CROCO

Coastal and Regional Ocean COmmunity model

Sediment dynamics

Introduction to (sand) sediment transport

rachid.benshila@legos.obs-mip.fr

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

Outline

Background

Modes of sediment transport

Cross-shore (sand) transport

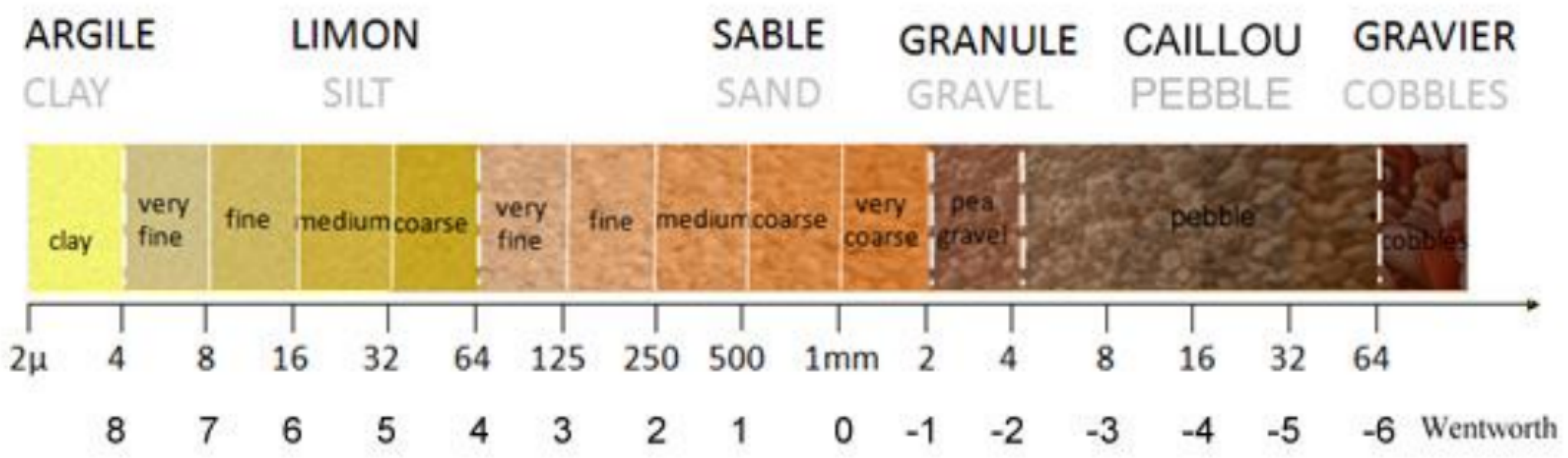
Longshore (sand) transport

Sediment balance

Background

Definition

Sediment properties



Sediment can be characterized by grain size

- cohesive : fine grain => in suspension in the surf zone on energetic coasts, deposit soon deeper areas (estuaries, lagons…)
- non cohesive from 0.1 mm to 64 mm, erosion and deposition :
    - set in motion by **waves**
    - cross-shore and alongshore exchanges

  => context of this presentation : sand beaches and waves

Definitions

Transport

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 drive, wind-drive

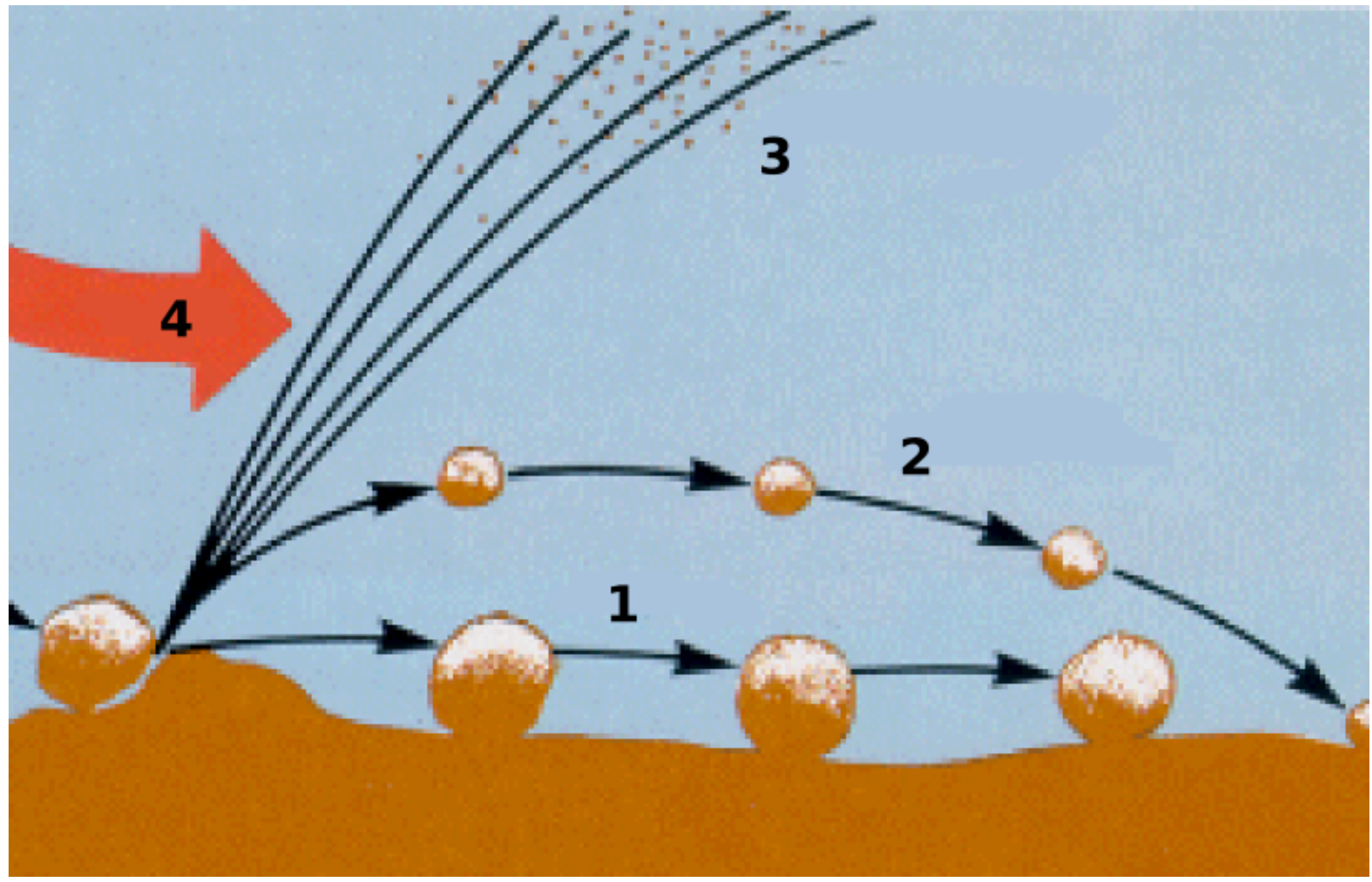
Direction of net transport of sediment : the balance of all

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

Definitions

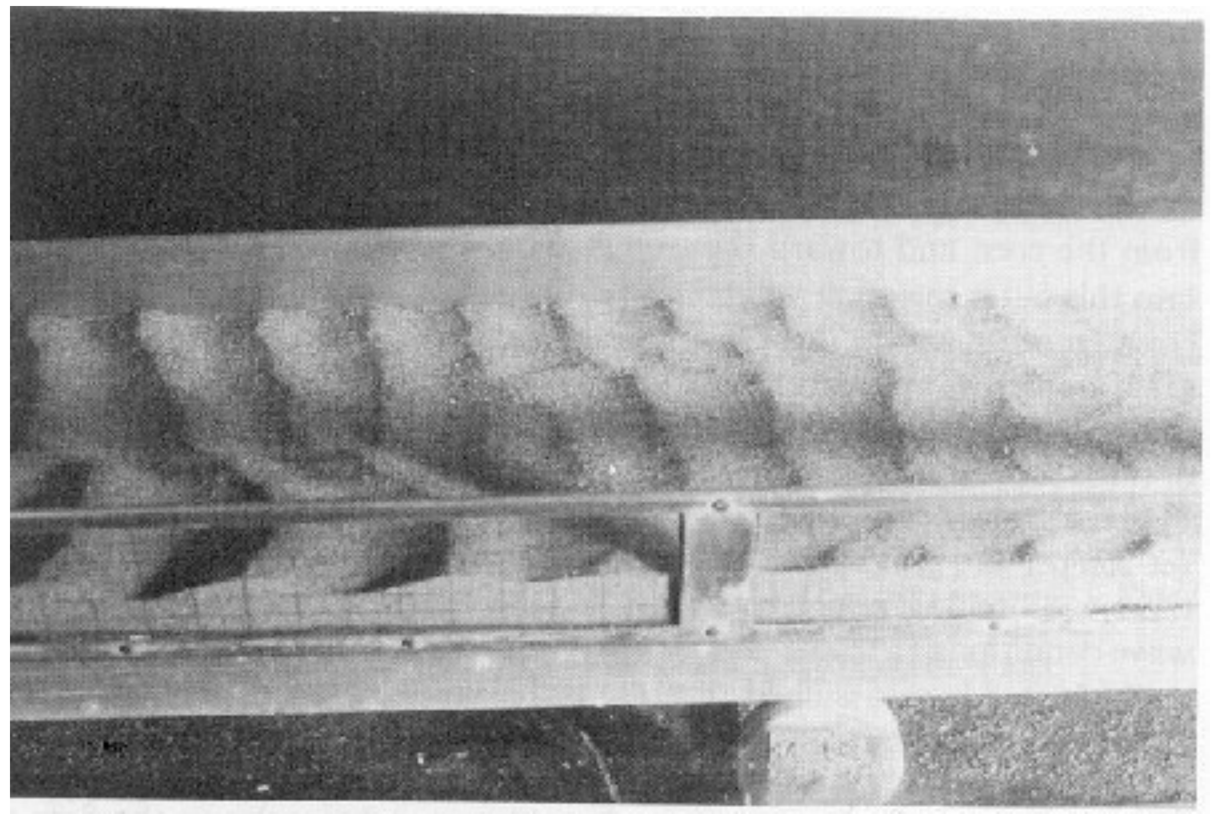
Bedload

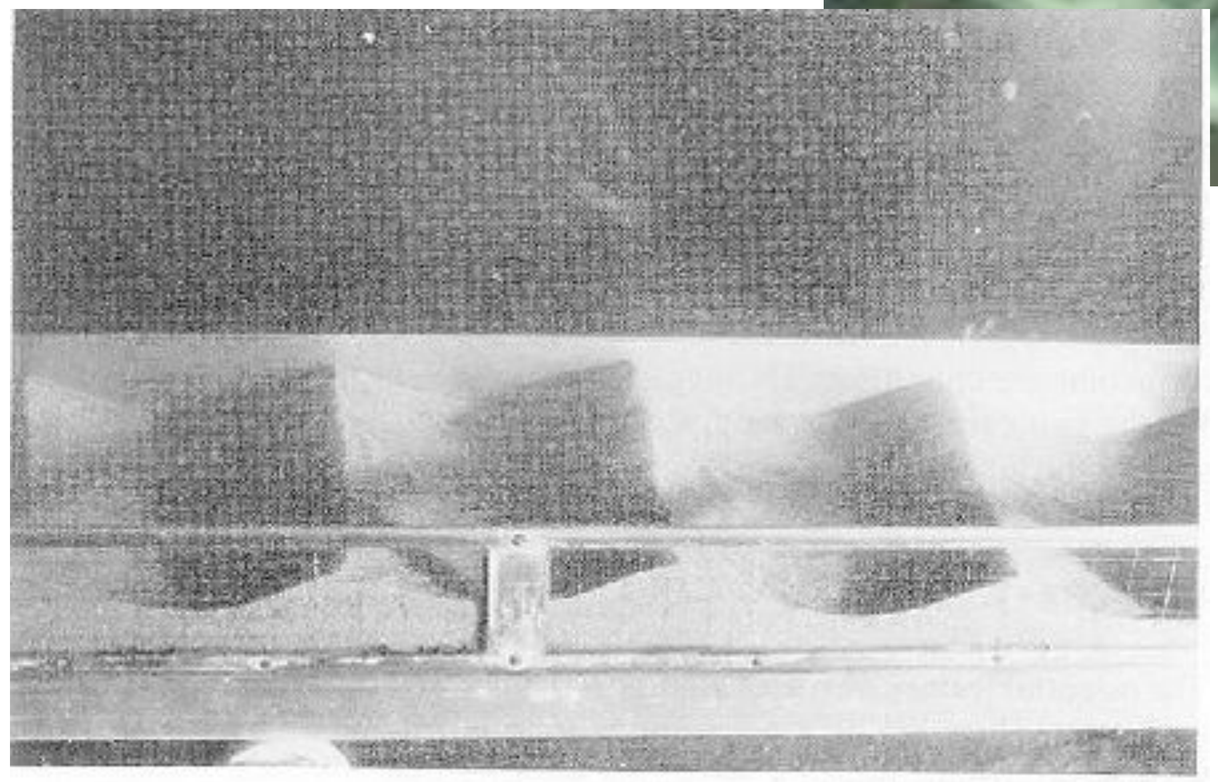
Transport in contact with the bed : rolling, sliding
- during storms
- in the breaking zone



Generation of ripples, dunes :
- sediment in suspension close to the bed
- vortex from breaking

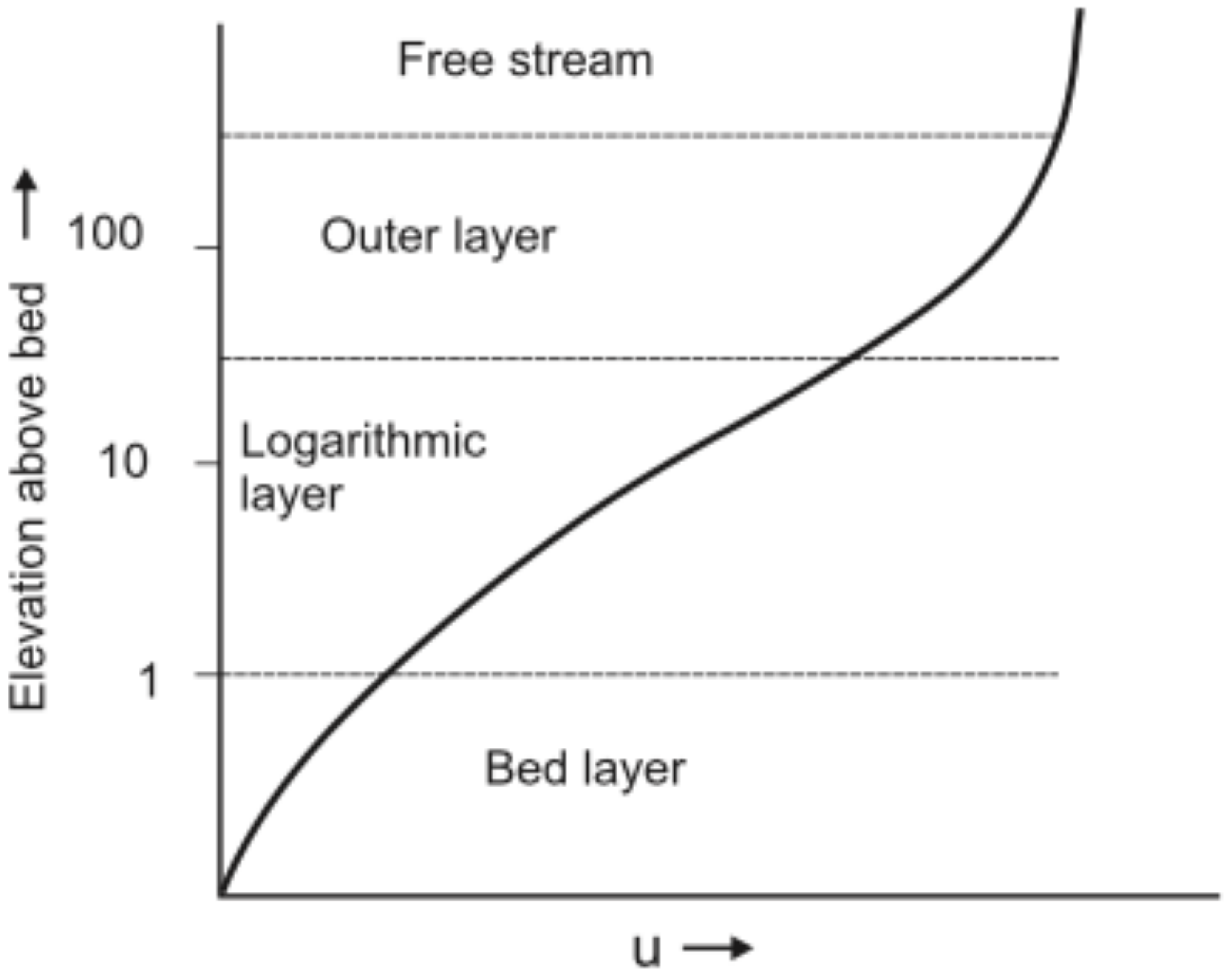
Hard to mesure, large uncertainty



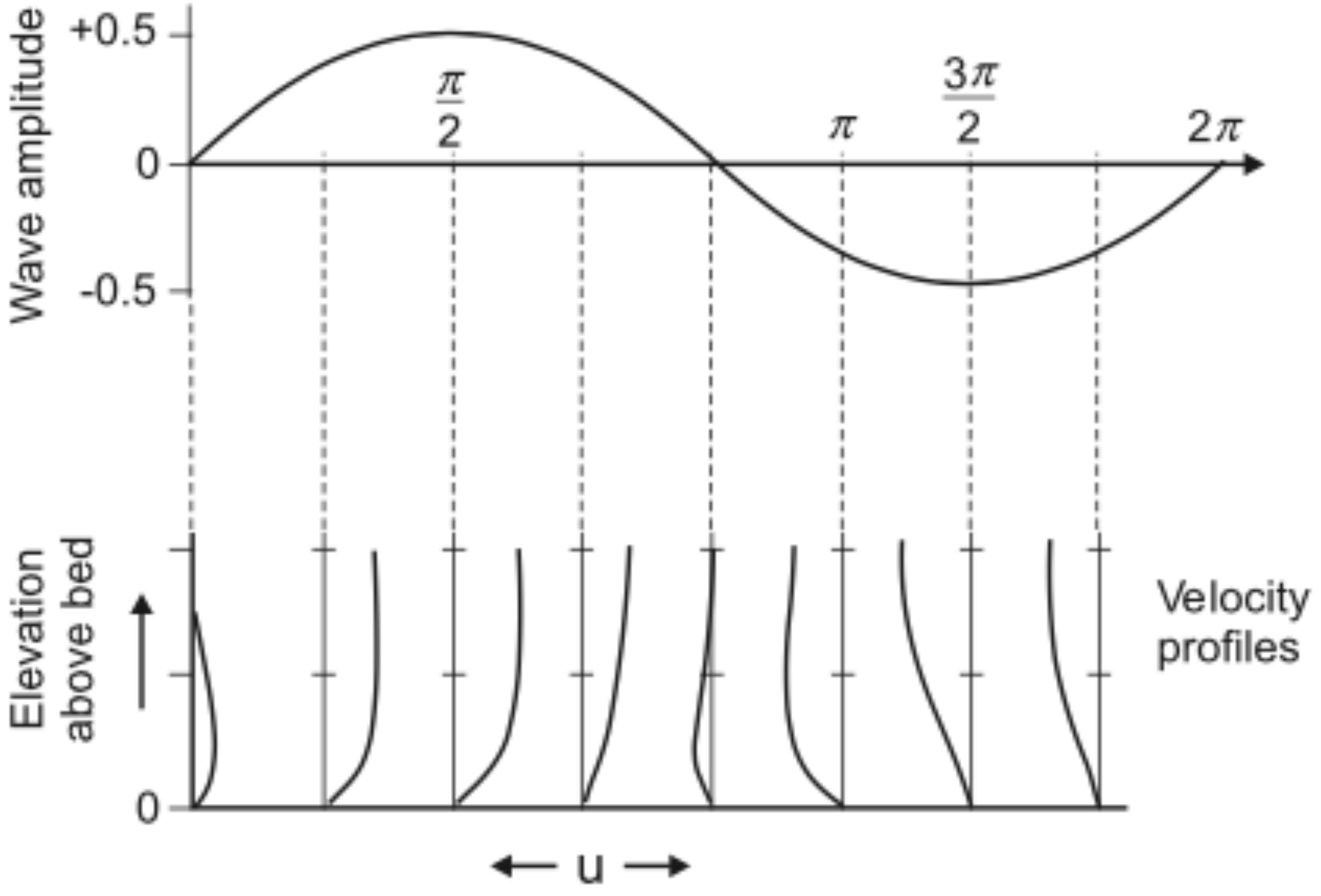


Definitions

Boundary layer, shear stress



Unidirectionnel current
(tide, rip, wind)



Single wave

Boundary layer :

- flow velocity increasing away from the bed to a maximum

-flow above unaffected by conditions at the bed.

- effect of roughness and bedrooms

$$\tau \sim \frac{\partial u}{\partial z}$$

Definitions

Shear stress

Usually derived from the slope of the velocity profile :
- unidirectionnel flow : permanent thick boundary layer
- oscillatory flows (wave cycle) : grows and diminish, reversal of currents => max under through and crest

=> effect on measurement and modeling

Max orbital velocity (from linear theory) $$u_0 = \frac{\pi H}{T sin\ kh}$$

Estimation of shear stress $$\tau_w = 0.5 \rho f_w u_0^2$$

Wave friction parameter $$f_w \sim exp\left(\frac{K_s}{d_0}\right)$$

Definition

Shield number

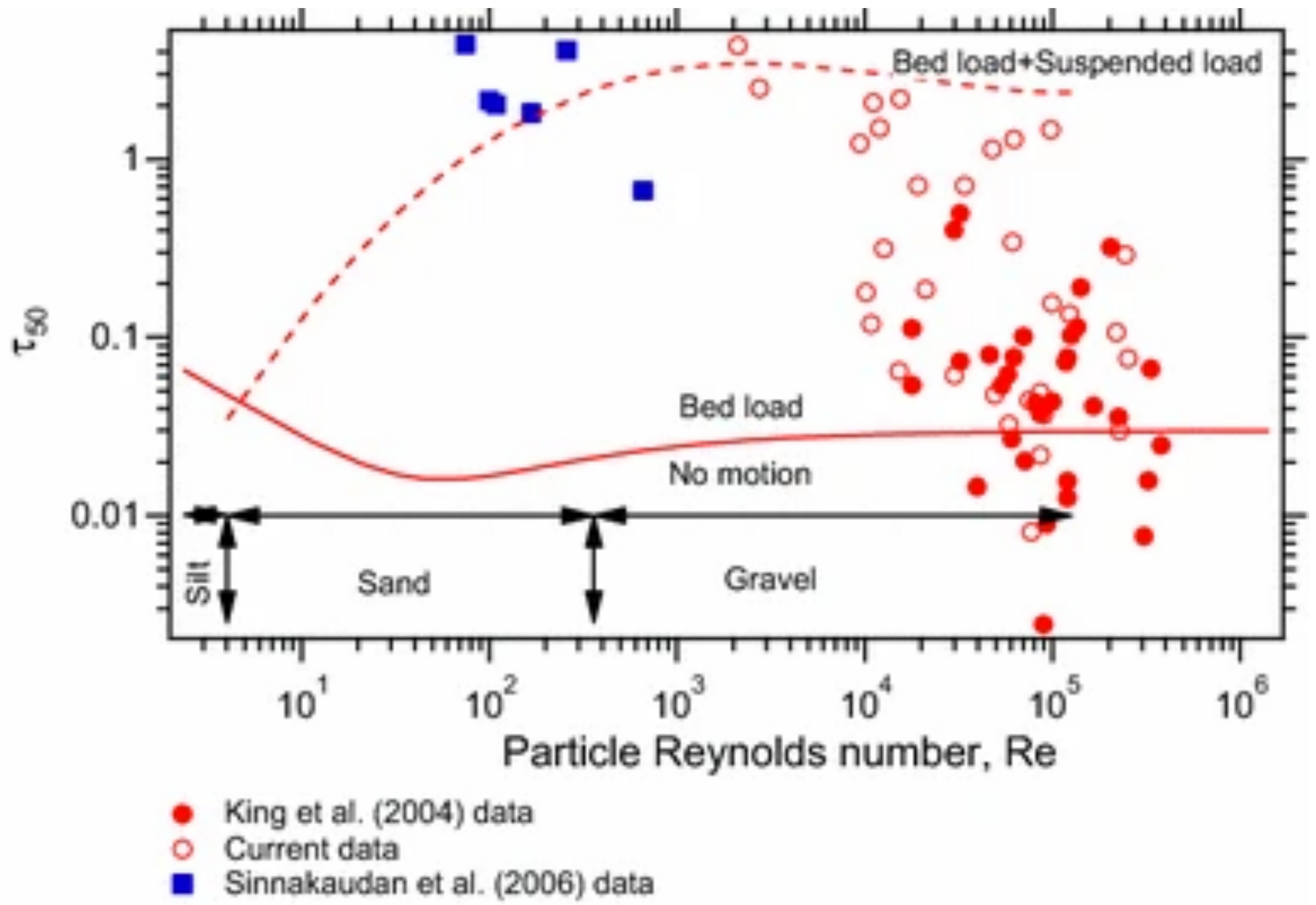
Reynolds parameter= inerty/viscosity= $\mathbf{Re} = \frac{u_* d}{\nu}$ (~fluid instability)

in which ν is the kinematic viscosity and the shear velocity u_* is defined as $u_* = \left(\frac{\tau_b}{\rho}\right)^{1/2}$

Shield's parameter= drag/gravity= $\frac{\tau_c}{(\rho_s - \rho) g d}$

(Dimensionless stress, critical threshold ~sediment instability)

With bed shear stress $\tau_b = \frac{1}{8}\rho f U^2$



1. lowest Shields stress in the sand range (0.06-2.00 mm). Small mass but too large for adhesion forces to play.
2. Silt/clay, smaller size, but higher shear stress for motion. Large adhesion forces
3. Shields parameter constant 0.06 for gravel => Shields stress here becomes a simple function of grain size.

Definition

Non-cohesive particles

Sediment particles vertical displacement is subject to their weight:

$$P = \frac{\pi}{6}(\rho_s - \rho) g D^3$$

And drag force:

$$F = \frac{1}{2}\rho C_x \left(\frac{\pi D^2}{4}\right) W^2$$

where *W* is the fall velocity ("settling velocity")
W presents various forms, depending of the Reynolds number value

$$Re_w > 1000 \Rightarrow W = \sqrt{\frac{8}{3}\rho' g D}$$

$$Re_w < 1 \Rightarrow W = \frac{\rho' g D^2}{18\nu}$$

where $\rho' = (\rho_s - \rho)/\rho$
and ν the kinematic viscosity

Definition
Depth of closure

The offshore depth beyond which beach profiles is ~constant is known as the **depth of closure**.
Seaward of this, although waves can move sediment, net sediment transport is not significant.

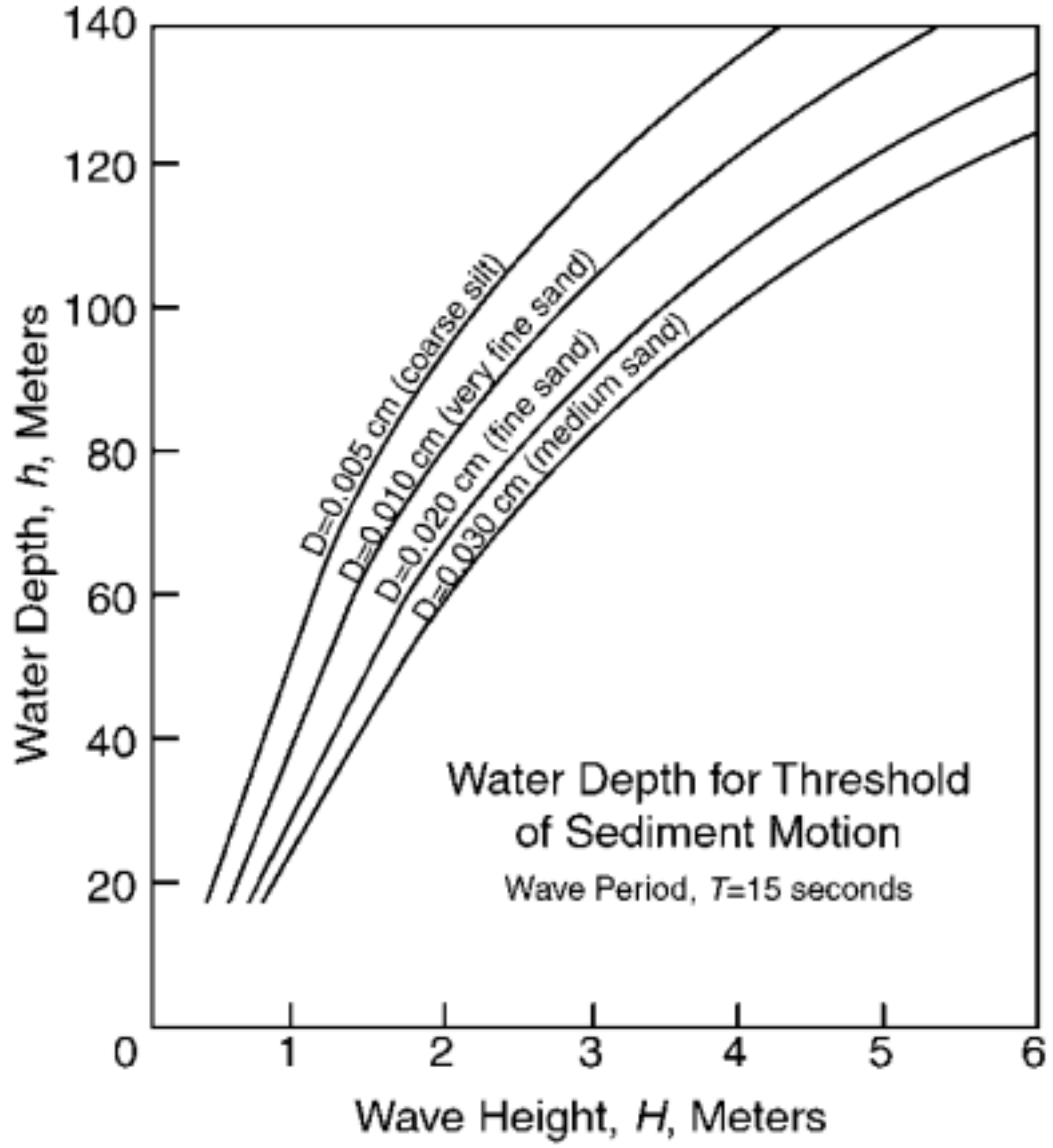
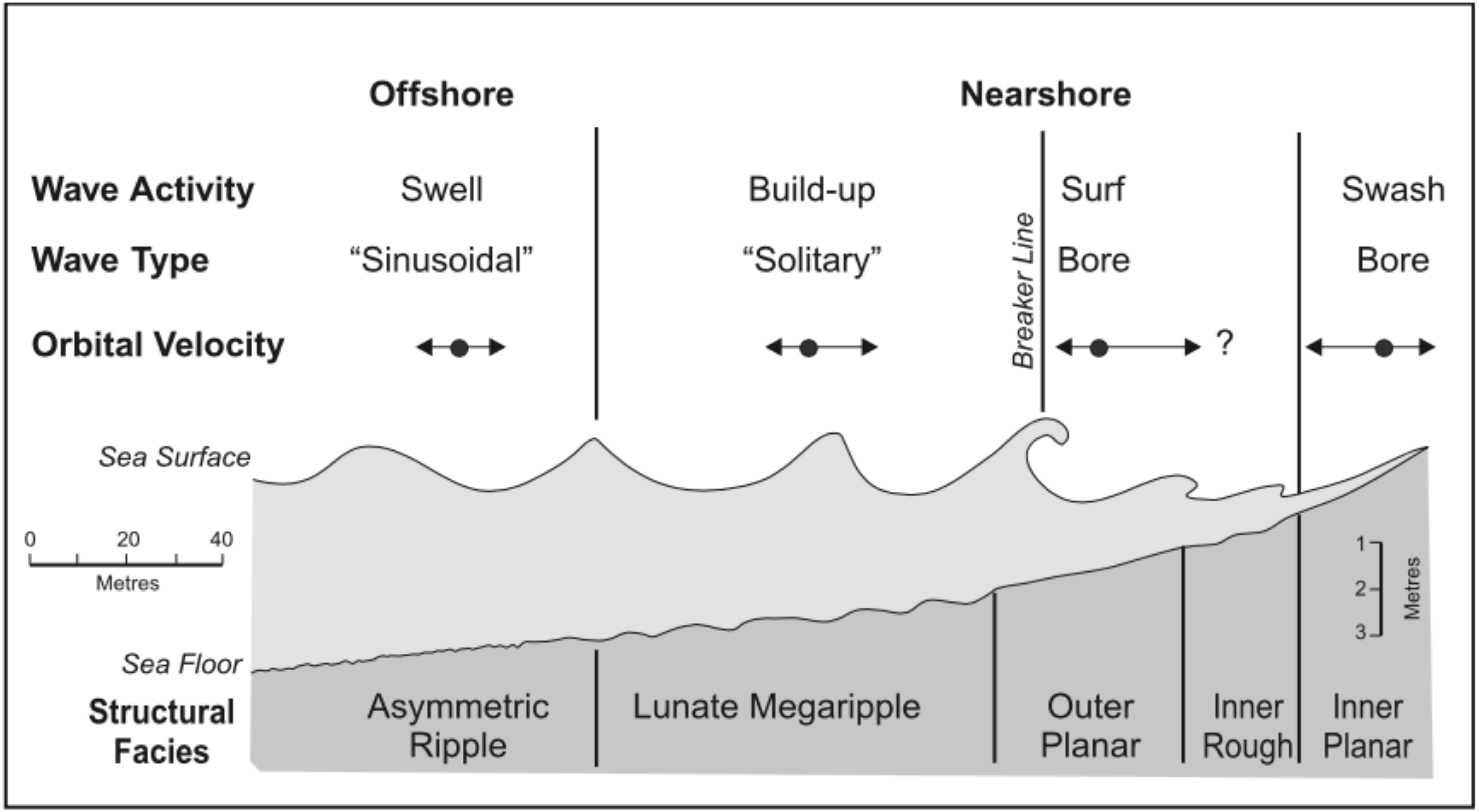


Figure 8.6 Wave heights and water depths for incipient motion for a wave with a 15-s period (from Komar and Miller 1975).

$$h_c = 2.28H_e - 68.5\left(\frac{H_e^2}{gT_e^2}\right)$$

based on the assumption that $(\rho_s - \rho)/\rho = 1.65$.

Waves at nearshore



Sediment transport

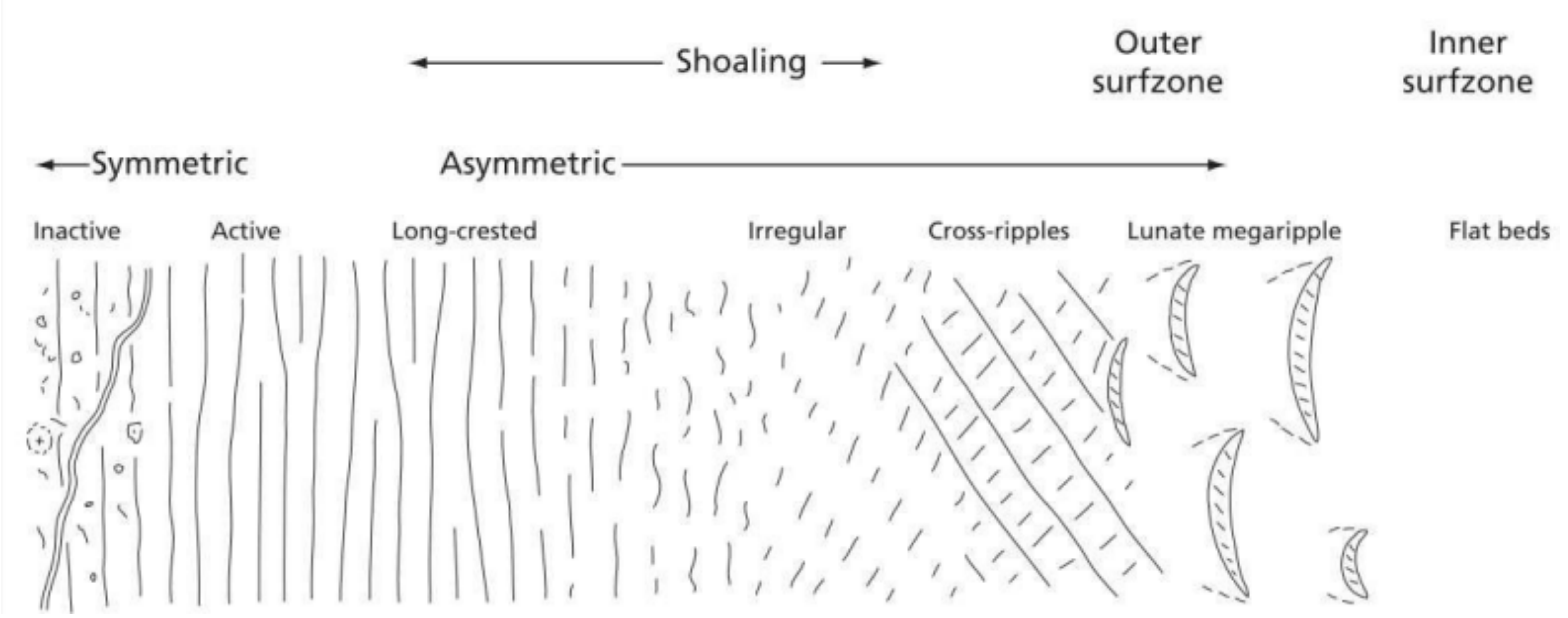
In general

- Sediment and Waves :
  - as soon as waves feel the sea bed, sediment will be in motion
  - waves tends to stir the sediment
- Transport modes :
  - Bed load (grain-to-grain interactions)
  - Suspended load (‘in the fluid’ - turbulence versus gravity)
  - By flow and waves
  - **Crosshore** and alongshore

Cross-shore transport

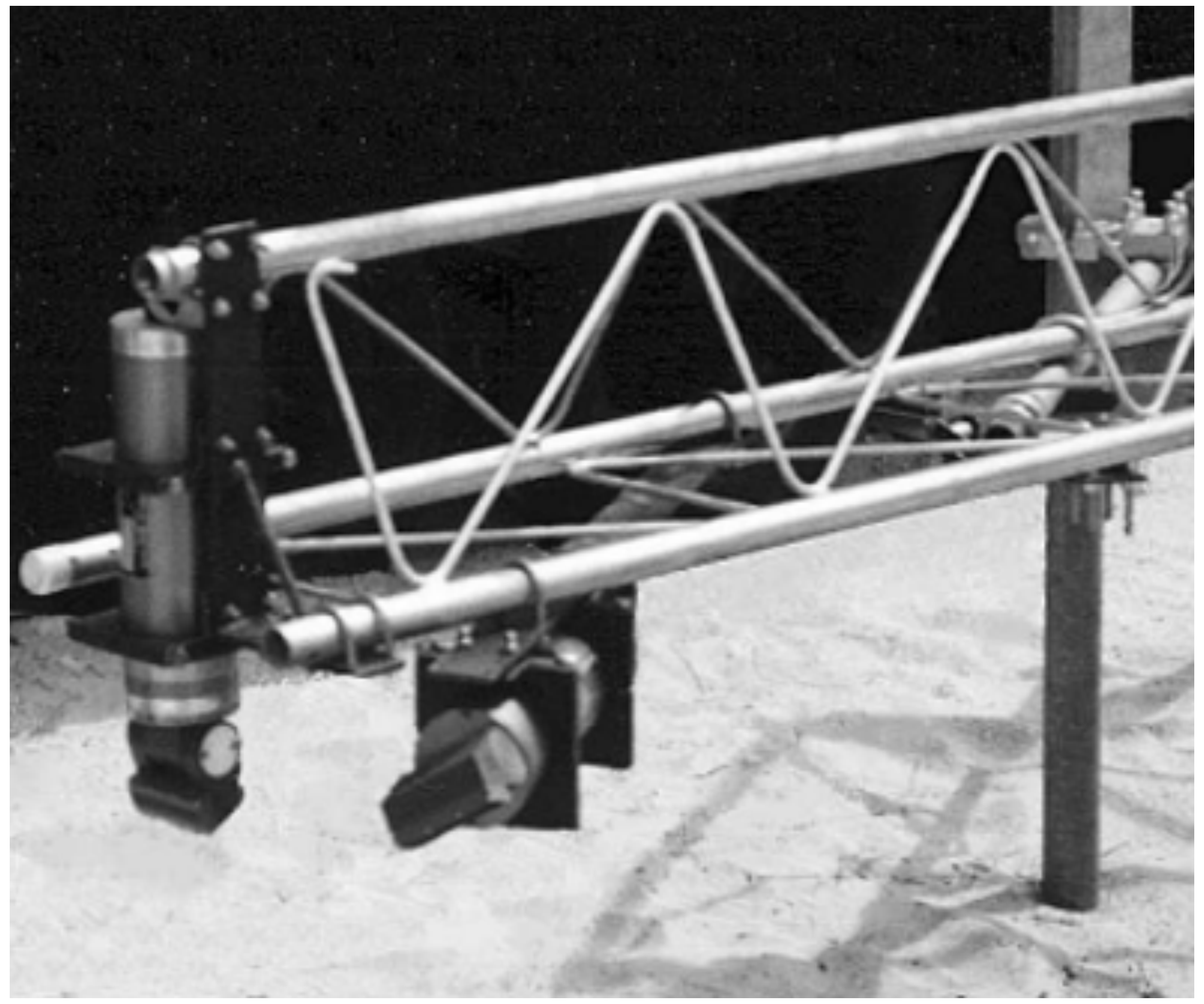
Bedload

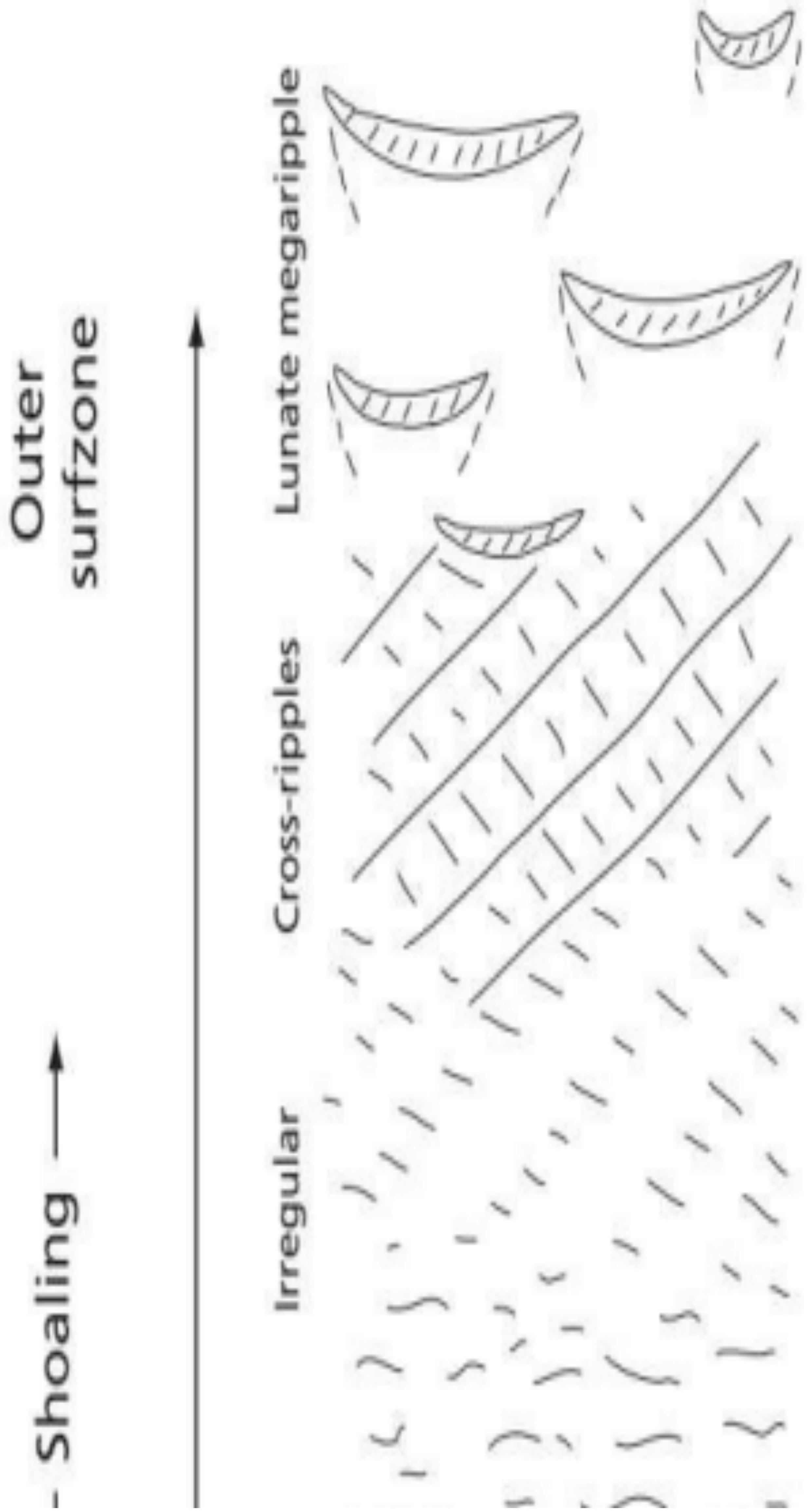
Moving sediment can be organized in small bedrooms (ripples, mega ripples)

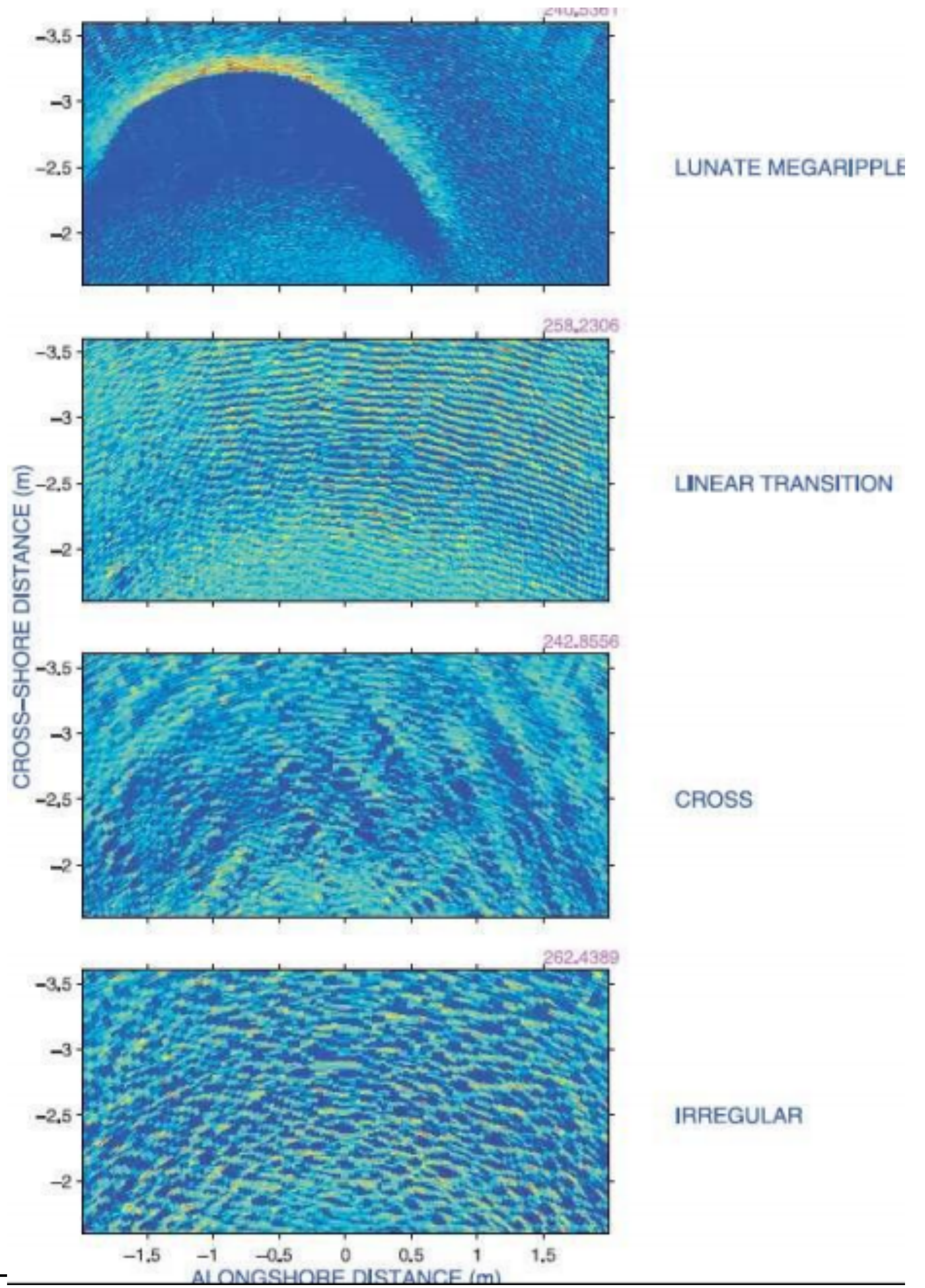


Cross-shore transport

Bedload

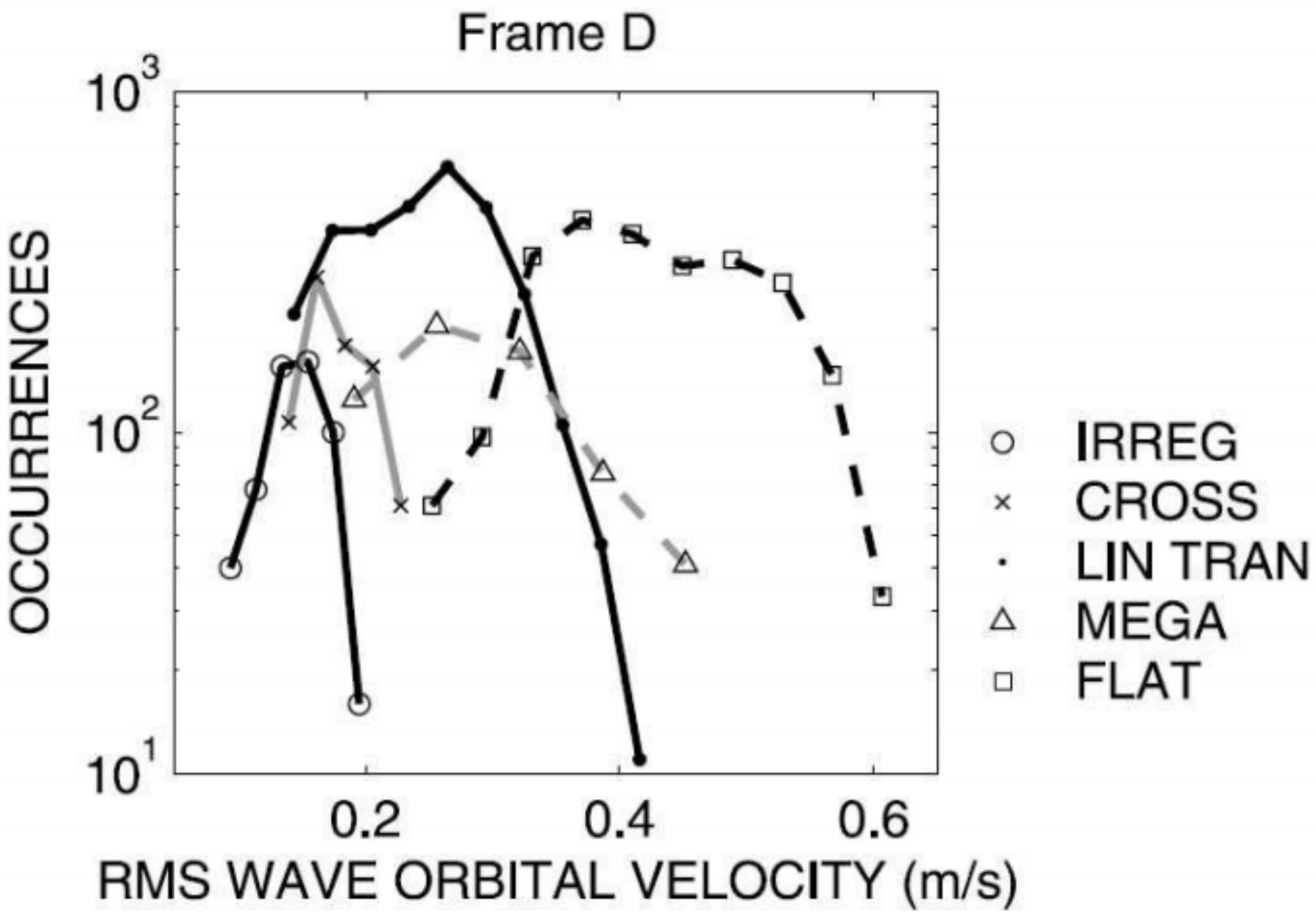






Cross-shore transport

Bedload



Cross-shore transport

Water column

$$q = u \cdot C$$

q : sediment concentration

u : velocity

C : concentration

$$u = \overline{u} + \tilde{u}_{hf} + \tilde{u}_{lf}$$

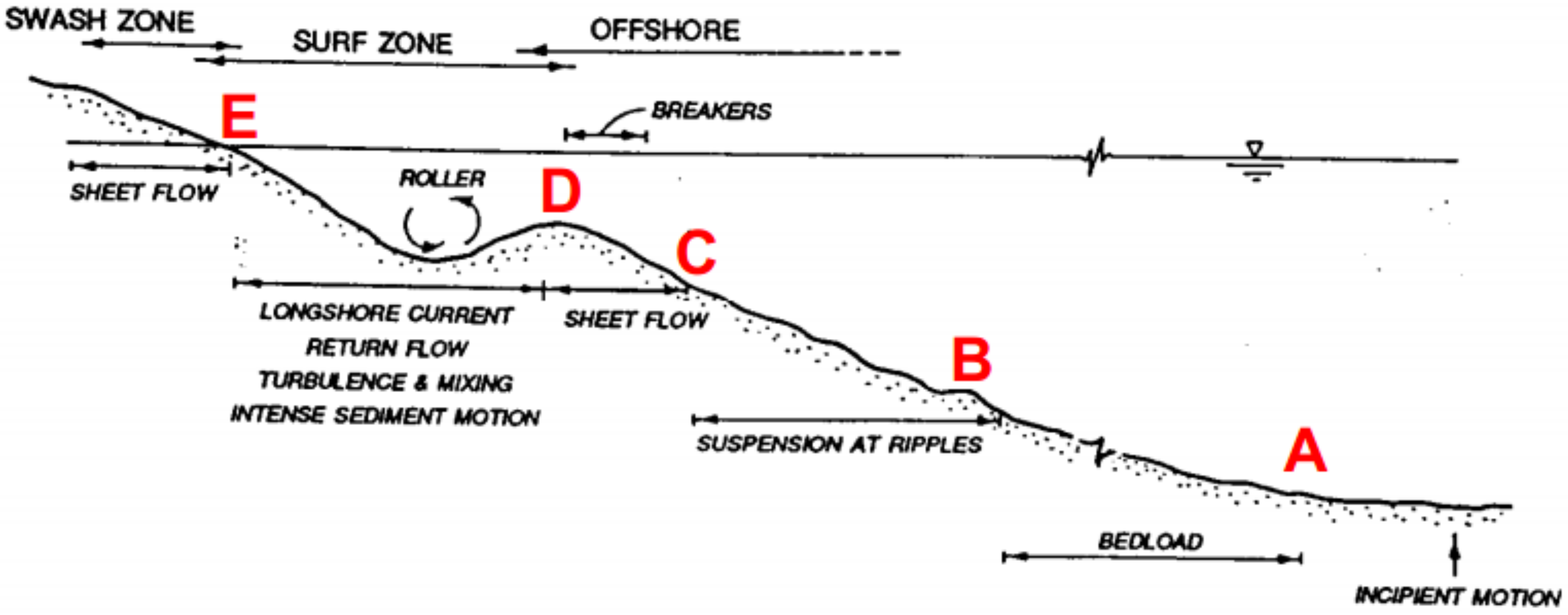
$$C = \overline{C} + \tilde{C}_{hf} + \tilde{C}_{lf}$$

lf : low frequency

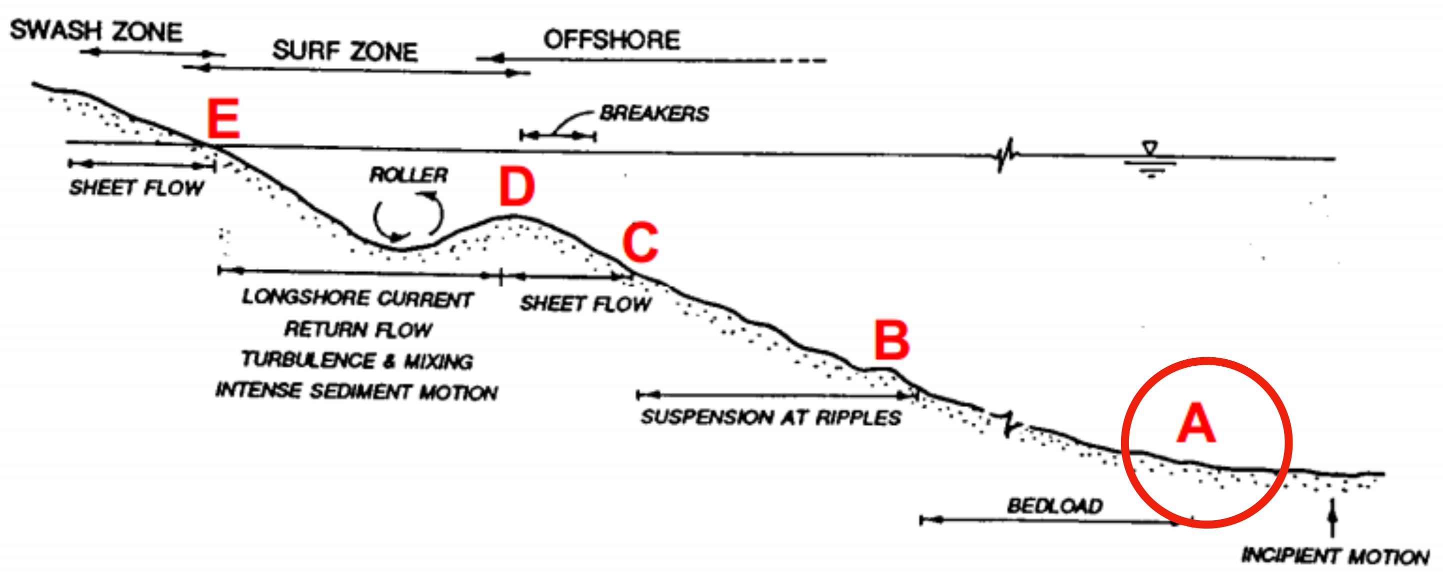
hf : high frequency

$$q \approx \overline{u}\overline{C} + \tilde{u}_{hf}\tilde{C}_{hf} + \tilde{u}_{lf}\tilde{C}_{lf}$$

Cross-shore transport

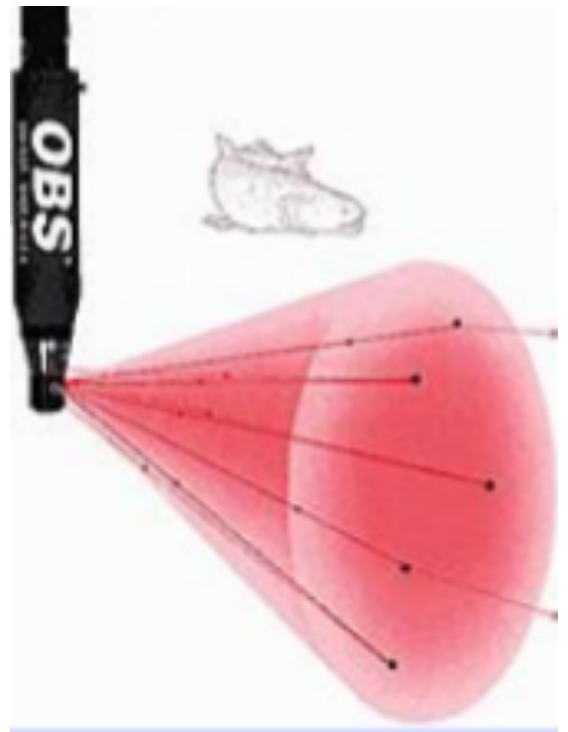


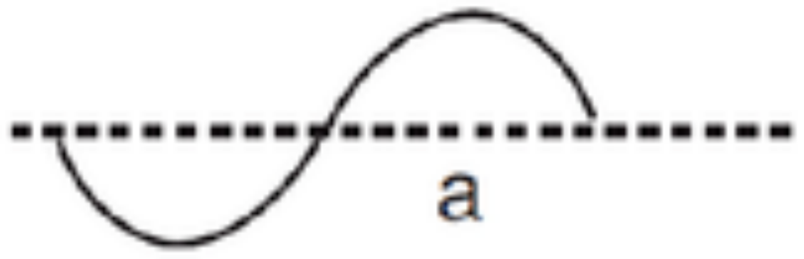
Cross-shore transport

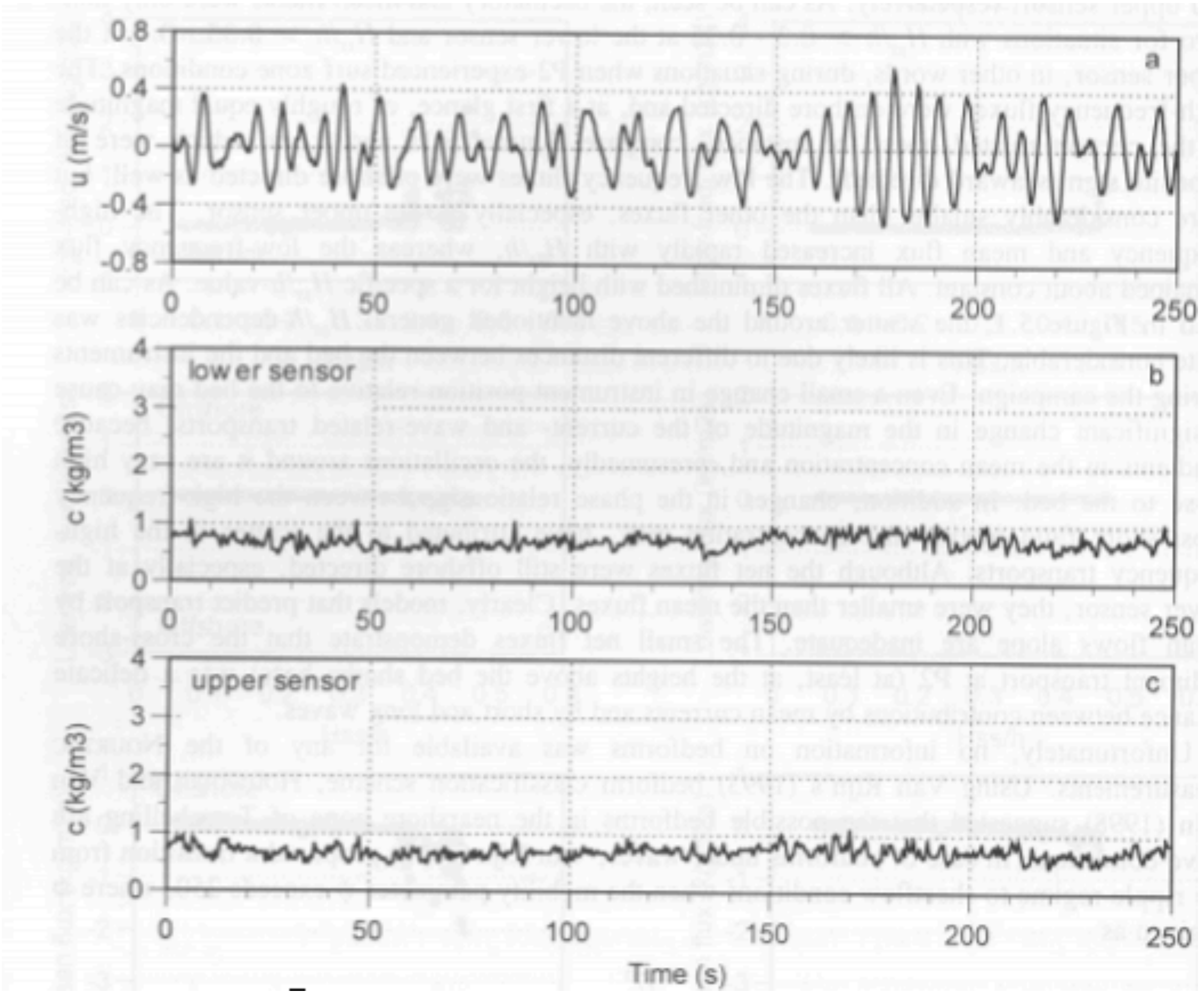


Location A :

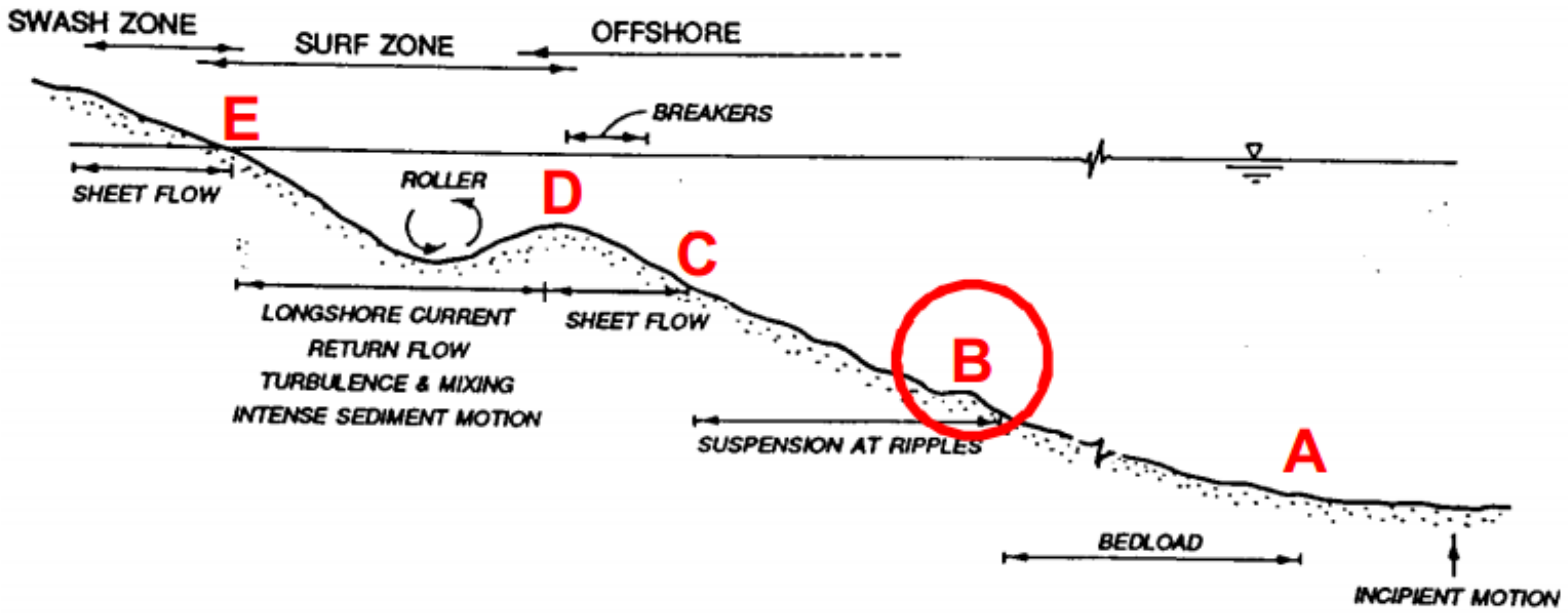
- symmetric waves
- inactive bed
- transport = 0







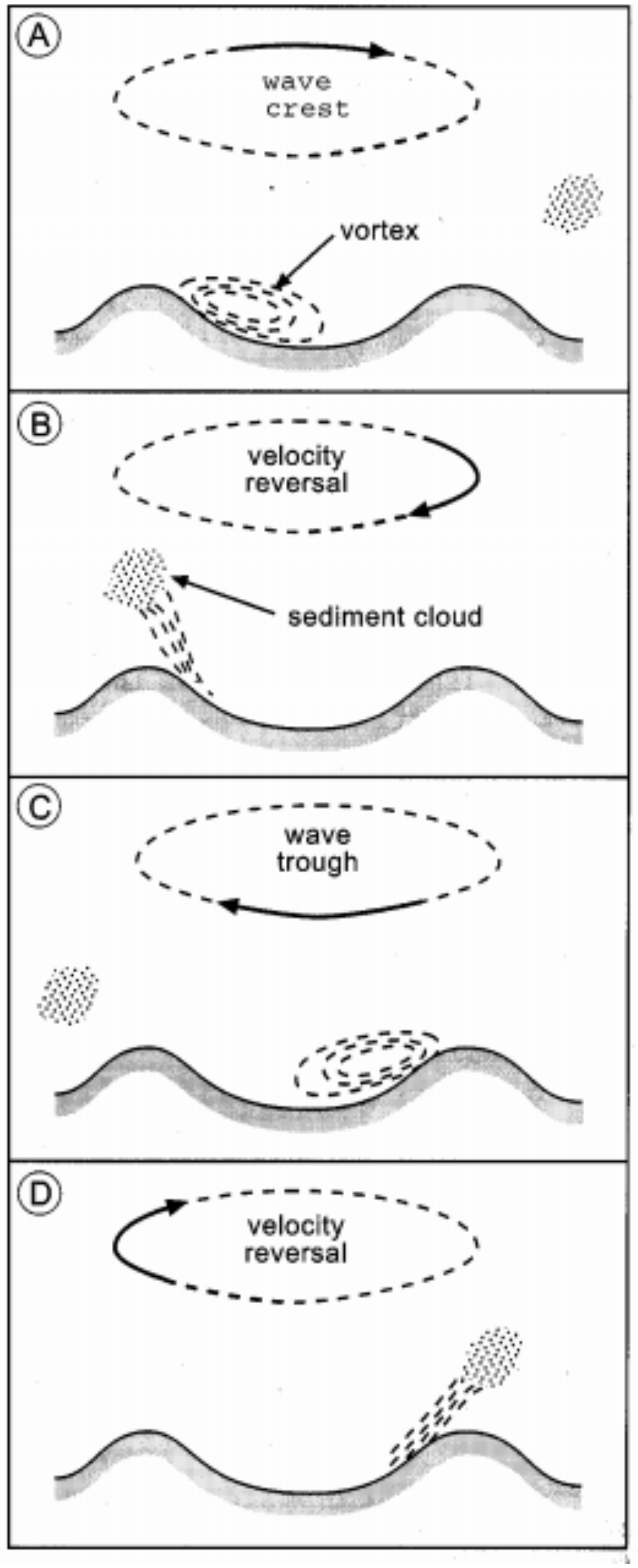
Cross-shore transport

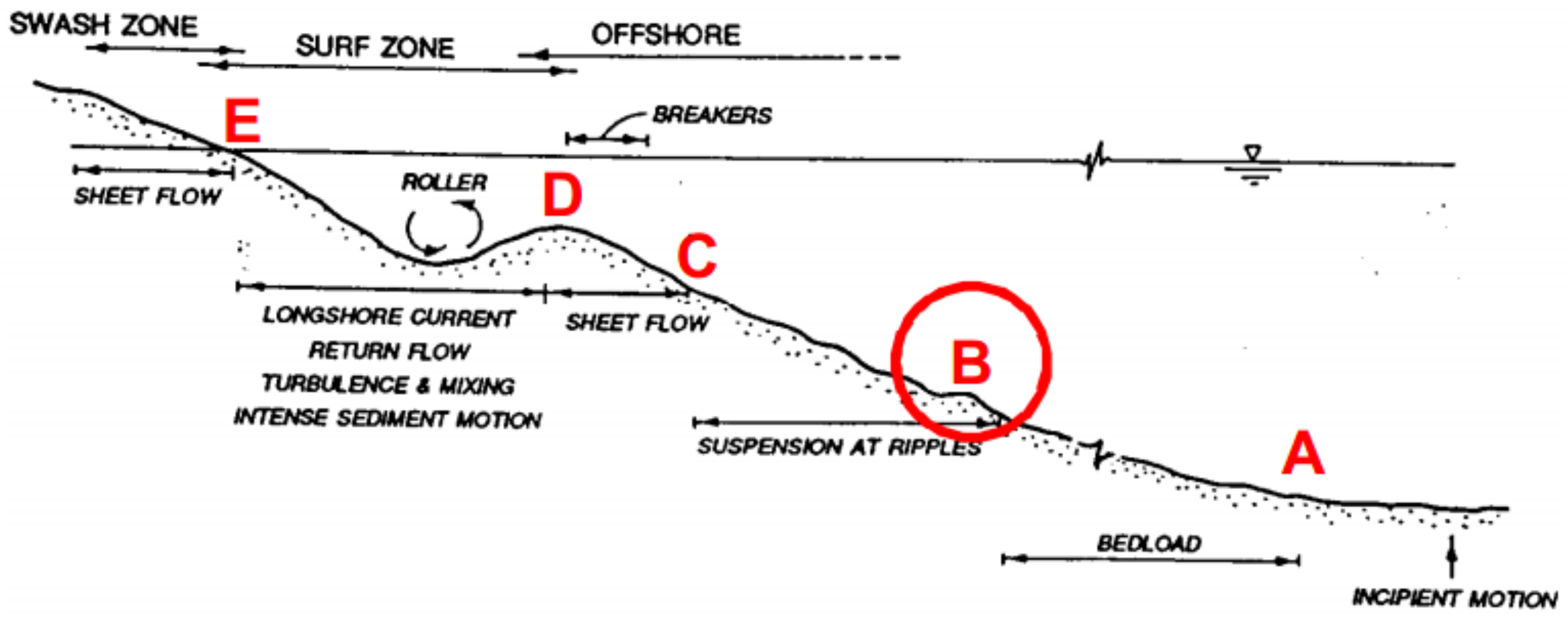


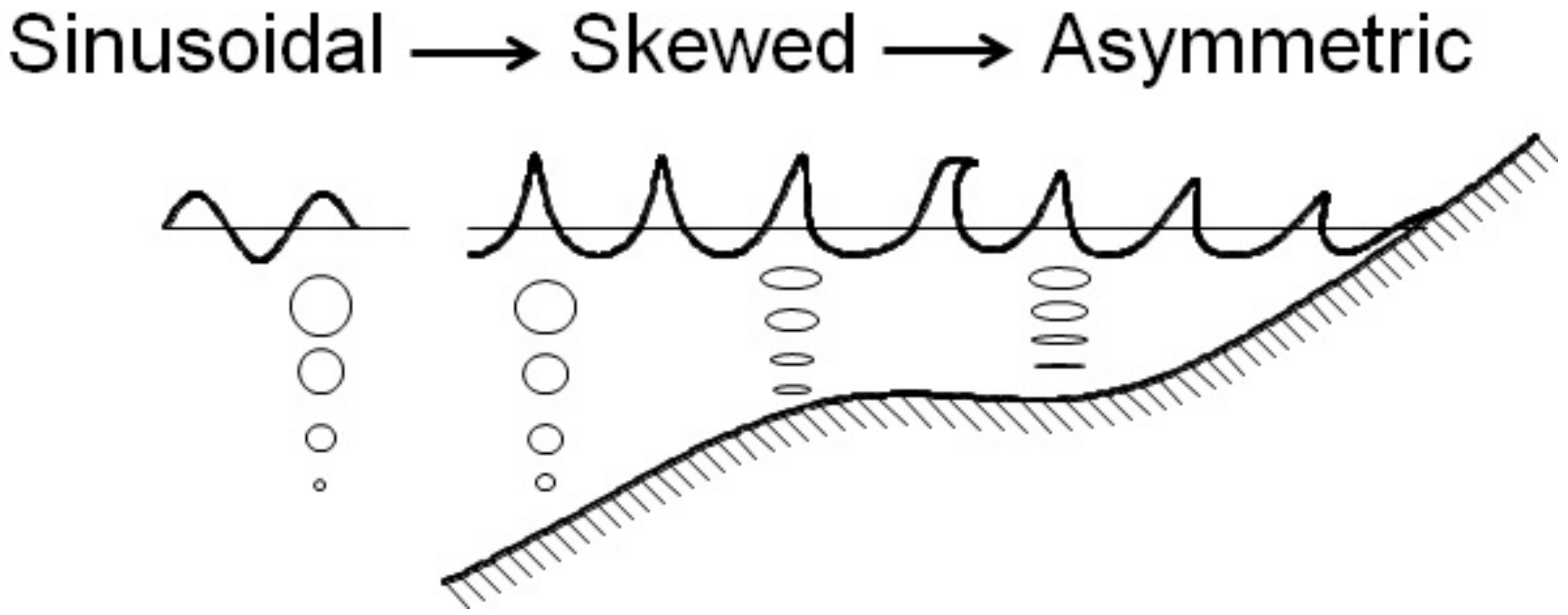
Cross-shore transport

Location B :

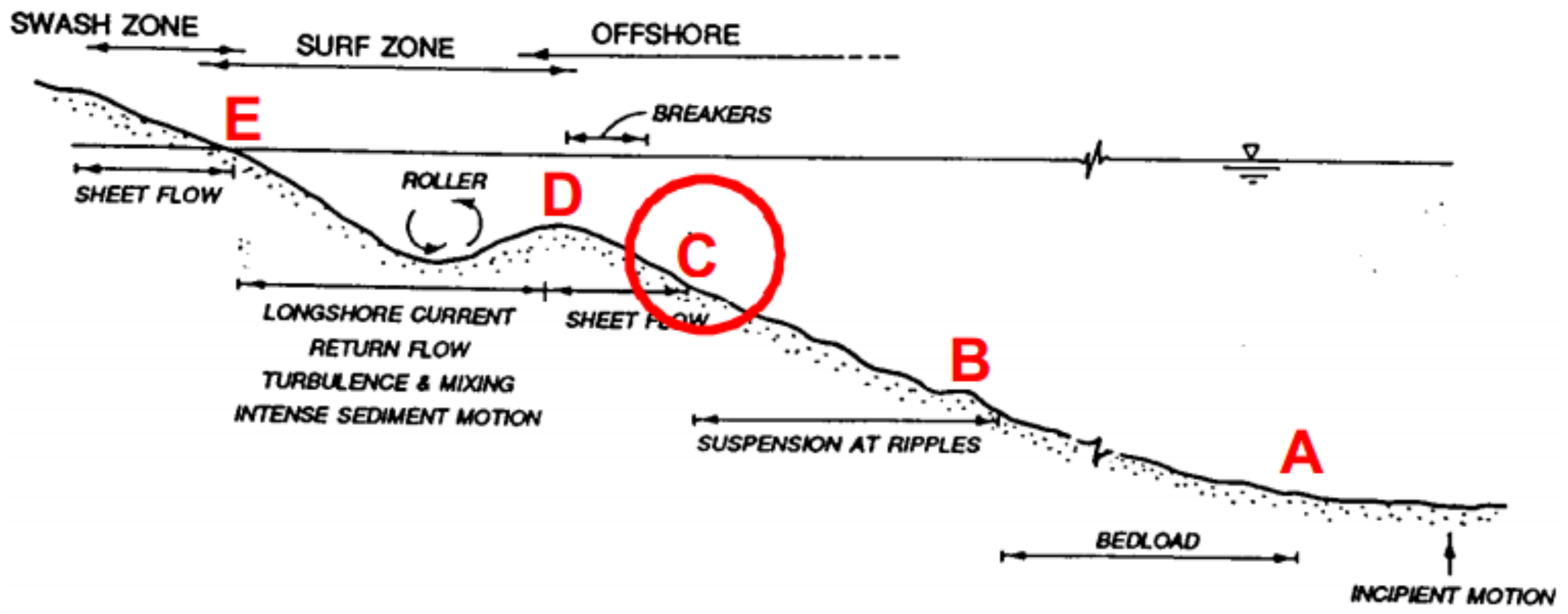
- skewed waves
- ripple on sea bed







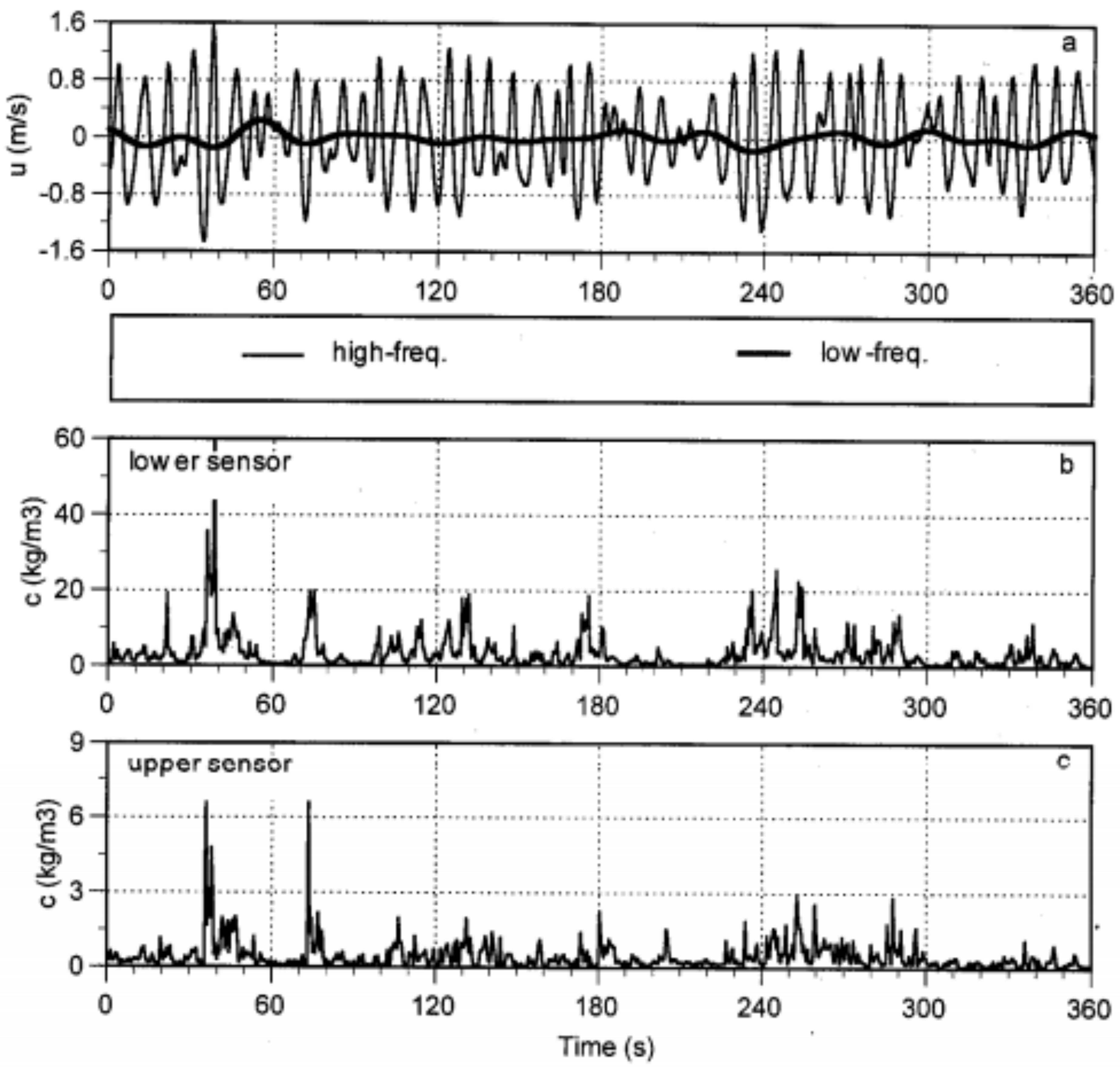
Cross-shore transport

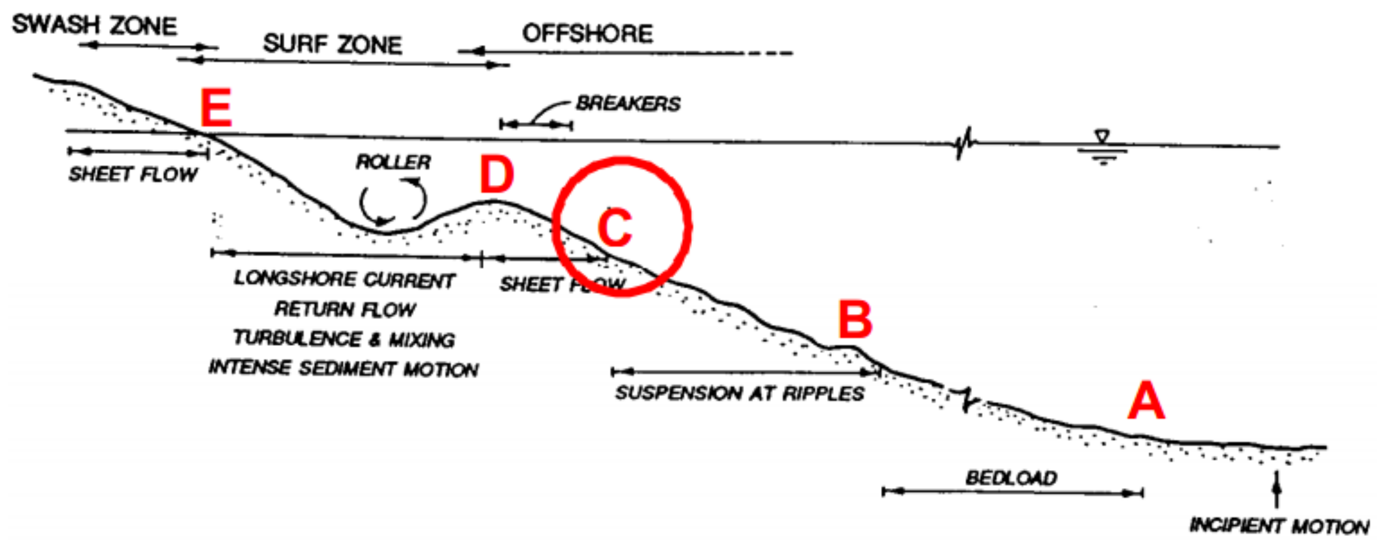


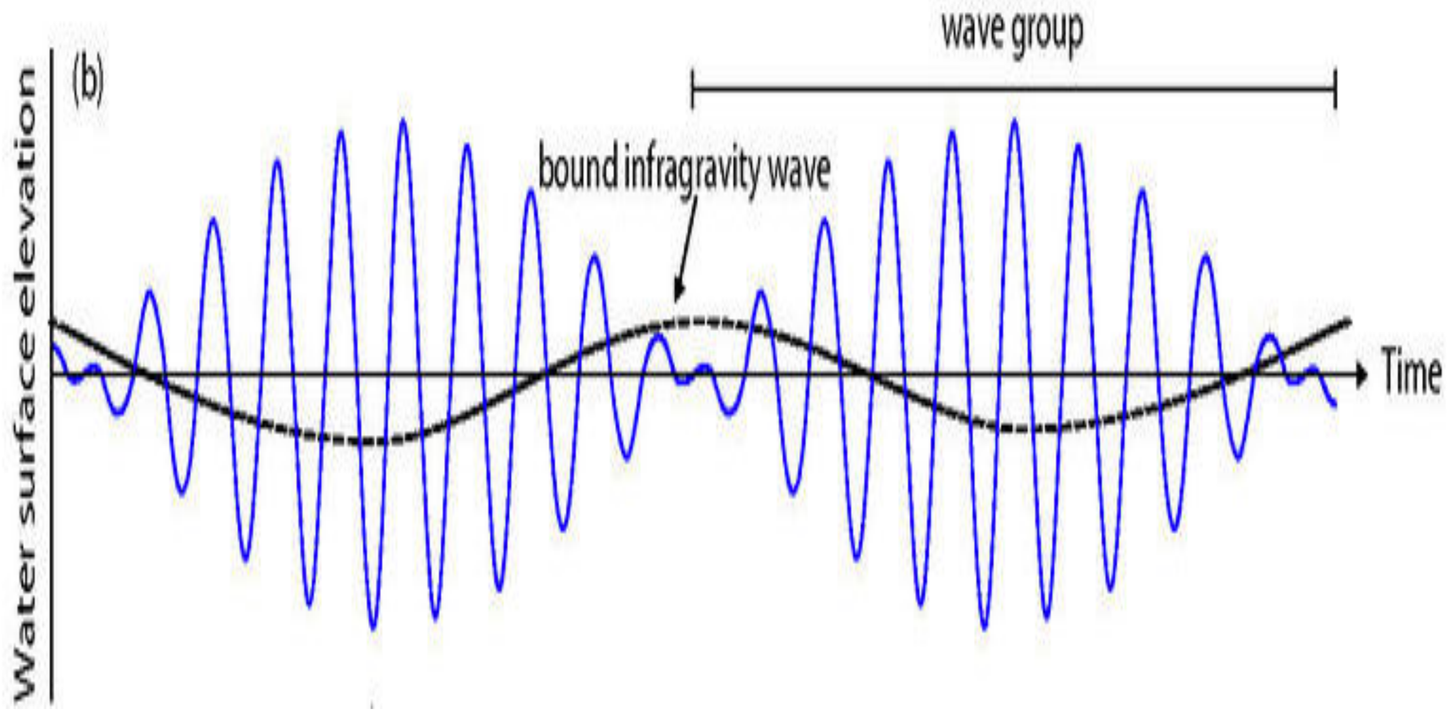
Cross-shore transport

Location C :

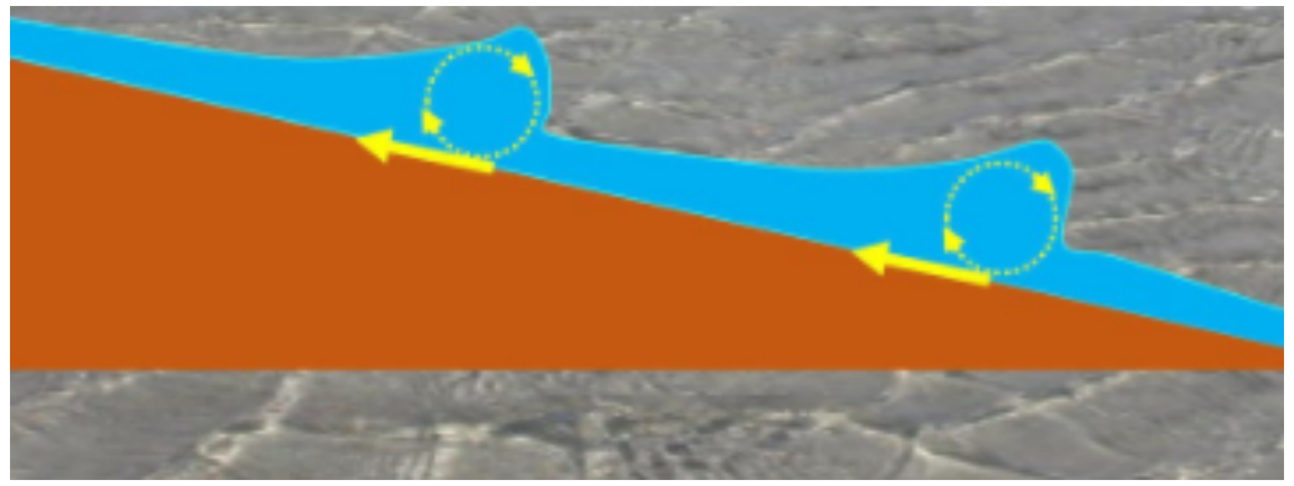
- sheet flow (flat bed)
- skewed waves
- bound infra gravity waves

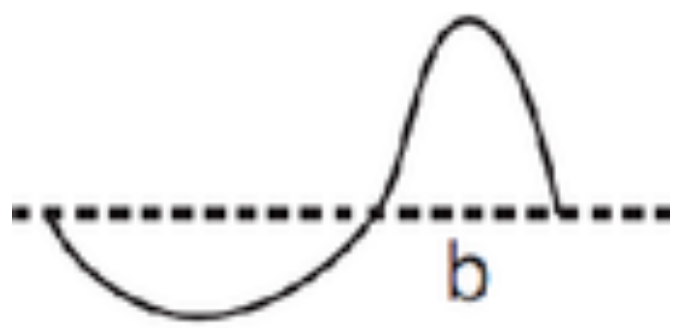




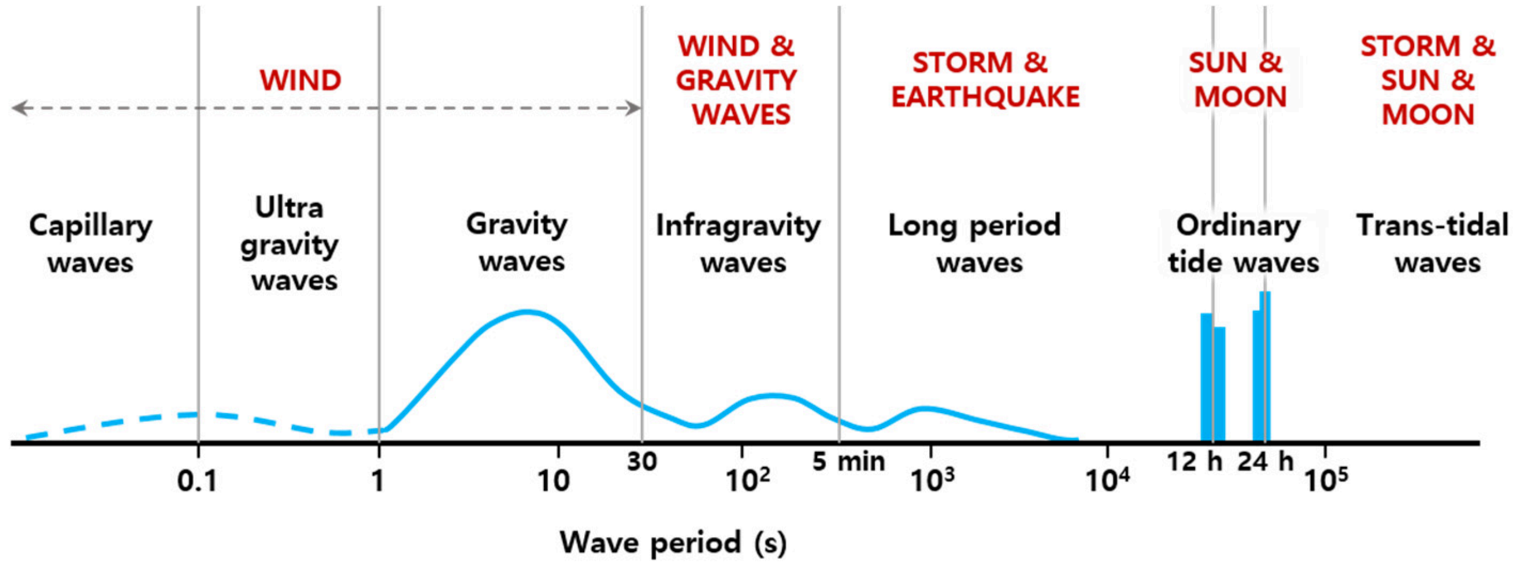


Sub-harmonic interactions



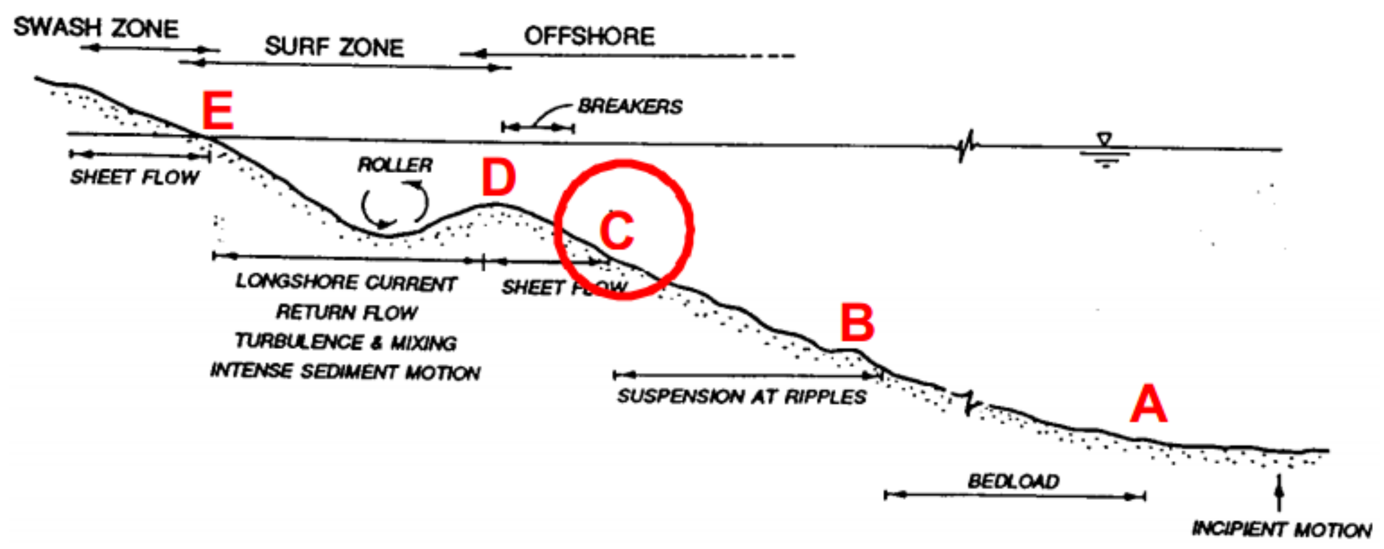


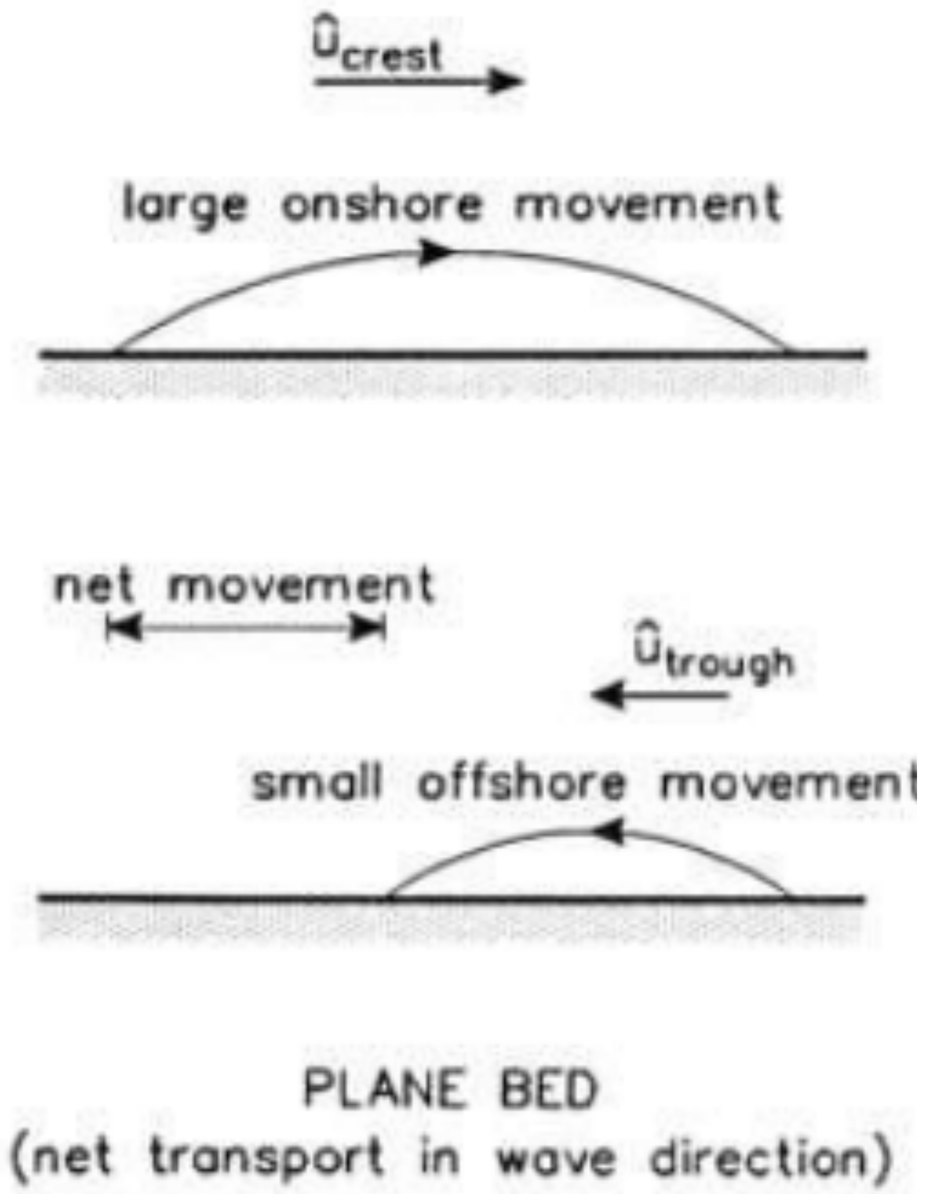
Skewed

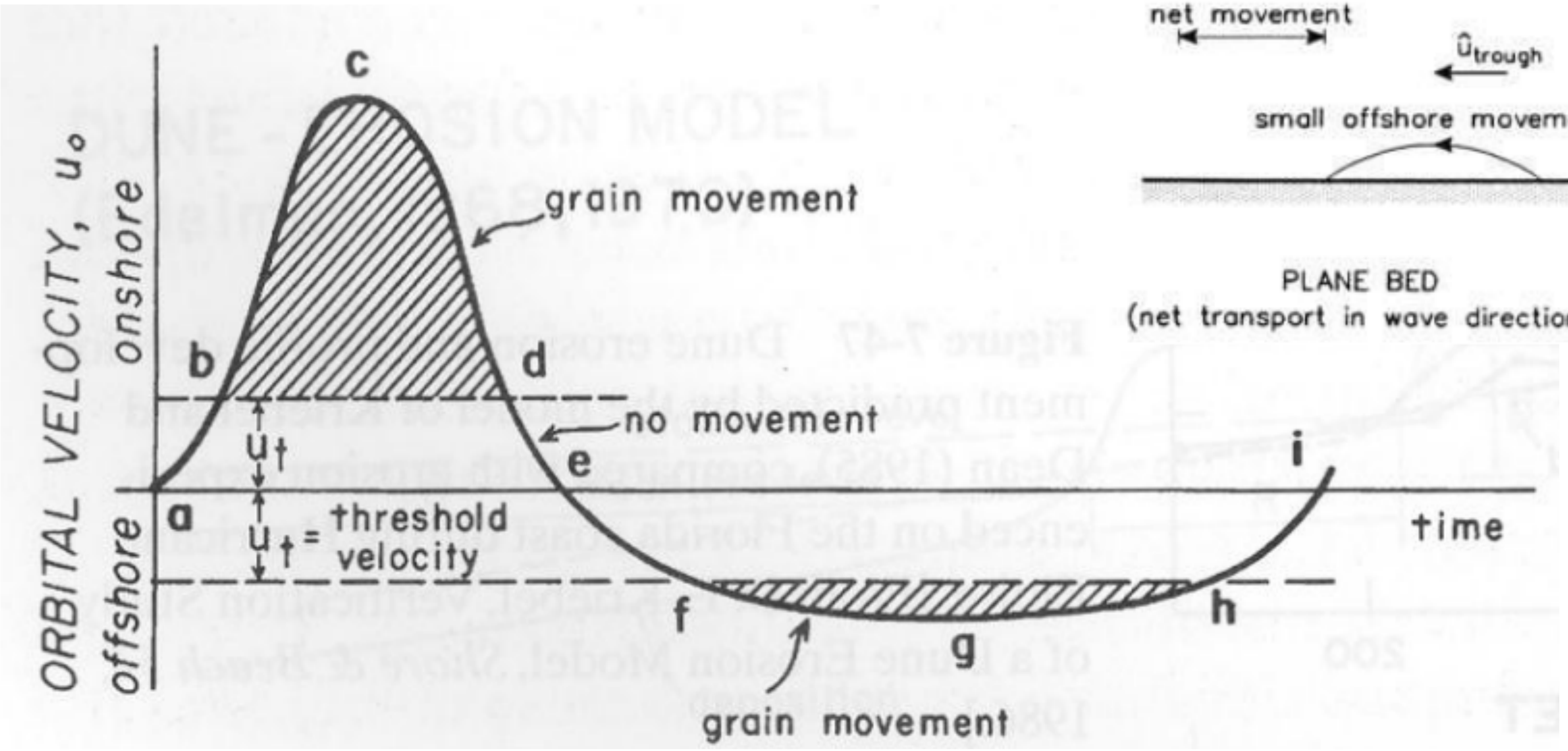


Cross-shore transport

Skewed waves

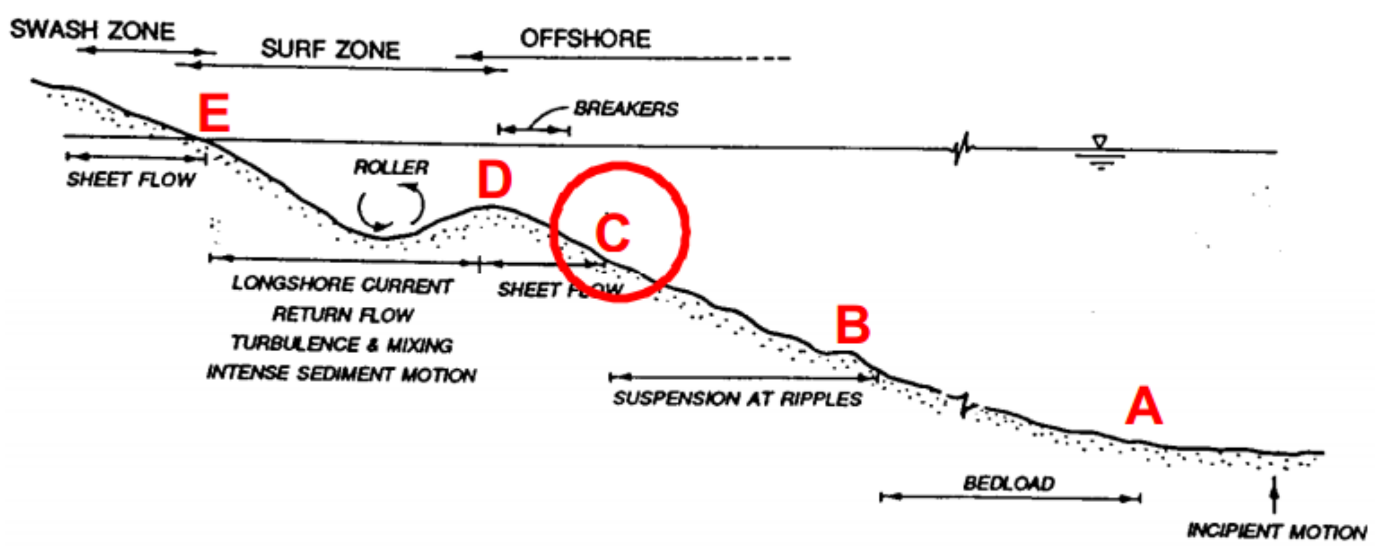






Cross-shore transport

Skewed waves

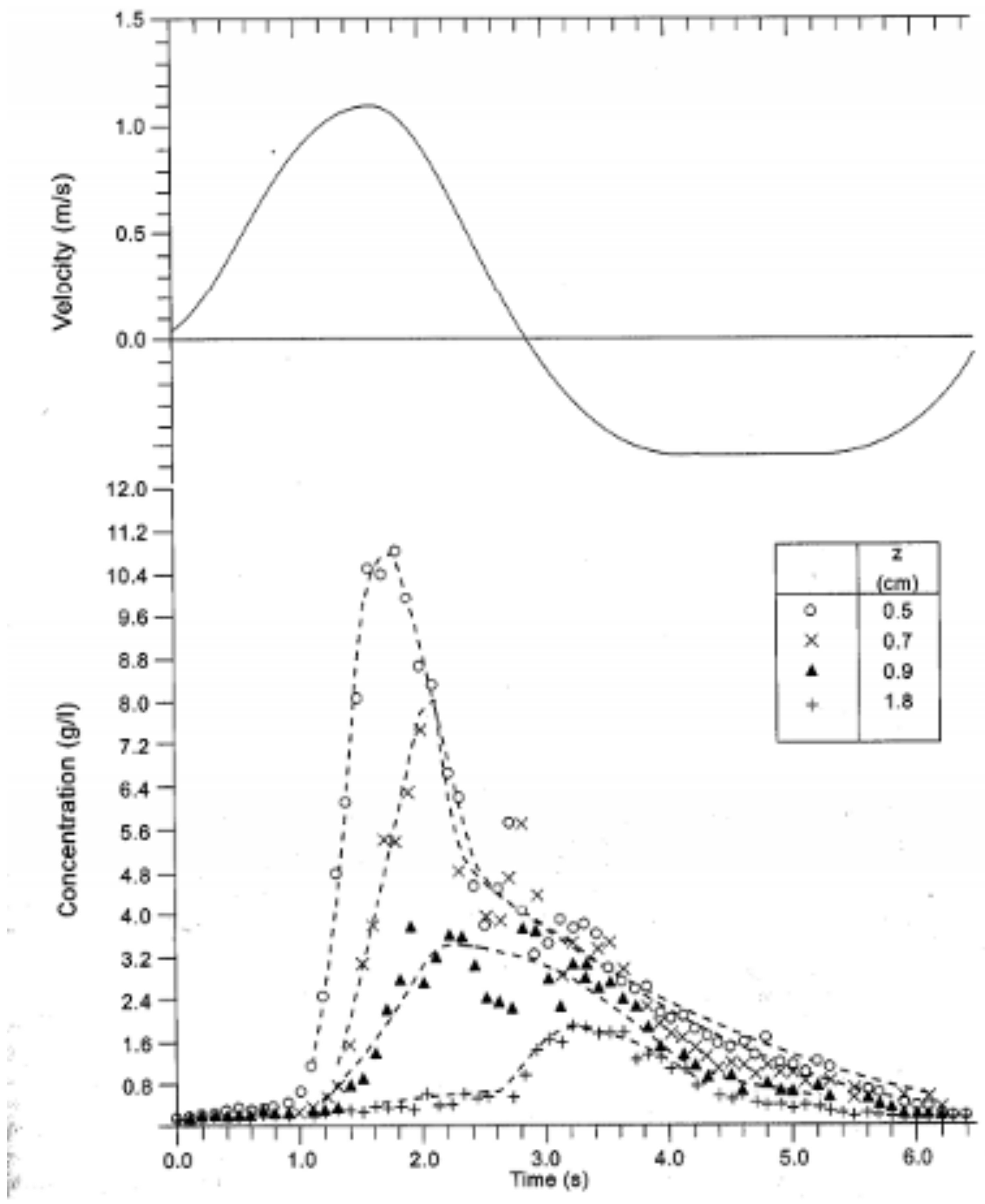


- Skewed waves stir and transport sediment

- Near the bed concentration in phase with u
  => onshore transport

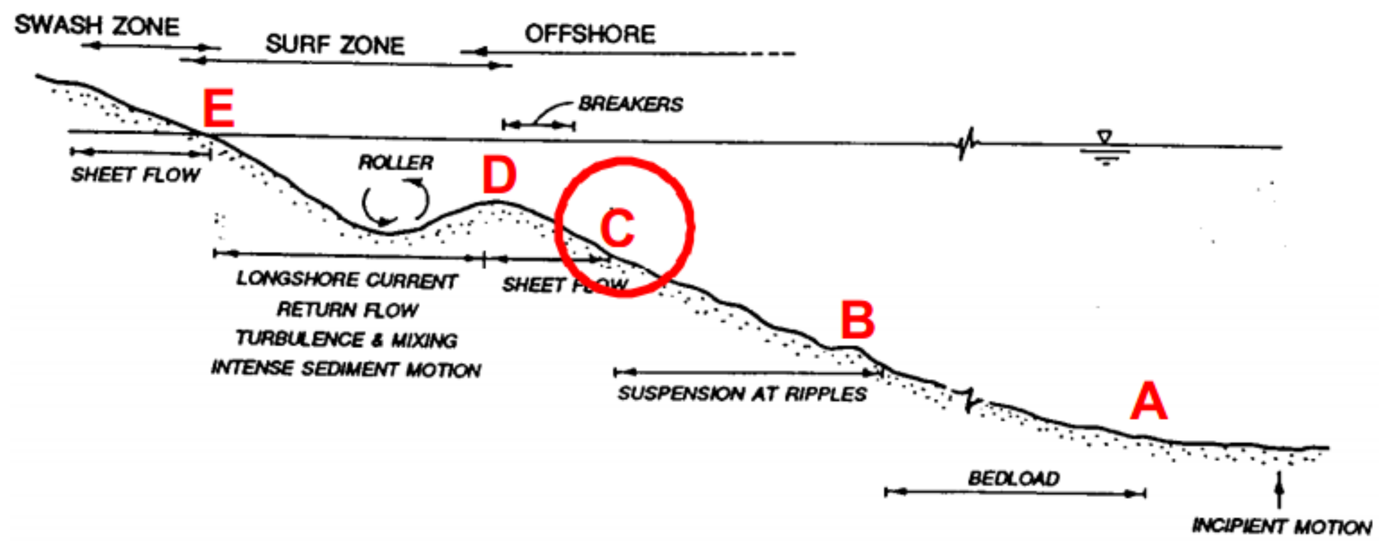
- Higher up in the vertical, lower concentration and phase shift
  => small offshore transport

- Overall effect
  => onshore transport



Cross-shore transport

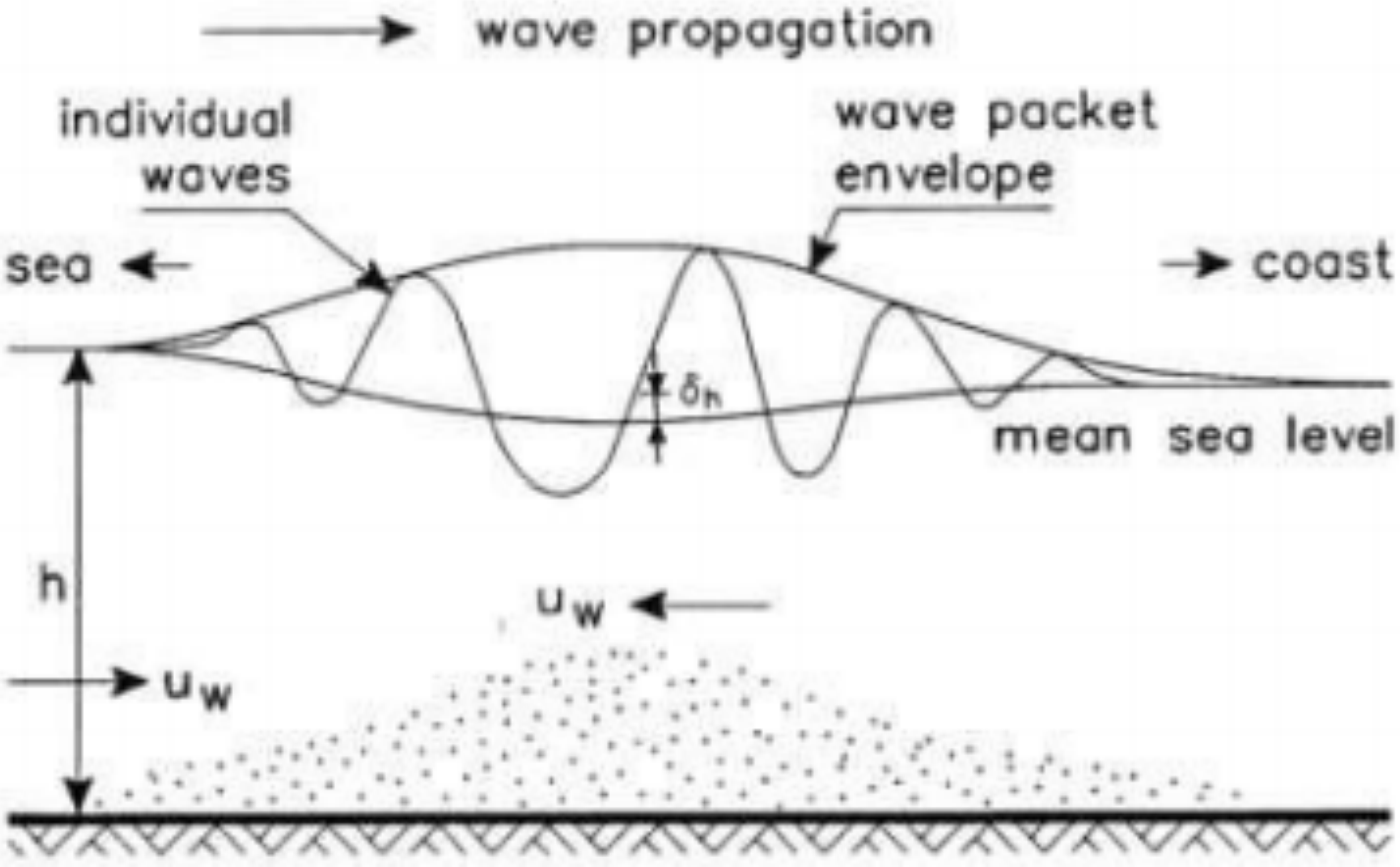
Infragravity



- Bound infra gravity waves transport sand stirred by gravity waves

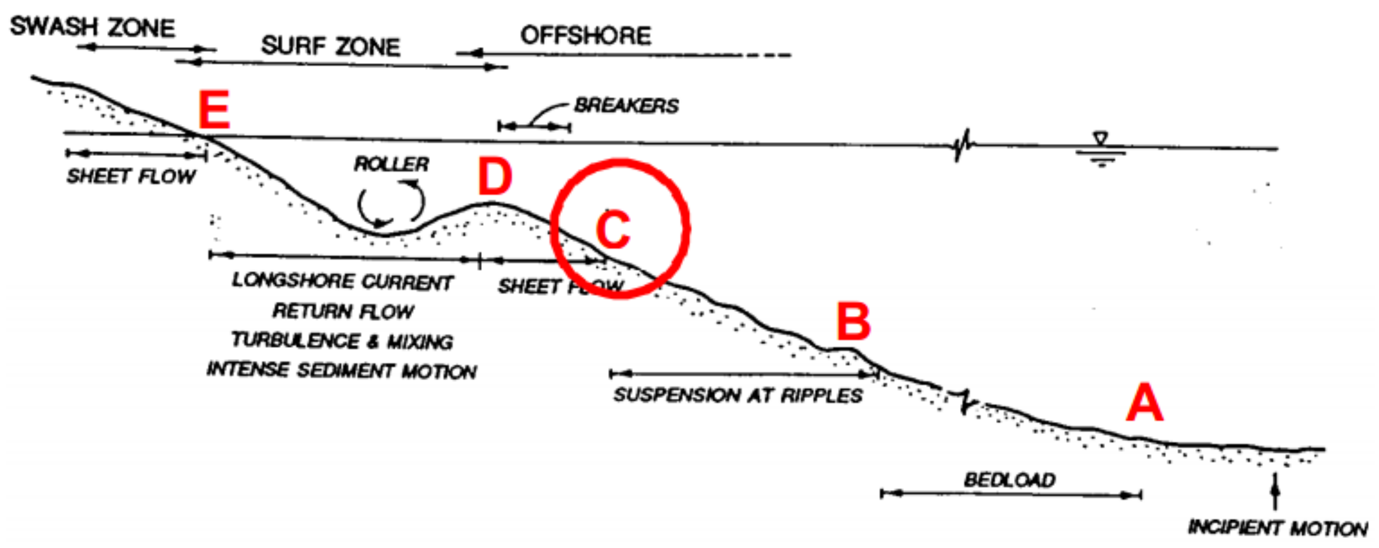
- Large concentrations under high waves in the group coincide with bound infra gravity trough (offshore infra gravity orbital motion)

- Overall effect
  => offshore transport



Cross-shore transport

Balance

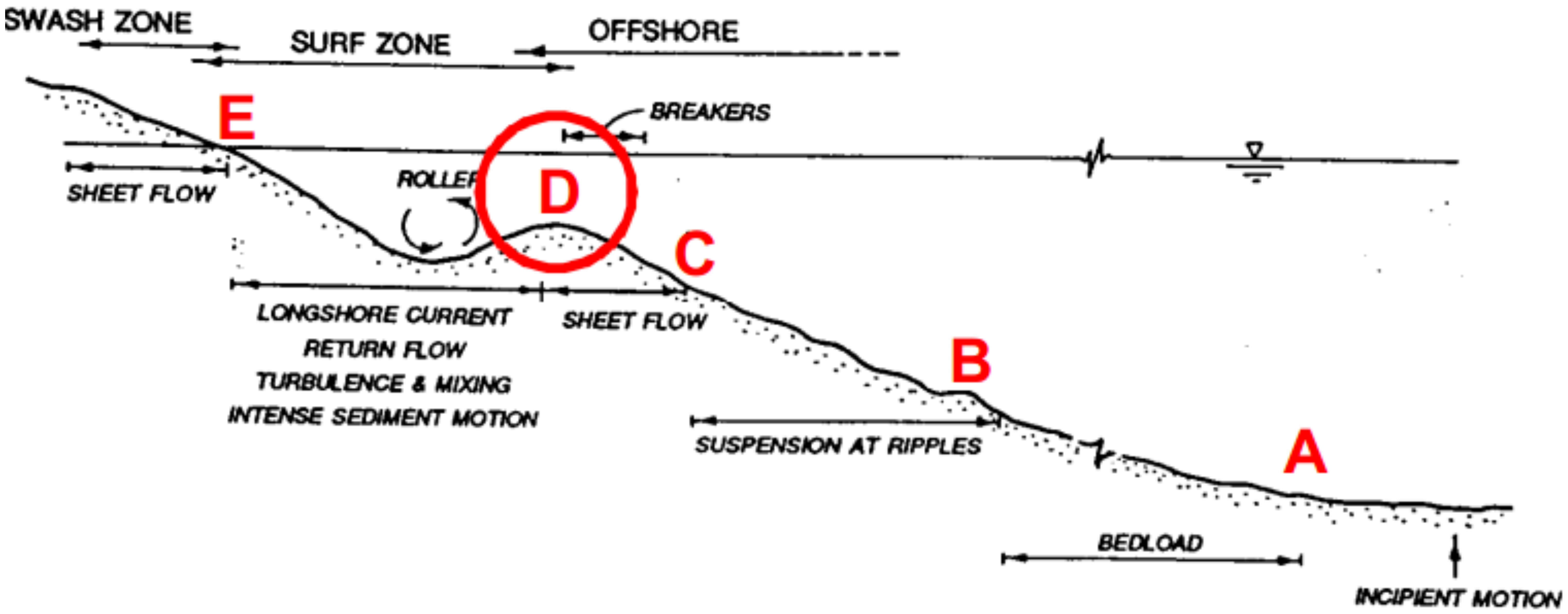


- Skewed waves : onshore transport

- Bound infragravity waves : offshore transport

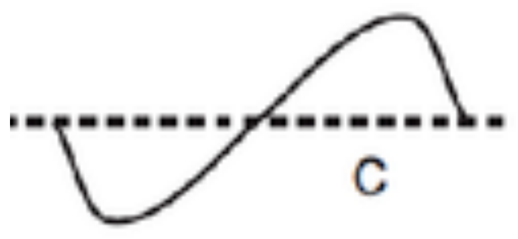
Overall effect
=> onshore >> offshore

Cross-shore transport

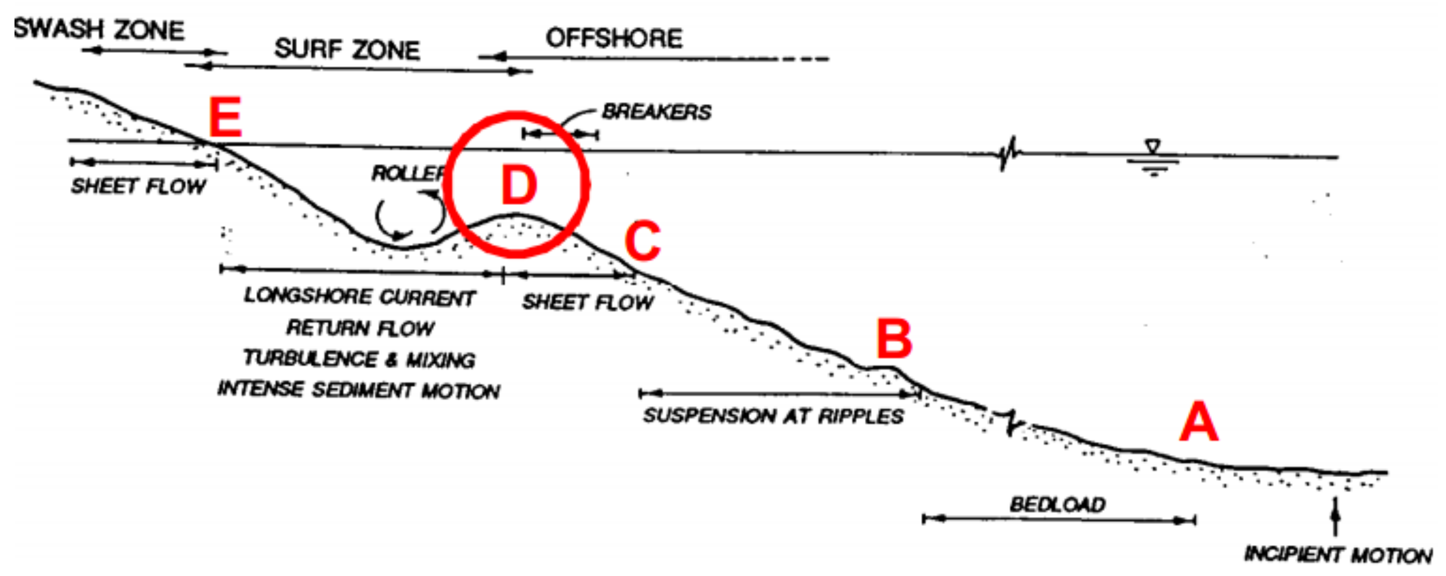


Cross-shore transport

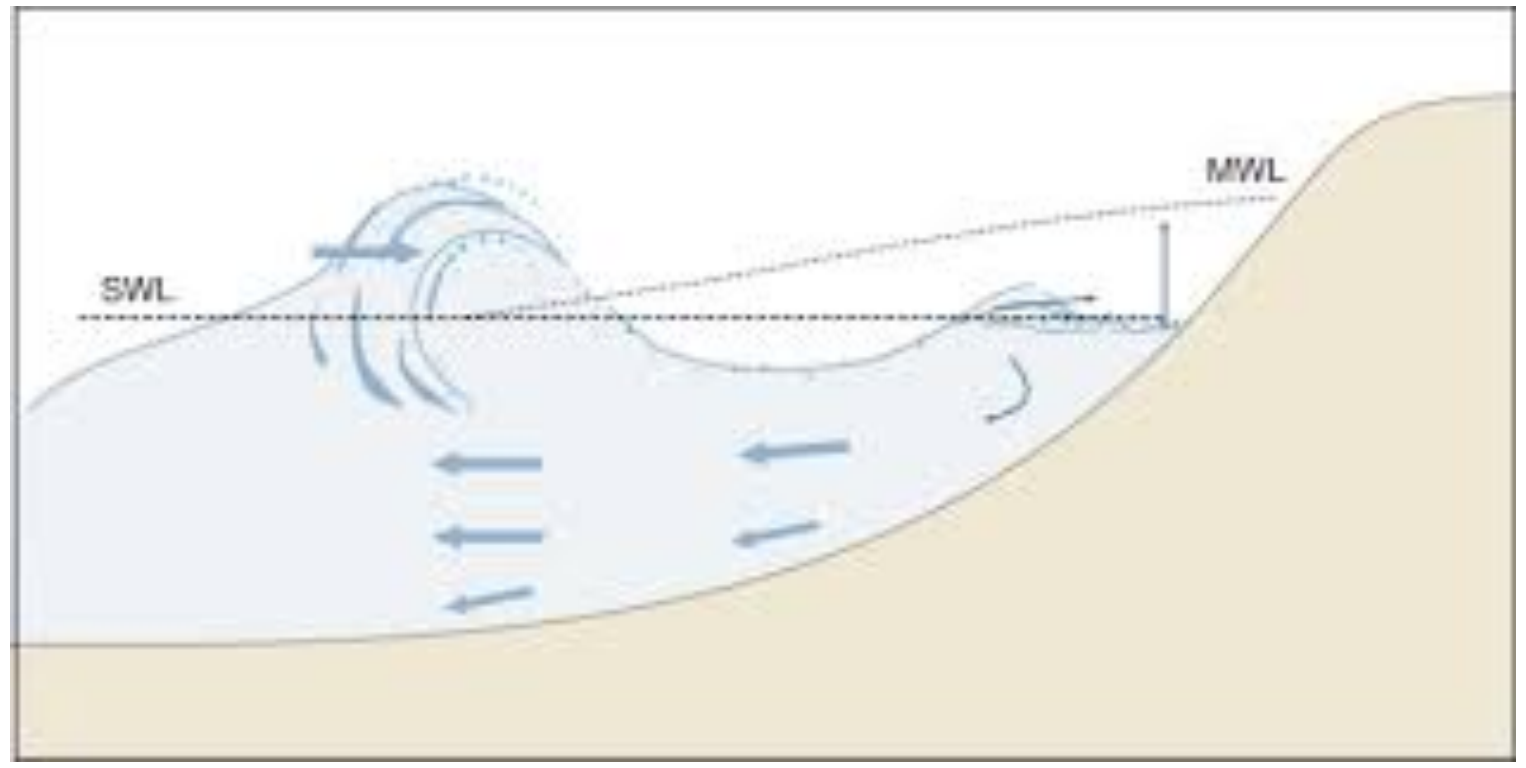
Asymmetry

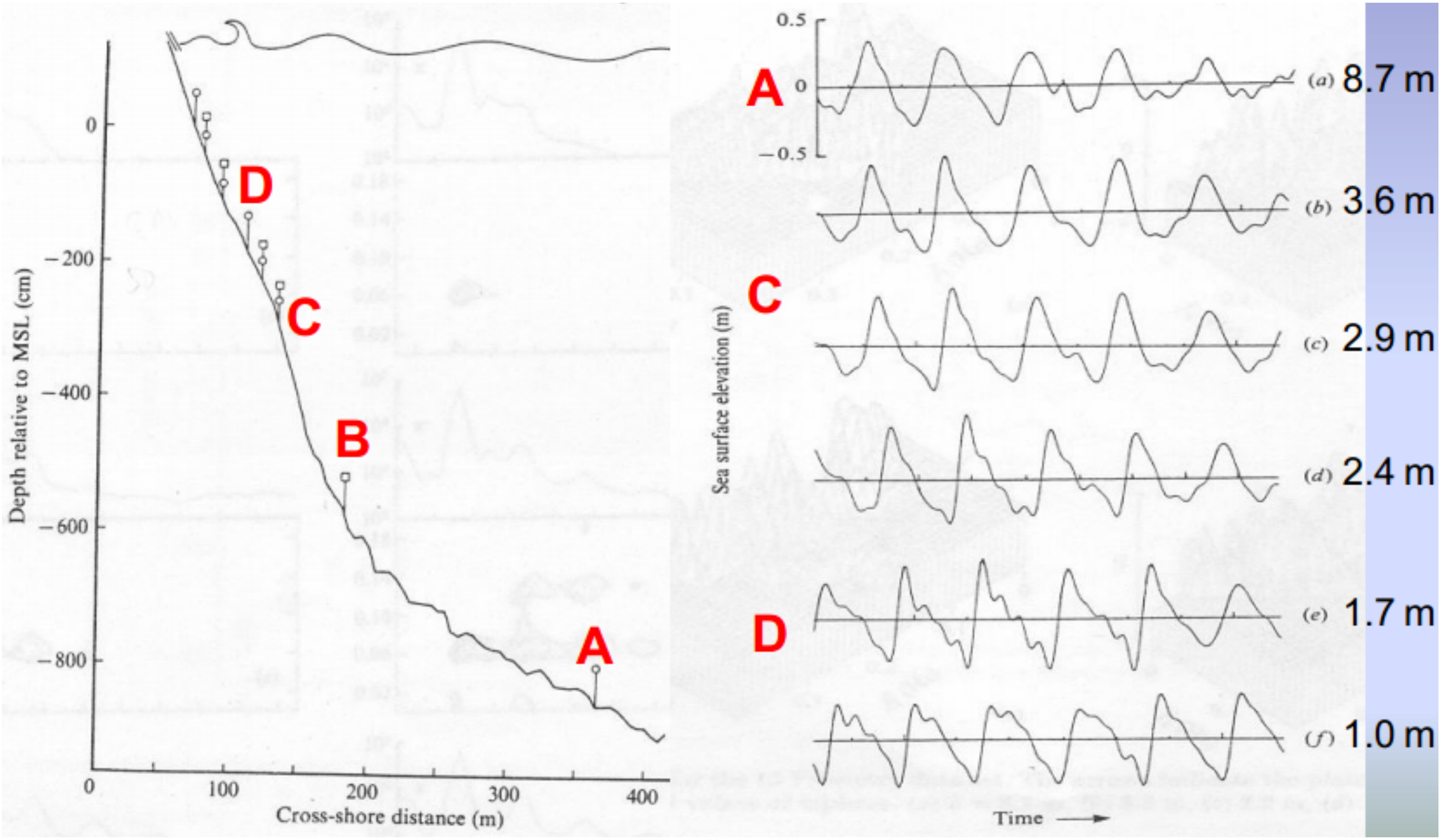


Asymmetric



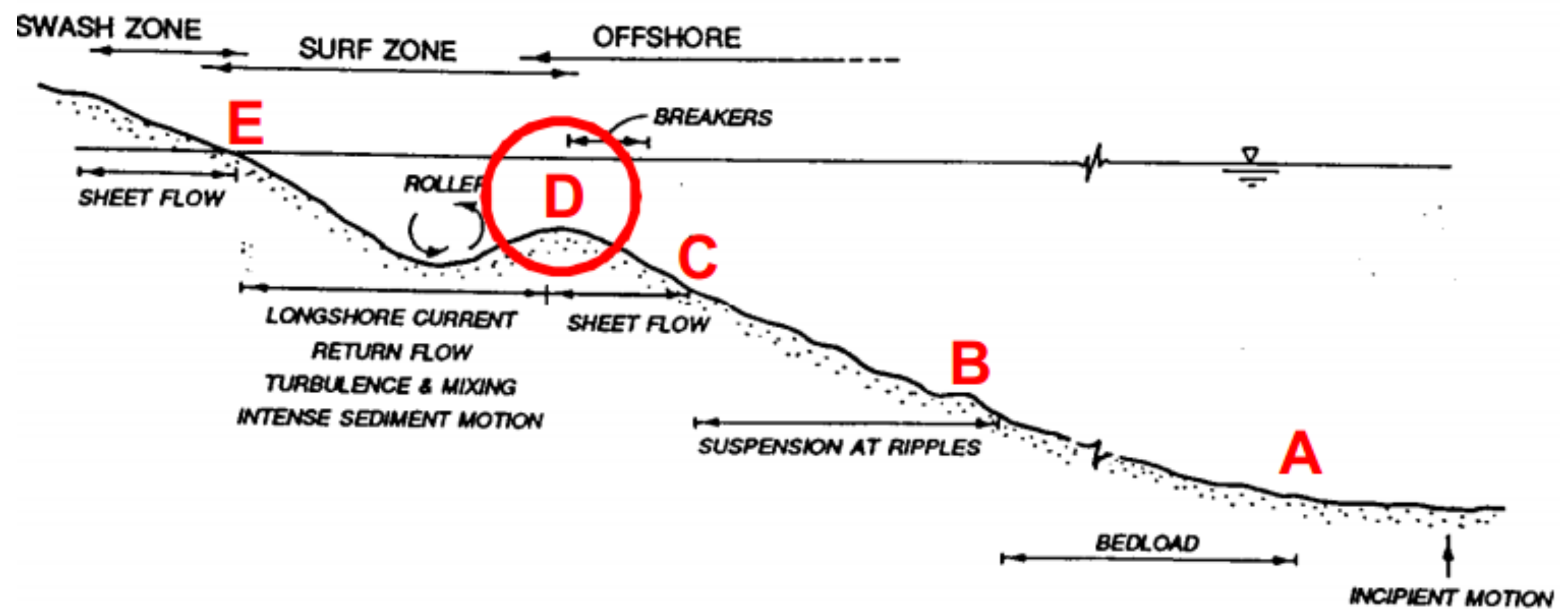
Location D :
- Asymmetric waves
- Undertow
- Breakers

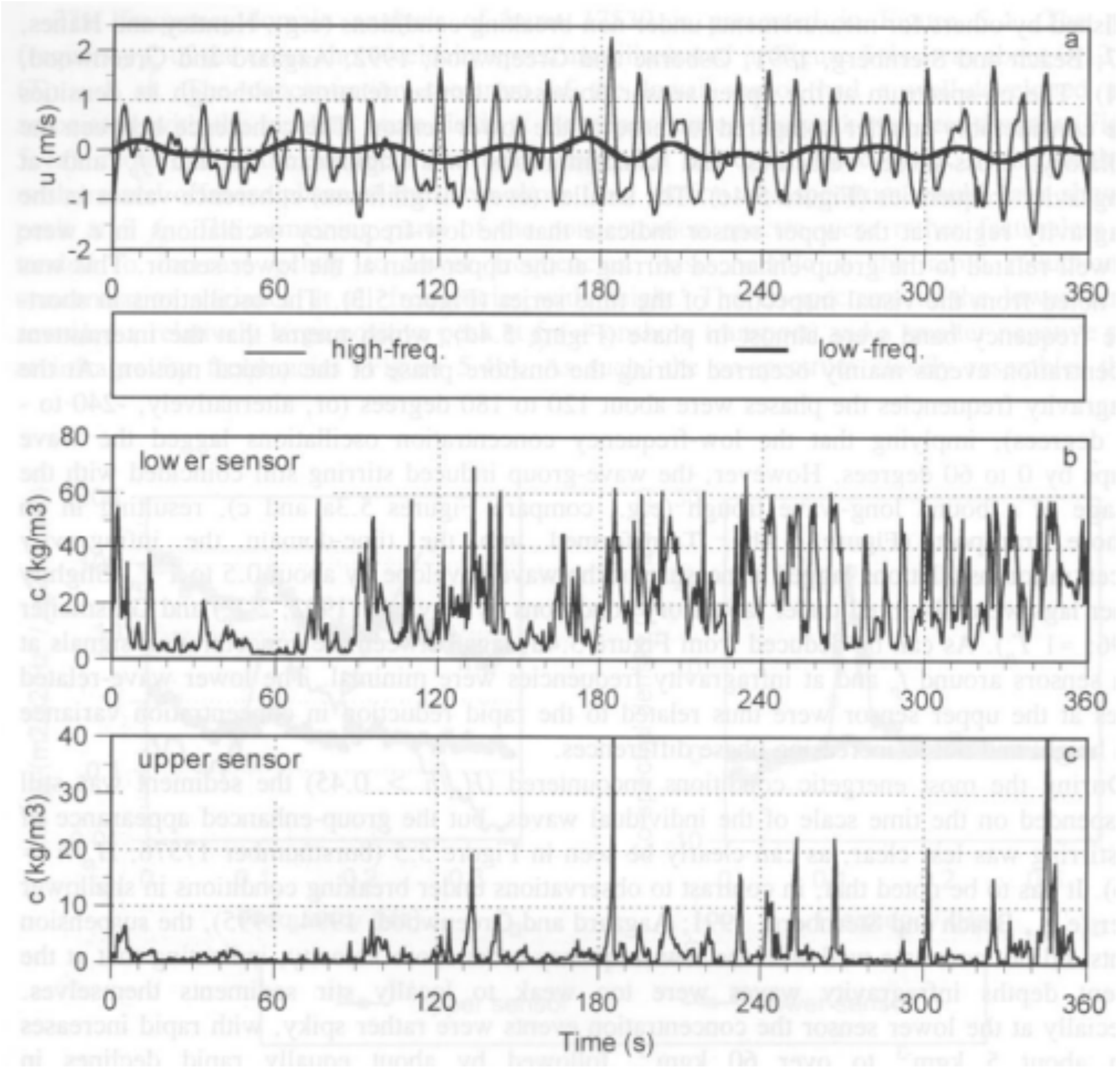




Cross-shore transport

Undertow



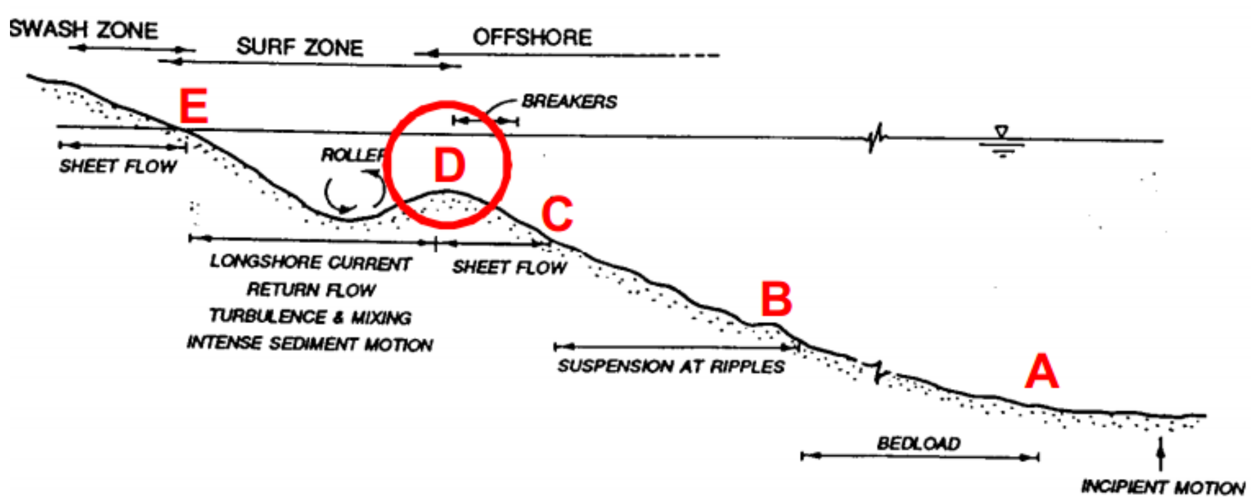


Undertow

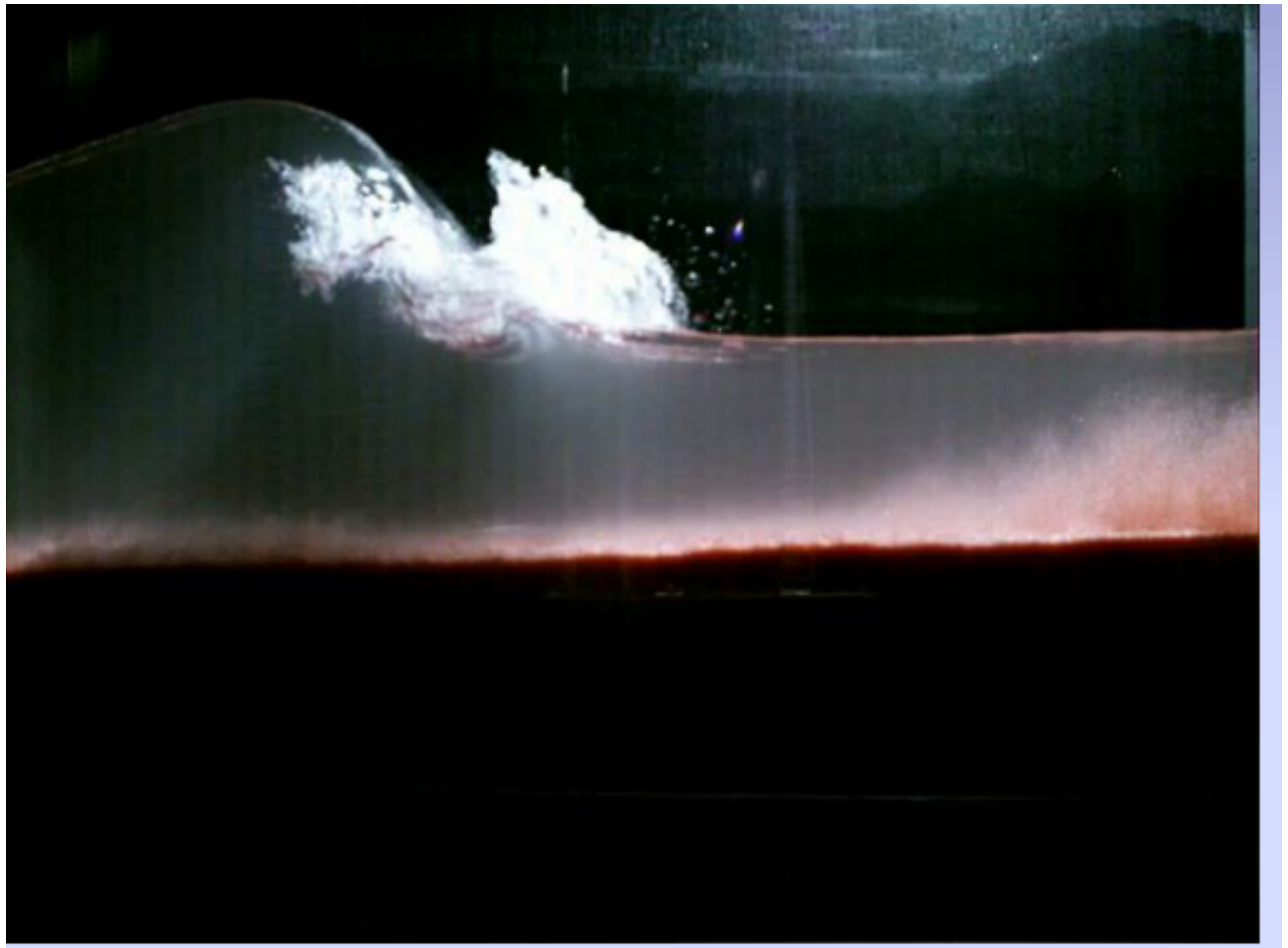
Breaking

Cross-shore transport

Breakers



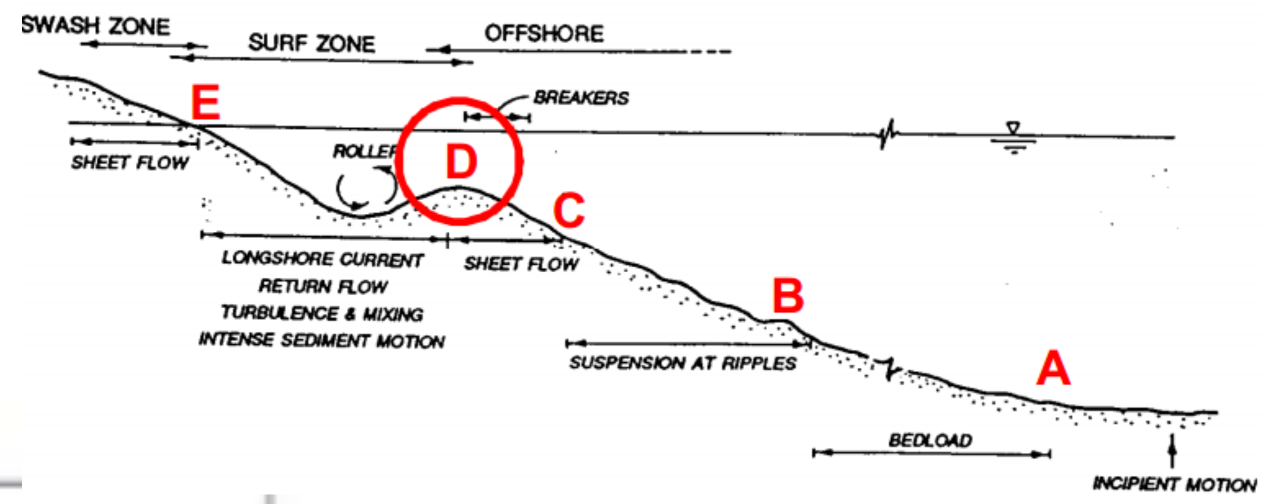
very large sediment concentrations under plunging breakers



Sediment is stirred by breaking-induced turbulence, not by near-bed wave-driven flow. Effect on transport is unclear.

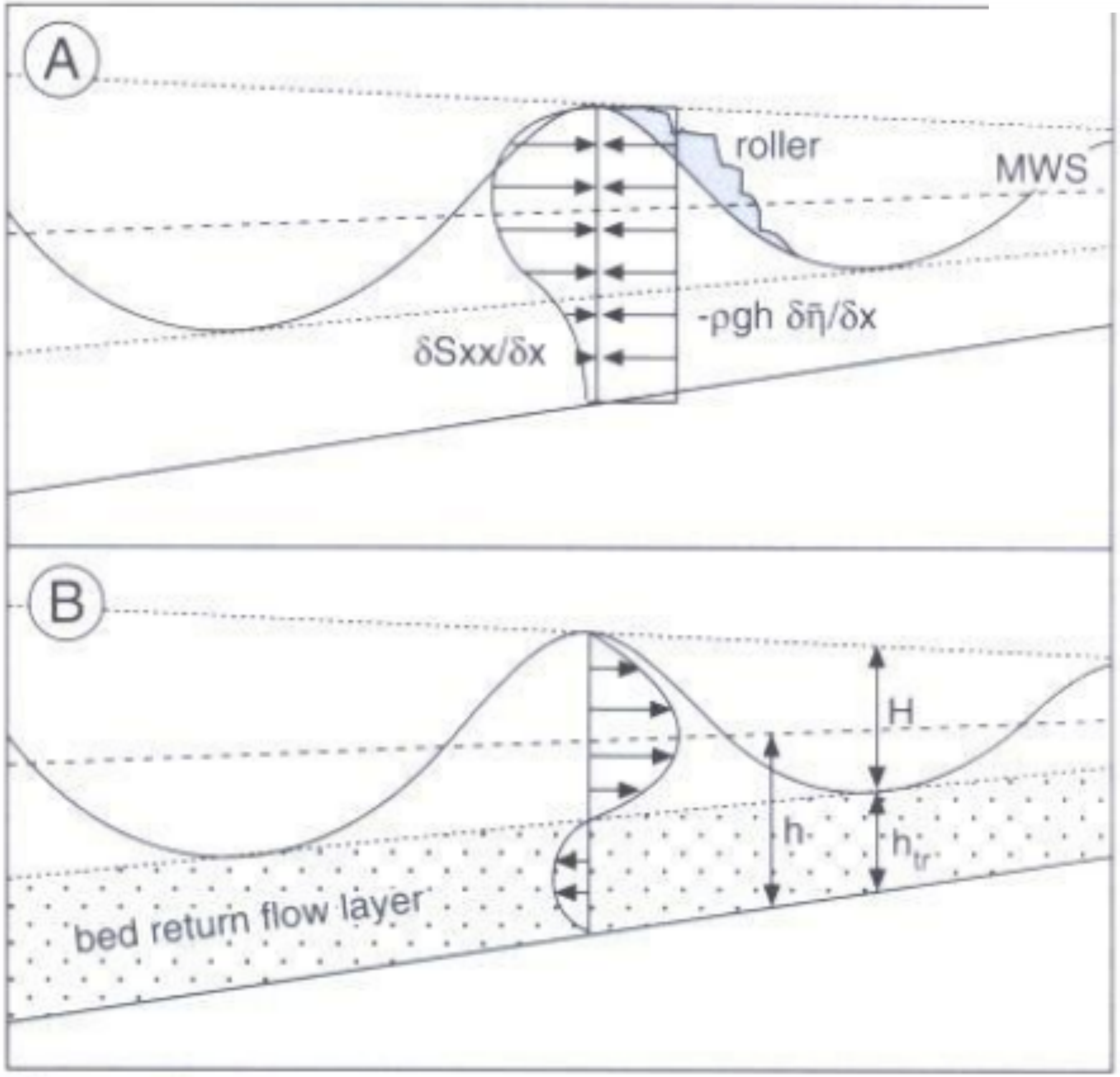
Cross-shore transport

Breakers



- large sediment concentrations
- undertow

=> transport direction ??



Cross-shore transport

Breakers

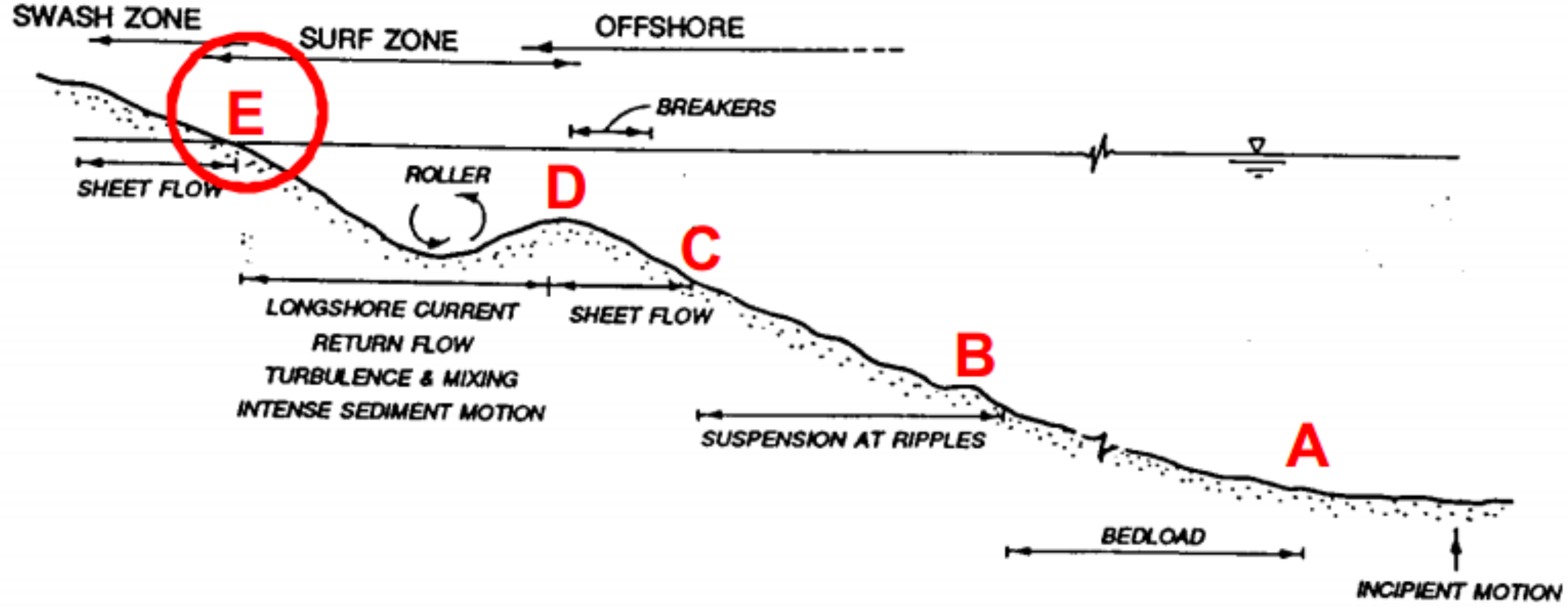
Breaking waves zone :

- Breaking, asymmetric gravity waves stir sediment

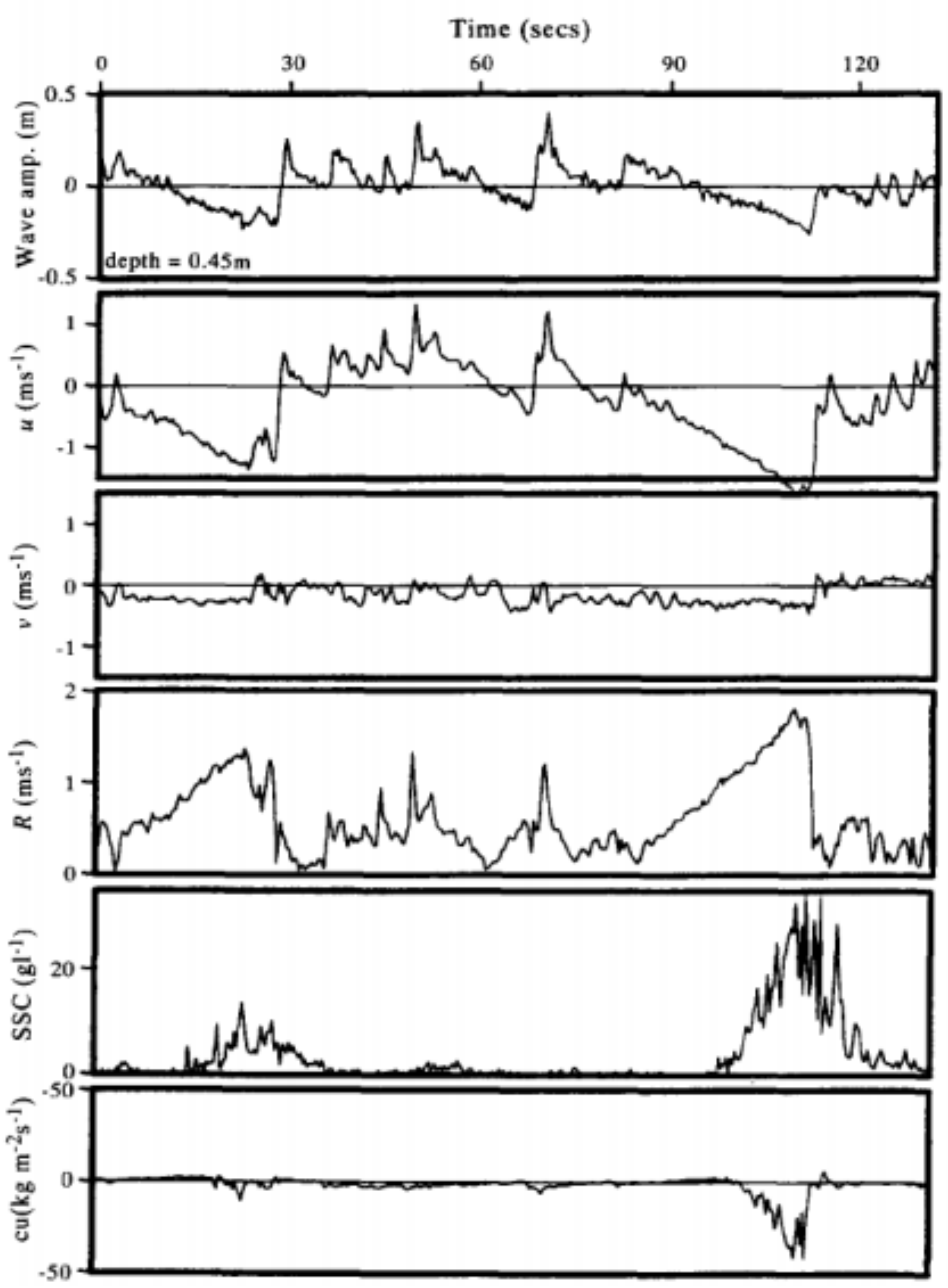
- Sediment transport
  - Onshore by asymmetric waves
  - Offshore by undertow

- In general
  => few breaking waves => onshore transport
  => many breaking waves => offshore transport

Cross-shore transport



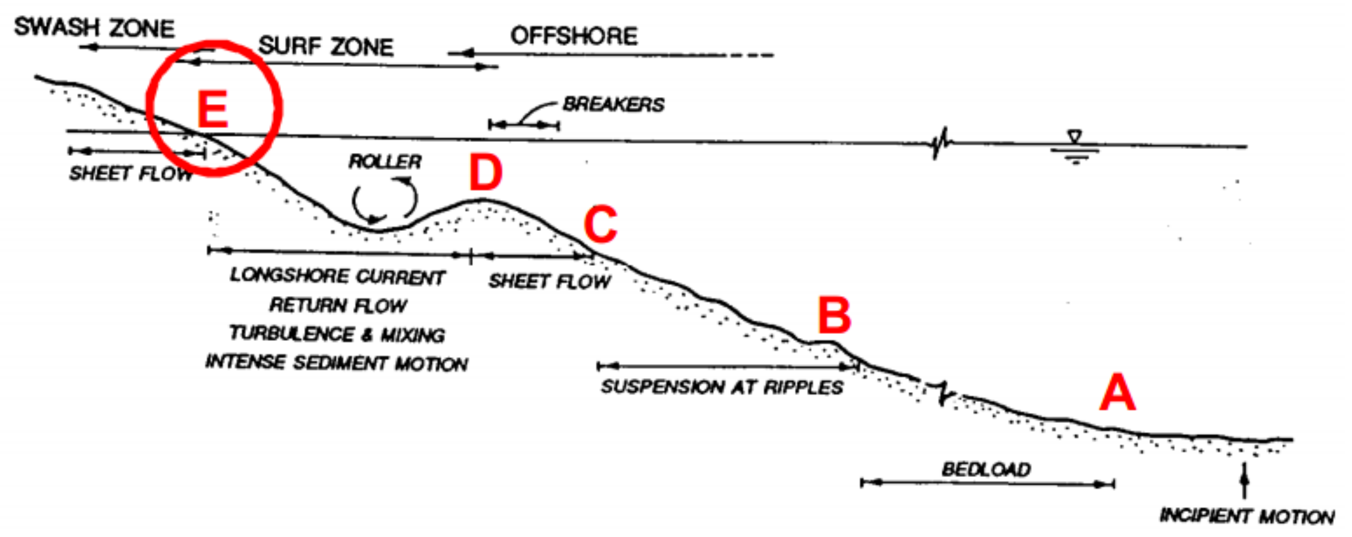
Cross-shore transport



U

C

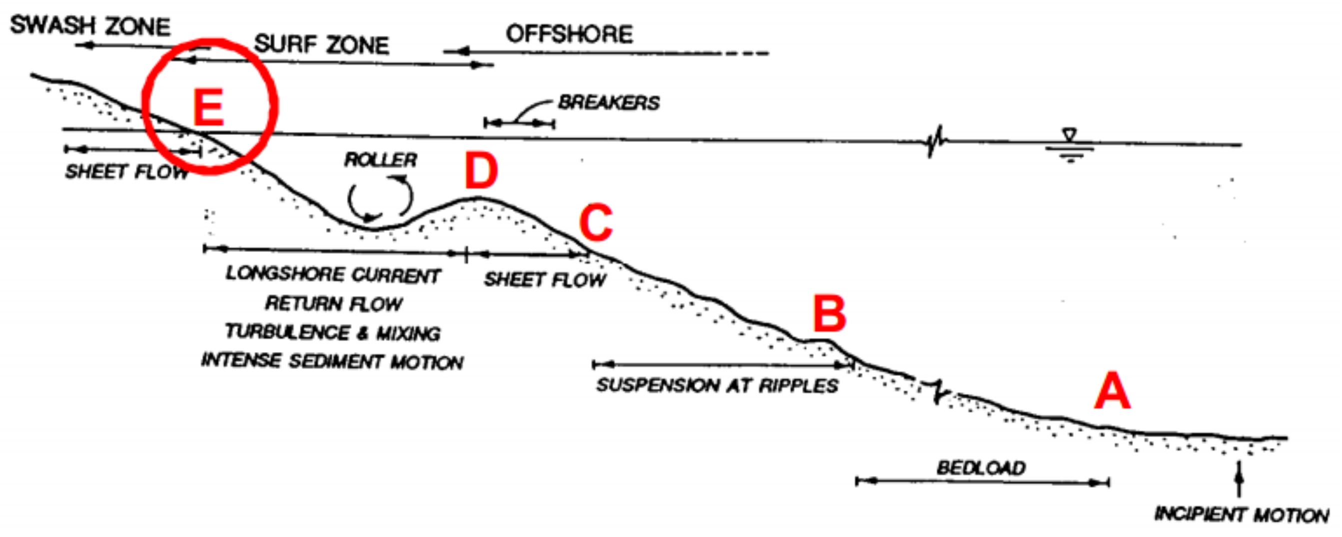
U.C



Location E :

- infragravity waves
- Undertow

Cross-shore transport



Swash zone (storm case) :

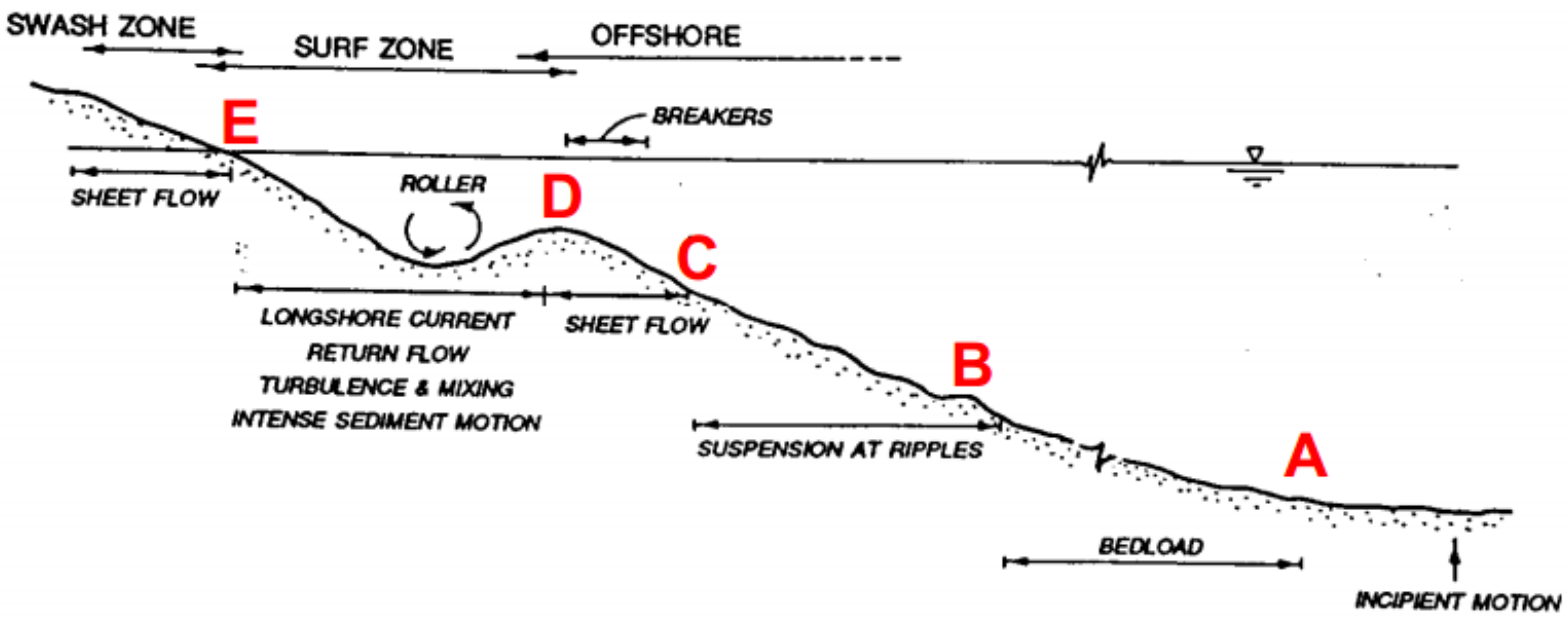
- Water motion dominated by infragravity waves

- Large concentrations (breaking-induced turbulence)

- Sediment transport :
  - unclear
  - field experiments : onshore and offshore …

- Potential offshore contributions by undertow

Cross-shore transport



A : no transport
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 :

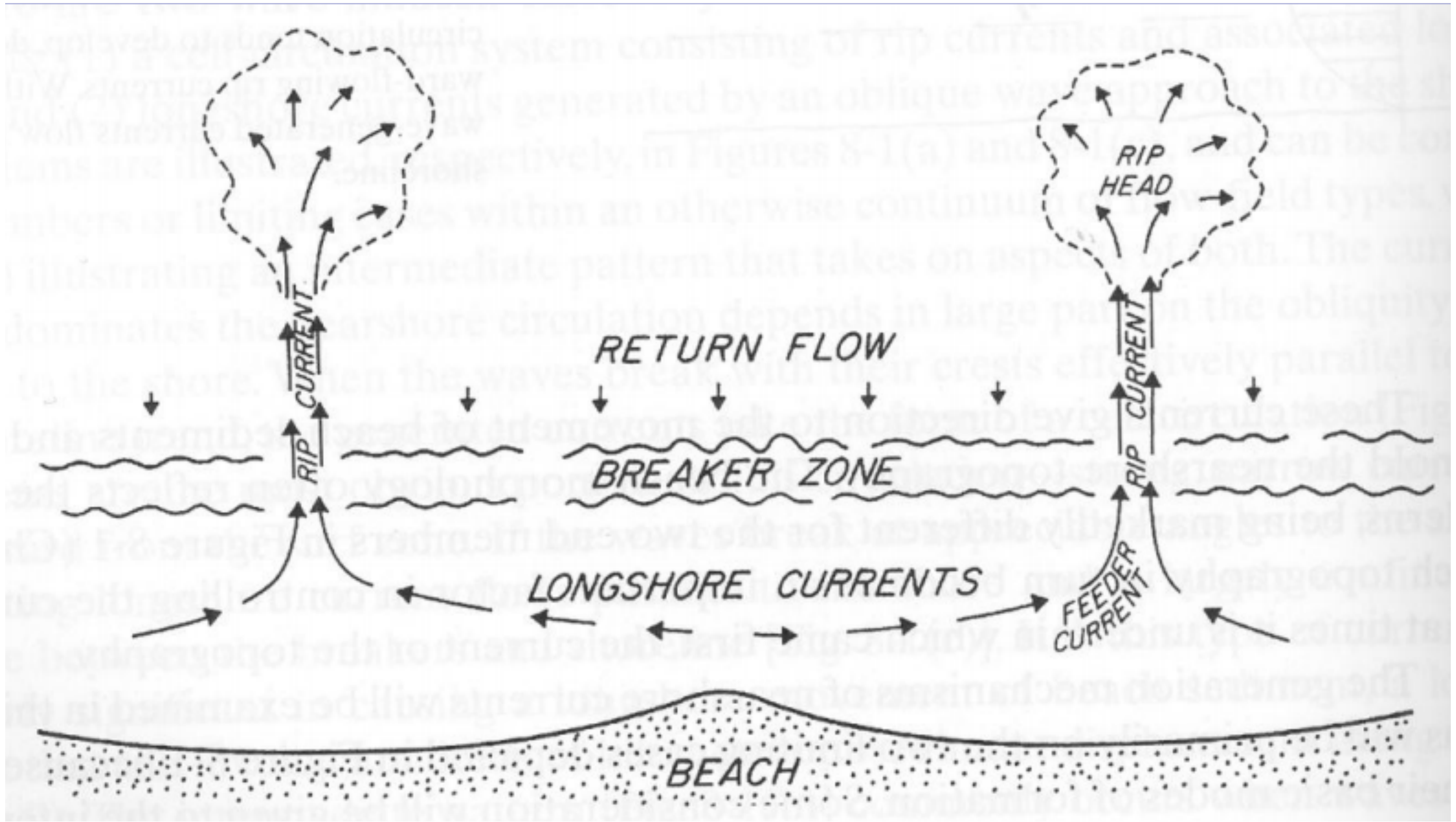
- Locations A-D shift as a function of offshore wave conditions
- A specific cross-shore location experiences many different conditions during a year

- 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

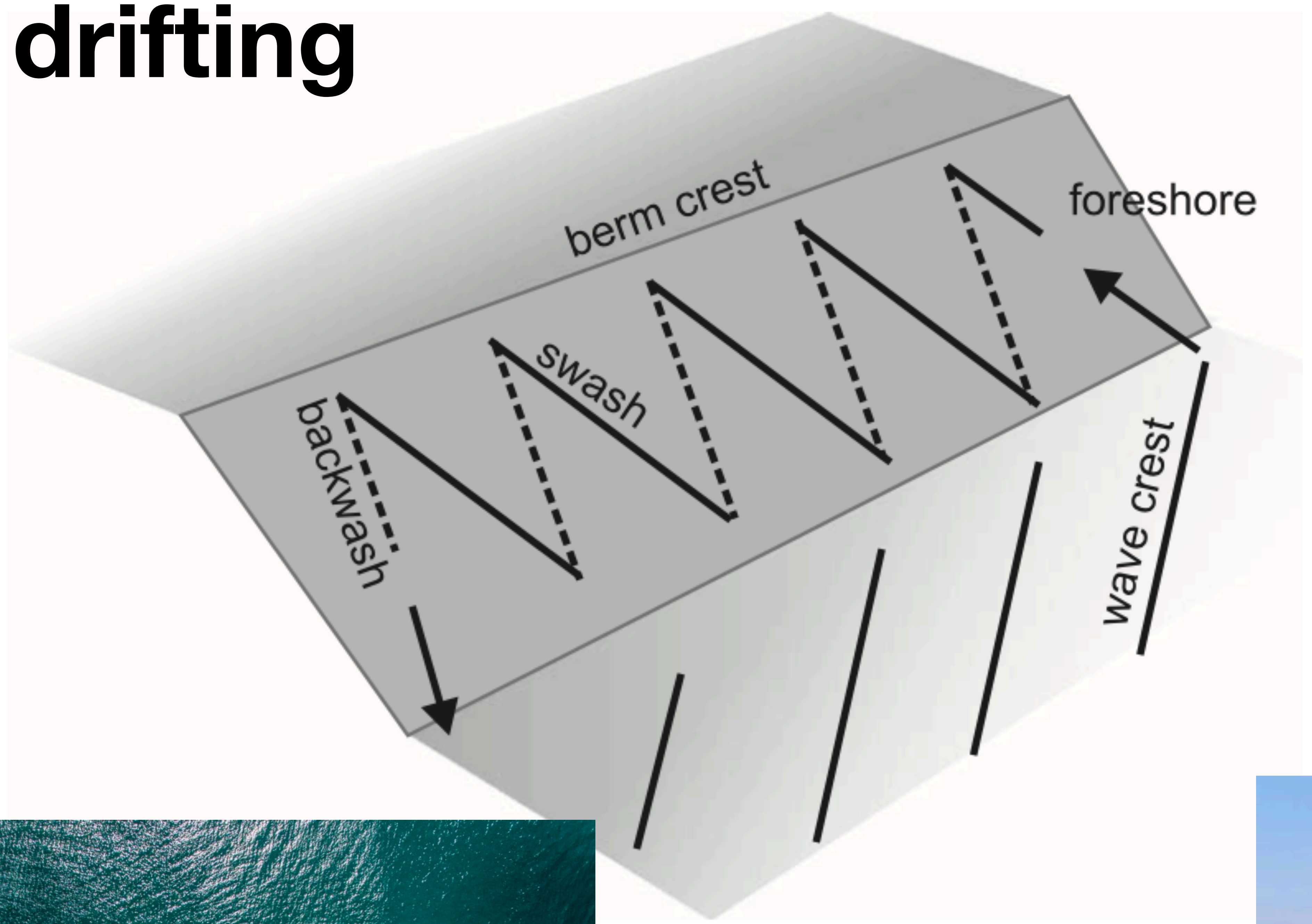
Gravity waves stir sediment
Breaking induced alongshore current transport sediment
=> Littoral drift

Drivers of sediment transport in the beach and nearshore zone :

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

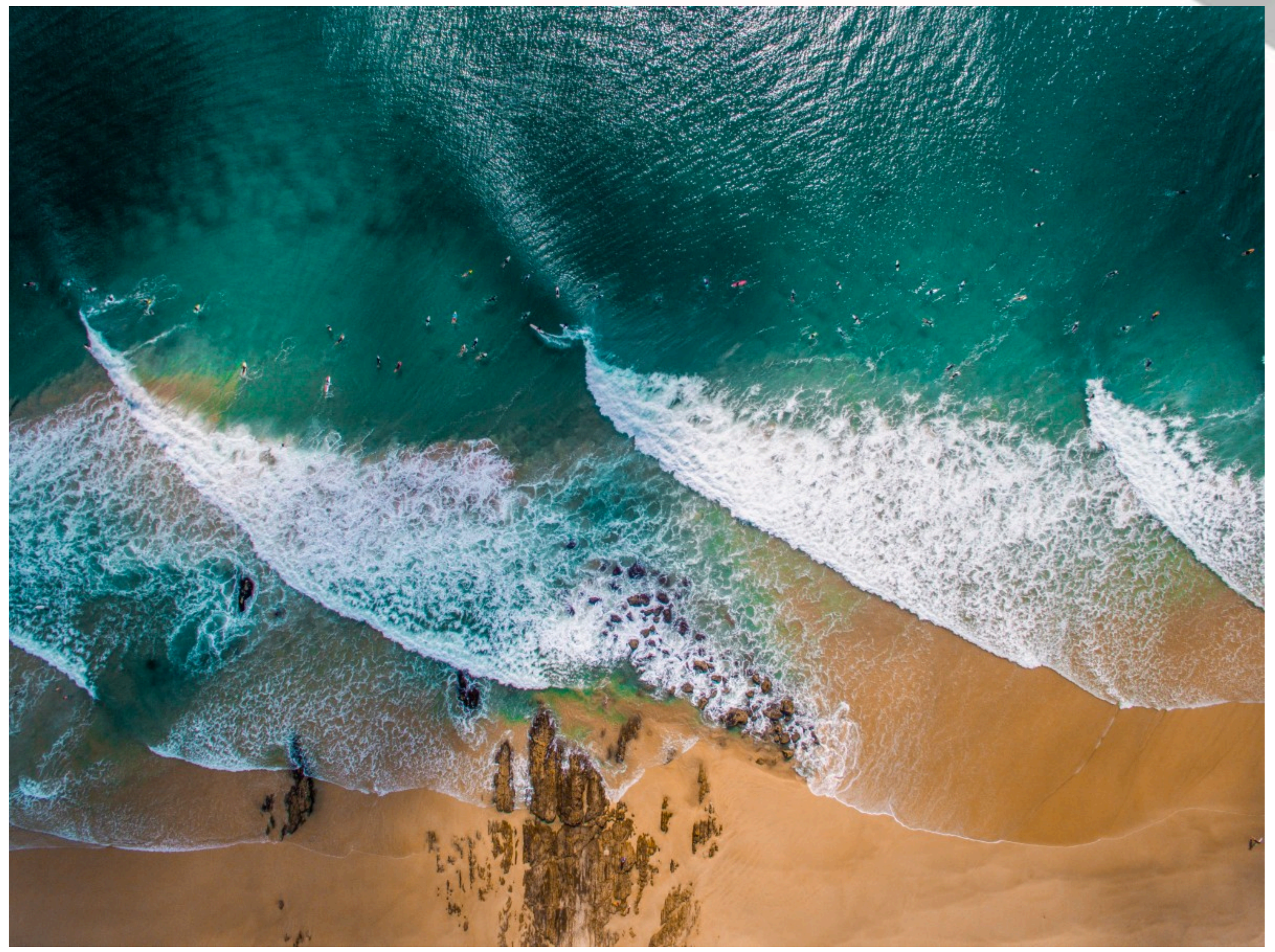
Alongshore transport

Beach drifting



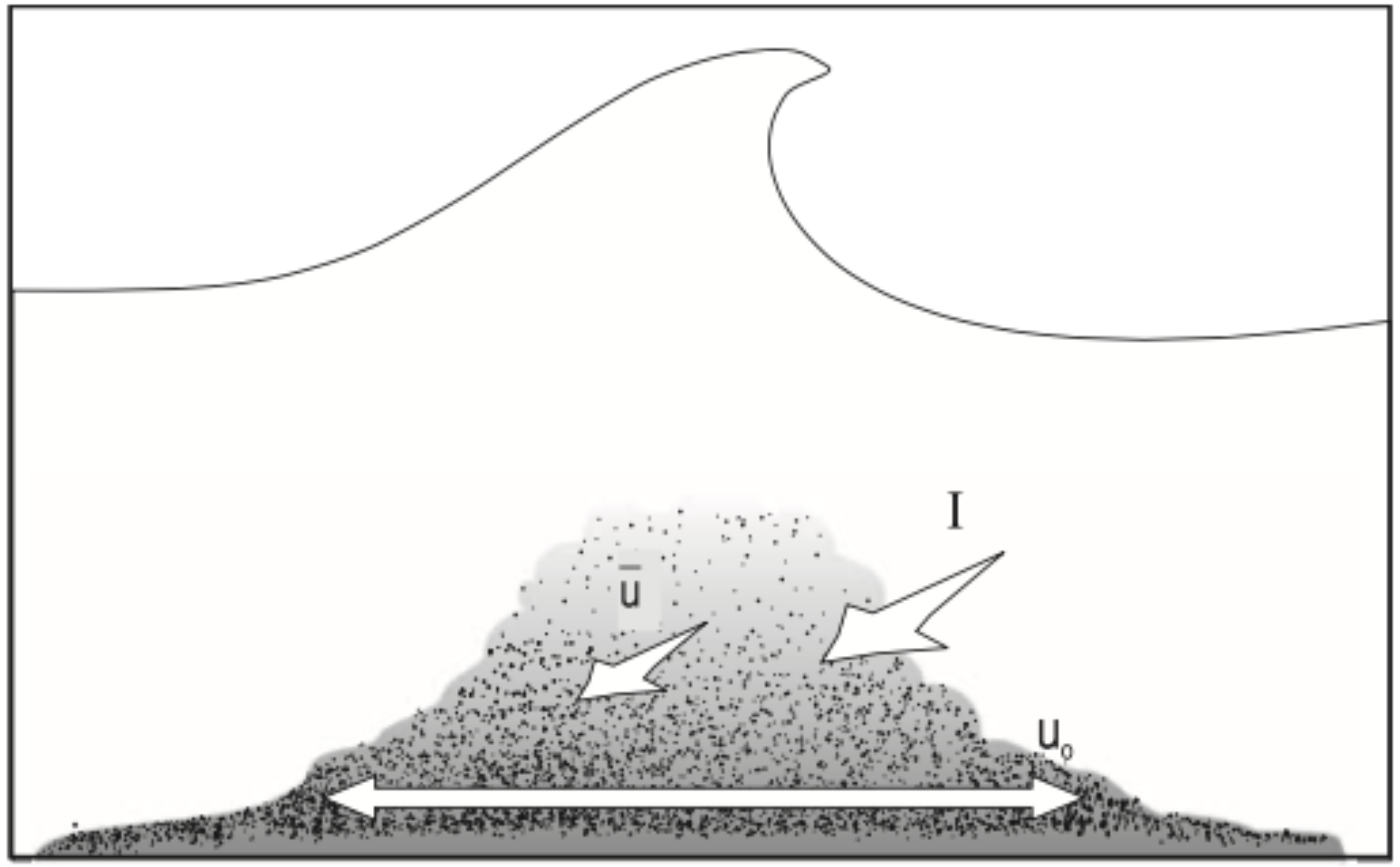
- Swash run-up perpendicular to the wave crest
- Return flow in the backwash occurs parallel to the beach slope (gravity)

=> saw-tooth alongshore motion



Alongshore transport

Surf zone transport : summary



- no transport from oscillatory wave motion
- sediment motion set by wave motion and breaking induced current
- alongshore currents generated in the surf zone by waves breaking at an angle to the shoreline
- wind and tides currents

Alongshore transport

Examples

Alongshore transport

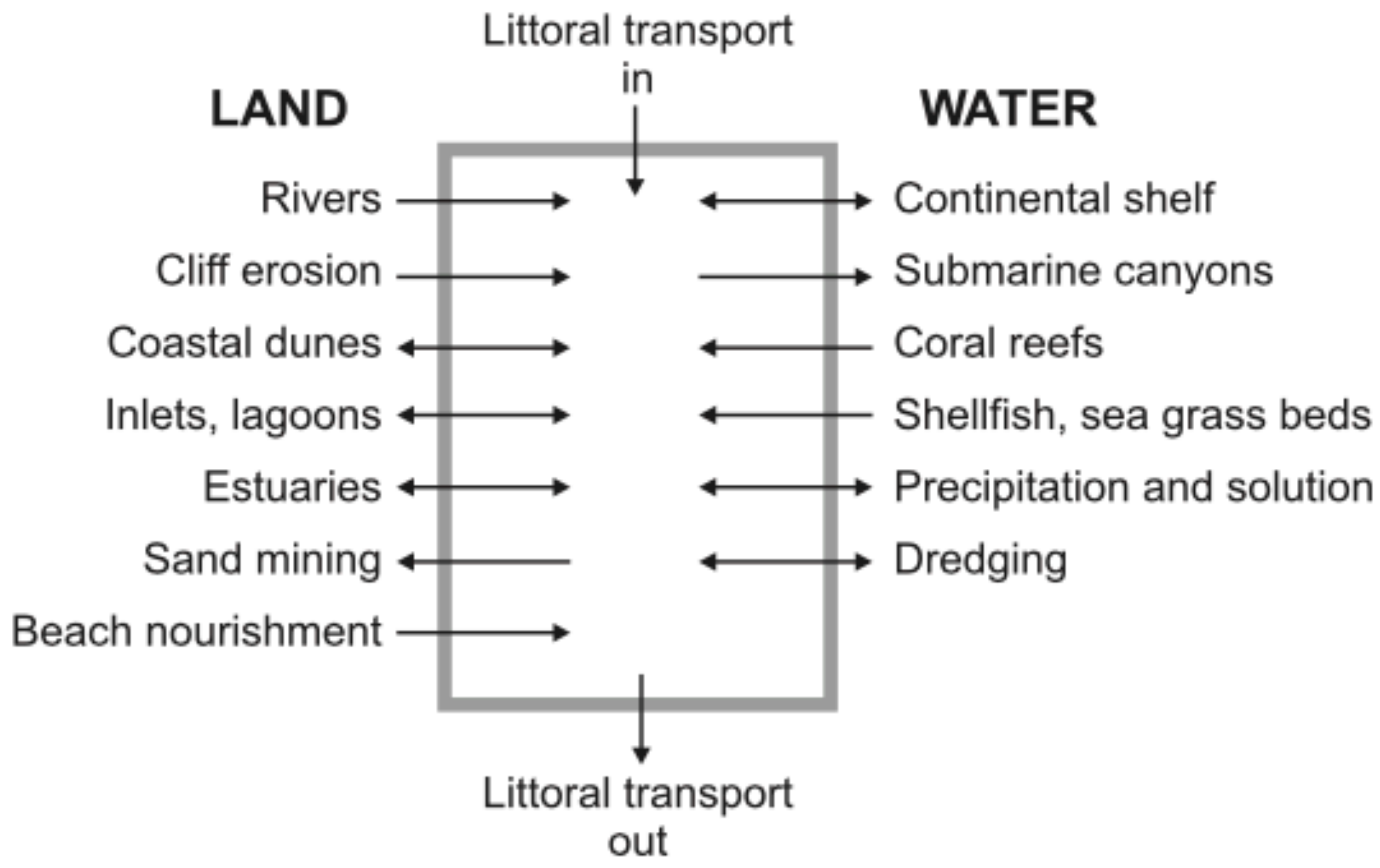
Prediction

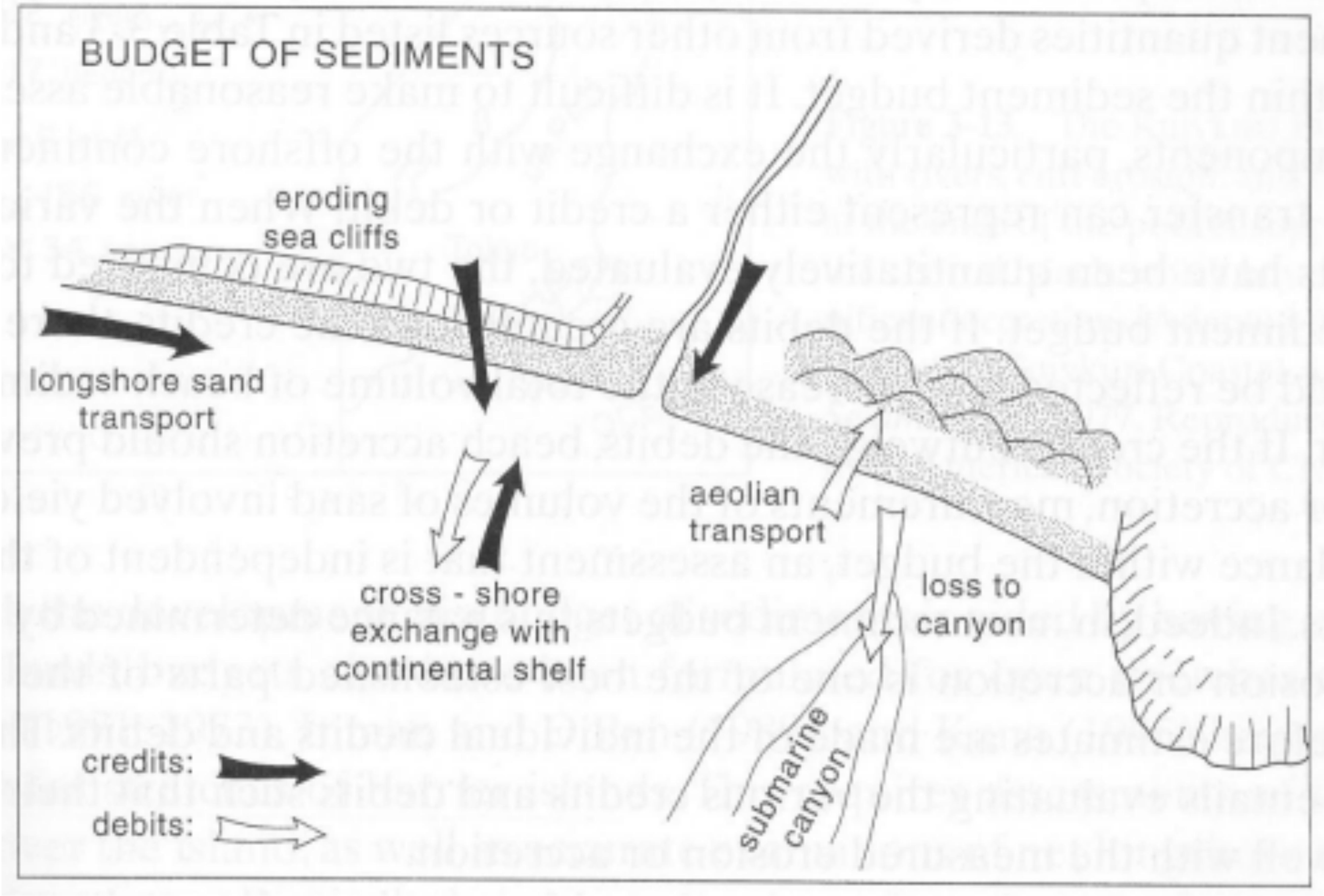
Longshore transport empirical formulae :

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)

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

Conclusion

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

- Very fast review, non-exhaustive :
  - Cohesive sediments (floculation in the water column) ?
  - Gravels
  - Mangroves, estuaries …

Let’s dive into CROCO !!