Reevaluating Depositional Models for Shelf Shales*

Janok Bhattacharya[1]

Search and Discovery Article #50242 (2010)
Posted January 19, 2010

*Adapted from oral presentation at AAPG Annual Convention, Denver, Colorado, June 7-10, 2009.
Please refer to closely related article listed in References below by Bhattacharya, J.P., and MacEachern, J.A. (2009a) and an extended abstract by them (Bhattacharya, J.P., and MacEachern, J.A., 2009b).

[1]Earth and Atmospheric Sciences, University of Houston, Houston, TX (jpbhattacharya@uh.edu)

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 and suggest a corresponding 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.

References

Allison, M.A., and C.F. Neill, 2003, Development of a modern subaqueous mud delta on the Atchafalaya Shelf, Louisiana, *in* E.D. Scott, A.H. Bouma, and W.R. Bryant, eds., Siltstones, Mudstones and Shales: Depositional Processes and Characteristics: SEPM, CD-ROM, p. 23–34.

Allison, M.A., G.C. Kineke, E.S. Gordon, and M.A. Goni, 2000, Development and reworking of a seasonal flood deposit on the inner continental shelf off the Atchafalaya River: Continental Research, v. 20, p. 2267–2294.

Bentley, S.J., Sr., 2003, Wave-current dispersal of fine-grained fluvial sediments across continental shelves: the significance of hyperpycnal plumes, *in* Scott, E.D., Bouma, A.H., and Bryant, W.R., eds., Siltstones, Mudstones and Shales: Depositional Processes and Characteristics: SEPM, CD-ROM, p. 35–48

Bhattacharya, J.P. and J.A. MacEachern, 2009a, Hyperpycnal rivers and prodeltaic shelves in the Cretaceous seaway of North America: Journal of Sedimentary Research, v. 79, p. 184-209. AAPG Datapages Pay-per-View 2009 article http://search.datapages.com/data/sepm/journals/079/079004/184_gsjsedres790184.htm

Bhattacharya, J.P. and J.A. MacEachern, 2009b, Re-evaluating depositional models for shelf shales: Gulf Coast Association of Geological Societies Transactions, v. 59, p. 81-83; Search and Discovery article #90093, GCAGS 2009 meeting abstracts Re-Evaluating Depositional Models for Shelf Shales, Janok P. Bhattacharya and James A. MacEachern.

Bhattacharya, J.P. and R.G. Walker, 1992, Deltas, *in* R.G. Walker, N.P. and James, eds., Facies Models: Response to Sea Level Change: Geological Association of Canada, p. 157–177.

Boggs, S., Jr., 2001, Principles of Sedimentology and Stratigraphy, Third Edition: Upper Saddle River, New Jersey, Pearson Prentice Hall, 726 p., also Fourth Edition, 2006, 662 p.

Friedrichs, C.T. and M.E. Scully, 2007, Modeling deposition by wave-supported gravity flows on the Po River prodelta: from seasonal floods to prograding clinoforms: Continental Shelf Research, v. 27, p. 322–337.

Kineke, G.C., R.W. Sternberg, J.H. Trowbridge, and W.R. Geyser, 1996, Fluid-mud processes on the Amazon continental shelf: Continental Shelf Research, v. 16, p. 667–696.

Kineke, G.C., K.J. Woolfe, S.A. Kuehl, J.D. Milliman, T.M. Dellapenna, and R.G. Purdon, 2000, Sediment export from the Sepik River, Papua New Guinea: Evidence for a divergent dispersal system: Continental Shelf Research, v. 20, p. 2239–2266.

Leckie, D.A., J.P. Battacharya, J. Bloch, C.F. Gilboy, and B. Norris, 1994, Cretaceous Colorado/Alberta Group of the Western Canada Sedimentary Basin; *in* G. Mossop, and I. Shetson, eds., Geological Atlas of the Western Canada Sedimentary Basin, CSPG/Alberta Research Council, Calgary, p. 335-352.

Mulder, T. and J. Alexander, 2001, The physical character of subaqueous sedimentary density currents and their deposits: Sedimentology, v. 48, p. 269–299.

Mulder, T. and J.P.M. Syvitski, 1995, Turbidity currents generated at river mouths during exceptional discharges to the world's oceans: Journal of Geology, v. 103, p. 285–299.

Mulder, T., J.P.M. Syvitski, S. Migeon, J.-C Faugeres, and B. Savoye, 2003, Marine hyperpycnal flows: initiation, behavior and related deposits. A review: Marine and Petroleum Geology, v. 20, p. 861–882.

Nakajima, T., 2006, Hyperpycnites deposited 700 km away from river mouths in the Central Japan Sea: Journal of Sedimentary Research, v. 76, p. 60–73.

Nemec, W., 1995, The dynamics of deltaic suspension plumes, *in* M.N. Oti and S. Postma, eds., Geology of Deltas: Rotterdam, Balkema, p. 31–93.

Nichols, G., 1999, Sedimentology and Stratigraphy: London, Blackwell, 355 p.

Plint, A.G., 2000, Sequence stratigraphy and paleogeography of a Cenomanian deltaic complex: the Dunvegan and lower Kaskapau formations in subsurface and outcrop, Alberta and British Columbia, Canada: Bulletin of Canadian Petroleum Geology, v. 47, p. 43–79.

Plink-Bjorklund, P. and R.J. Steel, 2004, Initiation of turbidity currents: outcrop evidence for Eocene hyperpycnal flow turbidites: Sedimentary Geology, v. 165, p. 29–52.

Prothero, D.R. and F. Schwab, 2004, Sedimentary Geology: An Introduction to Sedimentary Rocks and Stratigraphy, Second Edition: New York, W.H. Freeman and Company, 557 p.

Schieber, J., J. Southard and K. Thaisen, 2007, Accretion of mudstone beds from migrating floccule ripples: Science, December 14, 2007, v. 318. no. 5857, p. 1760–1763.

Re-evaluating depositional models for shelf shales:

Examples from the Cretaceous Seaway of North America

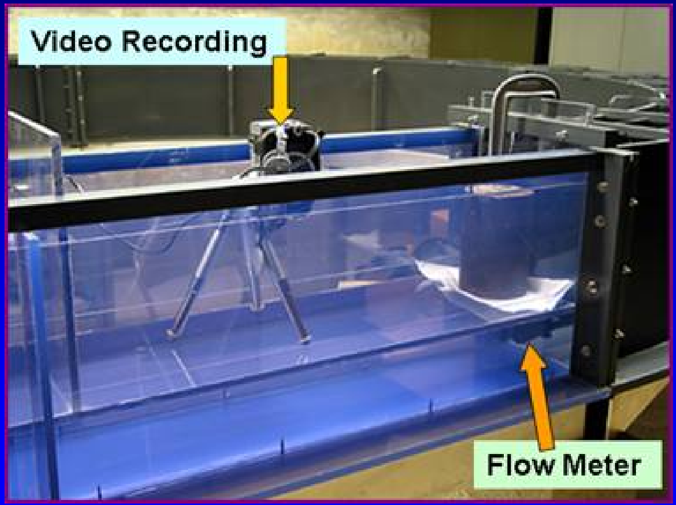
Janok P. Bhattacharya

UNIVERSITY *of* HOUSTON

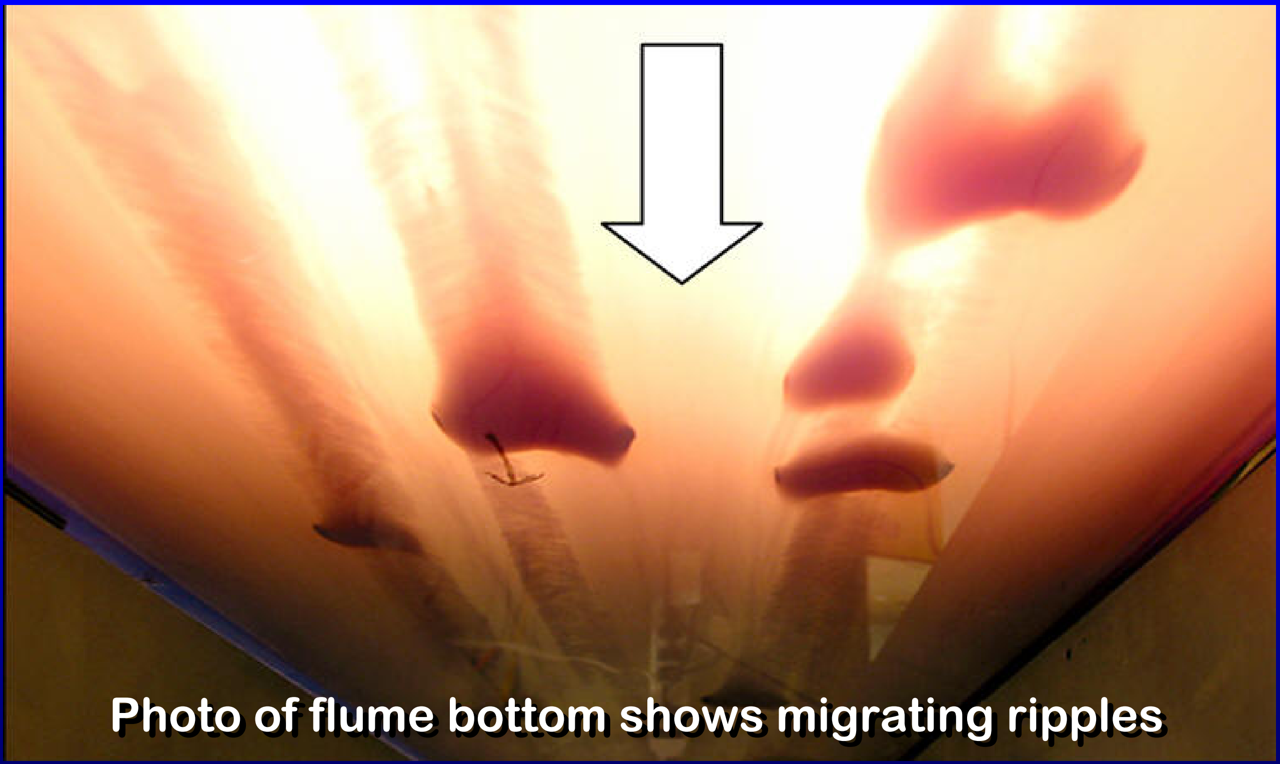
Key Problems

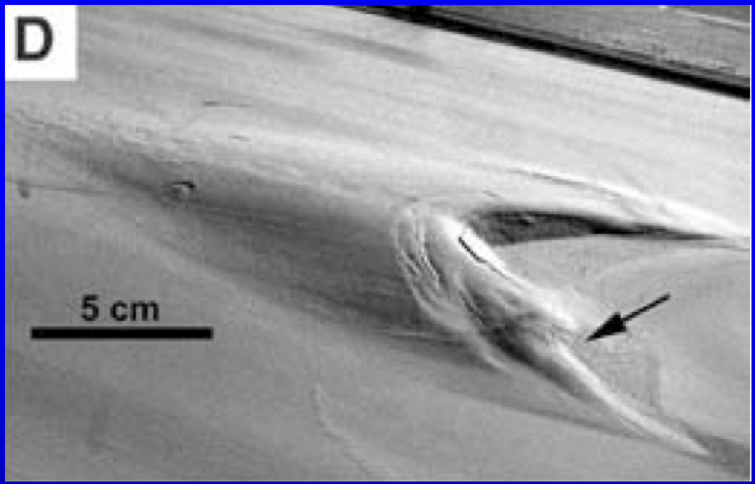
- **The textbooks tell us:**
  - The prodelta is the area where fine material *settles quietly out of suspension* (Bhattacharya and Walker, 1992).
  - The finest-grained deposits of the delta front occur in the deeper water (prodelta) area where deposition is *mainly from suspension* (Nichols, 1999).
  - 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).

However 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.

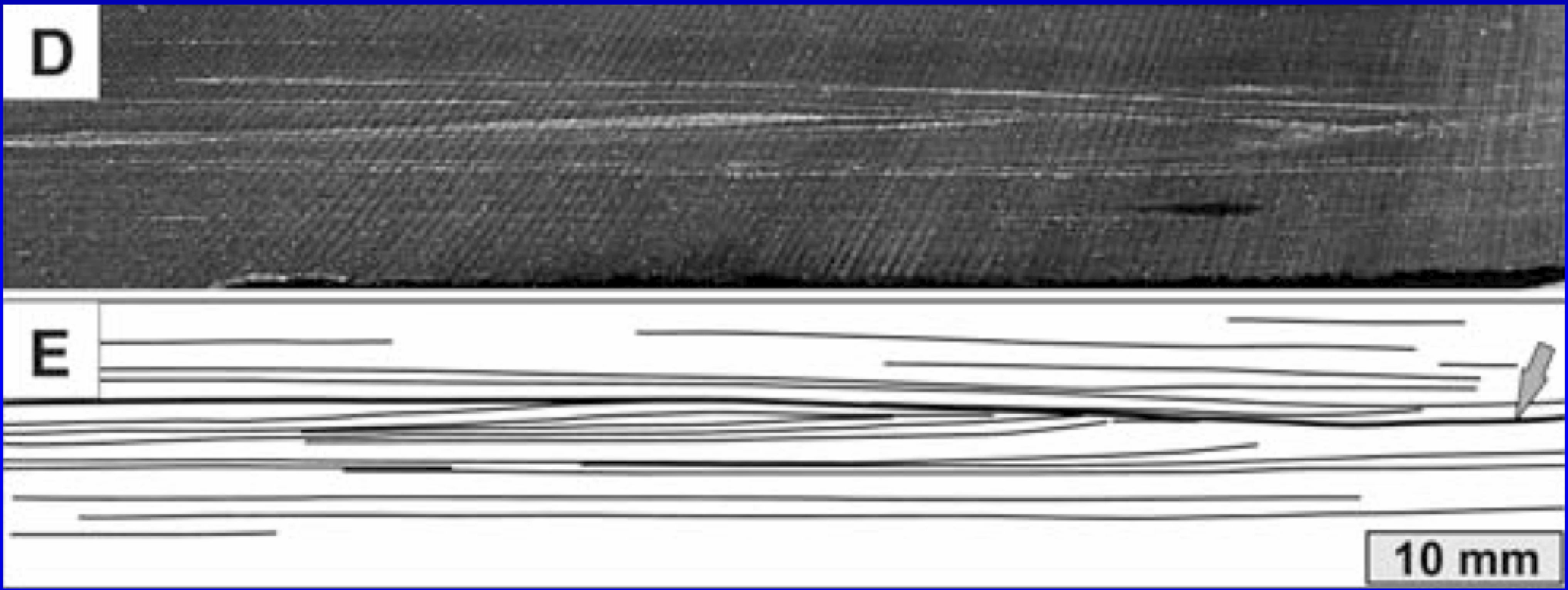




Oblique view of mud ripple (from Schieber et al., 2007, Science)

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

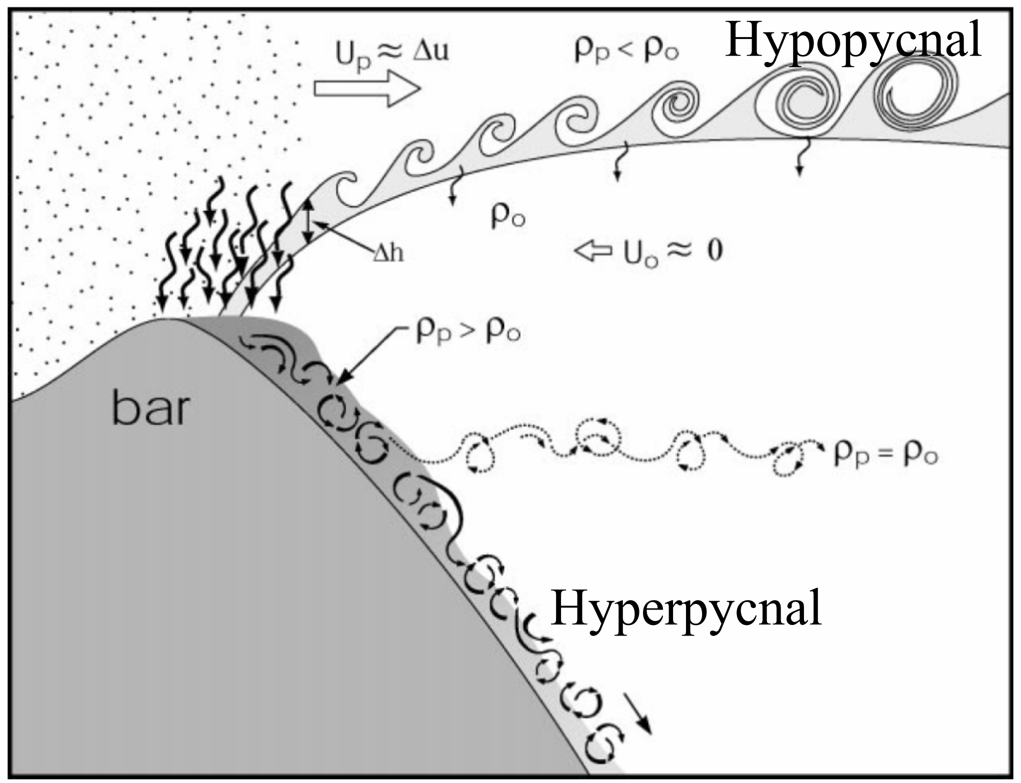
Bedload Mud



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

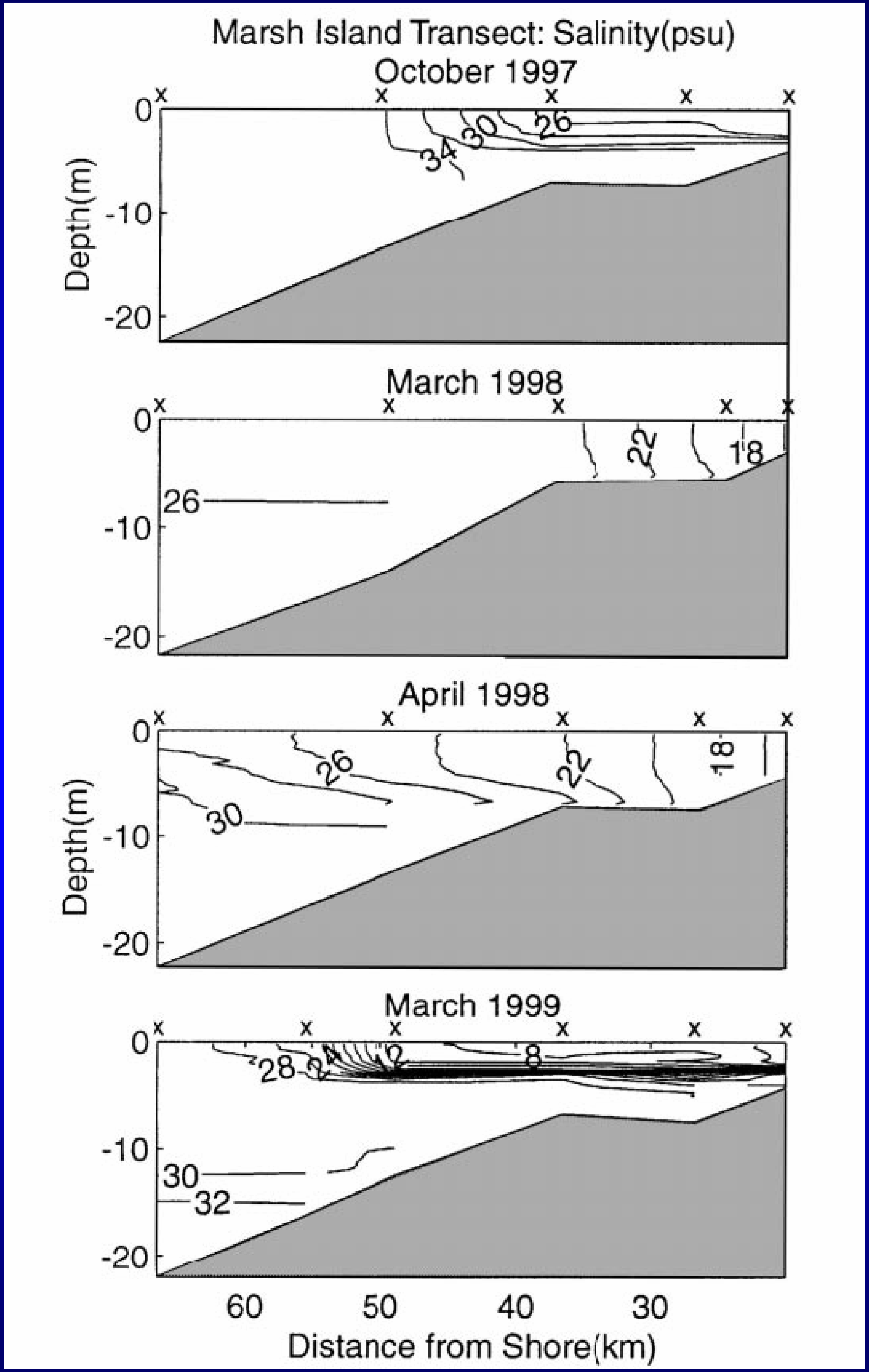
- **Newer oceanographic studies emphasize:**
  - **Importance of rapidly deposited fluid muds**
    - **(Kineke et al., 1996; 2000)**
  - **Importance of hyperpycnal mud plumes**
    - **(Nemec, 1995; Kineke et al., 2000; (Mulder and Syvitsky, 1995; Mulder and Alexander, 2001; Piret-Björklund and Steel, 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

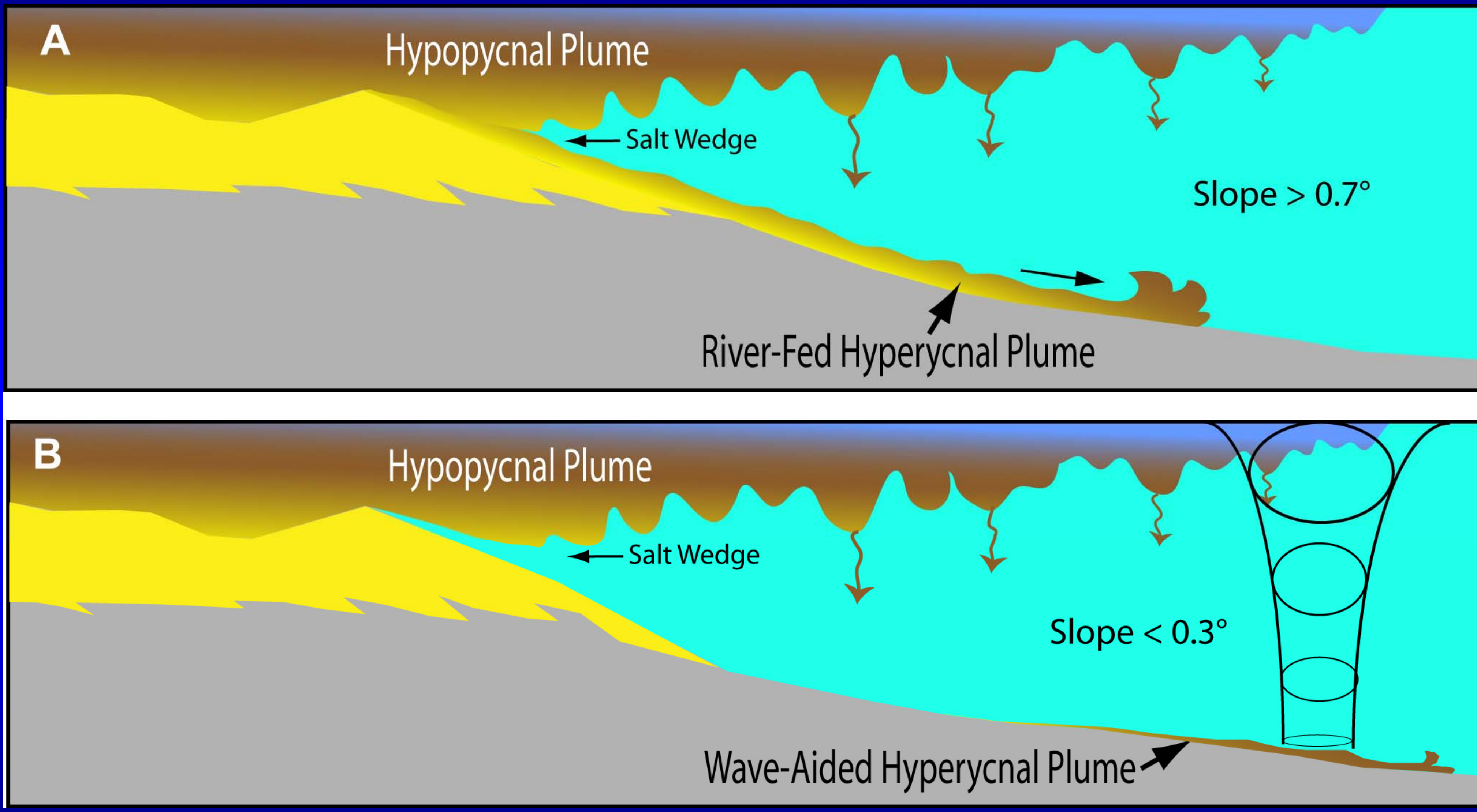
What is needed for hyperpycnal flows

- **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!**



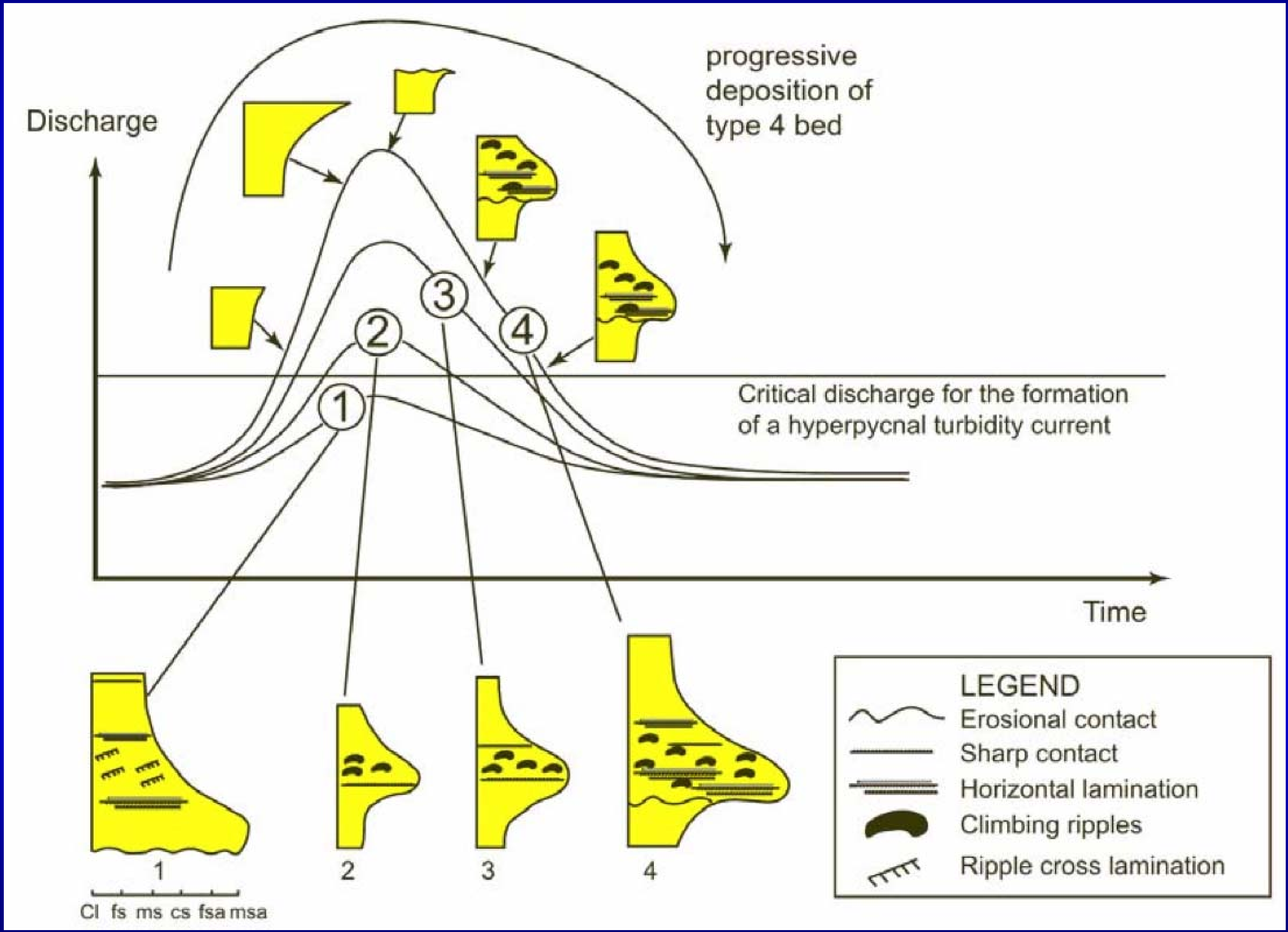
Depressed salinities following river floods in Atchafalaya Bay (from Allison et al., 2000)

Types of Delta Plumes



From Bhattacharya (2009)

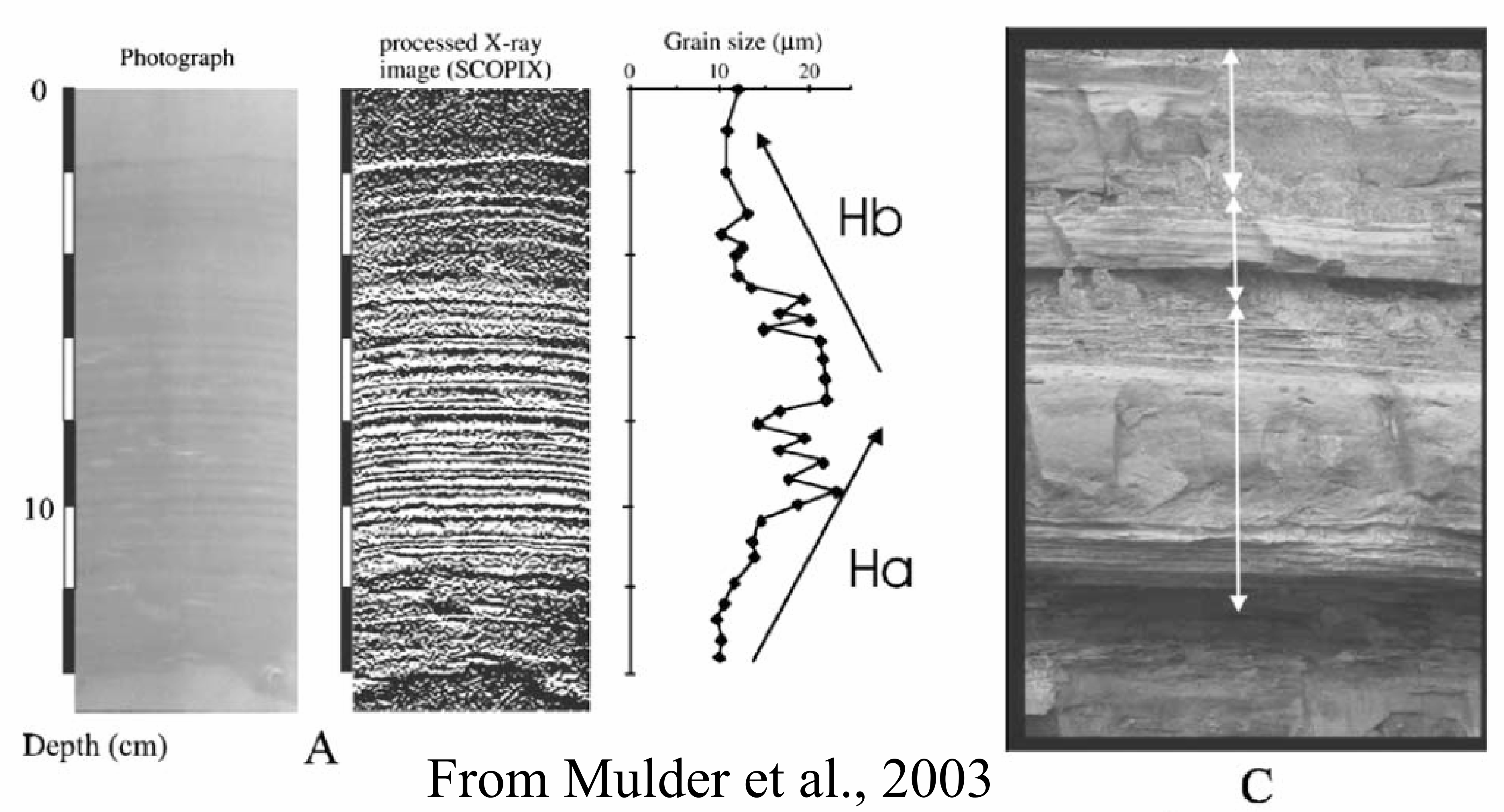
Hyperpycnite Facies Model



From Mulder et al., 2003

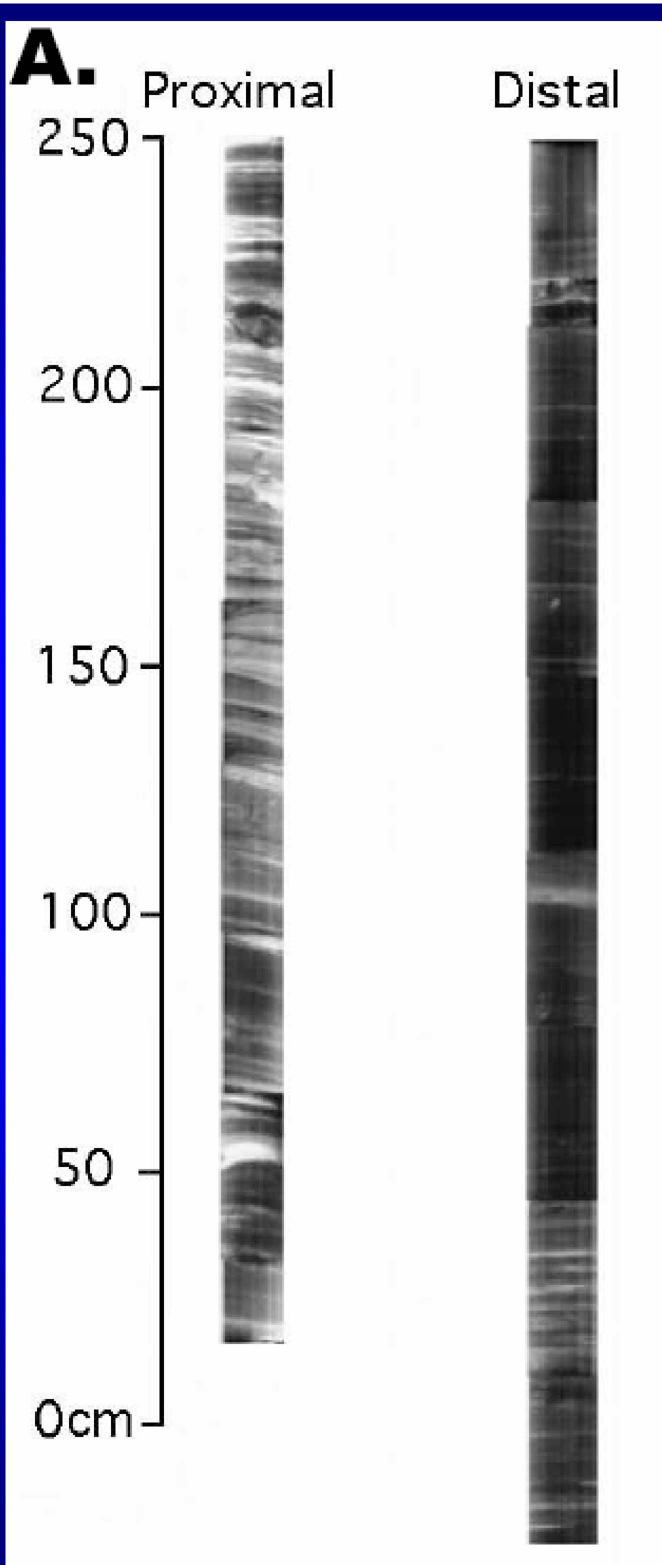
Types of Hyperpycnites

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.**
- **Low level of burrowing**
- **Normal grading**
- **Some cross lamination**

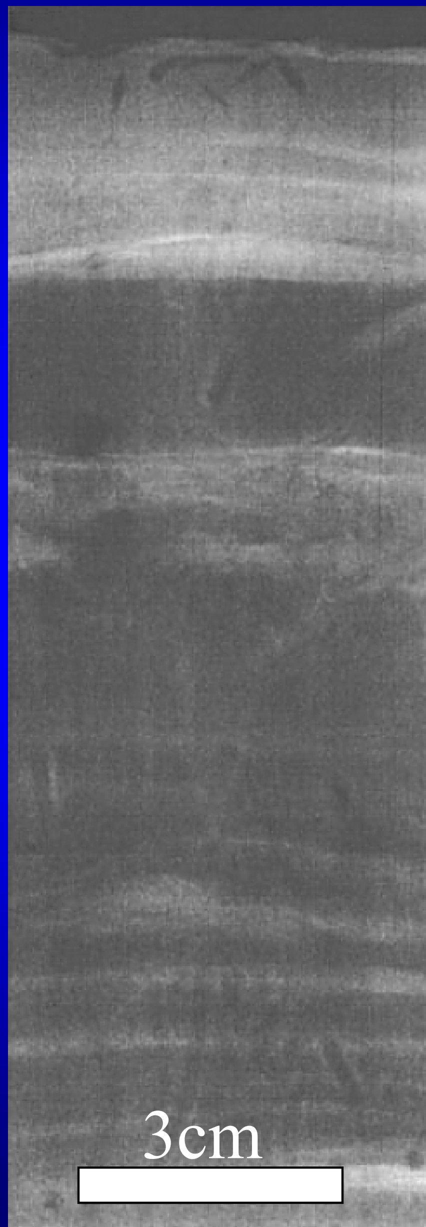
From Bhattacharya and MacEachern after Allison and Neill, 2003

Hyperpycnites

Eel

Mullenbach and Nittrouer, 2000

Atchafalaya



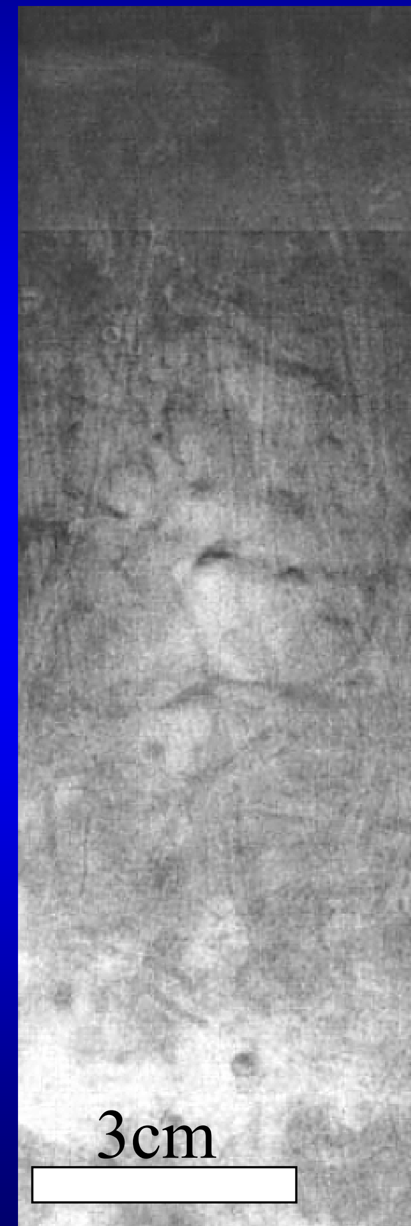
Allison et al., 2000

Modern examples of hyperpycnal flow deposits:

- **Criteria for recognition:**
  - **Graded beds**
  - **Limited burrowing**
  - **Dewatering**
  - **Cross lamination (indicating bedload transport and wave reworking)**

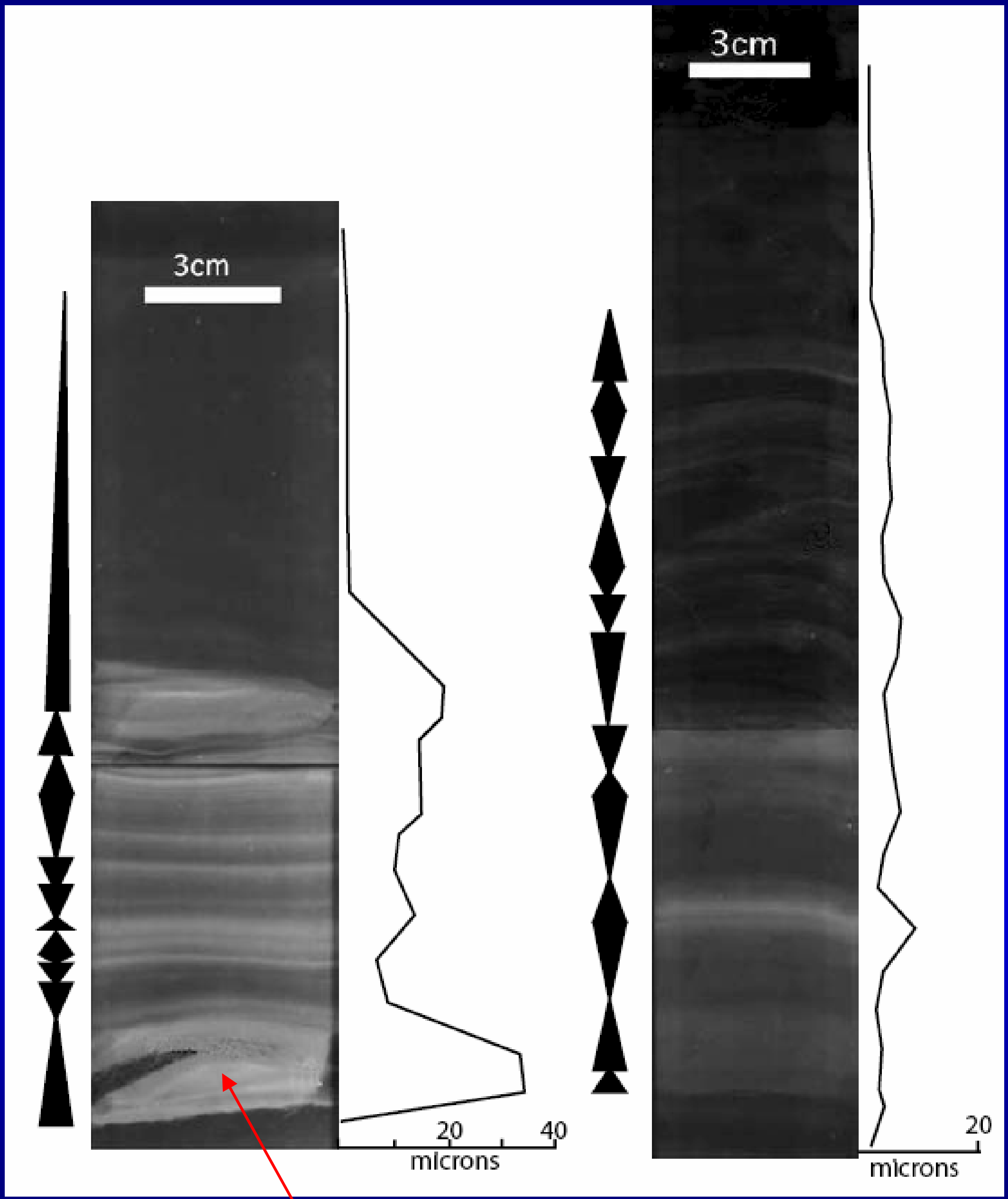
Offshore Shelf

Atchafalaya



Allison et al., 2000

Modern Hyperpycnites from Japan

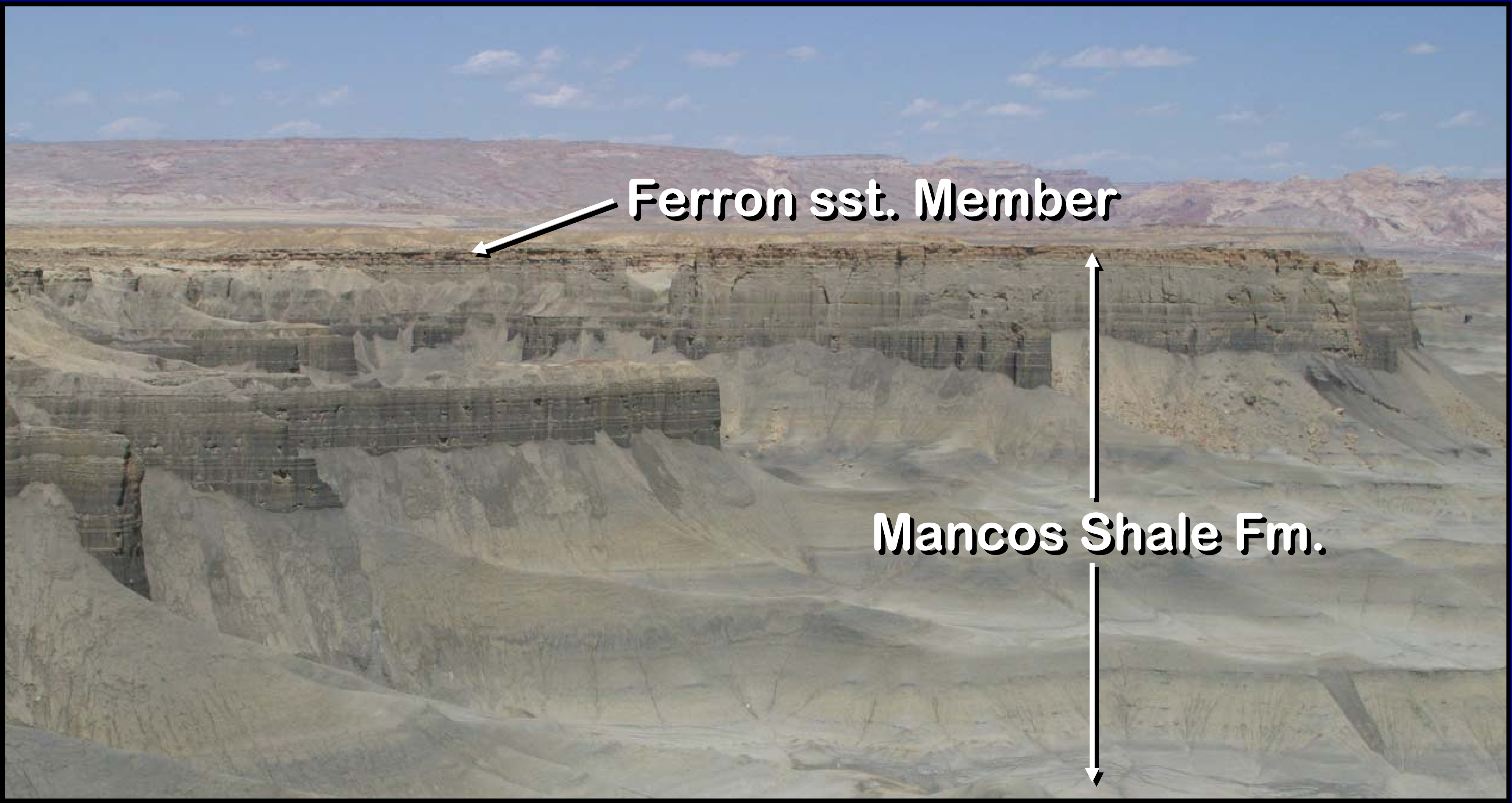


Note cross lamination

- These are deposited 700 km from the shoreline in 3000m water depth.
- Note inverse and normal grading

From Bhattacharya and MacEachern after Nakajima, 2006

What about the Cretaceous in Utah?



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

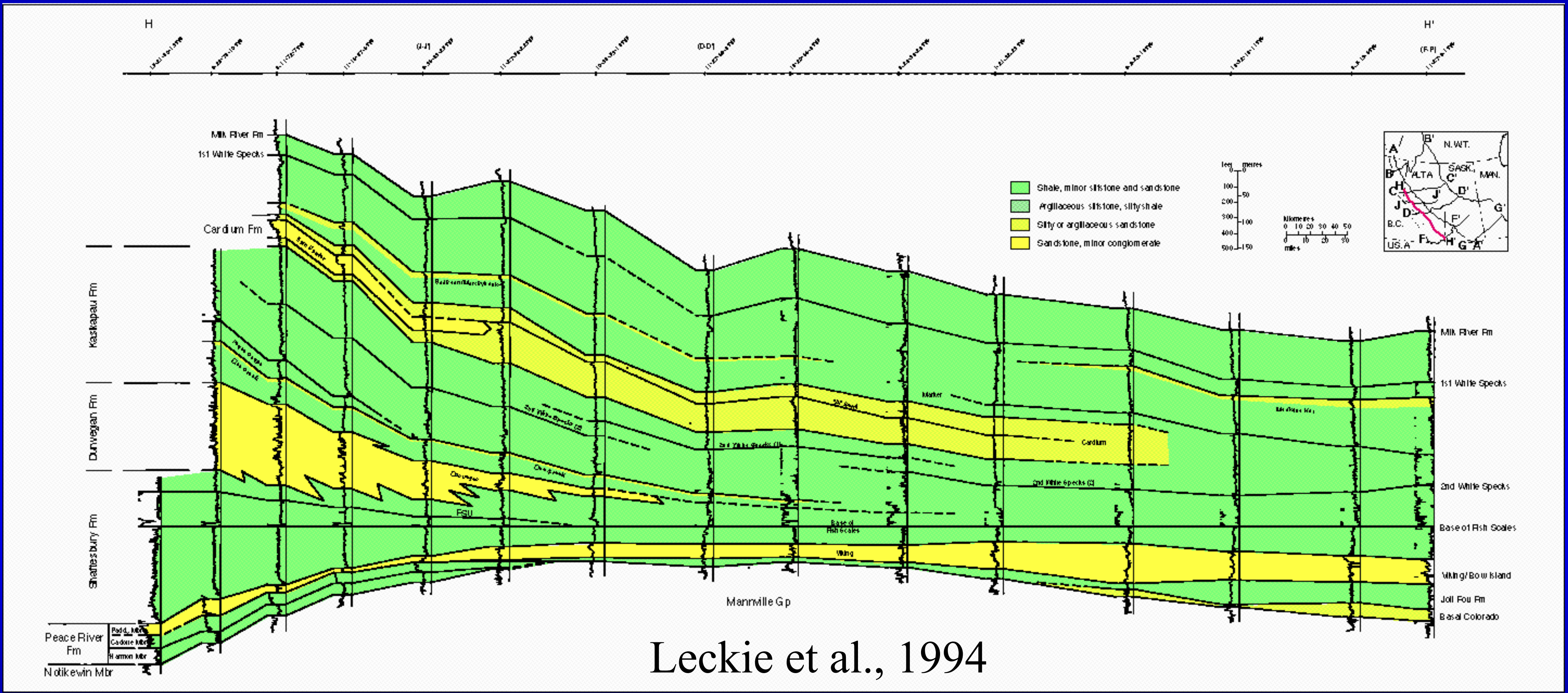
Key Problems

- Are hyperpycnal processes important in building the stratigraphic record?
- Can modern examples be used to interpret ancient "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.

What do the rocks look like?

- **Prodelta to delta-front facies successions form upward-coarsening deposits**

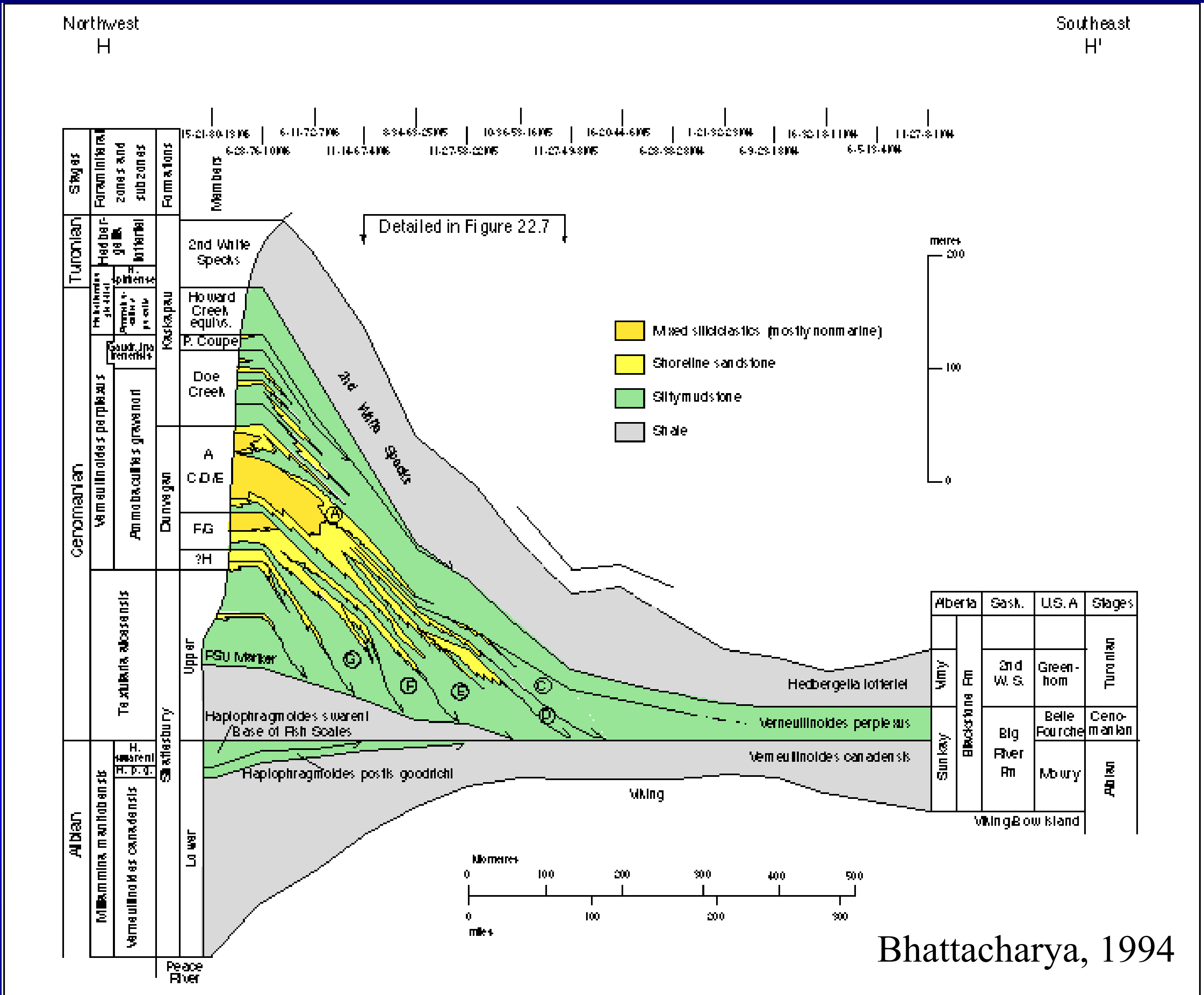
Colorado Alberta Gp. Shales, Western Canada Sedimentary Basin, Alberta



Leckie et al., 1994

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

Dunvegan Fm., Alberta



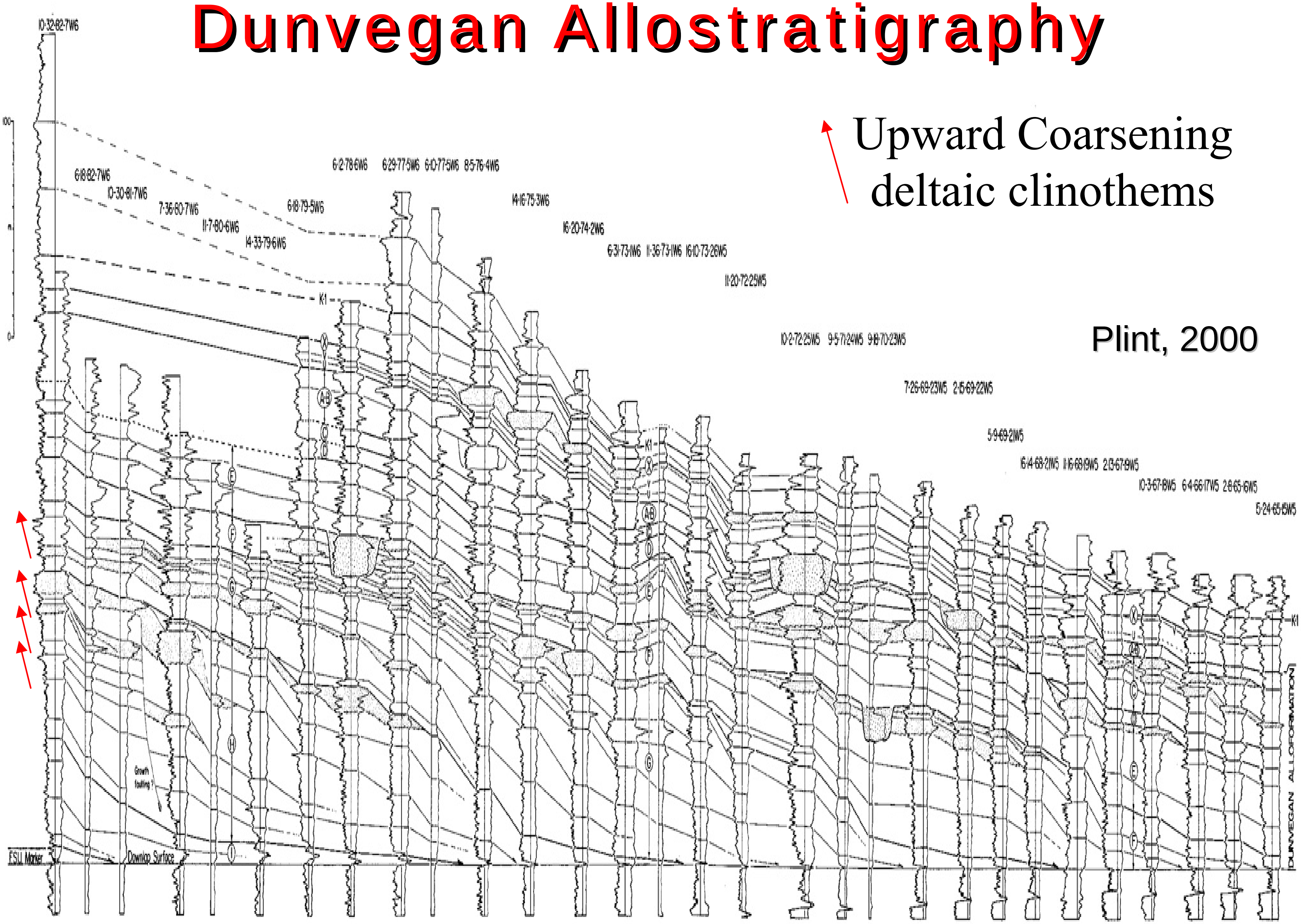
Bhattacharya, 1994

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

Dunvegan Allostratigraphy

Upward Coarsening deltaic clinothems

Plint, 2000



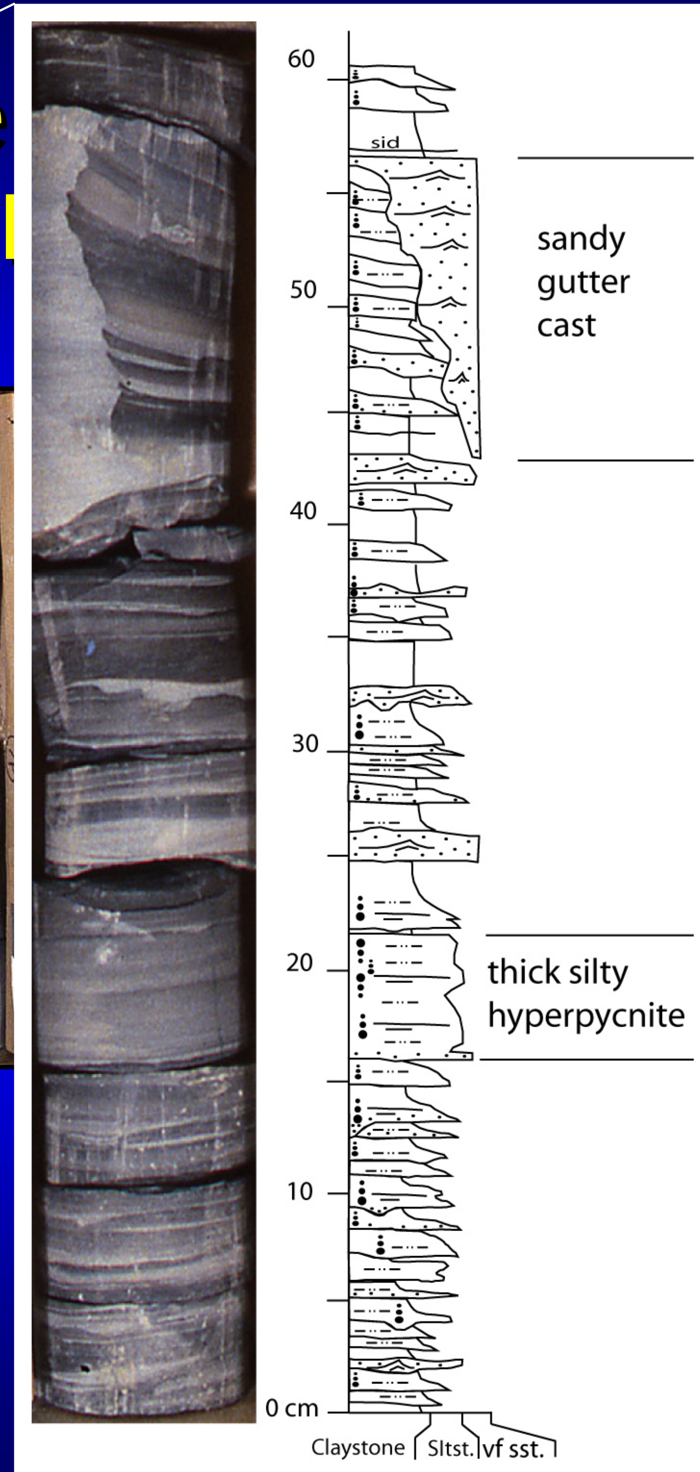
- Wedge-shaped formations show clinoforms.
- Tabular organic-rich units show a more “railroad track” style of correlations in well logs.

Cretaceous Prodelta Facies, Dunvegan Fm.

Prodelta **Delta Front**

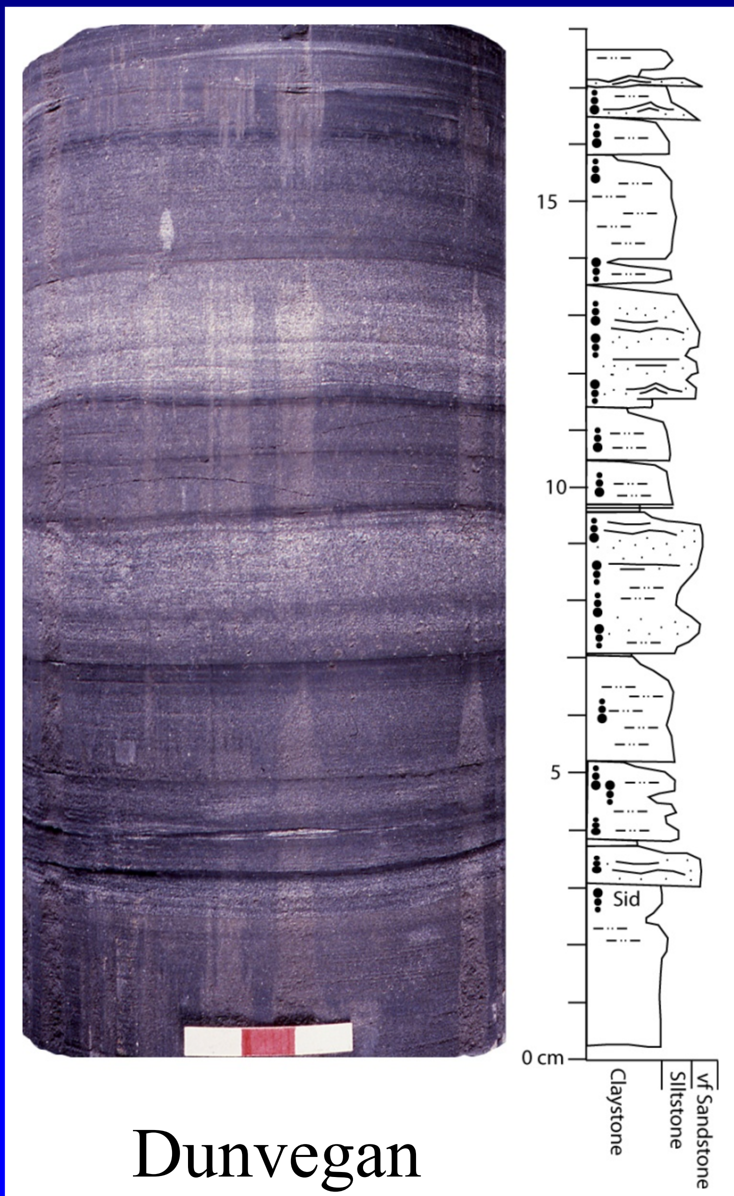
Facies in a clinoform deposit

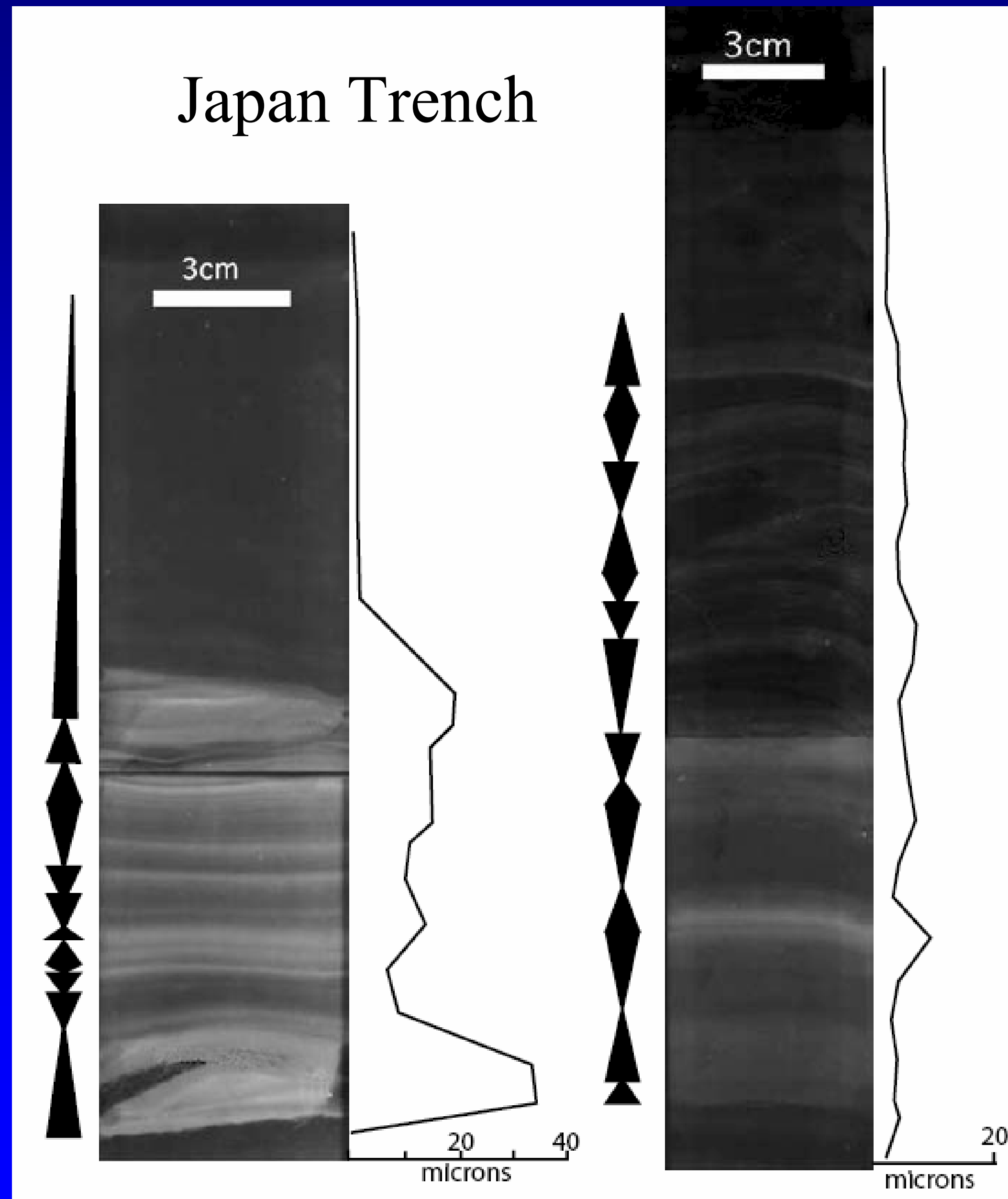
Cretaceous Prode
Dunvegan I



Prodelta Facies

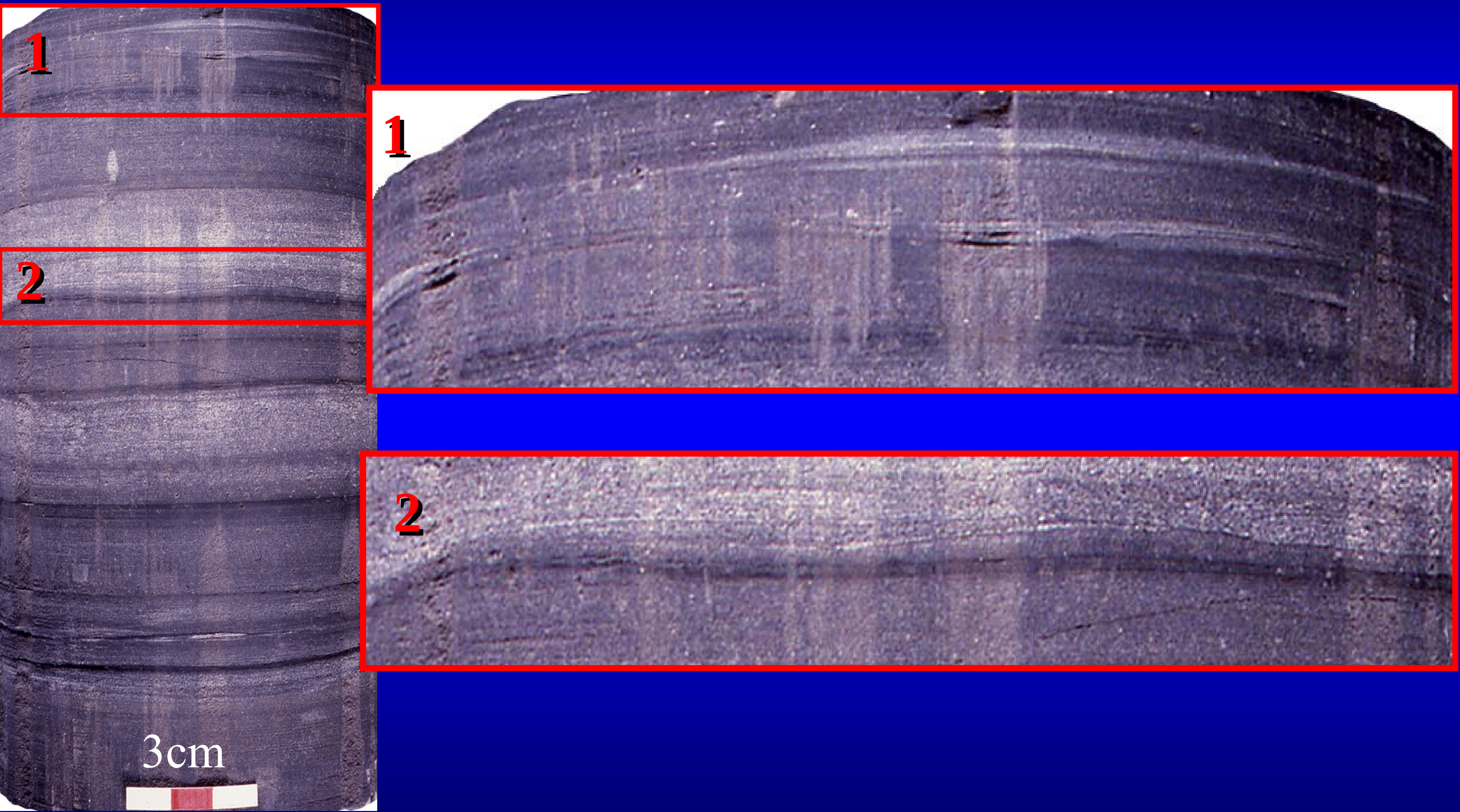
- **Normal and inverse graded siltstones and very fine ssts.**





From Bhattacharya and MacEachern (2009) after Nakajima, 2006

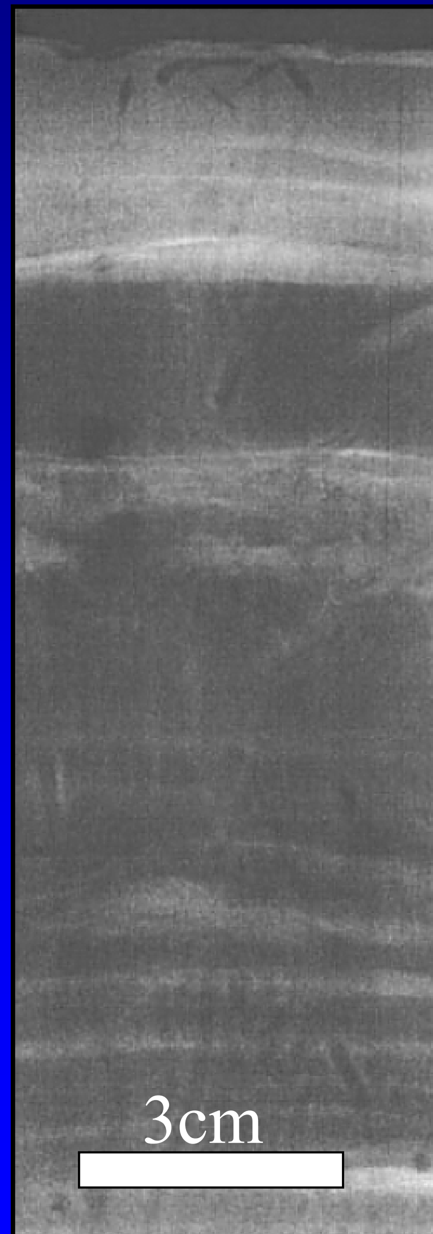
Low-angle cross lamination also suggests mud ripples



Prodelta Facies

- **Lack of burrowing reflects fluvial influence (high sedimentation rate).**

Dunvegan prodelta

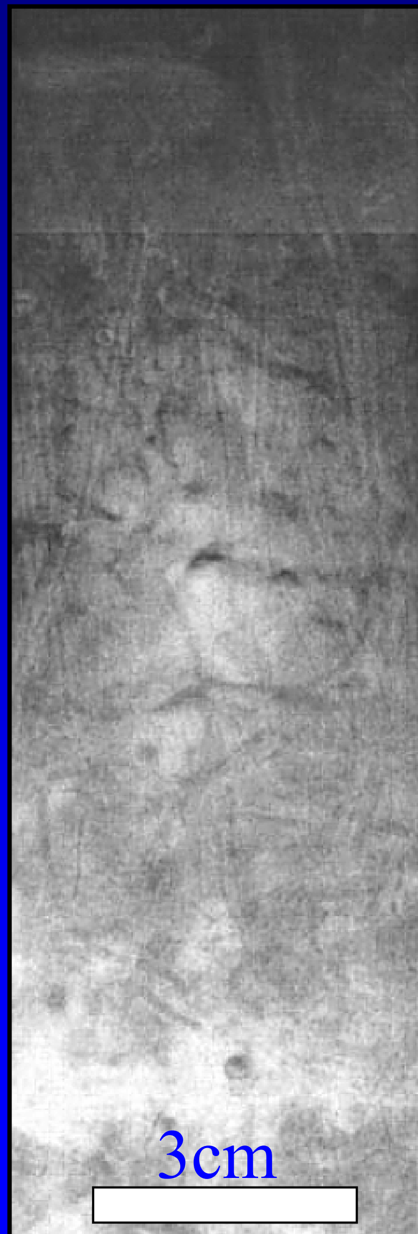


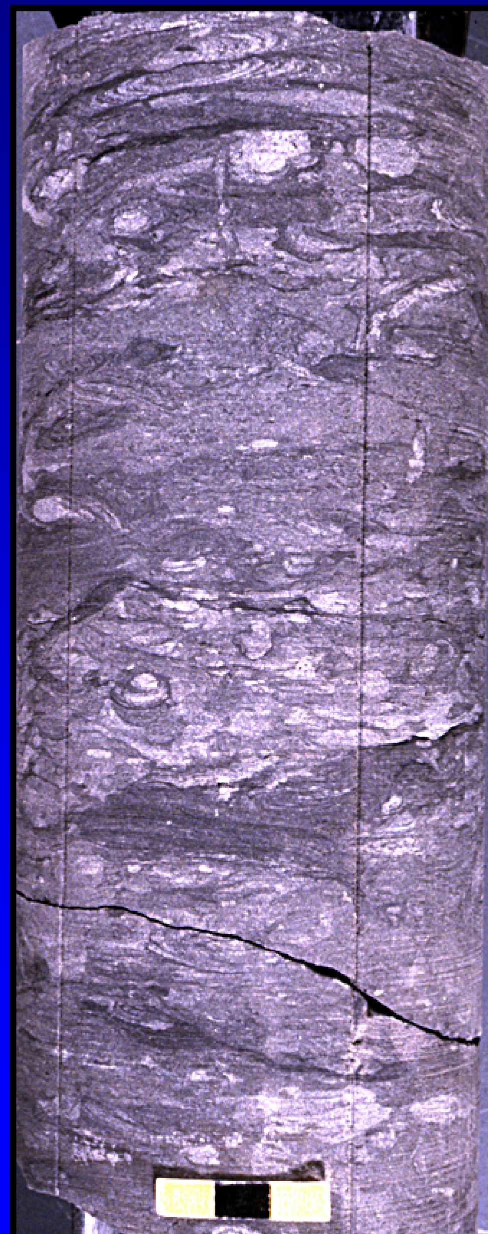
Atchafalaya Prodelta

Prodelta Facies

- Higher burrowing non-deltaic shelf (lower sedimentation rate).

Burrowed offshore shelf muds from Atchafalaya resemble non-deltaic Dunvegan facies.

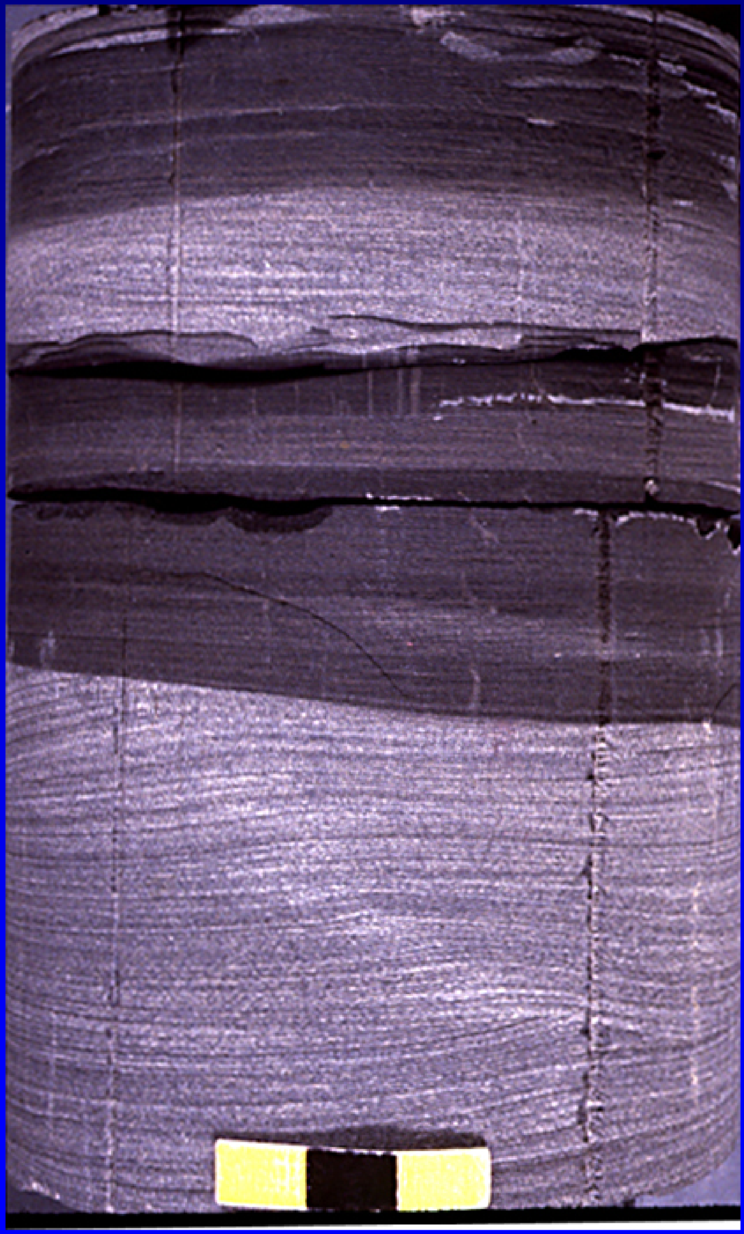




Highly burrowed shelf mudstones, Cretaceous Dunvegan Formation, Alberta. Slow sedimentation rates indicate far from fluvial influence.

Low burrowing and wave ripples suggest wave-aided transport

Wave-rippled sandstones and interbedded lightly burrowed laminated mudstones, Cretaceous Dunvegan Formation, Alberta.



Aggrading wave ripples suggest rapid sediment fall-out during a significant storm.

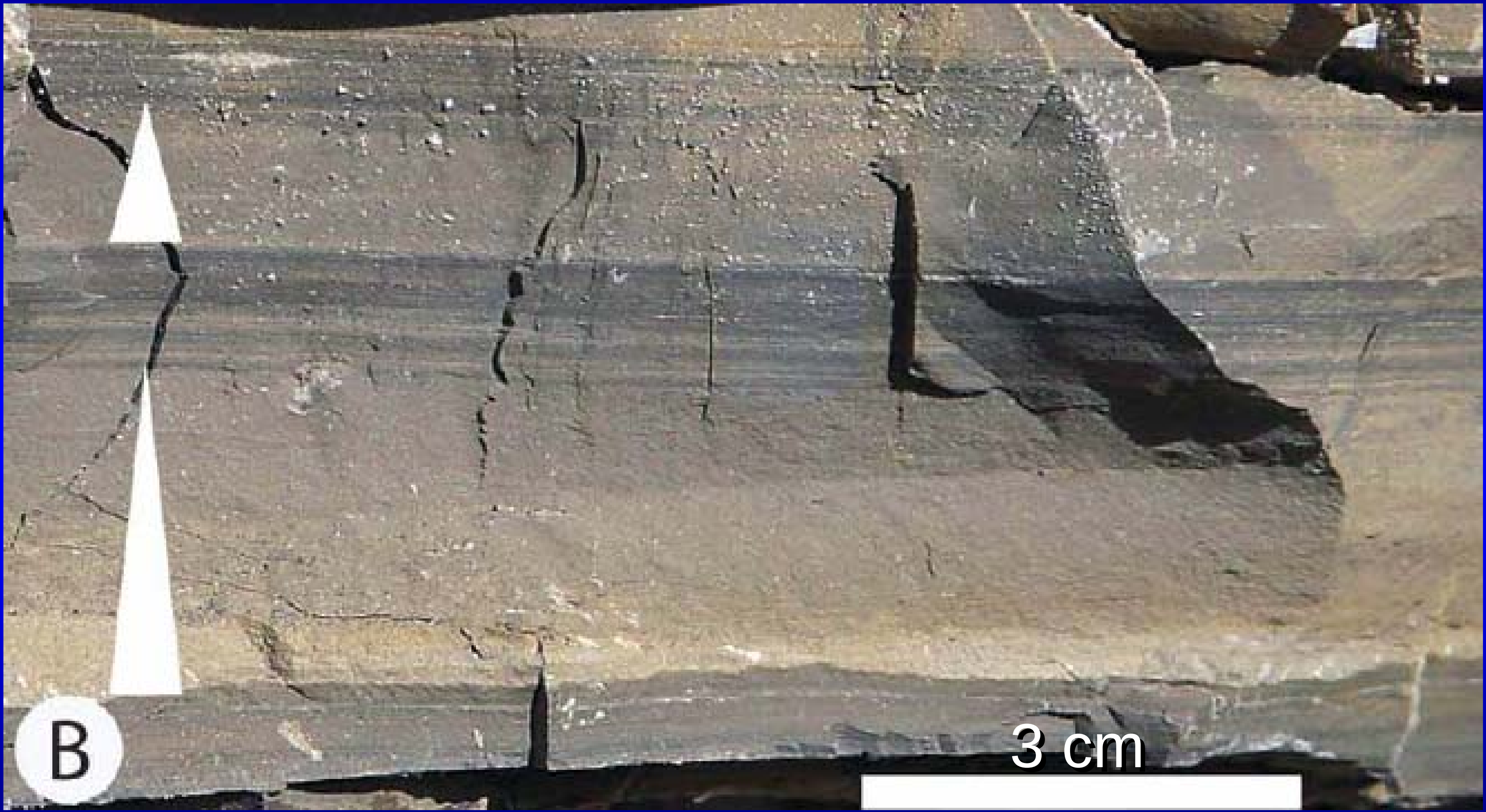
Ferron prodelta facies

Note graded siltstone beds that lack burrowing

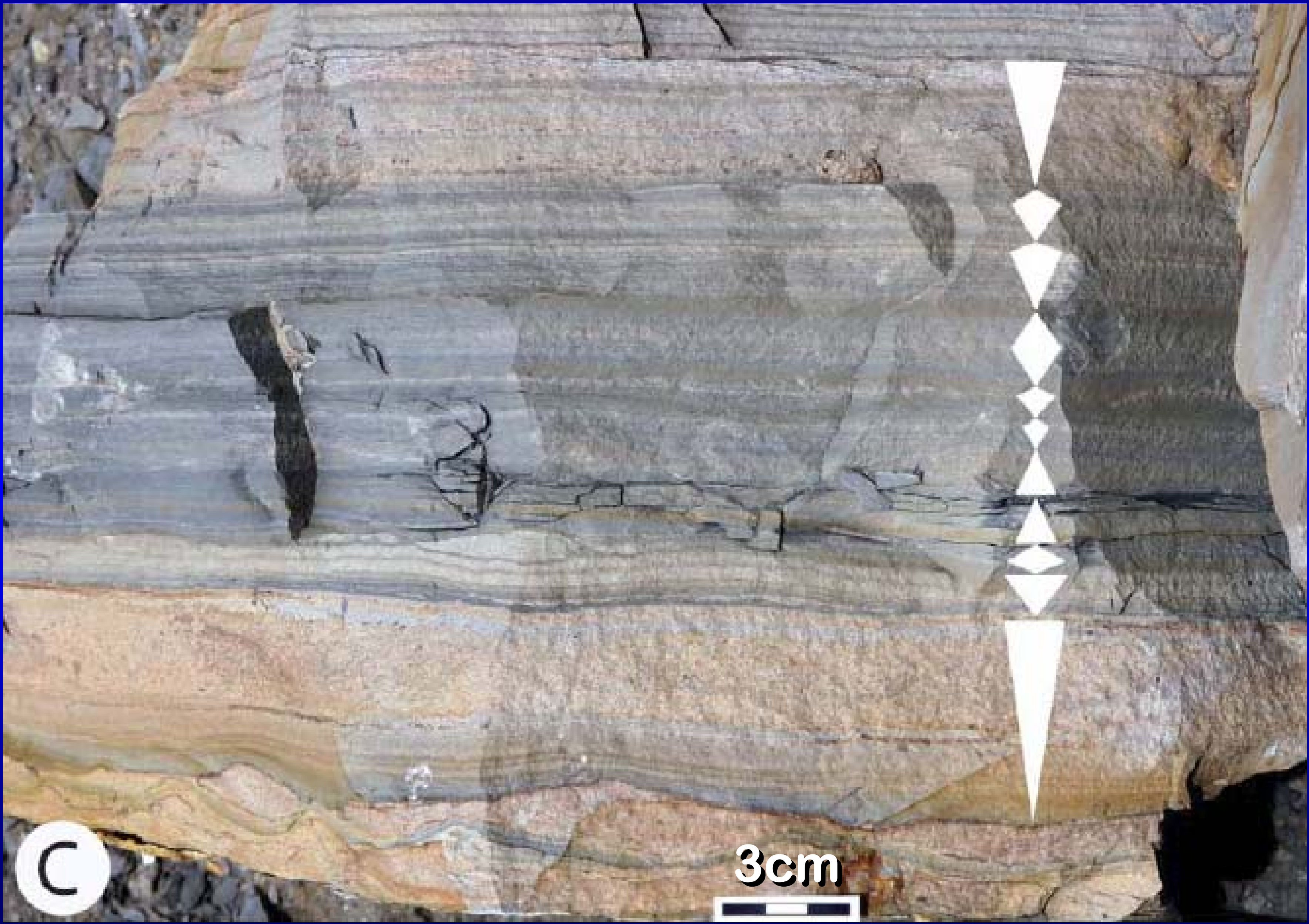
Close-up of Ferron prodelta facies

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

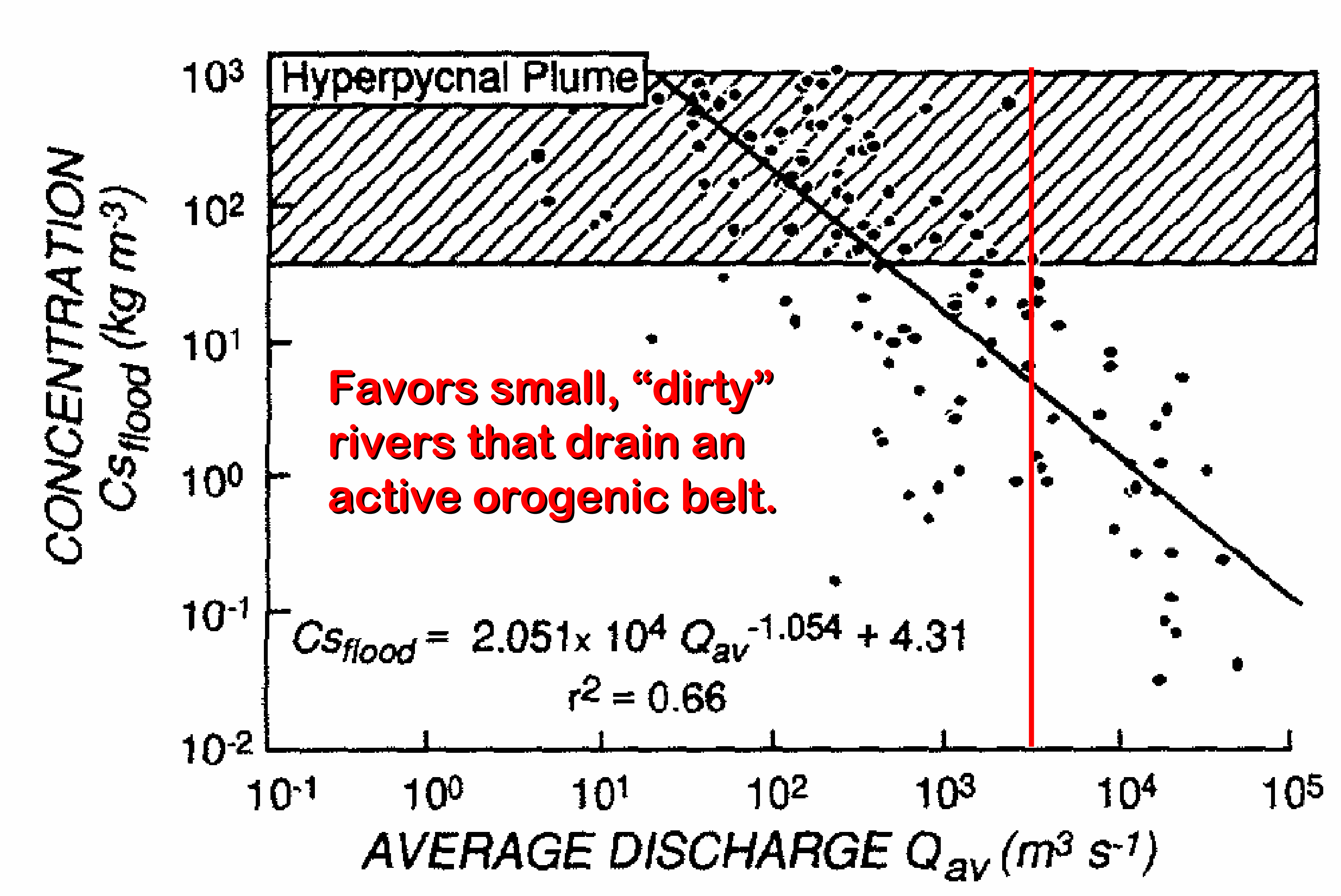
Close-up of Ferron prodelta facies



Normal and inverse grading suggests hyperpycnal flows



Theory: Hyperpycnal Flows less likely in rivers with discharge > 6,000m³/s



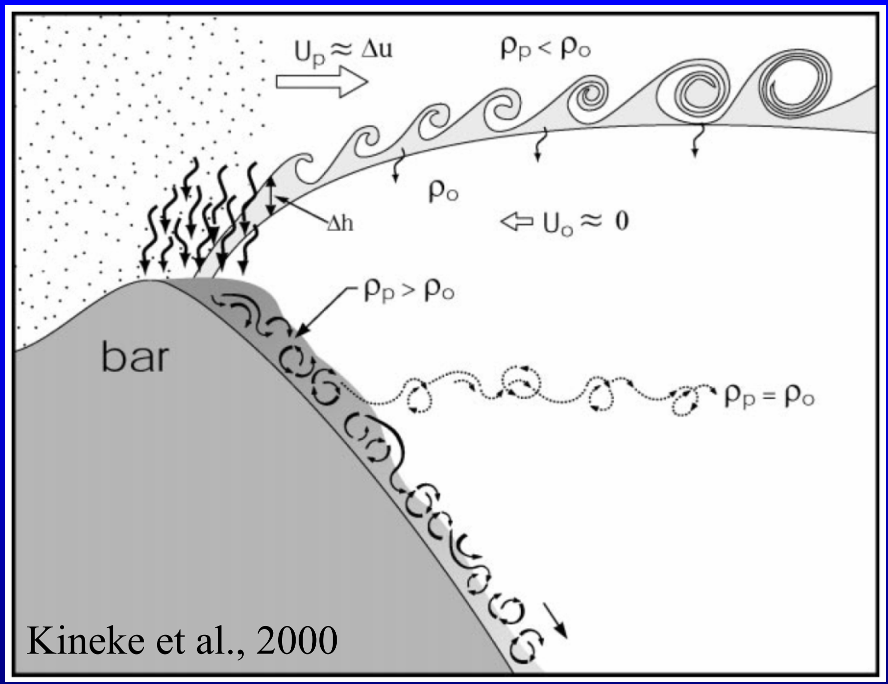
Mulder and Syvitsky, 1995

What is needed for hyperpycnal flows

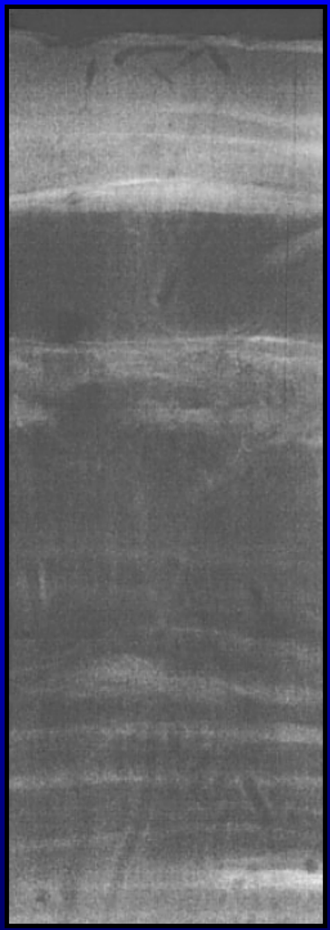
- **High Relief**
  - **Rocky Mountains**
- **High Rainfall**
  - **Humic paleosols, abundant coals and wetlands, tropical to temperate climate, global greenhouse.**
- **Small to intermediate, dirty mountain rivers**
- **Brackish coastal area**
  - **Stormy, shallow, epeiric sea**
- ***Cretaceous interior seaway has all of these essential characteristics to generate hyperpycnal flows.***

Conclusions

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

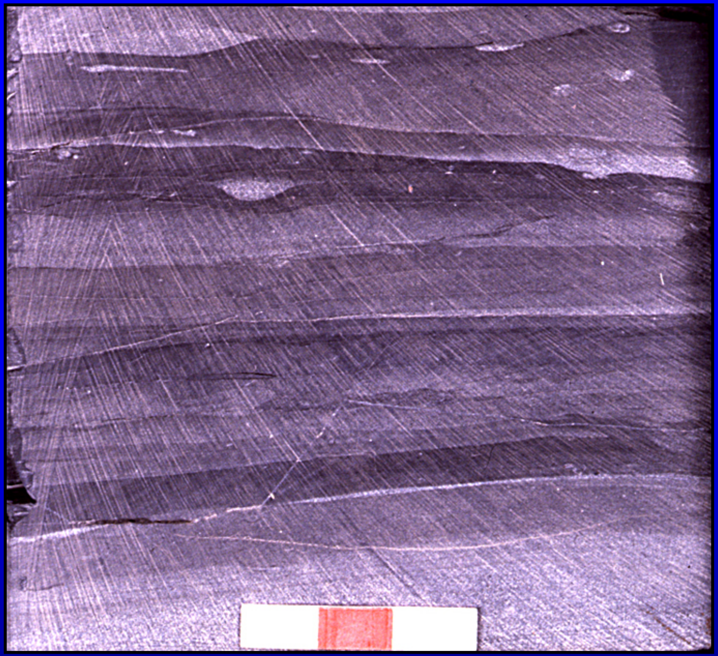


Kineke et al., 2000



Conclusions

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



Dunvegan Prodelta

Ferron Prodelta

Conclusions

- **50% of “shelf” mud may be hyperpycnal.**