Re-evaluating Depositional Models for Shelf Shales: Examples from the Cretaceous Seaway of North America*

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Abstract

Despite the assumption that the bulk of marine "shelf" mud is deposited by gradual fallout from suspension in quiet water, modern muddy shelves and their associated rivers show that they are dominated by hyperpycnal fluid mud. This has not been widely applied to the interpretation of ancient sedimentary shale successions. We analyze several ancient Cretaceous prodelta shelf systems and their associated river deposits. Paleodischarge estimates of trunk rivers show that they fall within the predicted limits of rivers that are capable of generating hyperpycnal plumes. The associated prodeltaic mudstones match modern hyperpycnite facies models, suggesting a correspondingly hyperpycnal character. Physical sedimentary structures include diffusely stratified beds that show both normal and inverse grading, indicating sustained flows that waxed and waned. They also display low intensities of bioturbation, which reflect the high physical and chemical stresses of hyperpycnal environments. Hyperpycnal conditions are ameliorated by the fact that these rivers were relatively small, dirty systems that drained an active orogenic belt during humid temperate to subtropical "greenhouse" conditions. During sustained periods of flooding, such as during monsoons, the initial river flood may lower salinities within the inshore area, effectively "prepping" the area and allowing subsequent floods to become hyperpycnal much more easily. Although shelf slopes were too low to allow long-run-out hyperpycnal flows, the storm-dominated nature of the seaway likely allowed fluid mud to be transported for significant distances across and along the paleo-shelf. Prodelta hyperpycnites form leaner, gas-prone source rocks, prone to the generation of overpressure, versus more slowly deposited, organic-rich, anoxic laminites and condensed-section shales.

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Re-evaluating depositional models for shelf shales:

Examples from the Cretaceous Seaway of North America

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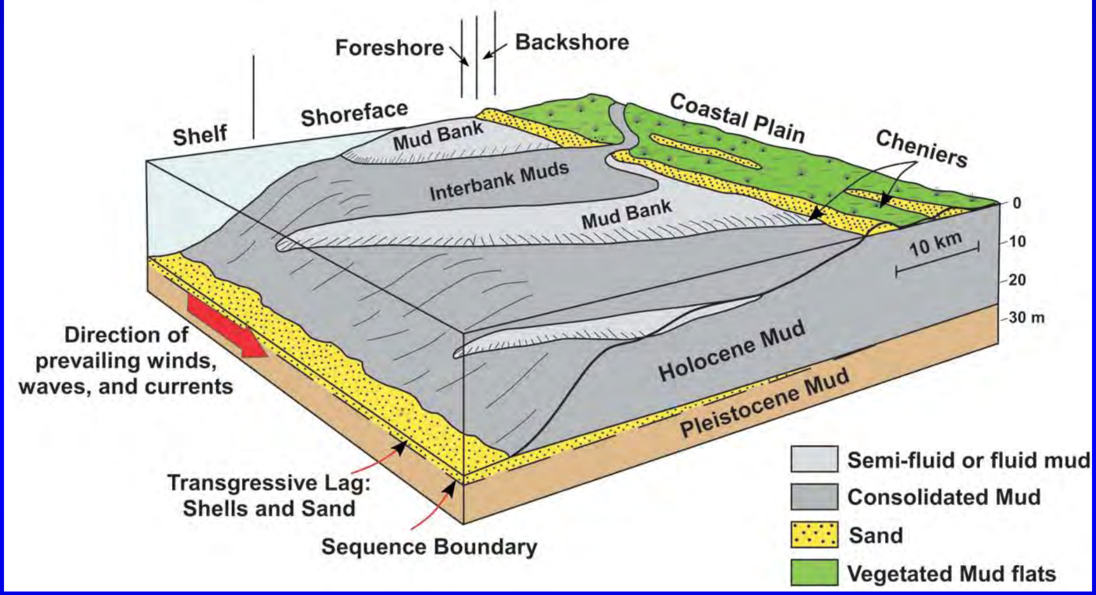
Key Problems

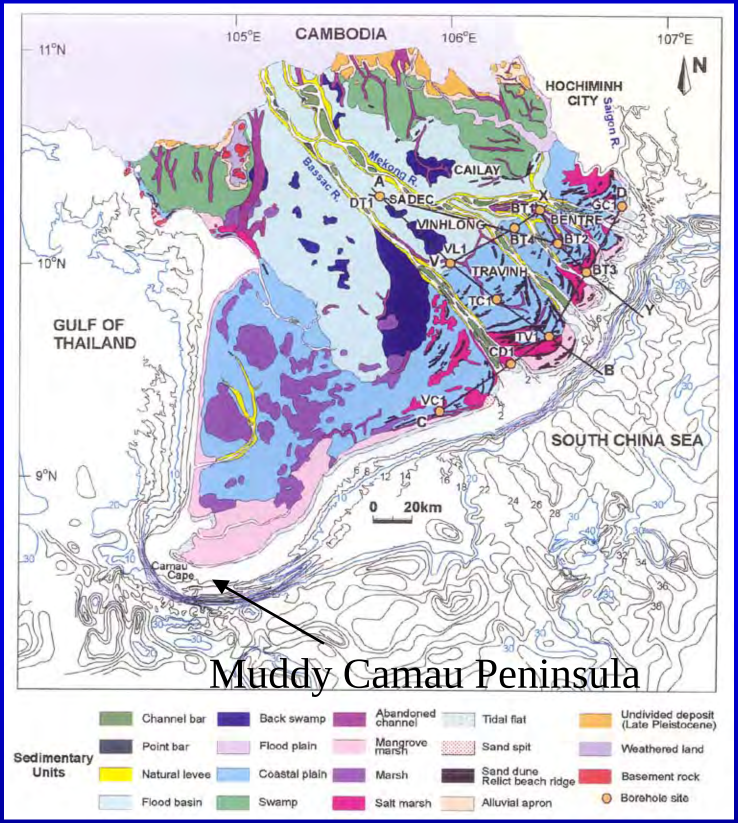
- **The textbooks tell us:**
  - The prodelta is the area where fine material *settles quietly out of suspension* (Bhattacharya and Walker, 1992).
  - The finest-grained deposits of the delta front occur in the deeper water (prodelta) area where deposition is *mainly from suspension* (Nichols, 1999).
  - Shales form under any environmental condition in which sediment is abundant and water *energy is sufficiently low to allow settling of suspended fine silt and clay* (Boggs, 2001).
  - Relatively *weak transporting currents* deposit mudrocks. Sedimentary structures in mudrocks are difficult to see and are of limited use in interpretation (Prothero and Schwab, 2004).

But, many modern wave-dominated coastlines are muddy



Suriname Coast Chenier

(from Suter, 2006 after Rine and Ginsburg, 1985)



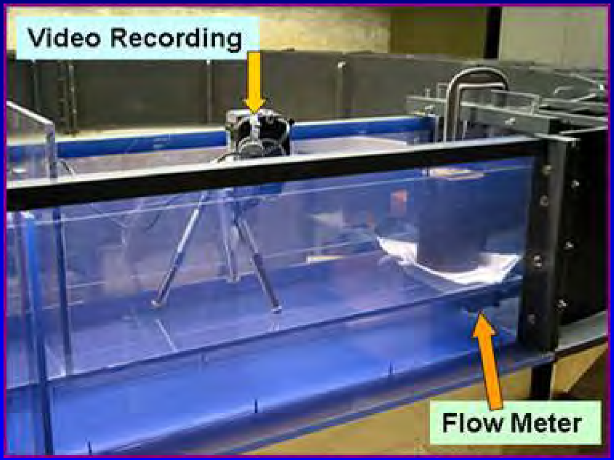
Mekong Delta

(Ta et al., 2005)

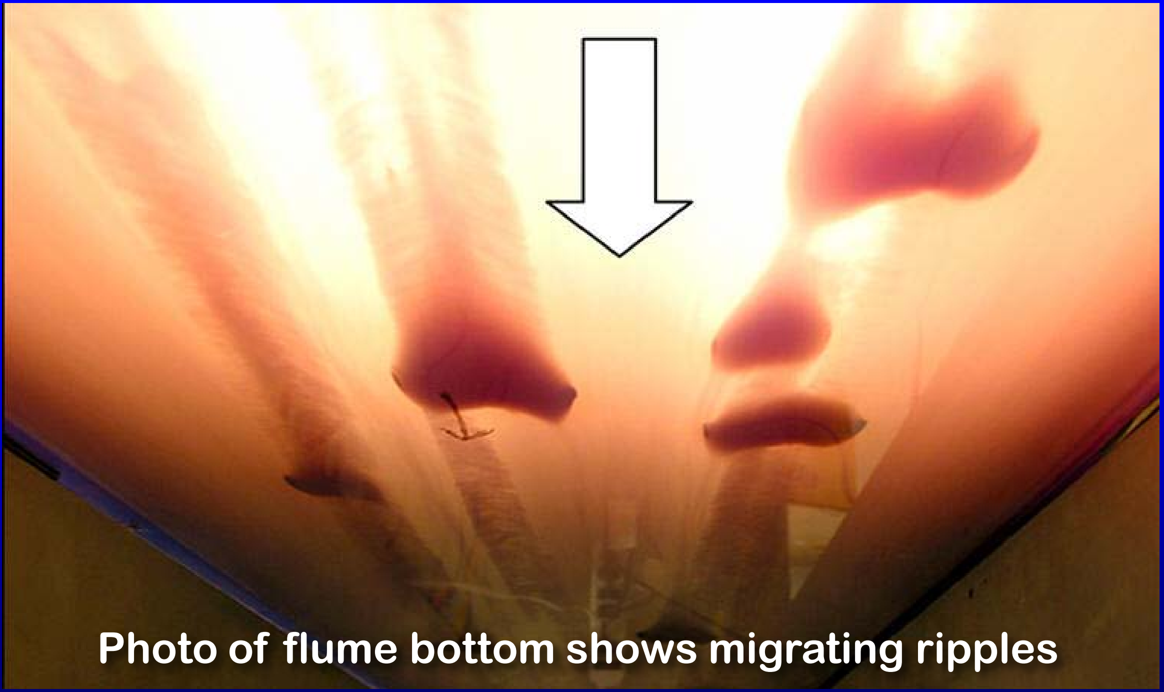
and, many modern fluvial-dominated coastlines are muddy

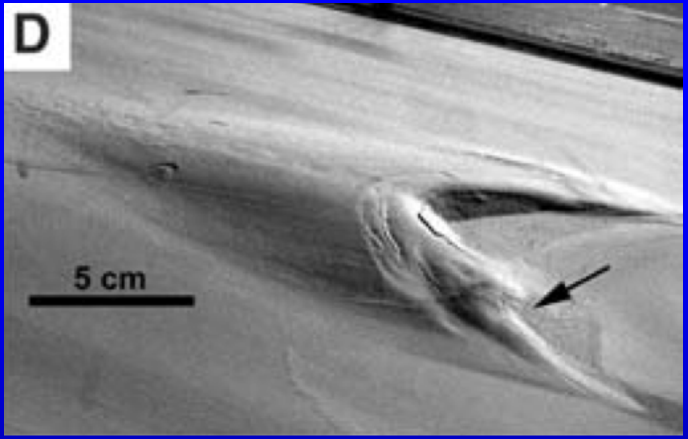
Mississippi and Atchafalaya Coastline (Suter 2006)

Mud can move as bedload!



World's first circulating mud flume, built by J. Schieber, shows that clays invariably flocculate and migrate as bedload ripples at velocities of about 20 cm/s.

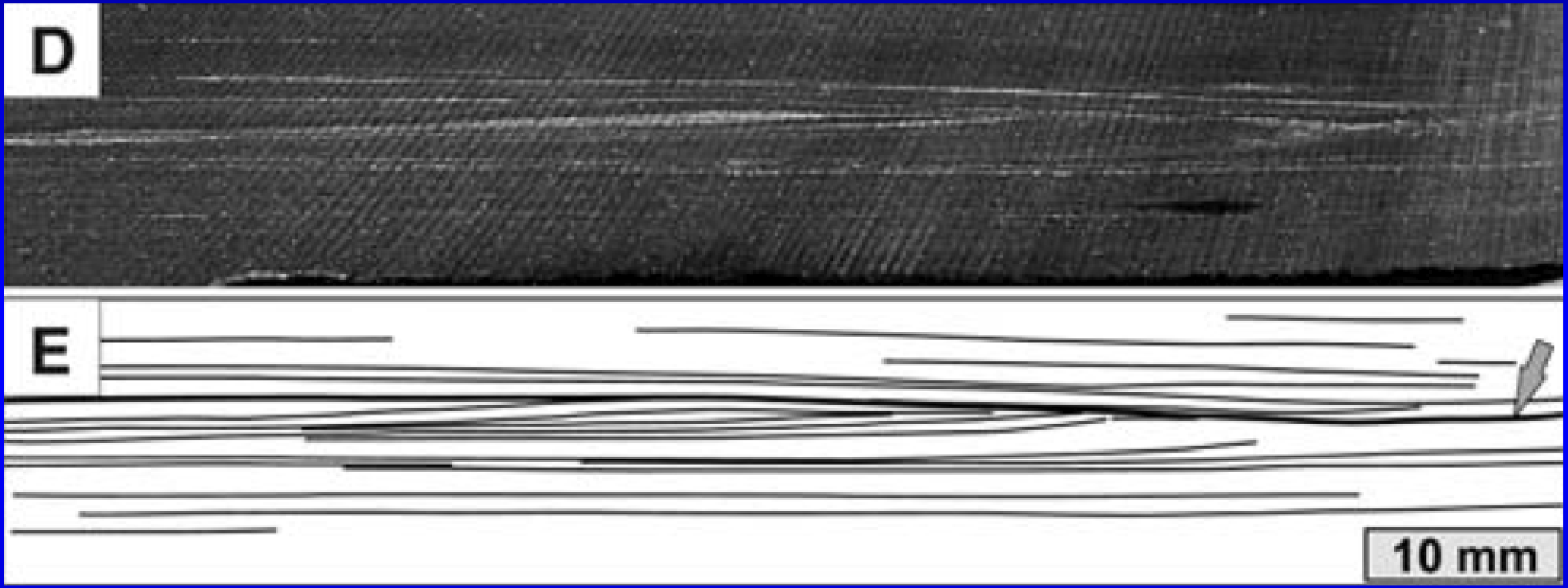




Oblique view of mud ripple (from Schieber et al., 2007, Science)

http://mypage.iu.edu/~jschiebe/Shale-Studies.htm

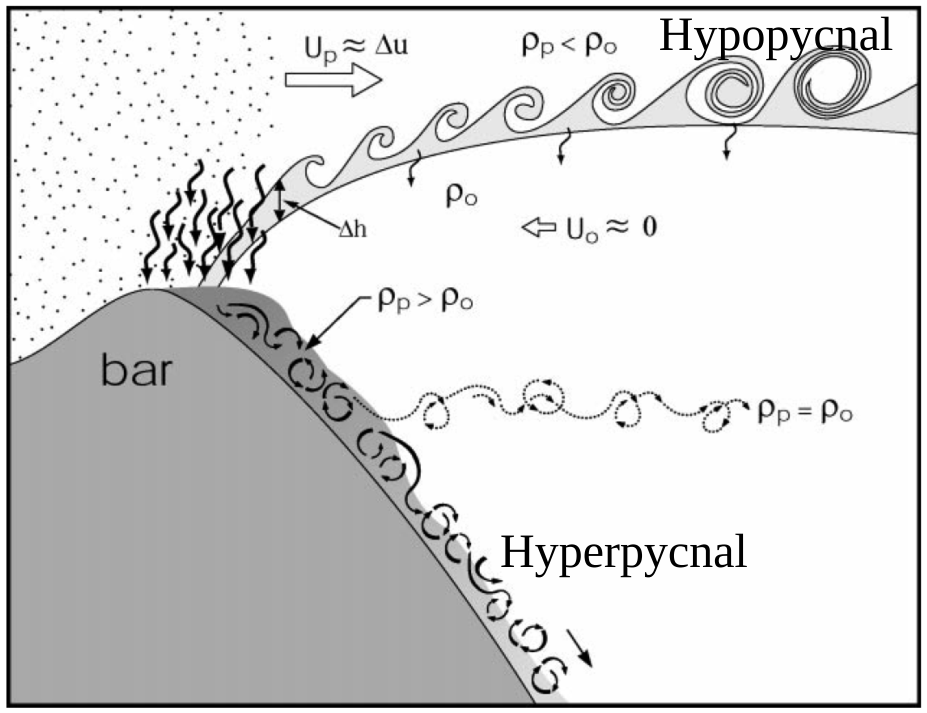
Bedload Mud



Cross-lamination in Devonian Black Albany Shale shows evidence of bedload transport, probably by storms (from Schieber et al., 2007, Science).

Mud delivery to the shelf

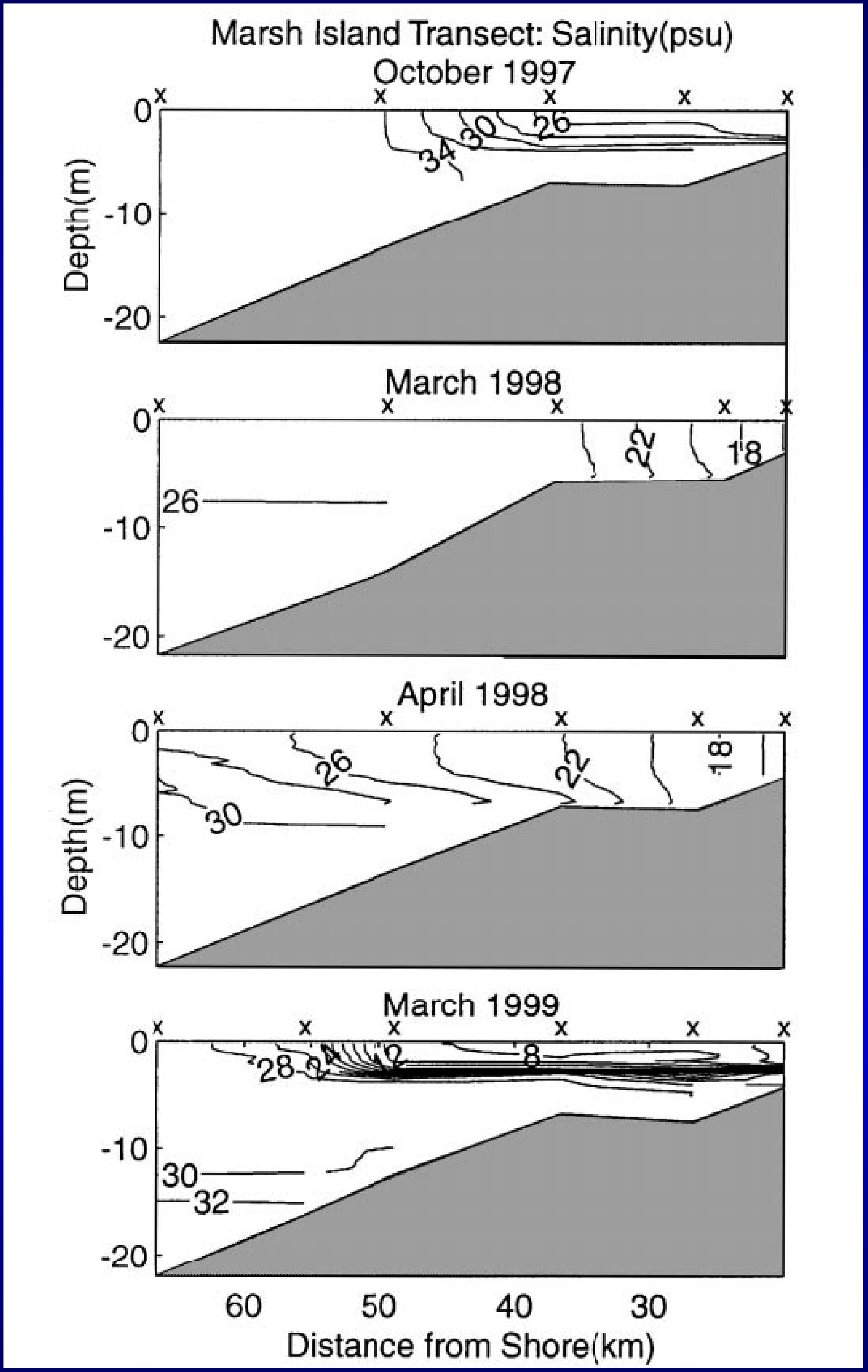
- Newer oceanographic studies emphasize:
  - Importance of rapidly deposited fluid muds
    - (Kineke et al., 1996; 2000)
  - Importance of hyperpycnal mud plumes
    - (Nemec, 1995; Kineke et al., 2000; (Mulder and Syvitsky, 1995; Mulder and Alexander, 2001; Piret-Björklund and Steel, 2004).
  - Importance of storms that aid gravity transport of mud on sea floor and across shelf.
    - (Bentley, 2003; Friedrichs and Scully, 2007)



Kineke et al., 2000

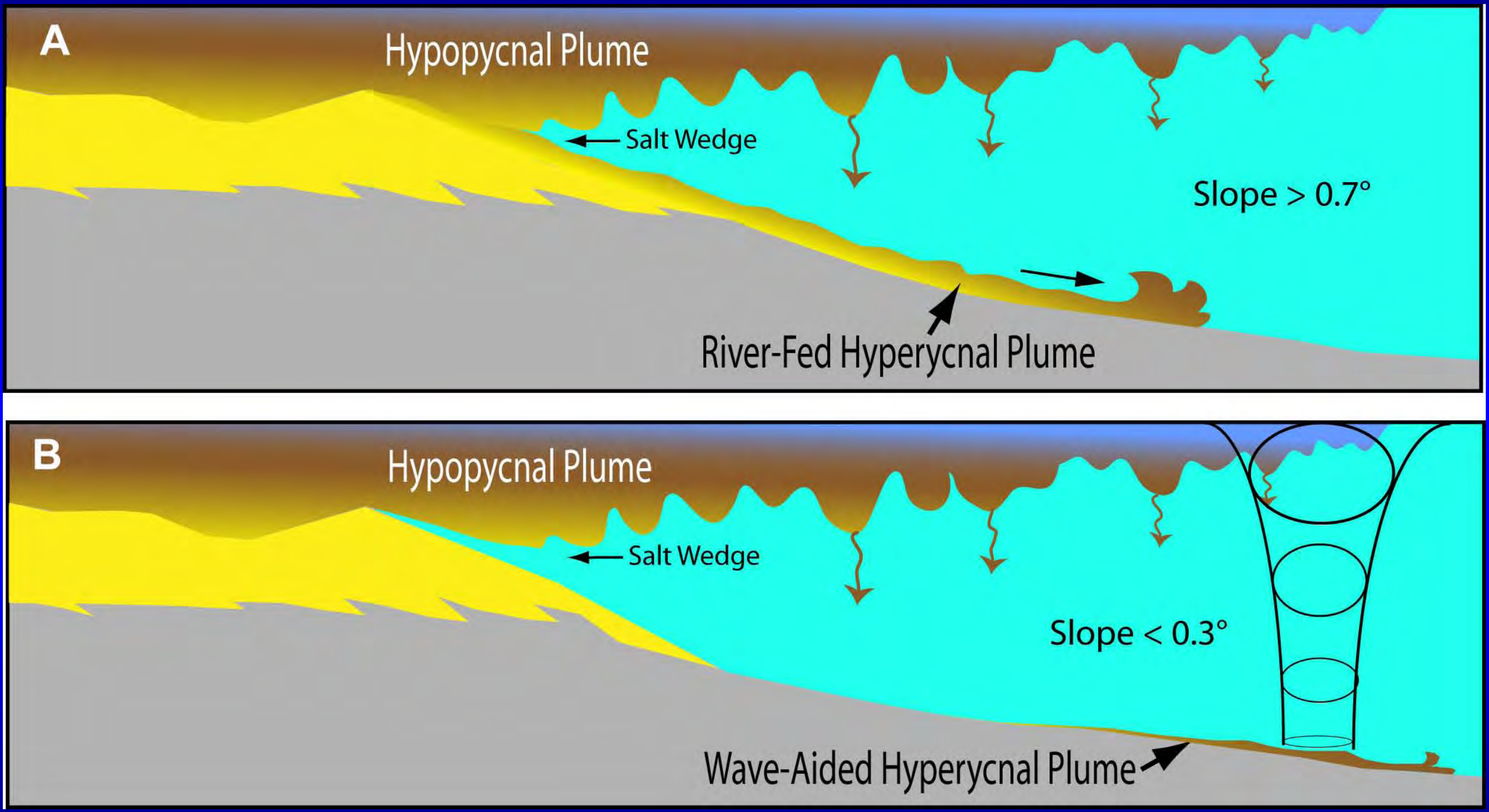
What is needed for hyperpycnal flows

- **During successive floods, salinity is lowered, especially in shallow water settings.**
- **This enhances ability of feeding river to go hyperpycnal.**
  - **Atchafalaya, Orinoco**
- **Bays get prepped!**



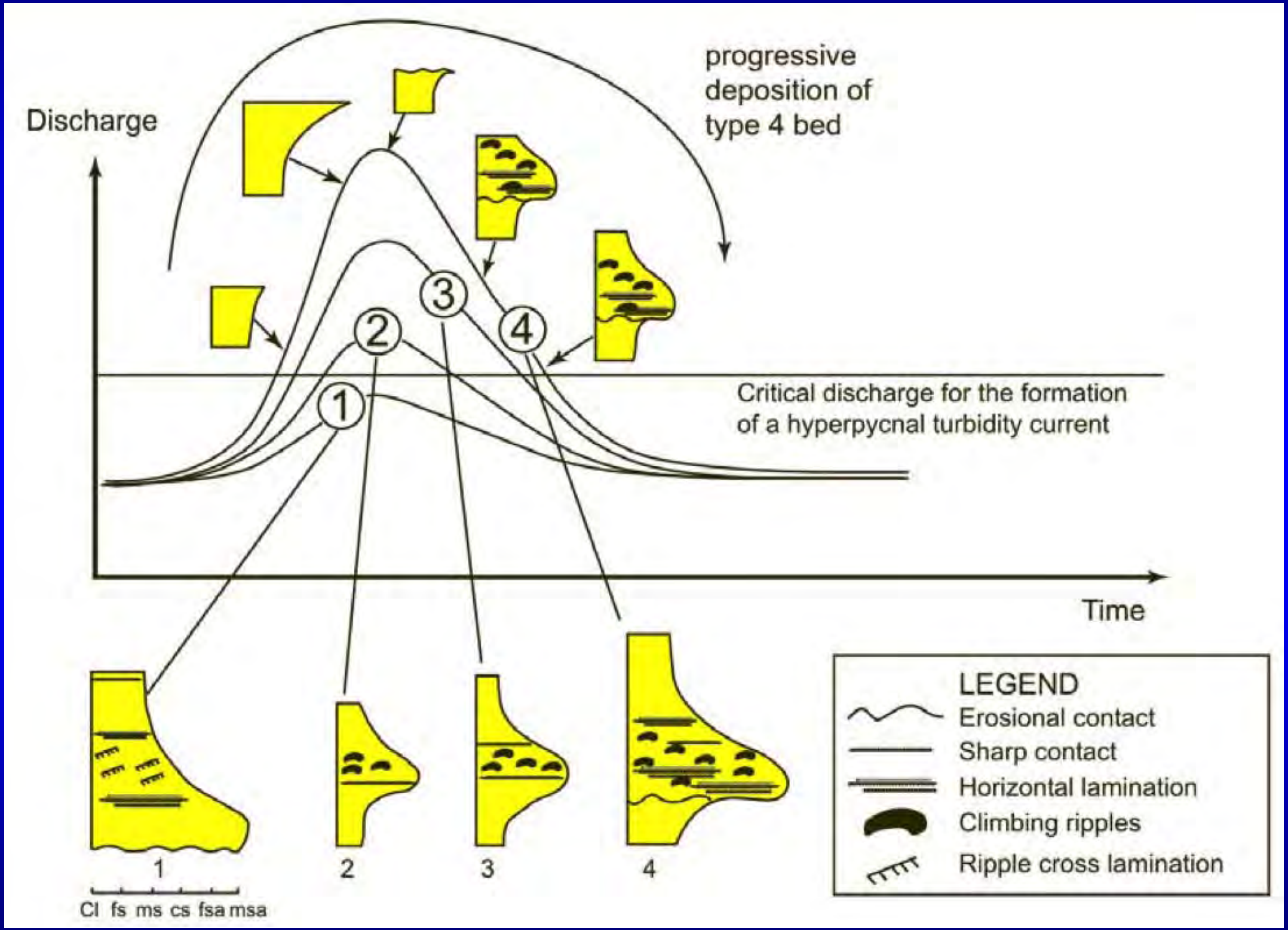
Depressed salinities following river floods in Atchafalaya Bay (from Allison et al., 2000)

Types of Delta Plumes



From Bhattacharya and MacEachern (2009) after Bentley, 2002 and Suter, 2006

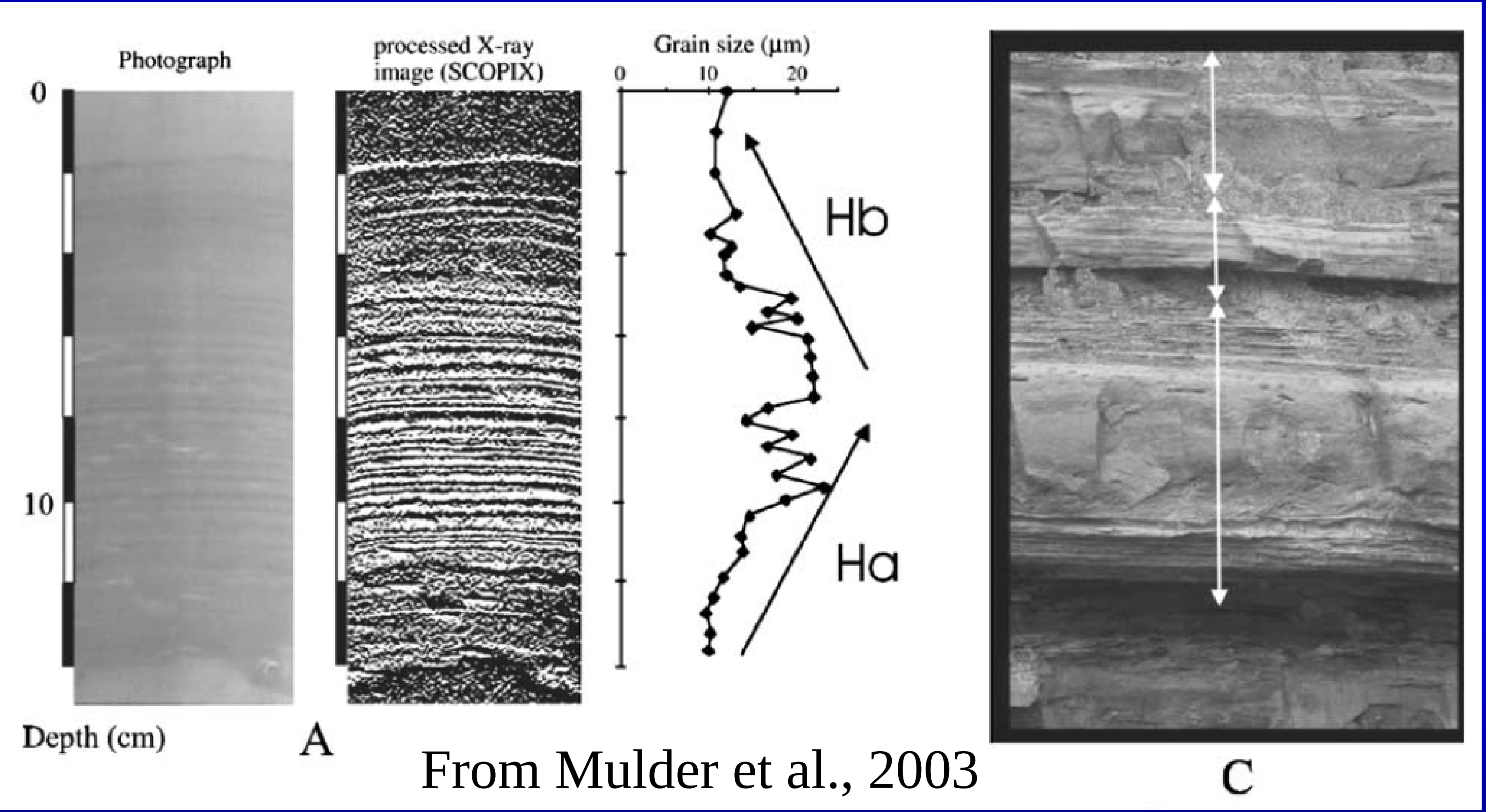
Hyperpycnite Facies Model



From Mulder et al., 2003

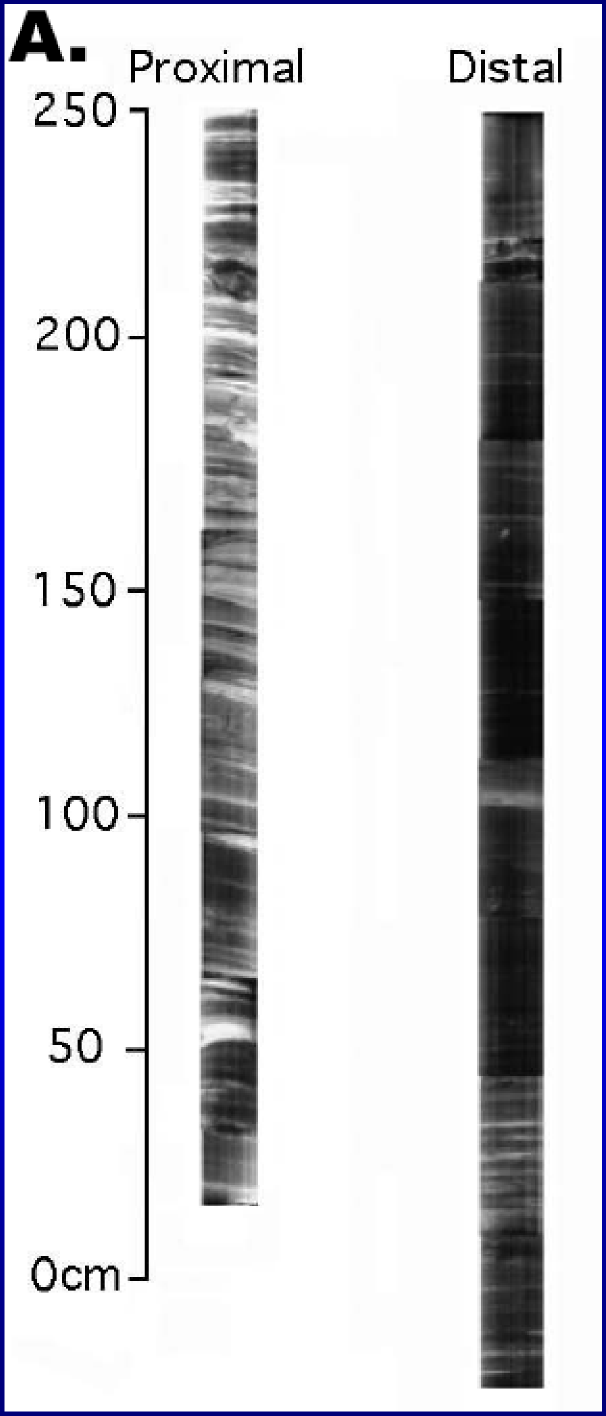
Types of Hyperpycnites

Var Delta **Oligocene example, Italy**



From Mulder et al., 2003

Note superposition of inversely (Ha) and normally (Hb) graded layers.



Modern Prodelta Hyperpycnites: Atchafalaya, GOM

- Heterolithic clays, silts, and very fine sand.
- Deposited at rates of 20cm/year
- Low level of burrowing
- Normal grading
- Some cross lamination

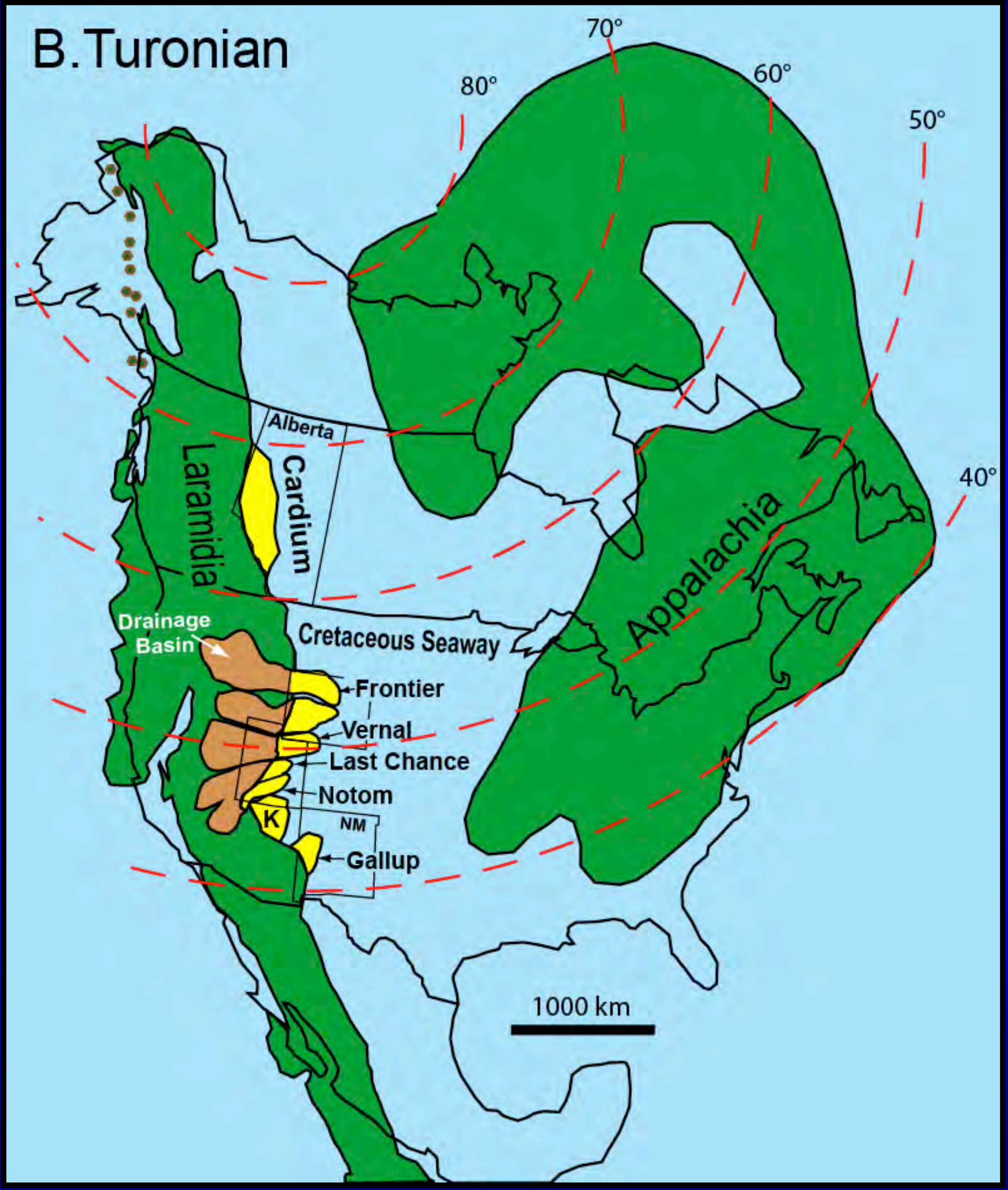
From Bhattacharya and MacEachern after Allison and Neill, 2003

Key Problems

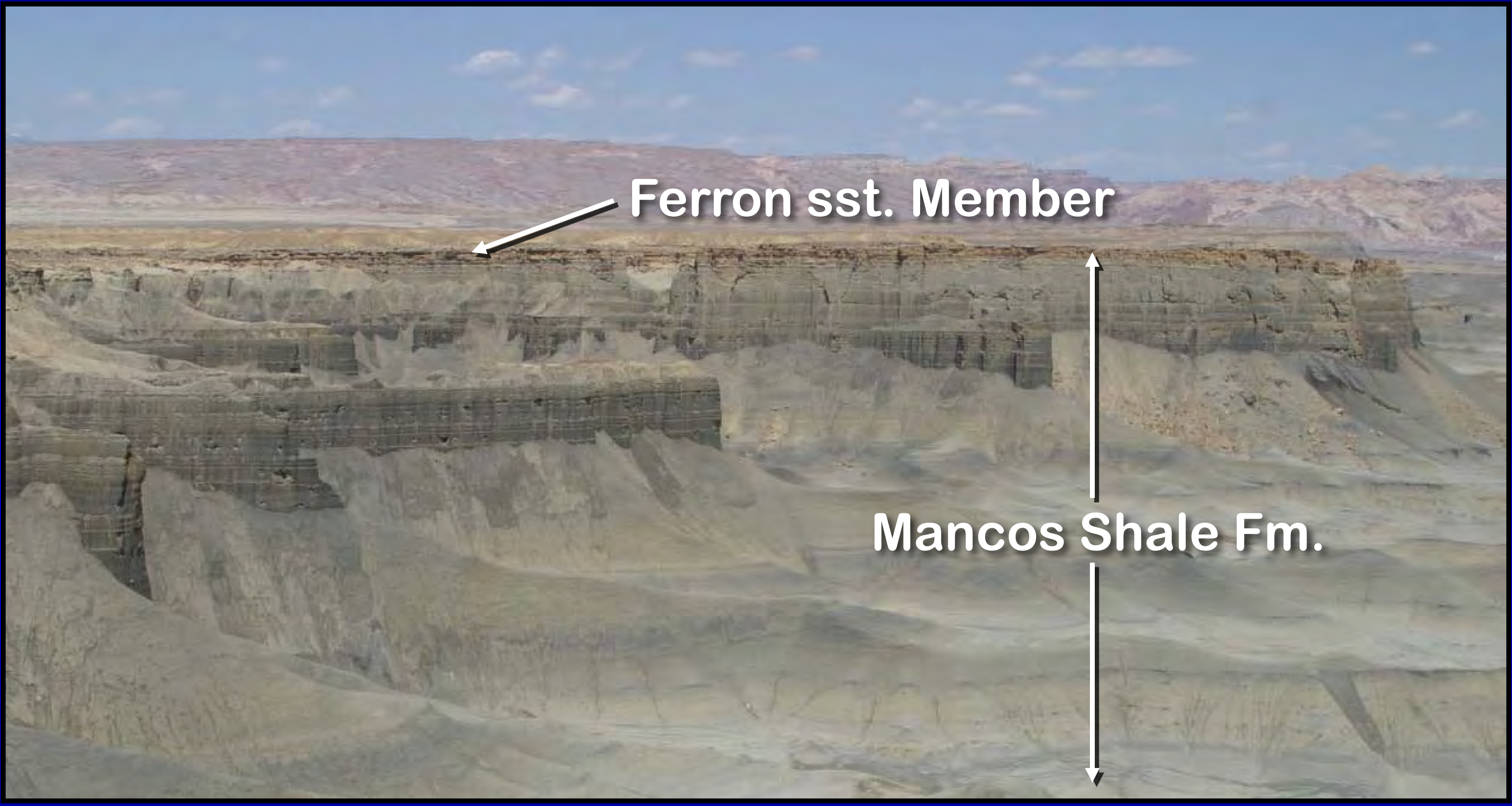
- Are hyperpycnal processes important in building the mudstone stratigraphic record?
- Can modern examples be used to interpret ancient muddy “hyperpycnites”?
  - Facies models
- Is bedload transport more important than suspension settling in forming these mudstones?
- Muddy coastlines and cheniers are common in the Holocene, but there are very few ancient examples.
  - Most “shelf” mudstones are historically interpreted as distal offshore.

The Cretaceous Seaway

- Humid
- Tropical
- Deltas form adjacent to an active mountain belt.
- 'Lotsa' data (outcrop, core, well log)



Cretaceous mudstones in Utah



- Note thick prodelta Mancos shales below Ferron shoreline sandstones.
- Where on earth does all this mud come from?

Ferron prodelta facies

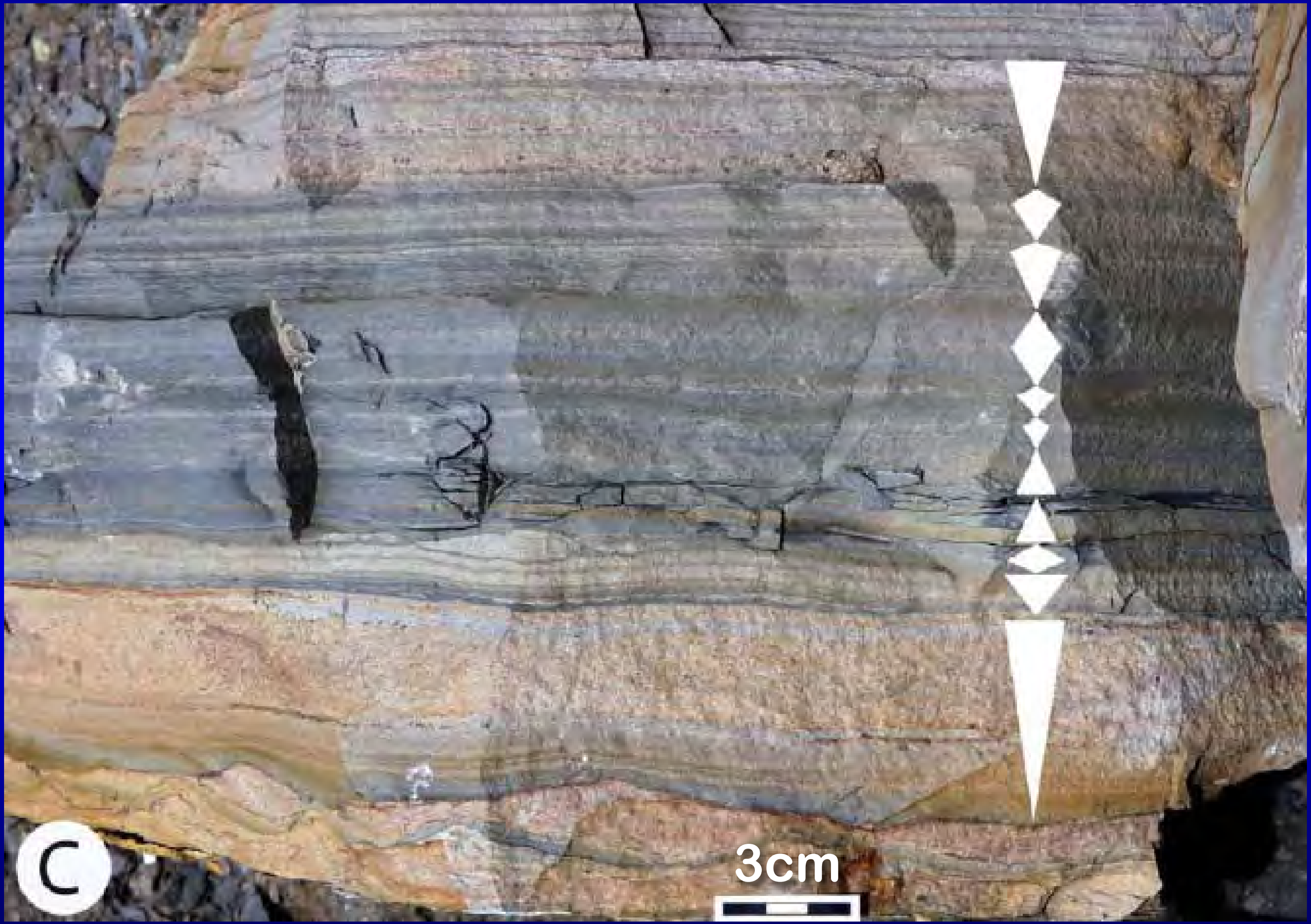
Note graded siltstone beds that lack burrowing

Close-up of Ferron prodelta facies

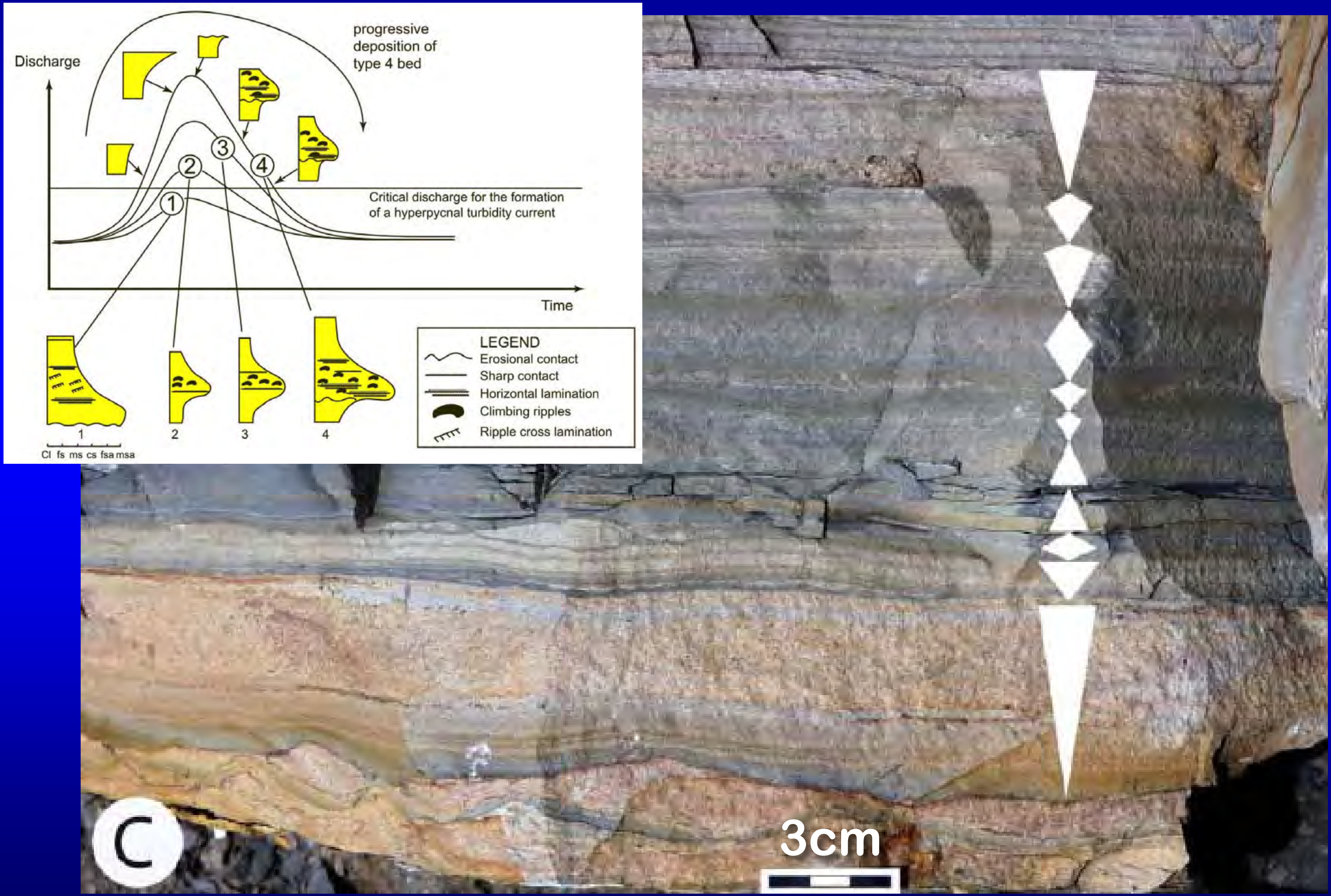
- Normal and inverse grading suggest a fluid-mud, hyperpycnal origin.
- Thinner beds show cross lamination, suggesting some bedload transport

Close-up of Ferron prodelta facies

Normal and inverse grading suggests hyperpycnal flows



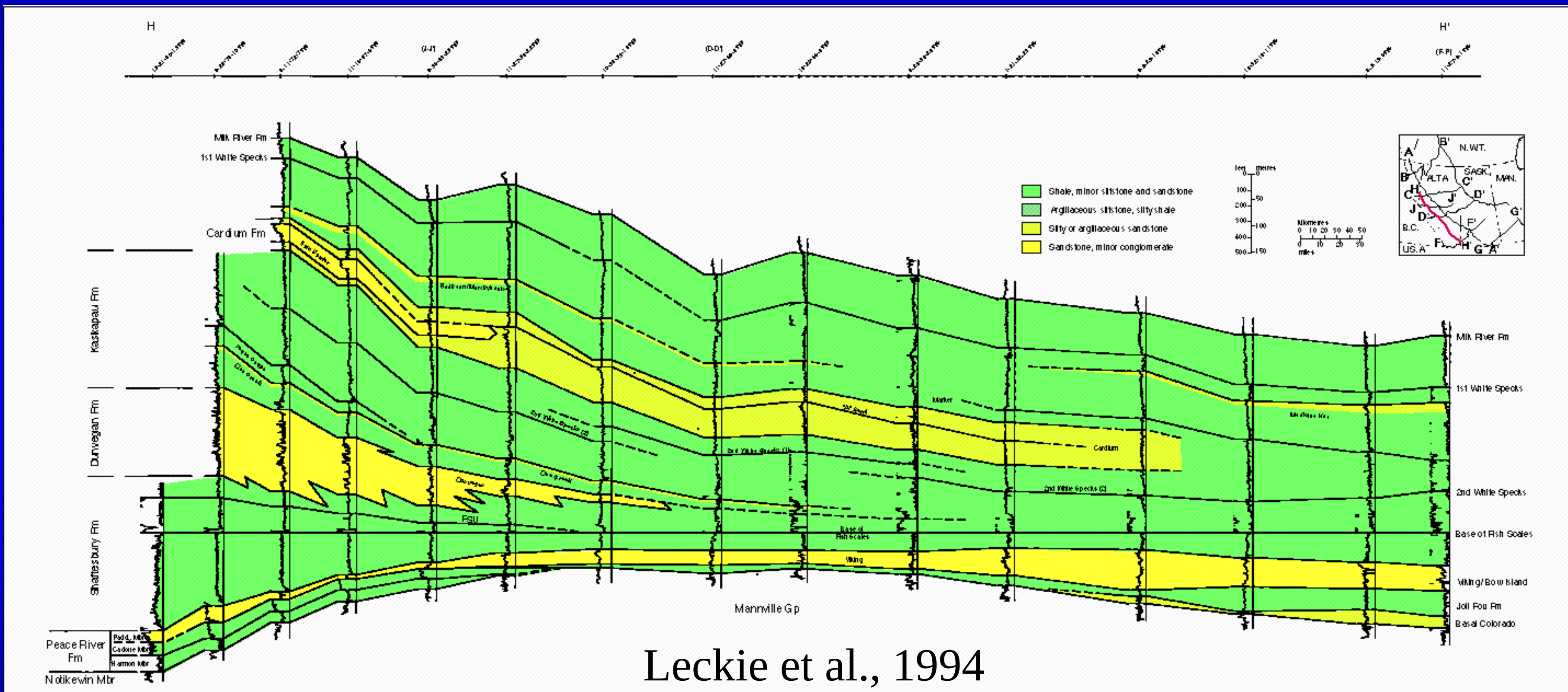
Normal and inverse grading suggests hyperpycnal flows



Dunvegan

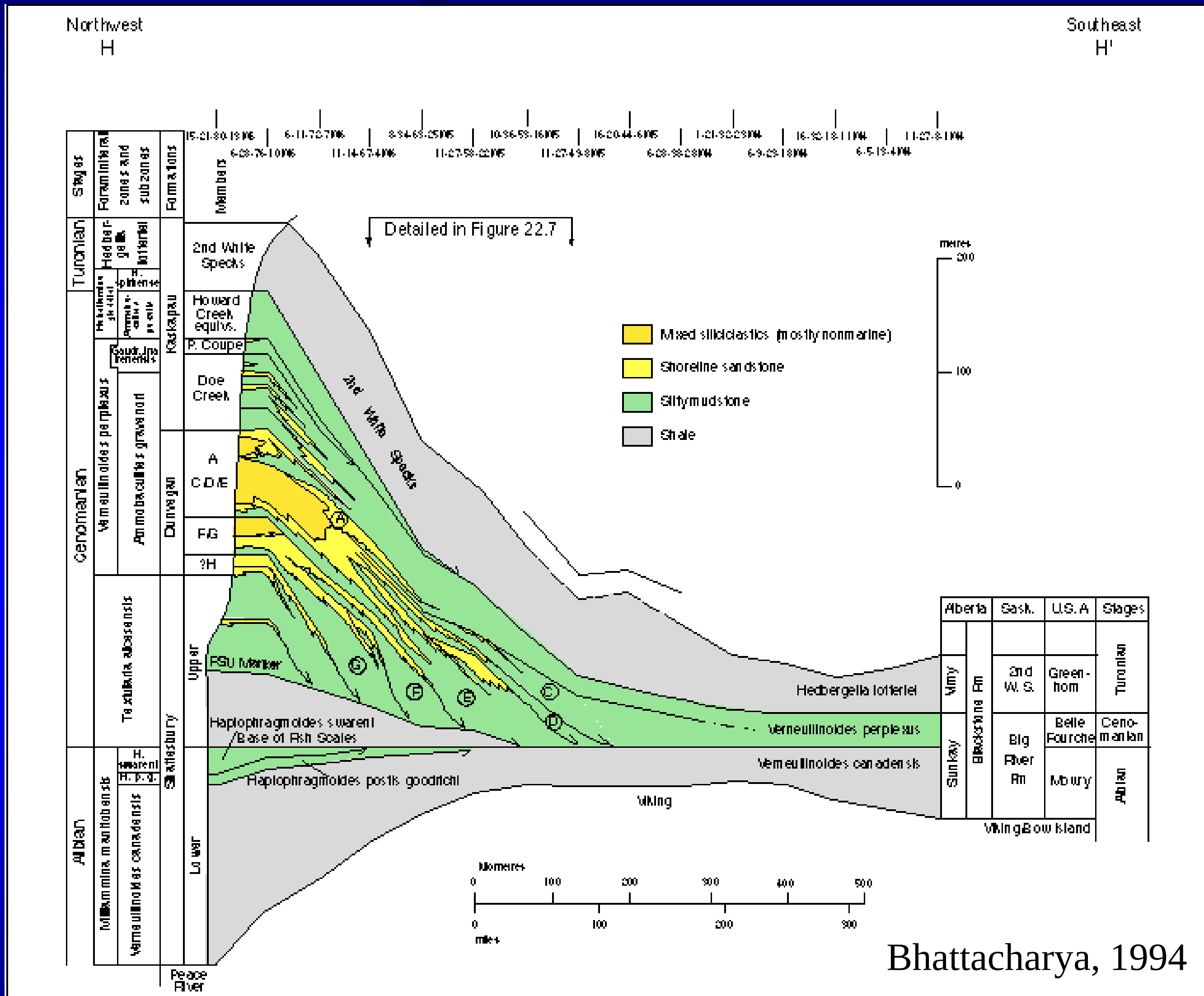
- Enclosed seaway may have led to brackish conditions.
- Temperate, humid climate.
- Small, high relief drainage basins.

Colorado Alberta Gp. Shales, Western Canada Sedimentary Basin, Alberta



Well-log correlations show alternation of sandy clastic wedges with muddy distal clinoforms versus tabular more organic-rich source-rock shales.

Dunvegan Fm., Alberta

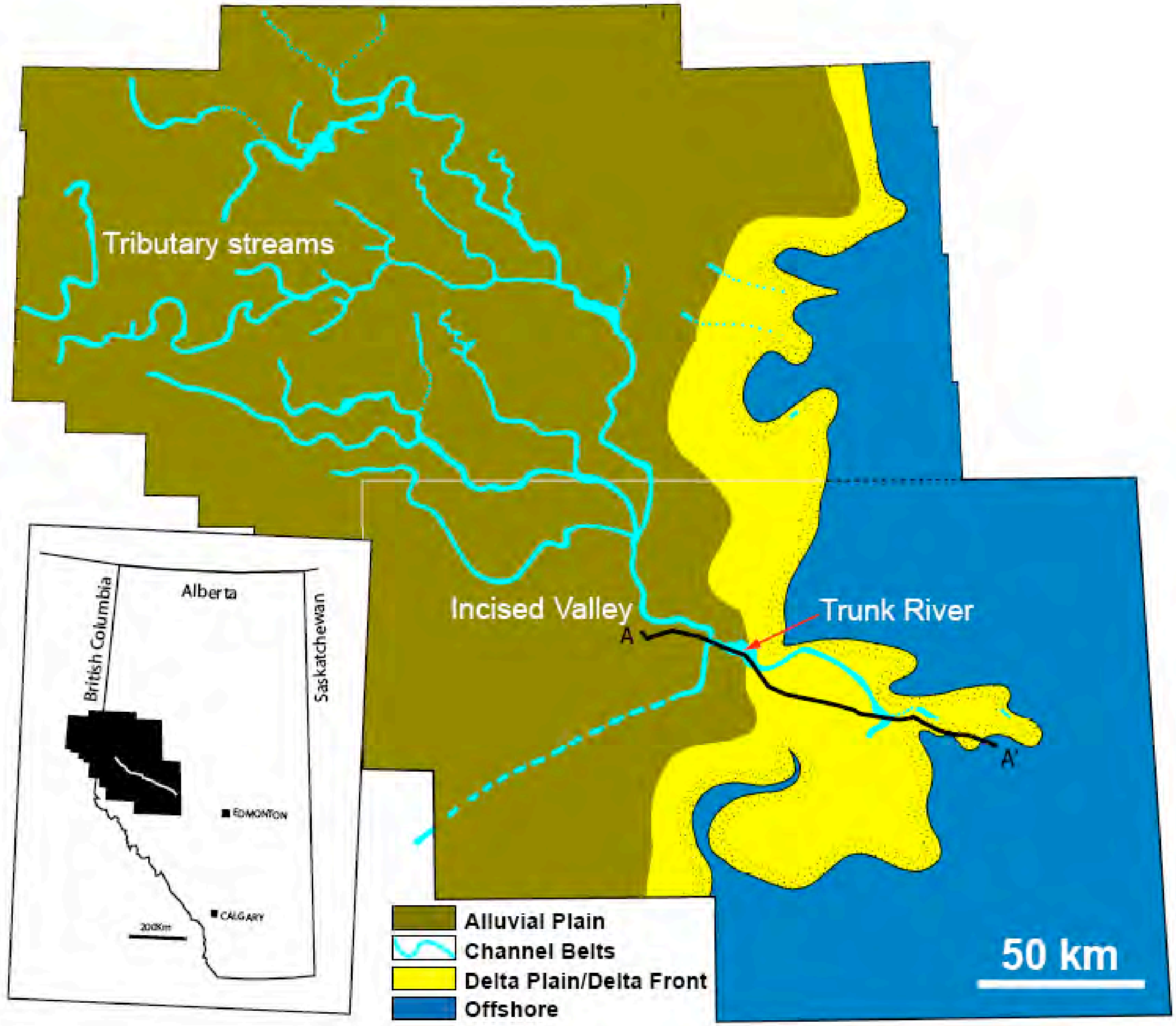


Bhattacharya, 1994

- Wedge-shaped formations show clinoforms.
- Tabular organic-rich units show a more “railroad track” style of correlations in well logs.

Dunvegan Paleogeography

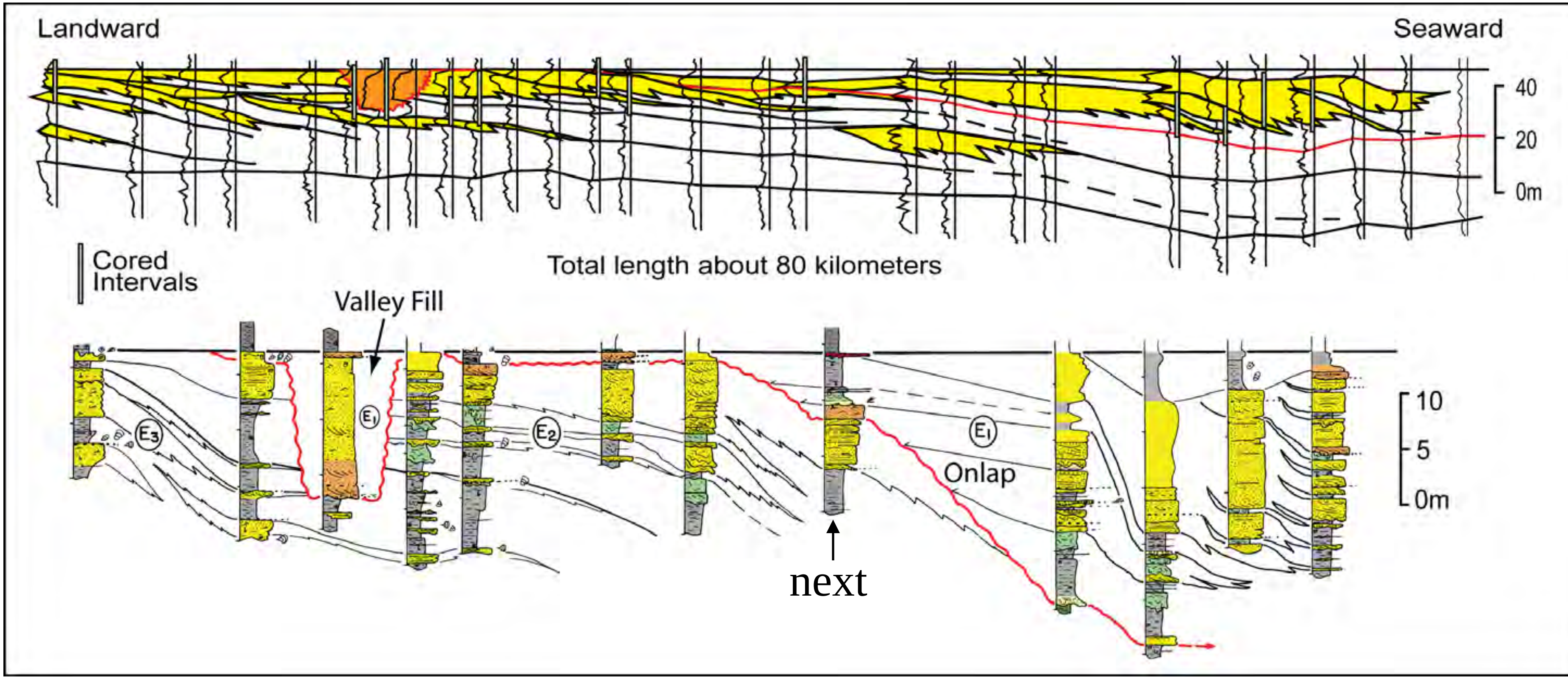
- Tributive valley systems feed trunk rivers and major delta lobes.
- Feeder valleys can be linked to delta and prodelta.
- Cross section A-A' in next slide.



Plint and Wadsworth, 2003

Dip Cross section Allomember E

A A’

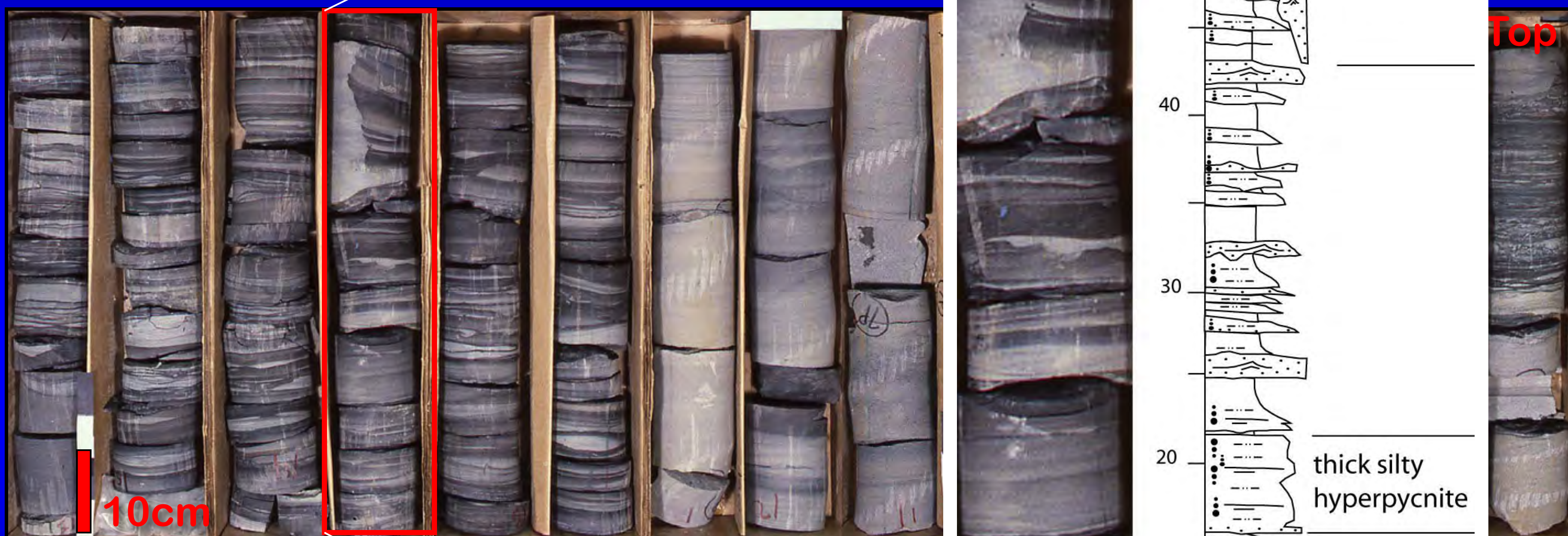


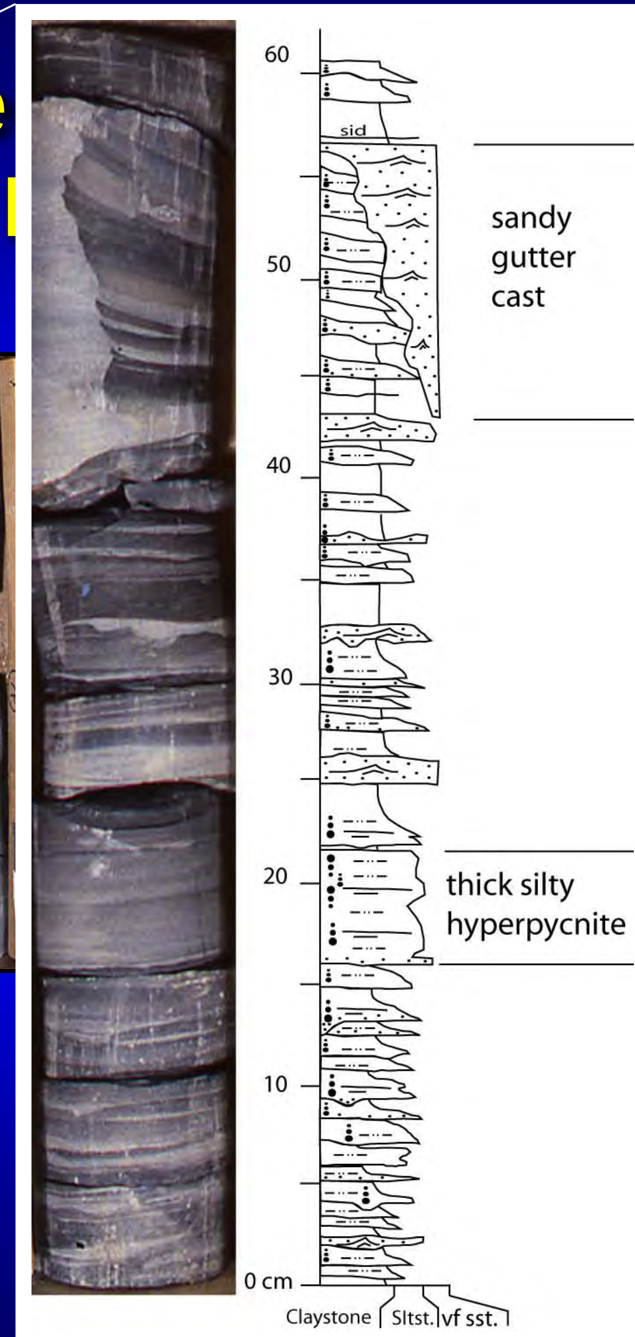
- **Feeder valleys can be linked to age-equivalent delta and prodelta facies.**

Cretaceous Prodelta Facies, Dunvegan Fm.

Facies in a clinoform deposit

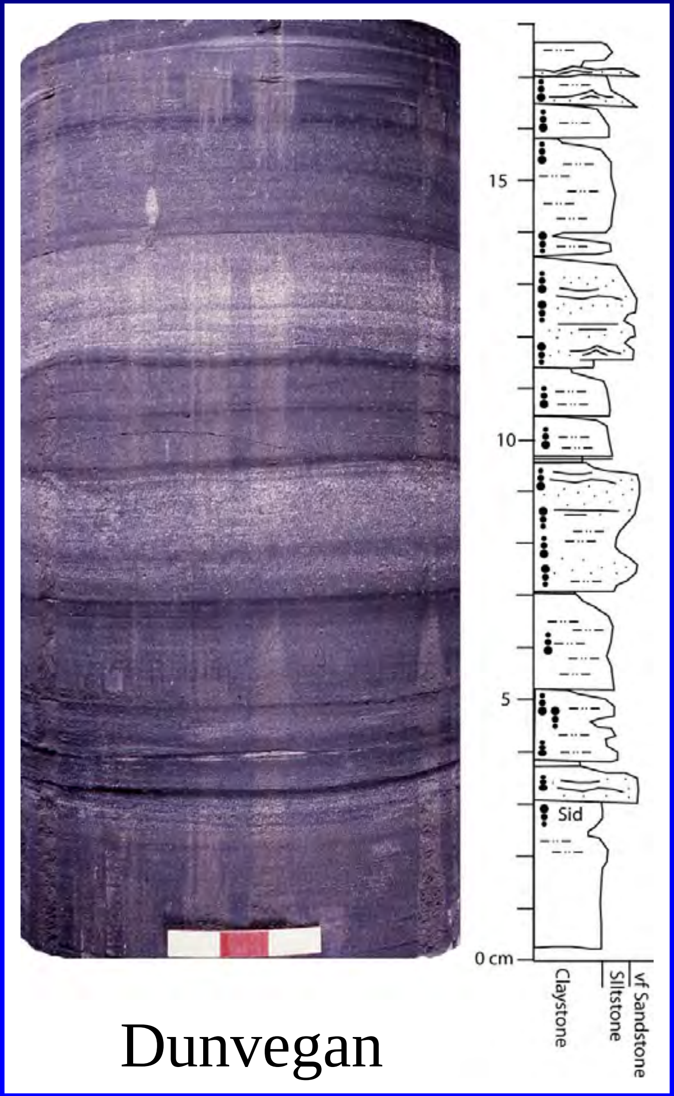
Cretaceous Prode
Dunvegan

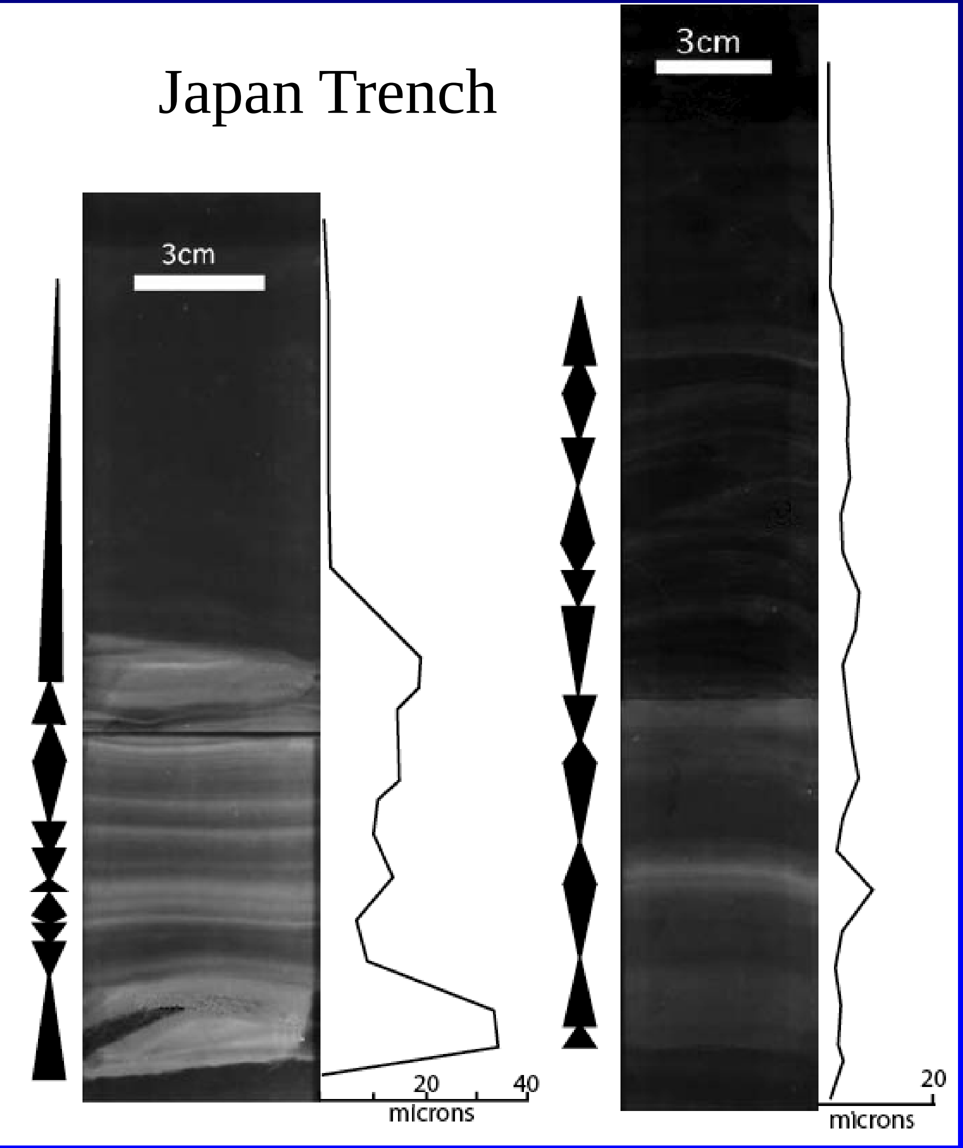




Prodelta Facies

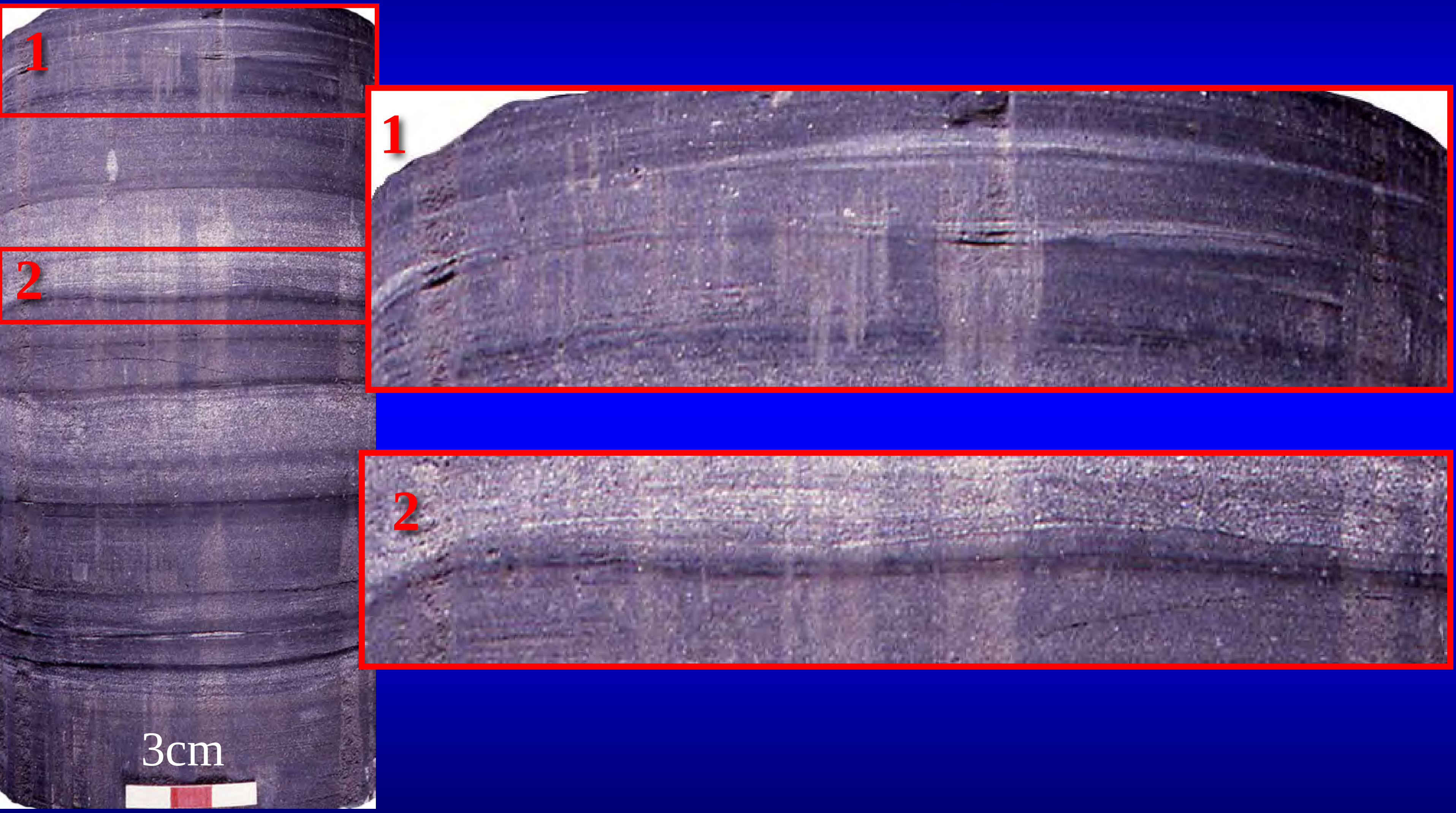
- Normal and inverse graded siltstones and very fine ssts.



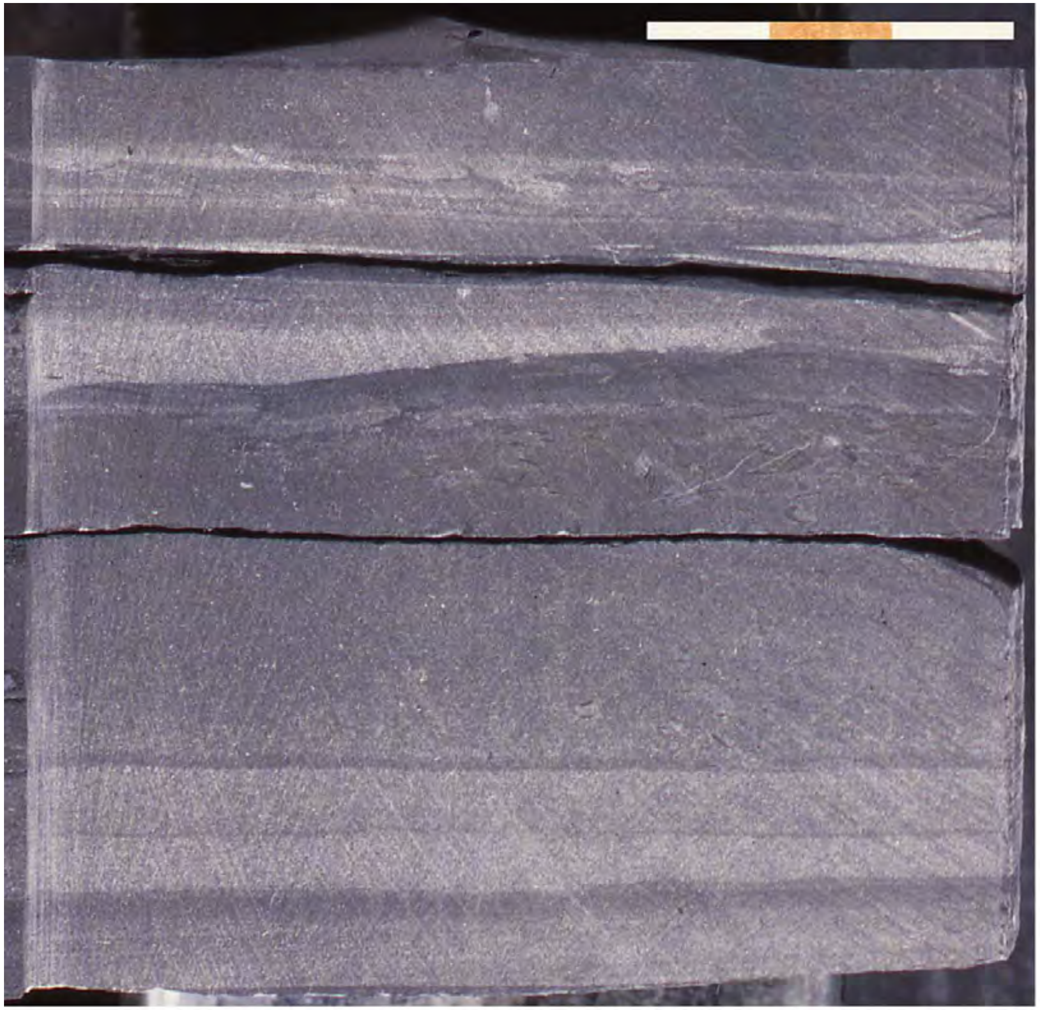


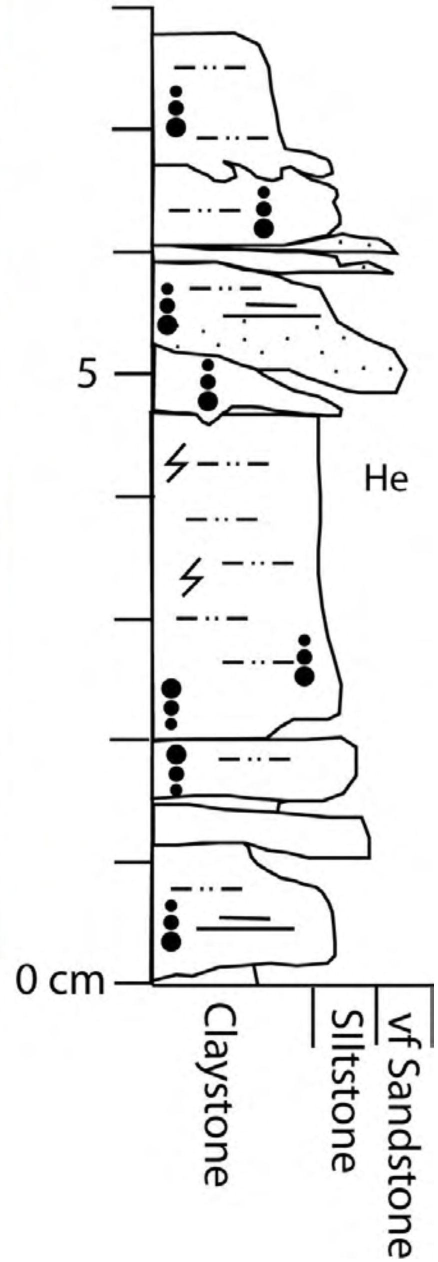
From Bhattacharya and MacEachern (2009) after Nakajima, 2006

Low-angle cross lamination also suggests mud ripples



Prodelta Facies

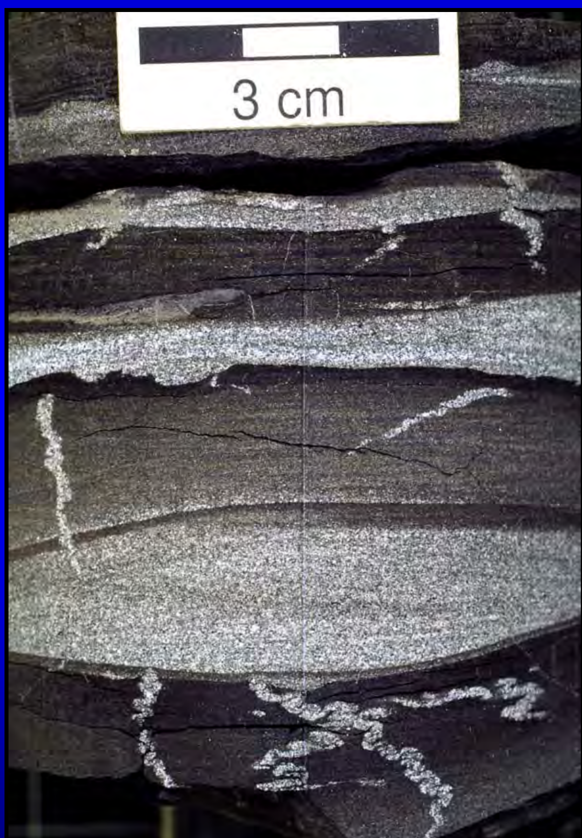


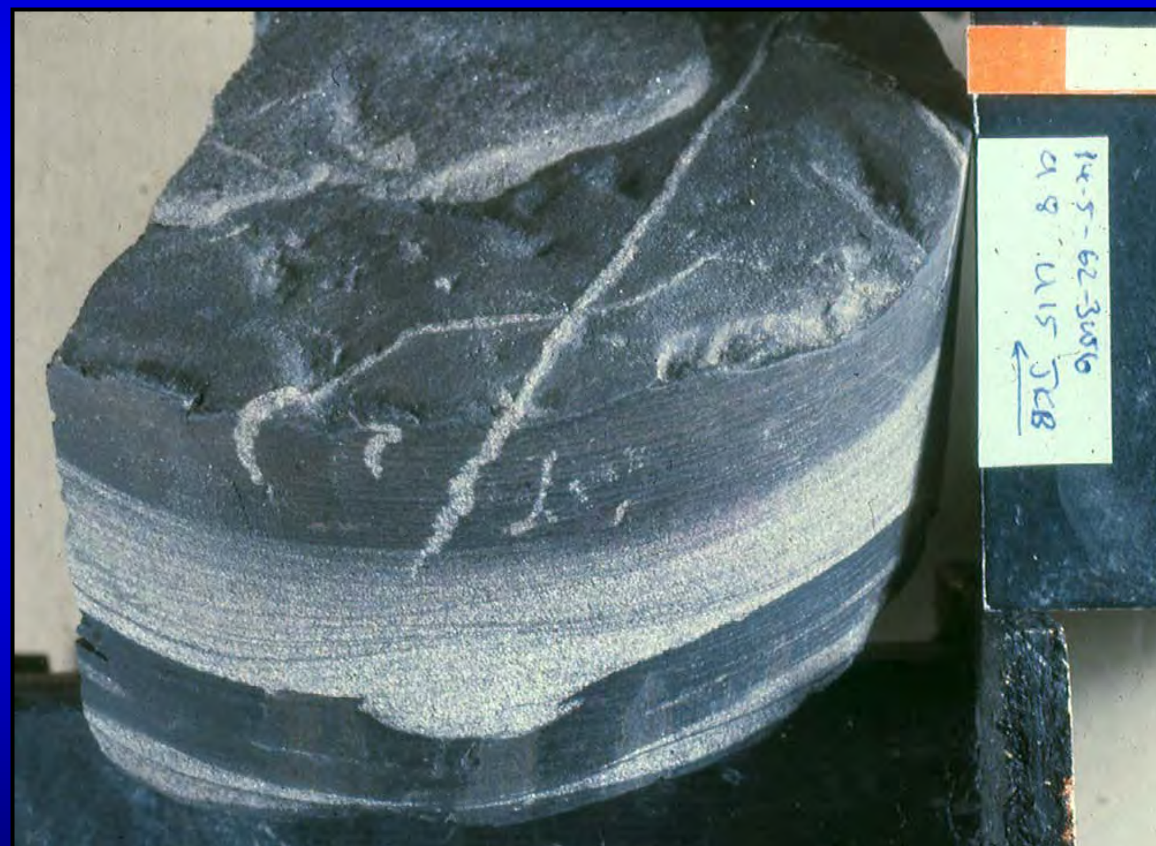


- Normal and inverse graded siltstones and very fine ssts.
- Mantle and swirl structures

Dewatering Structures

- Subaqueous shrinkage cracks
  - Synerisis and dewatering
  - Unfolding of wiggly crack suggests about 50% compaction.

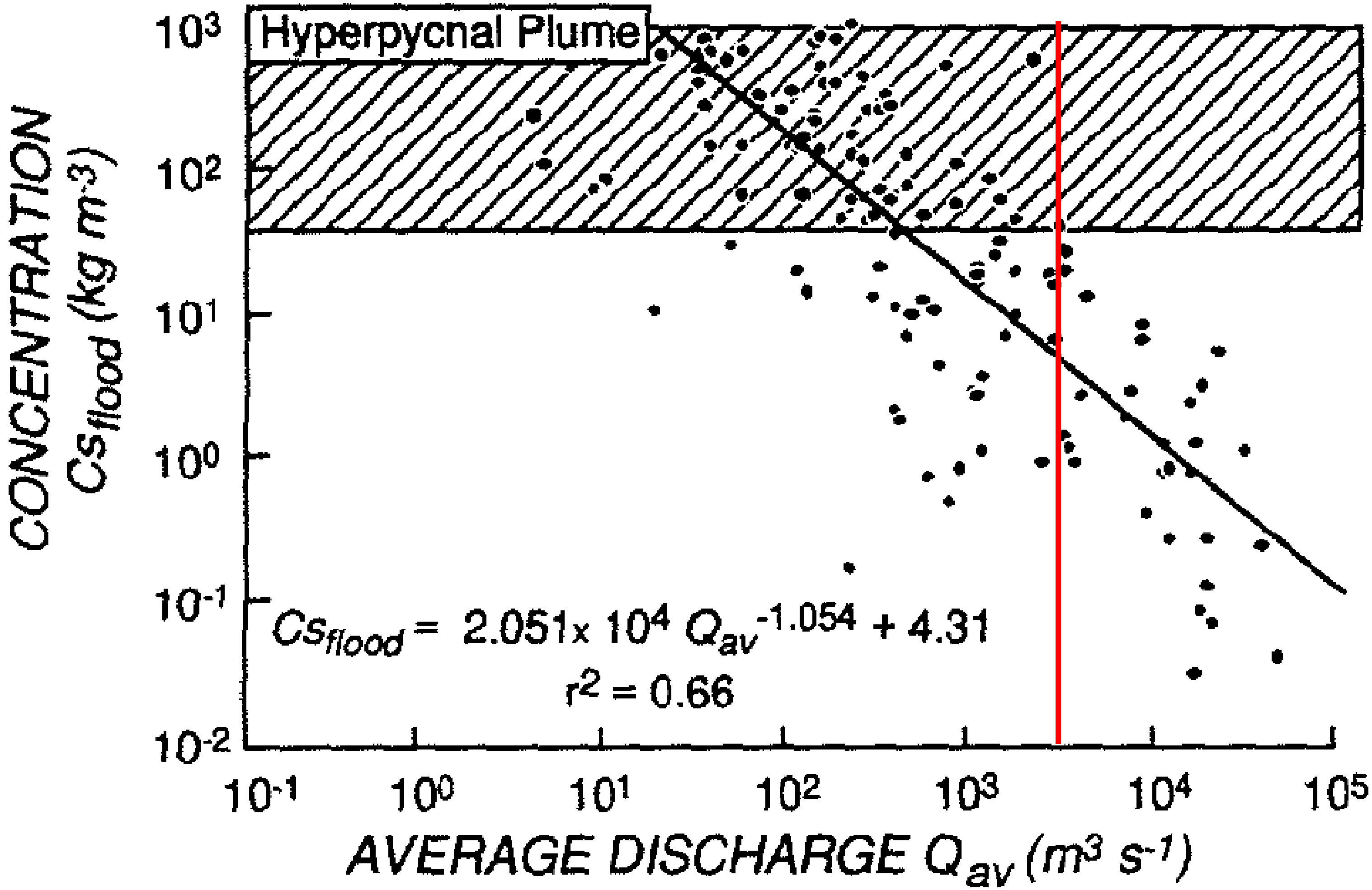




Subaqueous syneresis cracks, Cretaceous, Alberta

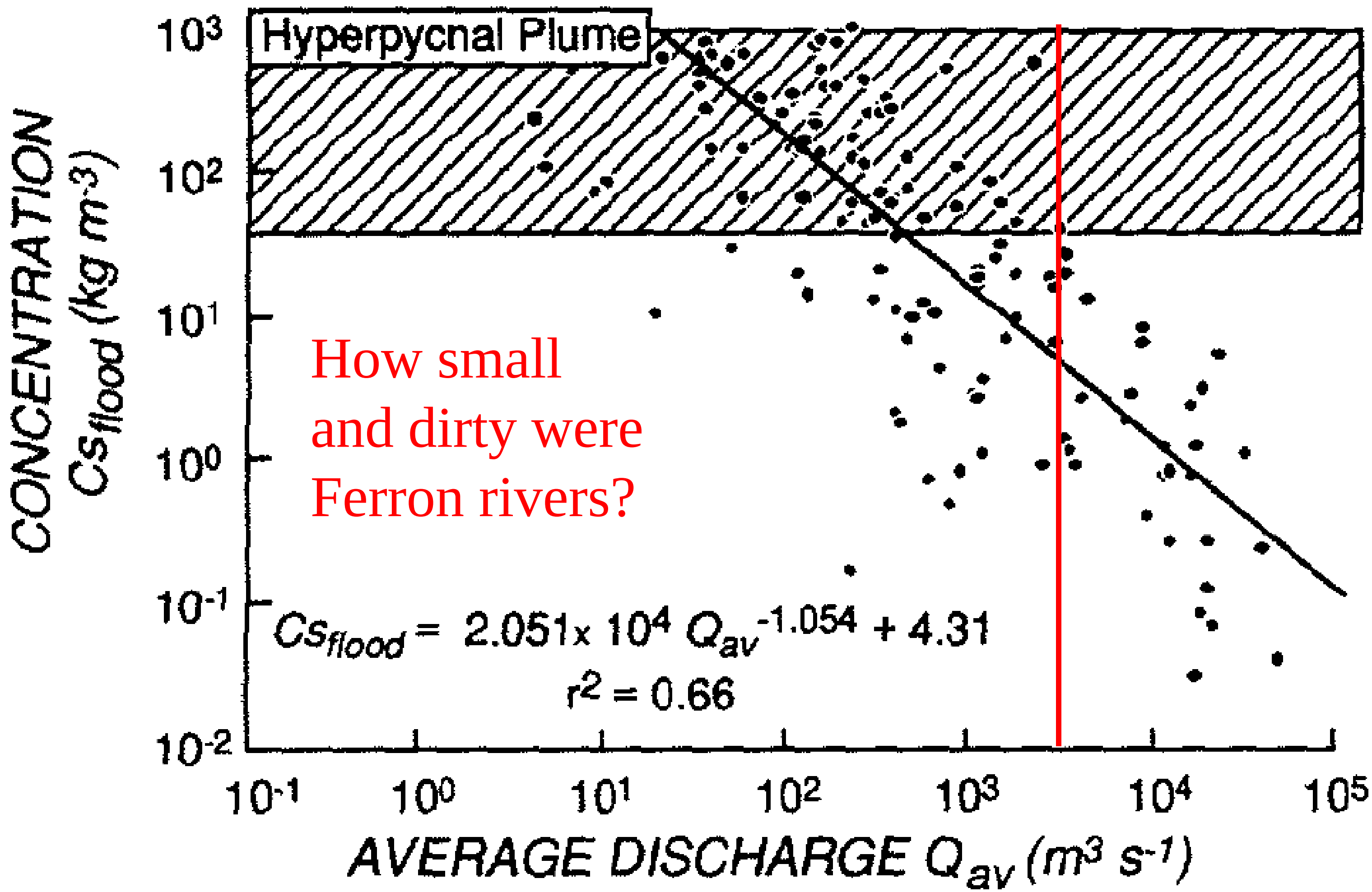
Back to Theory - Key problem

- What is the propensity of rivers to go hyperpycnal?
- Smaller discharges favour hyperpycnal conditions.
  - Small "dirty", mountainous rivers.



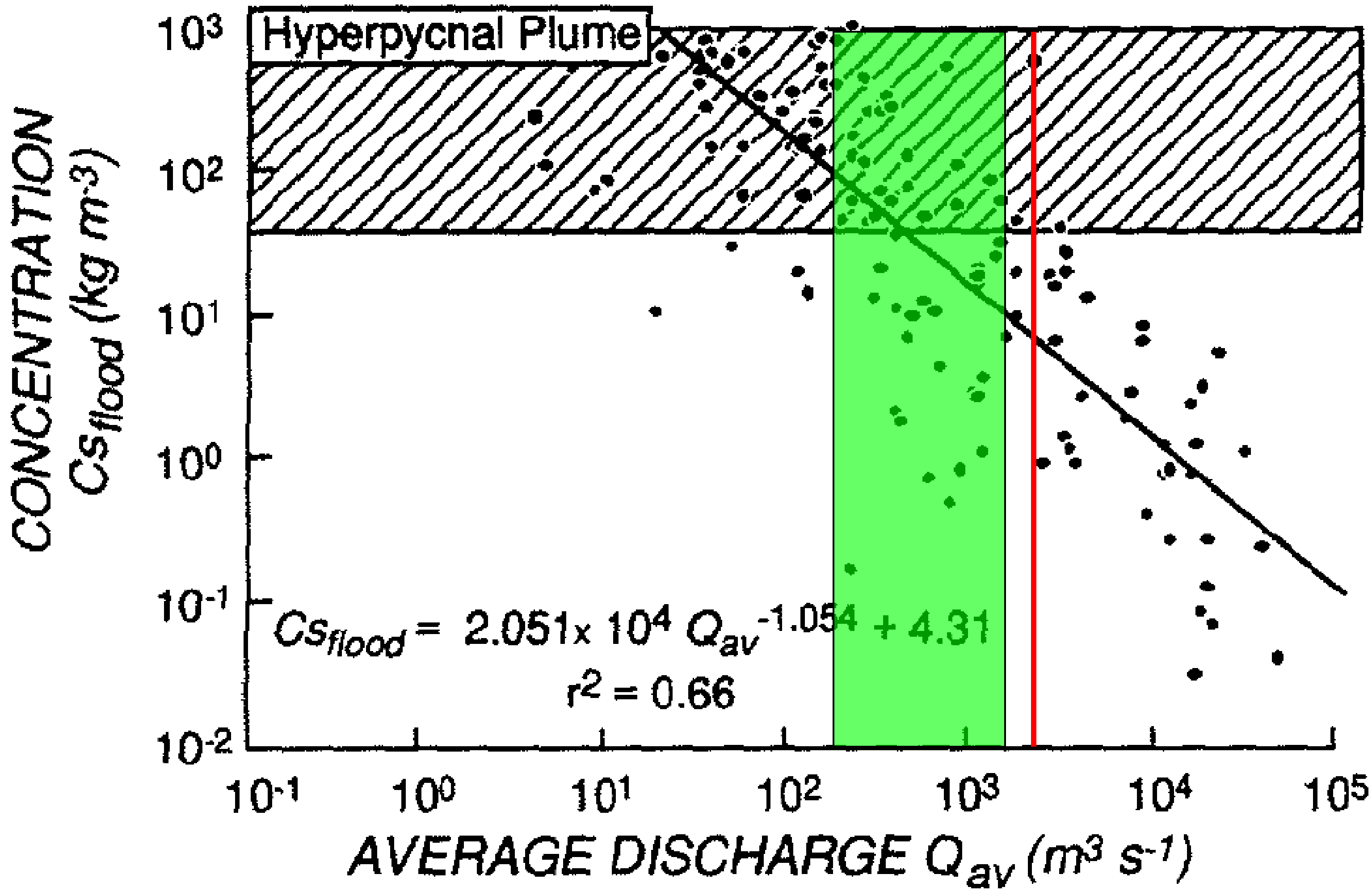
Mulder and Syvitsky, 1995

Theory: Hyperpycnal Flows less likely in rivers with discharge > 6,000m^3/s



Mulder and Syvitsky, 1995

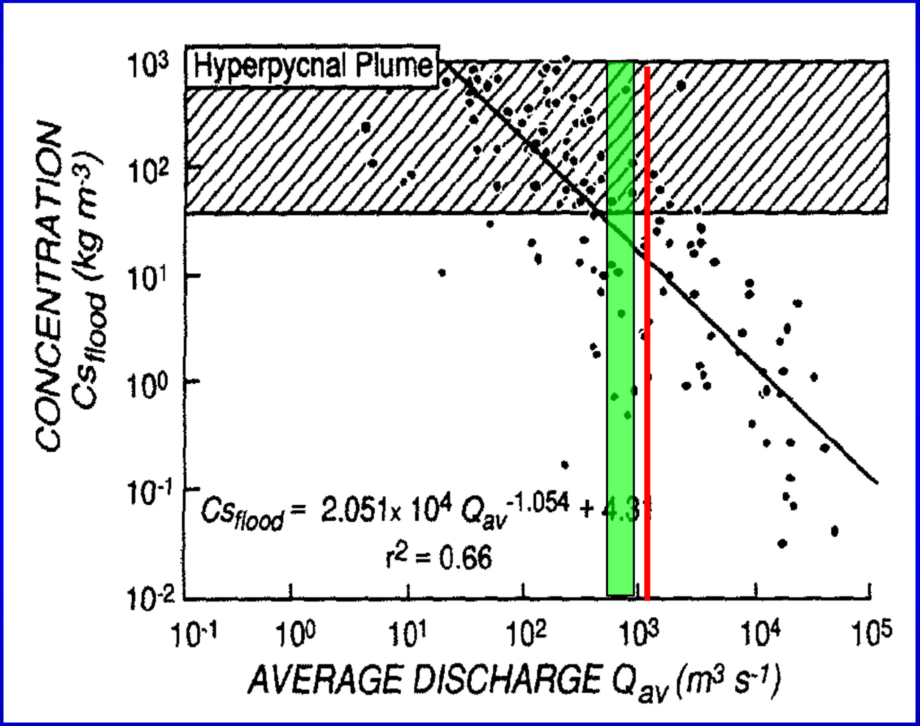
Ferron rivers could generate hyperpycnal flows



Mulder and Syvitsky, 1995

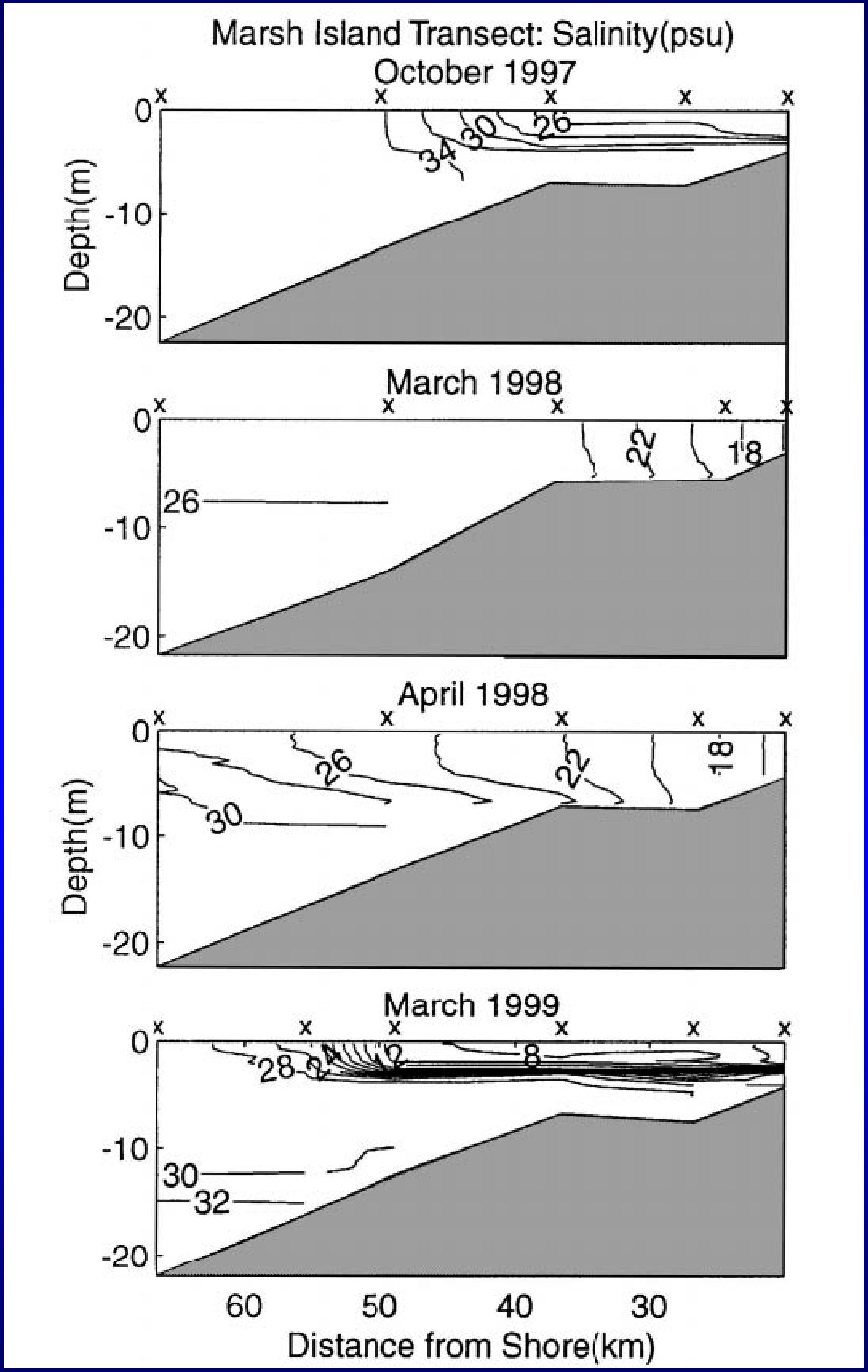
Paleodischarge of Dunvegan Trunk Rivers

- Channel Depth: 16 m
- Width: 170m
- Velocity: 1.5m/s
- Q = 4,080 m^3/s
- Larger river than Ferron, but still below hyperpycnal threshold.



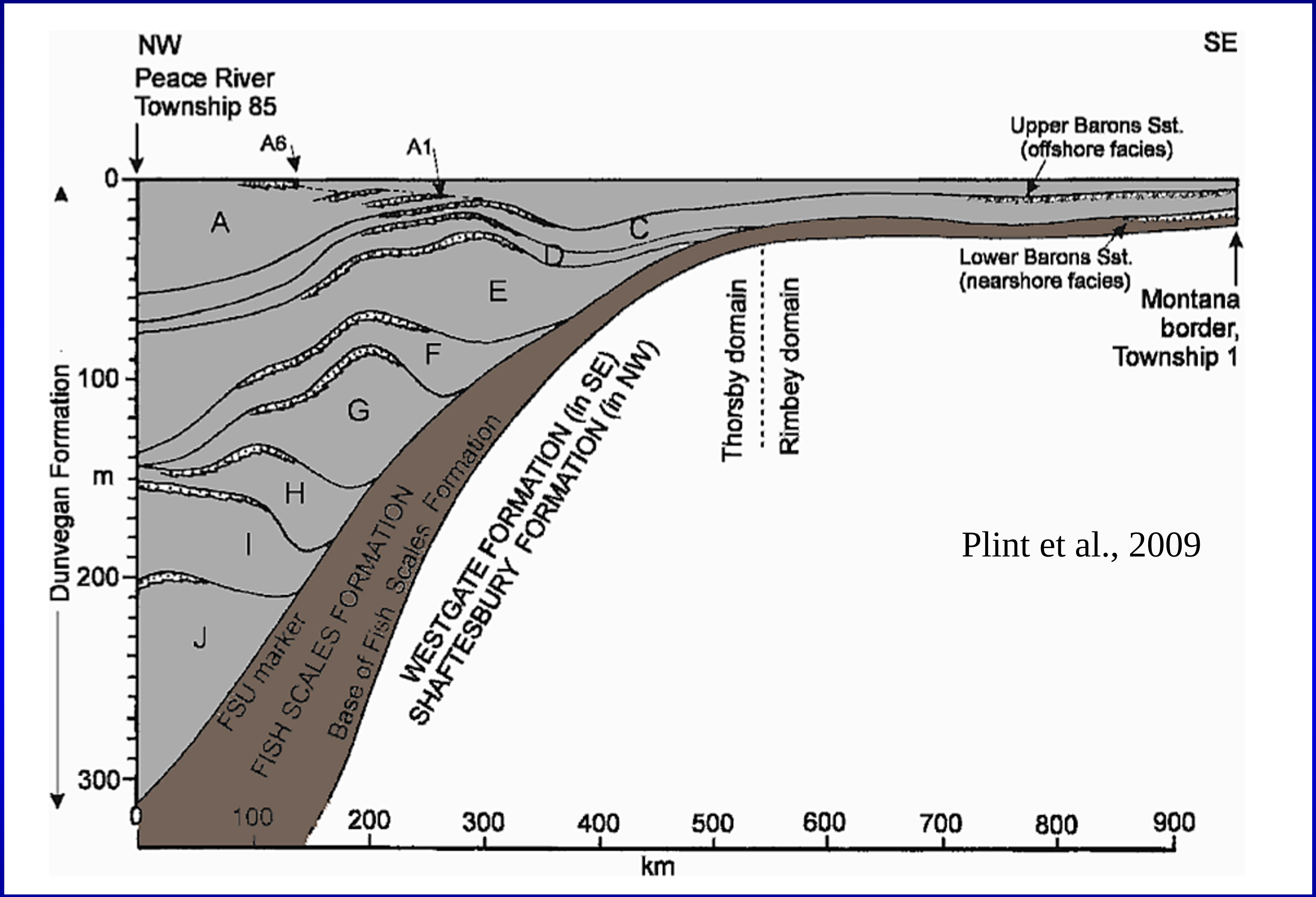
What is needed for hyperpycnal flows

- During successive floods, salinity is lowered, especially in shallow water settings.
- This enhances ability of feeding river to go hyperpycnal.
  - Atchafalaya, Orinoco
- Bays get prepped!



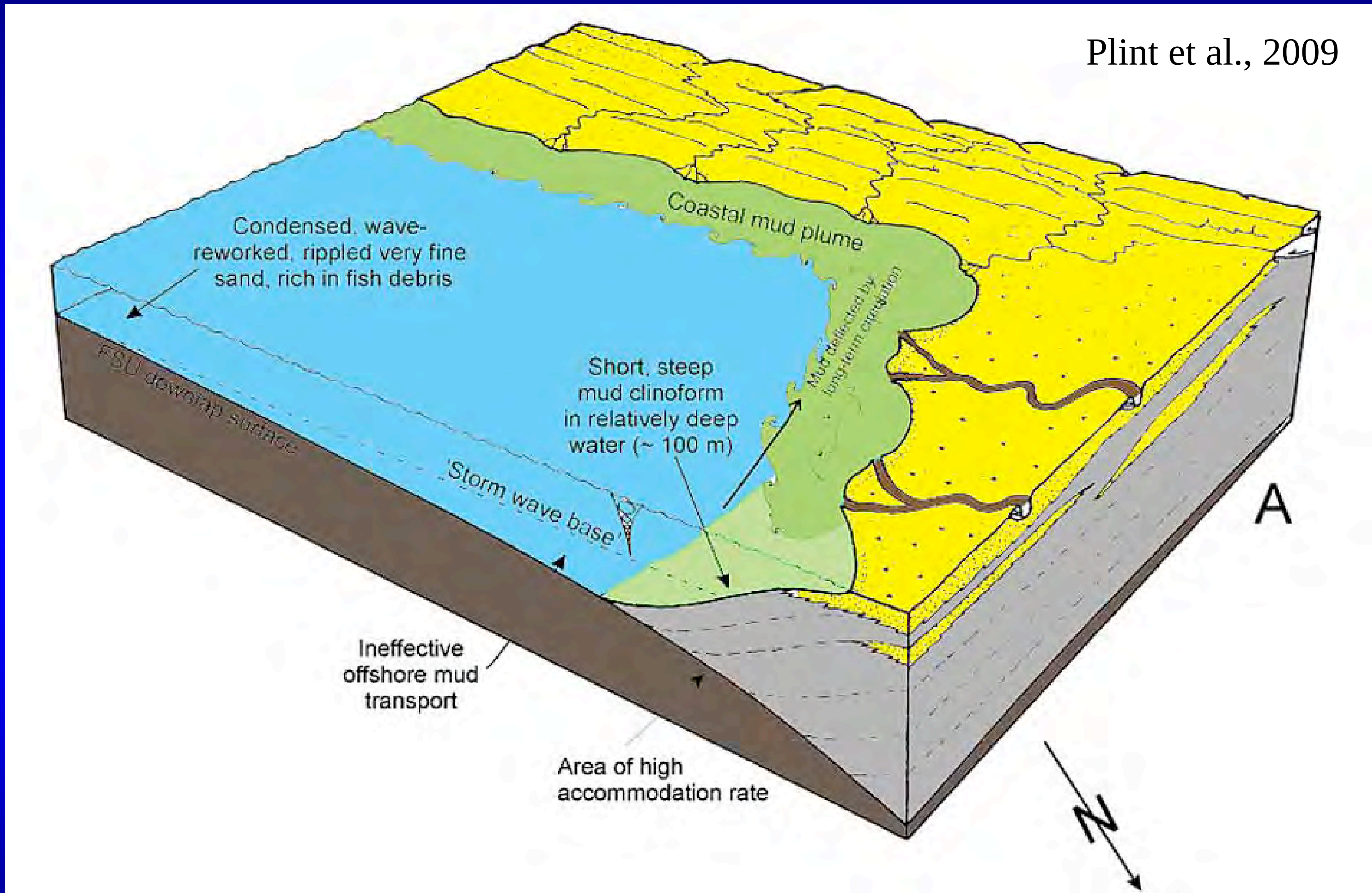
Depressed salinities following river floods in Atchafalaya Bay (from Allison et al., 2000)

Basin stratigraphy



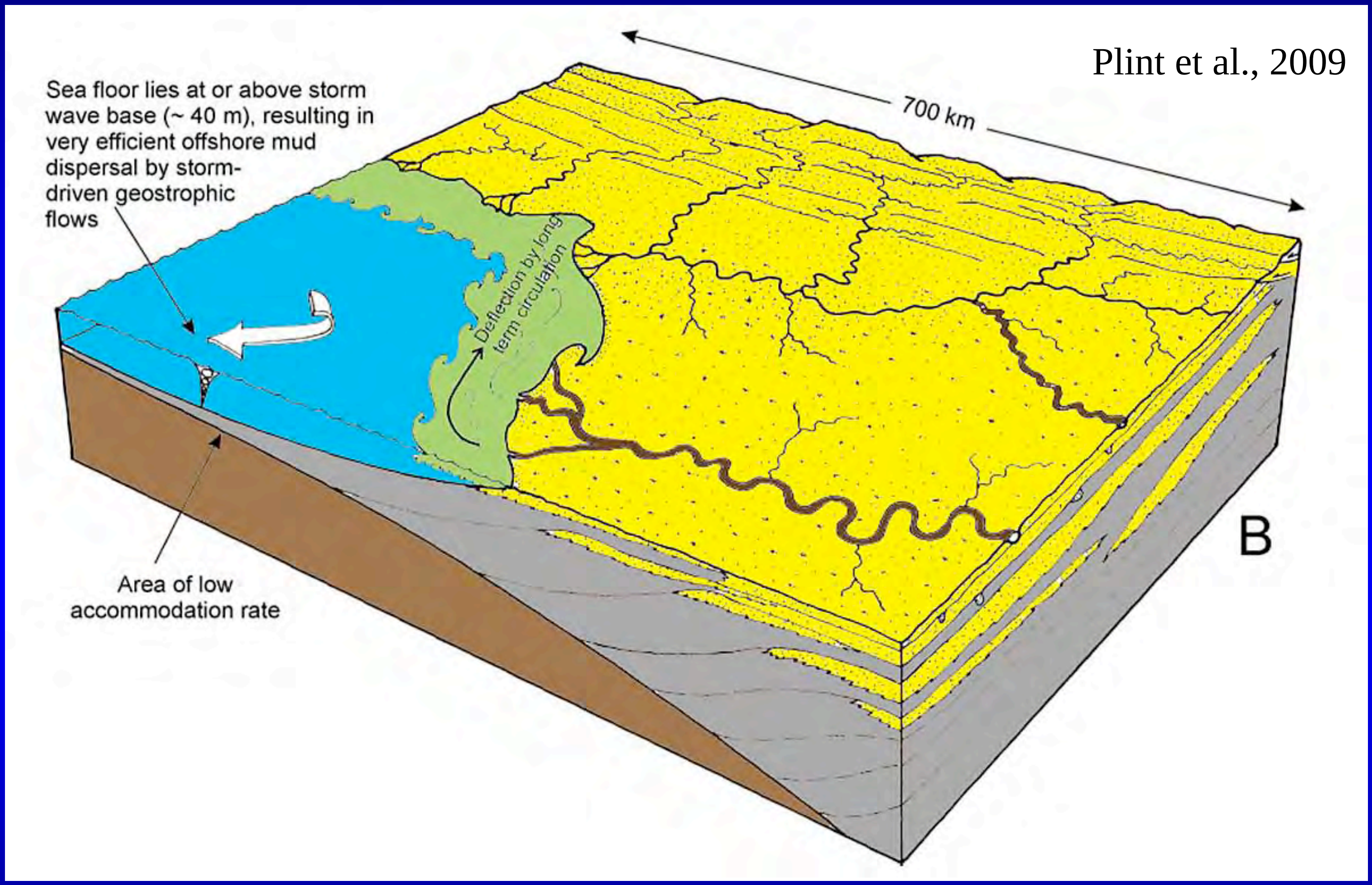
- Wedge-shaped formations show clinoforms.
- Tabular organic-rich units show a more “railroad track” style of correlations in well logs.

Dunvegan mud dispersal



River-dominated hyperpycnal flows keeps mud in inner shelf when foreland subsidence is deep and basin is underfilled.

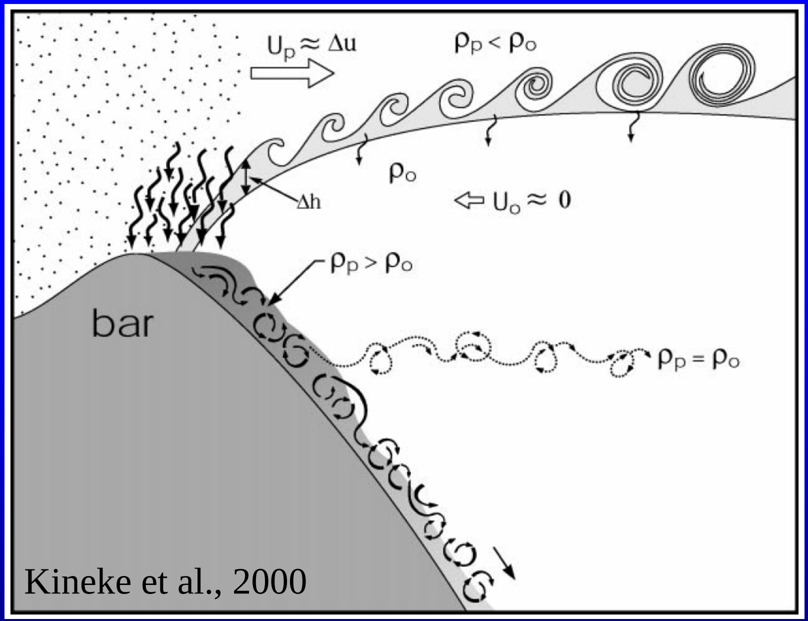
Mud dispersal, overfilled basin

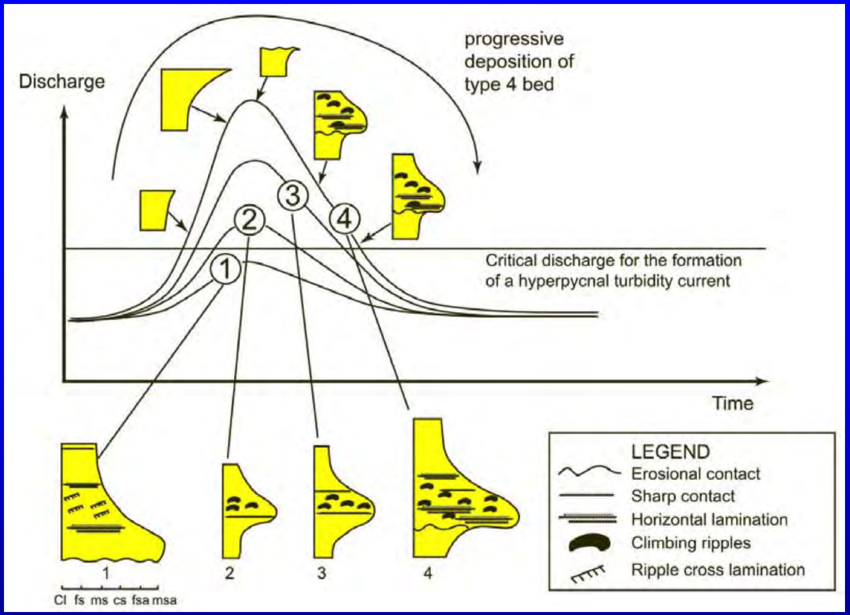


Storm-aided hyperpycnal flows allow mud dispersal across the shelf when foreland subsidence is slow and basin is overfilled.

Conclusions

- We have improved understanding of the importance of hyperpycnal flows in modern settings and how they are recognized.





Conclusions

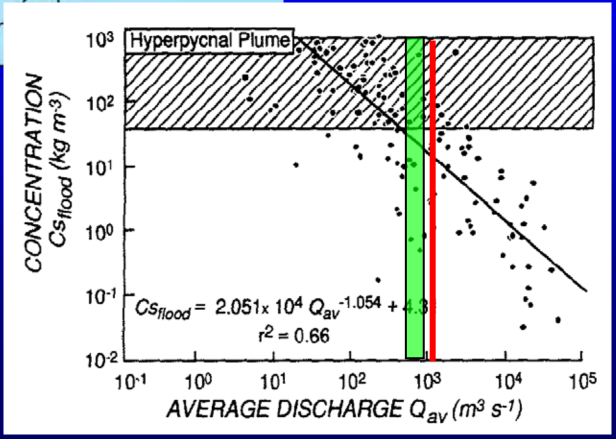
- **Ancient Cretaceous systems show evidence of abundant prodelta muddy "hyperpycnites".**

Dunvegan Prodelta

Ferron Prodelta

Cretaceous interior seaway has all of the essential characteristics to generate frequent hyperpycnal flows

- **High Relief**
  - Rocky Mountains.
- **High Rainfall**
  - Humic paleosols, abundant coals and wetlands, tropical to temperate climate, global greenhouse.
- **Small to intermediate, dirty mountain rivers.**
- **Brackish coastal area**
  - Stormy, shallow, epeiric sea.



Conclusions

- **50% of "shelf" mud may be hyperpycnal.**