Estuaries: Classification, Mixing, and Coastal Biogeochemistry Part I

OCN 623 – Chemical Oceanography
04 Apr 2017

Today’s Outline

Review today’s handouts, read Libes before Thursday

- Definitions & types of estuaries
- Estuarine circulation
- Mixing processes
- The mid-estuary turbidity maximum

The Coastal Zone - **Coastal Ocean extends from the high-tide line to the shelf break**

This region is responsible for nearly 30% of the total net oceanic primary production and nearly 90% of the global fish catch

Estuaries

- Estuary is derived from the Latin word for tide - "aestus"

  Aestuarium – low ground covered by the sea at high water

- Estuaries and lagoons comprise 80-90% of coastline along Atlantic & Gulf Coast and 10-20% on Pacific Coast

- Nearly 900 individual estuaries in the continental US

- Atlantic & Gulf Coasts - border broad continental shelf - have extensive marshes - older

- Pacific Coast - formed by tectonic activity, deep, narrow shelf, salt marshes small or absent - younger

Definitions of "Estuary"

Two major components involved:

- Transition from fresh (river) water to saline (ocean) water
- Tidal influence

One definition:

> "An estuary is a semi-enclosed coastal water body that extends to the effective limit of tidal influence, within which sea water is significantly diluted with freshwater from land drainage"

ESTUARY DEFINITIONS

- Pritchard (1967) - a semi-enclosed coastal body of water which has a free connection with the open sea and within which seawater is measurably diluted with freshwater derived from land drainage

- Fairbridge (1980) – an inlet of the sea reaching into a river valley as far as the upper limit of tidal rise, usually being divisible into three sectors: a) a marine or lower estuary, in free connections with the open sea; b) a middle estuary subject to strong salt and freshwater mixing; and c) an upper or fluvial estuary, characterized by freshwater but subject to strong tidal action. The limits between these sectors are variable and subject to constant changes in the river discharges.

- Day (1980) - a partially-enclosed body of water which is either permanently or periodically open to the sea and within which there is a measurable variation of salinity due to the mixture of seawater with freshwater derived from land drainage

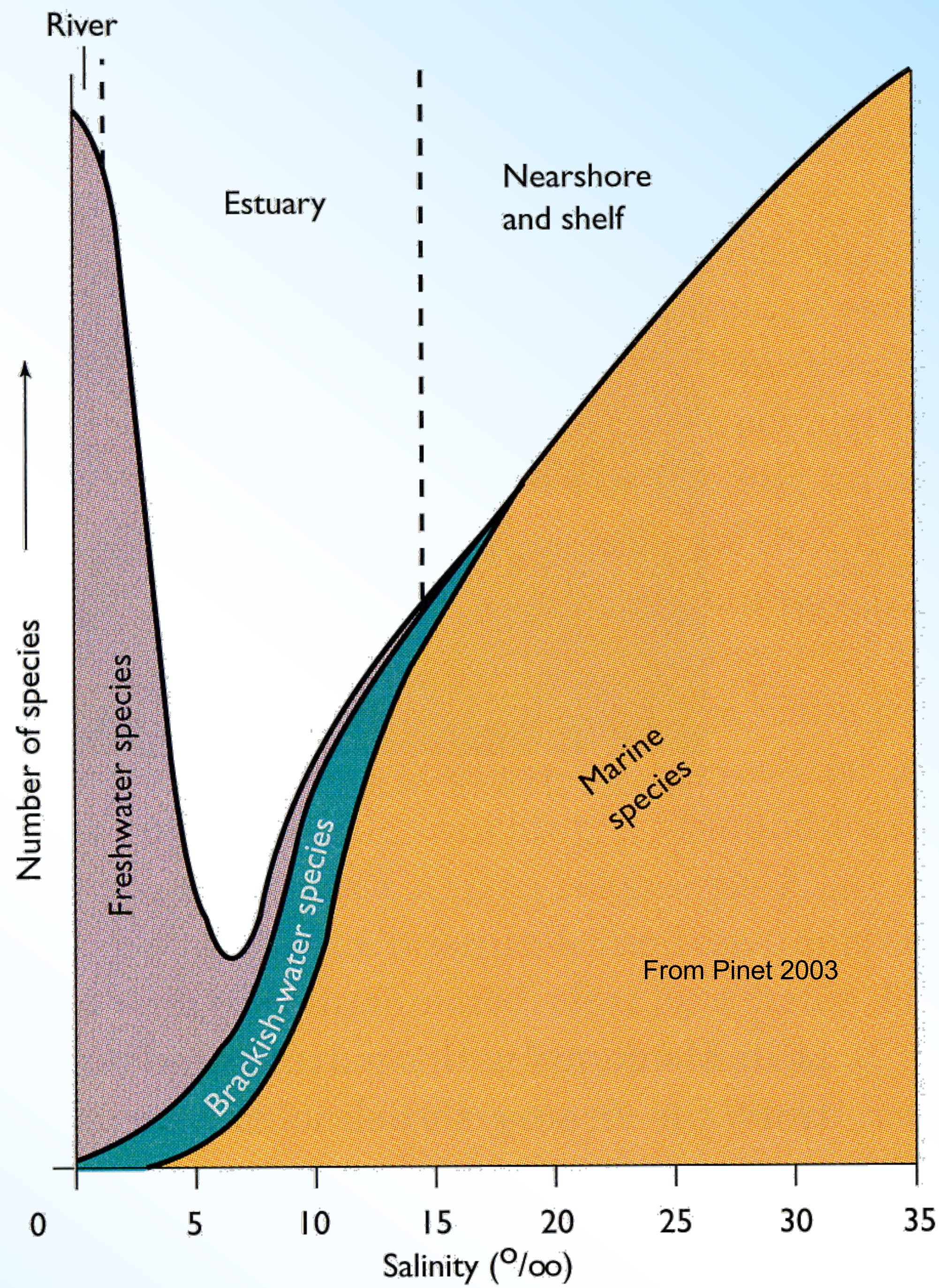
- Kjerfve (1989) - a coastal indentation that has a restricted connection to the ocean, remains open at least intermittently, and has a tidal river zone, a mixing zone, and a nearshore turbid zone

Transition zones (ecotones) occur between two or more diverse communities or habitats.

Species that have highest abundance in ecotones are called *"edge species"*

Odum (1971) - estuaries are ecotones between freshwater and marine habitats

Estuaries can be conceptualized as physical and biological mixing zones



The shallow and intertidal areas are usually bordered by salt marsh or mangrove vegetation (in the tropics)

Estuaries are very efficient “traps” for nutrients, sediments, and pollutants - Usually present in high concentrations

http://dcm2.enr.state.nc.us/ims/wetlands/salt_marsh.jpg

http://www.nmfs.noaa.gov/habitat/habitatprotection/piclink9.htm

High socio-economic relevance

Salt Marshes - Geomorphology

Extent of channelization depends on the tidal range (more tide → more channels)

www.agpix.com

Salt marshes: geomorphology & hydrology

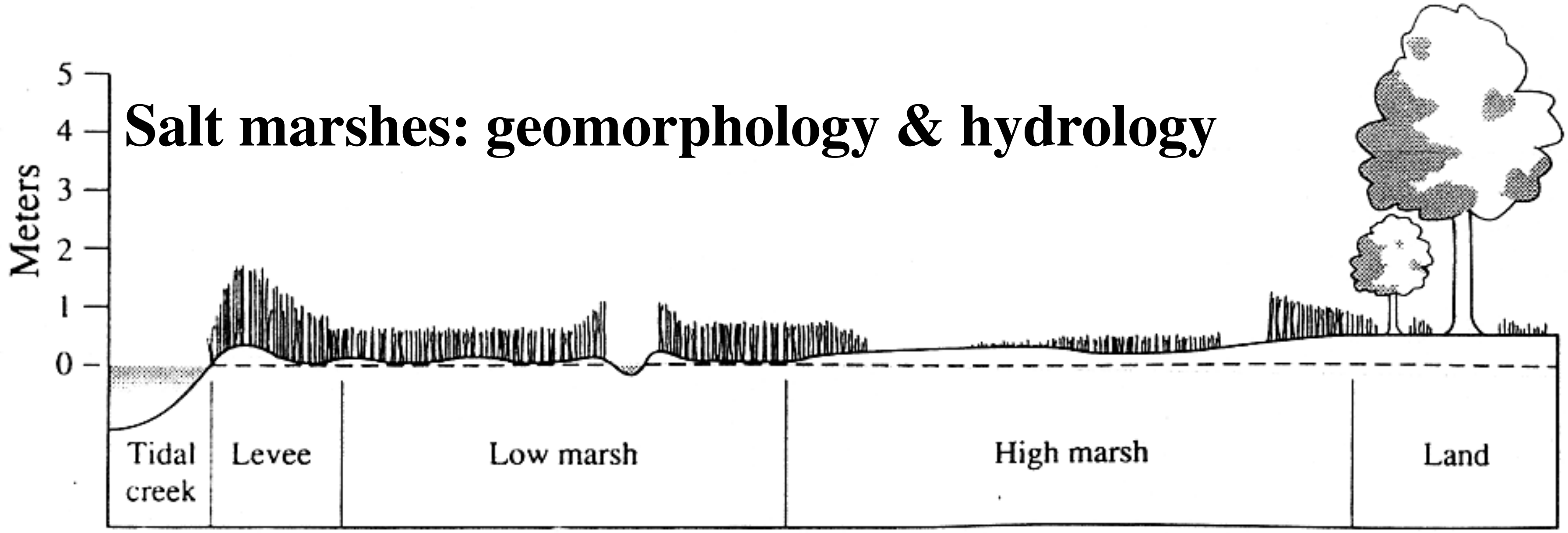


Figure 8.9 Schematic cross section through a salt marsh, showing the relationship between various components of the salt marsh ecosystem and the open waters of the estuary. From Wiegert et al. (1981).

- Salt marsh vegetation exists in dynamic equilibrium between rate of sediment accumulation and rate of coastal subsidence, or sea level rise.

  - as deposits accumulate, erosion and OM oxidation increase, slowing rate of further accumulation

  - as sea level rises, marsh is inundated more frequently, and accumulation rate of sediment and peat increases.

  -When rate of sedimentation does not kept up with subsidence, marshland is lost.

  - Sea level rise due to global warming could accelerate loss of marshland.

Salt marshes: geomorphology & hydrology (cont'd.)

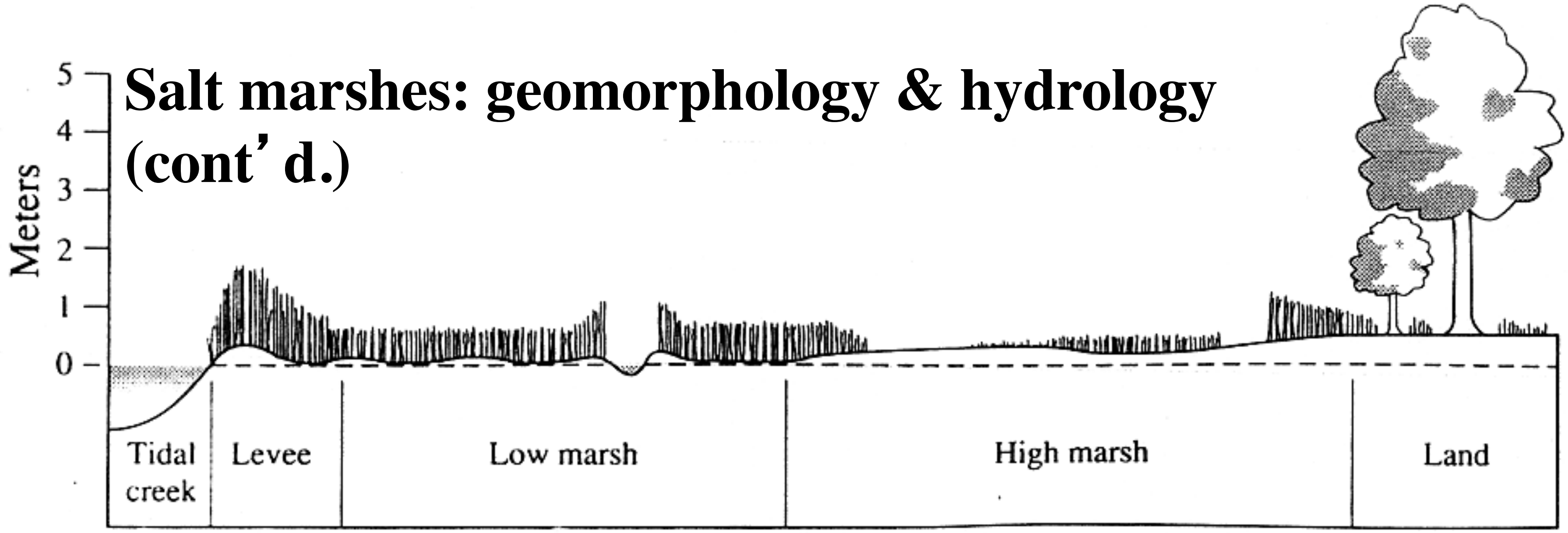


Figure 8.9 Schematic cross section through a salt marsh, showing the relationship between various components of the salt marsh ecosystem and the open waters of the estuary. From Wiegert et al. (1981).

- Salt marsh soils undergo daily cycle of changing aeration and, thus, redox state.

  -high tide: soils are inundated, anaerobic conditions may develop

  - low tide: soils drain, high redox potential re-established in surface layers

- Tide-induced flushing, combined with groundwater flow from land, leads to large amounts of import(export) from(to) tidal creeks.

  - low tide: low salinity due to flushing of marsh by freshwater runoff from land

  - high tide: marsh is inundated with seawater, highest salinities observed

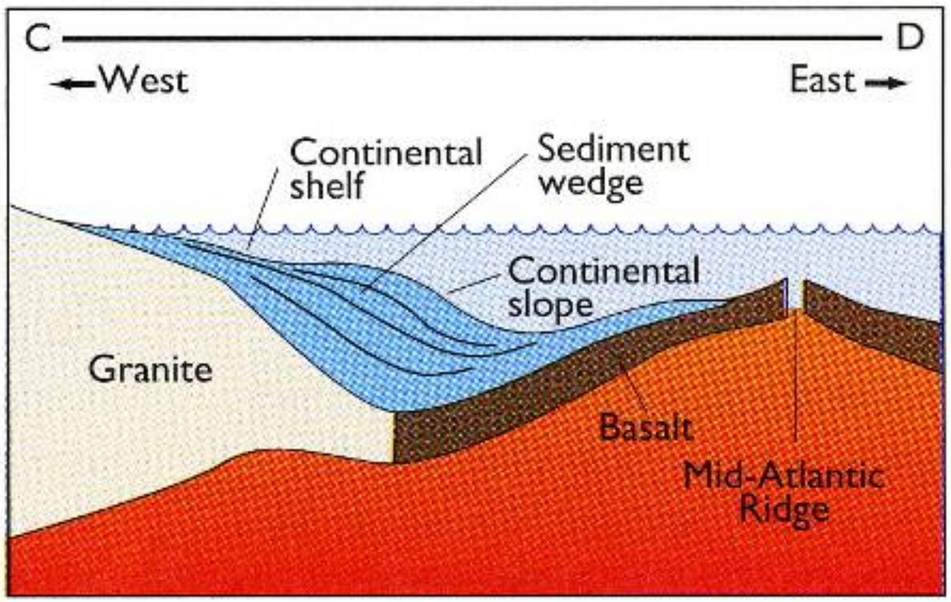
Continental Margins

Passive (Atlantic-type) Margins

Atlantic coast and shelf is subsiding because it is a passive margin

The lithospheric plate cools and thickens with age and distance
from the spreading center and sinks (subsides)

Isostatic sinking occurs as sediment accumulates on the shelf
and sediment layer thickens (GOM)



(d) EASTERN NORTH AMERICAN NONTECTONIC MARGIN (PASSIVE MARGIN)

From Pinet 2003

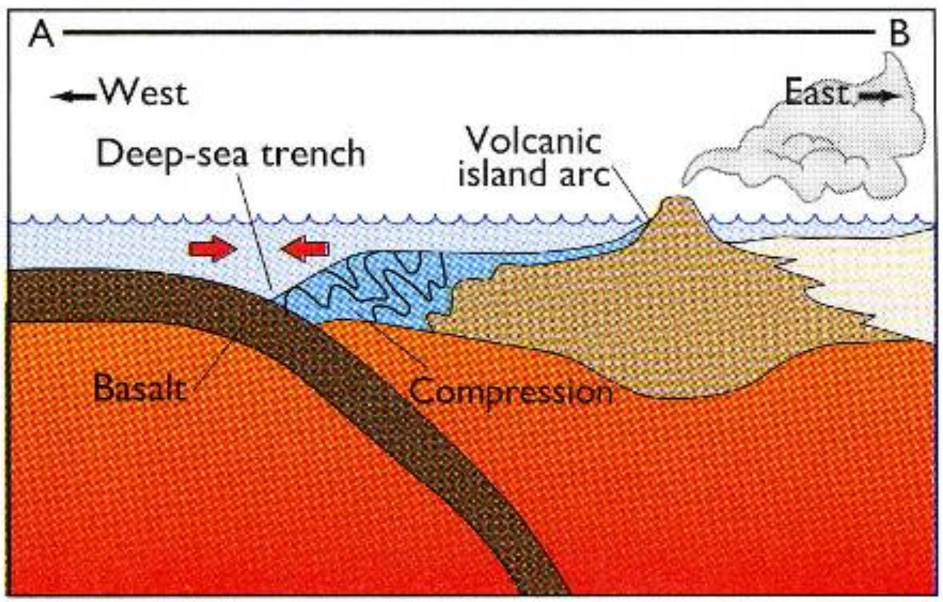
Active (Pacific-type) Margins

Tectonic activity occurs along the margin

The lithospheric plate is subducted beneath the continental plate

Crust is pushed upward to produce an emergent coast

Active continental margins usually have narrow shelves…..Passive margins have wide shelves

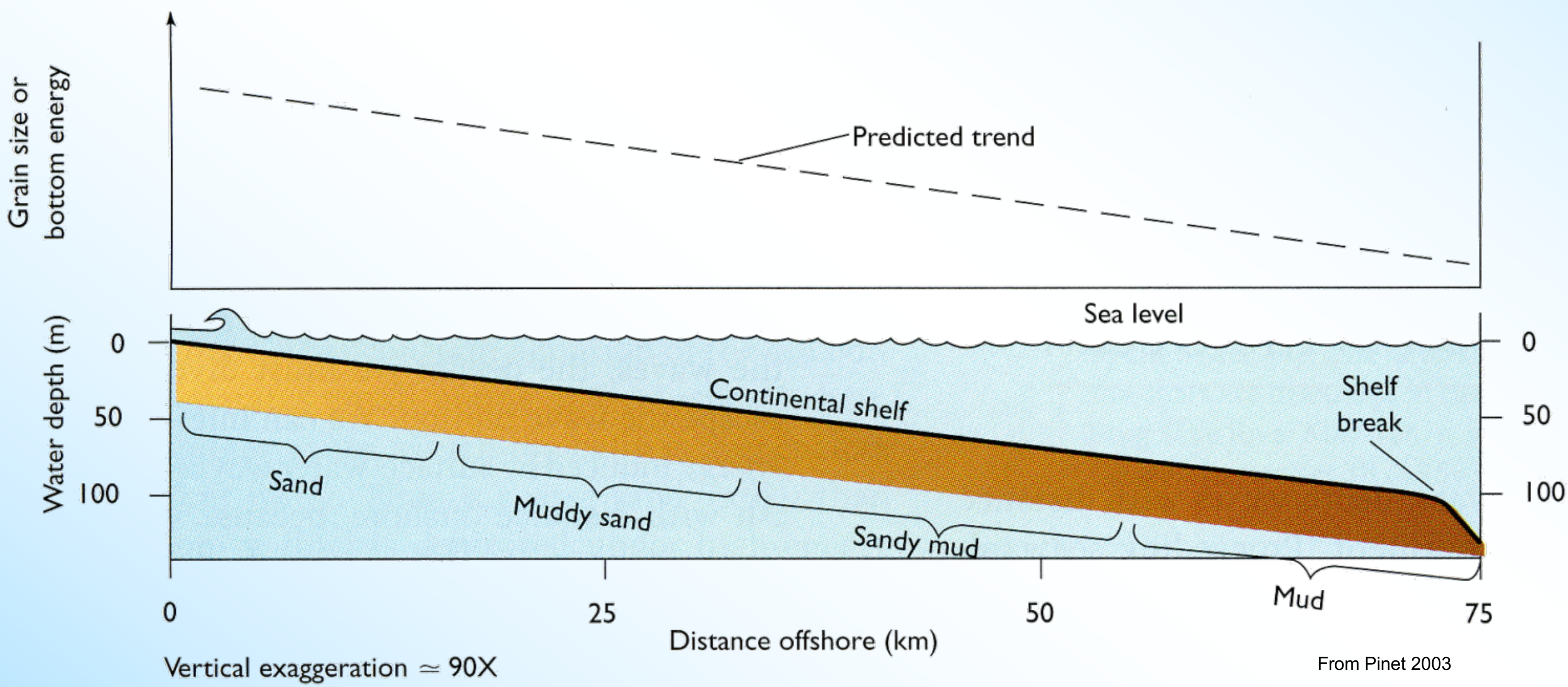


(c) WESTERN NORTH AMERICAN TECTONIC MARGIN (ACTIVE MARGIN)

From Pinet 2003

Shelf Sediments

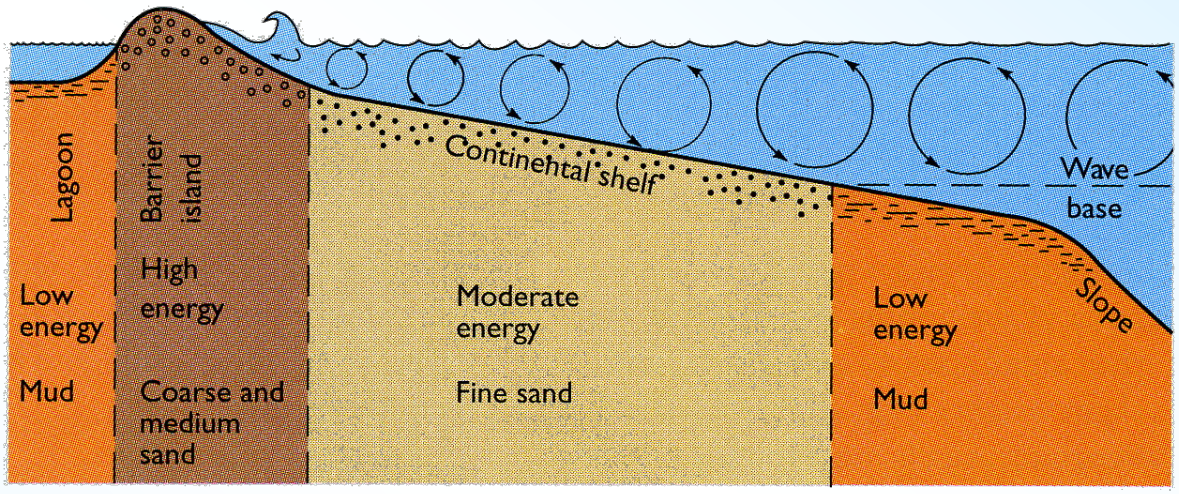
Sediment grain size decreases as you go further offshore due to wave energy and currents



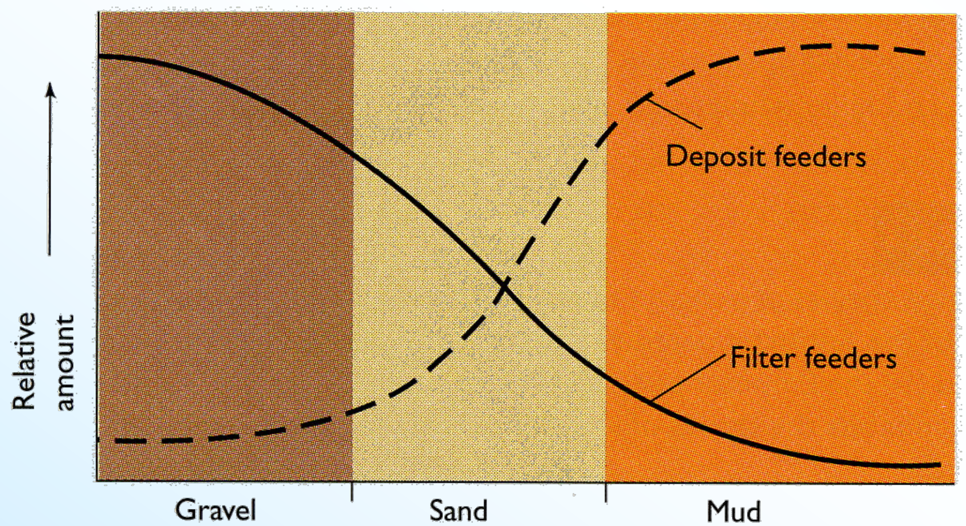
From Pinet 2003

Shelf Sediments

Sediment grain size and feeding strategies



(a) BOTTOM ENERGY BANDS



(b) BENTHOS AND SUBSTRATE TYPE

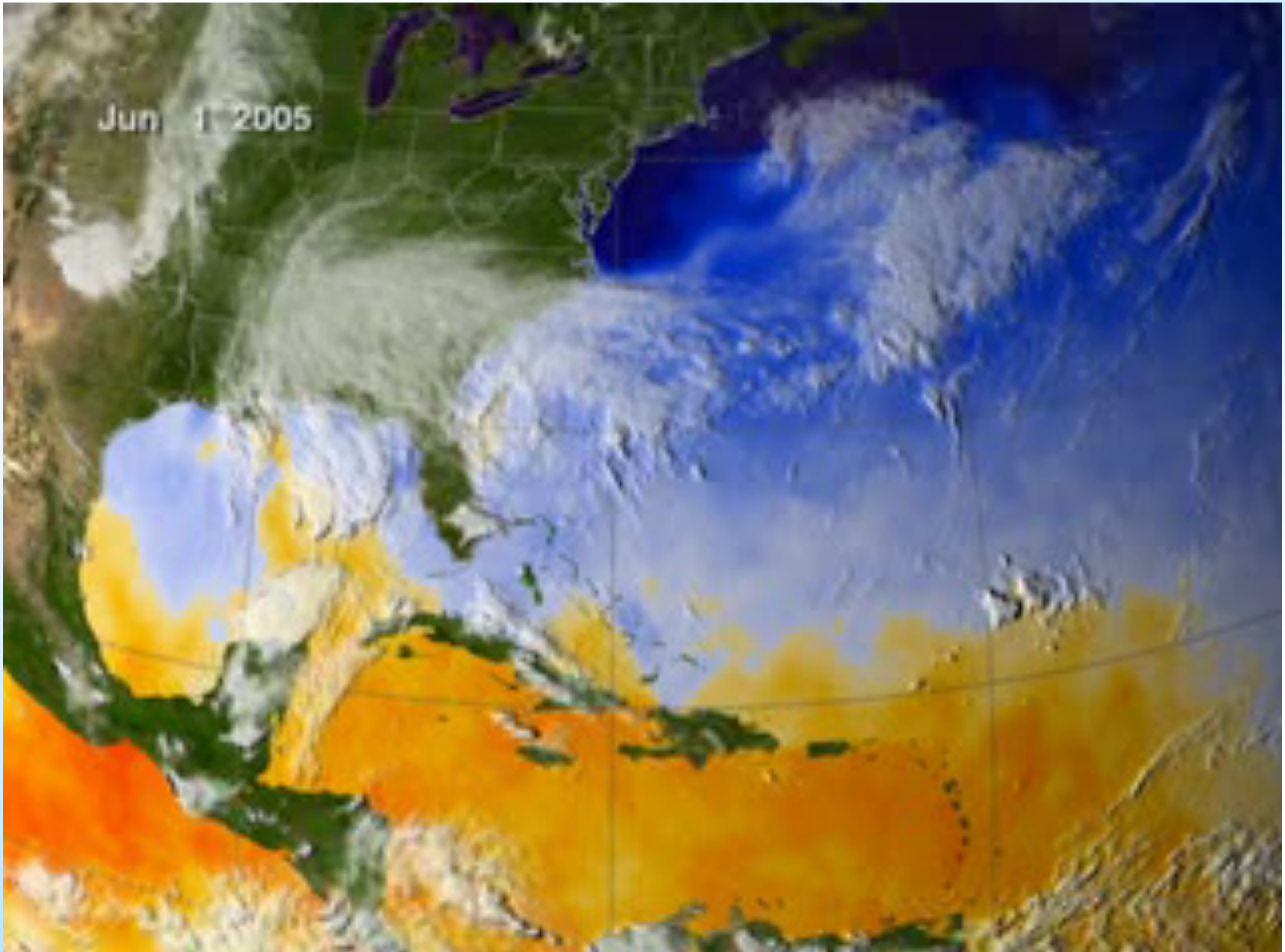
From Pinet 2003

Major Factors that Determine Processes on Shelves

- Presence or absence of large rivers
- Presence or absence of upwelling
- Location of ocean boundaries
- Shelf width

All of these factors are influenced by climate, hurricanes, El Niño, La Niña, global weather patterns

2005 Hurricane Season



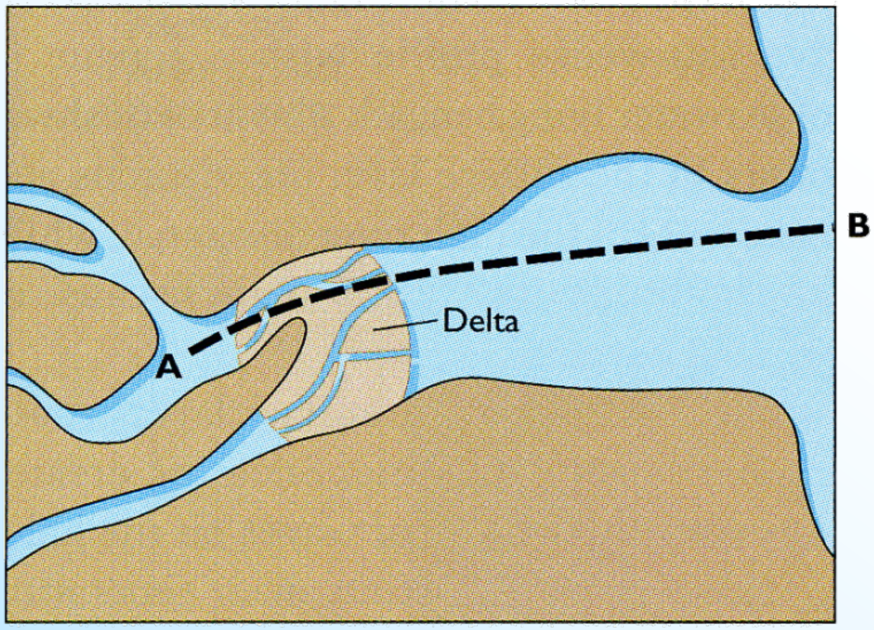
Based on Geomorphology

Drowned River Valleys or Coastal Plain estuaries (most common)

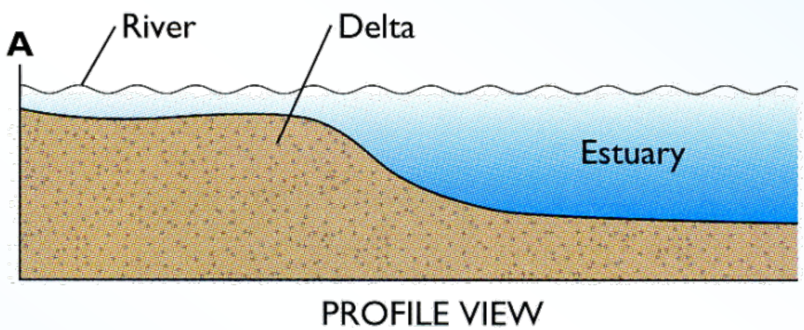
Formed by sea level rise during the Holocene

tide and river dominated

Examples: Chesapeake Bay, Delaware Bay, Charleston Harbor



(a) DROWNED RIVER VALLEY



From: Pinet 2003

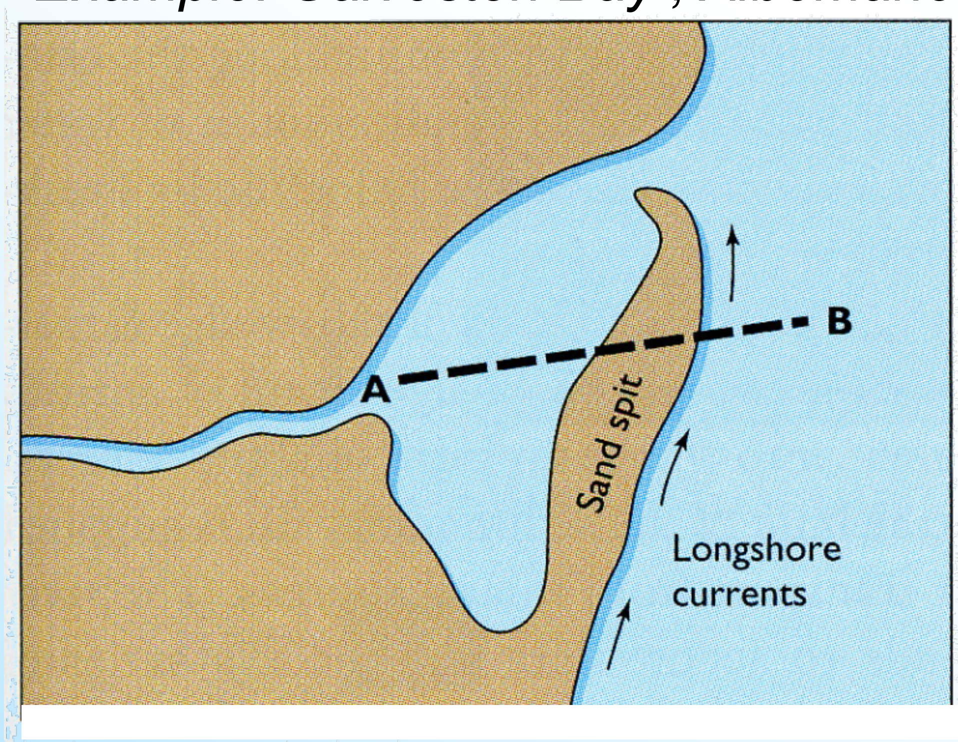
Coastal Plain, Bar-Built Estuaries

longshore currents form a sand bar or sand spit across an embayment

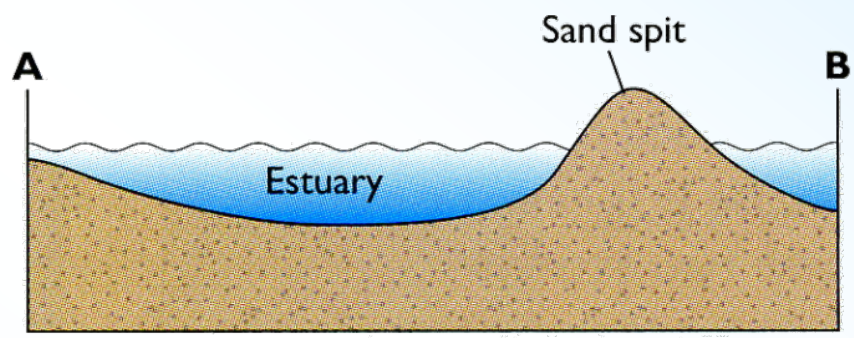
Lack a major river source

These estuaries are usually shallow (<2 m) and wind-dominated

Example: Galveston Bay , Albemarle-Pamlico Sound



(c) BAR-BUILT ESTUARY



PROFILE VIEW

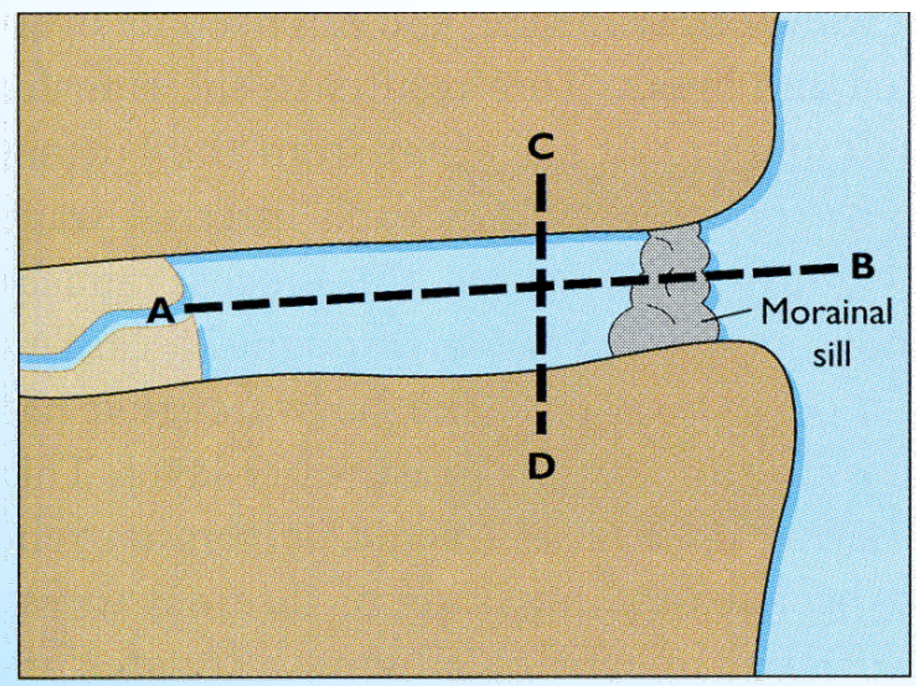
From: Pinet 2003

Fjord-Type Estuaries

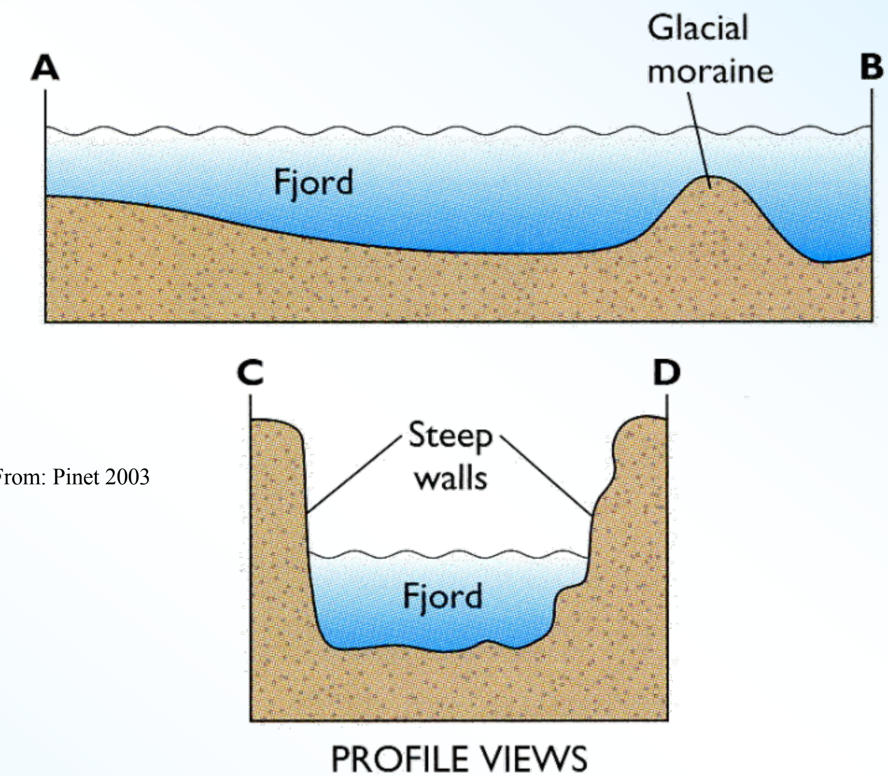
deep (>100 m), built by glaciers, shallow sill (terminal moraine)

sill may trap bottom water that may be anoxic

Examples: Puget Sound, coasts of Norway and British Columbia



From: Pinet 2003



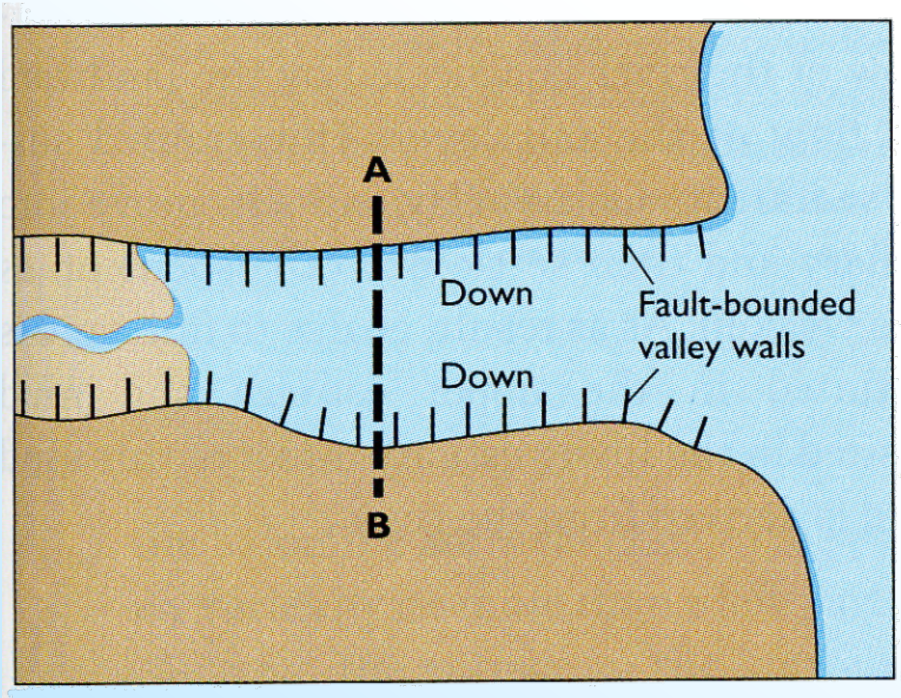
Tectonically-Produced Estuaries

formed by earthquakes and block faulting

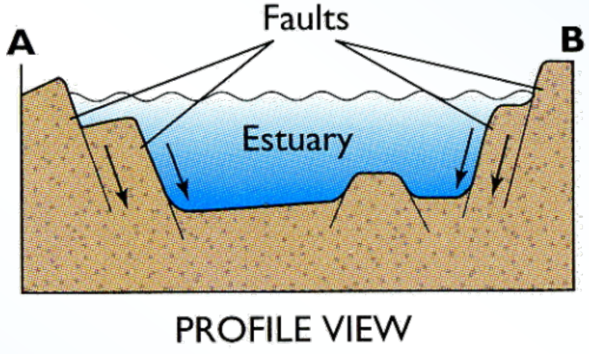
common on active coasts

creates basins that become filled with water

Examples: San Francisco Bay, Tomales Bay



(d) TECTONIC ESTUARY



From: Pinet 2003

Based on Physiography

Fairbridge Classification (1980)

7 Categories based on relative relief and degree of blocking at the mouth of the estuary

- Fjord (fjärd)
- Ria
- Coastal Plain
- Bar-built
- Blind
- Delta front
- Tectonic

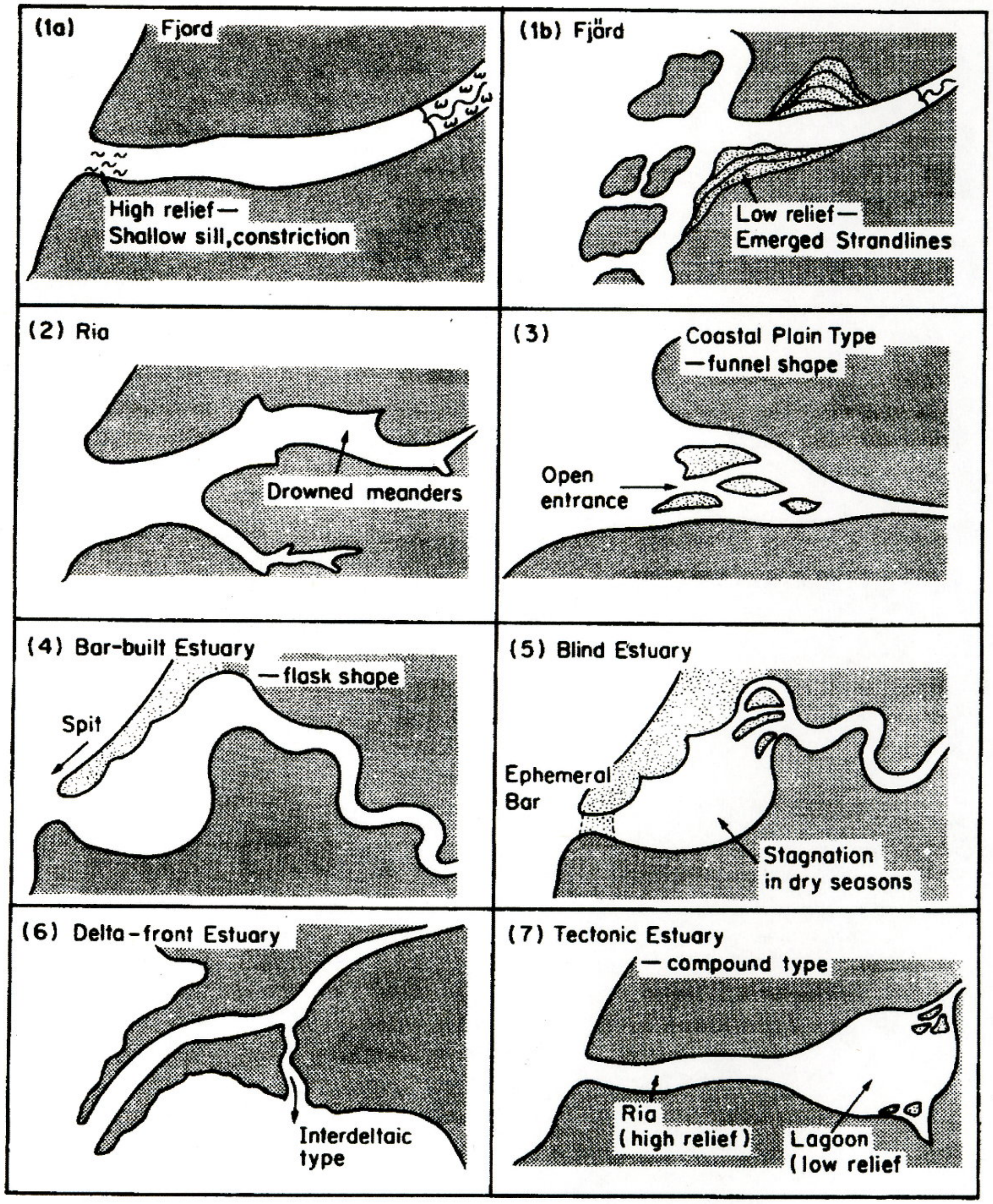


FIGURE 7. Illustrations of the seven basic physiographic types of estuaries. (From Fairbridge, R. W., in *Chemistry and Biogeochemistry of Estuaries*, Olausson, E. and Cato, I., Eds., John Wiley & Sons, Chichester, 1980, 1. Copyright 1980 John Wiley & Sons, Ltd. Reprinted by permission of John Wiley & Sons, Ltd.)

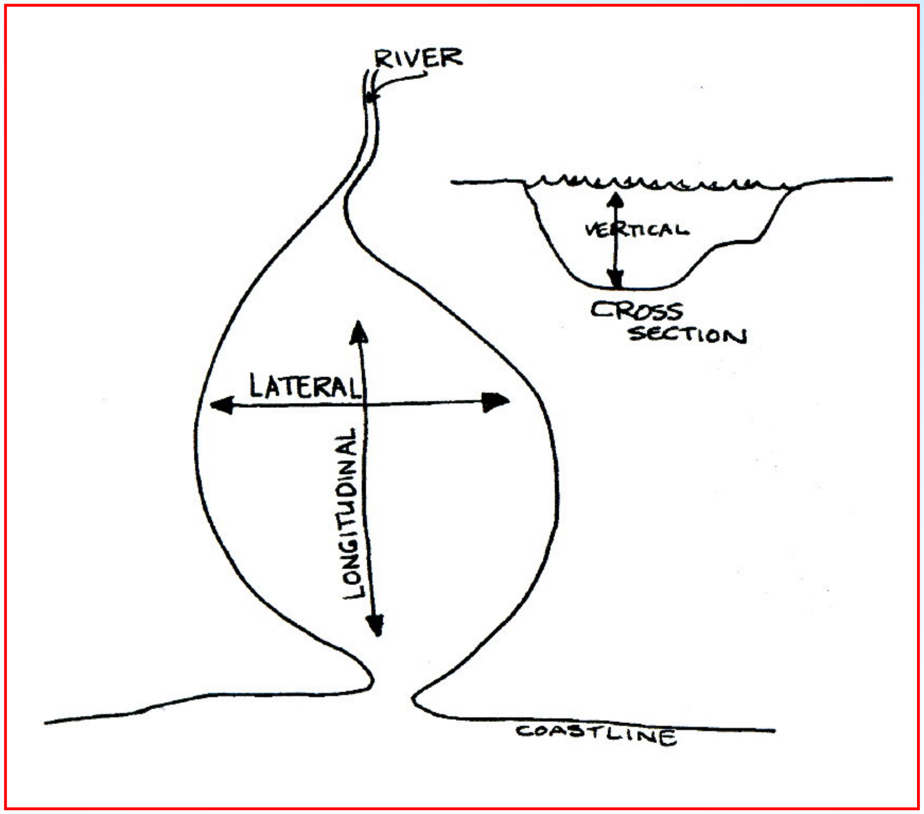
Based on Circulation and Hydrography

Water circulation and stratification influence chemistry and biology

For *most* estuaries, **NET** flow is **OUT** at the surface and **IN** along the bottom

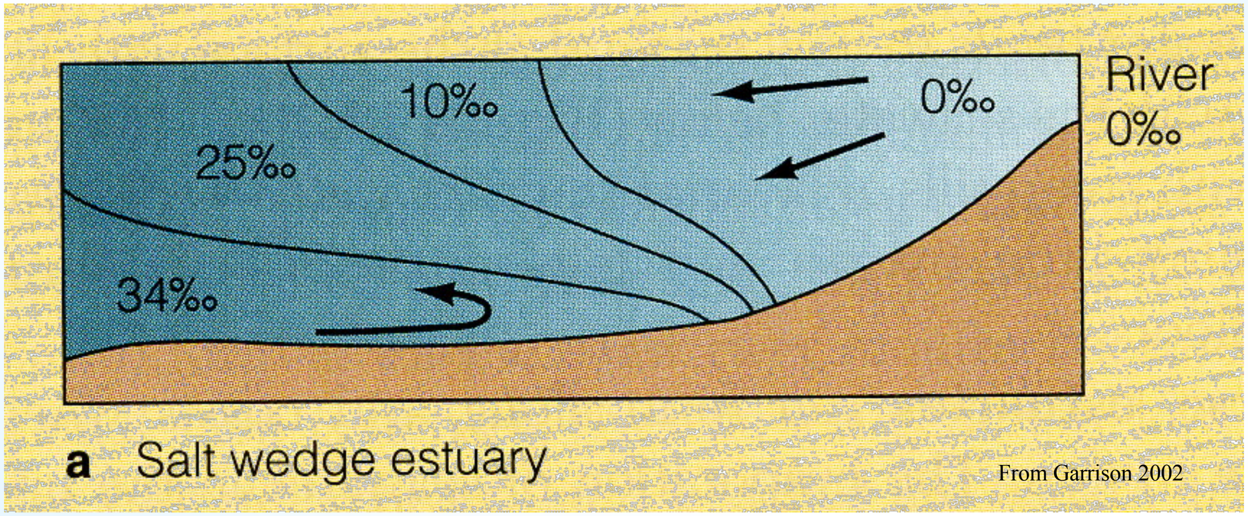
Two-layered circulation

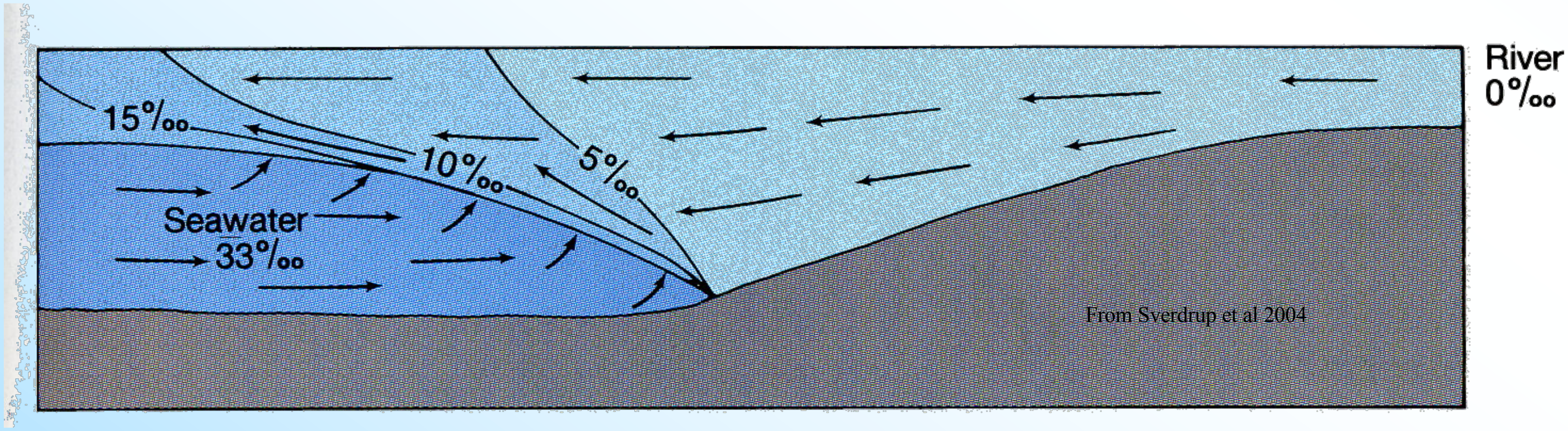
Longitudinal, lateral, and vertical circulation patterns are important



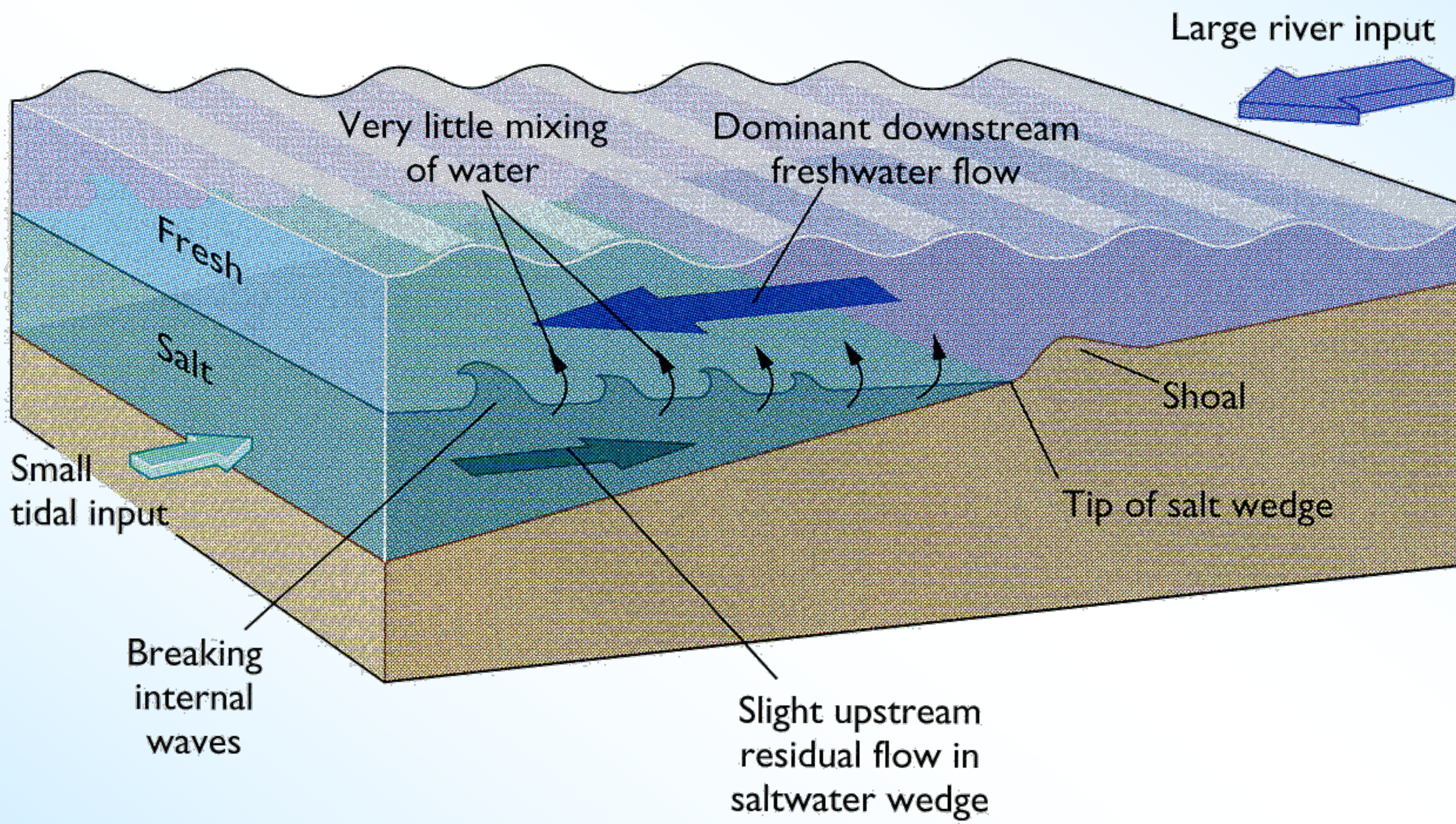
Estuarine Classification Based on Circulation

Type A - Highly stratified, salt wedge estuary - river discharge dominates over tidal action
Salt exchange by vertical advection across the fw/sw interface (halocline). *Example: Mississippi River*





Estuarine Classification Based on Circulation

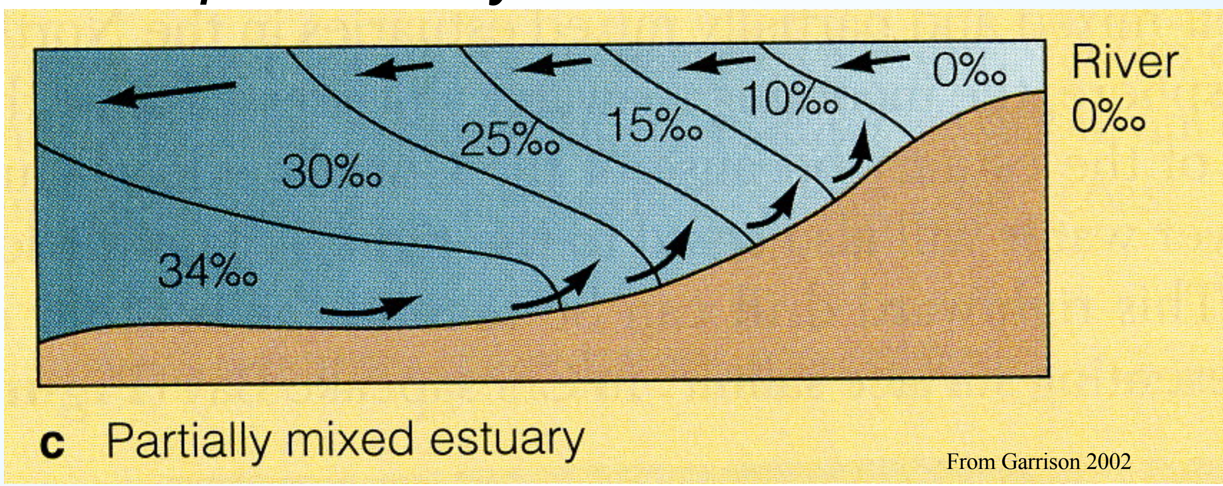


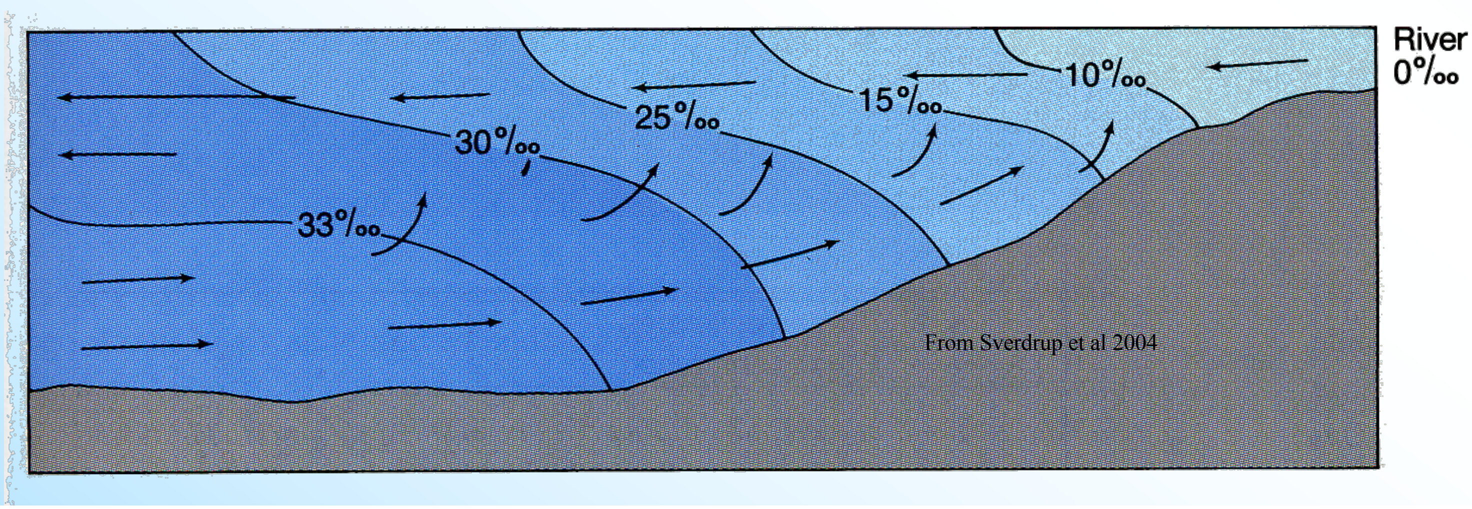
(a) SALT-WEDGE ESTUARY

From: Pinet 2003

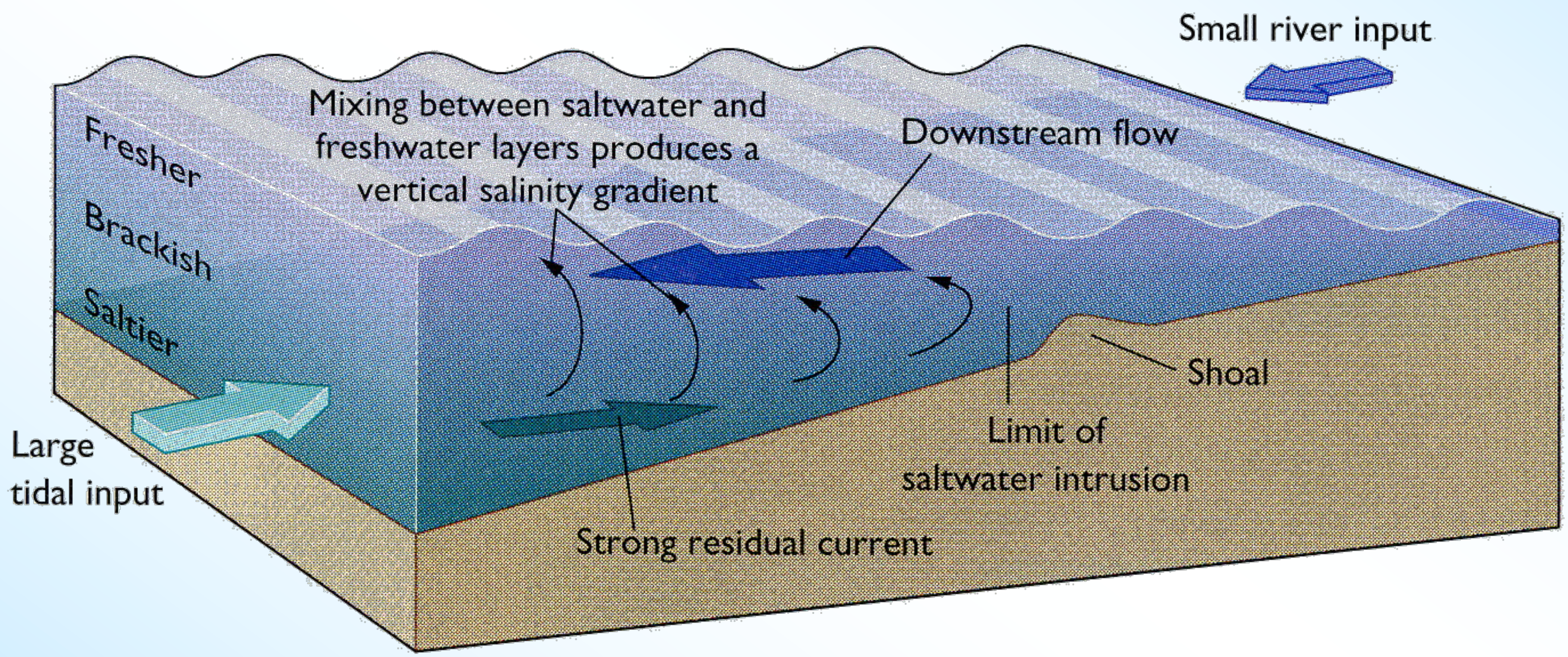
Estuarine Classification Based on Circulation

Type B - Partially mixed, moderately stratified - tidal flow increases relative to river discharge
Vertical advection and turbulence mix the system
Example: Chesapeake Bay





Estuarine Classification Based on Circulation

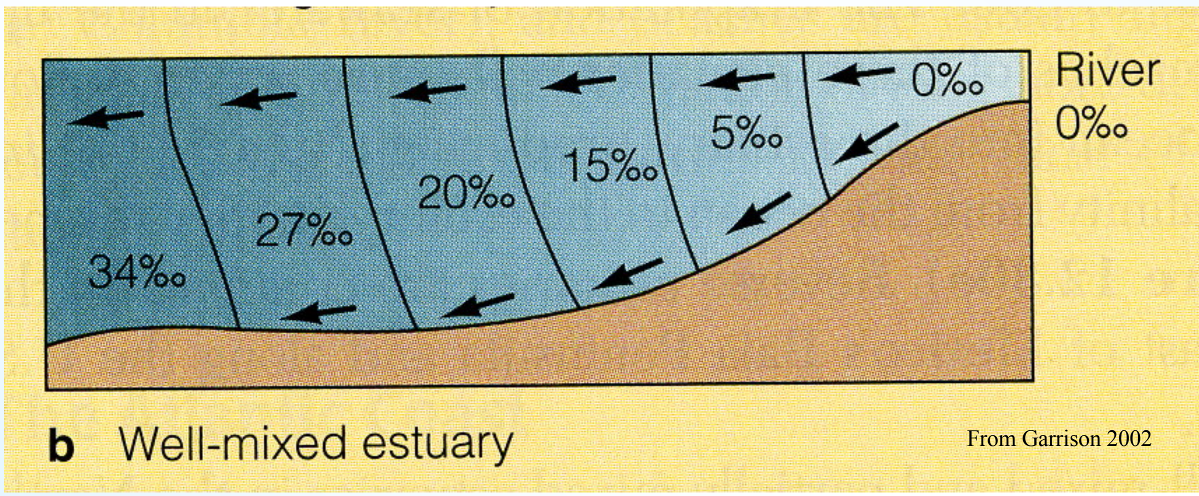


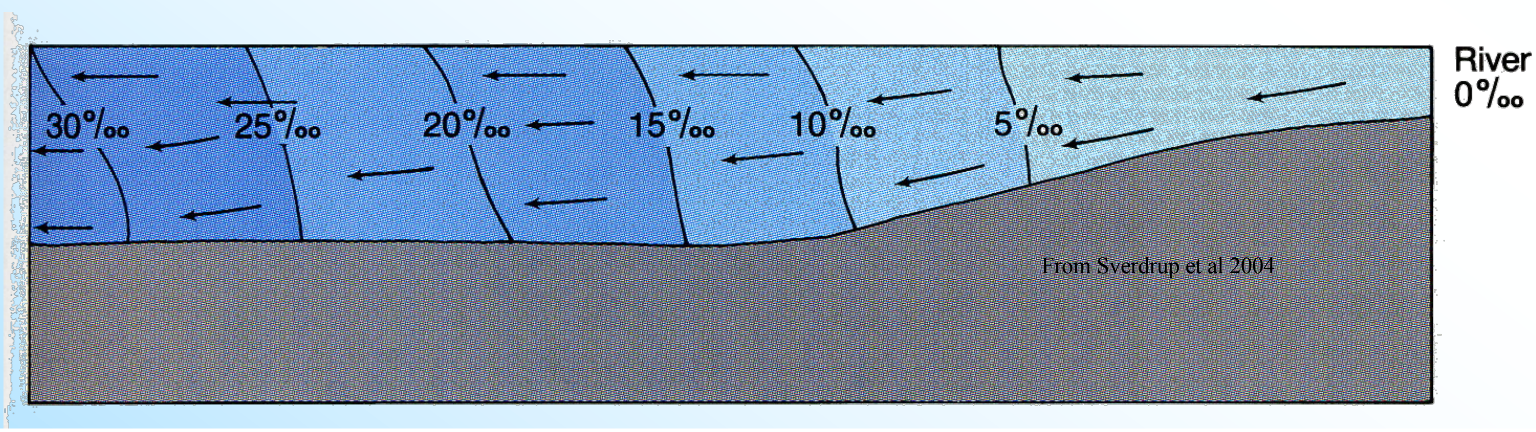
(b) PARTIALLY MIXED ESTUARY

From: Pinet 2003

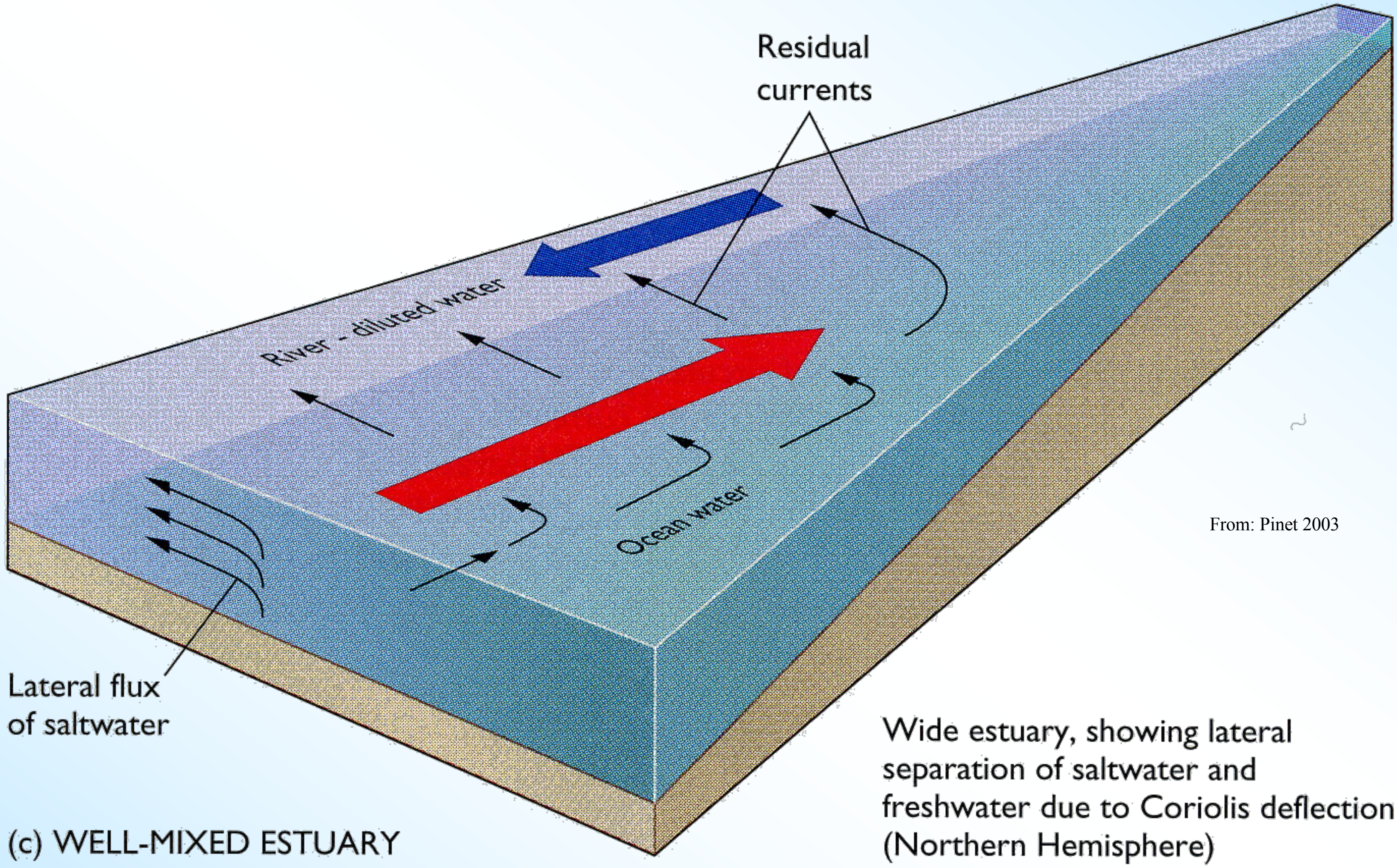
Estuarine Classification Based on Circulation

Type C - Vertically homogeneous and well-mixed
Intense tidal flow and strong turbulent mixing, lateral heterogeneity sometimes caused by strong winds
e.g., Delaware Bay





Estuarine Classification Based on Circulation

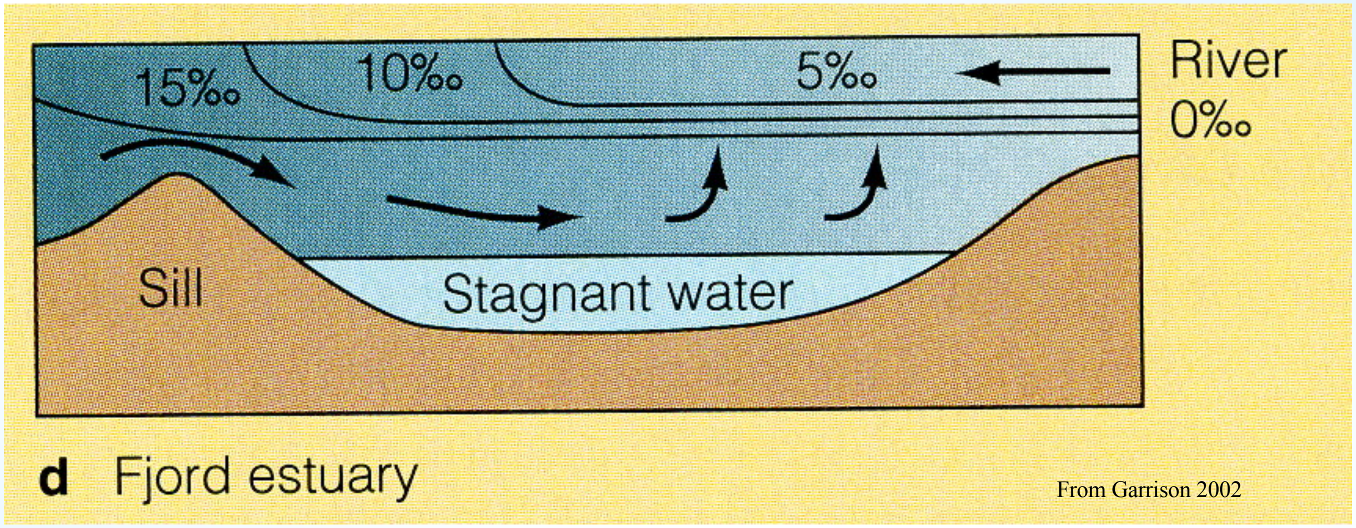


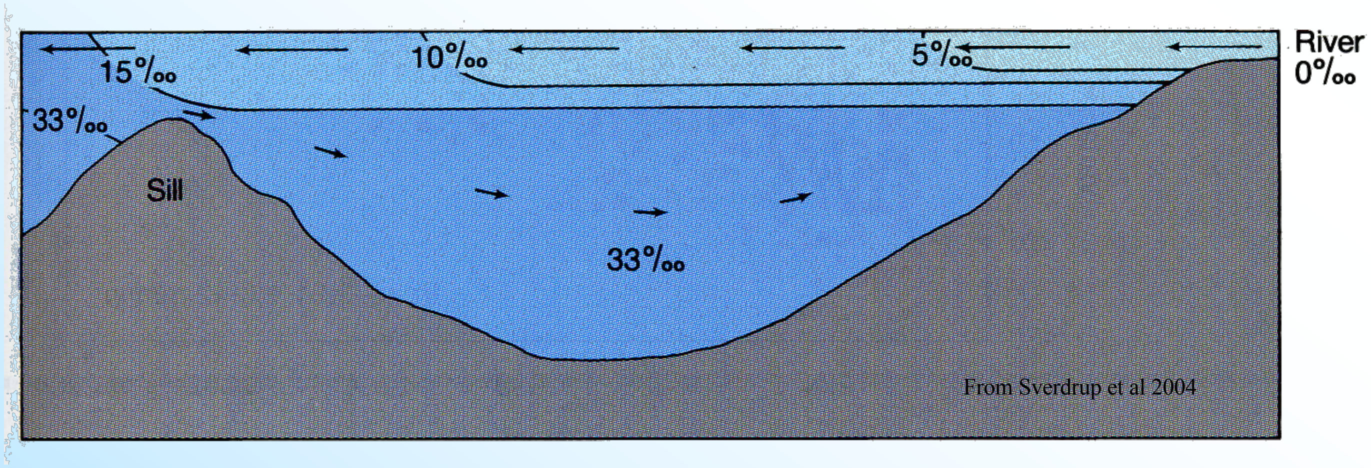
From: Pinet 2003

Wide estuary, showing lateral separation of saltwater and freshwater due to Coriolis deflection (Northern Hemisphere)

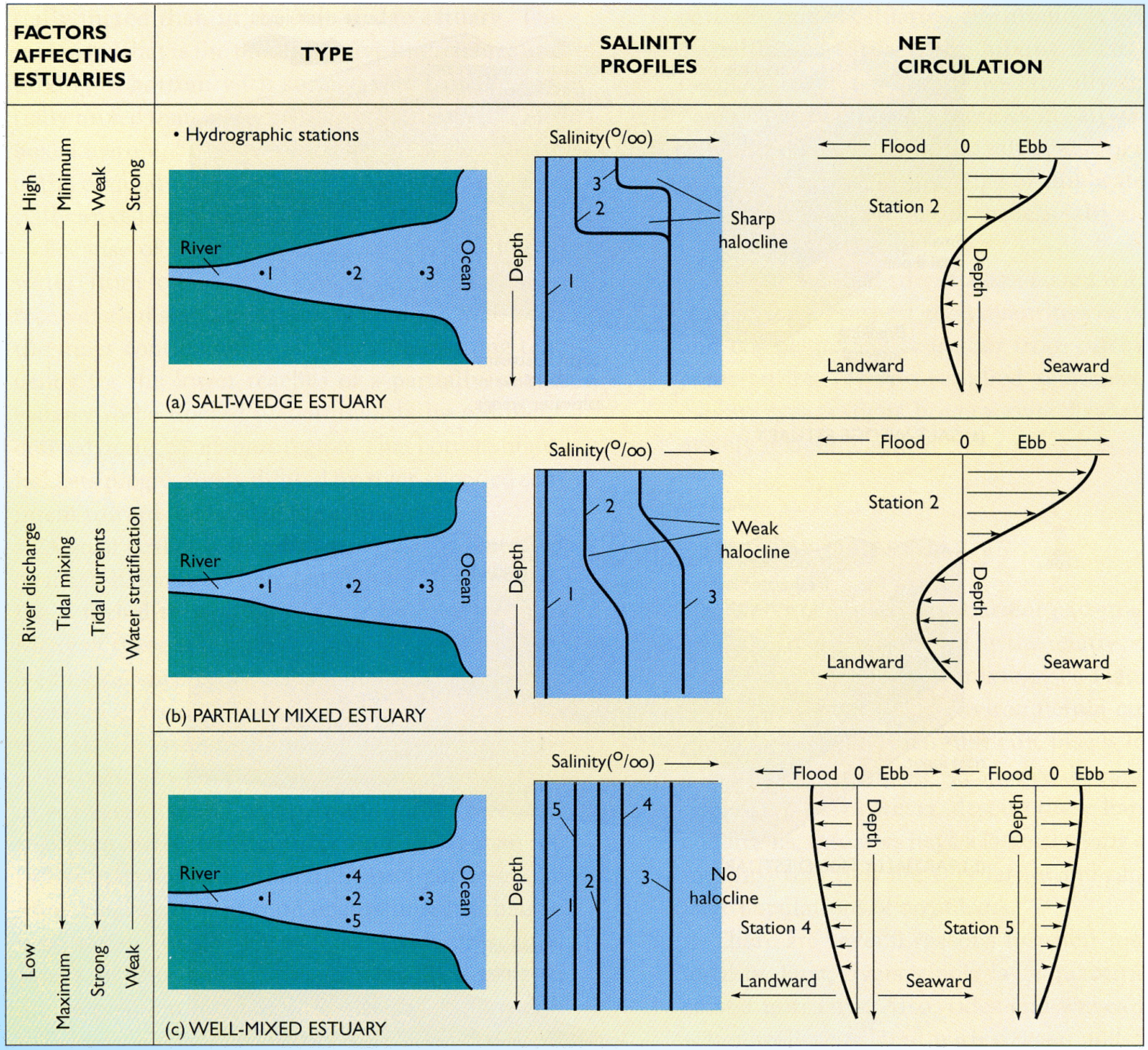
Estuarine Classification Based on Circulation

Type D - Fjord - sill results in “stagnant” bottom waters
Usually highly-stratified





Estuarine Classification Based on Circulation



From: Pinet 2003

Estuarine Classification Based on Salinity and Tidal Characteristics

Salinity Regime - positive, negative (inverse), & neutral types

Mediterranean-type circulation

Salinity Zonation - Venice system with 6 distinct zones

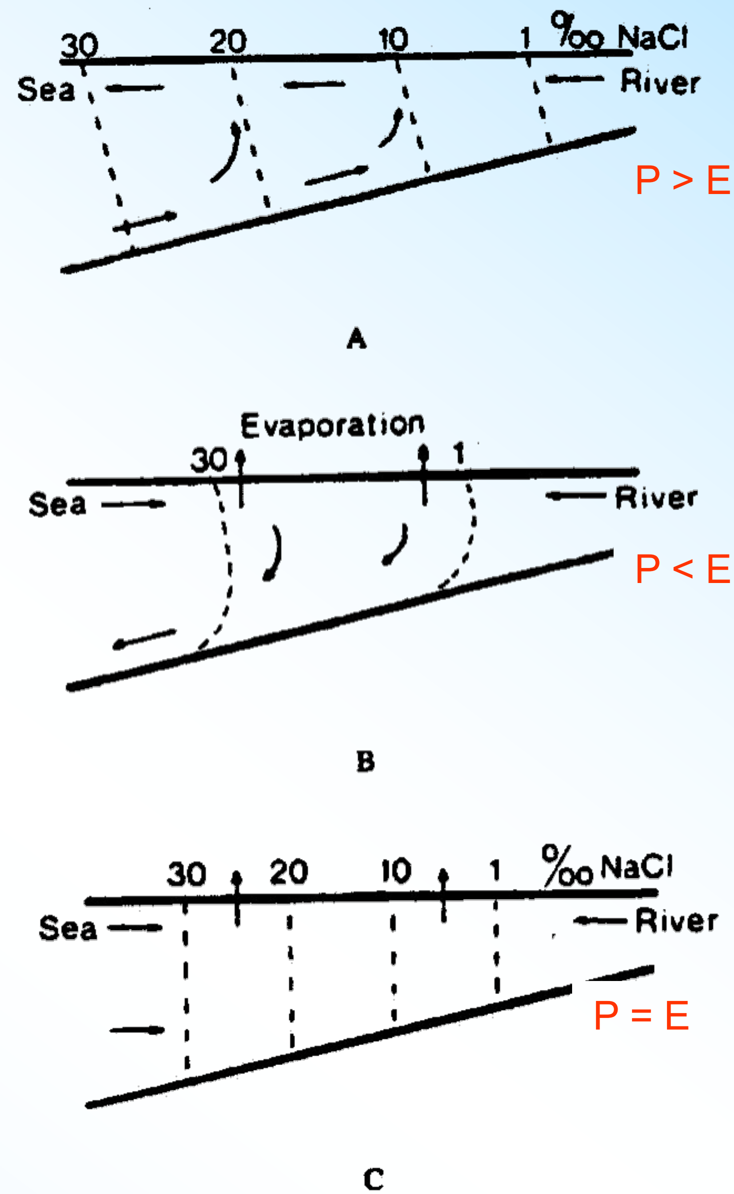
Tidal Range

microtidal (0 - 2 m) - Galveston Bay

mesotidal (2 - 4 m) - SC and GA estuaries

macrotidal (> 4 m) - Bay of Fundy (Canada)

Salinity Ranges – FW to SW?



Estuarine Classification Based on Salinity and Tidal Characteristics

Table 3
VENICE SYSTEM FOR THE CLASSIFICATION OF ESTUARIES

	Venice system	
Section of estuary	Salinity (‰)	Zone
River	< 0.5	Limnetic
Head	0.5—5	Oligohaline
Upper reaches	5—18	Mesohaline
Middle reaches	18—25	Polyhaline (Low)
Lower reaches	25—30	Polyhaline (High)
Mouth	30—40	Euhaline
—	>40	Hyperhaline (Hypersaline)

From Carriker, M. R., in *Estuaries*, Lauff, G. H., Ed., Publ. 83, American Association for the Advancement of Science, Washington, D.C., 1967, 442.

ESTUARINE CLASSIFICATION SUMMARY

Many ways to classify an estuary…

Geomorphology Physiography

Circulation and Hydrography Salinity and Tidal Characteristics

Sedimentation Ecosystem Energetics

Estuaries are dynamic in space and time, highly influenced by meteorology (precipitation, hurricanes, El Niño, etc.)

Are a continuum - come in a variety of sizes and shapes

What are the implications for systems ecology and ecosystem processes?

…ESTUARINE CIRCULATION

"residual water movement"

Solar heating or gravitational forcing

Physics of coastal/ocean waters

Major Types of Circulation

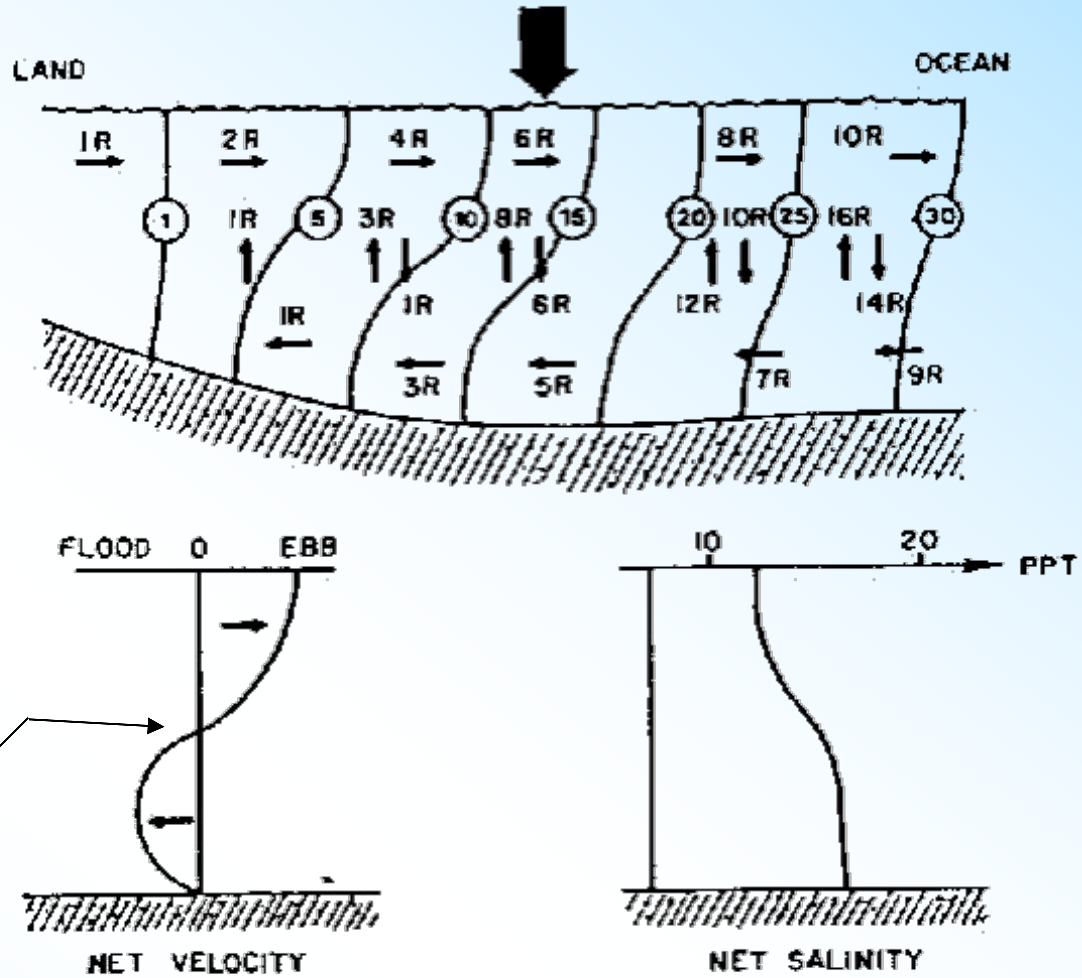
1. Gravitational Circulation

Induced by density and elevation differences between freshwater runoff and salt water

Is responsible for classical 2-layer circulation

The direction of pycnocline tilt relative to the vertical is the direction of flow

Equipotential Surface - surface along which net flow is zero



Usually due to salinity differences but may be temperature driven in shallow lagoons

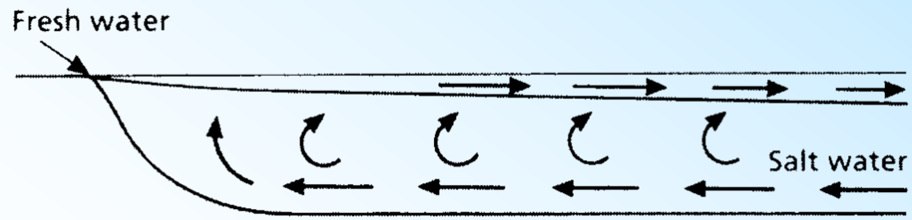
Coriolis Effect - higher salinities on NE side of large estuaries

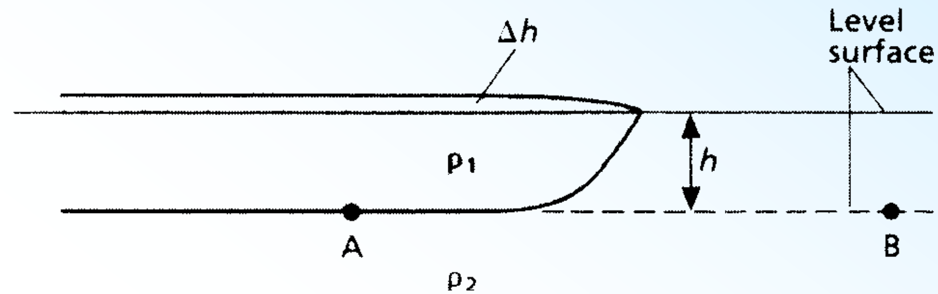
Gravitational Circulation

Freshwater near-surface flow out
Deep flow of saltier water

The upper layer gets thicker as it moves away from the source of fresh water because salt water is entrained from below.

A pool of light water, r_1, lies on top of and beside water of greater density, r_2. If the pressures at A and B are the same (an equipotential surface), the height of the sea surface above A must be higher than above B.





Δh = the difference in the height of the surface water in the two regions A and B
the pressure gradient….water flows downhill!

$$\Delta h = h(r_2 - r_1) / r_1$$

Example:

From: Mann & Lazier 2006

r_1 = density of freshwater layer = 1000 kg m^{-3}
r_2 = density of saltwater layer = 1025 kg m^{-3}
h = depth of equipotential surface at B = 2 m
Therefore……. Δh = 0.05 m = 5 cm

Major Types of Circulation

2. Tidal Circulation (tidal pumping) - occurs in the absence of density gradients and wind stress (?!)

Results when tidal currents interact (non-linear interaction) with boundaries

important in shallow depths, large tidal ranges

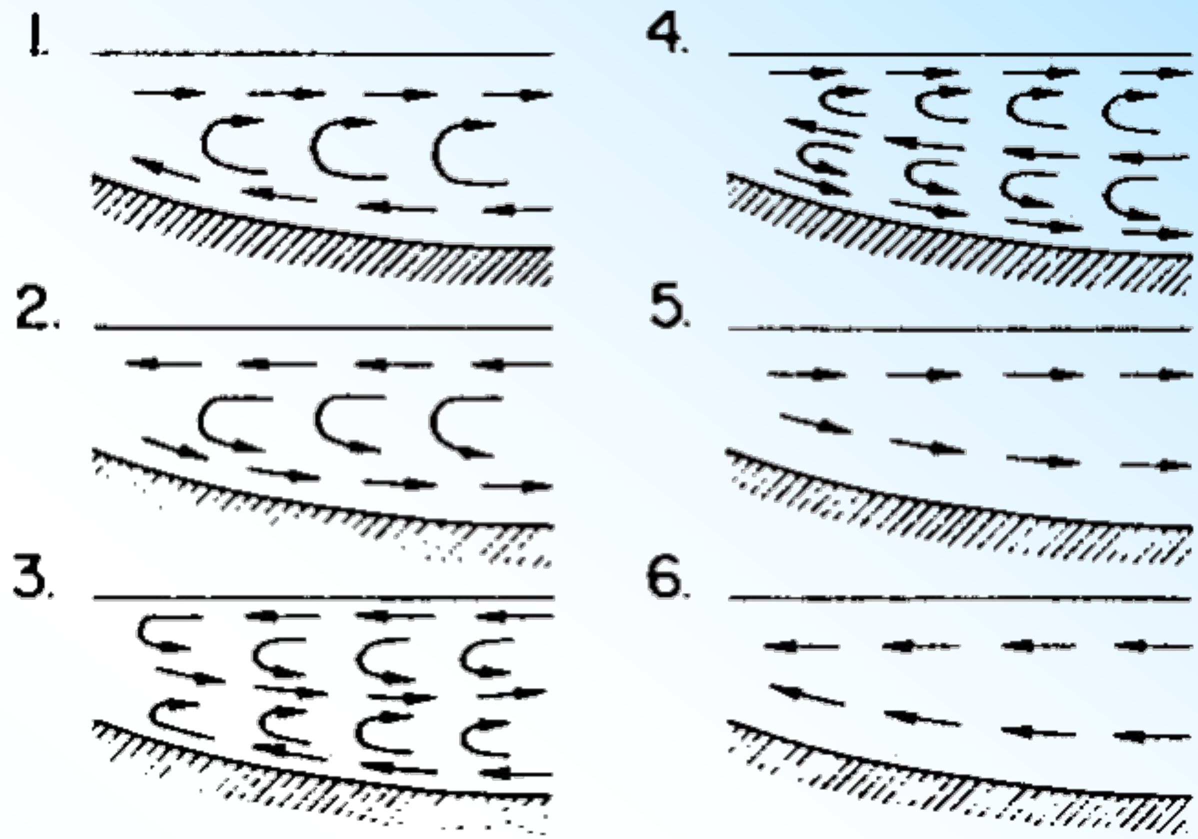
3. Wind-Driven Circulation - most important in shallow lagoons with large expanses of open water

Can produce “wind tides” and seiches

Note: All three types of circulation may occur in varying degrees in all estuaries...make it difficult to model circulation

Circulation Modes

1. Classical
2. Reverse
3. Three-layered
4. Reverse 3-layered
5. Discharge
6. Storage



From Kjerfve 1989

Far-Field Effects - Events that happen outside the estuary (on the shelf or open ocean) but affect circulation in the estuary. High and low pressure weather systems, SSH, El Niño, etc.

…MIXING PROCESSES

Mixing Processes

Estuaries are “mixing zones” where freshwater is combined with saltwater

Mixing - the process whereby a water parcel or water mass is diluted by, or redistributed within, other water masses *(Kjerfve 1989)*

Sloshing - time-averaged flux of particles by oscillatory tidal currents - is a dominant longitudinal mixing process.

Shear Effect - mixing over a tidal cycle due to systematic covariations of velocity and particle concentrations
Shear results from different velocities of parallel currents

Also known as *Shear-Induced Mixing*

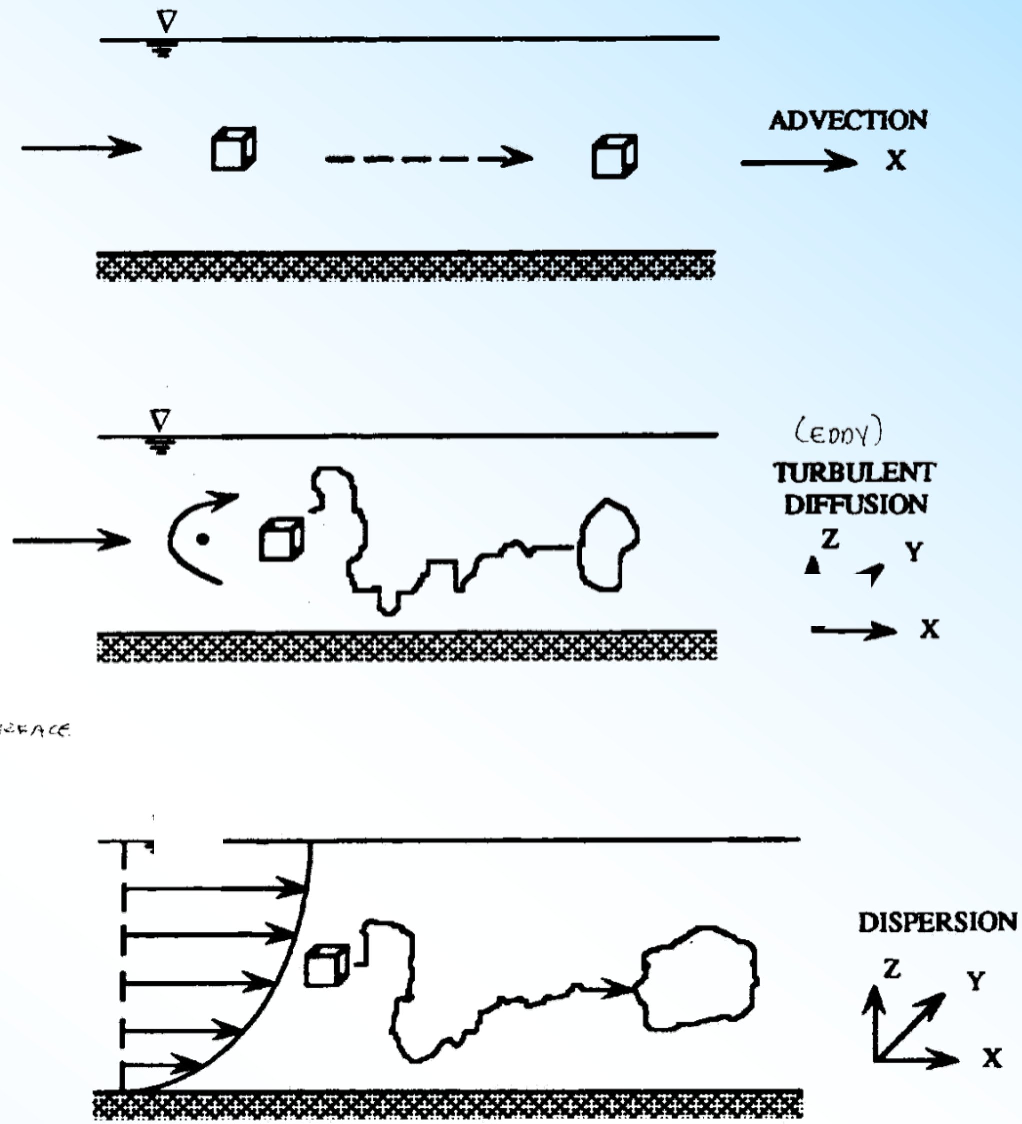
Mixing Processes

Advection – the water mass remains intact, but is transported

Diffusion - random scattering of water parcels or particles by either random molecular or eddy (turbulent) motions - molecular diffusion usually much less than eddy diffusion

Important at the sediment/water interface

Dispersive Mixing - the scattering of water parcels or particles dissolved in the estuary due to tidal sloshing, shear effects, eddy (turbulent) diffusion, or tidal trapping

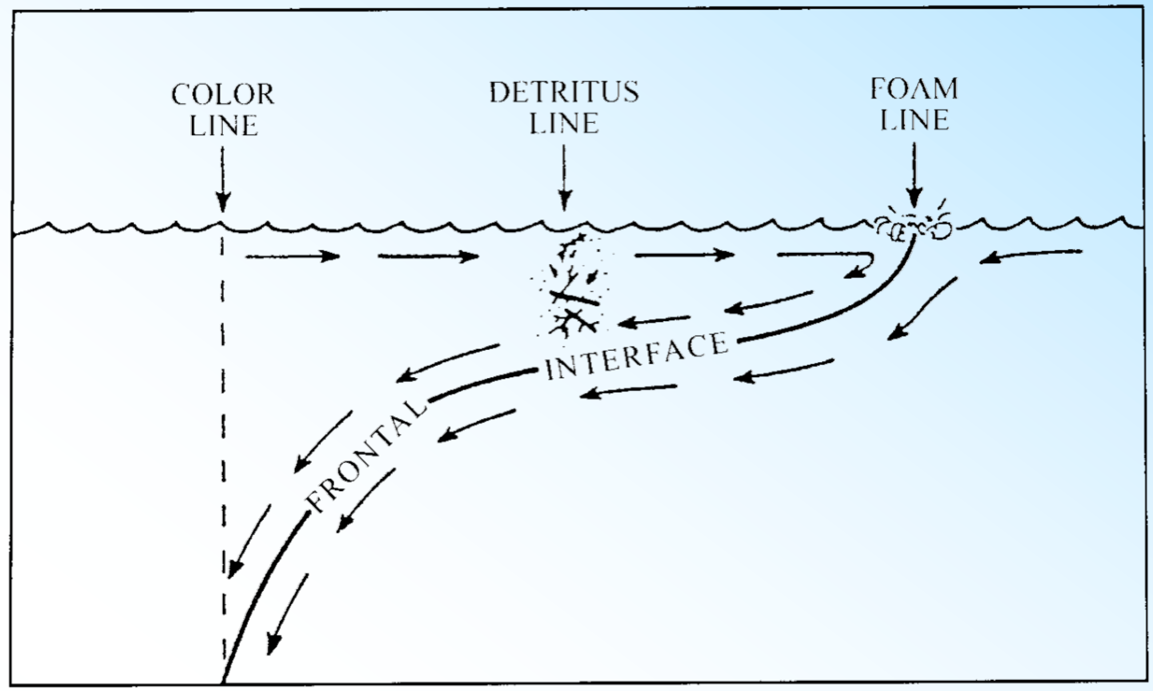


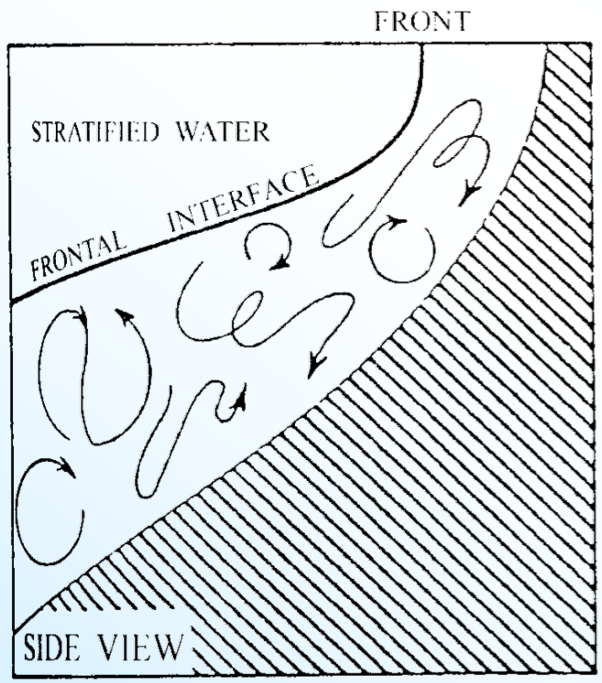
Estuarine Fronts

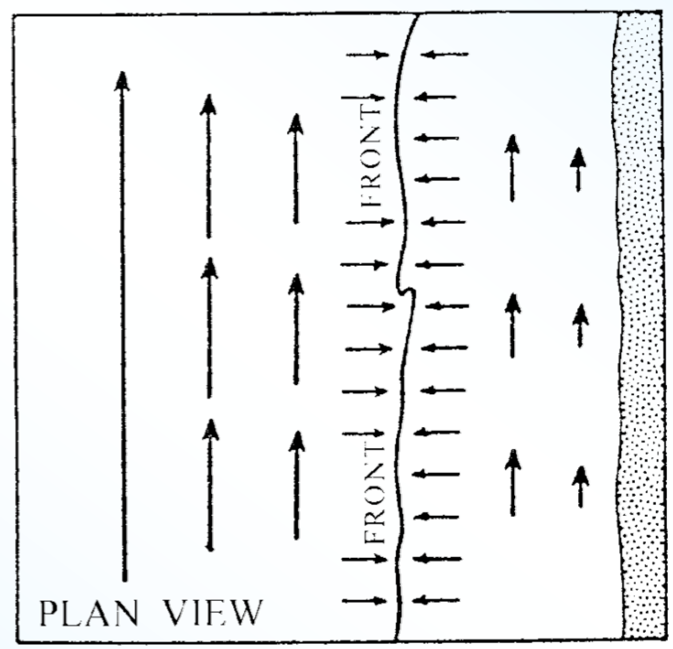
Boundary between two dissimilar water masses. Commonly form at freshwater/saltwater interface of estuaries and plumes

Surface convergence and advection downward - accumulate particulates at the surface (flotsam & foam lines)

Are different from Langmuir circulation cells - which are driven by friction between wind and water surface







River-water and Sea-water Concentrations

Average abundances of nutrient and major ions in river-water and sea-water[a]

Element	Concentration in river-water ($\mu g\ l^{-1}$)	Concentration in sea-water[b] ($\mu g\ l^{-1}$)
Cl	8×10^3	$1{\cdot}987 \times 10^7$
S	$3{\cdot}7 \times 10^3$	$9{\cdot}28 \times 10^5$
Br	20	$6{\cdot}8 \times 10^4$
F	100	$1{\cdot}4 \times 10^3$
B	10	$4{\cdot}5 \times 10^3$
Na	9×10^3	$11{\cdot}05 \times 10^6$
Mg	$4{\cdot}1 \times 10^3$	$1{\cdot}326 \times 10^6$
Ca	$1{\cdot}5 \times 10^3$	$4{\cdot}22 \times 10^5$
K	$2{\cdot}3 \times 10^3$	$4{\cdot}16 \times 10^5$
Sr	50	$8{\cdot}5 \times 10^3$
N	$2{\cdot}5 \times 10^2$	500
P	20	70
Si	$6{\cdot}1 \times 10^3$[c]	1000

[a] Data from Riley and Chester (1971).
[b] Salinity = 35‰.
[c] Data from Livingstone (1963).

rw << sw

rw ≈ sw

Nutrients are different!

River-water / Sea-water Ion Ratios

TABLE 21.12
Comparison of the Major Ion Ratios in River Water and Seawater

Ion Ratio	*River Water*	*Seawater*
Na^+/K^+	2.5	50
Na^+/Mg^{2+}	4	5
Na^+/Ca^{2+}	2	0.2
K^+/Mg^{2+}	2	0.1
K^+/Ca^{2+}	4.5	10
Ca^{2+}/Mg^{2+}	9	1

Two major factors:

• Na^+/K^+ difference reflects lower affinity of marine rocks for sodium, as compared to potassium (ocean is a less effective sink for sodium)

• Ca^{2+}/Mg^{2+} difference reflects preferential removal of calcium in the ocean as biogenic calcite (ocean is a is more effective sink for calcium)

Mixing Curve

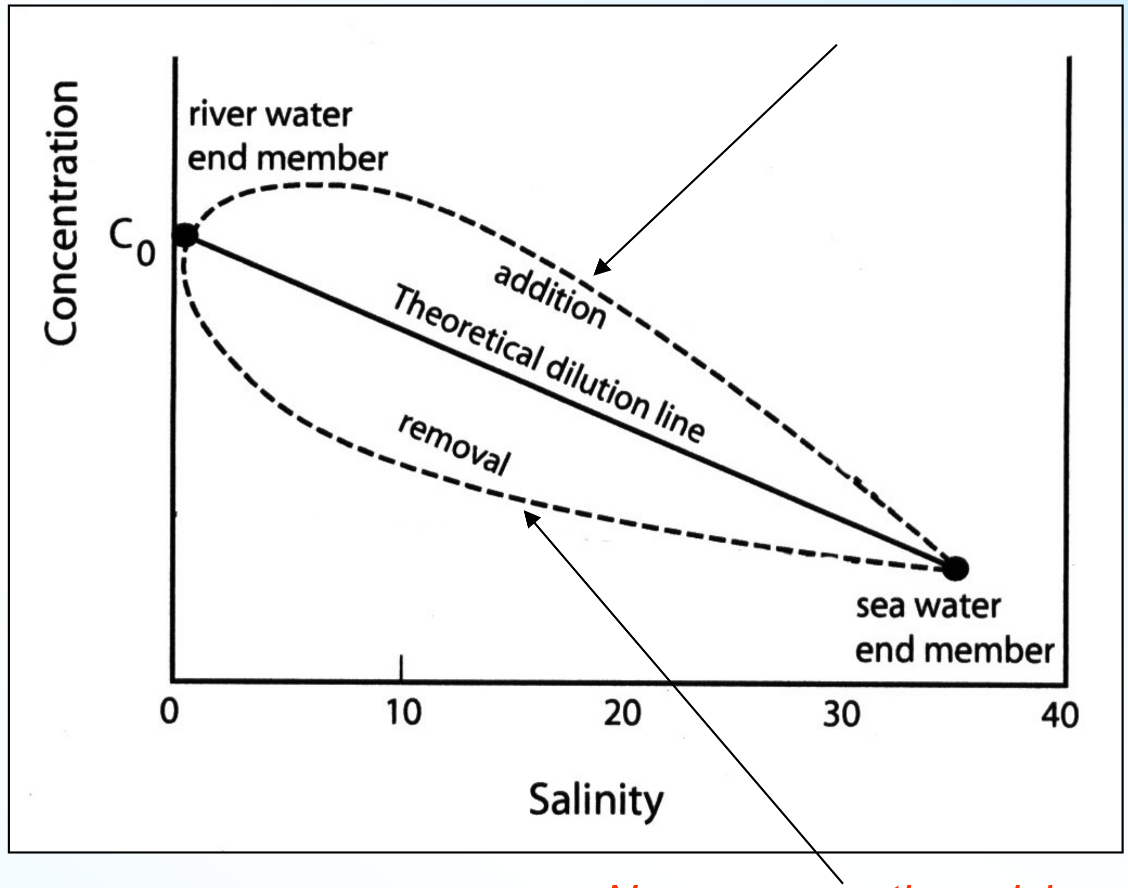
Salinity is a conservative constituent in estuaries and is a good indicator of mixing

Constituent plotted against salinity to determine if distribution is attributable to mixing processes (as opposed to non-conservative processes; nutrient uptake, flocculation, biodegradation, etc.)

If concentration vs. salinity is LINEAR, then the chemical/particle exhibits *conservative* behavior

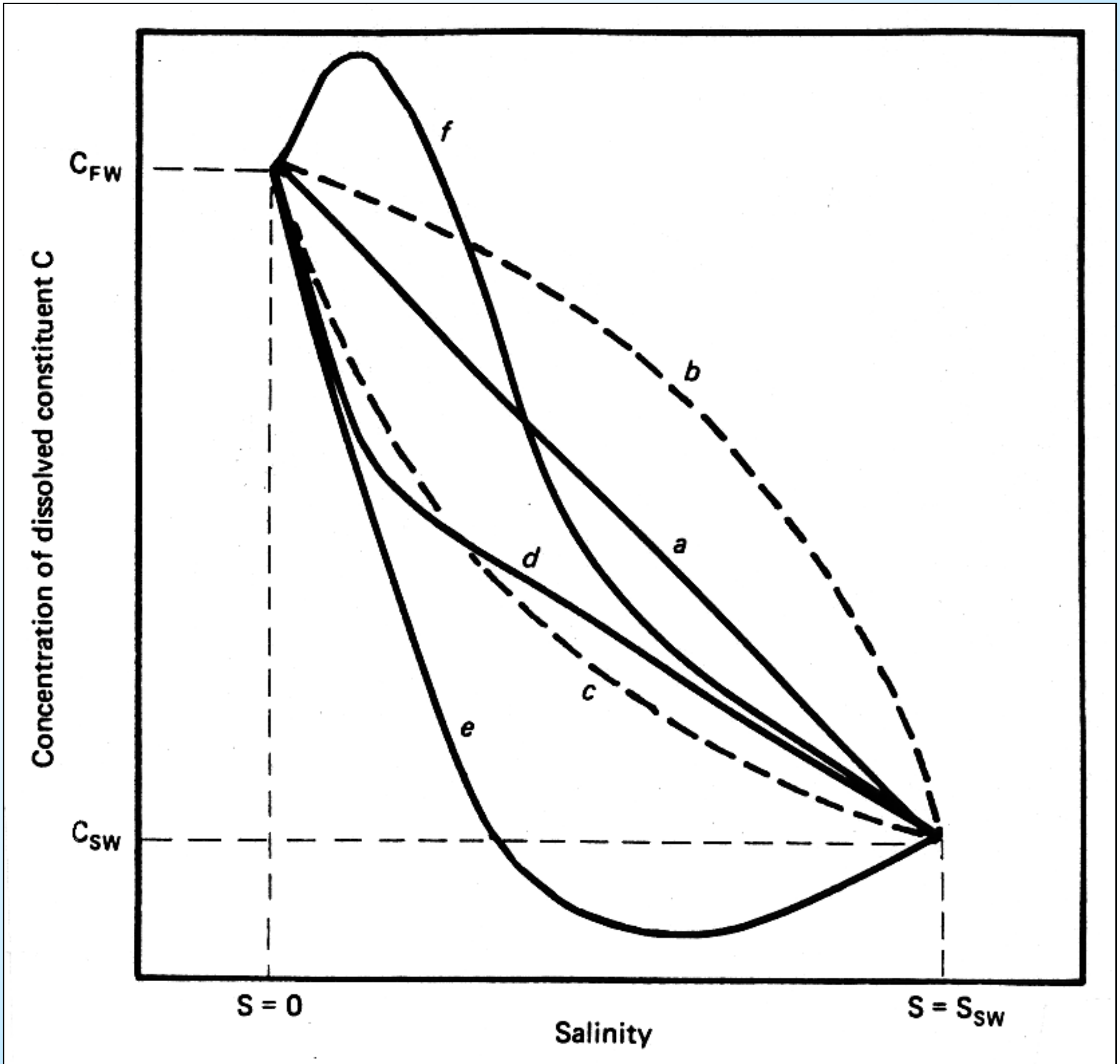
If plot of concentration vs. salinity is NOT LINEAR, then the chemical/particle exhibits *NON-conservative* behavior

Non-conservative mixing (source)



Non-conservative mixing (sink)

Assumes end-members are constant over the flushing time of the estuary



C_{FW}
C_{SW}
Concentration of dissolved constituent C
f
b
a
d
c
e
S = 0
$S = S_{SW}$
Salinity