CROCO

Coastal and Regional Ocean COmmunity model

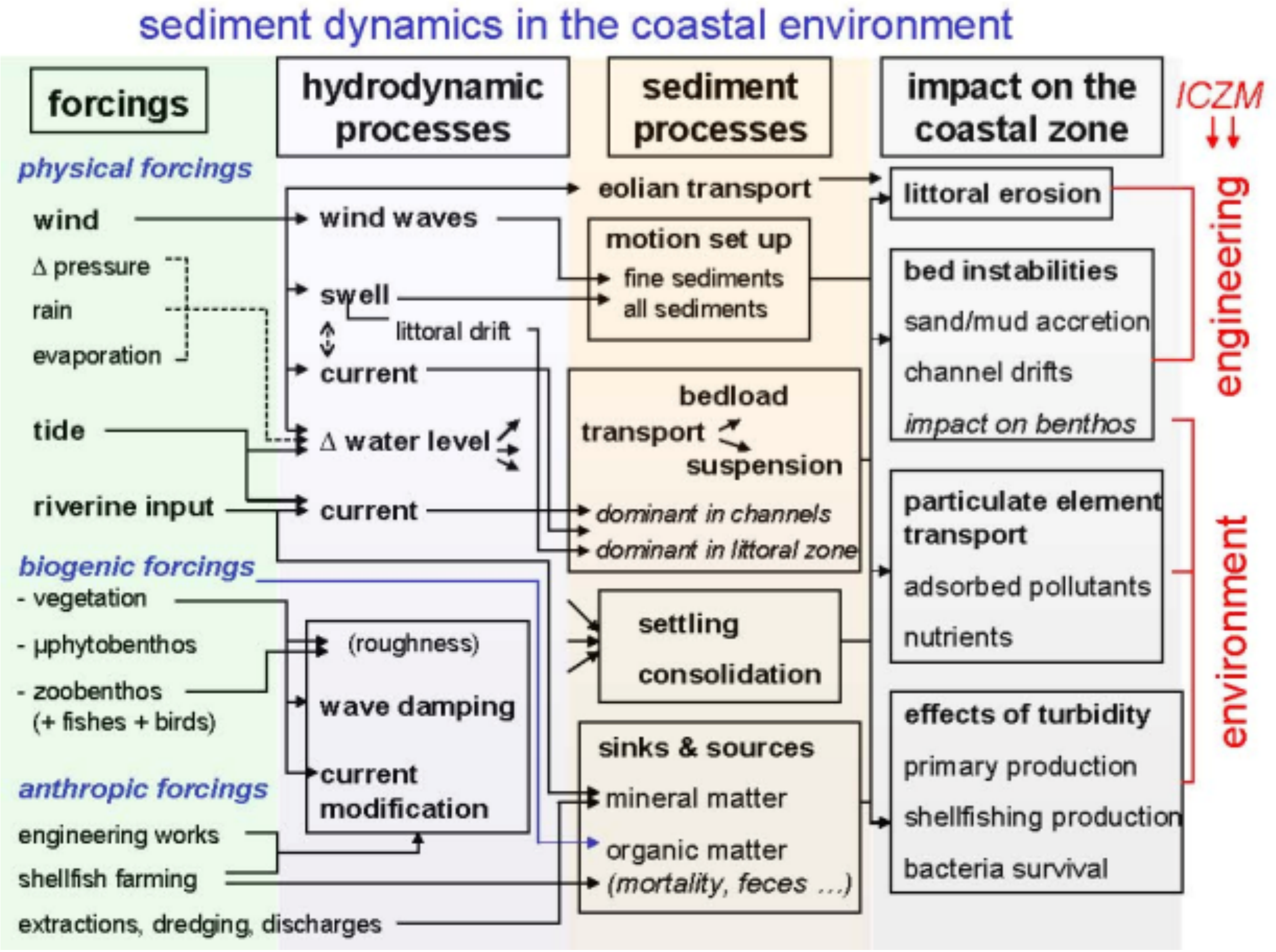
Sediment dynamics

Introduction to sediment transport

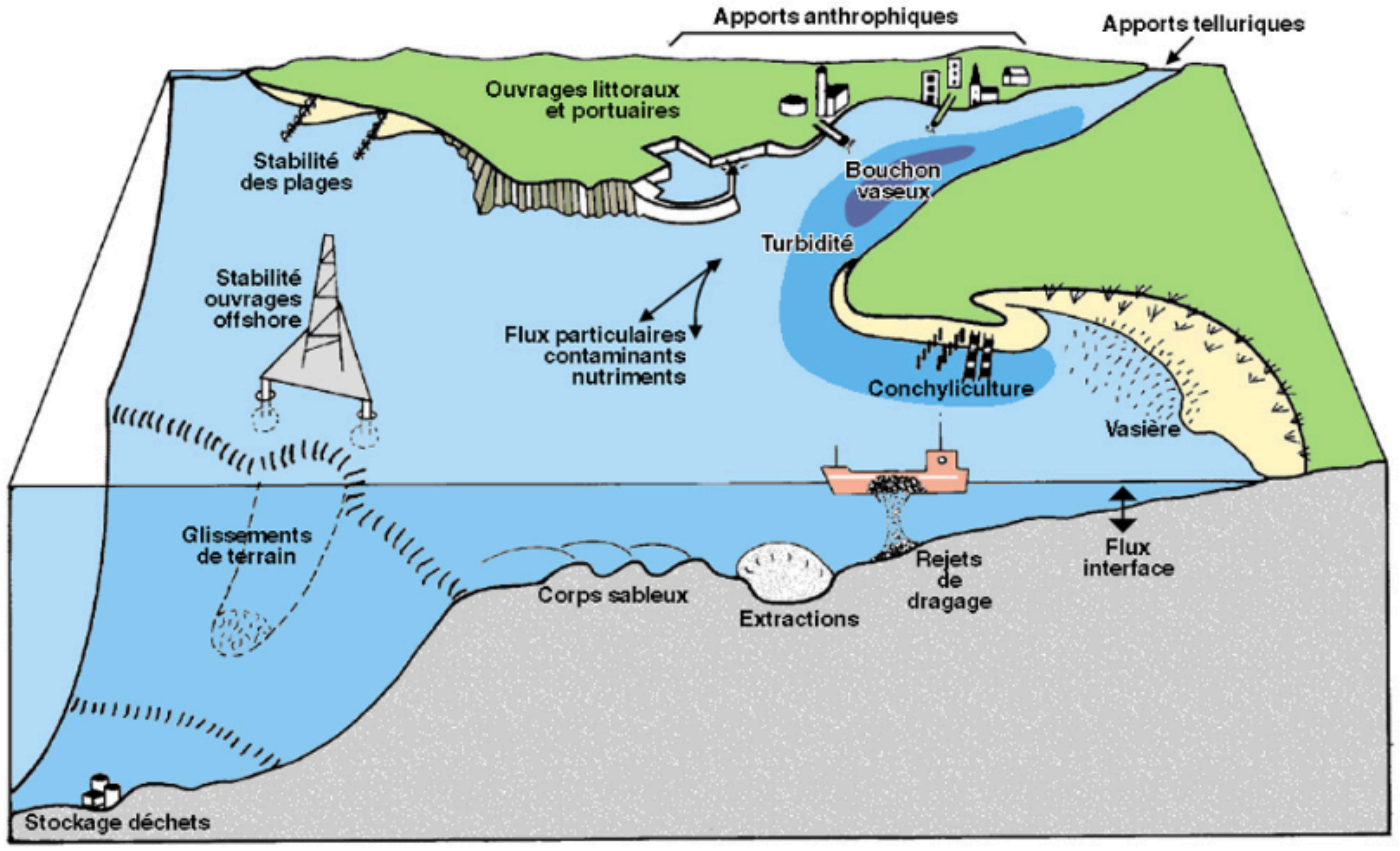
rachid.benshila@legos.obs-mip.fr
guillaume.morvan@legos.obs-mip.fr
solene.le.gac@ifremer.fr

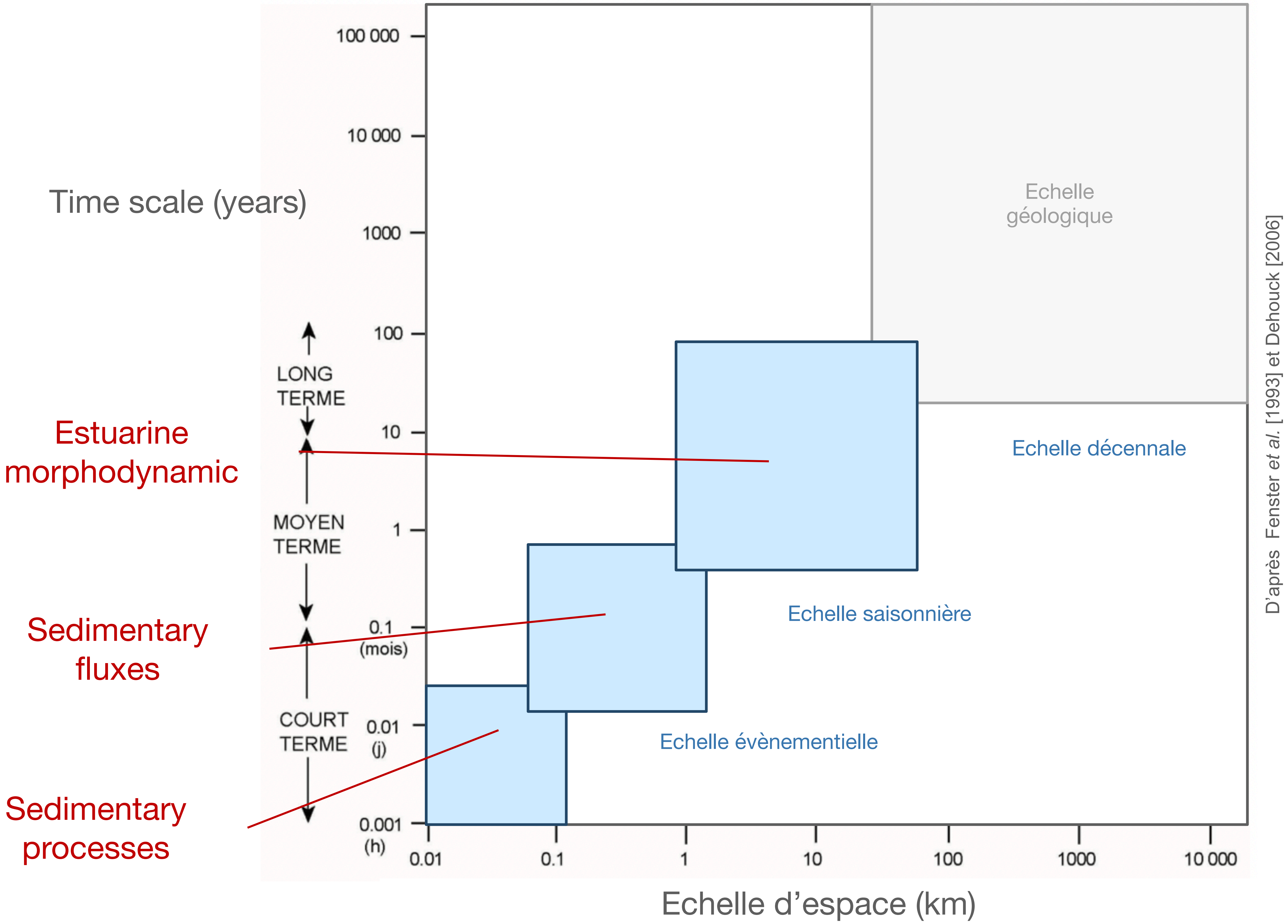
https://croco-ocean.gitlabpages.inria.fr/croco_doc

Introduction



Introduction





Outline

Forcing drivers : roughness and bed shear stress, currents and waves

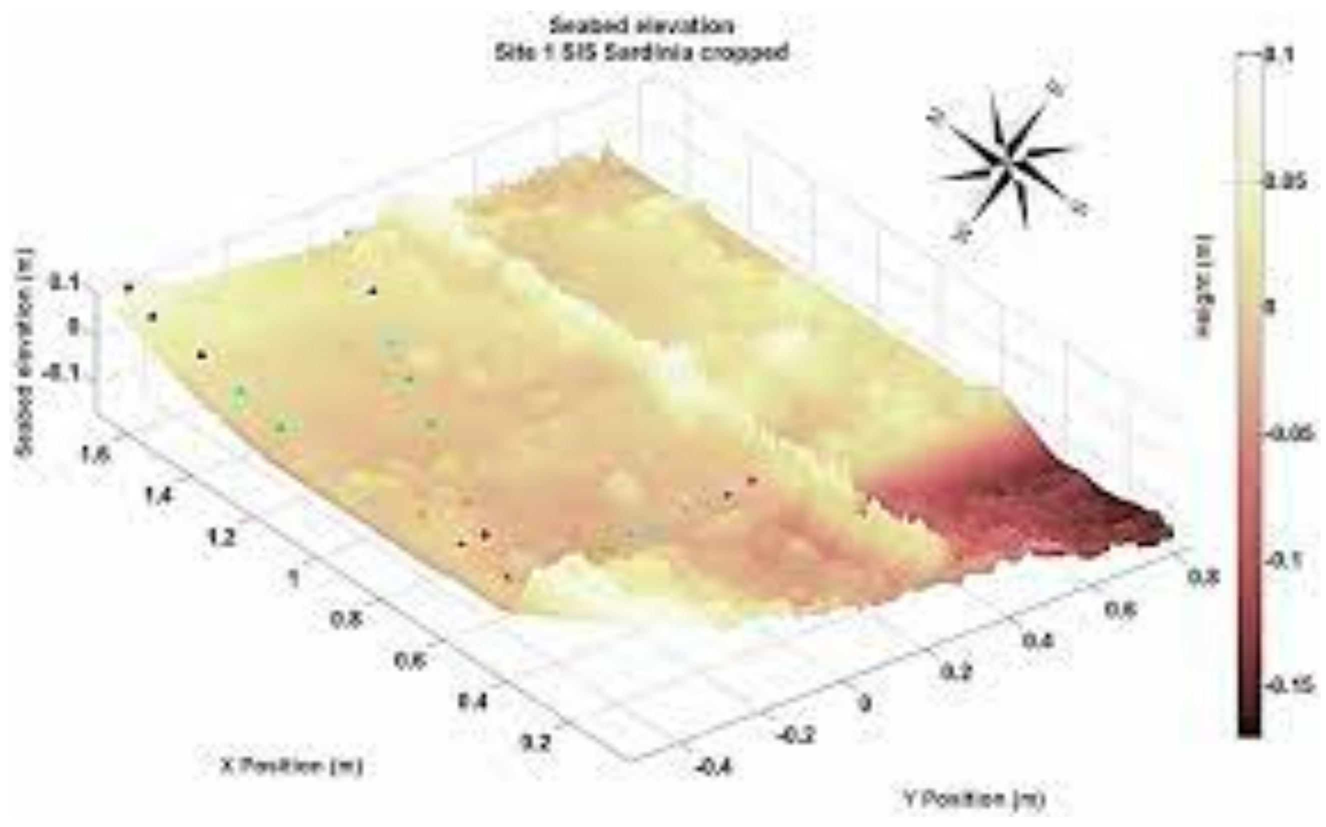
Sediment properties and behaviors

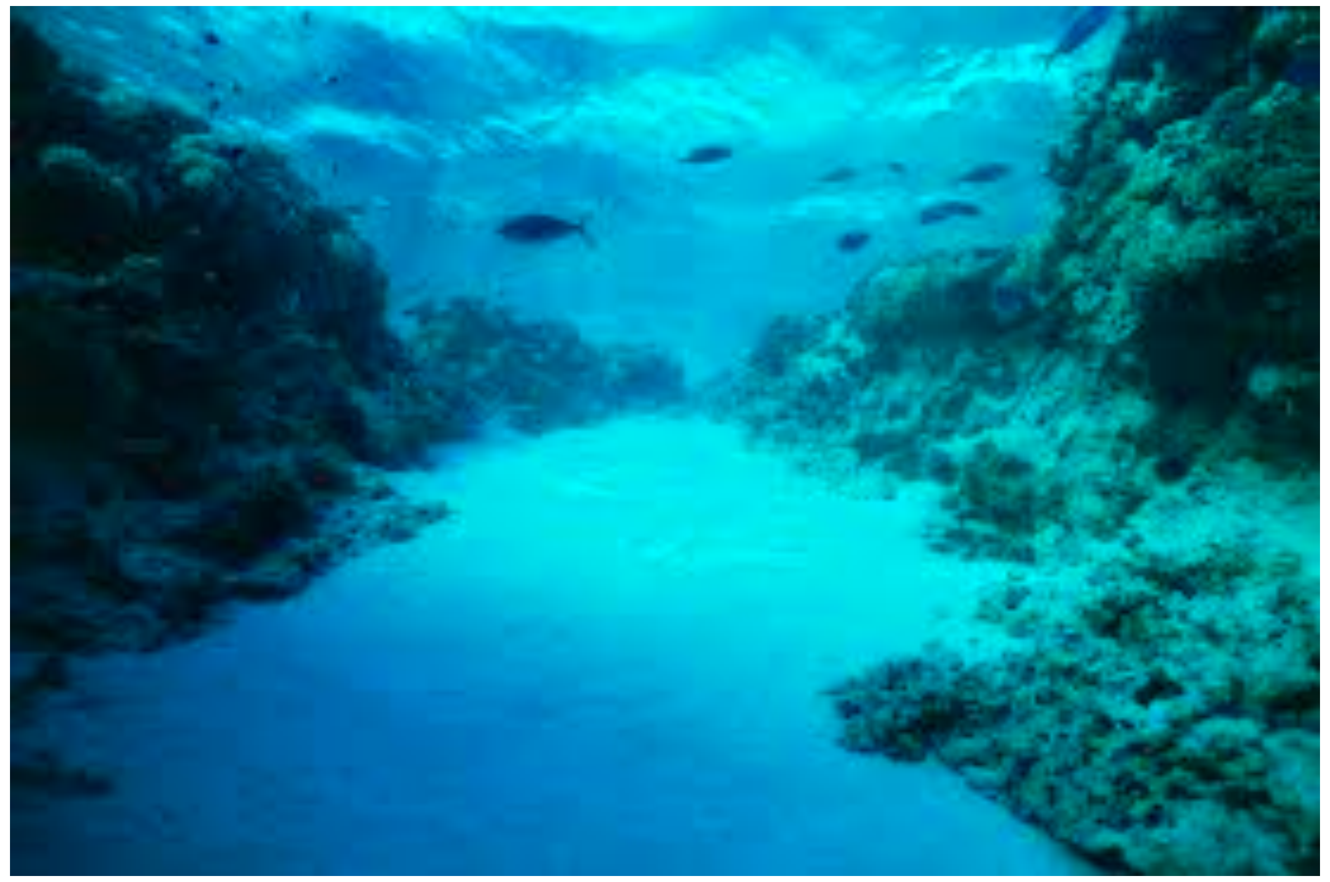
Modes of sediment transport

- In general
- Tidal estuary mud transport
- Wave driven transport near shore

Modelling strategies

Forcing drivers : roughness and bed shear stress, currents and waves





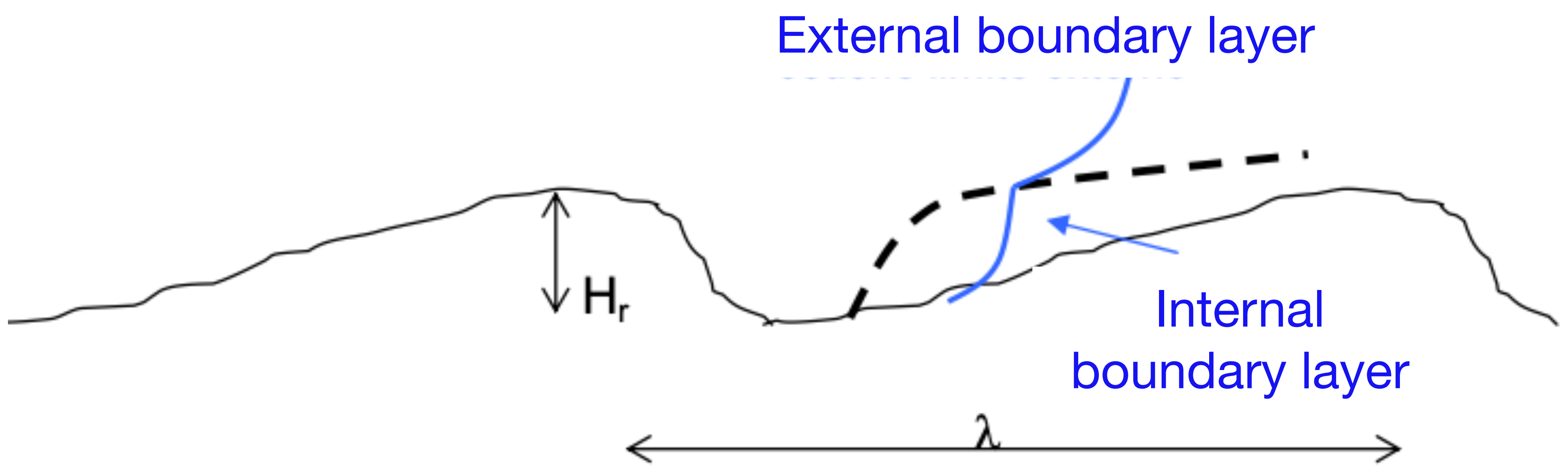
Forcing

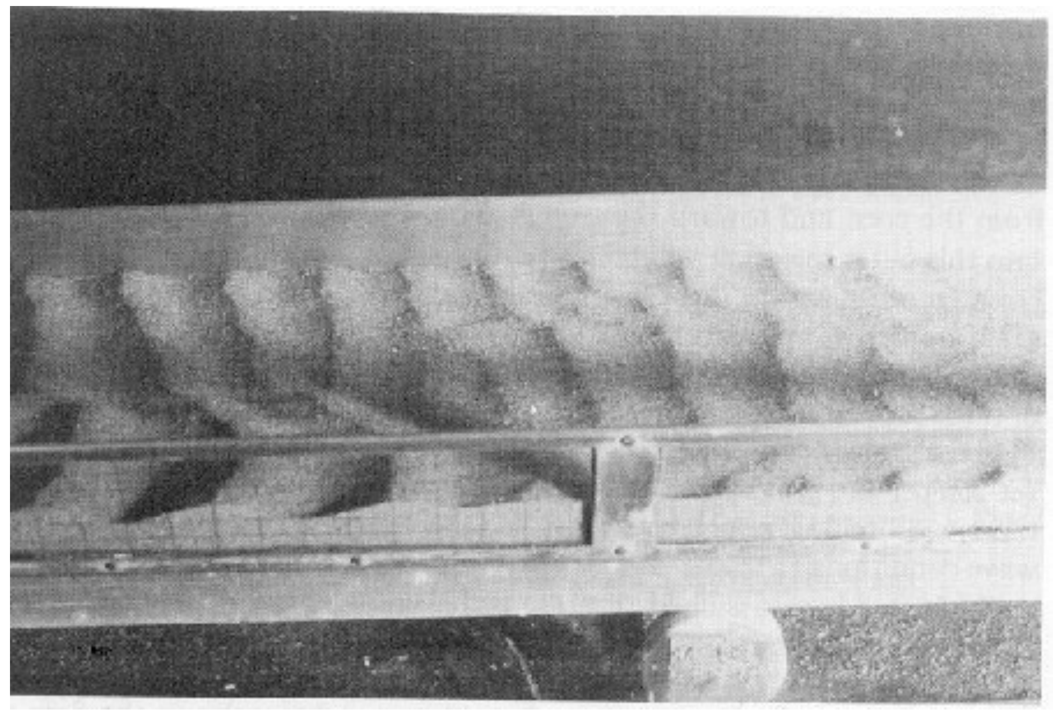
Roughness length - distinguish grain or form related

=> Depends on sea bed nature : smooth, rough, rippled

- Grain related : Nikuradse formula z0=ks/30 with ks=2.5D

- Form related :
- ripple prediction formulation from current/wave shear stress
- roughness with ripple bed (Grant and Madsen 1982, Wiberg and Rubin 1988, Van Rijn 1989)





Forcing

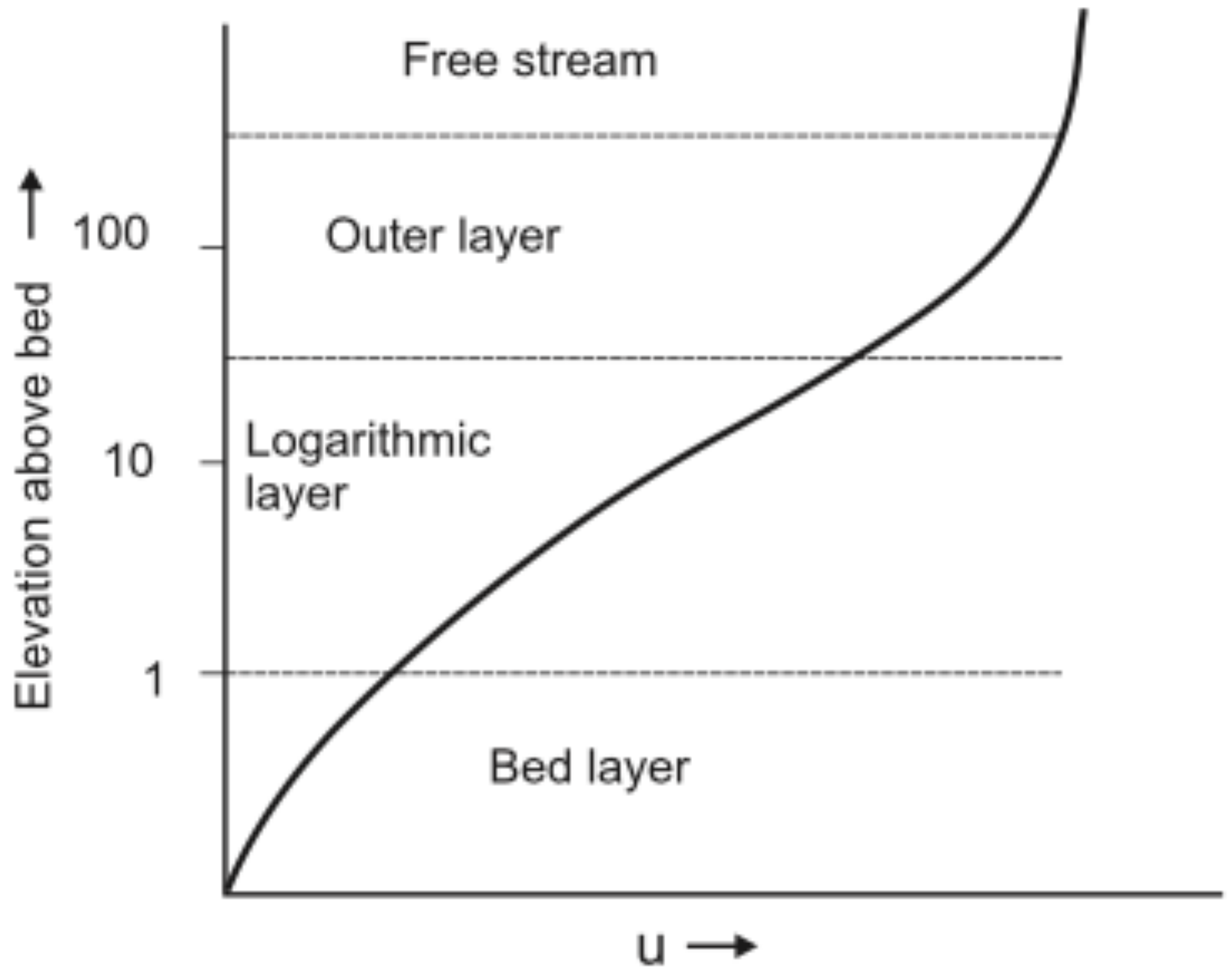
Current and wave shear stress

- account for current stress at the bottom
- account for wave shear stress
-

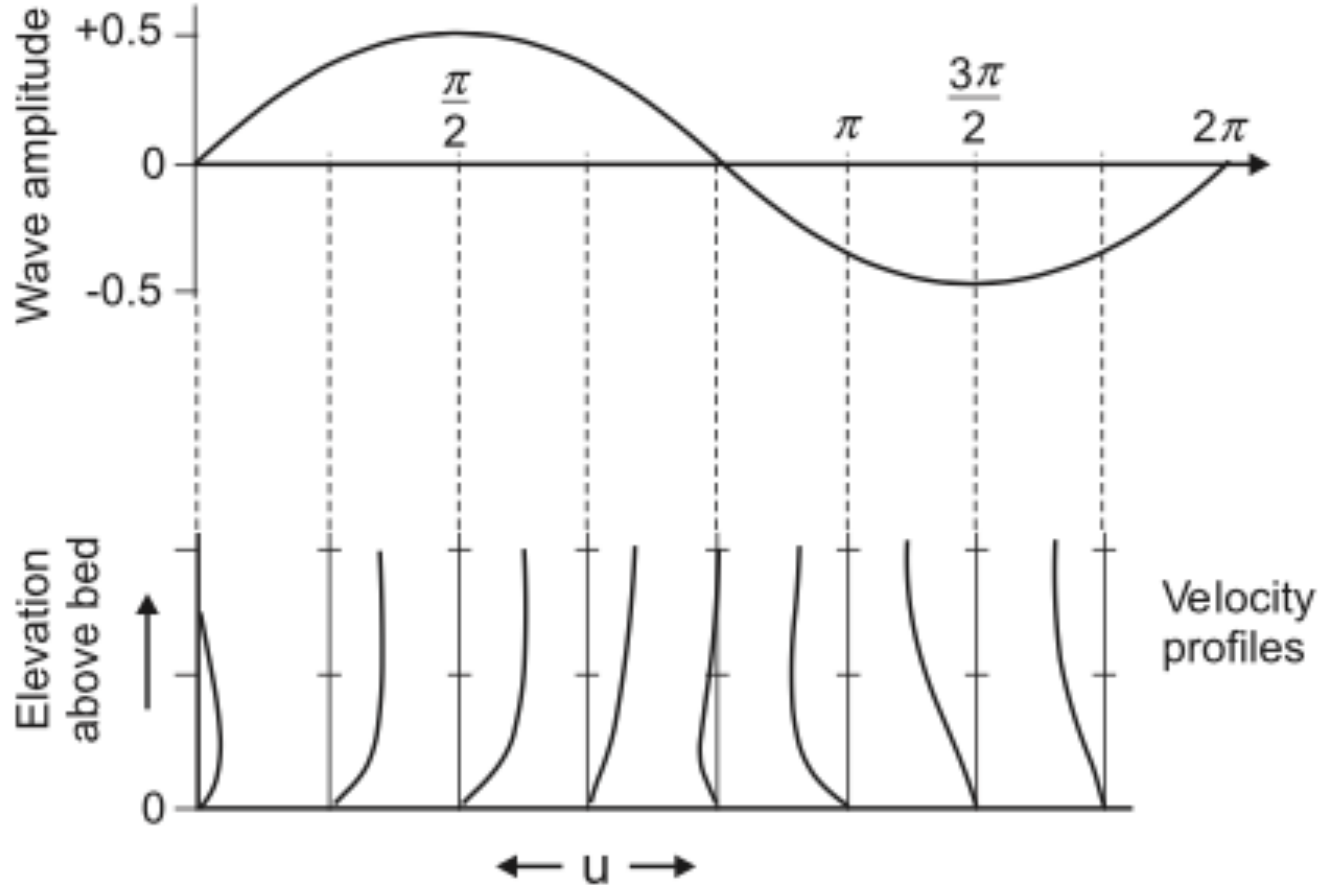
$$\bar{\tau}_{wc} = \tau_c \left(1 + 1.2 \left(\frac{\tau_w}{\tau_w + \tau_c}\right)^{3.2}\right)$$

$$\tau_c = \frac{\kappa^2}{\ln^2(z/z_0)} |u|^2$$

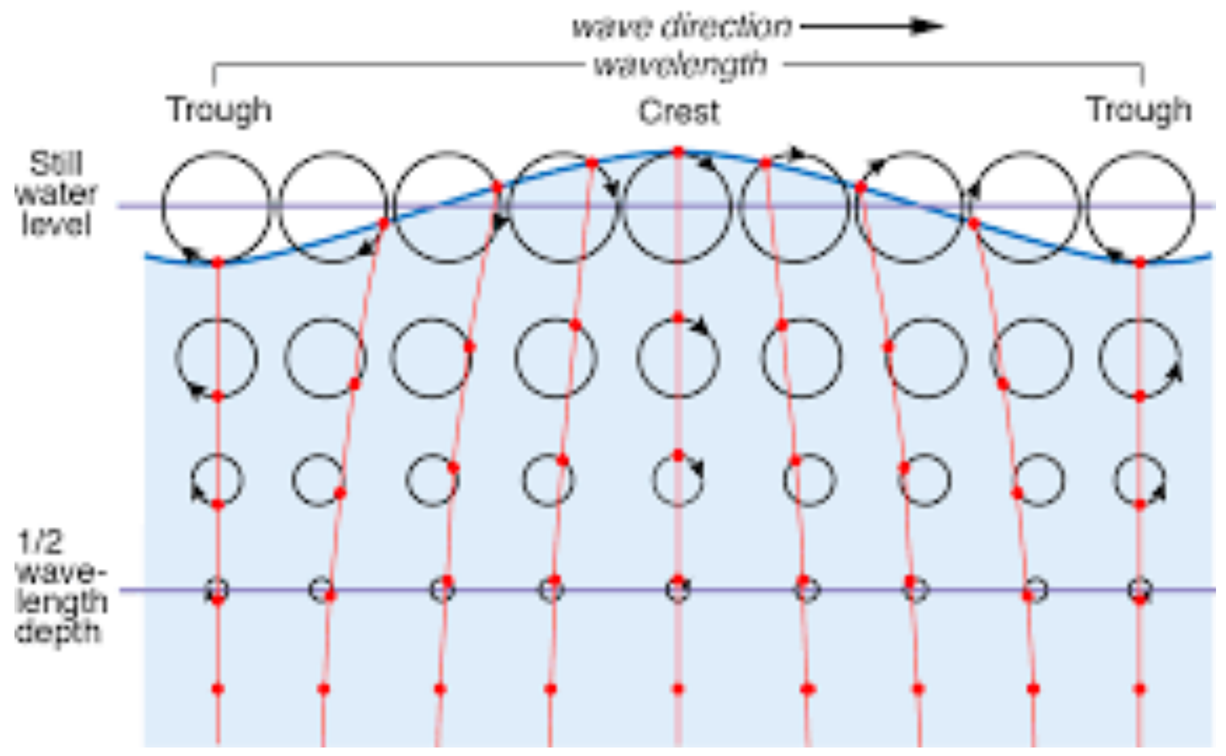
$$\tau_w = 0.5 \rho f_w u_b^2$$



Unidirectionnel current
(tide, rip, wind)



Single wave



Forcing
Summary

Use skin friction with roughness length depending on bed composition

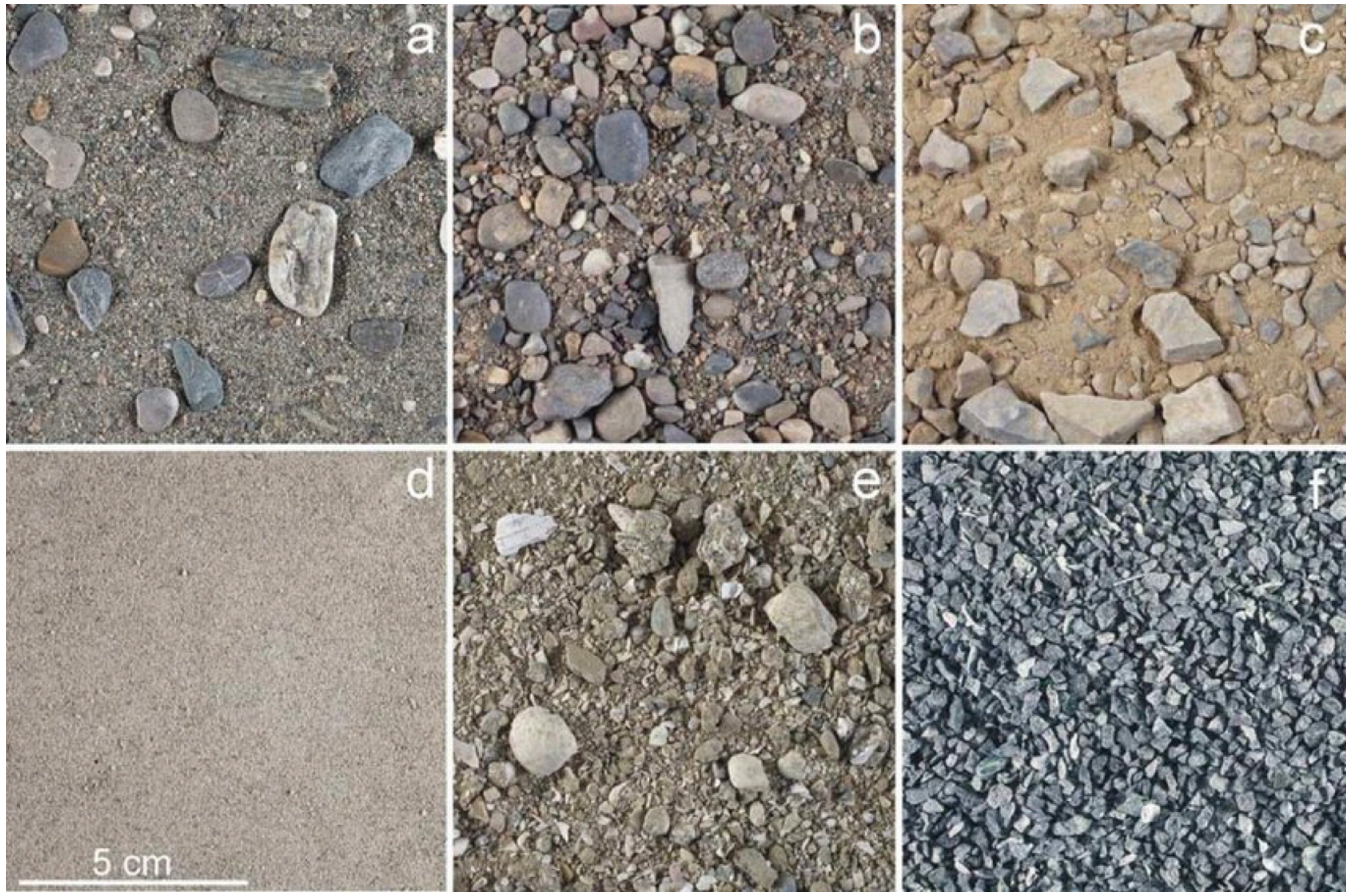
Z0sed $\neq$ Z0hydro

Interaction between current and wave : combination of shear stresses

Needs to know hydrodynamic variables :

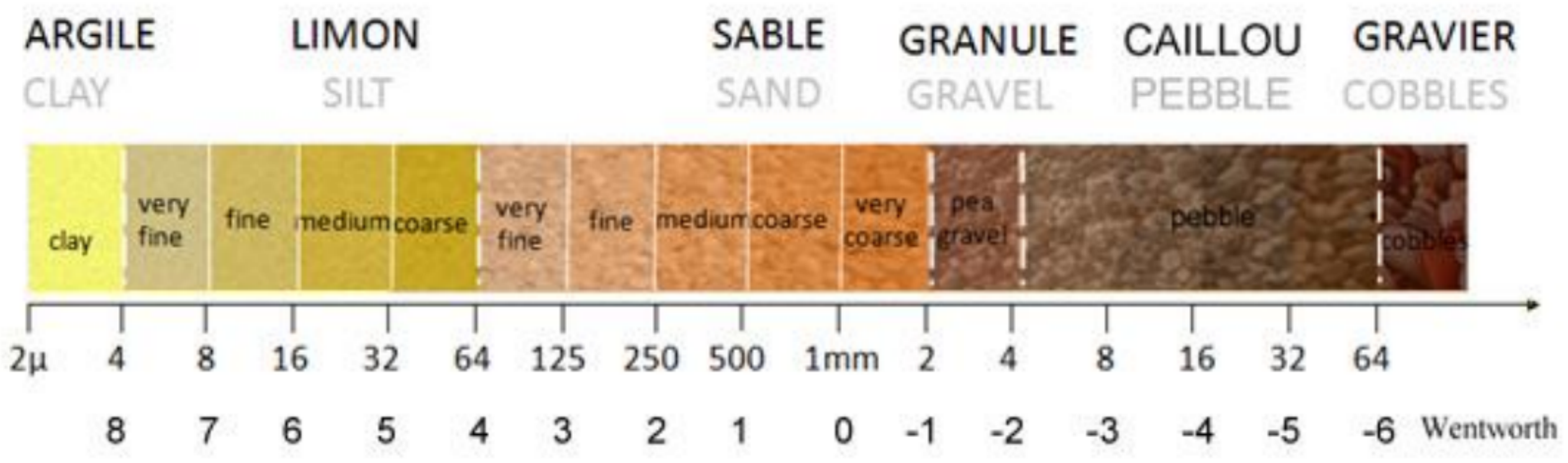
depth, current, wave period, wave orbital velocity,
water density, bed roughness length

Sediment properties and behaviors



Sediment properties

Grain size



Sediment can be characterized by grain size (d50, d90)

- **cohesive** : mud (clay, silt)
  - transport in suspension
  - flocculation, variable settling velocities
  - bed consolidation

- **non cohesive** : sand to cobble
  - transport in suspension and/or bedload

Sedment properties

Settling velocity

Cohesive

Stokes if isolated grains

Links between grains leads to variable settling velocities (flocculation, hindered effect)

→ Several formulations (Migniot, Thorn & Parsons, Van Leussen) or modeling approaches (Winterwerp, Wolanski)

Non cohesive

No link between grains
Hindered effect with high concentration

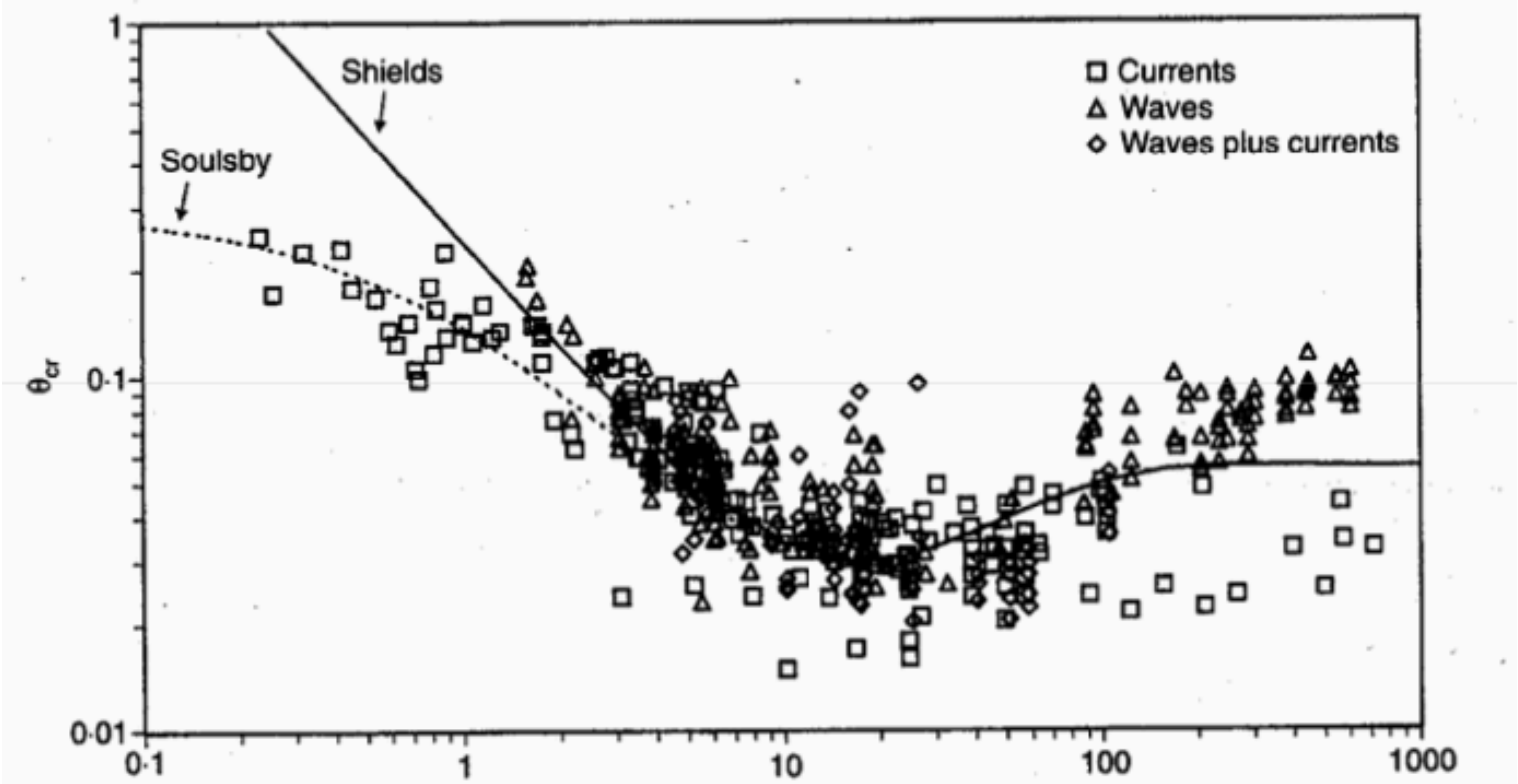
Wide range of values
~1 cm/s for ~100 μm grain size
~10 cm/s for ~800 μm grain size

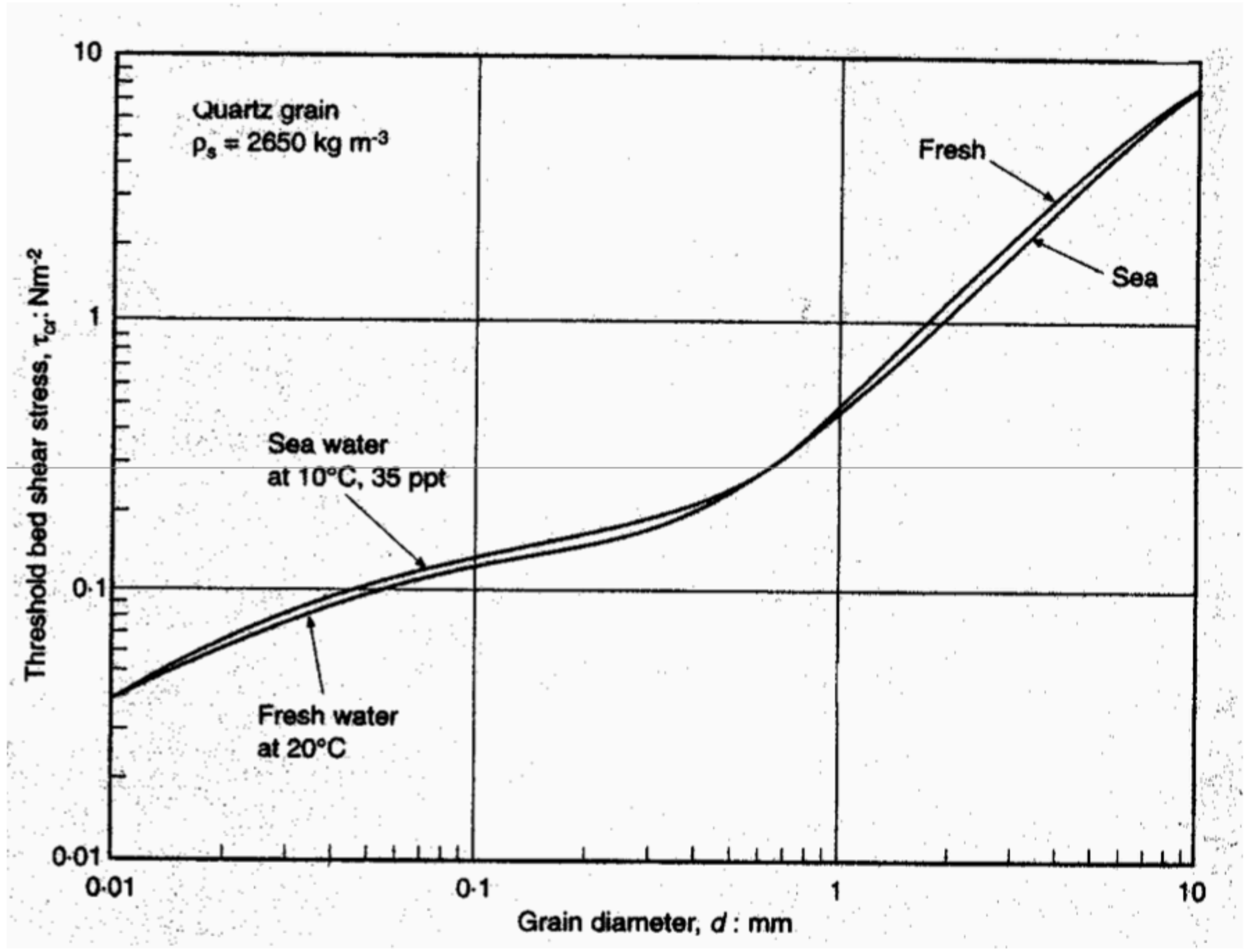
Soulsby (1997)

$$W_s = \frac{\nu}{D}\left[(10.36^2 + 1.049 D_*^3)^{0,5} - 10.36\right] \qquad \text{avec } D_* = D\left[\frac{g(s-1)}{\nu^2}\right]^{1/3}$$

Sedimentproperties

Motion threshold - non cohesive case





Soulsby (1997)

$$\theta_{cr} = \frac{0.3}{1+1.2D_*} + 0.055\left[1-\exp(-0.02\,D_*)\right]$$

Motion threshold - cohesive case

Depends on consolidation and cohesion of the sea bed

Sedimentation properties

Mixed sediment, multi class : sorting, bed armoring, mask-exposure

Modification of threshold of motion from sediment granulometry repartition in sea bed

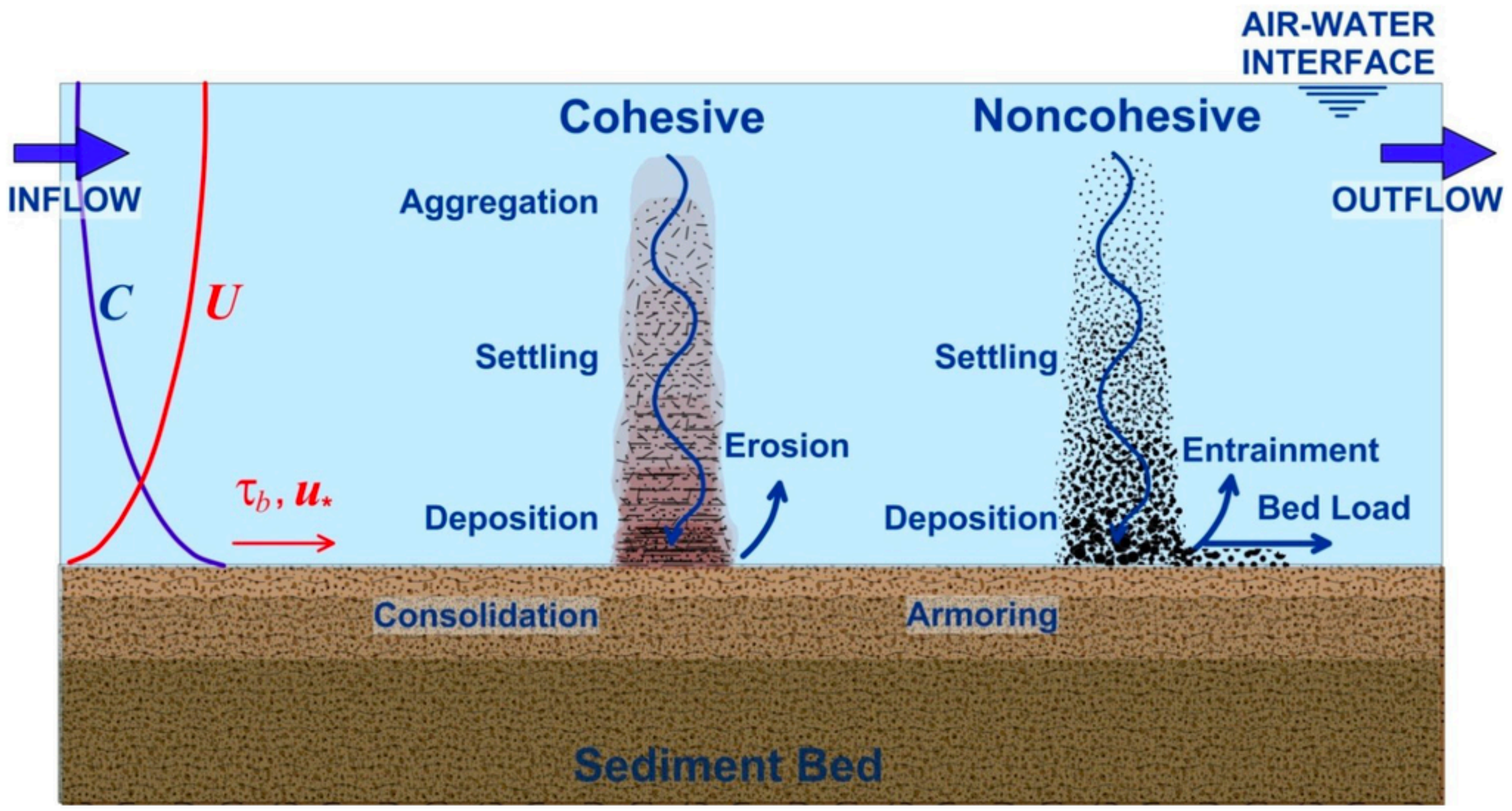
Modification of transport capacity (hindering coefficient)

Modification of erosion fluxes depending on fraction of cohesive sediment in bed (cohesive, intermediate or non-cohesive)

Modification of porosity (deposition of fine sediment in coarse bed)

Modes of sediment transport :

- In general
- Tidal estuary mud transport
- Wave driven transport near shore



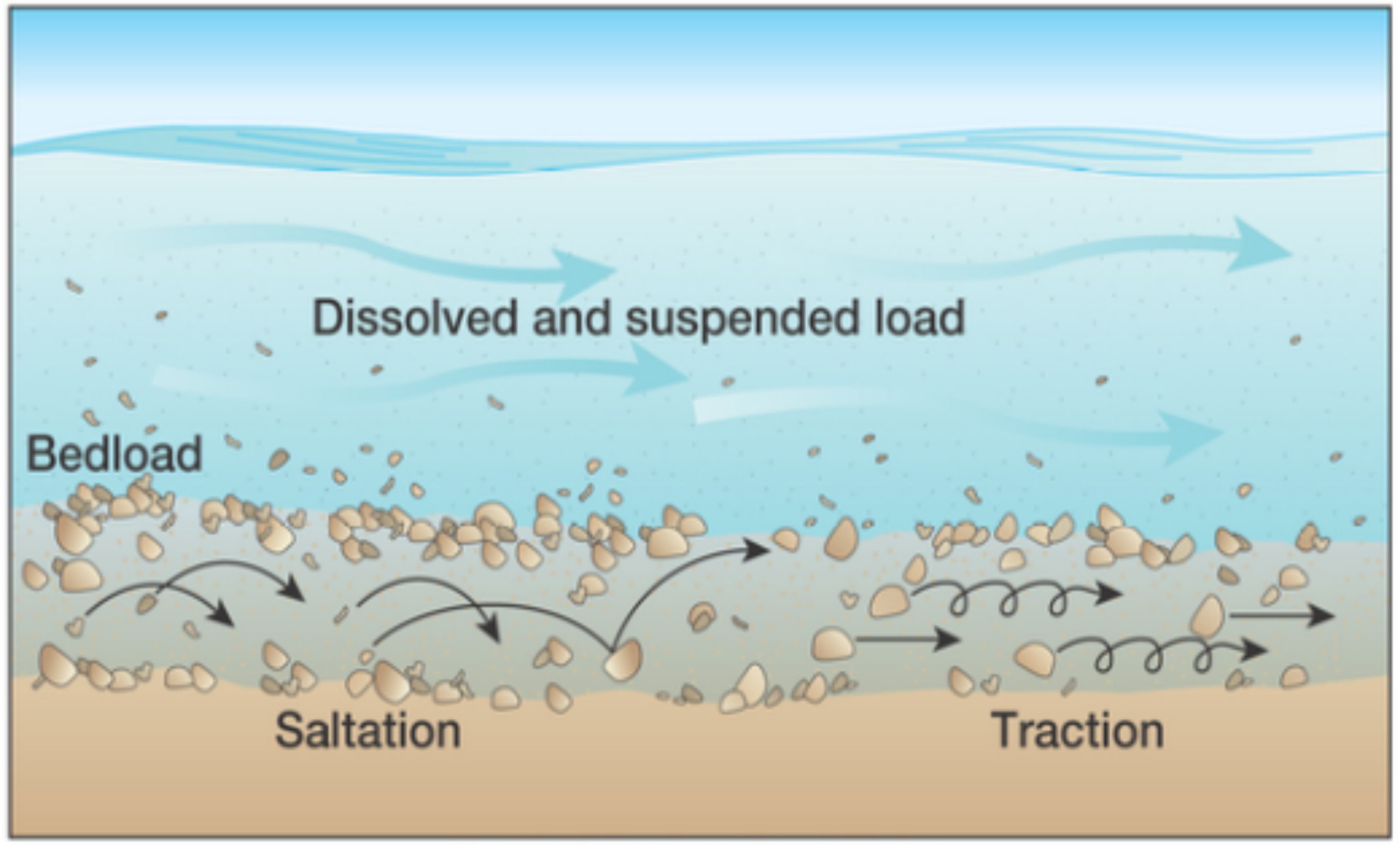
Modes of sediment transport

BEDLOAD

Transport in contact with the bed : rolling, saltation

SUSPENSION

Transport in water

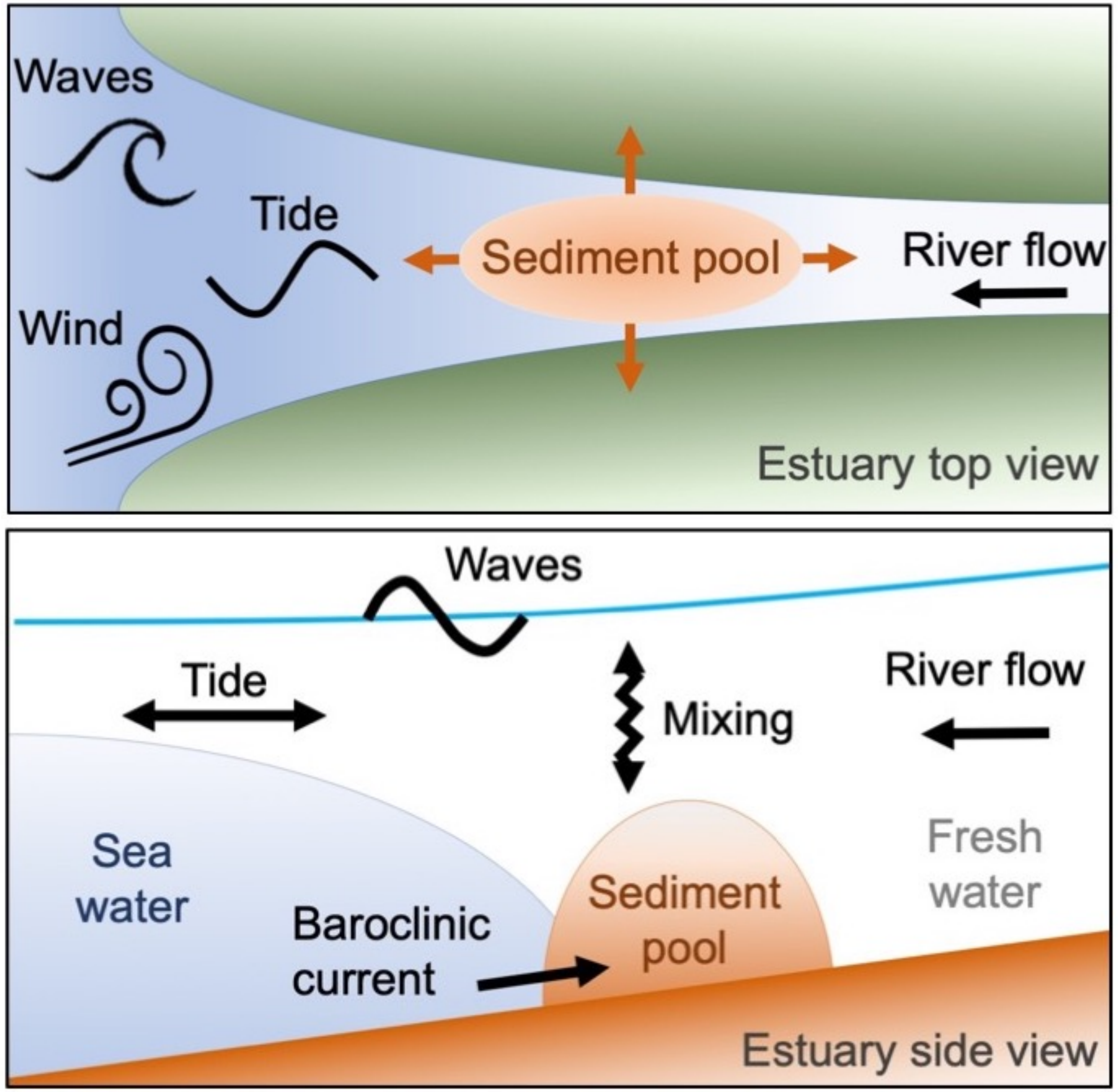


All simultaneously

Tidal estuary mud transport

- Forcings
  → Oceanic (tide)
  → Méteorological (wind, waves, surges)
  → Fluvial (liquid and solid flows)

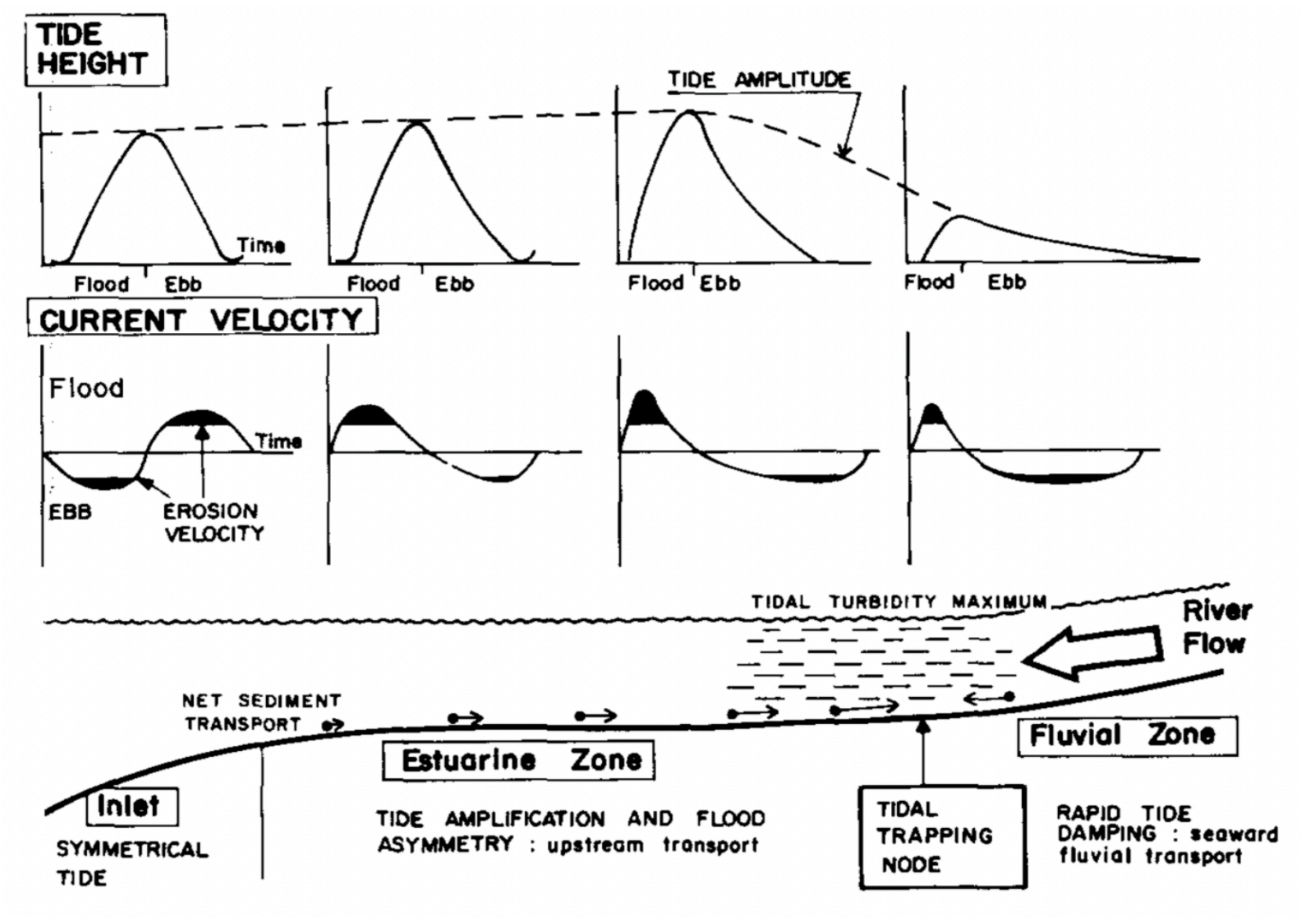
- Area of high turbidity
  → Suspension of sediments
  → Sediment convergence



From Burchard *et al.* [2018]

Tidal estuary mud transport

- River flow
  - → Downstream transport
- Tidal assymetry
  - → Tidal pumping
  - → Upstream transport
- Baroclinic circulation
  - → Difference in density : fresh water /salt water
  - → Upstream transport



Allen *et al.* [1980]

Wave driven transport near shore

We distinguish :

- processes that lead to net transport of sediment onshore or offshore (cross-shore transport)
- processes tending to move sediment alongshore (longshore sediment transport)

=> Both occurs simultaneously

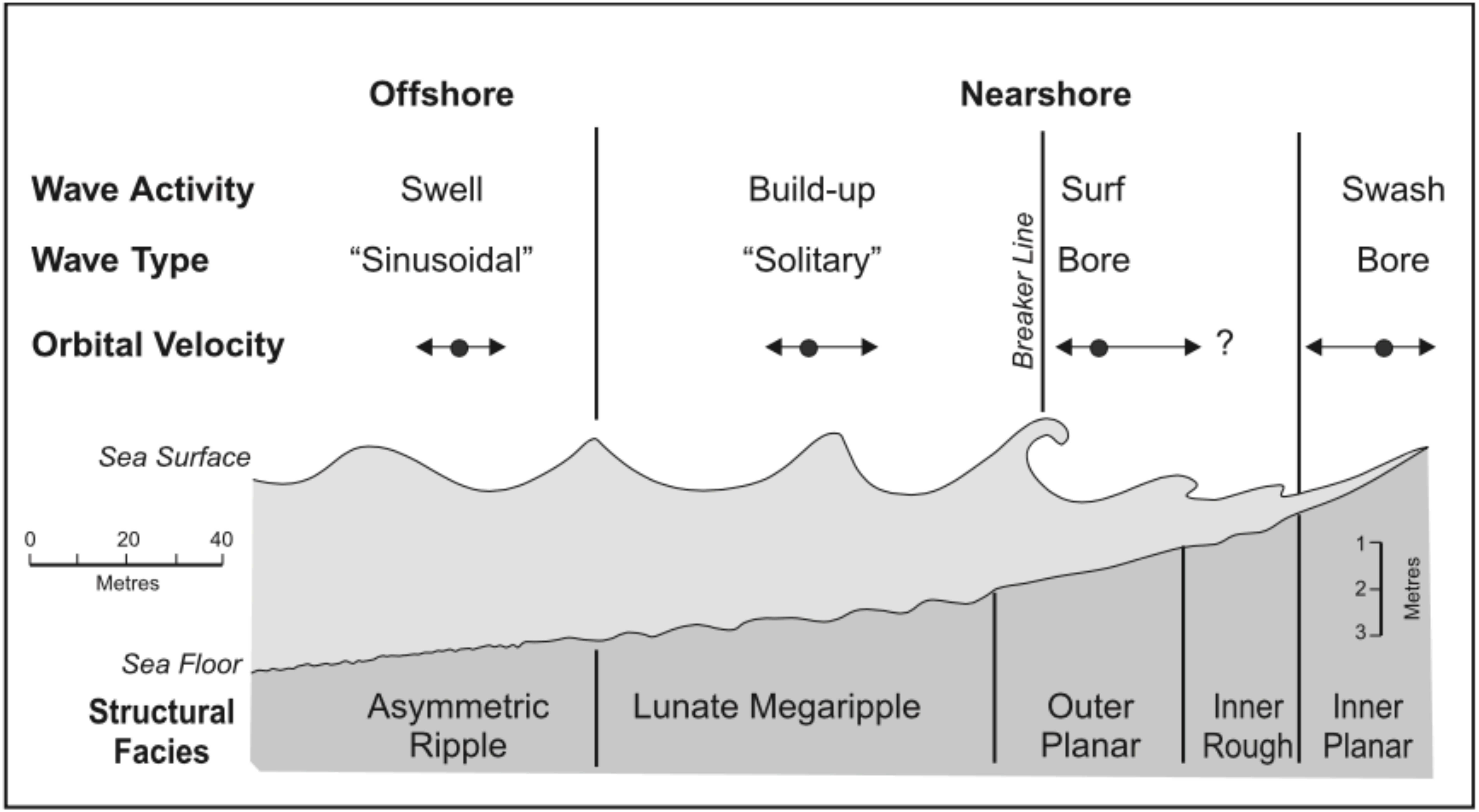
Set of motion :

- generally no erosion and transport by unidirectional currents (except RIP, strong longshore drift)
- Instead :
    - motion by oscillatory currents due to waves and wave-breaking turbulence
    - transport by mean flow : undertow, stokes drift, wind-drift

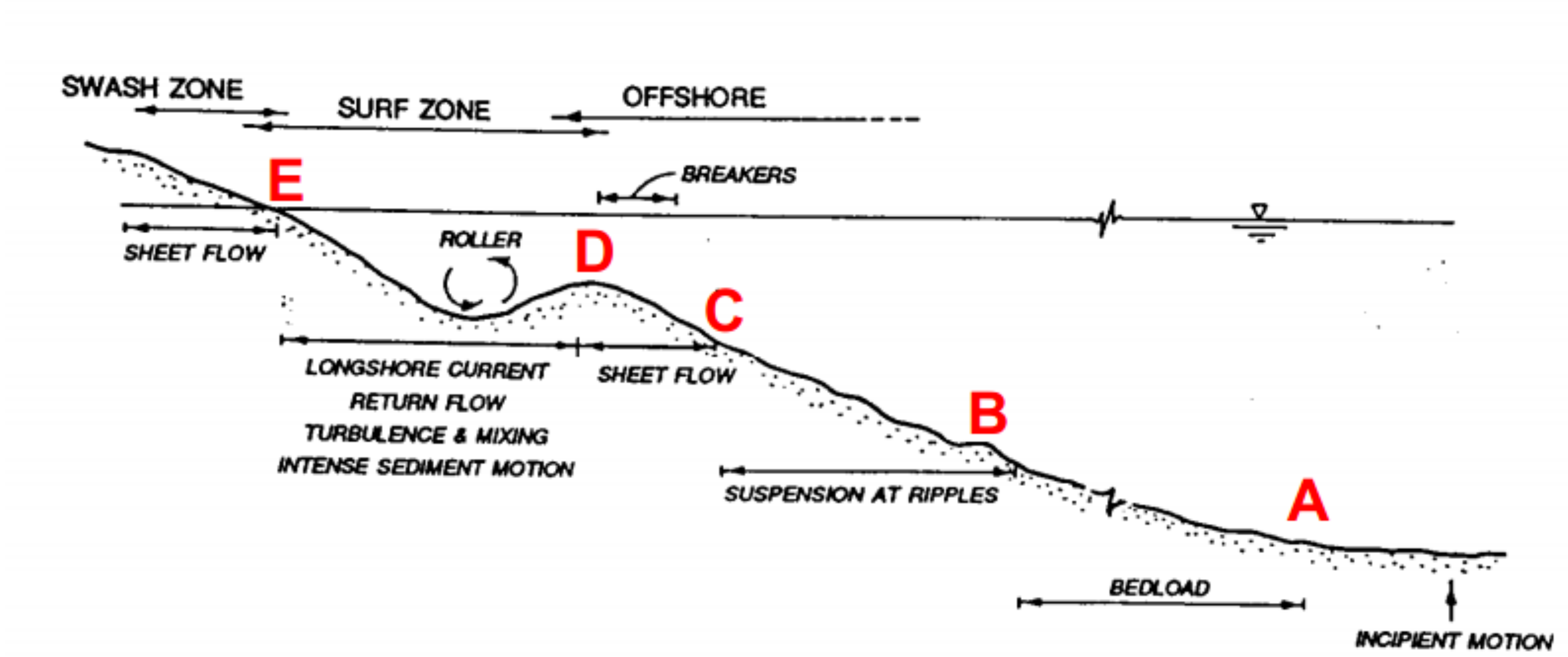
Direction of net transport of sediment : the balance of all

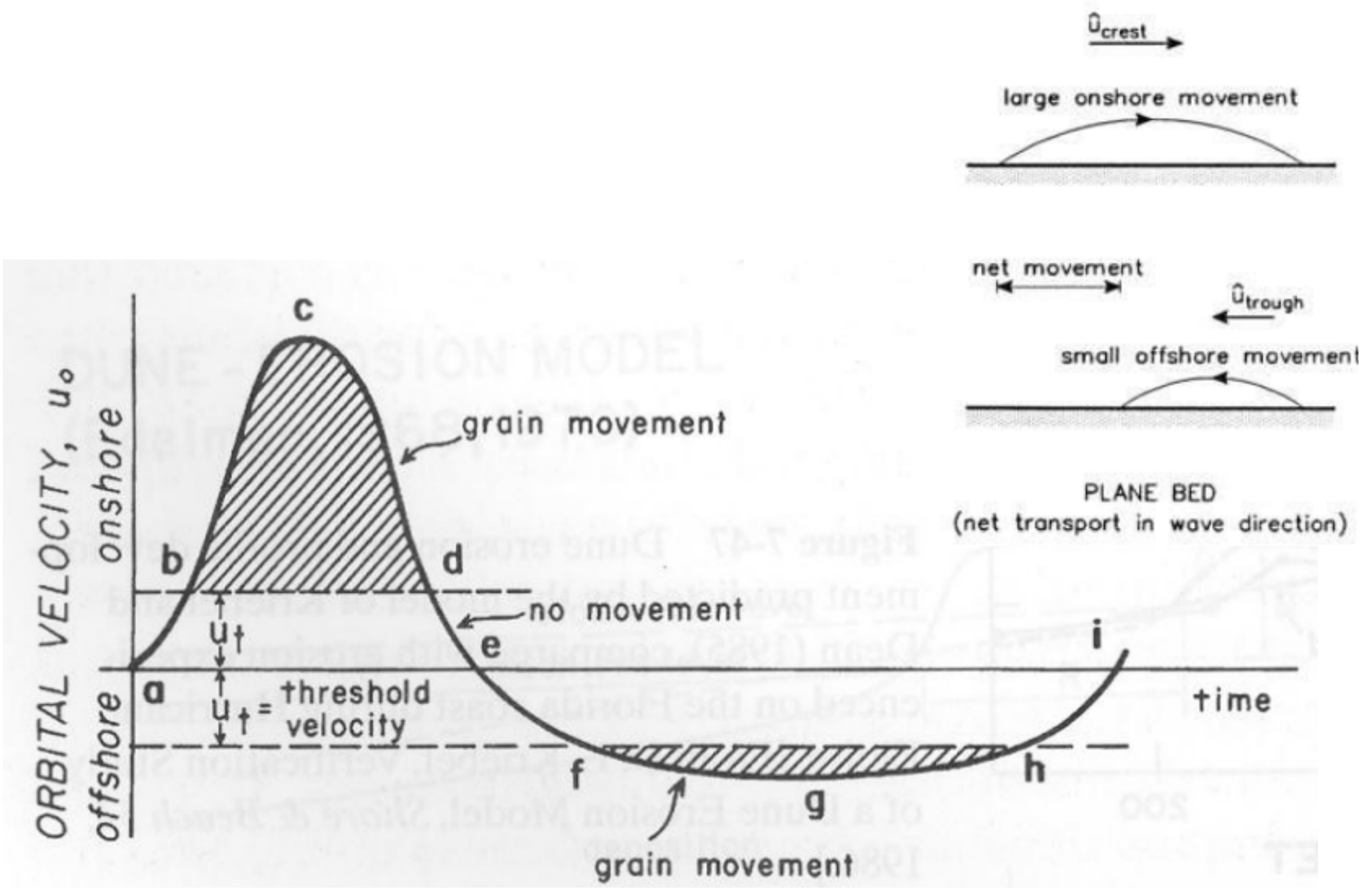
- incident and wave-generated on/offshore and alongshore flows
- wind-driven currents
- tidal flows

Waves at nearshore

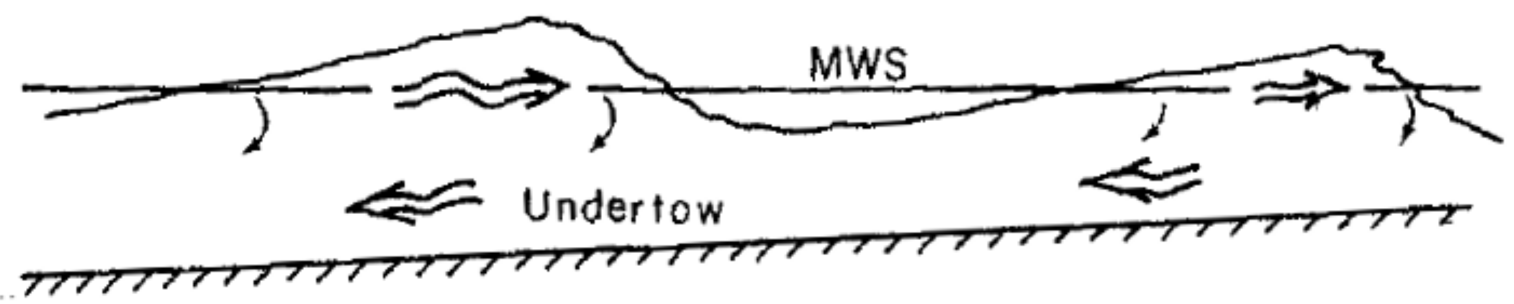


Cross-shore transport

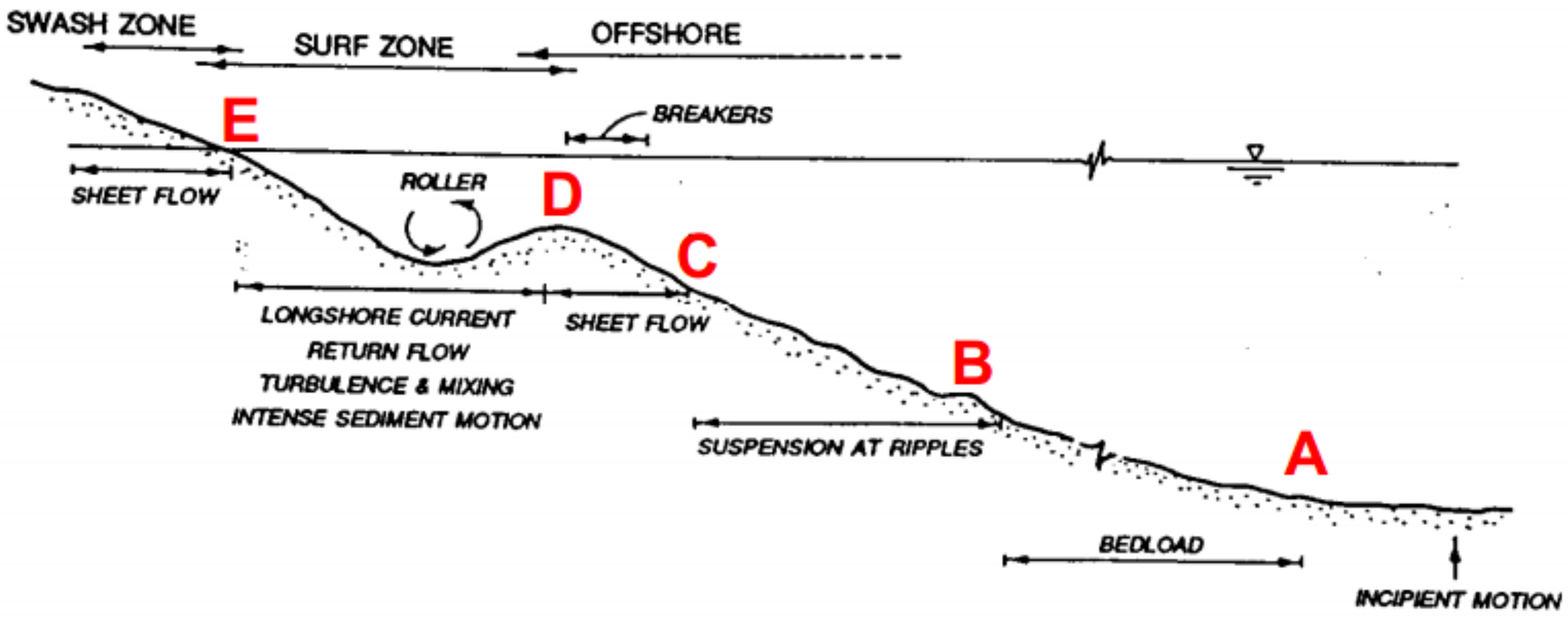




A : no transport (symmetric waves, inactive bed)
B : little transport (skew waves and ripples)
C : onshore transport in shoaling zone (skewed waves)
D : on/offshore transport in break-in zone (asym waves / undertow)
E : on/offshore transport in swash zone (infra gravity waves)
=> transport rate increase



Cross-shore transport



Toward long term :

- Locations A-D shift as a function of offshore wave conditions
- A specific cross-shore location experiences many different conditions during a year

- Which are dominant :
  - Frequent low energy conditions ?
  - Occasional storm ?

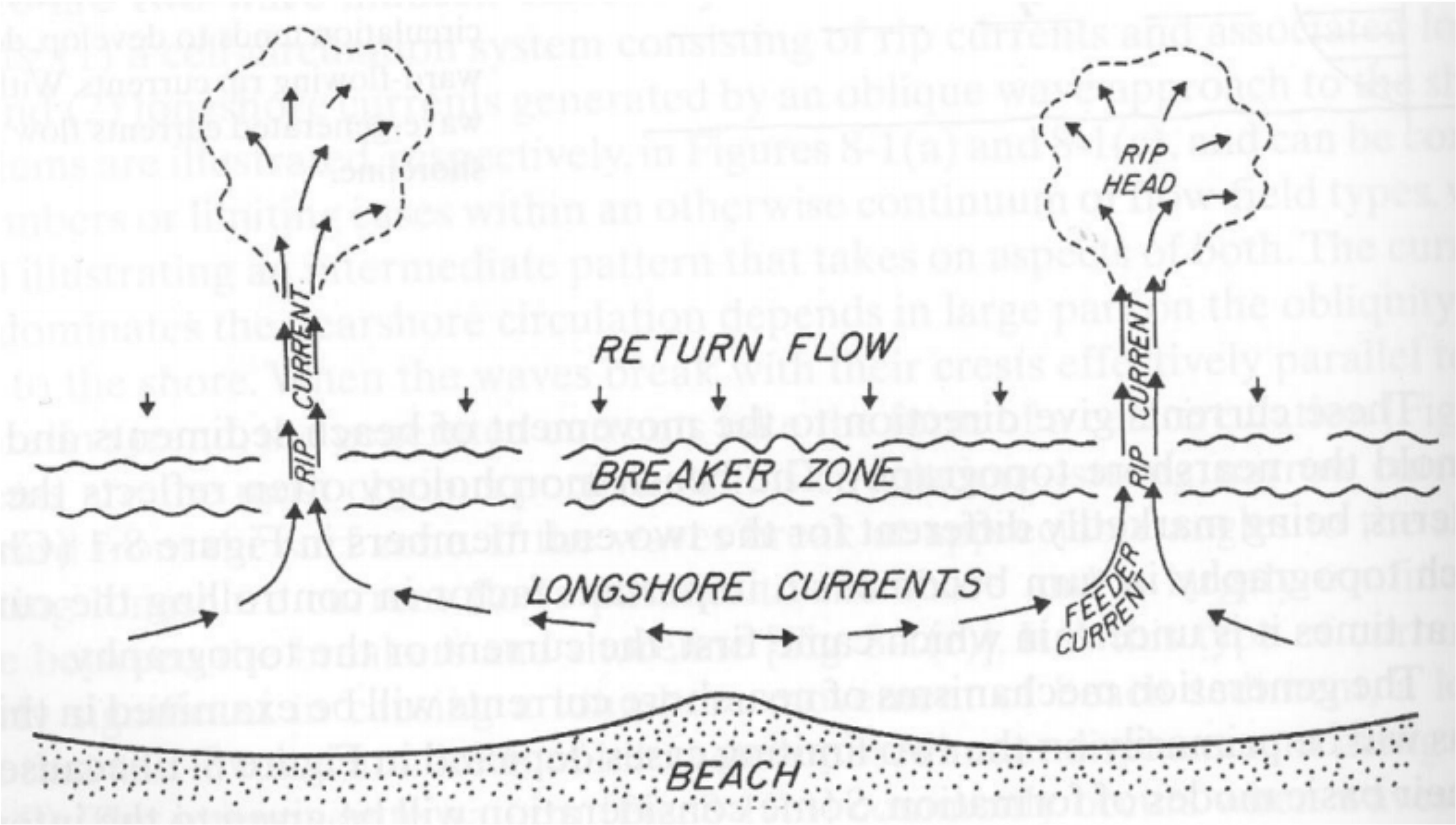
Cross-shore transport

Particular case of rip currents :

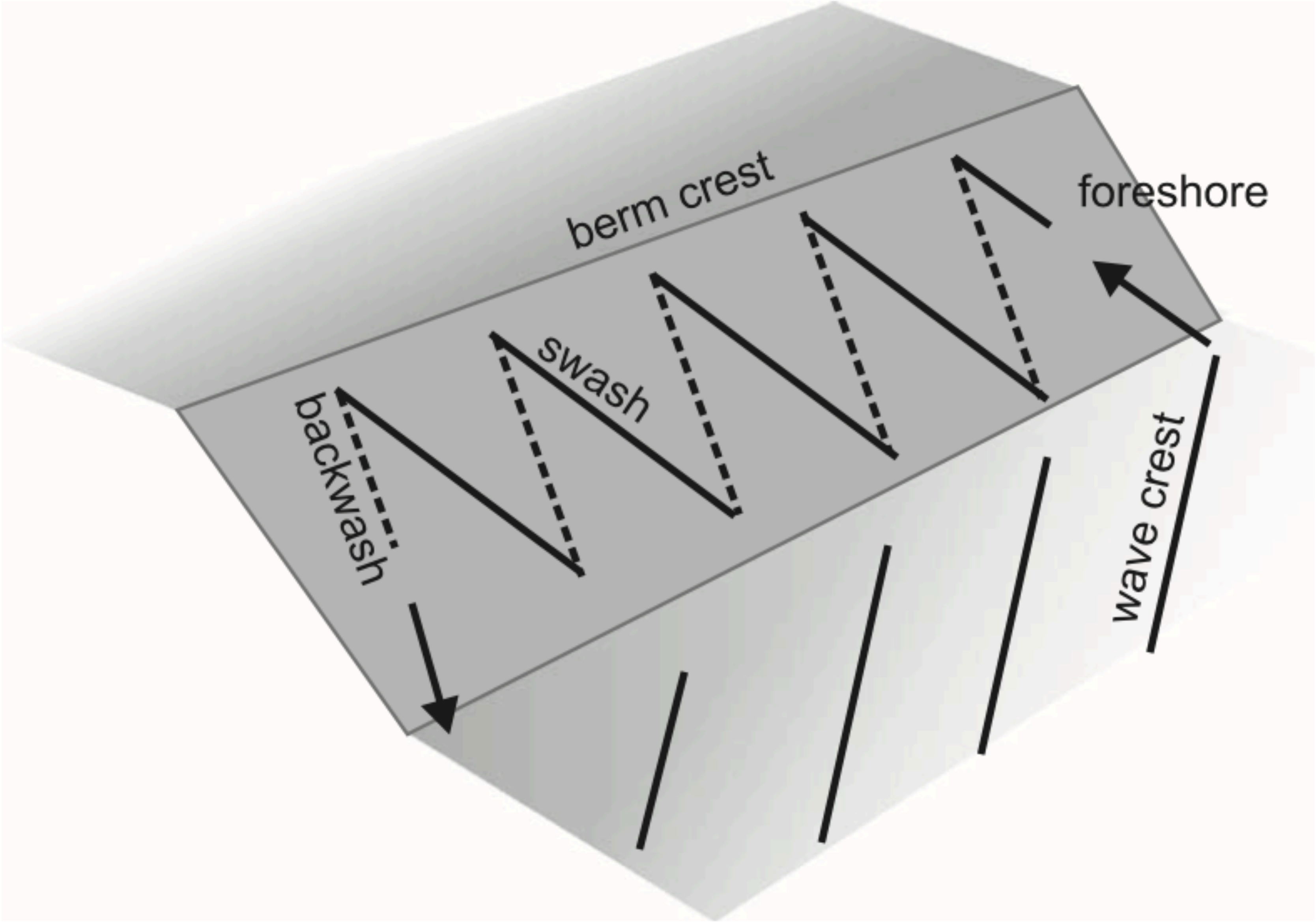
- Sediment stirred by gravity waves, transported by currents

- Minor role (onshore) in between the rip currents

- Other mechanisms minor (no undertow!)



Alongshore transport



Gravity waves stir sediment
Breaking induced alongshore current transport sediment
=> Littoral drift

Drivers of sediment transport in the beach and nearshore zone :

- beach drifting on the swash slope driven primarily by oblique wave action (saw-tooth alongshore motion)
- transport by wave-generated longshore currents in the surf zone
- transport seaward of the breaker zone by residual tidal currents and wind-driven currents.

Alongshore transport

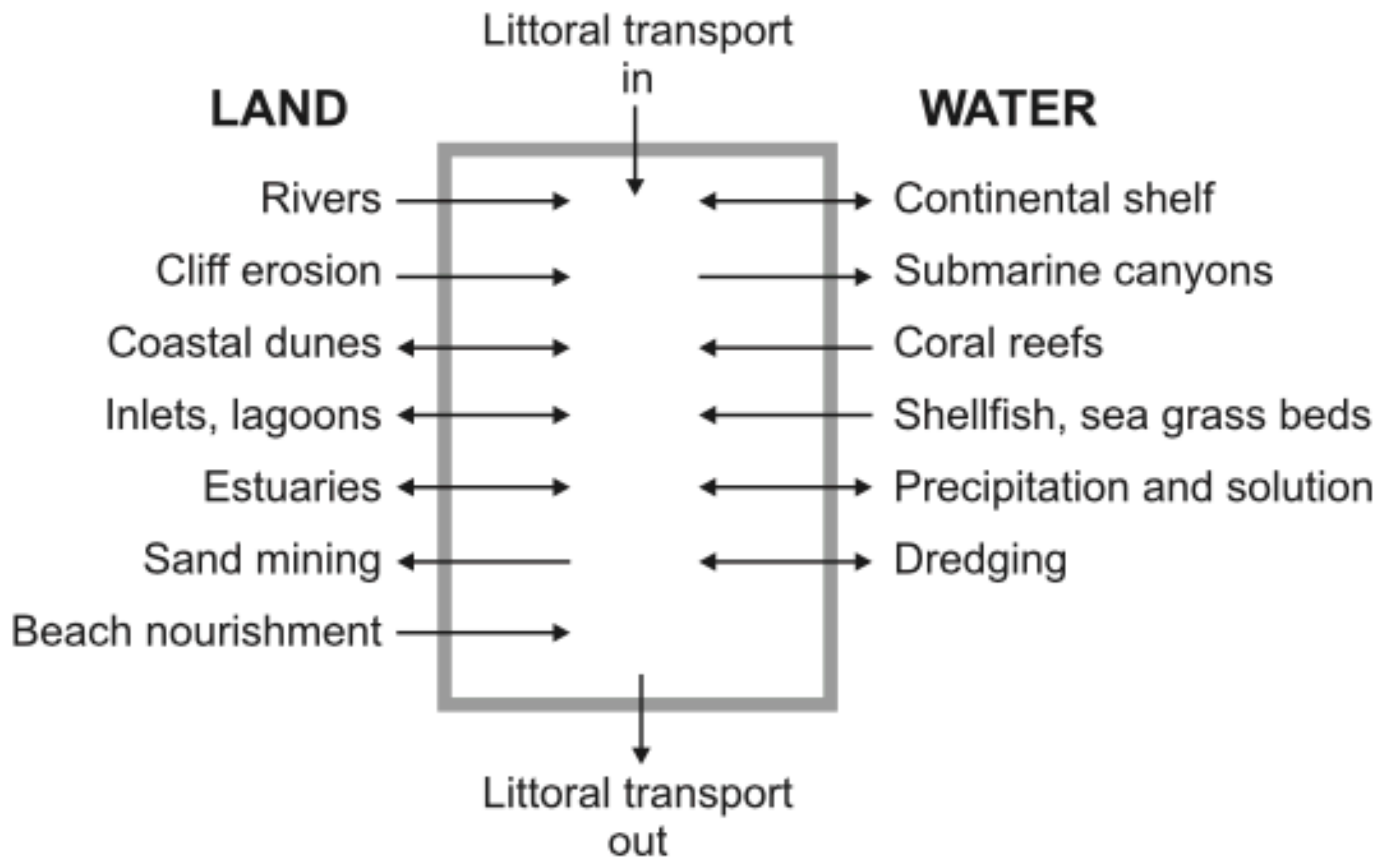
Prediction

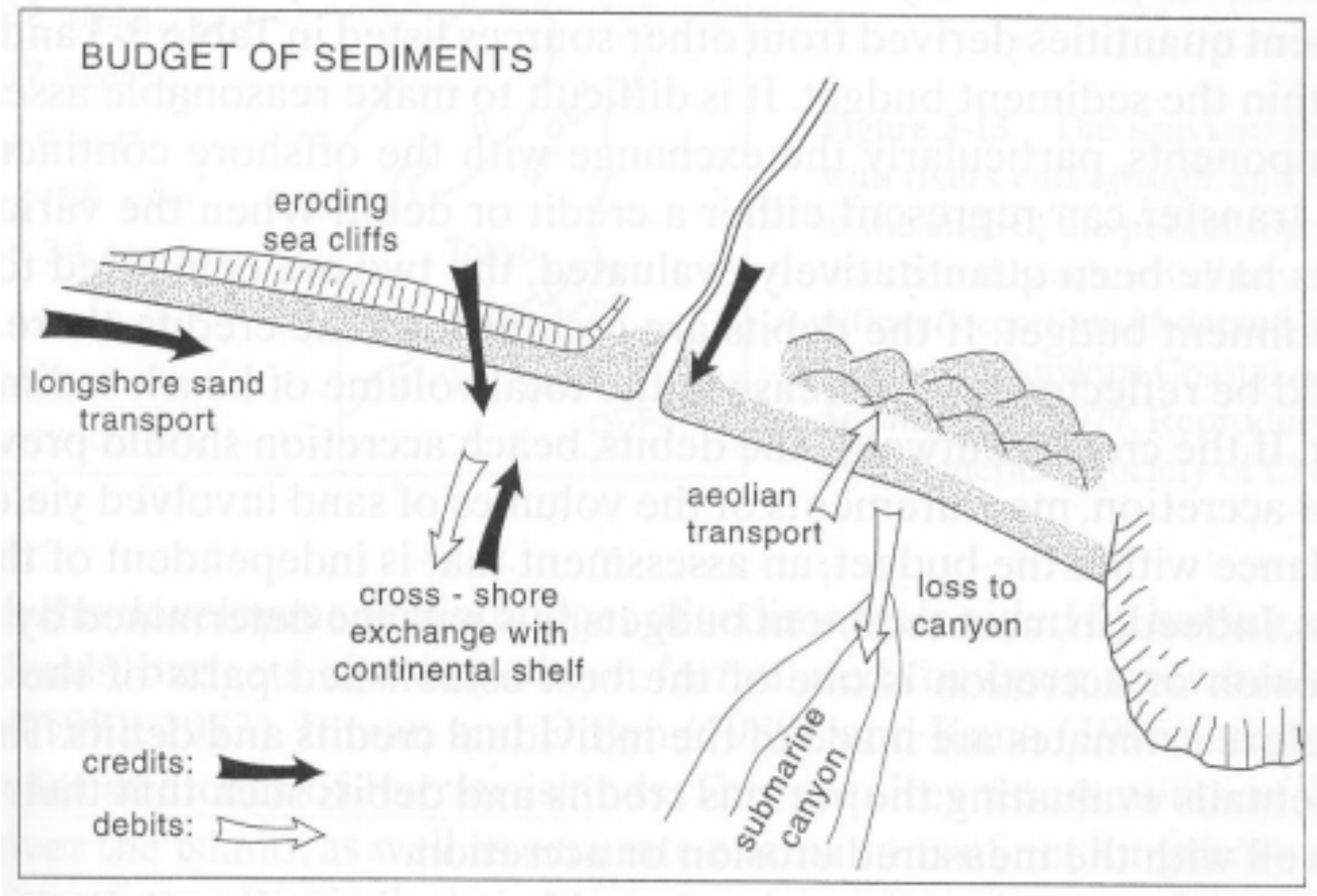
Longshore transport empirical formulae (ex CERC formula, Shore Protection Manual, 1984) :

Correlated with longshore wave energy flux : $q \sim \rho g^{1.5} H_b^{2.5} \sin\theta_b \cos\theta_b$

- Shore normally incident (theta=0° transport is 0)
- Transport increases when wave height increases
- Transport is maximum for theta = 45°

Sediment balance





- bed levels changes are a result of **gradients** in the sediment transport rates
- mass balance equation (Exner equation)

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = \frac{\partial z}{\partial t}$$

Modeling strategies

Suspended Sediment

- Sediment-diffusion balance (equilibrium):

$$u_s C(1-C) + \varepsilon_s \frac{\partial C}{\partial y} = 0$$

downward settling + upward diffusion

$$q_s = \int_a^h uC\,dy$$

Total suspended load

- Rouse equation:

$$\frac{C}{C_a} = \left[\frac{d-y}{y} \cdot \frac{a}{d-a}\right]^z$$

$$z = \frac{u_s}{\beta \kappa u_*}$$

Bedload Transport Equations

Wilcock & Crowe (2003)

$$W_i^* = \frac{(s-1) g q_{bi}}{F_i u_*^3}$$

Reference threshold condition

$$\frac{\tau_{ri}}{\tau_{rs50}} = \left(\frac{D_i}{D_{s50}}\right)^b$$

Hiding function

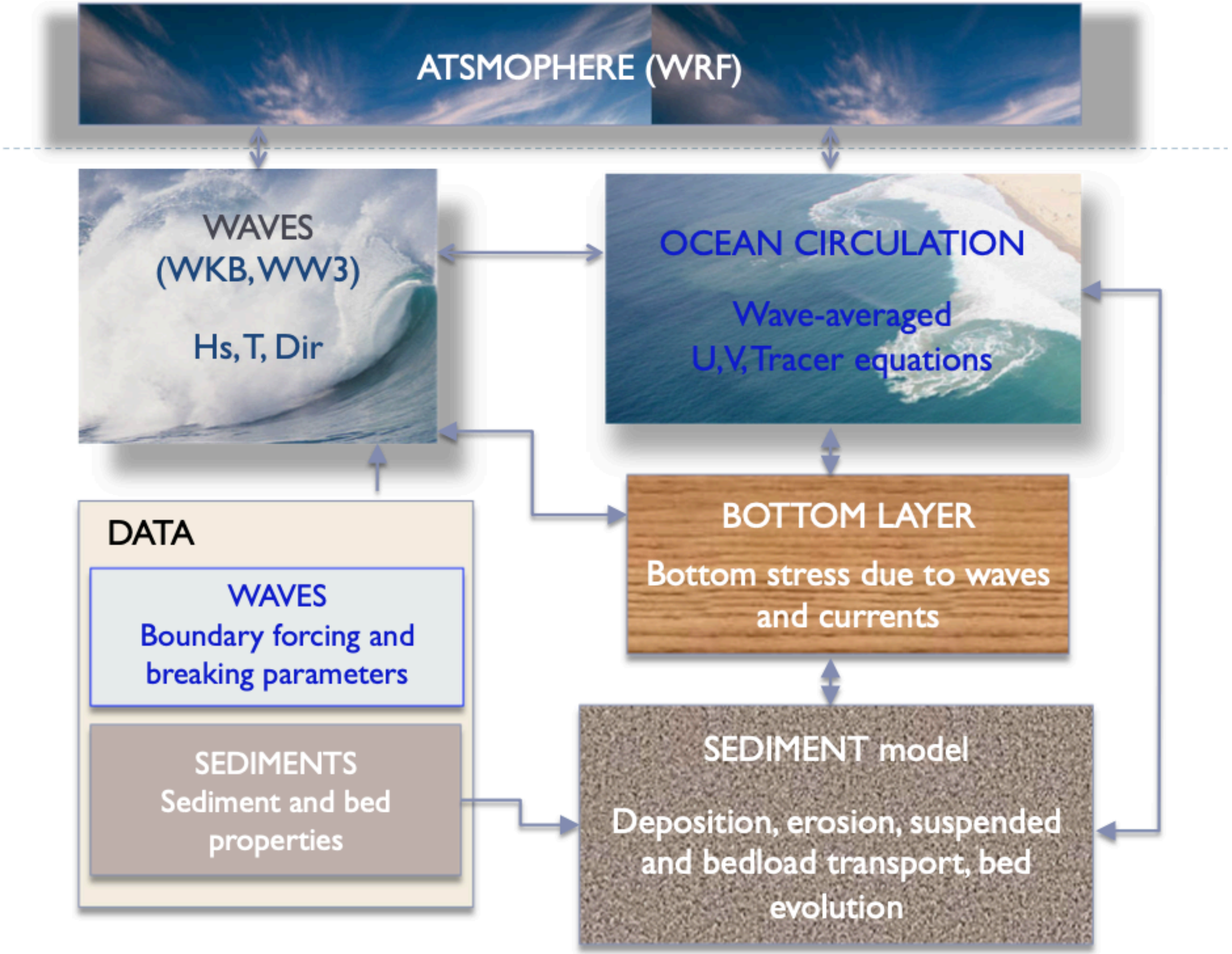
$$\tau_{rm}^* = 0.021 + 0.015 \exp[-20 F_s]$$

Reference dimensionless shear stress for median size base don fraction of sand

$$W_i^* = \begin{cases} 0.002\phi^{7.5} & \text{for } \phi < 1.35 \\ 14\left(1 - \frac{0.894}{\phi^{0.5}}\right)^{4.5} & \text{for } \phi \geq 1.35 \end{cases}$$

Transport rate based on τ/τ_r

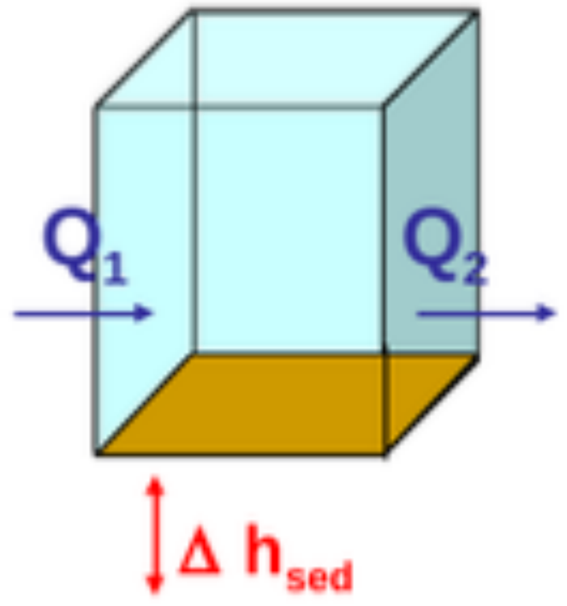
Modelling strategies



Modelling strategies

- **Transport at equilibrium**
  A lot of formulas available :
    Bedload, suspension load, total load
    Current only, current and wave
    Wave asymmetry

  + Slope effect



Transport at equilibrium :
« transport capacity»

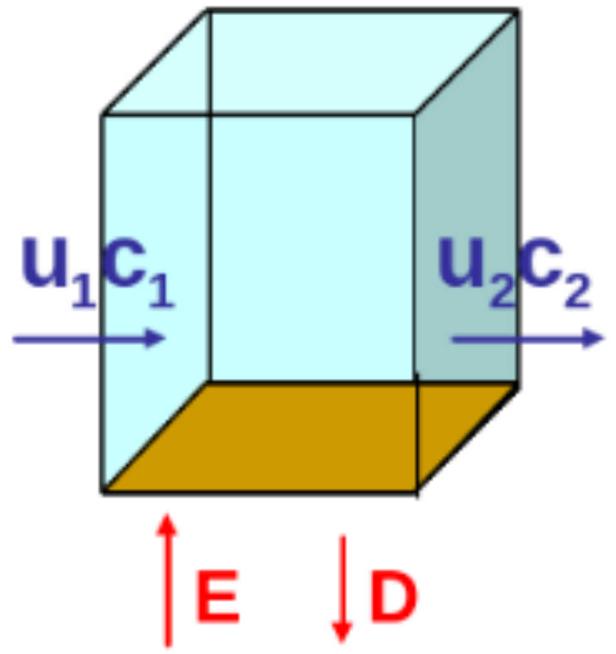
Q = f(cond. Hydro., param. Sed.)

Bottom evolution:

$$(1-p)\frac{\partial h_{sed}}{\partial t} = \frac{\partial Q}{\partial x}$$

- **Non-equilibrium transport**
  Erosion-deposition fluxes

suspension:
$u_{part.} = u_{eau}$



Erosion flux : ***E = f(cond. Hydro., param. Sed.)***

Deposition flux: $D = W_s C(1 - \frac{\tau}{\tau_d})$

Eq. Advection/dispersion:

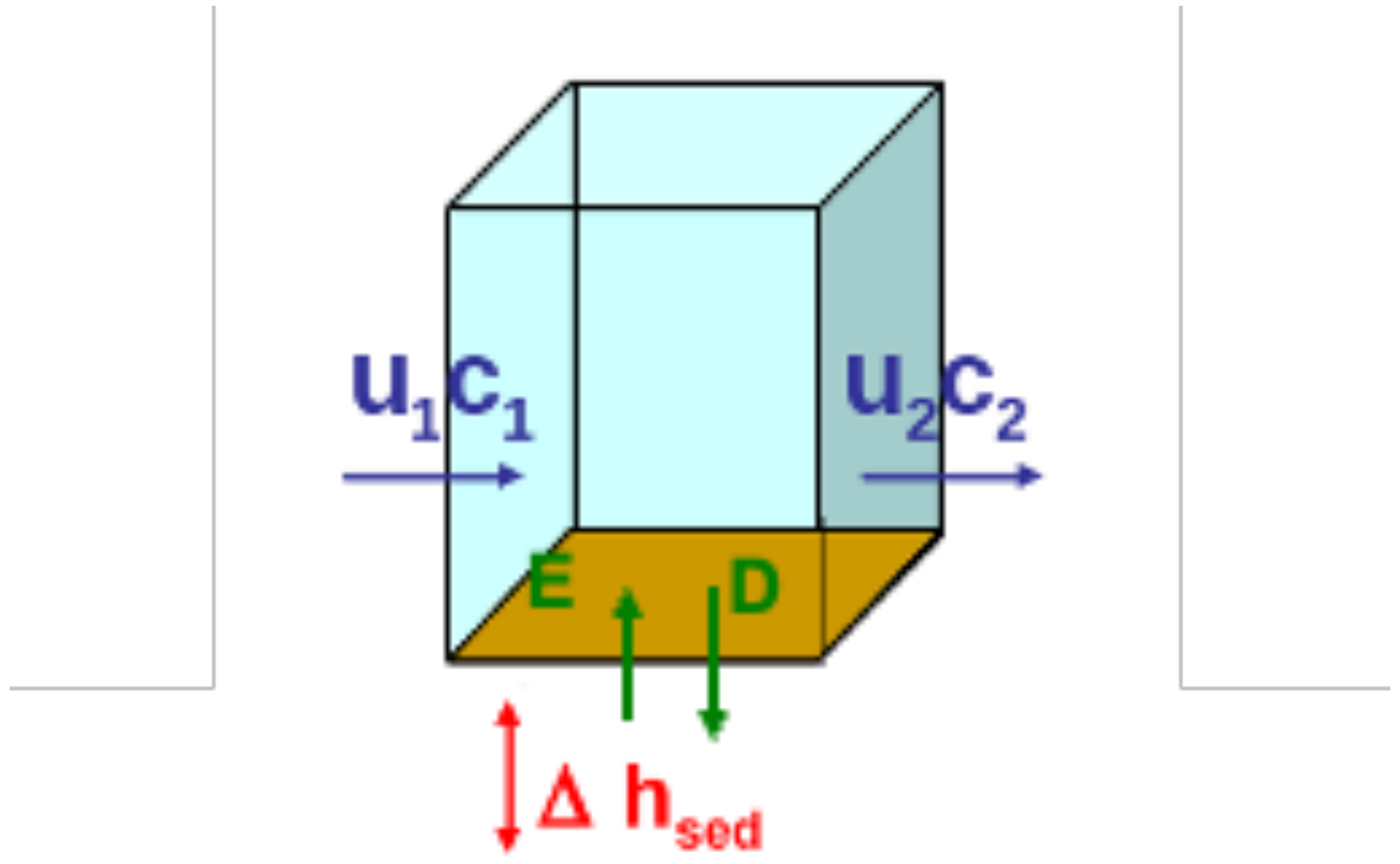
$$\frac{\partial hC}{\partial t} + \frac{\partial hUC}{\partial x} = E - D$$

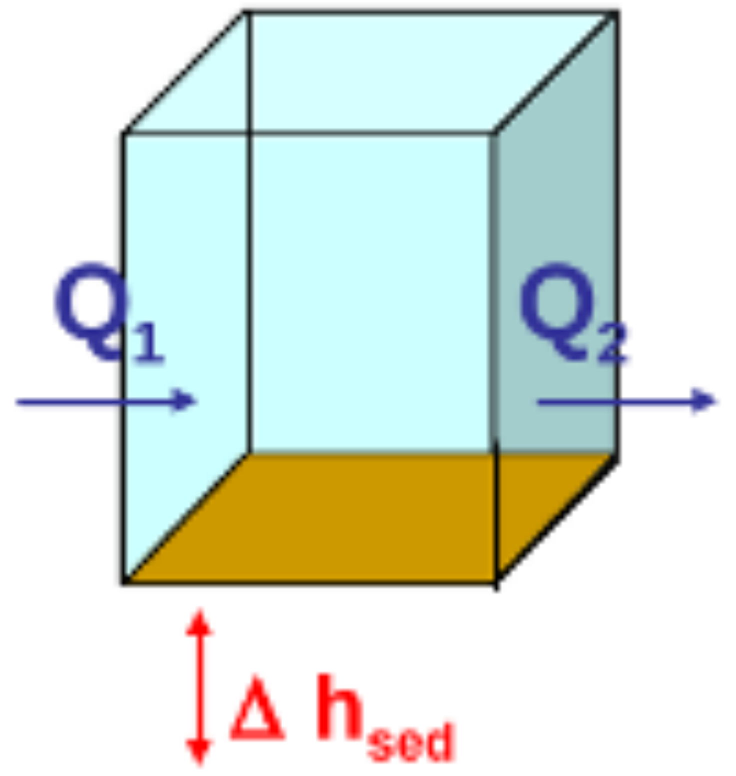
Bottom evolution: $\frac{\partial h_{sed}}{\partial t} = \frac{1}{C_{sed}}(D - E)$

Models in CROCO

Sediment modeling : main processes in CROCO

- Transport in the water column
- Erosion / deposition
- Bedload transport
- Bed evolution (sand, mud, mixed)
- Morphological evolution





Models in CROCO

Sediment modeling

2 models available :

- USGS model : cpp key **#SEDIMENT**
  - « legacy » model
  - originally included in ROMS-AGRIF
  - available in ROMS-RUTGERS and OAWST

- IFREMER model : cpp key **#MUSTANG**
  - french model
  - originally included in MARS3D
  - available since 1.2 (released Jan 2022)

Conclusion

- Wide range of complex phenomena at different scales
- Drivers : currents, waves and depth
- Complexity => hard to observe and model

- Very fast review, non-exhaustive

Let’s dive into CROCO !!