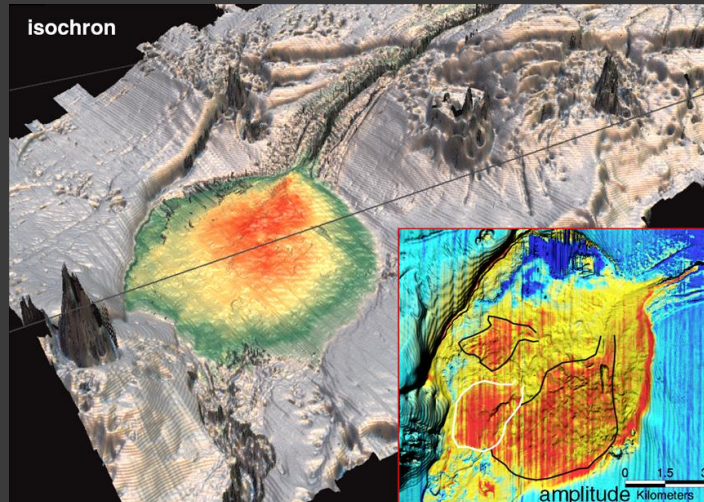


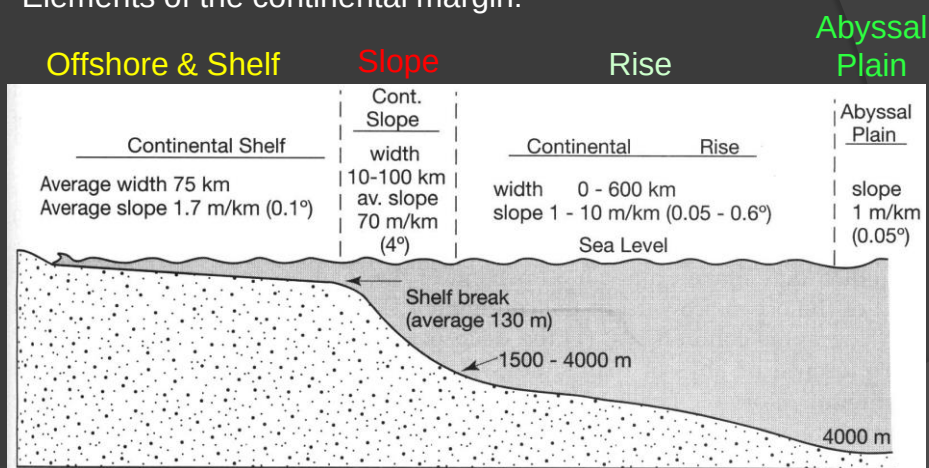
Lecture 6 – Shelf, Slope & Deep Sea: Storm & Sediment-Gravity Flow Deposits



Facies Models 4: Chapter 12

Shelf, Slope and Deep Sea

Elements of the continental margin:



Drake and Burk, 1974

The Shelf

Shelf: General Characteristics

Shelves are composed of 3 main types of sediment:

- 1) Modern Sediments:** sediments that are transported onto and deposited by processes **currently operating** on the shelf, or generated *in situ* by shelf **processes** (chemical/biochemical sediments [carbonates]).
 - dominated by **siliciclastic muds and sands**.

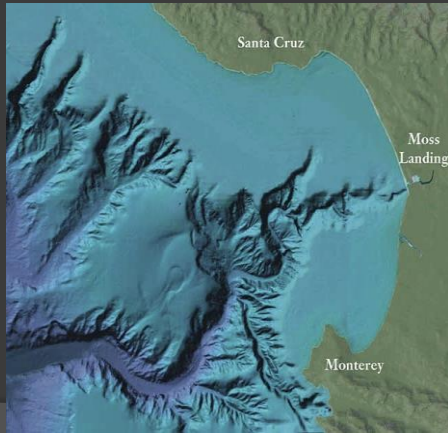


image courtesy of NASA

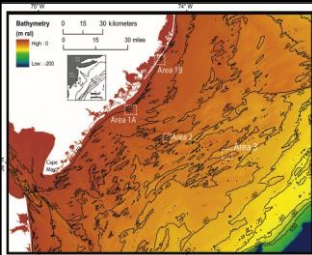


Shelf: General Characteristics

2) Relict Sediments: derived from land sources and transported to shelf by rivers or glaciers during lowered sea level. During successive transgression, these are stranded or trapped on the shelf *and are immobile*.



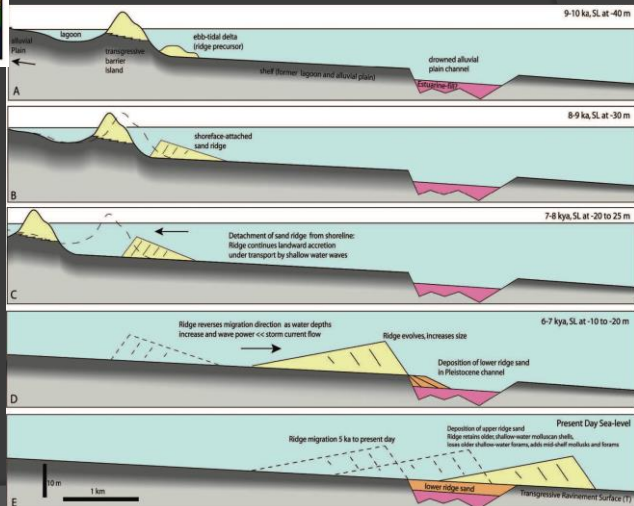
Shelf: General Characteristics



Snedden et al., 2011

3) Palimpsest sediments:

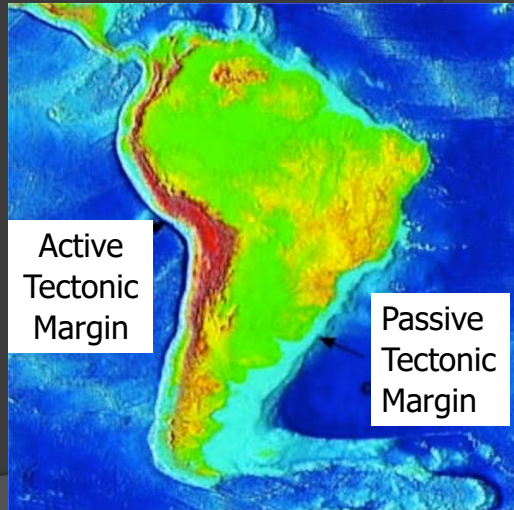
Sediment that starts off as relict sediments, but become *remobilised by shelf processes* after transgression.



Shelf: General Characteristics

Shelf margins vary greatly in character – one important factor is the *tectonic setting* of the continental margin.

Active margins tend to be narrow; Passive margins *tend* to be broad, although obviously there are exceptions!



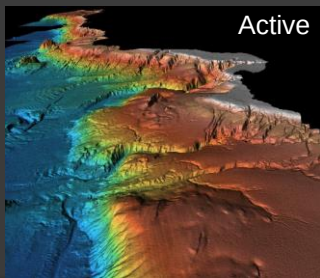
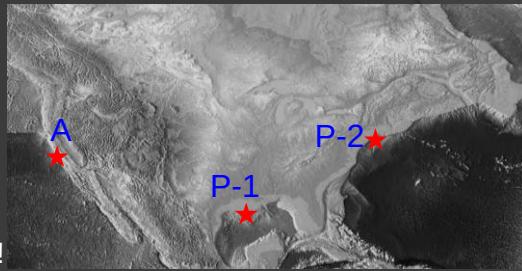
Active
Tectonic
Margin

Passive
Tectonic
Margin

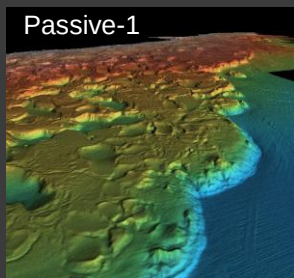
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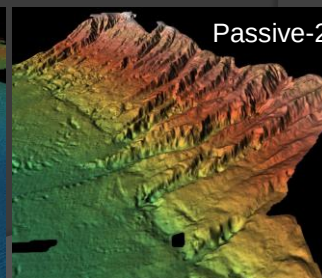
Active margins tend to be narrow; Passive margins *tend* to be broad, although obviously there are exceptions!



Active



Passive-1



Passive-2

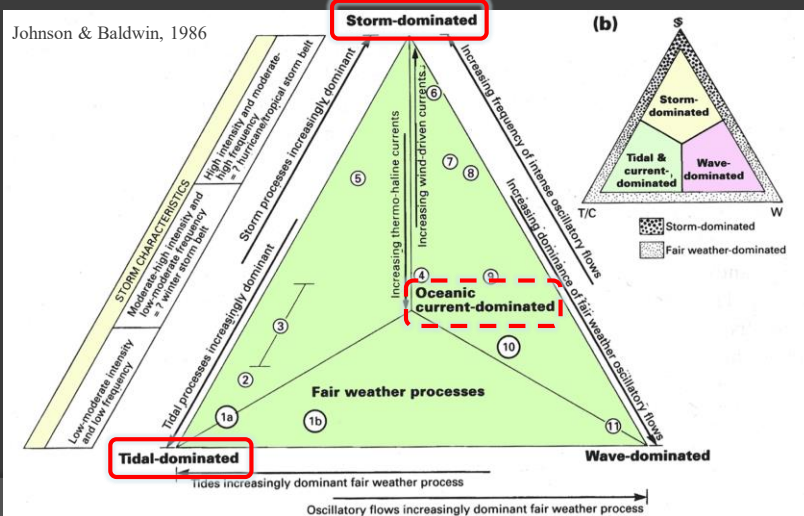
(Pratson and Haxby, 1996)

3000 2000 1000 Depth (m)

3000 2000 1000 Depth (m)

Shelf: General Characteristics

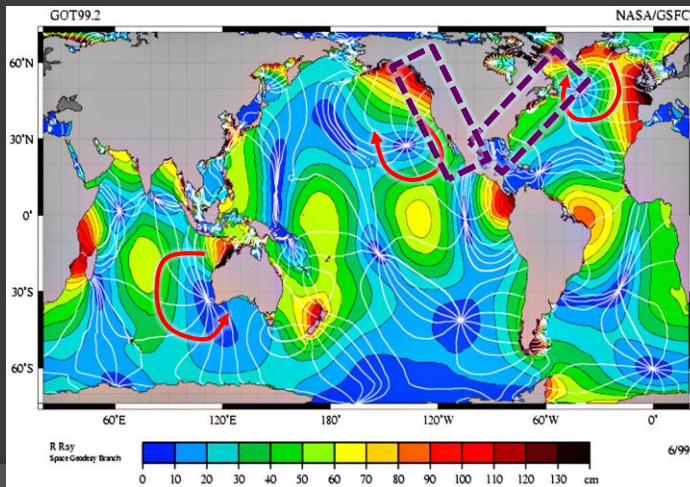
Typically subdivided into **tide-dominated shelves**, **storm-dominated shelves** and **shelves dominated by intruding ocean currents** (rare and not considered further).



Tide-Dominated Shelves

Tidal waves circulate around oceanic basins (8000+ km wavelength) and are forced into shallow water and amplified onto the shelf.

Can generate strong tidal currents on the shelf.

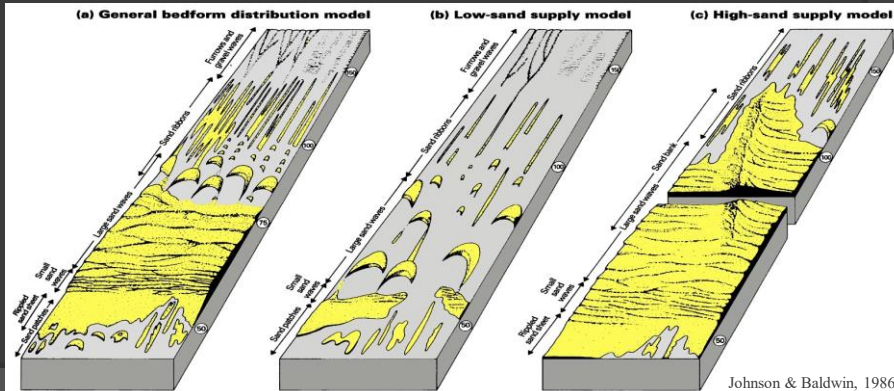


Tide-Dominated Shelves

Characterised by the presence of **tide-generated** sand bodies: made up of **large dunes** (originally called sandwaves) a few metres to more than 20 m in height!

Form **tidal sand ridges** or **sand ribbons**, oriented nearly parallel to tidal flow.

Also generates **sand sheets**, **sand patches** and **gravel sheets**, characterized by small-scale bedforms.



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Cross-bedded
glauconitic
sandstone, Antarctica



Tide-Dominated Shelves

Sediments are dominated by various scales of **trough cross-bedding** and **current ripple lamination**

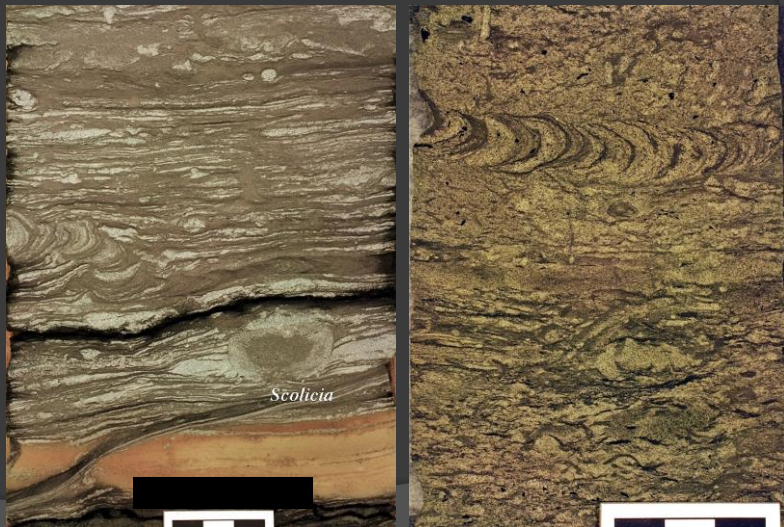
Lesser **horizontal, parallel laminated plane beds**



Tide-Dominated Shelves

Patches of **bioturbated mudstones** in areas protected from tidal flow

Sediments are dominated by various scales of **cross-stratification**



Storm-Dominated Shelves

Typically subdivided into *tide-dominated shelves*, **storm-dominated shelves** and *shelves dominated by intruding ocean currents* (rare and not considered further).

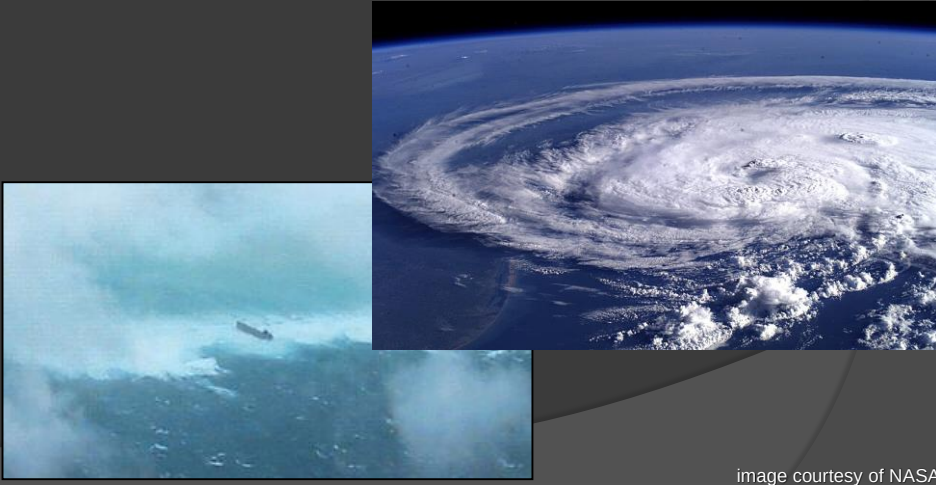


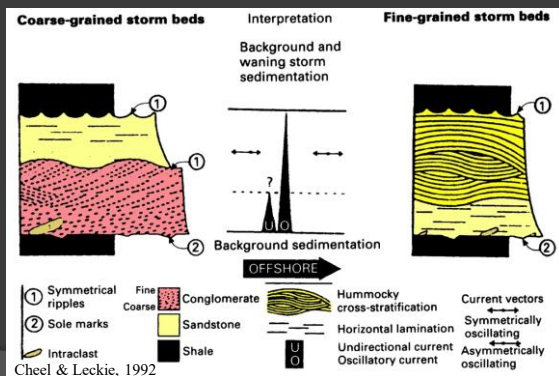
image courtesy of NASA

Storm-Dominated Shelves

Dominate most of the world's coasts and shelves.

Low velocity tidal currents and relatively shallow fairweather wave base (<15 m) leads to little coarse sediment reaching the shelf, **except during intense storm activity**.

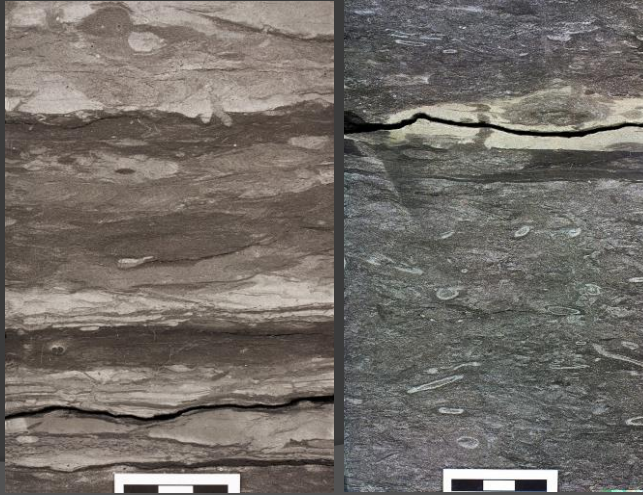
Most sandstone beds consist of **hummocky cross-stratification** (HCS), characterised by low-angle curvilinear parallel lamination (tempestites). These beds alternate with **bioturbated mudstone** deposited between storm events.



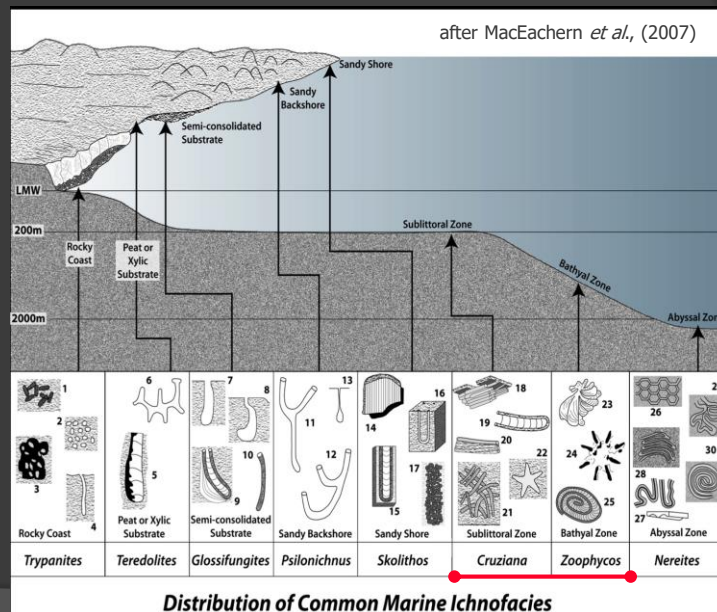
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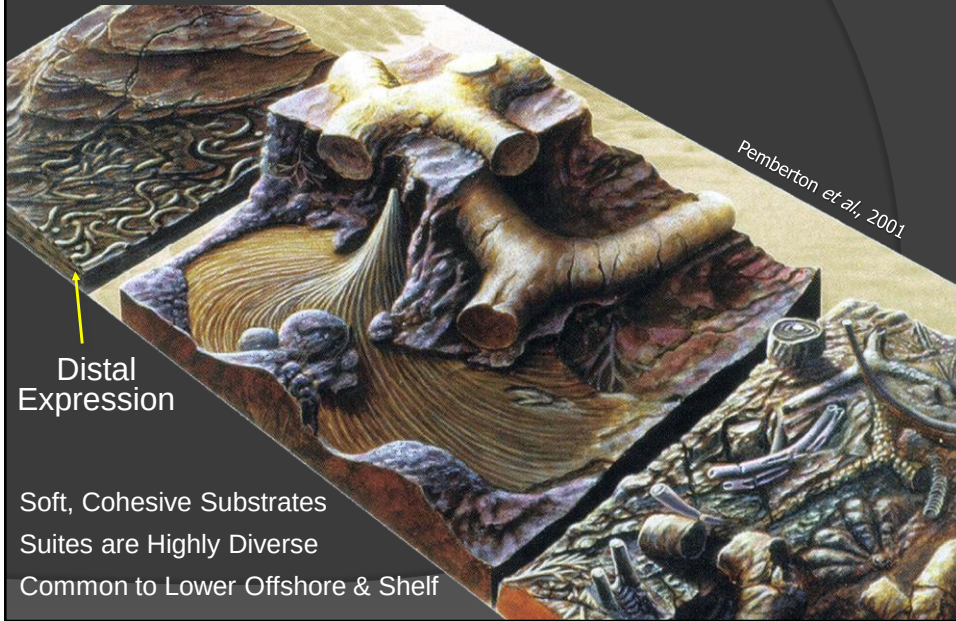
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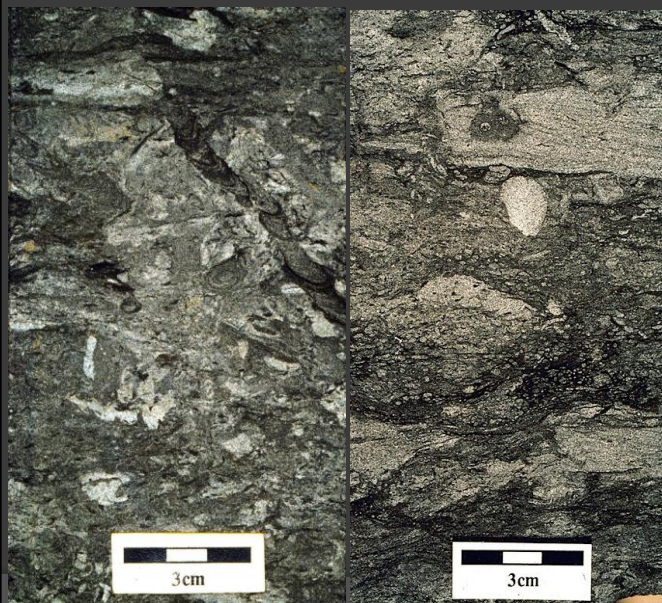
Shelf Ichnology



Cruziana Ichnofacies



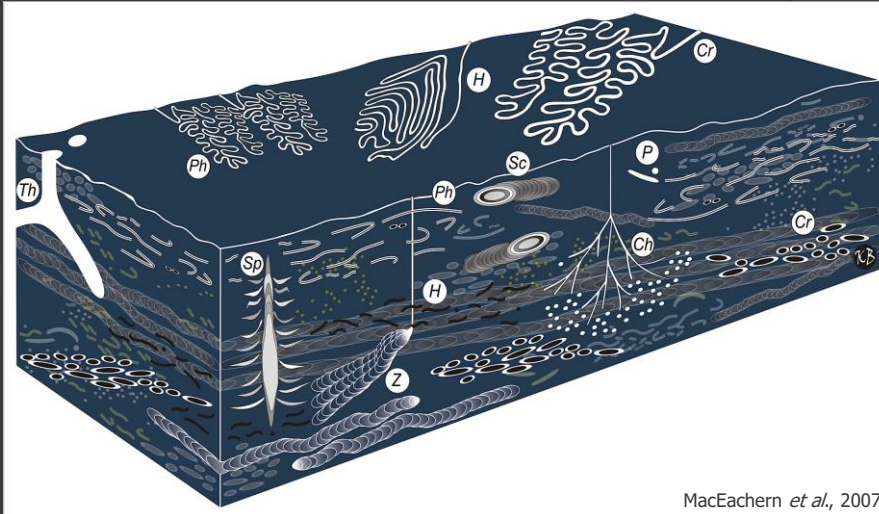
Cruziana Ichnofacies



Dominated by
deposit-feeding
structures and grazing
structures.

Ichnogenera include
Planolites, *Chondrites*,
Asterosoma,
Zoophycos, *Scolicia*,
Phycosiphon,
Thalassinoides,
Schaubcylindrichnus,
Rhizocorallium, and
Cosmorhaphe.

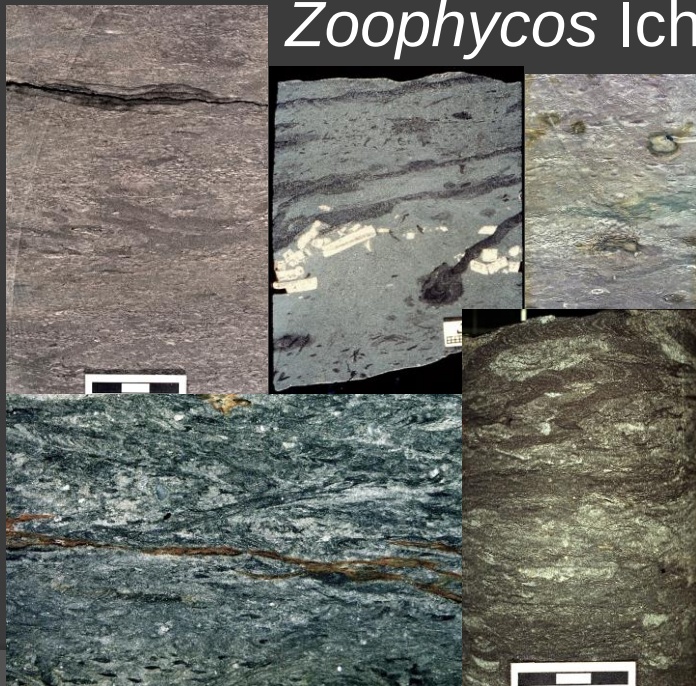
Zoophycos Ichnofacies



MacEachern *et al.*, 2007

Common traces include *Chondrites* (Ch), *Cosmorhapha* (Cr), *Phycosiphon* (Ph), *Planolites* (P), *Scolicia* (Sc), *Spirophyton* (Sp), *Thalassinoides* (Th), & *Zoophycos* (Z).

Zoophycos Ichnofacies



Dominated by grazing structures.

Subordinate diminutive deposit feeding structures.

Very rare, small diameter, silt-lined passive carnivore dwellings.

Typical of soft, muddy substrates in quiet-water shelf (below storm wave base) and slope settings.

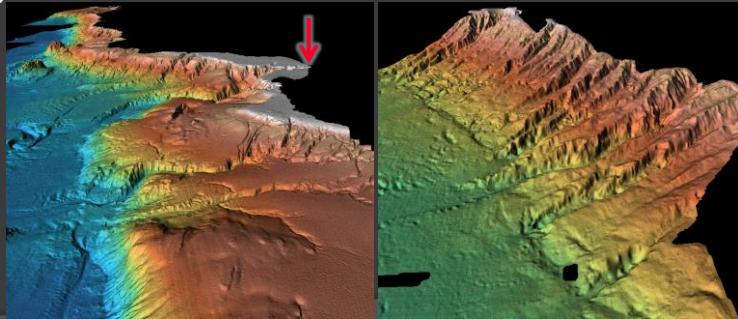
Deep-Water Depositional Systems (DWDS)

– General Characteristics

DWDS: General Characteristics

Coarse-sediment deposition in the ocean basin is largely controlled by the existence of the **continental slope**, which enables sediment transport from the shelf to deep water.

Many continental slopes are **incised** into by **submarine canyons**. Some of these canyons are actually **linked** shoreward with major river systems.



(Pratson and Haxby, 1996)

3000 2000 1000 Depth (m)

3000 2000 1000 Depth (m)

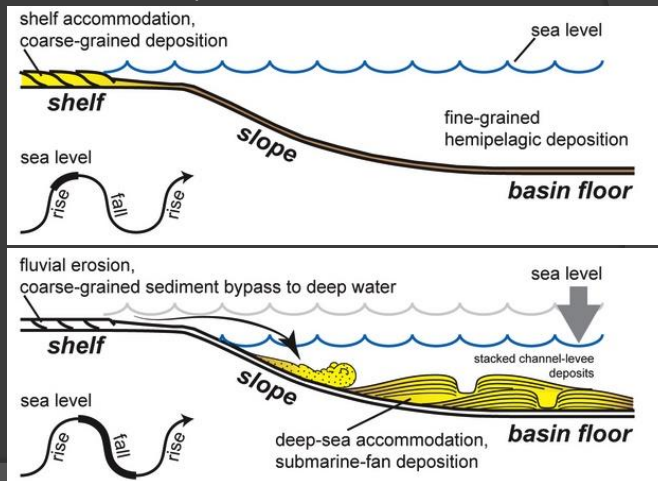
DWDS: General Characteristics

Sequence Stratigraphic Paradigm: increased sediment delivery to deep-sea during lowstand

During highstand, coarse material sequestered on shelf

During lowstand, incised valleys bring coarse material directly to shelf edge

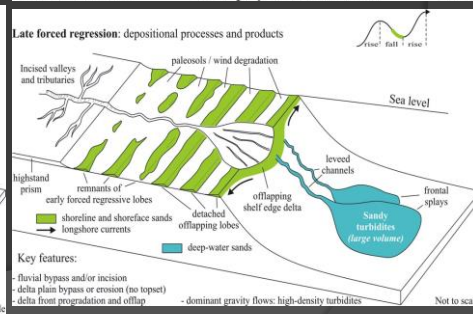
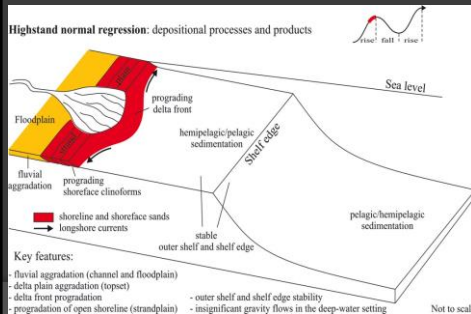
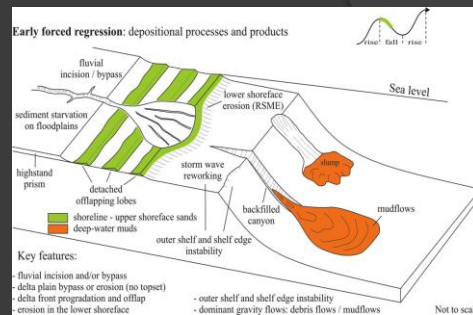
Shelf width controls storage capacity during highstand: strongly influenced by tectonic setting



From Covault, 2011 (modified after Catuneanu, 2002)

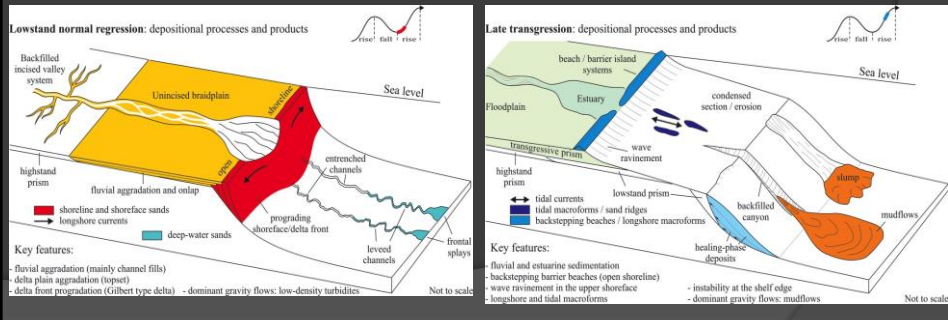
DWDS: General Characteristics

Sequence Stratigraphic Paradigm: increased sediment delivery to deep-sea during lowstand. During highstand, coarse material sequestered on shelf.



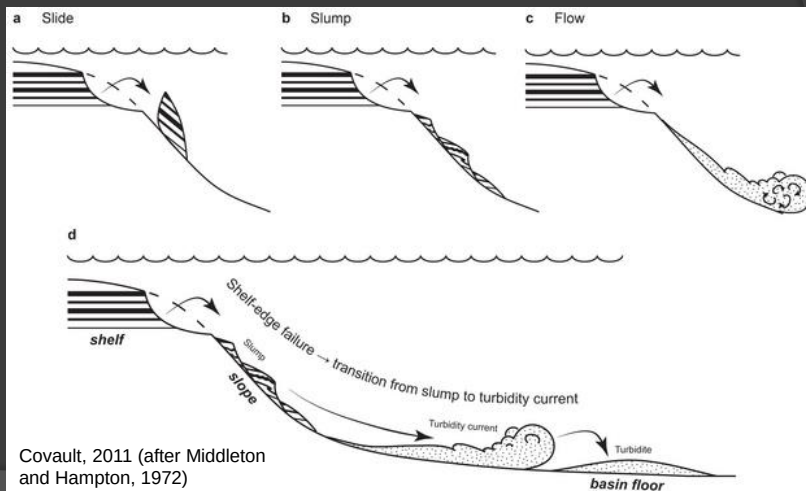
DWDS: General Characteristics

Sequence Stratigraphic Paradigm: increased sediment delivery to deep-sea during lowstand. During highstand, coarse material sequestered on shelf.



DWDS: General Characteristics

Sediment transported from the shelf to the slope and, continental rise, and abyssal plain via **turbidity currents** and **mass wasting events**.



DWDS: General Characteristics

Sediment transported from the shelf to the slope and, continental rise, and abyssal plain via **turbidity currents** and **mass wasting events**

Turbidity currents can be huge!



Dust Storm, Iraq

Turbidites

Scale of turbidity currents: e.g., **1929 Grand Banks earthquake**

Current velocities up to 67 km/hr (20 m/sec)!

Turbulent flow up to 400+ m thick!

Gravels moved hundreds of km!

Deposit traveled >1000 km!

Volume of Sediment: 185 km³.
This is enough sediment to fill 14,230,770 rail cars, which would wrap around the Earth 6.4 times!



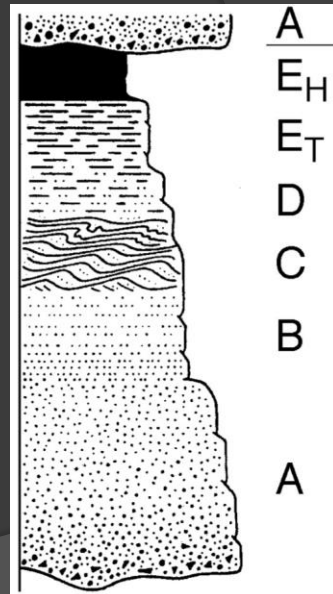
Slide courtesy of S. Hubbard

Turbidite: Bouma Sequence

Turbidites: A **turbidite** is the deposit of a **single turbidity flow**. Composed of **sand, silty sand or gravelly sand**. They are commonly interbedded with hemipelagic to pelagic clays.

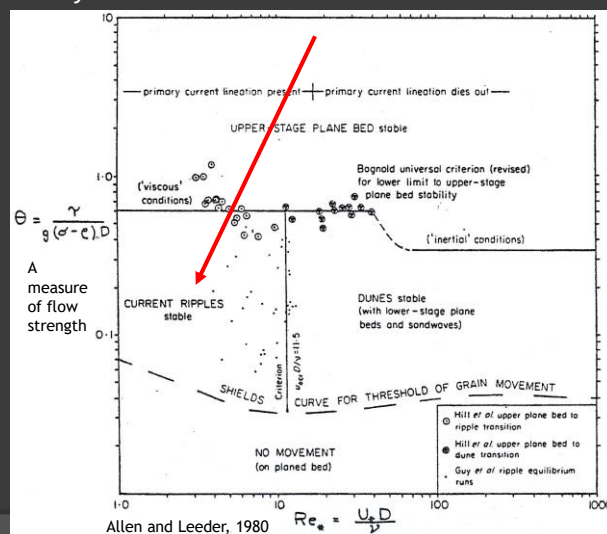
Idealised succession of beds within a turbidite was first proposed by Arnold Bouma (1962), termed a **Bouma Cycle** in his honour. These are now known as low-density turbidites

The ideal complete cycle consists of **5 units (A-E)**.

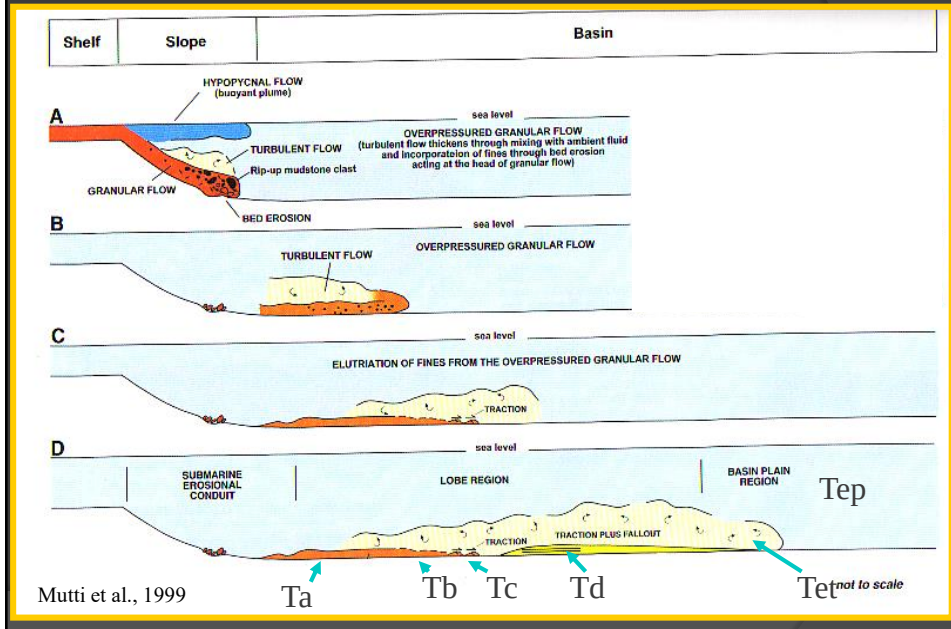


Low-Density Turbidites

Waning flow of a turbidity current recorded in a Bouma sequence: shift through sedimentary structures



Low Density Turbidites



Turbidite: Bouma Sequence

Surging turbidity currents result in alternating Bouma divisions



Slide courtesy of S. Hubbard

Hubbard, 2006

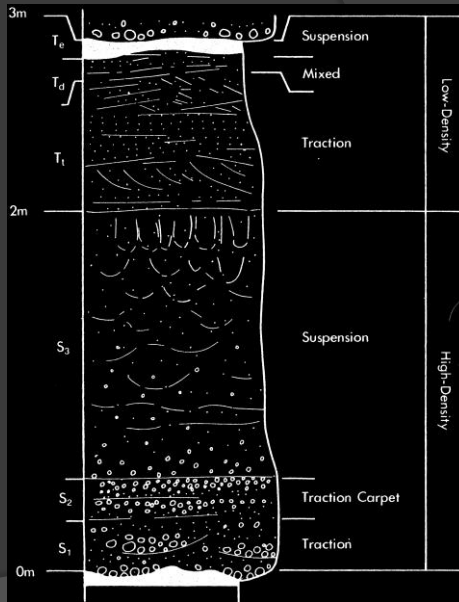
High-Density Turbidites

Bouma-type beds account for only a small percentage of reservoir quality deep-water turbidites.

Lowe (1982) describes a sequence of structures for thick-bedded turbidites

Graded units, the result of grain support by turbulence, dispersive pressure (grain collisions), hindered settling (concentration effect), and buoyancy effects (high-concentration mixture):

These represent the deposits of high-density or high-concentration turbidity currents.



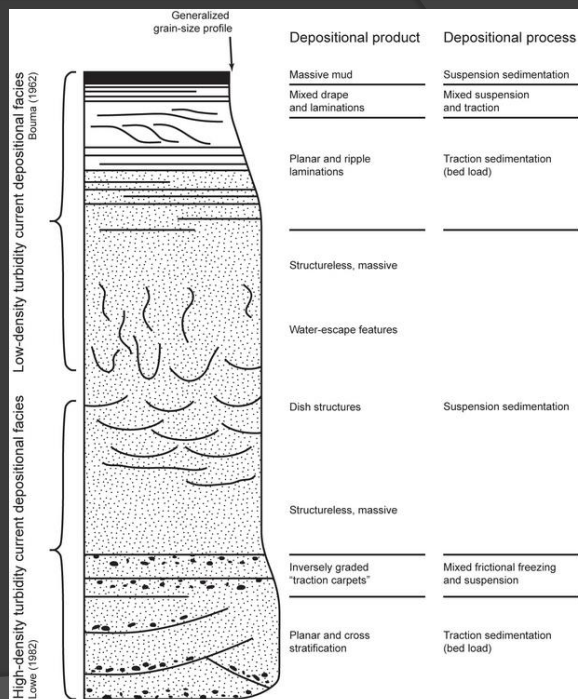
Slide courtesy of S. Hubbard

Lowe, 1982

High-Density Turbidites

These represent the deposits of high-density or high-concentration turbidity currents.

Form from coarse-grained and mixed fine- and coarse-grained material



Slide courtesy of S. Hubbard

High-Density Turbidites

Characteristics of high-density turbidity current deposits:

Massive sandstone linked to Bouma traction structure (A-B structures)

Dish structures and water escape pipes



Hubbard, 2006



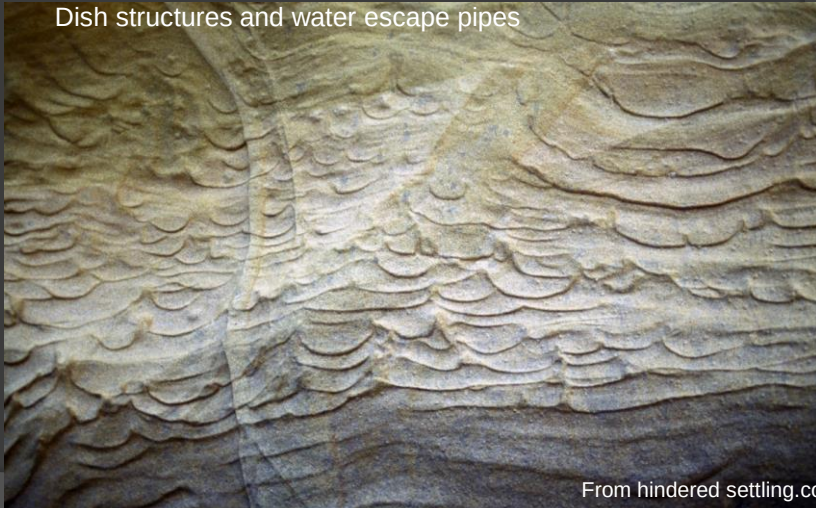
Tertiary deposits, Northern California coast

High-Density Turbidites

Characteristics of high-density turbidity current deposits:

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Dish structures and water escape pipes



From hindered settling.com

Turbidites: Paleocurrent indicators

Turbidites commonly display bed-scale paleocurrent indicators

- sole marks (flutes, gutters, tools)
- imbricated clasts(if traction transported), ripples, & dunes



Hubbard, 2006

Turbidites

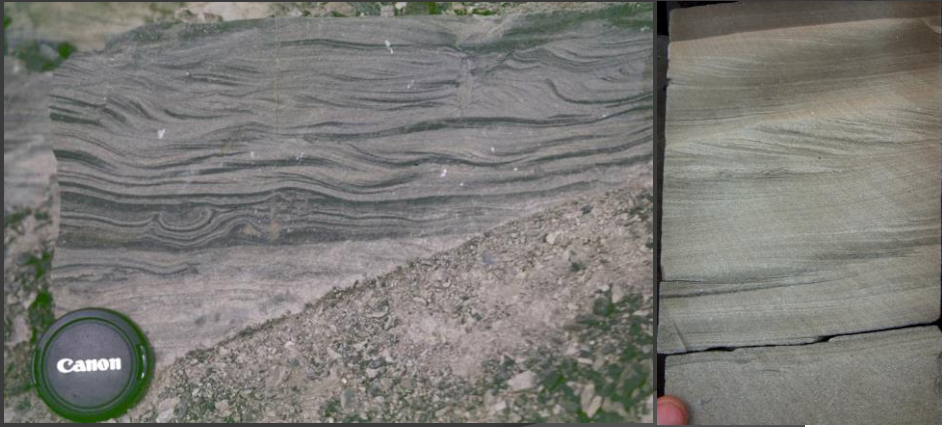
Other common features of deep-water beds... fluid injection structures (flame structures)



Hubbard, 2006

Turbidites

Other common features of deep-water beds... aggradational current ripples, soft-sediment deformation, top-down bioturbation

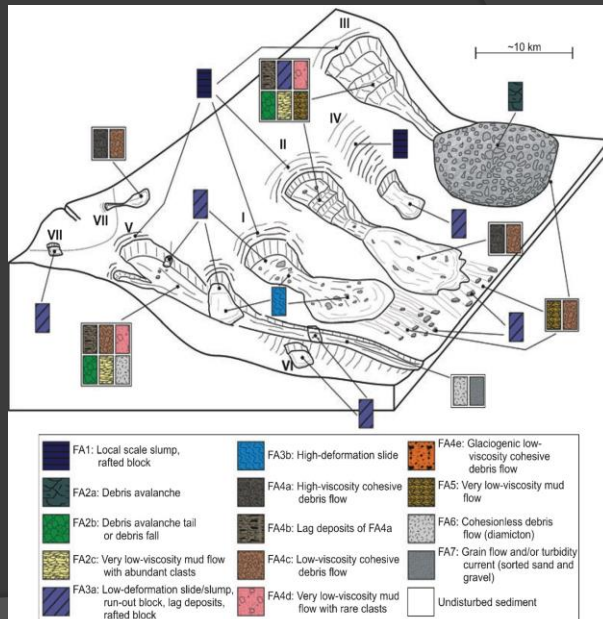


Hubbard, 2006

Mass Wasting Deposits

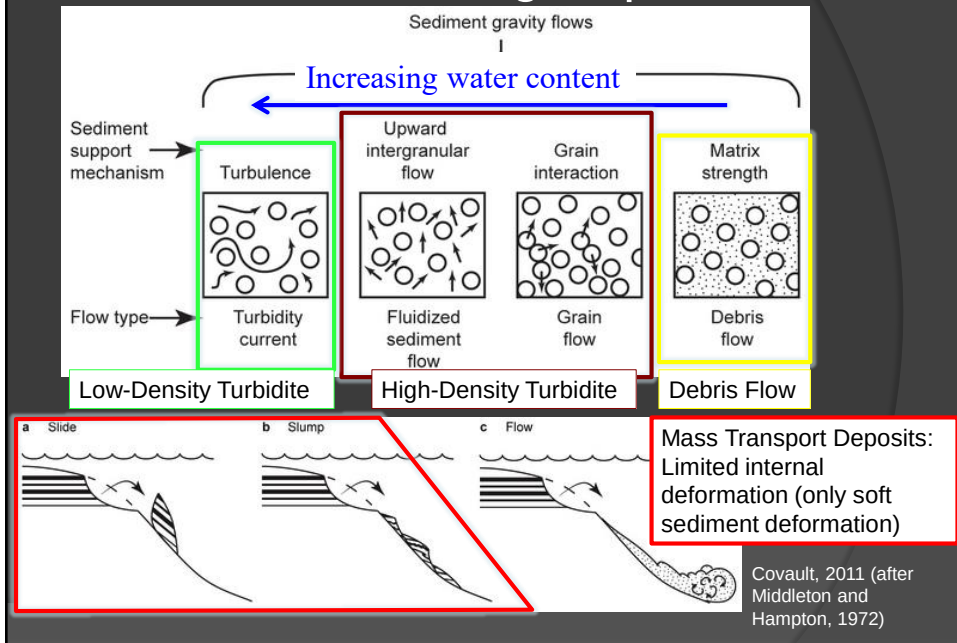
Mass Wasting Deposits include:

- I - landslide
- II - landslide-debris flow
- III - debris avalanche
- IV - slides / slumps
- V - canyons from failures
- VI - local slides / slumps
- VII - slides / slumps on river deltas



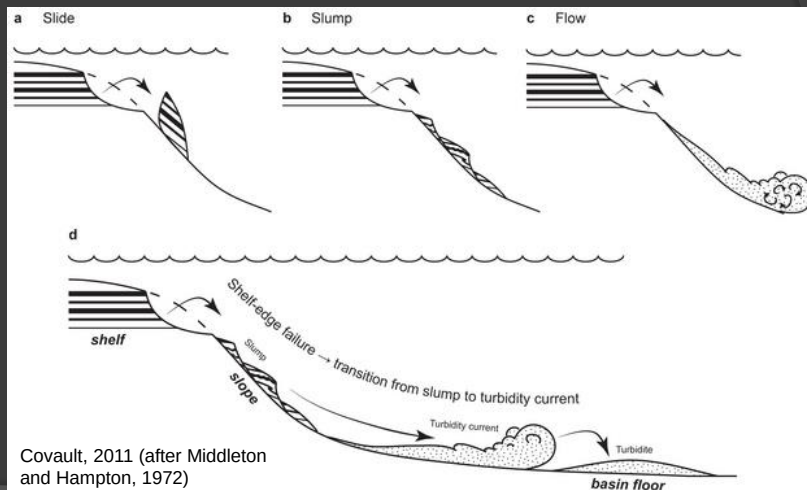
Tripsanas et al., 2008

Mass Wasting Deposits



Mass Wasting Deposits

Mass Transport deposits can evolve into turbidity flows as they move downslope and incorporate water into the flow.

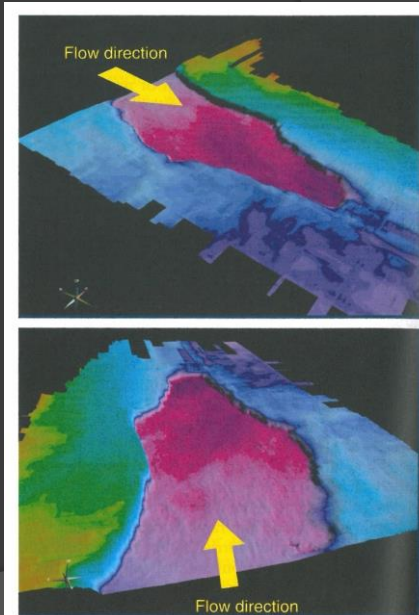
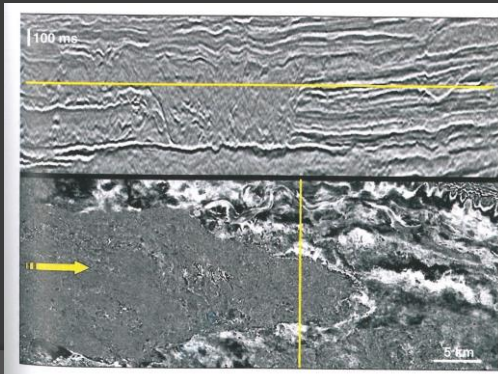


Mass Wasting Deposits

Debris Flow Deposits can be huge!

e.g., Single, Pleistocene debris flow in Gulf of Mexico: 30 km long, 12.5 km wide, 240 m deep

Catuneanu, 2006



Mass Wasting Deposits

Debris Flow Deposits

Grain support
from matrix
strength
(cohesiveness) =
matrix supported

Important
Component of
Mass Transport
Complexes



Hubbard, 2006

Mass Wasting Deposits

Mass Transport Complex

- characterized by chaotic architecture
- known to be transported >1000 km on the sea floor



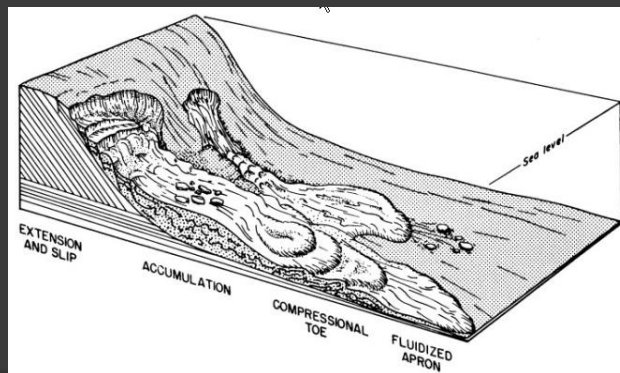
Tertiary deposits, Northern California coast

Hubbard, 2006

Mass Wasting Deposits

Mass Transport Complex (MTC)

- can be volumetrically immense!
- chaotic layering easily identified in seismic reflection data



Galloway and Hobday, 1996

Deep-Water Depositional Systems (DWDS) – Sedimentary Environments

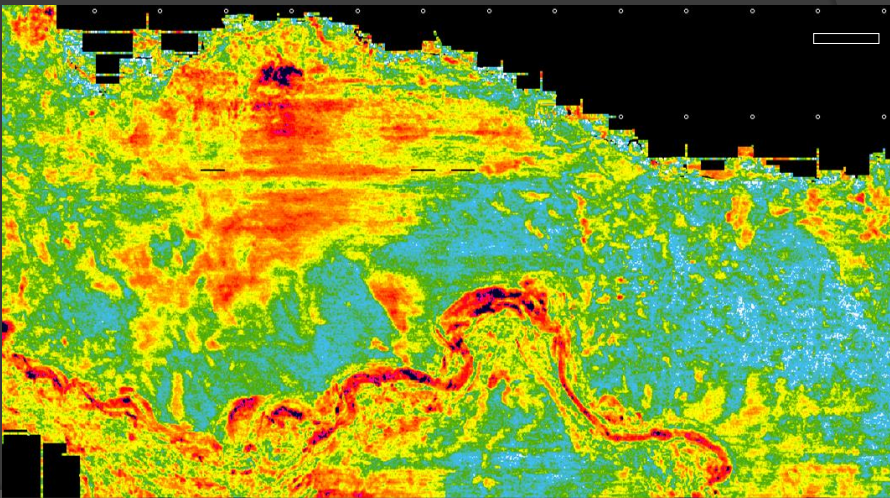
DWDS: Sedimentary Environments

Submarine canyons

Continental slopes

Channel-levee complexes

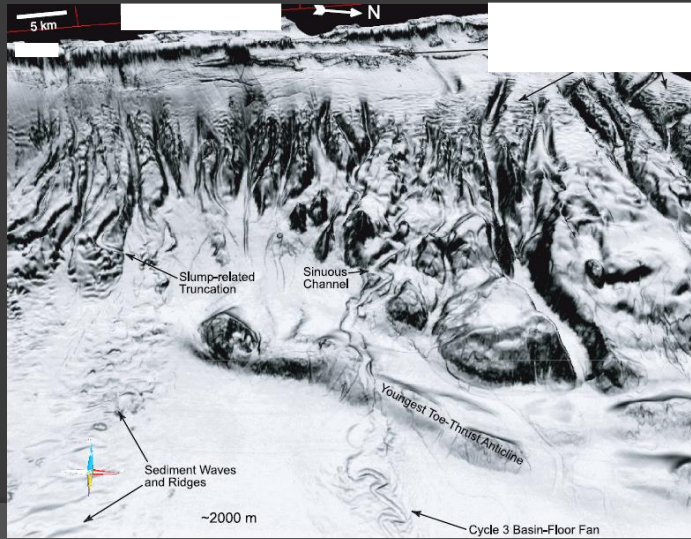
Basin floor fans



Slides courtesy of S. Hubbard

Submarine Canyons

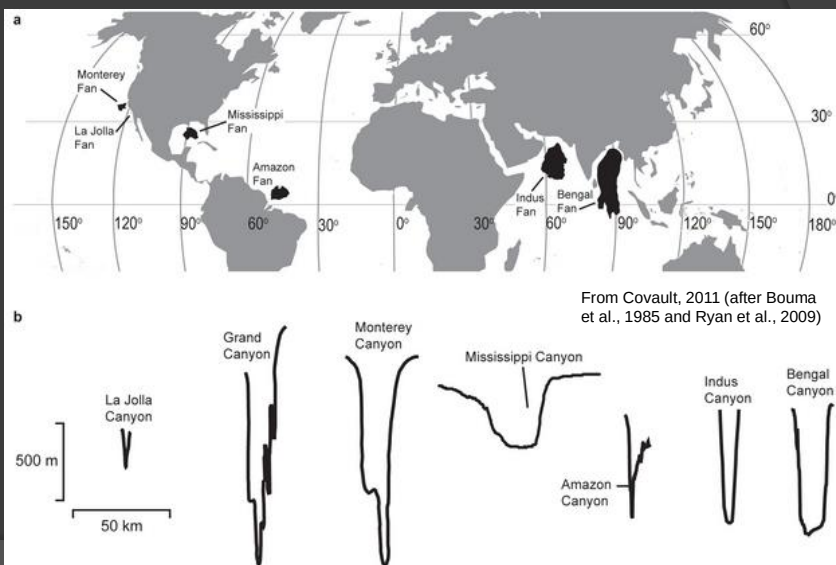
Submarine canyons: conduits for coarse-grained sediment transport to the deep-sea



Saller et al., 2004

Submarine Canyons

Submarine canyons can be exceedingly deep



From Covault, 2011 (after Bouma et al., 1985 and Ryan et al., 2009)

Submarine Canyons

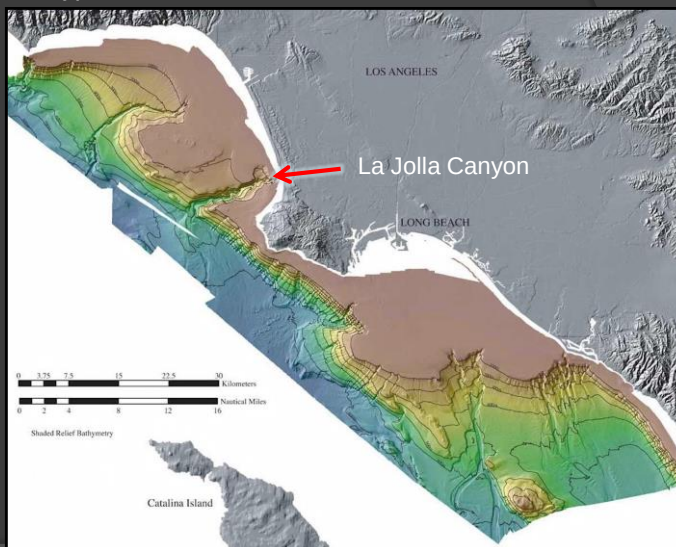
Dominated by sediment bypass rather than accumulation

Initiated through: 1) lowering sea-level (rivers incise across the shelf), 2) local slope failure (slumping), 3) turbulent scour

Location often controlled by faults

Sediment fed into canyons directly from rivers, or *via* littoral drift

Slide courtesy of S. Hubbard



Submarine Canyons

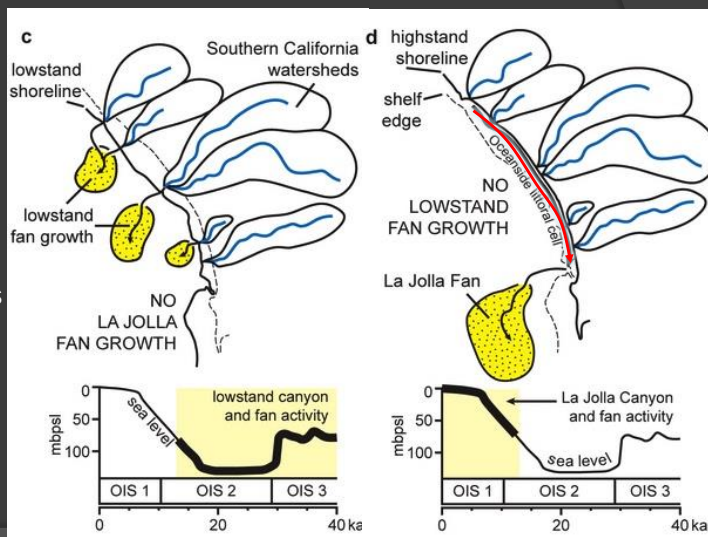
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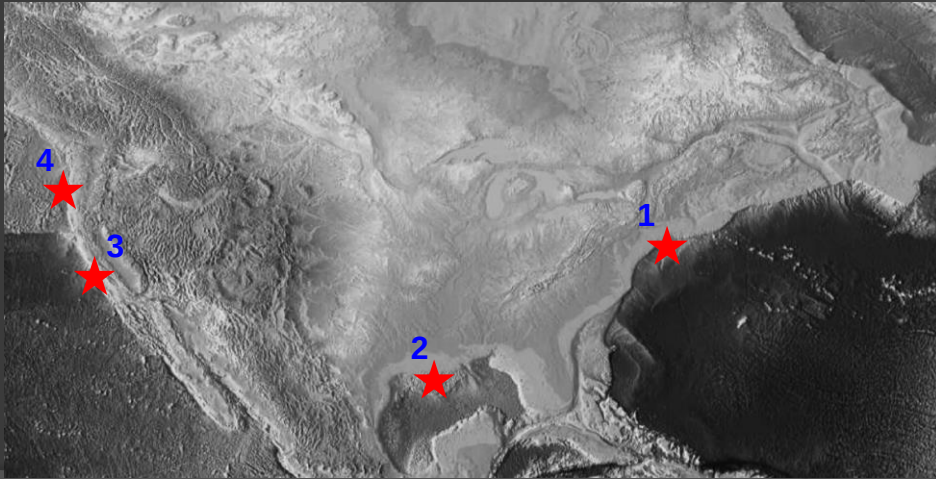
Sediment fed into canyons directly from rivers, or *via* littoral drift

Covault, 2011 (after Covault et al., 2007, 2011)



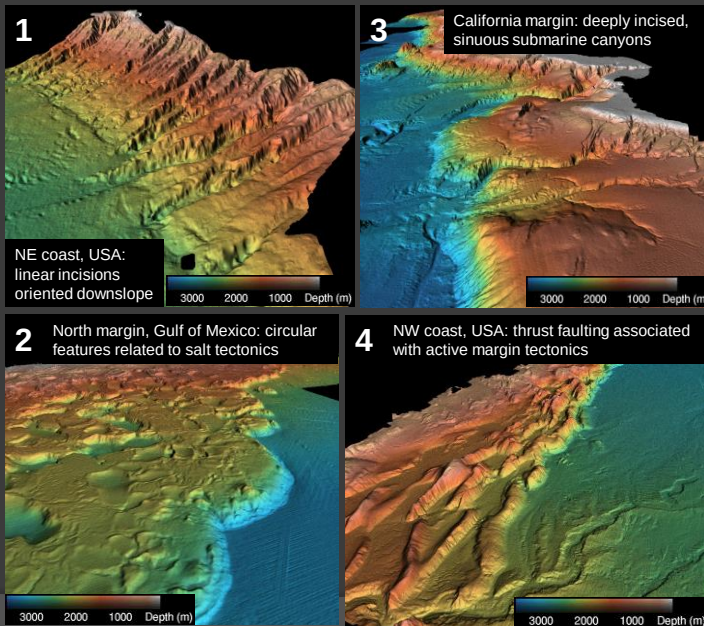
Continental Slopes

Highly variable slope angles and topography, which strongly affect the distribution and architecture of sediments



Continental slope variability, North America (Pratson and Haxby, 1996)

Continental Slopes

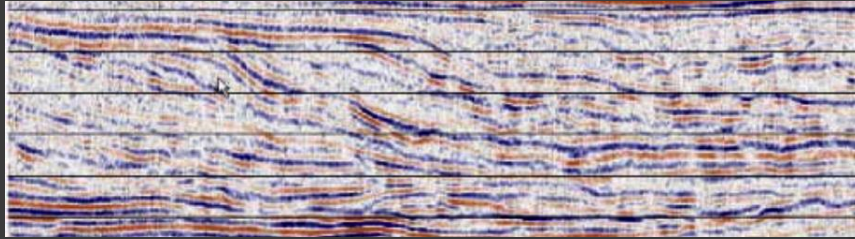


Highly variable slope angles and topography, which strongly affect the distribution and architecture of sediments.

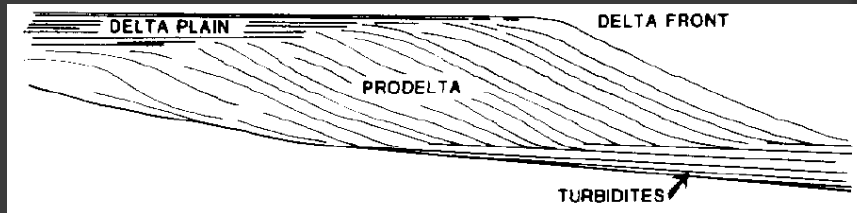
(Pratson and Haxby, 1996)

Continental Slopes

Slope Sedimentation – Progradation during lowstand



<http://strata.geol.sc.edu>

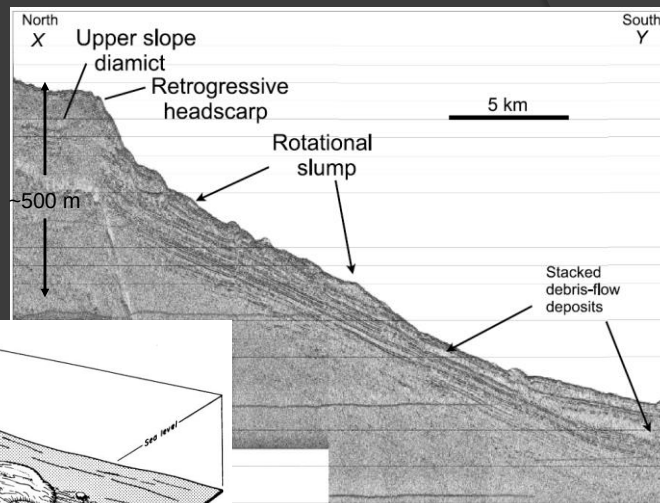
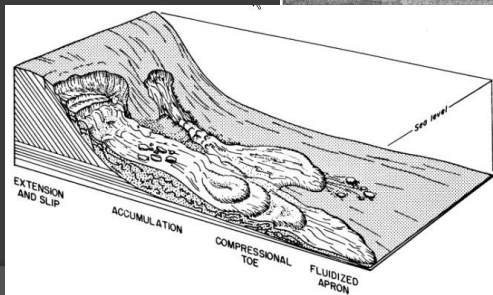


Sediment delivered to the shelf edge causes slope to prograde (only where deltas occur)

Continental Slopes

Dominated by slumping / mass wasting: MTCs (mass transport complexes)

Galloway & Hobday (1996)



Mosher et al. (2004)

offshore Nova Scotia

Continental Slopes

Dominated by slumping / mass wasting: MTCs (mass transport complexes)

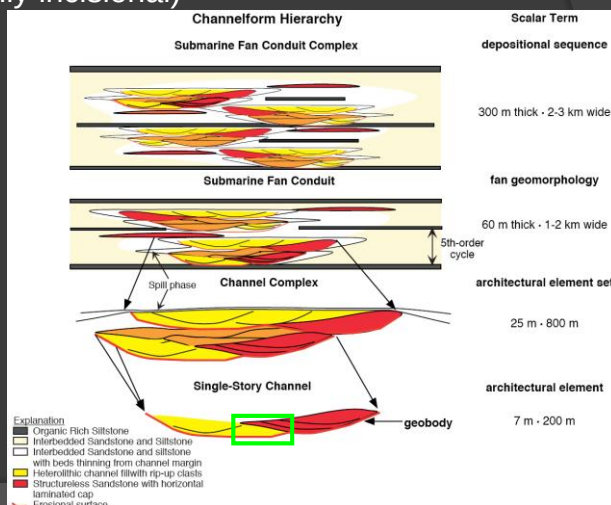


Shultz et al. (2005)

Continental Slopes

Sandstone deposition controlled by seafloor topography, which is commonly defined by the surface morphology of a MTC:
CHANNELS (typically incisional)

Reservoir heterogeneity complicated



Gardner & Borer, 2000

Continental Slopes

Sandstone deposition controlled by seafloor topography, which is commonly defined by the surface morphology of a MTC : CHANNELS (typically incisional)

Reservoir heterogeneity complicated

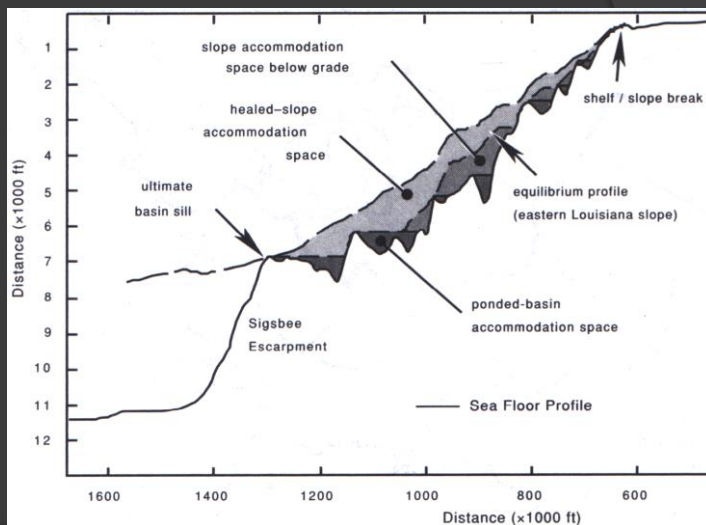
Hubbard (2006)



Continental Slopes

Sandstone deposition controlled by seafloor topography, which is commonly defined by the slope morphology : “**FILL AND SPILL**”

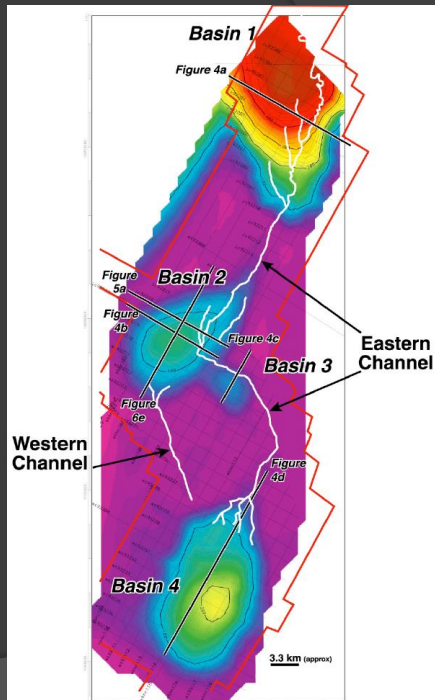
The filling of accommodation space on the slope is complex as a result of the dynamic nature of the slope surface (Prather et al., 1998).



Continental Slopes

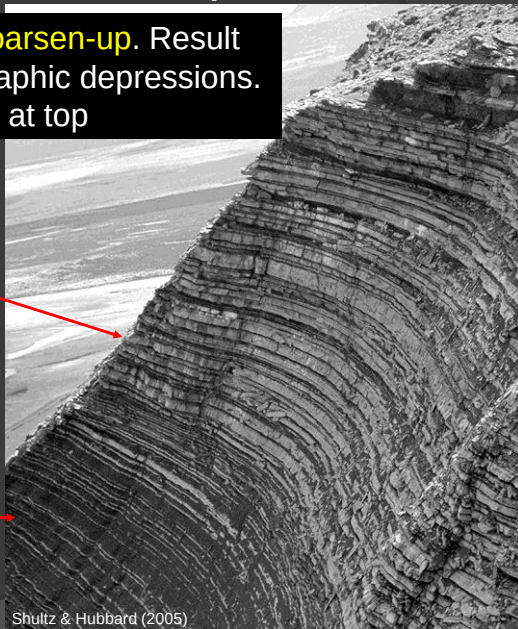
Sandstone deposition controlled by seafloor topography, which is commonly defined by the slope morphology: **"FILL AND SPILL"**

Beaubouef et al. (2000)



Continental Slopes

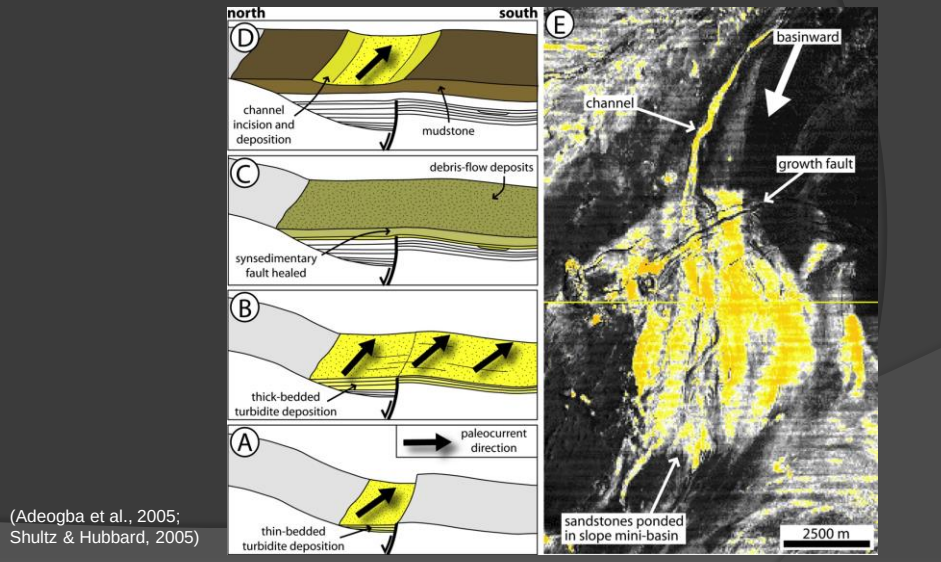
"FILL AND SPILL" strata coarsen-up. Result of progradation into topographic depressions. Sediment bypass recorded at top



Shultz & Hubbard (2005)

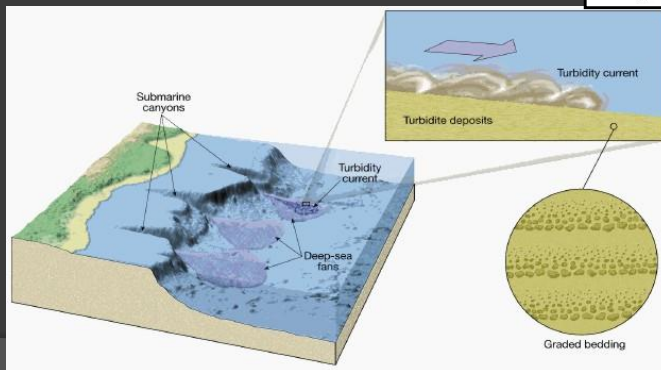
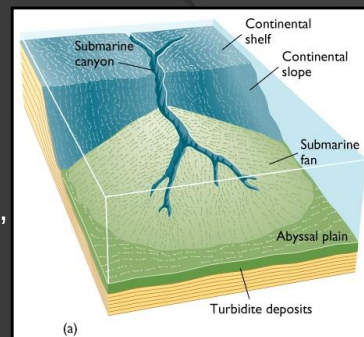
Continental Slopes

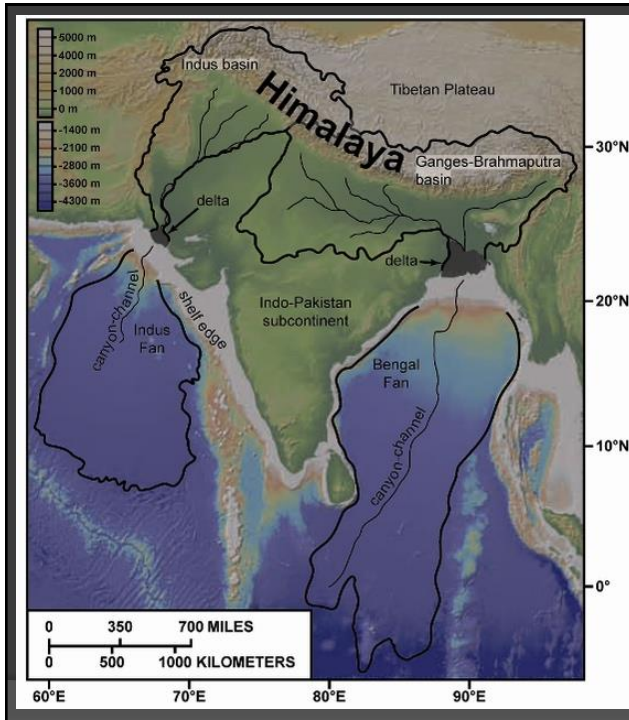
Sandstone deposition controlled by seafloor topography, which is often controlled by growth structures : “MINI-BASINS”



Basin Floor Fans

Submarine Fans: Most sites of turbidity flows are not restricted to single events, but are subjected to repeated events that **coalesce** to form **submarine fans**.





Basin Floor Fans

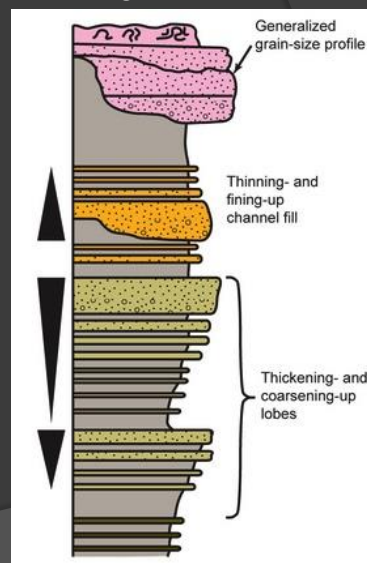
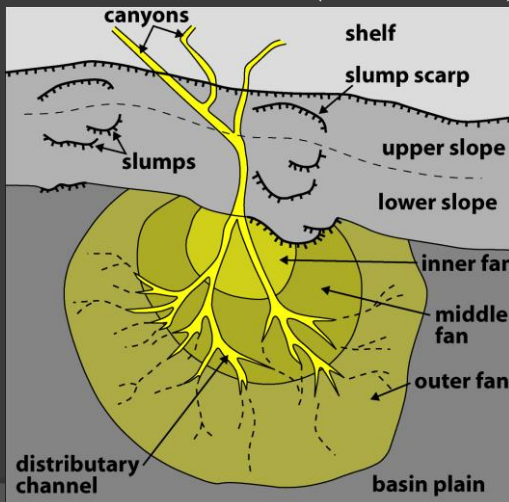
How much sand can we really expect to reach the deep-sea?

Covault, 2011 (after Ryan et al., 2009)

Basin Floor Fans

Early depositional models indicate a progradational package typically with proximal to distal fining

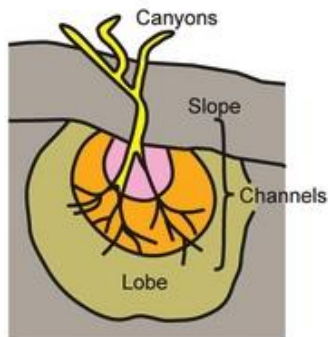
(Mutti & Ricci-Lucchi, 1972)



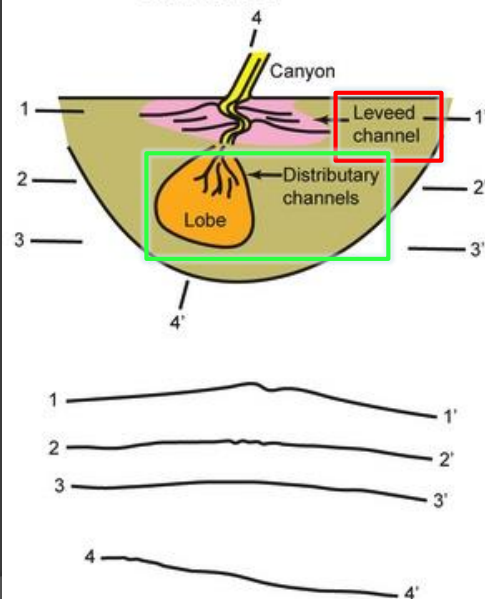
Basin Floor Fans

Work on modern fans indicate that the architecture is more complicated.

b Ancient fan model
Mutti and Ricci Lucchi (1972)



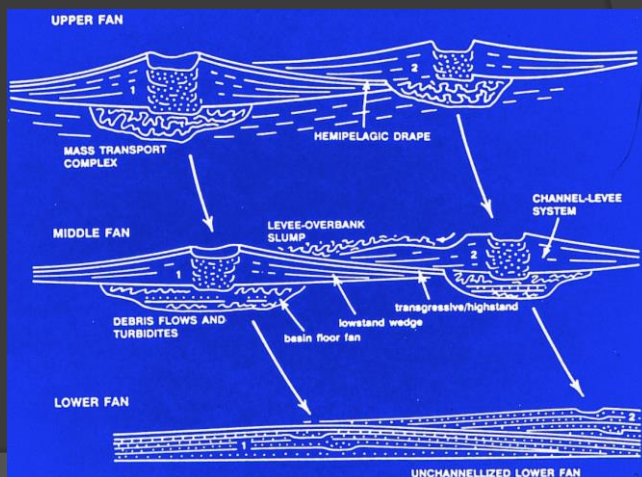
a Modern fan model
Normark (1970)



Basin Floor Fans

Four main, large-scale facies associations common to submarine fans:

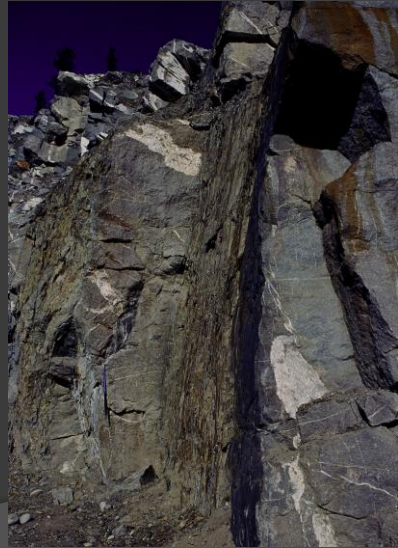
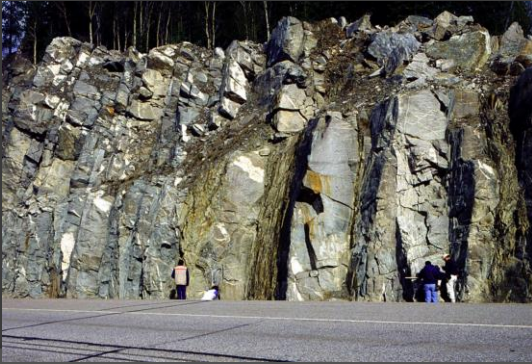
- 1) mass-transport complexes
- 2) slumps and debris flows associated with levee failure is extensive
- 3) submarine channel/levee systems
- 4) continuous, unchannelized sheet-like deposits between channels



Walker, 1992

Basin Floor Fans

Debris flows and slumps are most common near the head of the fan and in canyons on the continental slope and near the fan apex.

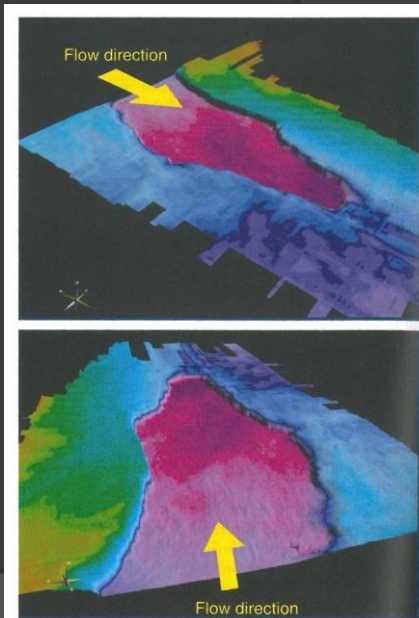
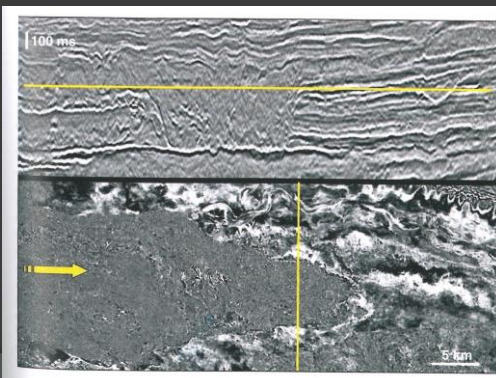


Basin Floor Fans

Debris Flow Deposits can be huge!

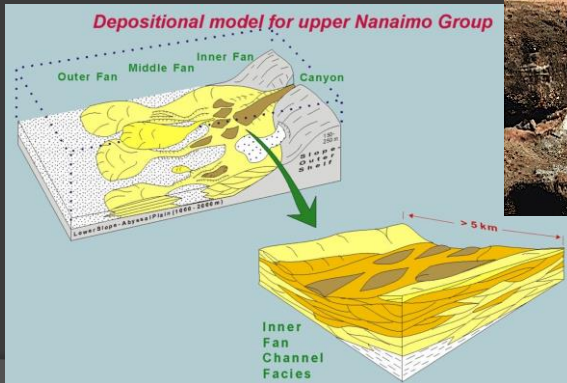
e.g., Single, Pleistocene debris flow in Gulf of Mexico: 30 km long, 12.5 km wide, 240 m deep

Catuneanu, 2006



Basin Floor Fans

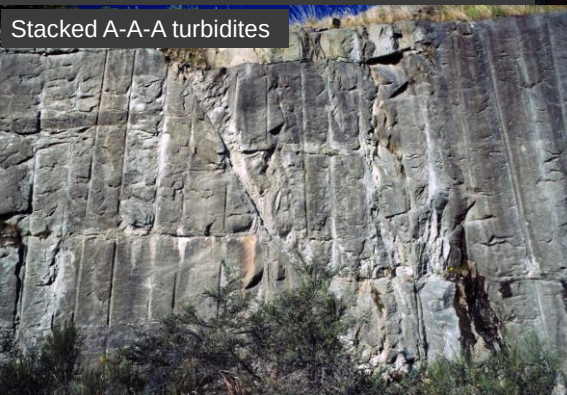
Fan apex may also contain thick dispersive grain-flow deposits (high-density turbidites) characterized by structureless pebbly sandstones, and conglomerates. Some units may show normal grading.



Slide courtesy of P. S. Mustard

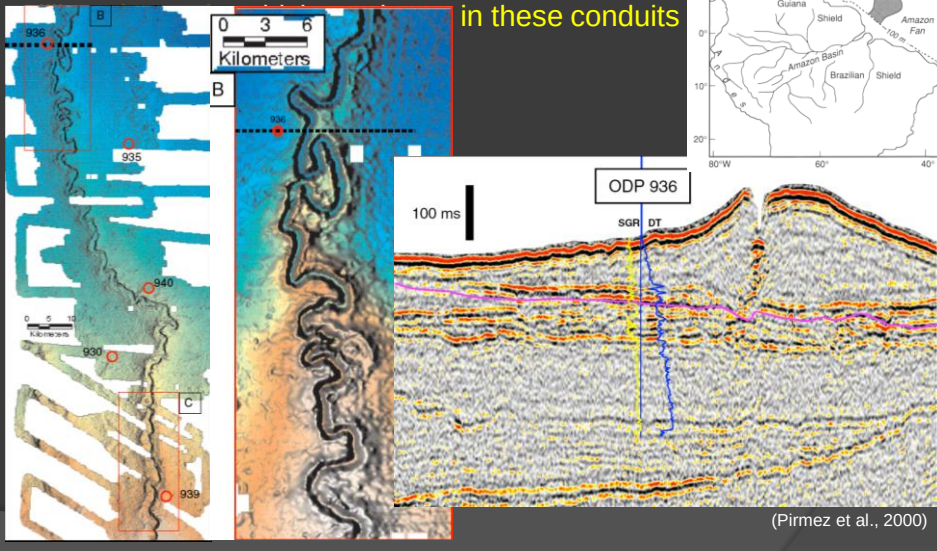
Basin Floor Fans

Coarse, sandy T_{AB} turbidites (high-density turbidites) dominate within upper fan, fan channels, and within the suprafan lobes (frontal splays).

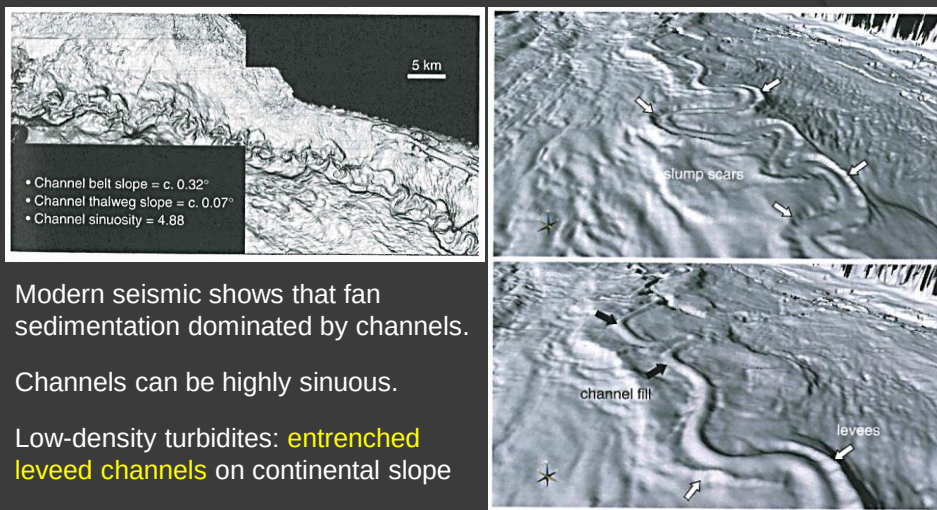


Channel-Levee Complex

Modern seismic shows that fan sedimentation dominated by channels



Channel-Levee Complex



Modern seismic shows that fan sedimentation dominated by channels.

Channels can be highly sinuous.

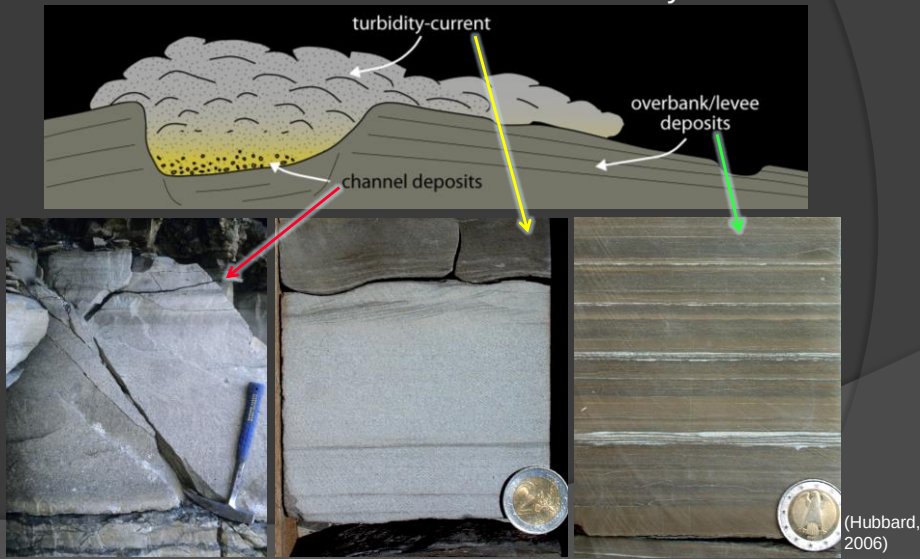
Low-density turbidites: **entrenched leveed channels** on continental slope

High-density turbidites: **aggradational leveed channels** on continental slope

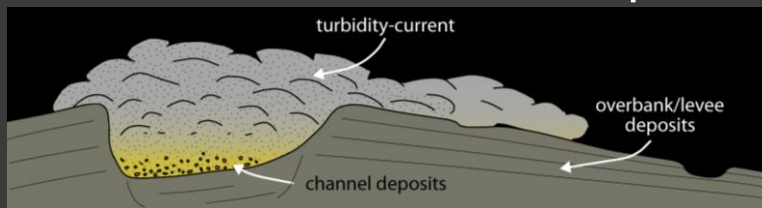
Catuneanu, 2006

Channel-Levee Complex

Channel processes and facies - “**CONSTRUCTIONAL**”:
Coarsest sediment restricted to channel fairway



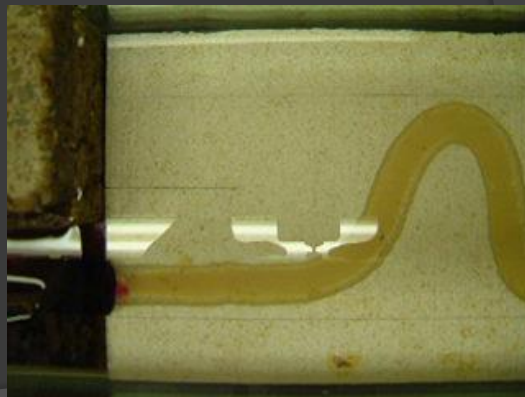
Channel-Levee Complex



Channel processes and facies:

Coarsest sediment restricted to channel fairway

Sedimentation in overbank area mostly from fine-grained, dilute tops of turbidity currents: **FLOW-STRIPPING**

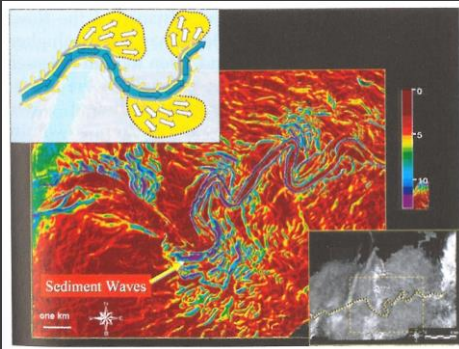


Channel-Levee Complex

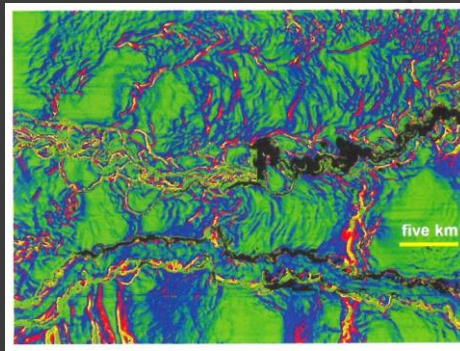
Channel processes and facies:

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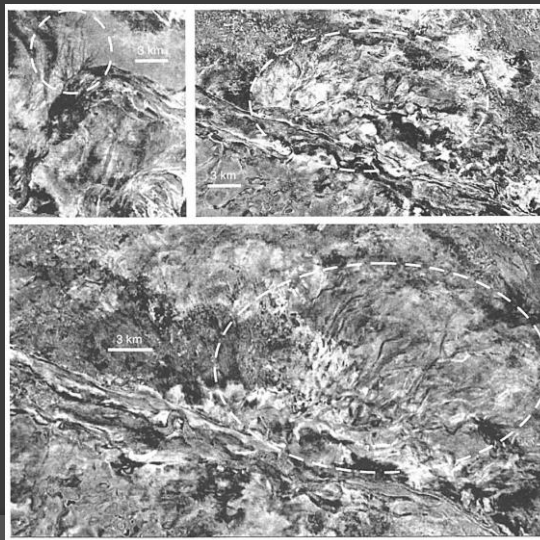
Sediment waves on levee. Produced by flow stripping (offshore Indonesia). Catuneanu, 2006



Sediment waves on levee. Produced by flow stripping (offshore Nigeria). Catuneanu, 2006

Channel-Levee Complex

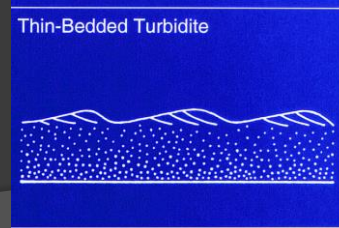
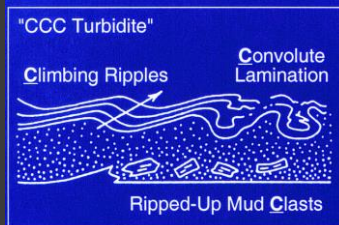
Sedimentation in overbank area mostly from fine-grained, dilute tops of turbidity currents: **OVERBANK SPLAYS**



Crevasse splays from a leveed channel (Catuneanu, 2006)

Channel-Levee Complex

Levees along the margins of channels are made up of thin-bedded co-called “CCC” turbidites (typically contain Climbing ripples, Convolute bedding and/or Clasts of ripped-up mud) near the margin of the channel (T_{BCE} and T_{CDE}) and thin bedded turbidites further out (T_{DE}).



Apparently, this is outdated nomenclature

Channel-Levee Complex

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Apparently, “CCC turbidite” is outdated nomenclature!



(Hubbard, 2006)

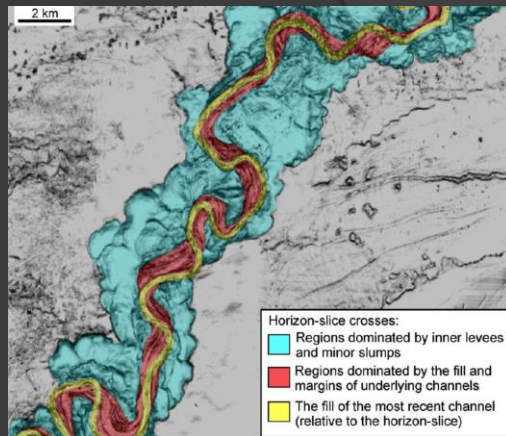
Channel-Levee Complex

Channel migration described as “**SWING AND SWEEP**”

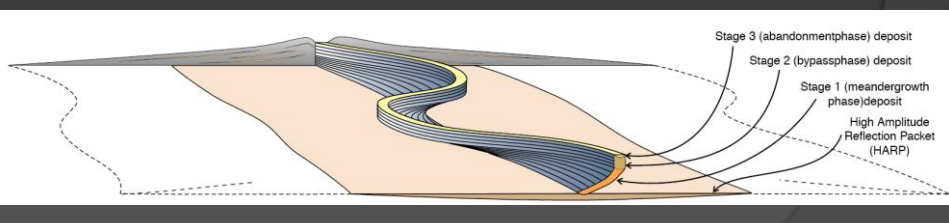
Overbank flow builds up confining levees

Sporadically active

(Peakall et al., 2000)



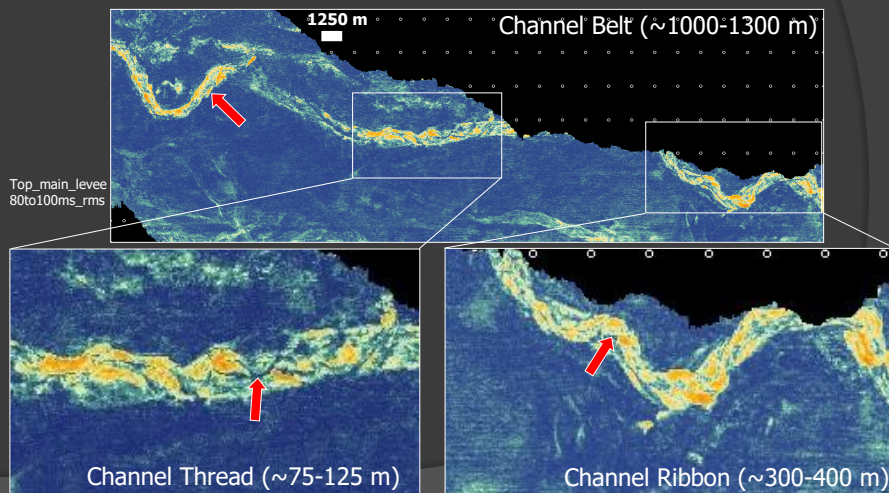
Holocene channel evolution off West Africa (Deptuk et al., 2003)



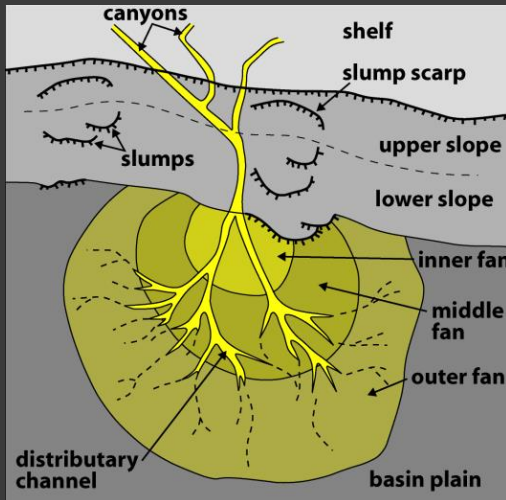
Channel-Levee Complex

Channel migration described as “SWING AND SWEEP”

Internal morphology: braiding, point-bars, etc.



Basin Floor Fans



(Mutti & Ricci-Lucchi, 1972)

Sand deposited in channels and overbank at distal end of fan

Amazon Fan: sand is 100s of km offshore!

Progradational model is not entirely accurate



By the time you reach the end of the channel, all the mud is gone due to flow-stripping

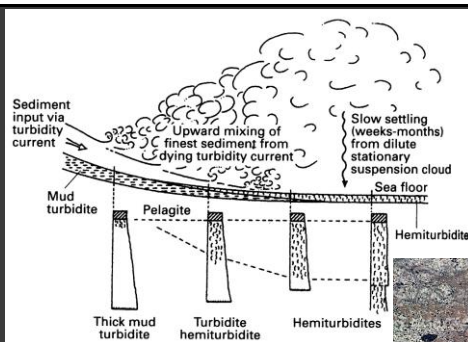
Basin Floor Fans

Thin-bedded T_{CDE} turbidites are characteristic of the interchannel sheet-like deposits between lobes, and dominate towards the outer or Lower Fan.



Basin Floor Fans

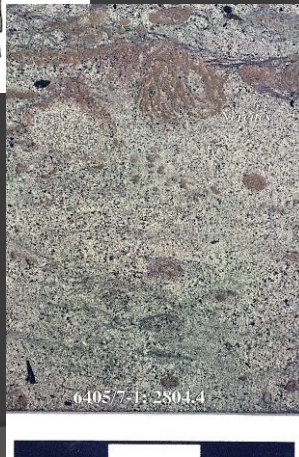
Thin-bedded T_{CDE} turbidites are characteristic of the **interchannel sheet-like deposits between lobes**, and dominate towards the outer or **Lower Fan**.



Stow and Wetzel, 1990

The **basin plain** is built up by **hemipelagic and pelagic muds** and oozes.

Ambient Basin Plain



Ambient Basin Plain - Ichnology

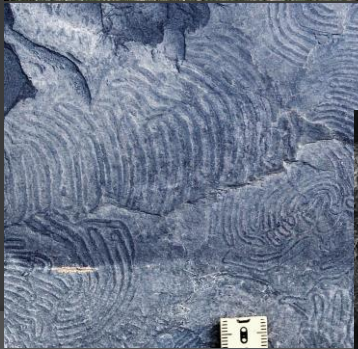


Nereites Ichnofacies

Traces include *Chondrites* (Ch), *Cosmorhaphe* (Cr), *Fustiglyphus* (Fg), *Helminthoida* (He), *Nereites* (Ne), *Paleodictyon* (Pd), *Scolicia* (Sc), *Spirophycus* (Sh), *Spirophyton* (Sp), *Spirorhaphe* (Sr), *Thalassinoides* (Th), and *Zoophycos* (Z).

Common to very slowly deposited muddy substrates; typically with reduced or limited food resources.

Nereites Ichnofacies



High diversity but low abundance.

Complex horizontal grazing traces and patterned feeding/dwelling structures: highly organized behaviour.

Numerous crawling and/or grazing traces and sinuous fecal castings (*Helminthoida*).

Structures associated with trapping and farming microbes within permanent open domiciles (*Paleodictyon*).

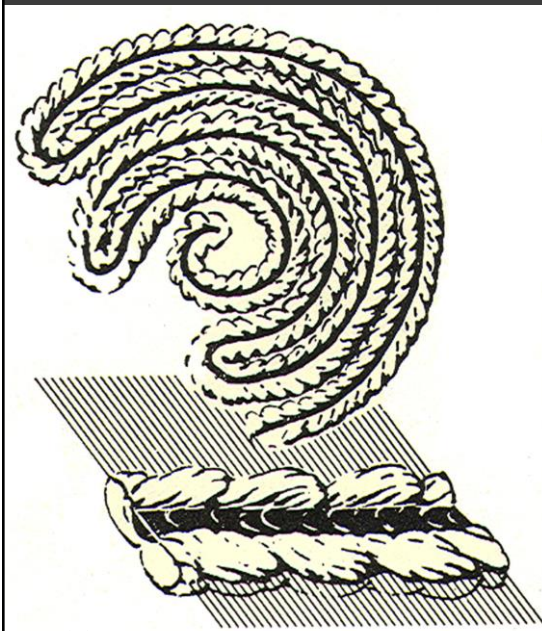
Oceanic (Deep-Water) Environment

Nereites Ichnofacies:

- *Nereites* Ichnofacies is the classical deep-sea (abyssal floor or deep oceanic) ichnofacies.
- Dominant traces are surface grazing (**graphoplyptids**) and deep penetrating deposit-feeding structures.
- These create common “patterned” sea floors.



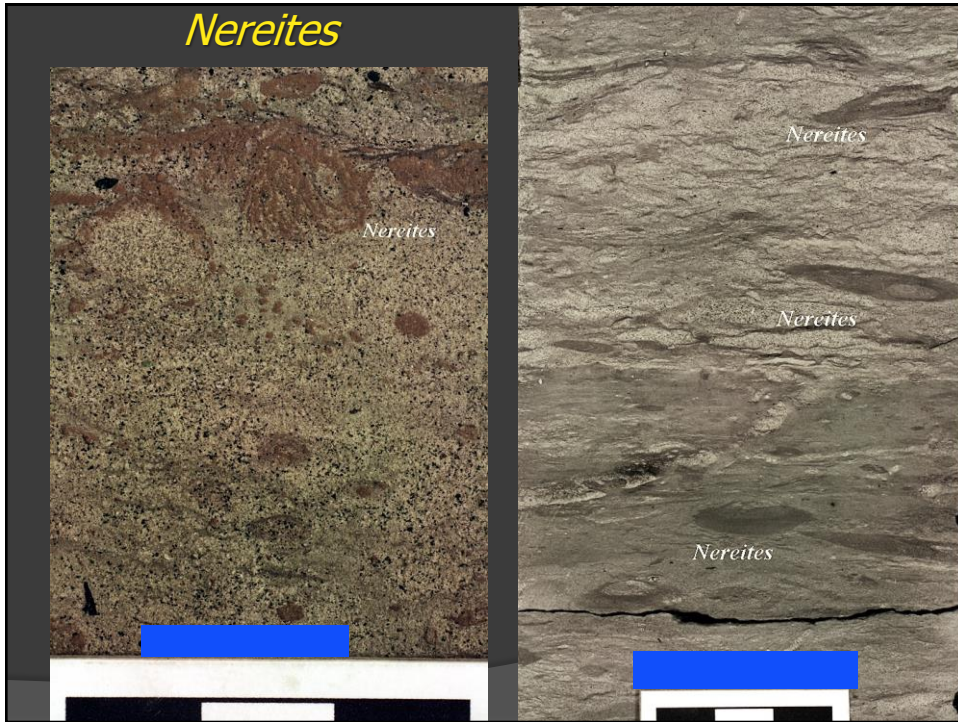
Nereites



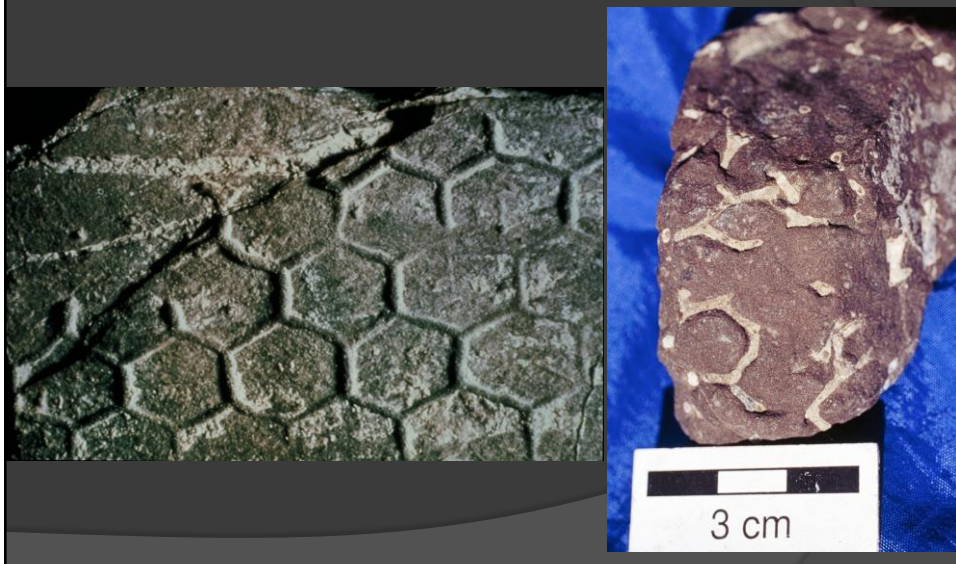
Häntzschel, 1975



Nereites



Paleodictyon





Rona & Seilacher, 2009



Paleodictyon:

Honeycomb-like network of ridges in hyporelief, comprising hexagonal polygons. Reticulate pattern varies in size, but mesh diameters constant within individual nets. Nets range from less than 1mm to 50mm. Mesh walls generally 0.5mm to 2mm

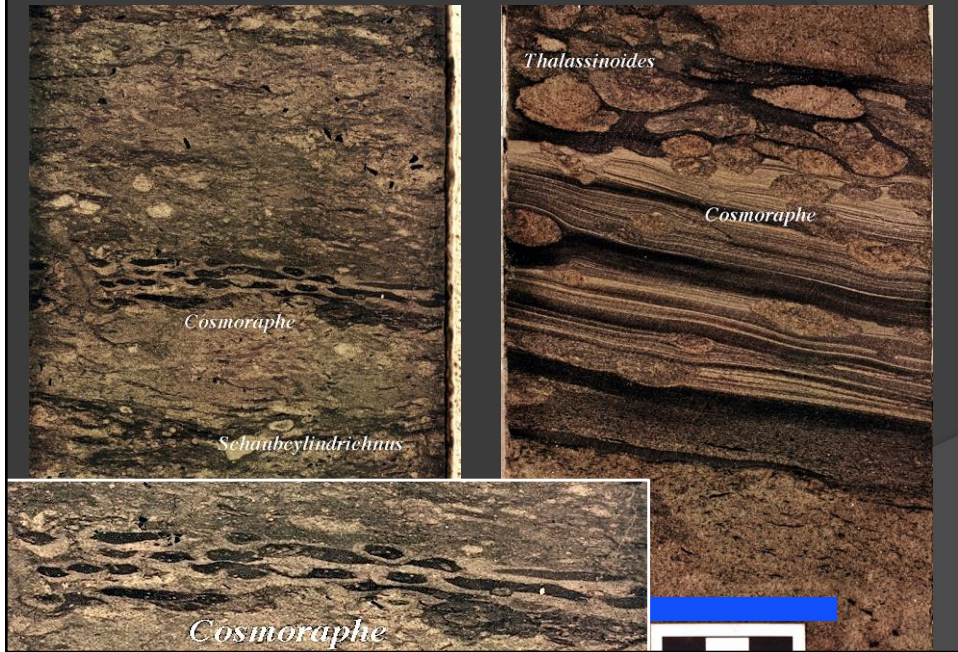
Nereites Ichnofacies:

Oceanic (Deep-Water) Environment

Cosmorhaphe



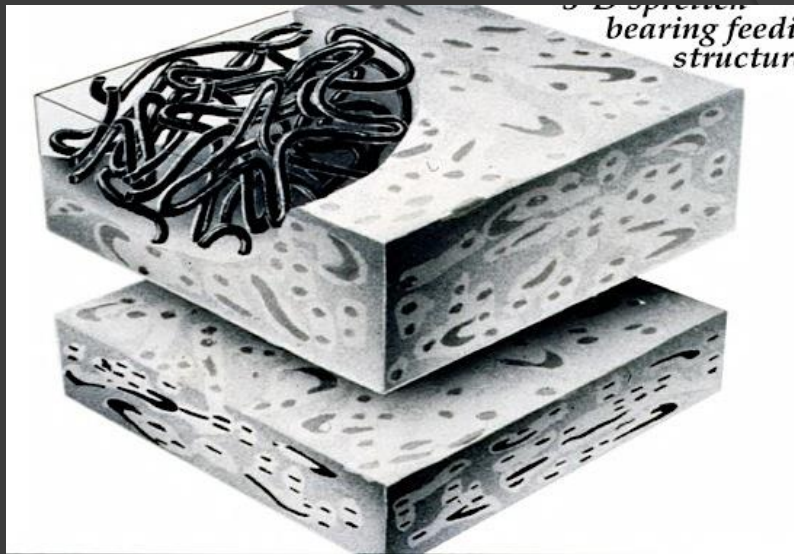
Cosmorhaphe



Spirorhaphe

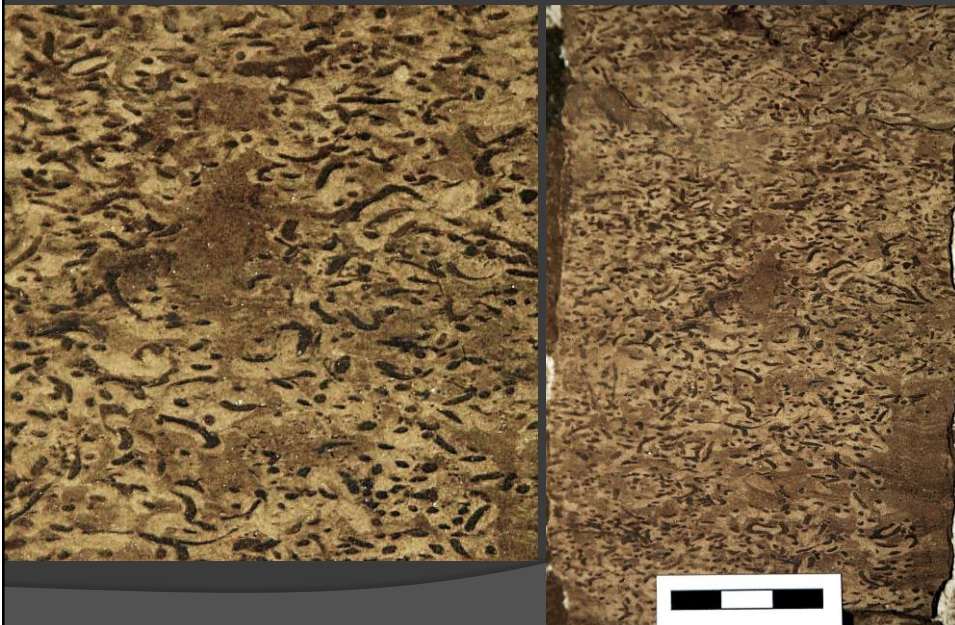


Phycosiphon

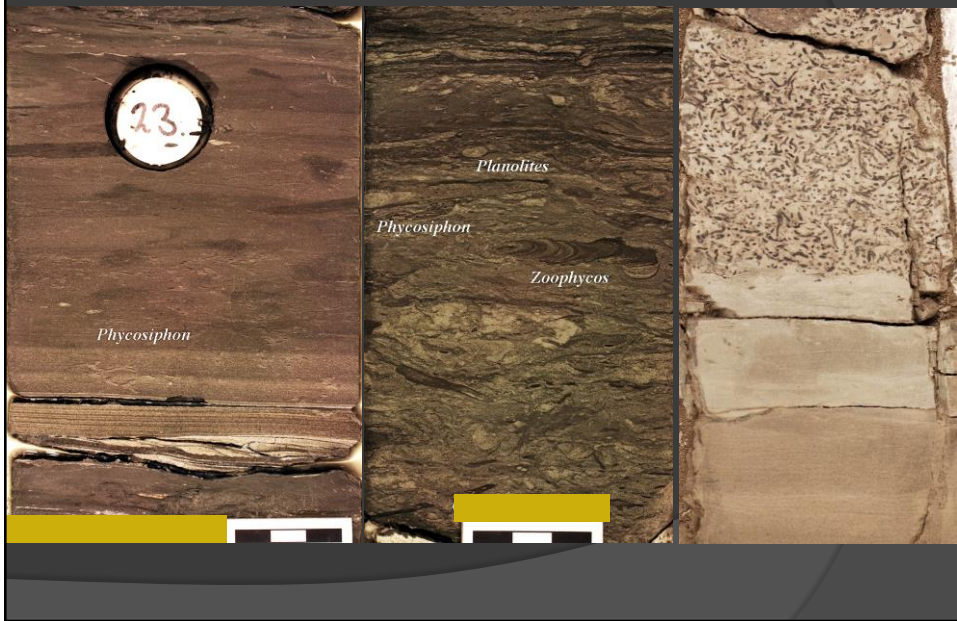


A variation on the *Zoophycos* behaviour pattern

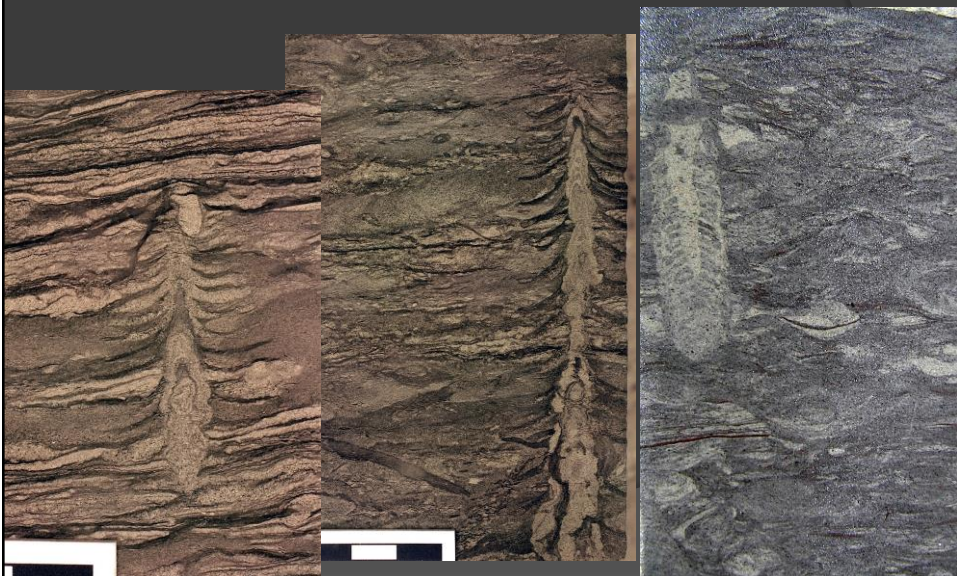
Phycosiphon

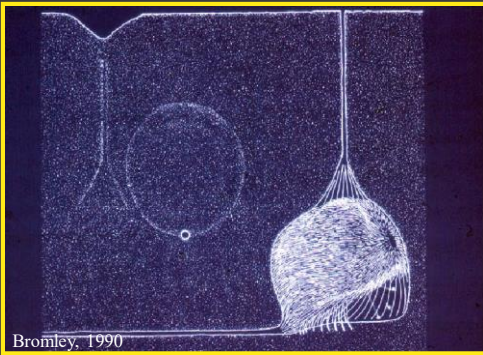


Phycosiphon



Spirophyton





Possible Tracemaker: Heart Urchin

Scolicia

Locomotion/mobile feeding
trace of the fully marine, deep-
water echinoid, the heart urchin



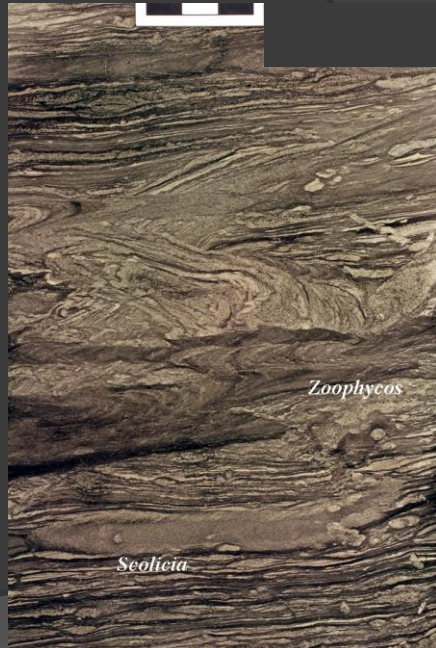
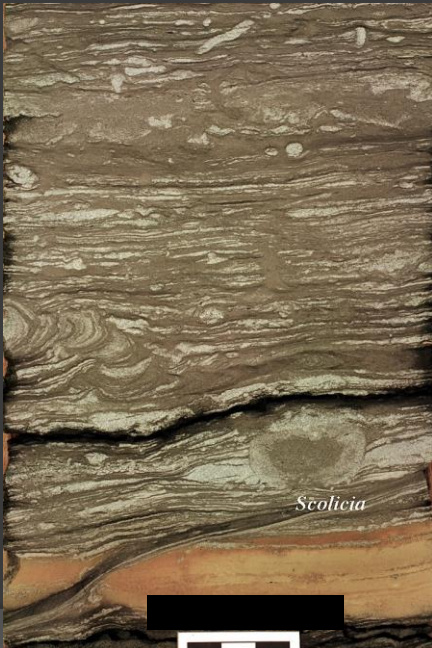
Modern Deep-Sea *Scolicia*-type Echinoid Trails



Scolicia



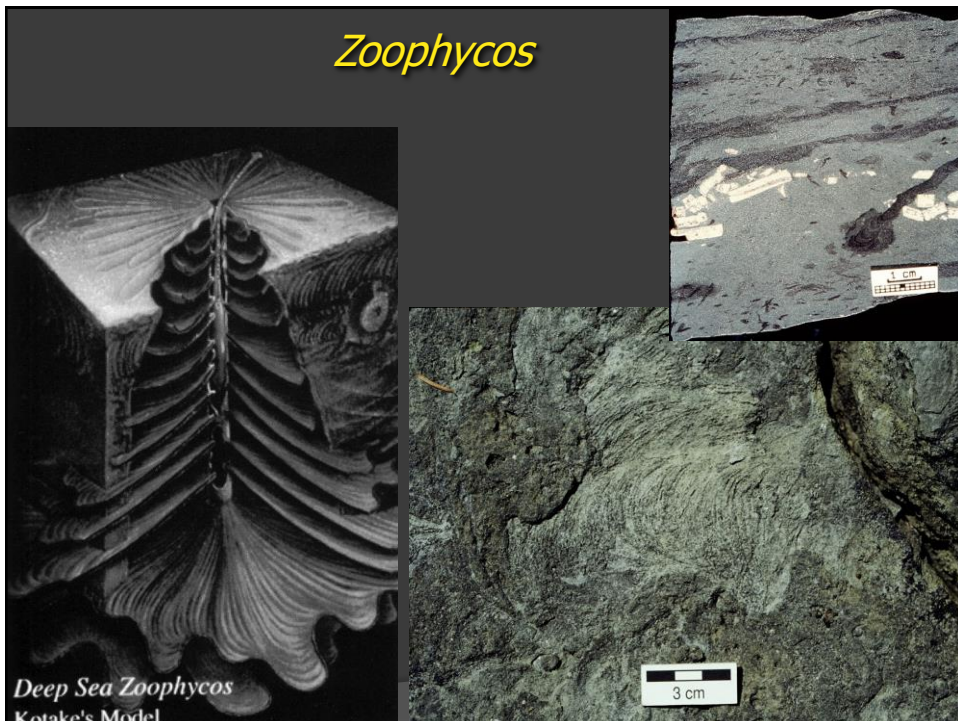
Scolicia



Scolicia



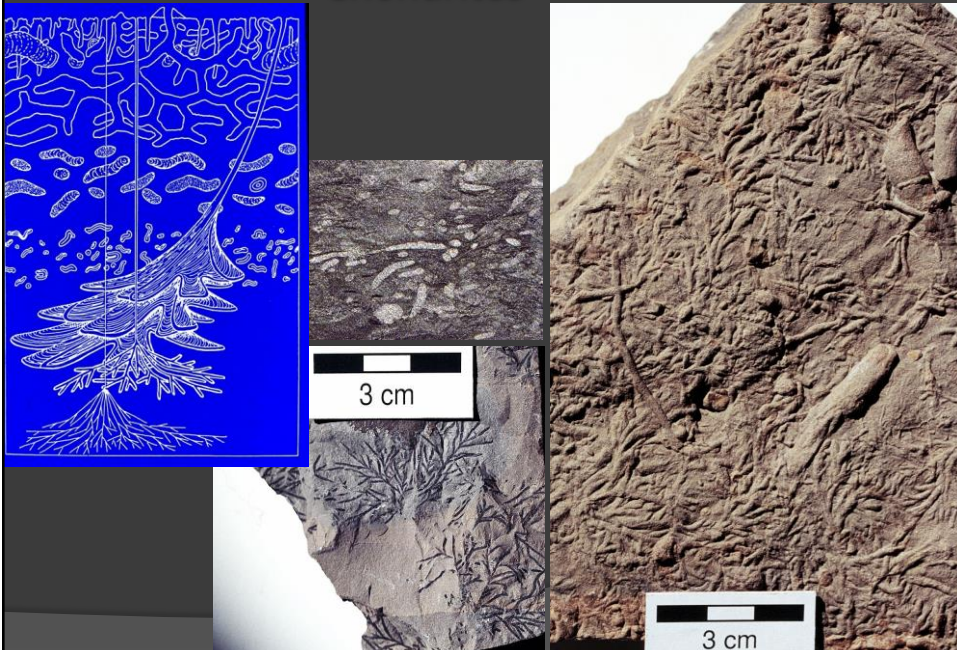
Zoophycos



Zoophycos



Chondrites



Ophiomorpha rudis



Turbidites locally contain post-event colonization, typically dominated by *Ophiomorpha*.

Sandstone-dominated intervals generally display low diversity suites of *Ophiomorpha* and fugichnia.

