the sediment mass be approximated as $m(t) = M\,e^{-t/\theta}$, eventually yielding

$$\phi(t,x,y) = \frac{M}{4\pi\theta\kappa_h t}\exp\left[-\frac{t}{\theta}-\frac{(x-ut)^2+y^2}{4\kappa_h t}\right] \tag{II.3.10}$$

This expression satisfies (II.3.9) and

$$M = \int_0^t \int_{\Re^2} \phi(t,x,y)\, dy\, dx\, dt \tag{II.3.11}$$

which is in accordance with elementary physical intuition.

• The sediment mass deposited on the ocean bottom per unit surface area, i.e., $\Phi(x,y)$ (kg m^{-2}), is

$$\Phi(x,y) = \int_0^\infty \phi(t,x,y)\, dt$$
$$= \frac{M e^{ux/(2\kappa_h)}}{2\pi\kappa_h\theta} K_0\left[\sqrt{\frac{4\kappa_h + u^2\theta}{4\kappa_h^2\theta}\left(x^2+y^2\right)}\right] \tag{II.3.12}$$

where K_0 denotes the zeroth-order modified Bessel function of the second kind.

II.4. Abrupt sediment release: impacted ocean floor surface area

• The centre of mass of the deposited layer is located at $(x_{cm},0)$, with

$$x_{cm} \triangleq \frac{1}{M} \int_{\Re^2} x\, \Phi(x,y)\, dy\, dx = u\theta \qquad \text{(II.4.1)}$$

This result is far from unexpected: on average, sediment particles stay in the water column for a period of time equal to residence time θ, and the distance travelled at speed u during time θ is $u\theta$, hence (II.4.1).

• The ocean bottom surface area impacted by sediment, S (m^2), may be derived from the position variance of $\Phi(x,y)$, i.e.,

$$S \triangleq \frac{1}{M} \int_{\Re^2} \left[(x - x_{cm})^2 + y^2 \right] \Phi(x,y)\, dy\, dx \qquad \text{(II.4.2)}$$

Substituting (II.3.12) into (II.4.2) yields

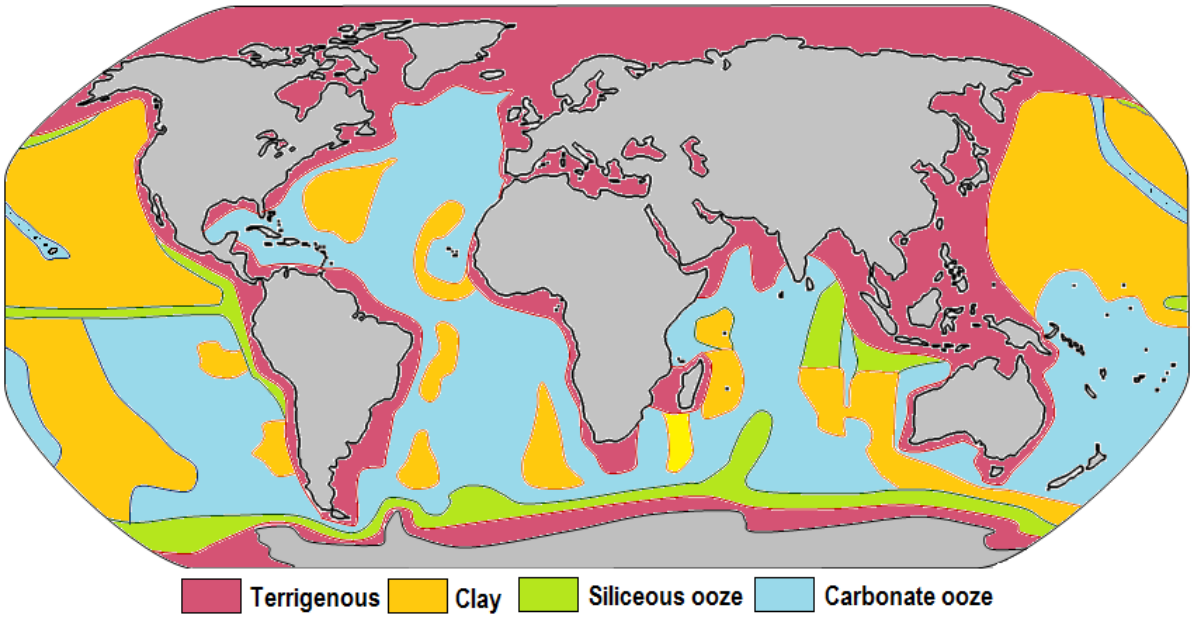
$$S = 4\kappa_h\theta + u^2\theta^2 = \frac{4\kappa_h(\kappa_v + wh)}{w^2} + \frac{u^2(\kappa_v + wh)^2}{w^4} \qquad \text{(II.4.3)}$$

if we **increase** (↑)	then the **impacted surface**
the height of the sediment release point (h)	increases (↑)
the horizontal velocity (u)	increases (↑)
the horizontal diffusivity (κ_h)	increases (↑)
the vertical diffusivity (κ_v)	increases (↑)
the settling velocity (w)	decreases (↓)

Of course, other approaches to the evaluation of the impacted surface area may be contemplated.

• Clearly, assuming that the sediment mass decreases exponentially is a potential weakness of the present approach. It should be assessed with the help of a numerical model. Fortunately, a one-dimensional, water column will do.

• It is assumed that the bottom of the domain of interest is covered by fine sediment (clay). See figure opposite.



Source: https://www.coastalwiki.org/wiki/File:SeafloorSediment.png (last viewed on 5 Nov. 2025)

These sediment particles are cohesive. Their actual properties depend, among other things, on the salinity (e.g., Whitehouse et al. 1960). The

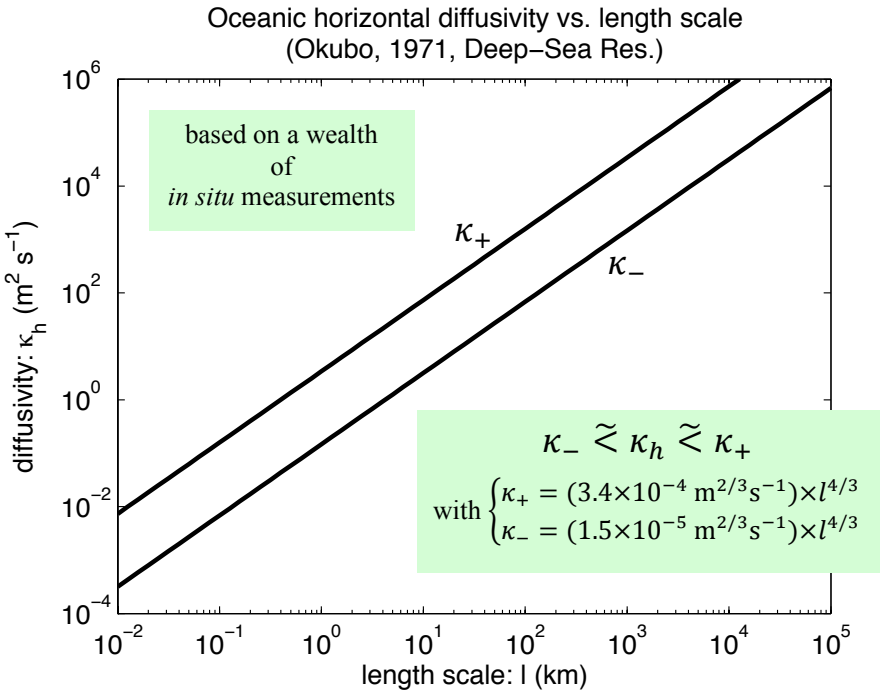
range of values of the settling velocity is hypothesized to be as follows:

$$10^{-4}\ \mathrm{m\,s^{-1}} \le w \le 10^{-1}\ \mathrm{m\,s^{-1}} \qquad \text{(II.4.4)}$$

The other model's parameters are assumed to obey

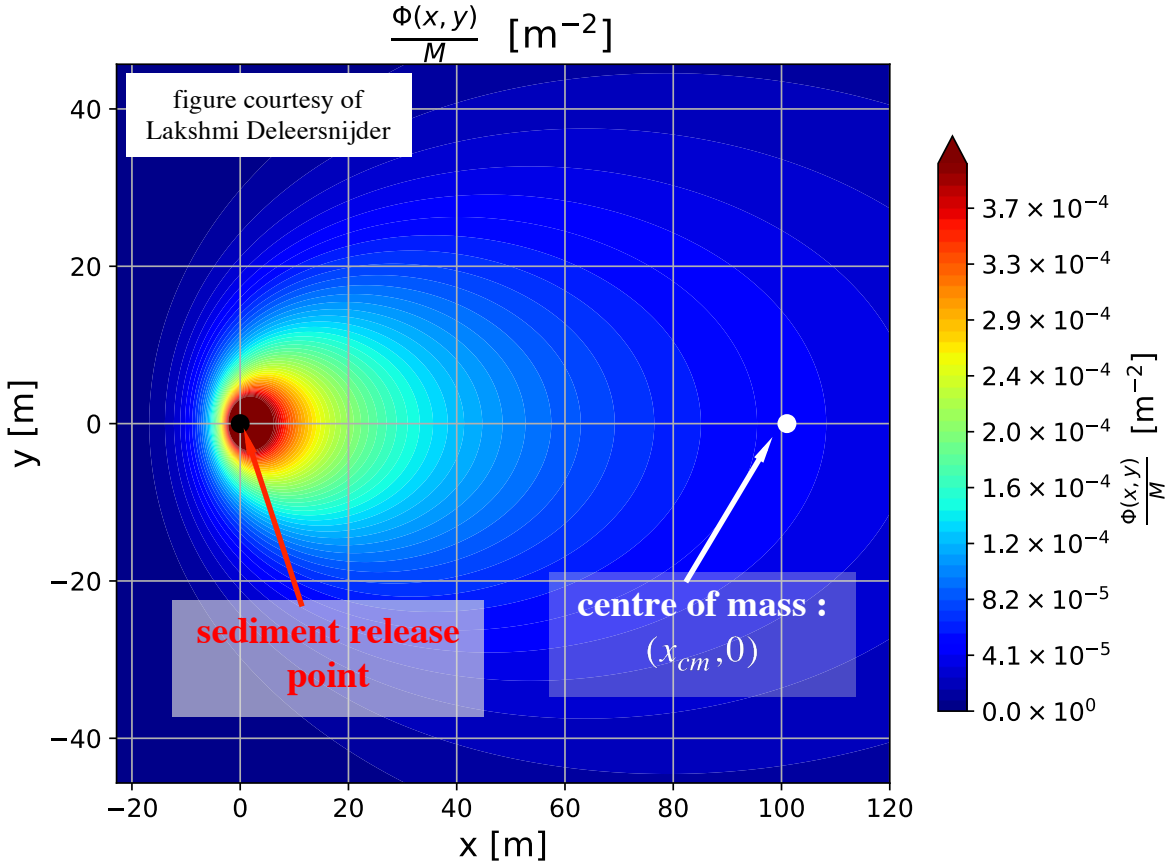
$$1\ \mathrm{m} \le h \le 10\ \mathrm{m} \quad \bullet \quad 10^{-2}\ \mathrm{m\,s^{-1}} \le u \le 10^{-1}\ \mathrm{m\,s^{-1}}$$
$$10^{-3}\ \mathrm{m^2\,s^{-1}} \le \kappa_v \le 10^{-2}\ \mathrm{m^2\,s^{-1}} \quad \bullet \quad 10^{-1}\ \mathrm{m^2\,s^{-1}} \le \kappa_h \le 10\ \mathrm{m^2\,s^{-1}} \qquad \text{(II.4.5)}$$

The range of supposedly acceptable values of horizontal diffusivity κ_h is derived from Okubo (1971) (see figure opposite) — although it is far from clear that this study applies to the vicinity of the ocean floor.



- The following values of the model's parameters are selected:

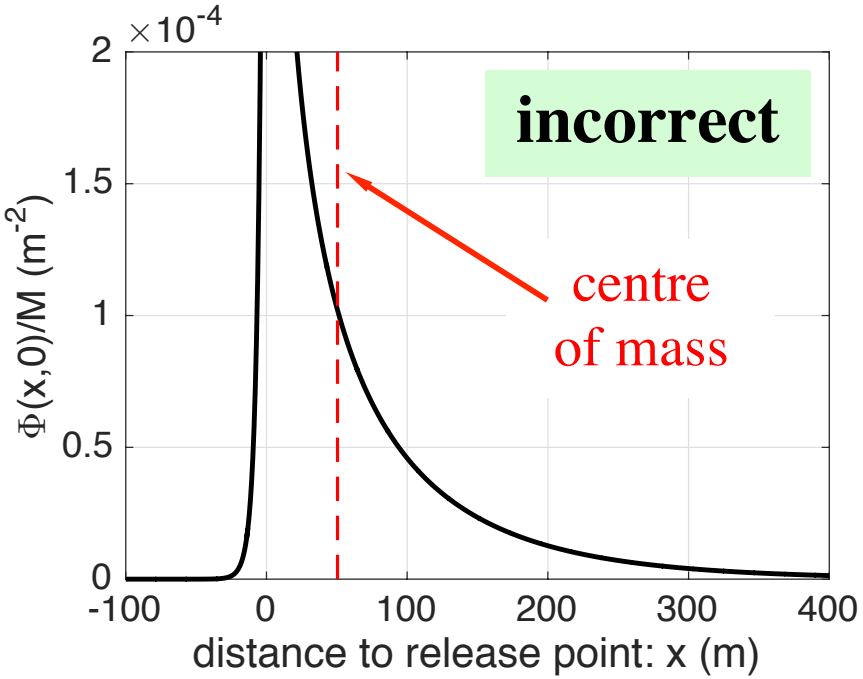
$$w = 10^{-2}\ \mathrm{m\,s^{-1}} \quad \bullet \quad h = 10\ \mathrm{m} \quad \bullet \quad u = 10^{-1}\ \mathrm{m\,s^{-1}}$$
$$\kappa_v = 10^{-3}\ \mathrm{m^2\,s^{-1}} \quad \bullet \quad \kappa_h = 5\times10^{-1}\ \mathrm{m^2\,s^{-1}} \qquad \text{(II.4.6)}$$

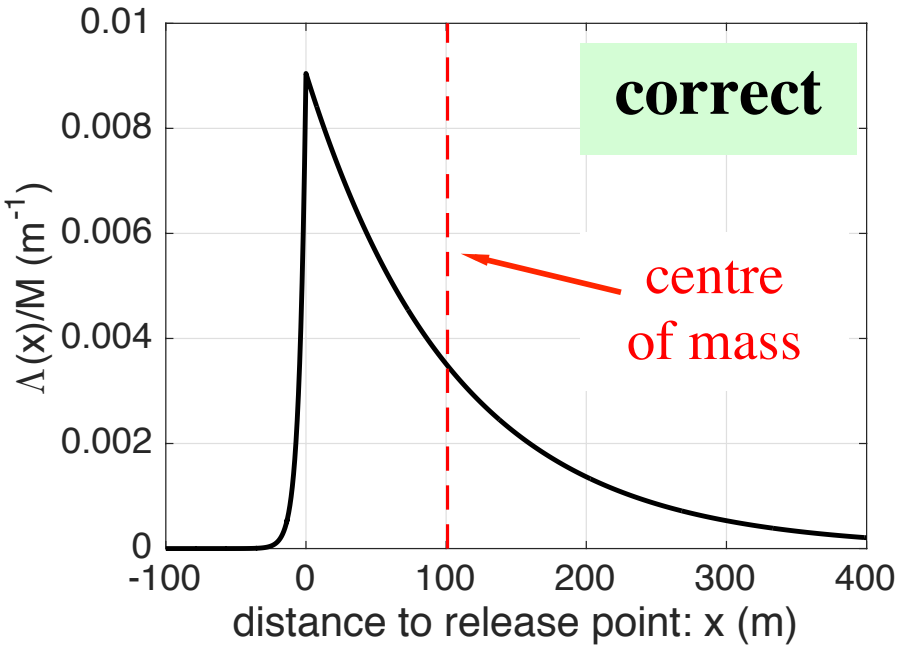


$$w = 10^{-2}\ \mathrm{m\,s^{-1}}$$
$$\theta = 1010\ \mathrm{s}$$
$$x_{cm} = 101\ \mathrm{m}$$
$$S \approx 1.2\times10^{4}\ \mathrm{m^2}$$

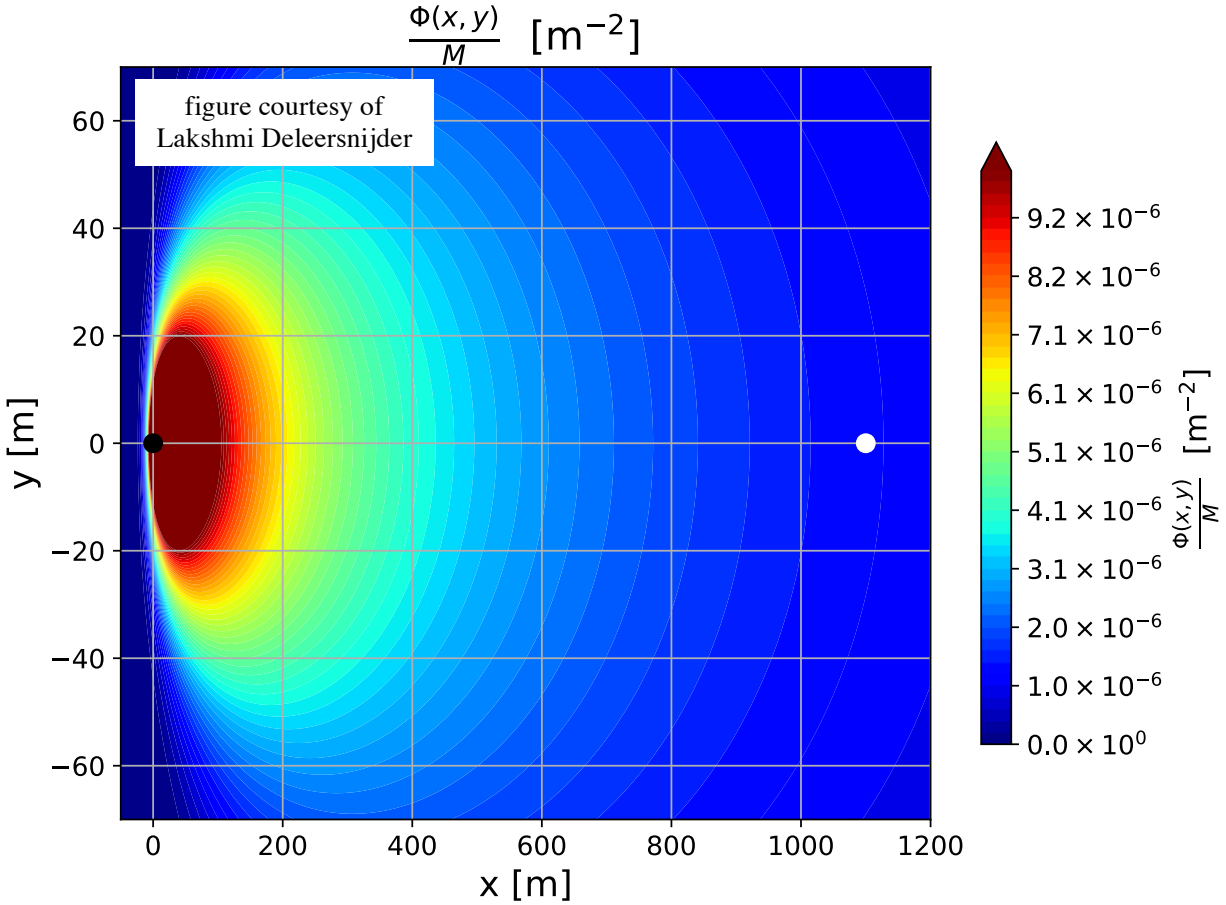
• Notice that x_{cm} does not correspond to the "centre of mass" of $\Phi(x,0)$. However, it is equivalent to the "centre of mass" of

$$\Lambda(x) = \int_{-\infty}^{\infty} \Phi(x,y)\, dy \qquad \text{(II.4.7)}$$





• The ocean floor surface area impacted by sediment deposition is very sensitive to the settling velocity. If the settling velocity is divided by a factor of 10, then S is about 100 times greater.



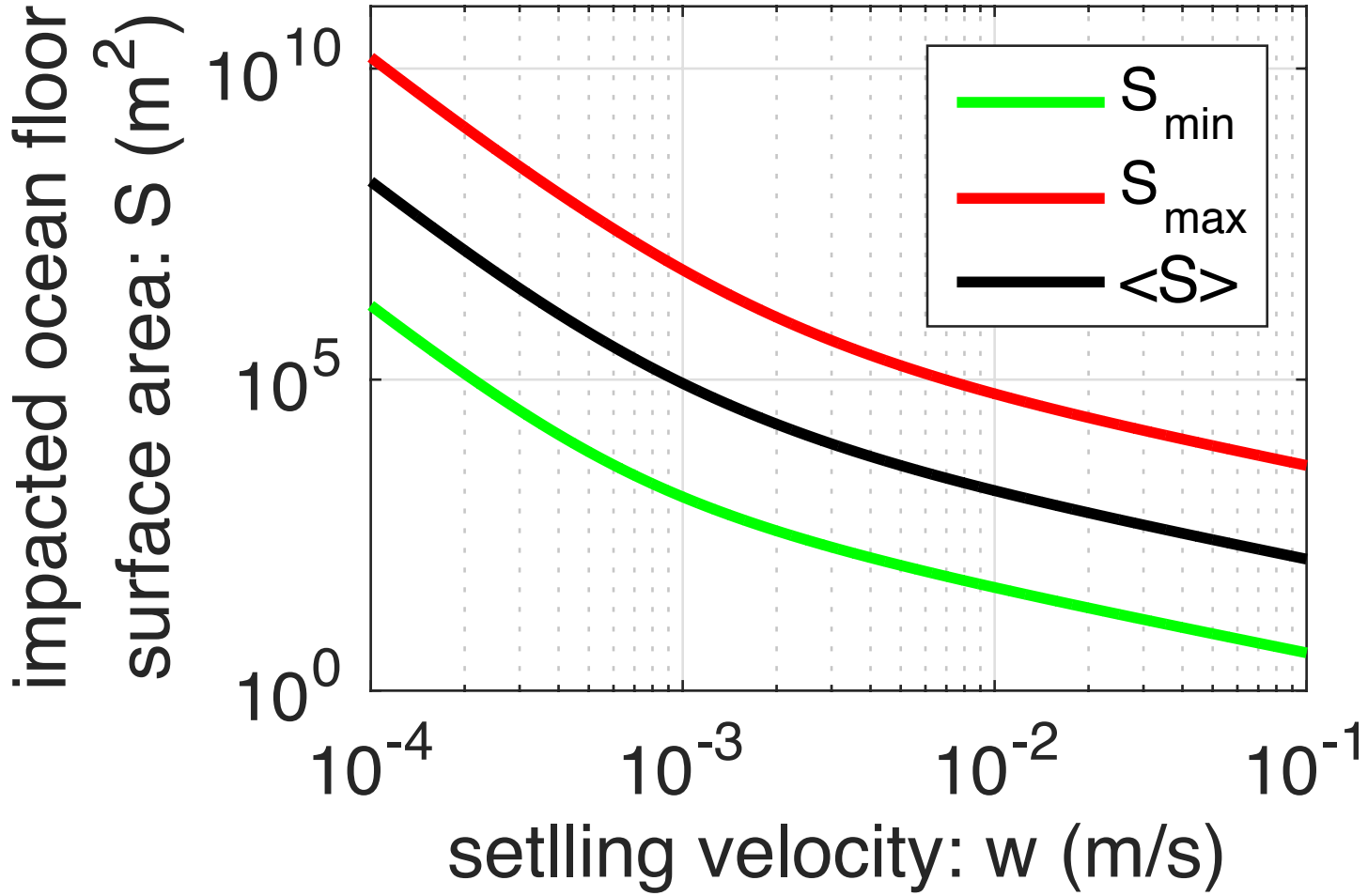
$$w = 10^{-3}\ \mathrm{m\,s^{-1}}$$

$$\theta = 1{,}010\ \mathrm{s}$$

$$x_{cm} = 1{,}100\ \mathrm{m}$$

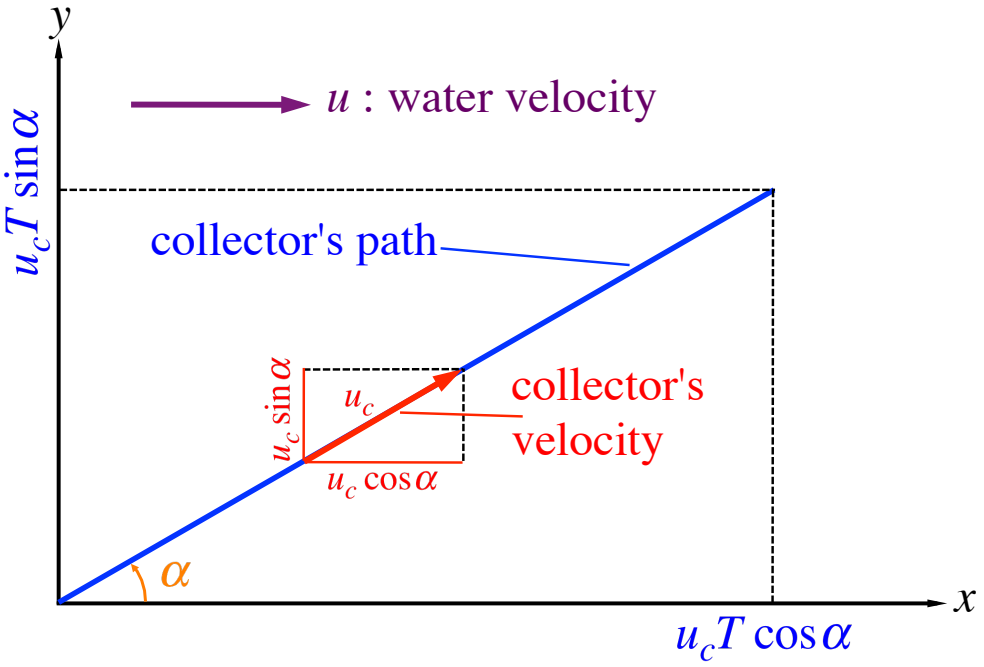
$$S \approx 1.2 \times 10^{6}\ \mathrm{m^2}$$

• Sensitivity of the impacted ocean floor surface area to the settling velocity and the other parameters as per (II.4.5), with $\langle S \rangle = \sqrt{S_{min}\, S_{max}}$.



II.5. Moving collector: impacted ocean floor surface area

• We now tackle a more realistic situation. A PMN collector moves at speed $u_c = 0.5$ m/s during time interval $0 \le t \le T$, with $T = 2{,}000$ s. Then, the length of the collector's path is $L = u_c T = 1{,}000$ m.



• The corresponding source term reads

$$\sigma(t,x,y,z) = q\,\Upsilon(T-t)\,\delta(x-u_{cx}t)\delta(y-u_{cy}t)\delta(z-h) \qquad \text{(II.5.1)}$$

where $\Upsilon(T-t)$ is the Heaviside (or step) function, i.e.,

$$\Upsilon(T-t) \;=\; \begin{cases} 1\,, \;\text{if}\;\; t<T \\ 0 \;\;\text{otherwise} \end{cases} \tag{II.5.2}$$

• Then, the ocean floor sediment settling flux ($\mathrm{kg\,m^{-2}\,s^{-1}}$) reads

$$\begin{aligned} \phi(t,x,y) \;=\; & \int_0^T \frac{q}{4\pi\theta\kappa_h(t-t')} \\ & \times\exp\left[-\frac{t-t'}{\theta}-\frac{(x-X)^2-(y-Y)^2}{4\kappa_h(t-t')}\right]\Upsilon(t-t')\,dt' \end{aligned} \tag{II.5.3}$$

with $X=u_{cx}t'+u(t-t')$, $Y=u_{cy}t'$, and $(u_{cx},u_{cy})=(\cos\alpha,\sin\alpha)u_c$.

• The corresponding sediment mass deposited on the ocean floor per unit surface area, i.e., $\Phi(x,y)$ ($\mathrm{kg\,m^{-2}}$), is obtained by integrating (II.5.3) over time

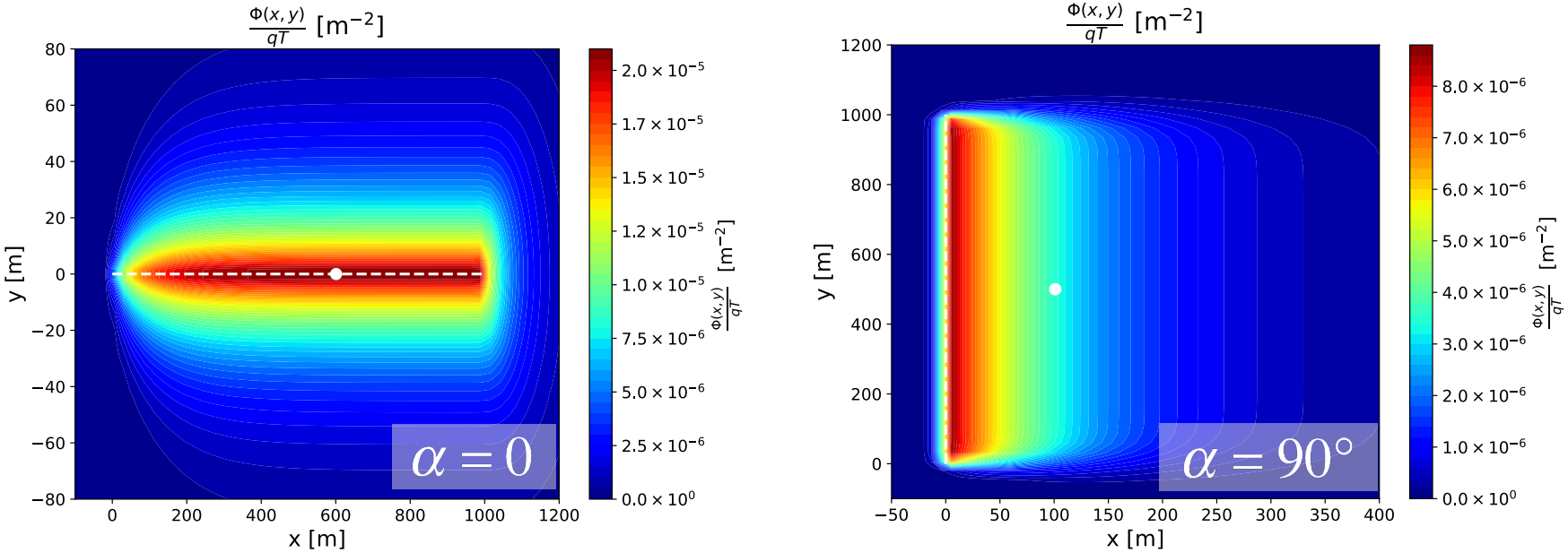
$$\Phi(x,y) = \frac{q}{2\pi\kappa_h\theta}\int_0^T \exp\left[\frac{(x-u_{cx}t')u}{2\kappa_h}\right] \times K_0\left[\sqrt{\frac{(4\kappa_h+u^2\theta)\left[(x-u_{cx}t')^2+\left(y-u_{cy}t'\right)^2\right]}{4\kappa_h^2\theta}}\right]dt' \quad \text{(II.5.4)}$$

• If we set $\sigma(t,x,y,z) = M\delta(t-0)\delta(x-0)\delta(y-0)\delta(z-h)$, the results associated with an abrupt sediment release are obtained, which lends credence to the present developments — but is not a proper validation of them.

• The location of the centre of mass of the sediment deposited on the sea floor is in line with elementary physical intuition:

$$(x_{cm}, y_{cm}) = \underbrace{(u\theta, 0)}_{\text{due to water flow}} + \underbrace{\left(u_{cx}T, u_{cy}T\right)/2}_{\text{due to collector's motion}} \qquad \text{(II.5.5)}$$

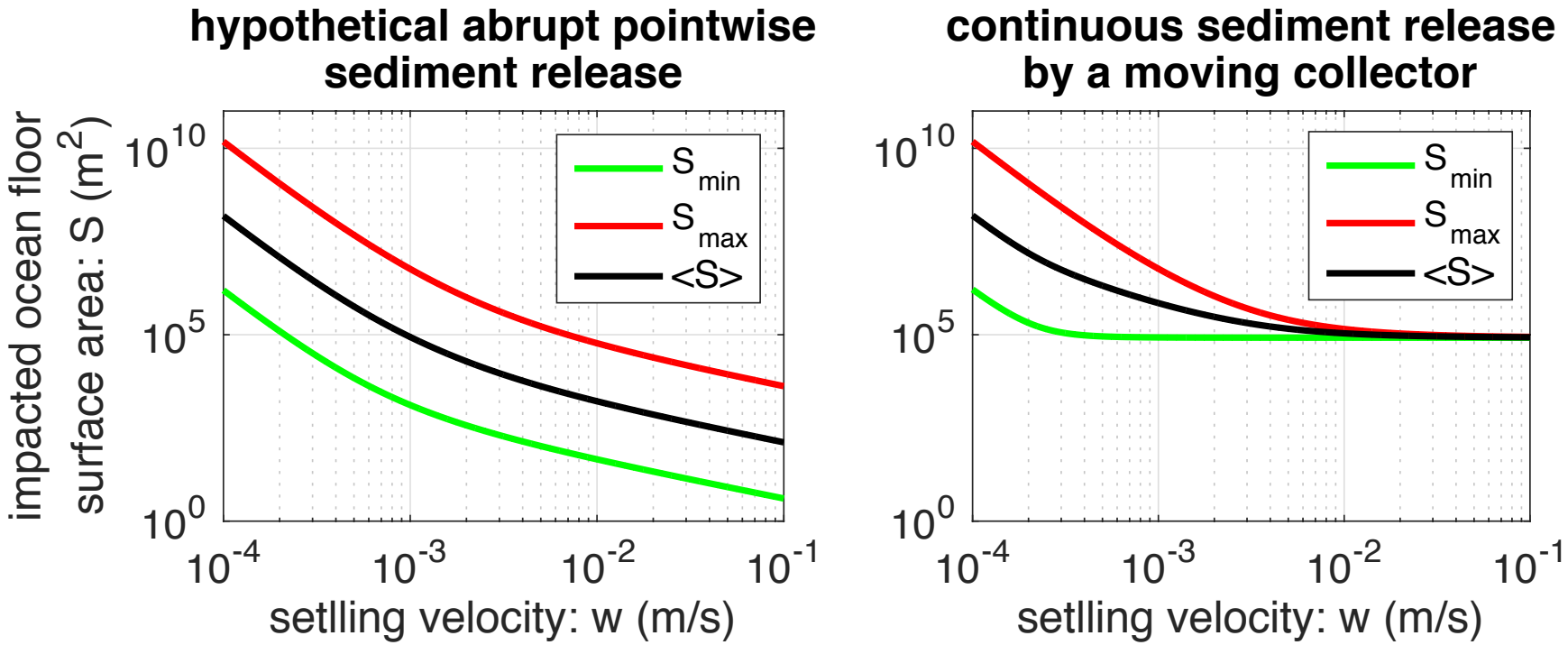
• Depiction of $\Phi(x,y)/(qT)$ if the water velocity is parallel to the collector's velocity ($\alpha = 0$) (left panel) and if these velocities are orthogonal to each other ($\alpha = 90°$) (right panel).



(figures courtesy of Lakshmi Deleersnijder)

- The ocean floor surface area impacted by sediment deposition reads

$$S = \underbrace{4\kappa_h\theta + u^2\theta^2}_{\substack{\text{unrelated to}\\ \text{collector's motion}}} + \underbrace{\frac{T^2}{12}u_{cx}^2 + \frac{(T-2\theta)^2+4\theta^2}{4}u_{cy}^2}_{\substack{\text{related to}\\ \text{collector's motion}}} \qquad \text{(II.5.6)}$$



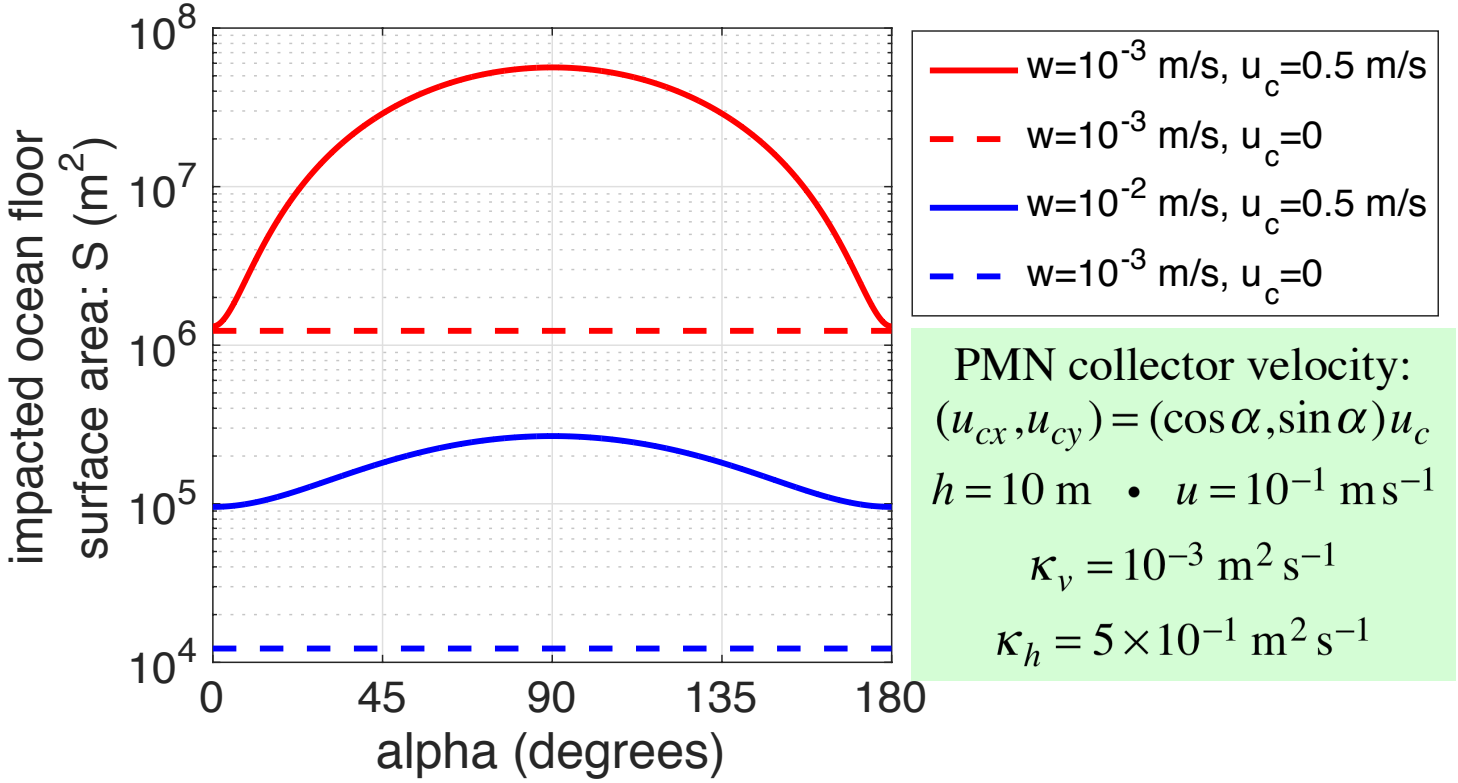
• The minimum surface area and the maximum one are obtained as follows:

$$\overbrace{4\kappa_h\theta + u^2\theta^2 + \frac{T^2}{12}u_c^2}^{\alpha=0 \text{ or } \alpha=\pi} \leq S \leq \underbrace{4\kappa_h\theta + u^2\theta^2 + \frac{(T-2\theta)^2+4\theta^2}{4}u_c^2}_{\alpha=\pi/2} \qquad \text{(II.5.7)}$$

where $T^2u_c^2 = L^2$. The minimum surface does not depend on the collector's speed.

• The impacted surface is minimum if the PMN collector's velocity is parallel to the water velocity, i.e., $\alpha = 0$ or $\alpha = \pi$. Accordingly, the minimum impacted surface is arrived at if the collector moves in the same direction as the water or in the opposite direction.

- If the direction of the collector's displacement is orthogonal to the water velocity ($\alpha = \pi / 2$), the impacted surface is maximum.
- The smaller the settling velocity, the greater the sensitivity to the collector's movement of the impacted surface.



II.6. Takeaways from the analytical developments

- Most, if not all of the key processes (e.g., Emanuel 2020) impacting sediment transport and settling have been taken into account — in a rather idealised manner.

- Despite the relative complexity of the analytical calculations, a simple expression of the surface area impacted by sediment deposition is derived.

- If the PMN collector velocity is parallel to the water velocity the impacted surface is minimum. If these velocities are orthogonal to each other the impacted surface area may be several orders of magnitude greater. This is all the more valid that the settling velocity is small.

- The obtained results are rather sensitive to the sediment transport model parameters (water velocity, vertical and horizontal diffusivities, settling velocity).

• Resorting to a water column model could help improve the approximate “vertical Green's function”. This weakness of the present analytical approach must be tackled so as to improve its relevance.

• The present analytical results are likely to be instrumental in the design of further numerical experiments, whose results might suggest new analytical developments, and so on...

II.7. Analytical developments: references

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Thank you!

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