BEDFORMS E STRATIFICAZIONE CON FLUSSI OSCILLATORI

Original slides by R.J.Cheel

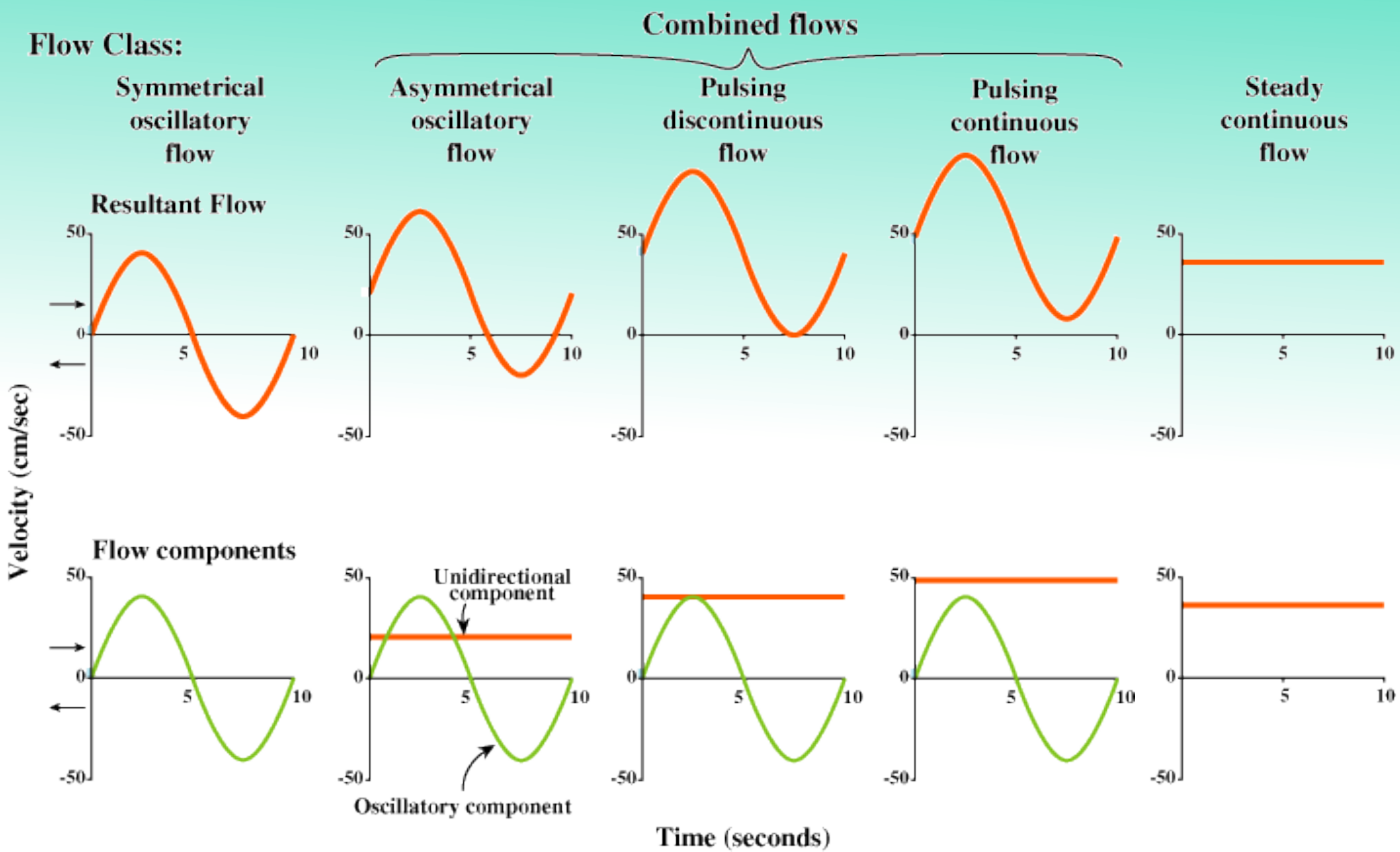
Introduction to Clastic Sedimentology

Chapter 6

http://spartan.ac.brocku.ca/~rcheel/teaching/sedimentology/

Chapter 6. Flow, bed forms and stratification under oscillatory and combined currents

The continuum from oscillating to unidirectional flows:

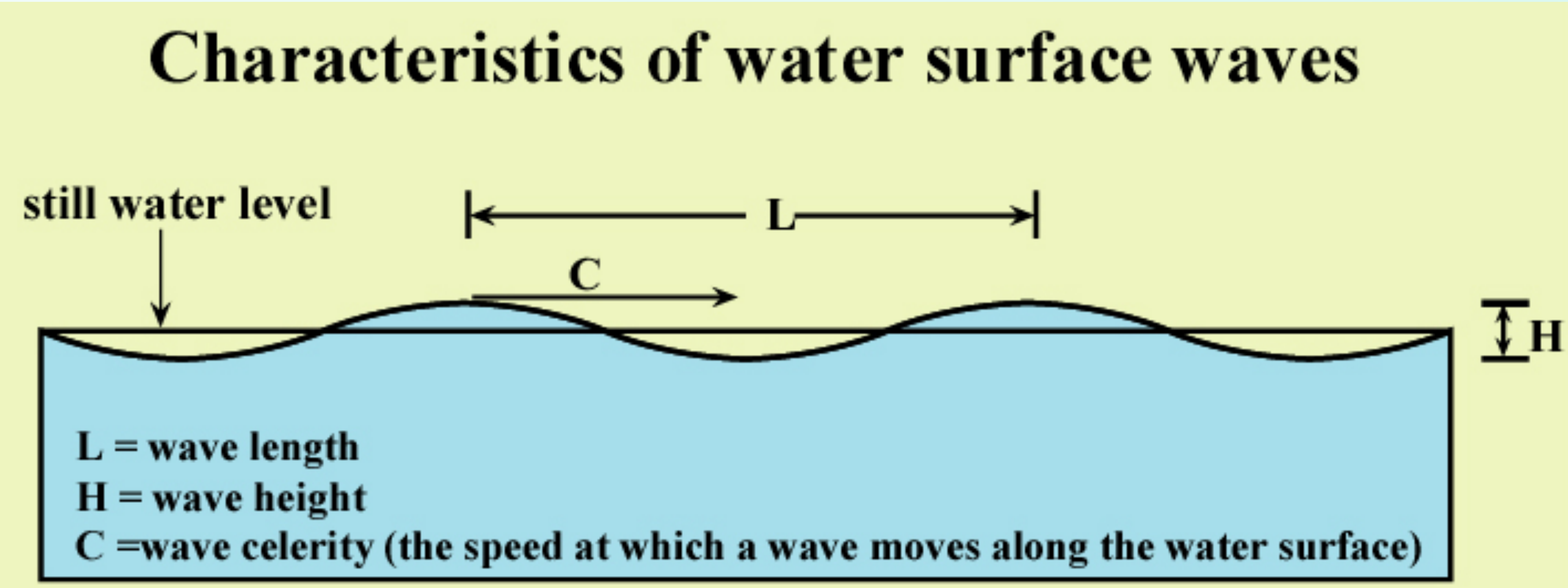


Waves

Waves on the surface of the oceans are an important process for erosion, sediment transport and deposition.

A wave propagates across the water surface its passage involves the rising and falling of the surface.

Most waves are sinusoidal in form and are characterized by their:



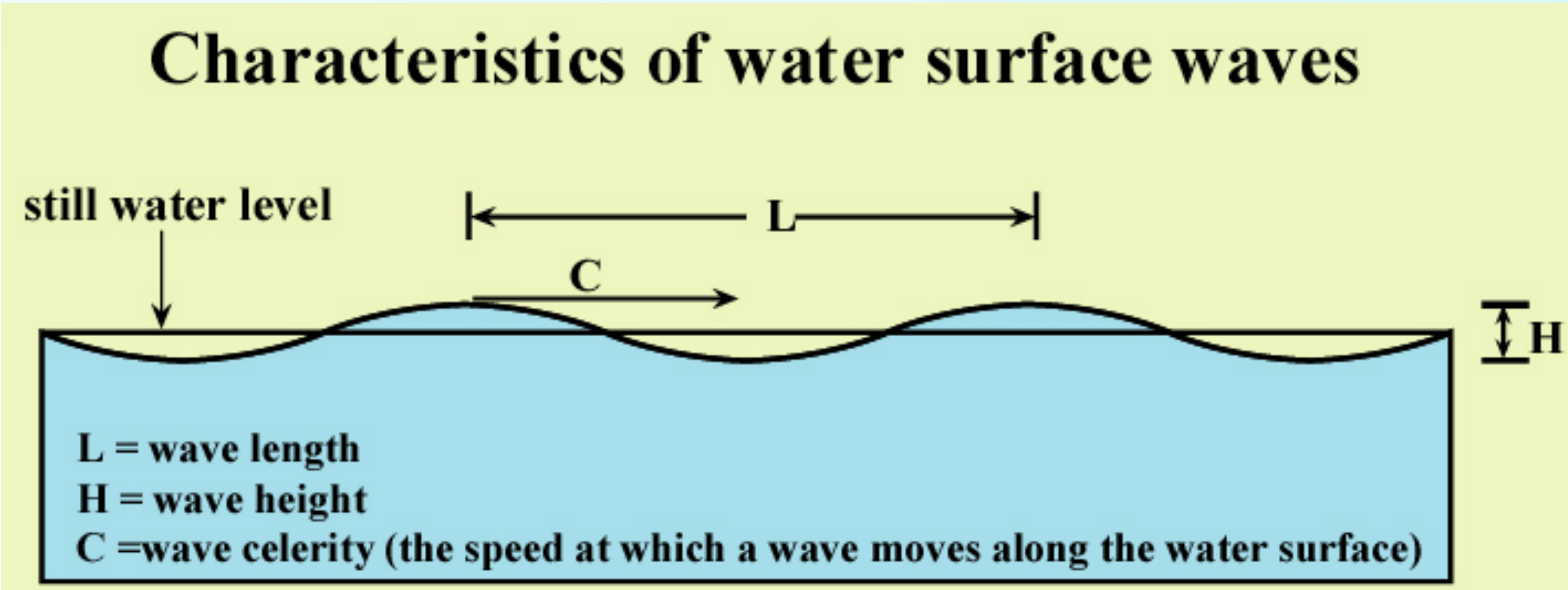
Length (L), the horizontal distance from crest to crest.

Height (H), the vertical distance from trough to crest.

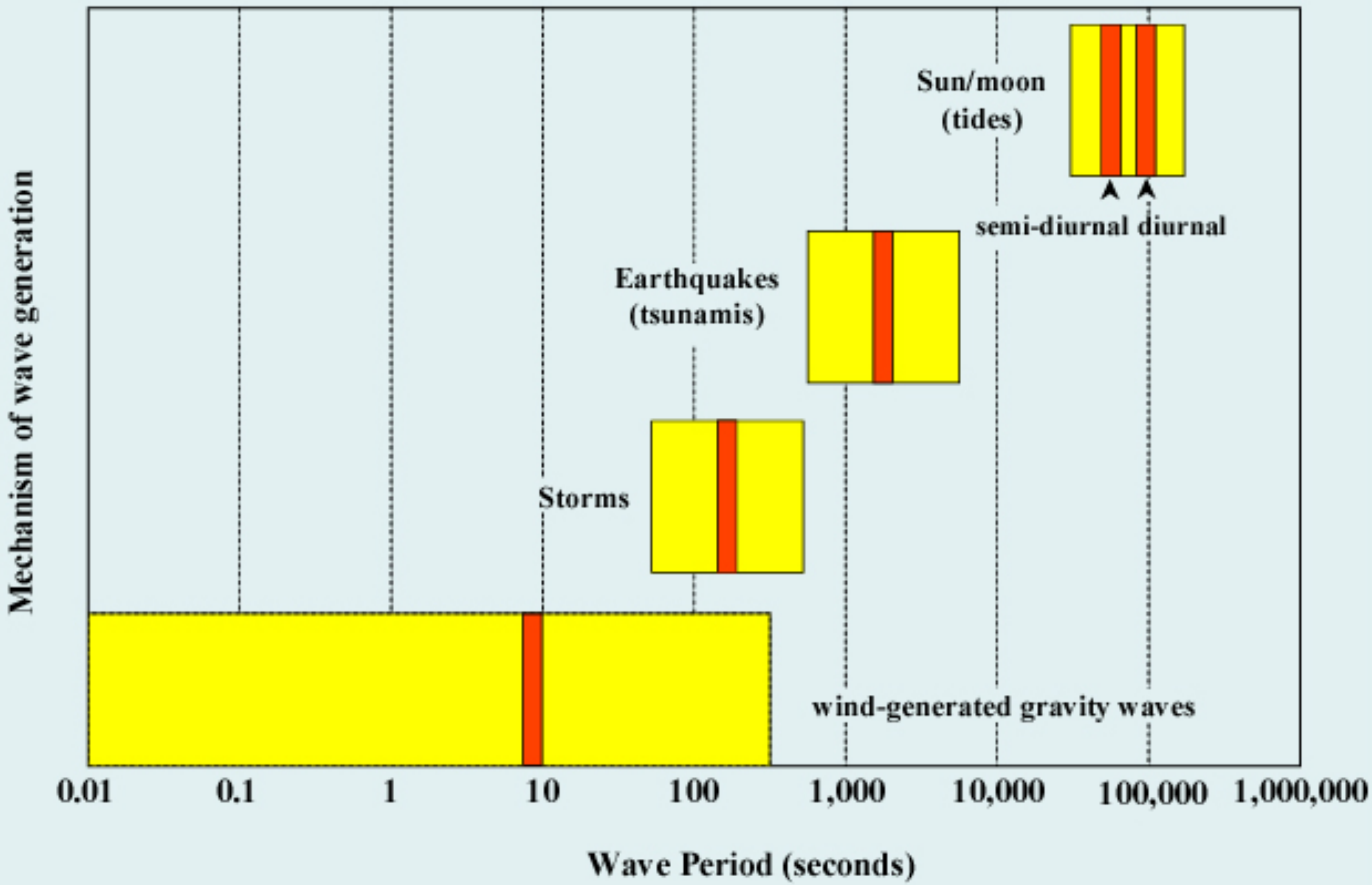
Celerity (C), the speed at which the wave travels.

Waves are commonly characterized by their **wave period (T)**, the time (usually in seconds) that it takes for one wavelength to pass a point on the water surface:

$$T = L/C$$



Waves of a wide range of scale are present in the world oceans.

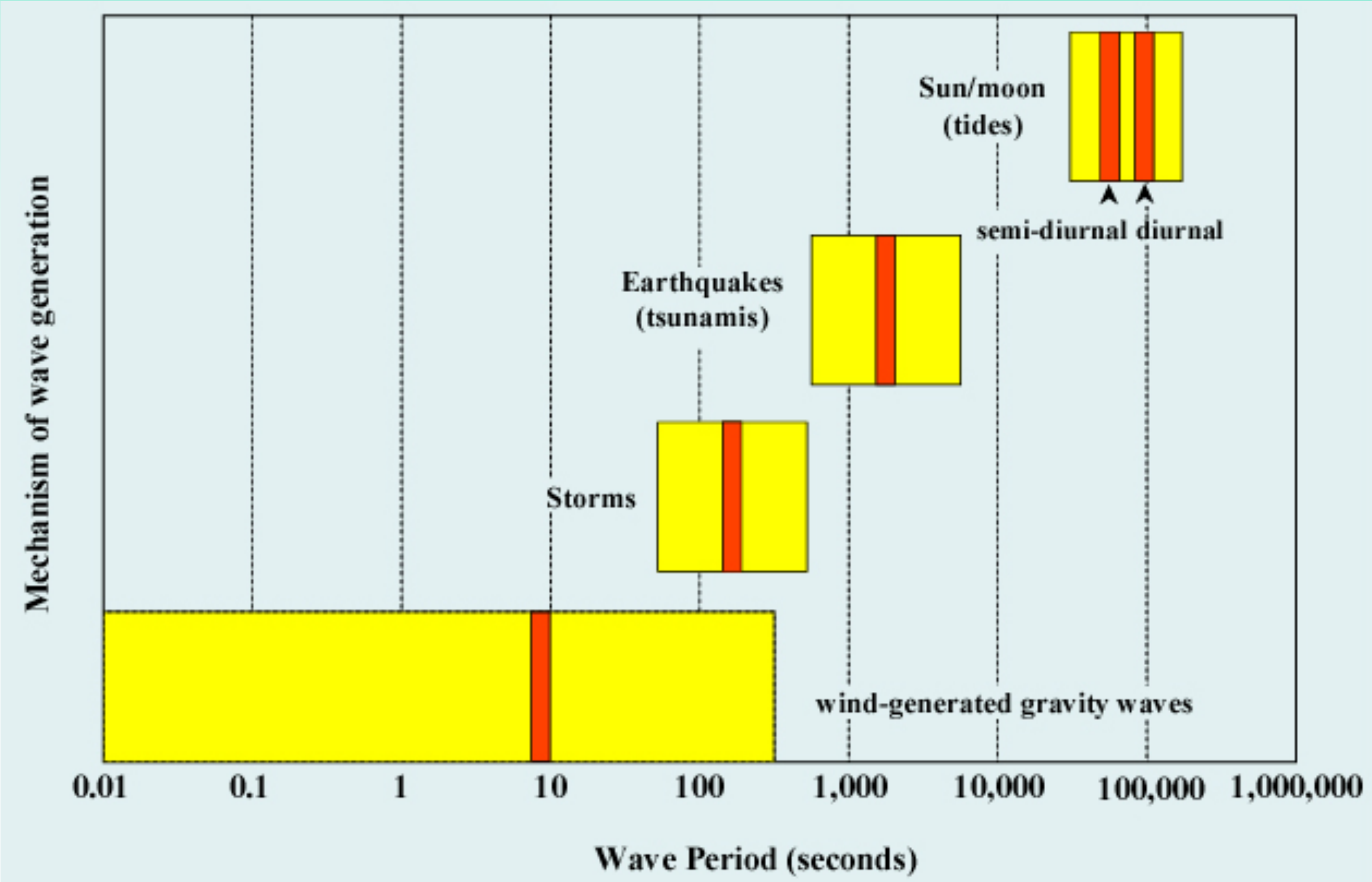


Wind-generated waves: waves the are produced by winds blowing over the water surface.

Storm waves: generated by particularly high winds during storms.

Tsunamis: the waves that are generated by underwater landslides, earthquakes and volcanic explosions.

Tides



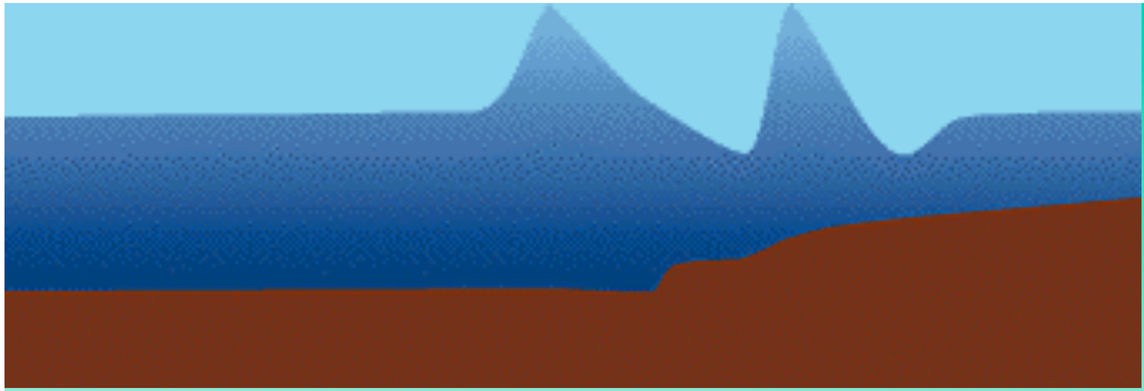
Tsunamis

Tsunamis are the second most powerful waves on the oceans.

Generated when ocean waters are displaced:

- Underwater earthquakes
- Underwater volcanic eruptions
- Underwater or coastal landslides
- Asteroid/comet impacts

Waves are generated above the disturbance and propagate outward from that point.

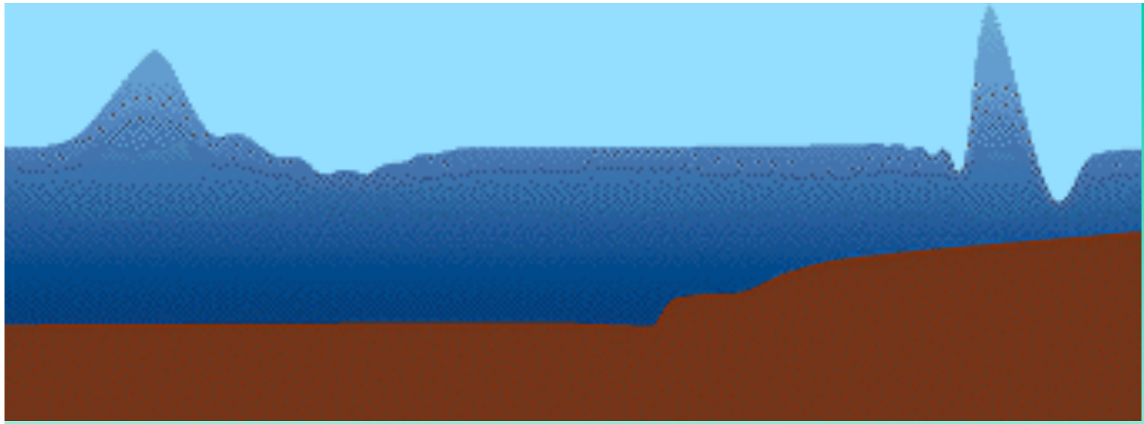


On the open ocean:

Wave length: 160 km

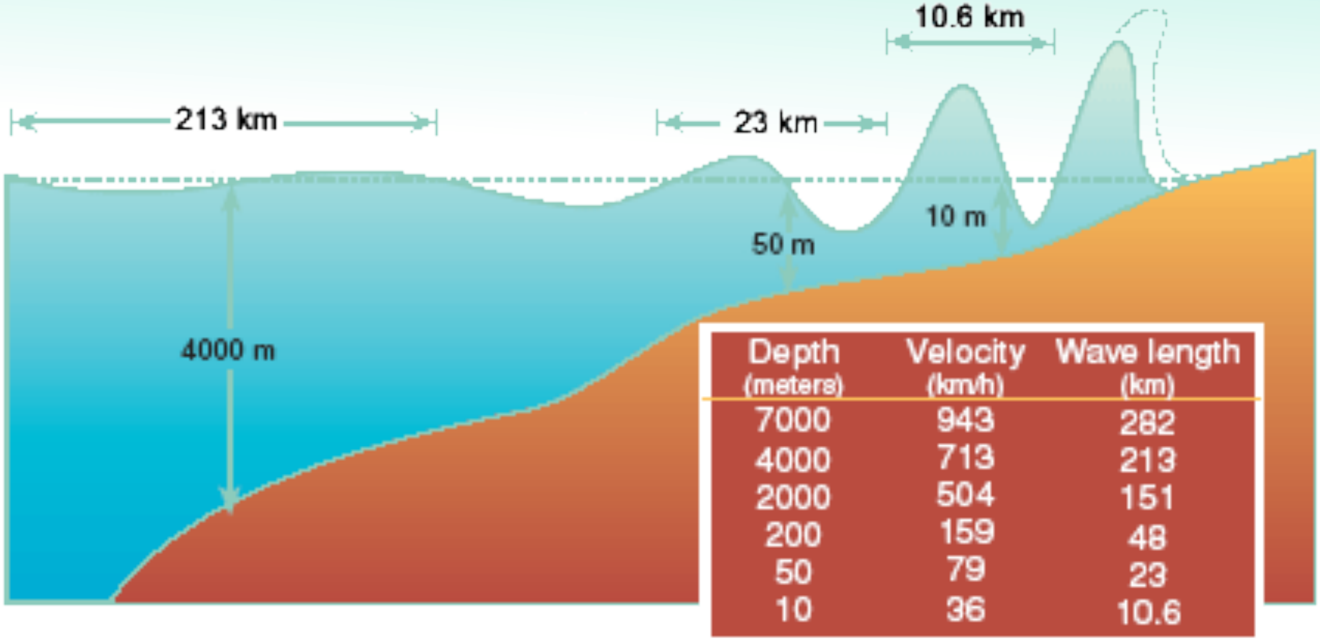
Wave height: commonly up to 0.5 metres on the open ocean.

Celerity: up to 800 km/hr

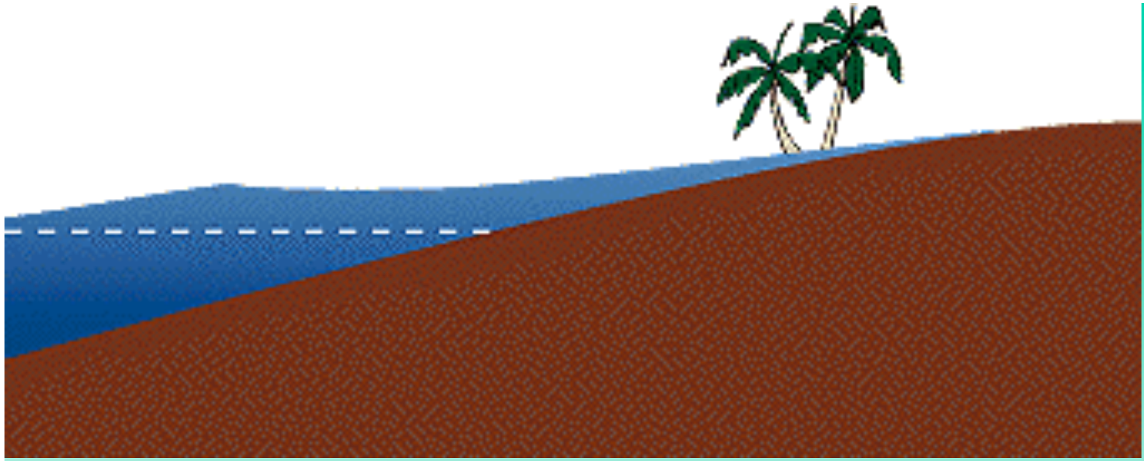


Amplification

As the wave enters shallow water as it approaches land it becomes higher and shorter (amplified).



Depth (meters)	Velocity (km/h)	Wave length (km)
7000	943	282
4000	713	213
2000	504	151
200	159	48
50	79	23
10	36	10.6



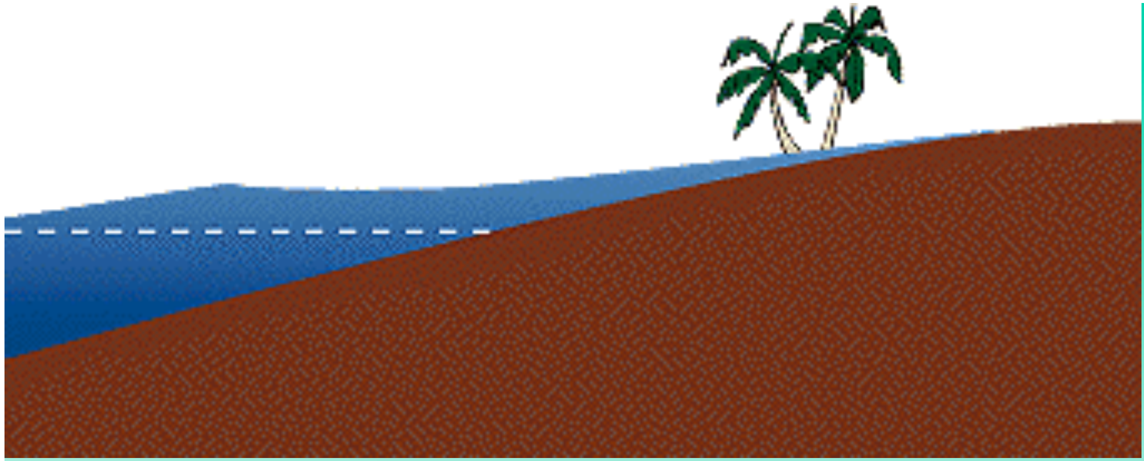
Runup

As the wave propagates towards land the water level rises.

In some cases a trough of the wave reaches land first and the water recedes from the shoreline and then returns as the wave reaches land.

Runup is the measure of the height of the wave (with respect to sea level) when it passes over land.

In most cases the wave does not form a “crashing” surf; the water rises and flows inland as a powerful current.



Following maximum runup the waters flow back offshore and may be followed by subsequent waves.

The first wave may or may not be the biggest and subsequent waves follow.

Largest recorded Tsunami at landfall:

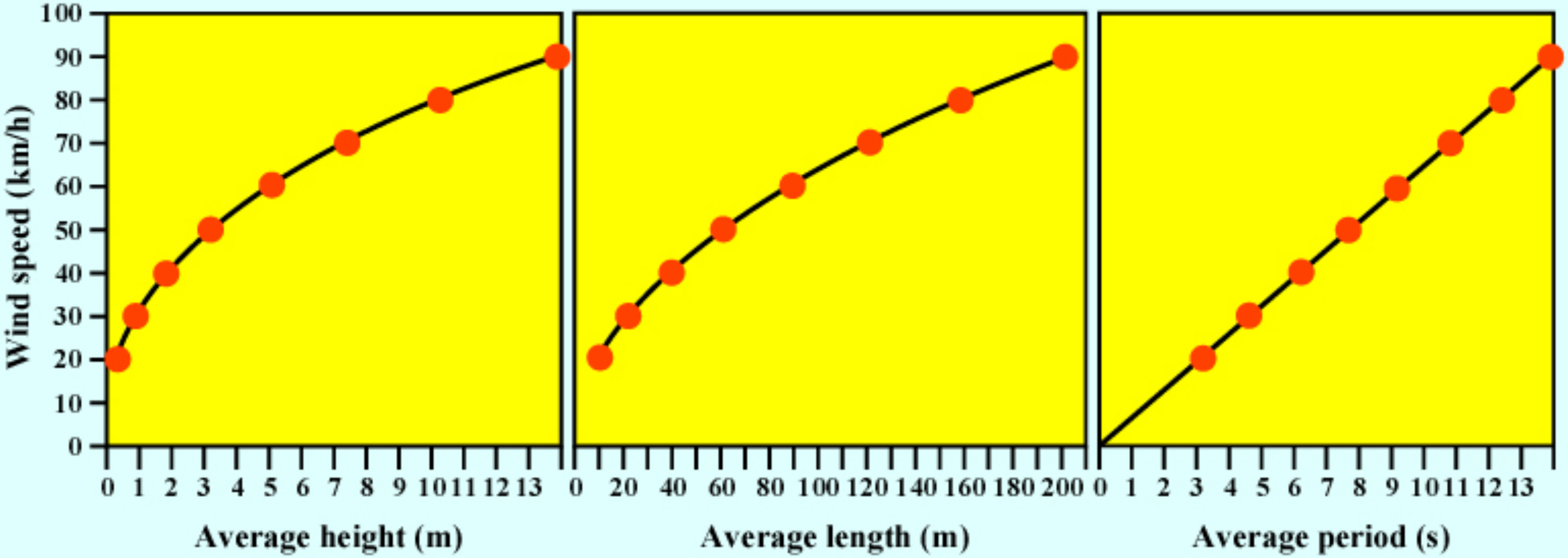
85 metres in height (at an Island south of Japan)

(Niagara Escarpment is about 50 m high at Brock)

Wind-generated waves are the most important process for erosion, sediment transport and deposition along many of the world's shorelines.

Waves can move sediment on the bottom out to the edge of the continental shelf.

Wind speed controls the size and energy of the waves.

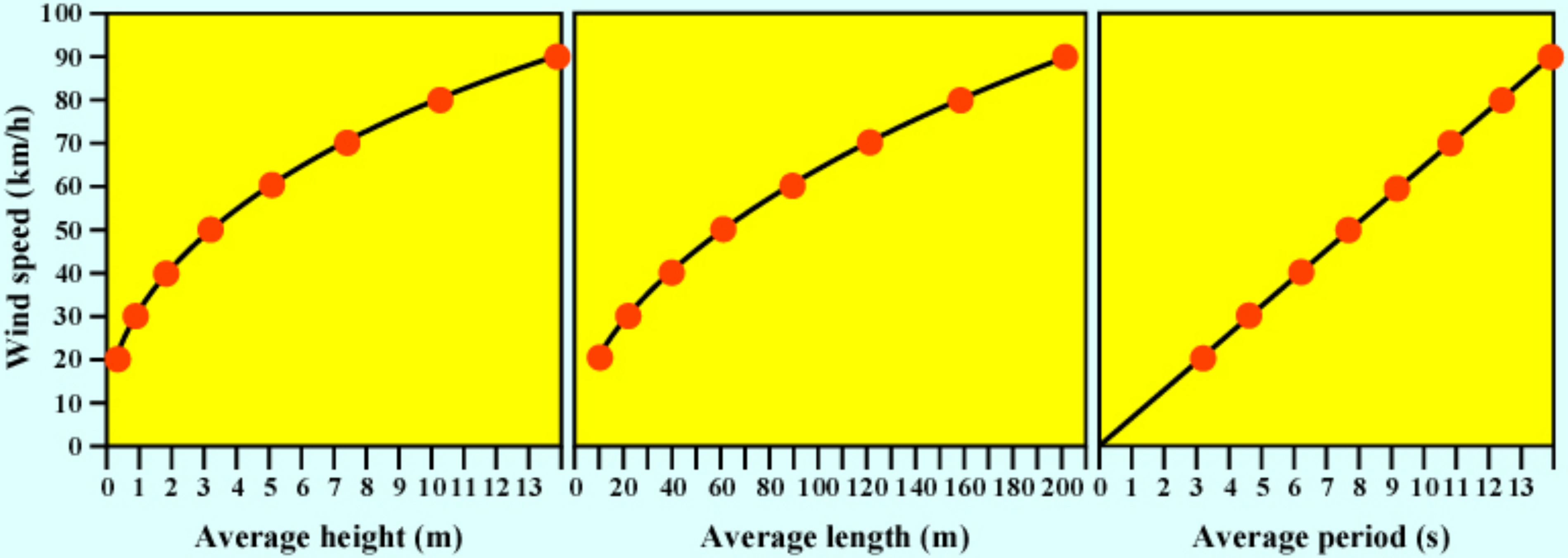


With increasing wind speed:

Wave length increases

Wave height increases

Celerity (and wave period) increase.

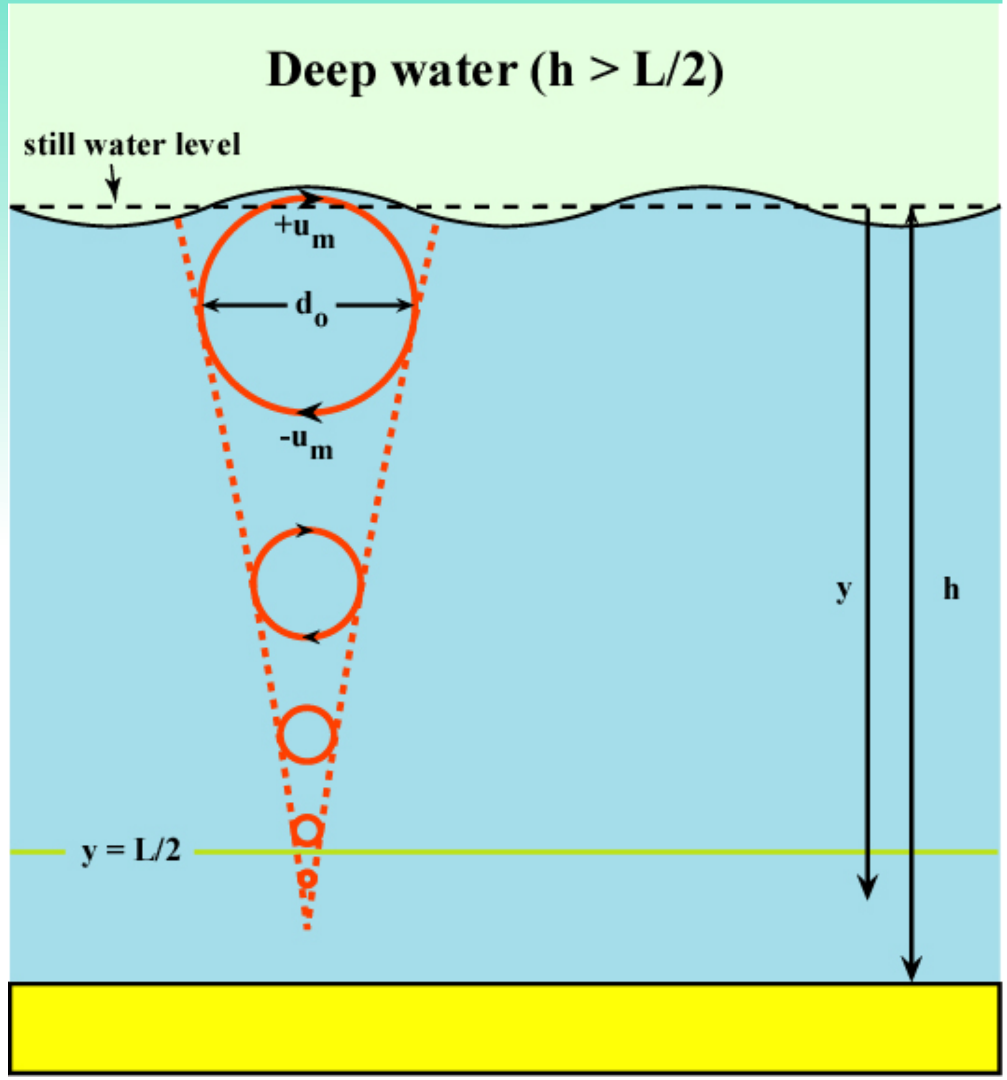


Fluid motion under surface waves

With the passage of a wave the water surface rises and falls.

Fluid beneath the wave follows a circular path called a wave orbital.

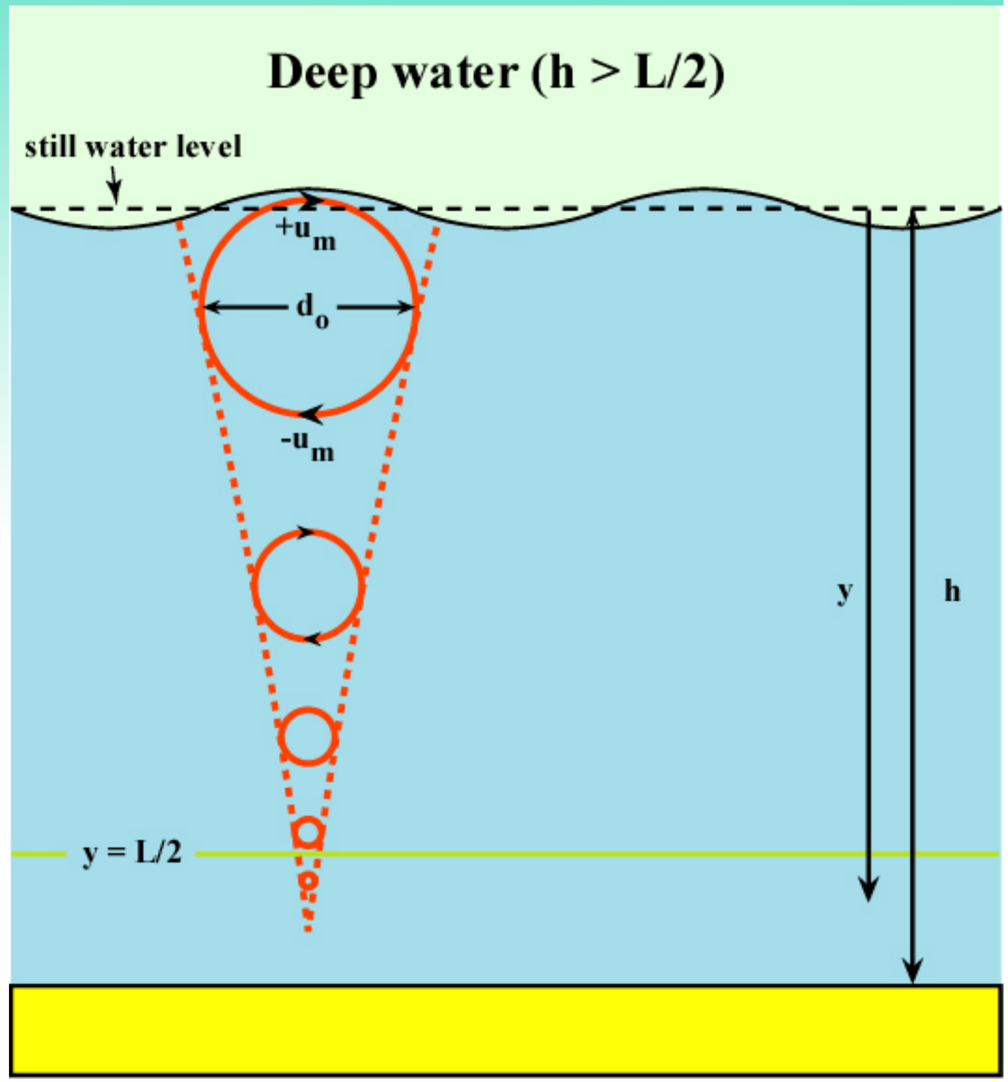
Wave orbital diameter depends on the height and length of the waves and the depth below the water surface.



Orbitals diameter diminishes with increasing depth beneath the surface.

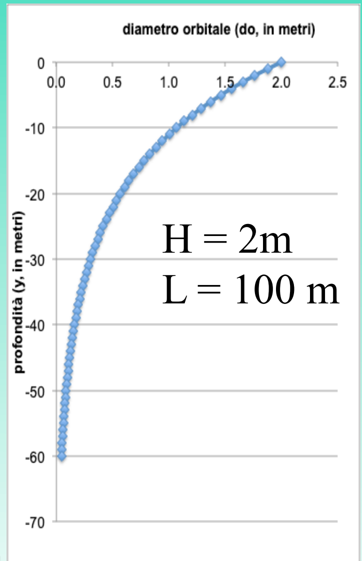
At a depth of ½ of the wavelength the orbitals are very small and fluid motion is negligible.

Deep water waves: when water depth is > ½ of a wavelength of the surface waves.



The diameter of the orbitals of deep water waves is related to the height and length of the waves and the depth below the water surface by:

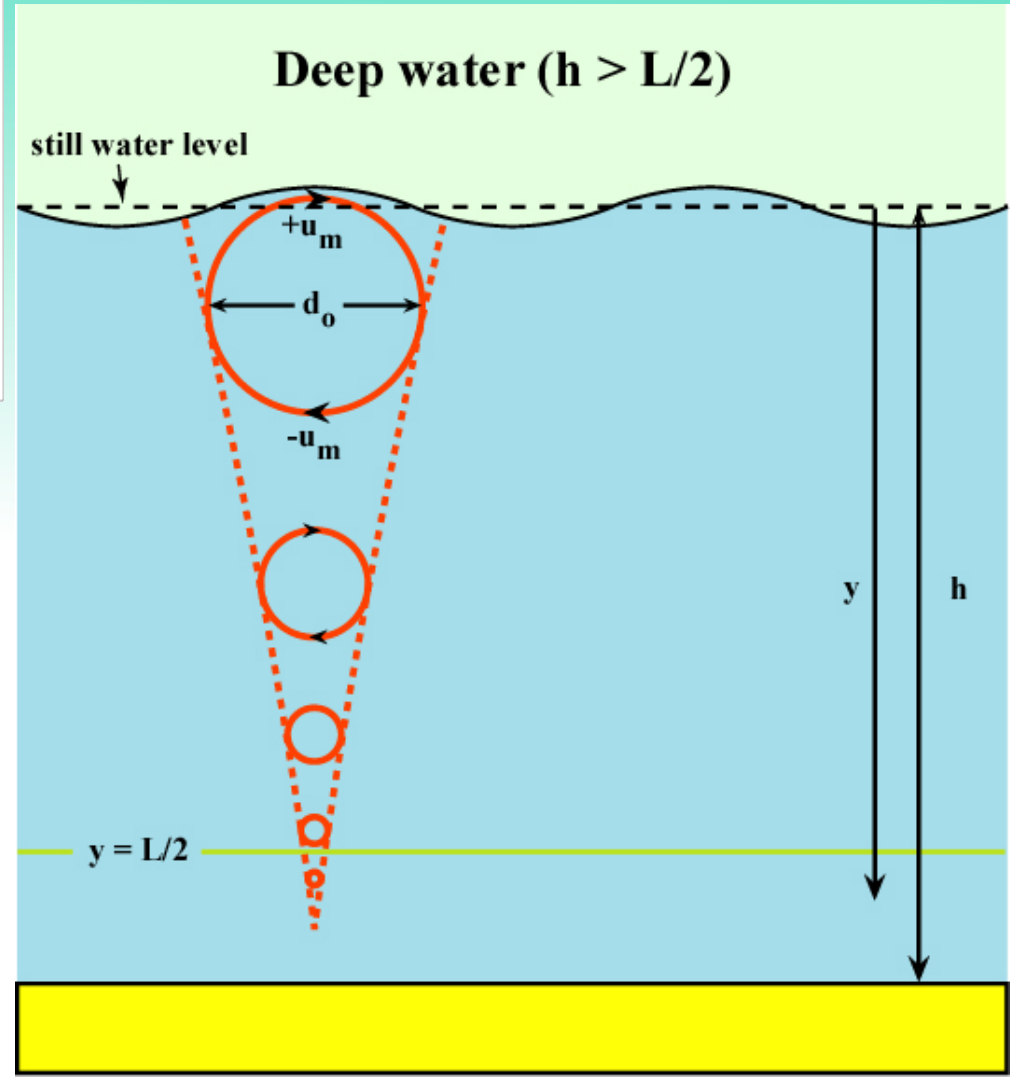
$$d_o = He^{\frac{2\pi y}{L}}$$



Note that d_o = H at the surface where (y=0)

U_m is the maximum orbital velocity and is given by:

$$U_m = \frac{\pi d_o}{T}$$

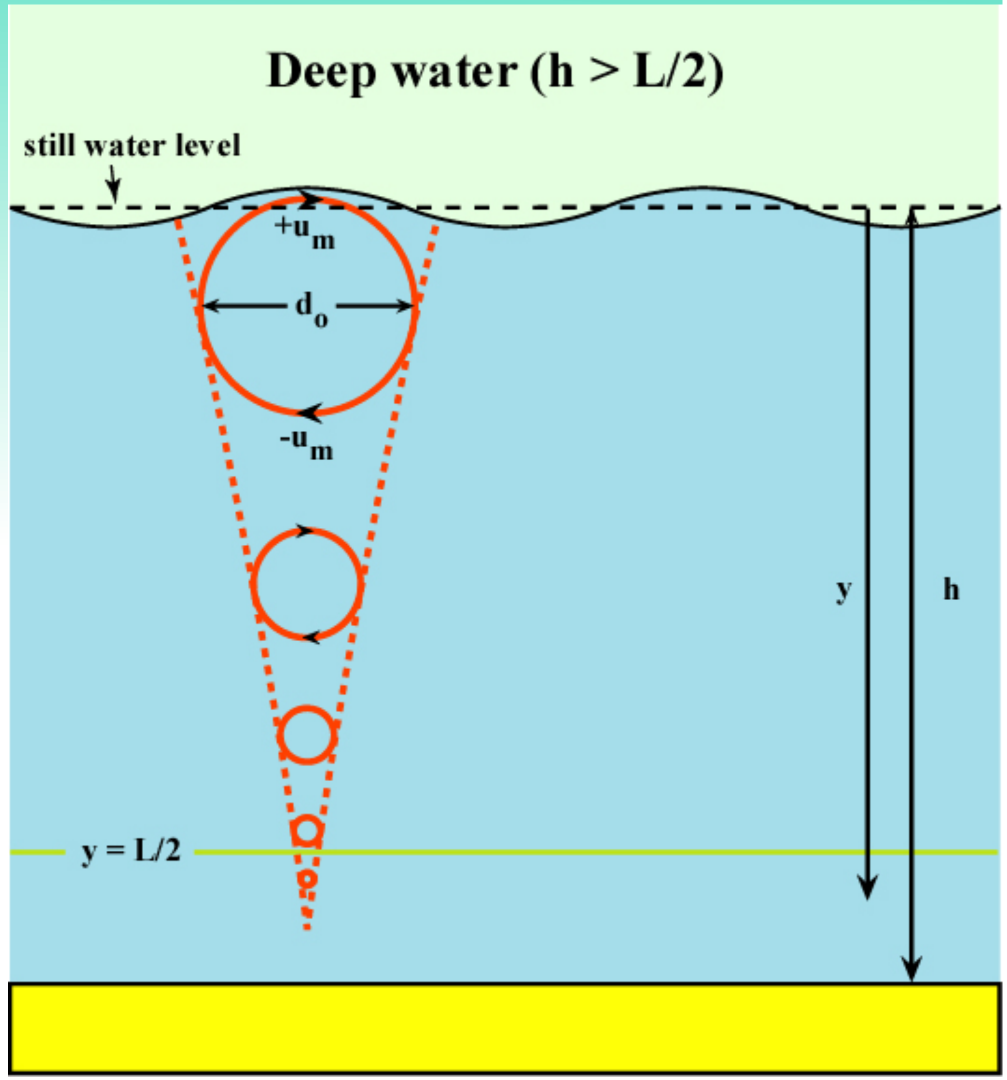


A depth of L/2 is referred to as *wave base*, the depth below which the waves no longer affect the water column.

Effective wave base is a more useful concept: the depth below which the fluid motion due to waves is not competent to move sediment on the bed.

Depends on wave and sediment properties.

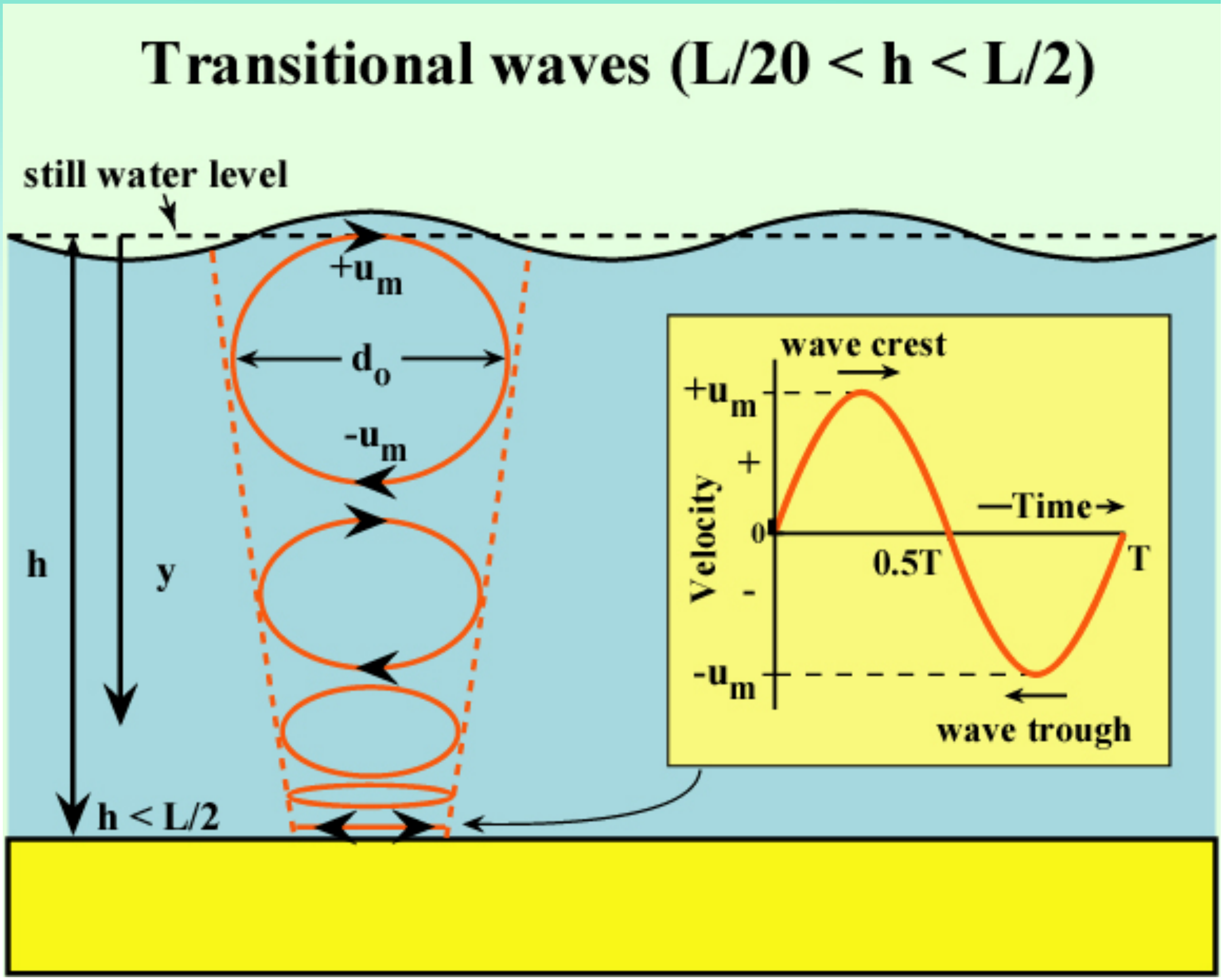
Deep water waves never affect the bed.



Transitional waves when water depth is <½ of a wavelength but >1/20 of a wavelength (waves with depth < 1/20 of wavelength are shallow water waves).

Under transitional waves the orbitals become flatter as they approach the bottom.

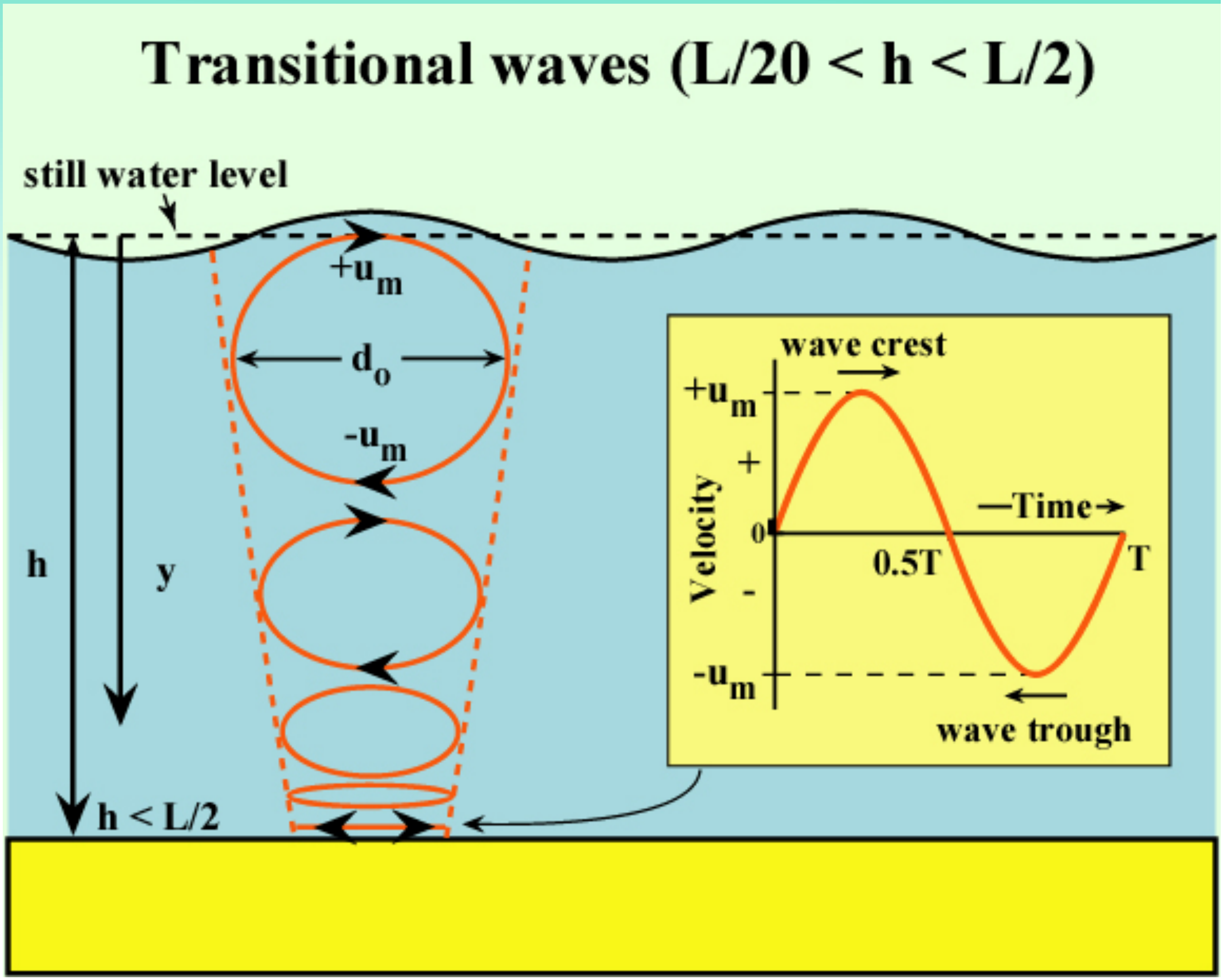
At the bottom the orbitals are flat and the motion of the water is back and forth (oscillating motion).

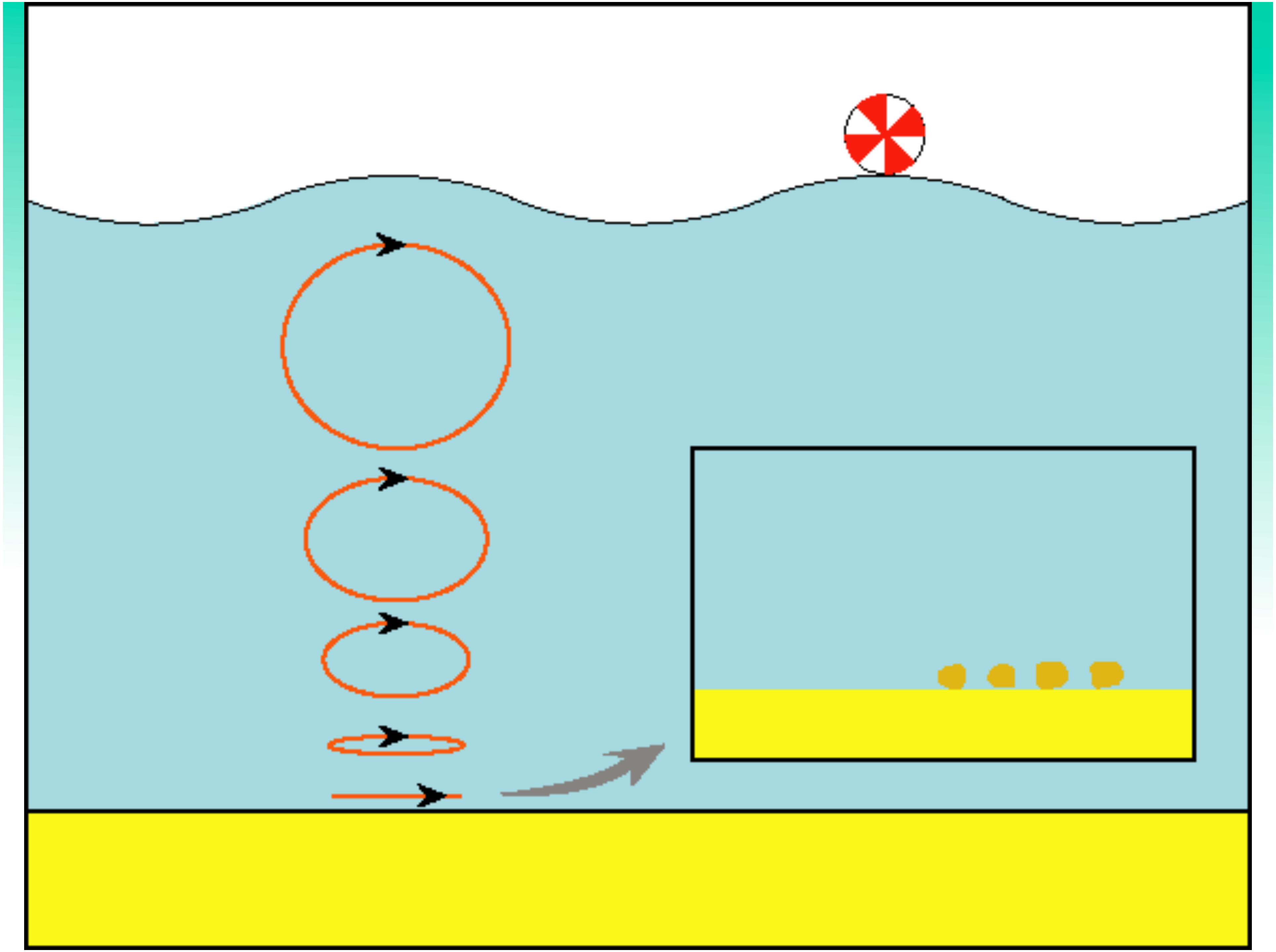


Orbital velocities are greatest under the crests and troughs but in opposite directions.

The motion of sediment on the bed is similarly, back and forth.

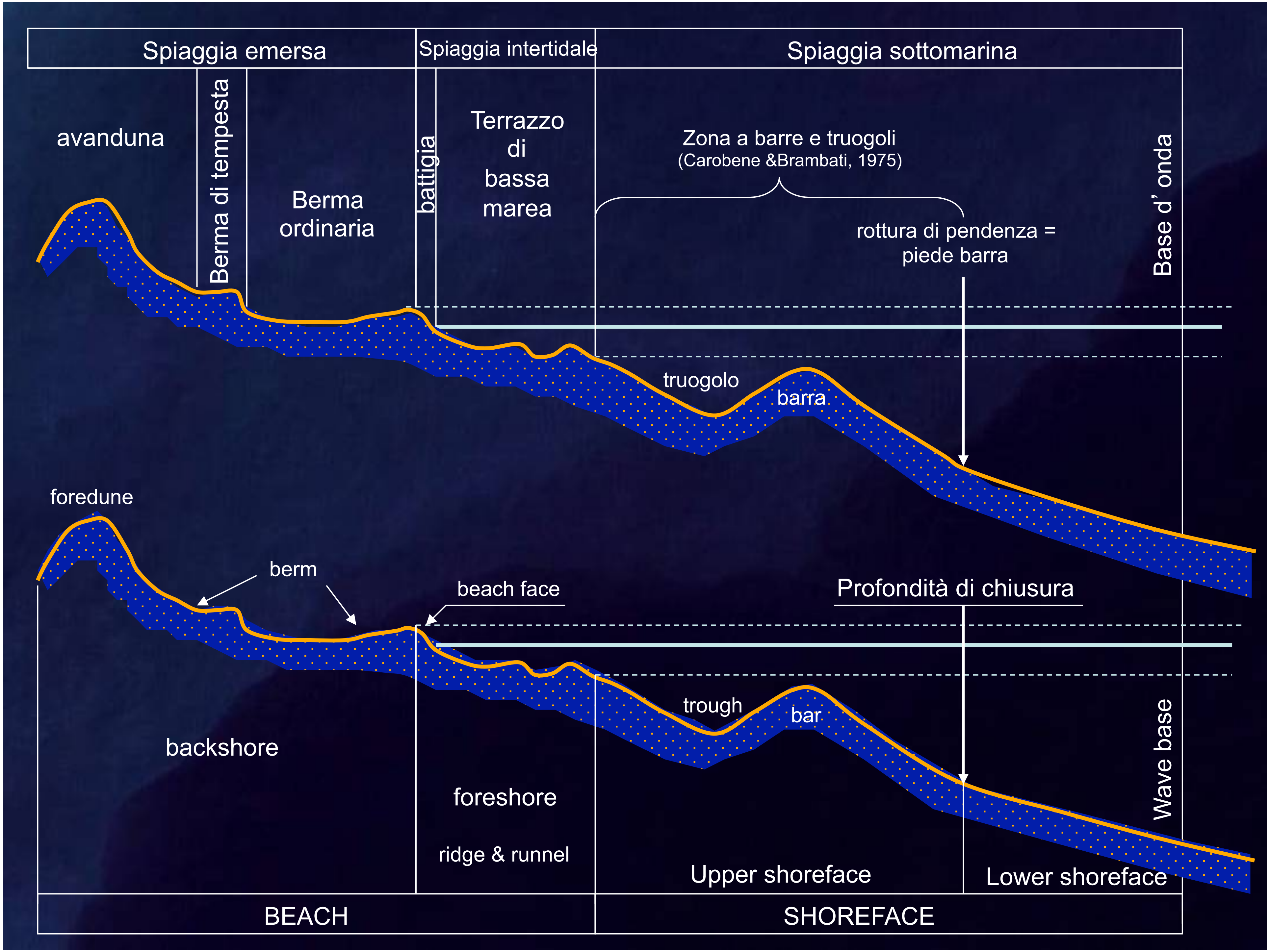
The larger height, length and period the more powerful the oscillating currents.





NOZIONI MORFODINAMICHE E SEDIMENTOLOGICHE SULLA SPIAGGIA

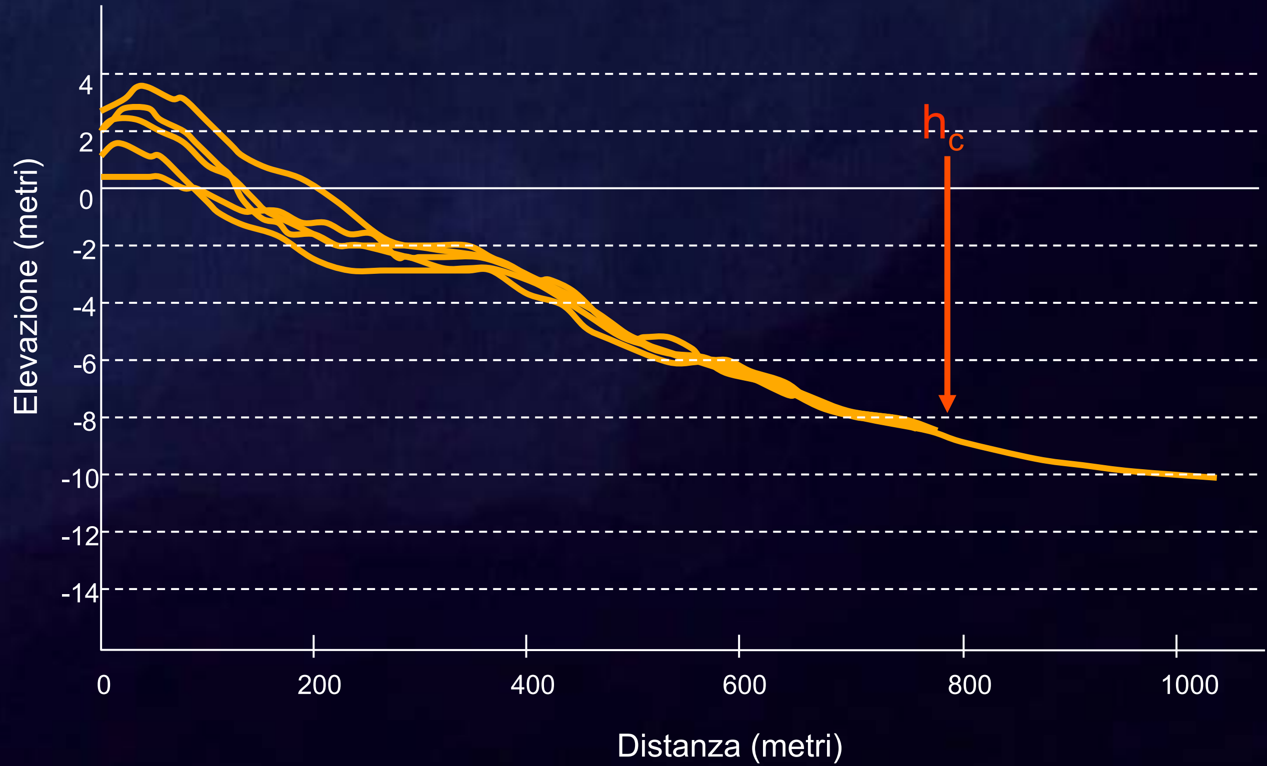
riprese dal corso di Sedimentologia e Regime dei Litorali


Spiaggia emersa
Spiaggia intertidale
Spiaggia sottomarina
avanduna
Berma di tempesta
Berma ordinaria
battigia
Terrazzo di bassa marea
Zona a barre e truogoli
(Carobene &Brambati, 1975)
rottura di pendenza = piede barra
Base d' onda
truogolo
barra
foredune
berm
beach face
Profondità di chiusura
trough
bar
backshore
foreshore
ridge & runnel
Upper shoreface
Lower shoreface
Wave base
BEACH
SHOREFACE

UPPER SHOREFACE (spiaggia sottomarina superiore)

E' la regione entro la quale i processi erosivi e accrezionari producono significative (= misurabili) variazioni di elevazione del fondo marino alla scala temporale annuale.
Per tale ragione, secondo alcuni Autori, questa regione può essere definita "ZONA ATTIVA".

Morfologicamente, si può identificare grazie all'inviluppo delle modificazioni del profilo di spiaggia, che risultano progressivamente meno apprezzabili verso il largo. Secondo Hallermeier (1981) le modificazioni convergono alla **profondità di chiusura**, h_c corrispondente a:

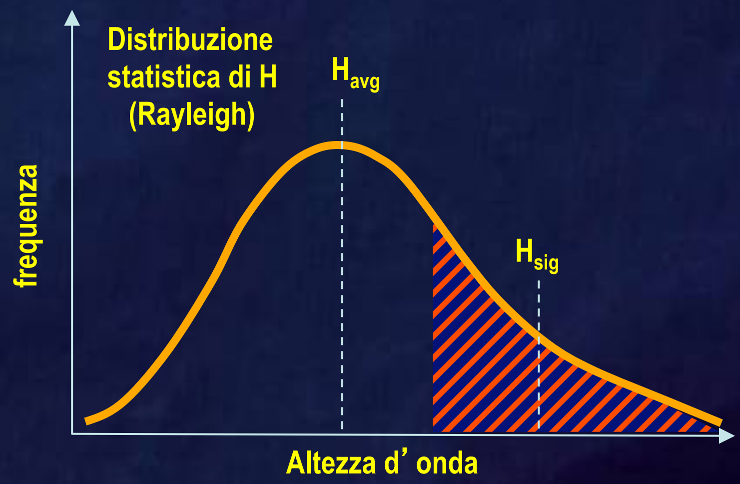


$$h_c \cong 2.28 \cdot H_{sx} - 68.5 \cdot \left(\frac{H_{sx}^2}{gT_e^2}\right)$$

dove H_{sx} è l'altezza d'onda di tempesta con occorrenza di 12 ore all'anno, T_e è il periodo associato all'onda e g è l'accelerazione di gravità

La relazione di Hallermeier evidenzia la stretta dipendenza del comportamento del profilo di spiaggia dal clima meteomarino.

In mancanza di una statistica precisa di moto ondoso, lo stesso autore propone una semplificazione basata sul valore di H_{sig}, cioè dell'altezza d'onda significativa, corrispondente alla media delle onde più elevate, pari a 1/3 di tutte quelle registrate, e della sua deviazione standard σ:



$$h_c \cong 2 \cdot H_{sig} + 11 \cdot \sigma$$

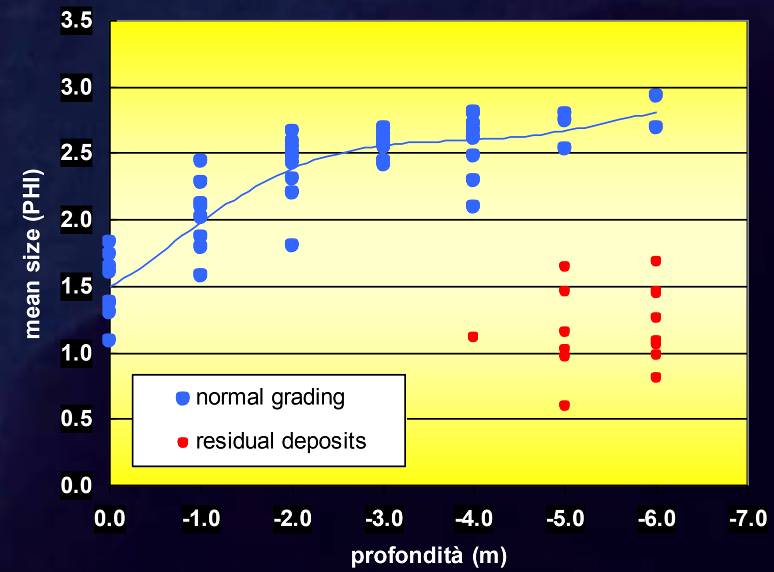
Alcuni esempi

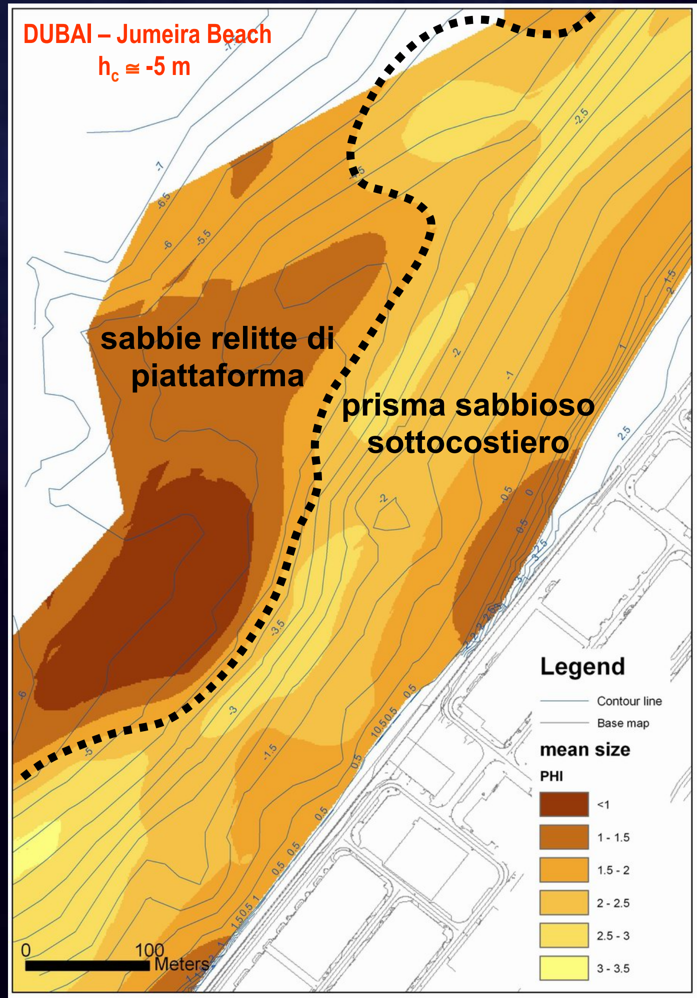
LOCALITA'		H_{sig}	σ	h_c
US Atlantico	Virginia beach	0.7	0.4	6.2
	Nags Head	1.0	0.5	7.9
US Pacifico	Huntington beach	0.9	0.3	5.3
	La Jolla	1.2	0.5	7.7
	Point Mugu	0.9	0.3	5.0
SE Australia		1.5	1.2	12.1
Olanda		1.2	0.8	10.7

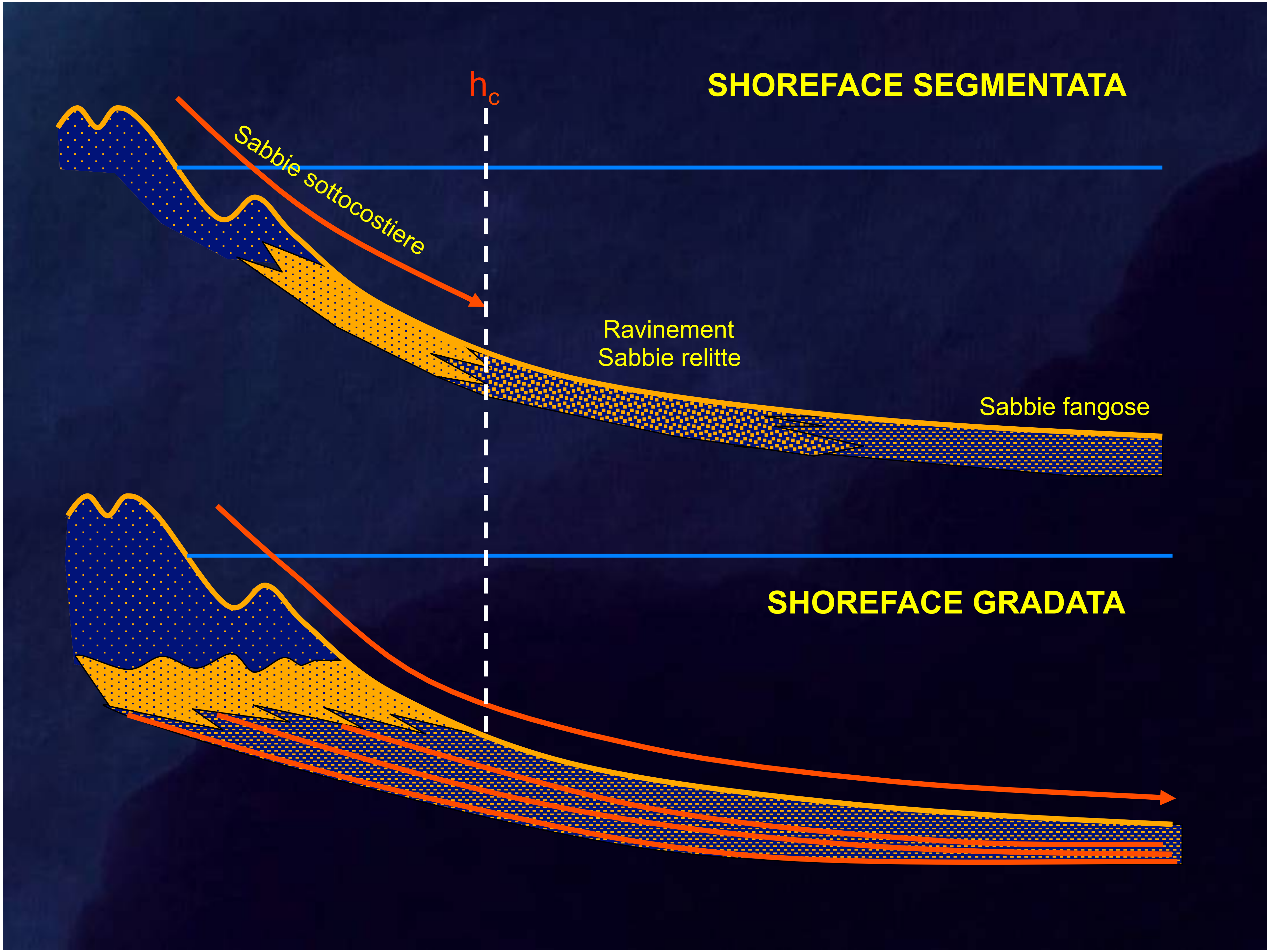
Il limite della profondità di chiusura non è sempre indentificabile da cambiamenti morfologici, poiché una spiaggia sottomarina non presenta sempre una barra a mare o rotture di pendenza.

I valori teorici di h_c hanno spesso (ma non sempre) una corrispondenza con una distintiva variazione nelle caratteristiche sedimentologiche dei fondali.

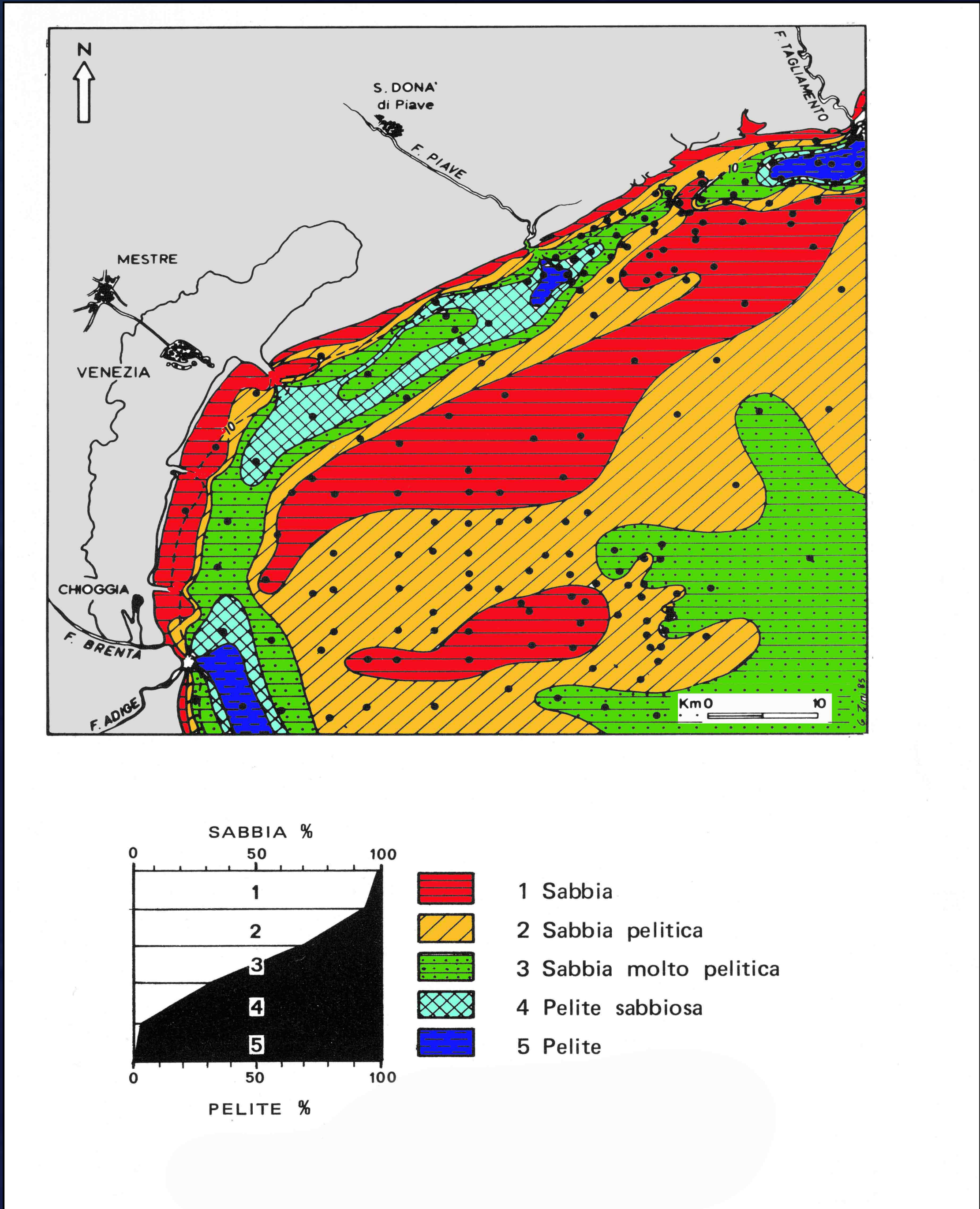
Il prisma sabbioso sottocostiero, contraddistinto da sabbie ben classate, tende infatti a presentare una progressiva diminuzione granulometrica verso il largo, con una transizione piuttosto brusca ad una certa profondità *d*, comparabile con h_c. Oltre tale profondità si osserva il dominio dei materiali fangosi o il passaggio alle **sabbie relitte di piattaforma**.







SHOREFACE SEGMENTATA
h_c
Sabbie sottocostiere
Ravinement
Sabbie relitte
Sabbie fangose
SHOREFACE GRADATA

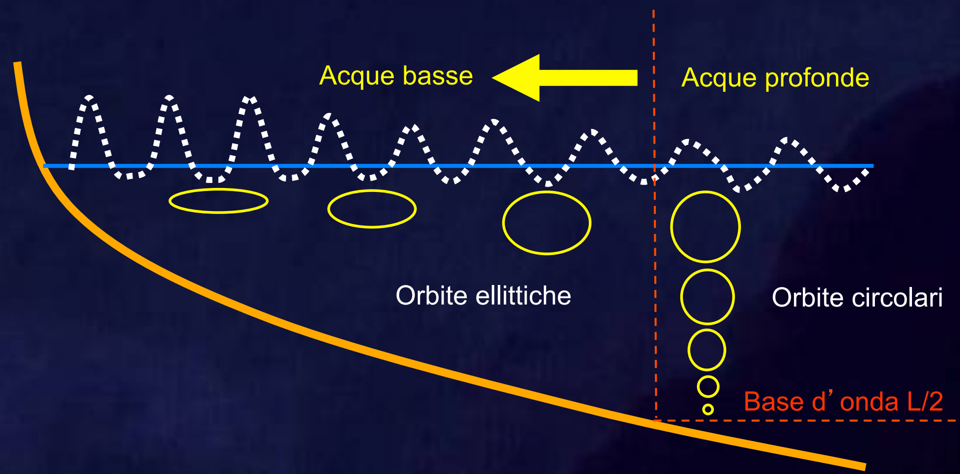


SHOREFACE SEGMENTATA

Un esempio tipico di shoreface segmentata è rappresentato dal nord-Adriatico:
Al largo della fascia sabbiosa sottocostiera si ritrovano sedimenti antichi e coperture fossili di sabbie costiere che attestano l’antica posizione della linea di riva all’inizio dell’Olocene (ca. 10.000 anni fa), quando il livello del mare era circa 20 m più basso dell’attuale.

LOWER SHOREFACE (spiaggia sottomarina inferiore)

E' la regione che si estende dal limite inferiore della upper shoreface (profondità di chiusura) alla **base d'onda**.
Convenzionalmente, la base d'onda viene considerata pari alla profondità alla quale inizia l'interferenza dell'onda sul fondale, ovvero L/2.



In acque profonde il valore di L può essere espresso in funzione del solo periodo:

$$L = \frac{g \cdot T^2}{2\pi} = 1.56 \cdot T^2$$

Sulla base di studi in campo e di ridefinizioni teoriche, Hallermeir (1981) propone quale profondità limite del trasporto on-offshore delle sabbie il valore espresso da:

$$h_i = \left(\overline{H}_{sig} - 0.3\sigma\right)\overline{T}_{sig}\left(g/2000 \cdot D\right)^{1/2}$$

dove ad H e T dell'onda significativa si aggiunge un parametro dimensionale D, pari al diametro medio o alla mediana del sedimento posto alla profondità d ~1.5 h_c

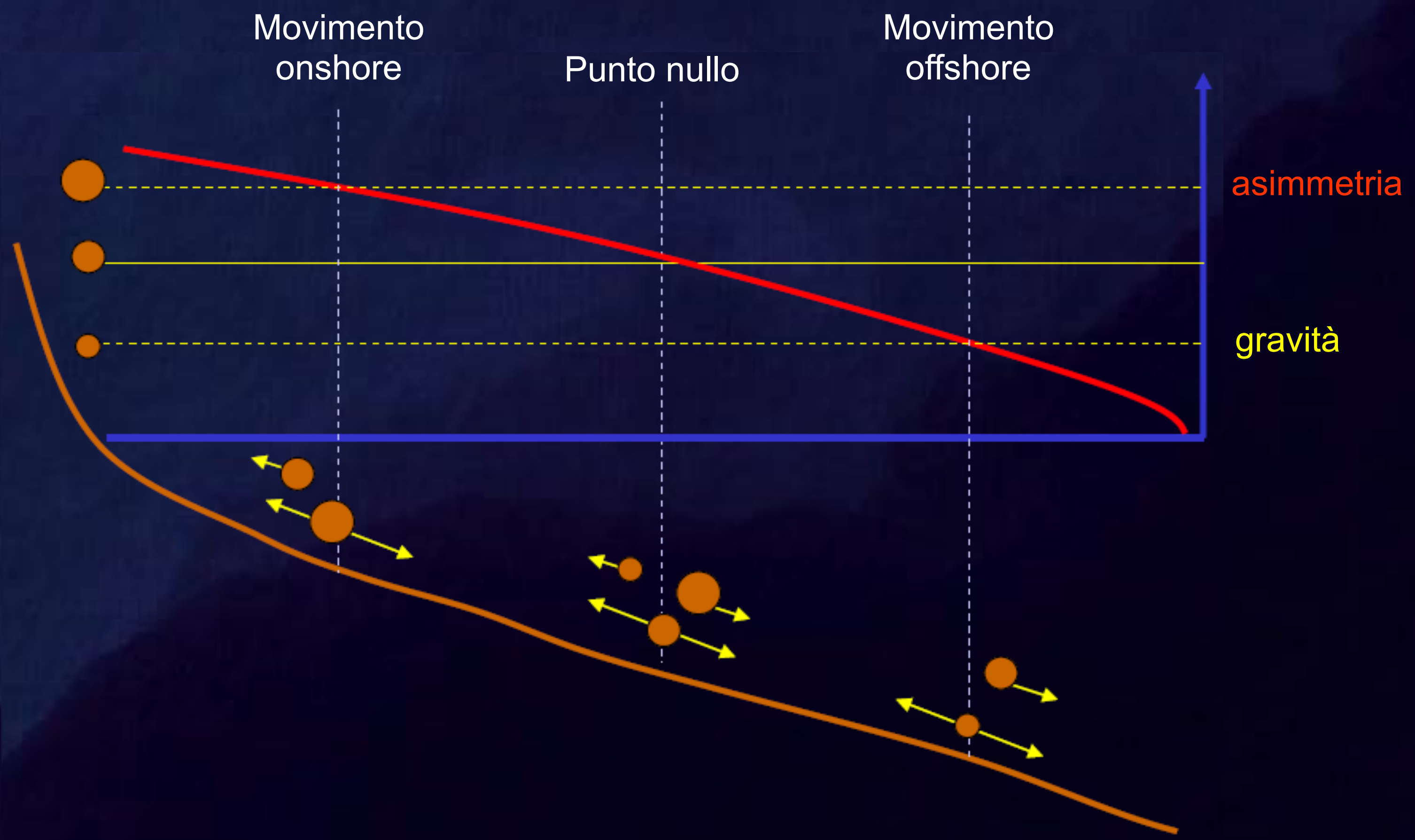
Dati sperimentali dimostrano che l'approccio deterministico di Hellermeir ha notevole riscontro sulla tipologia dei materiali di fondo e che il valore di h_i rappresenta una ottima approssimazione del valore della base d'onda.
Alcuni problemi possono derivare dal valore del diametro medio misurato alla profondità di 1.5 h_c, ove possono essere rinvenuti sedimenti relitti di piattaforma.

Già Komar (1976) aveva osservato che il valore convenzionale di L/2 è eccessivo e propose di dimezzare la base d'onda al valore L/4.
Confrontando le diverse proposte, è evidente la miglior corrispondenza tra h_i e il valore di L/4 indicato da Komar.

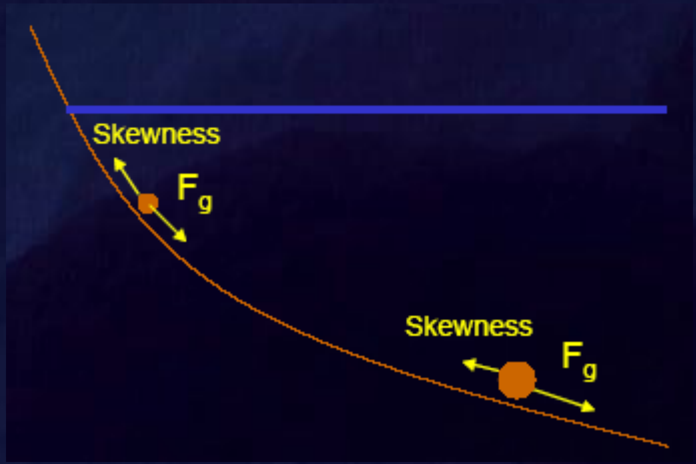
LOCALITA'		H_{sig}	σ	T_{sig}	H_i	H= L/2	H= L/4
US Atlantico	Virginia beach	0.7	0.4	8.3	21.1	53.7	26.9
	Nags Head	1.0	0.5	9.8	31.1	74.9	37.4
US Pacifico	Huntington beach	0.9	0.3	13.2	43.9	135.9	67.9
	La Jolla	1.2	0.5	12.0	52.6	112.3	56.1
	Point Mugu	0.9	0.3	14.4	52.5	168.5	84.3
SE Australia	Byron Bay	1.6	1.2	9.6	46.2	71.9	35.9
	Sydney	1.6	1.2	9.5	36.3	70.4	35.2
	Moruya	1.5	1.2	9.5	36.0	70.4	35.2
Olanda		1.2	0.8	5.0	13.4	19.5	9.7

IL BILANCIO SEDIMENTARIO

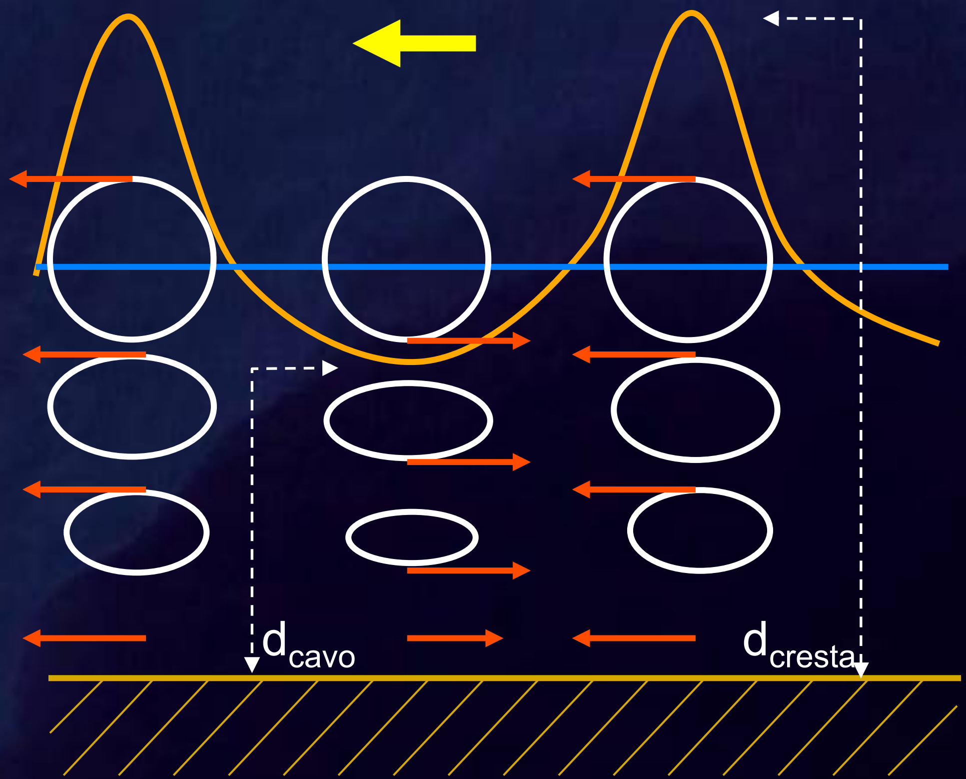
Cornaglia (1889) fu il primo a suggerire che deve esistere un bilancio tra le onde che trascinano il sedimento verso riva e la forza di gravità che tende a muoverlo verso il largo.
Il merito di Cornaglia è quello di aver riconosciuto che man mano che diminuisce la profondità aumenta l'asimmetria tra la forza di trascinamento diretta verso riva e quella diretta verso il largo associata all'onda, con il risultato di una componente netta di trasporto rivolta onshore.



Il modello del **punto nullo** prevede che la componente tangenziale di g sia costante per qualsiasi granulometria in un dato punto del profilo, mentre aumenta verso terra la componente di trasporto netta onshore. In questo modo dovremmo attenderci un aumento del materiale fine verso riva e di quello grossolano verso il largo.



In realtà il processo è opposto, in quanto studi effettuati con traccianti evidenziano una selezione di granulometrie maggiori onshore e di quelle inferiori offshore.



In effetti, la forma d'onda sottoriva, simile a quella asimmetrica di Stokes prevede:

- velocità **onshore** (associate alla cresta d'onda) di breve durata ma di alta magnitudine

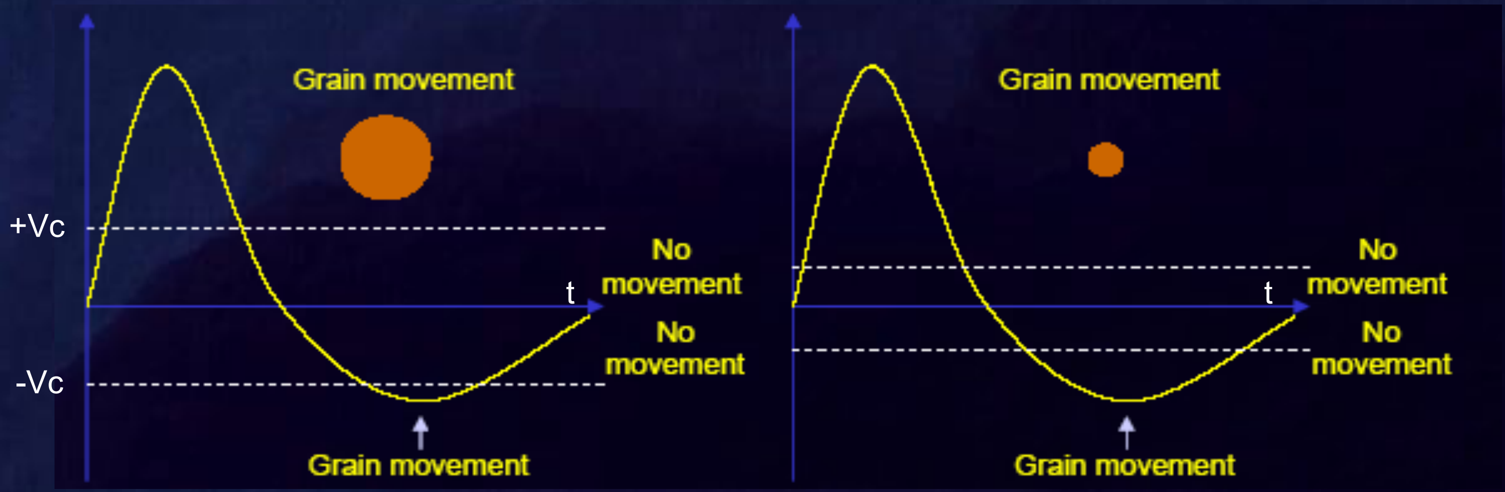
- velocità **offshore** (associate al cavo) di maggior durata a causa del rallentamento causato dall'attrito sul fondo, ma di minor intensità per il minor fondale

$$V = (g\,d)^{1/2}$$

Il risultato è un movimento verso riva più efficace nel trasportare il materiale grossolano:

- il materiale a granulometria maggiore non riesce ad essere preso in carico dalla corrente offshore

- il materiale fine si muoverà sia sotto la cresta che sotto il cavo d'onda, con deriva netta verso il largo



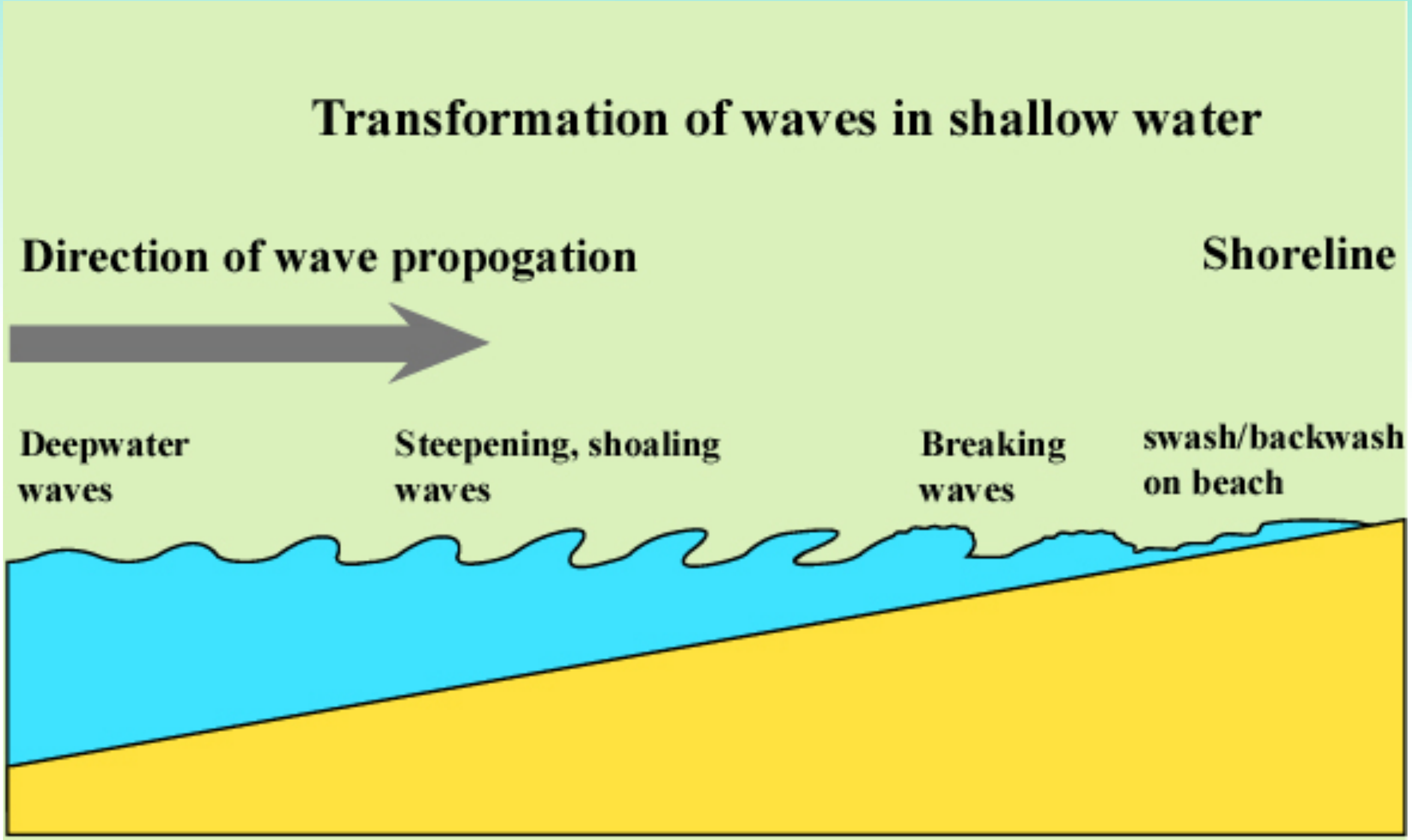
CASO A: Granulometria grossolana

- La velocità critica di erosione è superata sotto il passaggio della cresta e molto poco sotto il cavo
- componente netta di deriva: ONSHORE

CASO B: Granulometria fine

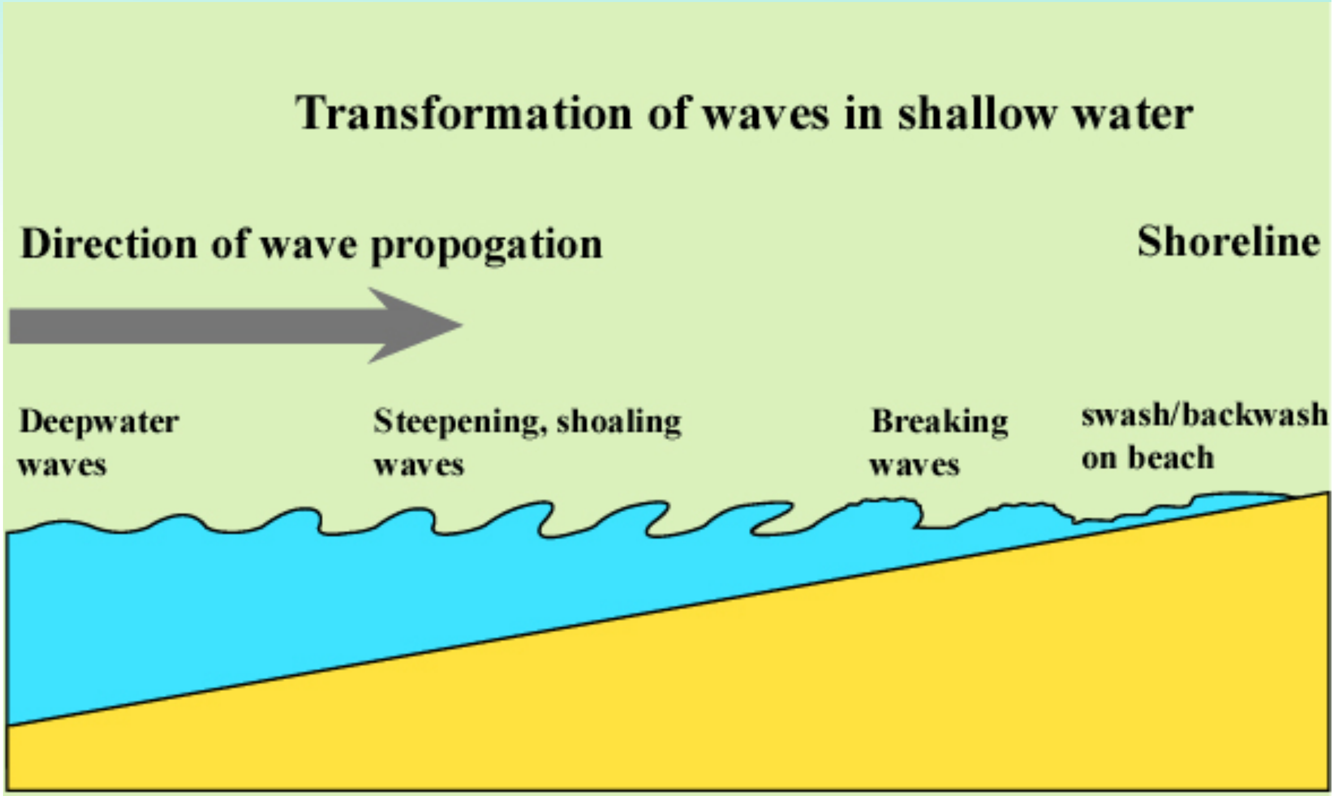
- La velocità critica di erosione è superata sia sotto il passaggio della cresta che sotto il cavo
- maggior durata della velocità al cavo
- componente netta di deriva: OFFSHORE

As waves approach a shoreline the water shallows and they change from deepwater to transitional waves and, finally shallow water waves, when $h < L/20$, and involve an onshore flux of water as the waves break and surge landward.



Waves undergo several changes as they approach the shoreline and progressively shallower water:

1. Wave height increases and the wave becomes steeper until the height reaches 75% of the water depth and the wave breaks in an onshore direction.

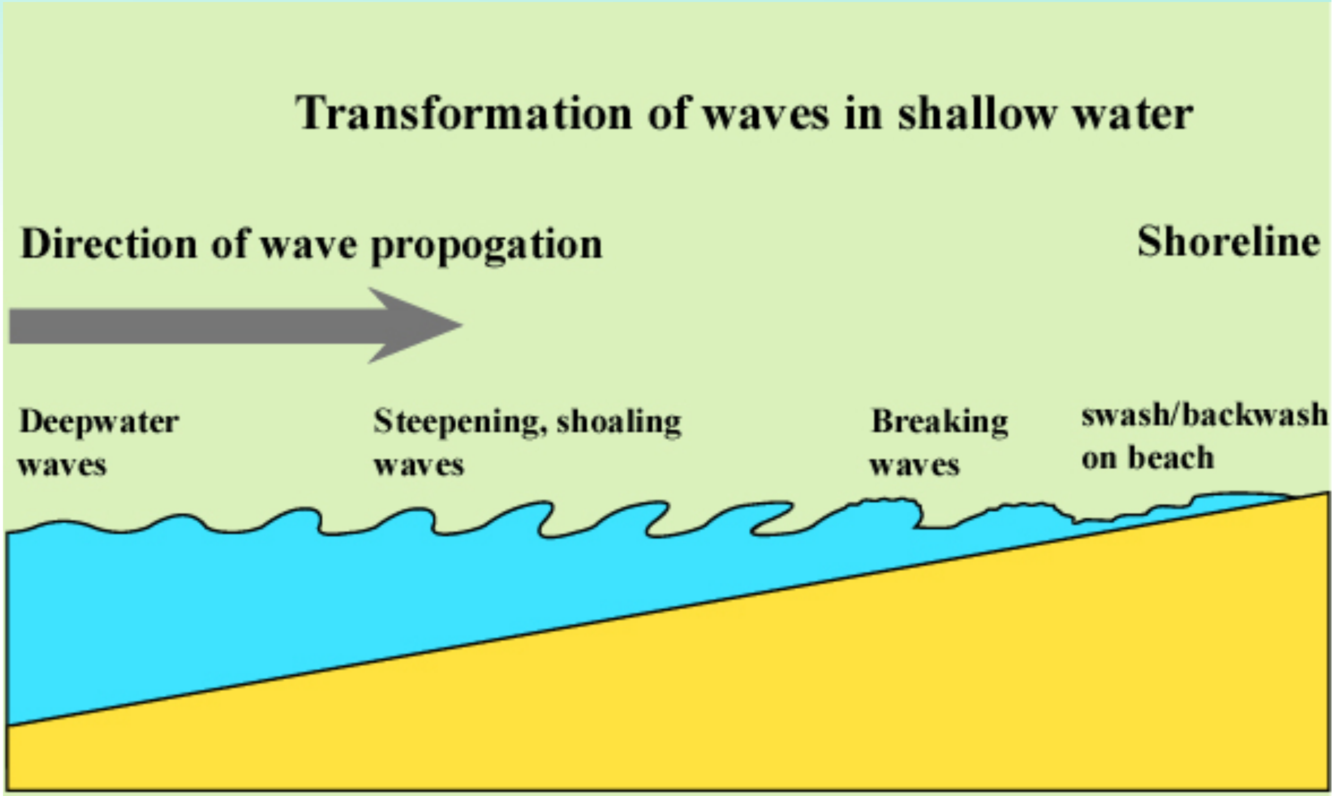


2. The rate of decrease in orbital diameter decreases with shallowing

For shallow water waves the orbital diameter is given by: $d_o = \frac{HT}{2\pi}\sqrt{\frac{g}{h}}$

and $U_m = \frac{H}{2h}\sqrt{gh}$

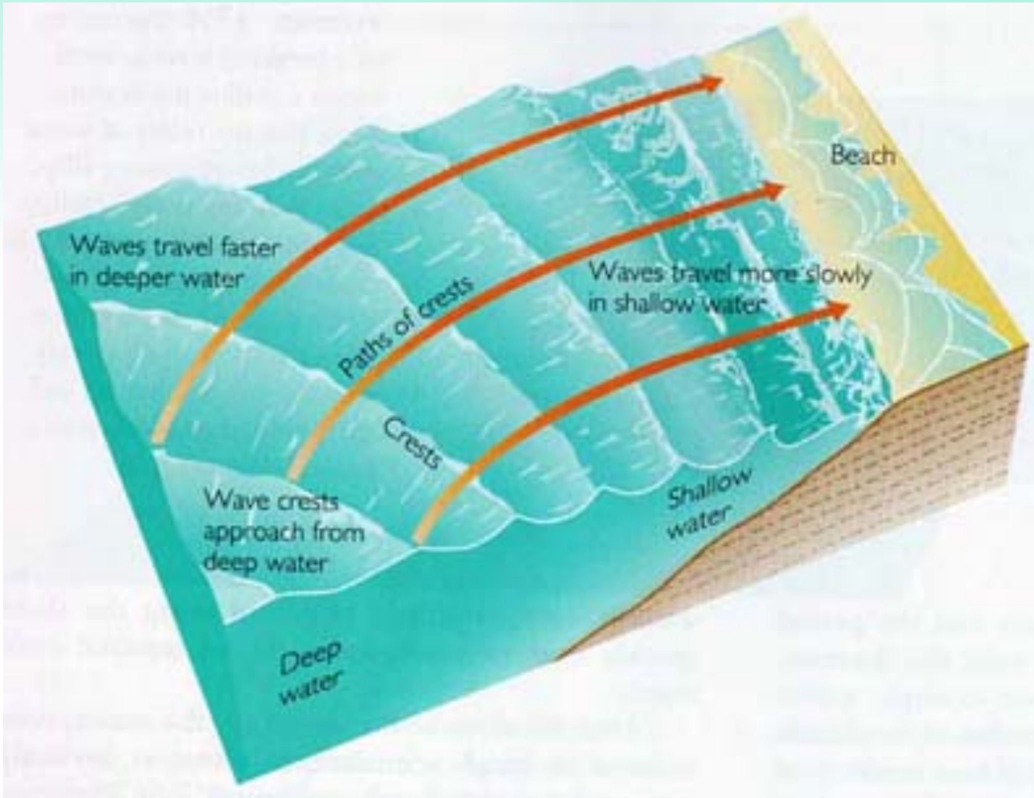
3. The oscillating current becomes increasingly asymmetrical with a more powerful onshore stroke.



4. When waves approach at an angle to a shoreline their crests bend to become more parallel to the shoreline (termed wave refraction).

The more nearshore portion of a wave will propagate more slowly than the more offshore portion due to the interaction with the bed.

As a result, the more offshore portion of a wave will "catch up" with the onshore portion so that it approaches the shore with a crest oriented more parallel to the shoreline.



Refraction

- In a time interval T (e.g. a single wave period) a wave crest in deep water travels exactly 1 wavelength (L_o)

- In shoaling depths, where celerity is reduced, the distance of travel will be less as it is inversely proportional to the depth (L_h)

- Wave crest travels different distances depending on the water depth

The initiation of sediment motion under waves

As for unidirectional flows, the condition for the initiation of sediment movement depends on:

ρ Fluid density.

ρ_s Density of the particles

D Grain size.

τ_o Boundary shear stress (related to U_m and d_o)

The threshold velocity for grain movement under waves (U_t) is:

$$\frac{\rho U_t^2}{(\rho - \rho_s) g d} = C \left(\frac{d_o}{d} \right)^n$$

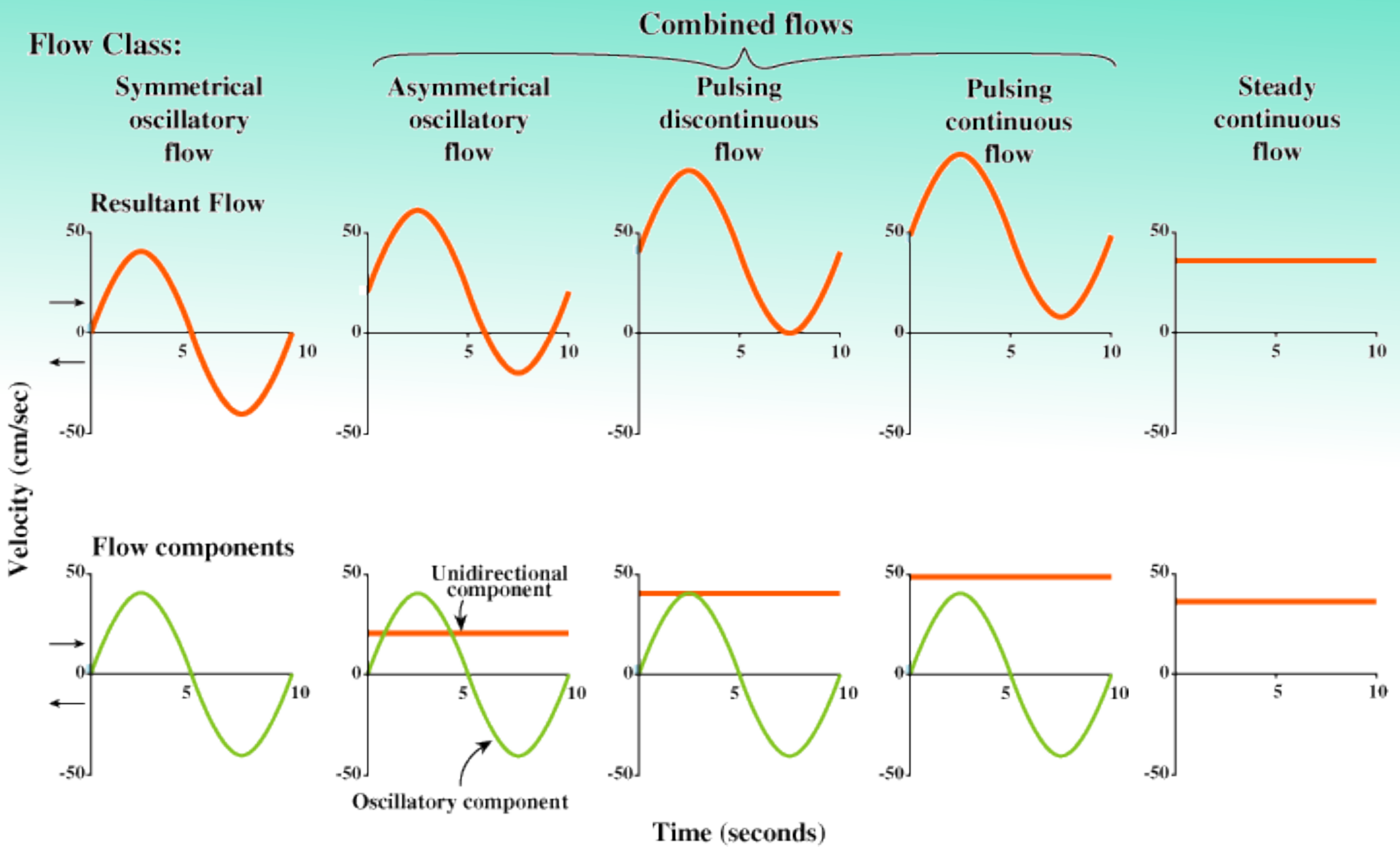
Where C=0.21 and n=0.5 if d < 0.5 mm.

Where C=1.45 and n=0.25 if d > 0.5 mm.

Difficult to use on ancient sediments as d_o must be known.
Remember that d_o is a function of H, L and depth (y).

Flow, bed forms and stratification under oscillatory and combined currents

The continuum from oscillating to unidirectional flows:



Bed forms under waves
(*pure oscillatory*)

Like unidirectional flows, oscillating flows produced by waves result in an ordered sequence of different bed forms.

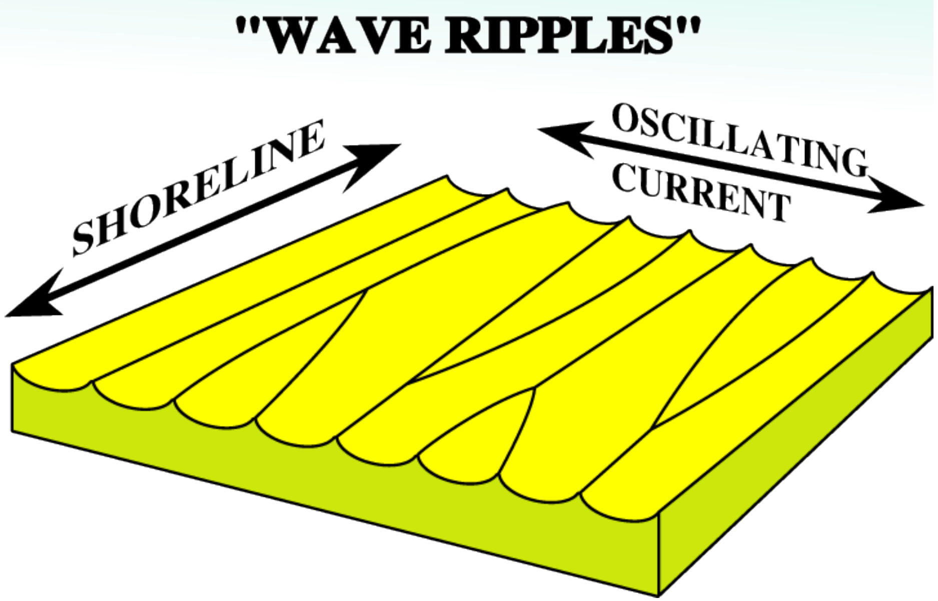
Before examining this sequence we will consider the classic wave-formed bed form “wave ripples” or “symmetrical ripples”.

Characterized by:

1. Symmetrical profile.

2. Peaked crests and broad troughs (more pronounce peaks in fine-grained sediment).

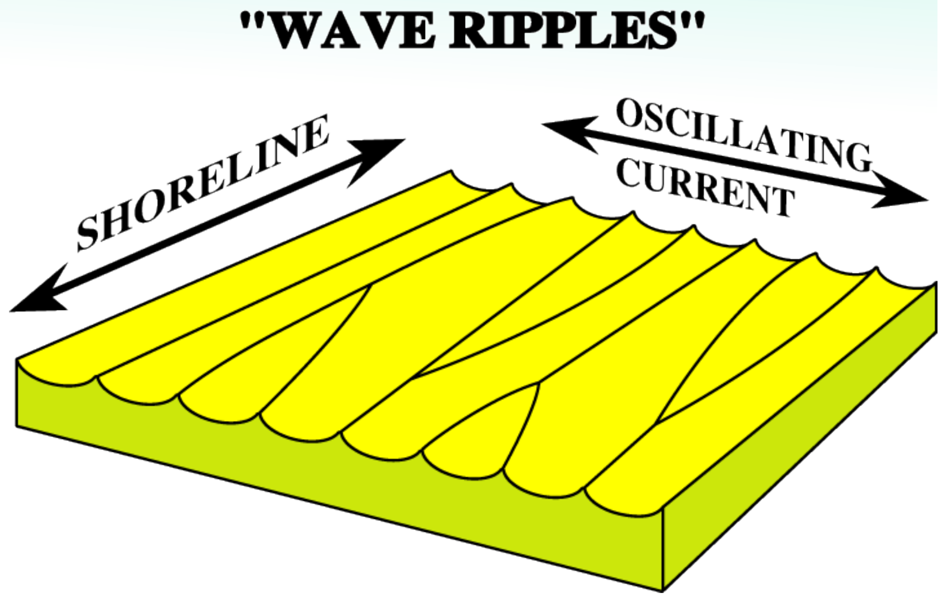
3. Straight, bifurcating crests.



The oscillating current acts at right angles to the crest of the ripples.

Ripple crests are parallel to the wave crests so that, on average, they are aligned parallel to the shoreline at the time of formation.

Ripple crest orientation is useful in determining *paleoshoreline* orientations.



Wave ripples from an intertidal area (red arrow points to a bifurcation of the crest).

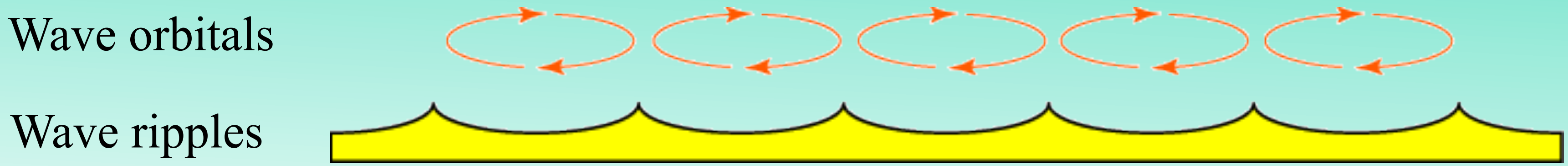
Note that these ripples have been modified by the ebb tidal current.

Interference ripples: the major symmetrical ripple crests (trending left to right) have secondary crests (top to bottom) superimposed.

This does not necessarily indicate formation under two sets of water surface waves.

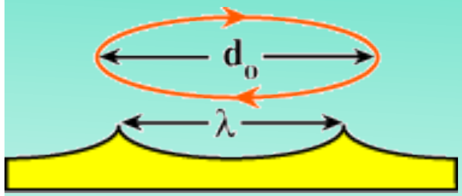
In the past the traditional view of wave ripples was to think in terms of wave orbitals residing in the troughs of the ripples.

….one orbital for every ripple trough.



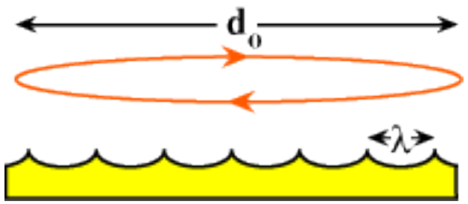
However, examination of wave ripples in natural settings where the orbital diameter is known suggests that wave ripples are more complicated.

Plots of ripple spacing (λ) versus the diameter of the wave orbital's forming the ripples delineate three ripple types:

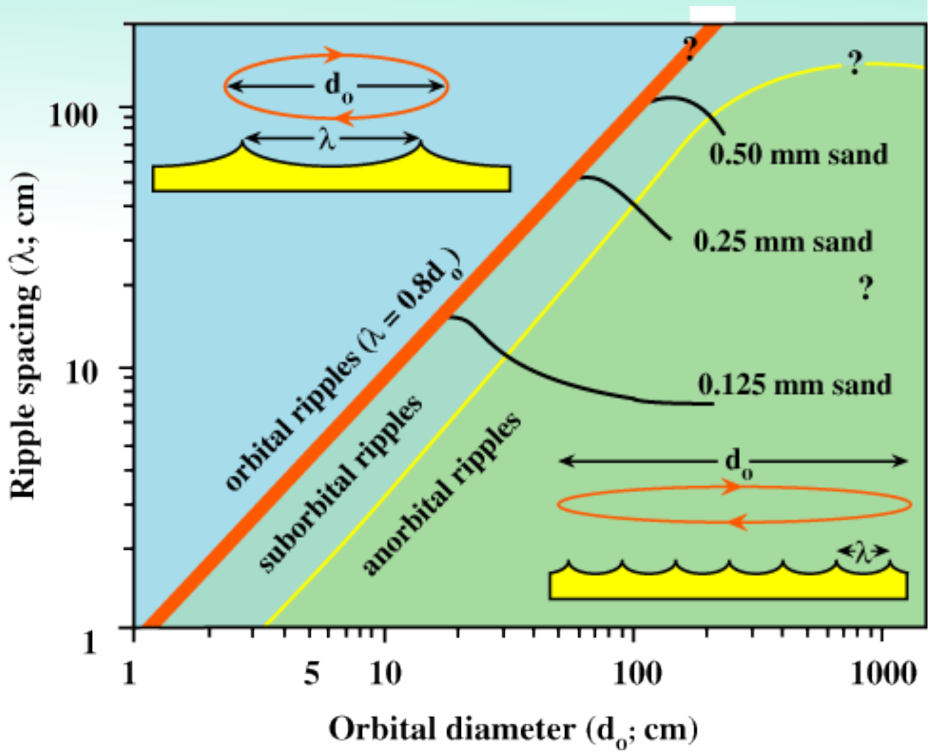


Orbital ripples; one orbital per ripple with the relationship: $\lambda = 0.8d_o$

Suborbital ripples: intermediate between orbital and anorbital ripples.



Anorbital ripples; where there are several ripples per orbital and $\lambda << 0.8d_o$

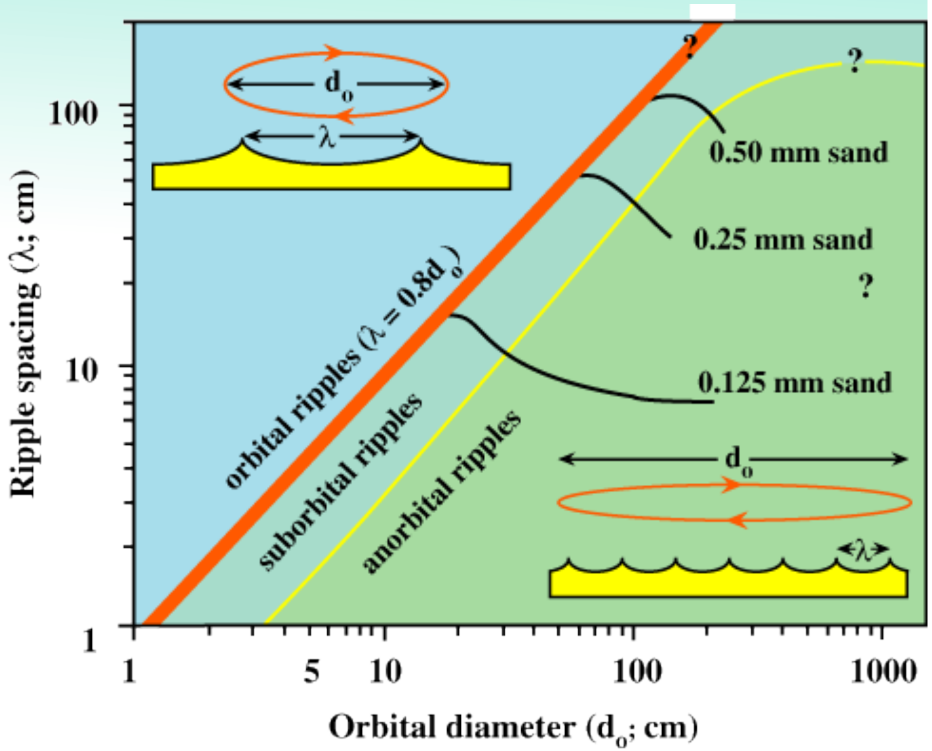


While orbital ripples increase with orbital diameter they have an upper limit to their spacing that is governed by grain size.

In the case of orbital ripples, the coarser the grain size the larger the ripples can become.

Beyond this limit the ripples become suborbital ripples and their spacing decreases.

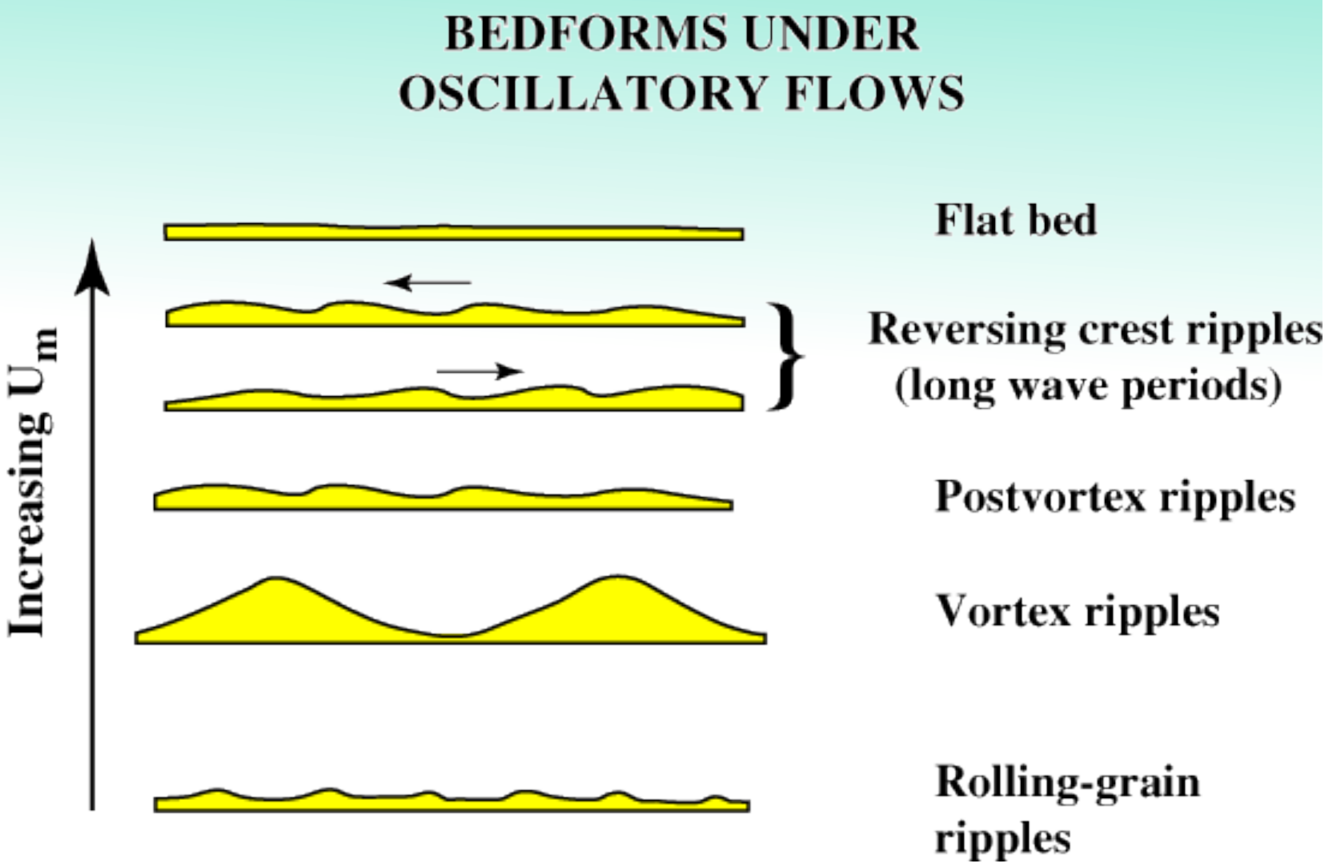
Anorbital ripples have shorter spacing for a given grain size then orbital and suborbital ripples.



Coarse-grained wave ripples in Wales (Photograph by Roger Suthren; borrowed from http://www.brookes.ac.uk/geology/sedstruc/wavrip/piccap.htm).

The sequence of bed forms under oscillatory flows

Like unidirectional flow bed forms, under oscillatory flows the type of bed form changes in a predicatable manner with increasing flow strength (e.g., U_m).

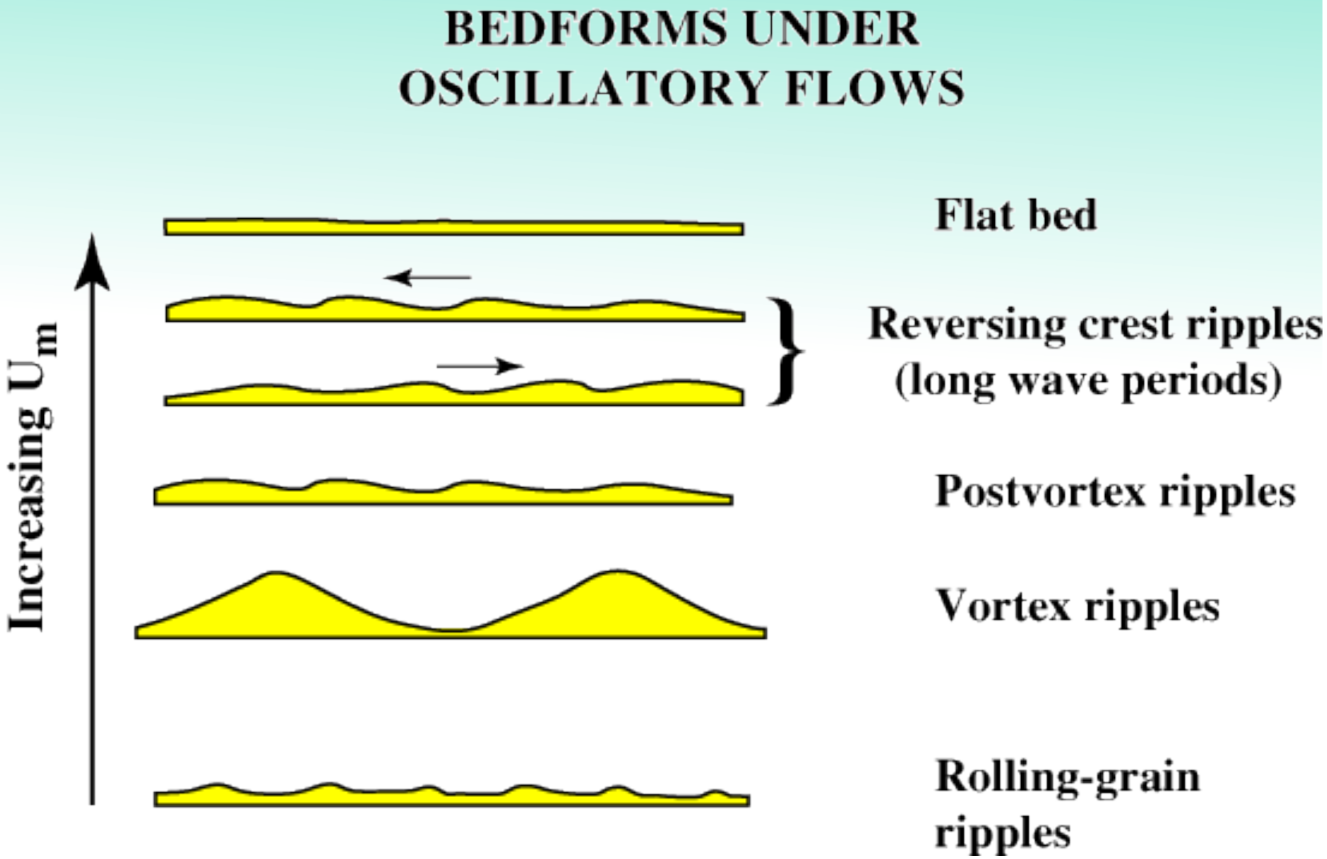


Rolling-grain ripples:

A few millimetres high, < 10 cm long.

Symmetrical and straight-crested; very low angle slopes.

May be a metastable bed form: will grow into vortex ripples if currents are sustained for sufficient duration.



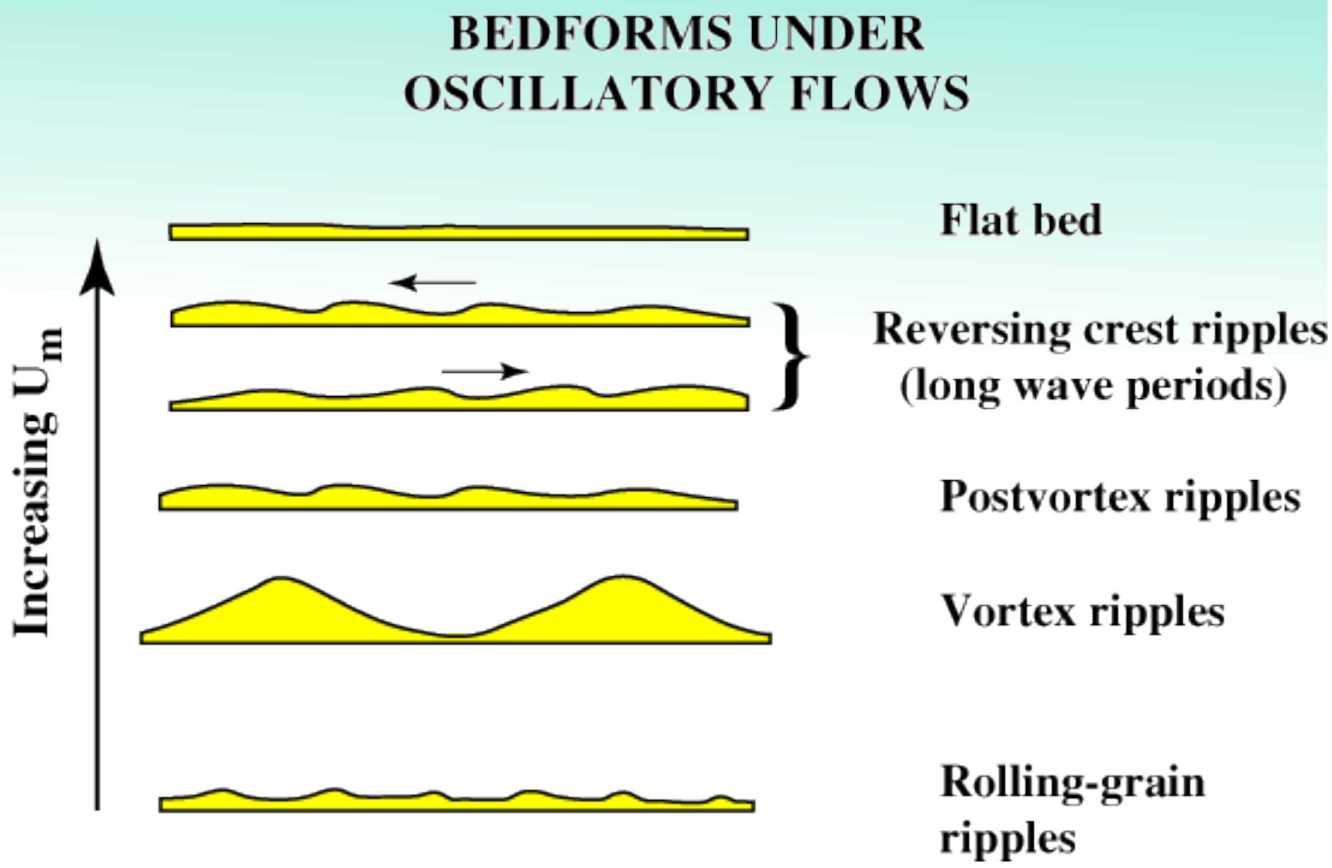
Vortex Ripples:

2-D vortex ripples form first; classic wave ripples.

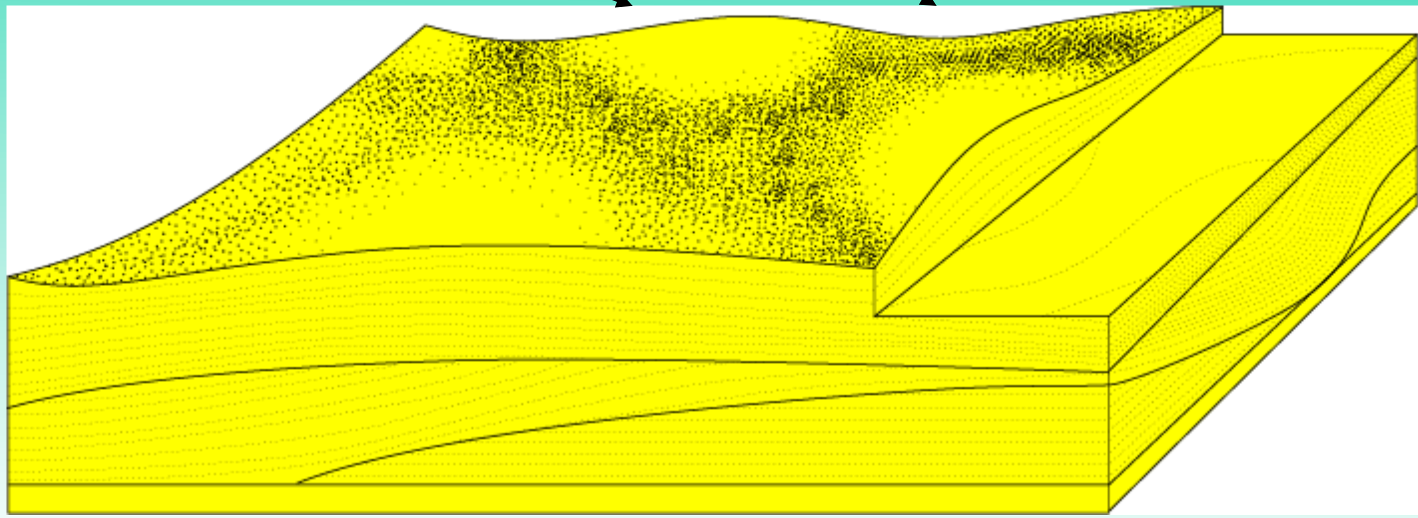
Broad troughs, peaked crests, straight to bifurcating crests.

3-D vortex ripples: longer and higher than 2-D vortex ripples.

Circular mounds and hollows (hummocks and swales).



Schematic of **hummocks** and **swales** of 3-D vortex ripples.

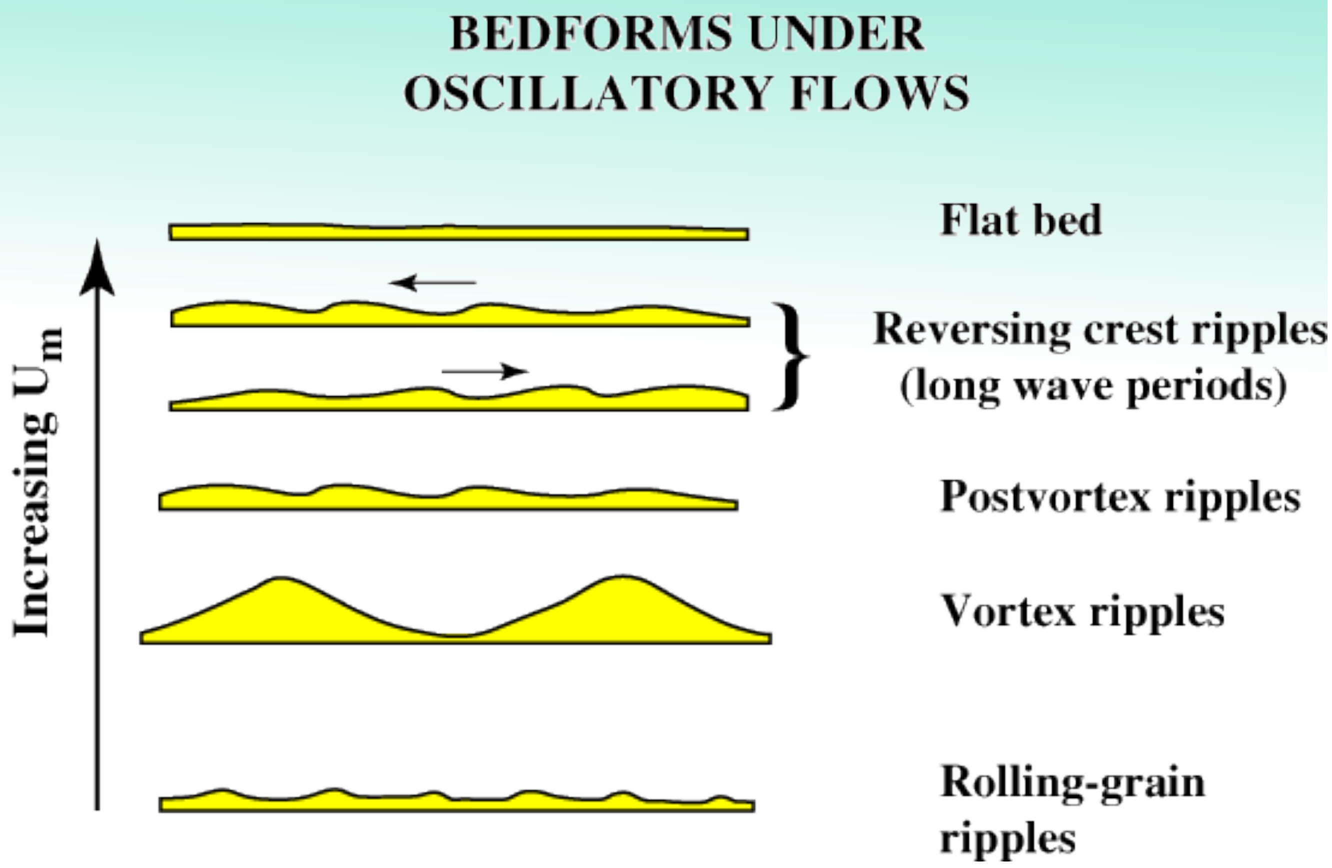


Post-vortex ripples:

Washed-out 3-D vortex ripples.

Longer and lower than 3-D vortex ripples.

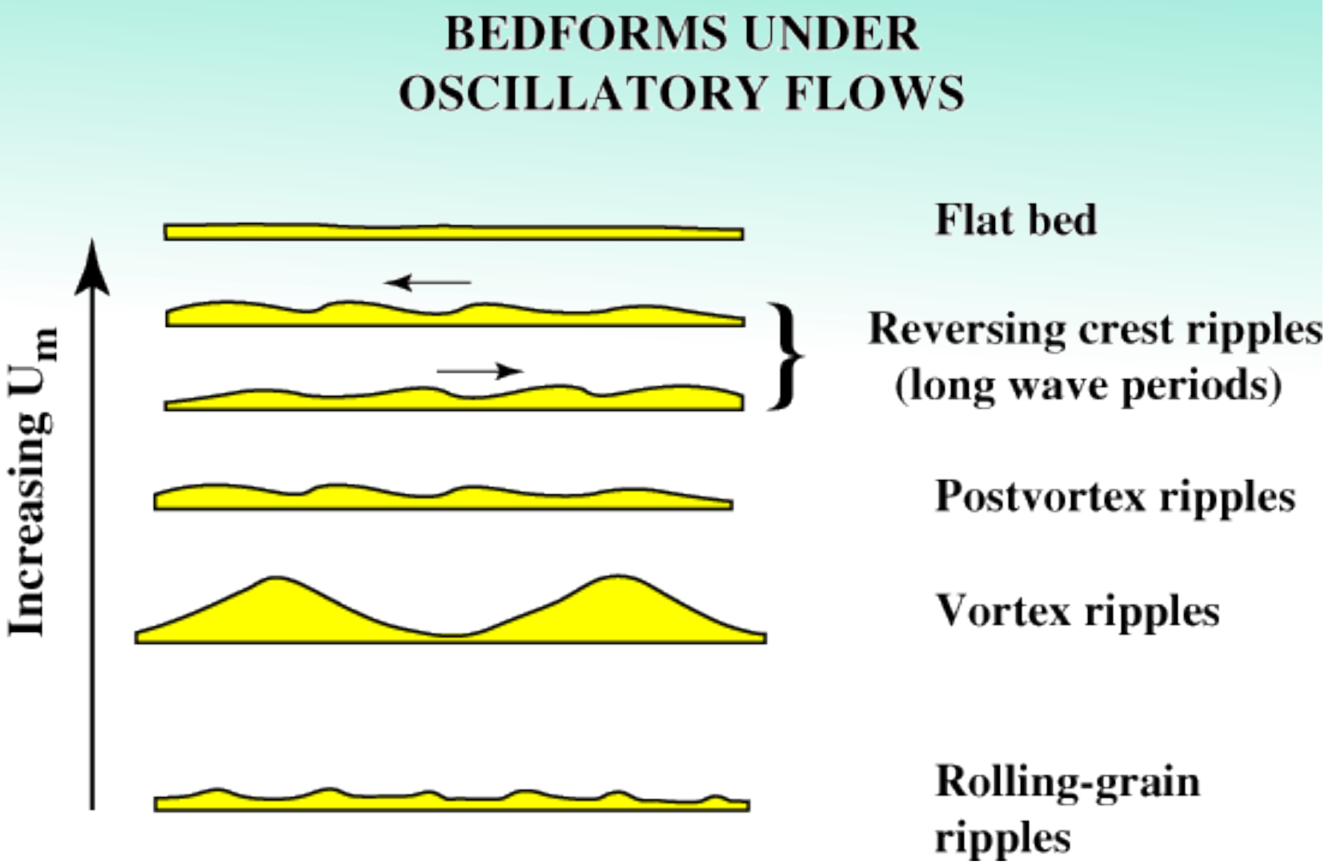
Transition to flat bed.



Reversing crest ripples:

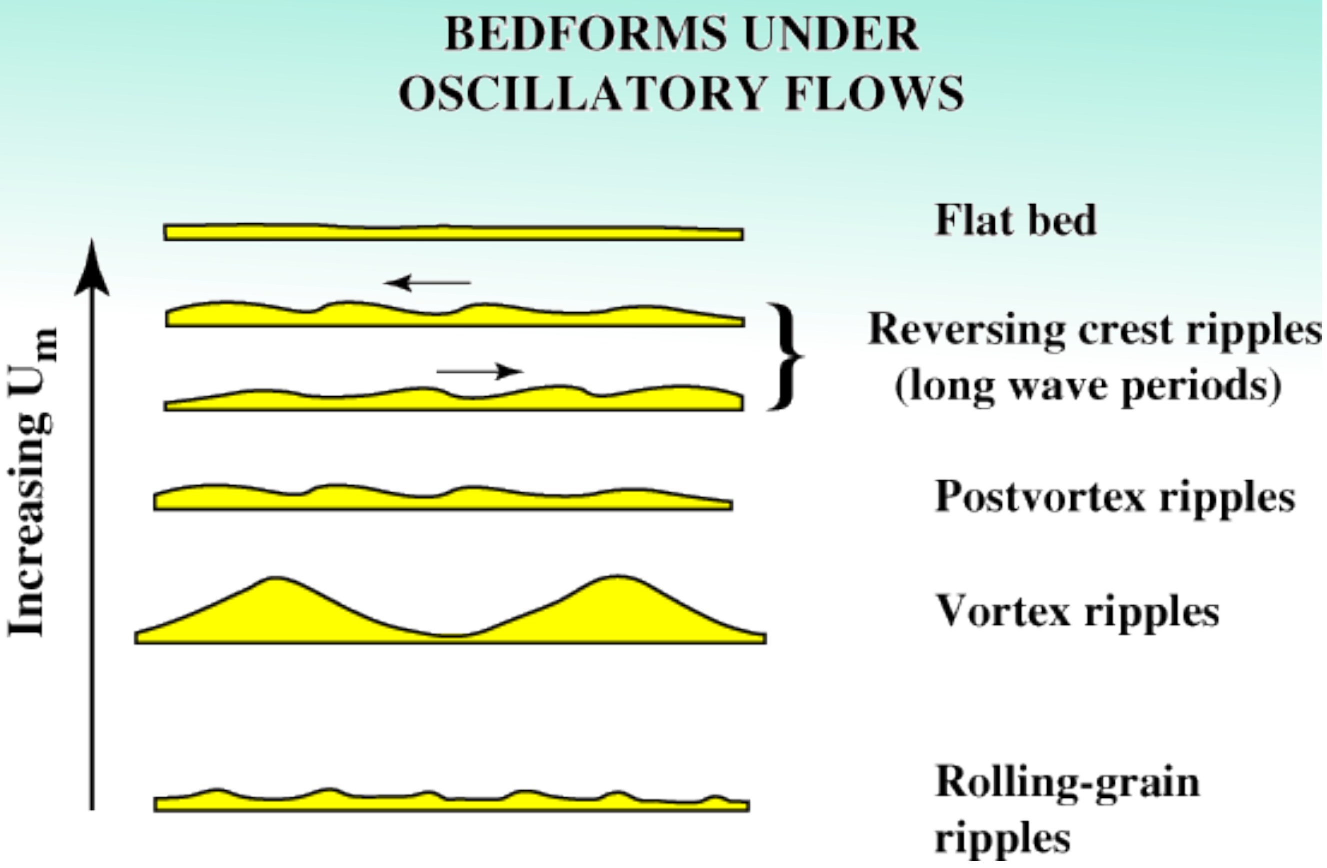
Asymmetric ripples that reverse in direction with every stroke of the wave.

ONLY form under relatively long period waves (long enough stroke in one direction to form an asymmetric ripple).



Flat bed:

A flat, featureless bed with rare parting and/or current lineation.



Bed form stability diagrams

Range of conditions under which bed forms are stable depends on:

U_m: maximum orbital speed.

d_o (T): orbital diameter and wave period (influence the duration of the flow in a given direction).

ρ: fluid density.

μ: fluid dynamic viscosity.

} Thought to be of secondary importance.

d: grain size.

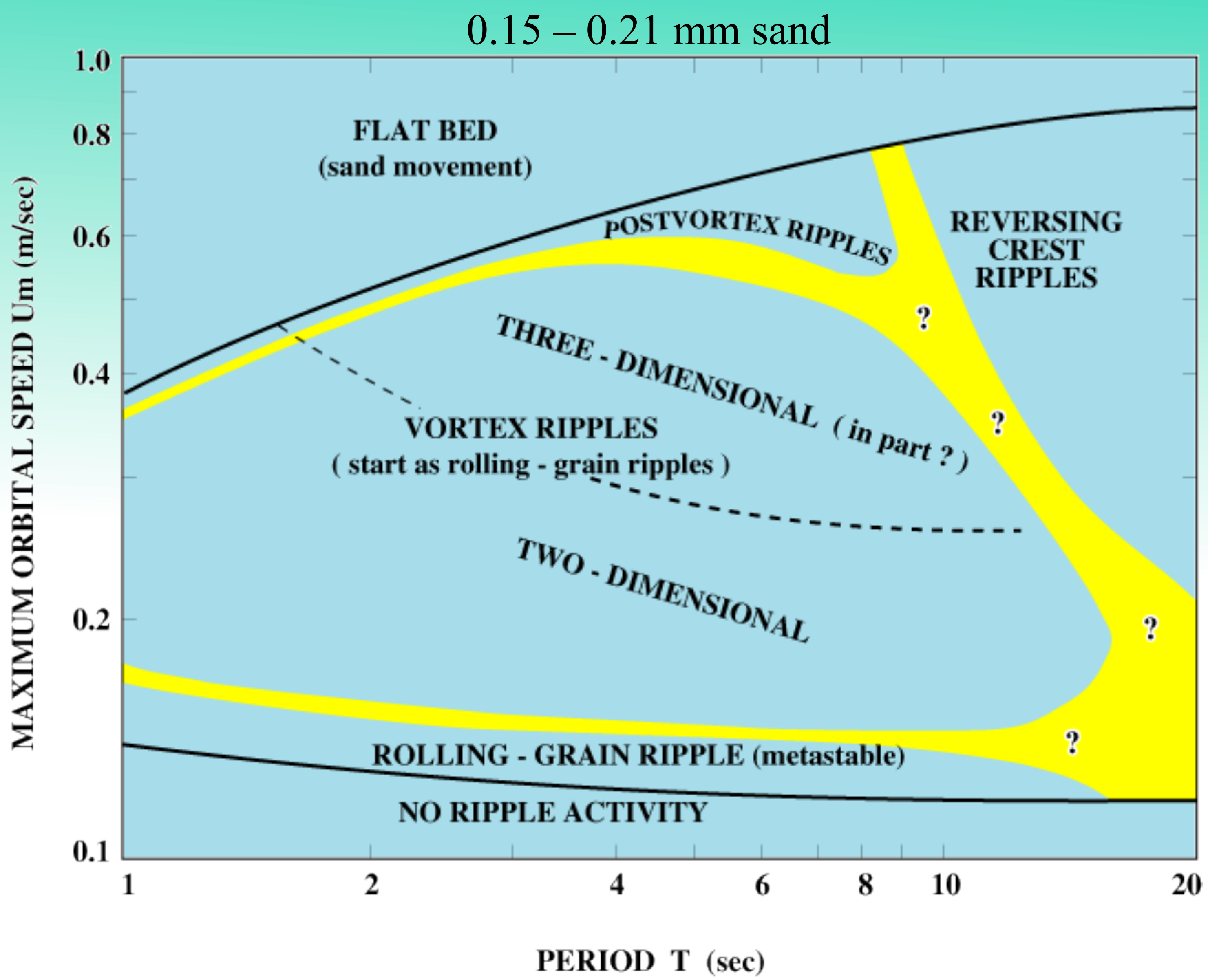
ρ_s: sediment density; assume quartz sand.

ψ: sphericity

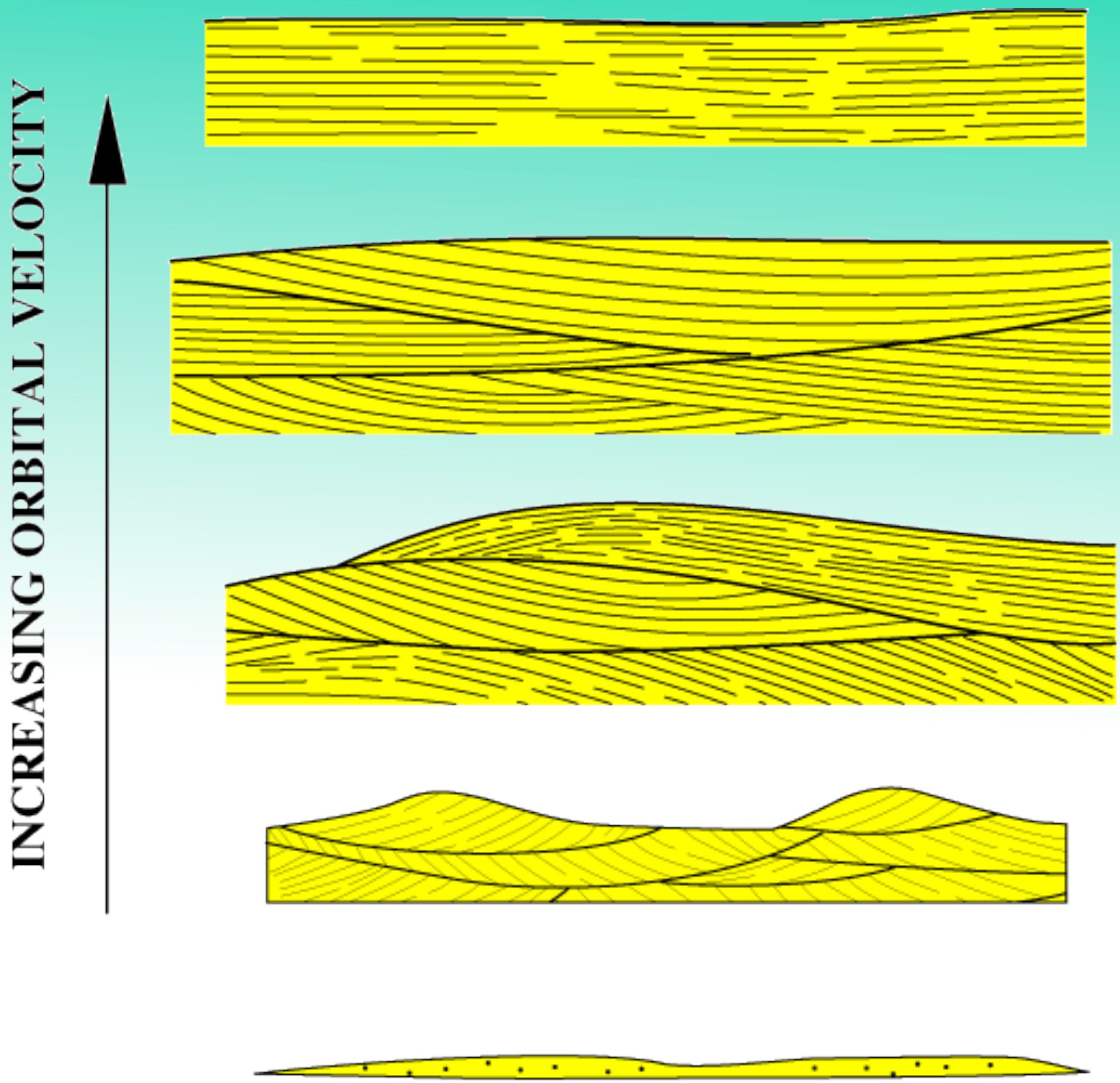
Grain shape

} Thought to be of secondary importance.

Bed form stability diagrams are normally plotted as U_m versus T for a narrow range of grain sizes.



Cross-stratification formed by oscillatory flow bed forms



Flat bed
Near - horizontal fine laminae

Three - dimensional vortex ripples
(flatter)
l dm - m, I 15 - 20
Swaley sets of cross laminae with set contacts sloping less than 10°, hummocks rarely preserved

Three - dimensional vortex ripples
(steeper)
l dm - m, I~10
Hummocky sets of cross laminae with set contacts sloping as much as 10 - 15°

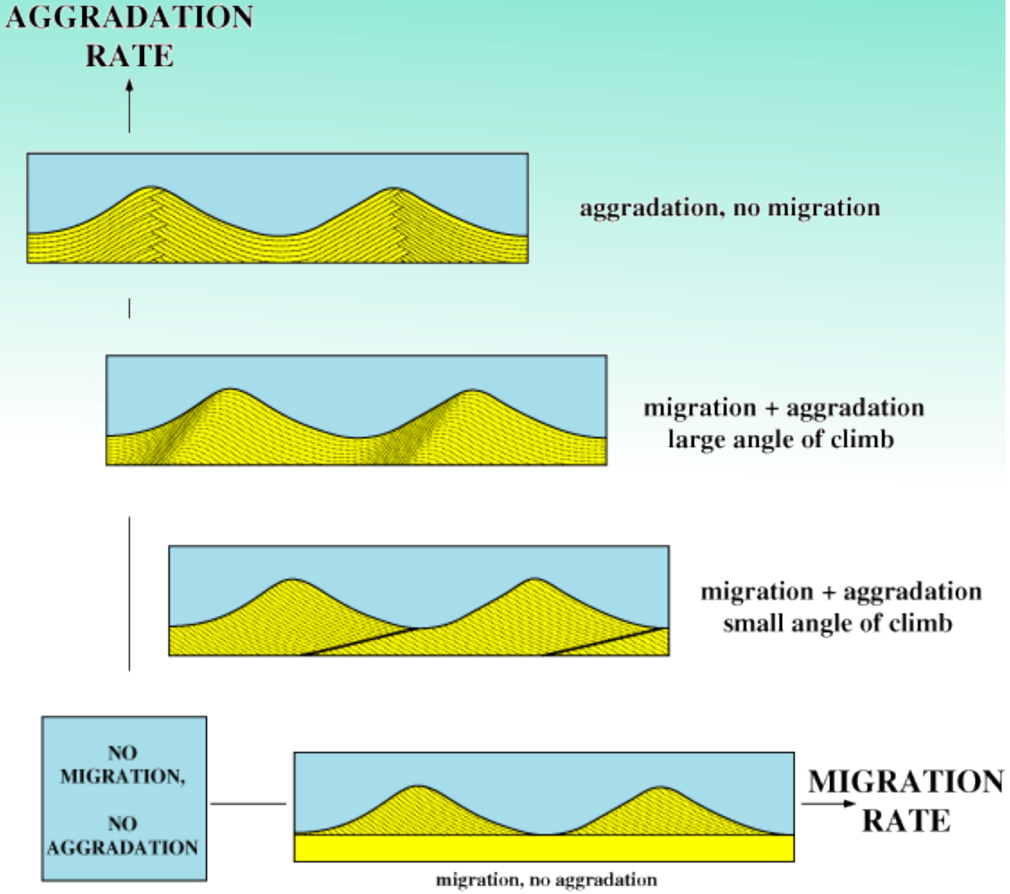
Two - dimensional vortex ripples
l cm - dm, I= 6 - 10
Small intricately "braided" sets of cross laminae

Rolling grain ripples
l cm, I large
Thin laminae, low angle cross lamination or flat lamination

Note I = L/H (L is the length of the ripple, H is the height) and is known as the “ripple index”

Under some conditions 2-D vortex ripples form braided sets dipping in opposite directions with curved bounding surfaces. Termed *chrevron cross-stratification*

Like ripples formed by unidirectional currents, the style of preservation of the cross-strata depend on the rate of migration of the ripples and the rate of aggradation of the bed.



Cross-stratification formed by 3-D ripples includes *hummucky cross-stratification (HCS)* and *swaley cross-stratification (SCS).*

Hummocky cross-stratification is characterized by:

1. Convex upward (hummocks) and concave upward (swales) laminae and internal bounding surfaces; spacing of hummocks and swales is commonly large, in excess of 1m.

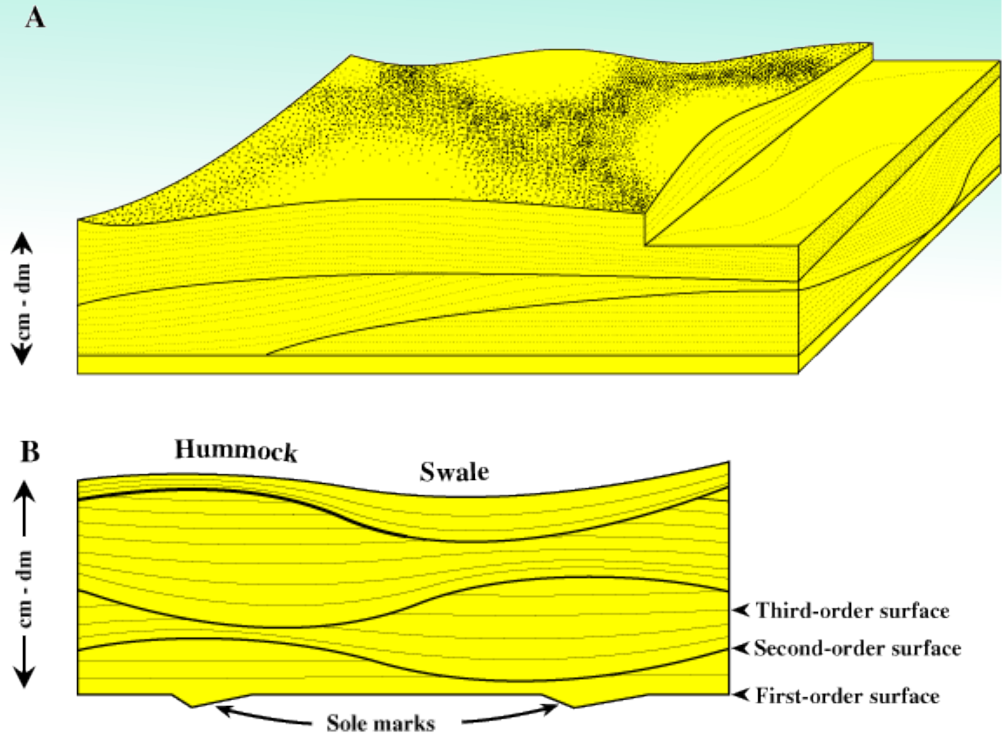
2. Low angle (generally less than 10° but up to 15°), erosional bounding surfaces.

3. Internal laminae that are approximately parallel to the lower bounding surfaces.

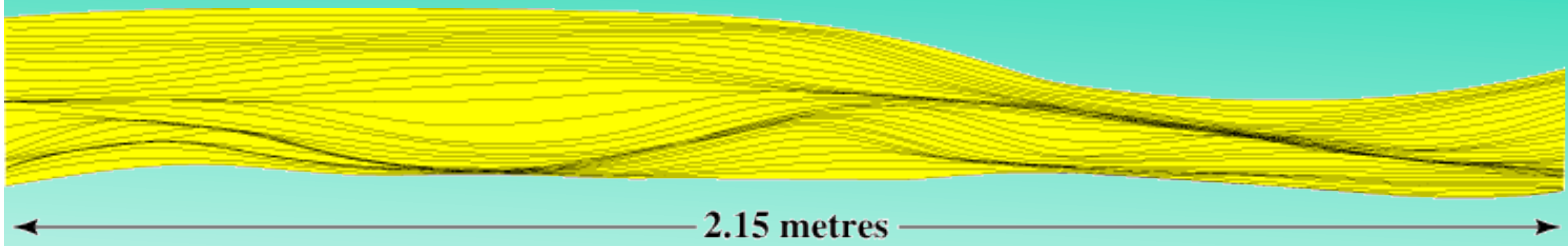
4. Individual laminae that vary systematically in thickness laterally and their angle of dip diminishes regularly.

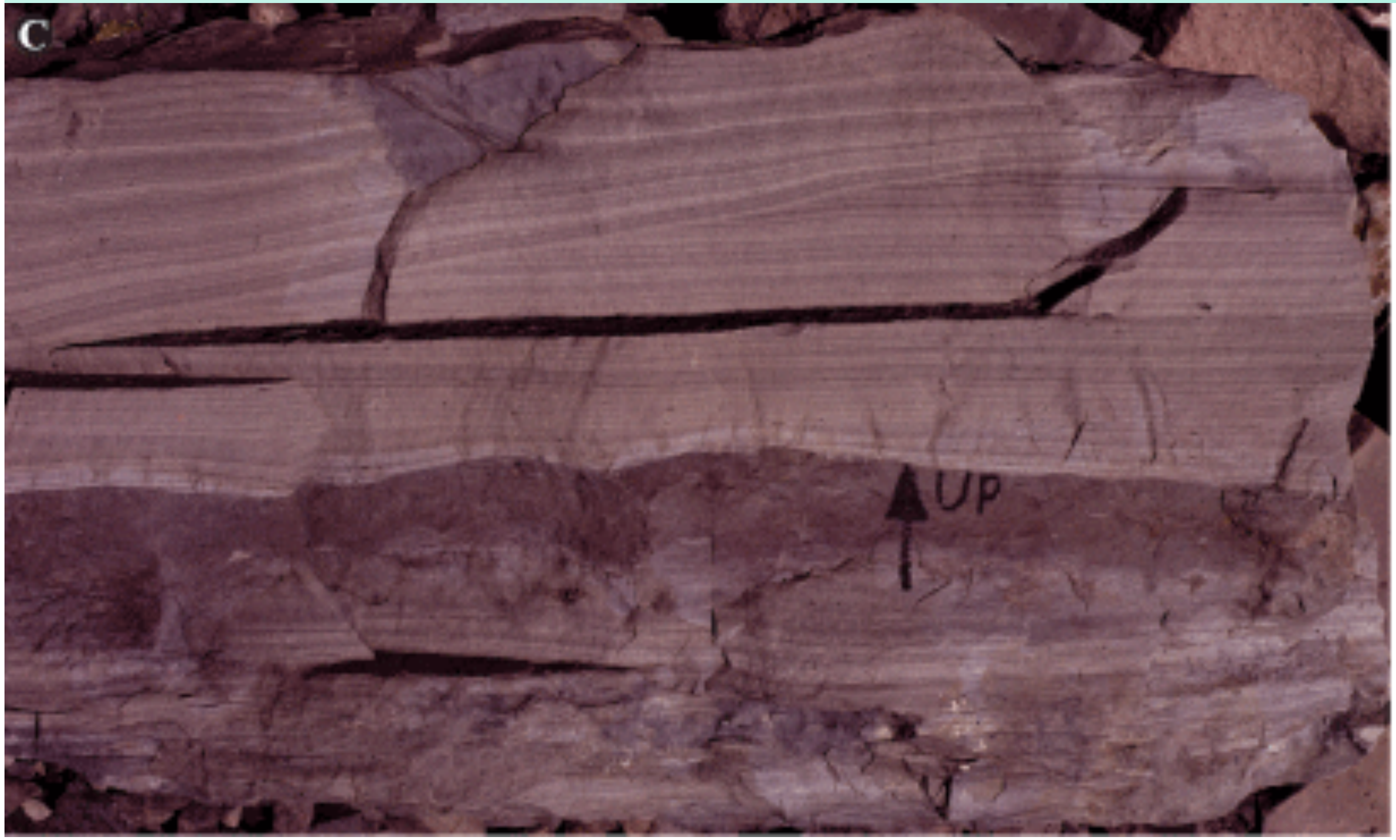
5. Internal laminae and bounding surfaces dip equally in all directions (i.e., they are isotropic).

HCS is best developed in coarse silt to fine sand.

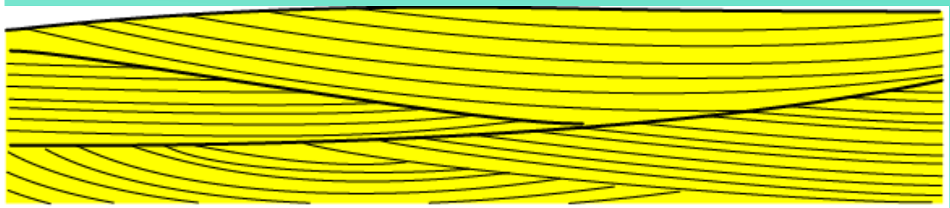


HCS produced in a wave duct at MIT.

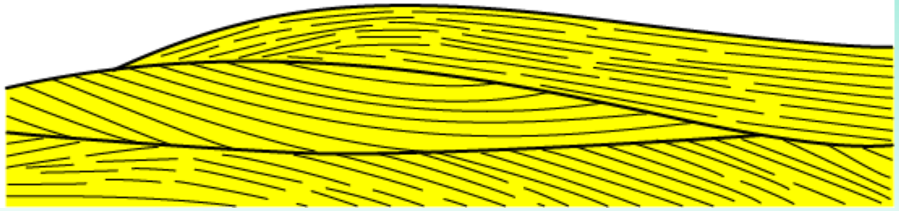




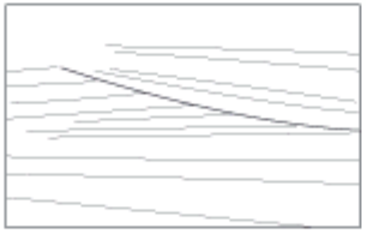
Swaley cross-stratification is similar to HCS but lacks hummocks and internal laminae and bounding surfaces commonly exceed 15°



SCS



HCS



Reversing crest ripples will produce a form cross-stratification with cross-strata dipping in opposite directions.

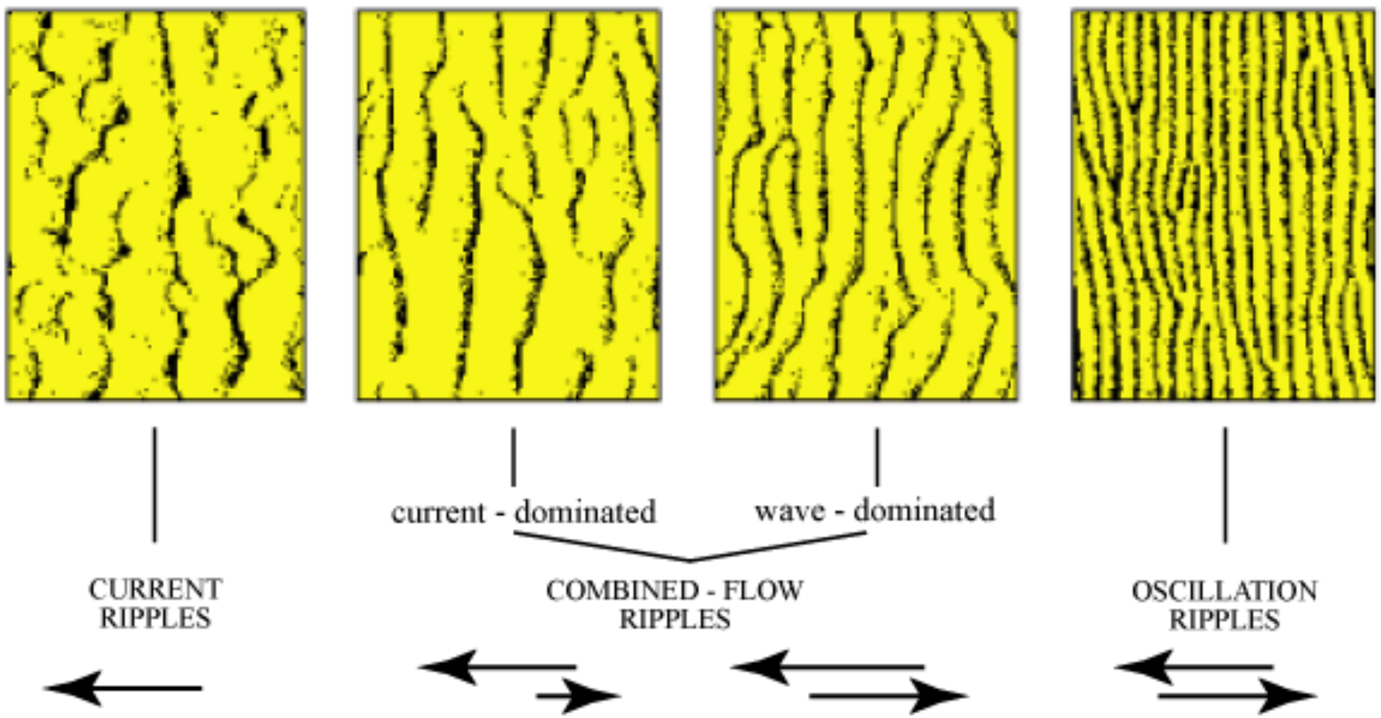
Presumably preservation requires relatively high rates of deposition so that the bed aggrades over a short period of time.

Flat bed will preserve a horizontal to gently undulating internal lamination.

Combined flow bedforms and stratification

The bed forms and stratification vary with the relative strength of the unidirectional and oscillatory flows.

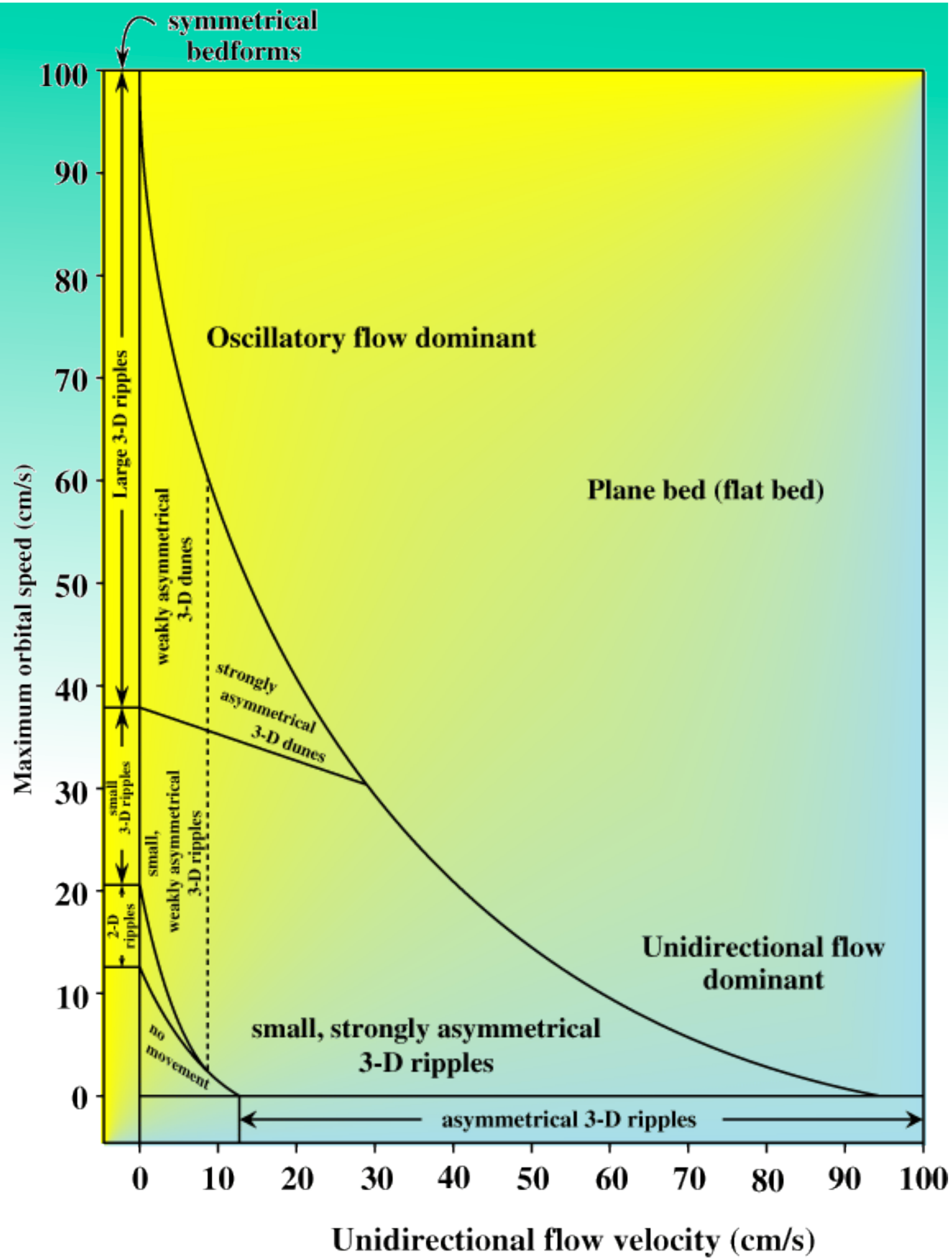
Ripples become more 2-D in plan form and symmetrical in cross-section as the flow ranges from purely undirectional to purely oscillatory.



3D vortex ripples become increasingly asymmetrical as the unidirectional component increases.

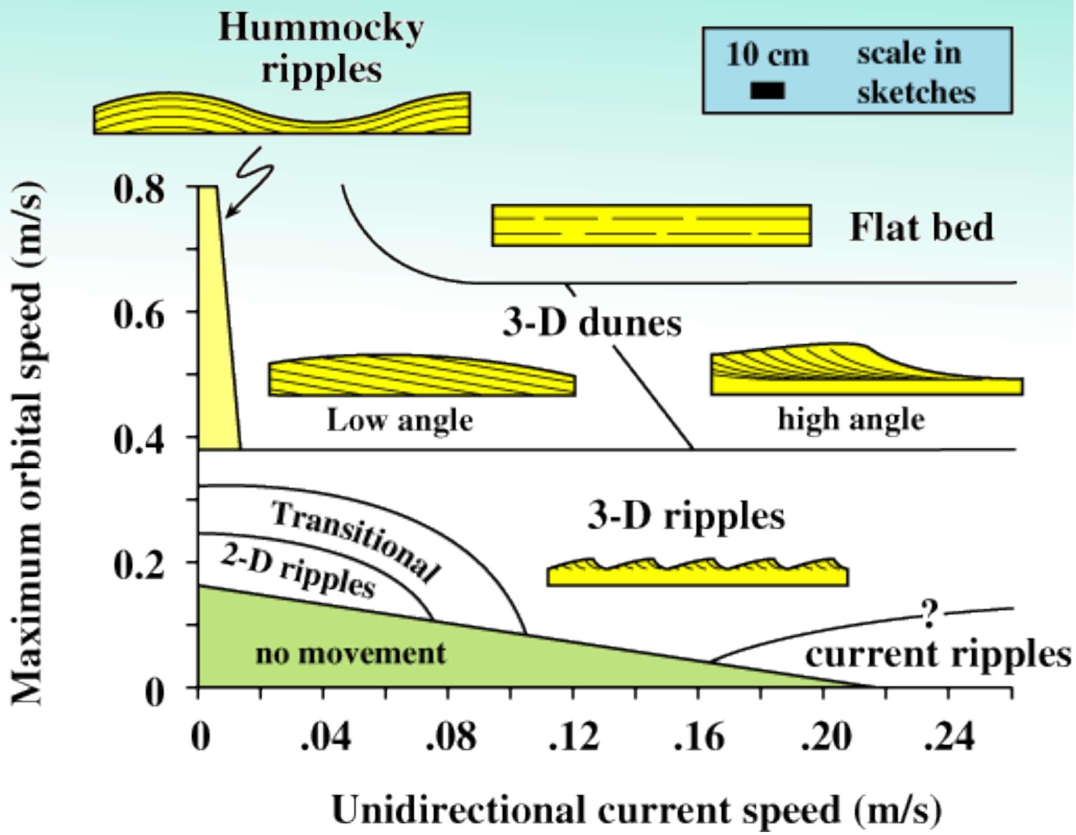
Only a very small unidirectional component will turn hummocky bed forms into asymmetrical bed forms.

Plane or flat bed is stable over a wide range of conditions under combined flows.

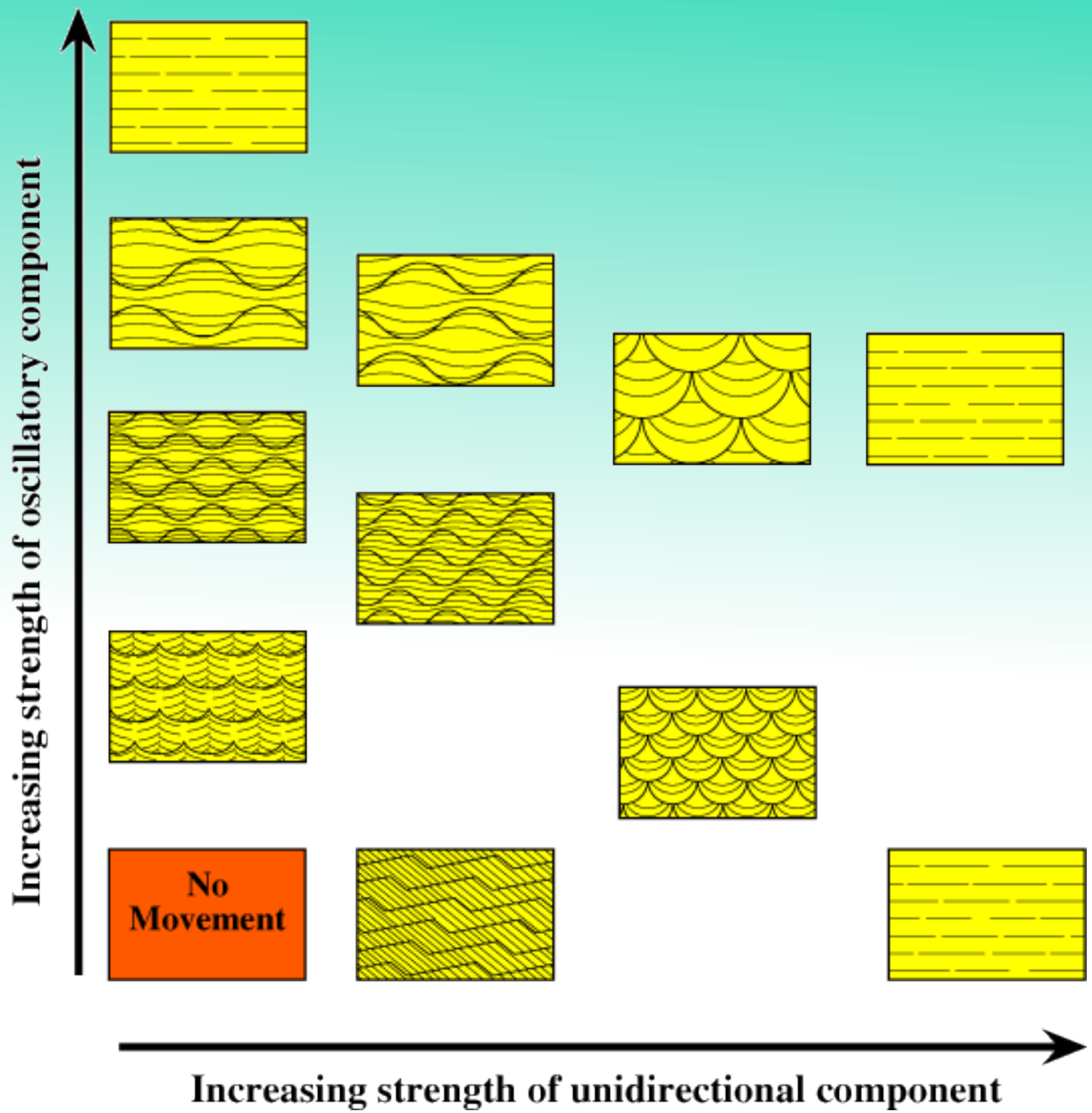


Internal stratification varies from that associated with purely wave-formed structures to that of purely undirectional flow structures.

With only a small unidirectional component HCS-like stratificaiton becomces anisotropic (not dipping equally in all directions).



A possible model for internal stratification produced by combined flows.




PURE BLISS
finest
Chocolates

"And that's all I have to say about that!"

Forrest Gump