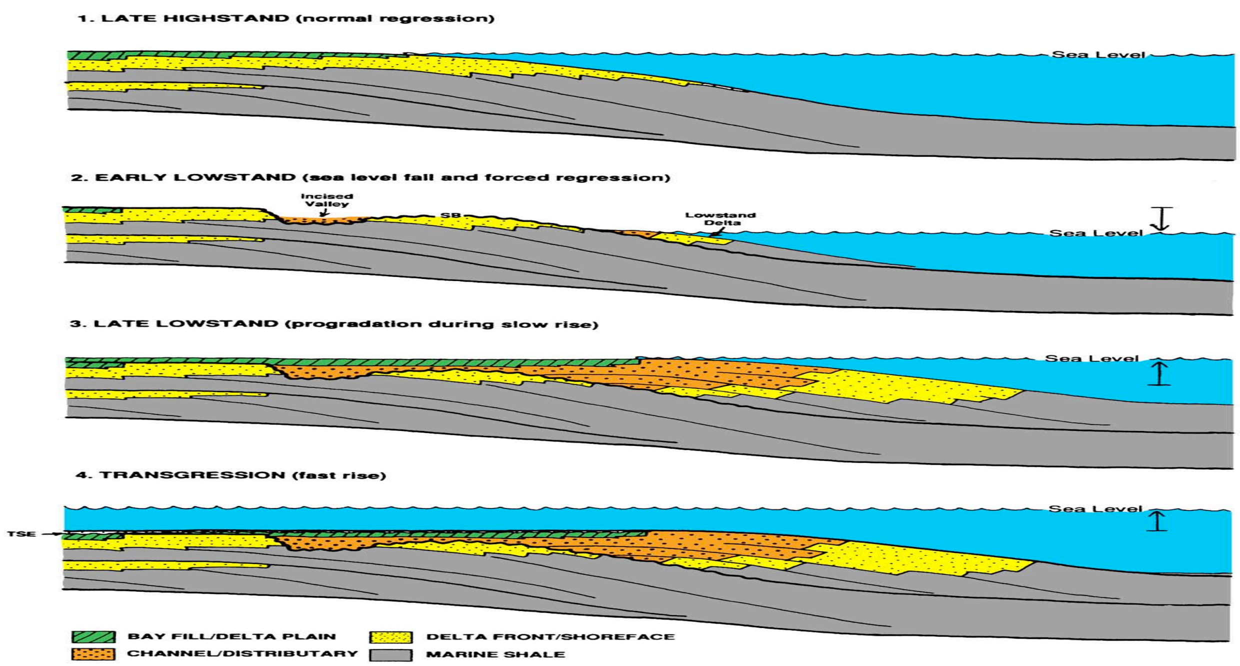
Sequence Stratigraphy: History, Theory and Applications

Dr. Janok P. Bhattacharya
Robert E. Sheriff Professor of Sequence Stratigraphy
University of Houston



AAPG SW Section Short Course
December 3 and 7th
Abilene/Fort Worth

Purpose:

This course is designed for exploration/production geologists and geological managers or reservoir engineers. The course will give you an overview of the history of stratigraphy from traditional lithostratigraphy and biostratigraphy through seismic stratigraphy, sequence stratigraphy and allostratigraphy. The course provides both a theoretical understanding of how sequences and systems tracts form as well as a practical methodology for undertaking stratigraphic systems using outcrop, core, well log, and seismic data. The course will be a combination of lectures and practical exercises.

Examples will be comprehensive and include seismic data, well logs, outcrops and cores from petroleum basins around the world. Students are encouraged to bring examples of their own work or data sets as discussion points.

Course Content & Major Topics

1. Introduction: Types of Stratigraphy
2. Base level concepts (accommodation and accumulation)
3. History of Sequence Stratigraphy
4. Seismic Stratigraphy
5. Sequence Stratigraphy Concepts
6. Sequence Stratigraphic Methodology
7. Shallow Marine Sequence Stratigraphy
8. Fluvial Sequence Stratigraphy and Incised valleys
9. Deep Water Sequence Stratigraphy

Instructor Biography:
Janok P. Bhattacharya is the Robert E. Sheriff Professor of Sequence Stratigraphy at the University of Houston. His research interests include fluvial and deltaic sequence stratigraphy and facies architecture, and the local control of structure on stratigraphy. He received his B.Sc. in 1981 from Memorial University of Newfoundland, and Ph.D. in 1989 from McMaster University, Hamilton, Ontario, both in Canada. Bhattacharya worked for ARCO and then the Bureau of Economic Geology at Austin before becoming a professor at the University of Texas at Dallas in 1998. He joined UH in the Fall of 2005. He has worked on a number of major fluvio-deltaic reservoirs, including the Supergiant Prudhoe Bay field in Alaska, for which he was awarded the ARCO Exploration Research and Technical Services Award of Excellence for Major Impact on Operations in 1993. He has won best speaker awards for talks on his deltaic outcrop analog work, presented to the AAPG, CSPG and Houston Geological Society and was the technical program coordinator for the 2004 Annual AAPG conference in Dallas. He was a 2005-2006 AAPG distinguished Lecture. In 2005 he was awarded an AAPG SW Section Distinguished educator award and in 2007 was awarded the AAPG Grover Murray Distinguished Educator Award. He is the 2007 GCSSEPM President-elect and SEPM Vice-Chair for the 2008 Annual AAPG Meeting. He has authored or co-authored over 40 technical papers and over 100 abstracts.

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Course Materials can be downloaded at: http://www.qsc.uh.edu/courses/index.php

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- The course provides both a theoretical understanding of how sequences and systems tracts form as well as a practical methodology for undertaking stratigraphic studies using outcrop, core, well log, and seismic data.

Syllabus: Topics

1. Introduction: Types of Stratigraphy
2. Historical Foundations of Sequence Stratigraphy
3. Seismic Stratigraphy
4. Sequence Stratigraphy Concepts
5. Surfaces
6. Sequence Stratigraphic Methodology
7. Base Level Controls
8. Shallow marine sequence stratigraphy
9. Fluvial Sequence Stratigraphy and Incised valleys
10. Deep Water Sequence Stratigraphy

How many types of stratigraphy can you name?

How many types of stratigraphy can you name?

- Lithostratigraphy
- Allostratigraphy
- Sequence Stratigraphy
  - Genetic Sequence stratigraphy
  - Depositional sequence stratigraphy
- Biostratigraphy
- Chronostratigraphy
- Cyclostratigraphy
- Magnetostratigraphy
- Pedostratigraphy
- Event Stratigraphy
- Morphostratigraphy

Formal Schemes

- Lithostratigraphy
- Allostratigraphy
- Sequence Stratigraphy
  - Genetic Sequence stratigraphy
  - Depositional sequence stratigraphy
- Biostratigraphy
- Chronostratigraphy
- Cyclostratigraphy
- Magnetostratigraphy
- Pedostratigraphy
- Event Stratigraphy
- Morphostratigraphy

Informal Schemes

- Lithostratigraphy
- Allostratigraphy
- Sequence Stratigraphy
  - Genetic Sequence stratigraphy
  - Depositional sequence stratigraphy
- Biostratigraphy
- Chronostratigraphy
- Cyclostratigraphy
- Magnetostratigraphy
- Pedostratigraphy
- Event Stratigraphy
- Morphostratigraphy

Formal Stratigraphy

Lithostratigraphy

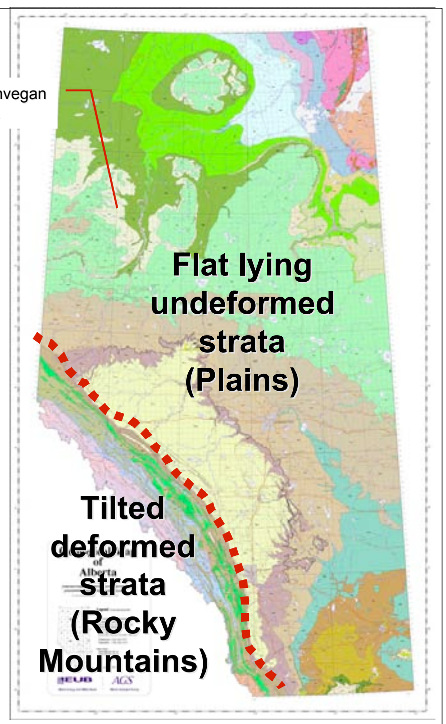
- Defined on basis of lithologic properties.
- Strataform bodies (i.e. sedimentary).
- Groups, Formations, Members, Beds.

Lithostratigraphy (NACSN)

- Traditional scheme available for formally naming rock units defined on the basis of:
  - lithology
  - distribution
  - age
  - stratigraphic position (typically in 1D vertical successions).
- Emphasizes mappability.
- Concept defined prior to availability of extensive subsurface data (e.g. seismic, well log, core).

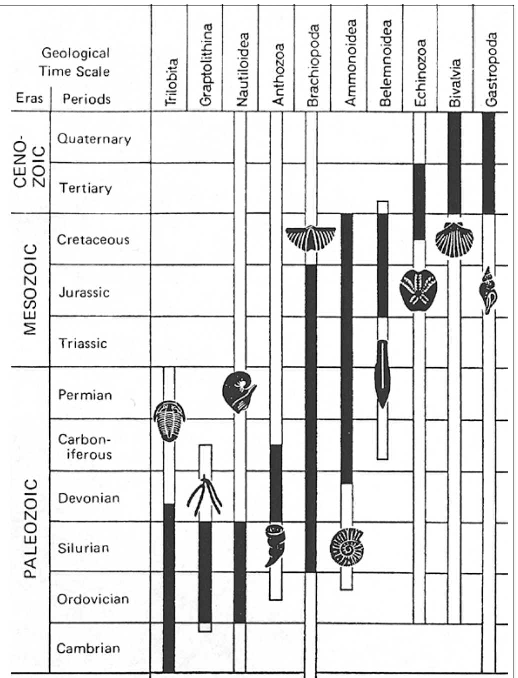
Mappability

- 1800-1940
  - Plan-view representation of intersection of rocks and strata with land surface.
- Emphasis on 1:50,000 topo mapping by geological surveys.
- Emphasis on mapping in outcrop.
  - Many formations defined prior to availability of extensive subsurface data (e.g. seismic, well log, core).



Biostratigraphy

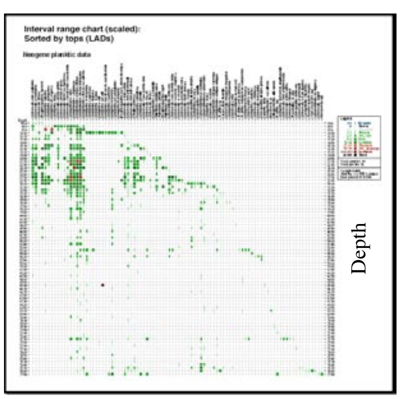
- **Formal Stratigraphic scheme**
- **Defined on basis of fossils and faunal succession**
- **e.g. Biozones.**



From Boggs (2005) after Thenius (1973)

Biostratigraphy

- Occurrence Chart



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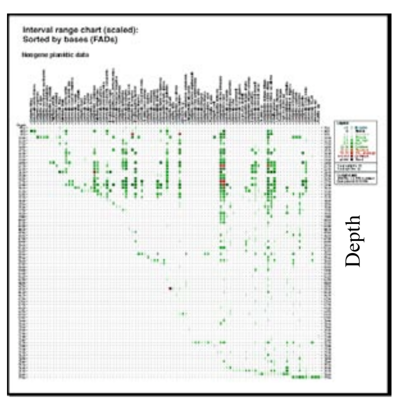


Courtesy Pierre Zippi

Informal Stratigraphy

Informal Stratigraphy

- Reflects the increasing importance of subsurface data and cross sectional views of sedimentary basins, rather than map-view.
- Importance of recognition of cyclic alternation of facies organized into larger scale stratigraphic packages.
- Reflect explosion of facies sedimentology in analysis of stratigraphic units.

Informal Stratigraphy

Some Informal Schemes

- Seismic Stratigraphy
  - Large-scale stratal packages identified on the basis of stratal geometry, seismic character (facies) and lapout relationships (Unconformities).
- Sequence Stratigraphy
  - Study of unconformity-bounded “sequences” in the context of accommodation and accumulation concepts.
- Event Stratigraphy
  - Mapping and correlation of specific beds or events (e.g. surfaces, bentonites, turbidites, storm beds).
- Cyclostratigraphy
  - Study of cyclic sedimentary packages driven by apparently cyclic phenomena (e.g. Milankovitch cycles, climate cycles).

Informal Stratigraphy

Earlier Informal Schemes

- **Formats** (Forgotson, 1957)
  - **well log marker defined units.**
- **PACS** (Goodwin & Anderson, 1985)
  - **punctuated aggradational cycles.**
- **GIS** (Busch, 1971)
  - **genetic increments of strata.**

Major Questions

- **What is the purpose of stratigraphy**
  - **Coherent naming of units?**
    - **There is glory in being the peron who names something!**
    - **Too many names causes confusion.**
  - **Correlation of units?**
    - **Rock versus time?**
  - **Exploration for reservoir?**
    - **Need to understand all the stratigraphic elements of the Petroleum System,**
      - *Source, seal and trap.*
  - **Tool for mapping?**

Major Arguments

- What is the purpose of stratigraphy
  - If different lithostratigraphic units are the same biostratigraphic age, should they be called the same or different units?
  - This caused an age-old fight between the biostratigraphers and lithostratigraphers.
    - Correlation versus nomenclature.
  - Correlation implies the physical linkage of facies.
  - This is what sequence stratigraphy addresses.

11

Part 2.
Wheeler's Confusion and the Seismic Revolution: How Geophysics Saved Stratigraphy

Janok P. Bhattacharya
Robert Sheriff Professor of Sequence Stratigraphy
University of Houston

Outline

- A brief history of Sequence Stratigraphy
- Lithostratigraphy in the mid-20th Century
  - failure
- The Seismic Revolution
- Conclusion

Historical Perspective

Foundations

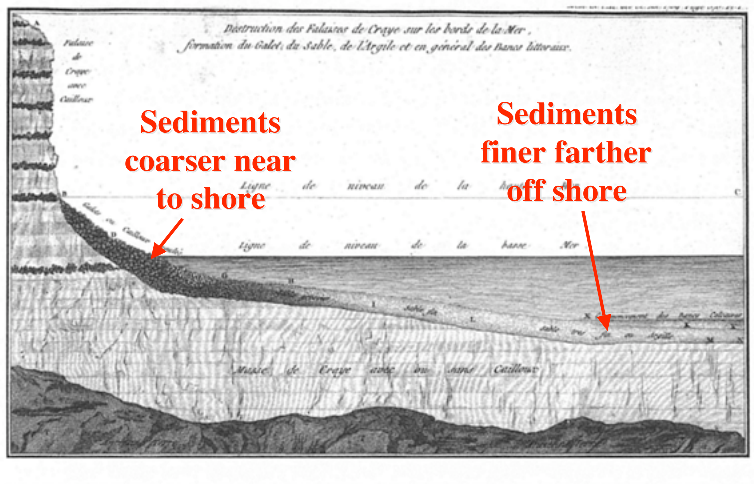
- Early worker's recognized importance of base-level as a control on sedimentation.
  - Antoine Lavoisier (1789)
  - Grabau (1906)
    - principles of sedimentary overlap
  - Barrell (1912, 1917)
    - defined concepts of base level and hiatuses
  - Blackwelder (1909)
    - recognized importance of unconformity-bounded sequences in North America

Historical Perspective

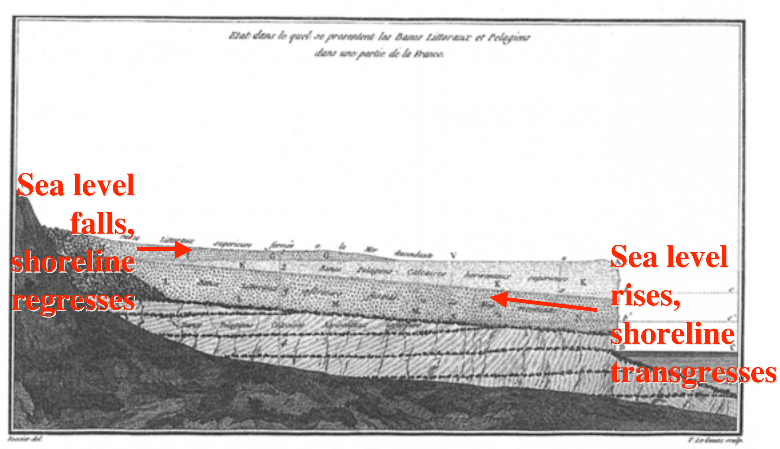
Founders of Sequence Stratigraphy

- Newer workers applied concepts to subsurface and presented more sophisticated schemes.
  - Harry Wheeler (1912?-1987)
    - Sequence concepts
  - Larry Sloss (1913-1996)
    - North American Sequence Stratigraphy
  - Daniel Busch (1972)
    - Genetic increments of strata (parasequences)
  - John L. Rich (1848-1956)
    - Fondoform, undaform and clinoform
  - Peter Vail et al. at Exxon
    - Applied Wheeler and Sloss ideas to interpretation of seismic data
    - Developed seismic stratigraphy

Antoine-Laurent Lavoisier (1789) recognized that sedimentary layers recorded distance from the shoreline.

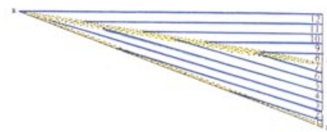


Lavoisier (1789) also recognized that Layers recorded rises and falls of sea level.

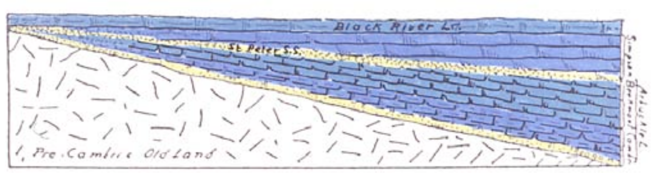


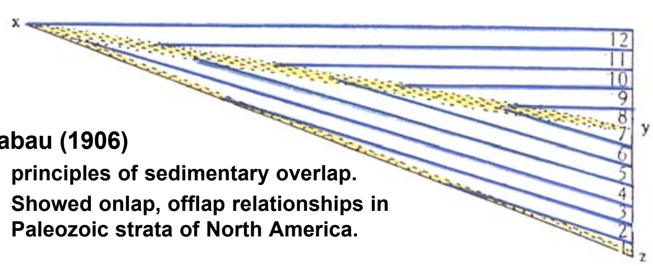
Amadeus W. Grabau

- Amadeus William Grabau 1870 - 1946
  - American stratigrapher
  - Principles of sedimentary overlap.
  - Showed onlap, offlap relationships in Paleozoic [illegible] North America.
  - Early authority on the Geology of China
  - MIT Faculty: 1892 - 1897
  - Rensselaer Polytechnical Institut, 1899- 1901
  - Died in Peking (Beijing) China



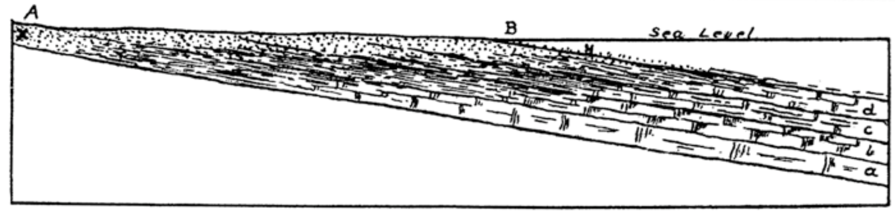
Amadeus Grabau

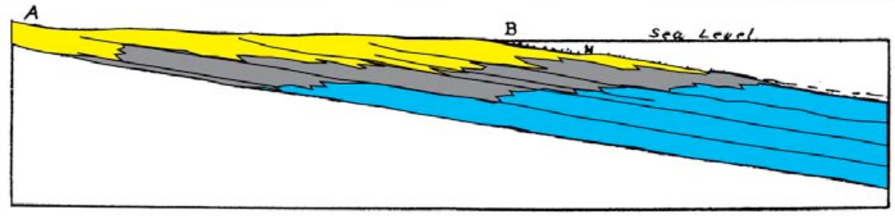




- Grabau (1906)
  - principles of sedimentary overlap.
  - Showed onlap, offlap relationships in Paleozoic strata of North America.

Offlap, facies and time lines

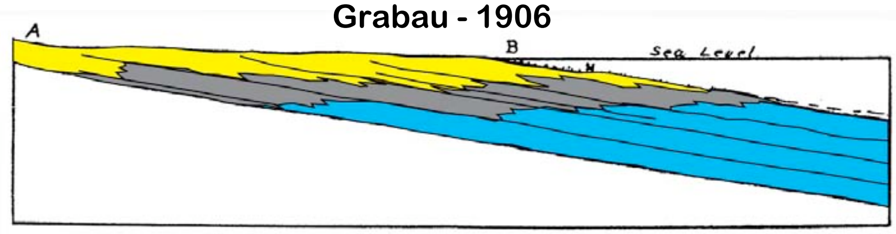




- Grabau (1906)
  - Showed offlap relationships in Paleozoic strata of North America.
  - Showed sequence stratigraphic relationships between facies and time in offlapping, regressive strata.

Offlap, facies and time lines - 94 years later

Grabau - 1906

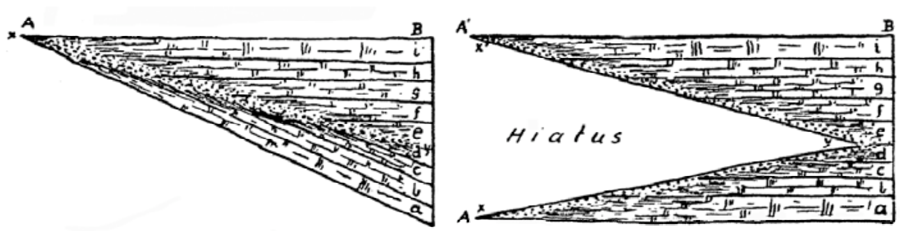


Van Wagoner et al., 1990

PROGRADATION OF PARASEQUENCE (**A**) DURING A TIME WHEN THE RATE OF DEPOSITION EXCEEDS THE RATE OF WATER-DEPTH INCREASE. BEDSETS COMPOSE THE PARASEQUENCE. THE YOUNGEST BEDSET SURFACE IS NONDEPOSITIONAL.

Historical Perspective

Time stratigraphy

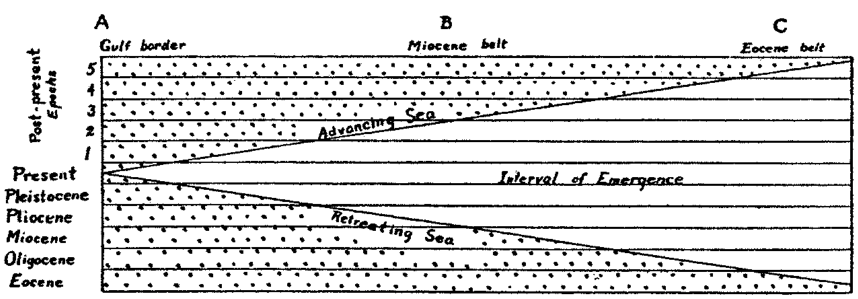


- Grabau (1906)
  - Illustrated time associated with a given unconformity.

Historical Perspective

Eliot Blackwelder

- Blackwelder (1909)
  - Extended Grabau's work and documented method to evaluate the time associated with an unconformity

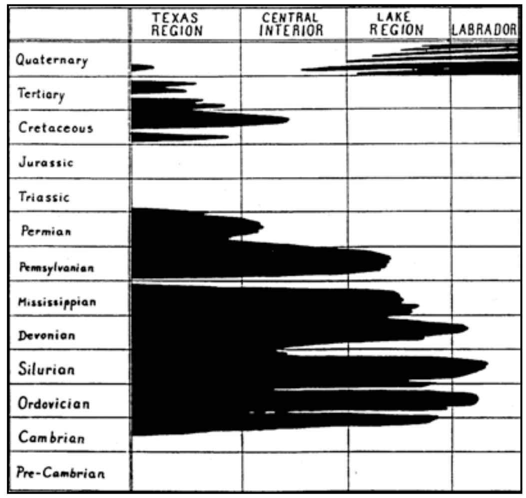


17

Historical Perspective

Continental Sequences

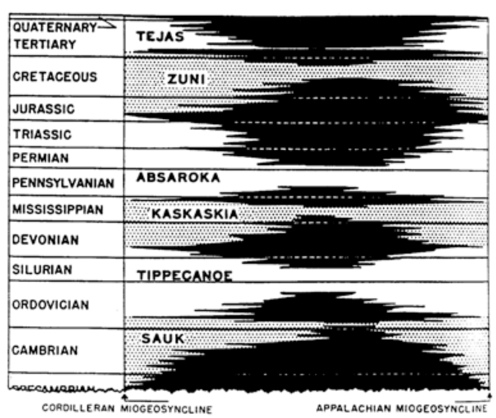
- **Blackwelder (1909)**
  - recognized importance of unconformity-bounded sequences in North America



Historical Perspective

Larry Sloss: Father of American Stratigraphy

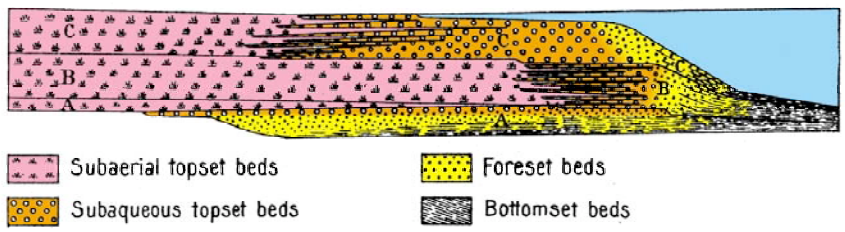
- Applied Blackwelder's and Wheeler's work to North America (1963).
- Named six major sequences in North American Stratigraphy, representing major tectono-eustatic events.
  - Sauk, Tippecanoe, Kaskaskia, Absaroka, Zuni, Tejas.
- Defined continent-wide unconformity-bounded units, which he termed sequences.
- Co-supervised graduate student Peter Vail at Northwestern University.



Historical Perspective

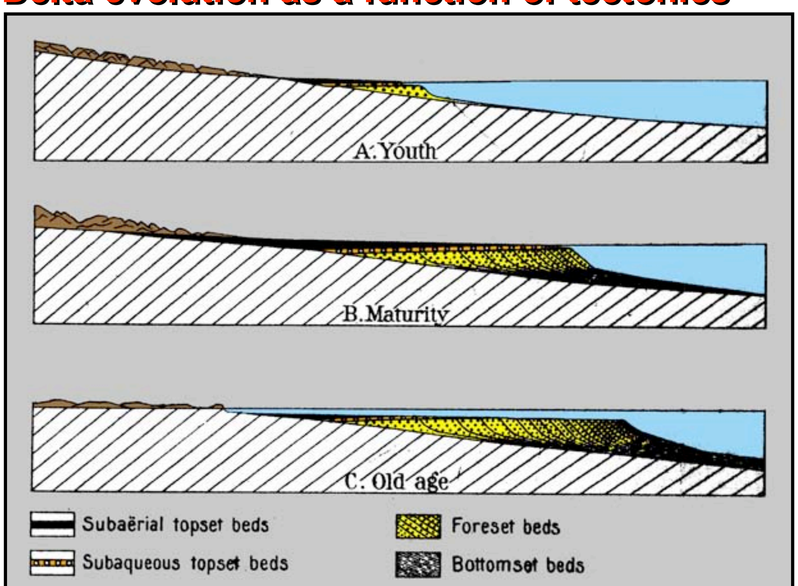
Joseph Barrell

- **Barrell (1912)**
  - **Showed evolution of deltaic facies as a function of changing subsidence**



Stage A: No sea level change (forestepping)
Stage B: Sea-level Rise = Accumulation (aggradation)
Stage C: Sea-level rise > Accumulation (backstepping)

Delta evolution as a function of tectonics



Barrell, 1912

Historical Perspective

Time in stratigraphy

- Barrell (1917)
  - recognized relationship between time and stratigraphy.
  - This figure was driven by early attempts to use sedimentation rates to calculate the age of the Earth.

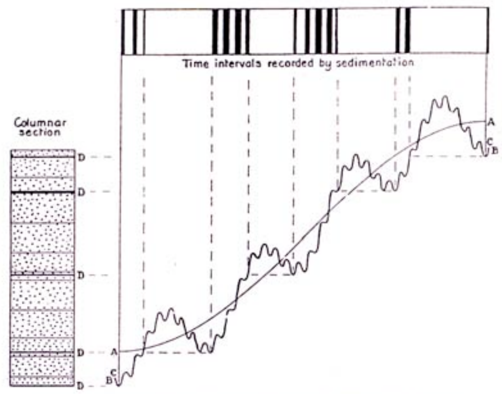


FIGURE 5.—*Sedimentary Record made by harmonic Oscillations in Baselevel*
A-A. Primary curve of rising baselevel.
B-B. Diastrophic oscillations, giving disconformities D-D.
C-C. Minor oscillations, exaggerated and simplified, due largely to climatic rhythms.

Foundations

- Van Wagoner et al. (1988) reproduced similar concepts.

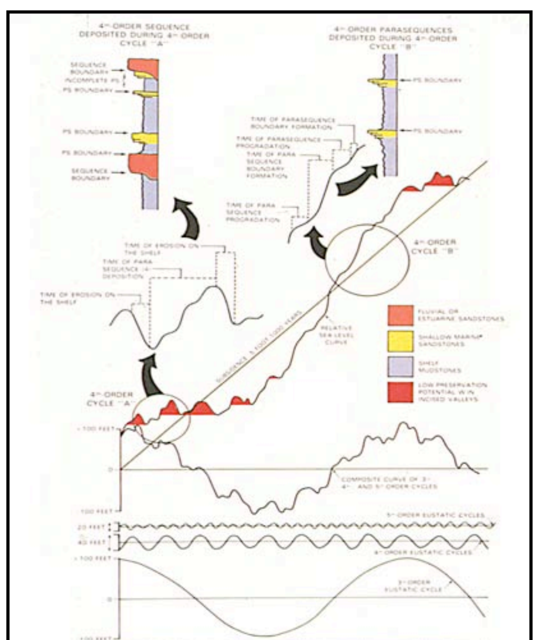
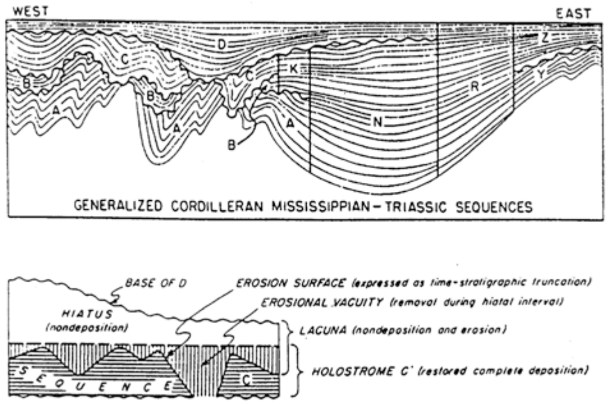


Figure 39—Interaction of eustasy and subsidence to produce parasequences and sequences.

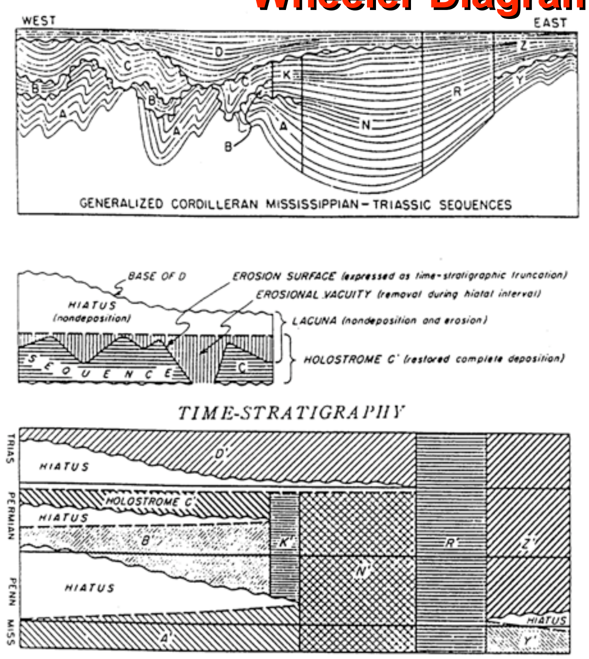
Historical Perspective

Harry Wheeler

- Wheeler depicted "exploded" stratigraphic cross sections with time on the vertical axis.
- Lacuna comprises time of non-deposition (hiatus) and time represented by rocks that once were there and have been eroded (vacuity).



Wheeler Diagrams



- Wheeler insisted on arbitrary vertical cutoffs to define different sequences.
- No correlative conformities.
- Unwieldy scheme resulted in a proliferation of sequence names!
- Why the confusion?

Wheeler, 1958

Historical Perspective

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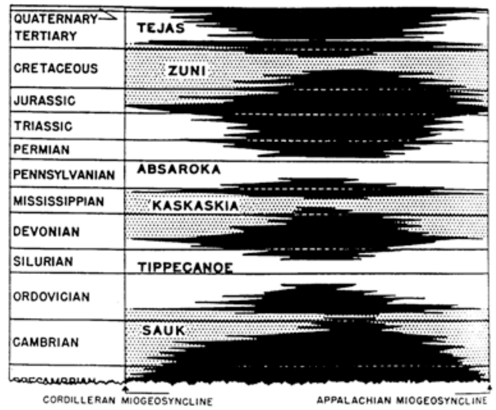

Historical Perspective

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- Mapped major unconformity bounded units across North America.

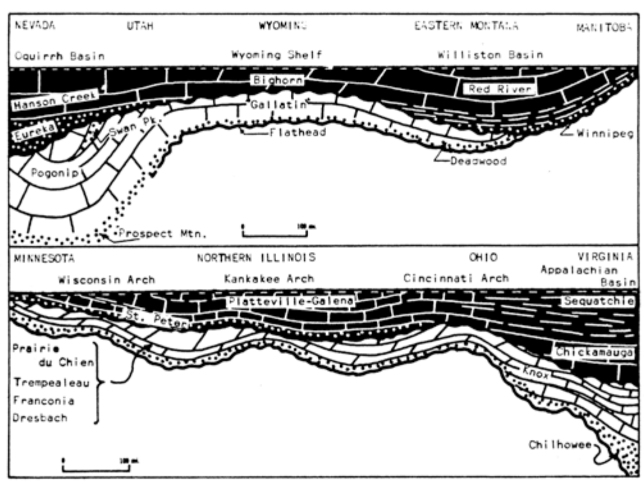

Figure 1. Diagrammatic cross sections of the Sauk Sequence (white) and the lower part of the Tippecanoe Sequence (black)

22

Historical Perspective

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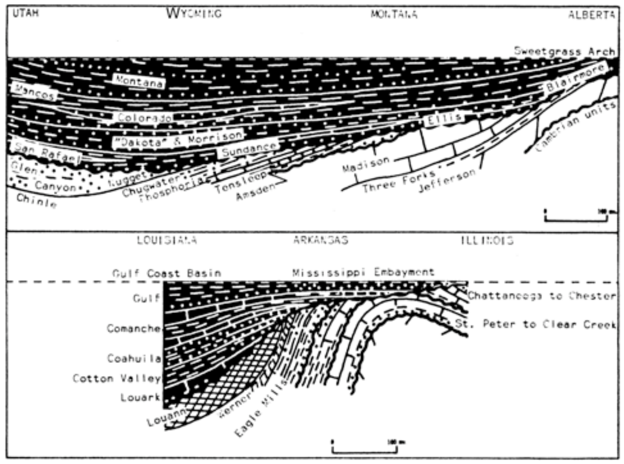
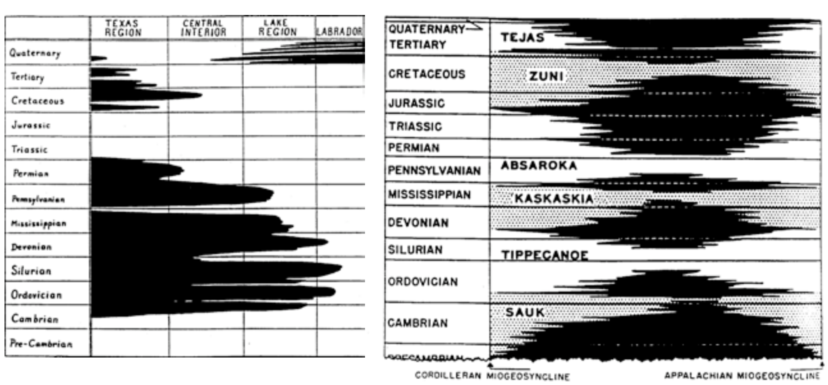


Figure 4. Diagrammatic cross sections showing relationships of lower part of Zuni Sequence (black) to older units (white). Sequence boundaries are shown by heavy wavy lines.

Historical Perspective

Larry Sloss: Father of American Stratigraphy

Blackwelder, 1909 Sloss, 1963



Sloss fully recognized Blackwelder's earlier contributions.

Larry Sloss

- Attempted to model sequences using variations of Sediment Quantity (Q) and Receptor Value (R).
- Now known as A/S ratio.
- Accommodation versus Sediment Supply
- Paper in AAPG, 1962.

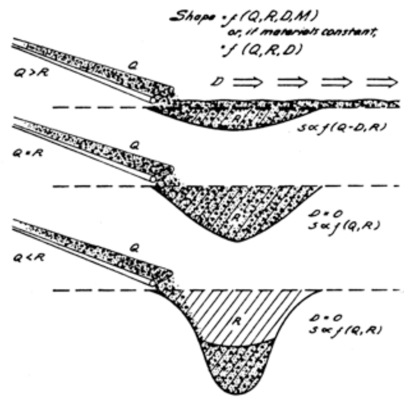


FIG. 1.—Process variables of stratigraphic models considered. Q, represented by endless belt which may run at varying rates, is *quantity* of clastic material supplied to depositional site. R is the *receptor value* of the depositional site, the space below baselevel created by subsidence (indicated by cross-hatching). D represents *dispersal* which tends to remove material from depositional site. M, *materials* supplied, is assumed to be of unvarying composition and texture during operation of each model. In upper diagram Q is less than R; D is effective in removing material from depositional site. In lower diagrams, D is ineffective and the shape of the resulting accumulation of sediment is function of Q and R.

Larry Sloss

- Showed that transgression and regression can be controlled either by changing subsidence or sediment supply.
- Final stratigraphic response is the same in his theoretical cases with different driving mechanisms.

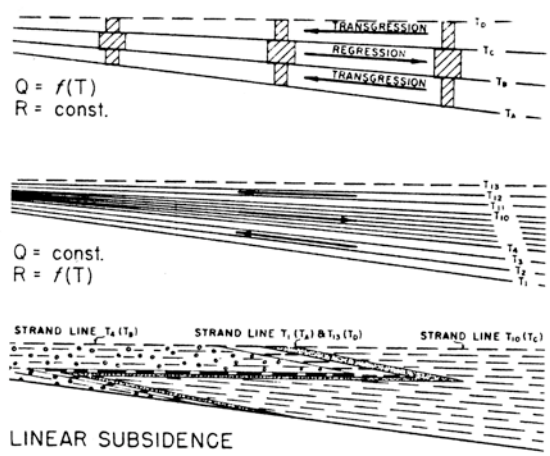


FIG. 6.—Linear subsidence models for alternate transgression-regression.

Upper diagram shows process model where Q is variable and R is constant; middle diagram shows process model where Q is constant and R is variable. Both may produce observable response model of lower figure.

Larry Sloss

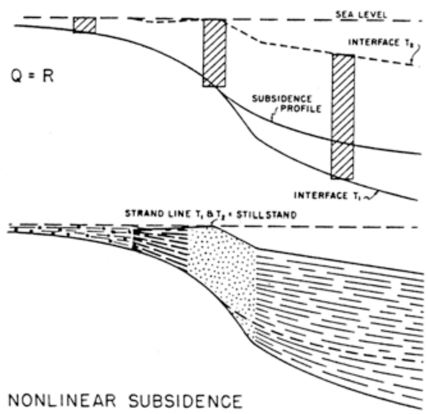


FIG. 7.—Non-linear subsidence models for stillstand.

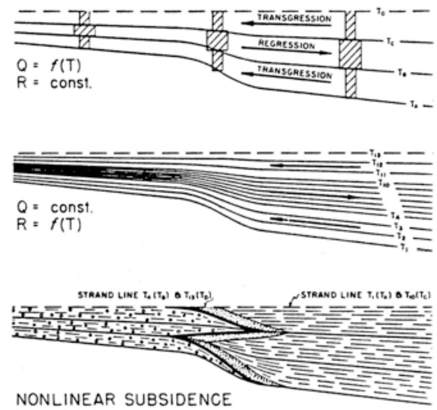


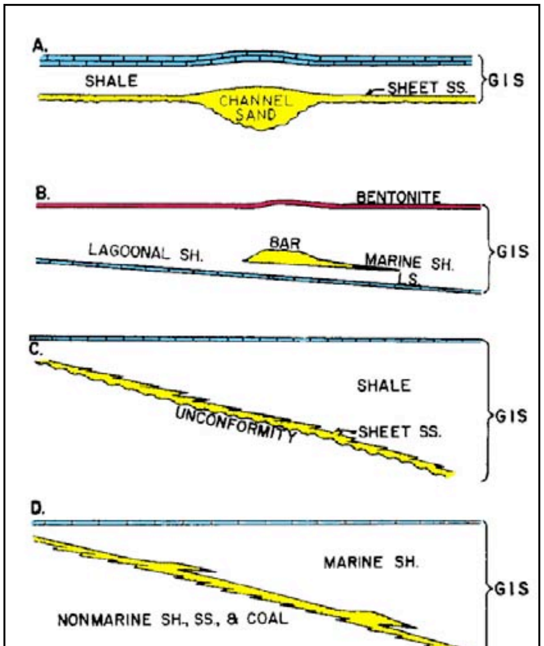
FIG. 8. Non-linear subsidence models for alternate transgression-regression. Two process models above; observable response model below.

Daniel Busch

- Recognized "Genetic Increments of Strata" (GIS)
  - "The GIS is a vertical sequence of strata in which each lithologic component is related genetically to all the others. It is defined at the top by a time-lithologic marker bed (such as a thin limestone or bentonite) and at the base by either a time-lithologic marker bed, an unconformity, or a facies change from marine to nonmarine beds. It generally consists of the total of all marginal marine sediments deposited during one stillstand stage of a shoreline, or it may be a wedge of sediments deposited during a series of cyclic subsidences or emergences."
- Recognized "Genetic Sequences of Strata" (GSS)
  - "The concept of transgression and regression, as determined from the overlapping relations of relatively shallow or deeper water facies, is extremely pertinent to the petroleum exploration geologist" (Busch, 1974).

Genetic Increments of Strata

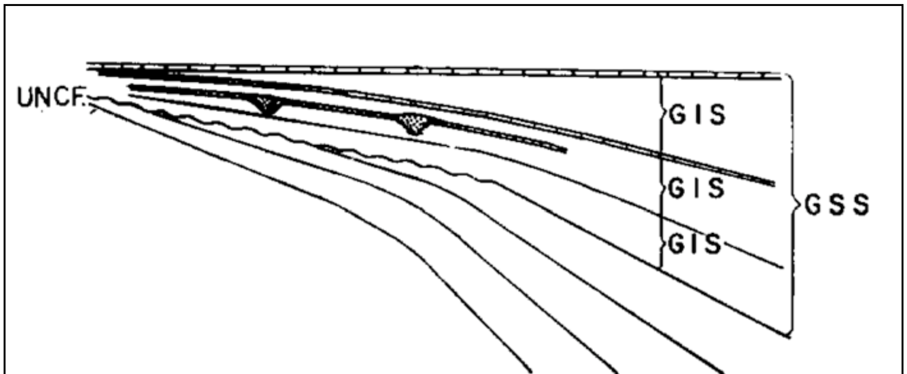
- Surface bounded succession of strata.
- Equivalent to a parasequence.



Busch, 1974

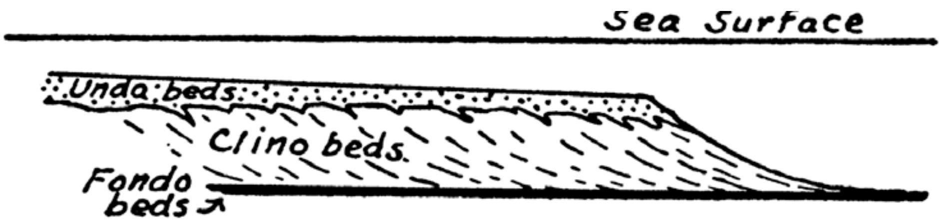
Genetic Sequence of Strata

- Group of GIS units = Sequence or systems tract.



Busch, 1974

J.L. Rich (1951)



- Fondoform
  - Bottomset, deep water
- Clinoform
  - Foreset, slope
- Undaform
  - Topset, shelf
- Only clinoform is retained in the literature

Outline

- A brief History of Sequence Stratigraphy
- Lithostratigraphy in the mid-20th Century
  - failure
- The Seismic Revolution
- Conclusion

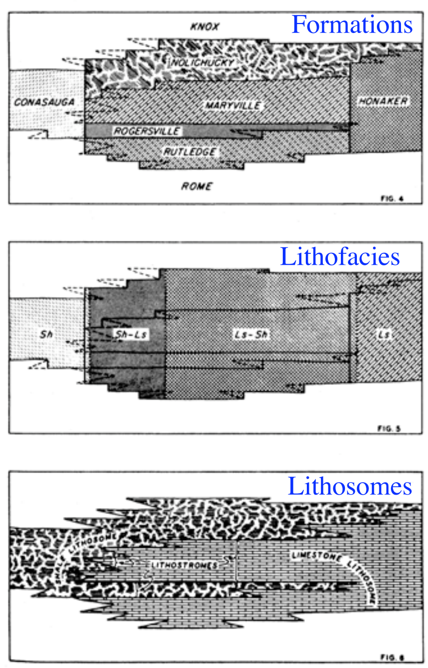
Lithostratigraphy

The Formation

- The basic unit of mapping.
- Units mapped at the regional to sub-regional scale.
  - 1:50,000
- Emphasis on mapping in outcrop.
  - Defined prior to availability of extensive subsurface data (e.g. seismic, well log, core).
- With outcrop data cross sections are derived from geologic maps
- Something to think about
  - In subsurface (2D seismic and well logs) maps are derived from cross sections.
  - **"A cross section is simply a map on its side!"** (Grant Mossop).

Lithostratigraphy in 1956

- **Formations**
  versus
  - **Lithofacies**
  - **Lithosomes**
  - **Lithostromes**

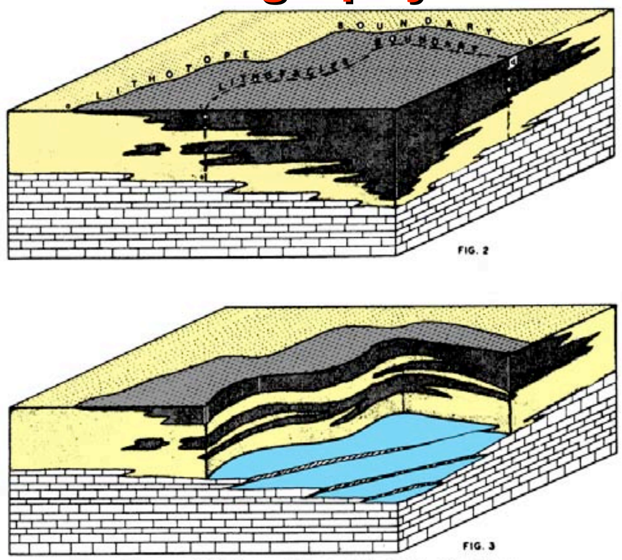


FIGS. 4-6.—Generalized stratigraphic cross sections illustrating vertically, laterally, and vertico-laterally segregated rock units in Cambrian of Tennessee, Kentucky, and Virginia.

Wheeler and Mallory, 1956

Facies *vs.* Stratigraphy

- Lithotope
- Lithofacies
- Lithosome



Figs. 1-3.—Block diagrams illustrating factors in lithofacies concept.

Wheeler and Mallory, 1956

Harry Wheeler

- How to name interfingering lithofacies?
  - Focused on how to formally designate Formations and Members as "mappable" units.
  - Lithofacies emphasis rather than correlation.
  - Very concerned about structural mis-interpretation of interfingering units as representing structurally repeated sections.

DESIGNATION OF STRATIGRAPHIC UNITS

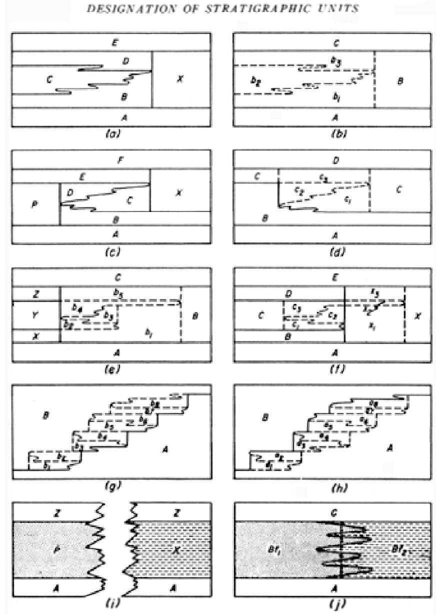


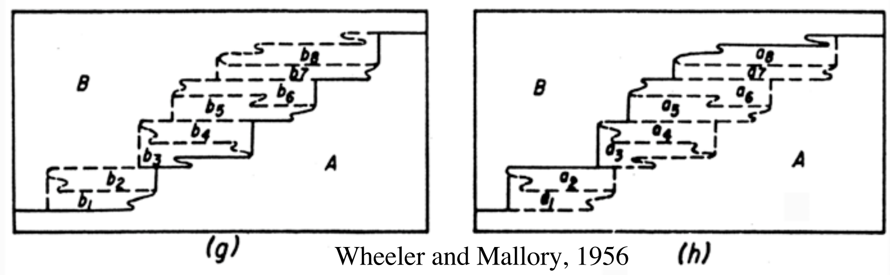
Fig. 1.—Diagrammatic sections (or strip maps) showing some possible choices in rock-unit designation. Units of formational rank indicated by capital letters, and their contacts and arbitrary cut-offs by solid lines. Units of member rank shown with lower-case letters and with dashed contacts and cut-offs.

Wheeler and Mallory, 1953

29

Inter-tonguing Units

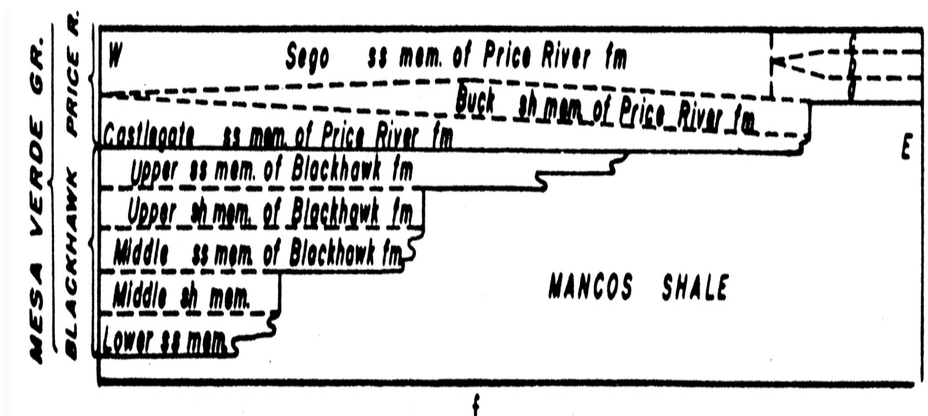
- Wheeler and Mallory addressed nomenclature of interfingering units, focusing on arbitrary vertical cutoffs.



Wheeler and Mallory, 1956

Example of Complex Nomenclature

- Interfingering units in the Book Cliffs, Utah.
- Note Buck Tongue shale is considered a member of the Price River Fm., *not* the Mancos Shale.



Wheeler and Mallory, 1953

Wheeler & Mallory

- Nomenclature of interfingering units, using vertical cutoffs.
- These are real stratigraphic units from around the south-central and western USA.

DESIGNATION OF STRATIGRAPHIC UNITS 2413

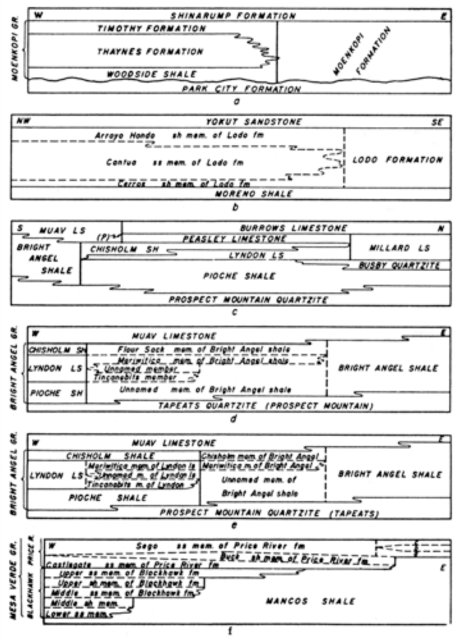
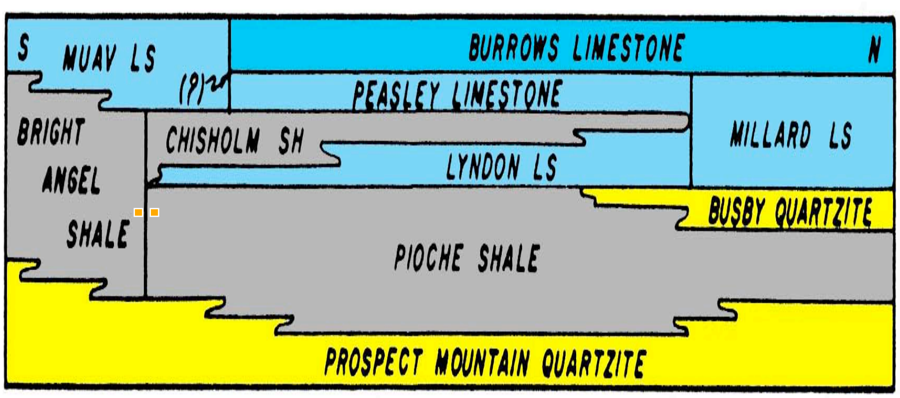


FIG. 2.—Generalized sections (not to scale) showing actual or recommended application of arbitrary cut-off in selection and naming of rock units. (a) Permian-Triassic of Utah; (b) Cretaceous-Tertiary of California; (c) Cambrian of Arizona-Nevada-Utah; (d, e) Cambrian of Grand Canyon; (f) Cretaceous of Utah-Colorado.

Wheeler and Mallory, 1956

State-of-the-art stratigraphy in 1953

- Who would place orange boxes in different Formations?
- Which of these boundaries would produce a seismic reflection?



Wheeler and Mallory, 1956

Flags or Reality?

31

Harry Wheeler

- **Good:**
  - **Wheeler (1958) formalized concept of time-stratigraphy**
  - **Wheeler recognized that hiatuses are as important as the rocks.**
  - **Wheeler depicted "exploded" stratigraphic cross sections with time on the vertical axis.**
  - **Wheeler defined sequences as unconformity bounded units.**
- **Confusing:**
  - **Wheeler's sequences were defined by arbitrary vertical cutoffs.**
  - **No correlative conformity.**
  - **Vertical cutoffs also were key in defining lithostratigraphic units.**
    - **This may not be widely appreciated!**

Stratigraphy in 1960

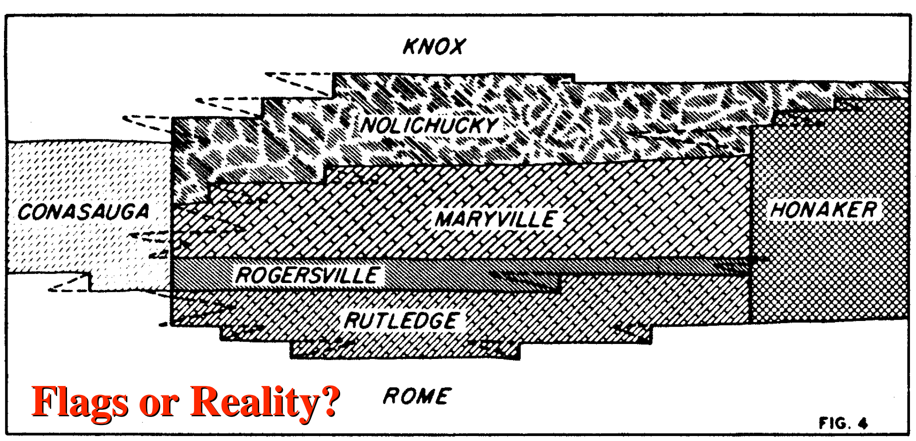
- *"Stratigraphy is the complete triumph of terminology over facts and common sense."*
  - **Paul D. Krynine, circa 1960**

Stratigraphy in mid-70's

- IN academia, stratigraphy was considered a largely dead field caricatured by endless debates about what to name units.
- Same lithologies with same-age fossils were placed in different Formations because of arbitrary vertical cutoffs.
- Sedimentologists became more focused on petrographic studies or on facies analysis.
- Facies models largely replaced stratigraphy in the classroom.
  - Daniel Busch, James Forgotson, Rich, Fraser, and Bob Weimer were all working on early versions of sequence stratigraphy at this time, and concepts were being applied within industry, but these ideas were not widely taught in North American or European Universities.

State-of-the-art stratigraphy in 1953

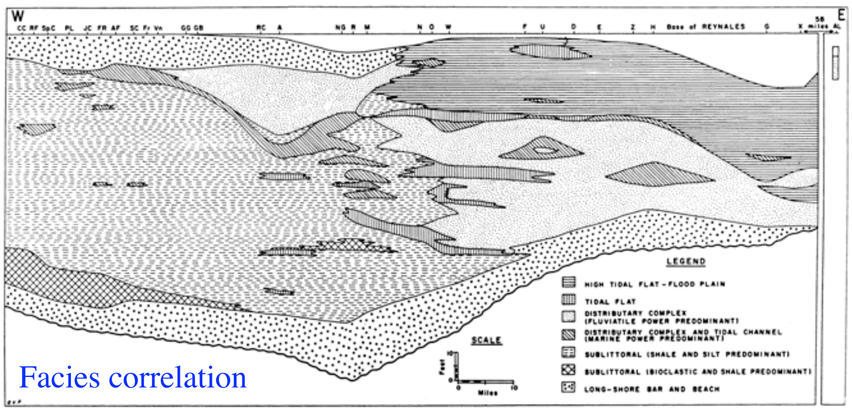
Which of these arbitrary lithostratigraphic units will produce a coherent reflection?



Wheeler and Mallory, 1953

State-of-the-art stratigraphy in 1971

Which of these arbitrary lithostratigraphic units will produce a coherent reflection?



Facies correlation

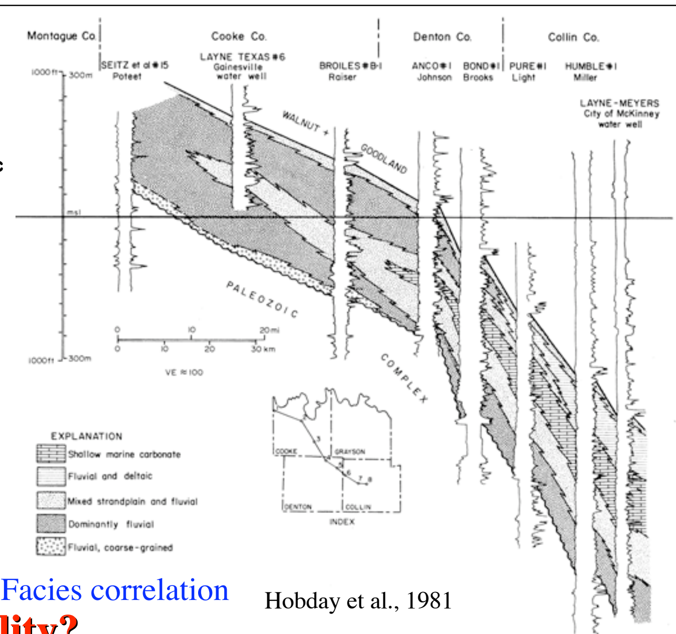
Fig. 4.—Schematic cross section of Medina Formation along Niagara escarpment, showing sequence of environments of deposition.

Flags or Reality?

Martini, 1971

State-of-the-art stratigraphy in 1981

- Which of these arbitrary lithostratigraphic units will produce a coherent reflection?
- Clearly facies analysis isn't getting us where we need to go!



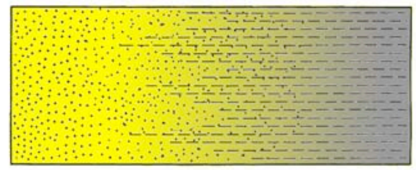
Facies correlation

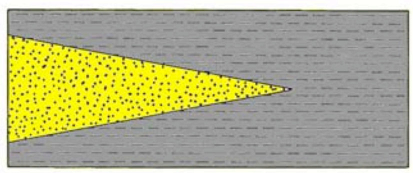
Hobday et al., 1981

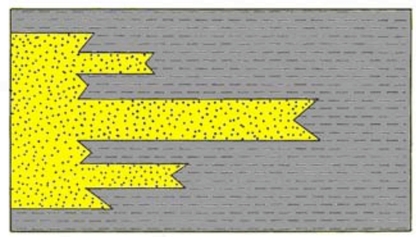
Flags or Reality?

Stratigraphy or Flags in 2001?

- Representations of lateral transitions.
- No outcrop or seismic line even vaguely resembles these geometries!
- This is what the latest textbooks teach to undergraduates.







Boggs, 2001

Outline

- A brief History of Sequence Stratigraphy
- Lithostratigraphy in the mid-20th Century
  - failure
- **The Seismic Revolution**
- Conclusion

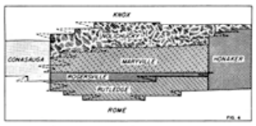
Seismic Stratigraphy

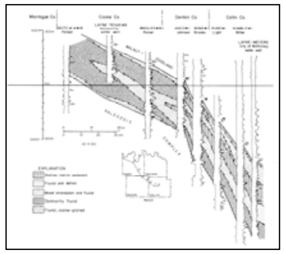
- Seismic reflections assumed to image bedding surfaces.
- Reflection character and geometry is related to lithology and facies architecture.
- Stratal discontinuities identified by reflection terminations (lapout).
- "*Depositional Sequences*" bounded by unconformities and their correlative conformities.
  - Maximum resolution of about 50m.

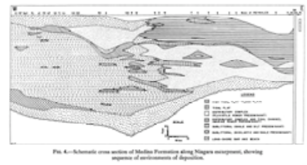
Chronostratigraphic significance of seismic reflections

- Why would anyone assume or assert that seismic reflections are effectively "time lines"?
  - *"Primary seismic reflections are generated by stratal surfaces which are chronostratigraphic rather than by boundaries of arbitrarily defined lithostratigraphic units"* Vail et al., 1977
- What does this mean?
- *The conclusion, that seismic reflectors are chronostratigraphic horizons "is clearly untenable in a literal sense… "*
  - Dickinson, 2003, The place and power of myth in geoscience, Am. Jour. Sci. v. 303, p.856-864.

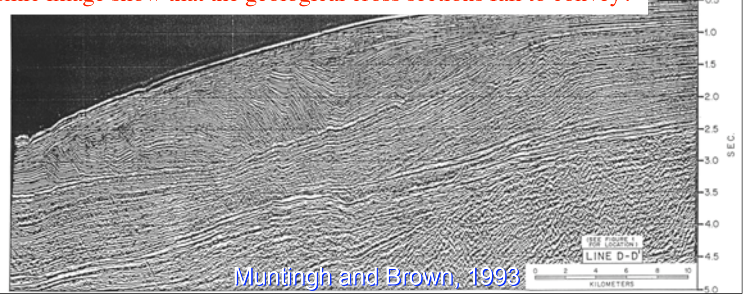
These stratigraphic depictions don't look like seismic lines!







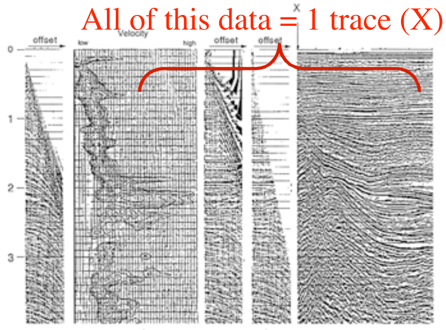
What does the seismic image show that the geological cross sections fail to convey?



Muntingh and Brown, 1993

Stacking greatly enhances the signal to noise ratio

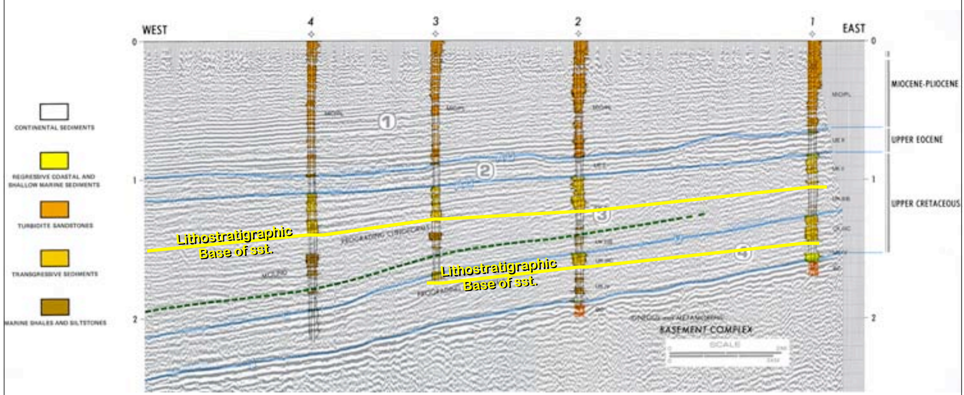
All of this data = 1 trace (X) on a seismic line



From Yilmaz (1987)

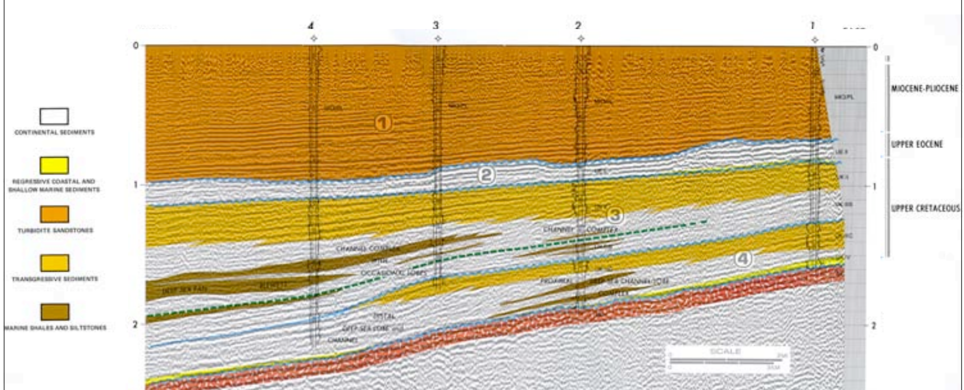
- Coherent reflections (off bedding surfaces) constructively interfere.
- Incoherent reflections (lithofacies shazams) destructively interfere.

Seismic *vs.* Well Logs



Vail, 1987

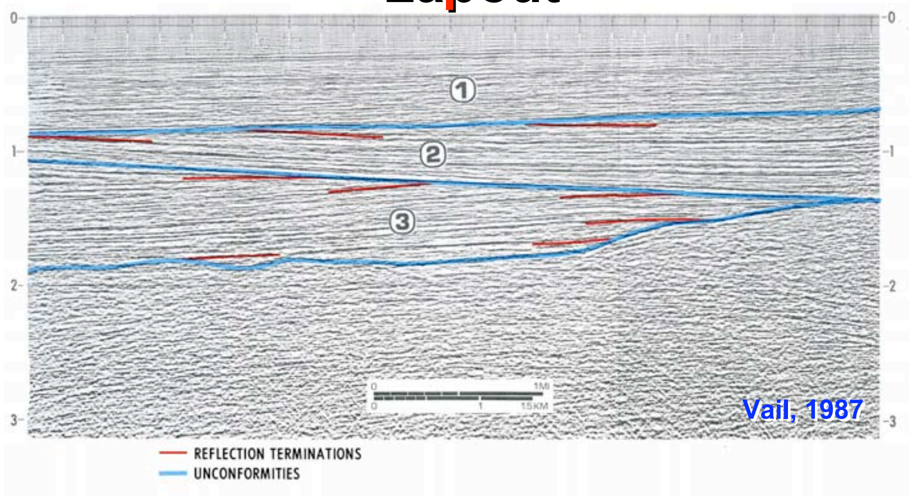
Facies versus Seismic



- **Lithostratigraphic facies boundaries are gradational and form “Shazam”-type, interfingering boundaries.**
- **Seismic reflections are interpreted to mark bed, bedset or parasequence boundaries.**
- **Bed, bedset or parasequence boundaries are typically sharply defined surfaces across which there is a marked lithological change.**

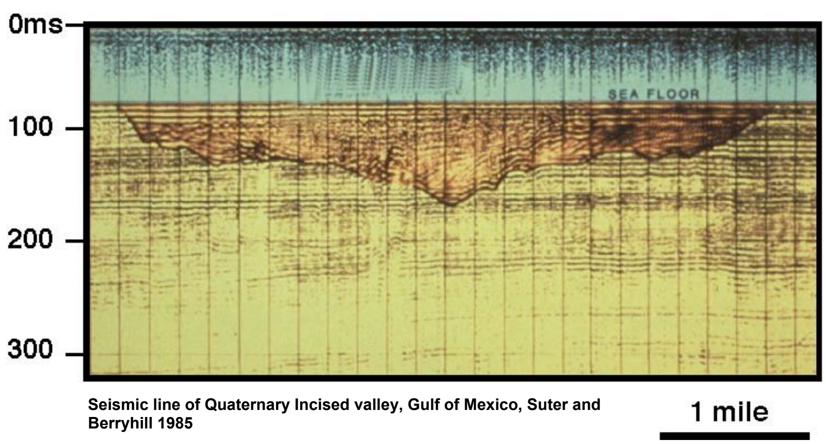
Vail, 1987

Lapout



- Termination of reflections termed lapout.
- Used to separate apparently conformable sedimentary units.

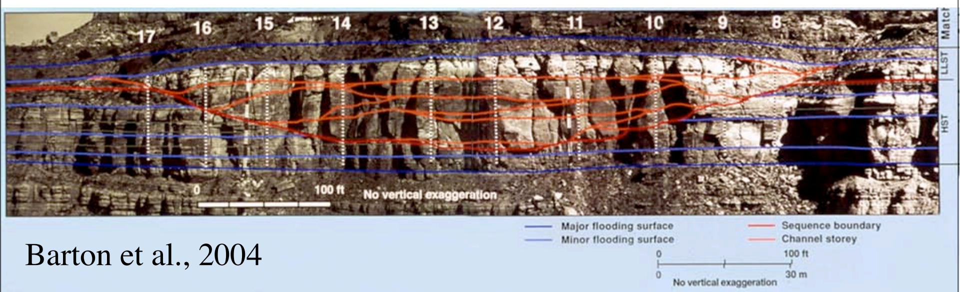
Incised Valleys



Seismic line of Quaternary Incised valley, Gulf of Mexico, Suter and Berryhill 1985

- **Truncation of strata at valley floor and margins.**
- **Onlap and downlap of strata within valley.**

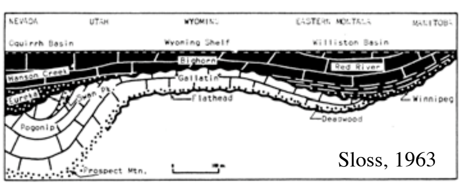
Ferron Valleys - Outcrop Example



Barton et al., 2004

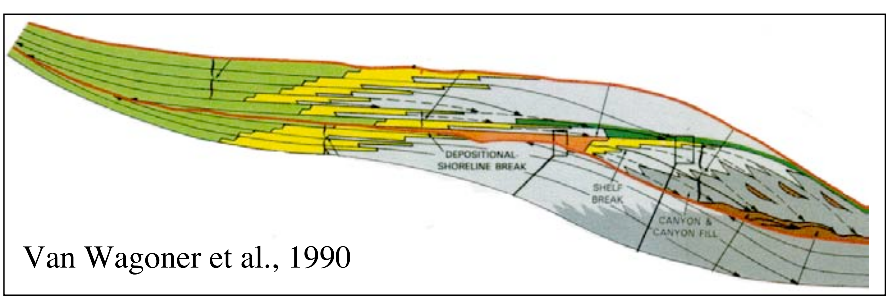
- **Truncation of strata at valley floor and margins.**
- **Onlap and downlap of strata within valley.**

Conclusions: What are Sequences Made of?



Sloss, 1963

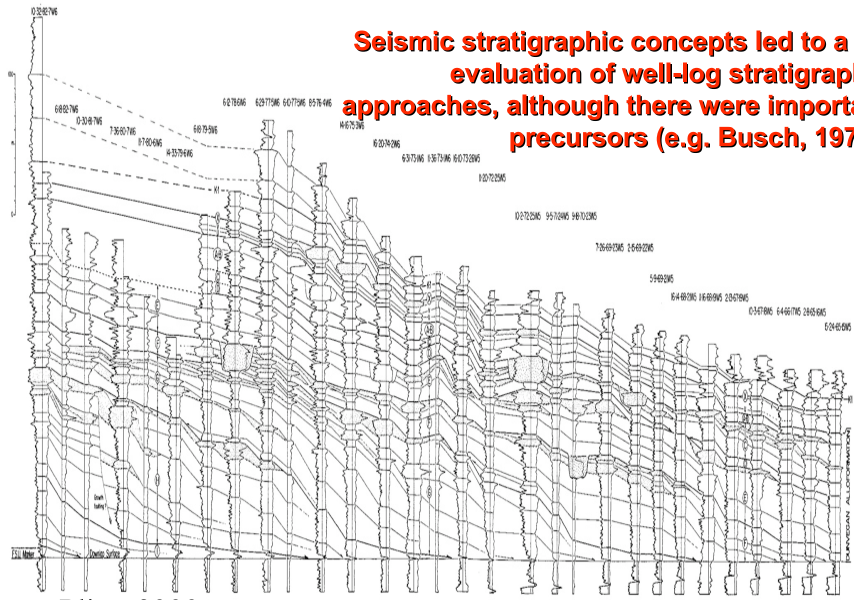
The seismic approach led to a more detailed application of Sloss and Wheeler ideas to the stratigraphic record.



Van Wagoner et al., 1990

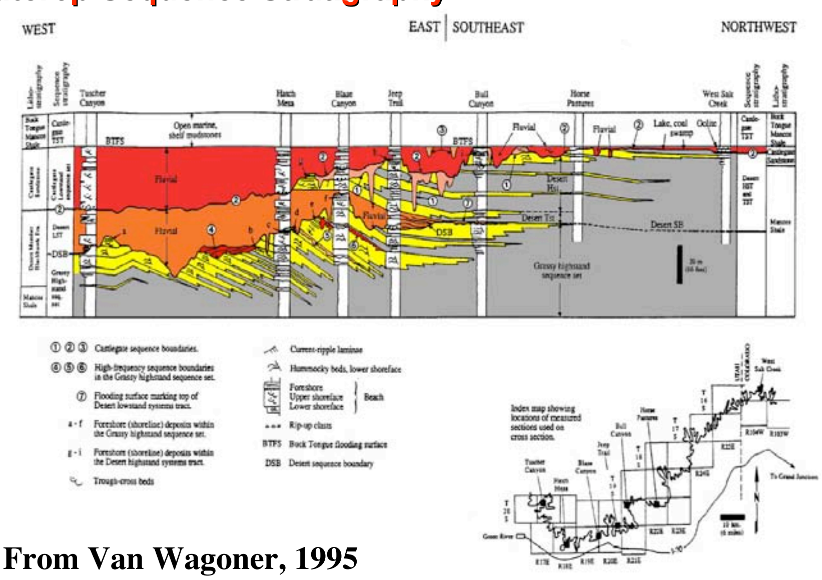
Conclusions:

Seismic stratigraphic concepts led to a re-evaluation of well-log stratigraphic approaches, although there were important precursors (e.g. Busch, 1972).



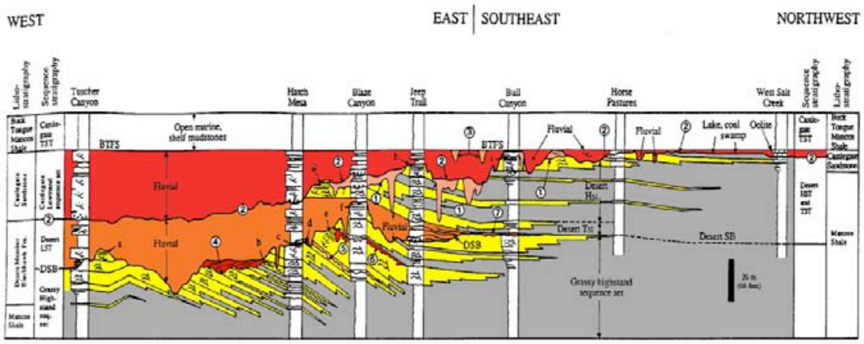
Plint. 2000

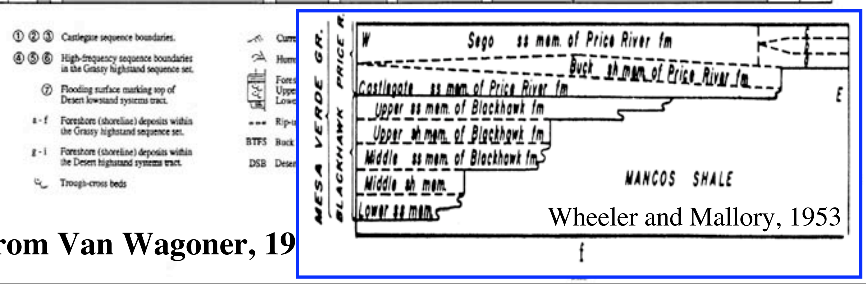
Conclusion: This revolutionized our approach to outcrop Sequence Stratigraphy



From Van Wagoner, 1995

Outcrop Sequence Stratigraphy





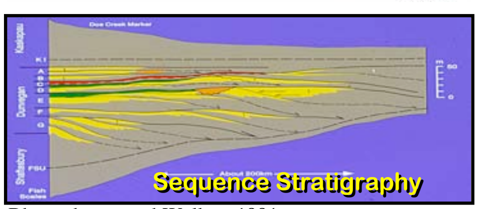
Wheeler and Mallory, 1953

From Van Wagoner, 19

Conclusion

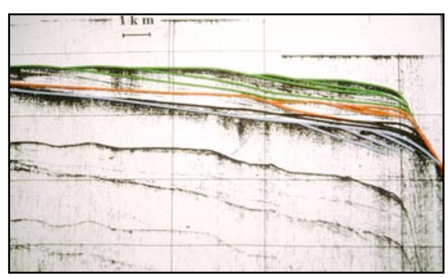
- If an outcrop or well log cross section looks like a seismic line, its probably right!

Cretaceous Dunvegan Fm., Alberta Subsurface



Bhattacharya and Walker, 1991

Seismic Stratigraphy, Modern Rhone shelf



Tesson et al., 1990

42

Seismic Stratigraphy

Seismic Stratigraphy

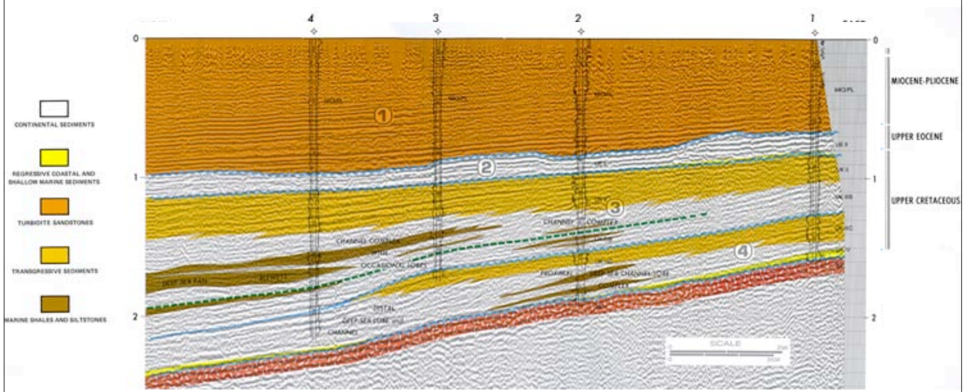
- Seismic reflections assumed to image bedding surfaces.
- Reflection character and geometry is related to lithology and facies architecture.
- Stratal discontinuities identified by reflection terminations (lapout).
- "*Depositional Sequences*" bounded by unconformities and their correlative conformities.
- Conventional exploration seismic data remotely senses geology.
- Maximum resolution of about 75m.

Seismic Stratigraphy

Chronostratigraphic significance of reflections

- *"Primary seismic reflections are generated by stratal surfaces which are chronostratigraphic rather than by boundaries of arbitrarily defined lithostratigraphic units"* Vail et al., 1977.
- Stacking enhances ability to see subtle changa across beds or other stratal boundaries.
- Diachronous facies boundaries do not usually form strong or coherent reflections.
  - But there are always exceptions.

Facies versus Seismic



- **Lithostratigraphic facies boundaries are gradational and form "Shazam"-type, interfingering boundaries.**
- **Seismic reflections are interpreted to mark bed, bedset or parasequence boundaries.**
- **Bed, bedset or parasequence boundaries are typically sharply defined surfaces across which there is a marked lithological change.**

Vail, 1987

Facies vs Clinoforms in Progading Carbonate Shelf

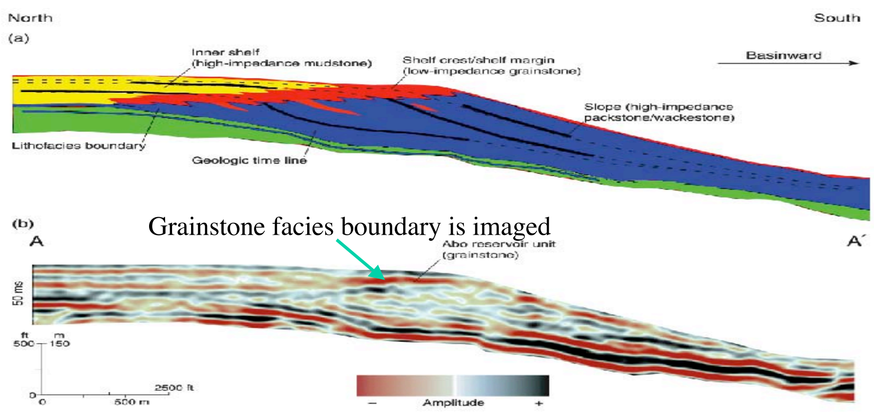


Figure 1. Progradational carbonate depositional sequence and its seismic response. (a) Depositional model. Time-stratigraphic units comprise clinoform deposits that consist of inner shelf, shelf-crest/shelf-margin, and slope facies. Three time-transgressive, lithostratigraphic units (inner shelf mudstone, shelf-crest/shelf-margin grainstone, and slope wackestone) develop when the system progrades basinward. Note that the lithostratigraphic units dip landward and cross depositional surfaces or geologic time lines. (b) A seismic line AA′ from a multichannel, migrated, P-wave 3-D data volume in Kingdom Abo field, west Texas, showing a slightly landward-dipping seismic reflection event that responds to the time-transgressive, shelf-crest/shelf-margin grainstone lithofacies (Abo reservoir unit). See Figure 5 for location of section AA′.

Zeng and Kerans, 2003

Remember Seismic Resolution!

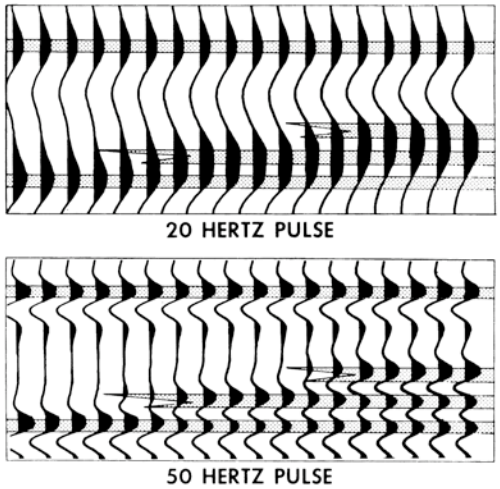
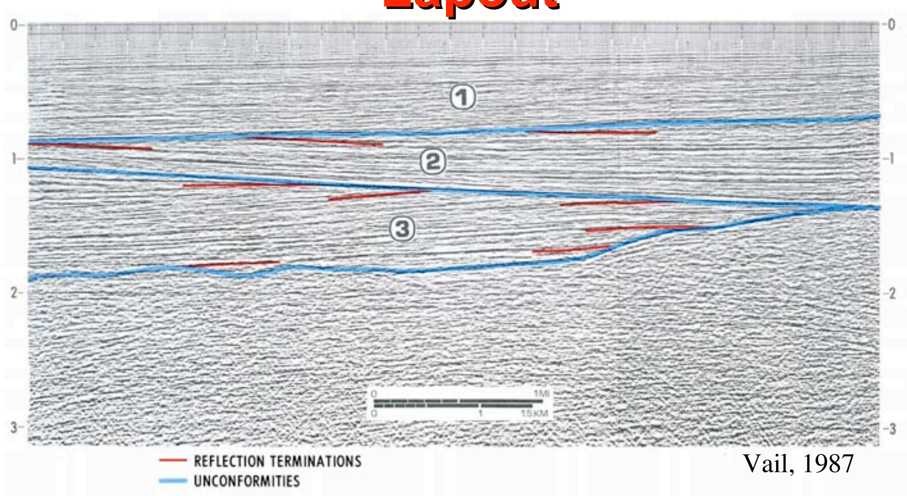


FIG. 17—Comparison of resolving power between 50-Hz and 20-Hz pulse.

Vail et al., 1977

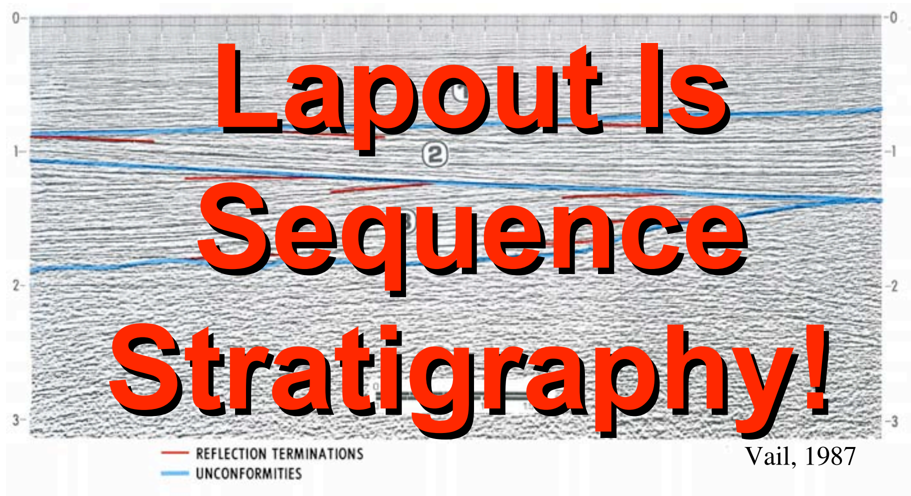
Lapout



Vail, 1987

- Termination of reflections termed lapout.
- Used to separate apparently conformable sedimentary units.

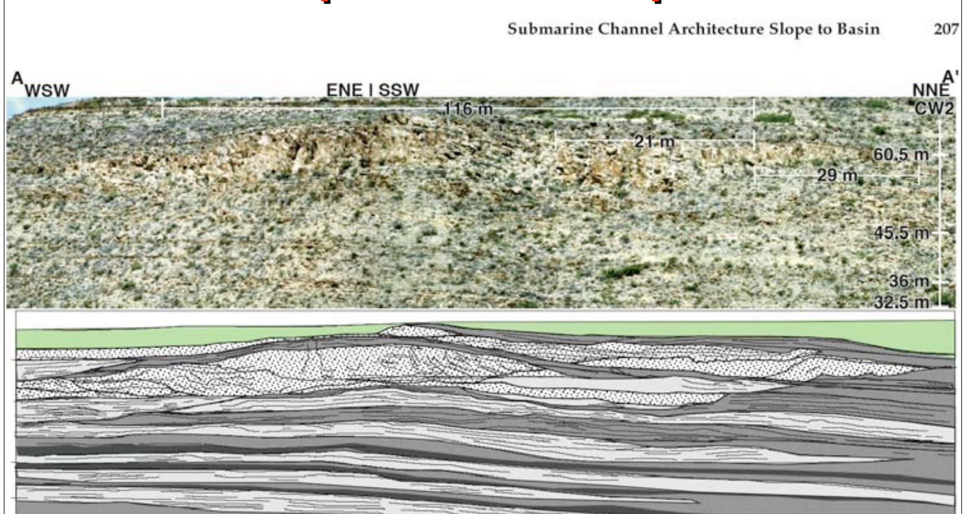
Lapout Is Sequence Stratigraphy!



Vail, 1987

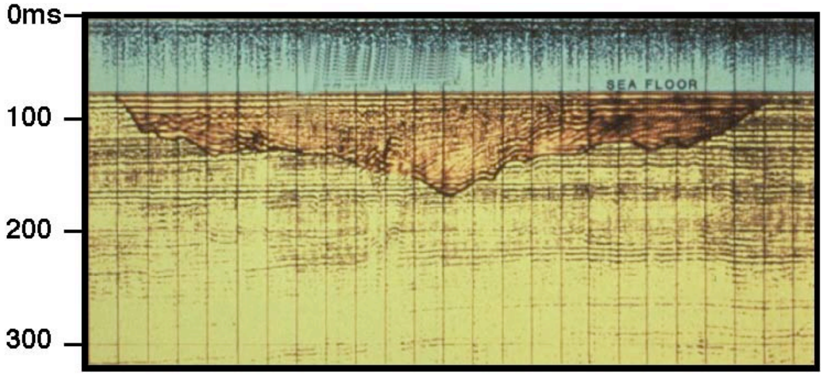
- If I was forced to describe sequence stratigraphy using only one word it would be "lapout".

Lapout in Outcrops



Permian Brushy Canyon (Gardner and Borer, 2000)

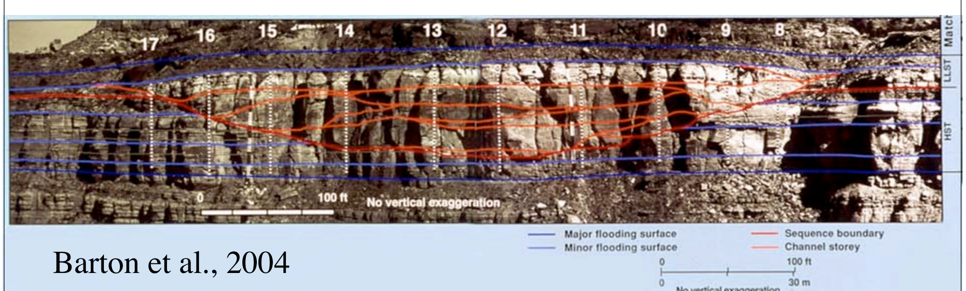
Incised Valleys in High Resolution Seismic Data



Seismic line of Quaternary Incised valley, Gulf of Mexico, Suter and Berryhill 1985,

Truncation of strata at valley floor and margins.
Onlap and downlap of strata within vallley

Ferron Valleys - Outcrop Example



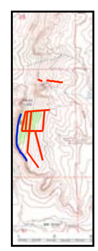
Barton et al., 2004

- Truncation of strata at valley floor and margins.
- Onlap and downlap of strata within valley.

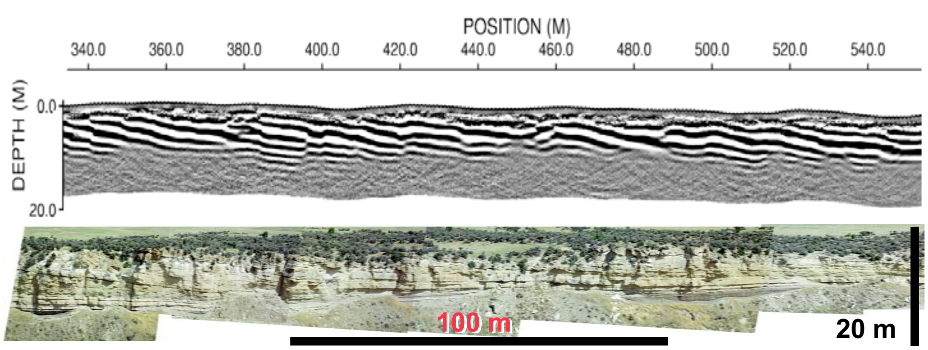
Offlapping and downlapping beds in a deltaic sandstone, outcrop example

Cretaceous Panther Tongue Sandstone, Utah

GPR and Photomosiac

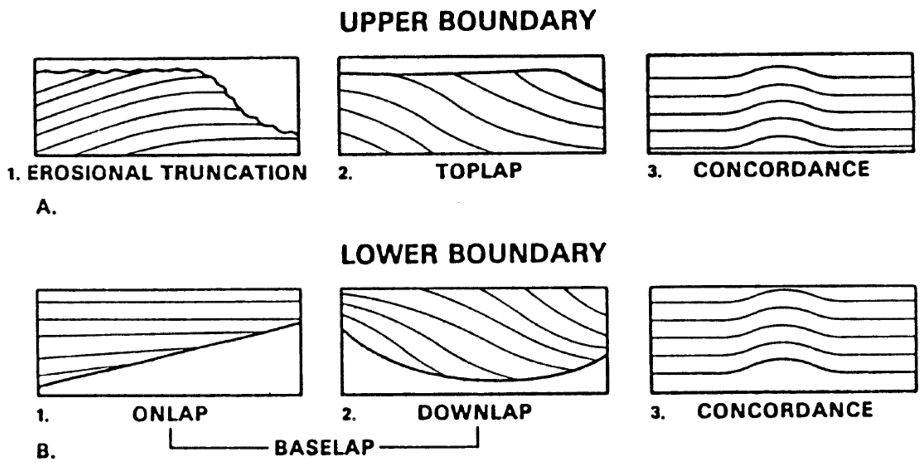


- Inclined (downlapping and offlapping) beds in a prograding delta are well imaged by Ground Penetrating Radar.
- These would be below typical 40Hz seismic resolution.



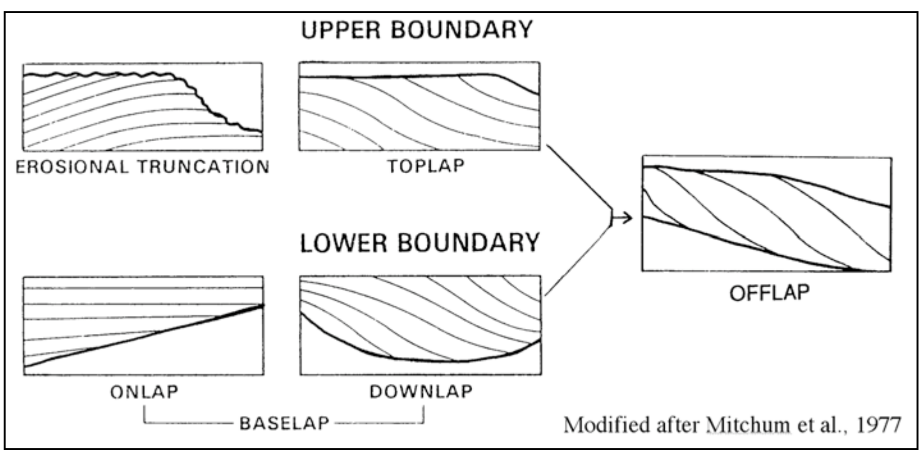
Lee et al., 2005

Types of Lapout



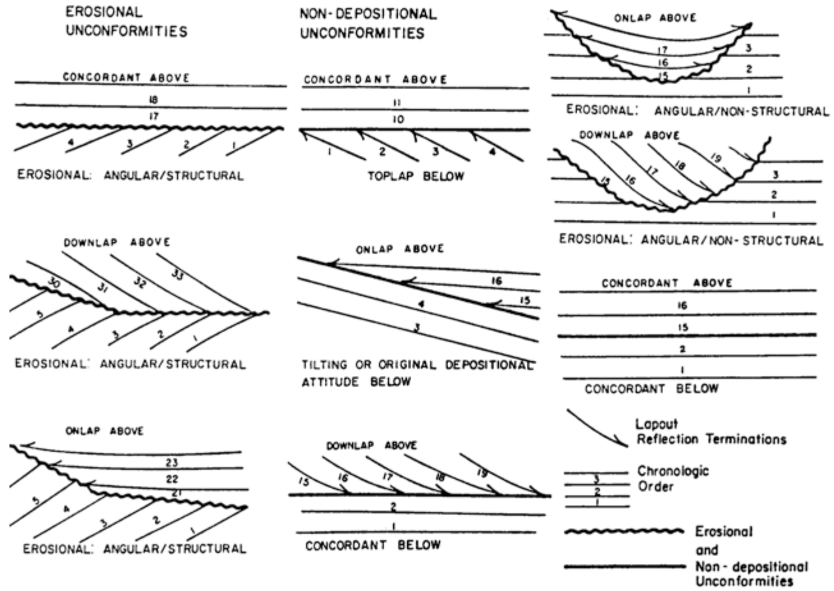
Various stratal terminations at sequence boundaries. From Mitchum and others, 1977a. Reprinted by permission of AAPG.

Types of Lapout



Modified after Mitchum et al., 1977

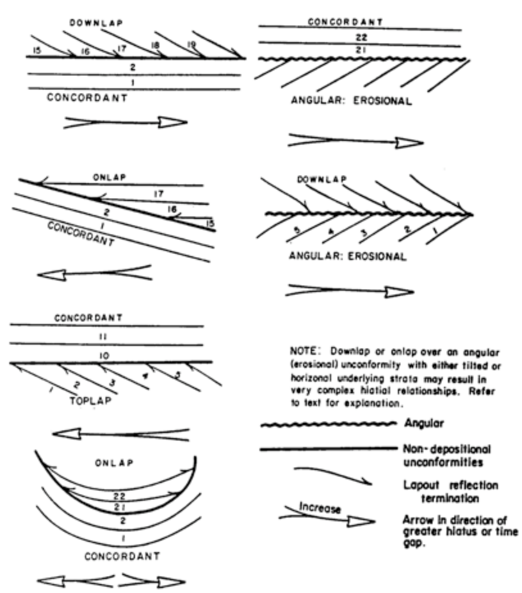
Lapout and Sratal Termination



Slide courtesy of Weldon Beauchamp

Interpretation of Lapout

Onlap and downlap relationships give evidence of regressions and transgressions. In Seismic stratigraphic interpretation these events are important to recognize to help to estimate time stratigraphic units.

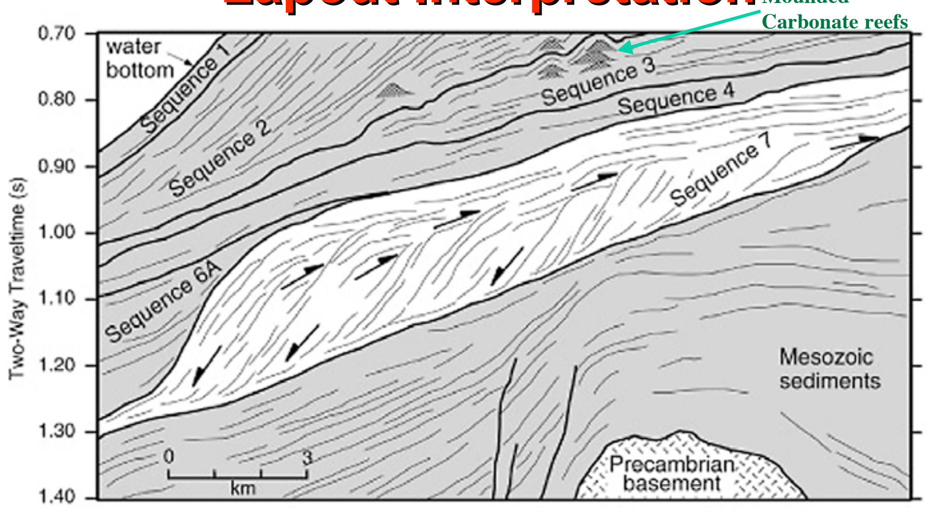


Slide courtesy of Weldon Beauchamp

Shelf Seismic data

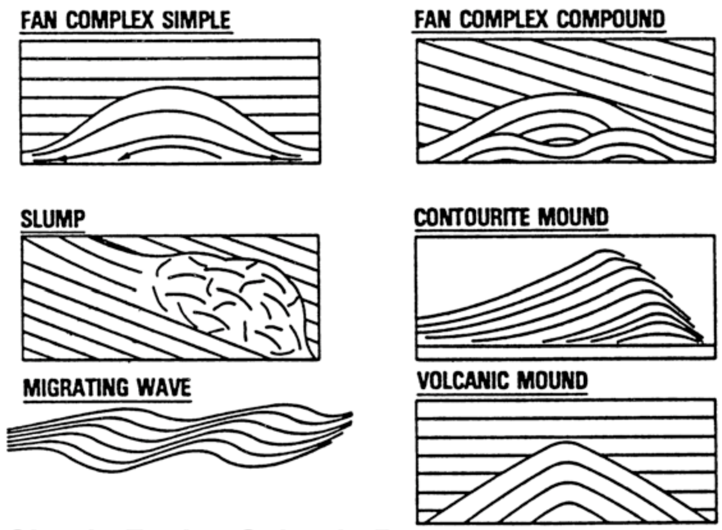
Seismic Line from offshore Australian continental shelf, (Feary and James, 1998)

Lapout Interpretation



Intrepretation of seismic line showing sequences defined by lapout relationships (Feary and James, 1998)

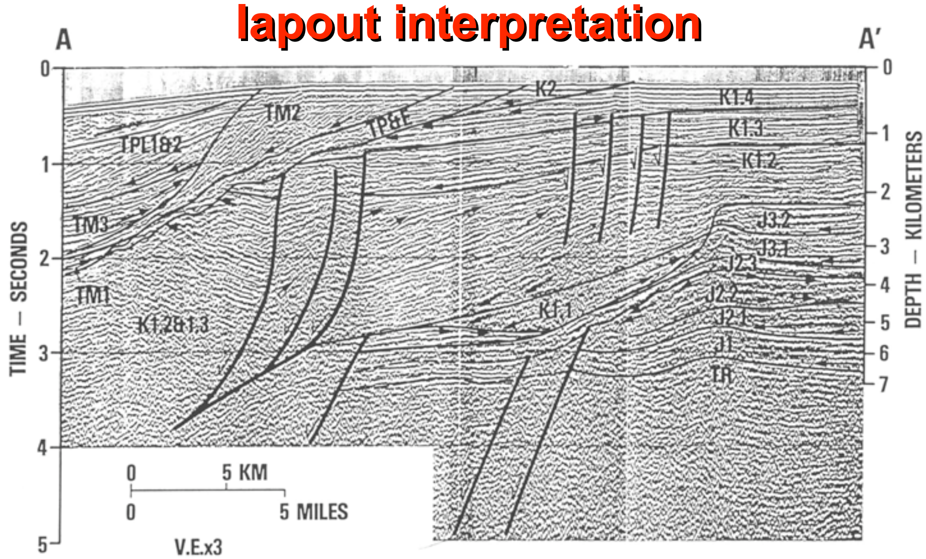
Seismic Facies



Clastic Facies Seismic Patterns

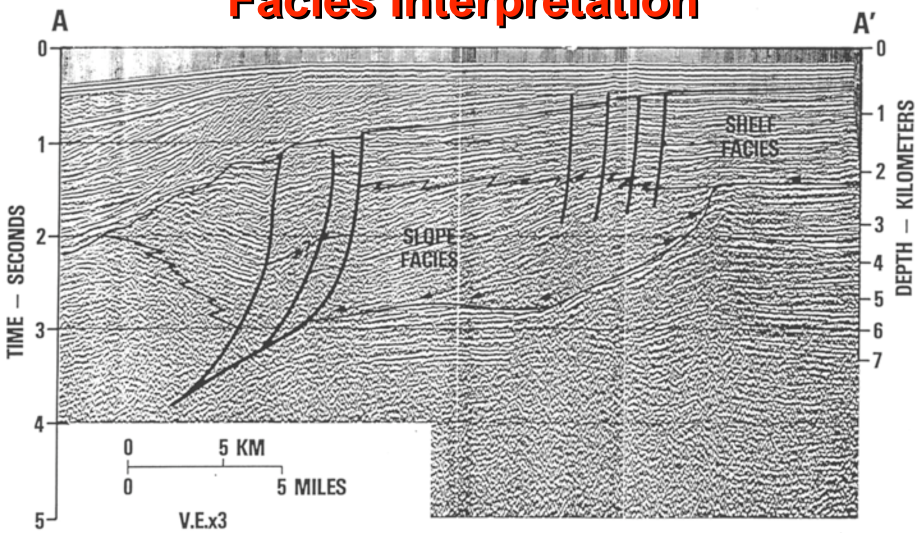
Mitchum et al., 1977

Seismic Stratigraphy: lapout interpretation



Seismic Line, offshore Morocco, from Mitchum et al., 1977.

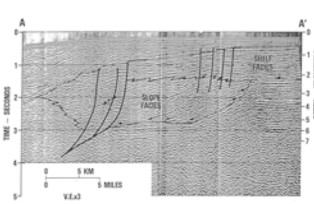
Seismic Stratigraphy: Facies Interpretation

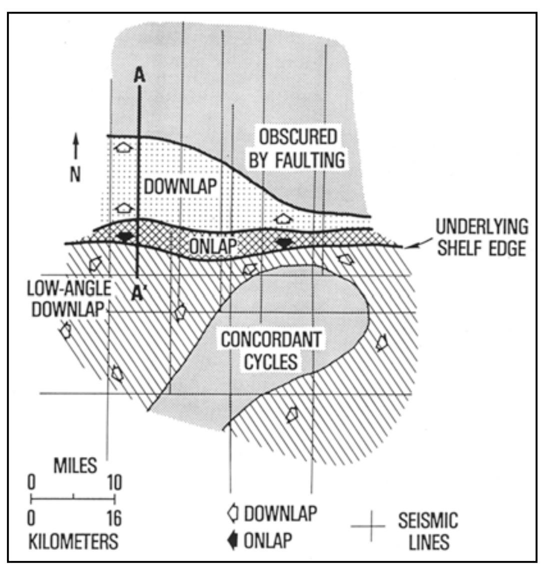


Seismic Facies, offshore Morocco, from Mitchum et al., 1977.

Seismic Facies Mapping

Seismic Facies Map, offshore Morocco, from Mitchum et al., 1977.





Slug Model: Lapout Only
Passive Continental Margin

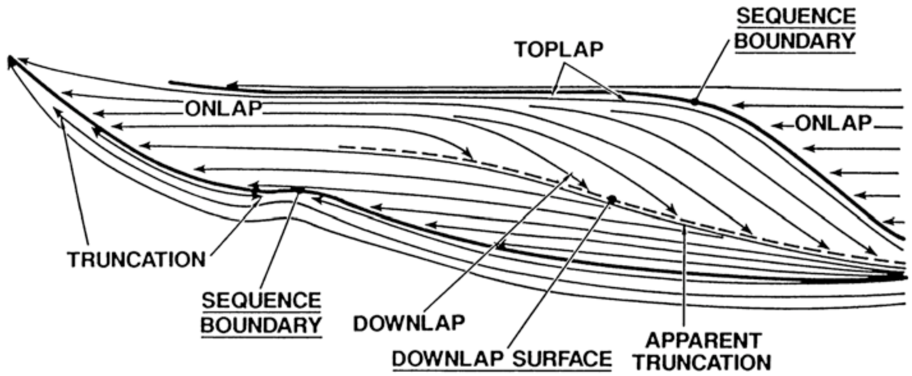


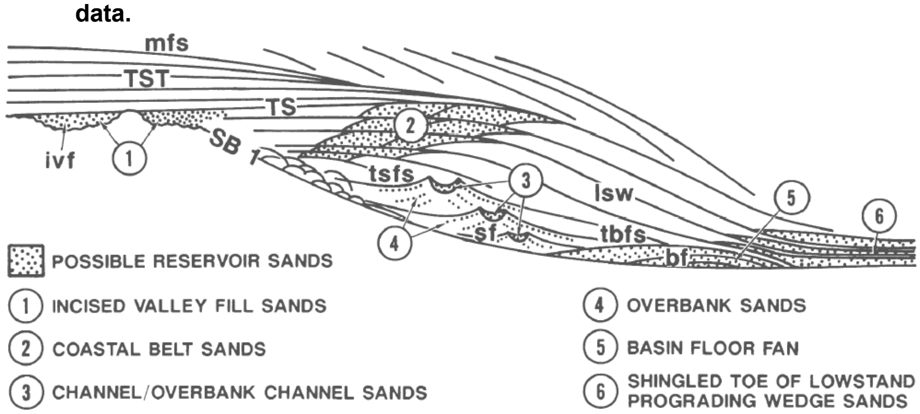
Diagram showing reflection termination patterns and types of discontinuities. From Vail, 1987. Reprinted by permission of AAPG.

Seismic stratigraphy involves the correlation of stratal packages bounded by discontinuities defined by stratal termination (Sequence Boundaries and other surfaces).

Vail, 1987

Slug Model: Lapout + Facies
Siliciclastic Margin

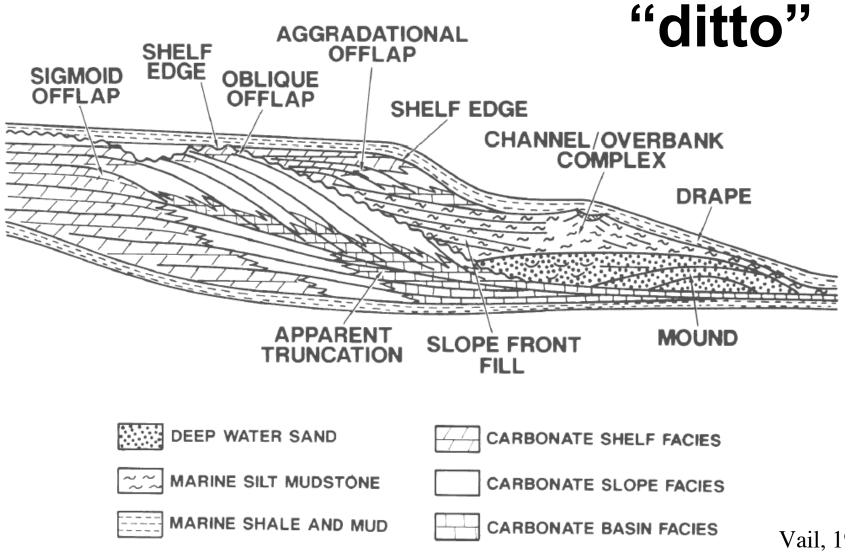
- **Lapout geometries and seismic facies are used to interpret depositional systems and facies.**
- **Facies interpretations are greatly enhanced if there is well log or core data.**



Vail, 1987

Slug Model: Lapout + Facies Carbonate Margin

"ditto"

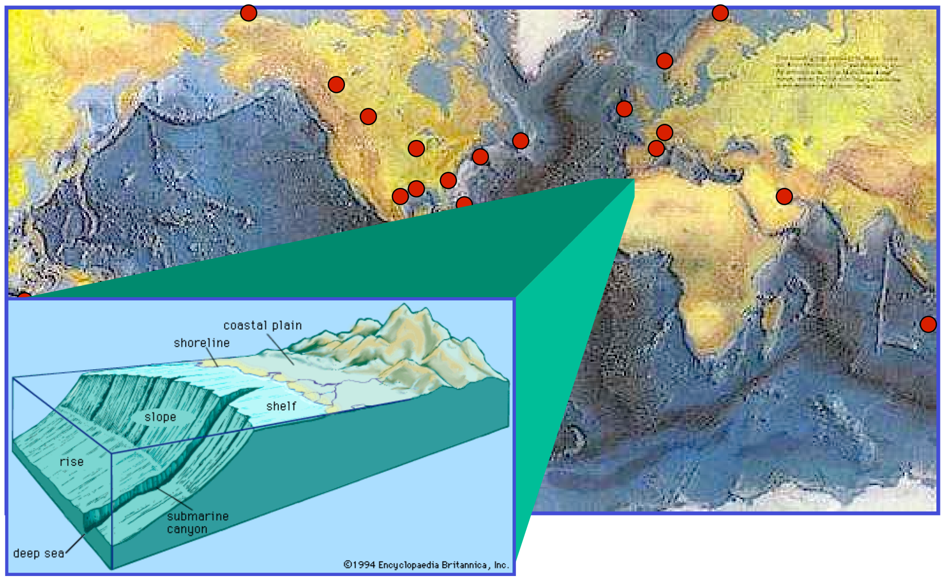


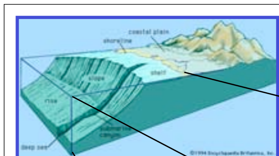
Vail, 1987

Seismic Stratigraphy and Sea-level Change

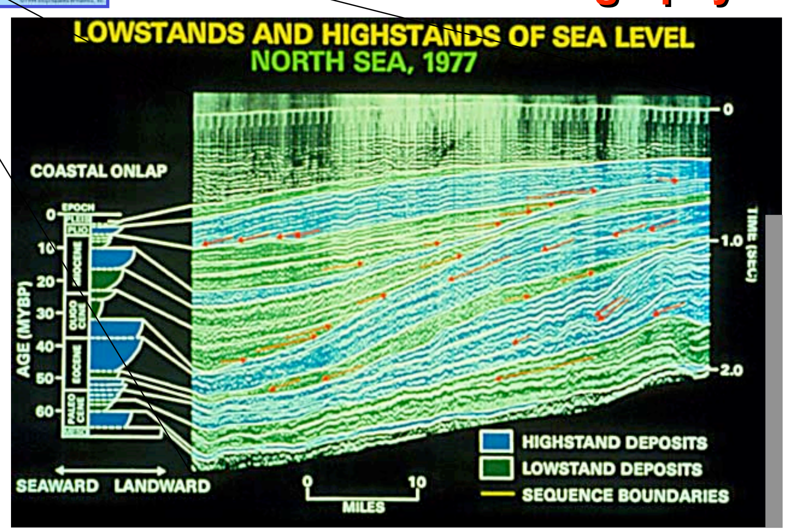
- Developed at Exxon Production Research Company.
- Theorized synchronous global changes in sea level.
  - Reservoir sands deposited during falls
  - Fossil-rich hydrocarbon source rocks deposited during rises.

Exxon had data from around the world



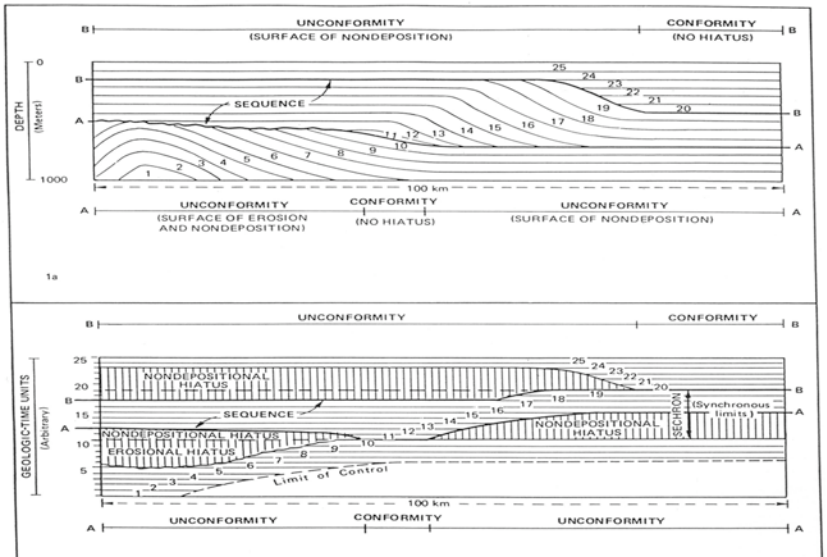


Seismic Data Give Image of Continental Margin Stratigraphy



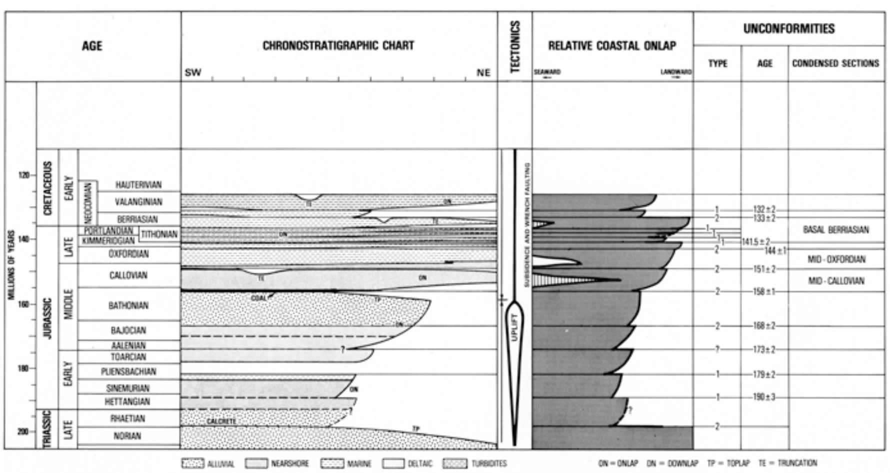
Slide courtesy of H. Posamentier, after Vail et al., 1977

Time Stratigraphic Analysis



Mitchum et al., 1977

Time Stratigraphic Analysis



Wheeler diagram of North Sea.

Vail et al., 1984

Onlap charts showed globally synchronous rises and falls of sea level (eustasy).

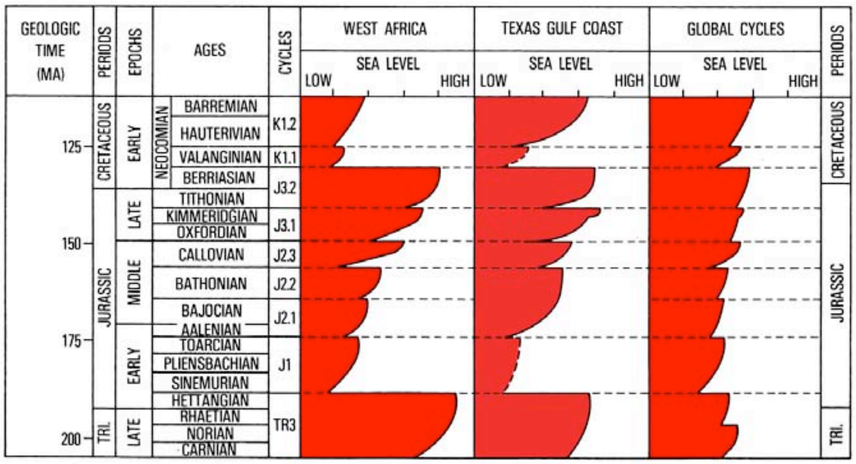
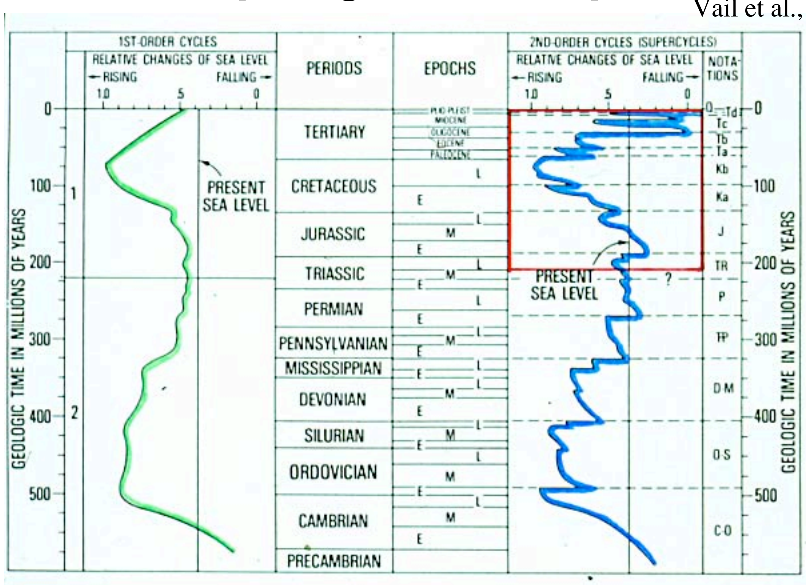


FIG. 14—Comparison of regional cycle charts offshore West Africa and Texas Gulf Coast with global cycle chart.

Todd and Mitchum, 1977

Developed global onlap chart

Vail et al., 1977



Mesozoic Global onlap chart lacked proprietary Cretaceous section.

Vail et al., 1977

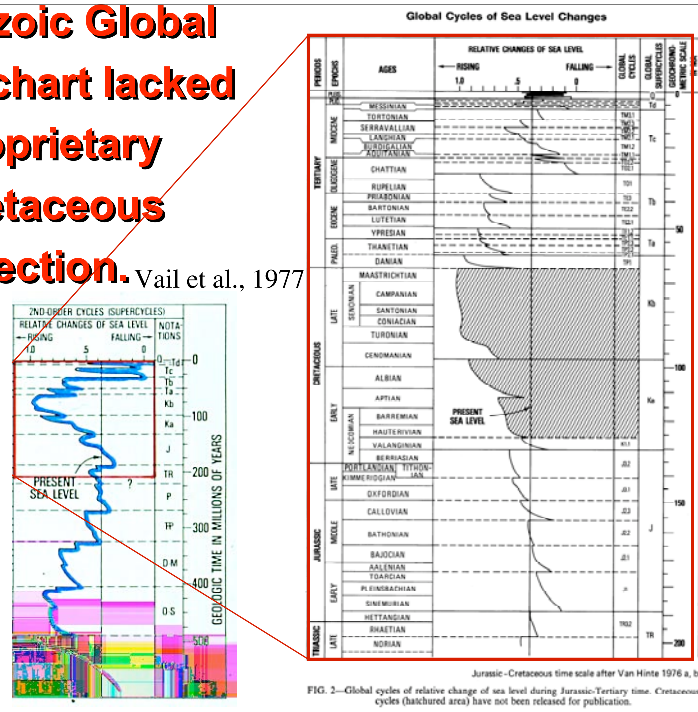


FIG. 2—Global cycles of relative change of sea level during Jurassic-Tertiary time. Cretaceous cycles (hatchured area) have not been released for publication.

Seismic Stratigraphy

Global Correlation and Eustasy

- **We know there is a structure, but is there any reservoir rock?**
- **Vail applied Wheeler's concepts to seismic cross sections.**
- **Observed similarity of coastal onlap between basins.**
- **Interpreted cause of apparent synchronicity to be eustasy.**
- **Global synchronicity allows lithology prediction in undrilled or little known basins.**
- **Reservoirs may lie farther in basin during development of unconformities.**
- **Publication of the first global sea level charts (Vail et al., 1977; Haq et al., 1987, 1988).**
- **Eustasy has been heavily criticized in recent years (Miall, 1997, Miall and Miall, 2003).**

Sequence Stratigraphy

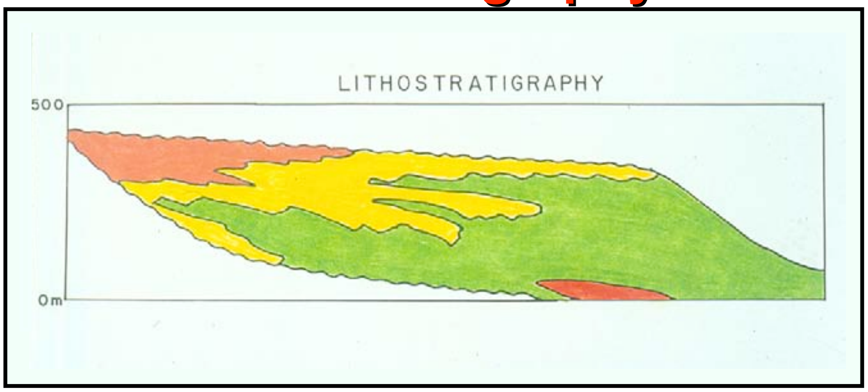
- Application of seismic stratigraphic principles to outcrop, core, well log data, and high resolution seismic data.
- Led to more theoretical understanding of how depositional systems change and are linked as a consequence of forcing parameters (accommodation/accumulation, Jervey 1988).
- Sequence stratigraphic concepts may be applicable at a wider variety of spatial and temporal scales than seismic stratigraphy.

Sequence Stratigraphy

Definitions

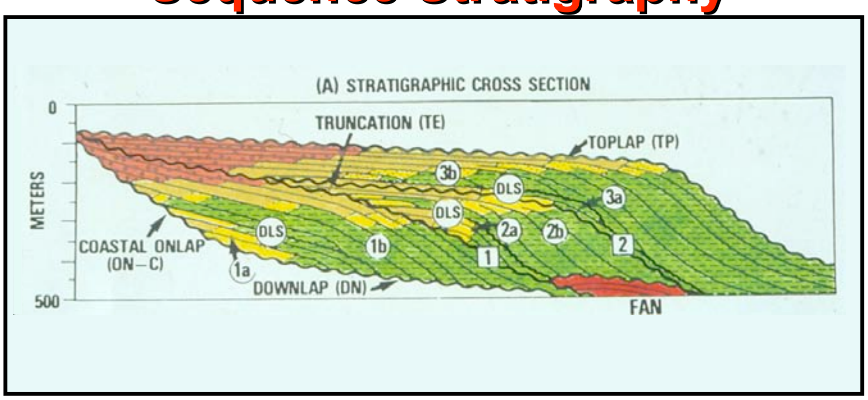
- *Sequence Stratigraphy = Rocks + Surfaces + Time*
- The study of rock relationships within a chronostratigraphic framework wherein the succession of rocks is cyclic and is composed of genetically related stratal units.
- The repackaging of the rocks into rock units bounded by unconformities and their correlative conformities.
- Sequences consist of depositional *systems tracts* and are interpreted in terms of accommodation/accumulation.

Lithostratigraphy



- "Simple" inter-tonguing of lithofacies

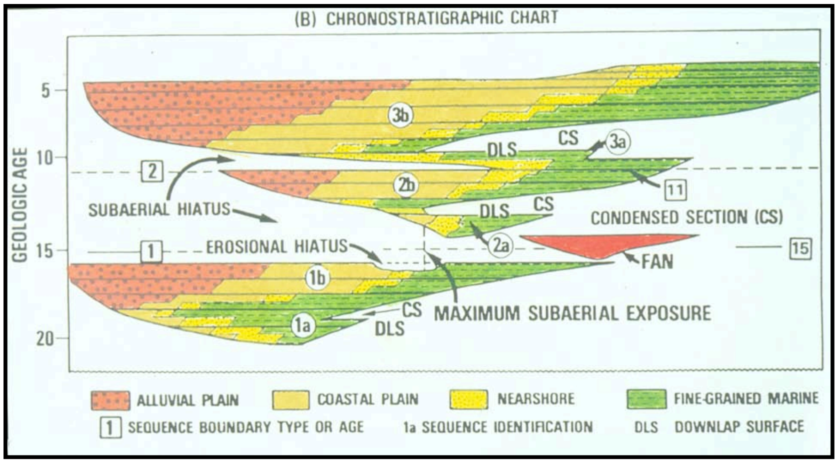
Sequence Stratigraphy



- Lithofacies and surfaces integrated.

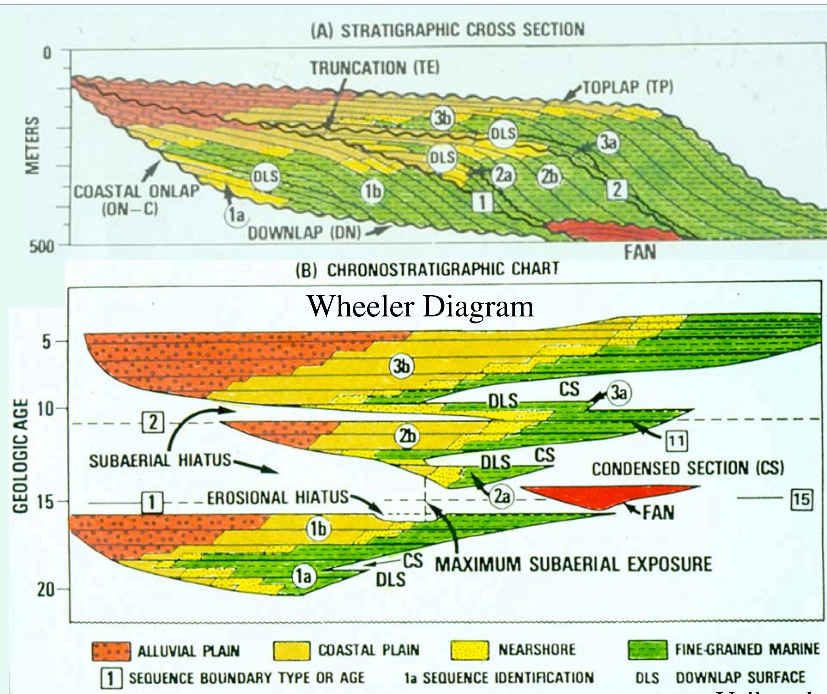
Vail et al., 1984

Wheeler Diagram



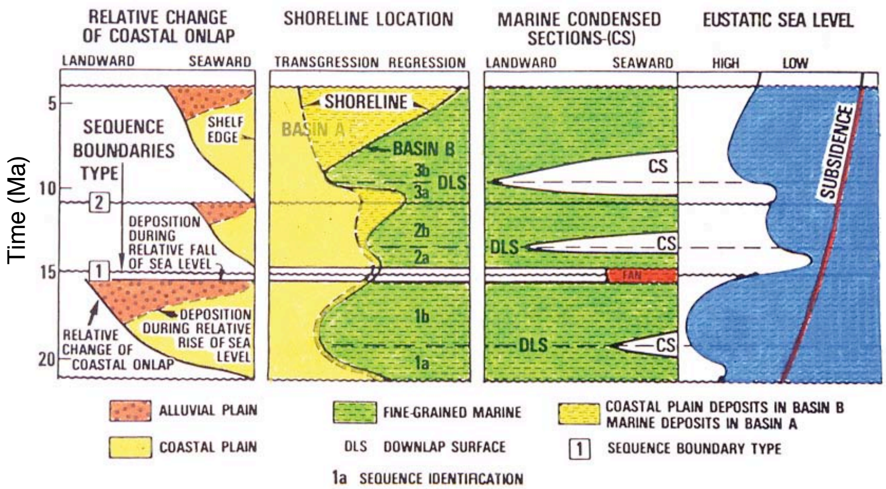
- **Time-stratigraphic analysis of sequence stratigraphic cross sections.**
  - **Ideally requires some time information**
    - **Biostrat, radiometric dates**

Vail et al., 1977

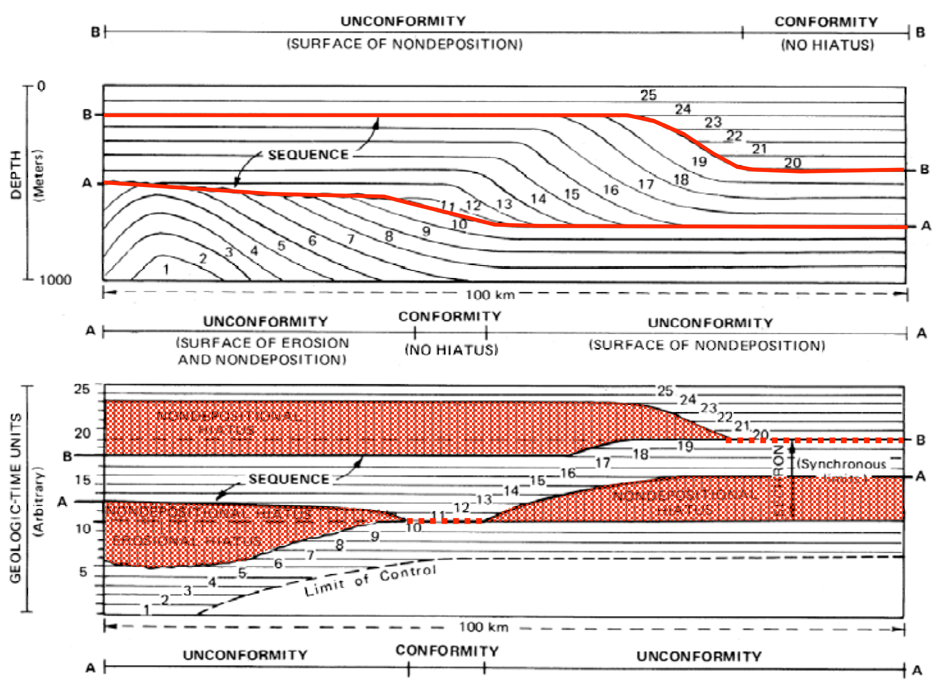


Vail et al., 1977

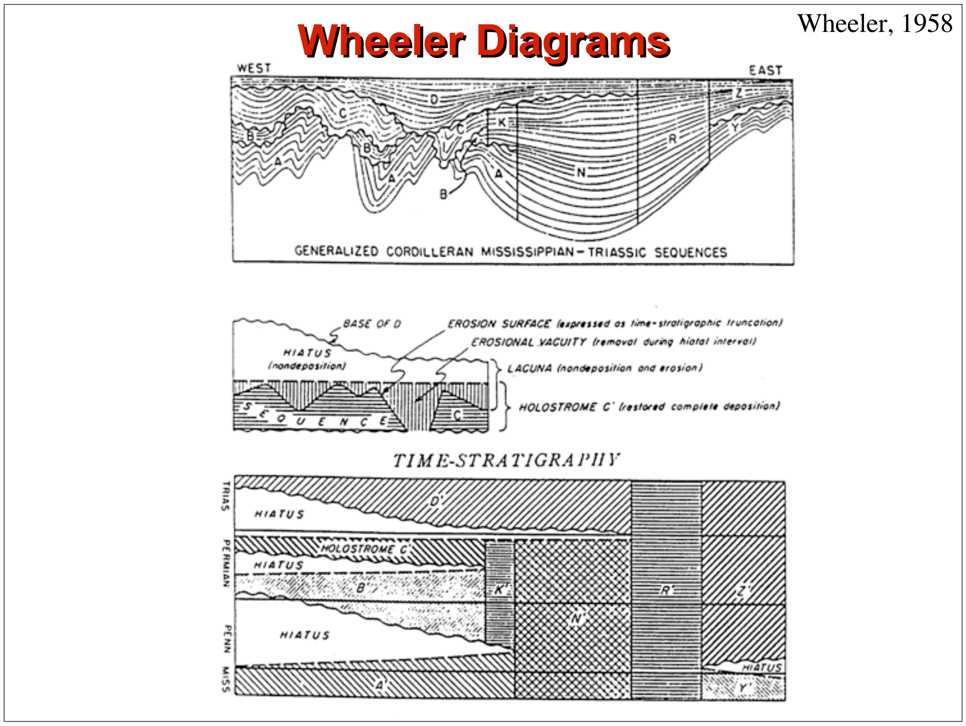
Sea-level curve

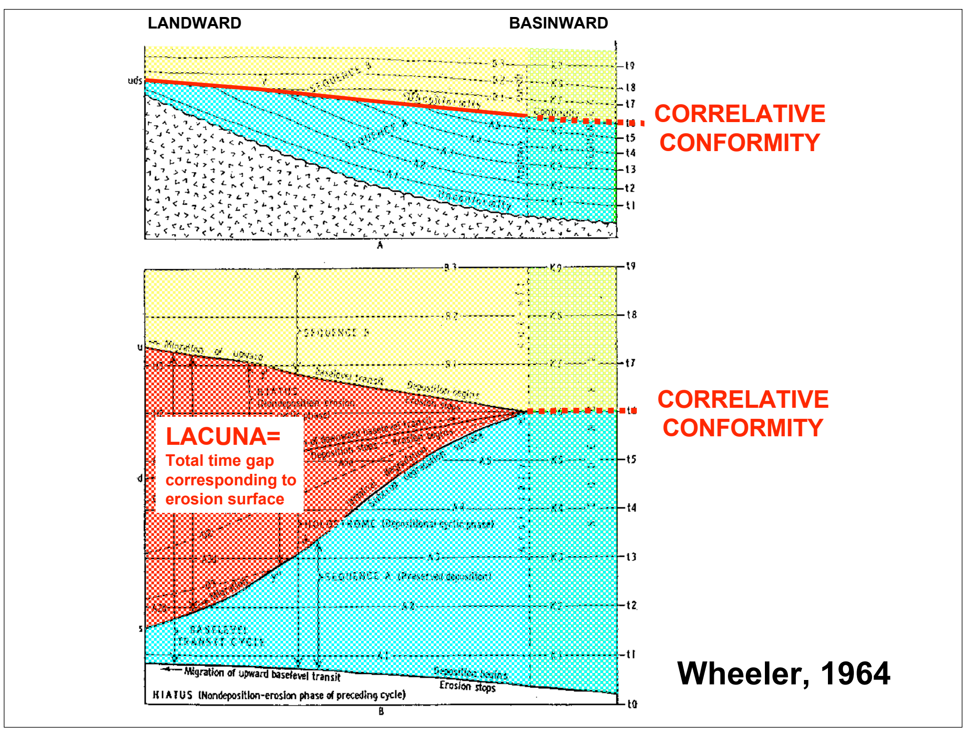


Vail et al., 1977



Mitchum et al., 1977

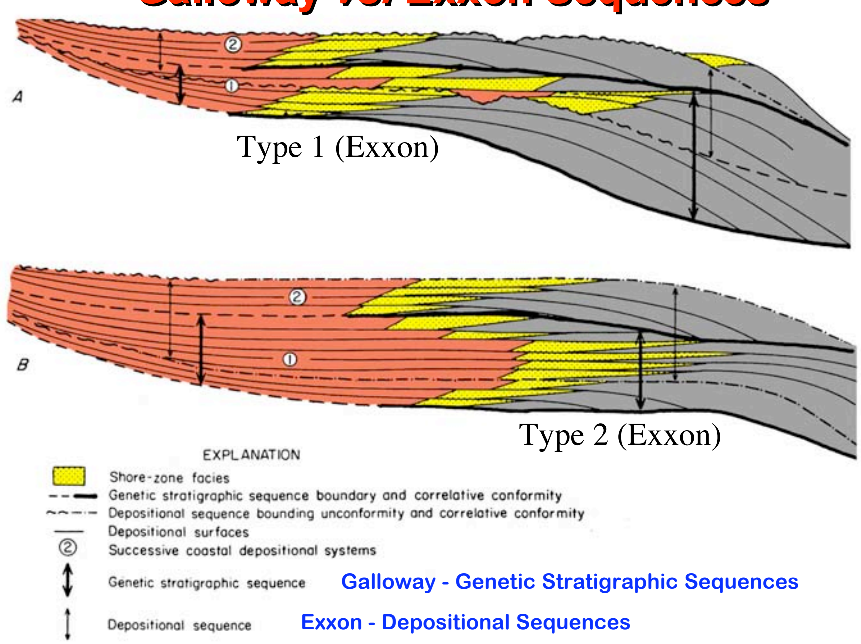

Wheeler Diagrams
Wheeler, 1958
WEST
EAST
GENERALIZED CORDILLERAN MISSISSIPPIAN-TRIASSIC SEQUENCES
BASE OF D
EROSION SURFACE (expressed as time-stratigraphic truncation)
EROSIONAL VACUITY (removal during hiatal interval)
HIATUS (nondeposition)
LACUNA (nondeposition and erosion)
HOLOSTROME C' (restored complete deposition)
SEQUENCE
TIME-STRATIGRAPHY
TRIAS
PERMIAN
PENN
MISS
HIATUS
HOLOSTROME C'


LANDWARD
BASINWARD
CORRELATIVE CONFORMITY
CORRELATIVE CONFORMITY
LACUNA=
Total time gap corresponding to erosion surface
Migration of upward baselevel transit
HIATUS (Nondeposition-erosion phase of preceding cycle)
Wheeler, 1964

How are Sequences Defined and Identified?

- A depositional sequence is defined as a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities (Mitchum, 1977).
- There are other types of sequences (e.g. genetic sequences of Galloway, 1989).
  - Stratal unit between maximum flooding surfaces.

Galloway *vs.* Exxon Sequences



How are Depositional Sequences Defined and Identified?

- Unconformity (Mitchum et al., 1977)
  - A surface of erosion or nondeposition that separates younger strata from older rocks and represents a significant hiatus (at least a correlatable part of a geochronologic unit is not represented by strata).
  - Periods of erosion and nondeposition occur at each global fall of sea level, producing *interregional unconformities*.
- Unconformity (Van Wagoner, 1995)
  - Surface separating younger from older strata, along which there is evidence of subaerial erosional truncation or subaerial exposure or correlative submarine erosion in some areas, indicating a significant hiatus. Forms in response to a relative fall in sea level.
  - This is a much more restrictive definition of unconformity than is commonly used or used in earlier works on sequence stratigraphy.

Types of Unconformities

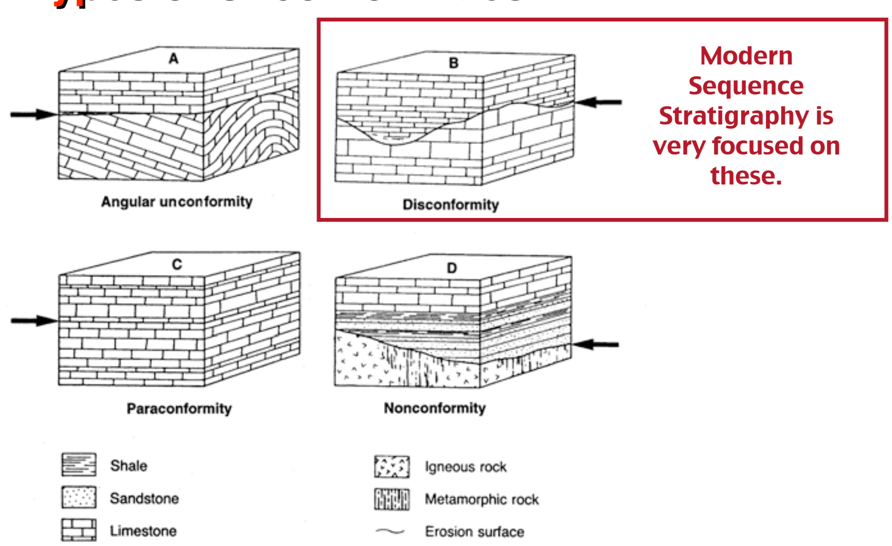
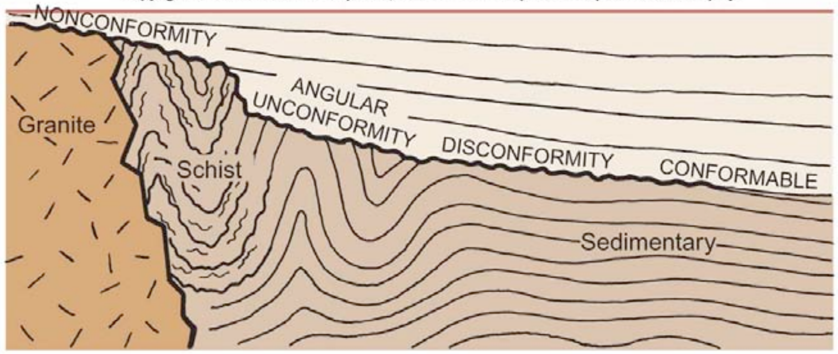


FIGURE 14.2 Four basic types of unconformities. Arrows point to unconformity surfaces. (After Dunbar, C. O., and J. Rodgers, 1957, Principles of stratigraphy: John Wiley & Sons, New York. Fig. 57, p. 117, reprinted by permission.)

Stratigraphy

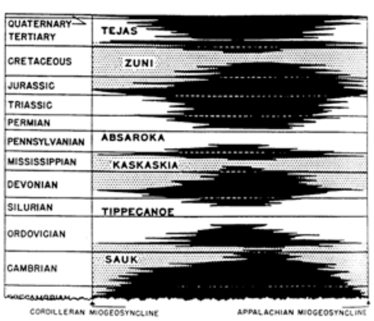
Types of Unconformities



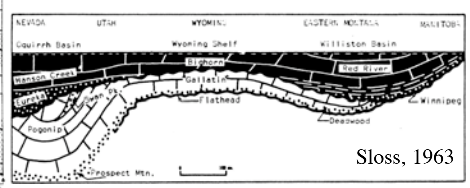
Prothero and Dott., 2005

One type of unconformity may grade laterally into another type.

Sloss Sequences



Angular Unconformities



Sloss, 1963

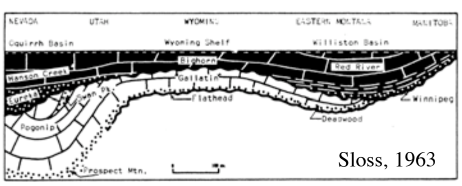
- **Six major sequences in North American Stratigraphy, represent major tectono-eustatic events.**
  - **Sauk, Tippecanoe, Kaskaskia, Absaroka, Zuni, Tejas.**
- **Unconformities are primarily angular and very widespread over the entire North American Craton.**

Sequence Stratigraphy

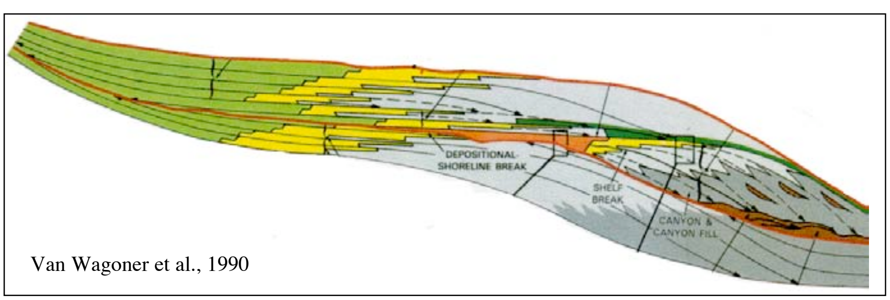
Applications of Sequence Stratigraphy

- Age model predictions
  - analysis of sequences for the purpose of extracting a eustatic signal to determine age.
  - assumes inherent validity of published global sea-level curves.
- Lithology prediction
  - Analysis of stratigraphic successions for the purpose of understanding temporal and spatial relationships between rocks in the context of relative sea level change.
  - The use of sequence stratigraphy for lithology prediction is thus independent of a belief in eustasy as the underlying mechanism.
  - The key to success is the correct identification and correlation of chronostratigraphically significant surfaces.
  - This approach requires the integration of facies successions and time-stratigraphy.

What are Sequences Made of?



Sloss, 1963



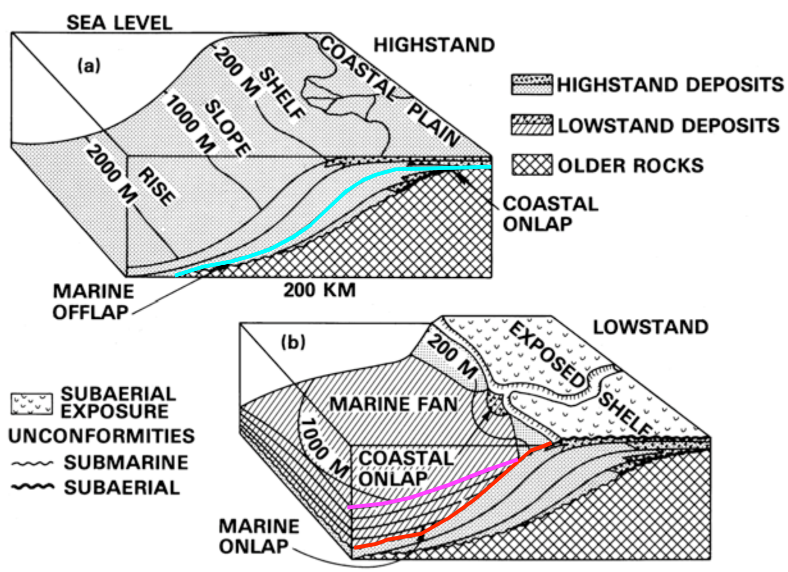
Van Wagoner et al., 1990

Sequence Hierarchies

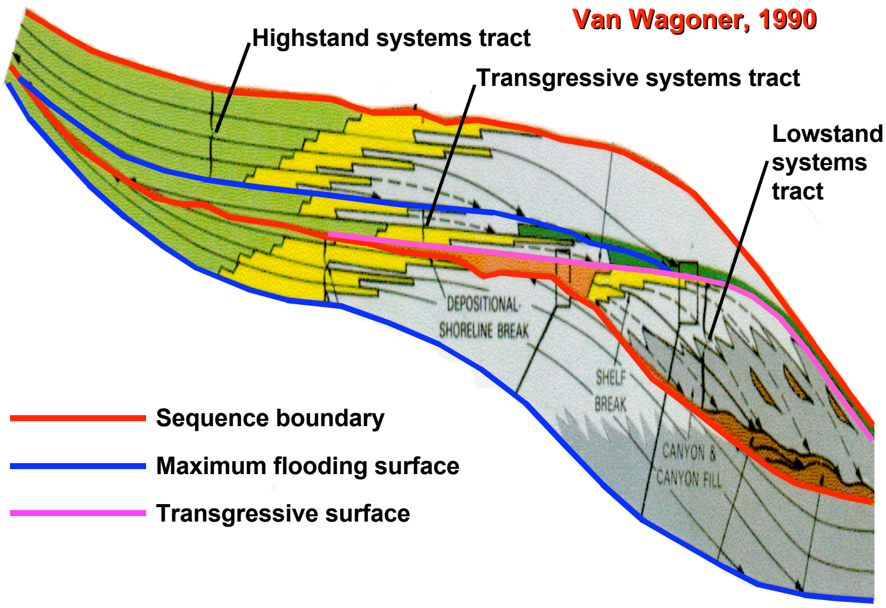
- EXXON School
  - Lamina
  - Laminaset
  - Bed
  - Bedset
  - Parasequence
  - Parasequence set
  - Sequence
- European/Texas School
  - Facies
  - Facies Association
  - Depositional System
  - Systems Tract
  - Sequence

Early Sequence Stratigraphy

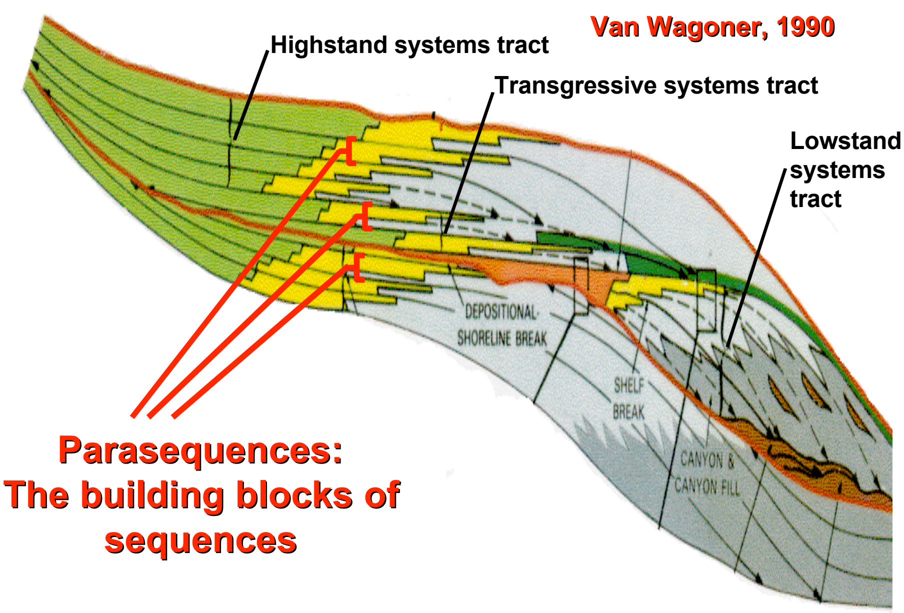
Vail et al., 1977



Modern sequence stratigraphy



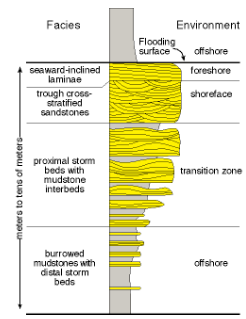
Modern sequence stratigraphy

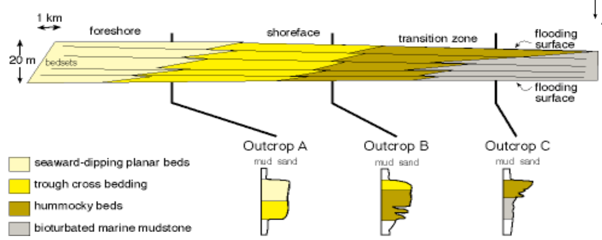


Sequence Stratigraphy

Parasequence

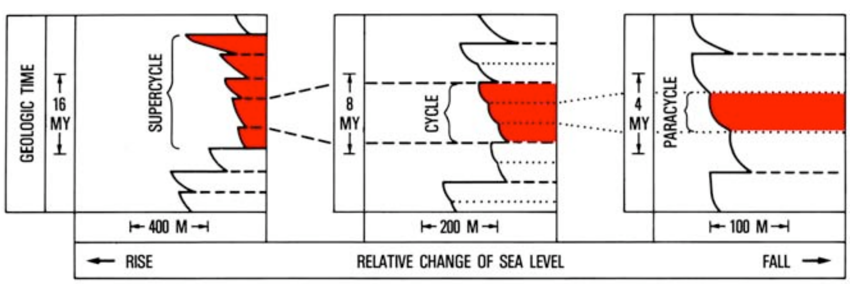
- Genetically related strata bounded by flooding surfaces or their correlative surfaces.
- Commonly characterized by a shoaling upward facies succession.





Sequence Stratigraphy

Parasequence



Vail et al., 1977

- Developed from older concept of a paracycle.
  - "The interval of time occupied by one regional or global relative rise and stillstand of sea level, followed by another rise with no intervening relative fall" (Mitchum, 1977).
  - Results in units bounded by flooding surfaces that lack evidence of subaerial exposure.

71

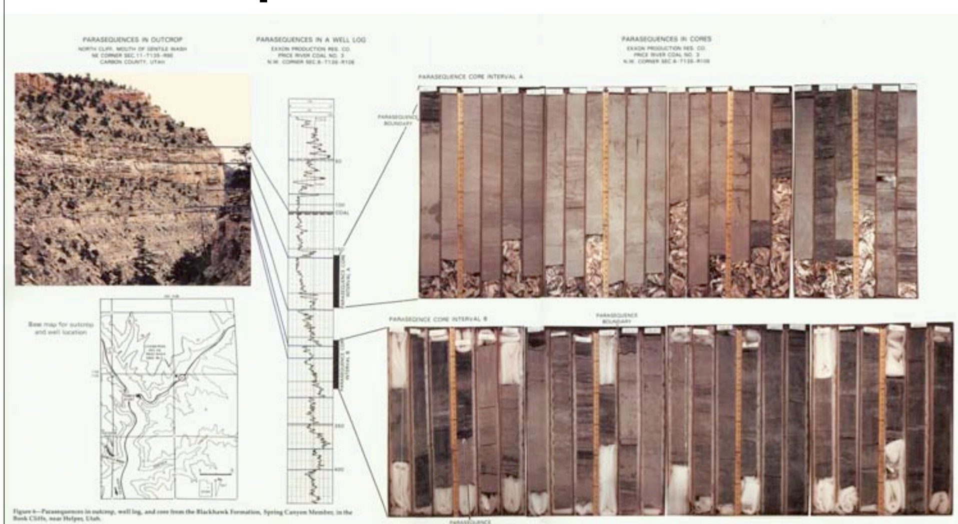
Sequence Stratigraphy

Parasequence

- Examples include
  - prograding delta lobe,
  - standard shallowing-upward carbonate "cycle".
- Can be autogenic in origin.

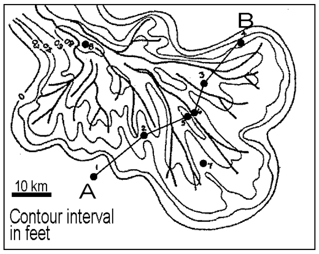
Sequence Stratigraphy

Parasequence

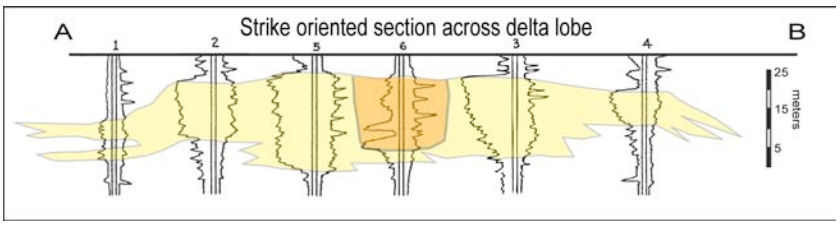


Van Wagoner et al., 1990

"Parasequences" in the modern Mississippi

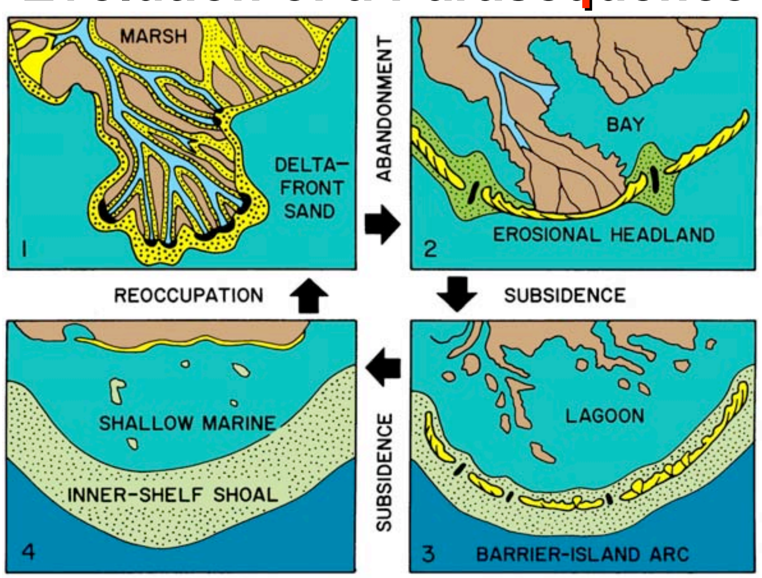


- Cross section through lobe shows upward coarsening parasequence.
- Parasequence extends over 50 km along strike and nearly 100 km down dip.
- These are extensive units, but will be smaller in a smaller-scale delta.



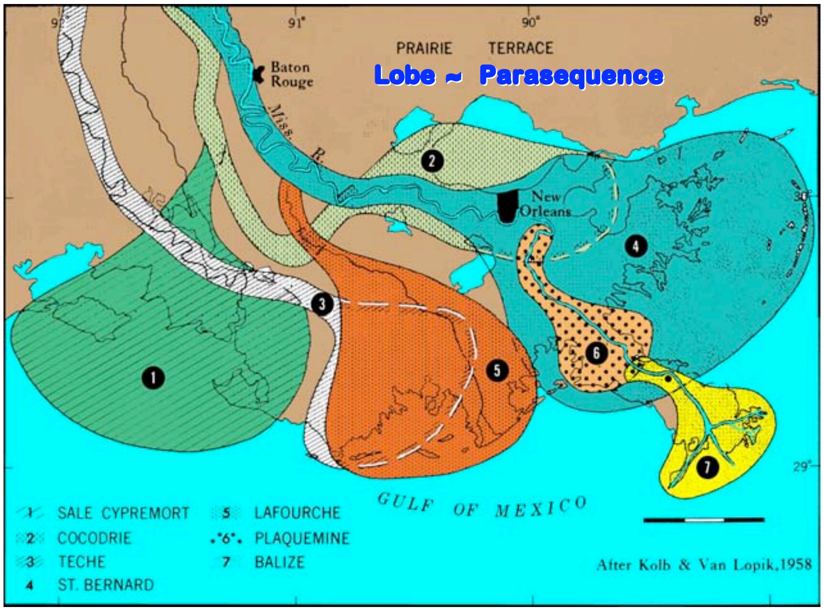
Modified after Coleman and Prior, 1980

Evolution of a Parasequence



From Boyd et al., 1989

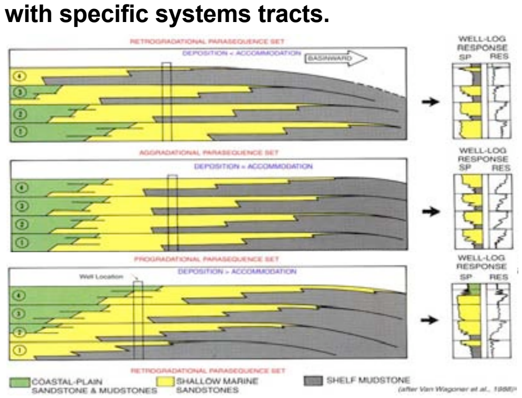
Autocyclic Lobes of the Holocene Mississippi Delta



Sequence Stratigraphy

Parasequence Sets

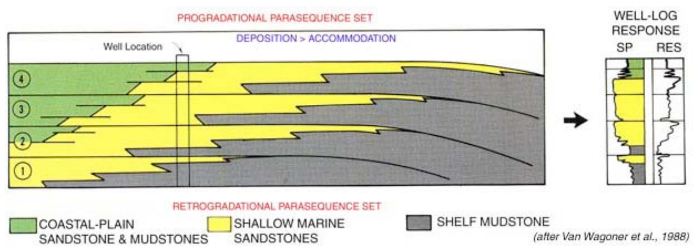
- Groups of parasequences organized into systematic stacking patterns.
- Typically associated with specific systems tracts.
- Progradational
  - Downstepping,
  - Forestepping,
  - Seaward stepping
  - Offlapping.
- Aggradational
  - vertically stacked.
- Retrogradational
  - Backstepping.



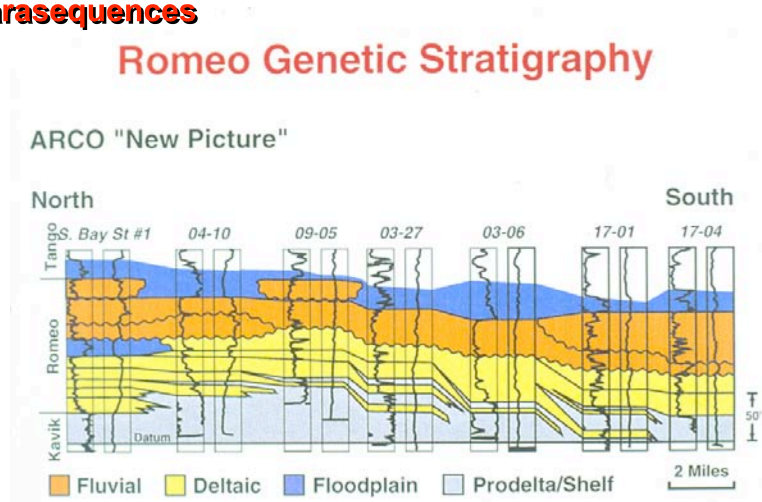
Sequence Stratigraphy

Parasequence Sets

- **Progradational**
  - **Downstepping,**
  - **Forestepping,**
  - **Seaward stepping**
  - **Offlapping.**



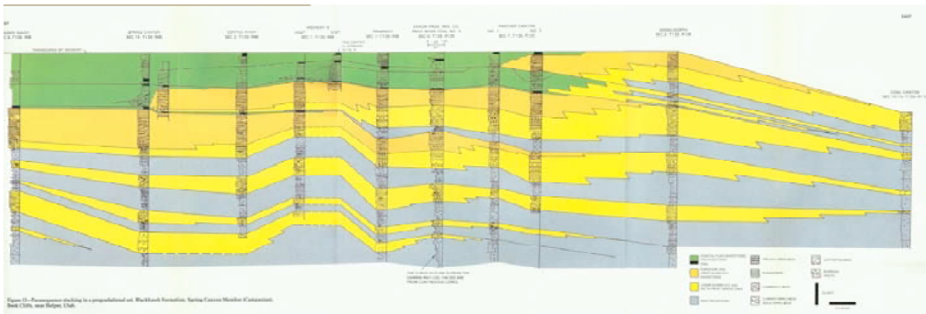
Example of progradational, seaward- to down-stepping parasequences



Ivishak sandstones, Prudhoe Bay, AK

Tye et al., 1999

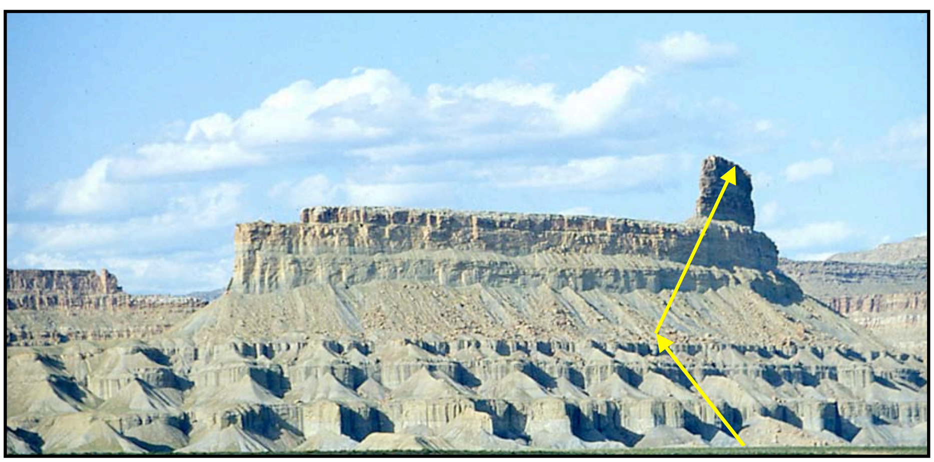
Example of Seaward-Stepping Parasequences



Cretaceous - Book Cliffs, Utah

From Van Wagoner et al., 1990

Example of Landward and Seaward-Stepping Parasequences

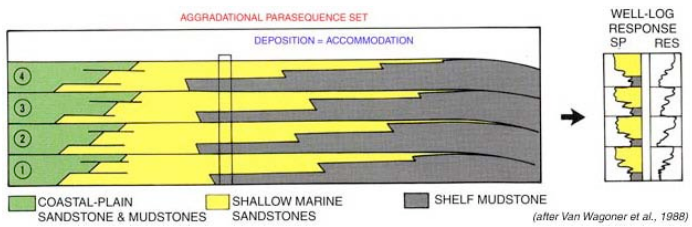


Cretaceous - Book Cliffs, Utah

Sequence Stratigraphy

Parasequence Sets

- **Aggradational**
  - **vertically stacked.**



(after Van Wagoner et al., 1988)

Example of Vertically Aggrading Parasequences

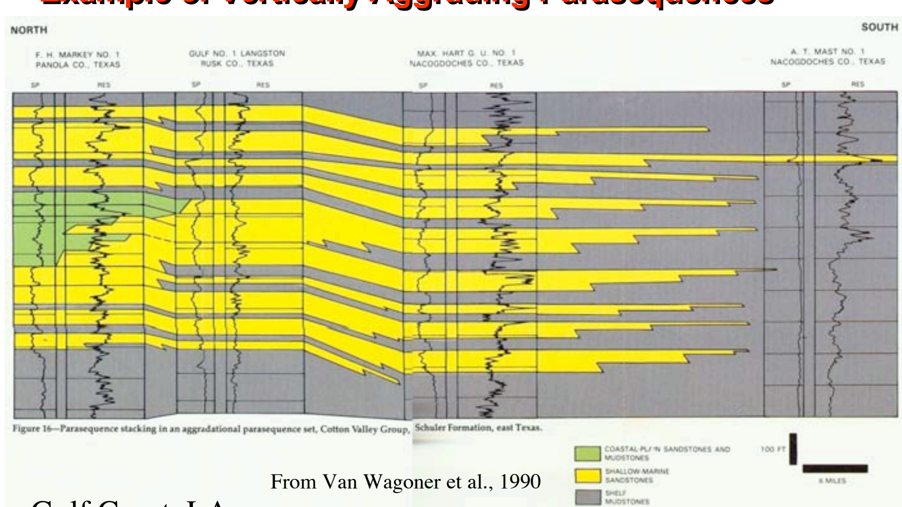


Figure 16—Parasequence stacking in an aggradational parasequence set, Cotton Valley Group, Schuler Formation, east Texas.

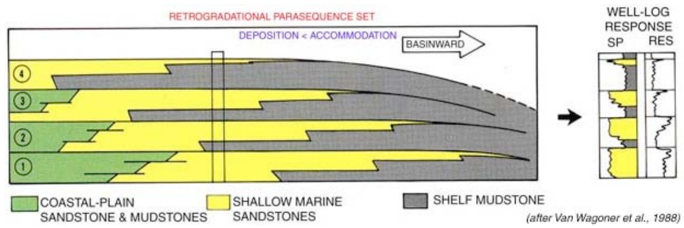
From Van Wagoner et al., 1990

Gulf Coast, LA

Sequence Stratigraphy

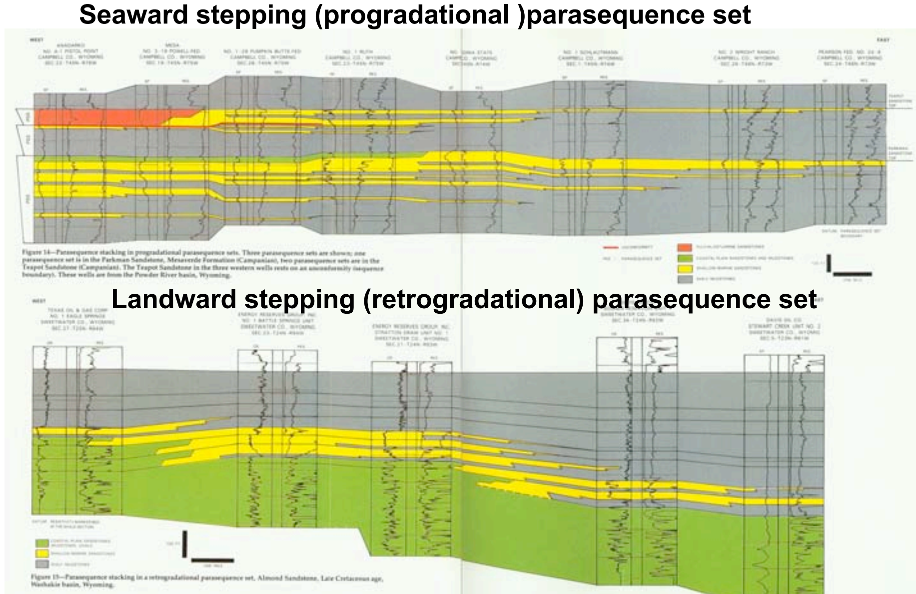
Parasequence Sets

- **Retrogradational**
  - **Backstepping.**



Examples of parasequence stacking patterns

Seaward stepping (progradational)parasequence set

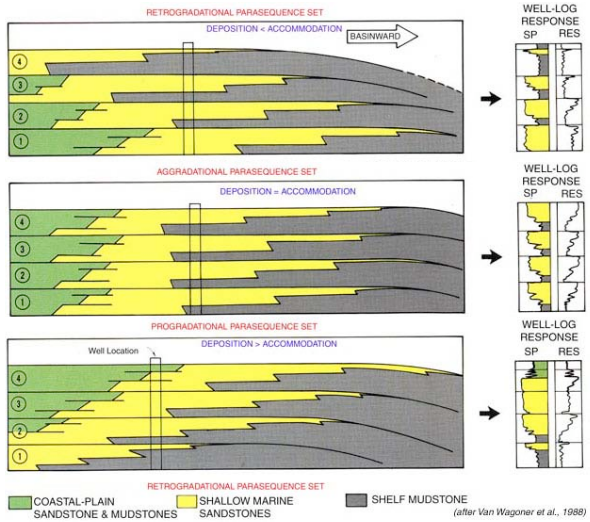


From Van Wagoner et al., 1990

Sequence Stratigraphy

Parasequence Sets

- Groups of parasequences may be organized into systematic stacking patterns.



Van Wagoner et al., 1990

Parasequence Sets

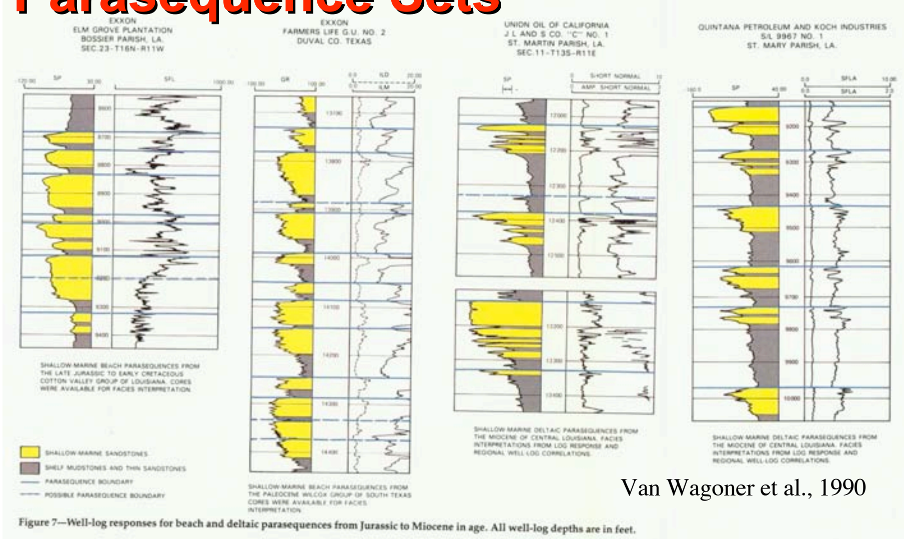
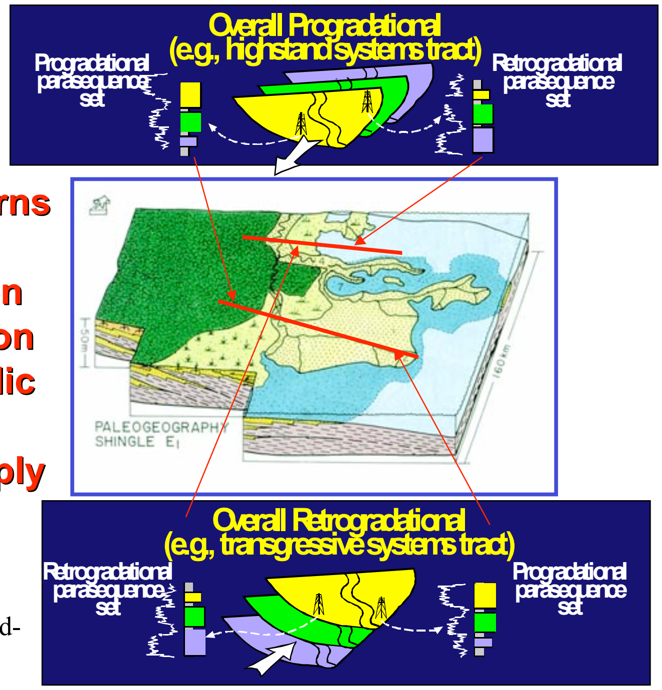


Figure 7—Well-log responses for beach and deltaic parasequences from Jurassic to Miocene in age. All well-log depths are in feet.

Van Wagoner et al., 1990

- Parasequence sets *__may__* be identified in a single well log.
- Great caution MUST be used.

Stacking patterns may reflect Transgression and Regression from Autocyclic Shifting of Sediment Supply



(Martinsen and Helland-Hansen, 1994)

Sequence Stratigraphy

Parasequence Sets

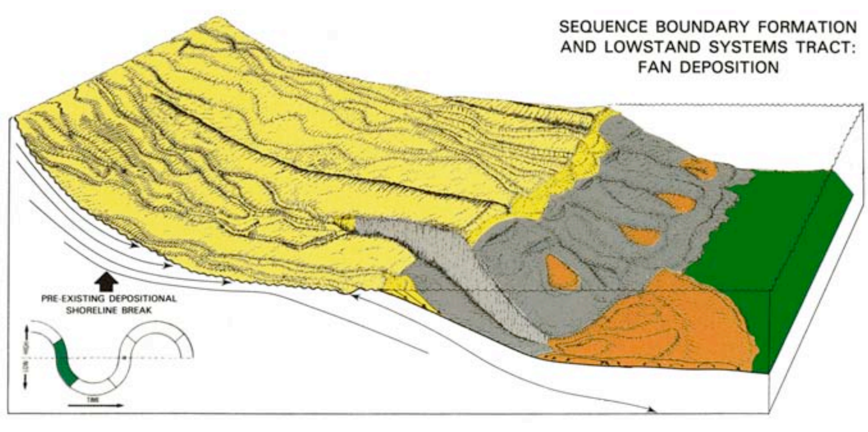
- Parasequence sets are bounded by more extensive surfaces than parasequences.
- Regressive facies successions may occur within *all* parasequence sets.
  - For example, regressive delta lobes can occur within a transgressive systems tract.
- This has caused much debate in the literature.
- Stacking patterns may be a function of autogenic controls.
- Stacking patterns can vary along strike.

Sequence Stratigraphy

Systems Tracts

- Linkage of contemporaneous depositional systems.
- Defined by physical position in a sequence and on the basis of *parasequence stacking patterns*.
- Bounded by specific surfaces.
- May be related to formation during an interval of relative sea-level change.
- Commonly interpreted in the context of changes in accommodation and accumulation.
- Big arguments about the “rock” paradigm versus the “Sea-level paradigm (Van Wagoner, 1995).

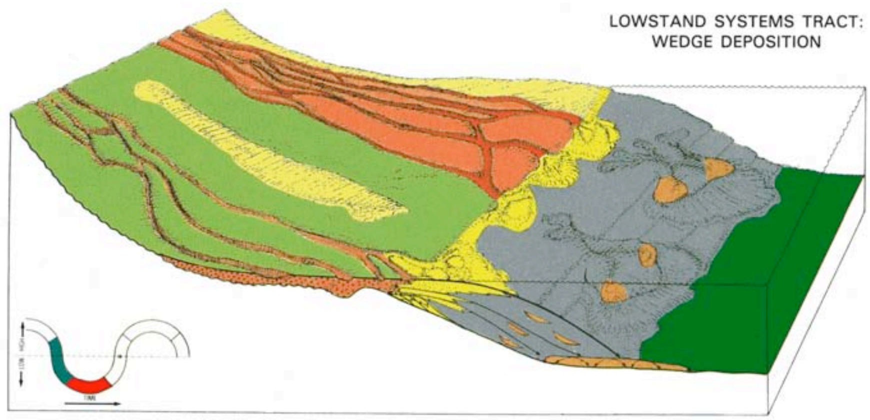
Systems Tracts



- Sequence Boundary (SB) inferred to form during rapid sea-level fall, which causes subaerial exposure and fluvial degradation on the newly exposed shelf.
- SB bounds the base of the LST.

Van Wagoner et al., 1990

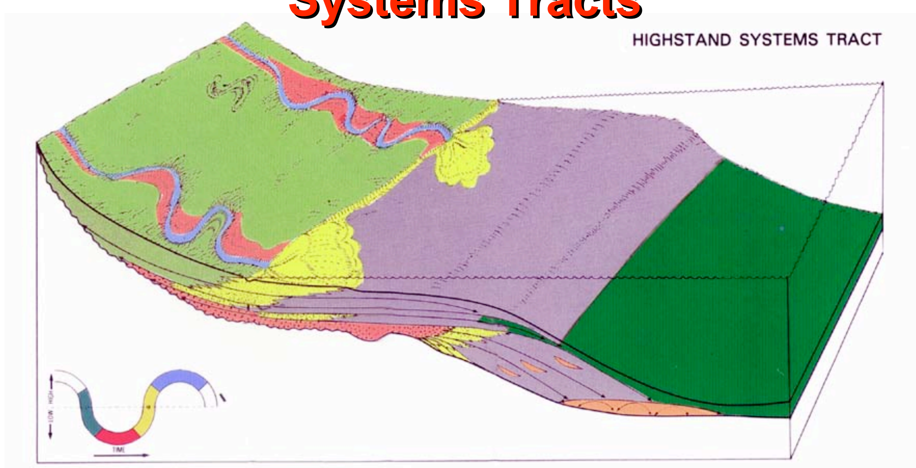
Systems Tracts



- As fall slows, sea-level stabilizes in a low position, and depositional systems start to deposit.
- Note, lowstand includes slightly falling and rising sea level in theoretical curve.

Van Wagoner et al., 1990

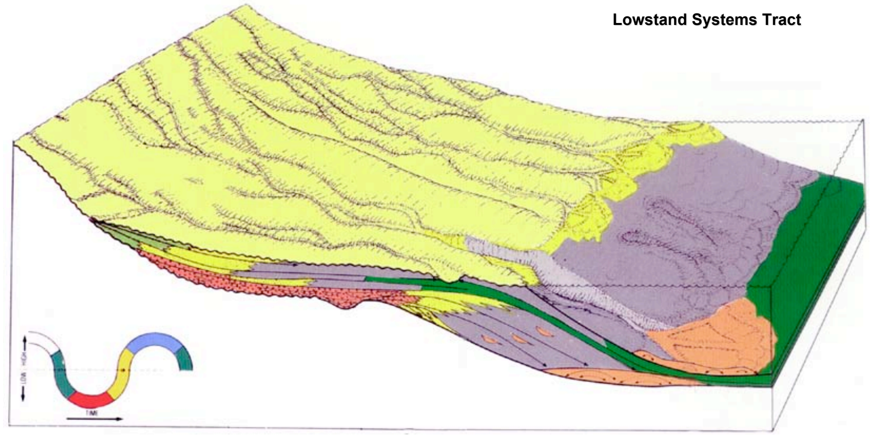
Systems Tracts



- At highstand of sea level, system again stabilizes and systems begin to prograde
  - Transgressive systems tract not sold separately.
- HST bounded below by the Maxiumu Flooding Surface and above by the SB.

Van Wagoner et al., 1990

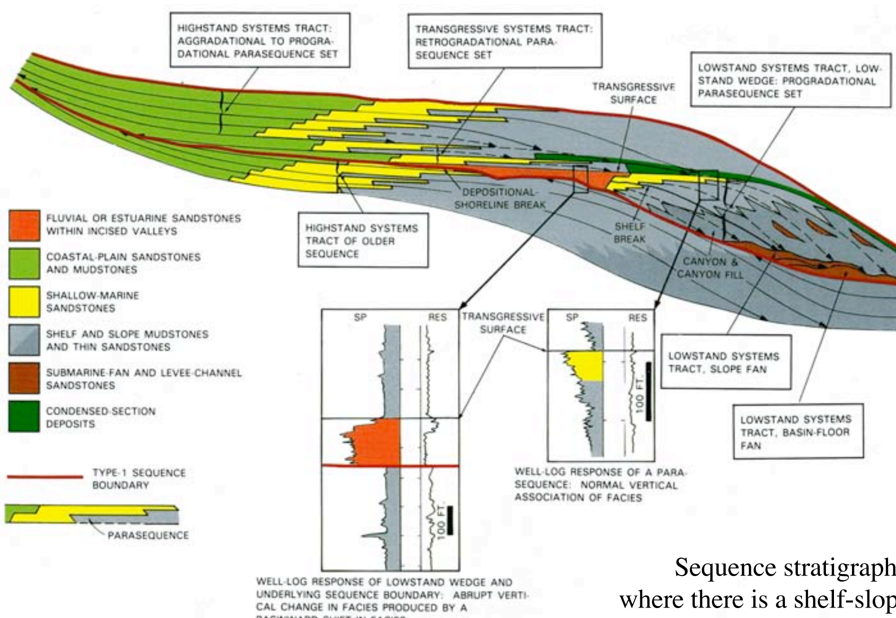
Systems Tracts



- New sequence boundary fall as rate of fall accelerates.
- Note, HST is largely eroded

Van Wagoner et al., 1990

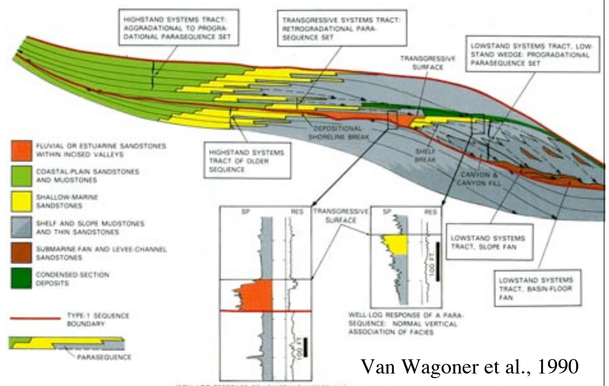
Type 1 Sequences



Van Wagoner et al., 1990

Sequence stratigraphy where there is a shelf-slope break

Lowstand Systems Tract

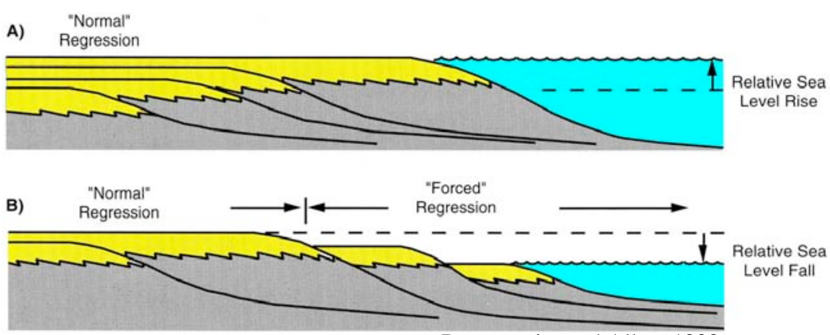


Van Wagoner et al., 1990

- Bounded below by the Sequence Boundary.
- Bounded above by "The Transgressive Surface".
- Lowstand systems tracts are interpreted to have been deposited during relative sea-level falls and subsequent lowstands.
- Characteristically deposited below the level of the coastal plain or shelf.
- Commonly are basinally-isolated.
  - attached versus detached
- May include linkage of incised valleys, lowstand shoreline, lowstand delta, and deep-water submarine fan.
- Downstepping, forestepping pattern or aggradational stacking pattern.
- Shorelines are observed to be regressive to stillstanding throughout the LST.

Systems Tracts

Falling Stage/Forced Regressive

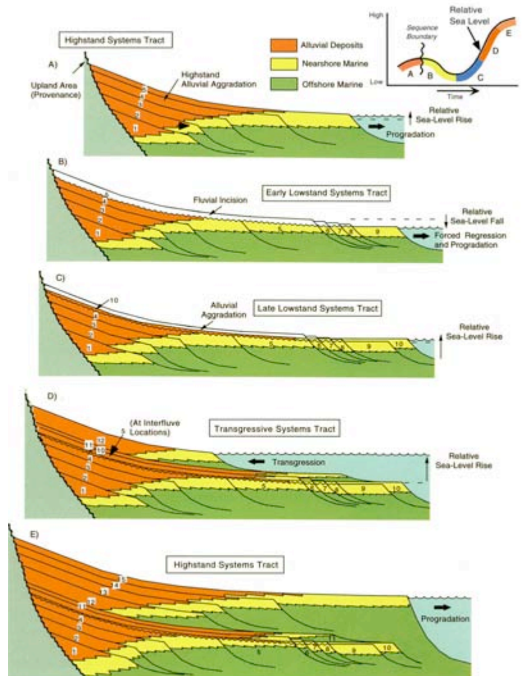


Posamentier and Allen, 1999

- Deposited during time of rapid sea-level falls.
- Commonly deposited on the shelf and common in ramp-type margins, without a shelf-slope break.
- Forestepping to downstepping stacking pattern.
- Lack of subaerial accommodation.

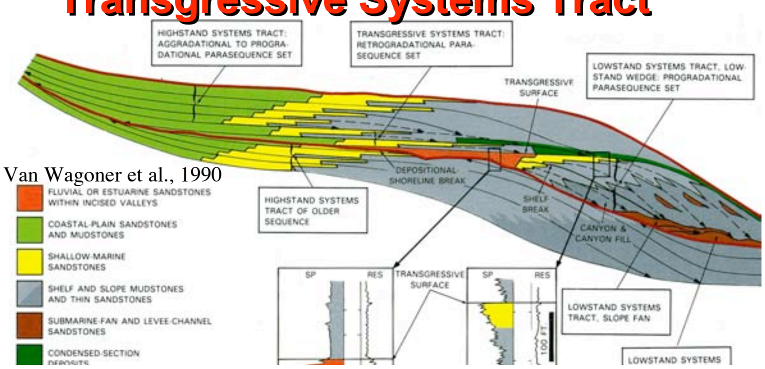
Falling Stage Systems Tracts

- Interpretation of systems tracts during cyclic sea-level changes.
  - The Posamentier and Allen view.
- SB becomes difficult to pick reliably.
- May predate full extent of subaerial unconformity and may underlie sequence boundary.
- Sometimes referred to as Late Highstand Systems Tract or as early Lowstand Systems Tract.



Posamentier and Allen, 1999

Transgressive Systems Tract

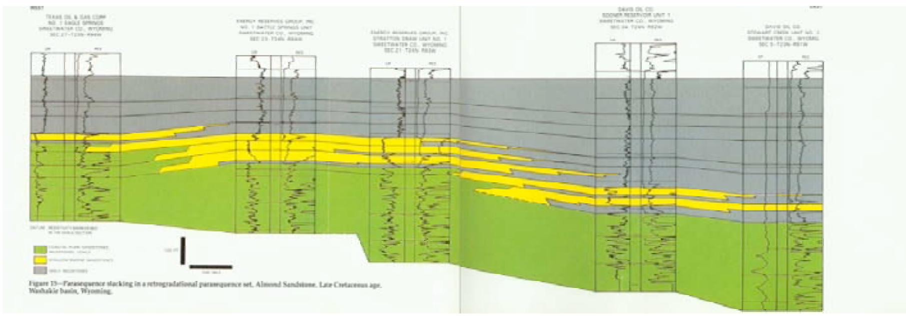


Van Wagoner et al., 1990

- The base is defined by the first regionally persistent flooding surface (The Transgressive Surface).
- Top defined by Maximum Flooding Surface
- Marks change from backstepping to progradational parasequence stacking pattern.
- Interpreted to have been deposited during intervals of rapid relative sea-level rise.
- Accumulation rate is exceeded by the rate of new space added on the shelf (i.e., new accommodation).
- Overall shoreline transgression occurs.
- This systems tract may include estuarine, shoreface, coastal plain, and deltaic depositional systems.

Transgressive Systems Tract

Landward stepping (retrogradational) parasequence set



From Van Wagoner et al., 1990

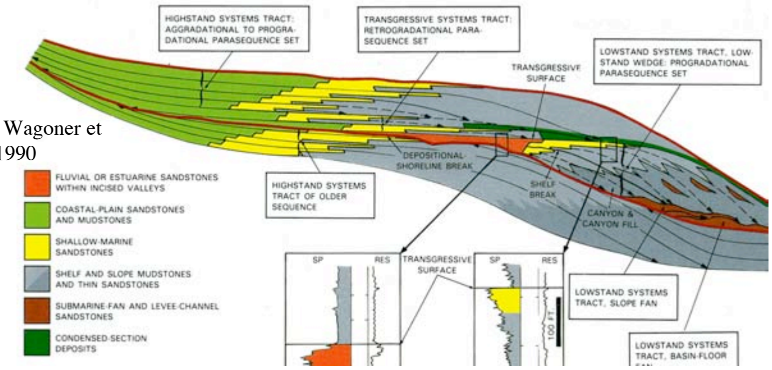
Examples of parasequence stacking patterns

Transgressive Systems Tract

- There has been much debate about transgressive facies within the lowstand systems tract versus the strictly-defined Transgressive Systems Tract.
  - Many valley-fills show a transgressive facies fill.
  - The valley-fill facies is interpreted as the LST, even if facies show a transgressive character.
  - Only when valleys are filled and the shelf floods, is the TST defined.
- Vail and others have lamented using the term "Transgressive Systems Tract" versus a more descriptive term.

Highstand Systems Tract

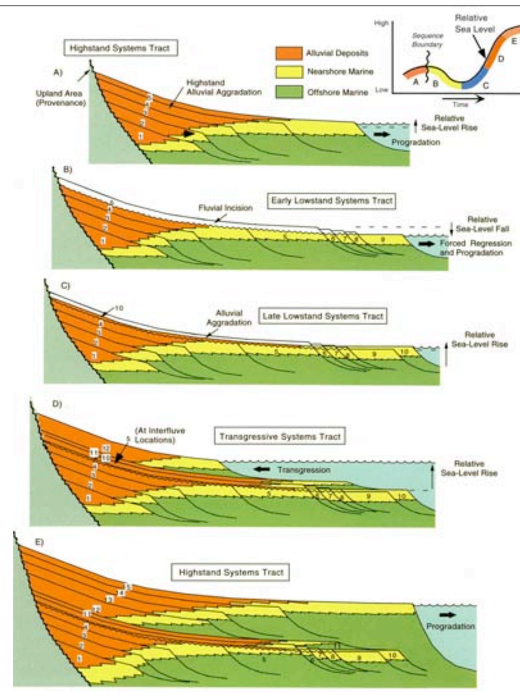
Van Wagoner et al., 1990



- Interpreted to be deposited during intervals of decelerating relative sea level rise and stillstand.
- Accumulation exceeds accommodation resulting in shoreline regression (normal regression).
- Aggradational to forestepping stacking patterns.
- Fluvial, shoreline, and deltaic depositional systems are most common.
- Shelfal carbonate systems are common in lower latitudes.
- Condensed section usually associated with highstand.

Highstand Systems Tracts

- Extensive subaerial accommodation.
- "Normal" regression.
- Lack of erosional discontinuities.
- In Posmantier and Allen view, HST is largely preserved.



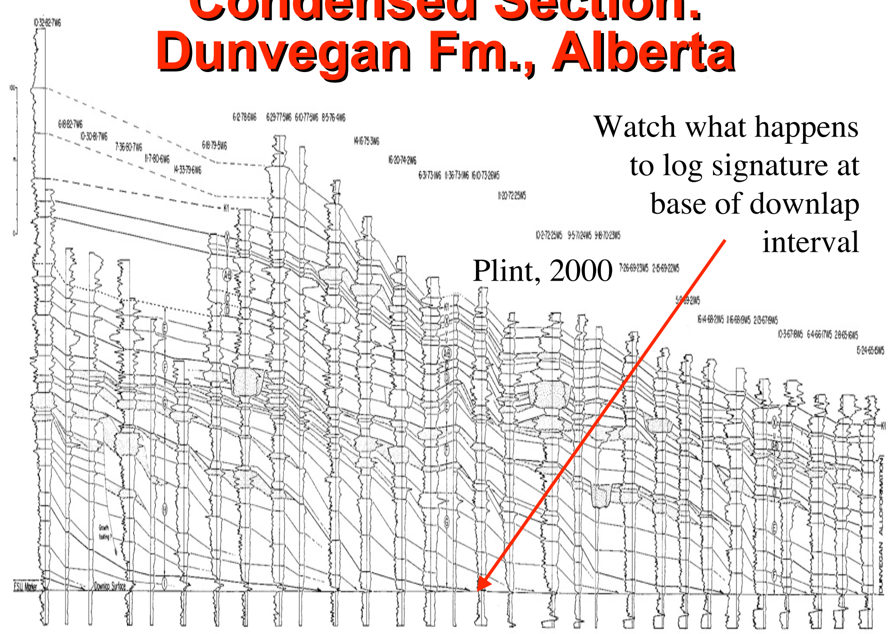
Posamentier and Allen, 1999

Systems Tracts

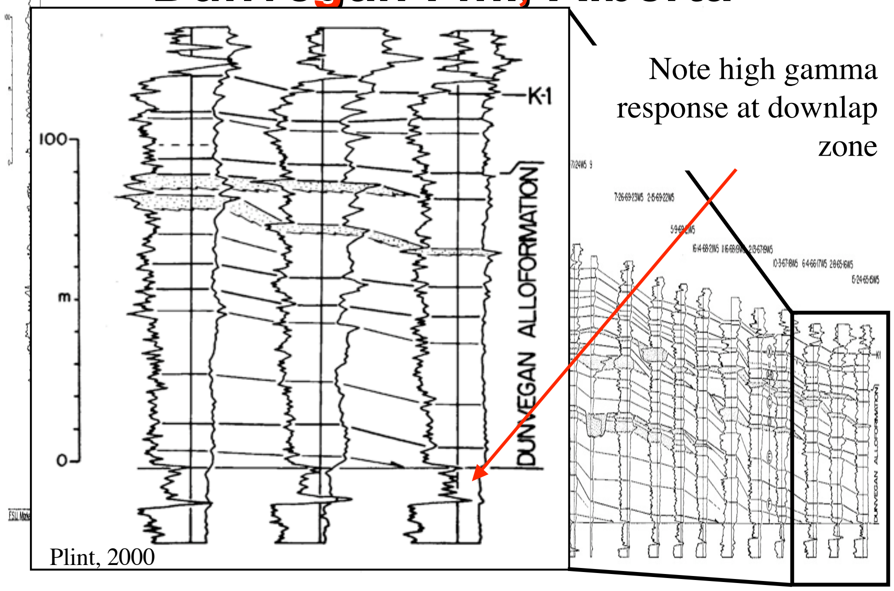
Condensed Sections

- Coeval facies equivalents seaward of all systems tracts.
- Develop beyond the influence of most terrigenous sedimentation.
- Significant amounts of time are represented by anomalously thin units.
- Characterized by a "hot" gamma ray log response and by faunal peaks.
- Also chalks, cherts, phosphorites.
- May be associated with marine “corrosion”.

Condensed Section: Dunvegan Fm., Alberta



Condensed Section: Dunvegan Fm., Alberta



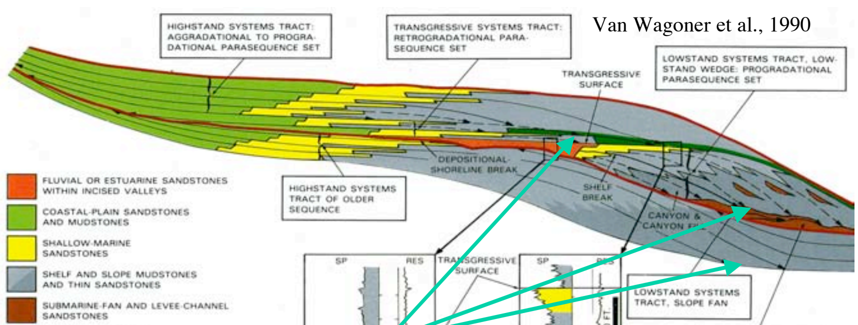
Note high gamma response at downlap zone

Plint, 2000

Systems Tracts

Condensed Sections

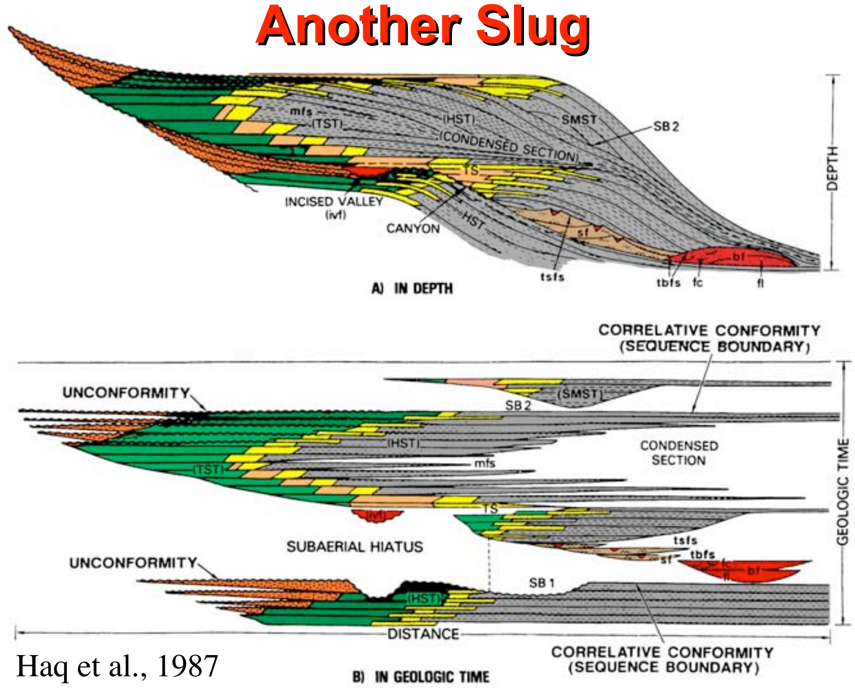
Van Wagoner et al., 1990



- **Condensed sections commonly associated with downlap surfaces.**
- **There is downlap within the lowstand systems tract and between the transgressive and highstand systems tract.**

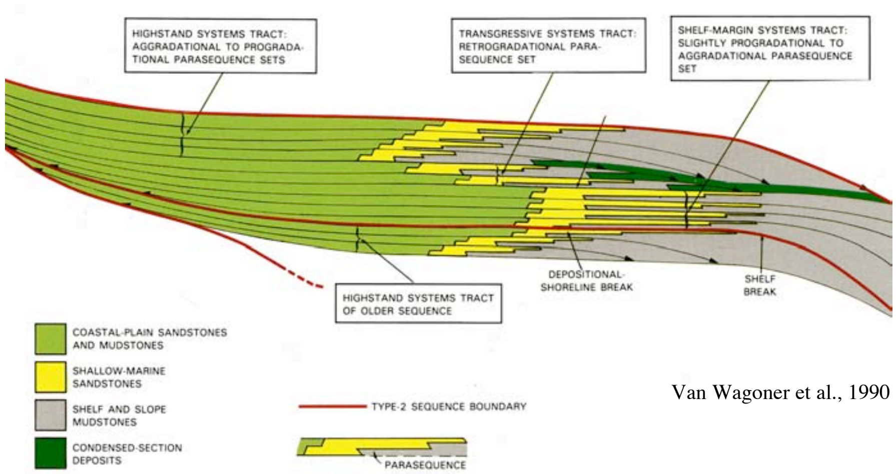
89

Another Slug



Haq et al., 1987

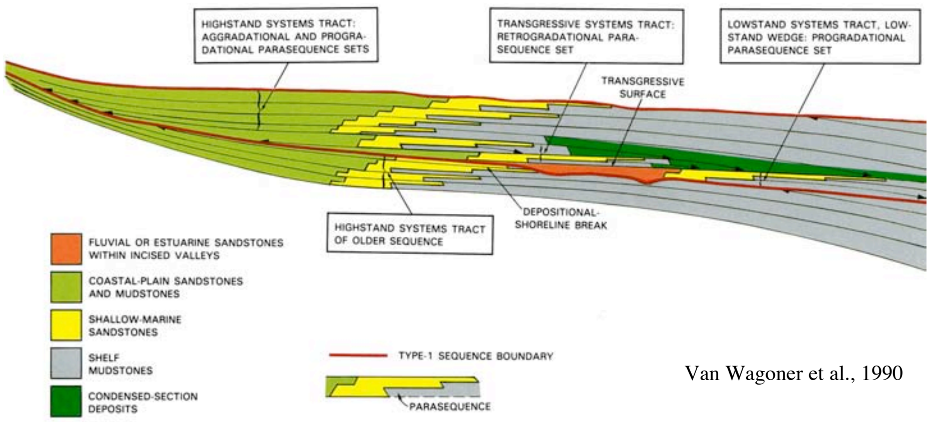
Type 2 sequences



Van Wagoner et al., 1990

Type 2 sequence where there is a shelf-slope break. Because the slope is never exposed, rivers do not incise (no nickpoints).

Type 1 Sequence in a Ramp Margin



Van Wagoner et al., 1990

Sequence stratigraphy where there is no shelf-slope break
- ramp setting

Contacts and Surfaces

- What is the difference between a contact, a boundary and a surface?
- Are all geological surfaces time lines or even chronostratigraphically significant?

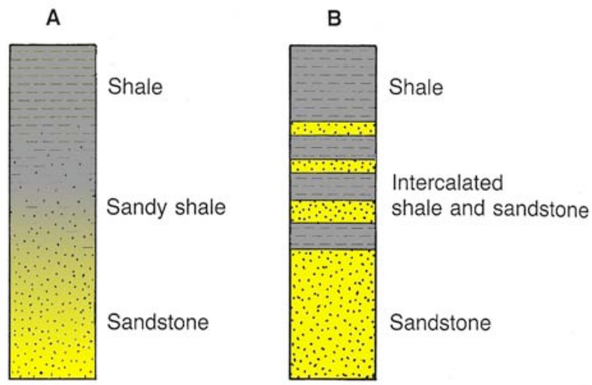
Contacts and Surfaces

- Lithostratigraphy
  - Point, surface or zone across which there is a lithologic boundary useful for mapping.
  - Note, formations are not supposed to contain unconformities.
  - Contacts can be highly diachronous.
- Sequence stratigraphy
  - "chronostratigraphically significant" contacts or surfaces useful in correlation and mapping.

Lithostratigraphy

Vertical Contacts

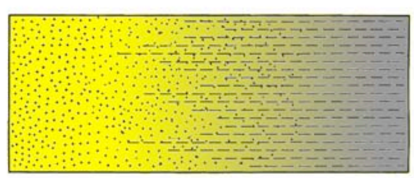
- **Smooth versus stepped vertical transitions.**
- **Where do you pick the formation contact?**

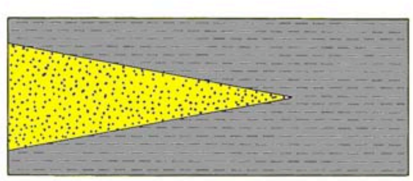


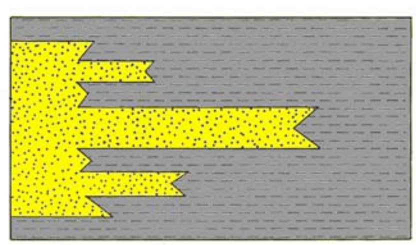
Boggs, 2001

Stratigraphy or Flags?

- **Representations of lateral transitions.**
- **No outcrop or seismic line even vaguely resembles these geometries!**
- **This is what the latest textbooks teach to undergraduates.**
- **We have to do better than this!**





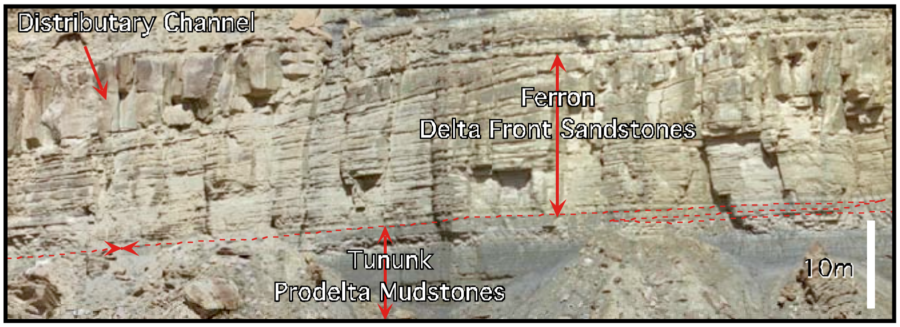


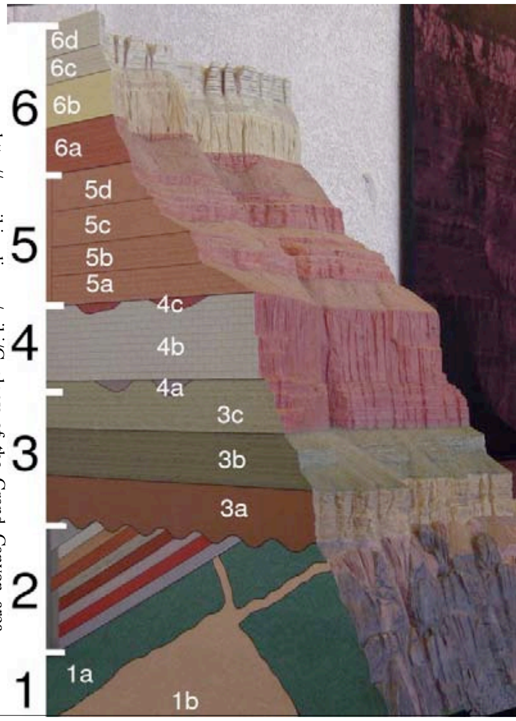
Boggs, 2001

Lithostratigraphy

Contacts

- Strata show a variety of vertical and lateral contacts.
- Contacts can be gradational.

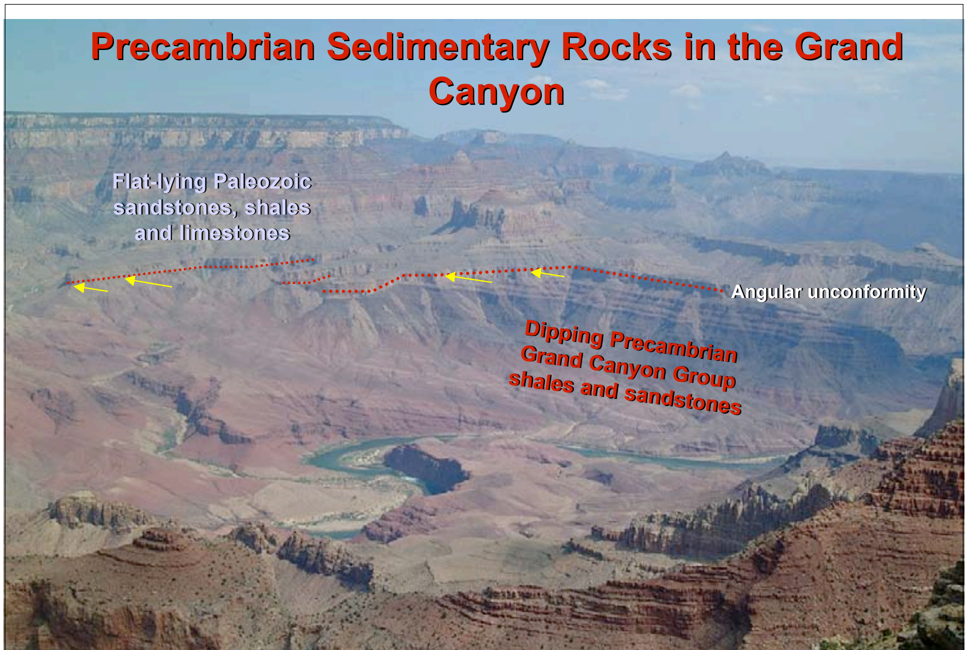




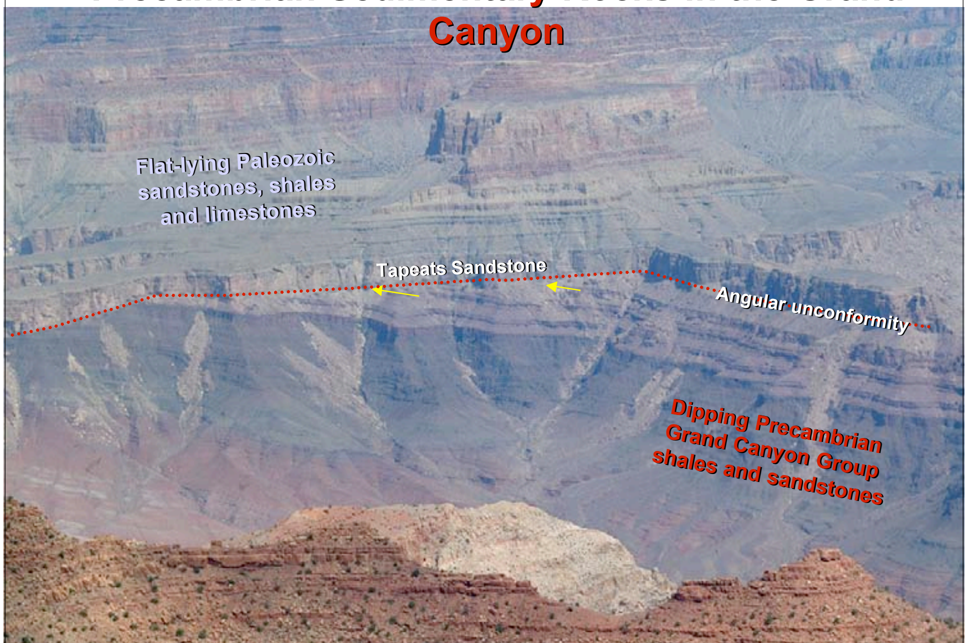
http://en.wikipedia.org/wiki/Geology_of_the_Grand_Canyon_area

Grand Canyon Stratigraphy

- 6 - Hermit, Coconino, Toroweap, and Kaibab
  - 6d - Kaibab Limestone
  - 6c - Toroweap Formation
  - 6b - Coconino Sandstone
  - 6a - Hermit Shale
- 5 - Supai Group
  - 5d - Esplanade Formation
  - 5c - Wescogame Formation
  - 5b - Manakacha Formation
  - 5a - Watahomigi Formation
- 4 - Temple Butte, Redwall, and Surprise Canyon
  - 4c - Surprise Canyon Formation
  - 4b - Redwall Limestone
  - 4a - Temple Butte Limestone
- 3 - Tonto Group (Cambrian)
  - 3c - Muav Limestone
  - 3b - Bright Angel Shale
  - 3a - Tapeats Sandstone
- 2 - Grand Canyon Supergroup
- 1 - Vishnu Group
  - 1b - Zoroaster Granite
  - 1a - Vishnu Schist

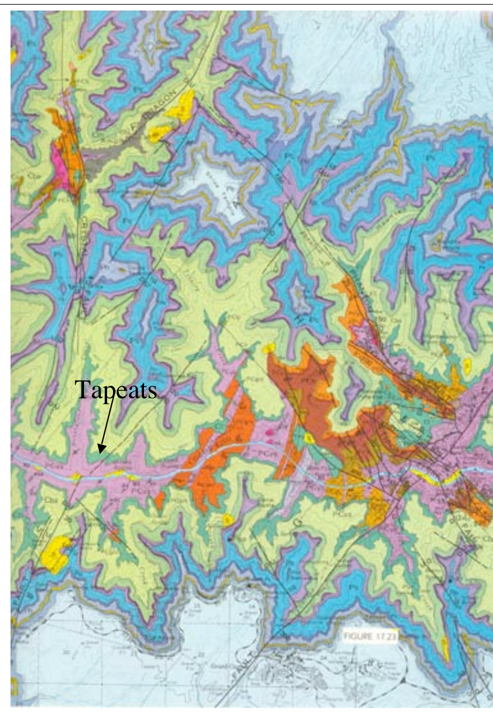


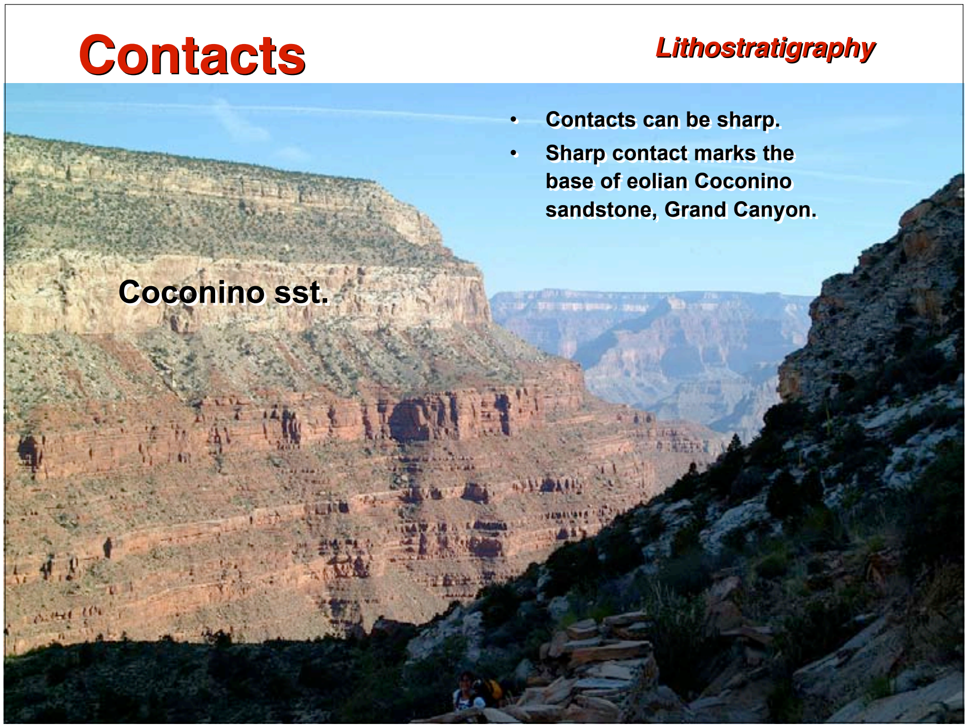
Precambrian Sedimentary Rocks in the Grand Canyon

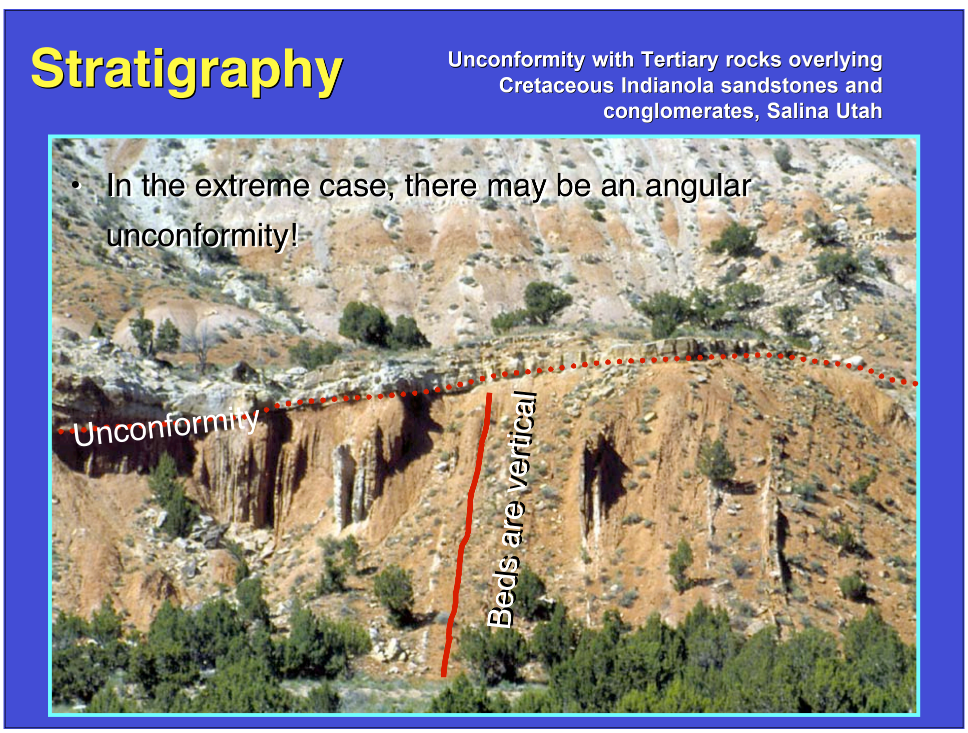


Grand Canyon Map

- Note increase in complexity of rocks below Tapeats sandstone.
- Formations represent mappable units.




Contacts
Lithostratigraphy
• Contacts can be sharp.
• Sharp contact marks the base of eolian Coconino sandstone, Grand Canyon.
Coconino sst.


Stratigraphy
Unconformity with Tertiary rocks overlying Cretaceous Indianola sandstones and conglomerates, Salina Utah
• In the extreme case, there may be an angular unconformity!
Unconformity
Beds are vertical

Lithostratigraphy

Types of Unconformities

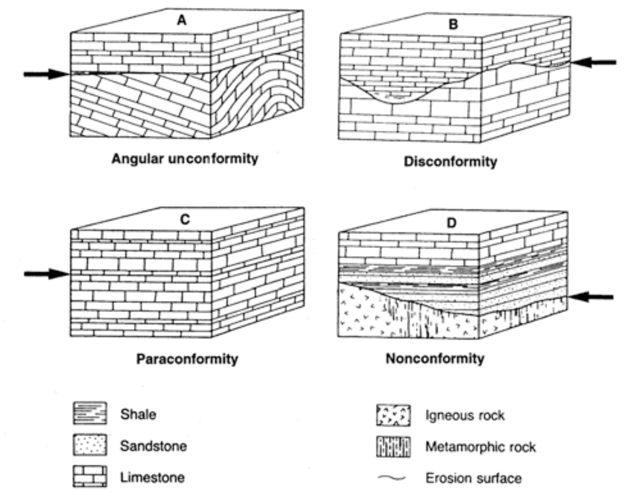
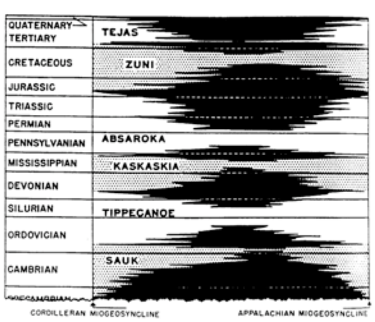
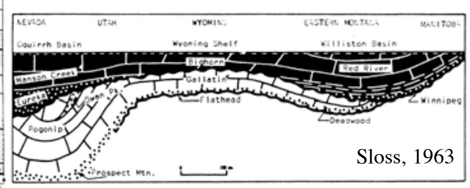


FIGURE 14.2 Four basic types of unconformities. Arrows point to unconformity surfaces. (After Dunbar, C. O., and J. Rodgers, 1957, Principles of stratigraphy: John Wiley & Sons, New York. Fig. 57, p. 117, reprinted by permission.)

Sloss Sequences



Angular Unconformities



Sloss, 1963

- **Six major sequences in North American Stratigraphy, represent major tectono-eustatic events.**
  - **Sauk, Tippecanoe, Kaskaskia, Absaroka, Zuni, Tejas.**
- **Unconformities are primarily angular and very widespread over the entire North American Craton.**

Lithostratigraphy

Contacts and Surfaces

- **Conformity**
  - **bedding surface with no stratigraphic break.**
- **Hiatus**
  - **a break in the geologic record (the hiatus refers to the break in time).**
- **Unconformity**
  - **a surface of erosion or non-deposition that separates older from younger rocks and that indicates a significant hiatus.**
    - **Angular Unconformity**
    - **Disconformity**
    - **Paraconformity**
    - **Nonconformity**
- **Diastem**
  - **Local erosion surface (e.g. base of fluvial channel, local scour).**

Definitions of Unconformity

- **Unconformity: Webster's Dictionary, 1990.**
  - Lack of continuity in deposition between rock strata in contact corresponding to a period of nondeposition, weathering, or erosion.
- **Unconformity: Bates and Jackson, 1987.**
  - A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession… It results from a change that caused deposition to cease for a considerable span of time, and it normally implies uplift and erosion with loss of the previously formed record. An unconformity is of longer duration than *diastem*.
- **Unconformity: Mitchum, 1977.**
  - A surface of erosion or non deposition that separates younger strata from older rocks and represents a significant hiatus (at least a correlatable part pf a geochronologic unit is not represented by strata).
- **Unconformity: Mitchum et al., 1977.**
  - Observable discordances in a given stratigraphic section that show evidence of erosion or nondeposition with obvious stratal terminations, but in places may be traced into less obvious paraconformities recognized by biostratigraphy or other methods.

Sequence Stratigraphy

Contacts and Surfaces

- **Sequence boundary**
  - **An unconformity and its correlative conformity.**
- **Unconformity: Van Wagoner, 1995, Sequence Stratigraphy definition**
  - A surface separating younger from older strata along which there is evidence of subaerial-erosional truncation and, in some areas, correlative submarine erosion, a basinward shift of facies, onlap, truncation, or abnormal subaerial exposure, with a significant hiatus indicated.
  - Local, contemporaneous erosion and deposition associated with geological processes such as point-bar development or aeolian-dune migration *(i.e. diastems)* are excluded from the definition of unconformity (Mitchum et al., 1977; Van Wagoner et al., 1990).

Sequence Stratigraphy

Contacts and Surfaces

- **Flooding surface**
  - A surface separating younger from older strata across which there is evidence of an abrupt increase in water depth. This deepening is commonly accompanied by minor submarine erosion or non-deposition, but not by subaerial erosion due to stream rejuvenation or a basinward shift in facies, including abnormal subaerial exposure, with a minor hiatus indicated. The amount of submarine erosion associated with a flooding surface varies, but probably ranges from a few inches to tens of feet, with several feet being most common. The flooding surface has a correlative surface in the coastal plain and a correlative surface on the shelf (Van Wagoner et al., 1987, 1988, 1990).

Key Surfaces

Key Surfaces

- At the outcrop or core scale of observation, seismic stratigraphic "discontinuity surfaces" may in fact represent a summation of a number of surfaces due to poor resolution of the seismic tool.
- Recognized by facies breaks and anomalous juxtaposition of facies.
- Includes:
  - Sequence Boundaries
  - Transgressive Surfaces
  - Maximum Flooding Surfaces.

Key Surfaces

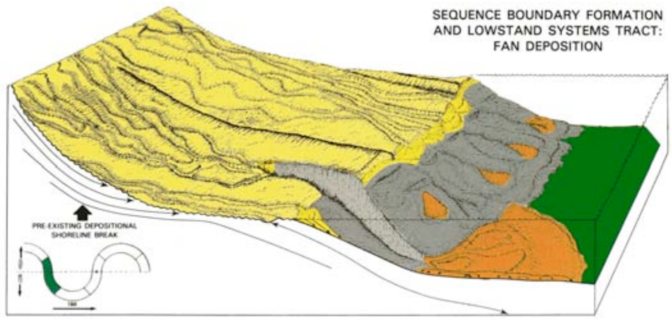
Sequence Boundaries

- Type 1 versus Type 2
- Angular (tectonic)
- Disconformities
- Paraconformities
- Includes correlative conformity
- Synonyms:
  - lowstand surface of erosion
  - regressive surface of erosion (debatable).

Key Surfaces

Attributes of Sequence Boundaries

- Interpreted to be formed because of a *relative sea level fall*.
- Accompanied by an abrupt seaward shift in facies and basinward shift in onlap.
- May be associated with the formation of incised valleys.
- Interfluves are associated with areas of widespread subaerial exposure.
  - paleosols
  - Karst



Van Wagoner et al., 1990

Sequence Boundaries and Knickpoints

- Exposure of steeper profile causes incision at knickpoints.
- Landward of knickpoints, relative sea level change may have no effect on stratigraphic architecture.
- New valleys may "capture" river.
- Abandoned valleys may have NO sandy reservoir facies.
- Areas between rivers (interfluves) may show evidence for subaerial exposure.
  - Paleosols
  - Mudcracks
  - Caliche
  - roots

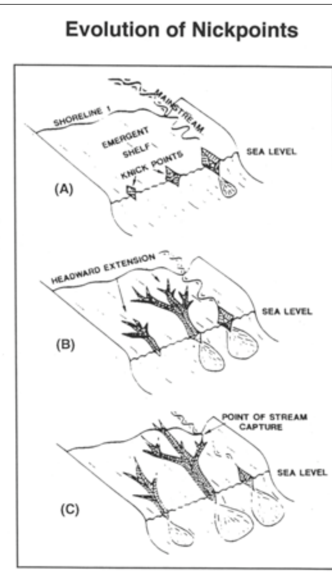
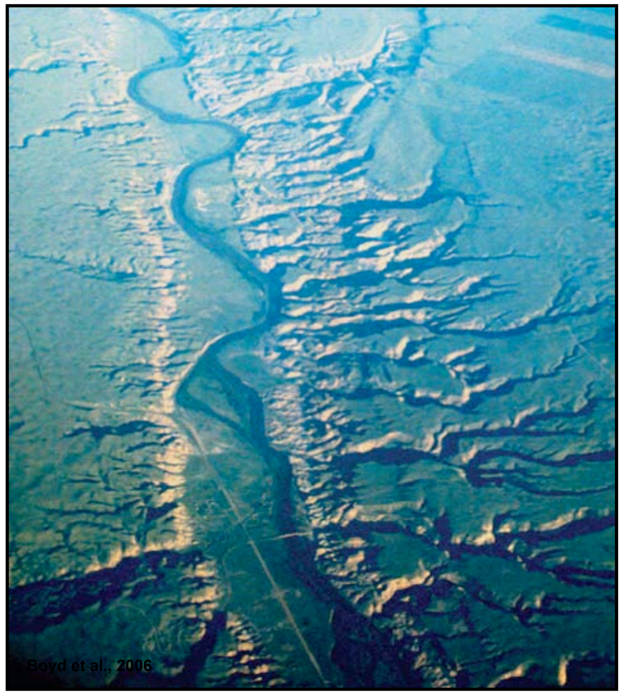


Figure 3—When sea level falls and exposes the shelf break, (A) the main stream incises and a knickpoint begins to migrate upstream. Additional knickpoints also form and (B) erode in the headward direction, forming new drainage systems on the previously submerged shelf. Continued headward extension intersects the pre-established fluvial system and (C) captures it by providing a steeper more efficient course to the sea.

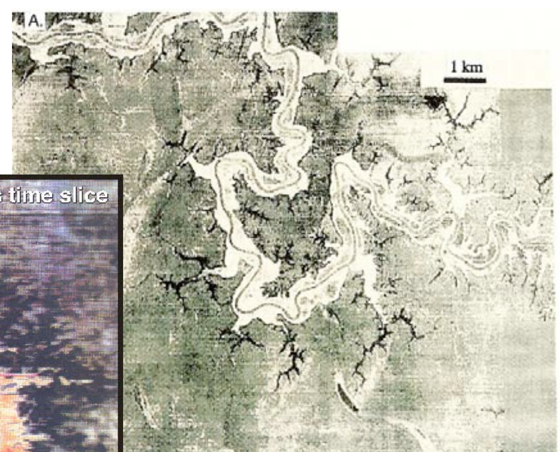
Wescott, 1993

Red Deer River Valley, Alberta

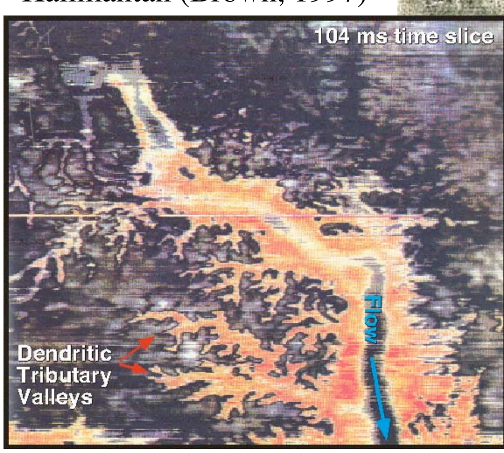
- Both river and floodplain are convined within valley.
- Note side drainages



Seismic Expression of Incised Valleys Southeast Asia



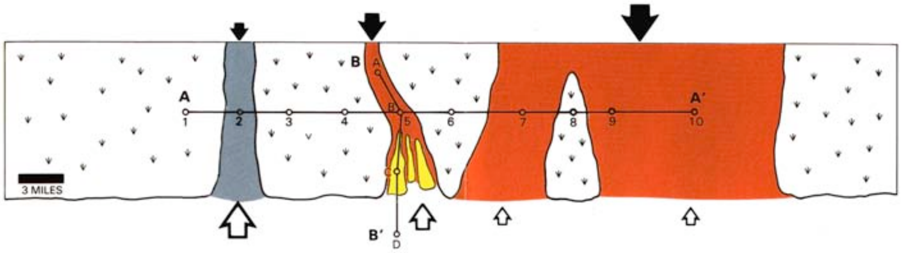
Kalimantan (Brown, 1997)



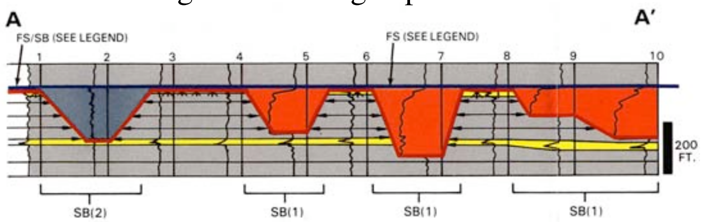
Offshore Thailand

Posamentier and Allen, 1999

Sequence Boundaries

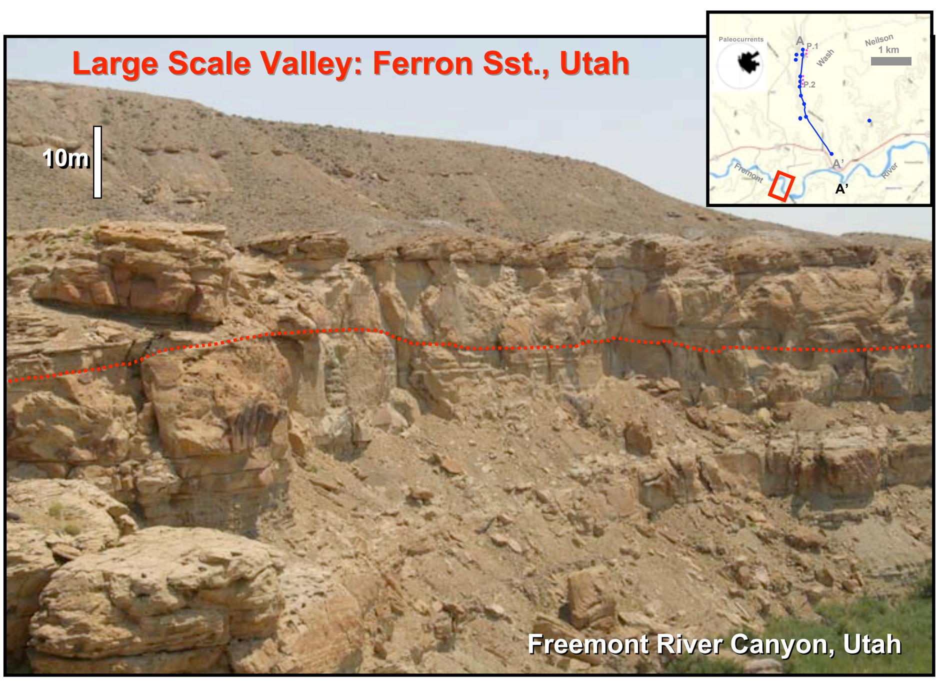


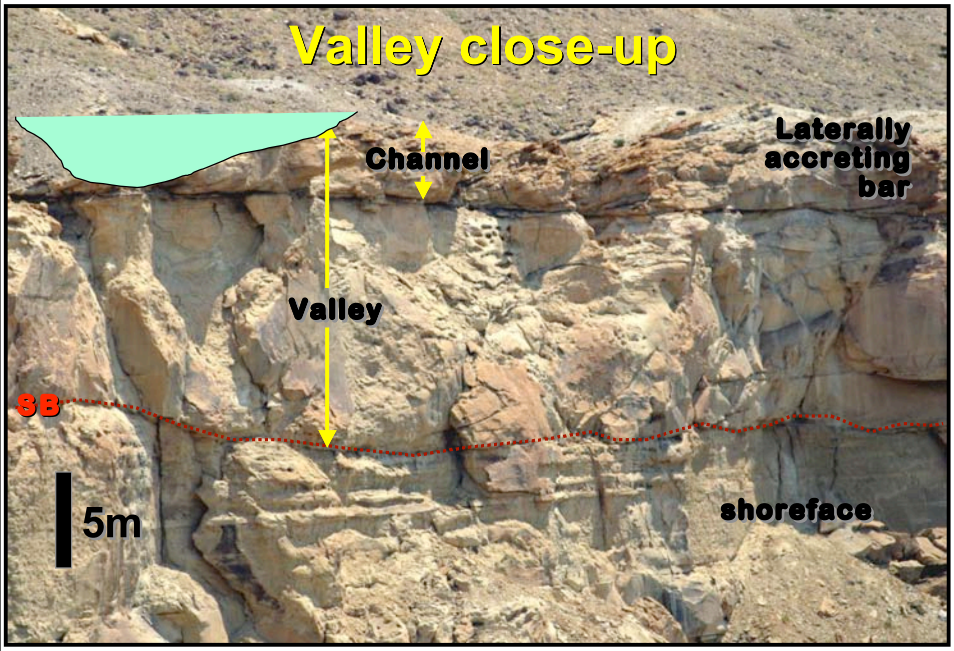
Change in SB along depositional strike



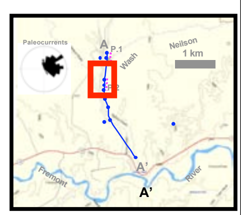
Van Wagoner et al., 1990

Large Scale Valley: Ferron Sst., Utah

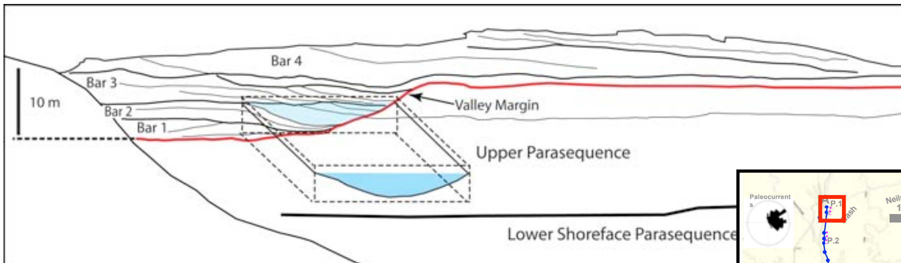


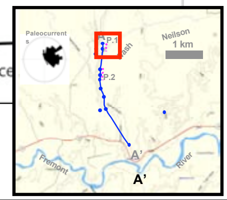


Mud-chip lag and extraformational pebbles mark valley base.



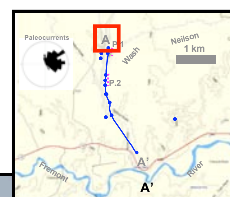
Nielsen Wash Valley

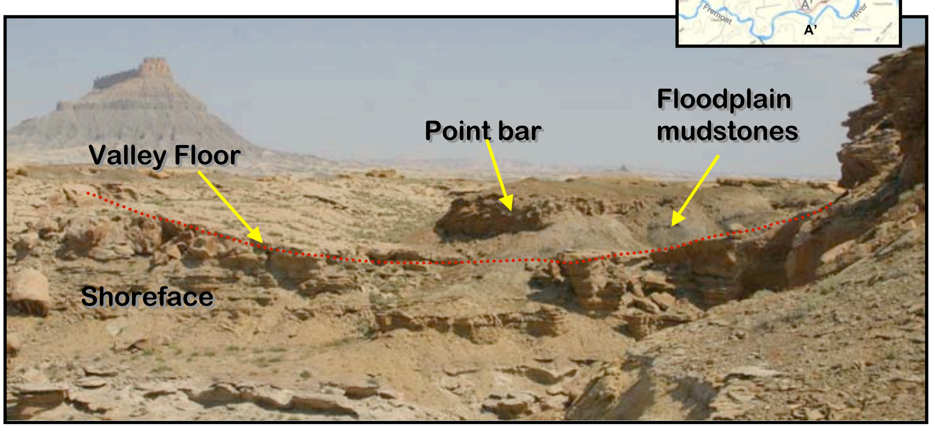




Multi-storey, multi-lateral fill.

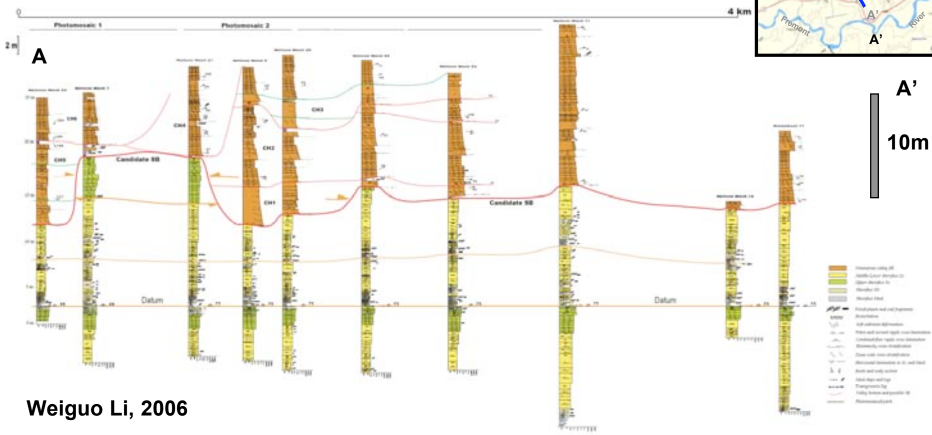
Exhumed Ferron Paleo-Valley at Nielsen Wash





Laterally migrating bar overlies floodplain mudstone, contained within larger erosional feature (valley).

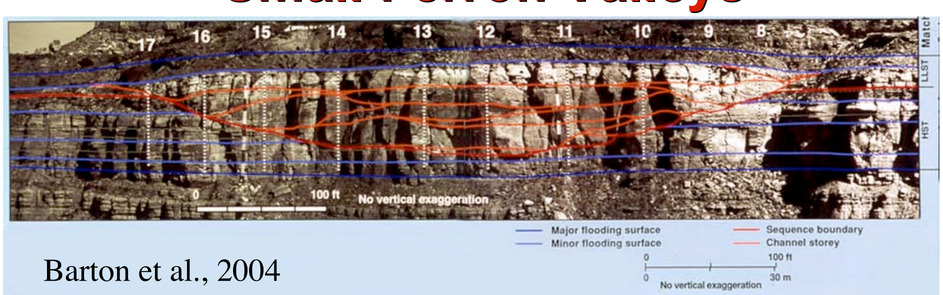
Strike Cross Section of Incised Valley



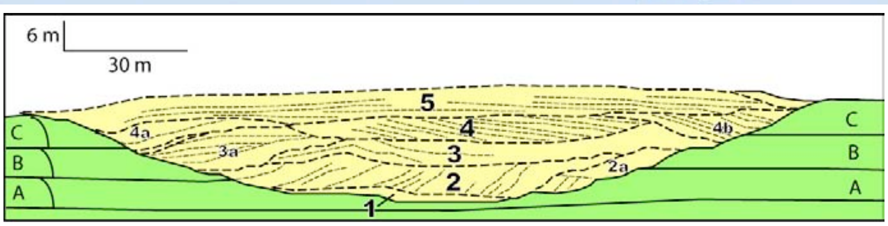
Weiguo Li, 2006

- Incised valley is indicated by truncation, onlap and rooted inter-fluve.
- Valley incises into storm-dominated marine parasequences.
- Valley has been traced for over 4 km along strike.

Small Ferron Valleys

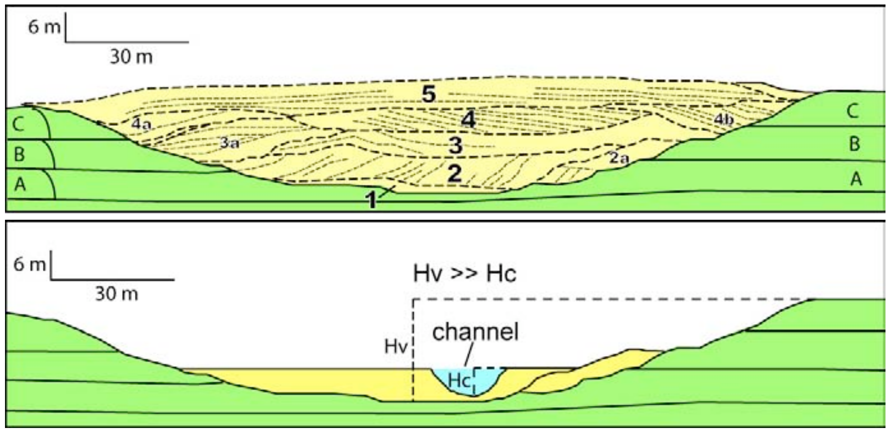


Barton et al., 2004



- Multistorey incision and fill, south side of I70.
- These incisions have been interpreted as distributary channels.
- Detailed analysis suggest that they are small, incised valleys.

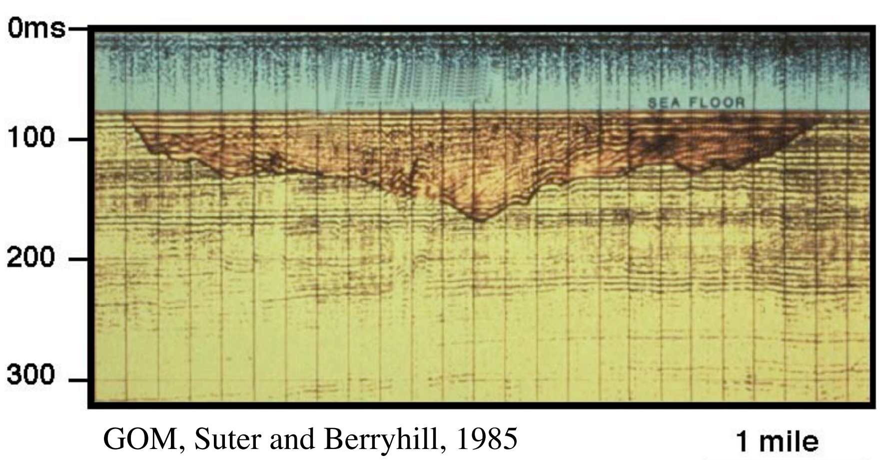
Ferron Valleys



- Depth of valley = 30m
- Maximum depth of channel = 9m
- Channel width = 30m to 250 m

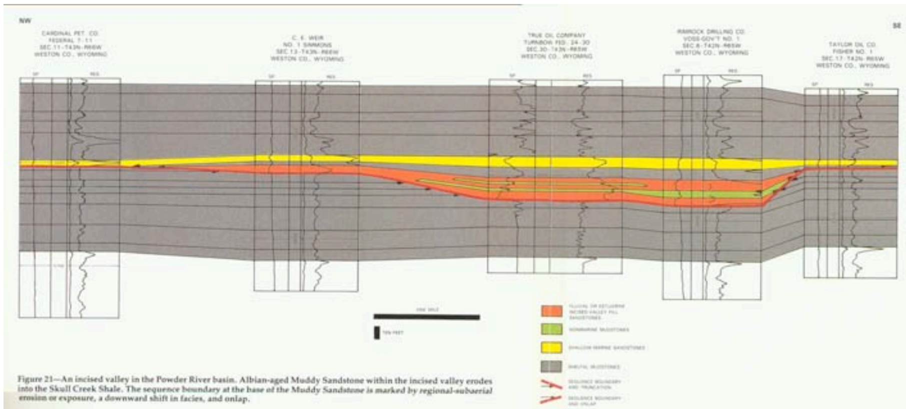
Bhattacharya and Tye, 2004

Seismic Examples of Incised Valleys



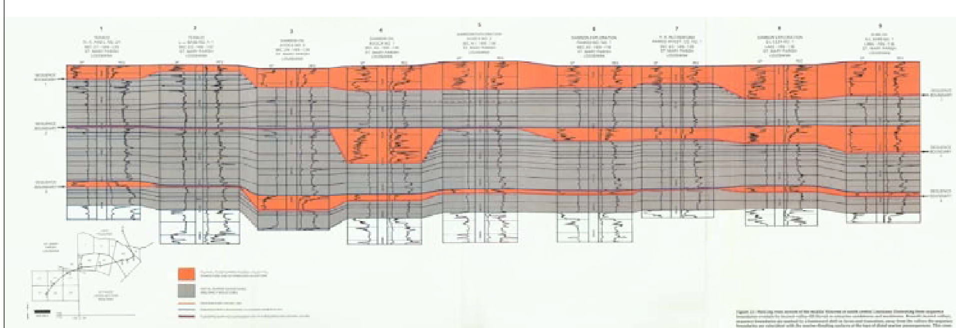
GOM, Suter and Berryhill, 1985

Well log cross section through a valley-fill



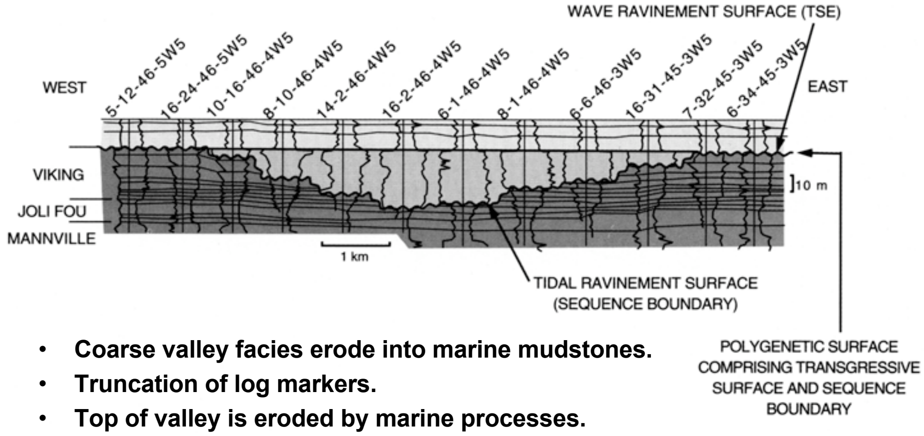
Van Wagoner et al., 1990

Abrupt lateral facies changes interpreted as valleys



Van Wagoner et al., 1990

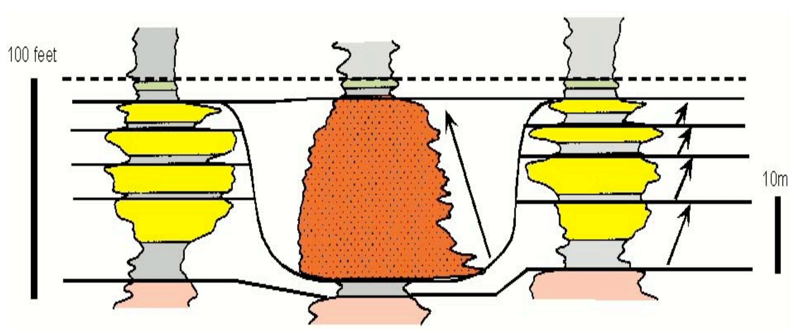
Viking Sandstone, Alberta



- Coarse valley facies erode into marine mudstones.
- Truncation of log markers.
- Top of valley is eroded by marine processes.

Posamentier and Allen, 1999

Fall River Sandstone, Wyoming

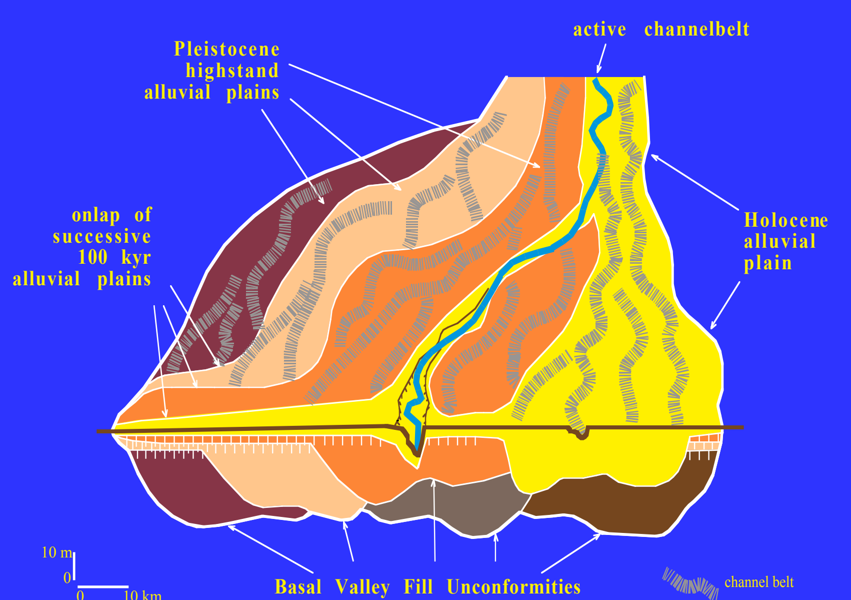


- Channel much thicker than associated upward coarsening delta deposits.
- Channel does not interfinger with adjacent marine facies.
- Channel is not contained within the delta front.
- Scale of channel is way too large (100 feet deep river?).

Willis, 1997

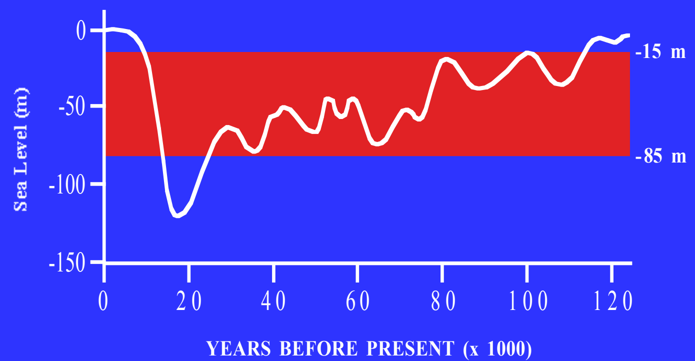
Texas Gulf Coast

QUATENARY ALLUVIAL PLAIN, COLORADO RIVER, TEXAS



Blum and Tornqvist, 2000

GLACIO-EUSTASY: 125 KA TO PRESENT



modified from Revelle (1990)

Note, valleys cut and fill over the last 120 Ka but sea-level has only just risen to the point where old valley can flood pre-120 Ka level

Composite Incised Valleys

Composite Valley Fill, Colorado River, Texas

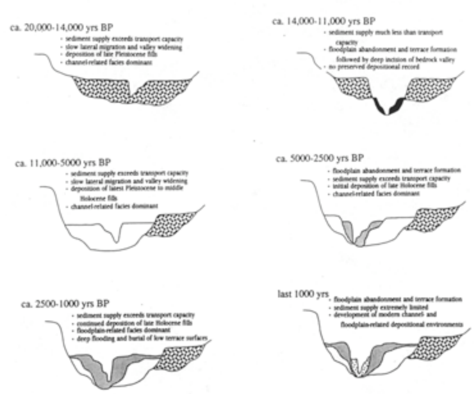
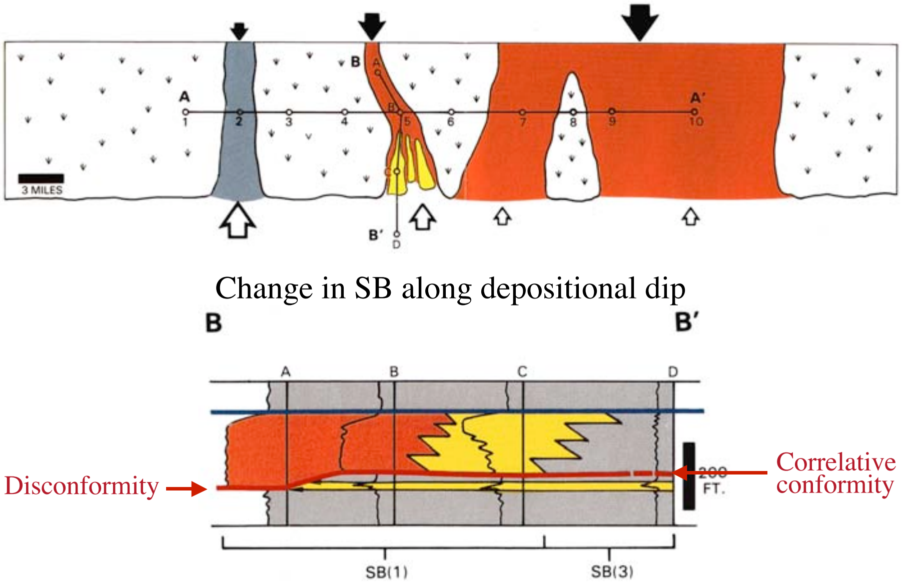


Fig. 13.11. History of alluvial incision and aggradation in response to postglacial climate change, Colorado River, Texas (Shanley and McCabe 1994, modified from Blum 1992, reprinted by permission). As discussed in Chap. 12, the major phase of valley incision within the 14-11 ka period corelates to the beginning of the last postglacial transgression

History of Colorado River valley fills, Blum, 1993

Sequence Boundaries



Van Wagoner et al., 1990

Key Surfaces

Preservation and Seaward Expression of Sequence Boundaries

- **Preservation potential depends on the depth of fluvial incision and amount of subsequent marine erosion during subsequent transgression (*ravinement*).**
- **In the marine realm the sequence boundary may be expressed as an erosional surface at the base of an incised shoreface.**
- **Farther seaward, marine erosion may occur in response to impingement by waves on the previously quiescent sea.**
  - **May see abrupt change in oxygenation on the substrate or change from laminated mudstones to bedded or bioturbated.**
- **Eventually, the sequence boundary passes into a correlative conformity.**

Key Surfaces

Transgressive Surfaces

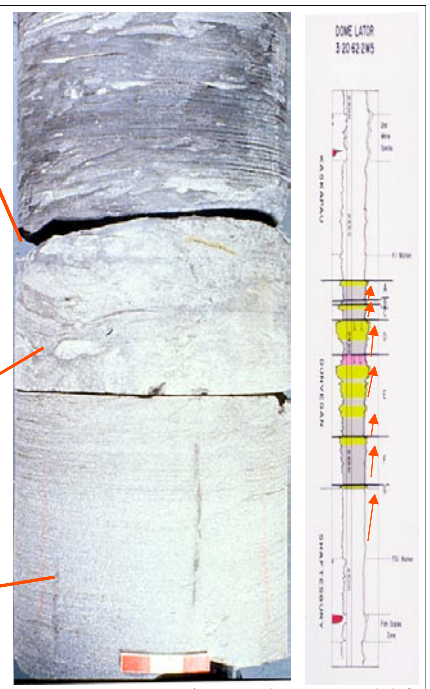
- Related to times of sea level rise.
- Transgression-related surfaces *tend* to be diachronous.
- May be considered geologically “instantaneous” at a regional to sub-regional scale, and particularly at the seismic scale.
- Transgression-related surfaces may be easier to identify in core, outcrops, and well-log data
- Can serve as useful correlation markers and as bounding discontinuities for allostratigraphic units.
- May merge landward with the sequence-bounding unconformity or seaward with the correlative conformity.
- Includes:
  - Flooding Surfaces (FS)
  - Transgressive Surface of Erosion (TSE)
  - TSE also called Ravinement.

Flooding Surfaces

Razor sharp contact between shallow water sandstone and deeper water marine mudstones records deepening.

Bioturbation shows marine working of previously exposed surface.

Roots record subaerial exposure.



Bhattacharya, 1993

Flooding Surfaces

Razor sharp contact between shallow water sandstone and deeper water marine mudstones records deepening.

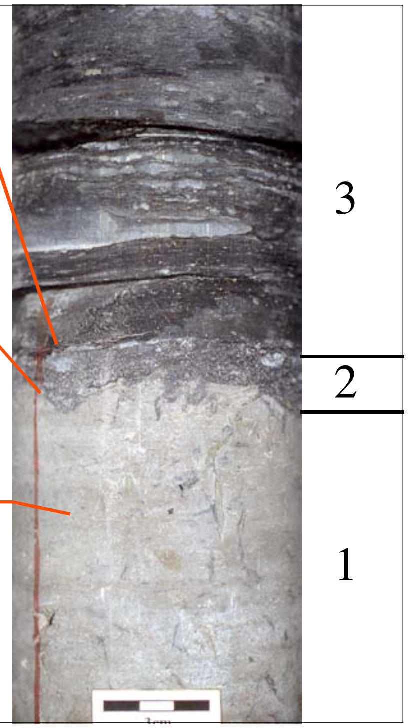
Facies 3 - burrowed marine mudstones.

Bioturbation shows marine working of previously exposed surface.

Facies 2 - bioturbated sandy mudstone

Roots and paleosol record subaerial exposure.

Facies 1 - paleosol



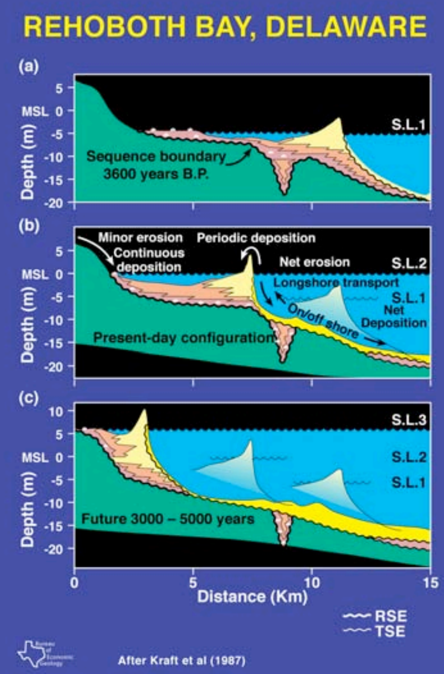
Top Mannville Fm., (slide courtesy of James MacEachern)

Transgressive Surfaces

- **Flooding implies inundation of previously dry (or subaerial) environment.**
  - **Correlative surfaces can be "deepening" surfaces, in which there is evidence of abrupt deepening across a surface that was always underwater.**
- **Flooding is commonly taken as a relatively passive process in which there is little to no erosion (a few meters or less).**
- **Where significant erosion can be demonstrated, the term "Transgressive Surface of Erosion" (TSE) is used.**
- **These are also referred to as Ravinement Surfaces.**

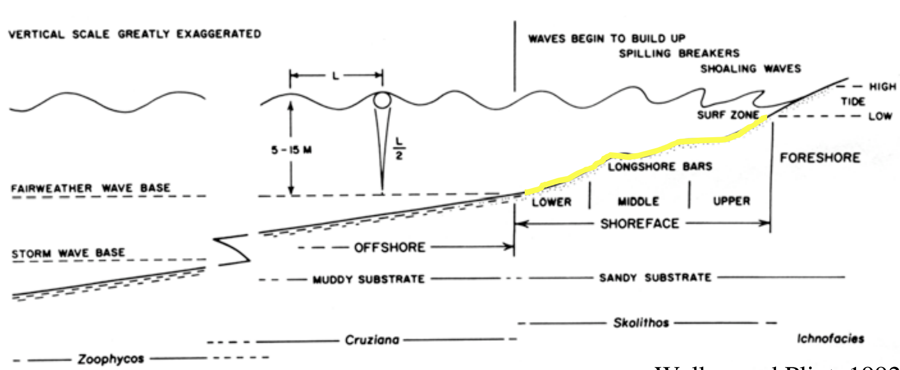
Modern Ravinement Surface

- A diachronous surface
- May erode up to 40m (Leckie, 1994).
- GOM ravinement averages 9m.
- Ravinement Surface may “replace” sequence boundary.



Ravinement is produced by shoreface retreat

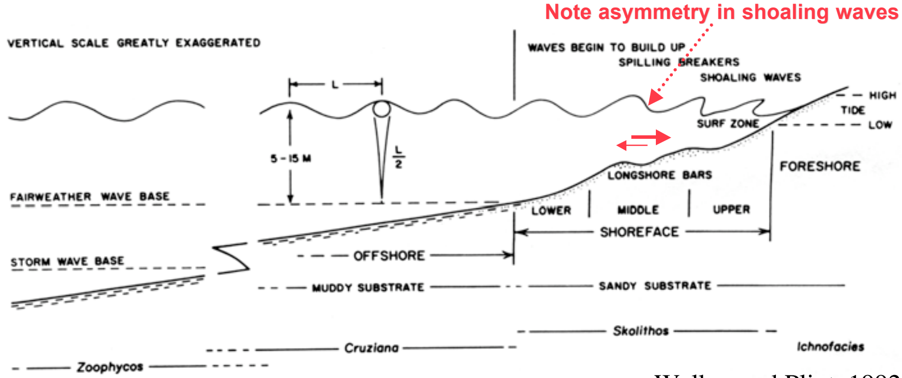
- **SHOREFACE**:
  - Steeply dipping slope that separates the subaerial from the subaqueous plane.
  - Forms in response to shoaling waves (fairweather processes).
    - Fairweather wave-base typically taken to be between 5-15 meters.
  - Mud typically unable to be deposited.
  - Shorefaces can be erosional (wave-cut terrace) or depositional.



Walker and Plint. 1992

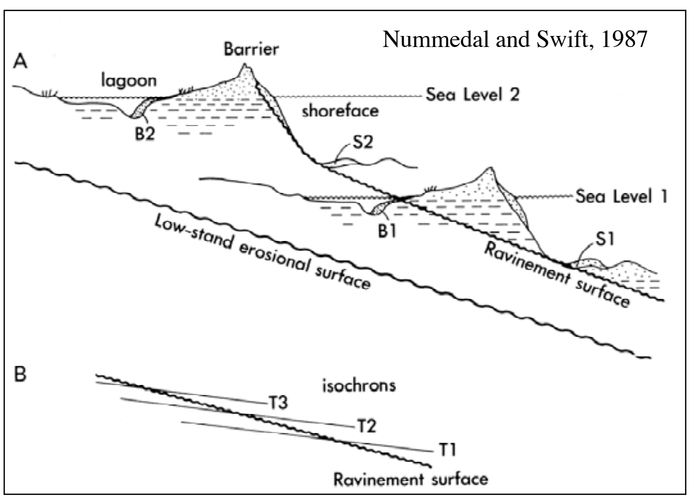
The Shoreface

- Forms in response to shoaling waves which tend to transport sand landward.
  - This is sometimes called the littoral fence.
- The shoreface usually marks the area where day-to-day transport of sand occurs (so-called fair-weather wave base).



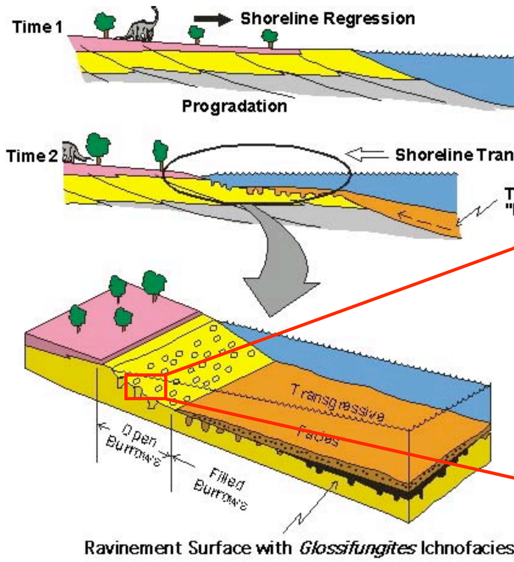
Walker and Plint. 1992

Ravinement



- **Landward migration of the shoreface produces an erosional "Ravinement" surface.**
- **Time lines cross this surface.**

Formation of a Ravinement Surface

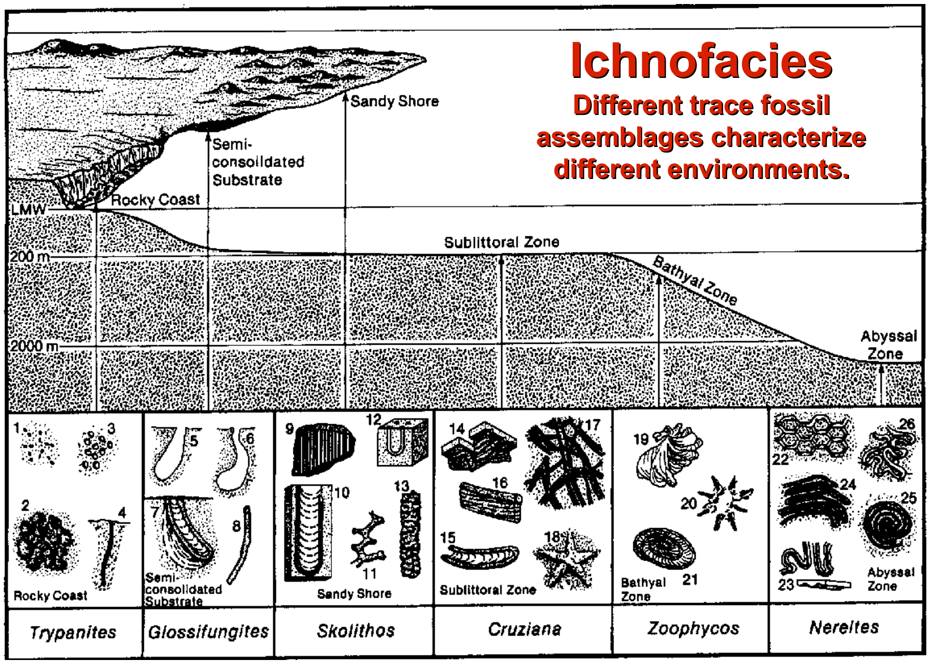


Ravinement surface in Gironde Estuary has lots of space between cobbles for animals to burrow.

After Posamentier and Allen, 1999

"Uh-oh, more terminology!" What is *Glossifungites*?

- Certain trace fossils are defined on the basis of the substrate type
  - Soupgrounds
  - Softgrounds
  - Firmgrounds (Glossifungites)
  - Hardgrounds (Trypanites)
  - Woodgrounds (Teredolites)
- These are as subset of the broader ichnofacies concept.



Pemberton et al., 1992 after Frey and Pemberton, 1985 and Seilacher, 1967

Substrate Dependent Ichnofacies

- Ichnofacies may be substrate specific
  - Soupground (no structures visible),
  - Softground (structures visible),

Softground, Cruziana to Zoophycos transition; Cretaceous Dunvegan Fm., Alberta

Glossifungites

- Firmground.
- May indicate partial erosion and exhumation of a firm substrate.
- Commonly associated with ravinement surfaces.

Sharp-walled, passively-infilled burrows from Panther Tongue Utah (above) and Kuparuk sandstone, Alaska (right)

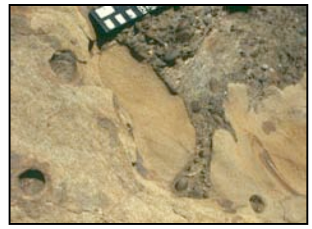
Glossifungites Ichnofacies

Sharp-walled, passively-infilled Thallasinoides network, Dunvegan Fm., Alberta, Canada

Sharp-walled, passively-infilled Pelecypod burrow, Wall Creek sandstone, Wyoming.

Trypanites Ichnofacies

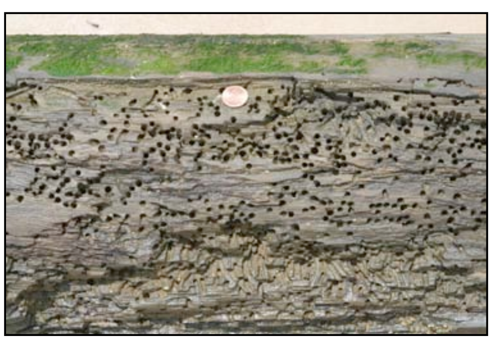
- Hardgrounds e.g. *Trypanites,* made by boring animals.
- Bored pebbles indicate a marine setting.
- Borings extremely common inmost carbonates



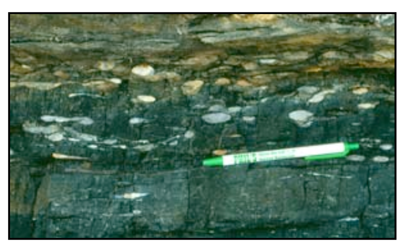
Pholad borings, infilled with transgressive conglomerate, Washington Coast

Teredolites Ichnofacies

- Woodgrounds e.g. *Teredolites,* made by boring animals.



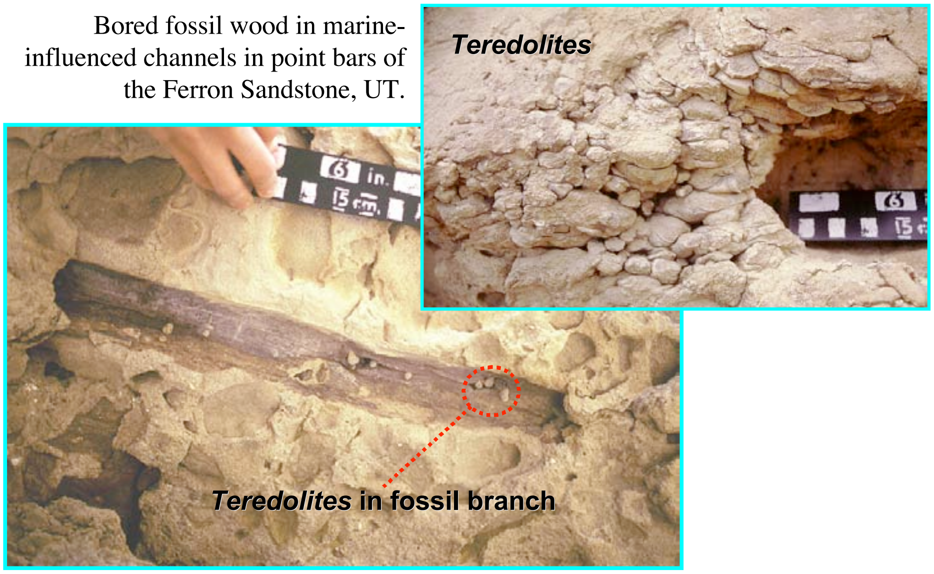
Teredolites borings, in log along Brazos Delta coast



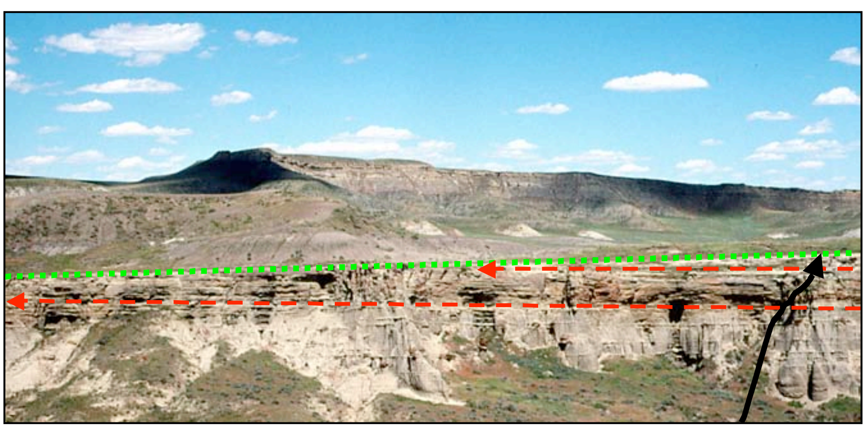
Fossilized Teredolites borings, in Coastal Plain coals of the Cretaceous Ferron Sandstone, Utah

Teredolites

Bored fossil wood in marine-influenced channels in point bars of the Ferron Sandstone, UT.

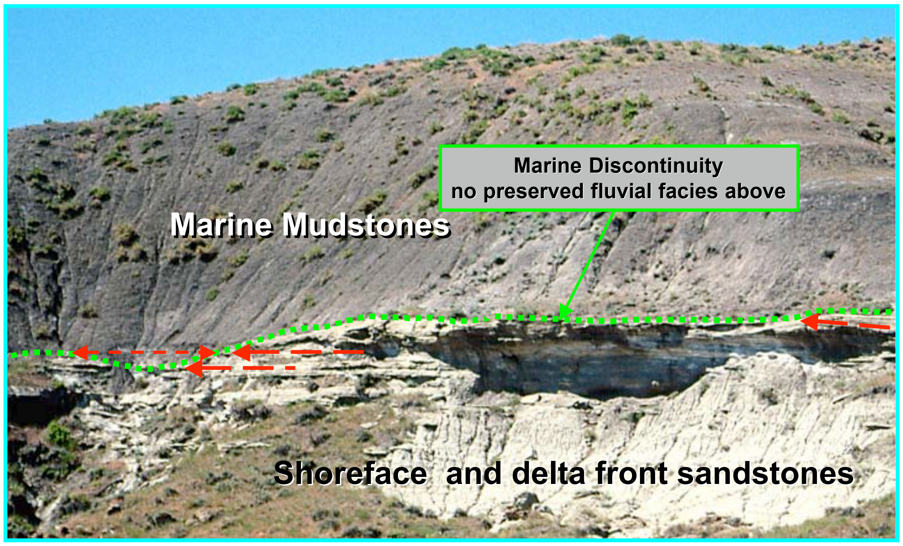


Back to Trangressive surfaces

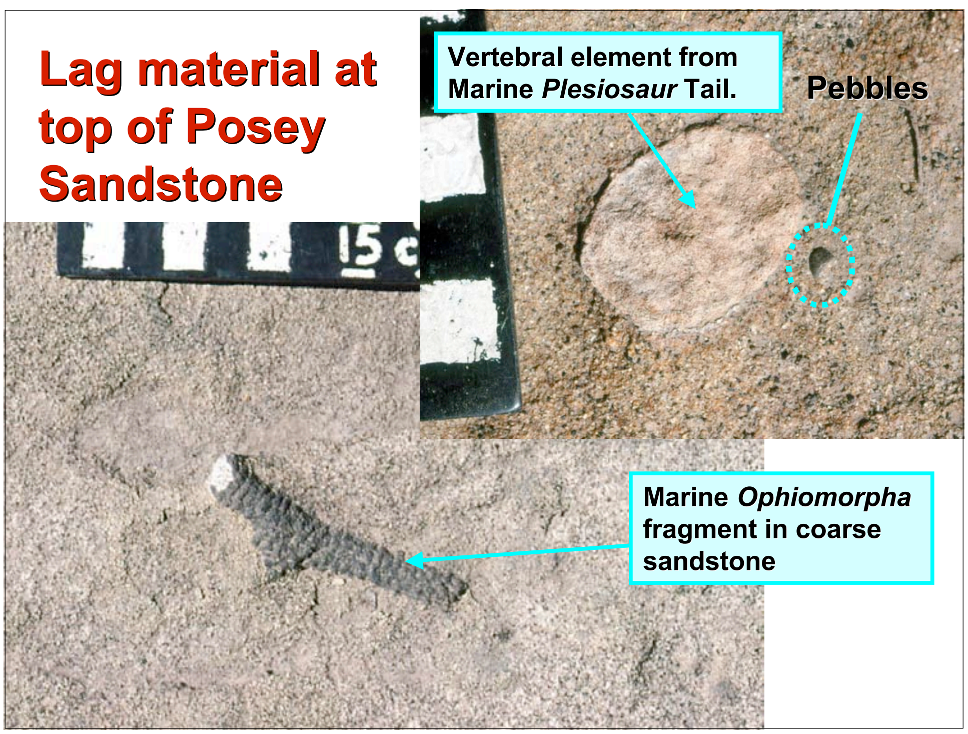


Razor sharp contact between shoreface sandstone and overlying marine mudstone. Posey Allomember, Belle Fourche Member, Frontier Formation, Wyoming, Cretaceous.

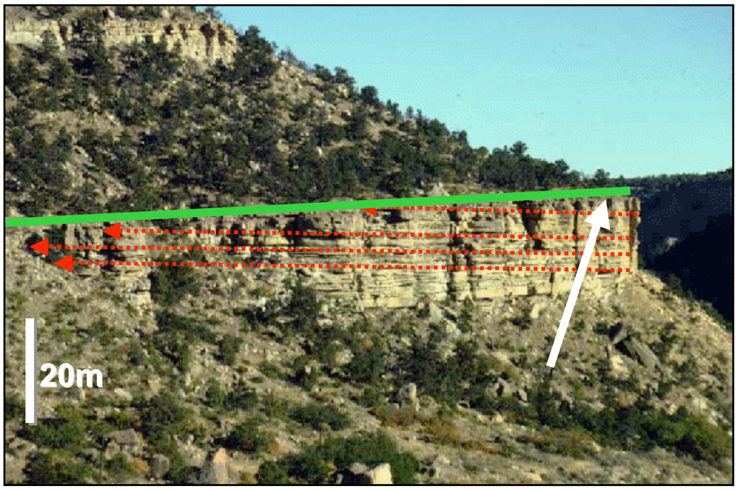
Posey Sandstone - Frontier Fm.



Lag material at top of Posey Sandstone

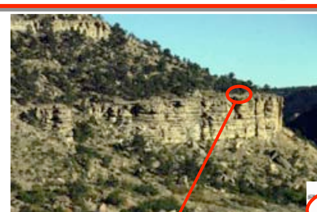


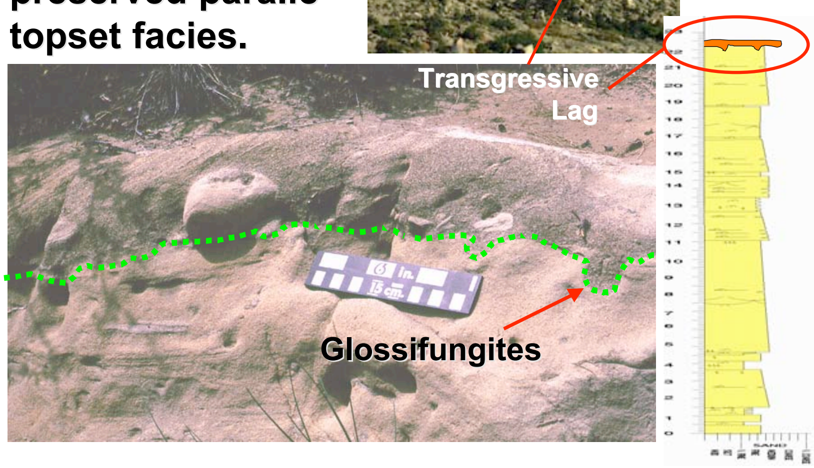
Cretaceous Panther Tongue Delta, Utah



Facies - Transgressive Lag

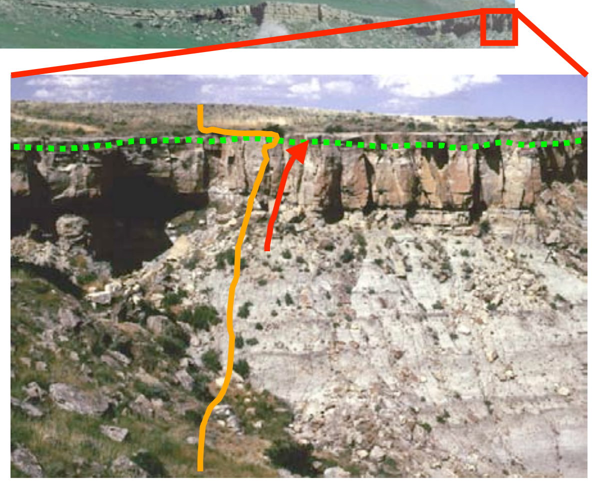
Delta is top-truncated, no preserved paralic topset facies.





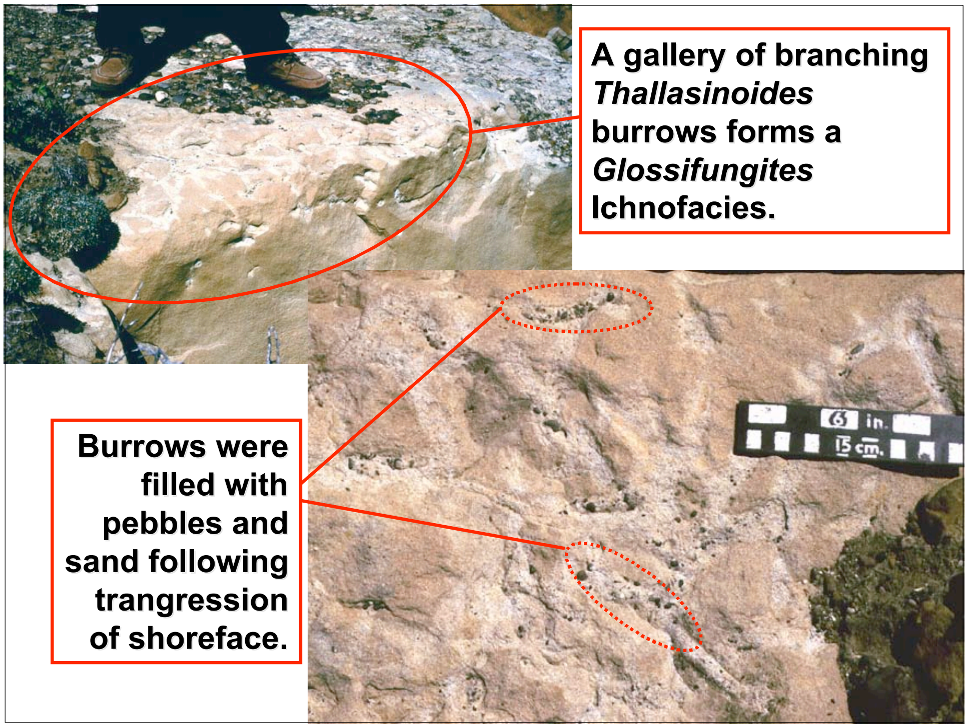
2nd Frontier Sandstone, WY

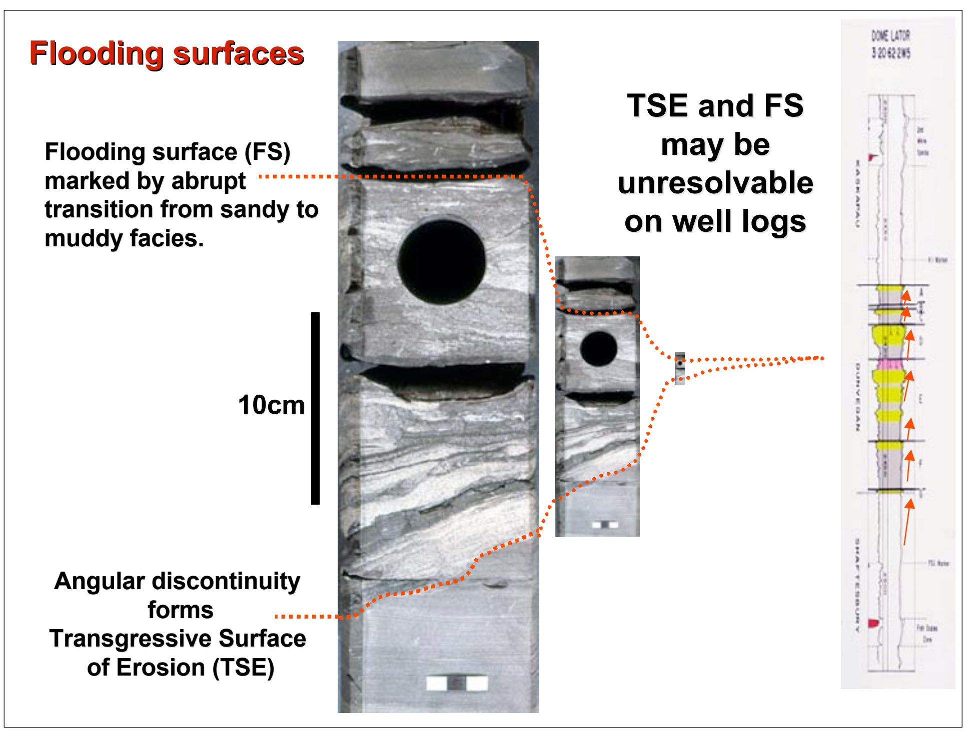
Gradationally-based, top-truncated, upward coarsening facies succession, interpreted as a shoreface.



2nd Frontier Sandstone, WY

- Cross-bedded pebbly sandstones overlie erosion surface.
- Pebbles concentrated from scattered pebbles in underlying facies.


A gallery of branching *Thallasinoides* burrows forms a *Glossifungites* Ichnofacies.
Burrows were filled with pebbles and sand following trangression of shoreface.
6 in.
15 cm.


Flooding surfaces
Flooding surface (FS) marked by abrupt transition from sandy to muddy facies.
10cm
Angular discontinuity forms Transgressive Surface of Erosion (TSE)
TSE and FS may be unresolvable on well logs

Transgressive Surfaces

Ravinement Surfaces

- Also called a Transgressive surface of Erosion.
- Tens of centimeters to tens of meters can be eroded.
- Erosion caused by shoreface retreat.
- May be associated with development of a firmground trace fossil suite (*Glossifungites*).
- Sediments transported seaward and landward, forming trangressive lag or relict sand body.
- Younger erosion surface can modify older sequence boundary
  - termed Flooding Surface/Sequence Boundary by Exxon (FSSB).

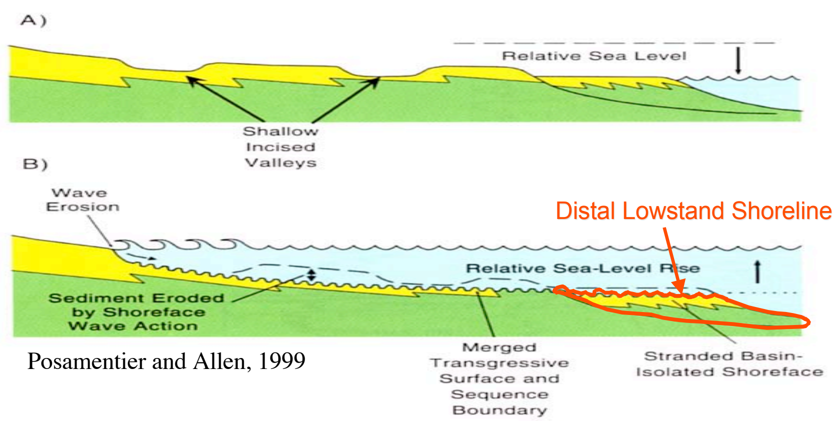
Transgressive Surfaces

Flooding Surfaces

- Think of this as a more “passive”.
- Commonly have little erosion.
- Can include offshore areas where water depth simply increases (deepening surface).
- May be of local extent (minor flooding surfaces).
- Hardcore Exxon literature does not distinguish ravinement from flooding (e.g. Van Wagoner et al., 1990).
- Hierarchy of flooding surfaces includes *minor* and *major* flooding surfaces.
- Also referred to as marine flooding surfaces.

Lowstand System Tract

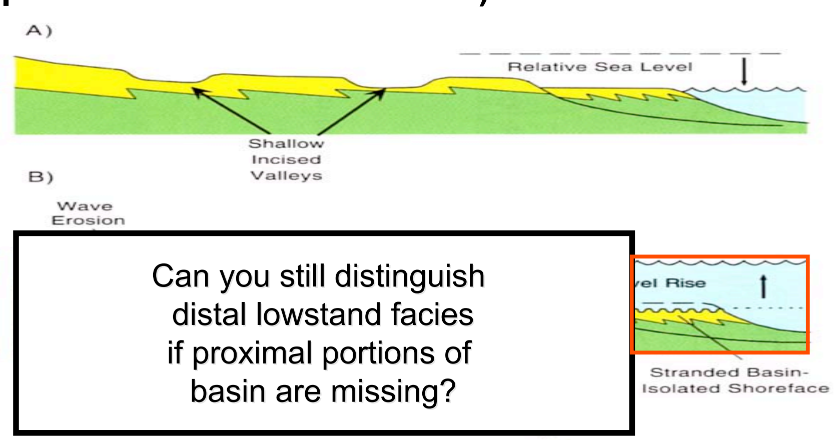
- **Definition**
  - **The lowstand systems tract overlies the *"sequence boundary" (includes correlative conformity).***
- **Distal lowstands overlie correlative conformities.**



Posamentier and Allen, 1999

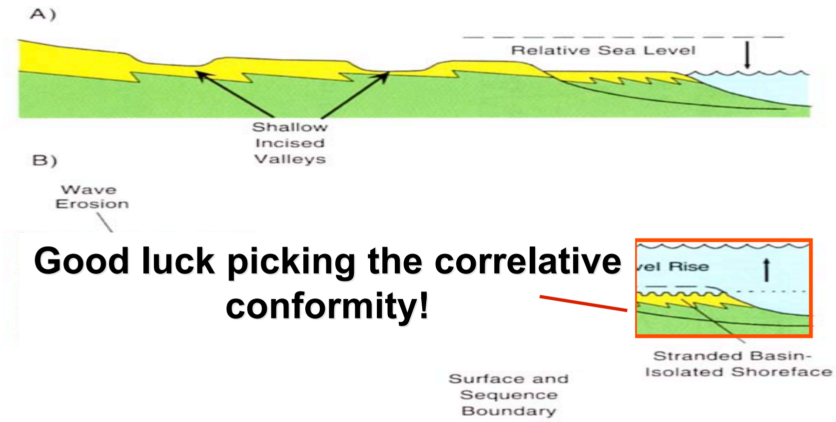
Correlative Conformities

Let's remove the proximal facies (a common problem in foreland basins)



Correlative Conformities

Let's remove the proximal facies, a common problem in foreland basins

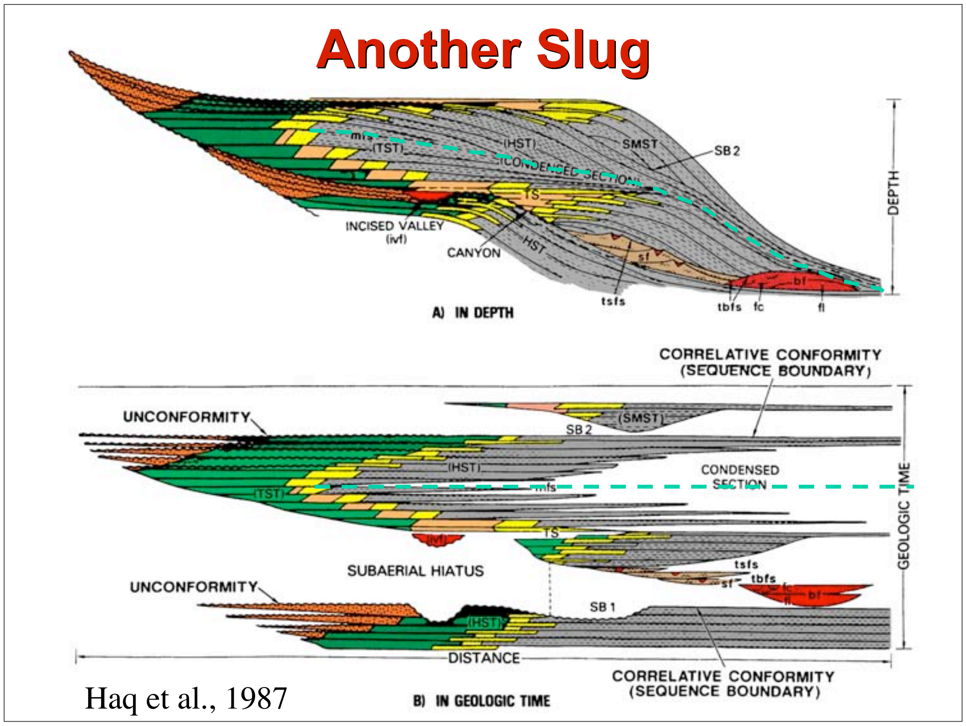


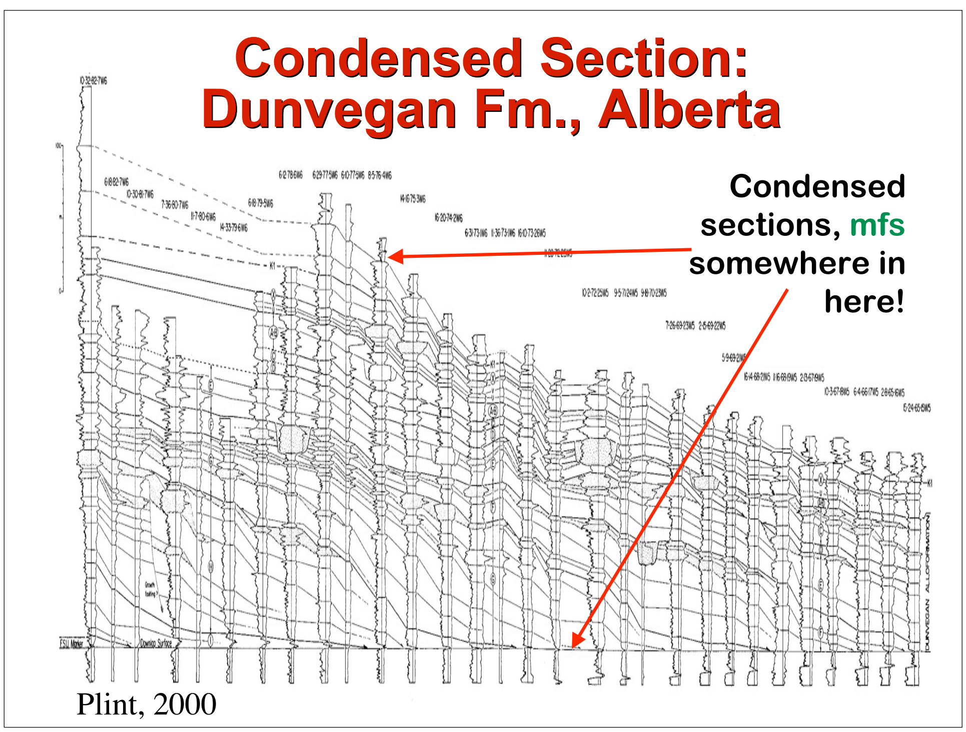
Good luck picking the correlative conformity!

Transgressive Surfaces

Maxiumum Flooding Surfaces

- **Surface associated with the time of peak transgression.**
- **Commonly associated with a condensed section.**
- **May be very difficult to pick.**
- **There may be several scales (hierarchy) of maximum flooding surface.**


Another Slug
mfs
(TST)
(HST)
CONDENSED SECTION
SMST
SB 2
DEPTH
TS
INCISED VALLEY
(ivf)
CANYON
HST
sf
bf
tsfs
tbfs
fc
fl
A) IN DEPTH
CORRELATIVE CONFORMITY
(SEQUENCE BOUNDARY)
UNCONFORMITY
(SMST)
SB 2
(HST)
CONDENSED
SECTION
(TST)
mfs
GEOLOGIC TIME
(ivf)
TS
SUBAERIAL HIATUS
tsfs
tbfs
sf
bf
UNCONFORMITY
SB 1
(HST)
DISTANCE
CORRELATIVE CONFORMITY
(SEQUENCE BOUNDARY)
Haq et al., 1987
B) IN GEOLOGIC TIME


Condensed Section:
Dunvegan Fm., Alberta
Condensed
sections, mfs
somewhere in
here!
Plint, 2000

Subsurface Stratigraphic Methods

Lithostratigraphy vs. Allostratigraphy

- Lithostratigraphy
  - Correlation of similar lithologies and the consequent packaging of rocks into litho-stratigraphic units.
  - Contacts may be highly diachronous.
  - Formal designations include groups, formations, and members.
- Allostratigraphy
  - Packaging of rock units bounded by stratigraphic discontinuities (bounding discontinuities).
  - Based on correlation of chronostratigraphically significant surfaces through rocks of potentially varying lithologies.
  - The bounding discontinuity must be a mappable surface.

Subsurface Stratigraphic Methods

Lithostratigraphy vs. Allostratigraphy

- Lithostratigraphy
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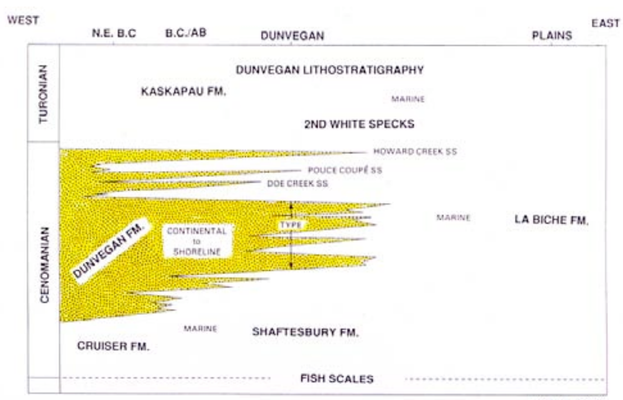
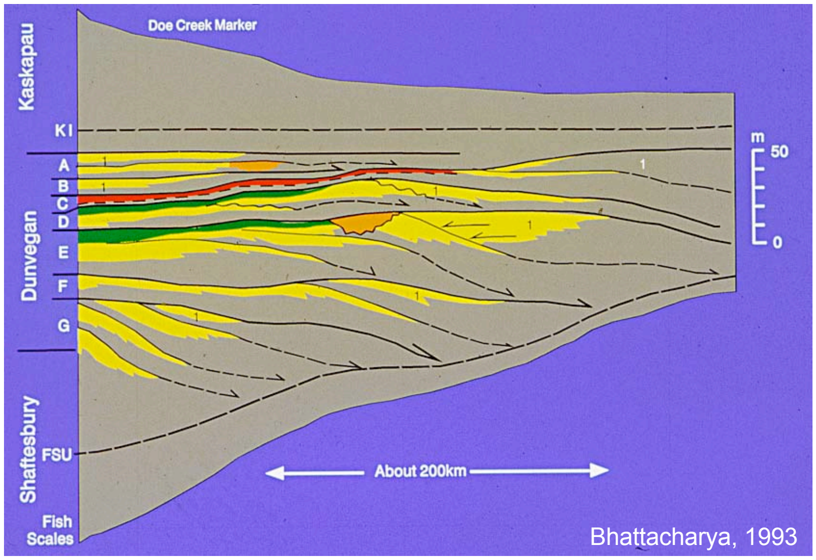


(Singh, 1983)

Subsurface Stratigraphic Methods

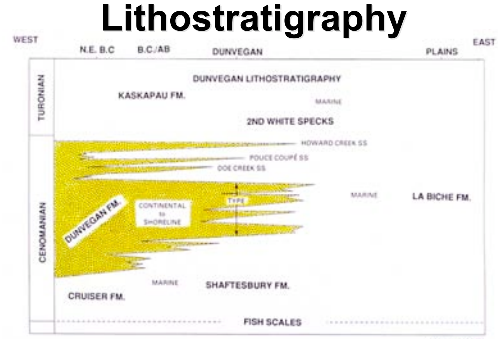
Lithostratigraphy vs. Allostratigraphy



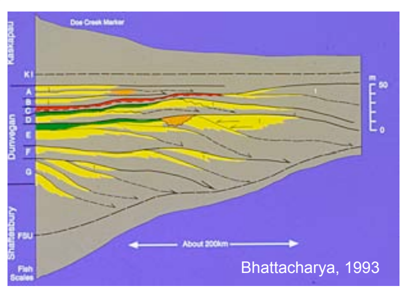
Subsurface Stratigraphic Methods

Lithostratigraphy vs. Allostratigraphy

Lithostratigraphy



Allostratigraphy



- **Allostratigraphy**
  - **Packaging of rock units bounded by stratigraphic discontinuities (bounding discontinuities).**
  - **Based on correlation of chronostratigraphically significant surfaces through rocks of potentially varying lithologies.**
  - **The bounding discontinuity must be a mappable surface.**

Subsurface Stratigraphic Methods

Allostratigraphy vs. Sequence Stratigraphy

- Formal way of defining and naming discontinuity-bounded rock successions.
- Does not place particular emphasis on which type of discontinuity should be used as the "fundamental" stratigraphic break.
- May include unconformity-bounded depositional sequences (Mitchum, 1977) and flooding surface bounded genetic stratigraphic sequences (Galloway, 1989).
  - Sequence Stratigraphy is a subset of Allostratigraphy (sort-of).
- Generic method of *defining and naming* discontinuity-bounded rock successions emphasizing mappability rather than origin in the context of sea level change.

Subsurface Stratigraphic Methods

Value of Allostratigrapic Approach

- Formal way of defining and naming discontinuity-bounded rock successions.
- Does not place particular emphasis on which type of discontinuity should be used as the "fundamental" stratigraphic break.
- May include unconformity-bounded depositional sequences (Mitchum, 1977) and flooding surface bounded genetic stratigraphic sequences (Galloway, 1989).
- Generic method of *defining and naming* discontinuity-bounded rock successions emphasizing mappability rather than origin in the context of sea level change.

Subsurface Stratigraphic Methods

Methodology

1. Evaluate previous work and regional seismic and well log data.
2. Establish depositional facies to determine correlation styles.
3. Identify Facies breaks which mark bounding discontinuities.
4. Establish facies correlation lengths from closely spaced data.
5. Expand correlations to larger scale.
6. Correlate sandstone bodies last.
7. Map sandstones.
8. Make time stratigraphic charts (Wheeler diagrams).

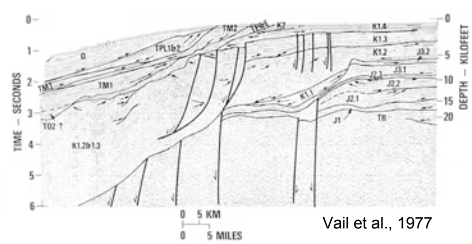
Subsurface Stratigraphic Methods

Methodology

- The methodology described next can be applied regardless of whether you are a sequence stratigrapher or an allostratigrapher.
- The methodology applies to well logs, cores and (to a lesser degree) outcrop studies.
- The methodology should be useful regardless of who you work for.
- In a later lecture I will discuss the merits of allostratigraphy versus sequence stratigraphy, but many people do not agree with me here, although some do!
  - Key question to ask is does it make any difference to how I correlate the data or what prediction I will make?

Methodology

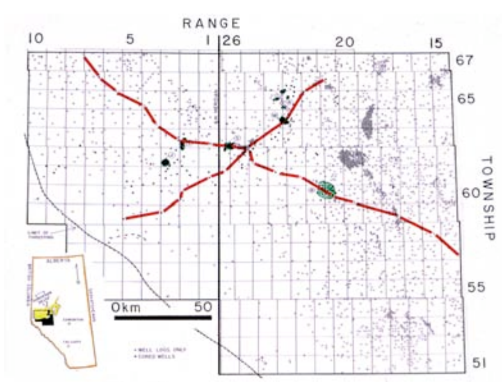
1. Evaluate previous work and regional seismic and well log data.
   – establish basin-scale paleogeography, age, and structure.



Vail et al., 1977

Methodology

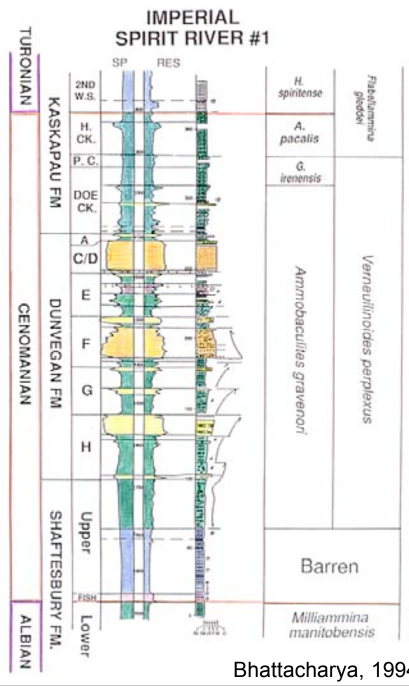
1. Evaluate previous work and regional seismic and well log data.
   – orient cross sections along depositional strike and dip



Bhattacharya and Walker, 1991

Methodology

1. Evaluate previous work and regional seismic and well log data.
   - Integrate paleontological data other available bio- or chrono-stratigraphic information.



Bhattacharya, 1994

Methodology

2. Establish depositional facies (cores, well log) to determine correlation styles.

Fluvial facies of the Morrison show relatively horizontal mudtone beds with flat-topped, erosionally based channel belts.

Outcrops provide key insights into how facies are organized.

Subsurface Stratigraphic Methods

Methodology

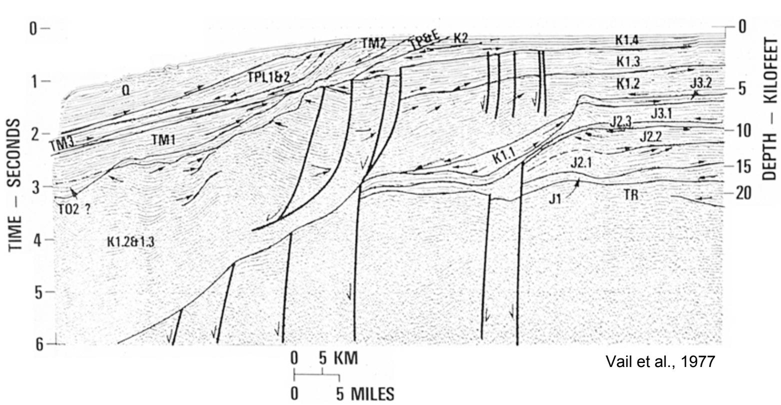
2. Establish depositional facies (cores well logs) to determine correlation styles.

Marine facies of the distal Blackhawk show upward-coarsening sandstones beds capped by regional flooding surfaces that dip subtly seaward.

Subsurface Stratigraphic Methods

Methodology

2. Establish depositional facies (seismic) to determine correlation styles.



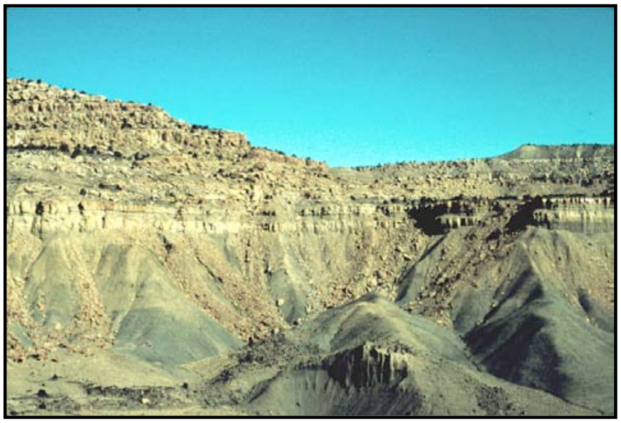
Vail et al., 1977

Seismic data show that surfaces dip seaward in marine units.

Subsurface Stratigraphic Methods

Methodology

2. Establish depositional facies to determine correlation styles.

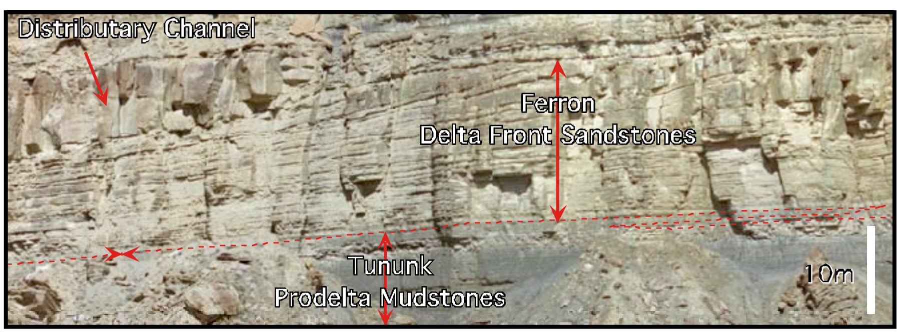


Marine facies of the Ferron show upward-coarsening sandstones beds capped by regional flooding surfaces that dip subtly seaward.

Subsurface Stratigraphic Methods

Methodology

2. Establish depositional facies to determine correlation styles.



Beds within Ferron delta front dip markedly seaward.

Subsurface Stratigraphic Methods

Methodology

2. Establish depositional facies to determine correlation styles.

Marine facies of the Posey sandstone show upward-coarsening sandstones beds capped by regional flooding surfaces. Beds within delta front dip markedly seaward.

Methodology

3. Identify facies breaks which mark bounding discontinuities.

Sharp sandstone top marks marine flooding surface

Subsurface Stratigraphic Methods

Bounding Discontinuities

- **Erosional lags**
  - **bases of channels and channel belts.**
  - **Mud-chips.**
- **Truncation**
  - **bases of channel belts or incised valleys.**
  - **May be seen on seismic data.**
- **Exposure surfaces**
  - **Paleosols, mudcracks.**
- **Flooding surfaces**
  - **Coals.**
- **Condensed sections**
  - **widespread lacustrine mudstones**
- **Commonly used as Reservoir Model Layers**

Subsurface Stratigraphic Methods

Methodology

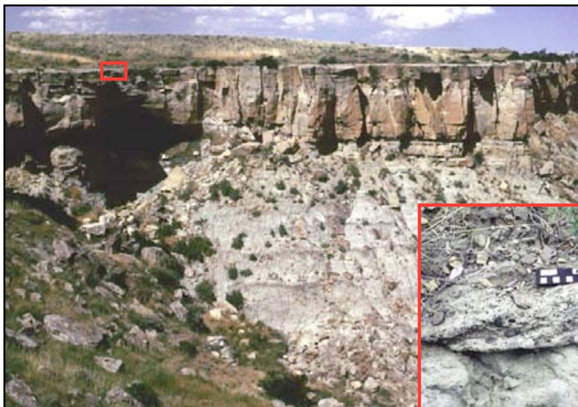
Angular Unconformities

– Truncation

Subsurface Stratigraphic Methods

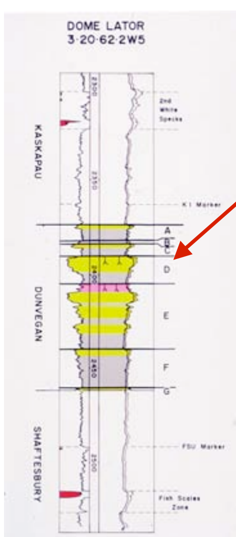
Methodology

3. Identify Facies breaks which mark bounding discontinuities.



Pebbly sandstone lags marks flooding surface

Well Log Stratigraphy

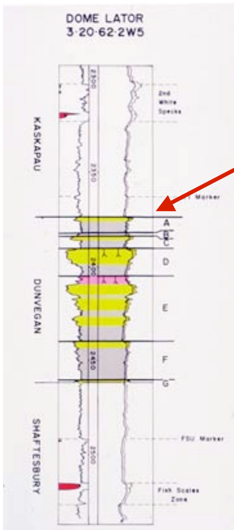


Bhattacharya, 1993

Flooding surface

- Core data allow sedimentary facies and well log patterns to be calibrated.

Well Log Stratigraphy



Flooding surface

- Core data allow sedimentary facies and well log patterns to be calibrated.

Marine Shale

Marine Sandstone

Non-Marine laminated mudstone

Subsurface Stratigraphic Methods

Methodology

3. Identify Facies breaks which mark bounding discontinuities.

Conglomerate marks sudden increase in energy. Possible erosional disconformity.

Cretaceous Buck Horn Conglomerate, Utah

Subsurface Stratigraphic Methods

Methodology

3. Identify Facies breaks which mark bounding discontinuities.

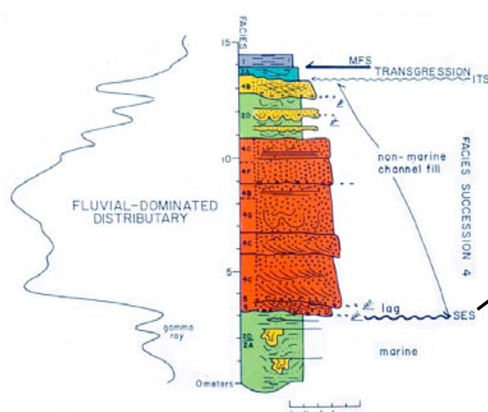
Shallow water sandstone erosively overlies prodelta mudstones.

Cretaceous Dunvegan Fm., Alberta

Subsurface Stratigraphic Methods

Methodology

Base of major channel/valley



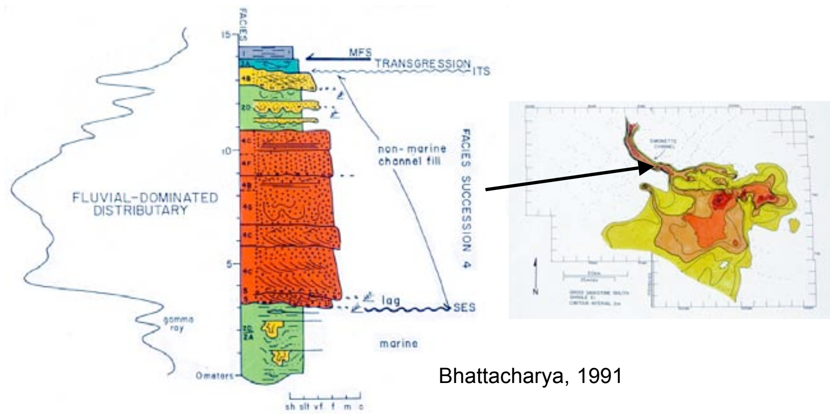
Bhattacharya, 1991

Cretaceous Dunvegan Fm., Alberta

Subsurface Stratigraphic Methods

Methodology

Sequence boundary marks base of major channel/valley that feeds a lowstand delta.



Bhattacharya, 1991

Cretaceous Dunvegan Fm., Alberta

Methodology

4. Establish facies correlation lengths from closely spaced data.

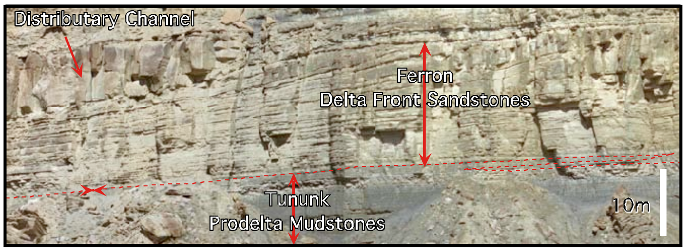
- Outcrop data.
- Statistics on sizes of depositional elements.

Overlapping marine sandstones, Frontier Fm., Wyoming will affect regional correlation of sandstone bodies.

Subsurface Stratigraphic Methods

Methodology

4. Establish facies correlation lengths from closely spaced data.
   - Use outcrop analogs.

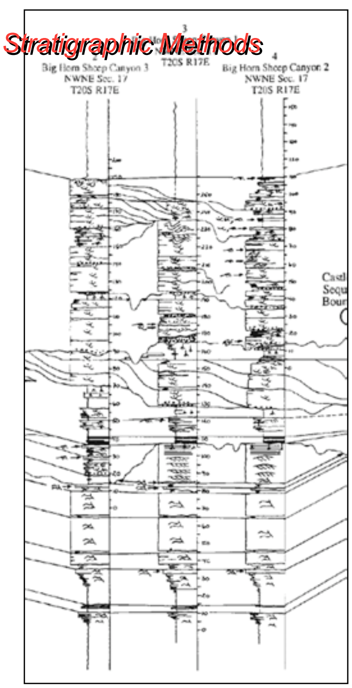


Dipping Ferron Delta front sandstones extend laterally a few hundred meters from top to base of sandstone body.

Subsurface Stratigraphic Methods

Methodology

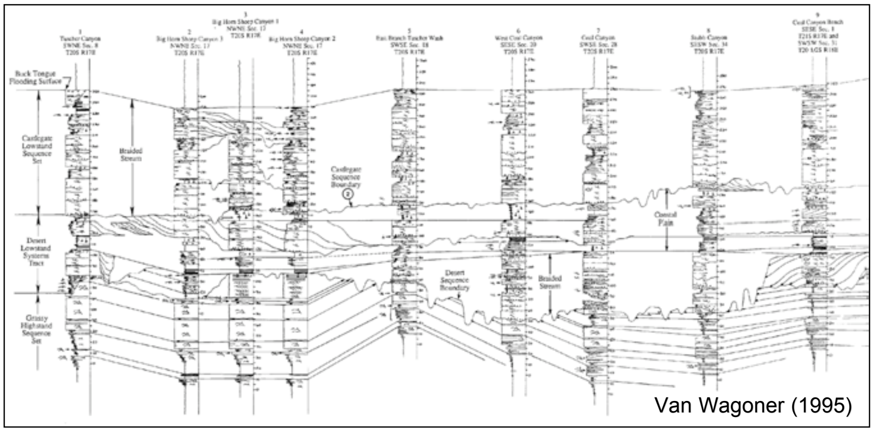
4. Establish facies correlation lengths from closely spaced data.
   - Use outcrop analogs.
   - Note closely spaced outcrop sections look similar.



Book Cliffs sections < 1km apart
(Van Wagoner 1995)

Subsurface Stratigraphic Methods

Methodology

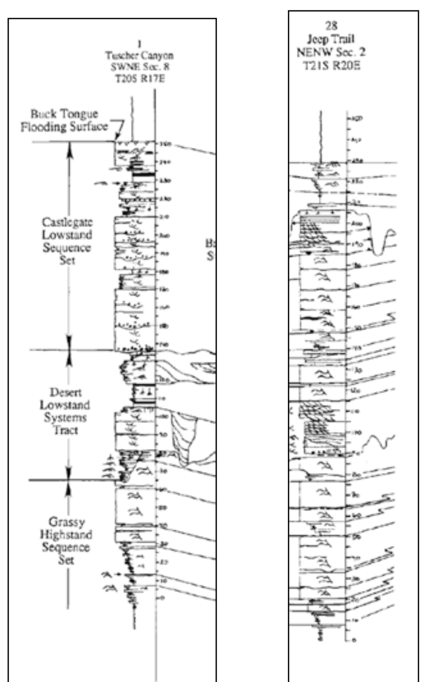


- **Note sections shows more change with distance**

Methodology

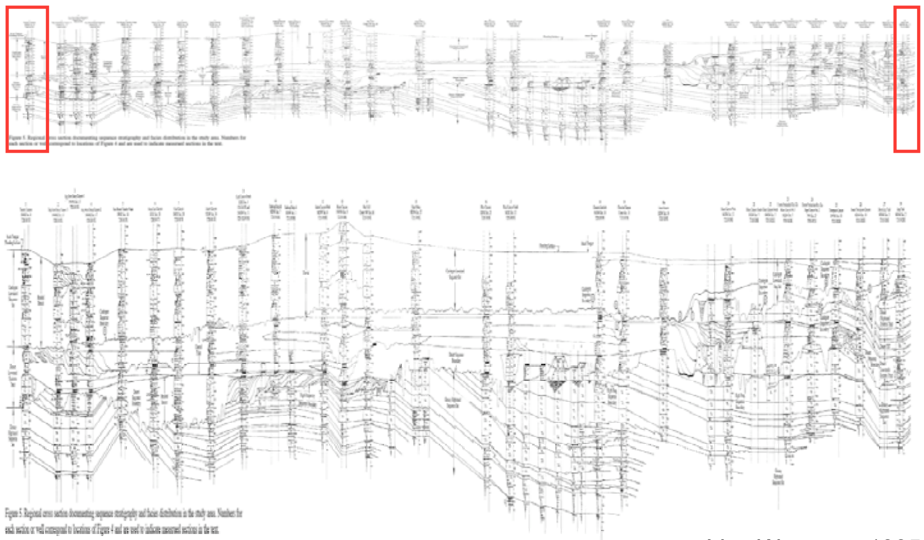
4. Close versus widely spaced data

- **Book Cliffs sections 100km apart.**
- **How would you correlate these?**
- **Woould you correlate these?**
- **Should you correlate these?**



Van Wagoner (1995)

Book Cliffs Stratigraphy



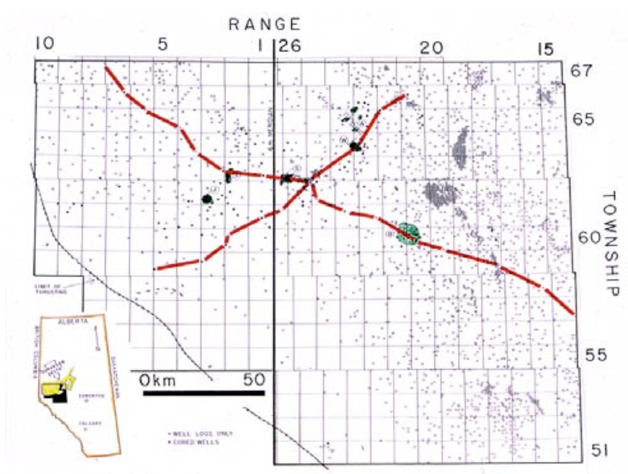
Van Wagoner, 1995

Subsurface Stratigraphic Methods

Methodology

4. Establish facies correlation lengths from closely spaced data.

- **Focus in producing fields, twinned or horizontal wells.**



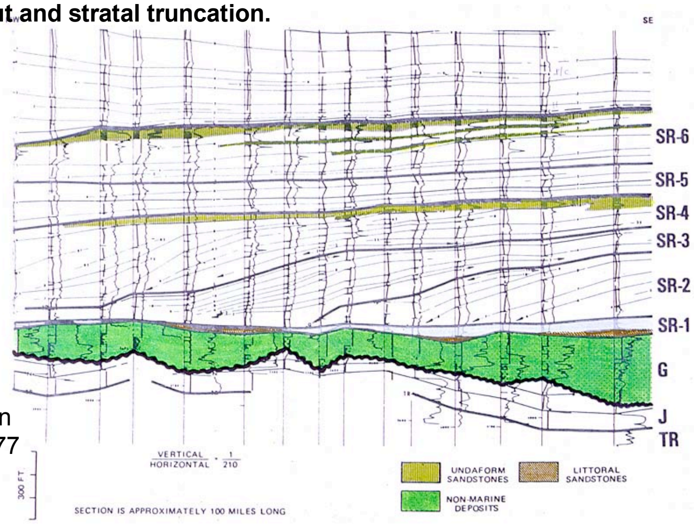
Wells are closely spaced in producing fields.

Ask yourself: Is it rational to correlate this specific layer across this distance?

Methodology

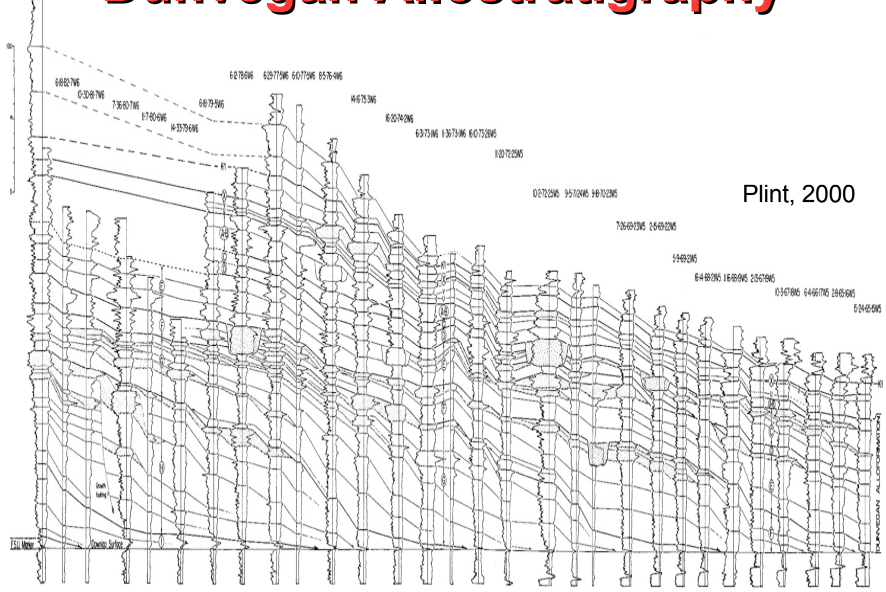
5. Expand correlations to larger scale.

- **Correlate everything that you can.**
- **Loop tie.**
- **Interpret lapout and stratal truncation.**



McCallum, 1977 in Mitchum et al., 1977

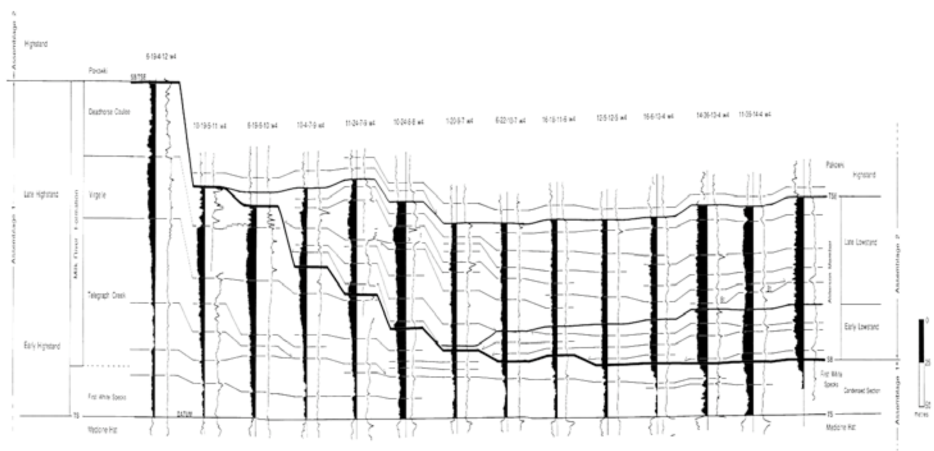
Dunvegan Allostratigraphy



Plint, 2000

Plint, 2000

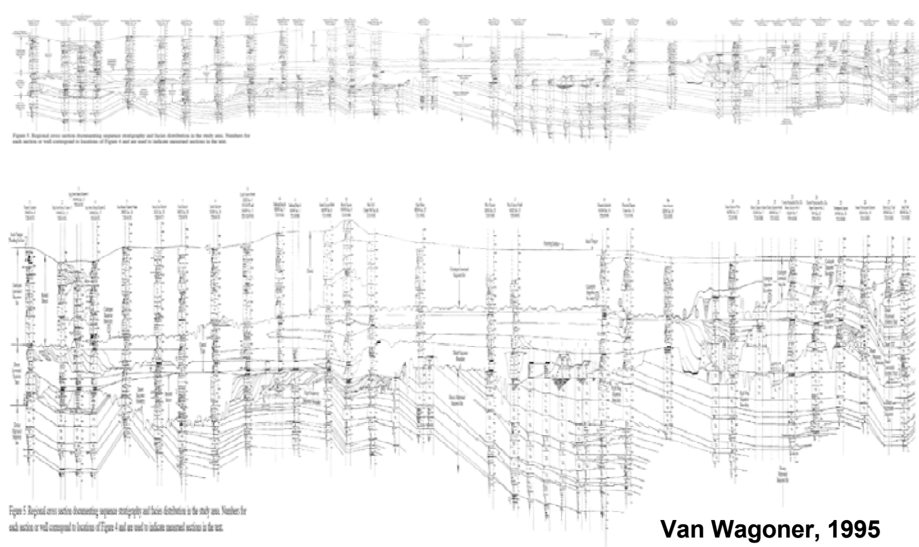
Subsurface Correlations



Cretaceous Milk River - Anderson member

O'Connell et al., 1995

Note Level of correlation detail in Outcrop Sections



Van Wagoner, 1995

Subsurface Stratigraphic Methods

5. Expand correlations to larger scale.

- Interpret lapout and stratal truncation.
  - Stratal lapout cannot be seen directly.
  - You must interpolate between wells.
  - You MUST use geological concepts and models to correlate.
    - Autocorrelation programs have a very difficult time with geological concepts.
  - You must be model driven but the trick is to pick the right model!
  - Use multiple-working-hypotheses.

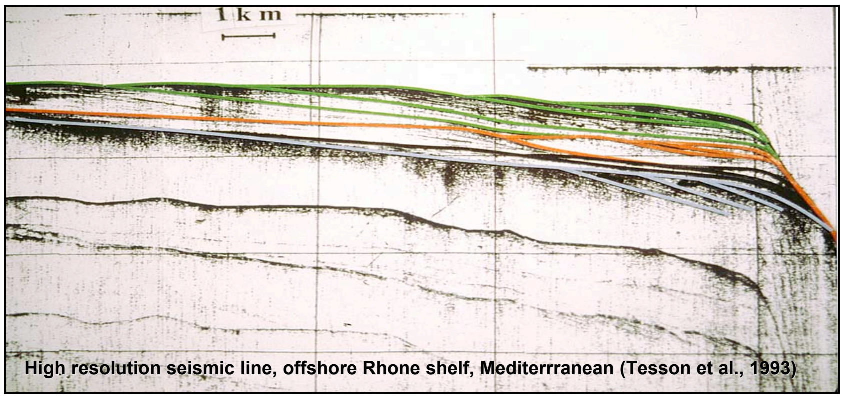
Correlation Methodology

- Correlate key markers within the mudstones first.
  - Mudstones record the most amount of time.
  - Mudtones provide key environmental information.
- Correlate sandstones last
  - Fit sandstones in between mudstones.

Subsurface Stratigraphic Methods

Datum Rules

- Beds may be smooth but are rarely flat.
  - Maybe flat in fluvial systems.
- Datum can distort the actual stratigraphic relationships.
- Use multiple datums to show accurate stratigraphy.



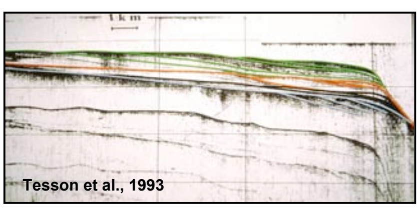
High resolution seismic line, offshore Rhone shelf, Mediterrranean (Tesson et al., 1993)

Subsurface Stratigraphic Methods

Datum Rules

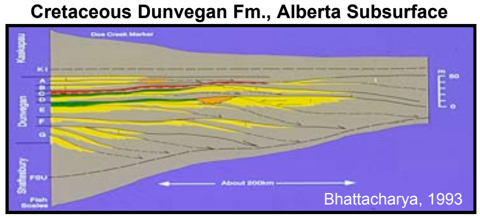
- Compare well log stratigraphic architecture with seismic analogs.

Modern Rhone shelf



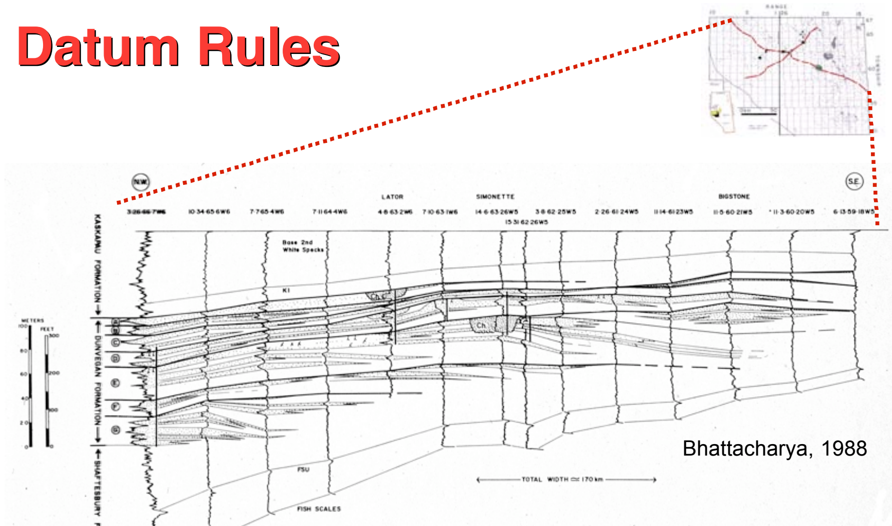
Tesson et al., 1993

Cretaceous Dunvegan Fm., Alberta Subsurface



Bhattacharya, 1993

Datum Rules

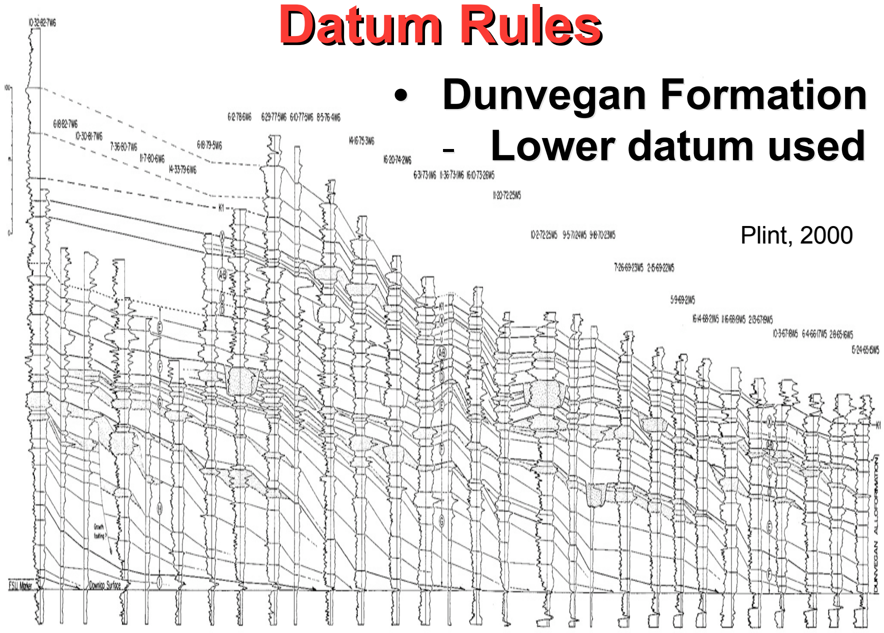


Bhattacharya, 1988

- Dunvegan Formation
  - Top Stratigraphic datum

Datum Rules

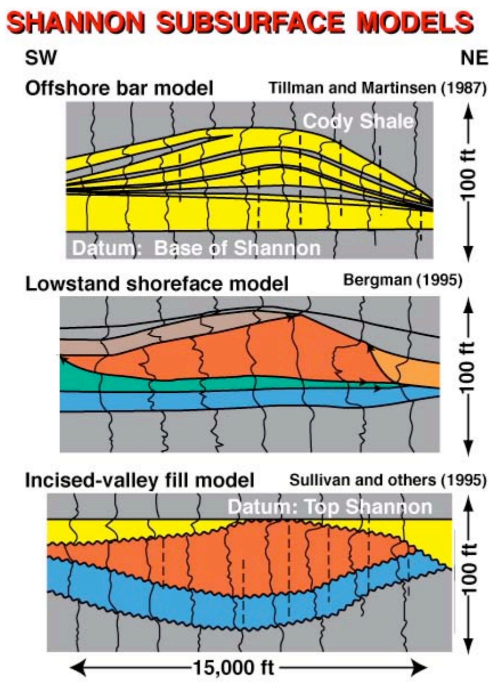
- **Dunvegan Formation**
  - **Lower datum used**



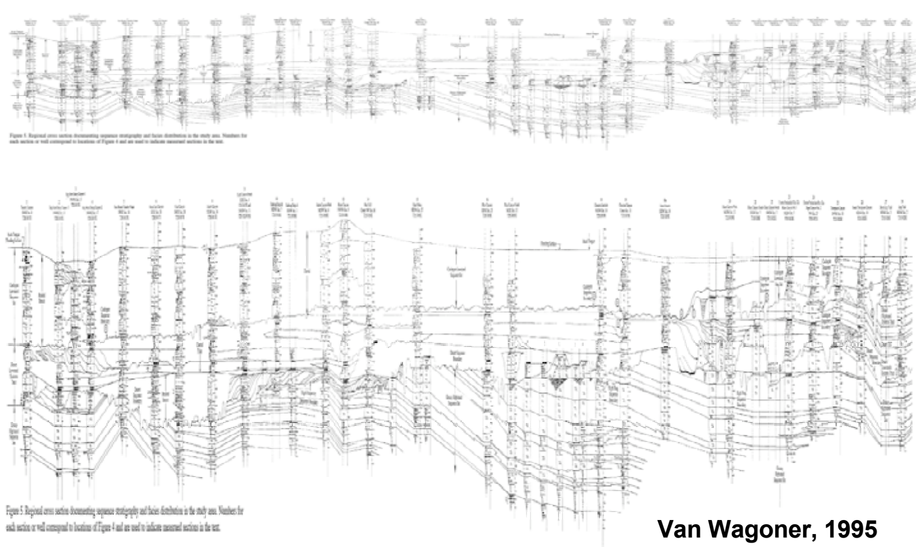
Plint, 2000

Datum Rules

- Various interpretation of Cretaceous Shannon Sandstone reflect diffferent choices of datum!

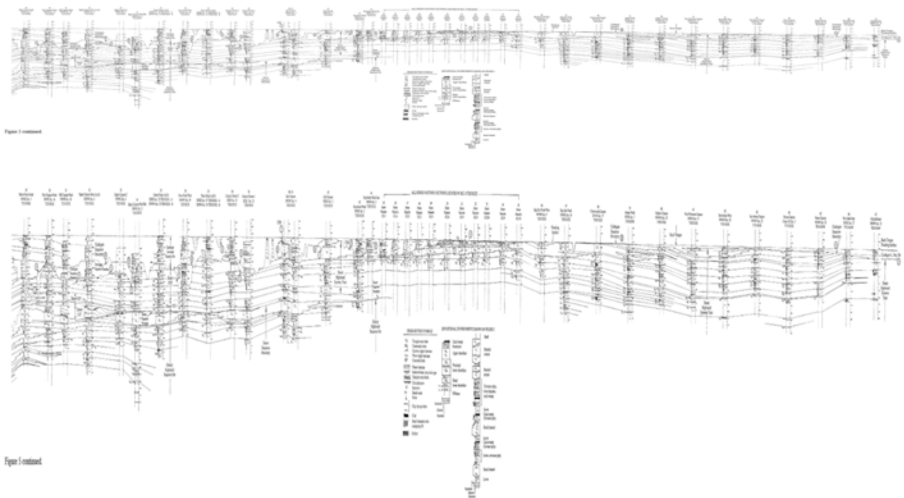


Note Parasequences dip landward and seaward



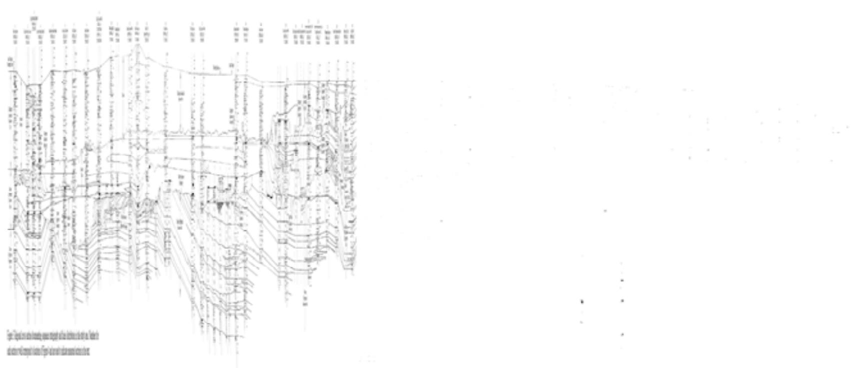
Van Wagoner, 1995

Note Parasequences dip landward and seaward



Van Wagoner, 1995

Note Parasequences dip landward and seaward



Top Datum distorts stratigraphy
Actually most datums distort stratigraphy

Van Wagoner, 1995 (This is an outstanding cross section, I am just pointing out how datum choice distorts stratigraphy)

Consequence of picking lithostratigraphic datum

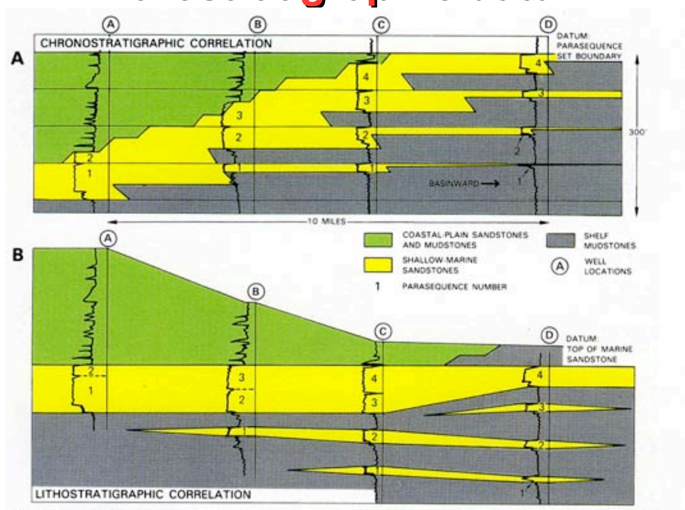
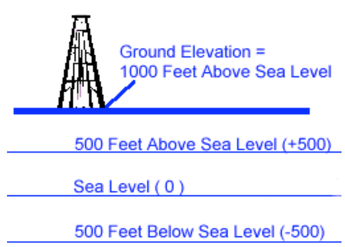


Figure 17—Comparison of (A) chronostratigraphic correlation and (B) lithostratigraphic correlation styles: progradational parasequence set.

Van Wagoner et al., 1990

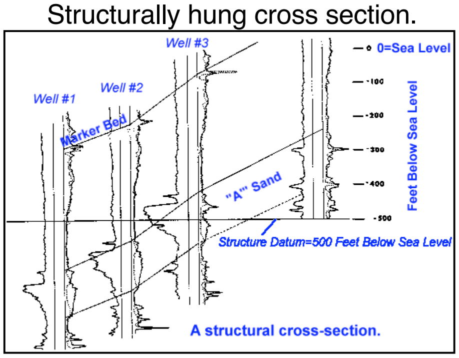
Well Log Stratigraphy

- Typically well logs are “Hung” on either a structural or stratigraphic datum.



How Datums Work

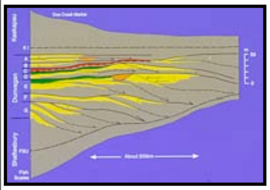
Structurally hung cross section.

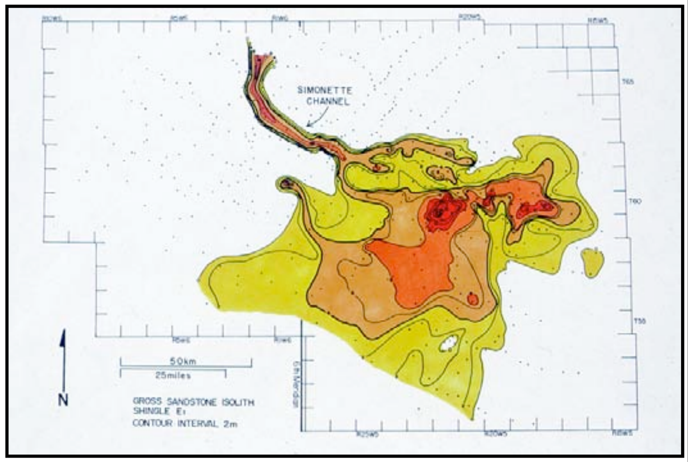


http://www.abix.com/Stratigraphic%20Cross-Sections.htm

Methodology

7. Map sandstones and explore for your reservoir.





Bhattacharya, 1991

Subsurface Stratigraphic Methods

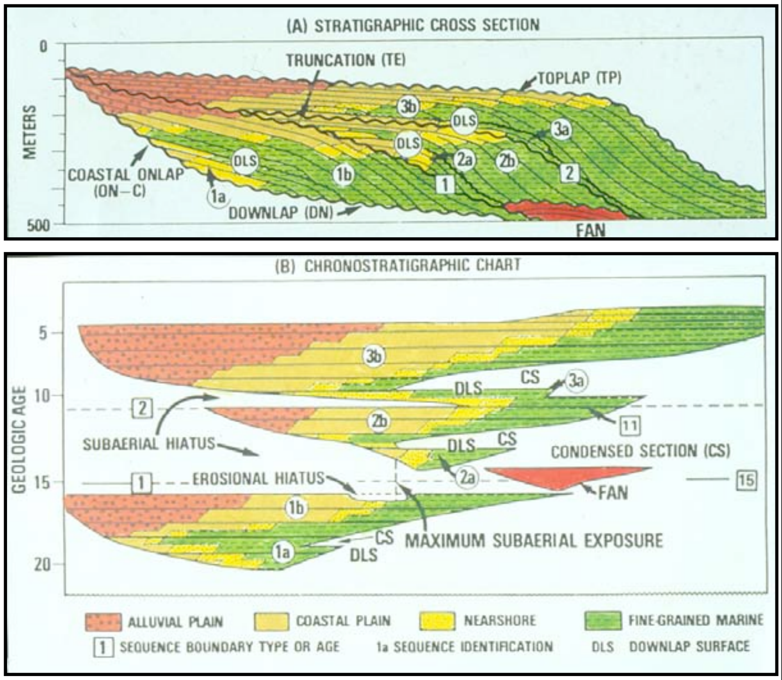
7. Map Sandstones

- Map anomalies may require revision to correlations.
- Stacking patterns are best seen in map view.
- Channel and channel belt patterns may be observed directly in 3D seismic data.
- Map may depict "fairways" rather than channel belts or channels.
- Be aware of scale of feature that you map compared to reasonable estimates of channel-belt width and thickness.

Subsurface Stratigraphic Methods

Last Optional Step

8. Make time stratigraphic charts (Wheeler diagrams).



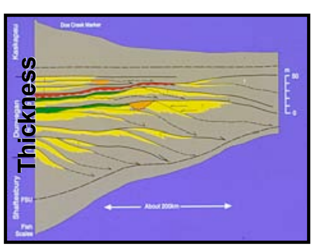
Vail et al., 1984

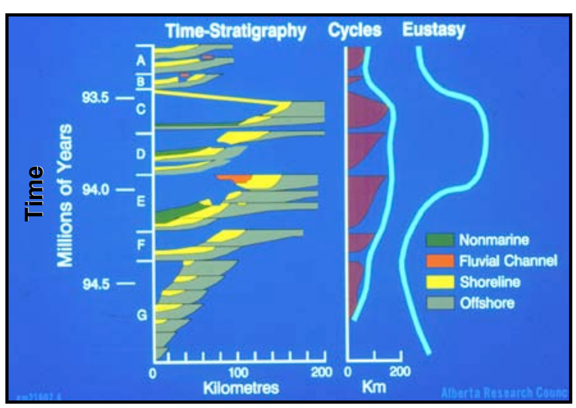
Subsurface Stratigraphic Methods

Last Optional Step

8. Make time stratigraphic charts (Wheeler diagrams).

- Helps find anomalous correlations.
- Can be compared with other chronometric data (magnetostratigraphy, biostrat, sea-level curves).





Bhattacharya, 1994

Subsurface Stratigraphic Methods

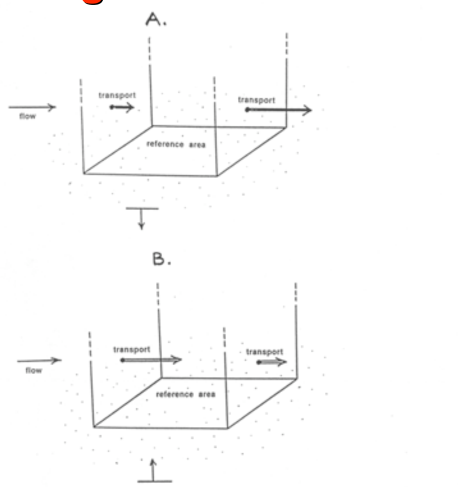
Methodology Conclusions

1. Evaluate previous work and regional seismic and well log data.
   - Integrate biostrat.
2. Establish depositional facies to determine correlation styles.
   - Use outcrop or seismic analog data.
3. Identify facies breaks which mark bounding discontinuities.
4. Establish facies correlation lengths from closely spaced data.
5. Expand correlations to larger scale.
   - Focus on mudstones.
6. Correlate sandstone bodies last.
7. Map sandstones.
   - This is relatively easy if correlations are good.
8. Make time stratigraphic charts (Wheeler diagrams).

Erosion & Deposition

Aggradation versus Degradation

- If sediment discharge (Qs) varies along-stream either erosion or deposition is taking place as long as sediment has no other way of entering the system.
- This is commonly controlled by a change in slope (changes bed shear stress).
  - Deposition is favored by decreasing slopes.
  - Erosion is favored by increasing slopes.



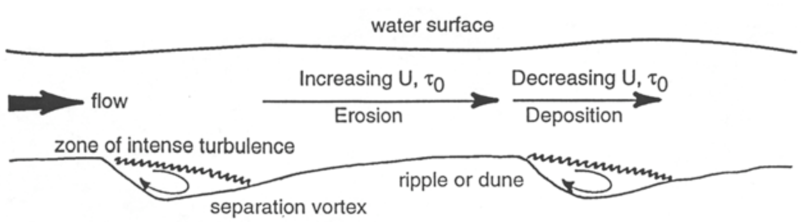
Sediment transport over the reference area. A: Sediment is being added to the flow from the bed somehow, so there's net erosion. B: Sediment is being added to the bed from the flow somehow, so there's net deposition.

(from Southard, 1993, unpublished notes)

Erosion & Deposition

Aggradation versus Degradation

- Decreasing water depth favors erosion on back of bedforms.
- Increase in water depth favors deposition in front of bedform
- Deposition is favored by decreasing slopes.
- Erosion is favored by increasing slopes.

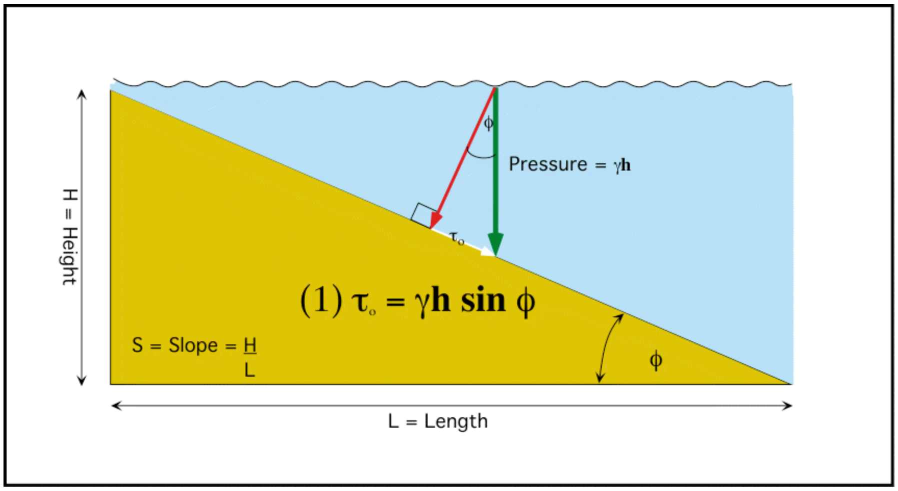


Flow and sediment transport over ripples and dunes.

Bridge, 2003

Shear Stress

- Reflects the downslope resolution of pressure
- The steeper the slope, the higher the shear stress.
  - Flow can do more work.



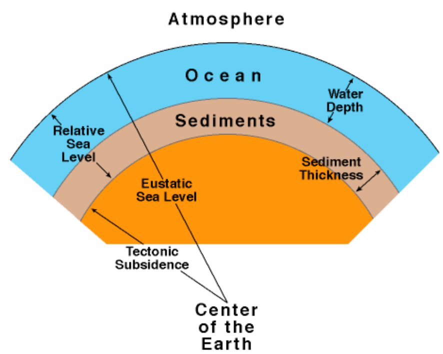
Erosion & Deposition

Base level

- Stratigraphic Base level
  - **Imaginary surface that separates erosion from deposition.**
- Systems tend towards an "equilibrium" profile.
  - **Graded river profile**
  - **Graded marine shelf**
  - **Angle of repose**
- Large and small-scale change in the profile can result in deposition or erosion both locally and regionally.
- Geomorphic base level:
  - **The lowest level to which the land surface tends**
  - **Approximately sea-level**
  - **Implies a flat surface**

Sea Level Concepts

- Eustasy
  - Absolute change in sea-level
- Relative Sea-level
  - Relative change compared to a datum



Base level

- Examples of "equilibrium" profiles.
  - Graded river profile
  - Graded marine shelf
  - Angle of repose

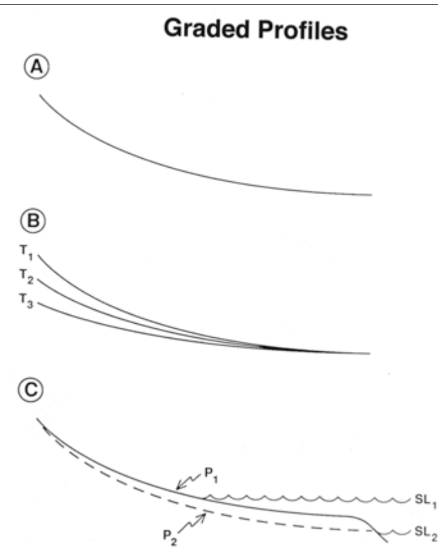


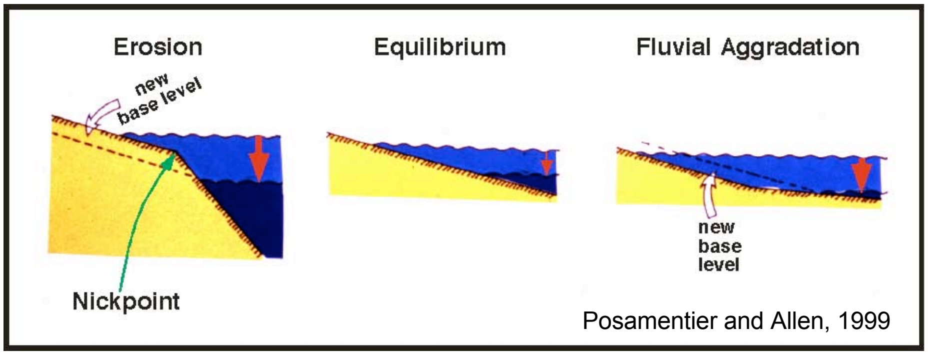
Fig. 1. Graded profiles. (A) the Gilbert–Mackin profile (steady-state equilibrium); (B) the Davis profile (dynamic equilibrium); (C) the Davis profile regraded in response to a sea-level fall.

(from Thorne & Swift, 1991, p.36)

Erosion & Deposition

Nickpoints

- Erosion commonly occurs at a break in slope, especially if it becomes exposed.
- The point at which this type of erosion occurs is called a “nickpoint”.



Posamentier and Allen, 1999

Evolution of Nickpoints

Nickpoints

- Headward erosion may occur following a drop in relative sea level.
- This may form a gullied slope.
- Gullies may later connect with trunk stream or river, forming an incised valley.
- Gullies may fill with mud during transgression.
- Nickpoints can also form in the submarine environment.

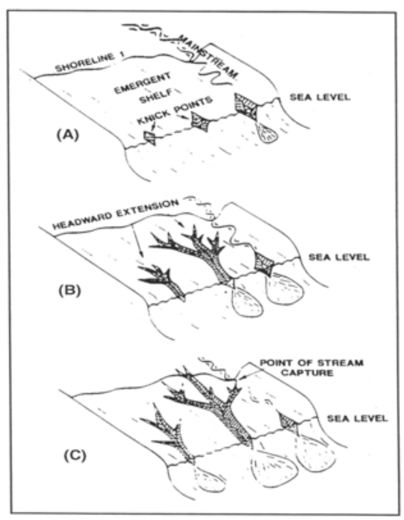
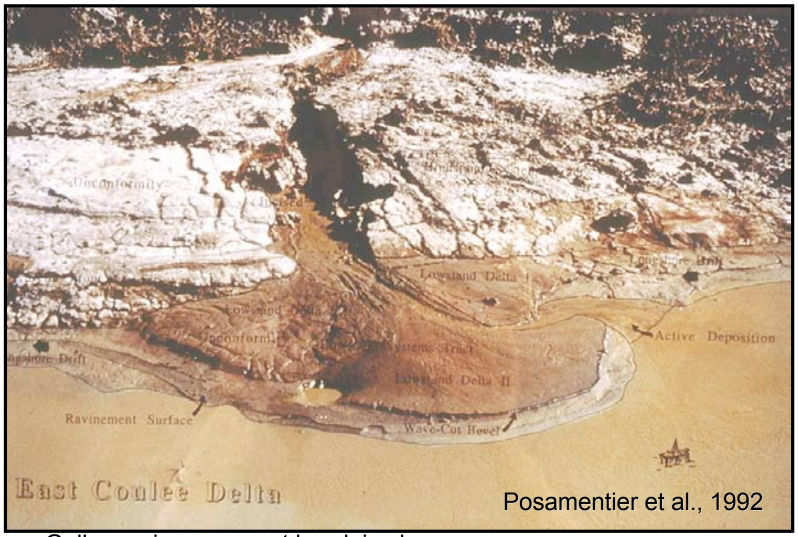


Figure 3—When sea level falls and exposes the shelf break, (A) the main stream incises and a knickpoint begins to migrate upstream. Additional knickpoints also form and (B) erode in the headward direction, forming new drainage systems on the previously submerged shelf. Continued headward extension intersects the pre-established fluvial system and (C) captures it by providing a steeper more efficient course to the sea.

Wescott, 1993

Nickpoints

Erosion & Deposition



- Gully erosion occurs at break in slope.
- Deposition occurs where slope flattens basinward

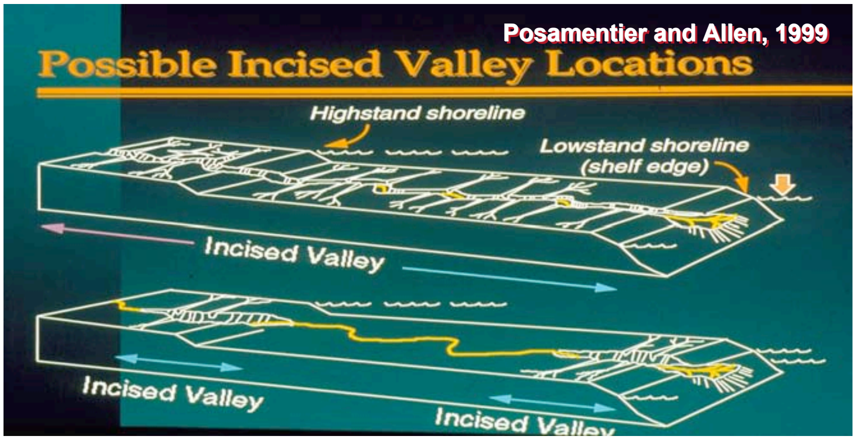
Nickpoints

Erosion & Deposition

- Gully erosion occurs at break in slope.
- Deposition occurs where slope flattens basinward.

Erosion & Deposition

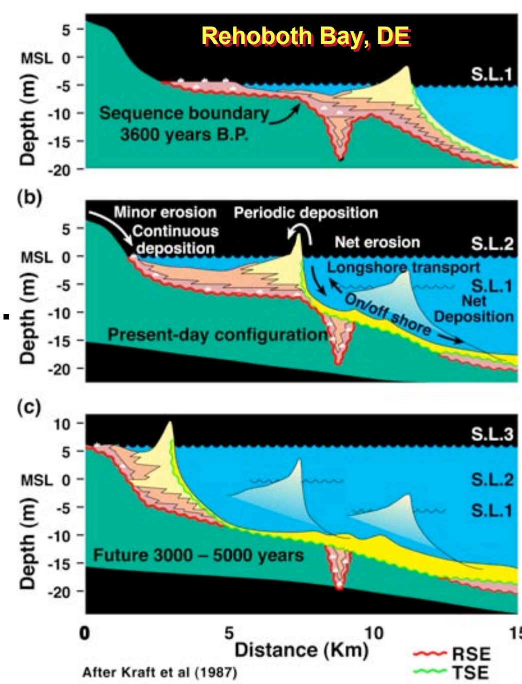
Nickpoints



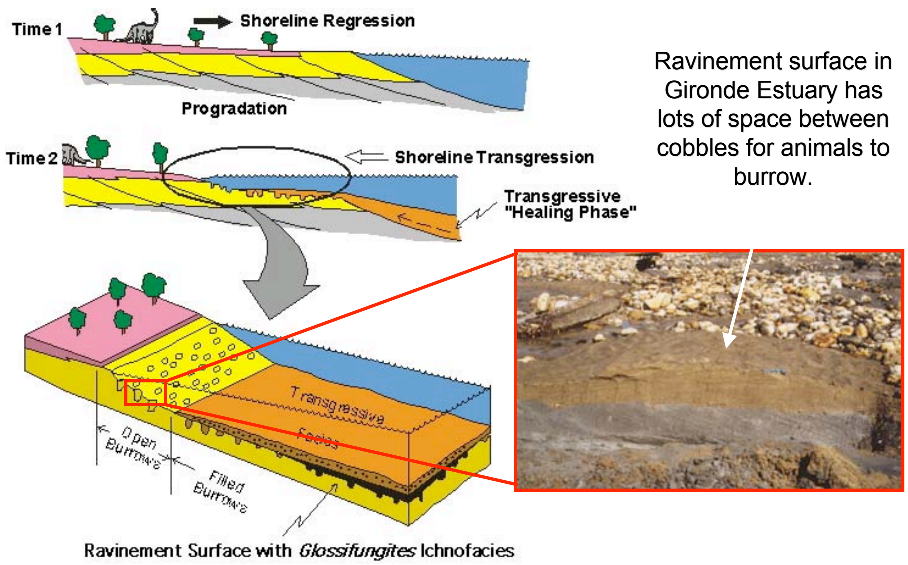
- Gully erosion occurs at breaks in slope.
- Several nickpoints may occur along a river path.

Modern ravinement

- A diachronous surface
- May erode up to 40m (Leckie, 1994).
- GOM ravinement averages 9m.
- May “replace” sequence boundary.



Formation of a Ravinement Surface



Ravinement surface in Gironde Estuary has lots of space between cobbles for animals to burrow.

After Posamentier and Allen, 1999

Erosion & Deposition

Accommodation/Accumulation

- Accommodation
  - The space available for sediment infilling.
  - The shape of the space can change.
  - The rate at which space is created or destroyed can change
- Accumulation
  - The sediment that fills the space.
  - Largely controlled by sediment supply.

Erosion & Deposition

Concepts

- The sedimentary/stratigraphic record is largely dependant on:
  - the size, shape, and rate at which accommodation increases or decreases,
  - the availability of sediment to fill that space (sediment supply).
- Accommodation is primarily controlled by:
  - changes in the volume of the oceans (eustasy),
    - As long as basin is linked to the sea!
  - changes in tectonic subsidence and uplift,
  - compactional subsidence.
- Physiography also controls accommodation:
  - Shape of the land surface,
  - Slope.
- Sediment availability is largely controlled by relief and climate.

Accommodation vs Sediment Supply

- **Basin fill patterns reflect Sediment Quantity (Q) and Receptor Value (R).**
- **Now known as A/S ratio.**
  - **Accommodation versus Sediment Supply**

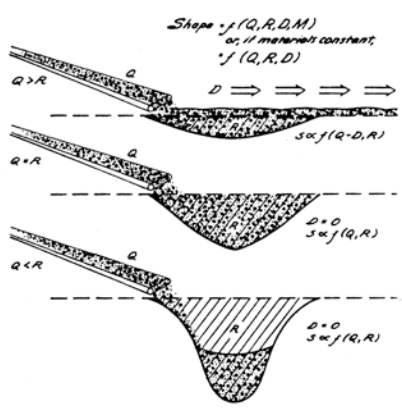
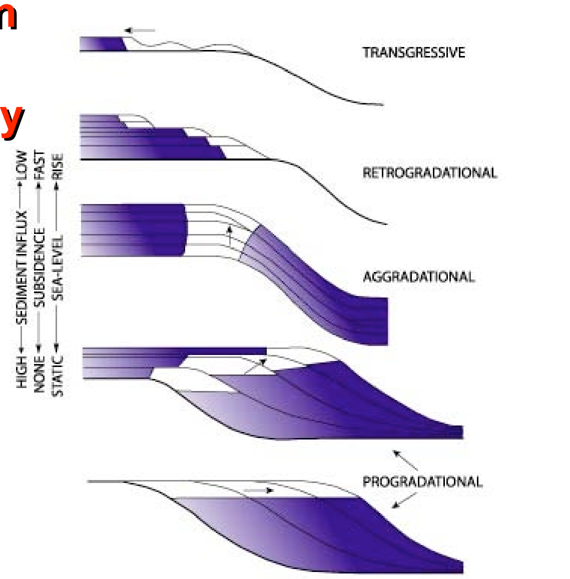


FIG. 1.—Process variables of stratigraphic models considered. Q, represented by endless belt which may run at varying rates, is *quantity* of clastic material supplied to depositional site. R is the *receptor value* of the depositional site, the space below baselevel created by subsidence (indicated by cross-hatching). D represents *dispersal* which tends to remove material from depositional site. M, *materials* supplied, is assumed to be of unvarying composition and texture during operation of each model. In upper diagram Q is less than R; D is effective in removing material from depositional site. In lower diagrams, D is ineffective and the shape of the resulting accumulation of sediment is function of Q and R.

Sloss, 1962

Accommodation vs Sediment Supply

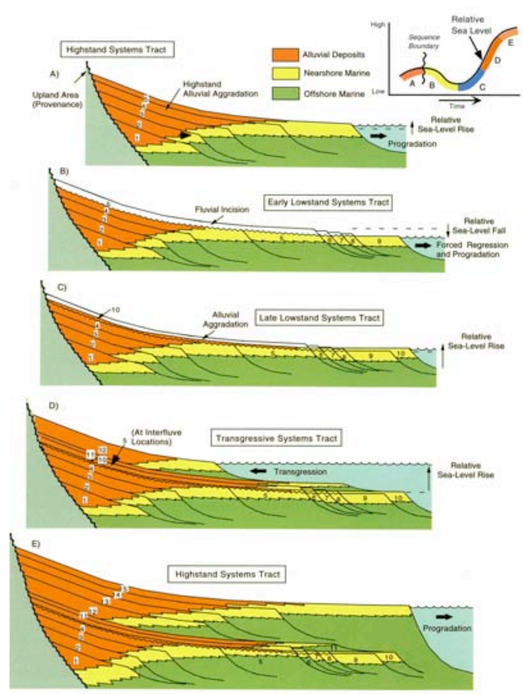
- Basin fill patterns reflect accommodation versus accumulation ratio.



Depostional Architectures as a Function of Accommodation Volume & Sedimentary Supply
(from Emery, 1999; after Galloway, 1989)

Sequences and Sea Level

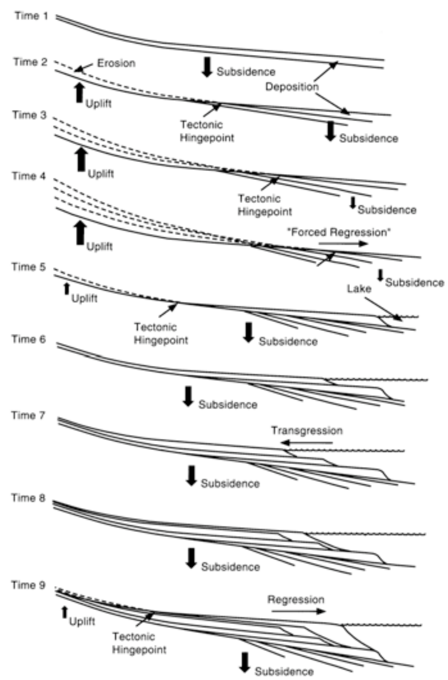
- Stratal patterns relate to changing accommodation and relative sea level curve.



Posamentier and Allen, 1999

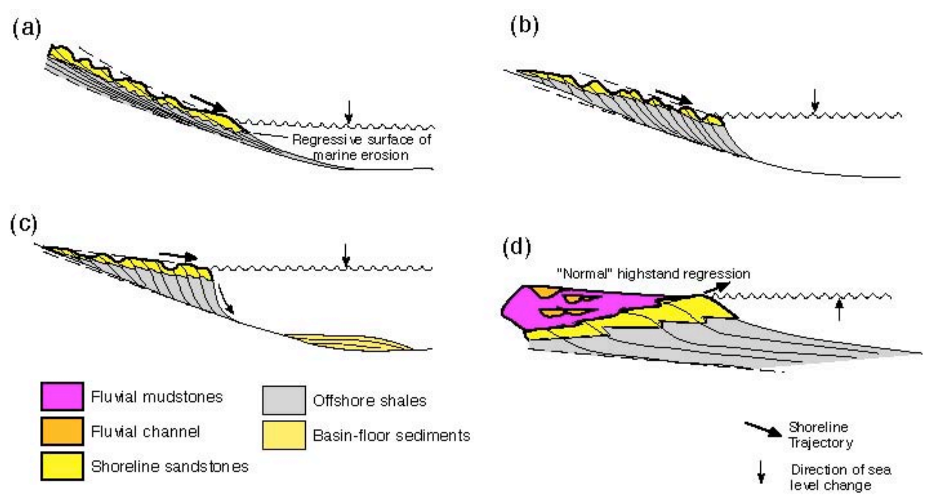
Sequences and Sea Level

- Stratal patterns also are influenced by changing tectonics.



Posamentier and Allen, 1999

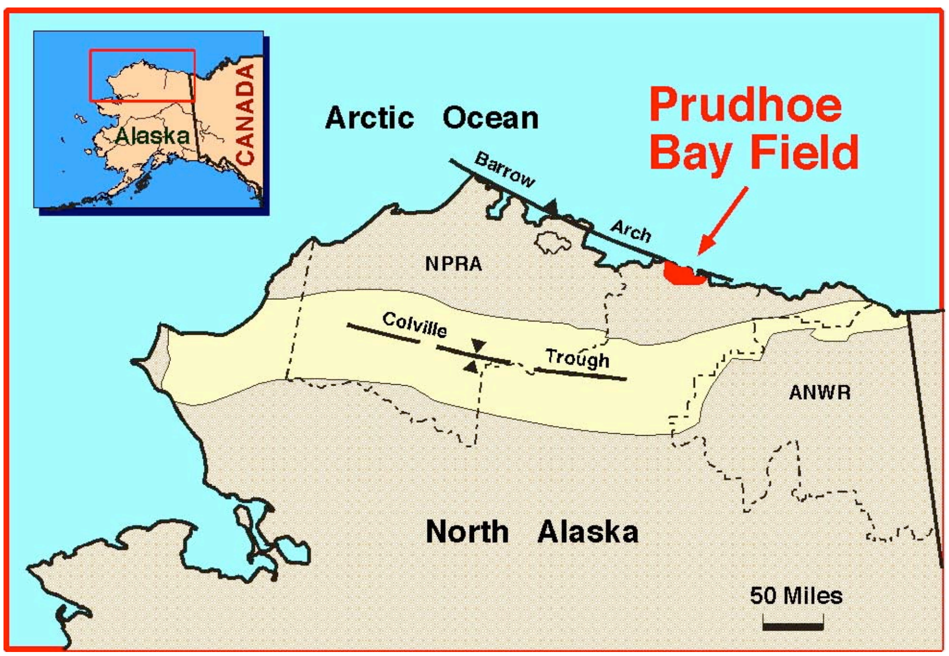
Shoreline Trajectory



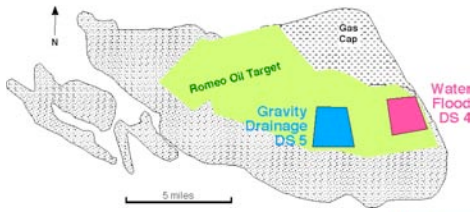
Gjellberg and Helland-Hansen, 1994

Trajectory Examples

- Prudhoe Bay - Subsurface
- Ferron Sandstone - Outcrop
- Forced Regressions

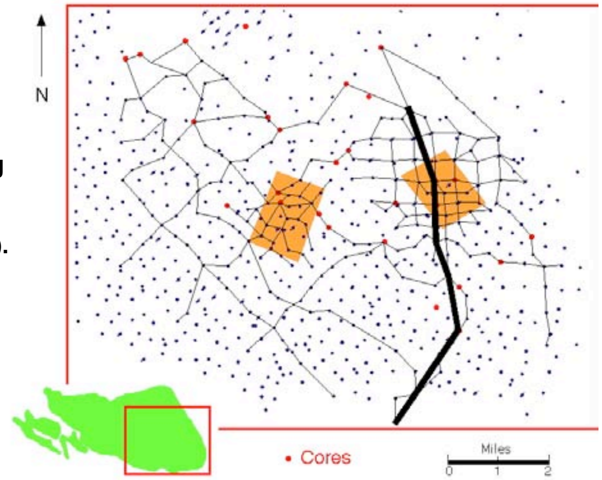


Tye et al., 1999

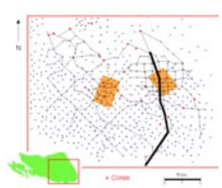


Area and Purpose

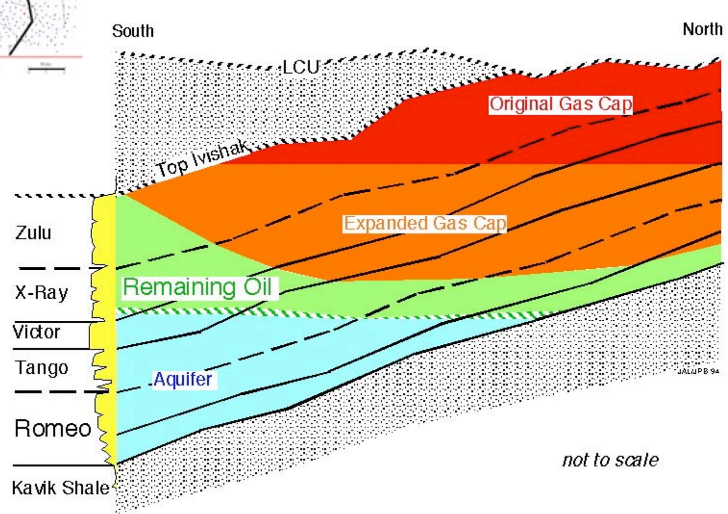
- **Purpose**
  - **Improve models fo lower-most deltaic strata for infill drilling and secondary recovery (waterflood).**



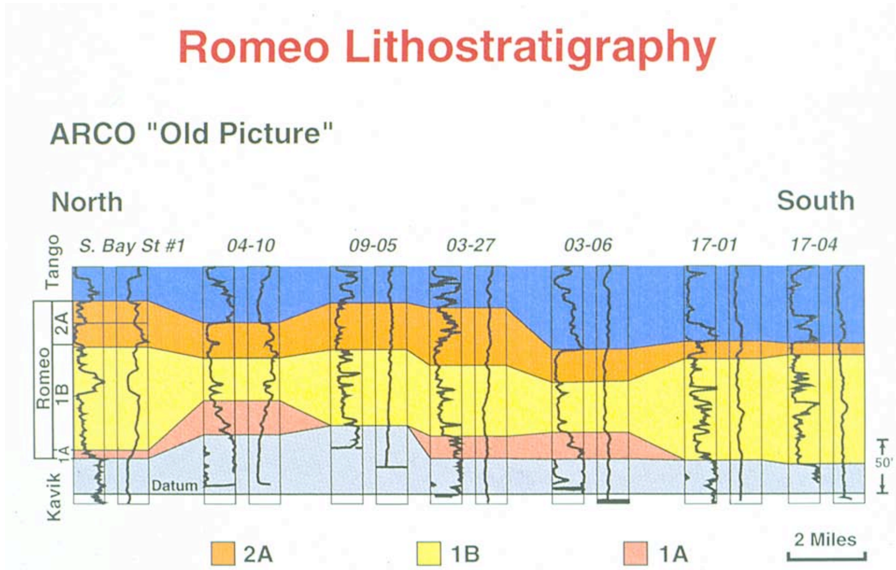
Tye et al., 1999



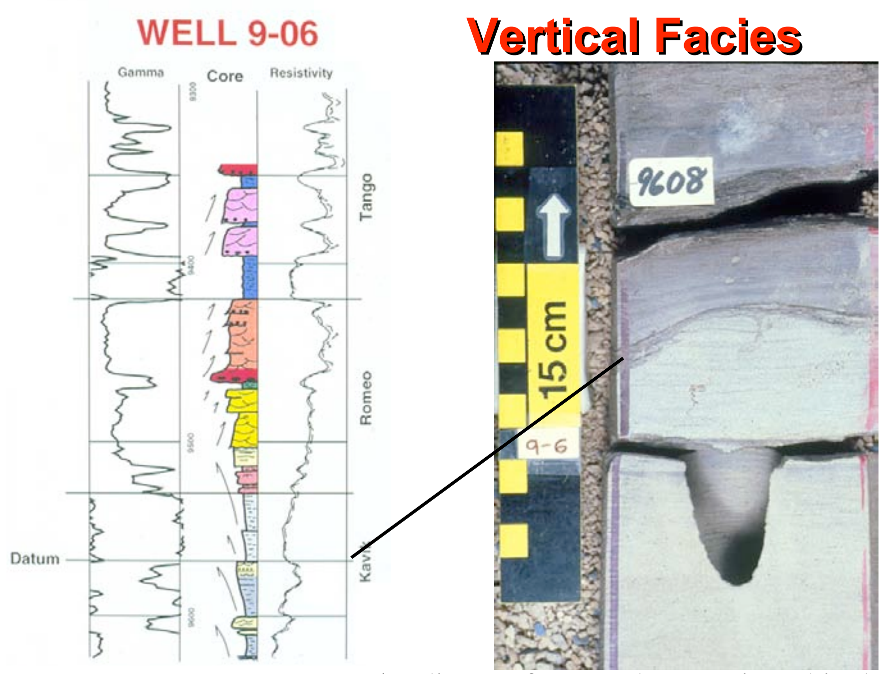
Cross Section



Tye et al., 1999



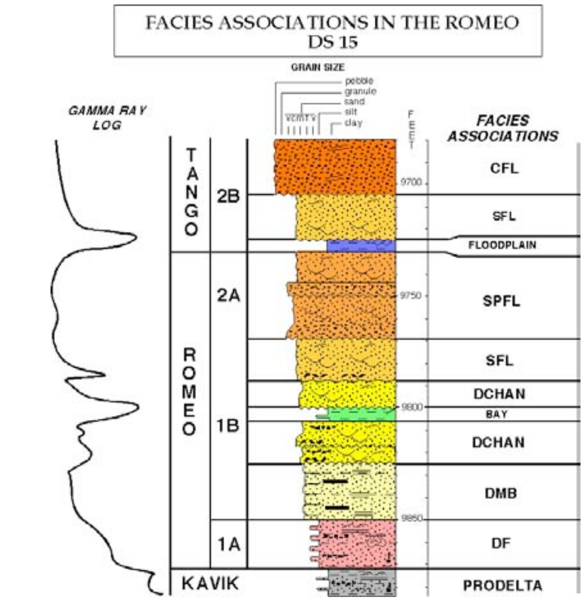
Tye et al., 1999



Tye et al., 1999

Flooding surface used as stratigraphic datum

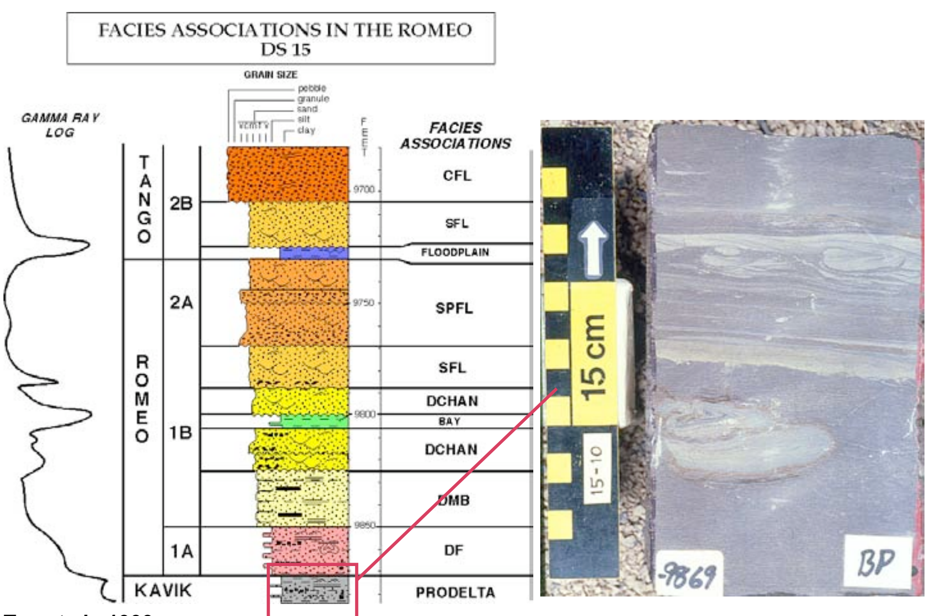
Vertical Facies



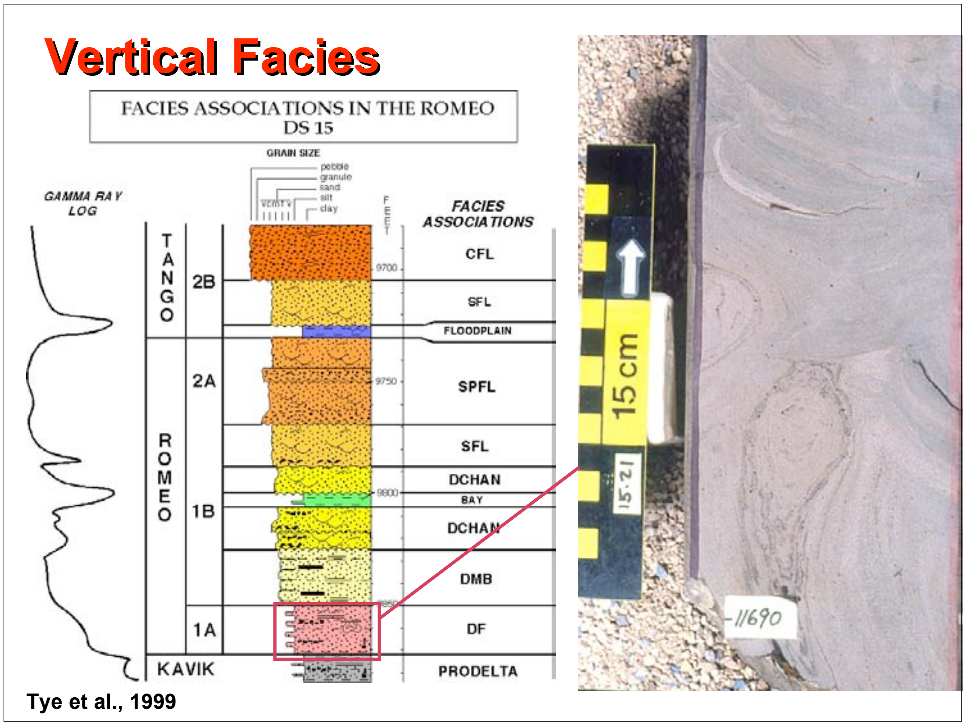
Upward coarsening succession reflecting superposition of fluvial over deltaic.

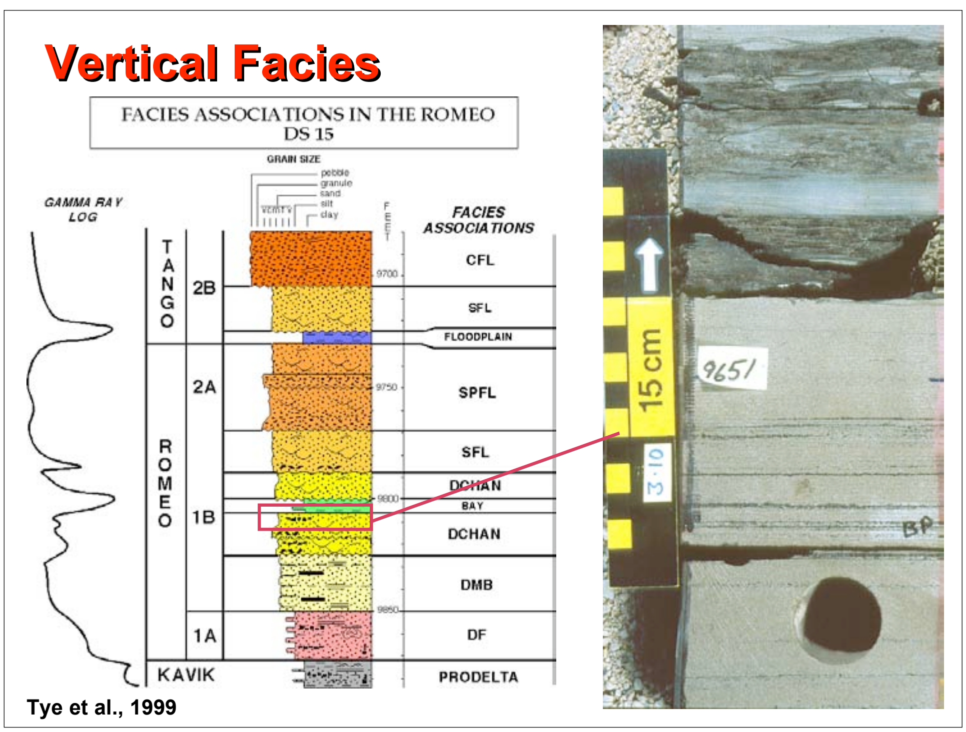
Tye et al., 1999

Vertical Facies



Tye et al., 1999


Vertical Facies
FACIES ASSOCIATIONS IN THE ROMEO
DS 15
GRAIN SIZE
pebble
granule
sand
silt
clay
GAMMA RAY LOG
FACIES ASSOCIATIONS
TANGO
ROMEO
2B
2A
1B
1A
KAVIK
CFL
SFL
FLOODPLAIN
SPFL
SFL
DCHAN
BAY
DCHAN
DMB
DF
PRODELTA
15 cm
15-21
-11690
Tye et al., 1999


Vertical Facies
FACIES ASSOCIATIONS IN THE ROMEO
DS 15
GRAIN SIZE
pebble
granule
sand
silt
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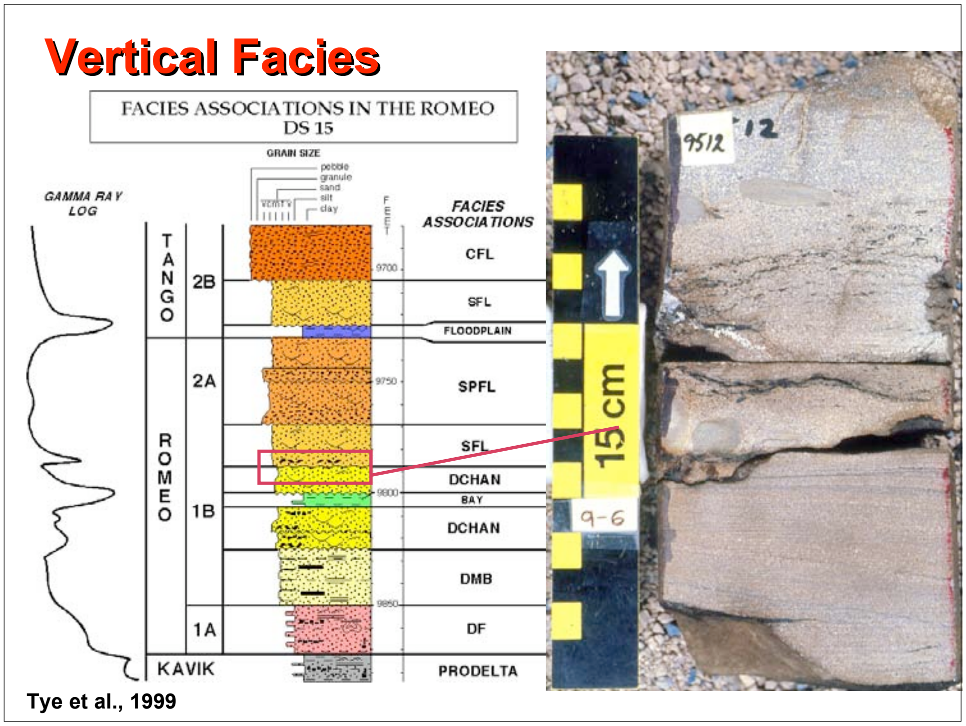
GAMMA RAY LOG
FACIES ASSOCIATIONS
TANGO
ROMEO
2B
2A
1B
1A
KAVIK
CFL
SFL
FLOODPLAIN
SPFL
SFL
DCHAN
BAY
DCHAN
DMB
DF
PRODELTA
15 cm
3-10
9651
BP
Tye et al., 1999


Vertical Facies
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FEET
FACIES
ASSOCIATIONS
TANGO
ROMEO
2B
2A
1B
1A
KAVIK
CFL
SFL
FLOODPLAIN
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DCHAN
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DMB
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PRODELTA
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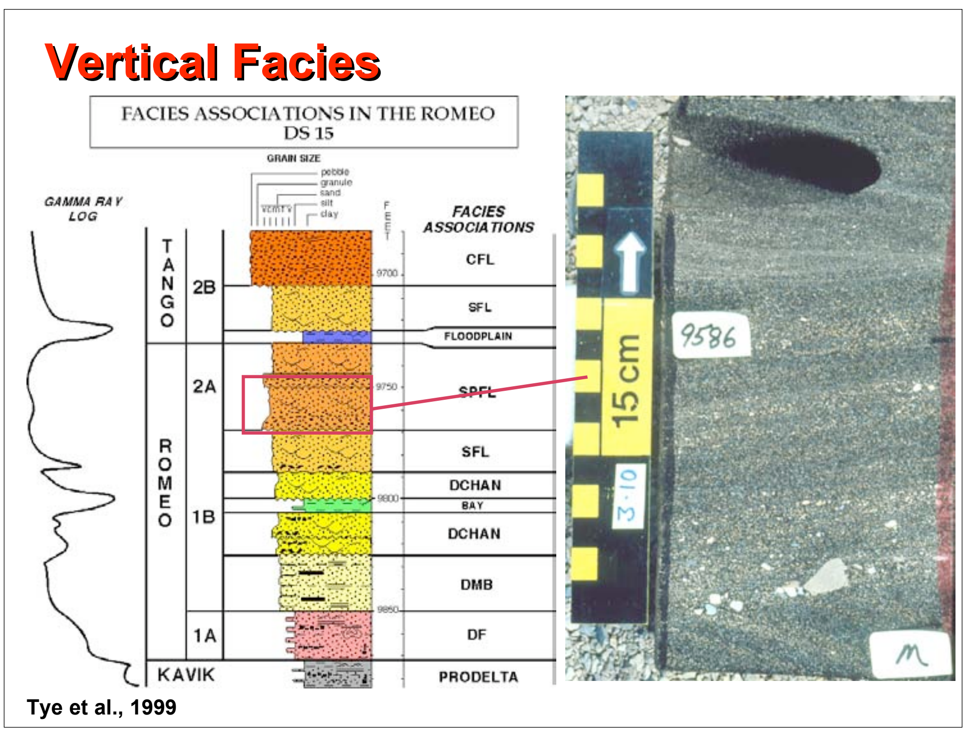
9750
9800
9850
15 cm
9512
9-6
Tye et al., 1999


Vertical Facies
FACIES ASSOCIATIONS IN THE ROMEO
DS 15
GRAIN SIZE
pebble
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sand
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GAMMA RAY
LOG
FEET
FACIES
ASSOCIATIONS
TANGO
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2B
2A
1B
1A
KAVIK
CFL
SFL
FLOODPLAIN
SPFL
SFL
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BAY
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DMB
DF
PRODELTA
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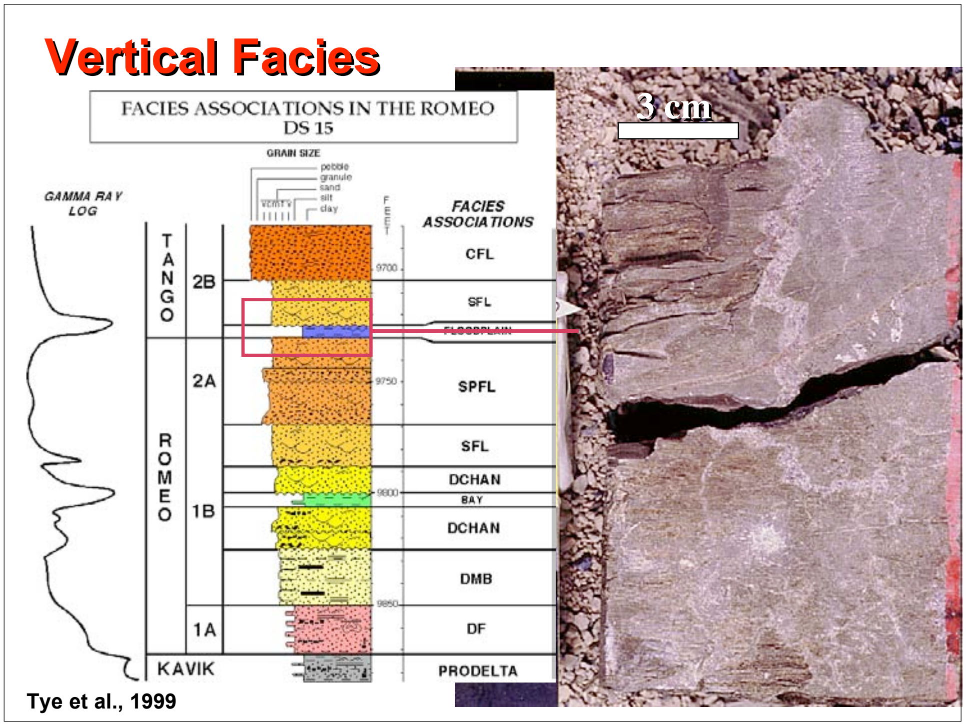
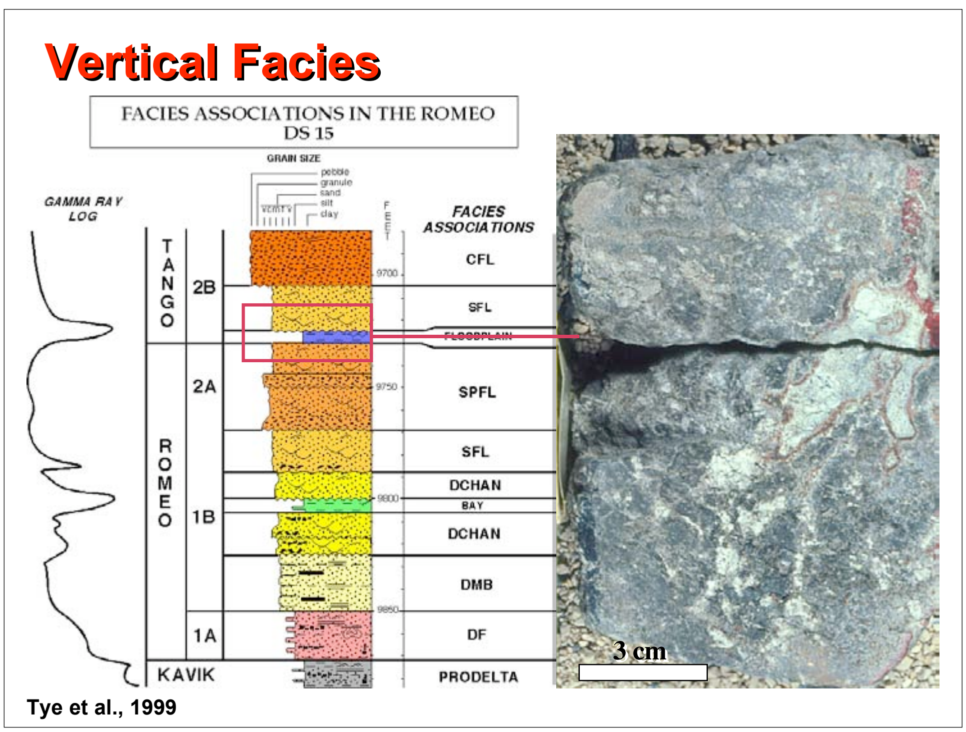
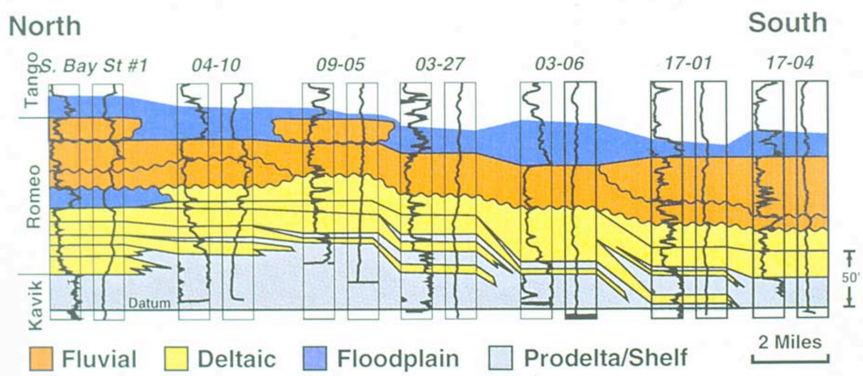
9750
9800
9850
15 cm
9586
3·10
Tye et al., 1999


Vertical Facies
FACIES ASSOCIATIONS IN THE ROMEO
DS 15
GRAIN SIZE
pebble
granule
sand
silt
clay
GAMMA RAY LOG
FEET
FACIES ASSOCIATIONS
TANGO
2B
2A
ROMEO
1B
1A
KAVIK
9700
9750
9800
9850
CFL
SFL
FLOODPLAIN
SPFL
SFL
DCHAN
BAY
DCHAN
DMB
DF
PRODELTA
3 cm
Tye et al., 1999


Vertical Facies
FACIES ASSOCIATIONS IN THE ROMEO
DS 15
GRAIN SIZE
pebble
granule
sand
silt
clay
GAMMA RAY LOG
FEET
FACIES ASSOCIATIONS
TANGO
2B
2A
ROMEO
1B
1A
KAVIK
9700
9750
9800
9850
CFL
SFL
FLOODPLAIN
SPFL
SFL
DCHAN
BAY
DCHAN
DMB
DF
PRODELTA
3 cm
Tye et al., 1999

Romeo Genetic Stratigraphy

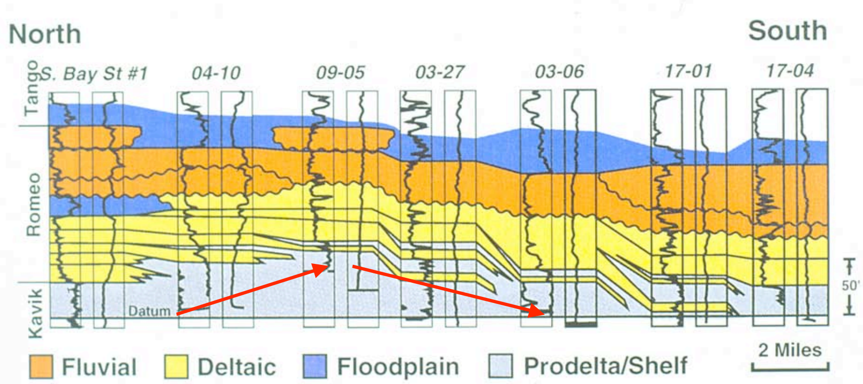
ARCO "New Picture"



Tye et al., 1999

Romeo Genetic Stratigraphy

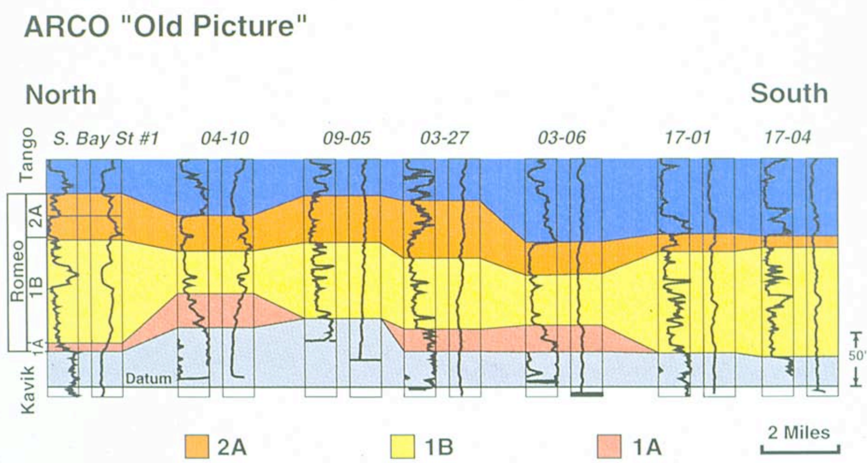
ARCO "New Picture"



Shoreline trajectory is positive and then negative. Floodplain mudstones build-up behind aggrading shoreline during positive trajectory.

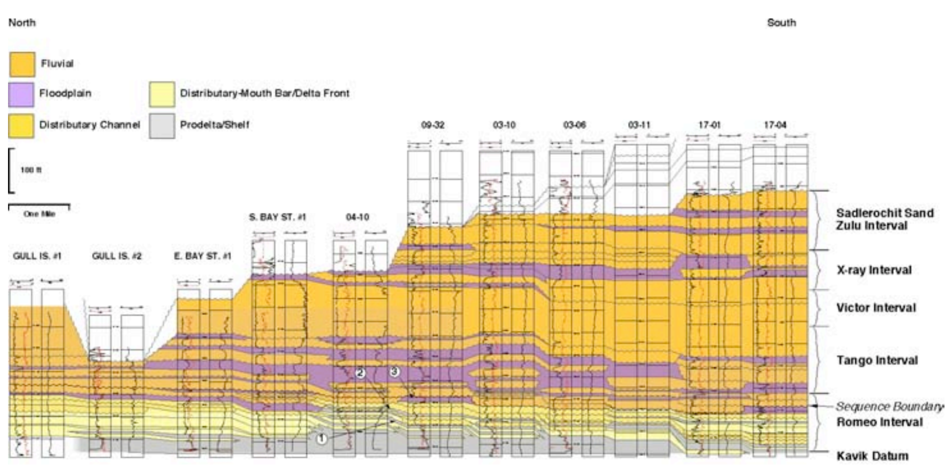
Tye et al., 1999

Romeo Lithostratigraphy



Tye et al., 1999

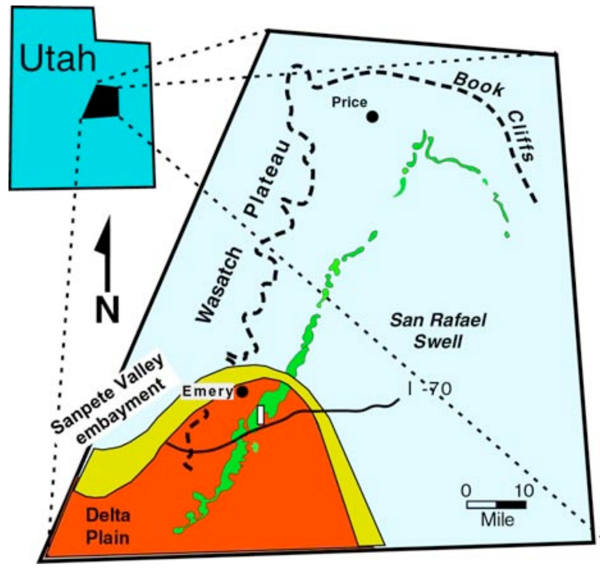
Prudhoe Bay Cross section



Tye et al., 1999

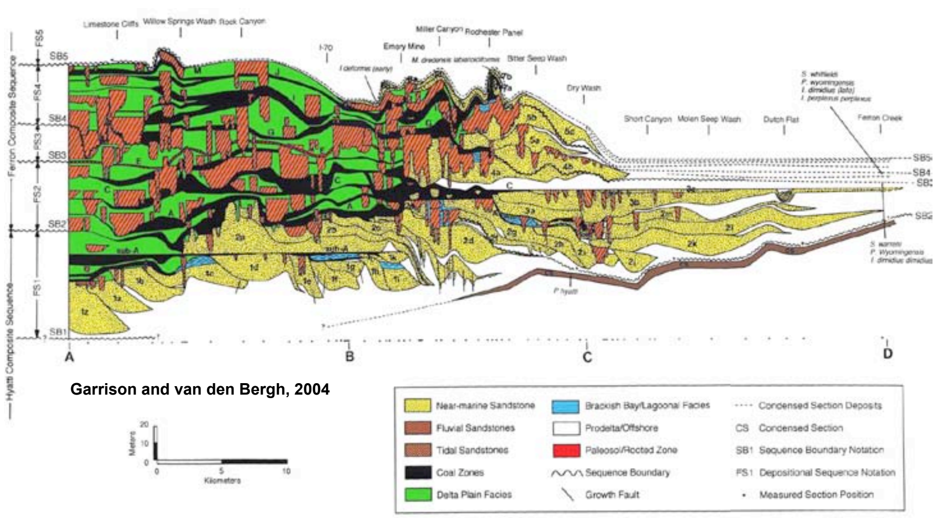
Ferron Example

- Ferron delta complex generally builds to the northeast.



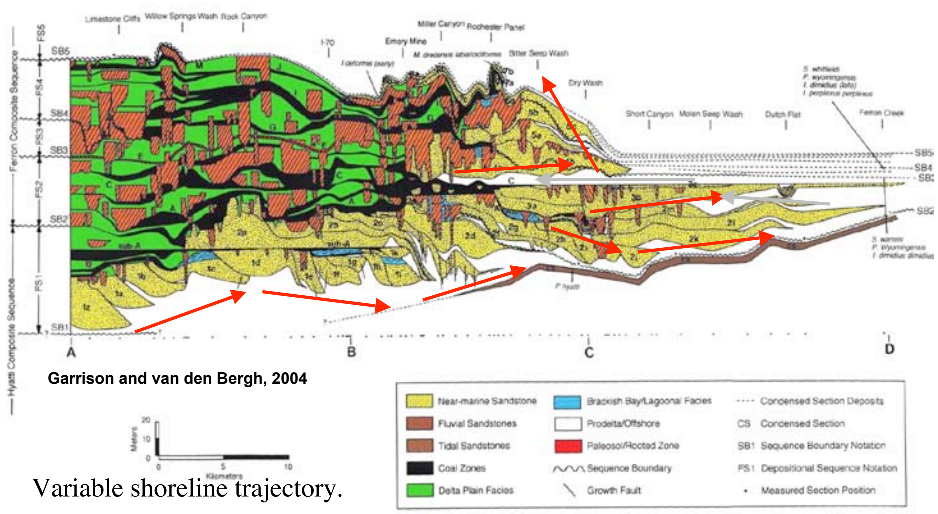
Bhattacharya and Davies, 2004

Ferron Cross-Section



Garrison and van den Bergh, 2004

Ferron Cross-Section



Garrison and van den Bergh, 2004

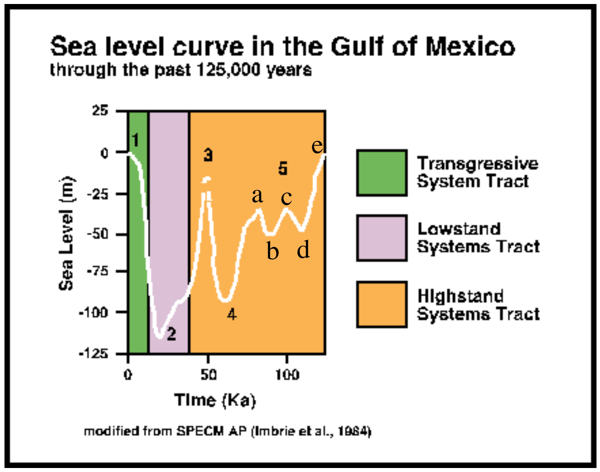
Variable shoreline trajectory.

Quaternary Examples

- Well constrained Sea level curve.
- High resolution seimsic data.
- Some cores
  - Platform borings
  - Research cores

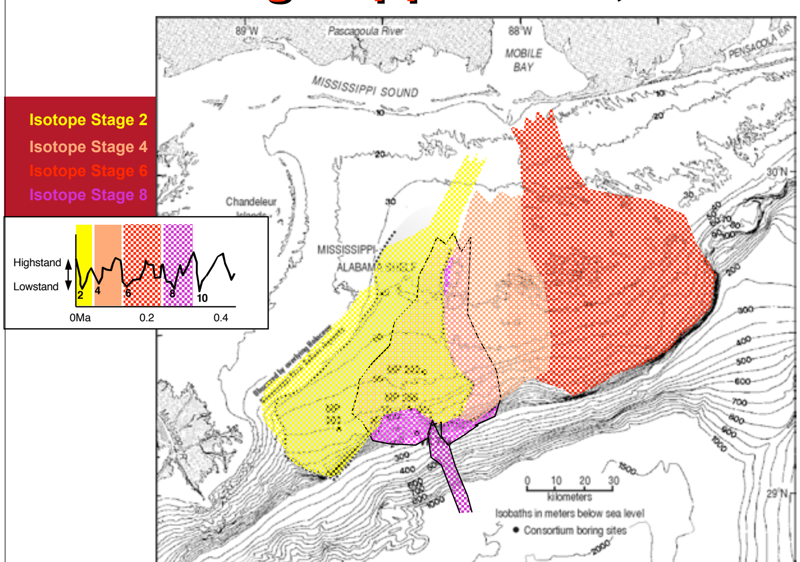
Gulf of Mexico

- Known sea level curve based on oxygen isotope record.



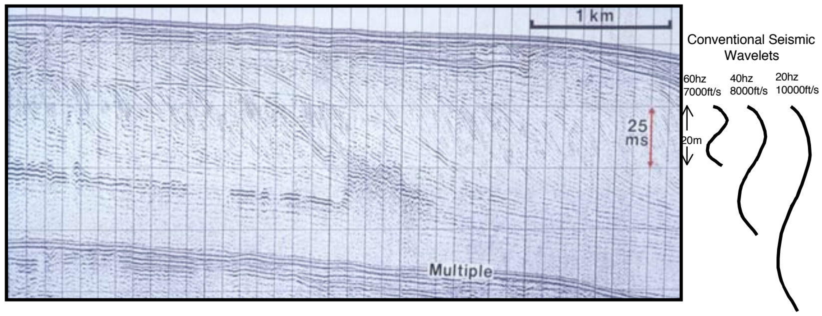
http://gulf.rice.edu/gulfmethods.html.

Lagniappe Delta, GOM



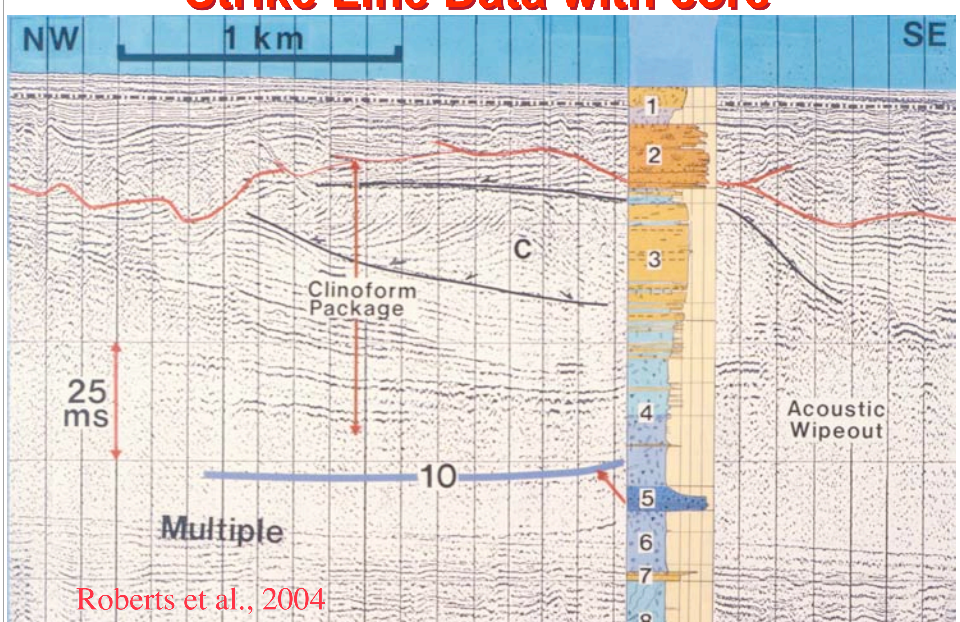
Roberts et al., 2004; Sydow, 2004

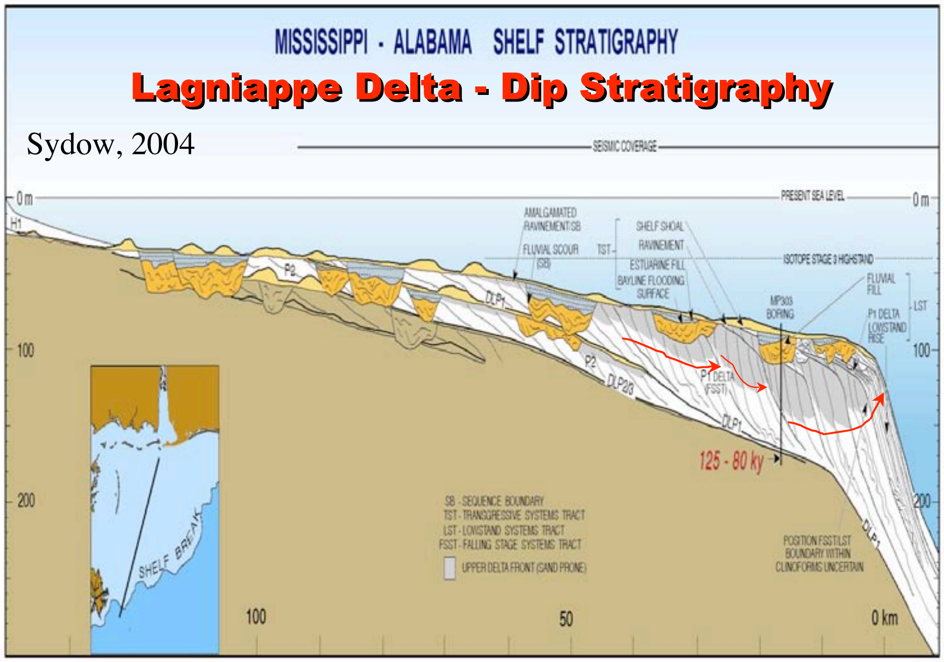
Lagniappe Delta, GOM



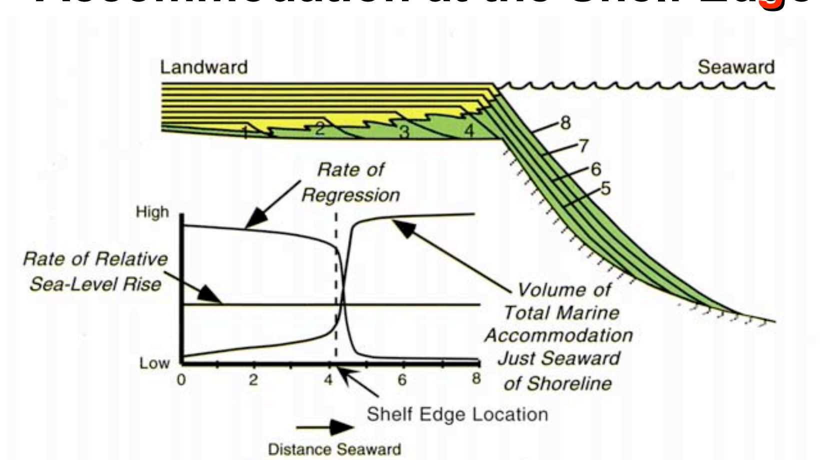
- Stratigraphic datasets calibrated against known sea-level curve.
- Provides high-res view of geometries and lithologic distributions within sequence systems tracts on a siliciclastic shelf
- Bridges the gap between seismic stratigraphy and detailed reality of the rock record
- In Neogene paralic systems 4th to 5th order eustatic and autocyclic (100ky-<1ky) processes are what dominate reservoir stacking patterns and internal architecture at the field scale. Conventional seismic strat is done mainly at the 3rd order (1-2my) scale

Strike Line Data with core



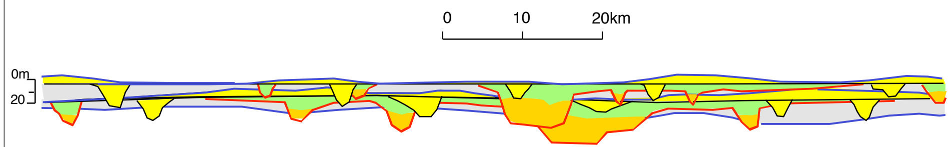


Accommodation at the Shelf Edge



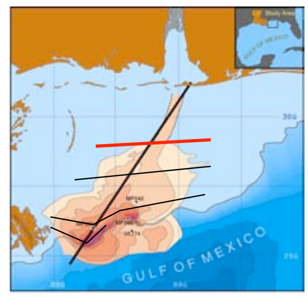
At the shelf edge, accommodation becomes very large and systems can no longer prograde, unless shelf edge is exposed by a sea-level fall (Posamentier and Allen, 1999). Clinoforms will typically steepen toward the shelf edge.

Inner Shelf Geometry

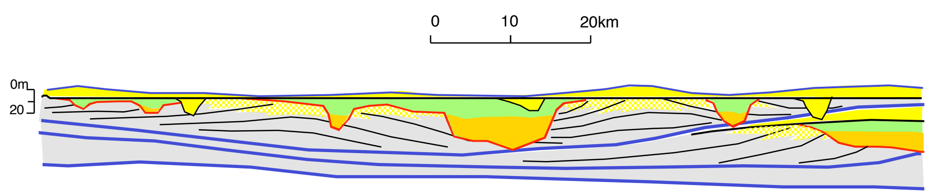


- MFS (~Condensed Section)
- Ravinement
- SB
- Parasequence FS
- transgressive shoals, tidal inlet fills
- estuarine/lagoonal
- fluvial
- delta front ss/shoreface ss
- prodelta/delta-front/offshore sh

Sydow, 2004

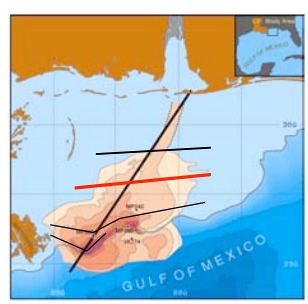


Middle Shelf Geometry

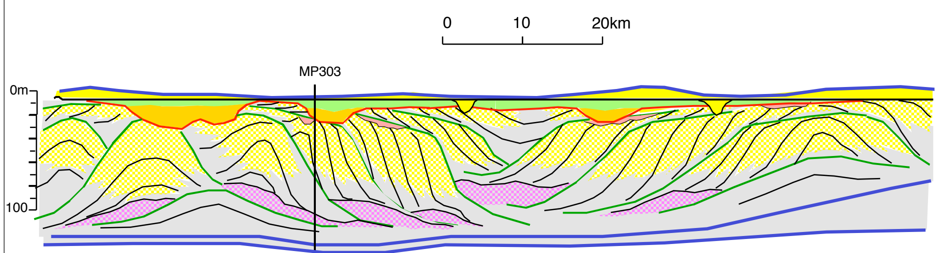


- MFS (~Condensed Section)
- Ravinement
- SB
- Parasequence FS
- transgressive shoals, tidal inlet fills
- estuarine/lagoonal
- fluvial
- delta front ss/shoreface ss
- prodelta/delta-front/offshore sh

Sydow, 2004

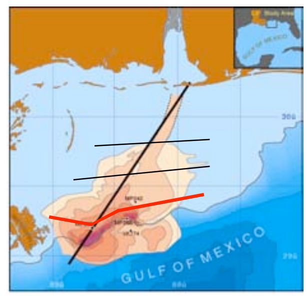


Outer Shelf Geometry

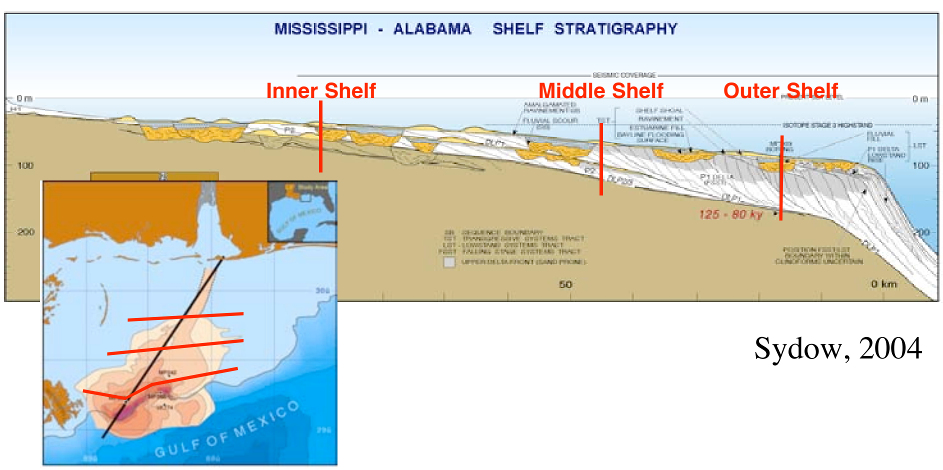


- MFS (~Condensed Section)
- Ravinement
- SB
- Parasequence FS
- transgressive shoals, tidal inlet fills
- estuarine/lagoonal
- fluvial
- distributary channel
- delta front ss/shoreface ss
- prodelta/delta-front/offshore sh
- MTC (slump, debris flow)

Sydow, 2004

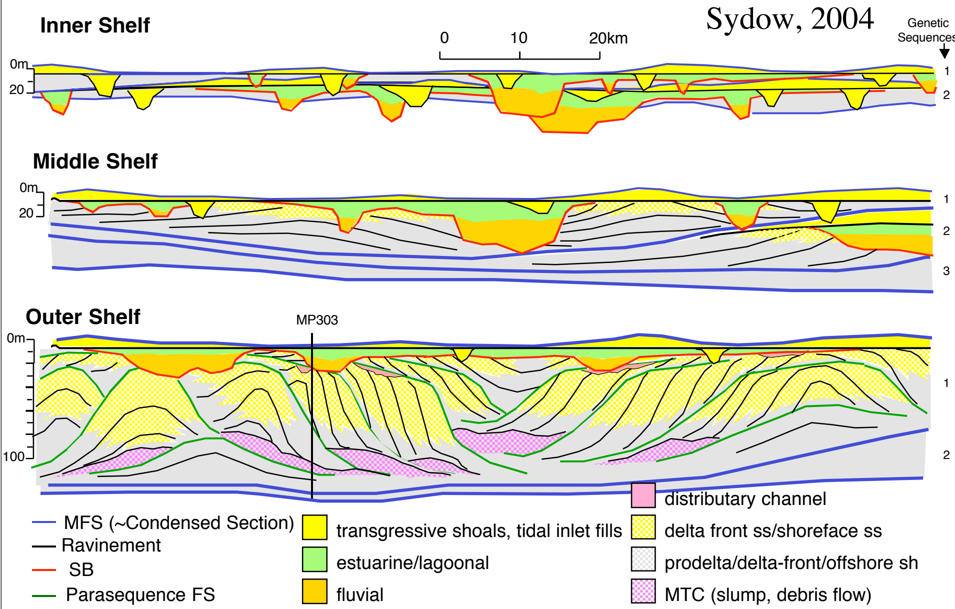


Dip Stratigraphy



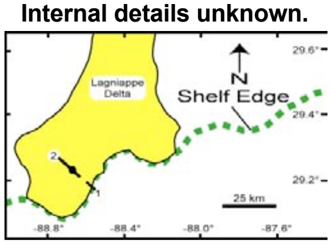
Sydow, 2004

Sequence Expression Inner to Outer Shelf

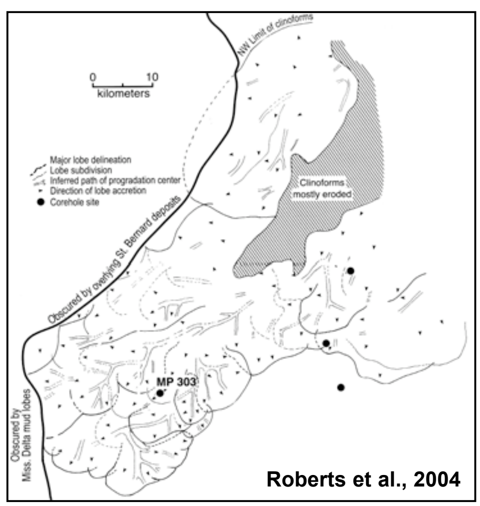


2D Seismic Plan-view Mapping of Distributary Channels in the Lagniappe Delta

2D seismic reveals general delta lobe shape. Internal details unknown.

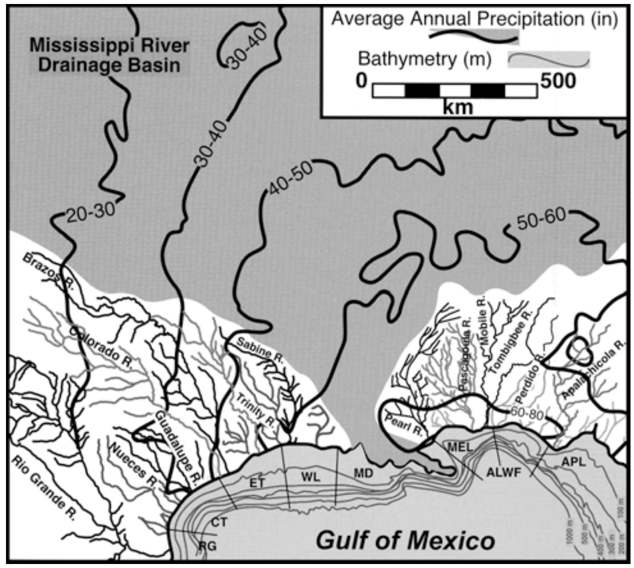


Detailed high-resolution seismic mapping reveals higher-order distributary channels within the delta lobe.



Gulf of Mexico

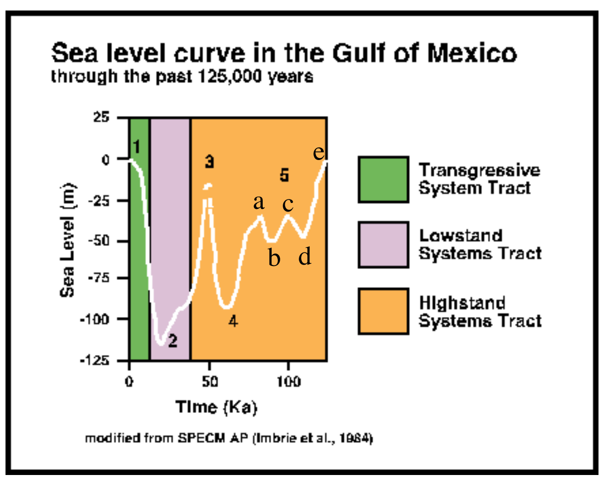
- Climate gradient in the Gulf of Mexico.
- Differences in rainfall and drainage basin areas allow contrast of seuence development in high versus low sediment supply systems given a known sea-level history.
- Also some differences in shelf width.



From Anderson et al., 2004

Gulf of Mexico

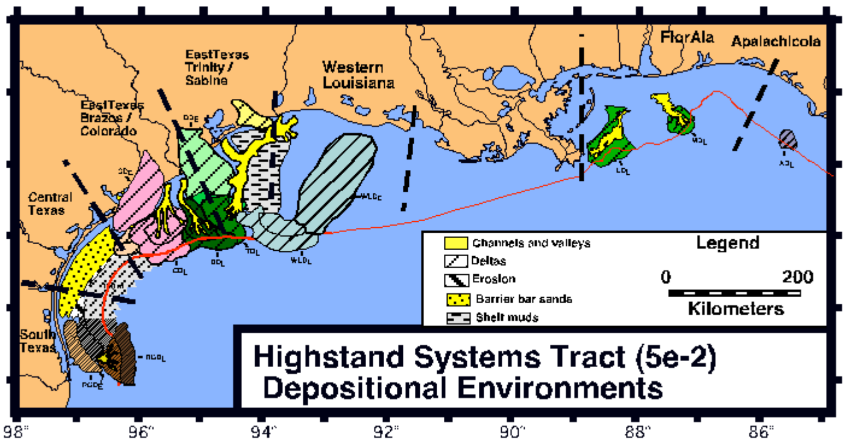
- Known sea level curve based on oxygen isotope record.



http://gulf.rice.edu/gulfmethods.html.

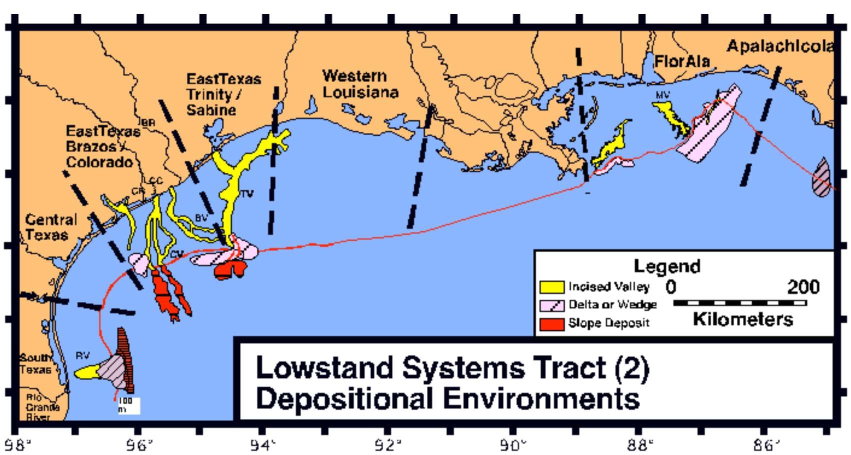
Gulf of Mexico

- Sea level change.



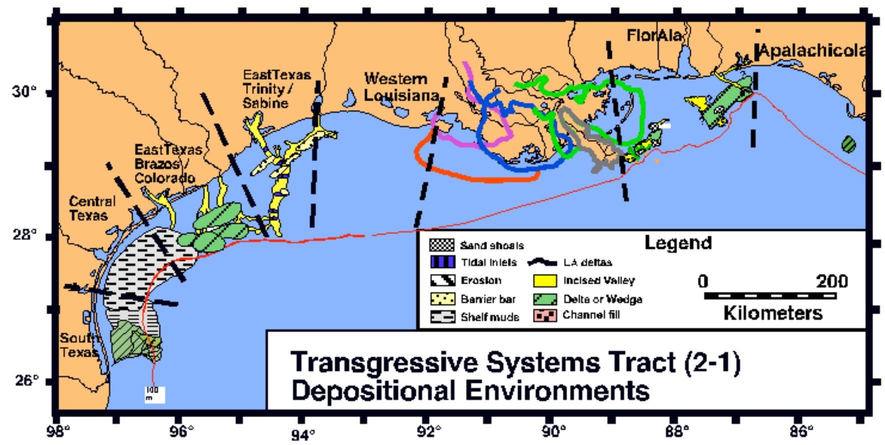
Gulf of Mexico

- Sea level change.

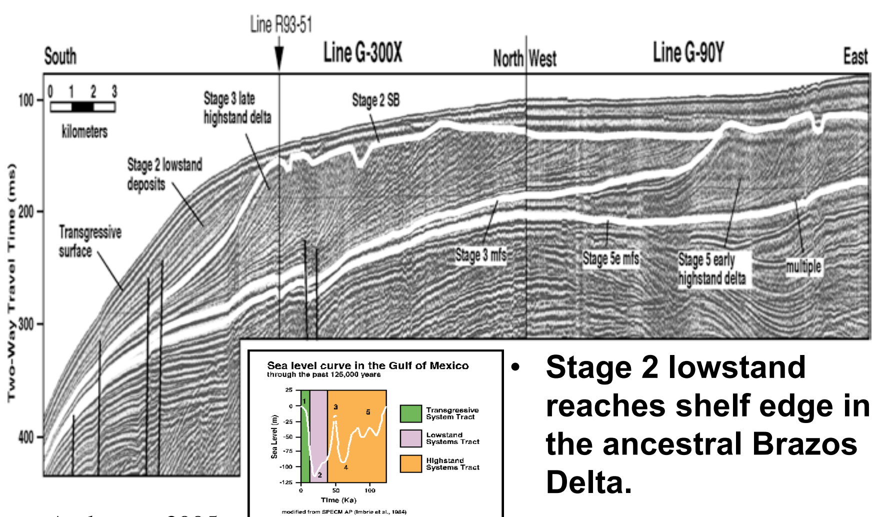


Gulf of Mexico

- Sea level change.



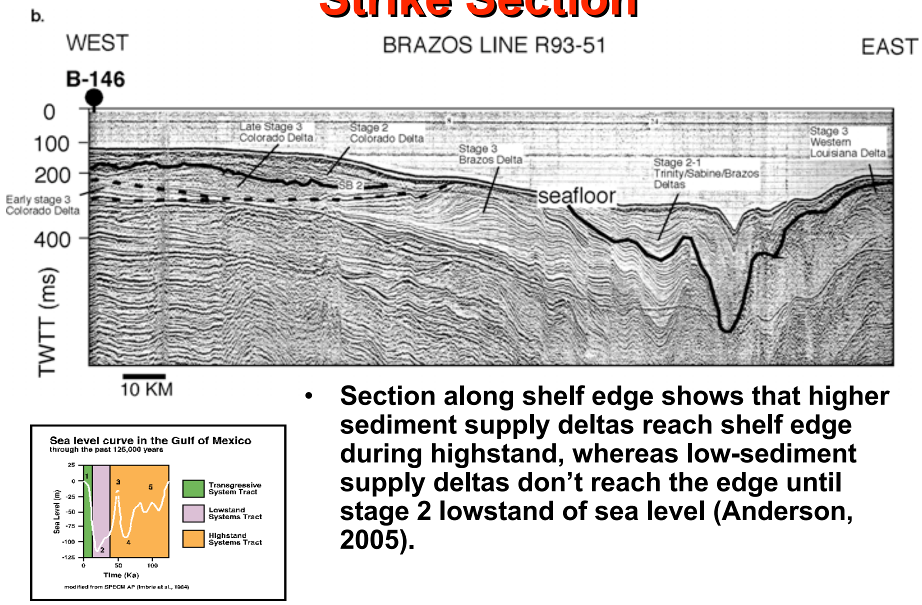
Brazos Lowstand



- Stage 2 lowstand reaches shelf edge in the ancestral Brazos Delta.

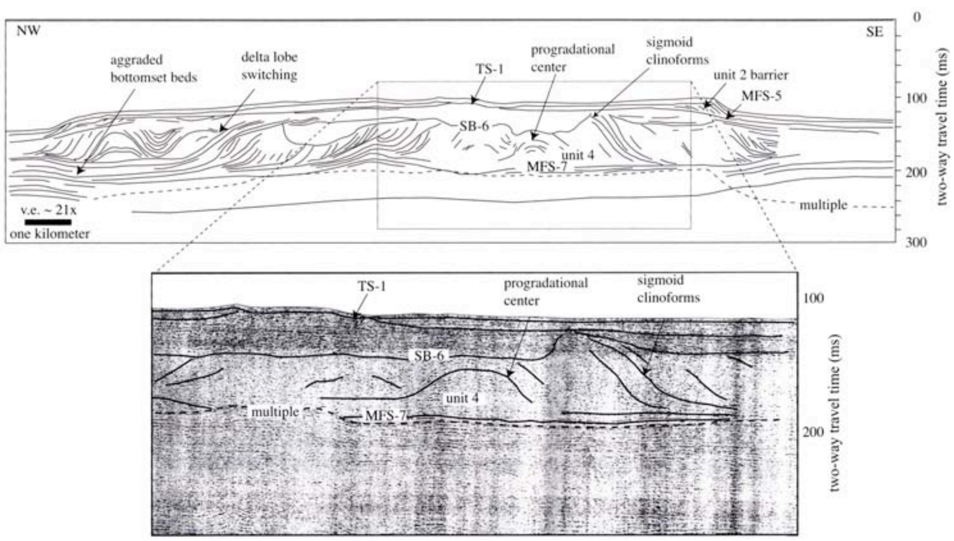
Anderson, 2005

Strike Section



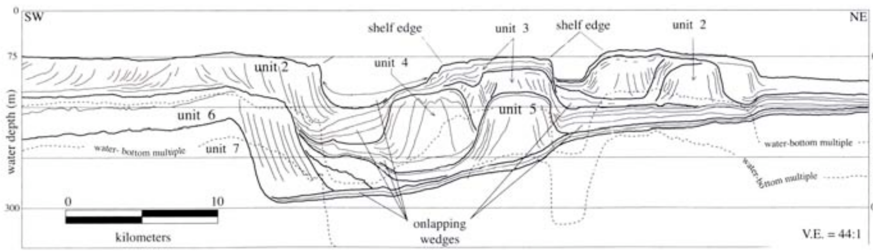
- Section along shelf edge shows that higher sediment supply deltas reach shelf edge during highstand, whereas low-sediment supply deltas don't reach the edge until stage 2 lowstand of sea level (Anderson, 2005).

Outer Shelf Geometry



Appalachicola Delta (McKeown et al., 2004)

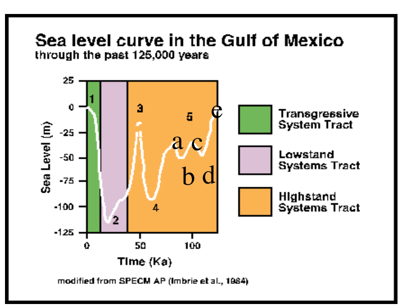
Strike Shelf Geometry

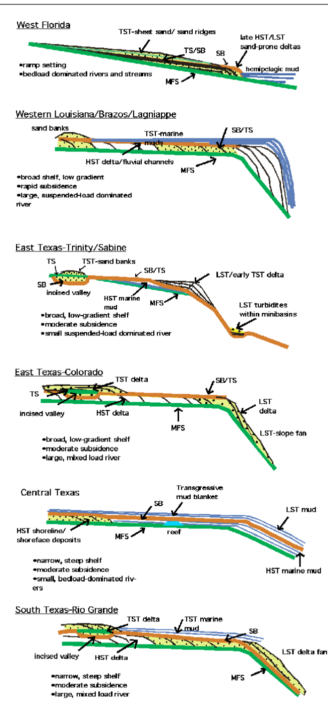


Pensacola Shelf, Florida (Bart and Anderson, 2004

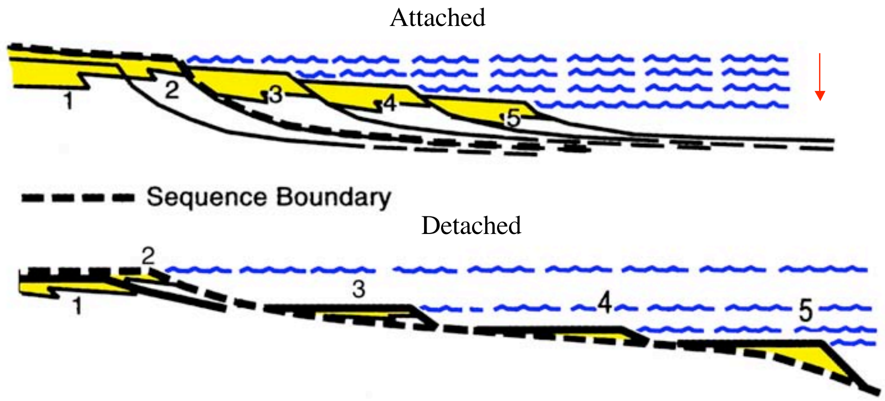
Gulf of Mexico

- Slug diagrams along the coast illustrate differing timing and geometries of sequences primarily controlled by sediment supply (Anderson et al., 2004)



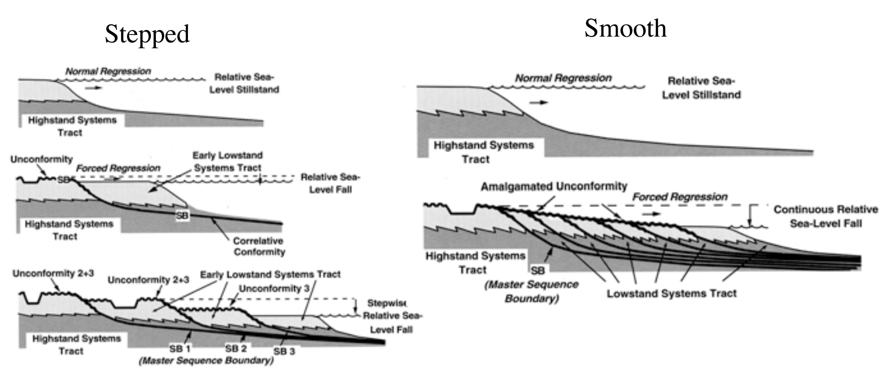


Attached versus Detached Forced Regressions



Related to the ability of shoreline sediments to keep pace with decreasing accommodation during fall (from Posamentier and Allen, 1999)

Sedimentological expression of forced regression



(from Posamentier and Allen, 1999)

Experimental forced regression

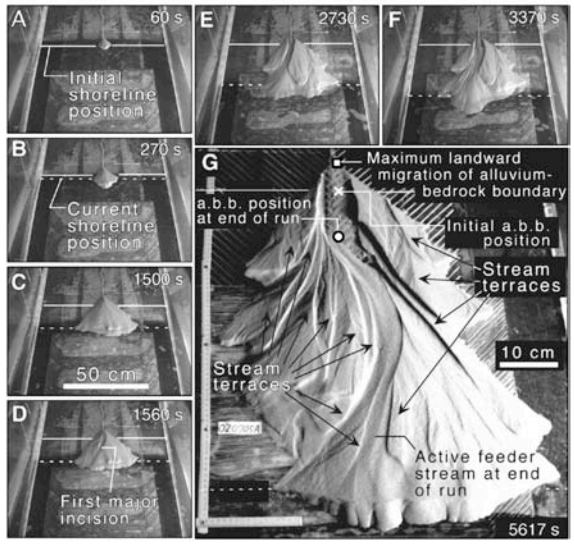
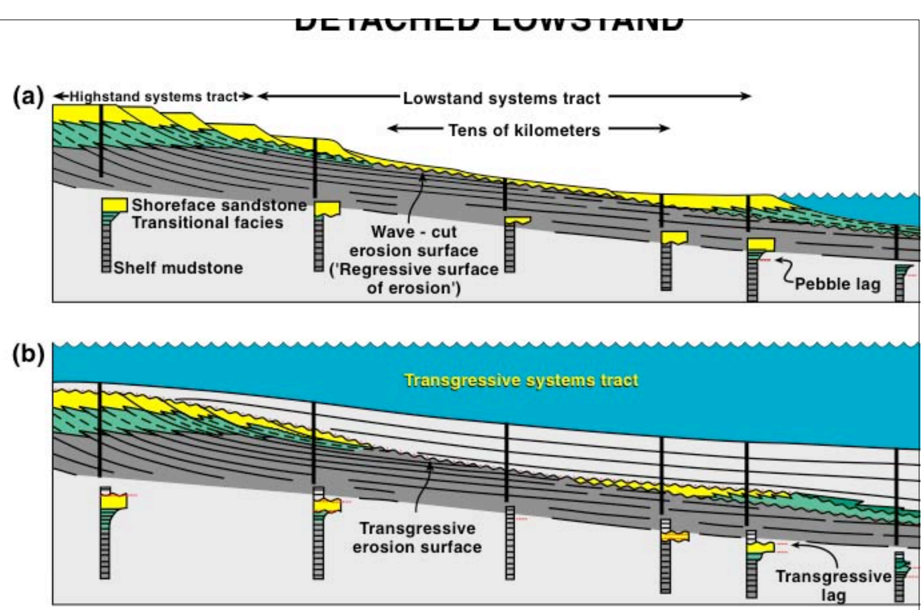


Figure 1. Photographs of evolving fluvial delta in representative run. Time from beginning of run is indicated in A–G. In spite of steady forcing (rate of relative sea-level fall, A = constant < 0, sediment discharge q_s = constant, water discharge q_w = constant), note that depositional system aggraded in early stages of development (A–C), but sudden major incision then occurred (D), after which delta never recovered its original valley-free geometry (E–G). Instead, numerous paired stream terraces formed along valley. See text for conditions of run. a.b.b.—alluvium-bedrock boundary.

- But stepped trajectory may be produced by continuous fall (see papers on autostepping, Muto and Steel, 2004)

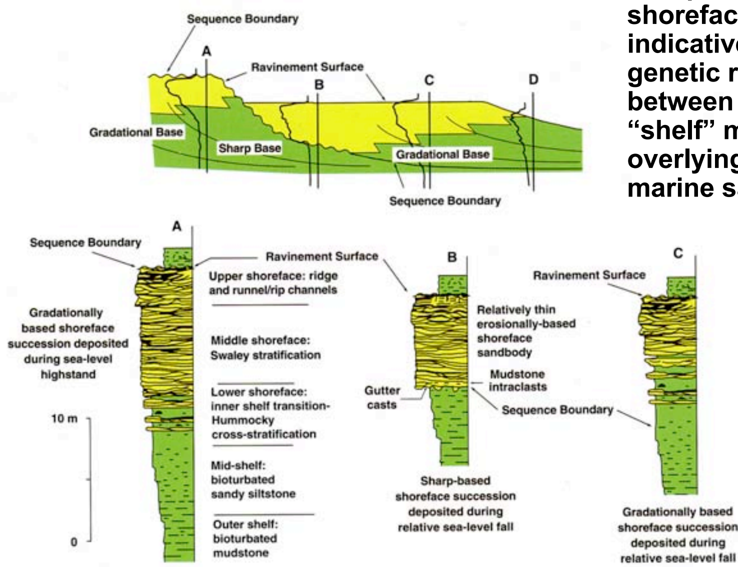
DETACHED LOWSTAND



After Plint and Walker (19

Sedimentological expression of forced regression

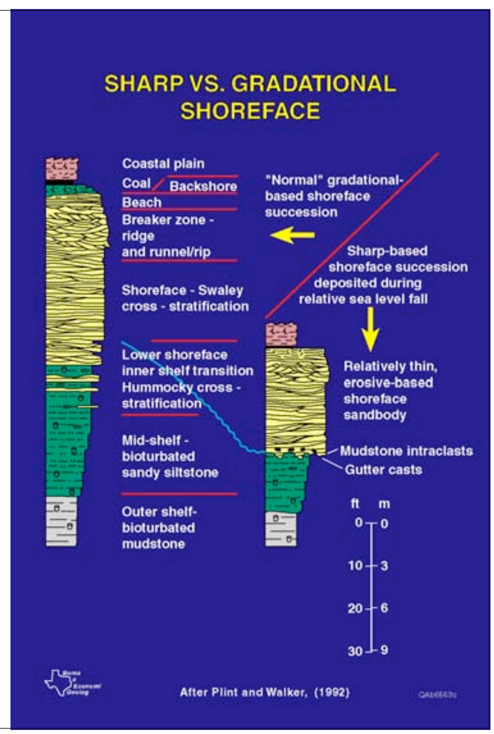
- Sharp-based shorefaces seen as indicative of non-genetic relationship between underlying "shelf" mudstone and overlying shallow-marine sandstone.



(from Posamentier and Allen, 199 after Walker and Plint, 1992)

Sedimentological expression of forced regression

- Sharp-based shorefaces seen as indicative of non-genetic relationship between underlying "shelf" mudstone and overlying shallow-marine sndstone



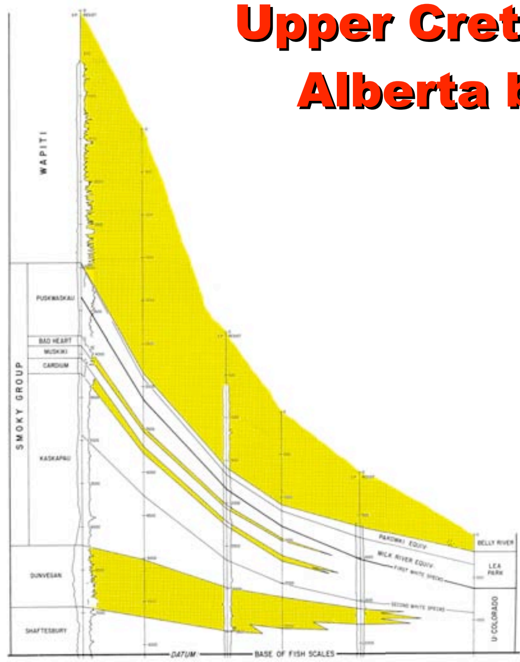
Correlation of the Chungo - Milk River

A tale of missed datums

Problem

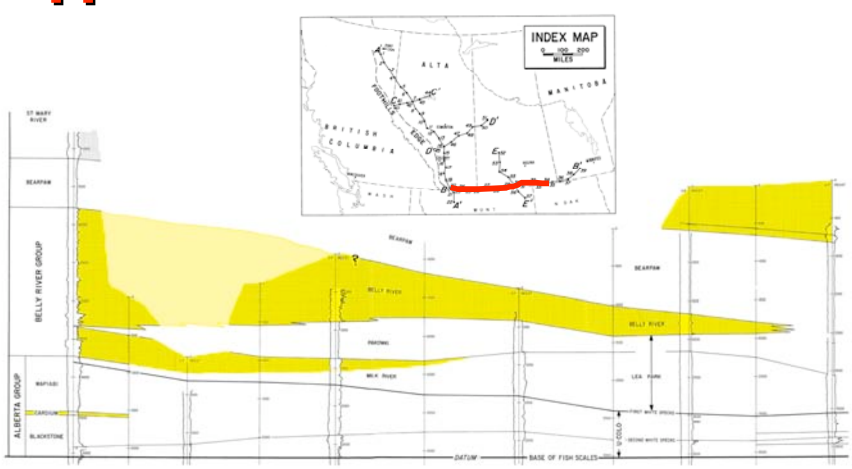
- Chungo - Milk River sandstones form the "first parasequences" below the Belly River Formation (equivalent to the Mesaverde).
- Lithostratigraphically thought to be the same unit.
- Are they?

Upper Cretaceous Alberta basin



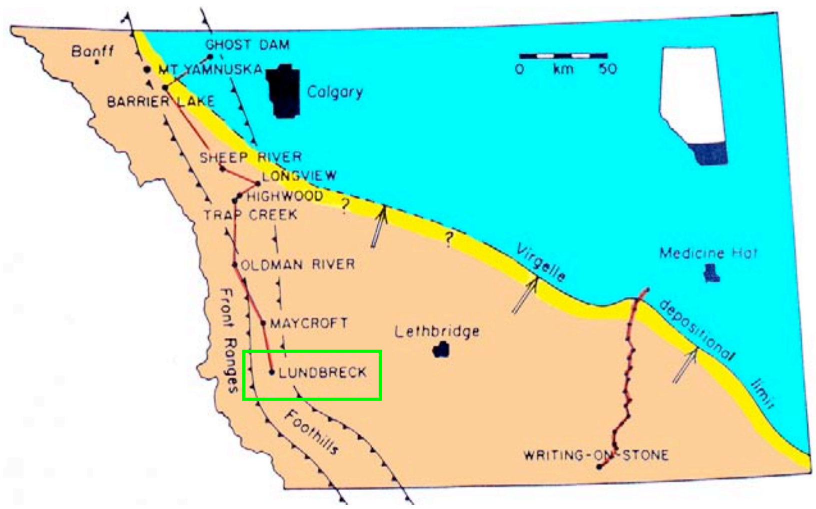
Several major prograding wedges prograde into a muddier section (modified after Williams and Burk, 1964).

Upper Cretaceous Alberta basin

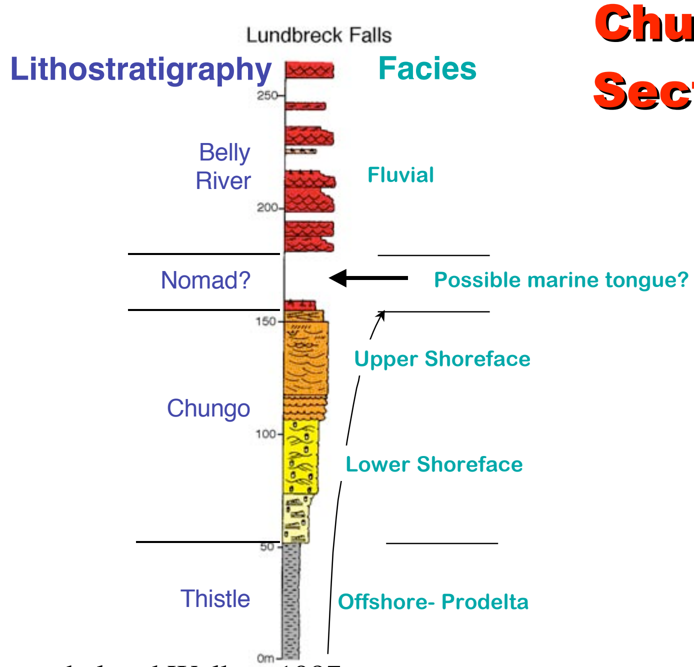


Several major prograding wedges prograde into a muddier section. Lower tongues more difficult to distingish landward (modified after Williams and Burk, 1964).

Base Map

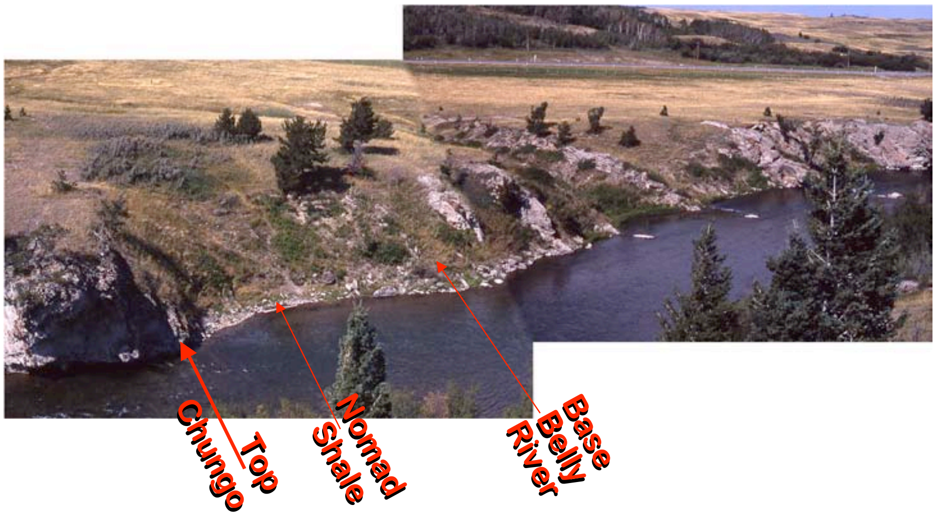


Chungo Section



Rosenthal and Walker, 1987

Outcrop of Chungo - Nomad - Belly River at Lundbreck Falls



Chungo Delta/Shoreface

Upward coarsening "shoreface" or delta front?

Chungo Prodelta

Section begins with thin to medium bedded sandstones and mudstones.

Chungo Prodelta

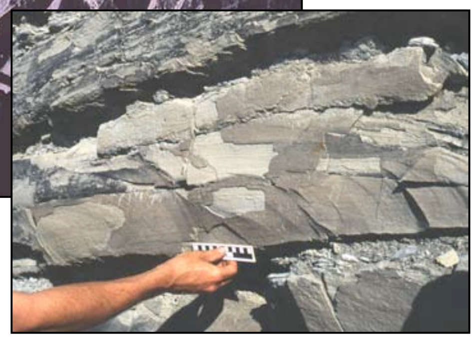
Thin bedded, lightly burrowed, with ripple cross lamination. Ripple formes suggest combined flows (wave + unidirectional).

Chungo Prodelta

Straight-crested, asymmetrical ripples suggest combined flows.

Chungo Delta Front

Soft-sediment deformation suggests rapid sedimentation.

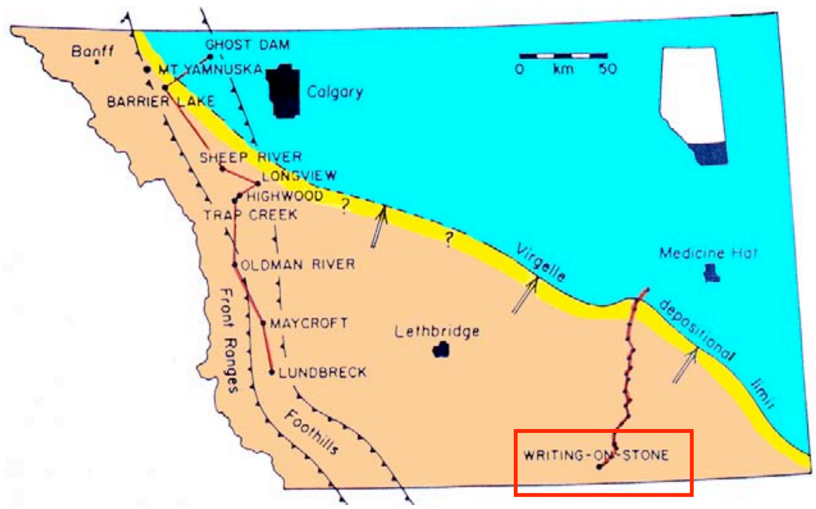


HCS suggests storms. Note lack of burrowing suggesting fluvial influence.

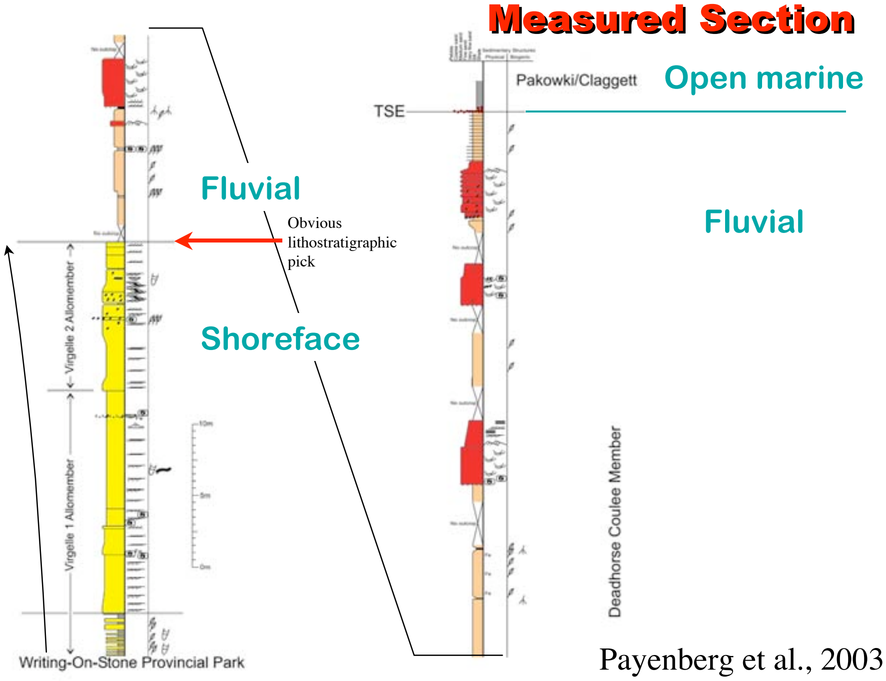
Chungo Delta Front

Large-scale cross strata in upper shoreface-delta top

Base Map

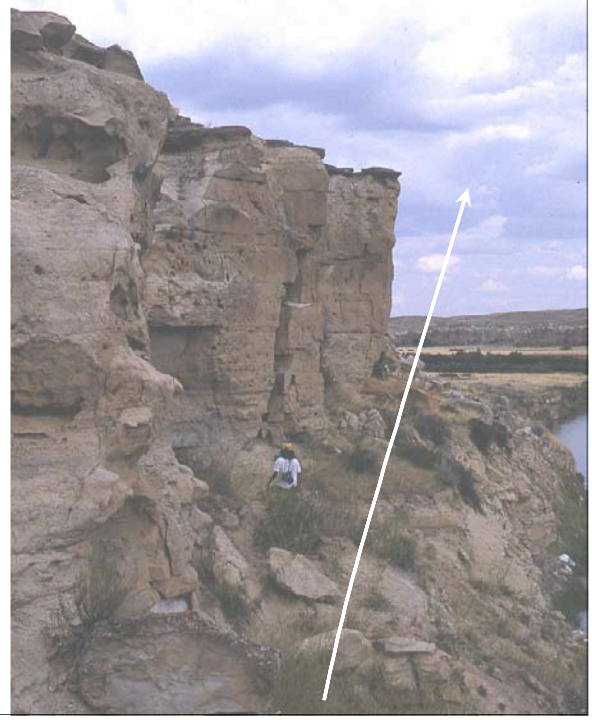


Measured Section



Payenberg et al., 2003

Milk River at "Writing on Stone"

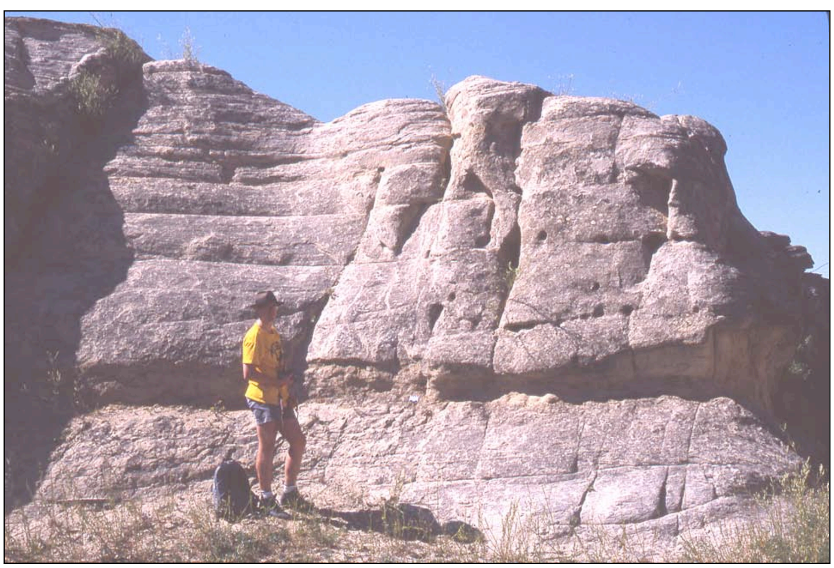


Base Milk River

Bioturbated, black mudstones suggest marine shelf. Mudstones grade into sandstones.

Milk River - HCS

Milk River - Shoreface sst.

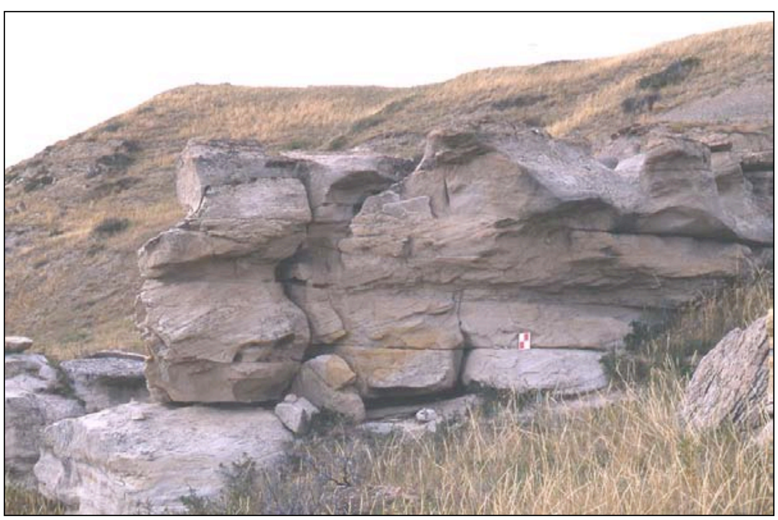


Milk River - Shoreface sst.

Ophiomorpha burrowed sandstones.

Rosellia

Milk River - Shoreface sst.



Landward directed cross-bedding interpreted as a tidal ramp.

Milk River - Non Marine

Poorly exposed muddy strata above shoreface.

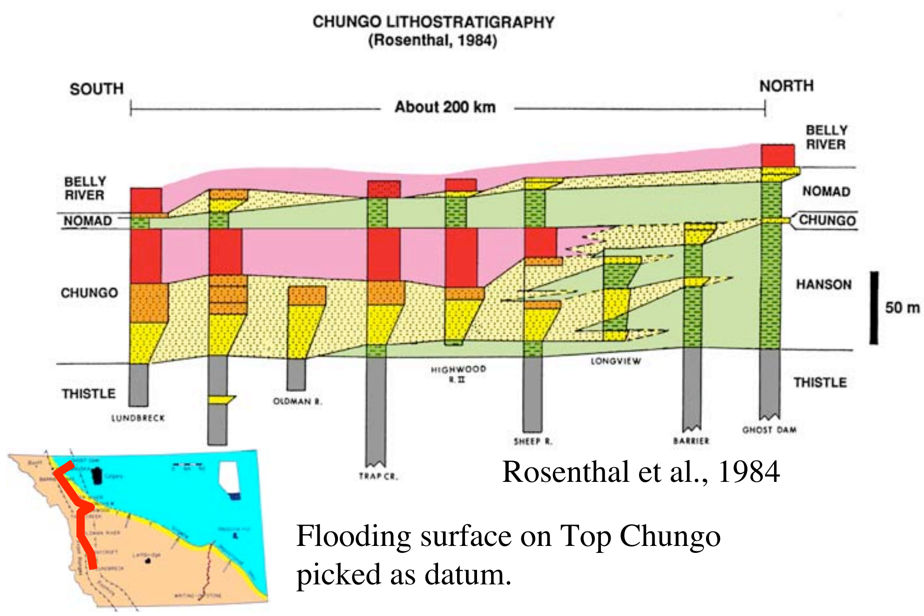
Milk River - Non Marine

Coal - (photo from Payenberg et al., 2003).

Milk River - Non Marine

Fluvial valleys cutting top of shoreface (photo from Payenberg et al., 2003).

Lithostratigraphic Correlations

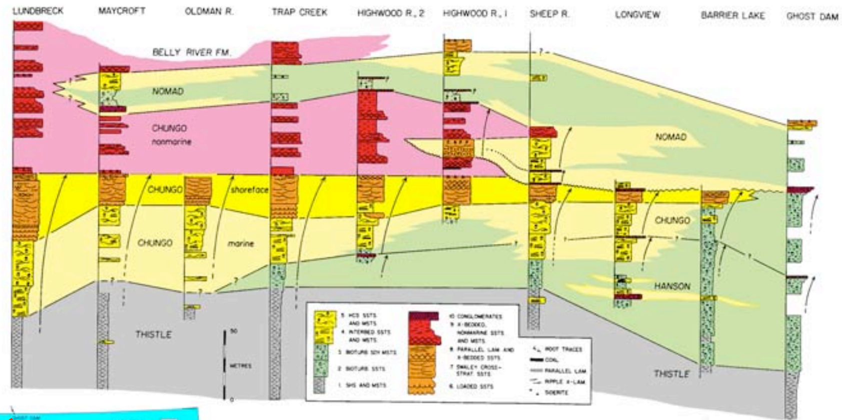


Rosenthal et al., 1984

Flooding surface on Top Chungo picked as datum.

Lithostratigraphic Correlations

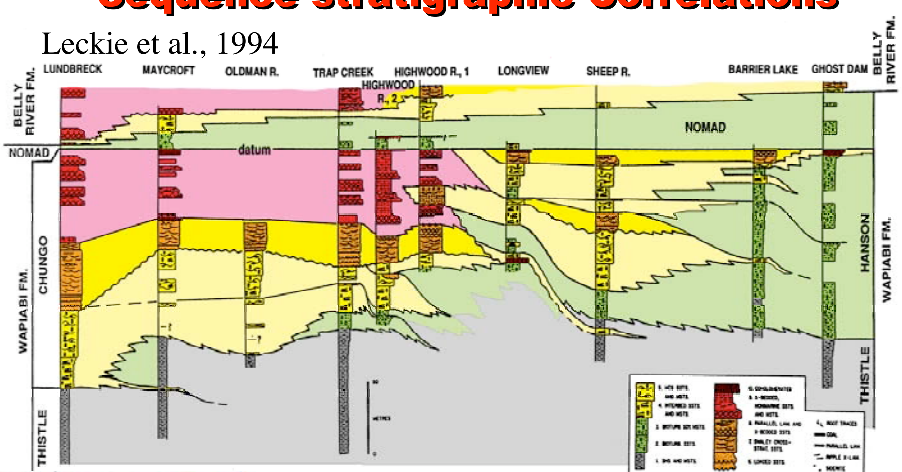
Rosenthal and Walker, 1987



Top Chungo shoreface picked as datum.

Sequence stratigraphic Correlations

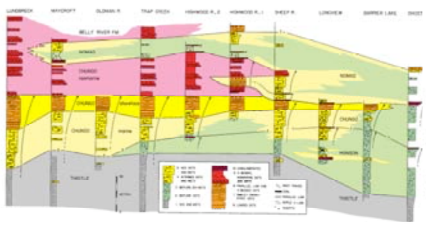
Leckie et al., 1994

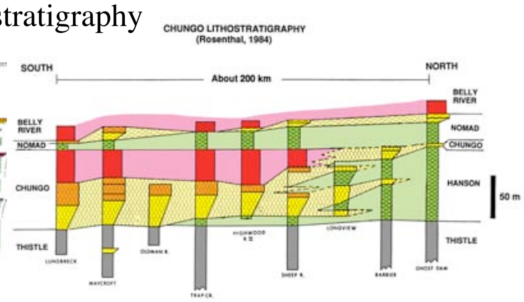


Flooding surface on Top Chungo again picked as datum. Note offlap.

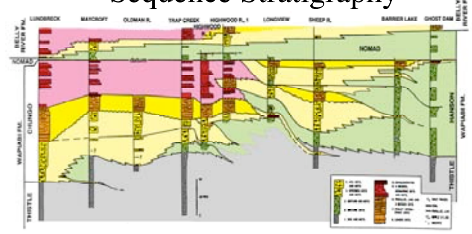
Alternate Correlations

Lithostratigraphy



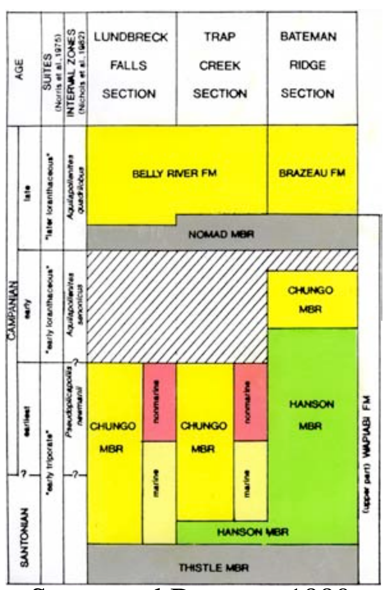


Sequence Stratigraphy



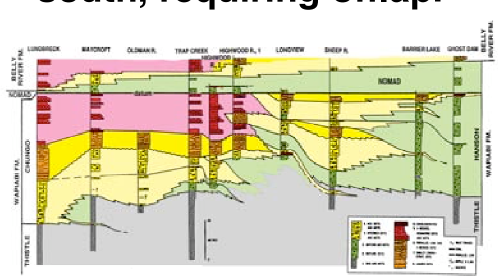
Which is correct?

Biostratigraphy

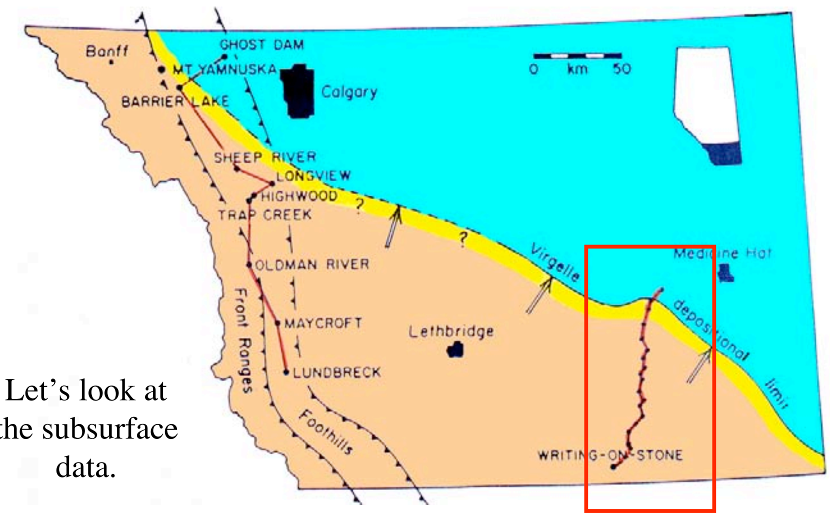


Sweet and Braman, 1990

- Chungo strata to the north are younger than Chungo in the south.
- Significant unconformity is measured in the south, requiring offlap.

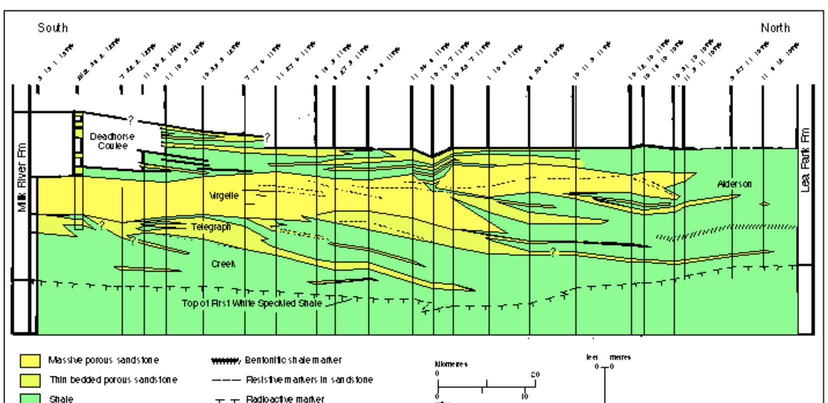


Base Map



Let's look at the subsurface data.

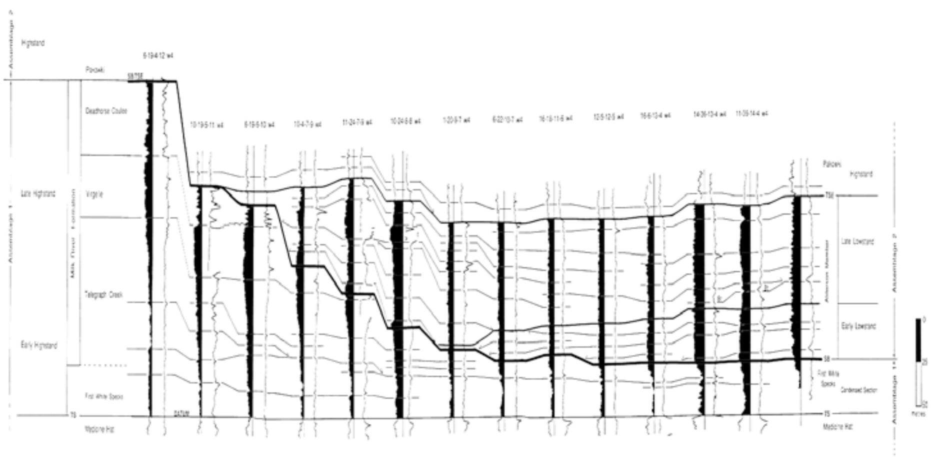
Subsurface Correlations



From Meijer Drees and Myhr, 1981

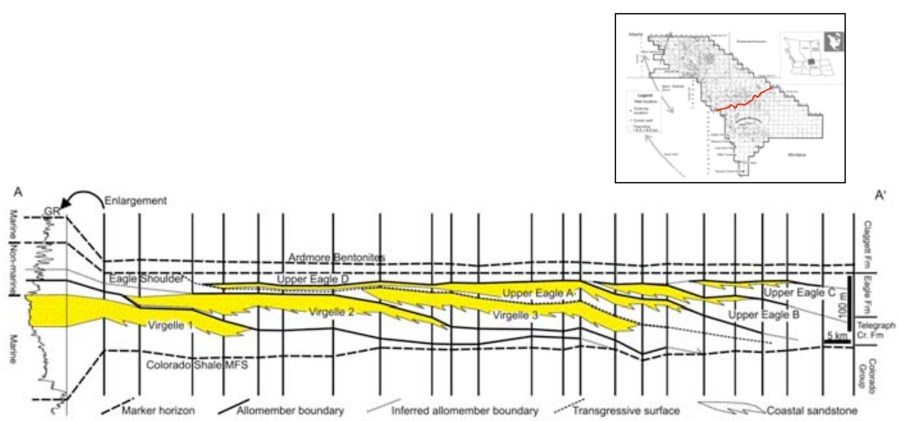
Subsurface correlations suggest offlap.

Subsurface Correlations



Subsurface correlations also show significant younging and offlap (O'Connell et al., 1989).

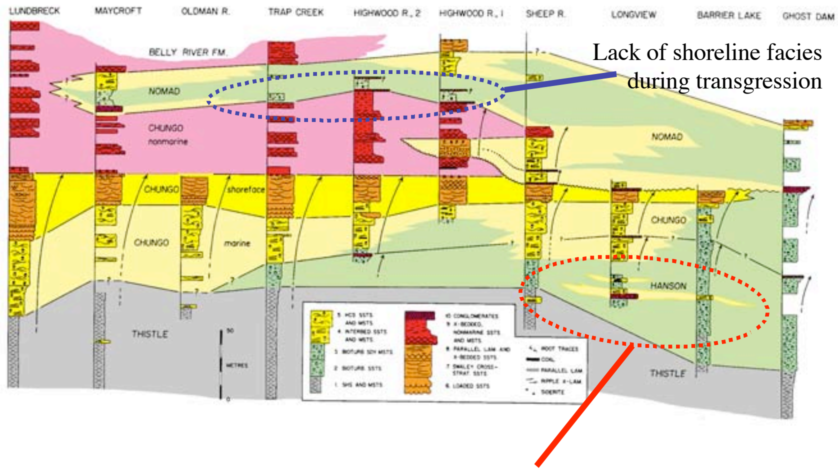
Subsurface Correlations



Subsurface correlations in Montana equivalents also show significant younging and offlap (Payenberg et al., 2003).

Lithostratigraphic Correlations

Rosenthal and Walker, 1987



Consequence of picking lithostratigraphic datum

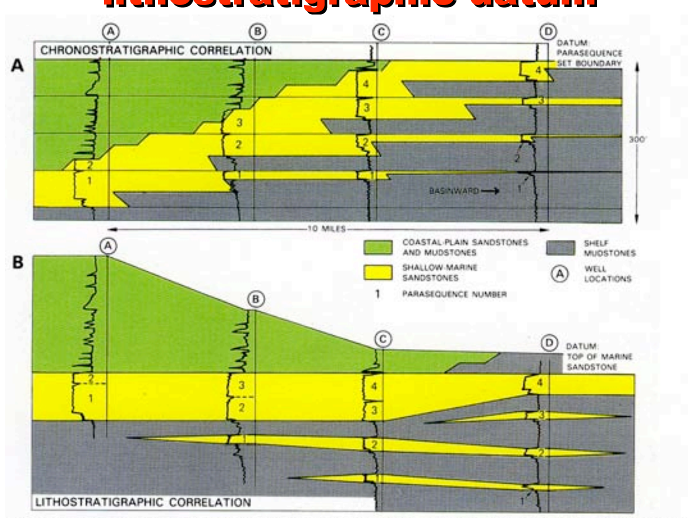
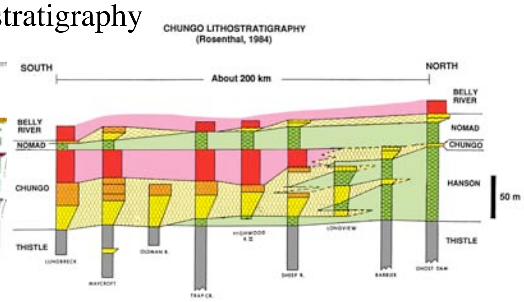


Figure 17—Comparison of (A) chronostratigraphic correlation and (B) lithostratigraphic correlation styles: progradational parasequence set.

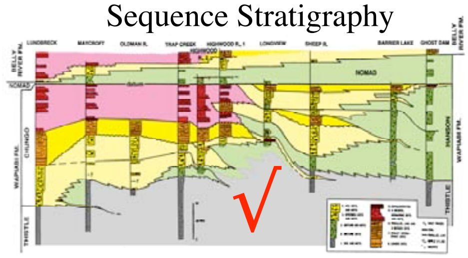
Van Wagoner et al., 1990

Alternate Correlations

Lithostratigraphy



Sequence Stratigraphy



Which is correct?

Conclusions

- Essential to pick the correct datum
- Must honor biostratigraphy
- Prograding shallow marine systems commonly offlap and young seaward.

212

Top-Truncated Deltas in a Sequence Stratigraphic Framework

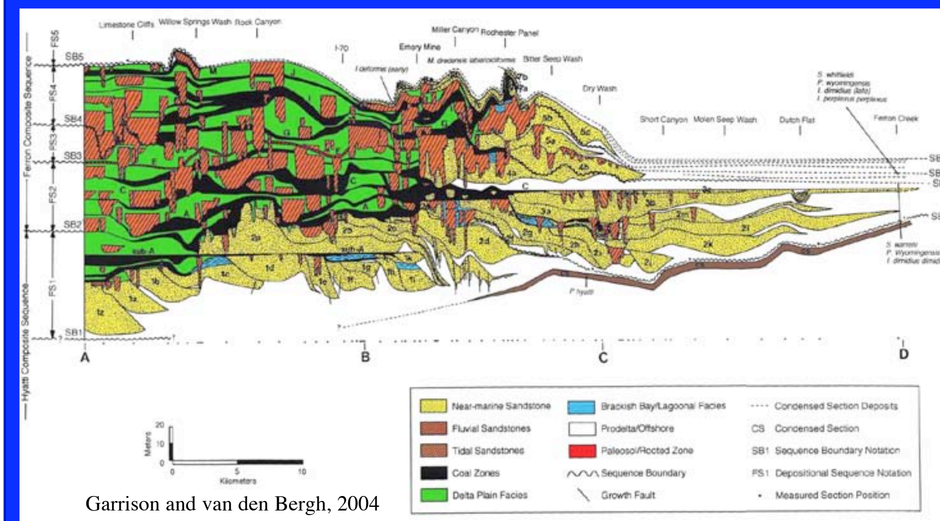
Janok P. Bhattacharya
M. Royhan Gani
Charles D. Howell
Cornel Olariu
Brian J. Willis

The Cretaceous laboratory

- Contain numerous examples of deltaic facies successions and facies architecture, both top-truncated and topset-preserved.

Topset Preserved Delta

- Ferron delta, Utah.

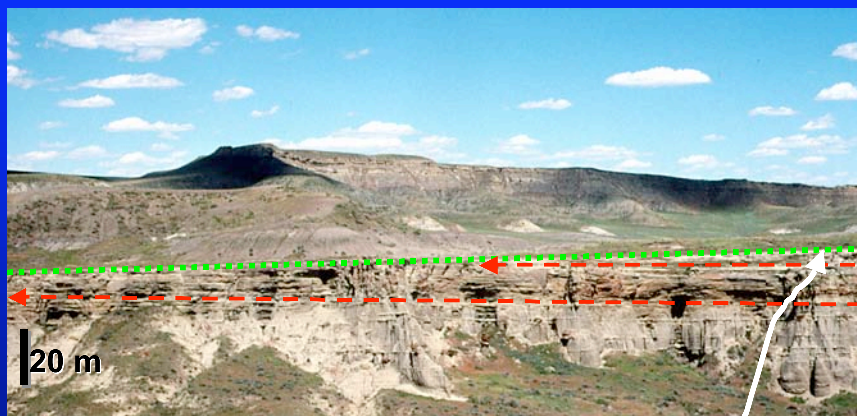


Garrison and van den Bergh, 2004

Topset Preserved Deltas

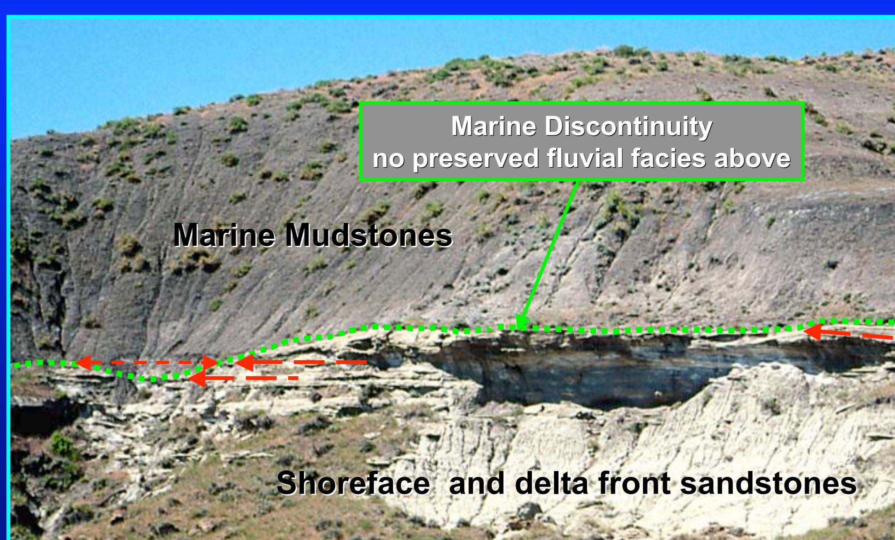
- Ferron delta, Utah.

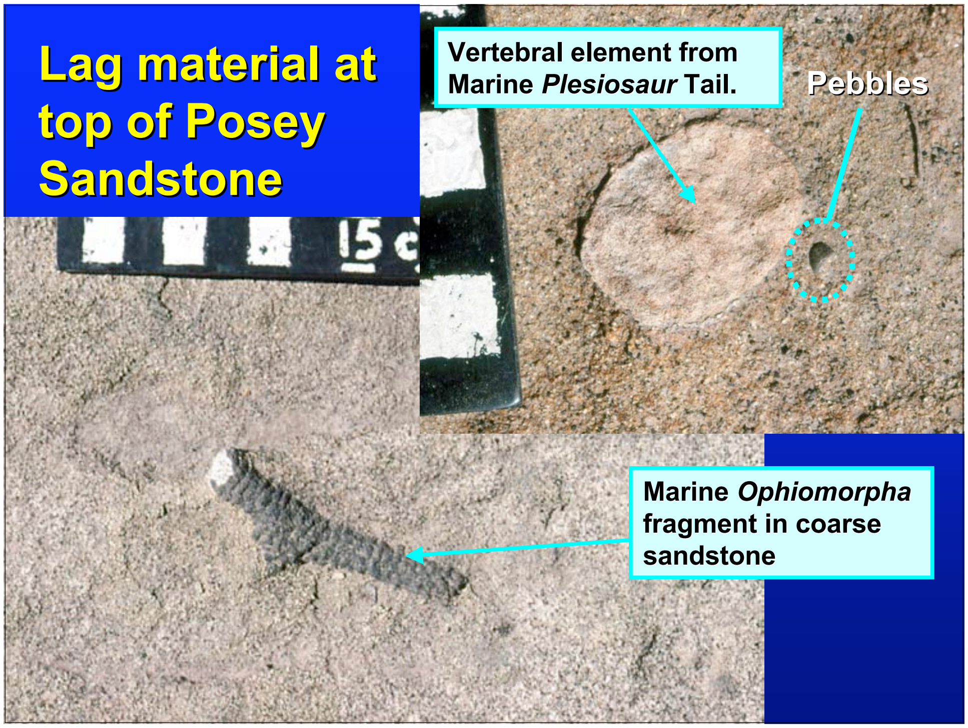
Top-truncated sandstones



- Gradationally-based, top-truncated upward-coarsening delta-front.
- Posey Allomember, Frontier Formation, Powder River Basin, Wyoming.

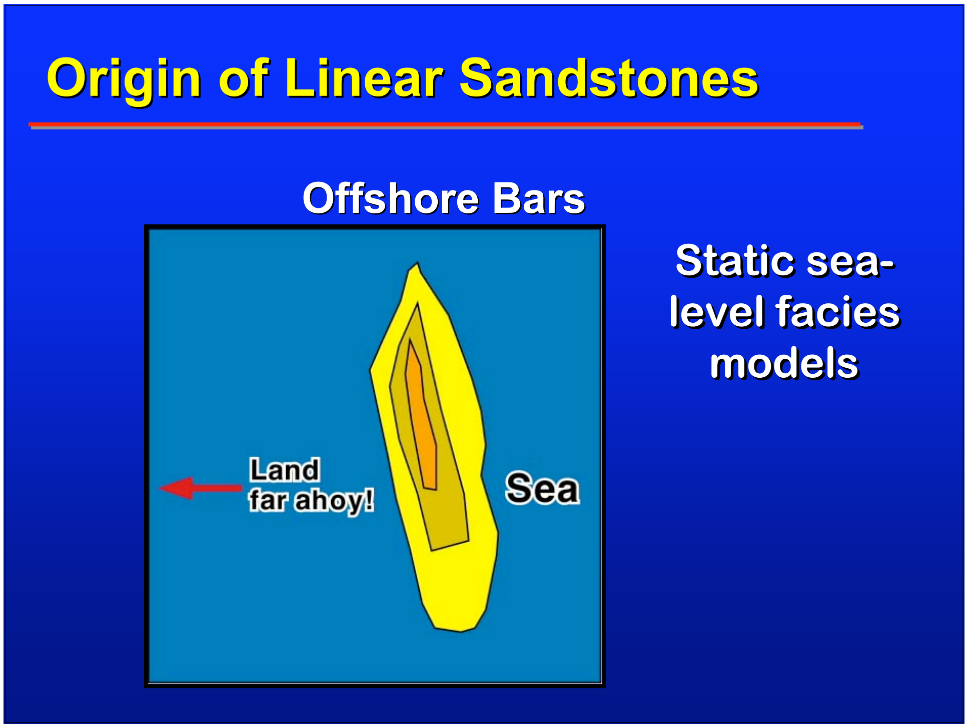
Posey Sandstone - Frontier Fm.

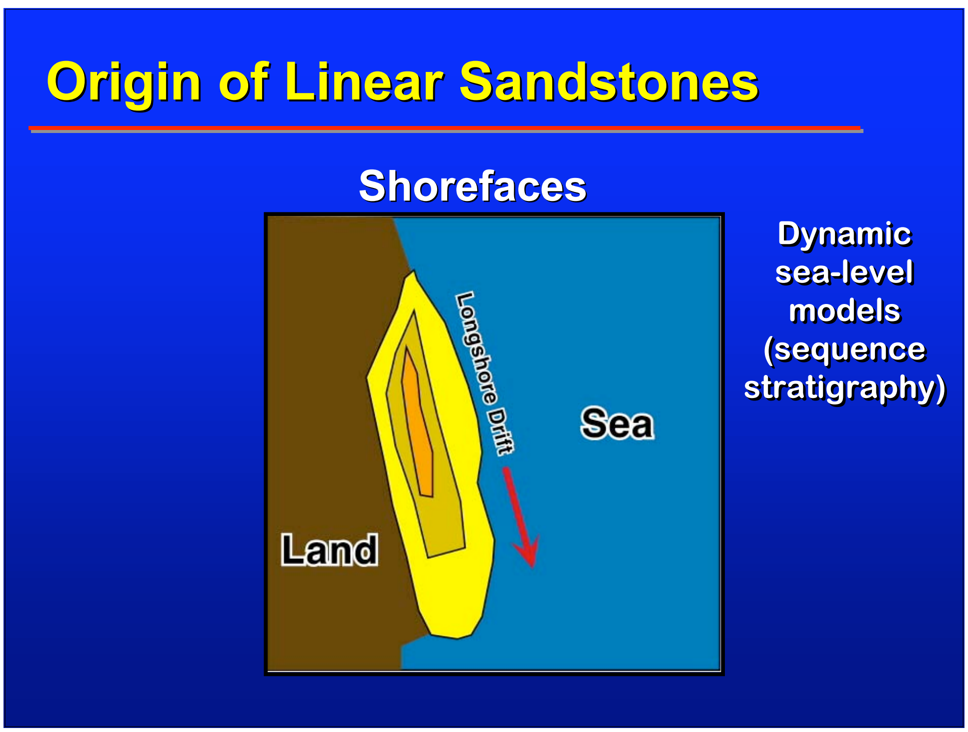


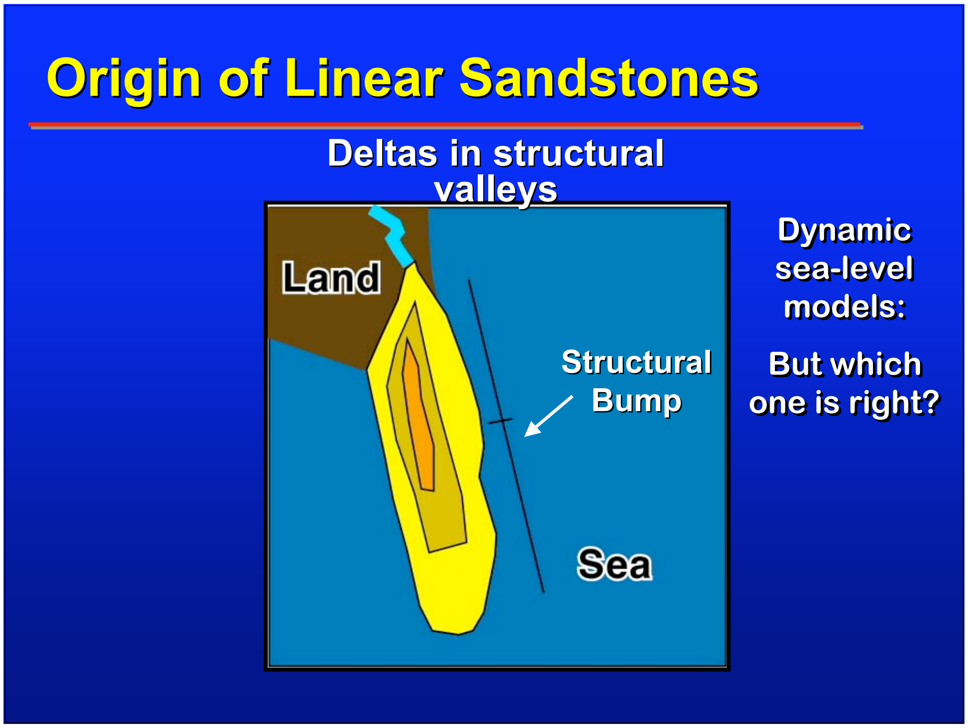


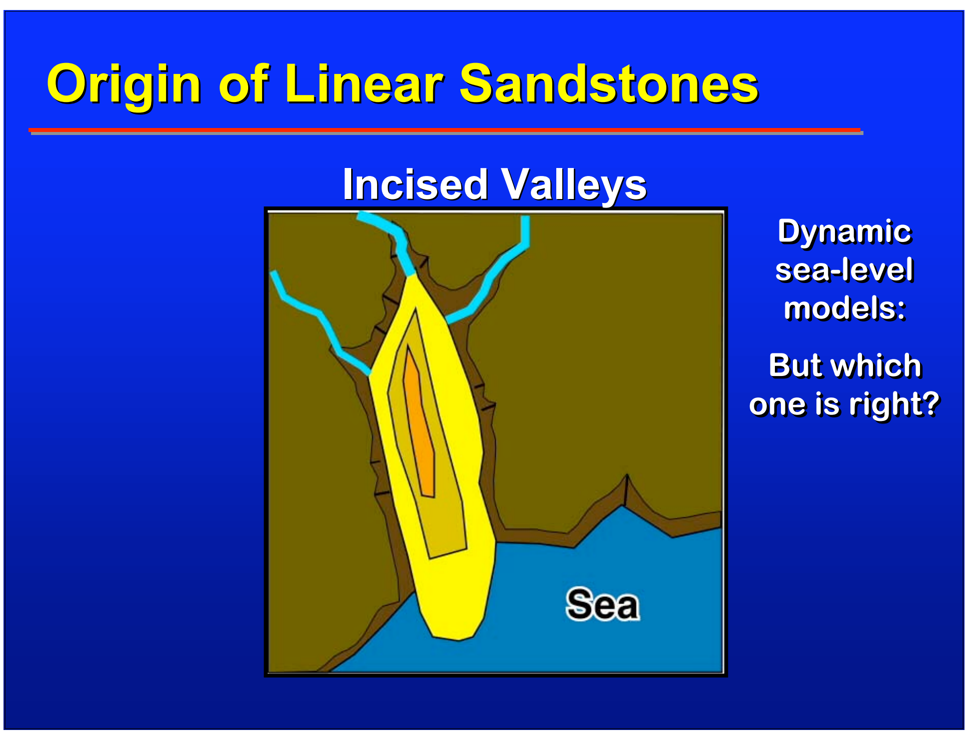
Problem

- The Cretaceous Interior Seaway remains at the center of debates about origin of elongate "shelf" sandstones encased in marine shales.
  - Lack of overlying non-marine facies led many away form a deltaic interpretation.
- Mutually exclusive interpretations.
- How are disparate interpretations resolved?

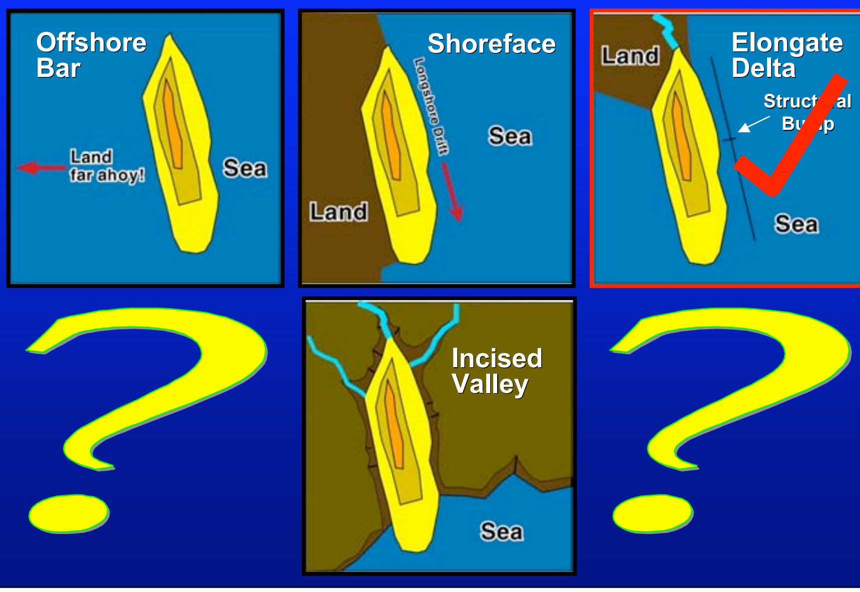

Origin of Linear Sandstones
Offshore Bars
Static sea-level facies models
Land far ahoy!
Sea


Origin of Linear Sandstones
Shorefaces
Dynamic sea-level models (sequence stratigraphy)
Longshore Drift
Sea
Land


Origin of Linear Sandstones
Deltas in structural valleys
Land
Structural Bump
Sea
Dynamic sea-level models:
But which one is right?


Origin of Linear Sandstones
Incised Valleys
Sea
Dynamic sea-level models:
But which one is right?

Origin of Linear Sandstones

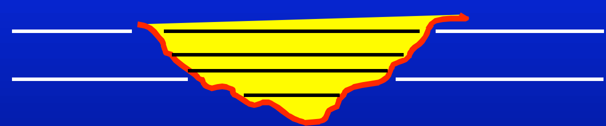


Types of Valleys

- River Valleys (incised)
- Subaerial Rift valleys (structurally-controlled).
- Subaqueous valleys (seascapes)
  - Not all valleys need be incised

Types of Valleys

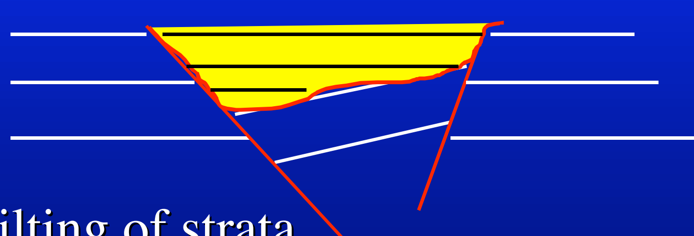
- Incised valleys caused by sea level falls commonly do not produce angular unconformities.
  - They produce disconformities



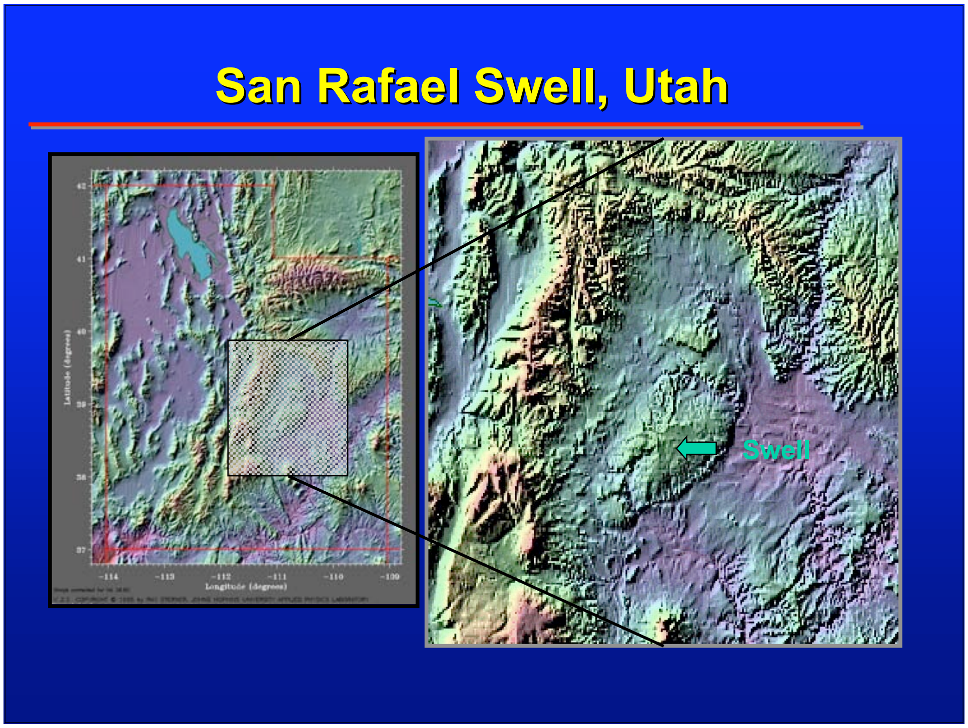
- No tilting of strata
- Simple truncation and onlap

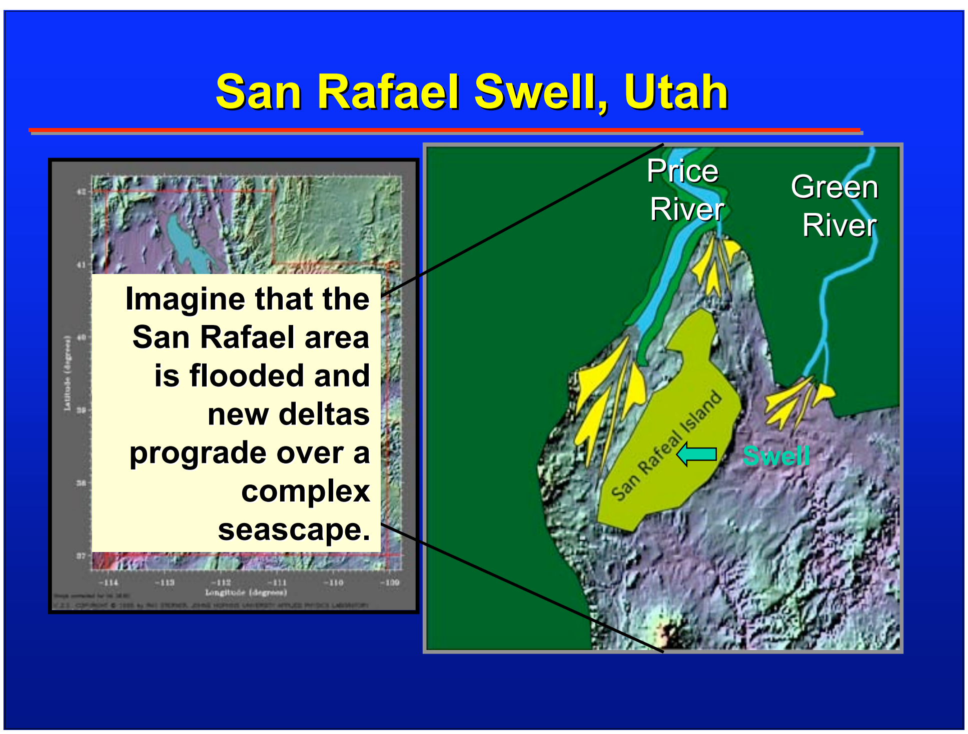
Types of Valleys

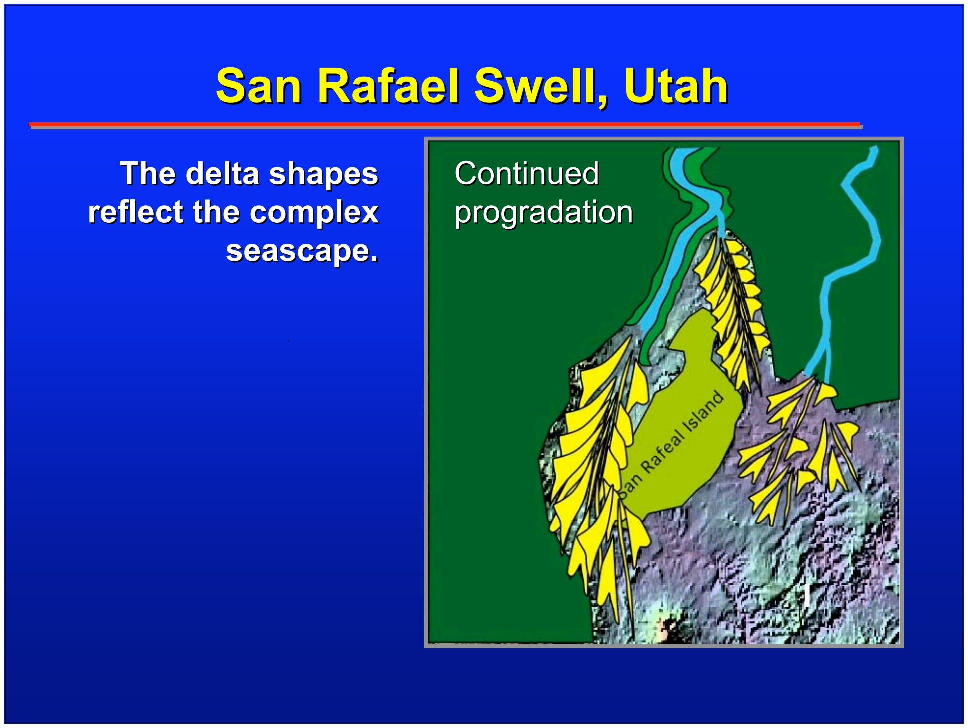
- Valleys caused by tectonics commonly produce angular unconformities.

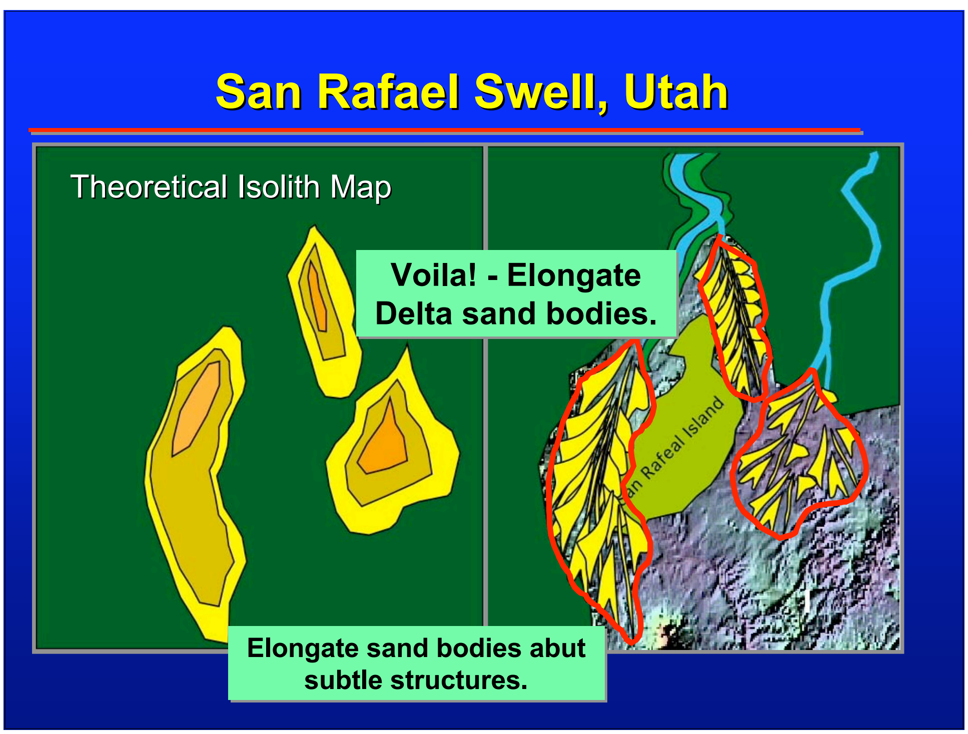


- Tilting of strata
- Complex truncation and onlap


San Rafael Swell, Utah
Swell

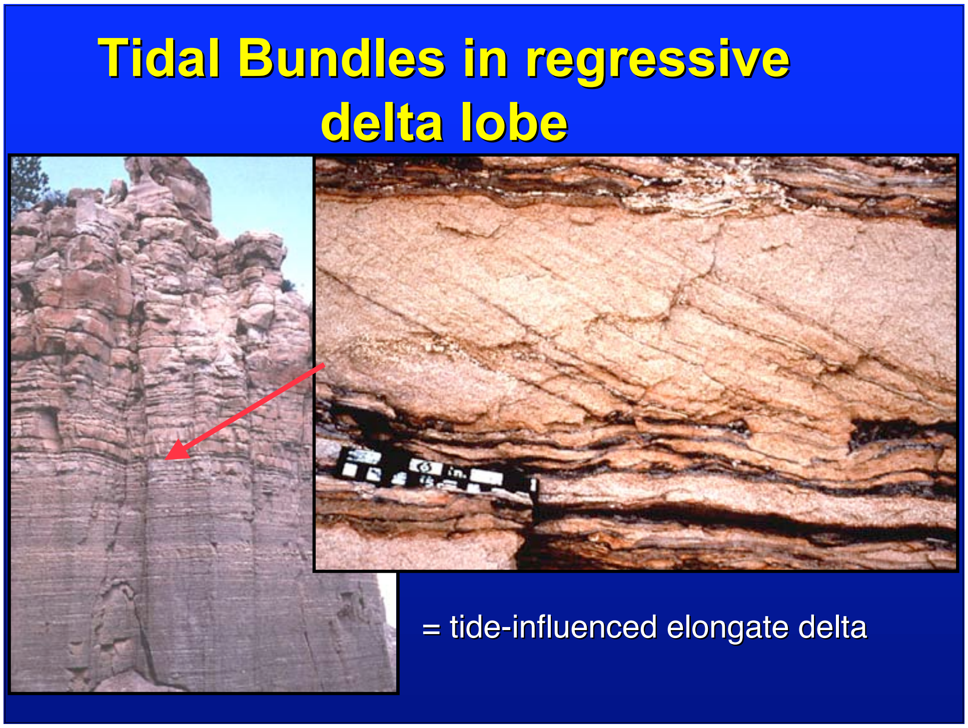

San Rafael Swell, Utah
Imagine that the San Rafael area is flooded and new deltas prograde over a complex seascape.
Price River
Green River
San Rafeal Island
Swell

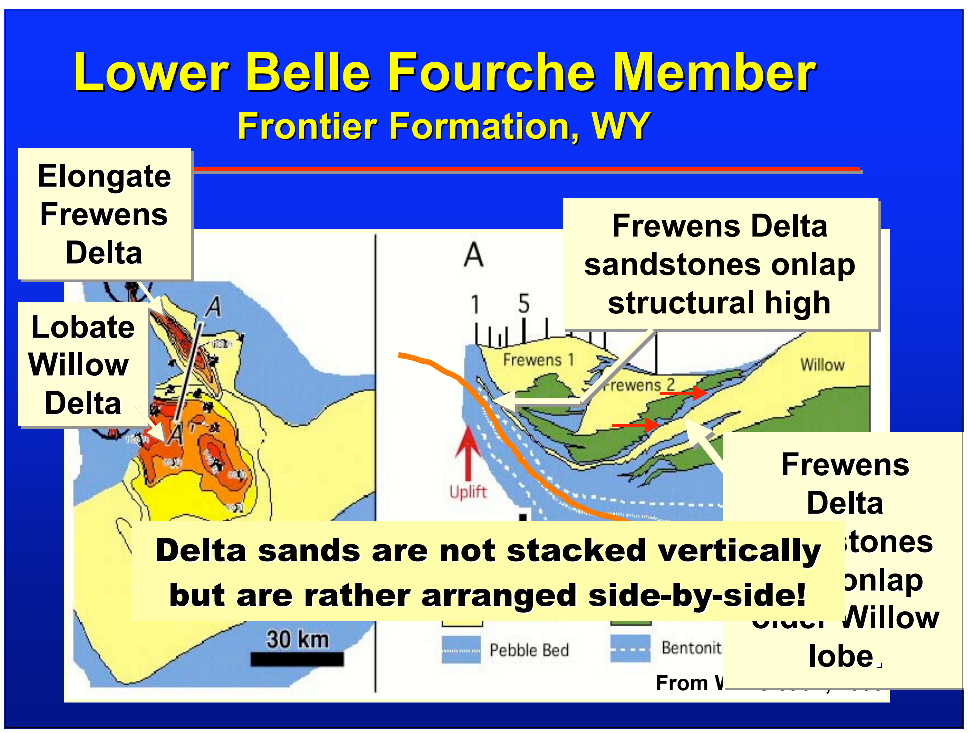

San Rafael Swell, Utah
The delta shapes reflect the complex seascape.
Continued progradation
San Rafeal Island

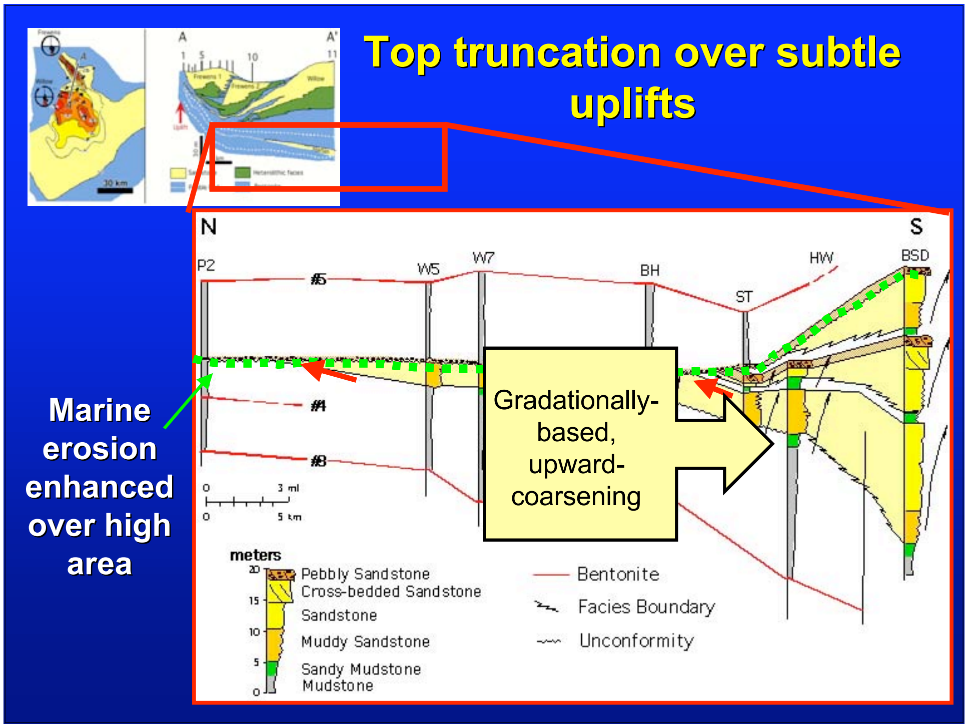

San Rafael Swell, Utah
Theoretical Isolith Map
Voila! - Elongate Delta sand bodies.
San Rafeal Island
Elongate sand bodies abut subtle structures.

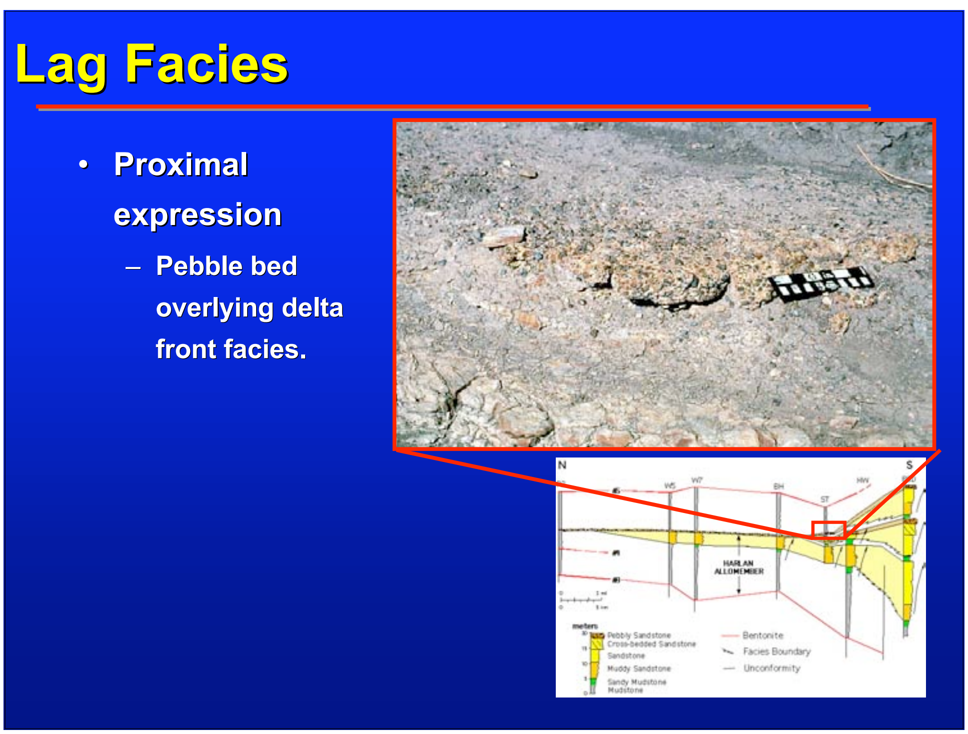

"Shelf" Sandstones show typical
Delta Front Facies Successions
• Coarsens upwards
• Seaward-dipping "clinoforms"


Linsen bedding at base of
upward-coarsening sand body
Lack of burrowing = fluvial influence
Heterolithic facies suggests tidal reworking.
6 in.


Tidal Bundles in regressive delta lobe
= tide-influenced elongate delta

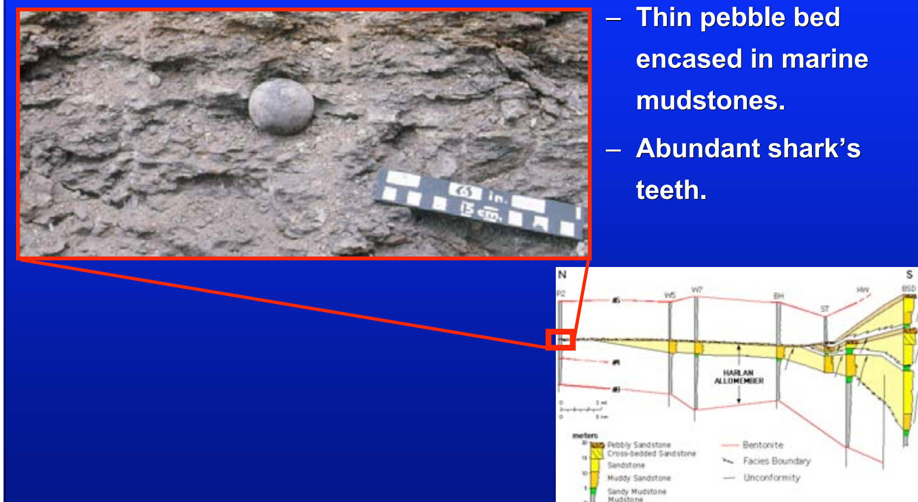

Lower Belle Fourche Member
Frontier Formation, WY
Elongate Frewens Delta
Lobate Willow Delta
Frewens Delta sandstones onlap structural high
A
1 5
Frewens 1
Frewens 2
Willow
Uplift
Frewens Delta
lobe
Delta sands are not stacked vertically but are rather arranged side-by-side!
30 km
Pebble Bed


Top truncation over subtle uplifts
Marine erosion enhanced over high area
Gradationally-based, upward-coarsening
N
S
P2
W5
W7
BH
ST
HW
BSD
#5
#4
#3
meters
Pebbly Sandstone
Cross-bedded Sandstone
Sandstone
Muddy Sandstone
Sandy Mudstone
Mudstone
Bentonite
Facies Boundary
Unconformity


Lag Facies
• Proximal expression
– Pebble bed overlying delta front facies.
HARLAN ALLOMEMBER

Lag Facies

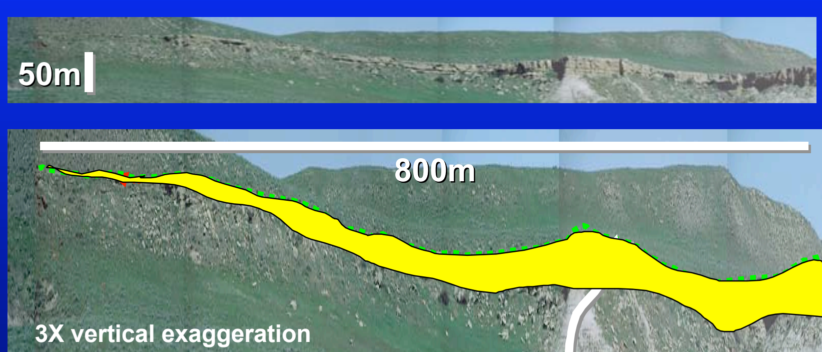
Big Pebbles in Mudstone



- Distal expression
  - Thin pebble bed encased in marine mudstones.
  - Abundant shark's teeth.

2nd Frontier Sandstone, WY

- Spectacular lateral pinchout of shoreface sandstone formed by top-truncation.

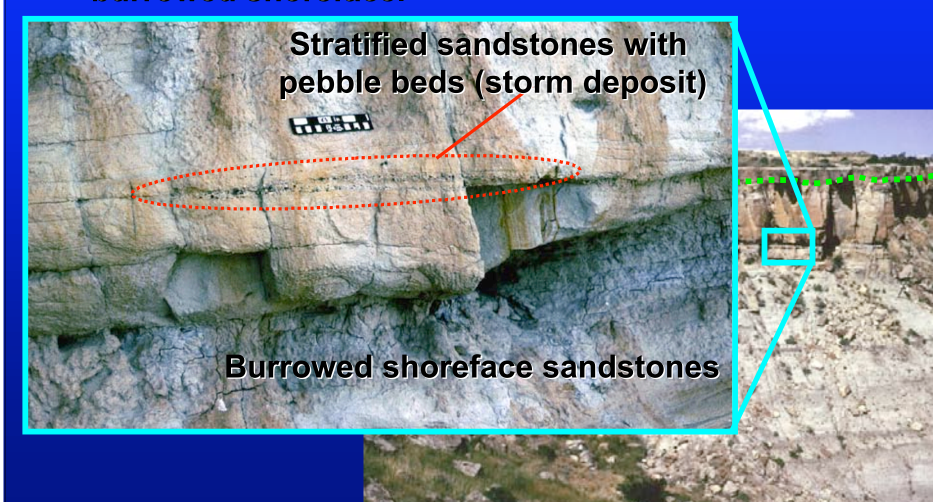


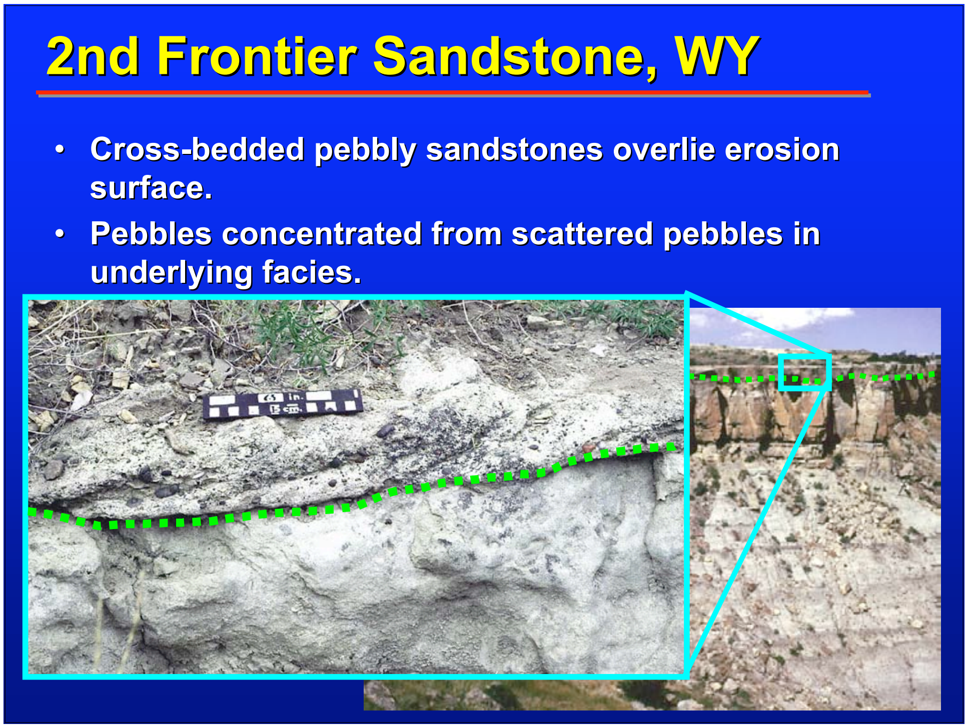
2nd Frontier Sandstone, WY

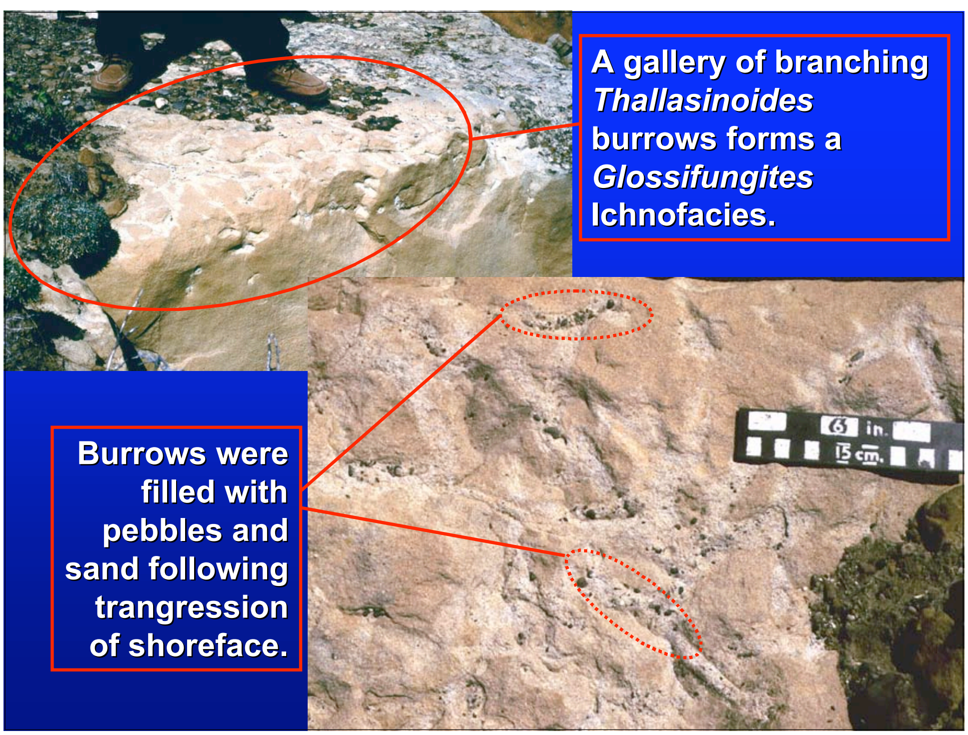
Gradationally-based, top-truncated, upward coarsening facies succession, interpreted as a shoreface.

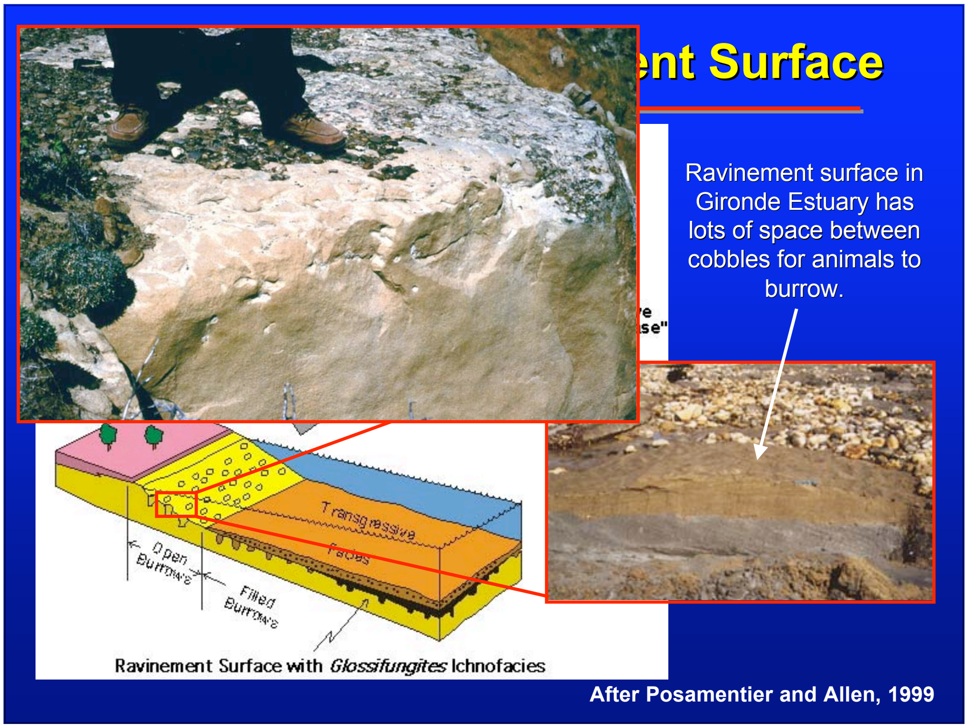
2nd Frontier Sandstone, WY

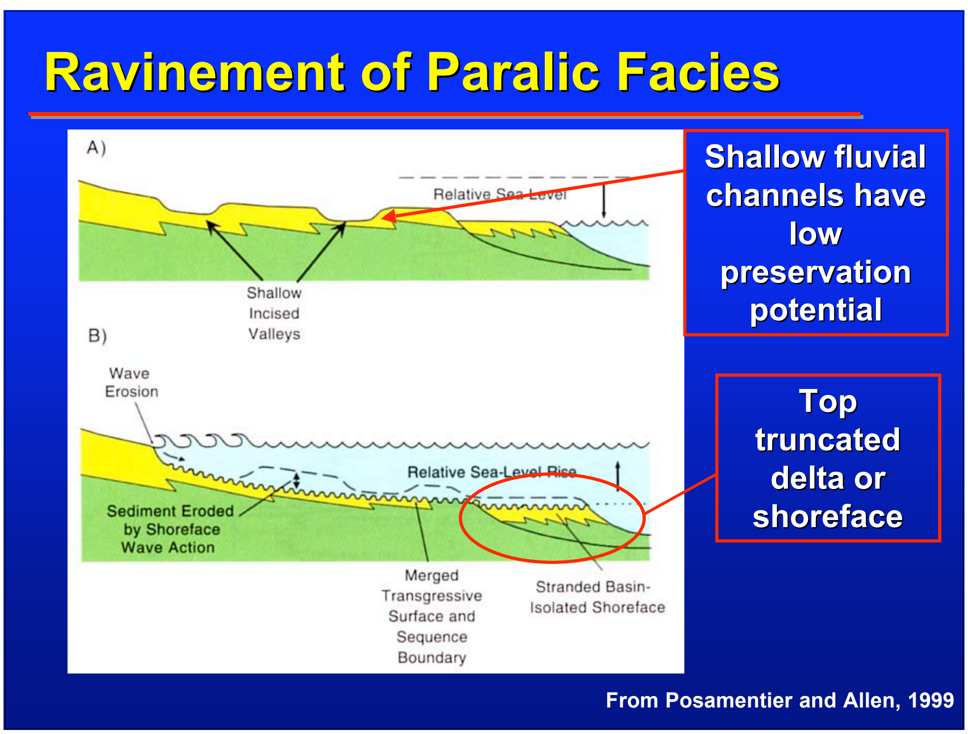
- Thin pebbly sandstone beds lie in lower burrowed shoreface.



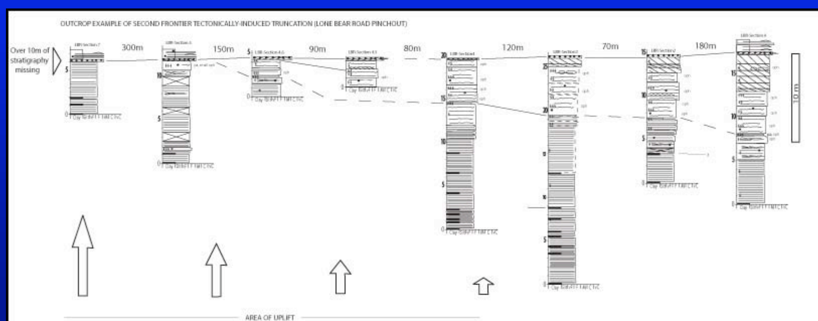

2nd Frontier Sandstone, WY
• Cross-bedded pebbly sandstones overlie erosion surface.
• Pebbles concentrated from scattered pebbles in underlying facies.


A gallery of branching *Thallasinoides* burrows forms a *Glossifungites* Ichnofacies.
Burrows were filled with pebbles and sand following trangression of shoreface.


ent Surface
Ravinement surface in Gironde Estuary has lots of space between cobbles for animals to burrow.
Transgressive Facies
Open Burrows
Filled Burrows
Ravinement Surface with Glossifungites Ichnofacies
After Posamentier and Allen, 1999

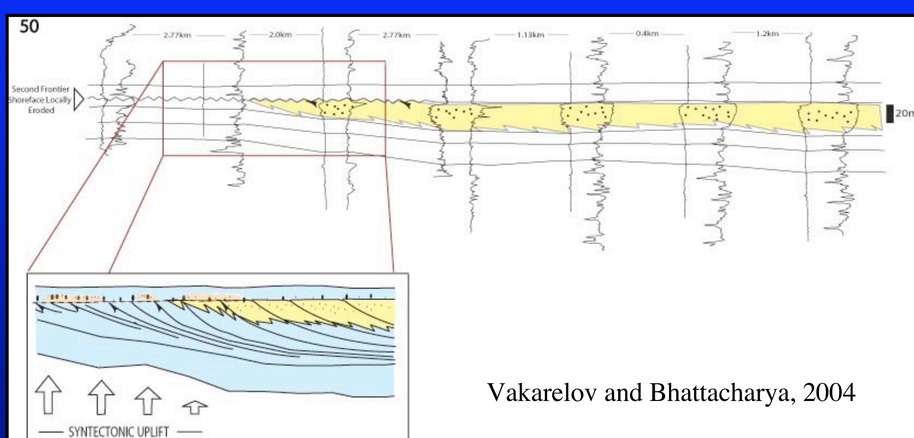

Ravinement of Paralic Facies
A)
Relative Sea Level
Shallow Incised Valleys
B)
Wave Erosion
Relative Sea-Level Rise
Sediment Eroded by Shoreface Wave Action
Merged Transgressive Surface and Sequence Boundary
Stranded Basin-Isolated Shoreface
Shallow fluvial channels have low preservation potential
Top truncated delta or shoreface
From Posamentier and Allen, 1999

Top Truncation in the "Second" Frontier Sandstone, Wyoming

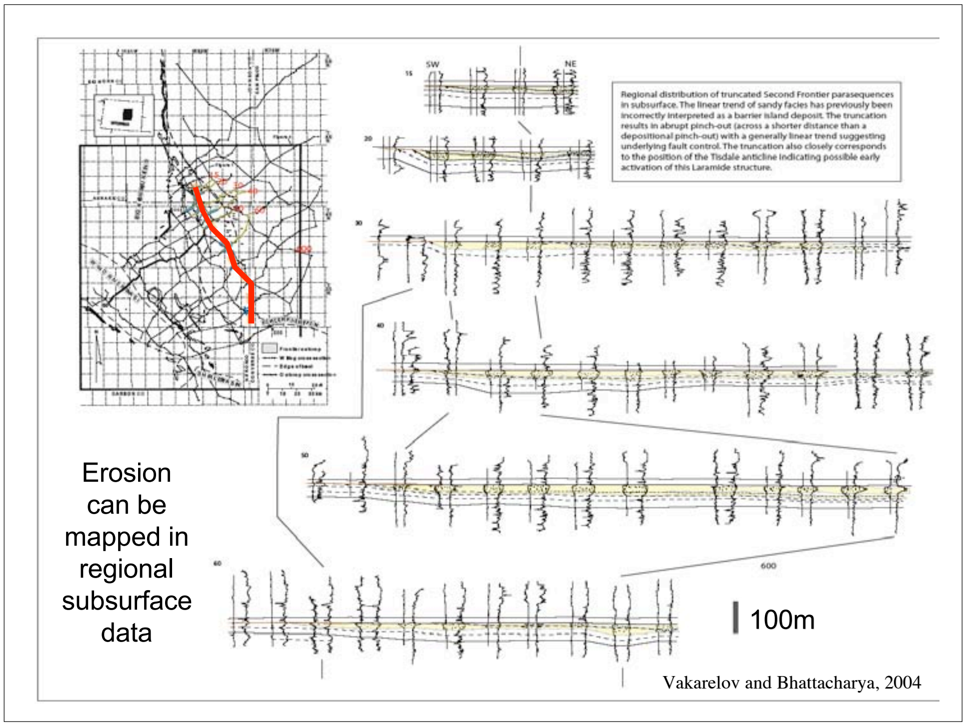


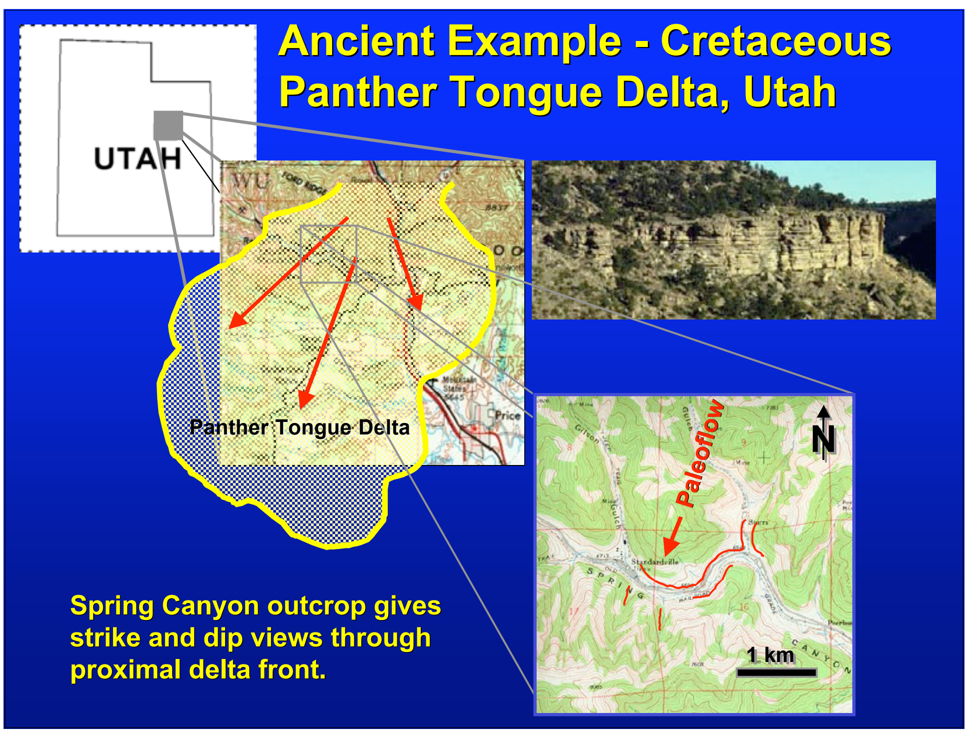
Vakarelov and Bhattacharya, 2004

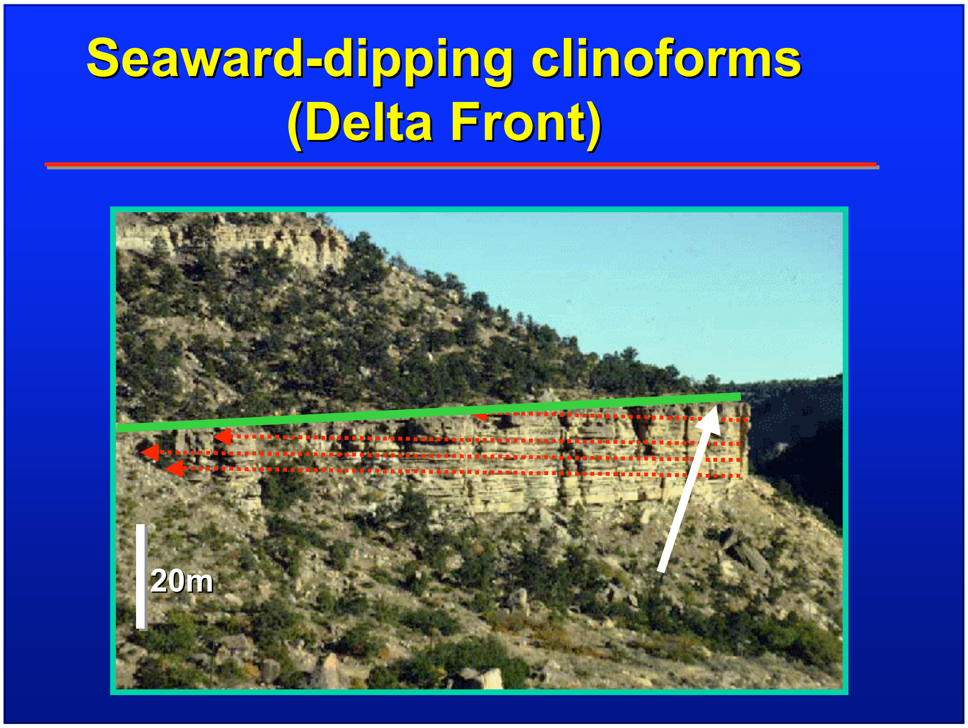
Erosion also seen in subsurface

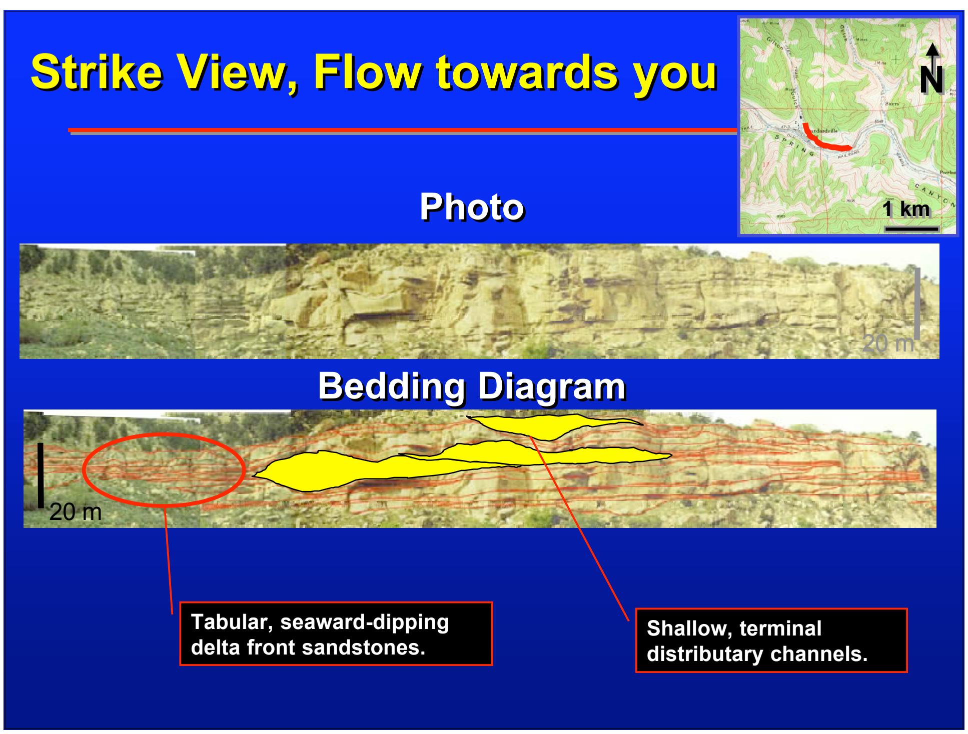


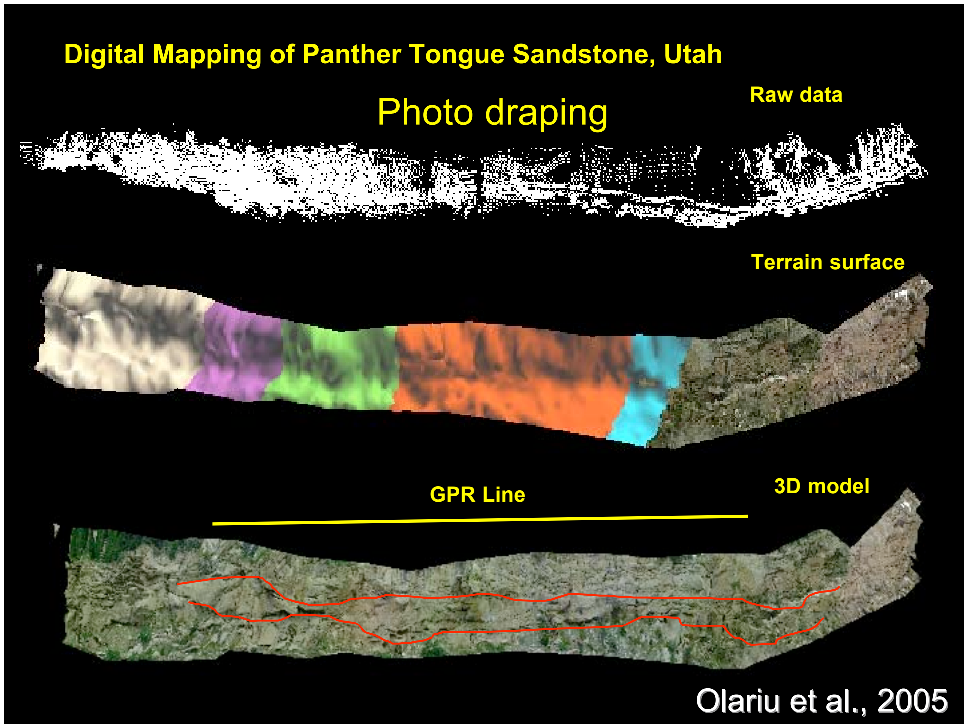
Vakarelov and Bhattacharya, 2004


SW
NE
Regional distribution of truncated Second Frontier parasequences in subsurface. The linear trend of sandy facies has previously been incorrectly interpreted as a barrier island deposit. The truncation results in abrupt pinch-out (across a shorter distance than a depositional pinch-out) with a generally linear trend suggesting underlying fault control. The truncation also closely corresponds to the position of the Tisdale anticline indicating possible early activation of this Laramide structure.
Erosion can be mapped in regional subsurface data
100m
Vakarelov and Bhattacharya, 2004


Ancient Example - Cretaceous Panther Tongue Delta, Utah
UTAH
Panther Tongue Delta
Price
Paleoflow
N
1 km
Spring Canyon outcrop gives strike and dip views through proximal delta front.

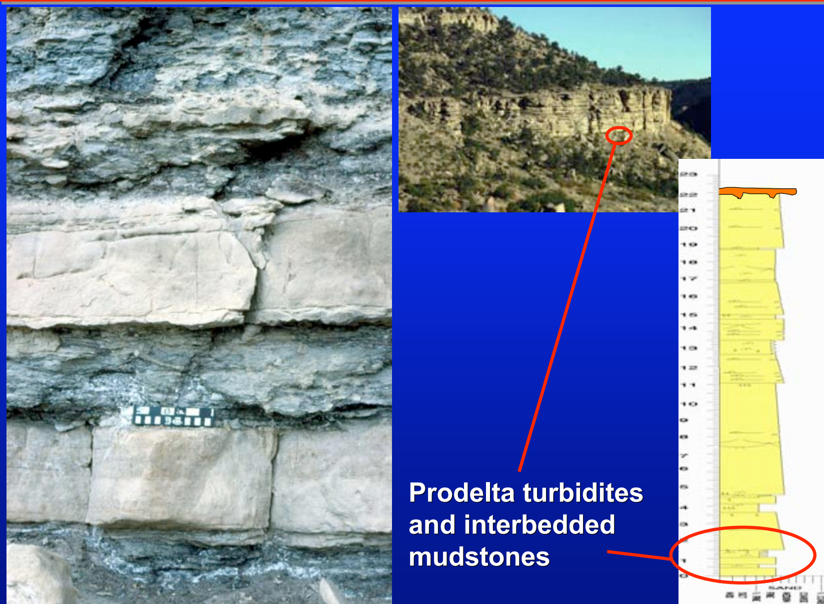

Seaward-dipping clinoforms
(Delta Front)
20m


Strike View, Flow towards you
N
1 km
Photo
20 m
Bedding Diagram
20 m
Tabular, seaward-dipping
delta front sandstones.
Shallow, terminal
distributary channels.


Digital Mapping of Panther Tongue Sandstone, Utah
Photo draping
Raw data
Terrain surface
GPR Line
3D model
Olariu et al., 2005

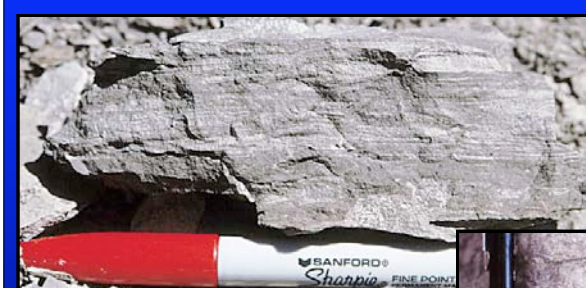

Photorealistic Movie of Panther Tongue Sandstone, Utah
Olariu et al., 2005

Facies - Prodelta

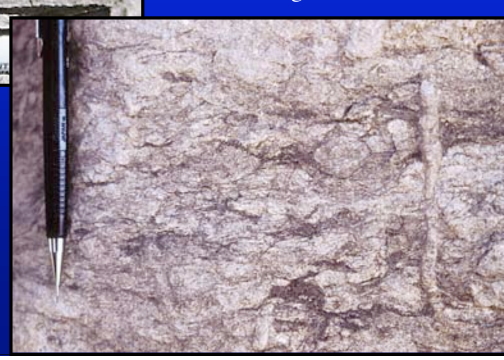


Prodelta Facies

- Burrowing reflects degree of marine versus fluvial influence as well as sedimentation rate.



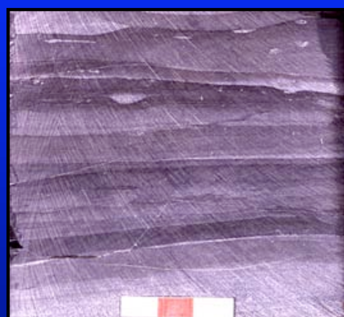
Laminated lightly burrowed prodelta mudstones, Cretaceous Panther Tongue sandstone, Utah.



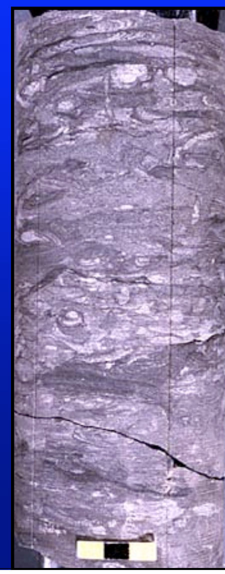
Highly burrowed shelf muddy sandstones, Cretaceous Panther Tongue sandstone, Utah.

Prodelta Facies

- Burrowing reflects degree of marine versus fluvial influence as well as sedimentation rate.

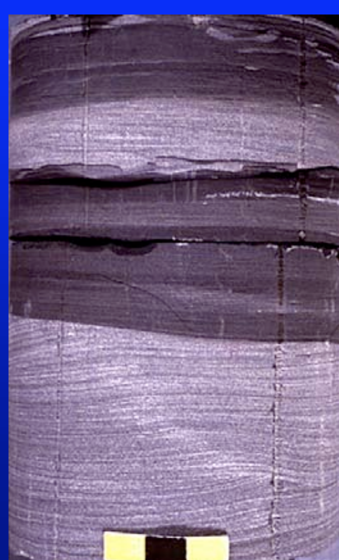


Laminated lightly burrowed prodelta mudstones, Cretaceous Dunvegan Formation, Alberta. Lack of burrowing probably indicates river influence.

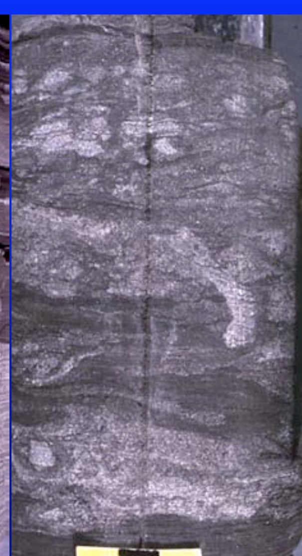


Highly burrowed shelf mudstones, Cretaceous Dunvegan Formation, Alberta. Slow sedimentation rates. Far from fluvial influence.

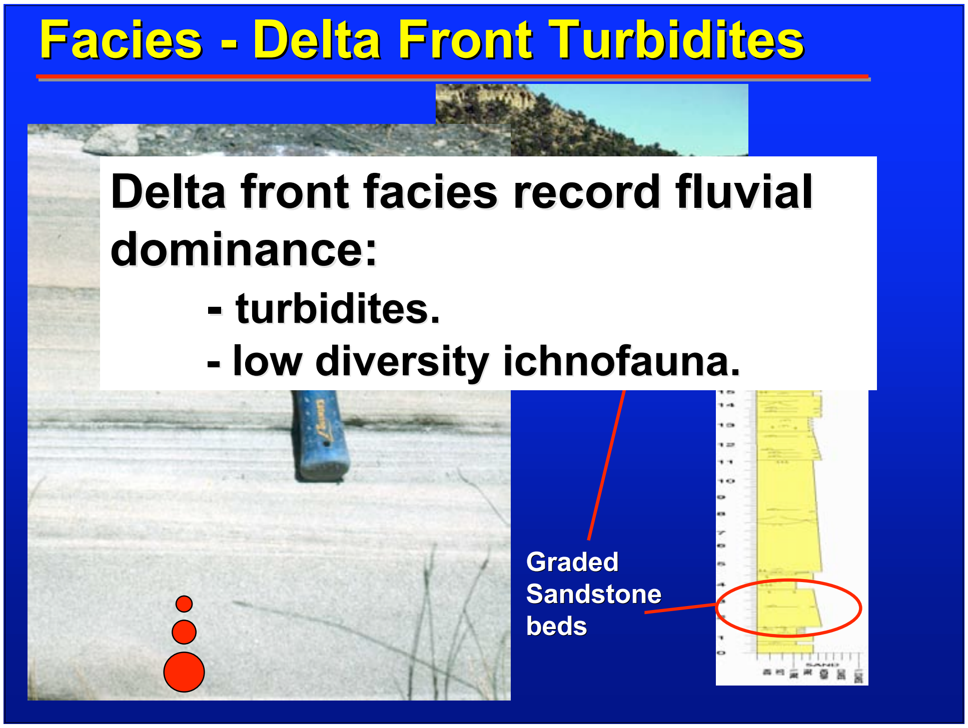
Distinguishing fluvial influence in shelf facies

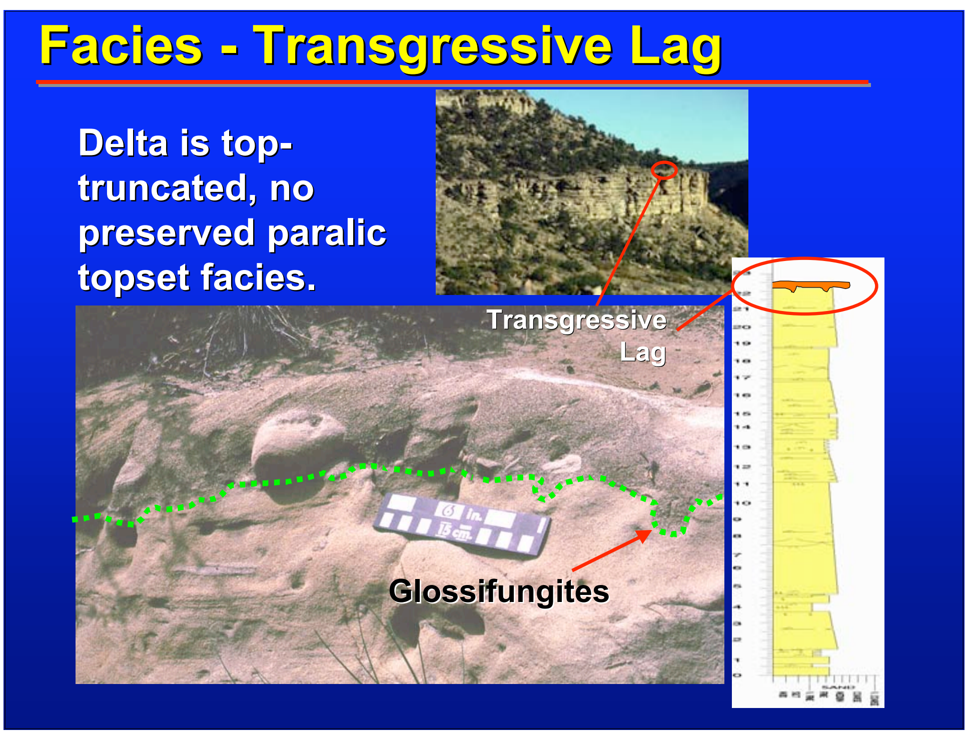


Wave-rippled sandstones and interbedded laminated mudstones, Cretaceous Dunvegan Formation, Alberta. Note very little burrowing.



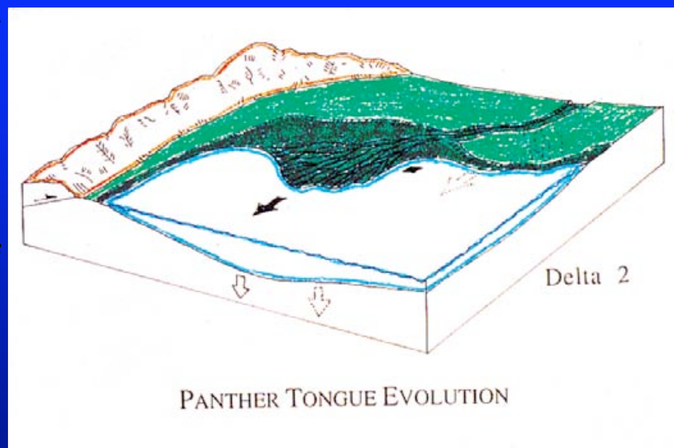
More highly burrowed shelf mudstones, Cretaceous Dunvegan Formation, Alberta.


Facies - Delta Front Turbidites
Delta front facies record fluvial dominance:
- turbidites.
- low diversity ichnofauna.
Graded Sandstone beds


Facies - Transgressive Lag
Delta is top-truncated, no preserved paralic topset facies.
Transgressive Lag
Glossifungites

Panther Paleogeography

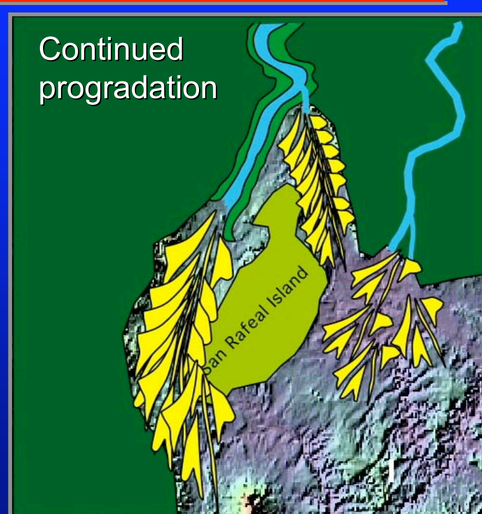
Panther tongue delta interpreted to build around paleohigh (early activation of San Rafael Swell)



Posamentier et al., 1995

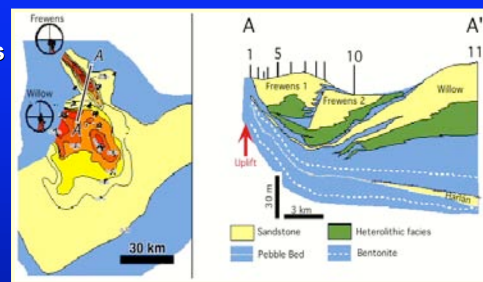
San Rafael Swell, Utah

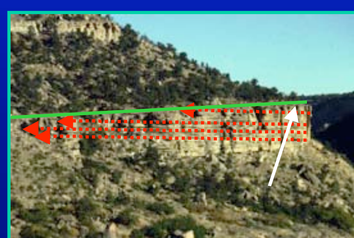
The delta shapes reflect the complex sea-floor topography.



Shelf Sand Solution

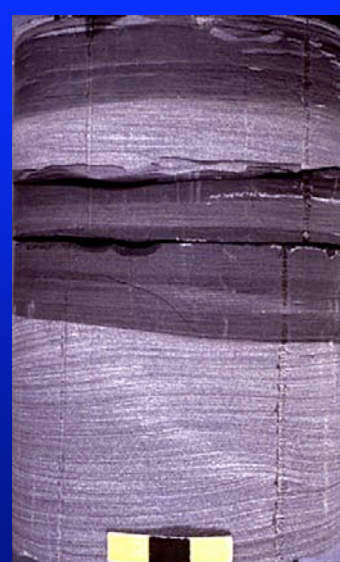
- We suggest that many of these deposits are top-eroded deltas formed where rivers delivered sediment to lowstand coastlines.
- Key Evidence:
  - Deltaic Depositional Systems
    - lobate to elongate geometry
    - radiating paleocurrents,
    - basinward dipping internal clinoform beds,
    - upward coarsening facies successions.



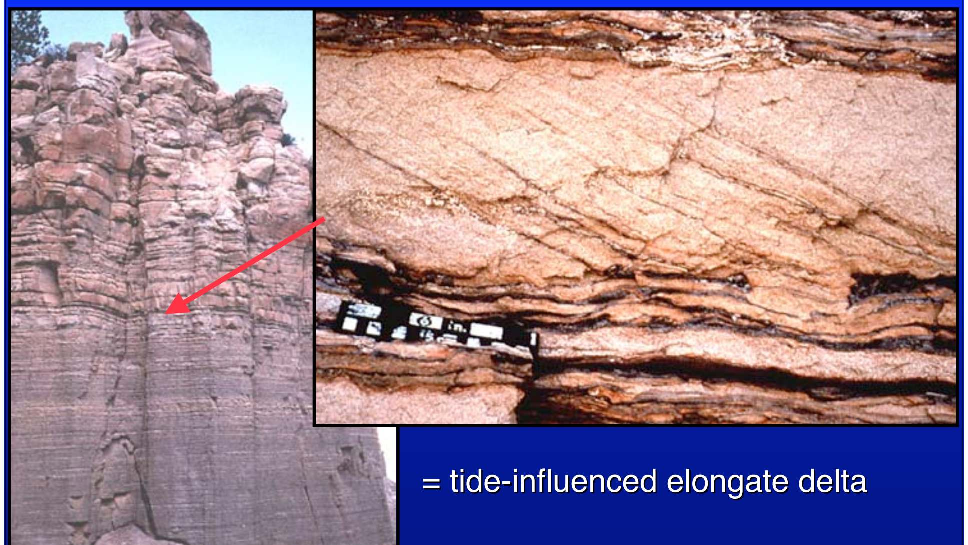


Shelf Sand Solution

- Despite erosion of topset facies, river-influence can still be detected.
  - Biofacies record river influence
    - Low to moderate abundance and diversity of trace fossils
    - high proportion of non-marine spores and pollen
    - few marine foraminifera, no calcareous forms.



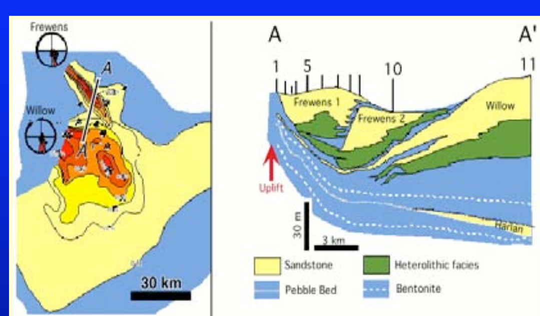
Tidal Facies may be preserved in lowstands



= tide-influenced elongate delta

Sequence Stratigraphic Implications

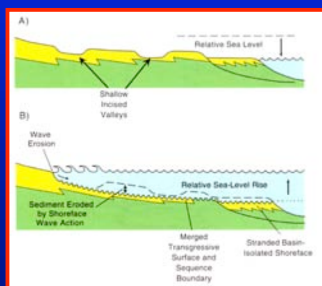
- Sequence stratigraphic terminology is difficult to use.

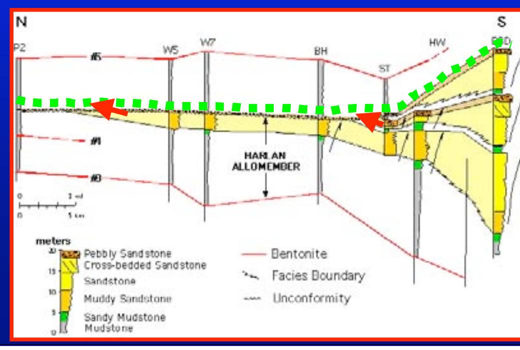


- Sandstones do not show simple vertical stacking patterns.
  - Low accommodation setting left little room for sandstones to stack vertically.
  - Successive episodes of delta progradation were offset along strike.

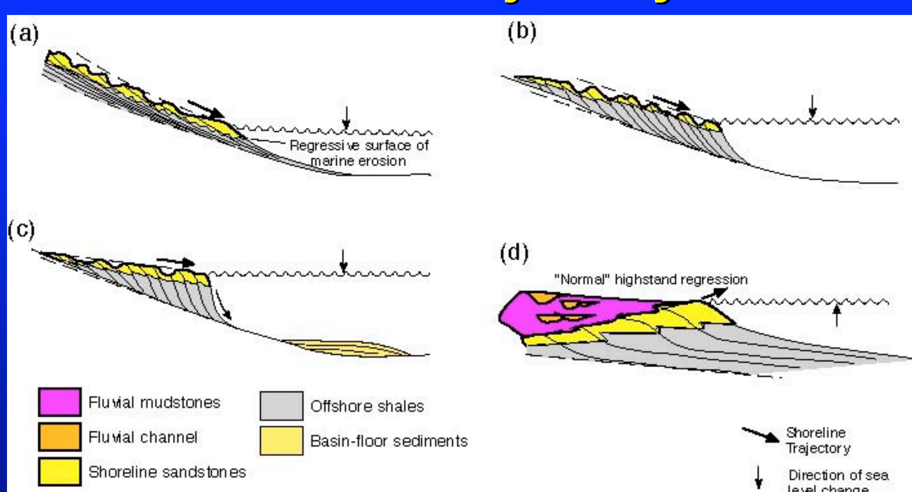
Sequence Stratigraphic Implications

- Major discontinuities form at the tops of sandstone bodies by wave erosion during transgression (ravinement) rather than by fluvial erosion.
- NO SHARP-BASED SHOREFACES!
- Minor syndepositional deformation of the basin floor exerts a first-order influence on sediment deposition and preservation.





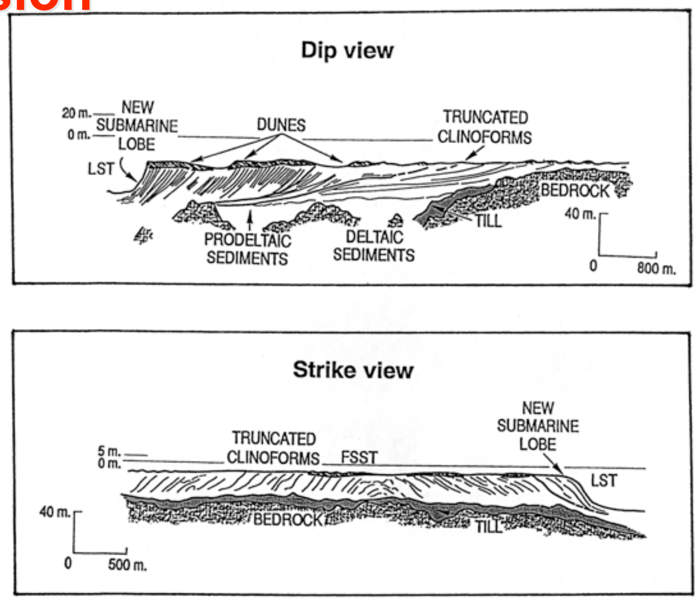
Shoreline Trajectory



Gjellberg and Helland-Hansen, 1994

Conclusion

- Top truncation also seen in seismic examples (not limited to Cretaceous)



Hart and Long, 1996

Conclusion

- Critical to integrate sedimentology, paleontology and mapping of bounding discontinuities.
- Structure and stratigraphy in foreland basins are a paired process.
- In low accommodation (basin distal, lowstand) settings,
  - Depositional remnants are common.
- Not all valleys are incised or even subaerially exposed.
  - Think about seascapes

Acknowledgements

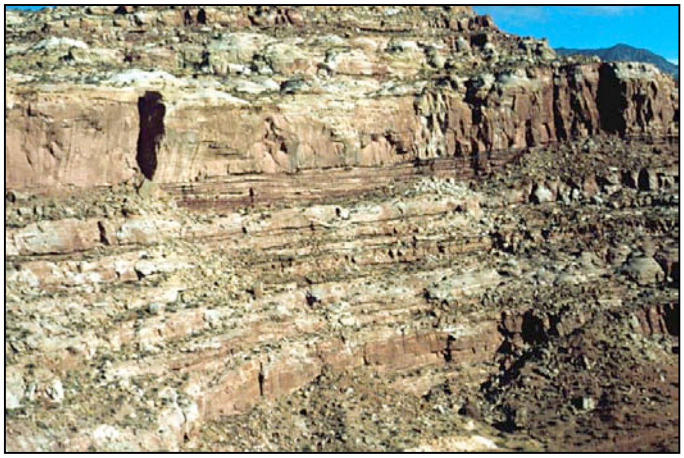
UTD

- This work was made possible through grants and gifts from:
  - DOE
  - Petroleum Research Fund
    - American Chemical Society
  - BP-Amoco/ Chevron-Texaco

ChevronTexaco

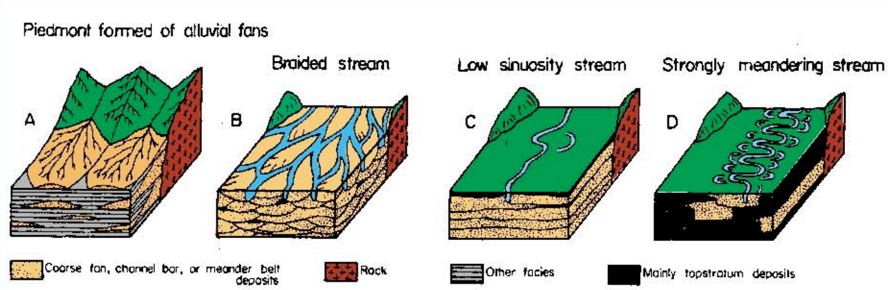
bp

Stratigraphy of Fluvial Systems



Salt Wash Member, Morrison Formation

Early Fluvial Stratigraphy Models

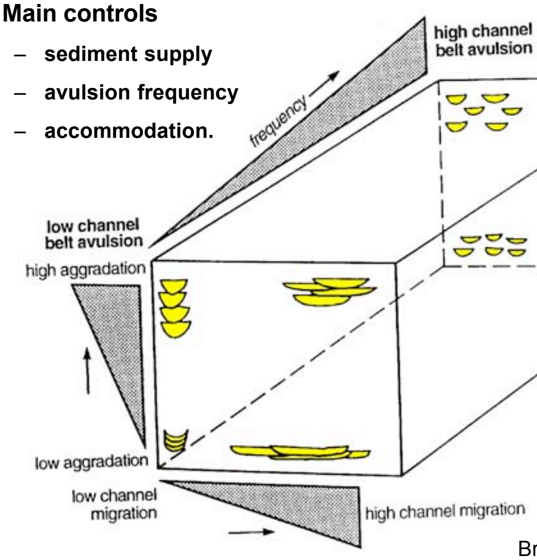


Friend, 1983

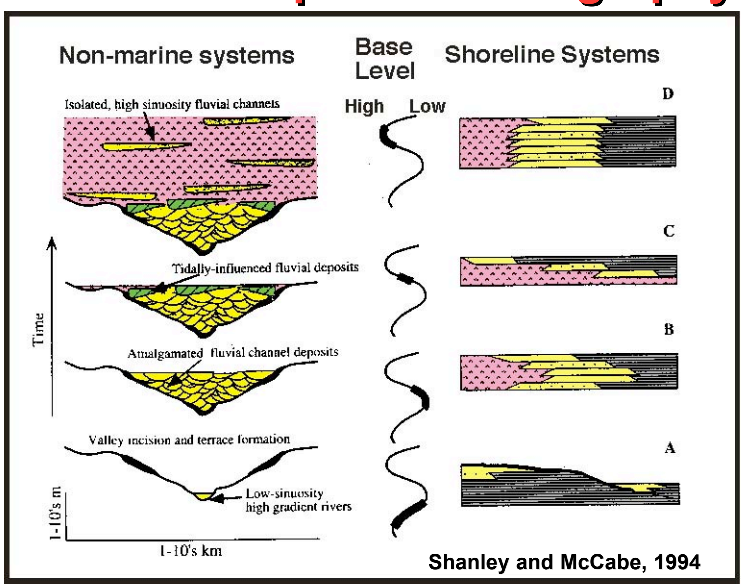
- Assumes that plan-view form of river is primary control on preserved proportion of mud versus sand.

Controls on Fluvial Architecture

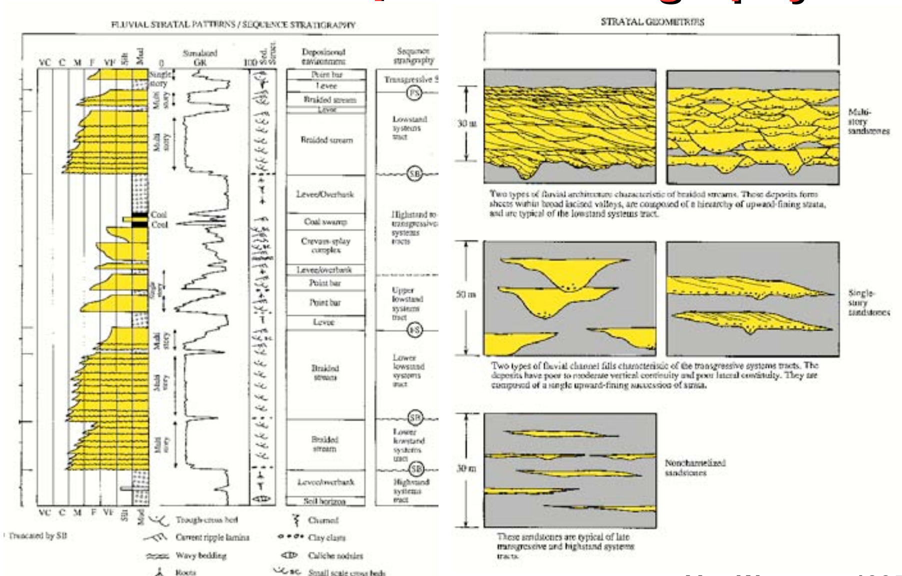
- Main controls
  - sediment supply
  - avulsion frequency
  - accommodation.



Non-marine sequence stratigraphy

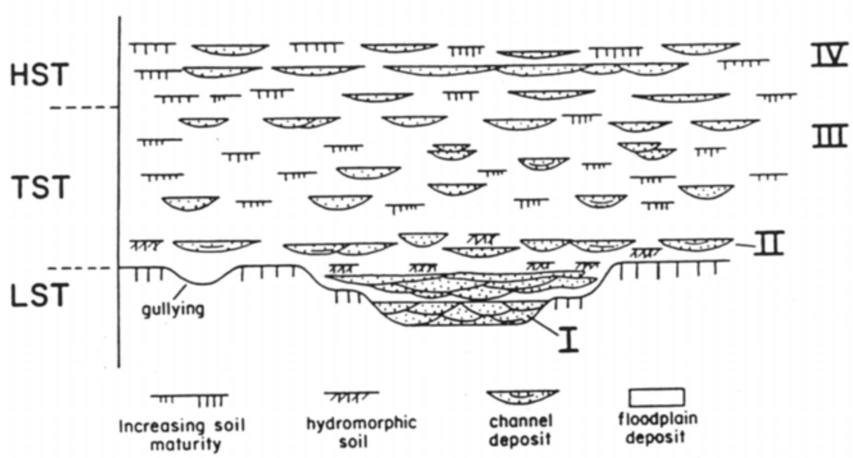


Non-marine sequence stratigraphy



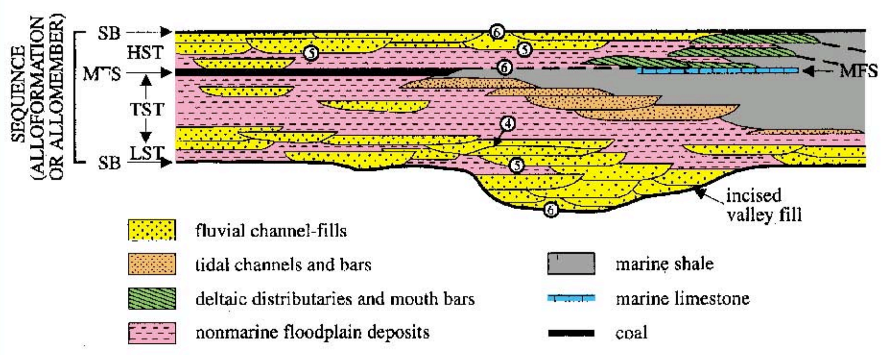
Van Wagoner, 1995

Non-marine sequence stratigraphy



Wright and Marriott, 1993

Non-marine sequence stratigraphy



Miall, 1997

Incised Valleys

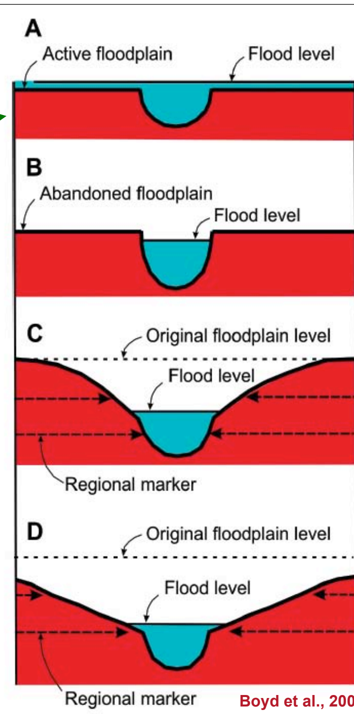
Incised Valley - Definition

- A valley is an elongate erosional feature that is significantly deeper than the river that now occupies it, and the walls of which do not routinely flood.

Grand Canyon is essentially a big valley!

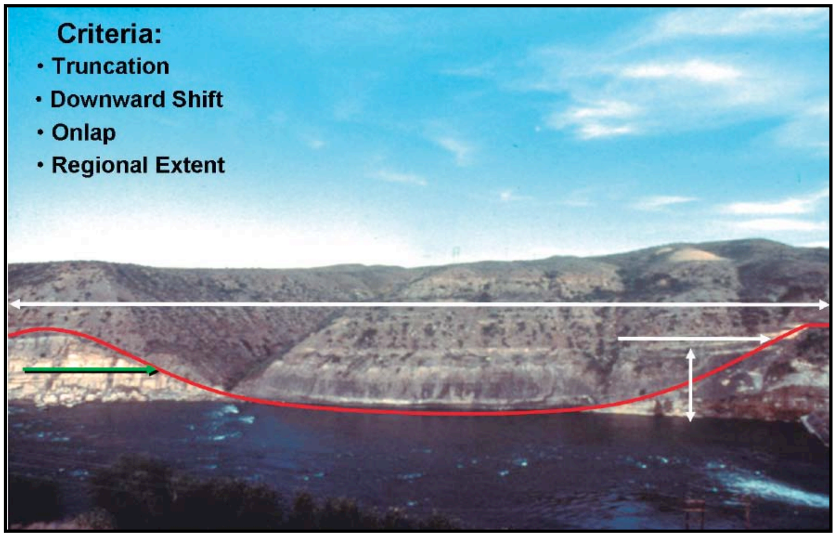
Colorado river is severely underfit.

Transition from unincised to incised



Boyd et al., 2006

Criteria For Valley Recognition

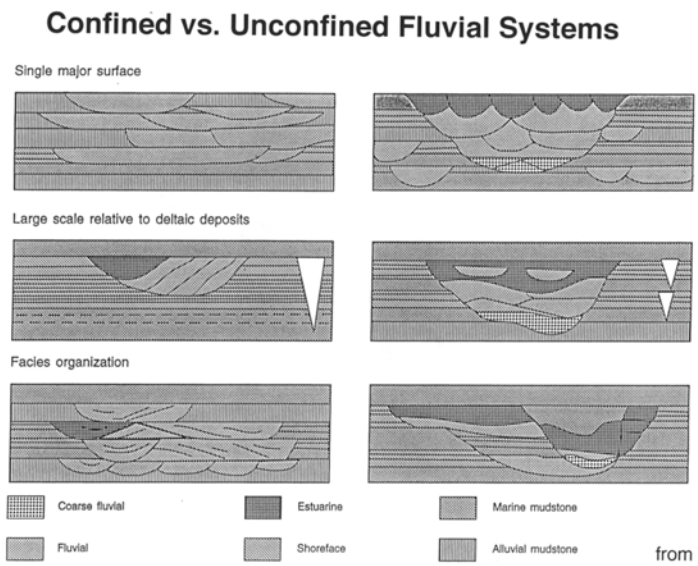


Boyd et al., 2006

Criteria For Valley Recognition

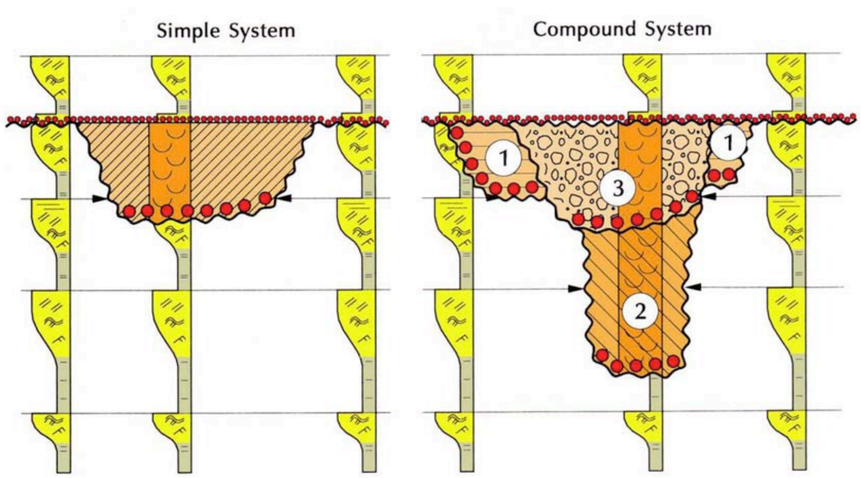
- Typically several storeys thick.
- Do not inter-finger with floodplain sediments.
  - Laterally confined by valley walls.
- Associated with widespread exposure
- Can have complex fluvio-estuarine fills.
- May be seen seismically.
  - Truncation below, onlap above
- May show multiple episodes of cut and fill.
- Incision decreases downstream unless a nickpoint is encountered.

Incised Valleys vs unconfined channels

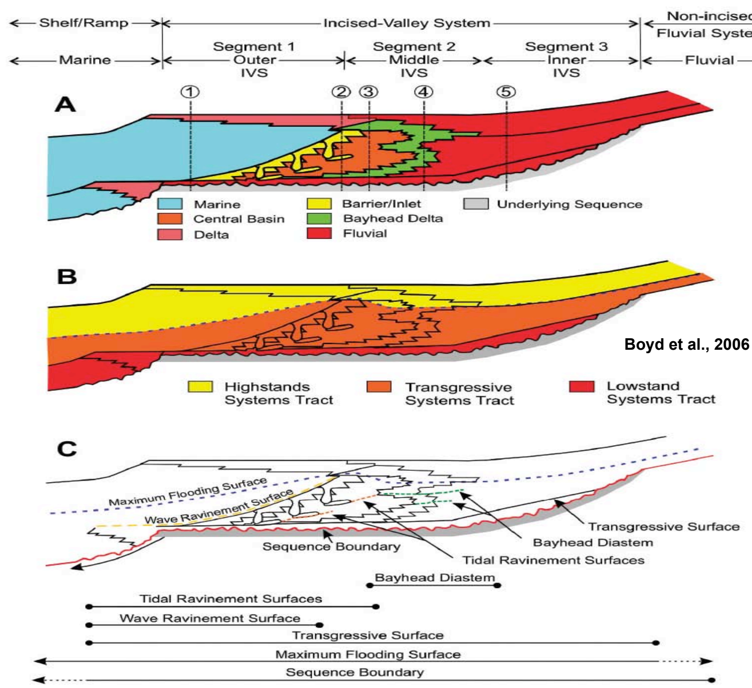


from Willis, 1996

Simple vs Compound Valleys

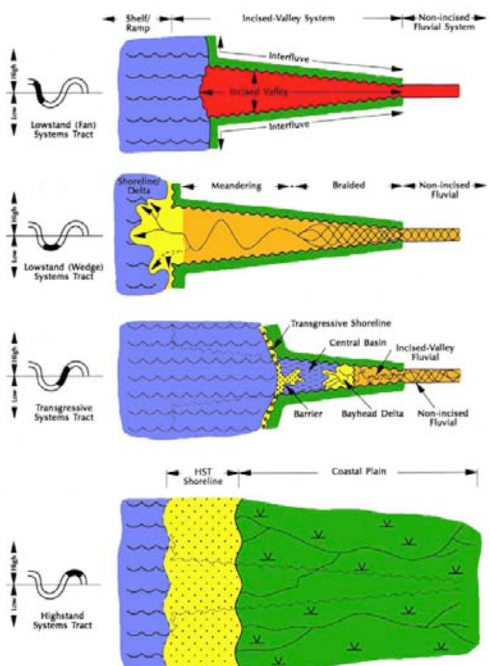


Modified after Zaitlin et al. 1994



Filling of a valley

- Theoretical map views of valley filled during a single sea-level cycle.

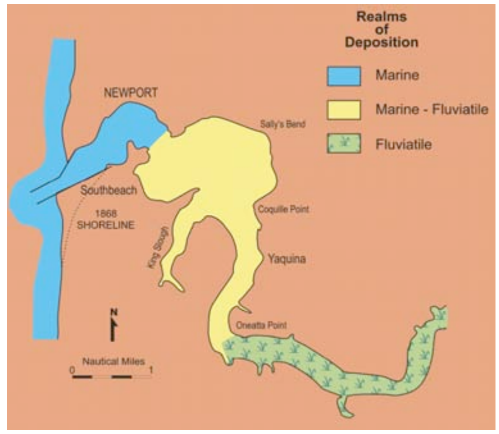


Slide courtesy of Garrison (2006)

Zaitlin et al. 1994

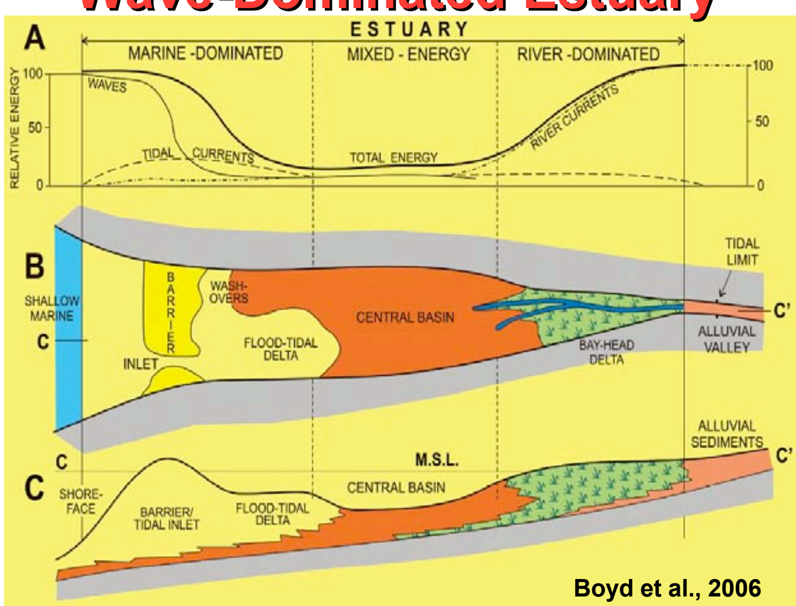
Eastuaries versus Valleys

- Tripartite fill
  - Marine
  - Mixed
  - Fluvial



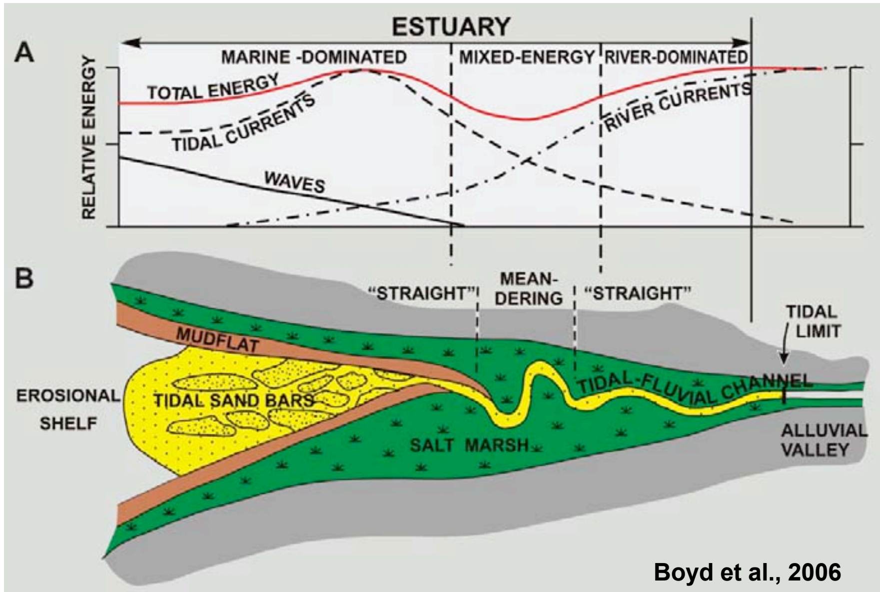
From Boyd et al. 2006 after Kulm and Byrne, 1967

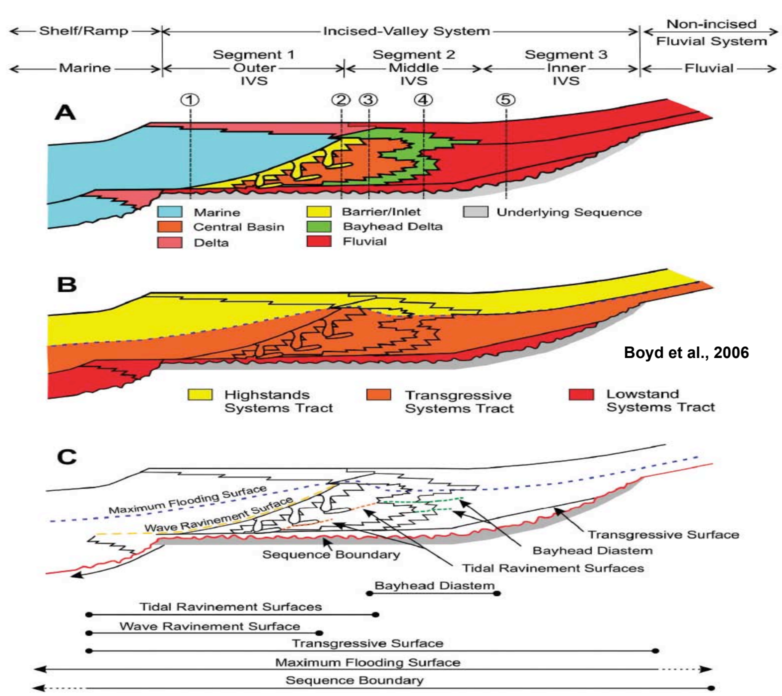
Wave-Dominated Estuary



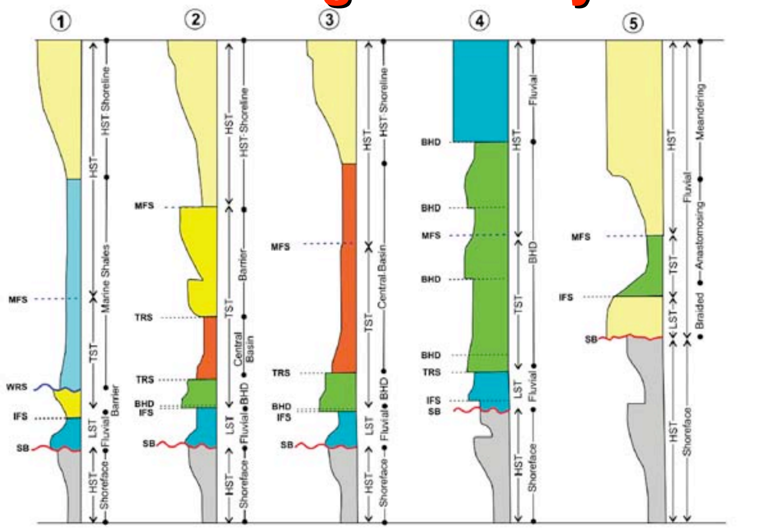
Boyd et al., 2006

Tide-Dominated Estuary



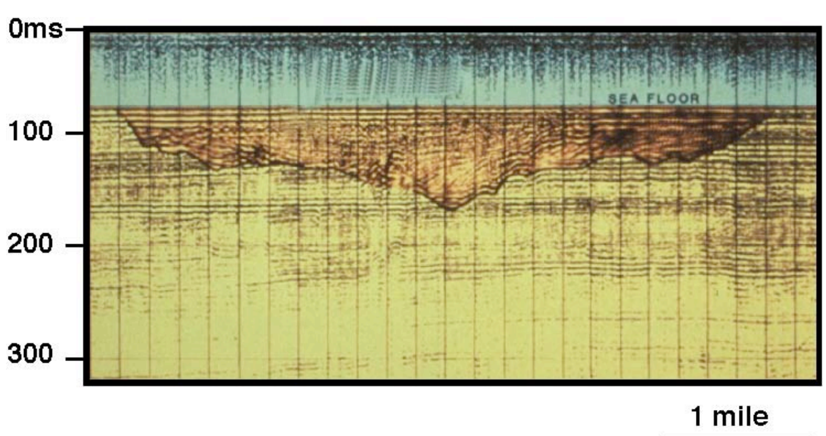


Idealized Cross Section Through a Valley

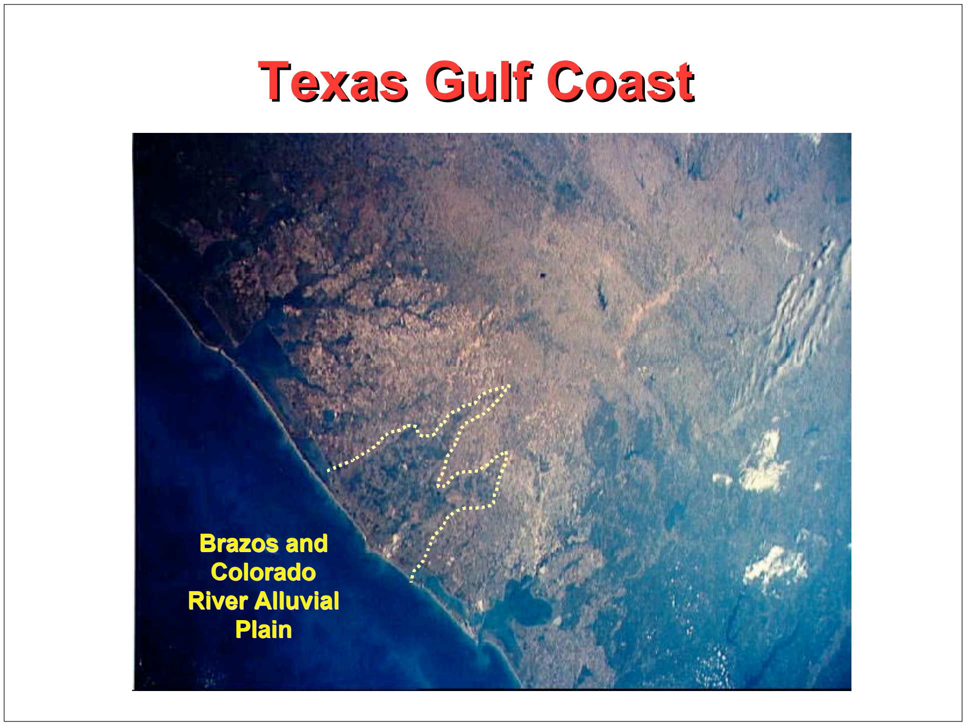


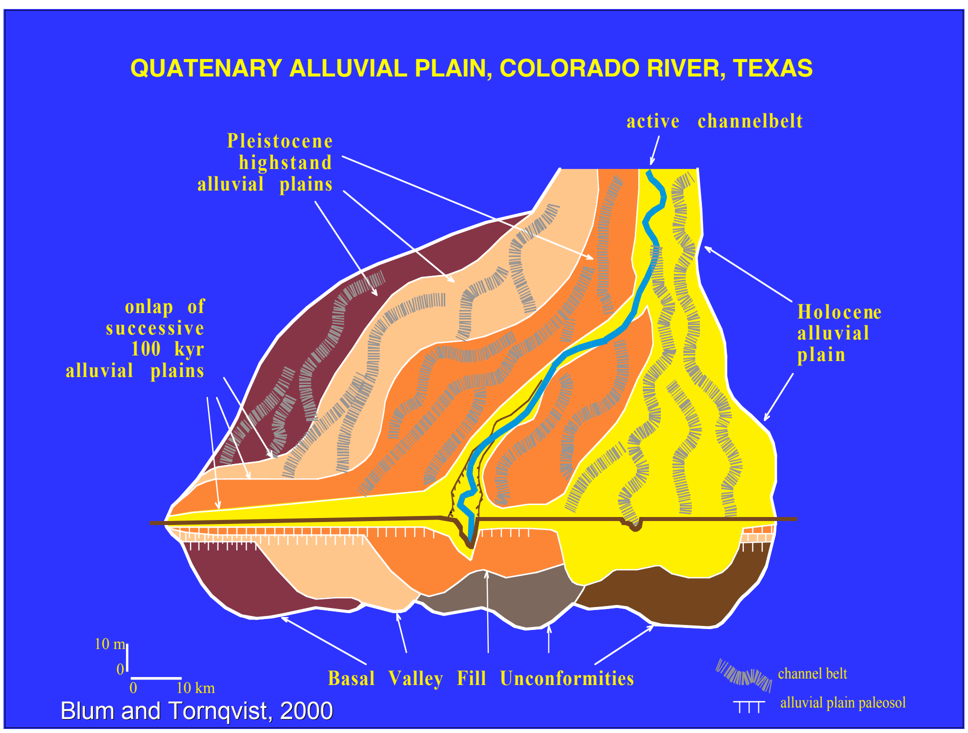
Boyd et al., 2006

Seismic Expression of Incised Valley



Seismic line of Quaternary Incised valley, Gulf of Mexico


Texas Gulf Coast
Brazos and
Colorado
River Alluvial
Plain


QUATENARY ALLUVIAL PLAIN, COLORADO RIVER, TEXAS
active channelbelt
Pleistocene
highstand
alluvial plains
onlap of
successive
100 kyr
alluvial plains
Holocene
alluvial
plain
10 m
0
0
10 km
Basal Valley Fill Unconformities
channel belt
alluvial plain paleosol
Blum and Tornqvist, 2000

Composite Valleys (GOM)

Composite Valley Fill, Colorado River, Texas

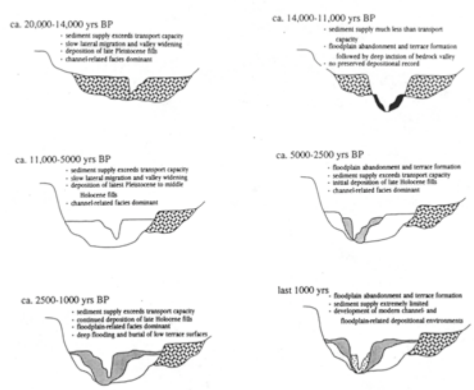
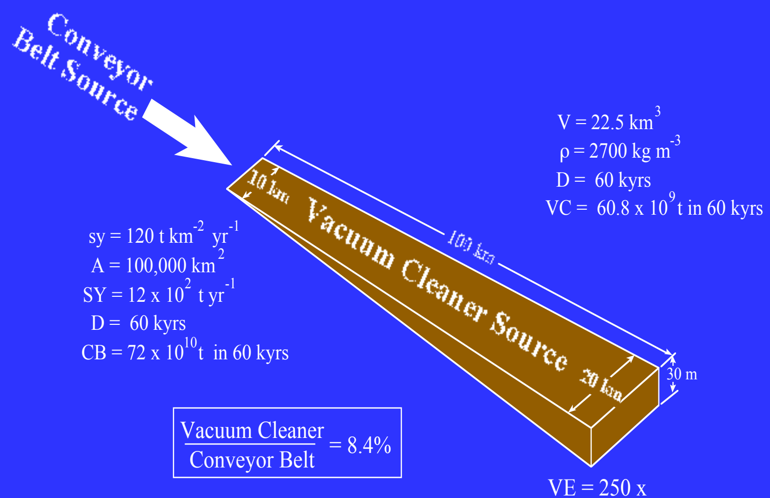


Fig. 13.11. History of alluvial incision and aggradation in response to postglacial climate change, Colorado River, Texas (Shanley and McCabe 1994, modified from Blum 1992, reprinted by permission). As discussed in Chap. 12, the major phase of valley incision within the 14–11 ka period corelates to the beginning of the last postglacial transgression

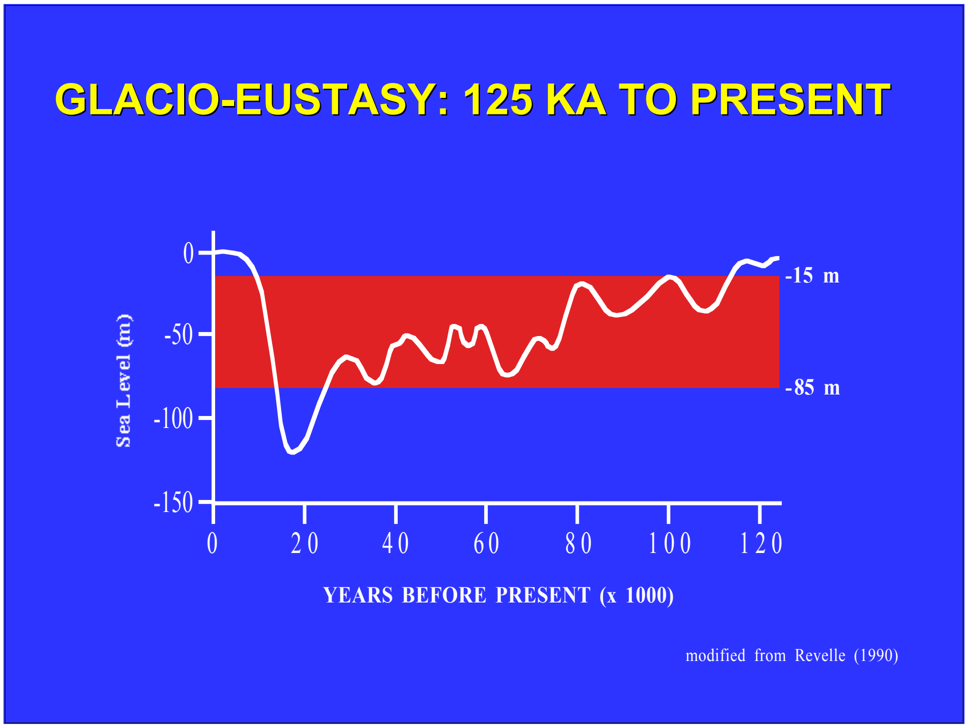
History of Colorado River valley fills, Blum, 1993

VACUUM CLEANER VS. CONVEYOR BELT MODEL FOR FALLING STAGE AND LOWSTAND SEDIMENT SUPPLY



$$\frac{\text{Vacuum Cleaner}}{\text{Conveyor Belt}} = 8.4\%$$

Blum and Tornqvist, 2000



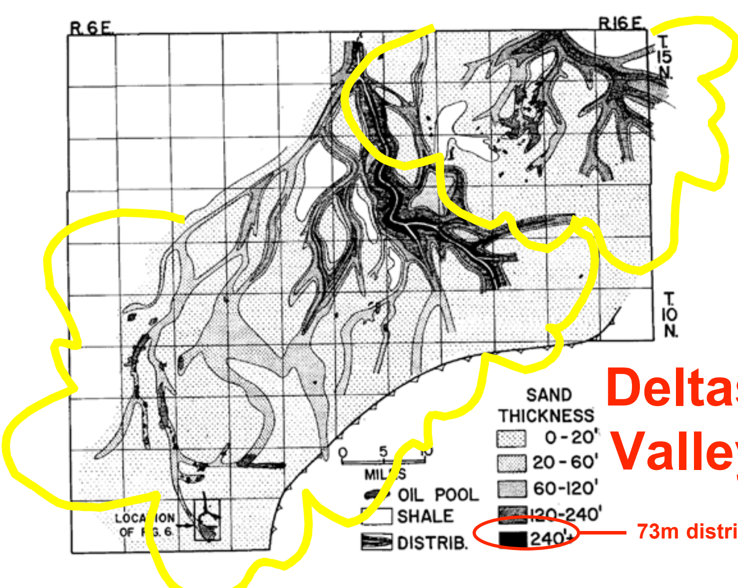
Colorado River Conclusion

- Bifurcating pattern originally thought to reflect switching of distributary channels.
- Actually reflects more complex history of valley incision, filling and sometimes valley switching over 100 KA time scales.
  - Related to Pleistocene glaciations and sea level changes.
- NOT simple autocyclic delta switching model.
  - Overuse of Mississippi models.

Ancient Examples in North America

- Distributary Channels or Valleys?
  - Pennsylvanian
  - Cretaceous

Pennsylvanian, Booch "Delta"



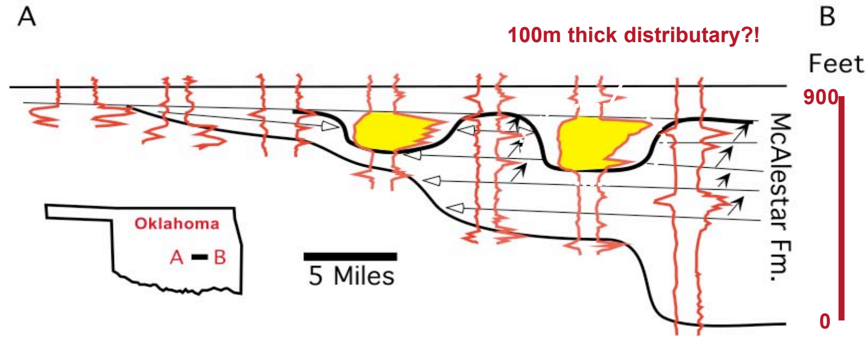
Deltas or Valleys?

73m distributary?

Busch, 1971

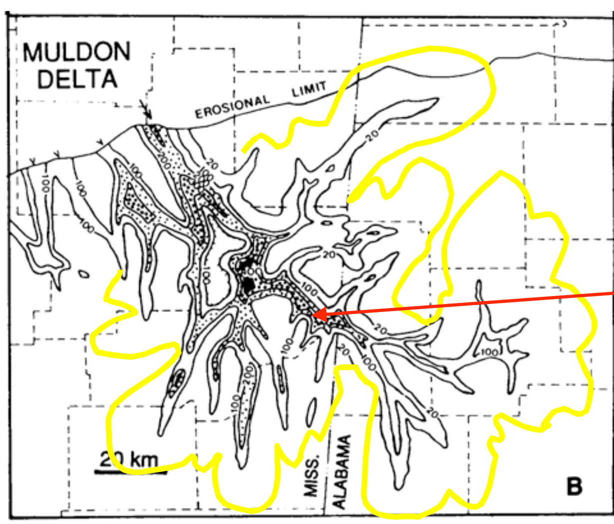
Stratigraphic cross section of Booch Sandstones, Oklahoma

- Mismatch between scale of upward coarsening delta front successions and the associated channels.
- Over-thick channels are more likely incised valleys.



After Busch, 1971

Which Way is The River Flowing?



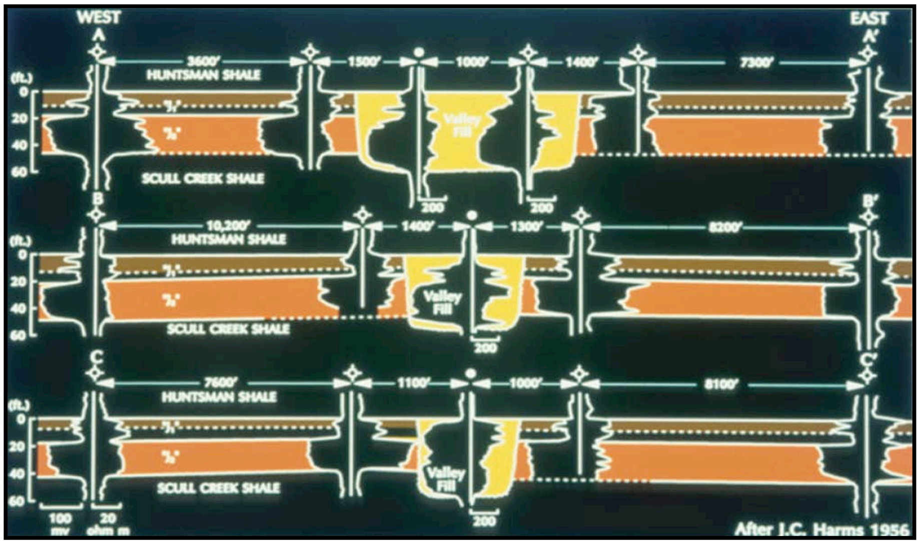
Why Are There No Mouth Bar Sands?

Distributary channels are 300 feet thick!

After Cleaves and Broussard, 1980

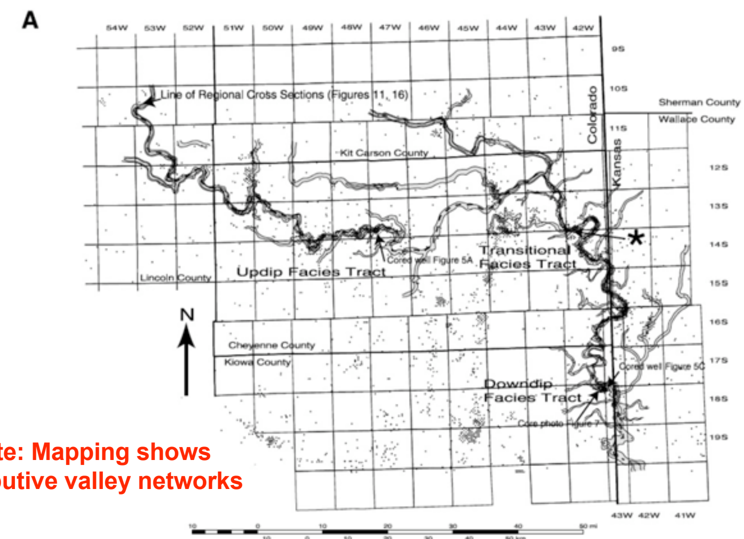
Pennsylvanian age

Morrow Sandstone



From Boyd et al., 2006

Pennsylvanian Morrow Sandstone

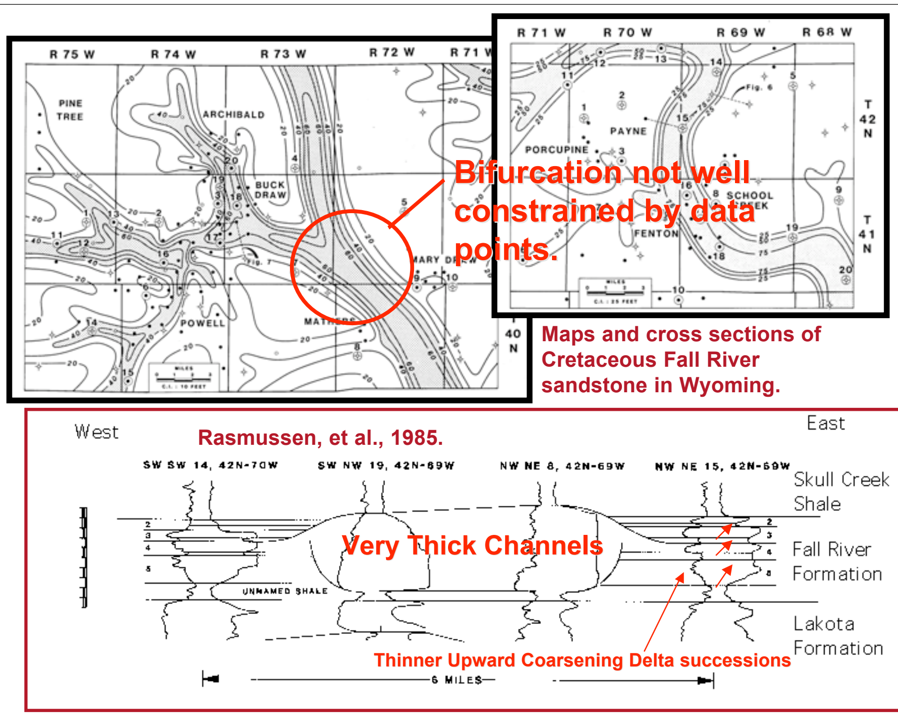


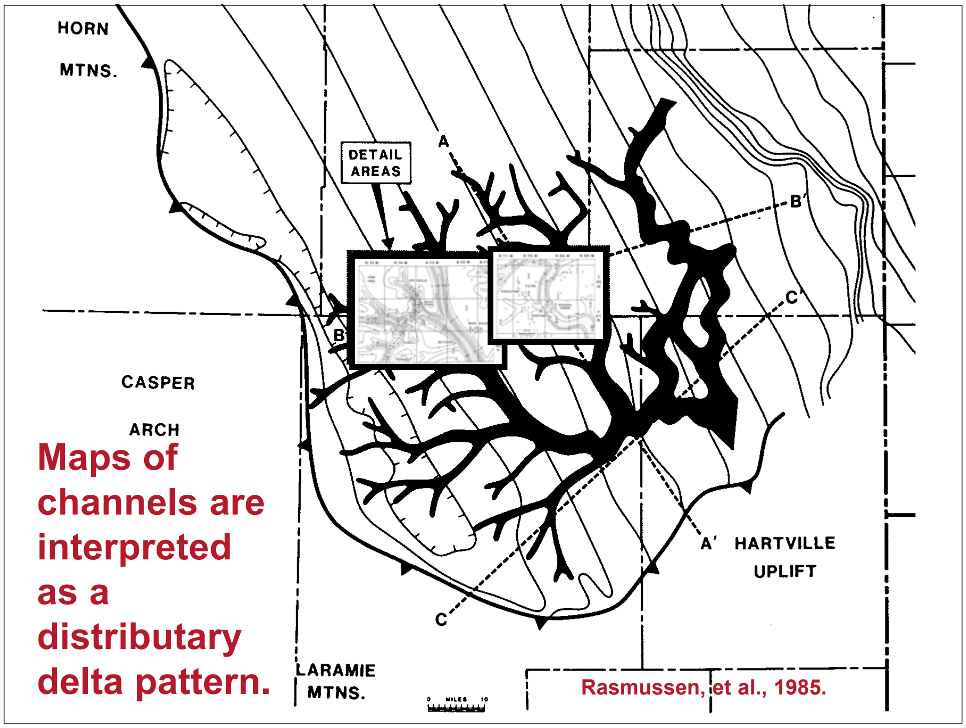
Note: Mapping shows
tributive valley networks

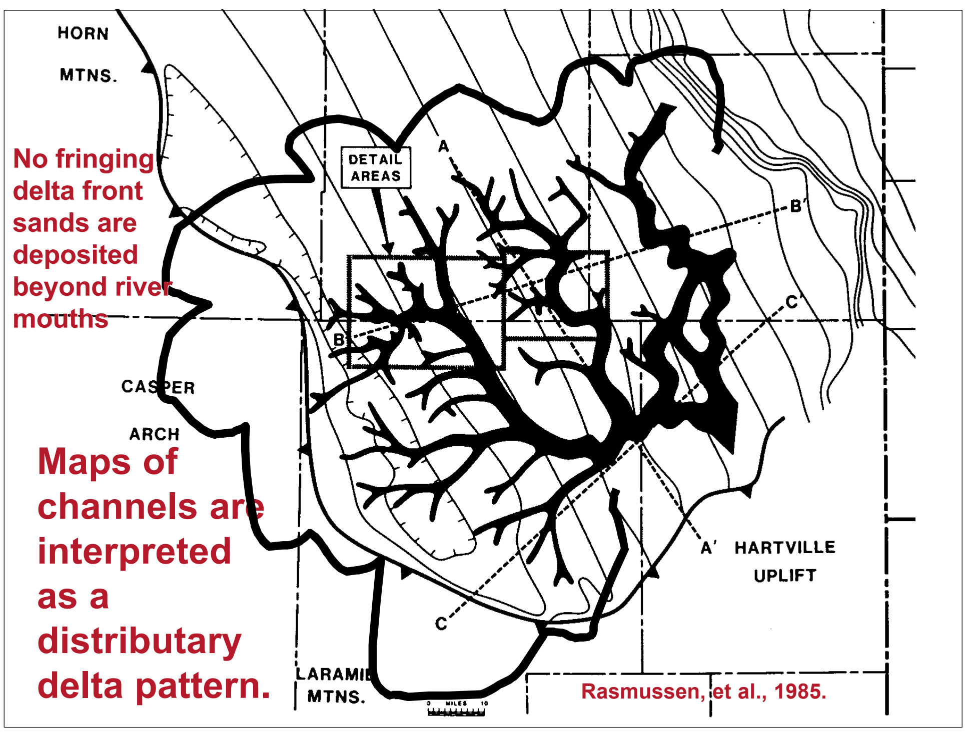
Bowen and Weimer, 2003

Ancient Examples in North America

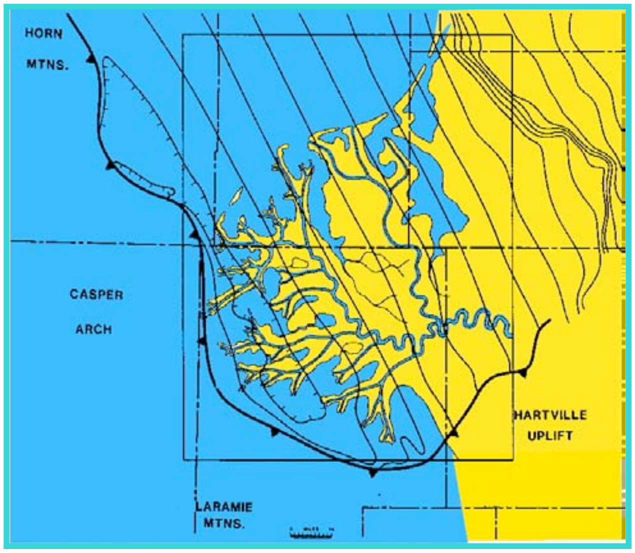
- Cretaceous




HORN
MTNS.
DETAIL AREAS
A
B
B′
C′
CASPER
ARCH
Maps of channels are interpreted as a distributary delta pattern.
A′
HARTVILLE
UPLIFT
C
LARAMIE
MTNS.
Rasmussen, et al., 1985.


HORN
MTNS.
No fringing delta front sands are deposited beyond river mouths
DETAIL AREAS
A
B
B′
C′
CASPER
ARCH
Maps of channels are interpreted as a distributary delta pattern.
A′
HARTVILLE
UPLIFT
C
LARAMIE
MTNS.
Rasmussen, et al., 1985.

Fall River Paleogeography



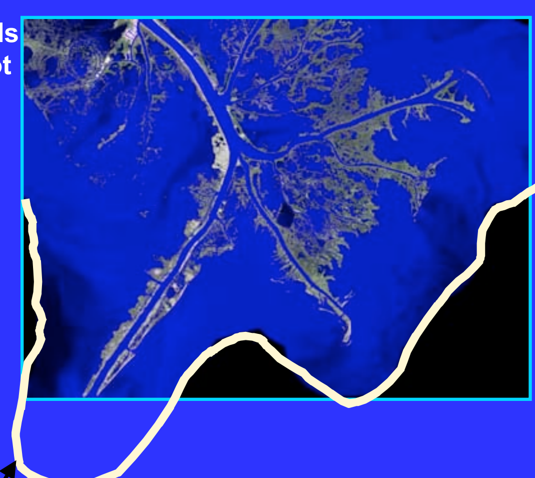
Fall River was interpreted as a Mississippi-type, birdfoot delta.

Modern Mississippi channels are mud-dominated versus Fall River which are sand dominated.

Rasmussen, Jump and Wallace, 1985

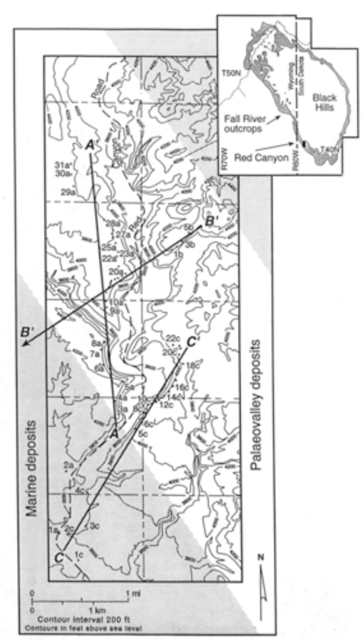
The Mississippi Delta

- Deep distributary channels of the Mississippi Birdfoot over-used as a modern analog.
- Scale not appropriate for smaller-scale interior seaway rivers.
- Interior epeiric seas are shallow.



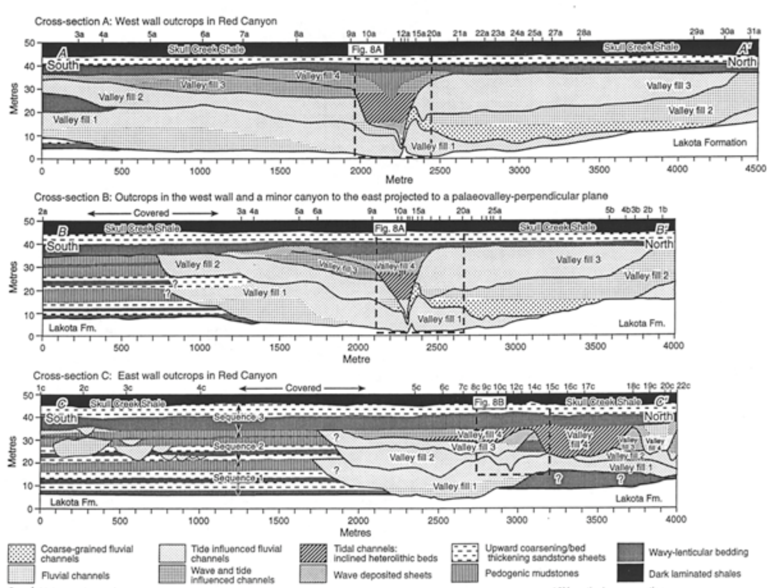
Fringe of sediment continues beyond channel mouths

Fall River Valley in Outcrop



Regional Cross Sections: Fall River Stacked Incised Valleys

from Willis, 1997



Cretaceous Incised Valley

Bedding Diagrams:
Multiple Channel Storeys in each Fall River Valley Fill

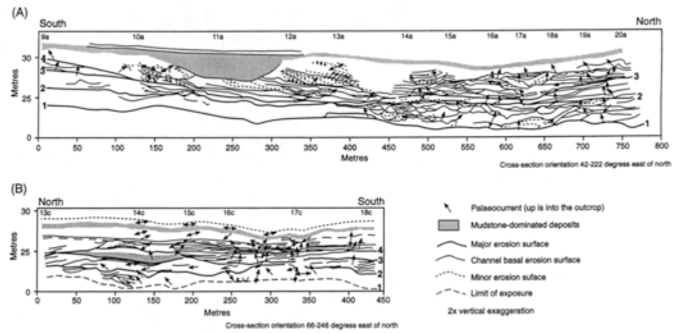


Fig. 8. Bedding diagrams showing stratal surfaces in the major sandstone-dominated body. (A) Outcrop located near the body axis. (B) Outcrop closer to the margin. Major erosion surfaces bound individual valley-fills (numbered 1–4), each containing many smaller-scale channel bodies. Numbered letters mark tops of measured sedimentologic logs. Note that Palaeocurrents are shown relative to an outcrop orthogonal (up is into the outcrop plane).

from Willis, 1997

Cretaceous Incised Valley

Correlated Vertical Sections Across Fall River Incised Valleys

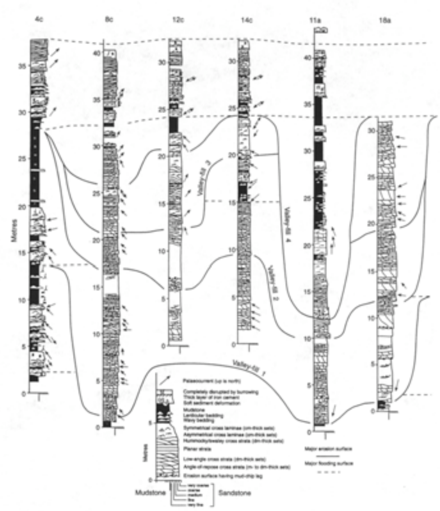
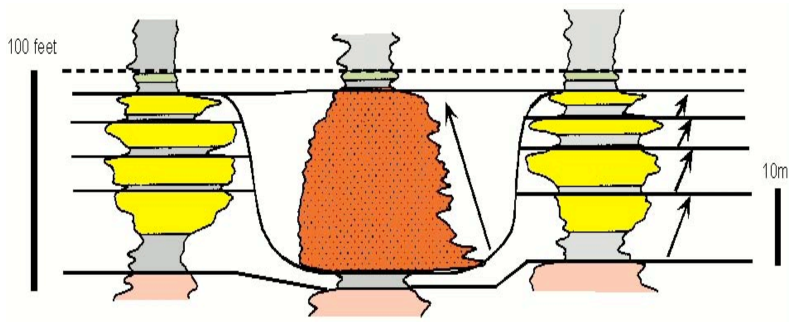


Fig. 4. Selected sedimentologic logs measured in Red Canyon. See Fig. 2 for location of logs within Red Canyon and the projected positions of logs on cross-sections in Fig. 3.

Willis, 1997

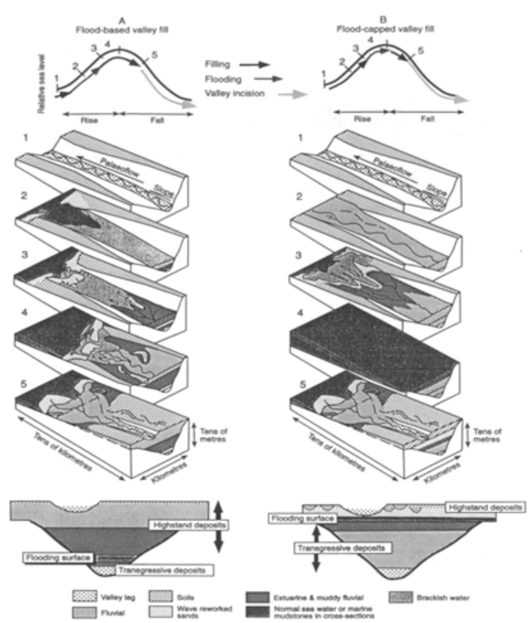
Fall River now interpreted as an Incised Valley (Willis, 1997)

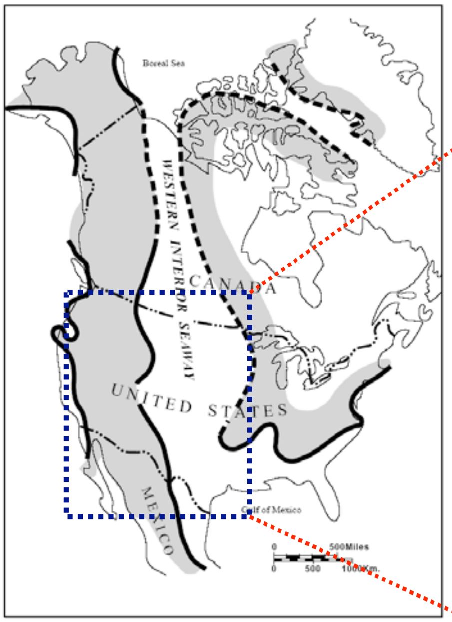


- Channel much thicker than associated upward coarsening delta deposits.
- Channel does not interfinger with adjacent marine facies.
- Channel is not contained within the delta front.
- Scale of channel is way too large (100 feet deep river?).

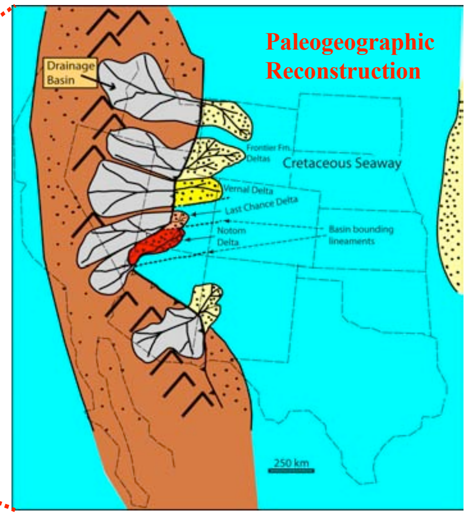
Model for Flood Capped versus Flood-Based Valley Fill

from Willis, 1997



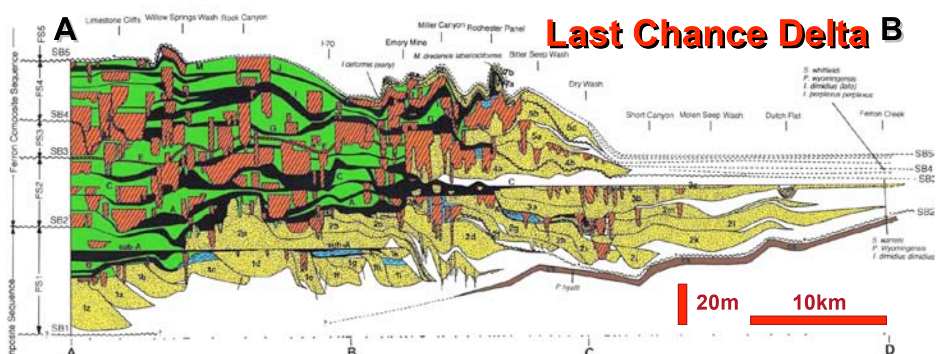


Outline of the Cretaceous Western Interior Seaway, North America.

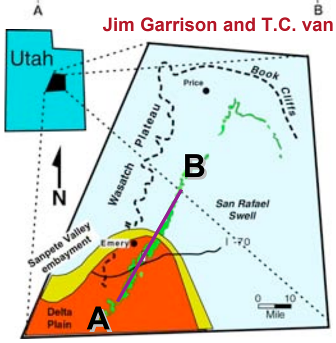


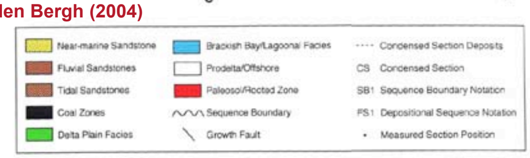
(from Krystinik and Dejarnett, 1995)

(from Bhattacharya and Tye, 2004)



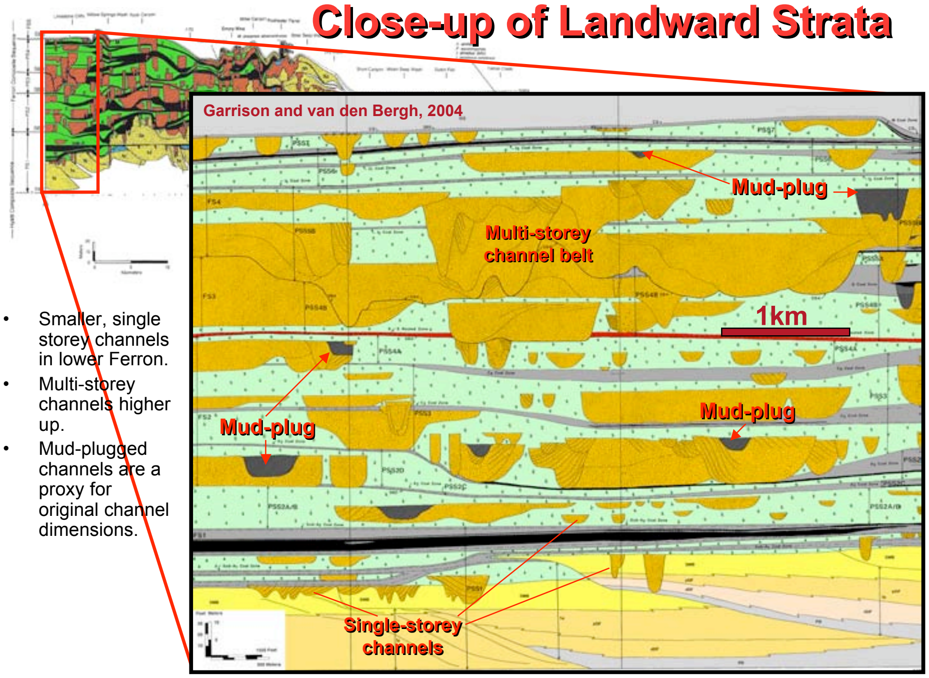
Jim Garrison and T.C. van den Bergh (2004)





- Dip-oriented regional cross section of the Last Chance Delta complex of the Ferron Sandstone (from Garrison and van den Bergh, 2004).
- Note multiple scales of channels and channel belts.

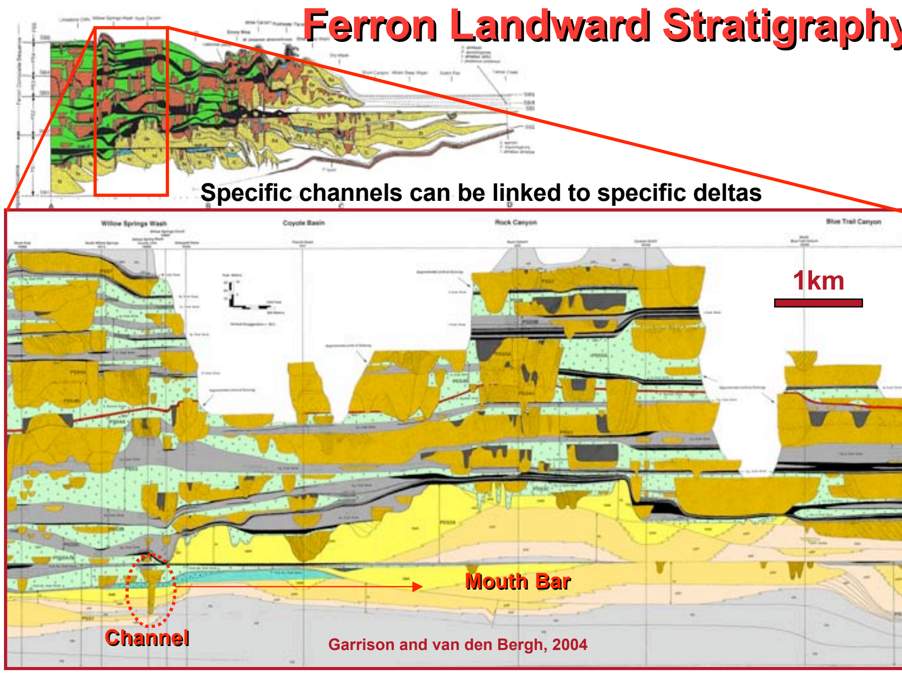
Close-up of Landward Strata



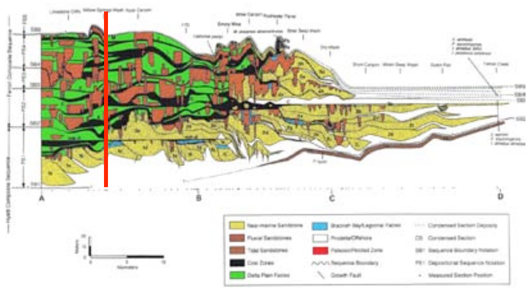
- Smaller, single storey channels in lower Ferron.
- Multi-storey channels higher up.
- Mud-plugged channels are a proxy for original channel dimensions.

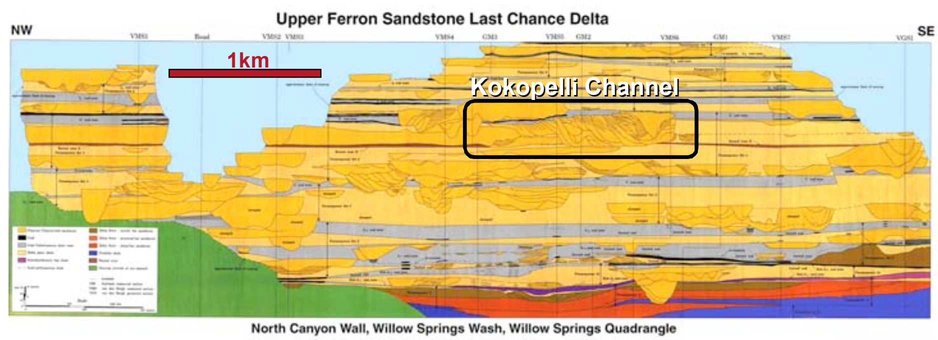
Ferron Landward Stratigraphy

Specific channels can be linked to specific deltas



Strike Panel



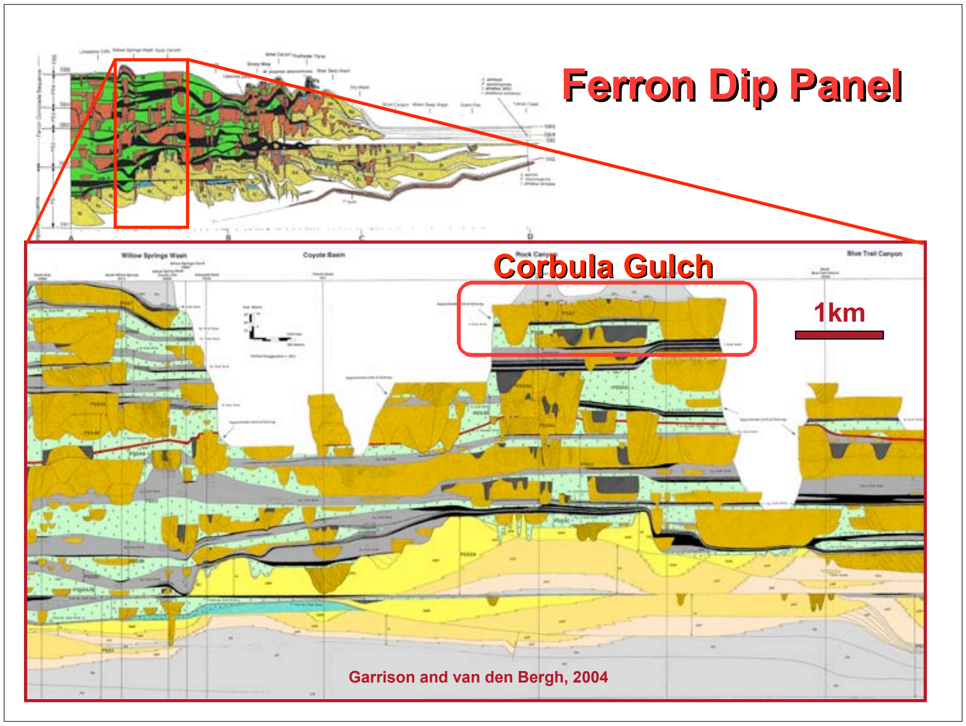


Garrison and van den Bergh, 2004

Kokopelli Channel Belt

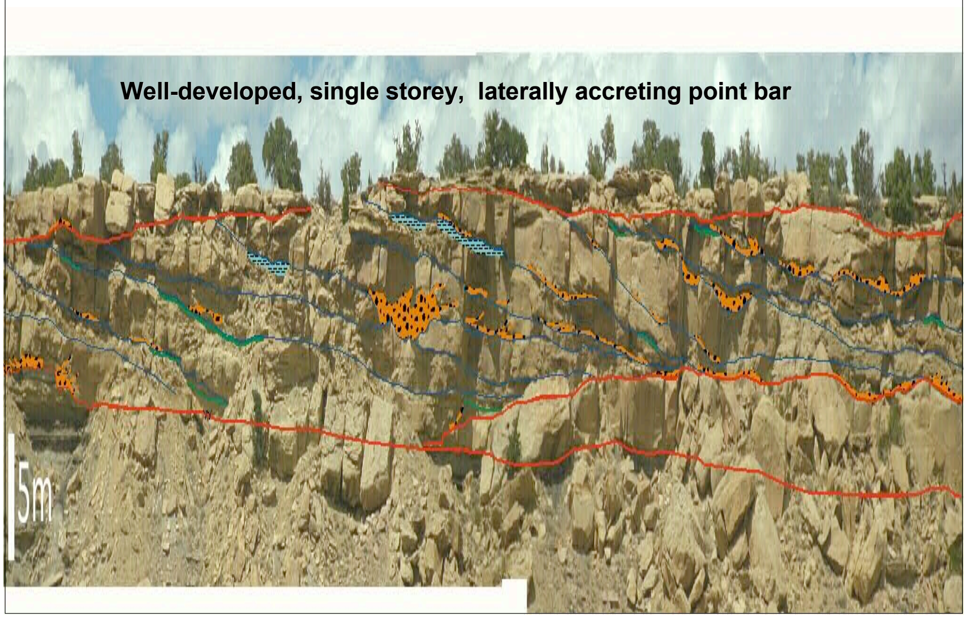
Garrison and van den Bergh, 2004

- Interfingering of the channel belt and adjacent floodplain.
- Unconfined channel.
- Multi-lateral and locally multi-storey.
- This is NOT a valley.
- Channel is about 10 meters deep.

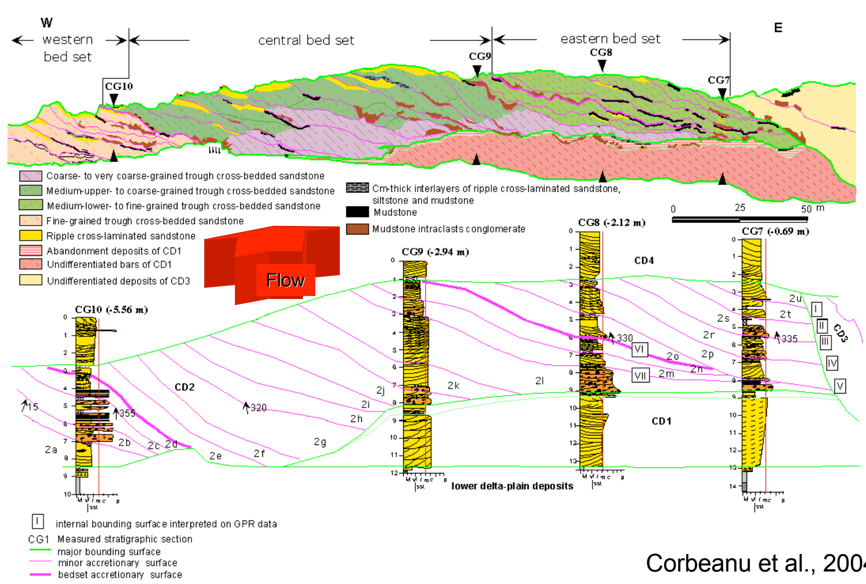

Ferron Dip Panel
Corbula Gulch
1km
Garrison and van den Bergh, 2004


Single-storey channels
200m
5m

Single-storey channels

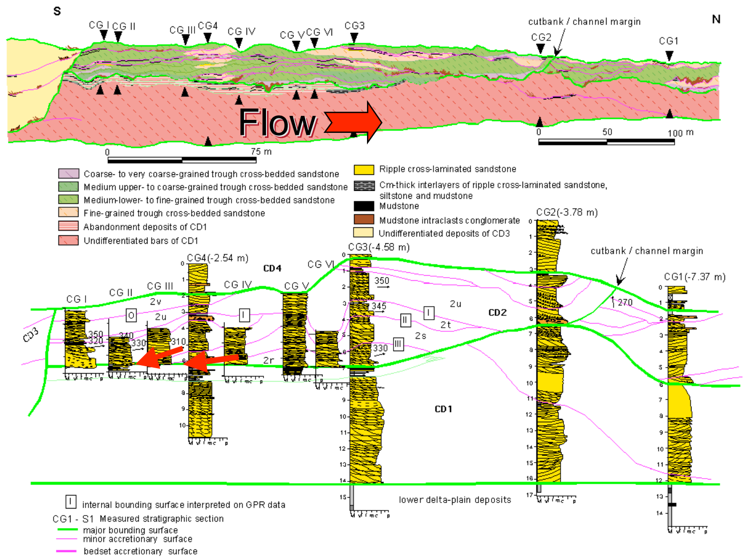


Facies Architecture - strike view



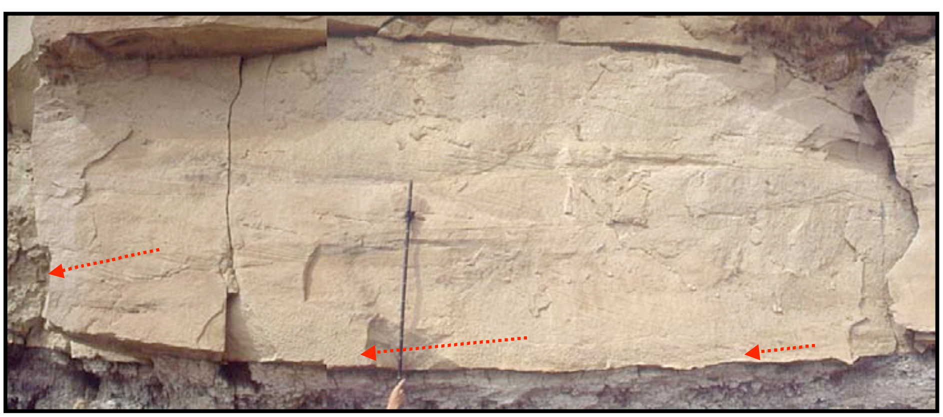
Corbeanu et al., 2004

Facies Architecture - dip view

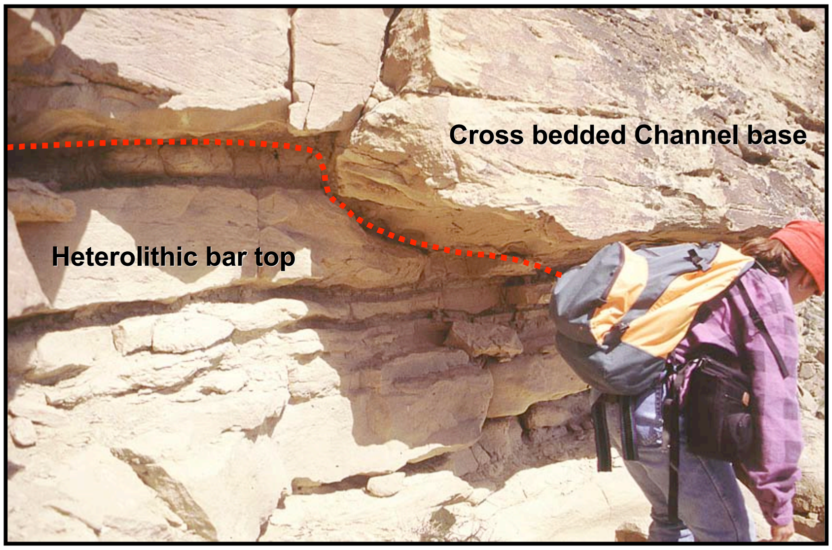


Corbeanu et al., 2004

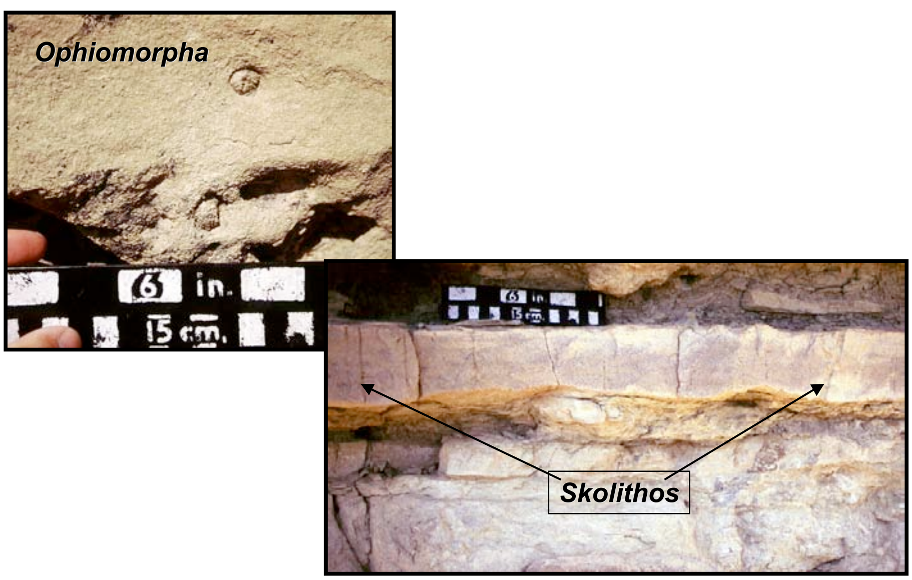
Climbing Trough Cross Strata



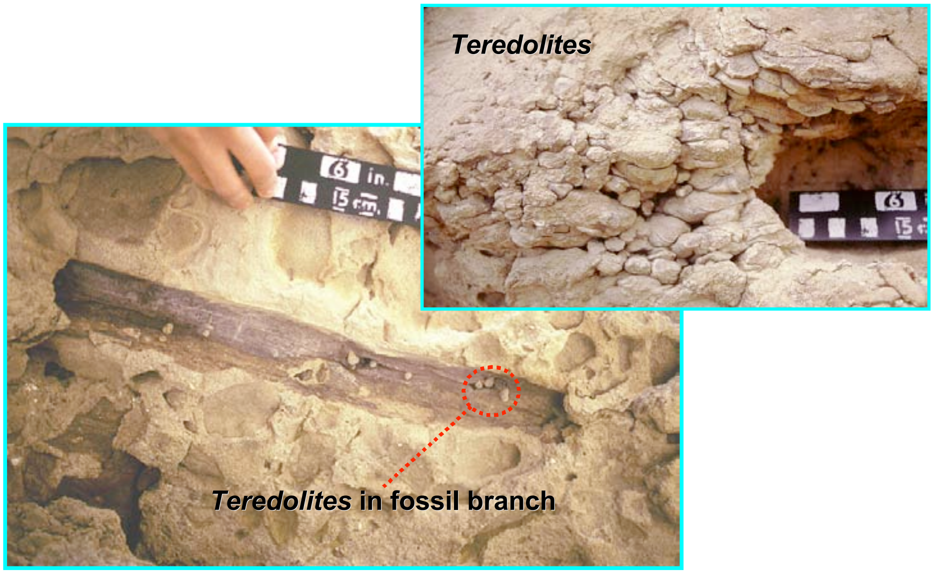
Marine-influenced point bar



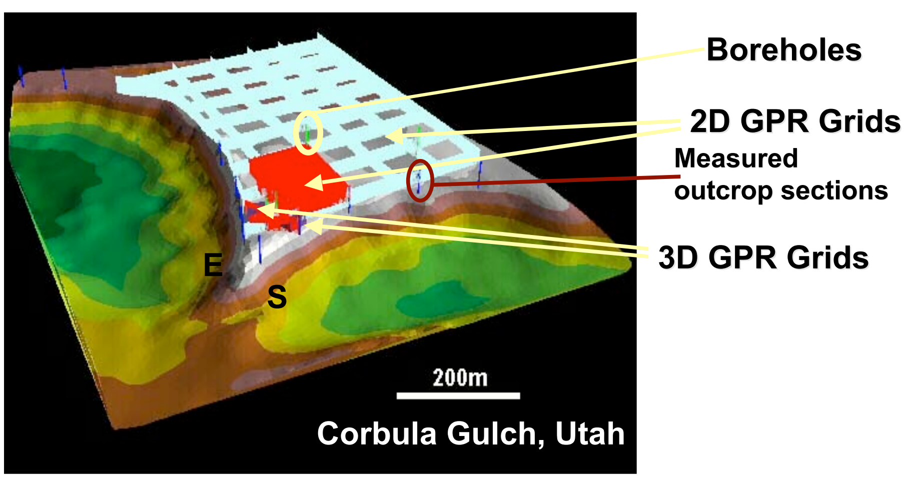
Marine-influenced point bar

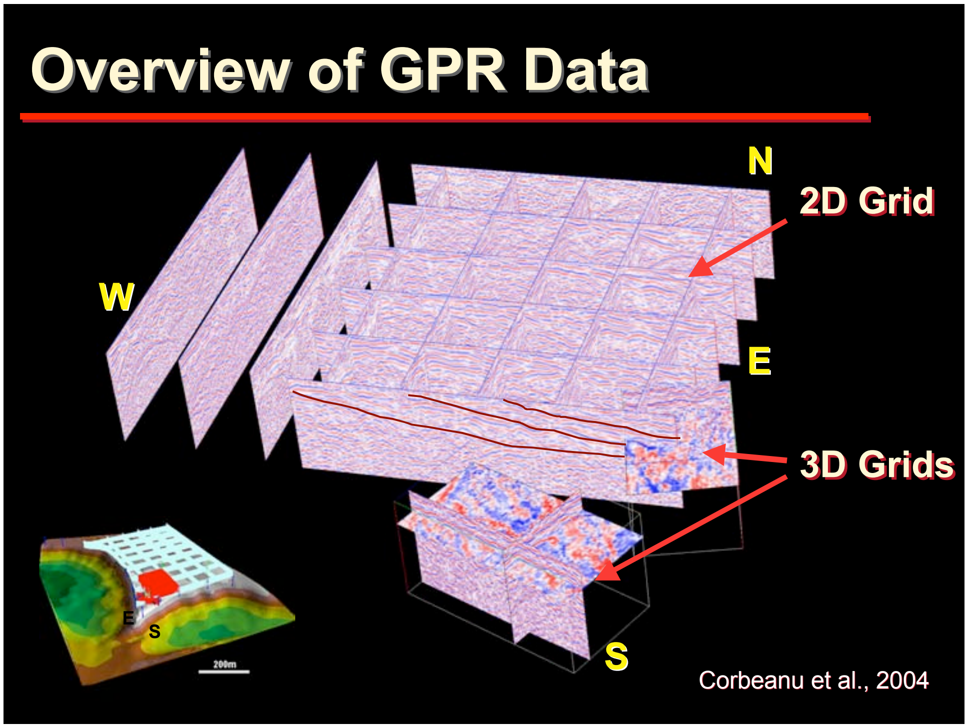


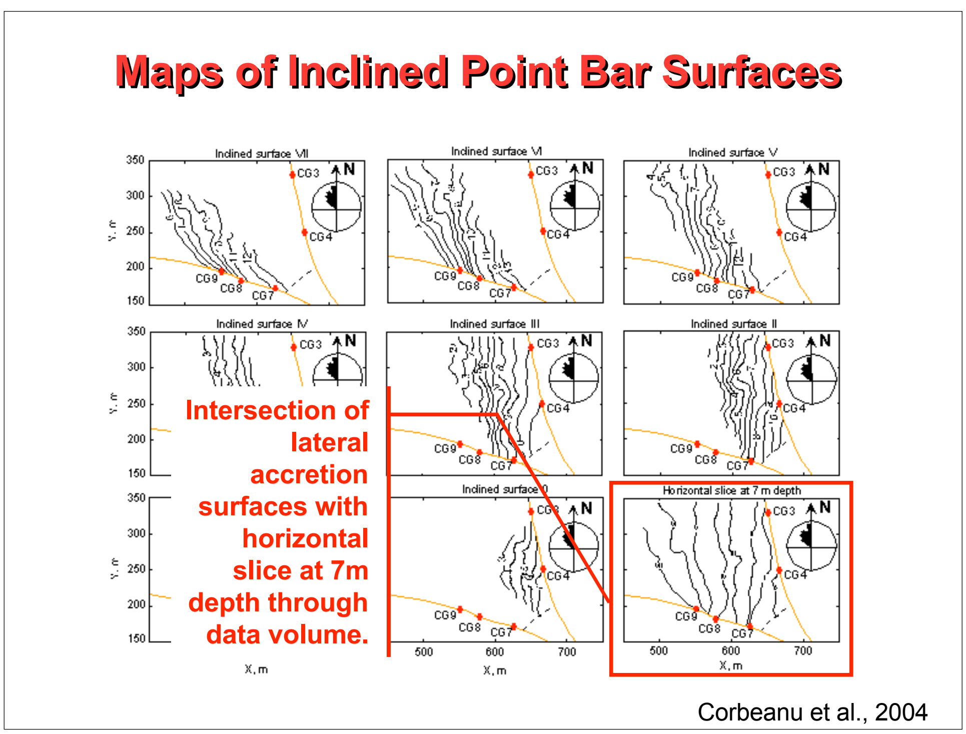
Marine-influenced point bar



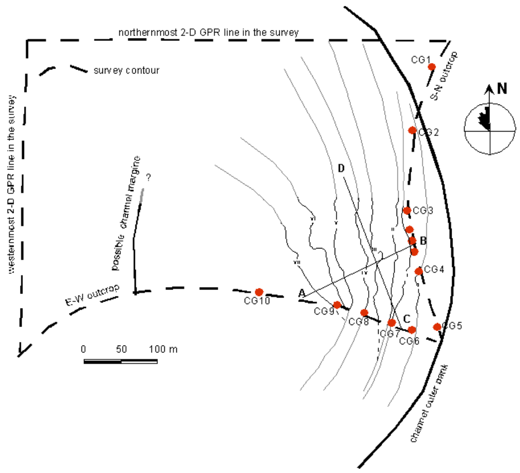
3D projection of data coverage, positioned on terrain map using GPS




Overview of GPR Data
N
2D Grid
W
E
3D Grids
S
Corbeanu et al., 2004


Maps of Inclined Point Bar Surfaces
Inclined surface VII
Inclined surface VI
Inclined surface V
Inclined surface IV
Inclined surface III
Inclined surface II
Inclined surface 0
Horizontal slice at 7 m depth
Intersection of lateral accretion surfaces with horizontal slice at 7m depth through data volume.
X, m
Y, m
Corbeanu et al., 2004

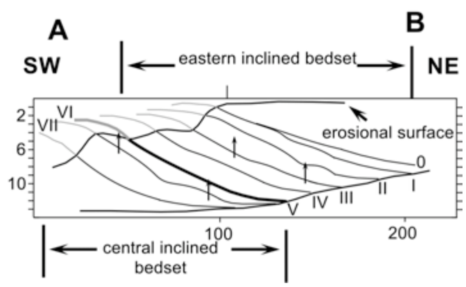
3D Paleochannel Reconstruction



- Paleochannel dimensions
  - bankfull width: 225 -150 m
  - bankfull depth: 3.9 - 5.2 m

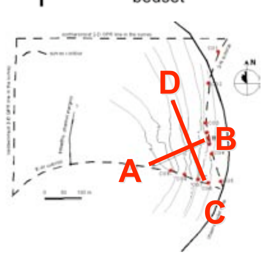
Corbeanu et al., 2004

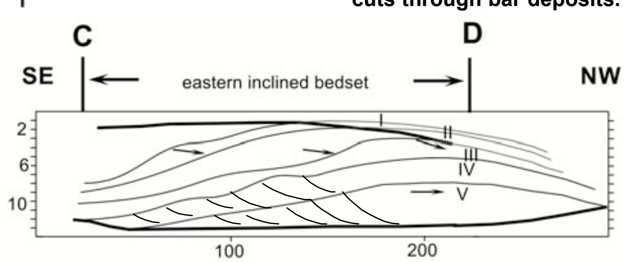
3D Paleochannel Reconstruction



- Laterally accreting distributary channel
  - not straight.

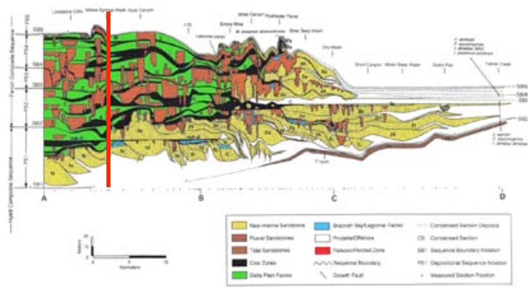
Upstream accretion seen in variable cuts through bar deposits.

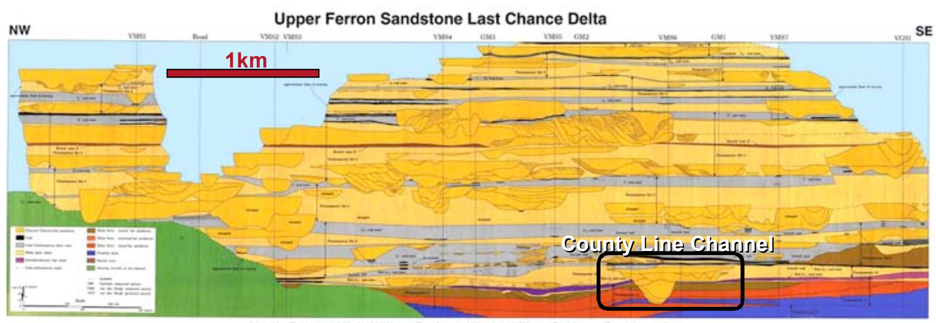




Corbeanu et al., 2004

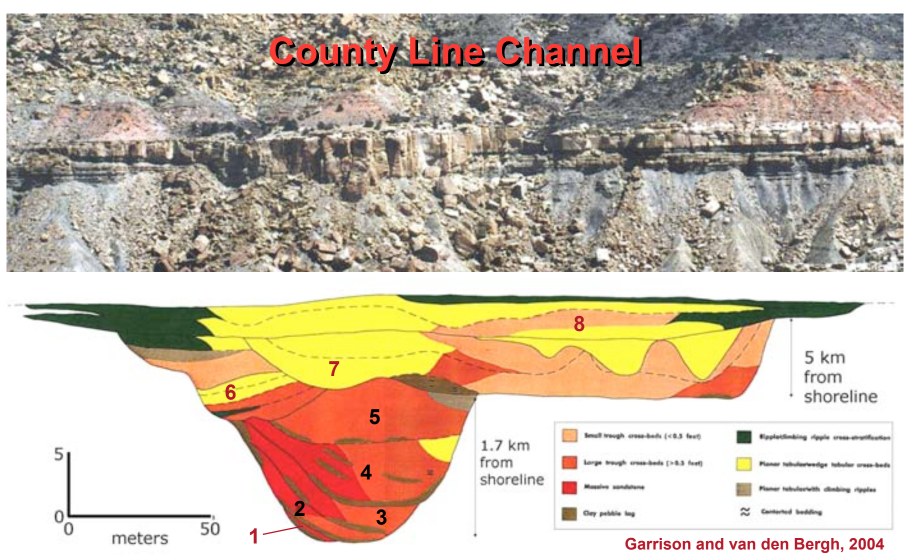
Incised Rivers





North Canyon Wall, Willow Springs Wash, Willow Springs Quadrangle

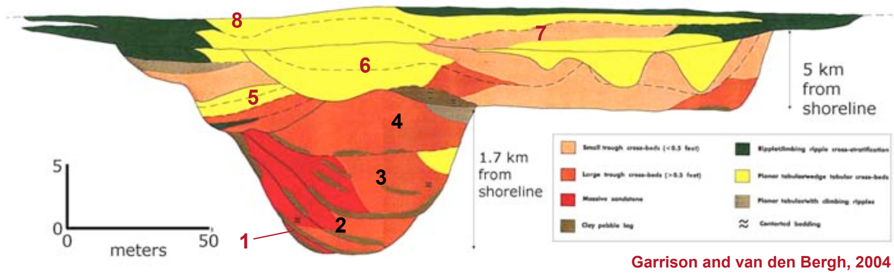
Garrison and van den Bergh, 2004



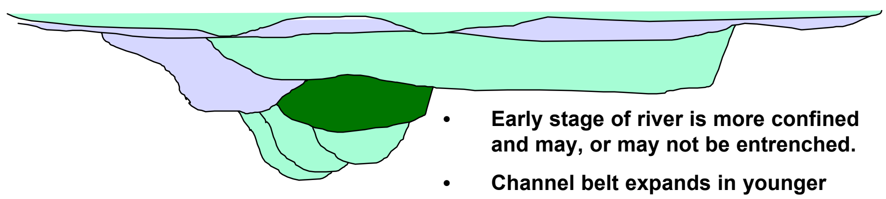
- Lower stories appear to be entrenched
- Upper stories inter-finger with floodplain

Garrison and van den Bergh, 2004

County Line Channel

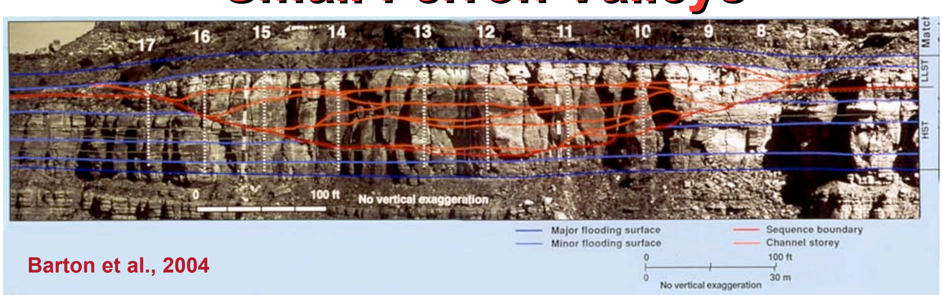


Garrison and van den Bergh, 2004

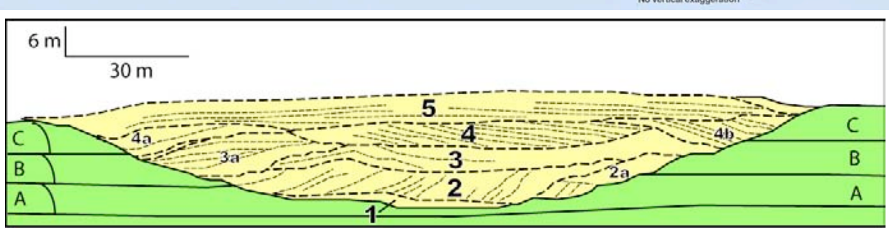


- **Early stage of river is more confined and may, or may not be entrenched.**
- **Channel belt expands in younger storeys.**

Small Ferron Valleys

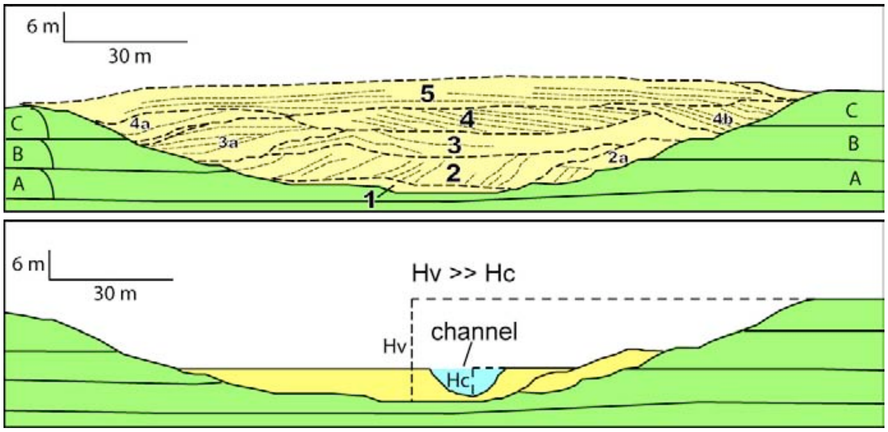


Barton et al., 2004



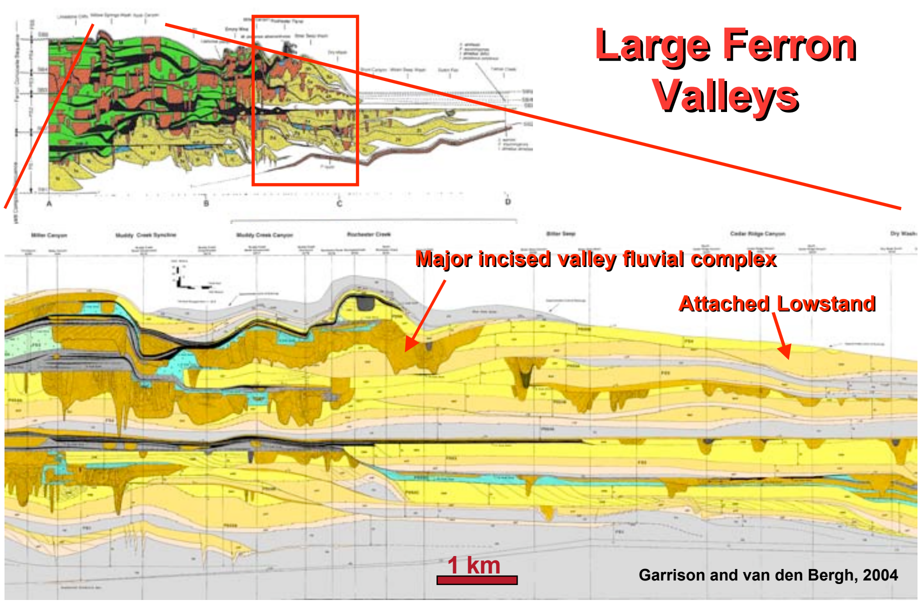
- 30 m deep, multistorey incision and fill, south side of I70.
- These incisions have been interpreted as Mississippi-scale distributary channels.
- Detailed analysis suggest that they are small, incised valleys.

Small Ferron Valleys

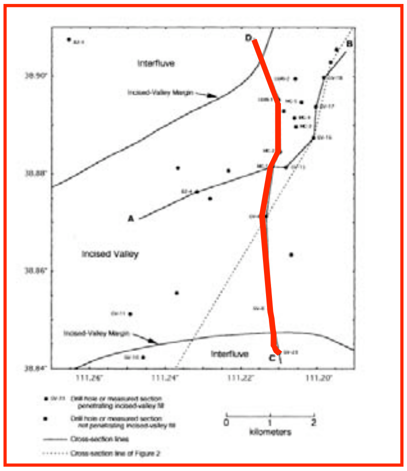


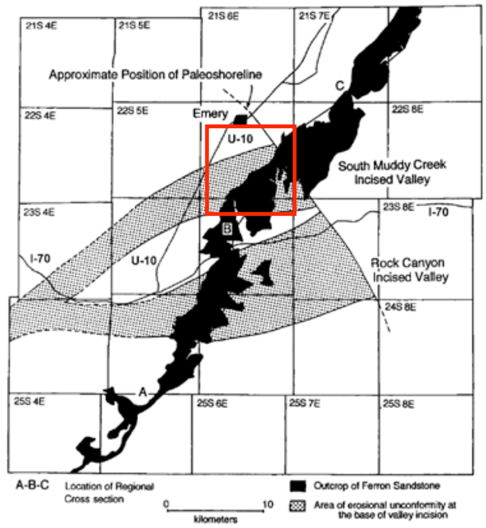
- Depth of valley = 30m
- Maximum depth of channel = 9m
- Channel width = 30m to 250 m

Large Ferron Valleys



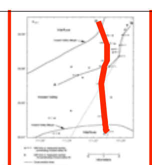
Wide Ferron Valleys
Last Chance Delta

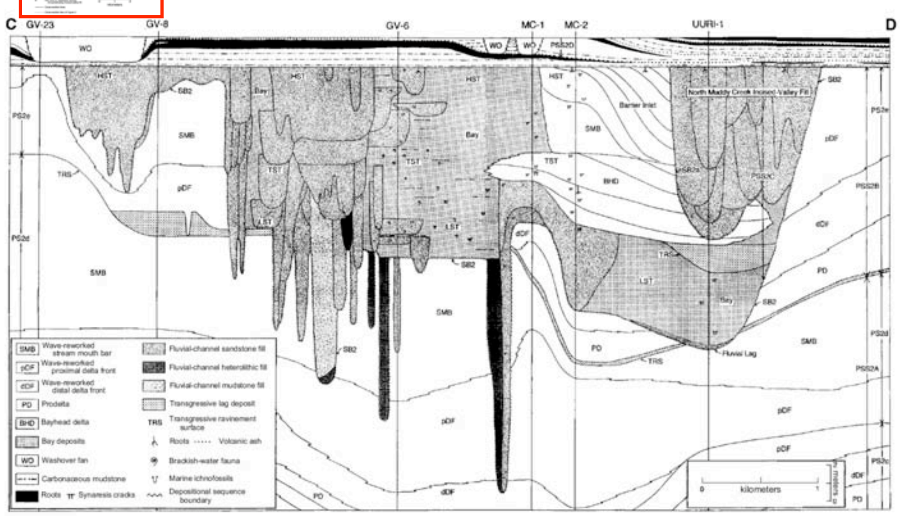




Garrison and van den Bergh (2006)

Wide Ferron Valleys

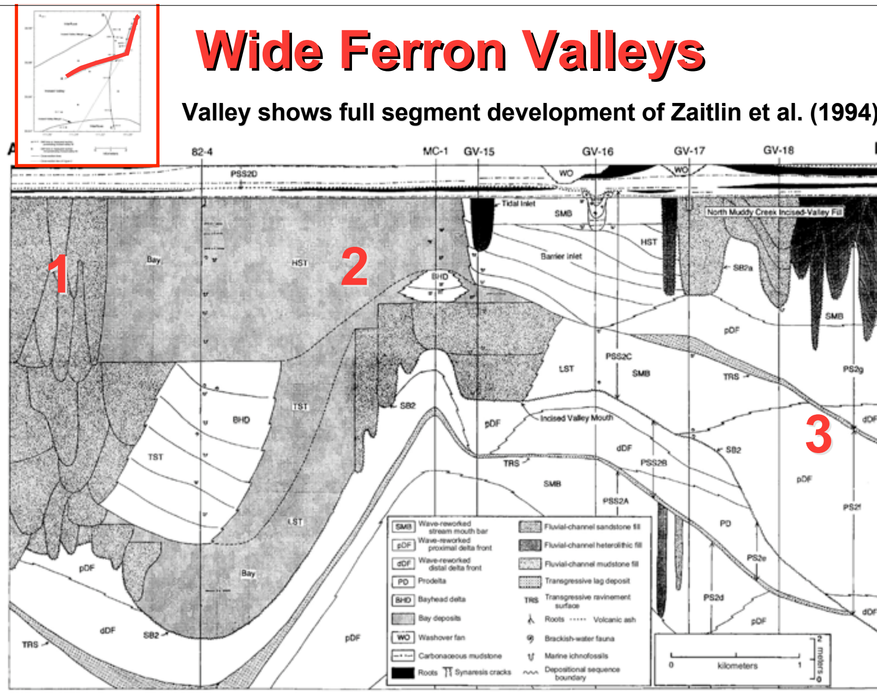




Garrison and van den Bergh (2006)

Wide Ferron Valleys

Valley shows full segment development of Zaitlin et al. (1994)

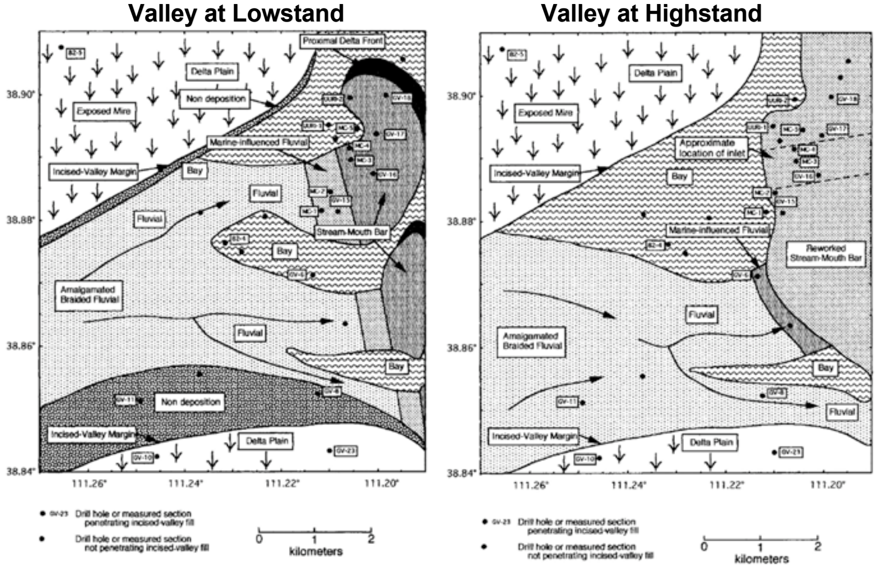


Garrison and van den Bergh (2006)

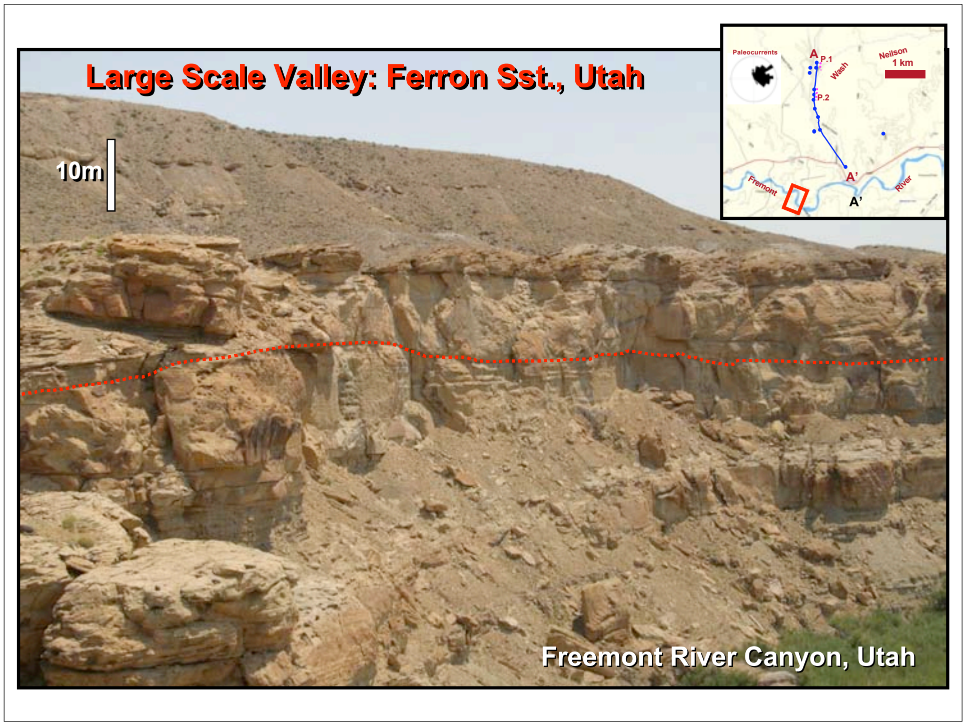
Wide Ferron Valleys

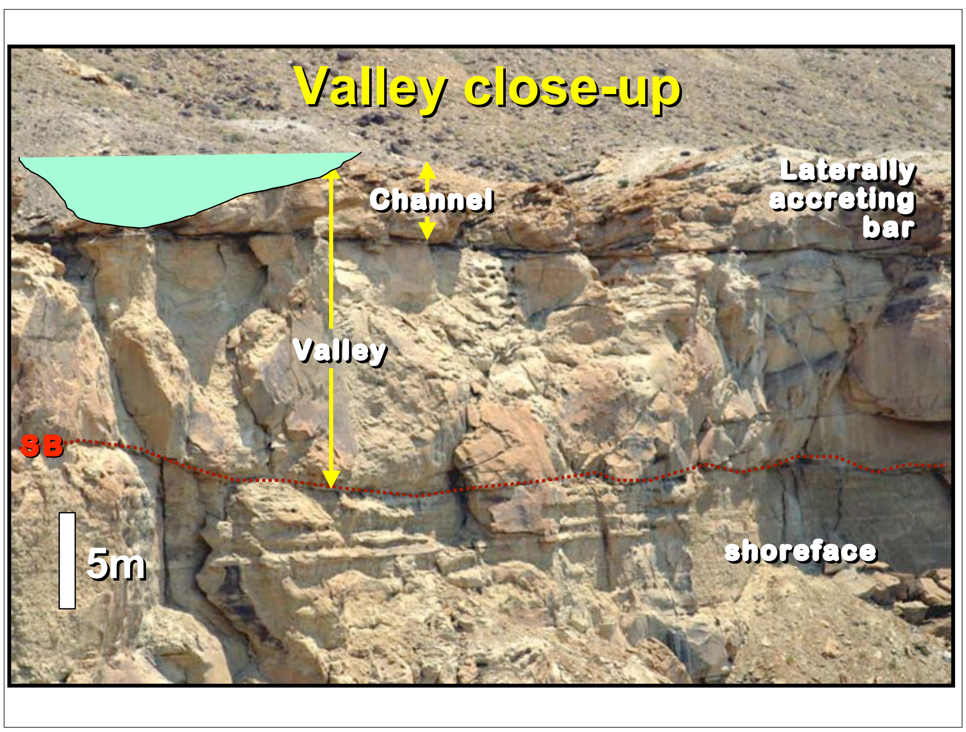
Valley at Lowstand

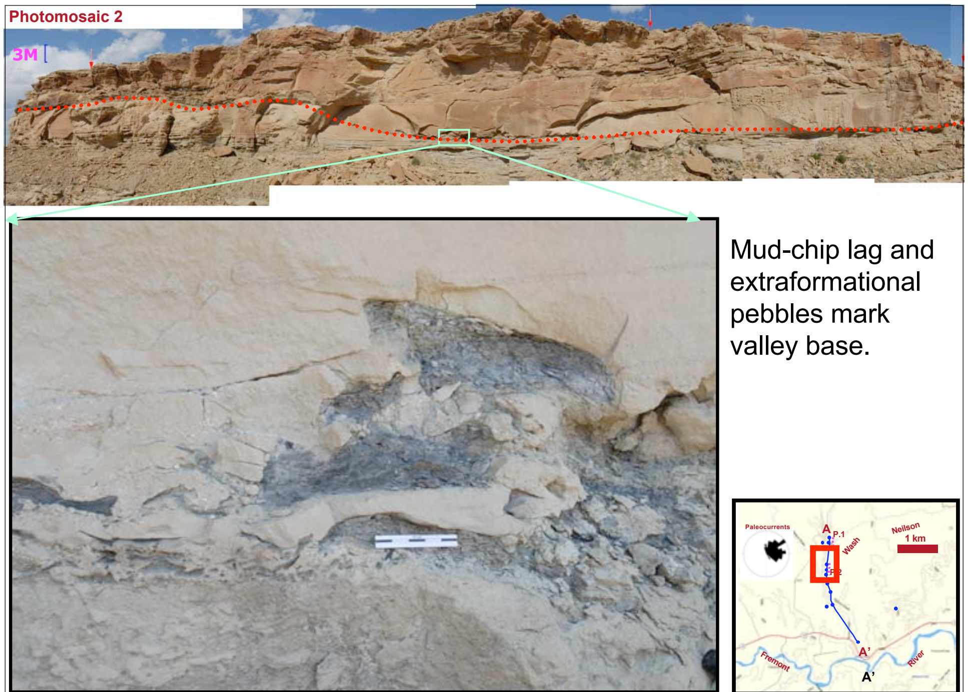
Valley at Highstand



Garrison and van den Bergh (2006)

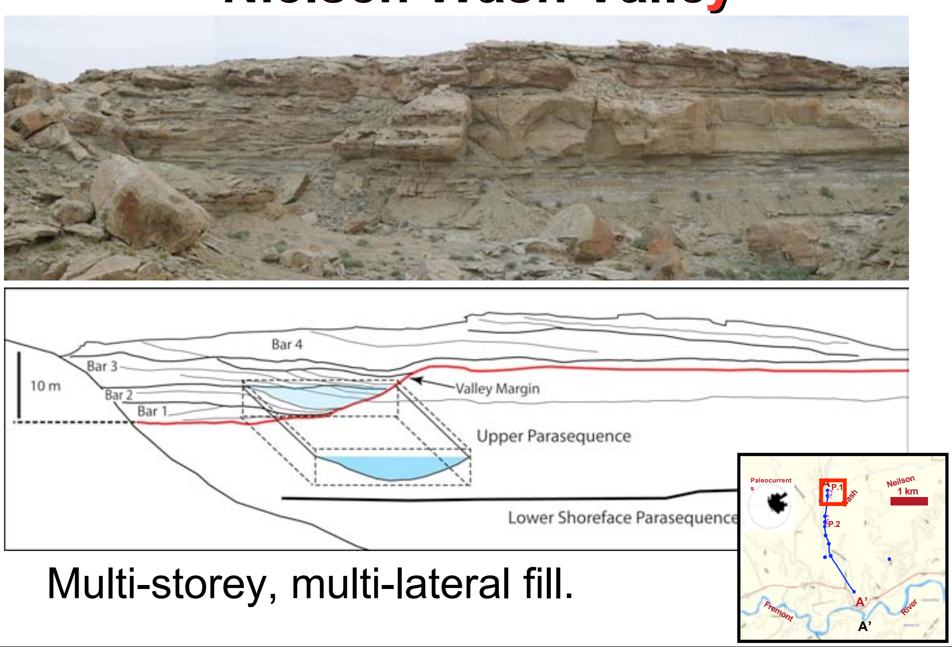

Large Scale Valley: Ferron Sst., Utah
10m
Paleocurrents
A
P.1
P.2
Wash
Neilson
1 km
A'
Fremont
River
A'
Freemont River Canyon, Utah


Valley close-up
Channel
Laterally accreting bar
Valley
SB
5m
shoreface



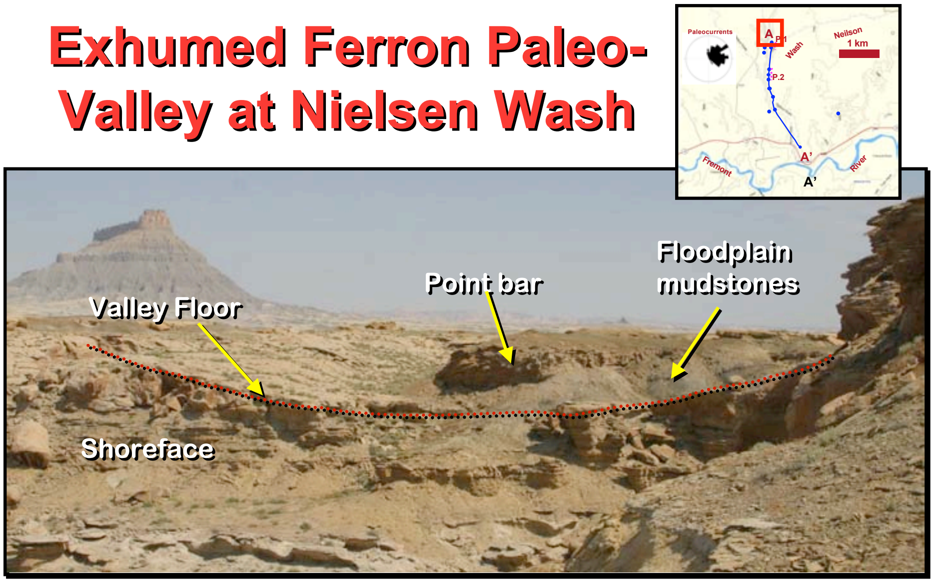
Mud-chip lag and extraformational pebbles mark valley base.

Nielsen Wash Valley



Multi-storey, multi-lateral fill.

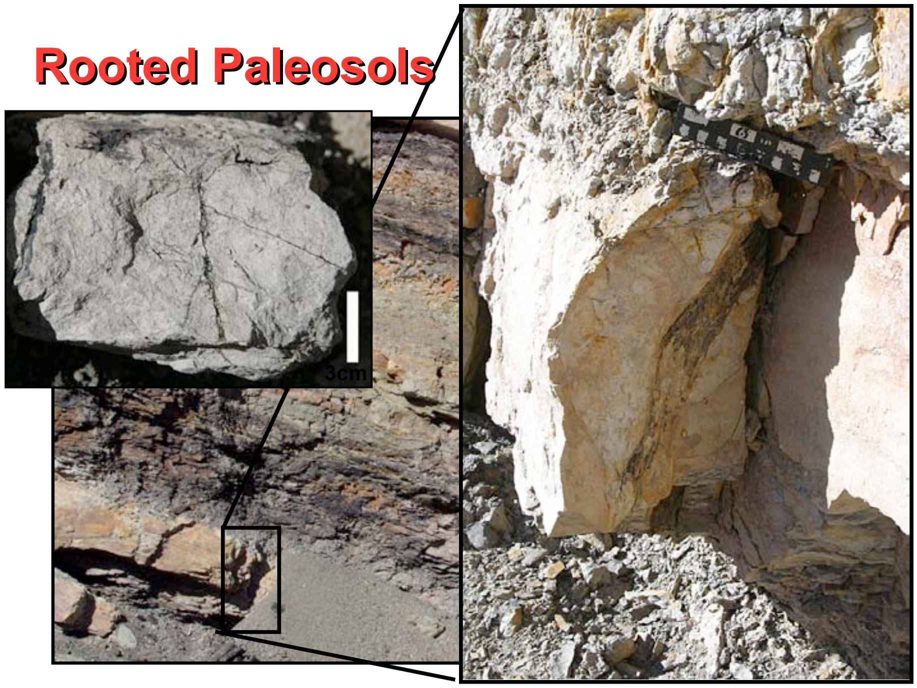
Exhumed Ferron Paleo-Valley at Nielsen Wash



Laterally migrating bar overlies floodplain mudstone, contained within larger erosional feature (valley).

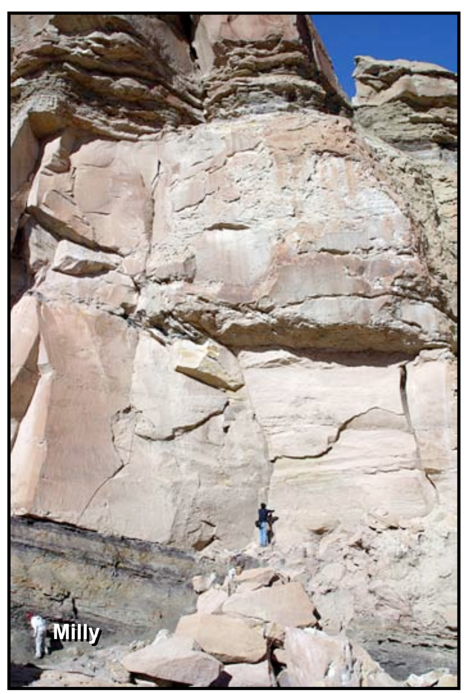
Floodplain to Fluvial Successions

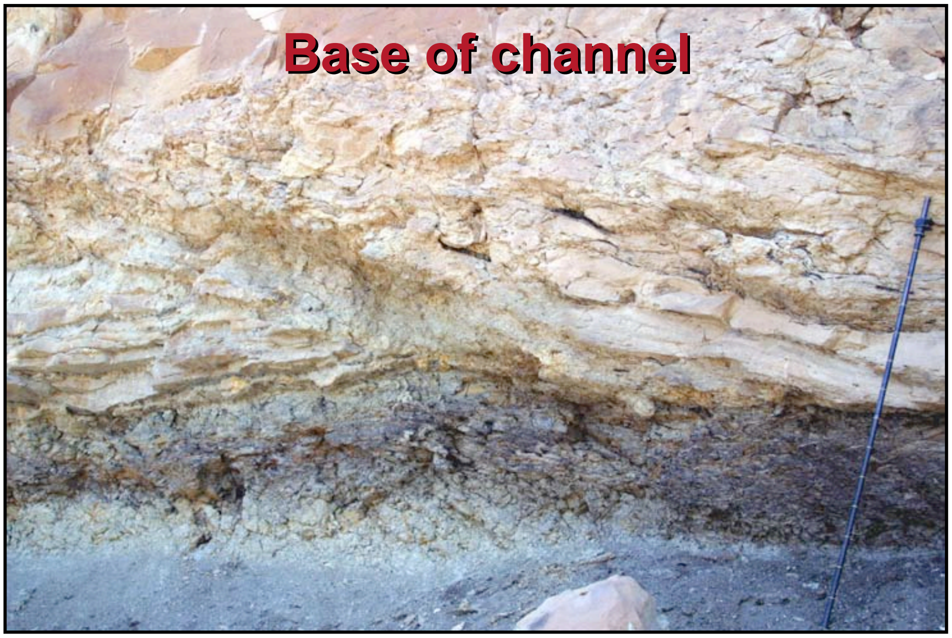
Rooted Paleosols

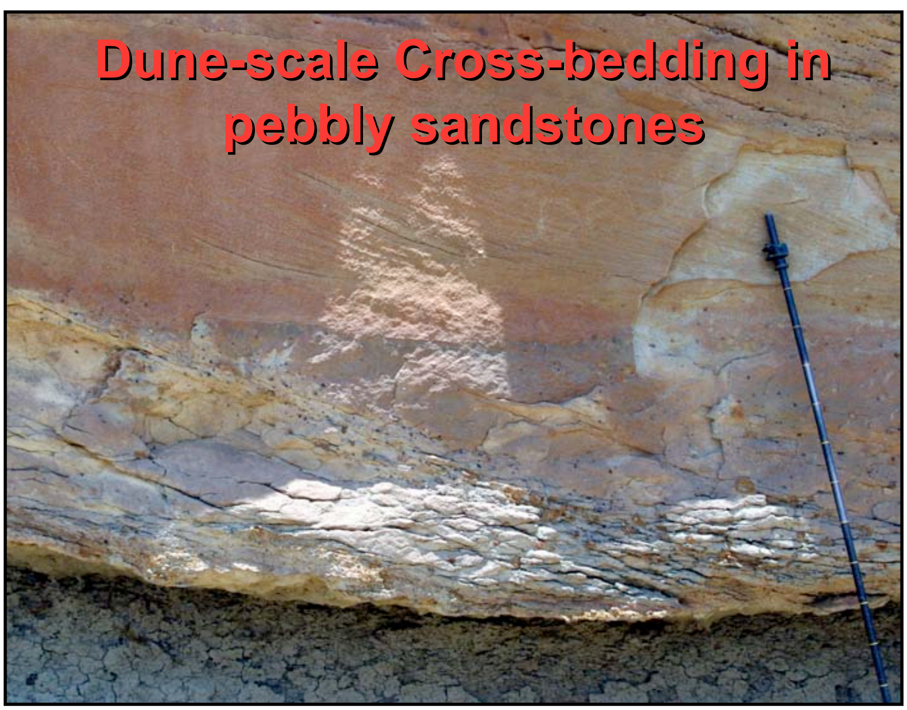


Thick Fluvial Channels overlie Floodplain Mudstones

Thickness of fluvial
sandstone body
suggests that it may be
a bvalley-scale feature

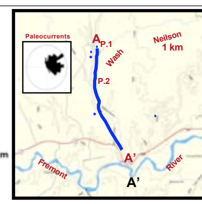


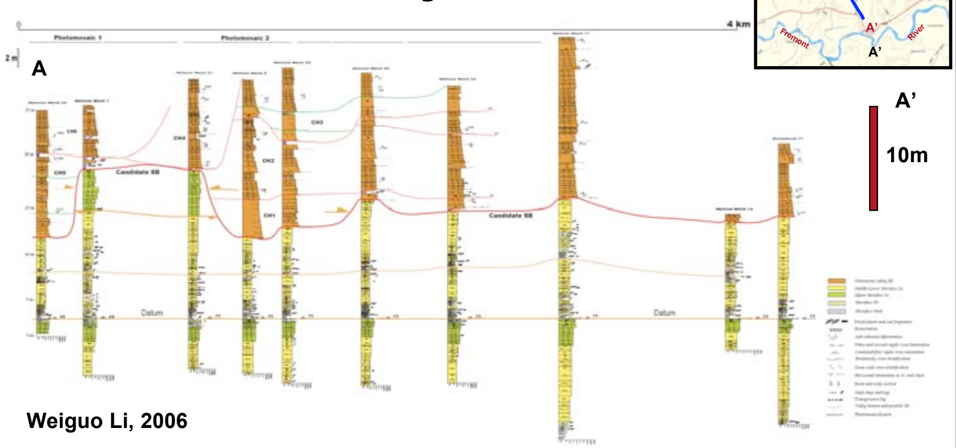

Base of channel


Dune-scale Cross-bedding in
pebbly sandstones

Channel fills locally conglomeratic

Strike Cross Section of Incised Valley





Weiguo Li, 2006

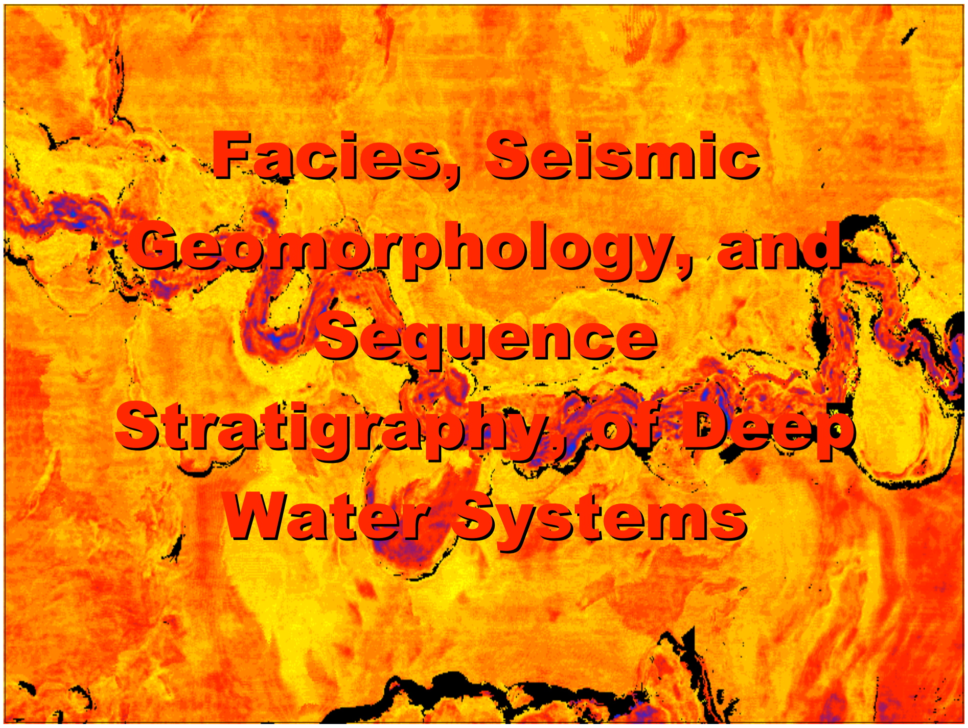
- Incised valley is indicated by truncation, onlap and rooted inter-fluve.
- Valley incises into storm-dominated marine parasequences.
- Valley has been traced for over 4 km along strike.

Non-Marine Sequence Stratigraphy

- Accommodation cycles can cause regular arrangement of sandstone stacking patterns (Shanley &McCabe, 1994).
- Accommodation cycles may be driven by tectonic changes, climate changes, and sea-level changes.
- A lot of research looking for 'Milankovitch' cycles in non-marine facies.
- Facies partitioning reflects accommodation
  - Is mud deposited on floodplain or transported and bypassed through system?
  - Is sand stored in channels or bypassed into marine or lacustrine system?
- Do sandstone-rich fluvial deposits reflect incised valleys or widespread change in accommodation?
  - Castlegate sandstone, Utah.

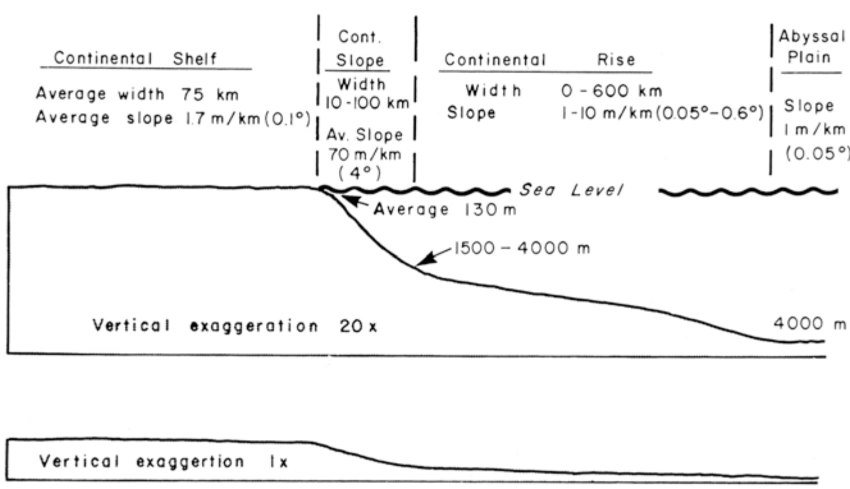
Accommodation vs. Fluvial Stacking Patterns

- Decreasing accommodation may be associated with fluvial bypass, formation of incised valleys, and fluvial terraces.
- Formation of incised valleys may be diminished in foreland basins.
- Slowly increasing accommodation may be associated with amalgamated channel and channel bell sandstones and fluvial-dominated valley fills.
- Rapidly increasing accommodation may result in estuarine-dominated valley fills, tidally-influenced fluvial deposits, and floodplain dominated fluvial deposits.
- Medium rates of increasing accommodation (e.g. highstand) may result in floodplain-dominated fluvial deposits.



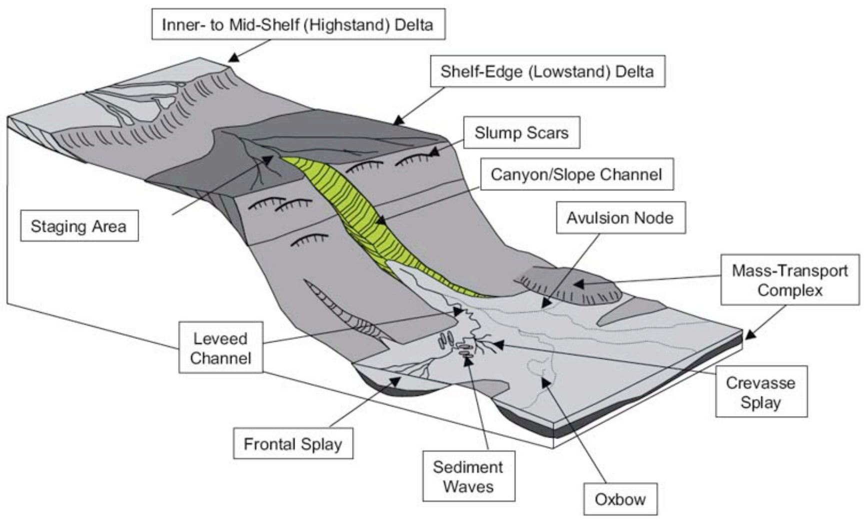
Deep Water Systems

Continental Margins



From Boggs, 1995, after Drake and Burk (1974), modified by Cook et al. (1982)

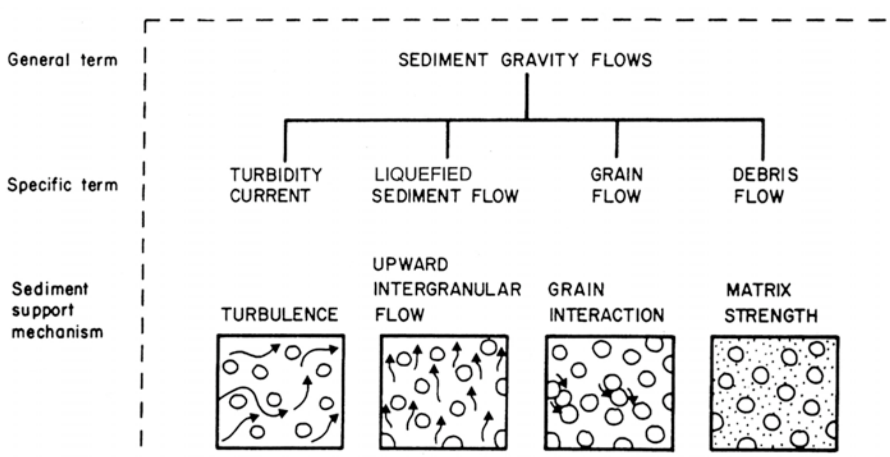
Deep Water Elements



Posamentier and Walker, 2006

Deep Water Systems

Sediment Gravity Flows

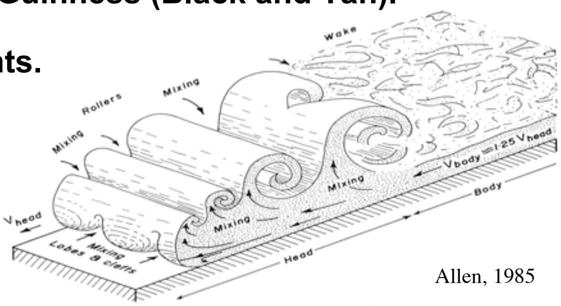


Middleton and Hampton, 1973

Deep Water Systems

Density Underflows

- Warm water flowing into cold water.
- Salt water flowing into fresh or brackish water.
- Bass overlying Guinness (Black and Tan).
- Turbidity currents.



Allen, 1985

Deep Water Systems

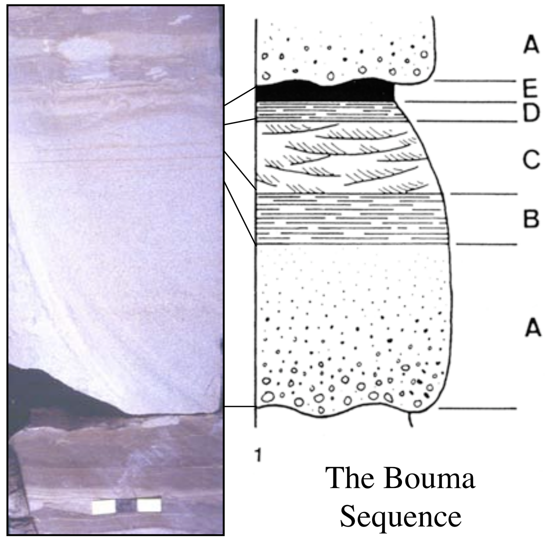
Ancient Turbidites

- Typically monotonous thick succession of interbedded shales and muddy sandstones (flysch, “classical” turbidites).

Deep Water Systems

Ancient Turbidites

- Bouma (1962) noted that individual beds showed a regular succession of sedimentary structures.

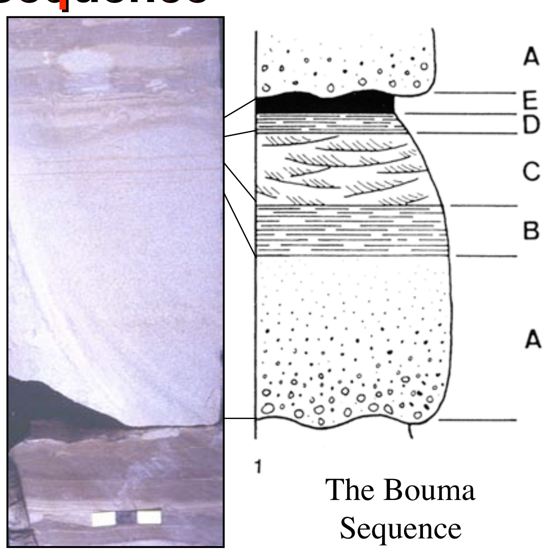


The Bouma Sequence

From Boggs, 1995 after Hsu, 1989

The Bouma Sequence

- T_a - Massive Division
- T_b - Parallel laminated
- T_c - Rippled Division
- T_d - Parallel Laminated
- T_e - Mud (Pelagic)

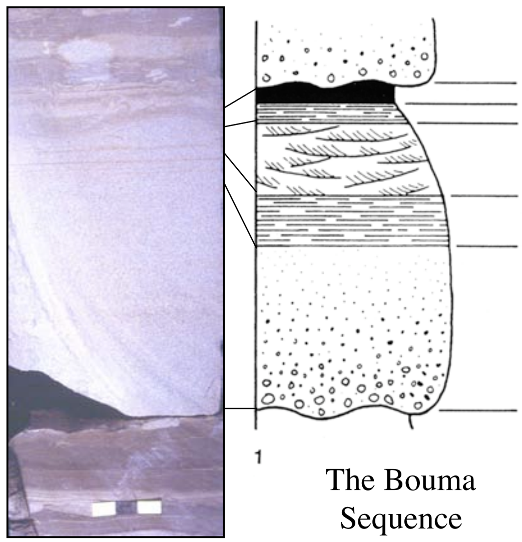


The Bouma Sequence

From Boggs, 1995 after Hsu, 1989

Mechanisms associated with Bouma Divisions

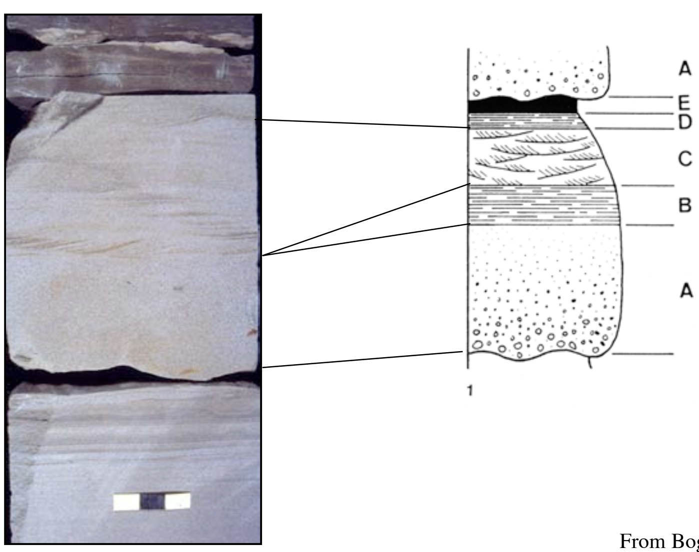
- T_a - Fluidization
- T_b - Traction
- T_c - Traction
- T_d - Suspension/Traction
- T_e - Suspension



The Bouma Sequence

From Boggs, 1995 after Hsu, 1989

The Bouma Sequence



From Boggs, 1995 after Hsu, 1989

Bouma Sequences

T_{acde} unit, Panther Tongue Delta, Utah

T_{abe} units, California

Bouma Sequences

T_{BC} units, North Slope, Alaska

T_{CDE} units Washington coast, note normal grading

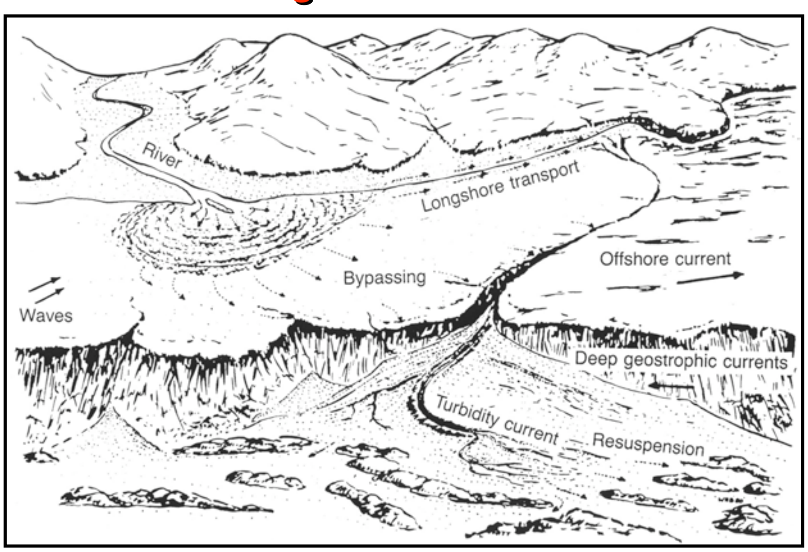
Deep Water Systems

Ancient Turbidites

- **Commonly show association with deepwater fossils or trace fossils, although shallow water fauna can be introduced into deeper water by turbidity current.**
- **Commonly sharp-based with unidirectional tool and flute marks.**

Deep Water Systems

Continental Margin Processes

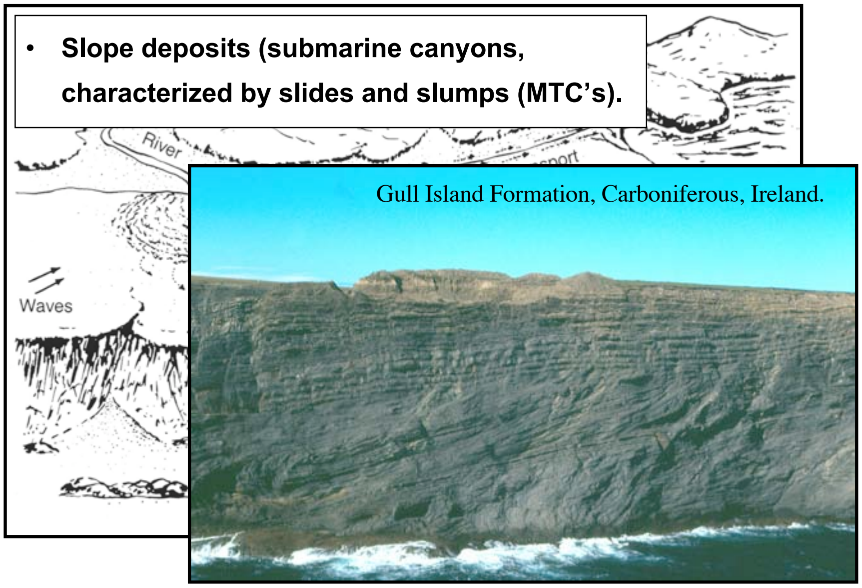


From Boggs, 1995 after Seibold and Berger, 1982

Deep Water Systems

Continental Margin Processes

- Slope deposits (submarine canyons, characterized by slides and slumps (MTC's).

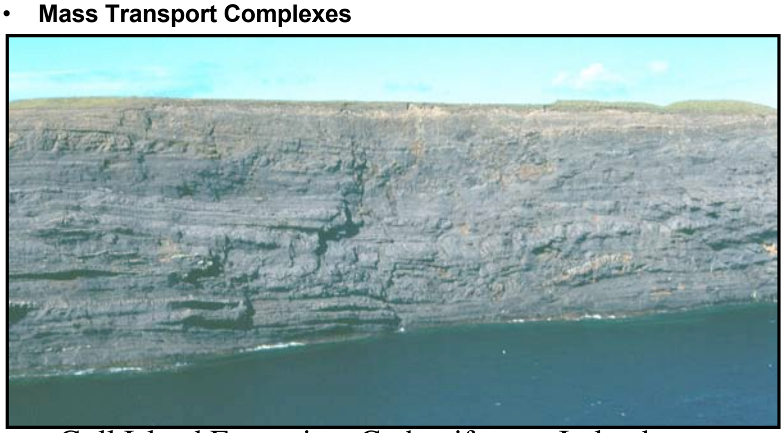


Gull Island Formation, Carboniferous, Ireland.

Deep Water Systems

Continental Margin Processes

- Slope deposits (submarine canyons, characterized by slides and slumps).
- Mass Transport Complexes



Gull Island Formation, Carboniferous, Ireland.

Deep Water Systems

Continental Margin Processes

- **Slope deposits**

Deformed mudstone, encased in bedded turbidites, Gull Island Formation, Carboniferous, Ireland.

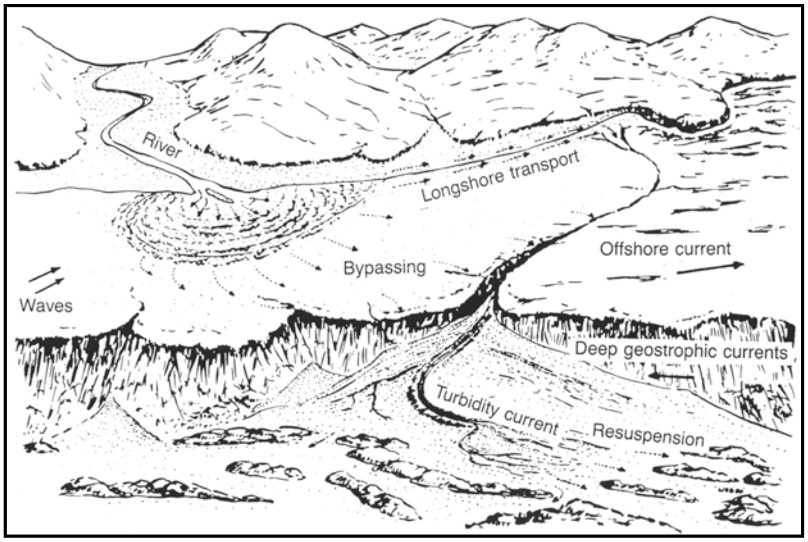
Deep Water Systems

Continental Margin Processes

- **Slope deposits**

Intraformational folding (syn-sedimentary), Waitemata Gp., Eocene,. New Zealand (courtesy of Posamentier and Walker, 2004).

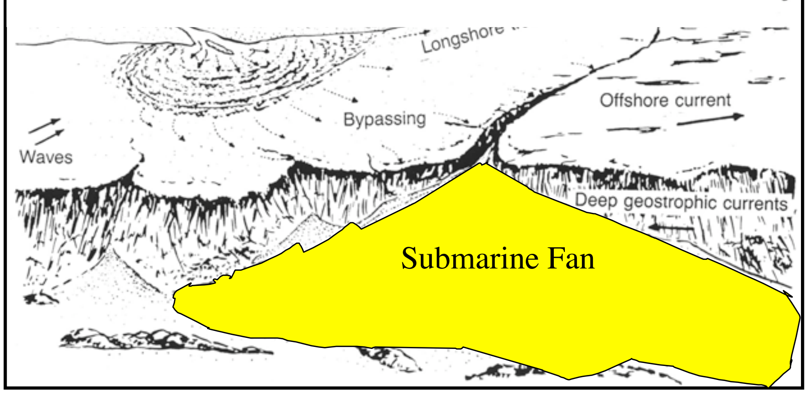
Continental Margin Processes



From Boggs, 1995 after Seibold and Berger, 1982

Deep Water Facies Models

- **Submarine Fans**
  - **Form at the base of slope and on the deep ocean basin floor.**
  - **Can be very large!**

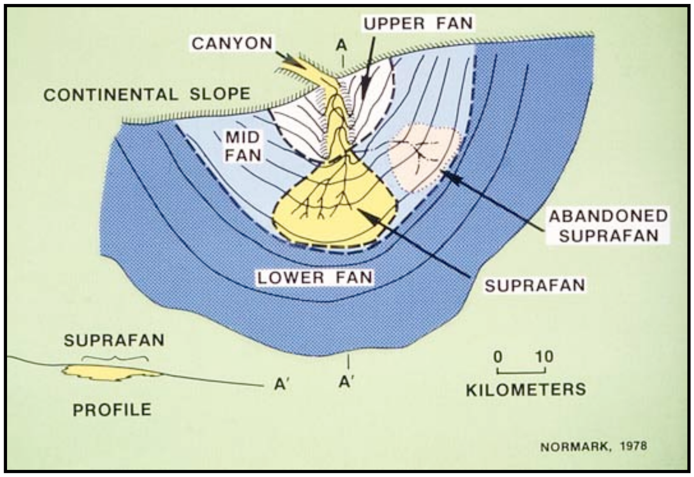


From Boggs, 1995 after Seibold and Berger, 1982

Deep Water Systems

Fan Models

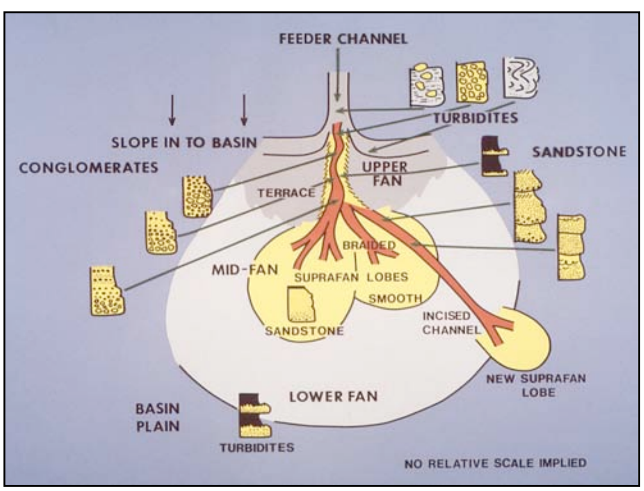
- Submarine Fan Models



Normark fan model, based on small, sandy California fans (e.g. Navy Fan).

Deep Water Systems

Fan Models



Walker fan model (1978)

1 - incorrect distribution of sand and mud

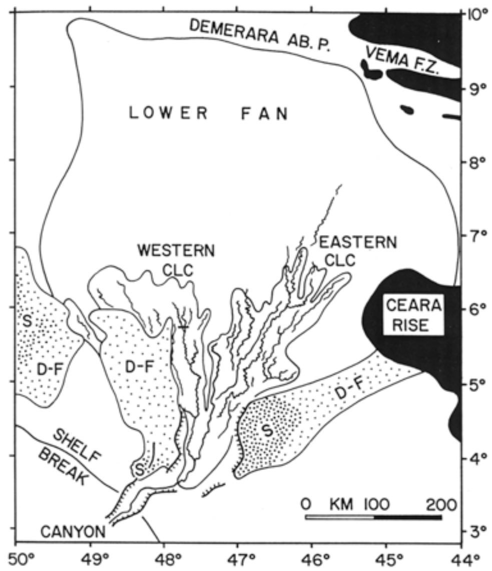
2 - no consideration of tectonic setting

3 - no consideration of grain size

4 - no consideration of sea level fluctuation

Submarine Fans

- Submarine Fans
  - Have numerous components.
  - Canyons
  - Channels
  - Levees
  - Distributary channels and lobes.
  - Debris flow complexes.



Map of the Amazon fan, a considerably larger system than the Navy Fan. (from Walker, 1992)

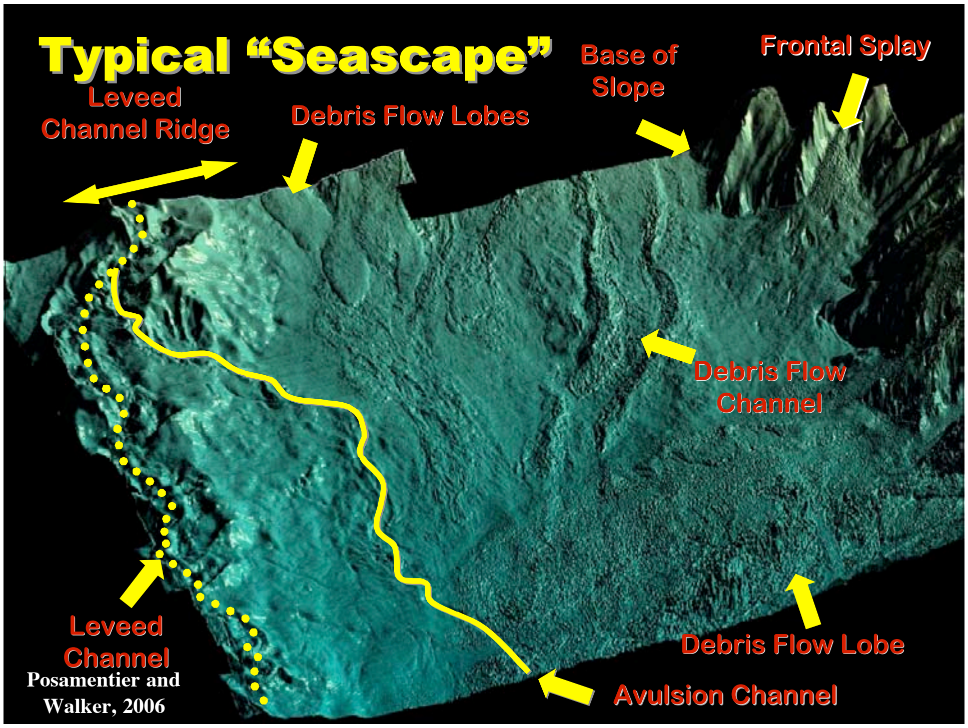
Deep Water Facies Models

- Submarine Fans
  - Can be very large!

Table1 *Dimensions of modern submarine fans.*

	Amazon	Rhone	Indus	Laurentian	Mississippi
Length km	700+	440	1500	700+	540
Width km	250-700	210	960	450	570
Area km^2	3.3×10^5	7×10^4	1.1×10^6	3×10^5	3×10^5
Thickness km	4.2	1.2	3 +	2	4
Volume km^3	7×10^5	1.2×10^4	1×10^6	1×10^5?	2.9×10^5

Walker, 1992



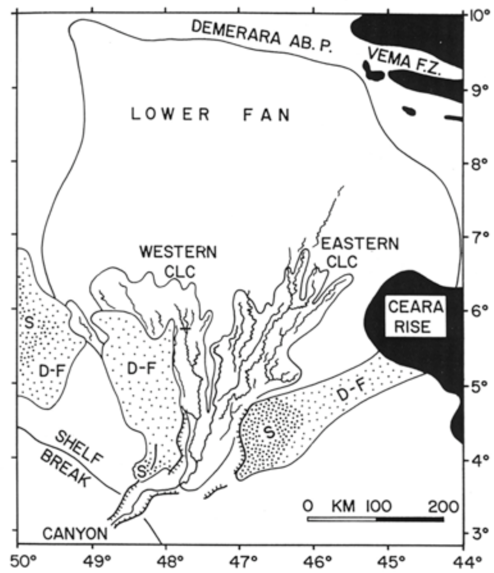
Deep Water Systems

Architectural Elements

- Attempt to use hierarchy of bounding surfaces related to morphogenetic elements.
- Newer ideas emphasize deep water provinces
  - Tributive incised canyon
  - Aggradational single channel-levee complex.
  - Distributive terminal system.
- Can be harder to apply to outcrops.

Deep Water Facies Models

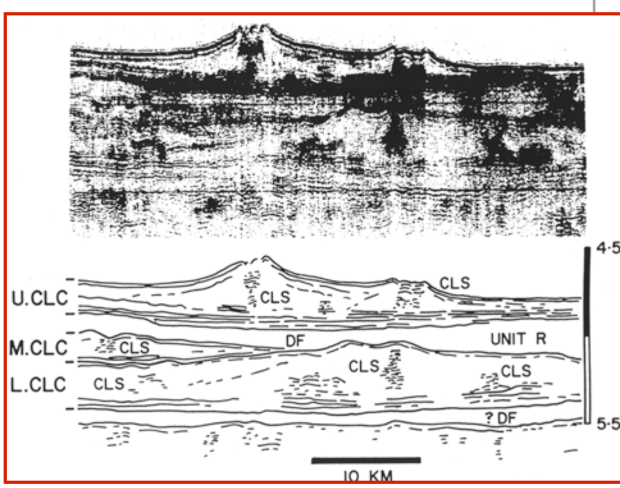
- Geophysical Imaging of Fans.
- Sea-floor bathymetry.
- Seismic imaging (2D and 3D).

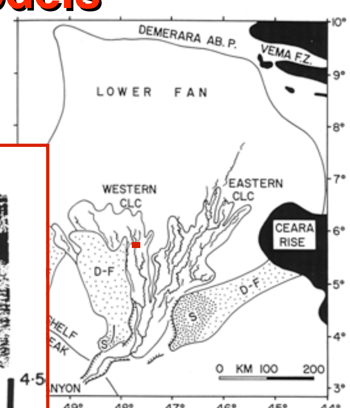


Walker, 1992

Deep Water Facies Models

- Seismic Imaging of Fans revealed aggradational channel-levee complexes.

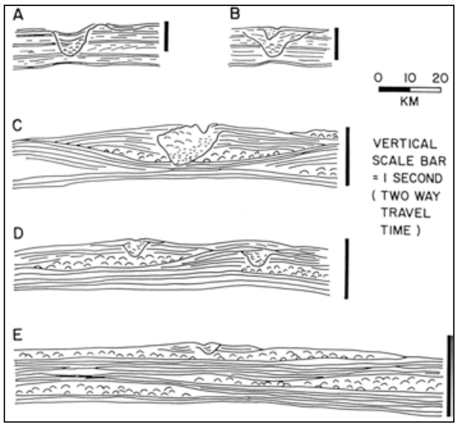




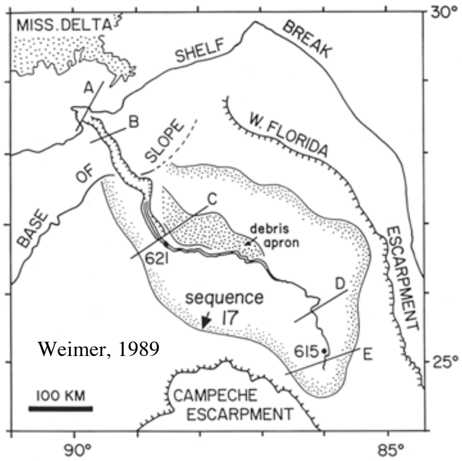
Walker (1992) simplified after Manley and Flood (1988)

Deep Water Facies Models

- Channel levee complexes commonly overlie chaotic debris flow complexes.

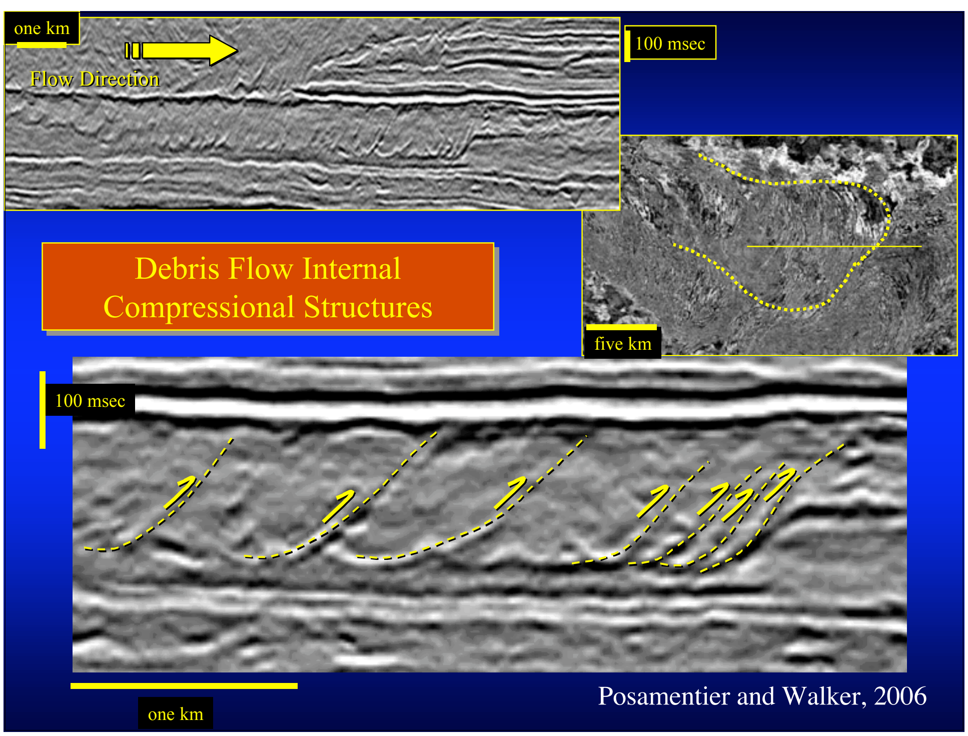


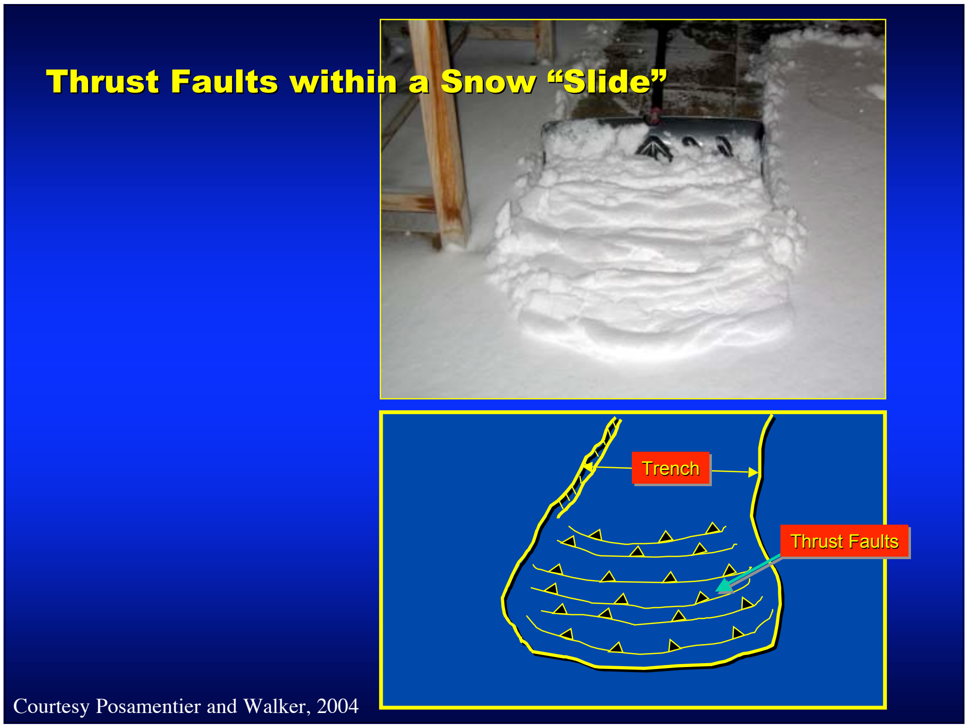
Walker (1992) after Bouma and Coleman (1985)

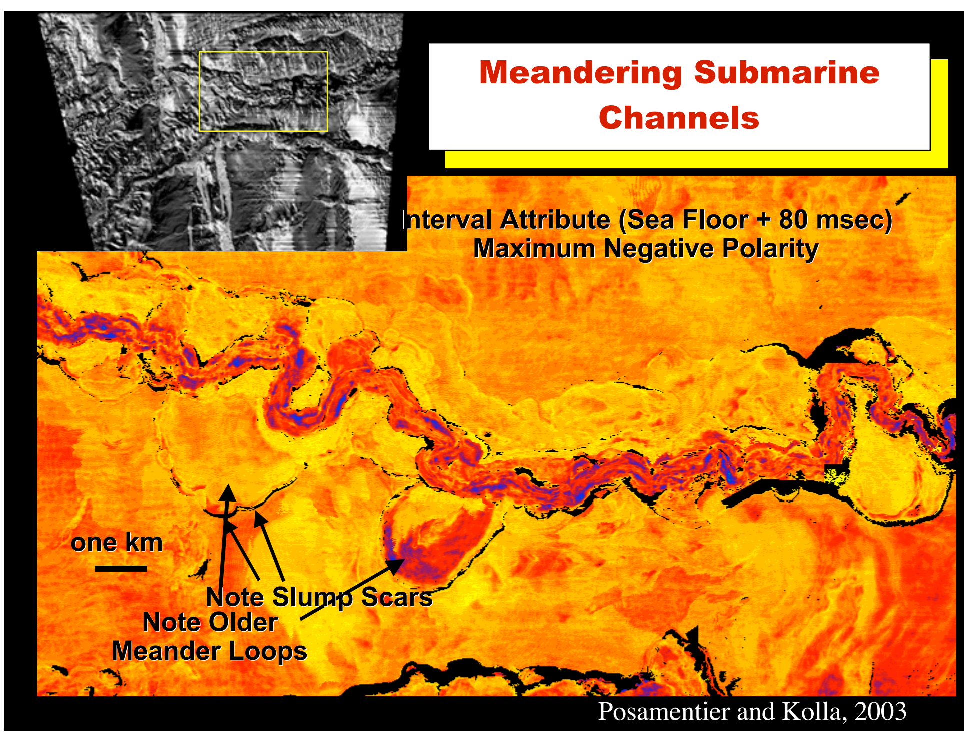


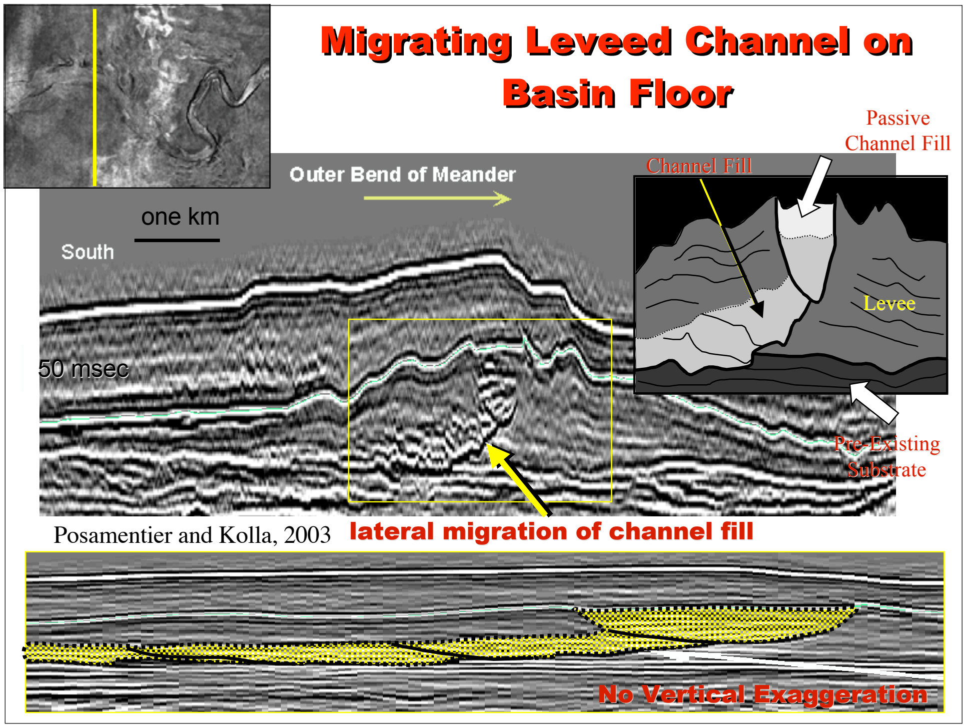
Weimer, 1989

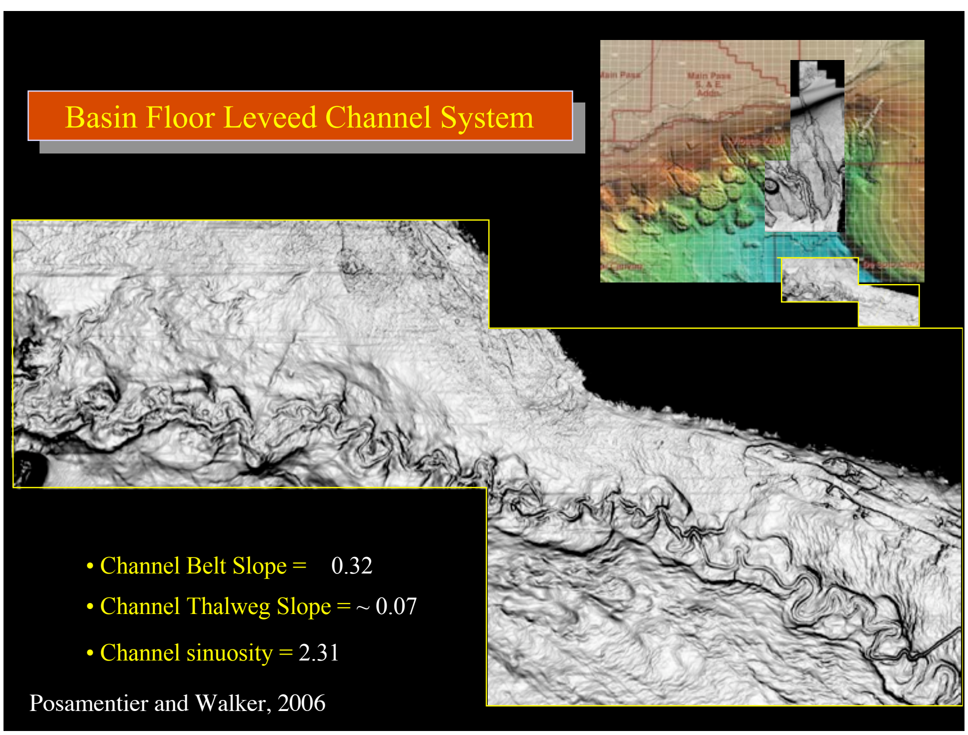
Incised feeder canyons feed distributive channels farther down slope.




Thrust Faults within a Snow "Slide"
Trench
Thrust Faults
Courtesy Posamentier and Walker, 2004


Meandering Submarine
Channels
Interval Attribute (Sea Floor + 80 msec)
Maximum Negative Polarity
one km
Note Slump Scars
Note Older
Meander Loops
Posamentier and Kolla, 2003


Migrating Leveed Channel on Basin Floor
Passive Channel Fill
Outer Bend of Meander
one km
South
Channel Fill
Levee
50 msec
Pre-Existing Substrate
Posamentier and Kolla, 2003
lateral migration of channel fill
No Vertical Exaggeration


Basin Floor Leveed Channel System
• Channel Belt Slope = 0.32
• Channel Thalweg Slope = ~ 0.07
• Channel sinuosity = 2.31
Posamentier and Walker, 2006

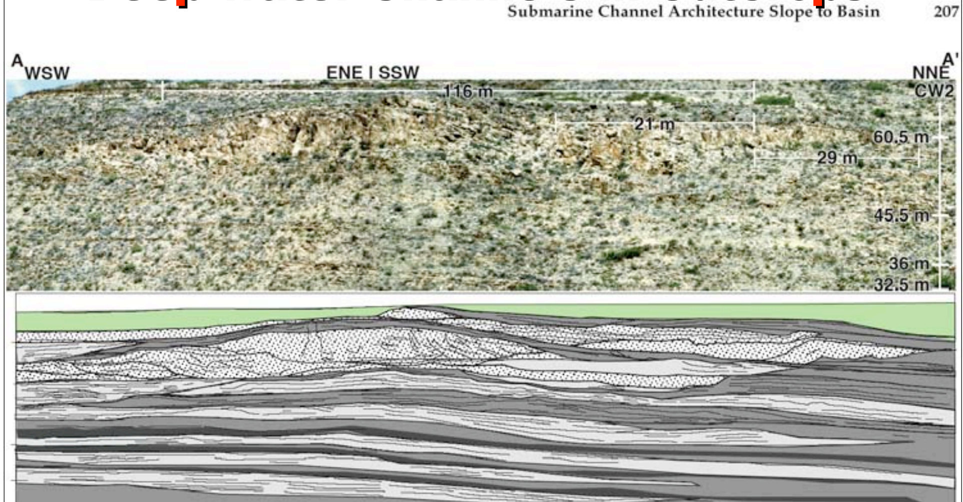
Deep water Channels in Outcrops

Upper Miocene, San Clemente, California (Posamentier and Walker, 2006)

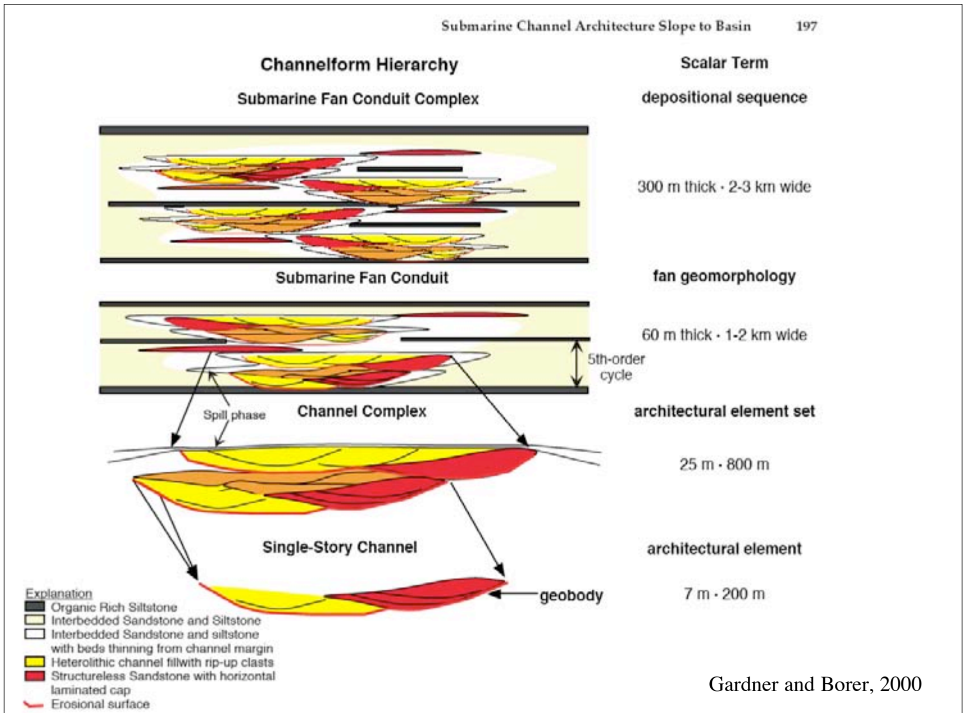
Deep water Channels in Outcrops

Upper Miocene, San Clemente, California (Posamentier and Walker, 2006)

Deep water Channels in Outcrops



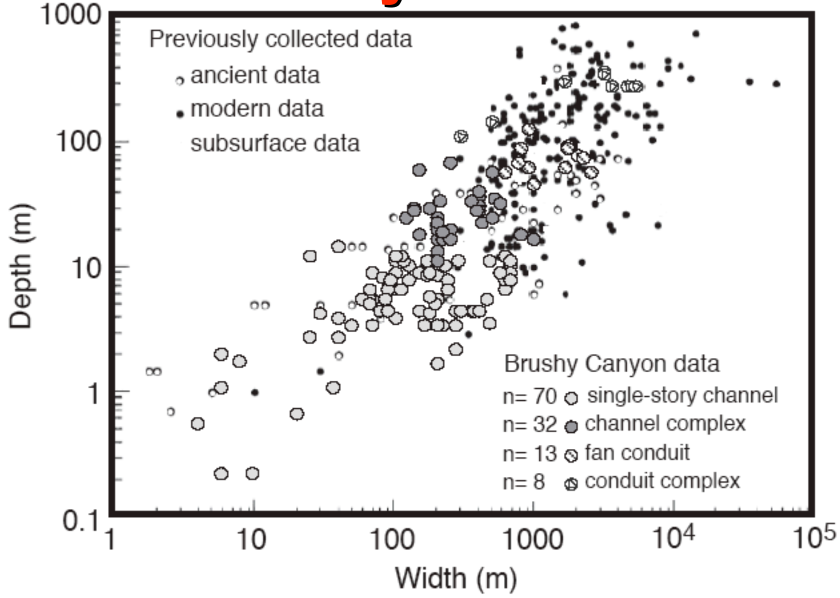
Permian Brushy Canyon (Gardner and Borer, 2000)



Gardner and Borer, 2000

196 Gardner and Borer, 2000

Sand Body Dimensions



Gardner and Borer, 2000

Submarine Channel Architecture Slope to Basin 205

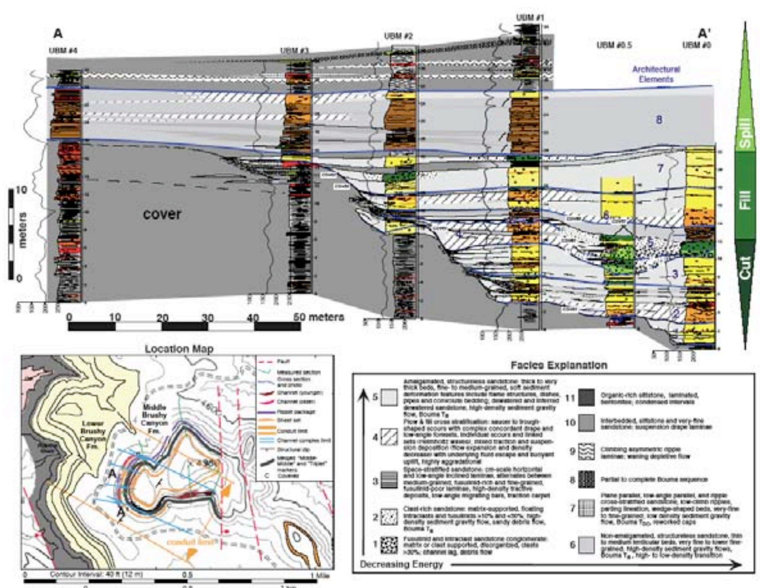
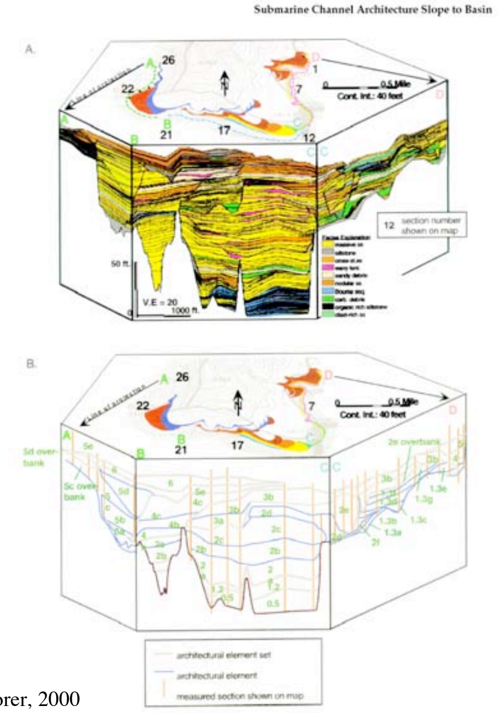


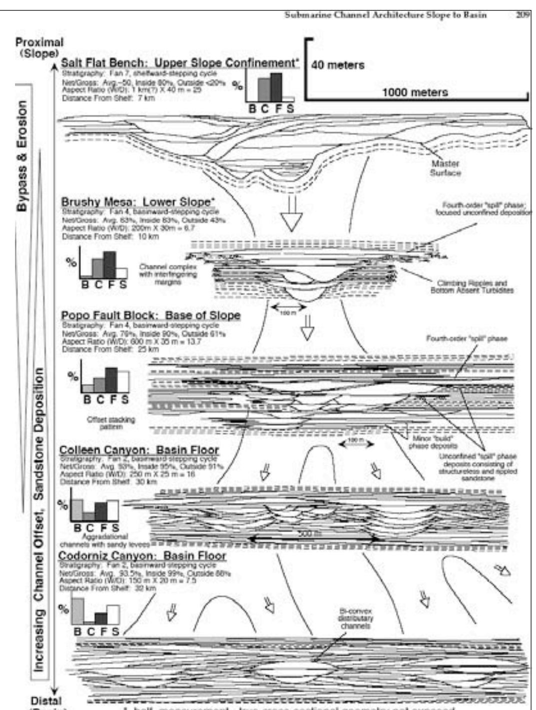
Figure 9—Facies cross section of a Fan 4 channel complex at upper Brushy Mesa (middle Brushy Canyon). Note the high degree of lateral facies change within the channel complex, which is typical of Fan 4 channel fills. Facies correlation length increases and facies diversity decreases upsection through the cut, fill, and spill phases. The channel is multistoried, with a highly serrated margin consisting of many identifiable 1- to 3-m cuts.

3D Facies Architecture and associated cliff exposures, Brushy Basin fan, Permian basin.

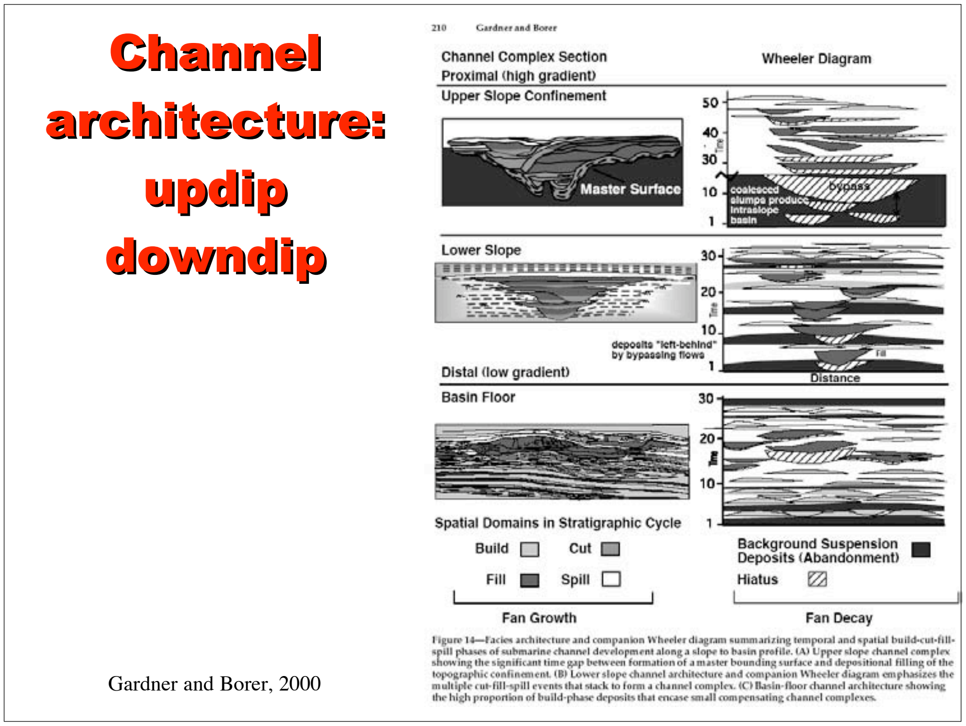


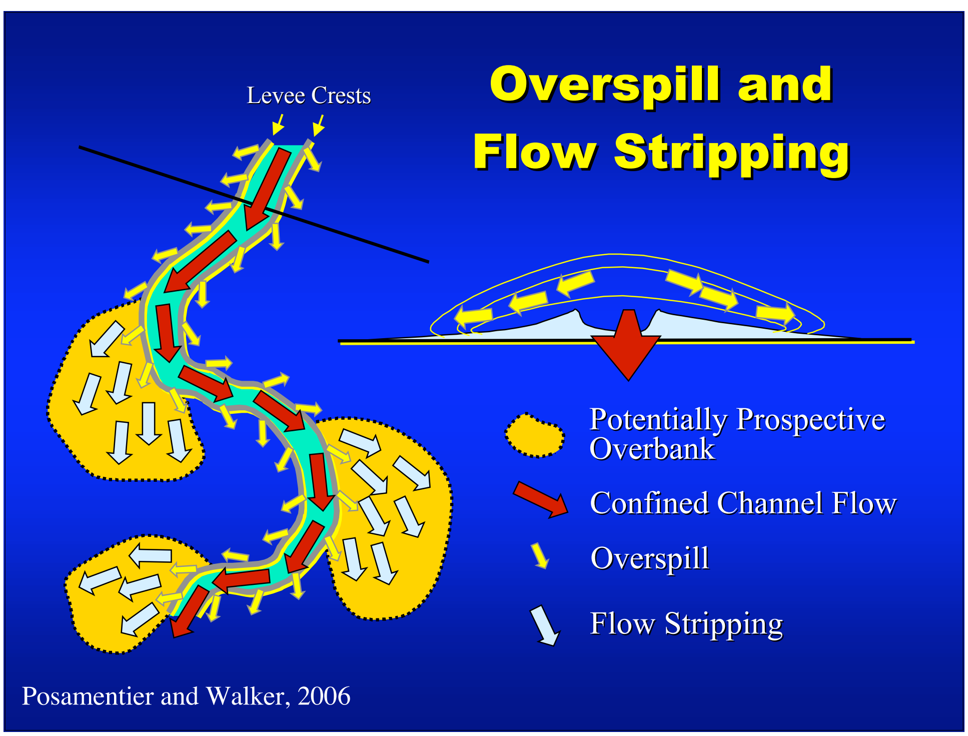
Gardner and Borer, 2000

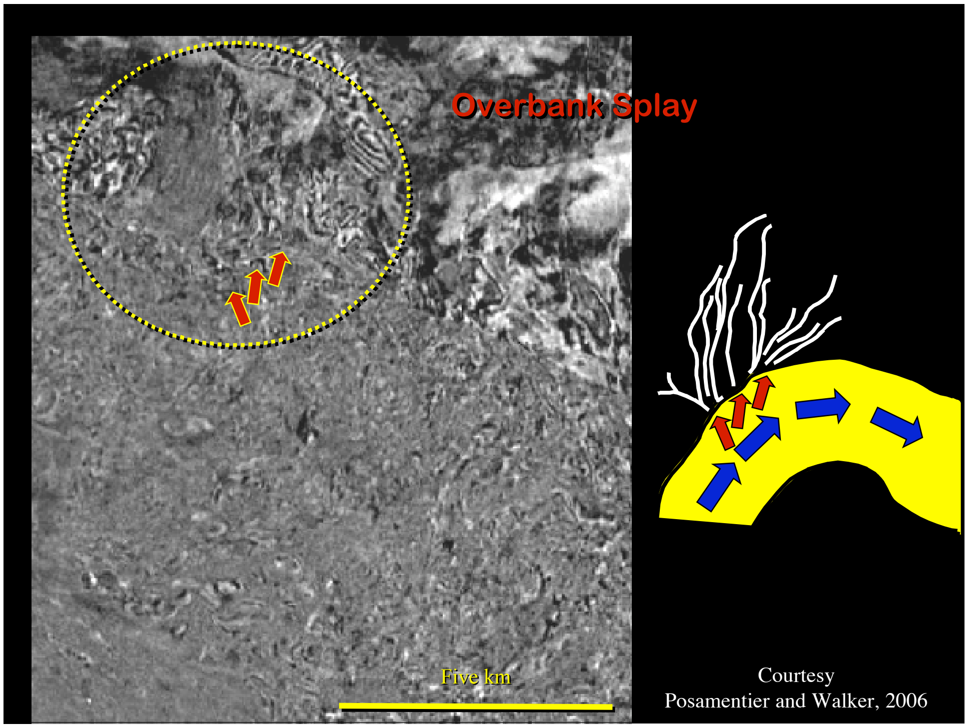
Channel architecture: updip downdip



Gardner and Borer, 2000


Channel architecture: updip downdip
210 Gardner and Borer
Channel Complex Section
Proximal (high gradient)
Wheeler Diagram
Upper Slope Confinement
Master Surface
coalesced slumps produce intraslope basin
Bypass
Lower Slope
deposits "left-behind" by bypassing flows
Fill
Distance
Distal (low gradient)
Basin Floor
Time
50
40
30
20
10
1
Spatial Domains in Stratigraphic Cycle
Build
Cut
Fill
Spill
Background Suspension Deposits (Abandonment)
Hiatus
Fan Growth
Fan Decay
Figure 14—Facies architecture and companion Wheeler diagram summarizing temporal and spatial build-cut-fill-spill phases of submarine channel development along a slope to basin profile. (A) Upper slope channel complex showing the significant time gap between formation of a master bounding surface and depositional filling of the topographic confinement. (B) Lower slope channel architecture and companion Wheeler diagram emphasizes the multiple cut-fill-spill events that stack to form a channel complex. (C) Basin-floor channel architecture showing the high proportion of build-phase deposits that encase small compensating channel complexes.
Gardner and Borer, 2000

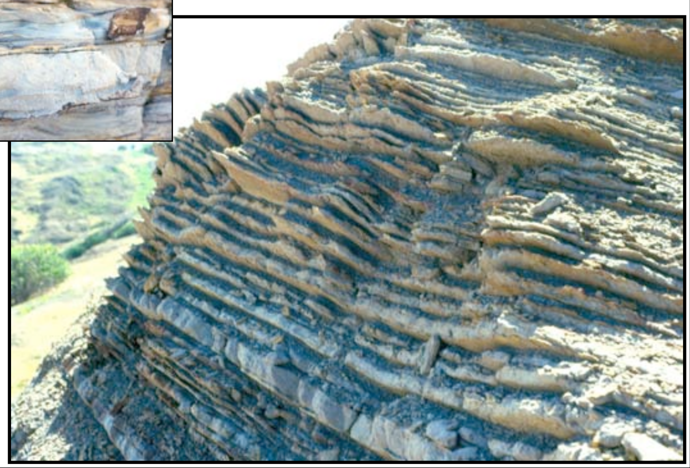

Overspill and Flow Stripping
Levee Crests
Potentially Prospective Overbank
Confined Channel Flow
Overspill
Flow Stripping
Posamentier and Walker, 2006



Deep Water Systems

Overbank Splays

- **Thin-bedded.**
- **Dominated by climbing ripples.**

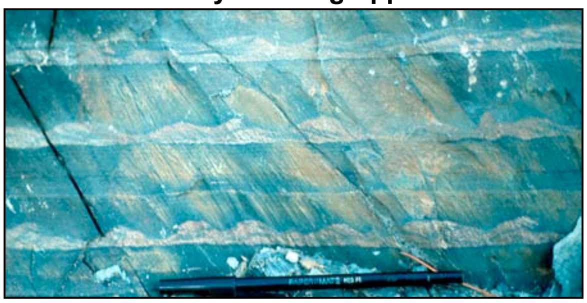


Levee facies, Scotland Fm., Barbados.

Deep Water Systems

Overbank Splays

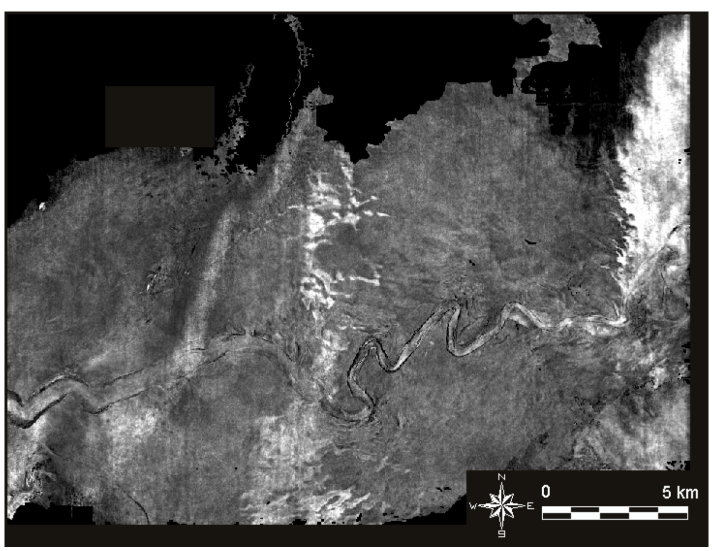
- **Thin-bedded.**
- **Dominated by climbing ripples.**



Levee facies, Jasper, Alberta.

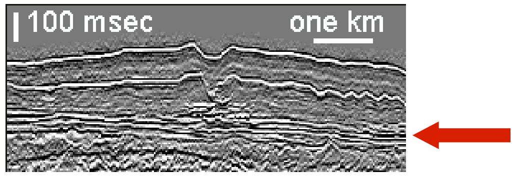
Thin-bedded muddy overbank facies, Alaska.

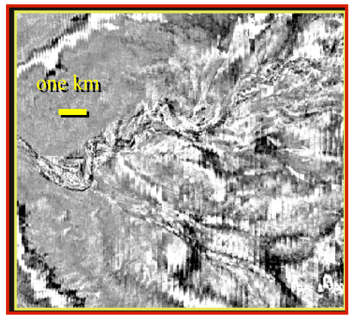
Frontal Splays (terminal lobes)



Posamentier and Walker, 2006

Paired Distributary Channel and Channel-Levee Complex



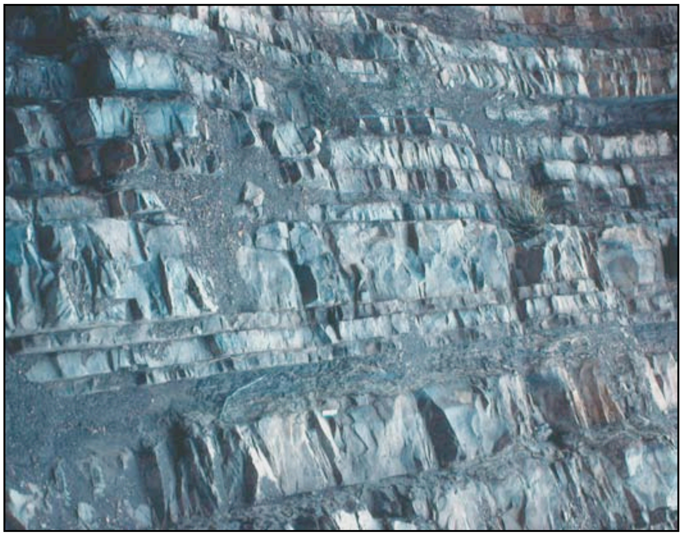


Posamentier and Walker, 2006

Distributary Channels and Sandy lobe Facies

Amalgamated channel sandstones, Carboniferous Ross Fm., Ireland

Distributary Channels and Sandy lobe Facies



Thickening-upward beds, Cretaceous Matilija Fm., California

Turbidite fans in the Permian Tanqua Karoo, South Africa

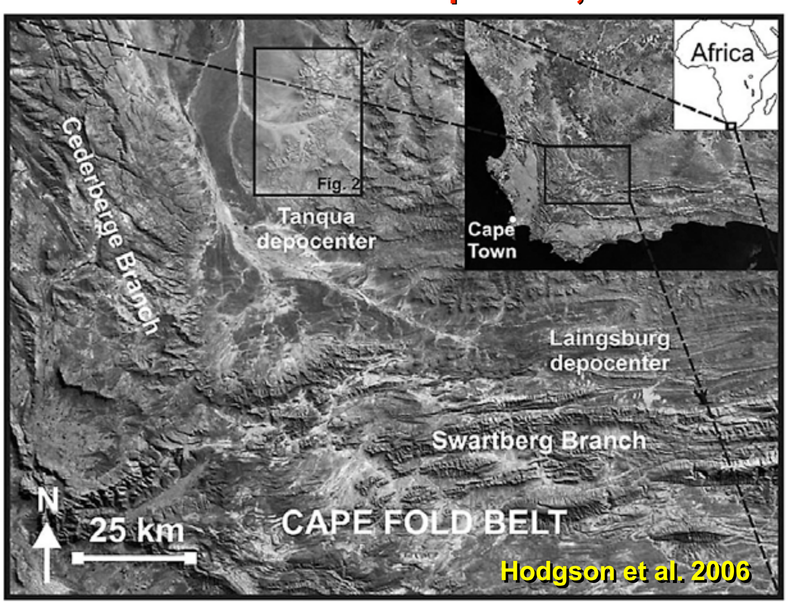


FIG. 1.—Landsat image of the SW Karoo Basin, South Africa with the Tanqua and Laingsburg depocenters marked. An oroclinal bend in the Cape Fold Belt bounds the Tanqua depocenter to the west (the N-S trending Cederberge branch) and to the south (the E-W trending Swartberg Branch). The box denotes the study area of the NOMAD research project; approximately 35 km × 25 km. Landsat image from: https://zulu.ssc.nasa.gov/mrsid/.

Turbidite fans in the Permian Tanqua Karoo, South Africa

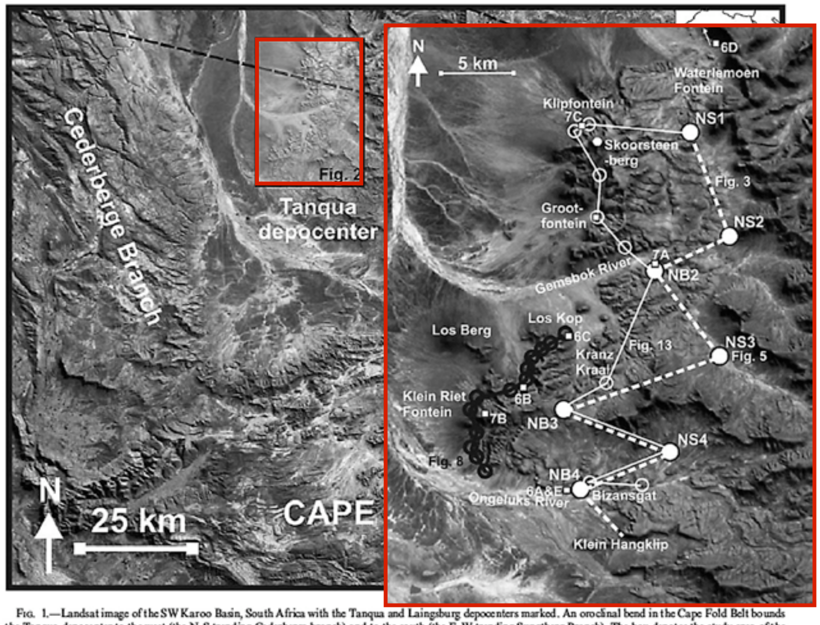


FIG. 1.—Landsat image of the SW Karoo Basin, South Africa with the Tanqua and Laingsburg depocenters marked. An oroclinal bend in the Cape Fold Belt bounds the Tanqua depocenter to the west (the N-S trending Cederberge branch) and to the south (the E-W trending Swartberg Branch). The box denotes the study area of the NOMAD research project; approximately 35 km × 25 km. Landsat image from: https://zulu.ssc.nasa.gov/mrsid/.

Measured sections

Cross section through distal fans showing upward thickening (progradational) facies successions (Hodgson et al. 2006)

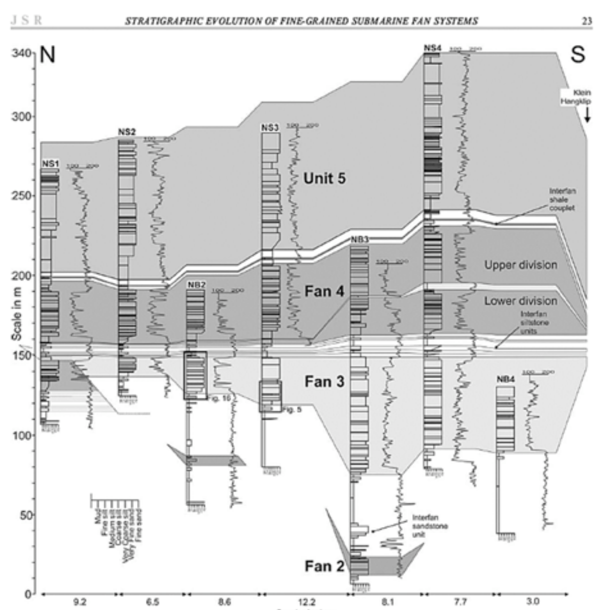
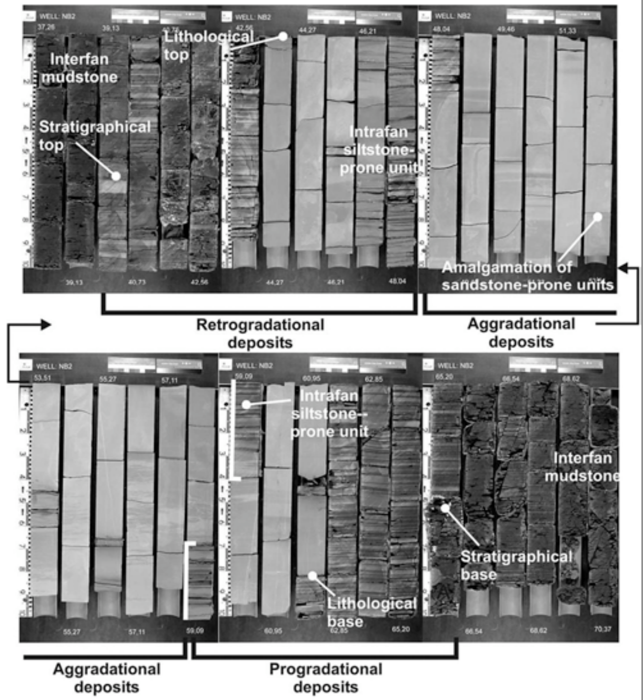


FIG. 3.—North-to-south-oriented correlation panel of the seven core and gamma-ray logs (wells NB2, NB3, NB4, NS1, NS2, NS3, and NS4) of three basin-floor fan systems (Fan 1 was not encountered) and the overlying slope system (Unit 5). The apparent lenses of Fan 2 are due to the changing plane of projection of the section line. A total of 1247 m of core was recovered. The core and gamma-ray logs are offset at the base of NS4 and NB3 due to the dip of the bedding, and a reverse fault was encountered in NS1 at the top of Fan 3. See Figure 2 for the location of the panel. Note that the grain-size scale is applicable to Figures 8, 10, 11, 13, 14, and 15 with a maximum grain-size of fine-grain sand.

Facies Successions from Cores

Note dominance of progradational deep-water “parasequences” (Hodgson et al. 2006).



Paleogeographic Maps

24 D.M. HODGSON ET AL. J S R

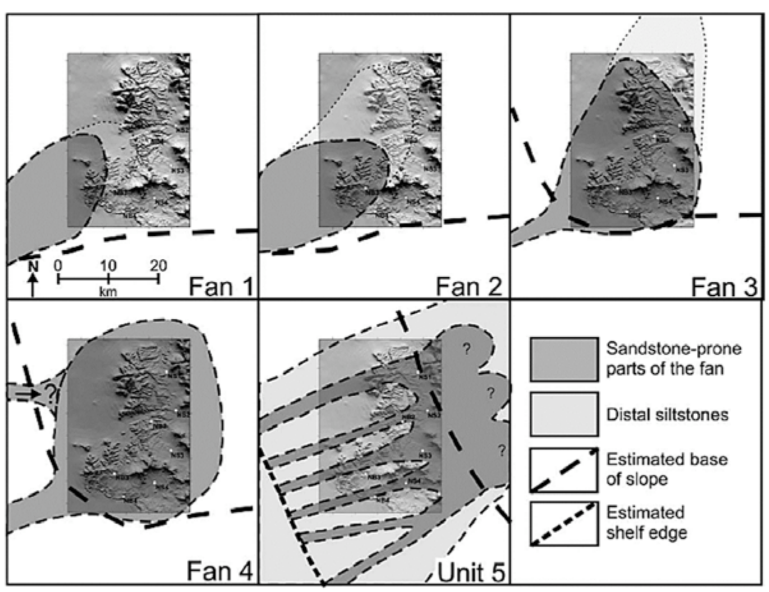


FIG. 4.—Paleogeographic reconstructions of the outlines of the fan systems, which have been refined from integration of the outcrop and NOMAD core and well-log data (white dots). Only the pinchout areas of Fans 1 and 2 are present at outcrop, and then original size and geometry is poorly constrained. Note the change in the style of slope delivery from point-sourced basin-floor fans (Fans 1–4) to multiple feeder systems in Unit 5.

JSR STRATIGRAPHIC EVOLUTION OF FINE-GRAINED SUBMARINE FAN SYSTEMS 29

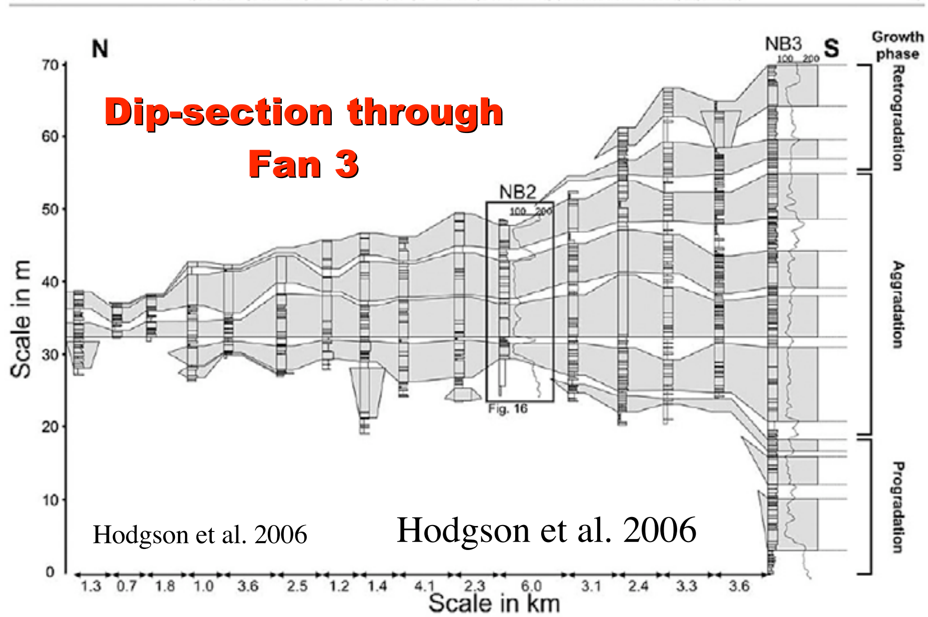


FIG. 10.—Dip correlation panel of Fan 3 stratigraphy from S to N, approximately down the axis of the fan. The correlation is based on alternating interfan sandstone- or siltstone-prone units. Note the thinning of the lower and upper units into the basin, the tabular nature of the central portions, and the channel forms at the base of the fan in distal locations. The channelized nature of the feeder system at Ongeluks River prevents robust correlation of the intrafan stratigraphy. Natural gamma logs are shown at well sites. Log positions are located in Figure 9A. See Figure 3 for grain-size scale.

30 D.M. HODGSON ET AL. 2006 JSR

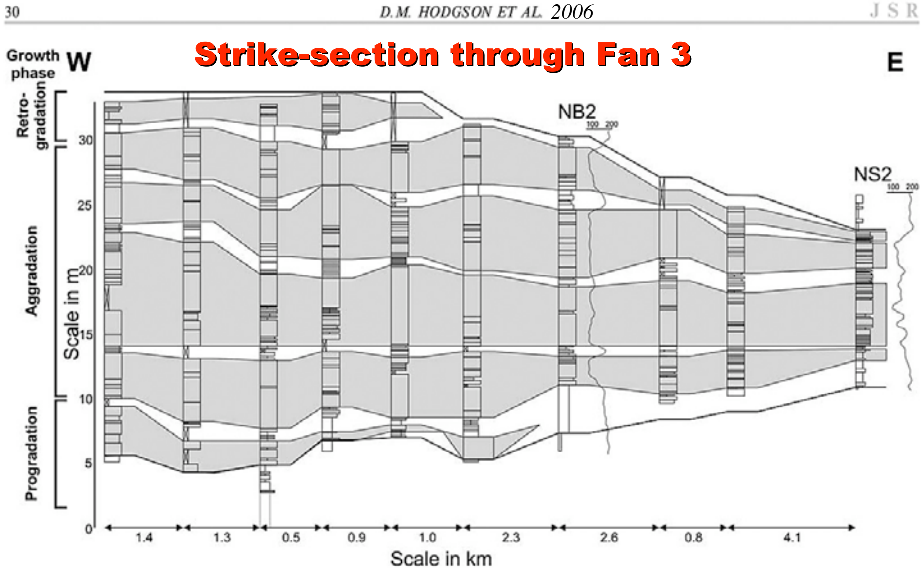


FIG. 11.—Strike correlation panel of Fan 3 stratigraphy from W to E, approximately across the fan at Gemsbok River. Note the thinning of the lower and upper units, and the tabular nature of the central portions. Natural gamma logs are shown at well sites. Log positions are located in Figure 9A. See Figure 3 for grain-size scale.

Evolution of Fans in dip-view

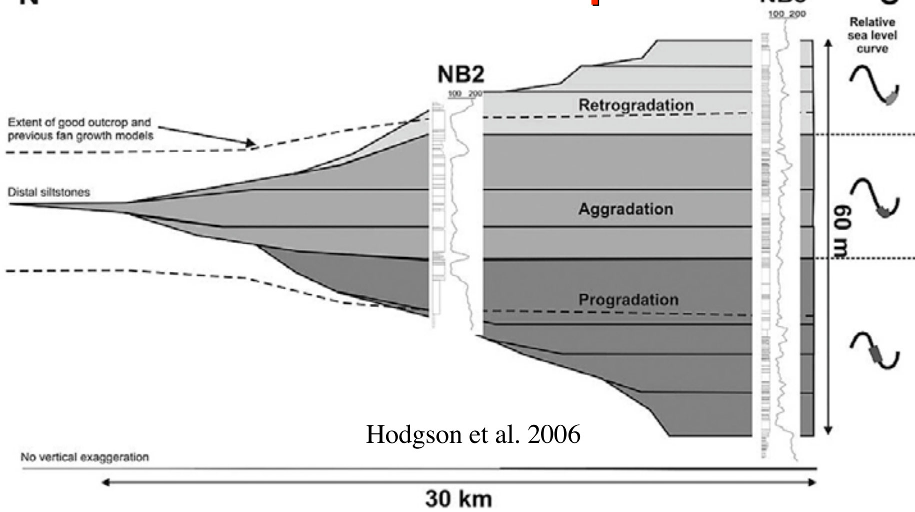


FIG. 14.—Cartoon to illustrate the internal divisions and down-dip distribution of the Tanqua fan systems. The progradational phase is related to the early lowstand systems tract (LST), the aggradational phase to the middle LST, and the retrogradational phase to the late LST. The cartoon is based on Fan 3 (wells NB3 and NB2 are the reference logs used), but all fan systems follow the same framework. However, only the aggradational phase is preserved at outcrop in Fans 1 and 2, and Fan 4 is dominated by the aggradational phase. For comparison the same cartoon is also shown below with no vertical exaggeration. See Figure 3 for grain-size scale.

Evolution of Fans in dip-view

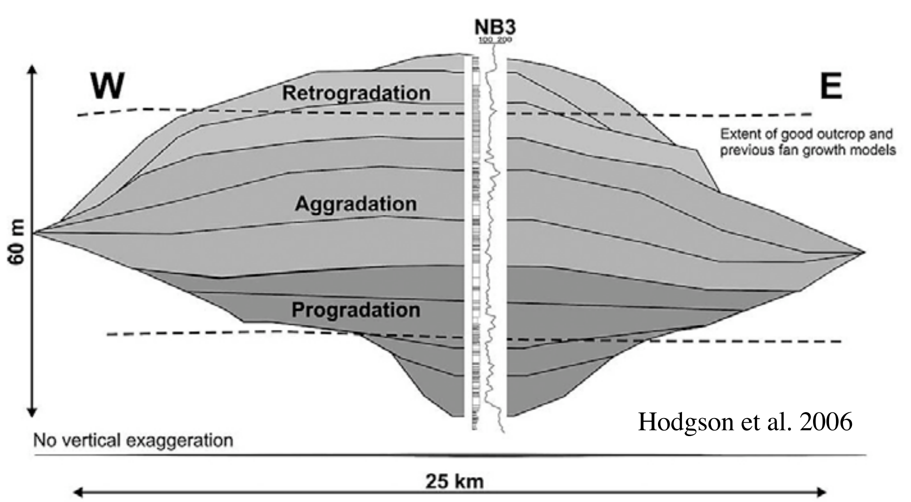
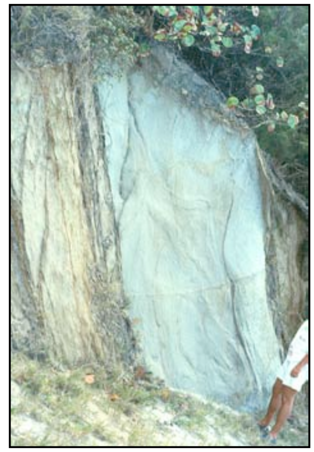


FIG. 15.—Cartoon to illustrate the internal divisions and along-strike distribution of the Tanqua fan systems (well NB3 is employed as a reference section). The retrogradational phase displays sidestepping as well as backstepping trends. For comparison the same cartoon is also shown below with no vertical exaggeration. See Figure 3 for grain-size scale.

Distributary Channels and Sandy lobe Facies

Partially dewatered channel normally graded sandstones with scours, Scotland Fm., Barbados.



Distributary Channels and Sandy lobe Facies

Normally graded to structureless sandstones with scours, Sespe Fm., California.

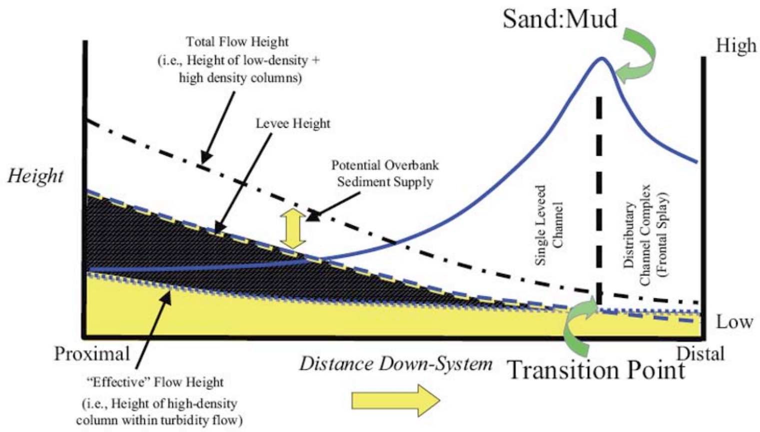
Deep Water Facies Architectural Elements

- Leveed Channels
- Overbank Deposits
- Frontal Splays
- Mass Transport deposits

Deep Water Facies Models

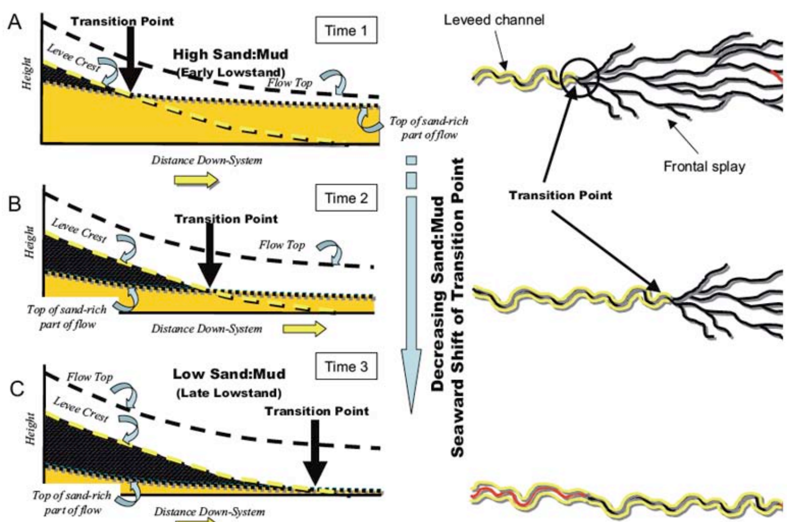
- Extremely high volumes of sediment associated with submarine fans.
- “Infinite” accommodation.
- Fill and spill in mini-basins (e.g. GOM).
- Large control of sea floor topography.
- Sediments can be reworked by marine currents (e.g. contourites).

Sand Mud Ratio versus Runout distance



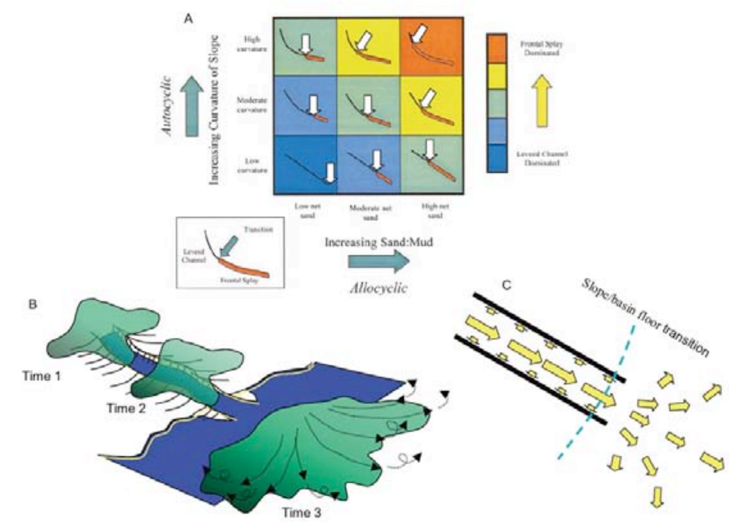
Posamentier and Walker, 2006

Sand Mud Ratio versus Runout distance



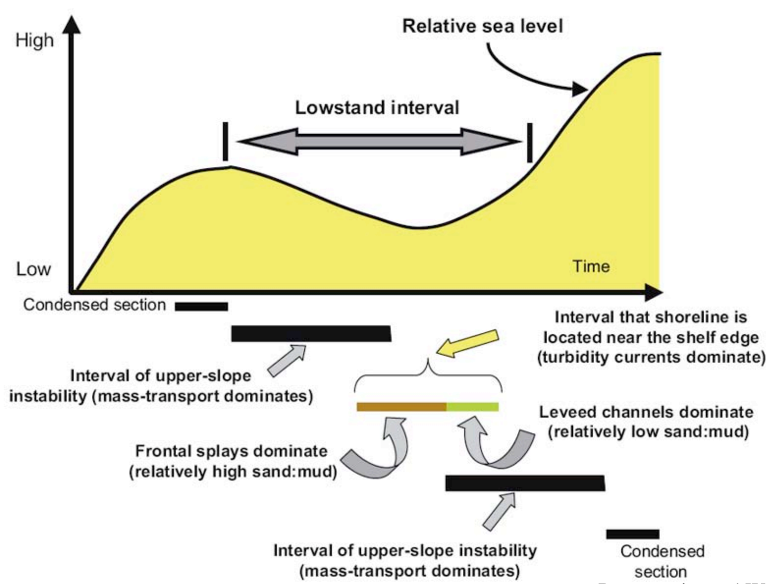
Posamentier and Walker, 2006

Runout Distance vs. Slope



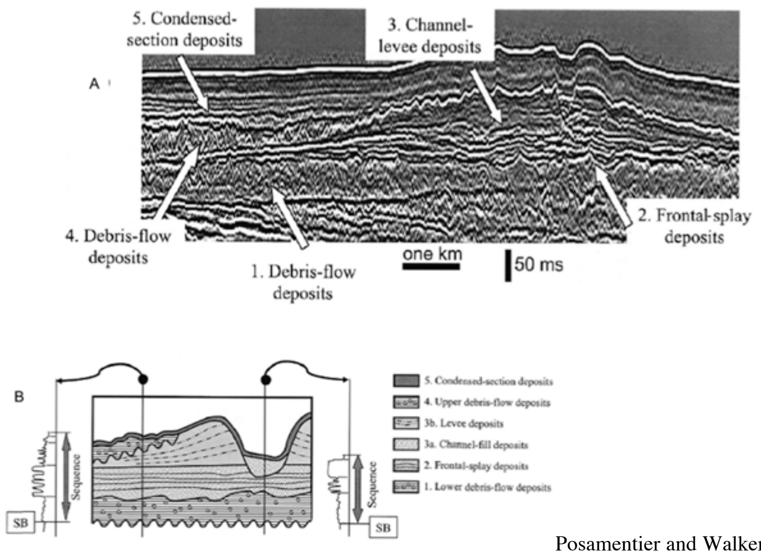
Posamentier and Walker, 2006

Deep Water Sequence Stratigraphy



Posamentier and Walker, 2006

Deep Water Sequence Stratigraphy



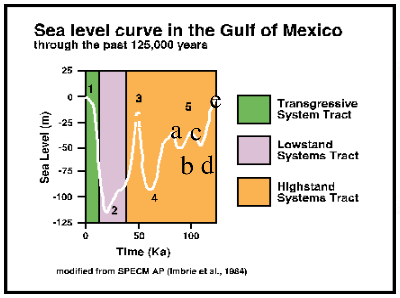
Posamentier and Walker, 2006

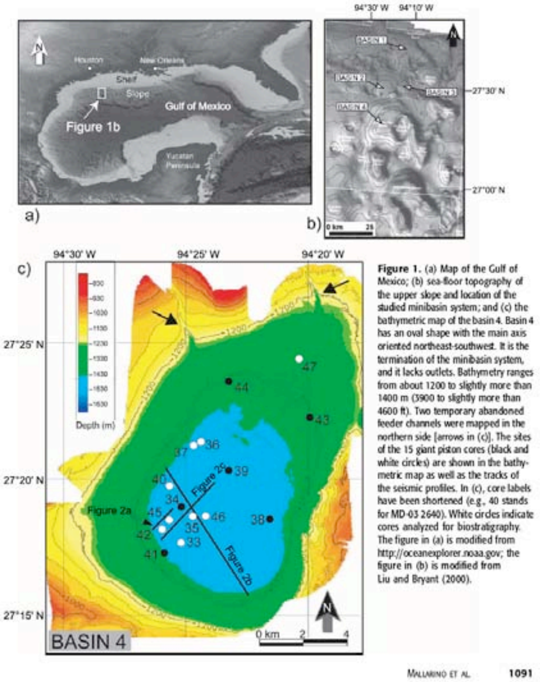
Confined, Mini-basins

- May or may not be salt related
  - e.g. tectonic mini-basins of Europe versus salt mini-basing of GOM.
- Basins successively fill and spill.
  - Salt basins are commonly syntectonic.
- Allocyclic controls (e.g. sea level lowstands) may still be required for sediment to reach basins.

Mini basins

- Filling of GOM Mini basins broadly correlated to sea level.

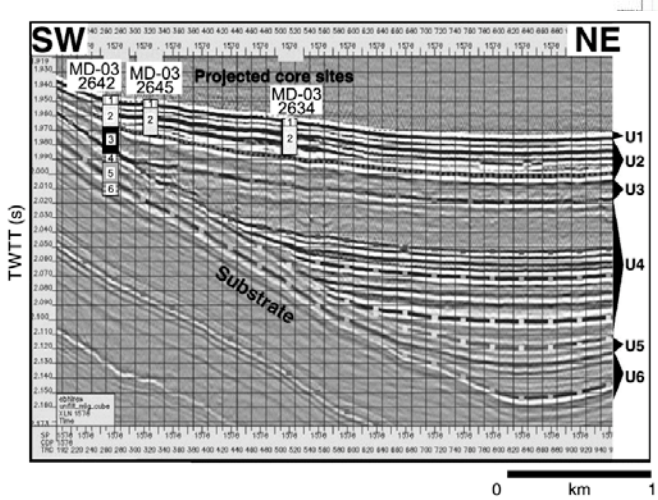


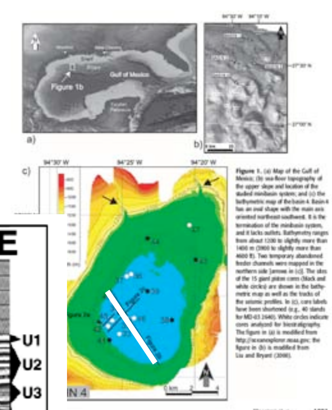


Mallarino et al. 2006

Mini basins

- Seismic expression

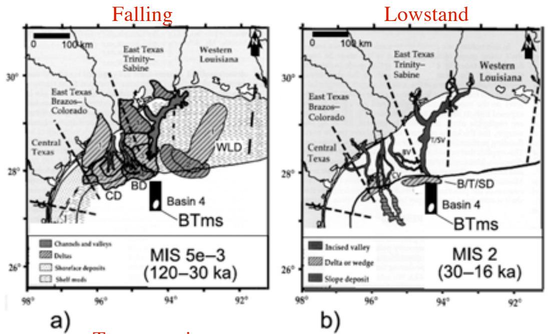




Mallarino et al. 2006

Mini basins

- Filling of GOM Mini basins broadly correlated to sea level.



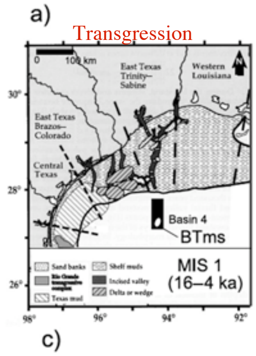


Figure 2. (a–c) Late Quaternary paleogeographic maps of the northwestern Gulf of Mexico shelf. The maps span a time interval from 120 to 4 ka (from MIS 5e to MIS 1) and illustrate the main depositional systems existing during that time interval on the shelf. During the last maximum lowstand of MIS 2 (map b), the Brazos River merged with the Trinity-Sabine river system, and sediments bypassed the exposed shelf margin nourishing the minibasin of the Brazos-Trinity slope system. Sediment source of the minibasin system during earlier stages is unknown. In all maps, dashed lines represent boundaries between areas of the Gulf margin (namely, central Texas, east Texas Brazos-Colorado, east Texas Trinity-Sabine, and western Louisiana) characterized by distinct settings such as sediment flux, margin physiography, and subsidence rates. In map 2a, numbers on delta lobes indicate their chronological order. CD = Colorado delta; BD = Brazos delta; WLD = western Louisiana delta; B/T/SD = Brazos-Trinity-Sabine delta; CV = Colorado lowstand incised valley; BV = Brazos lowstand incised valley; T/SV = Trinity-Sabine lowstand incised valley; BTms (black rectangle) = minibasins of the Brazos-Trinity slope system. The white oval represents the location of basin 4 (modified from Anderson et al., 2004).

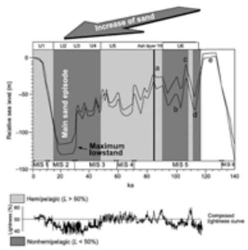


Figure 14. Chronostratigraphy of basin 4 associated with the sea level curve. The composed lightness curve (cores MD-2640 and 2643) allows differentiating hemipelagic from nonhemipelagic (sand, silt, and clay) deposits. Hemipelagic intervals were deposited during the MIS 5d–c and b–a transition, early MIS 3, and MIS 2–1 transition, time of overall transgression, and early highstands. Nonhemipelagic intervals, and specifically sand deposition, occurred during MIS 5d, MIS 5b, and late MIS 3 times of sea level regression. The largest amount of sand was delivered during the maximum sea level lowstand of the last glacial maximum when sea level was about 120 m (393 ft) below the present level. During MIS 4, despite a significant sea level fall, sedimentation consisted of hemipelagic deposits. It is unknown whether this episode was restricted only to basin 4 or it involved the other linked basins as well. In basin 4, the overall amount of sand delivered progressively increases through time, and it peaks during MIS 2. This trend matches the general progressive sea level fall that characterized the last glacial-interglacial cycle.

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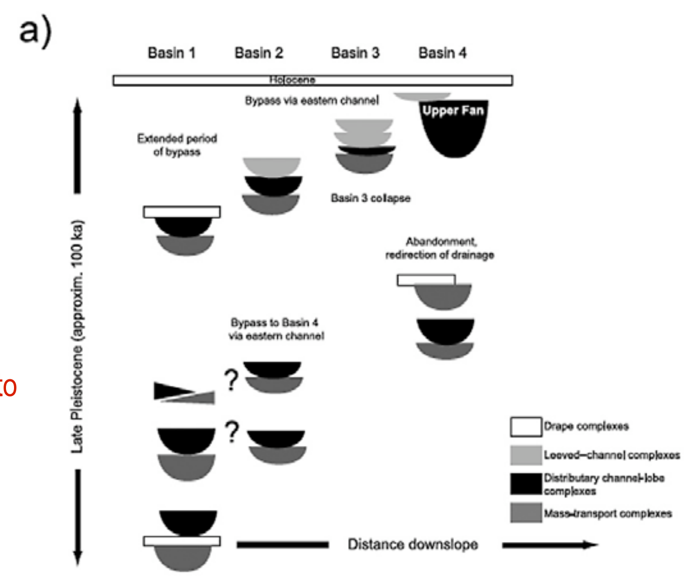
Mini basin fill history

Figure 3. (a) Model for the minibasin filling evolution in which deposition did not progress strictly from upslope to downslope basins, as basin 4 received sediment before the upslope basins were filled to spill point (variation of the fill-and-spill model (modified from Beaubouef and Friedmann, 2000).

- Fill-and-Spill approximately from proximal to distal with considerable local variation



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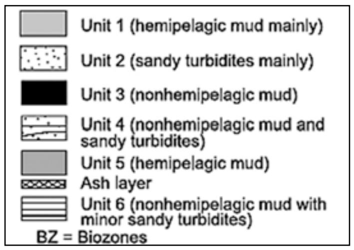
Mini basin fill history

Legend



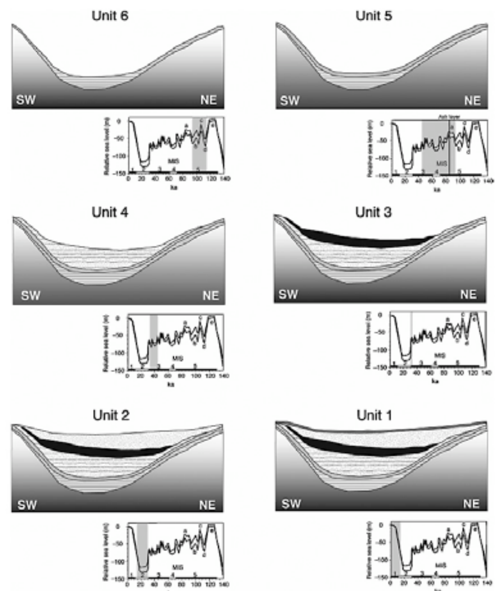


Figure 13. Diagrams illustrating the fill history of basin 4. The deposition of each unit is referred to the sea level curve and marine isotope stages. The sea level curve is modified from Lambeck and Chappell (2001).

1114 Nature and Timing of an Intraslope Minibasin

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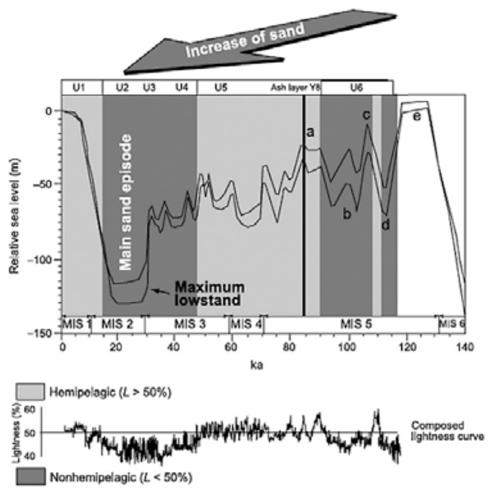
Facies versus Sea-level in a mini-basin



Note increase in turbidite sands as sea level reaches its maximum lowstand

Figure 14. Chronostratigraphy of basin 4 associated with the sea level curve. The composed lightness curve (cores MD-2640 and 2643) allows differentiating hemipelagic from nonhemipelagic (sand, silt, and clay) deposits. Hemipelagic intervals were deposited during the MIS 5d–c and b–a transition, early MIS 3, and MIS 2–1 transition, time of overall transgression, and early highstands. Nonhemipelagic intervals, and specifically sand deposition, occurred during MIS 5d, MIS 5b, and late MIS 3 times of sea level regression. The largest amount of sand was delivered during the maximum sea level lowstand of the last glacial maximum when sea level was about 120 m (393 ft) below the present level. During MIS 4, despite a significant sea level fall, sedimentation consisted of hemipelagic deposits. It is unknown whether this episode was restricted only to basin 4 or it involved the other linked basins as well. In basin 4, the overall amount of sand delivered progressively increases through time, and it peaks during MIS 2. This trend matches the general progressive sea level fall that characterized the last glacial-interglacial cycle.

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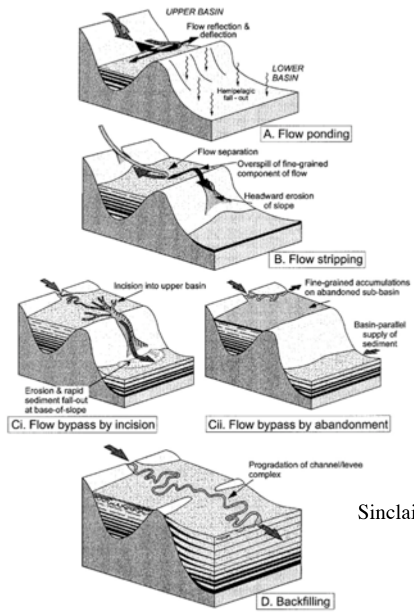
Fill and Spill in confined basins

DEPOSITIONAL EVOLUTION OF CONFINED TURBIDITE BASINS 453

Mechanisms and fill types in a progressively filled mini-basin pair (based on European outcrop and GOM examples).



Sinclair and Tommaso, 2002

FIG. 2.—Depositional model for the progressive infill of a confined turbidite basin and associated deposits at the base of the slope of a lower basin. See text for descriptions of the four stages.

Fill and Spill in confined basins

DEPOSITIONAL EVOLUTION OF CONFINED TURBIDITE BASINS 455

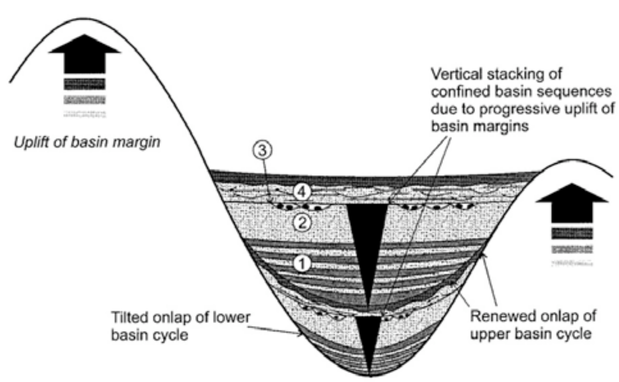


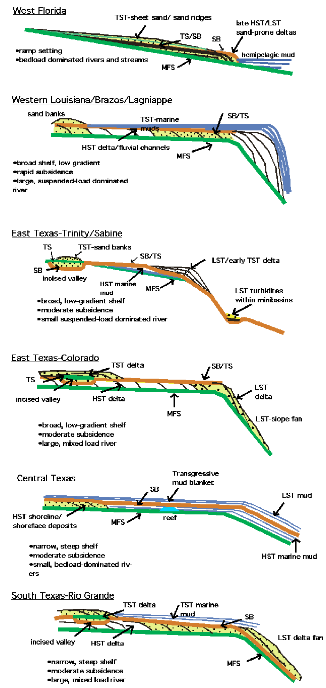
FIG. 3.—Vertical stacking of confined basin sequences generated by episodic uplift of basin topography. The circled numbers refer to the four phases in a typical confined-basin sequence as illustrated in Figure 2.

Sinclair and Tommaso, 2002

- Facies evolution in a spill and fill mini-basin.
- Note lack of MTC's, these are actually more common that shown in this paper.

Gulf of Mexico

- Slug diagrams along the coast illustrate differing timing and geometries of sequences primarily controlled by sediment supply (Anderson et al., 2004)



Conclusions: Deep Water Sequence Stratigraphy

- Staging area is critical
  - Need rivers near or at shelf edge to deliver sediment.
  - This usually requires a sea-level drop.
- MTC's typically represent remobilized slope mudstones
  - May form during rise of sea level that increases pore pressure.
  - Also can be triggered by local slope failure
    - e.g. earthquake

Conclusions: Deep Water Sequence Stratigraphy

- Fans can show progradational, retrogradational and aggradational stacking.
- Parasequences may be identified.

Conclusions: Deep Water Sequence Stratigraphy

- Slope and physiography are key drivers in locating incised, confined and unconfined elements.
  - Canyons
  - Channel Levee Complexes
  - Distributary fan lobe complexes
- Net-to-gross may reflect position on the fan, runout distance and caliber of supplied sediment.

Allostratigraphy (NACSN)

- Introduced by Quaternary stratigraphers to map units bounded by piedmont surfaces,
  - Q_{al} versus Q_t

Quaternary stratigraphy in a lithostratigraphic world

Different age units of alluvium (Q_{al}) can be seen, but are not designated as different stratigraphic units.

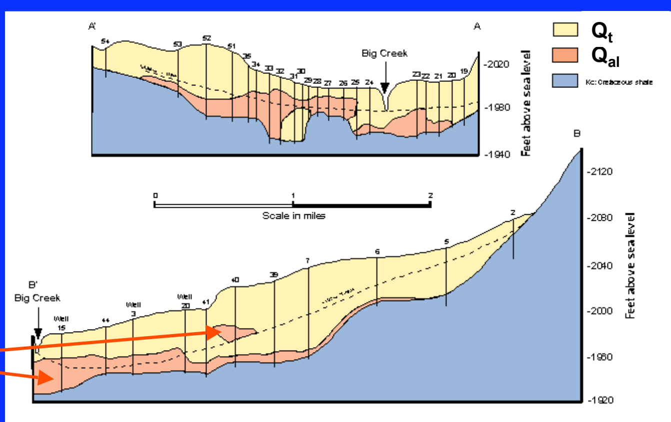
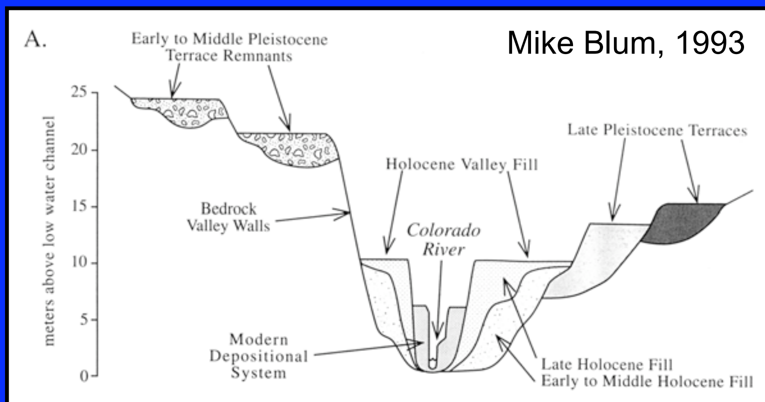


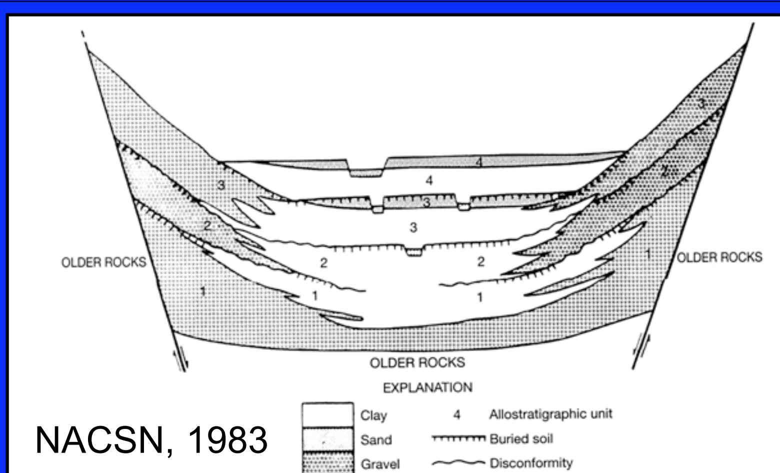
Figure 3. Cross-stream geologic section, Hays, KS. Both line oriented north-south, line B-B' lies along the eastern edge of the Hays city limits, A-A' lies 3.2 km to the west (Brikowski, 1997). After *Latta* (1948).

Quaternary sediments in an allostratigraphic world

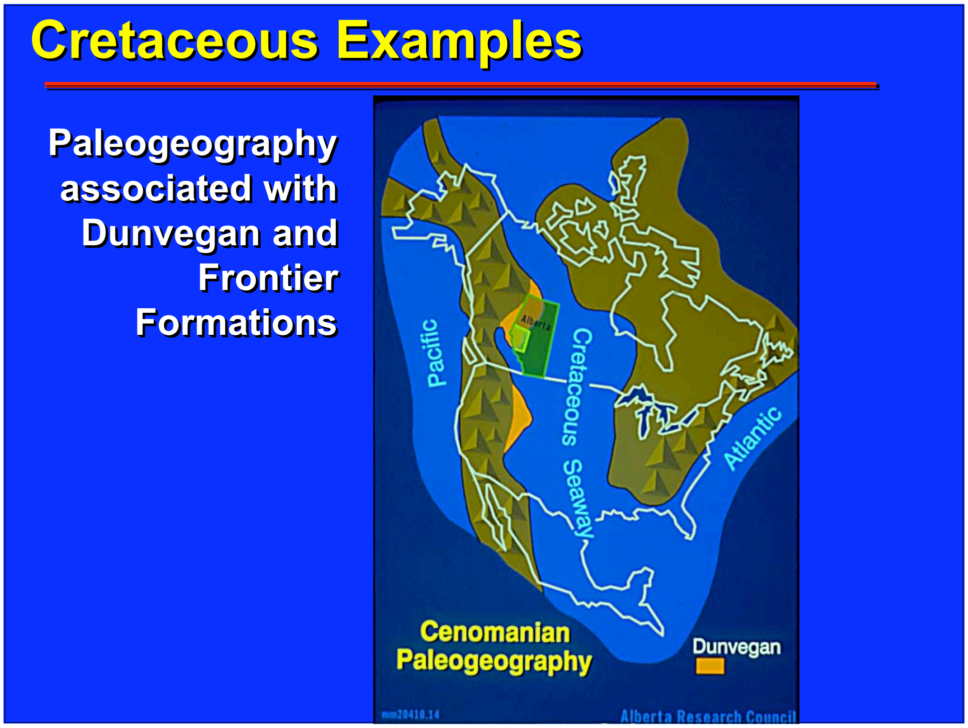


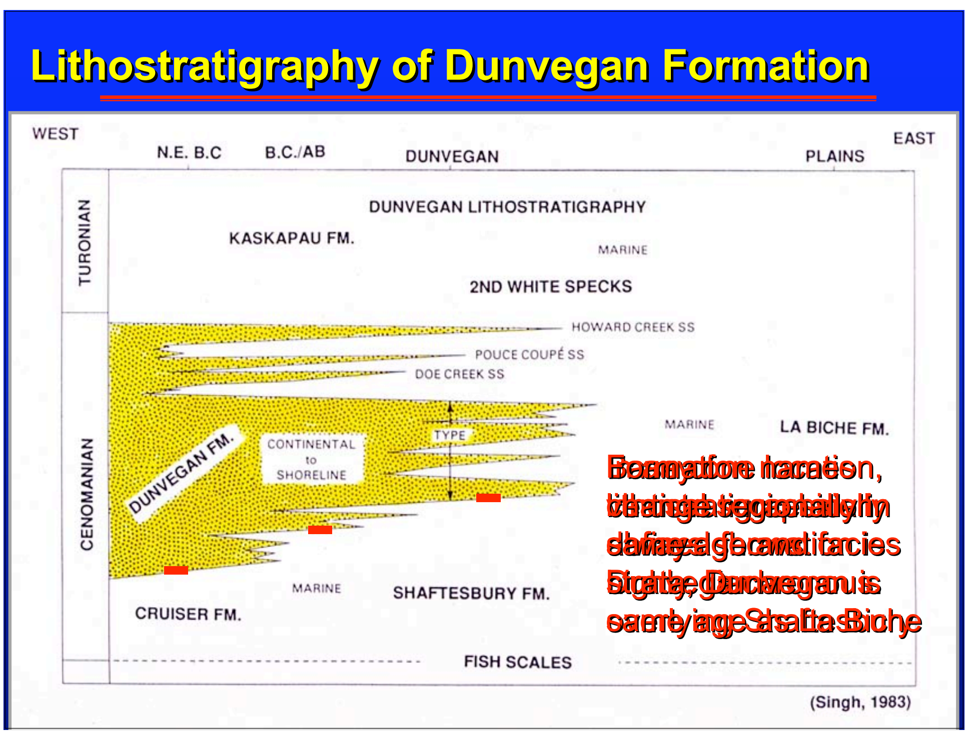
Different age terraces are defined as alloformations in recent studies of Colorado River valley deposits in Texas (Blum, 1993).

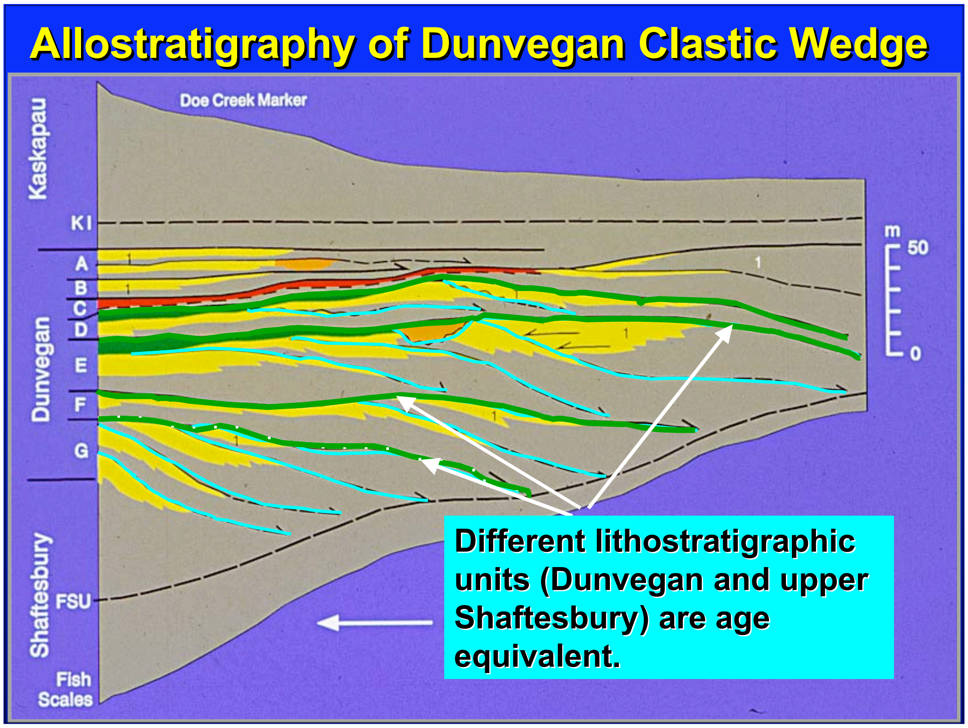
Definition of Allostratigraphic Units

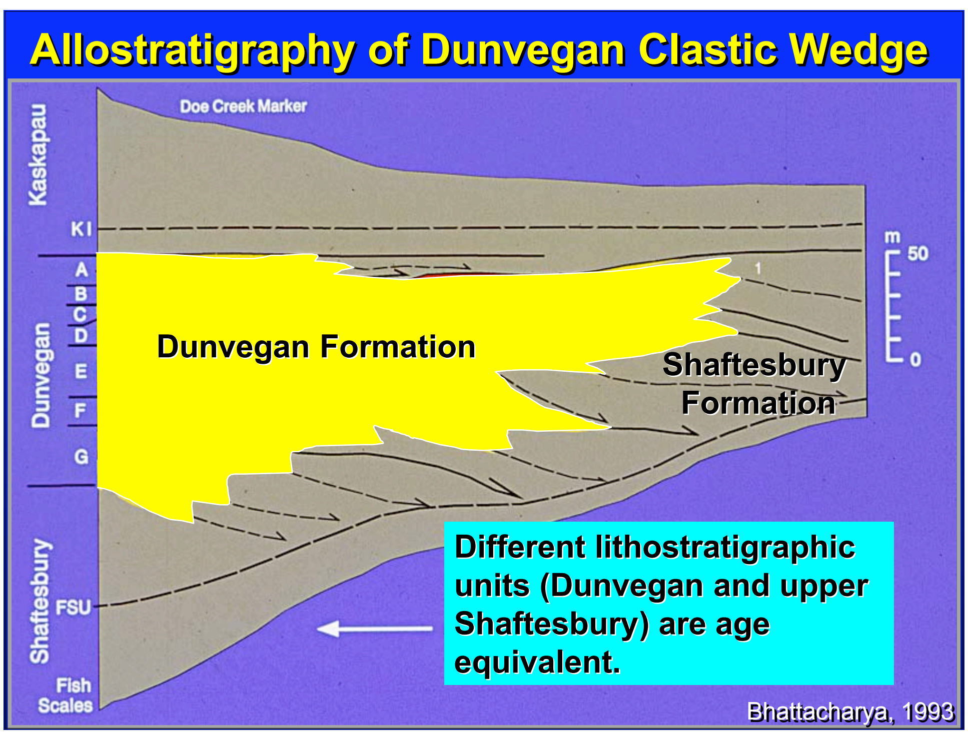


Alluvial sands and gravels and terrace clays define heterogeneous allostratigraphic units.


Cretaceous Examples
Paleogeography associated with Dunvegan and Frontier Formations
Pacific
Alberta
Cretaceous Seaway
Atlantic
Cenomanian Paleogeography
Dunvegan
Alberta Research Council

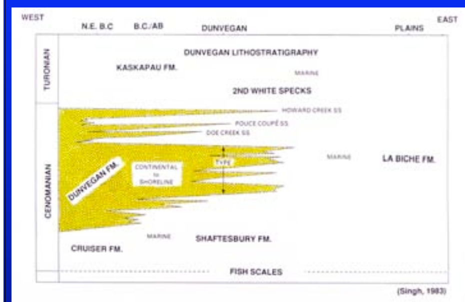

Lithostratigraphy of Dunvegan Formation
WEST
N.E. B.C
B.C./AB
DUNVEGAN
PLAINS
EAST
TURONIAN
CENOMANIAN
DUNVEGAN LITHOSTRATIGRAPHY
KASKAPAU FM.
MARINE
2ND WHITE SPECKS
HOWARD CREEK SS
POUCE COUPÉ SS
DOE CREEK SS
MARINE
LA BICHE FM.
TYPE
DUNVEGAN FM.
CONTINENTAL
to
SHORELINE
MARINE
SHAFTESBURY FM.
CRUISER FM.
FISH SCALES
(Singh, 1983)


Allostratigraphy of Dunvegan Clastic Wedge
Doe Creek Marker
Kaskapau
KI
A
B
C
D
E
F
G
Dunvegan
Shaftesbury
FSU
Fish Scales
m
50
0
Different lithostratigraphic units (Dunvegan and upper Shaftesbury) are age equivalent.


Allostratigraphy of Dunvegan Clastic Wedge
Doe Creek Marker
Kaskapau
KI
A
B
C
D
E
F
G
Dunvegan
Shaftesbury
FSU
Fish Scales
m
50
0
Dunvegan Formation
Shaftesbury Formation
Different lithostratigraphic units (Dunvegan and upper Shaftesbury) are age equivalent.
Bhattacharya, 1993

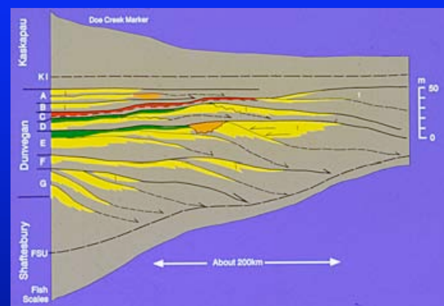
Allostratigraphy vs. Lithostratigraphy

Lithostratigraphy



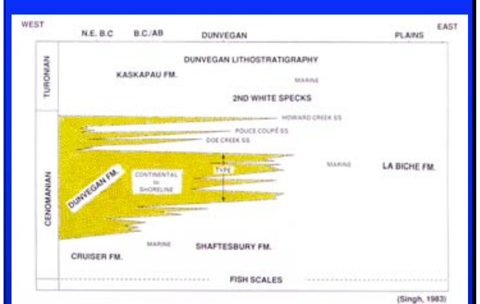
- Mappable units
- Lithologically homogeneous
- Diachronous boundaries

Allostratigraphy

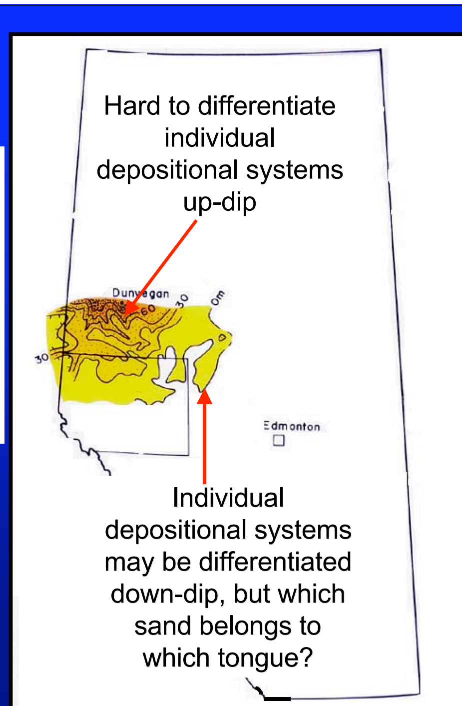


- Mappable units
- May be heterolithic
- Discontinuity bounded

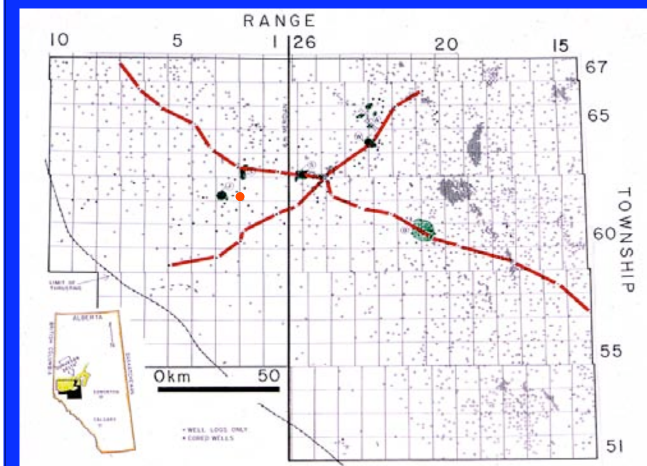
Lithostratigraphy as a basis for mapping

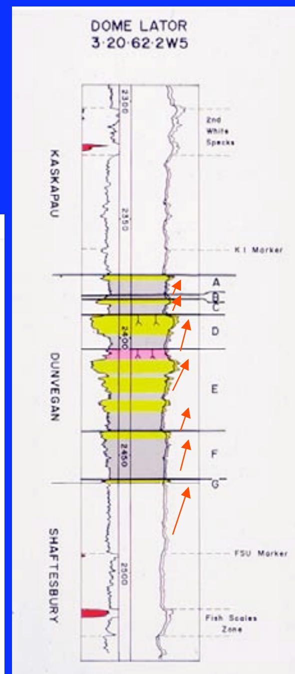


- Undifferentiated mapping of sandstones in entire wedge.
- Individual "tongues" hard to map.



Data and Area



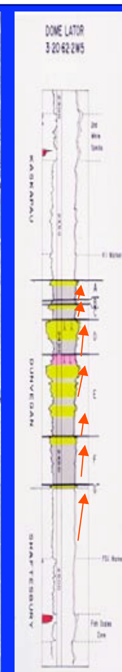


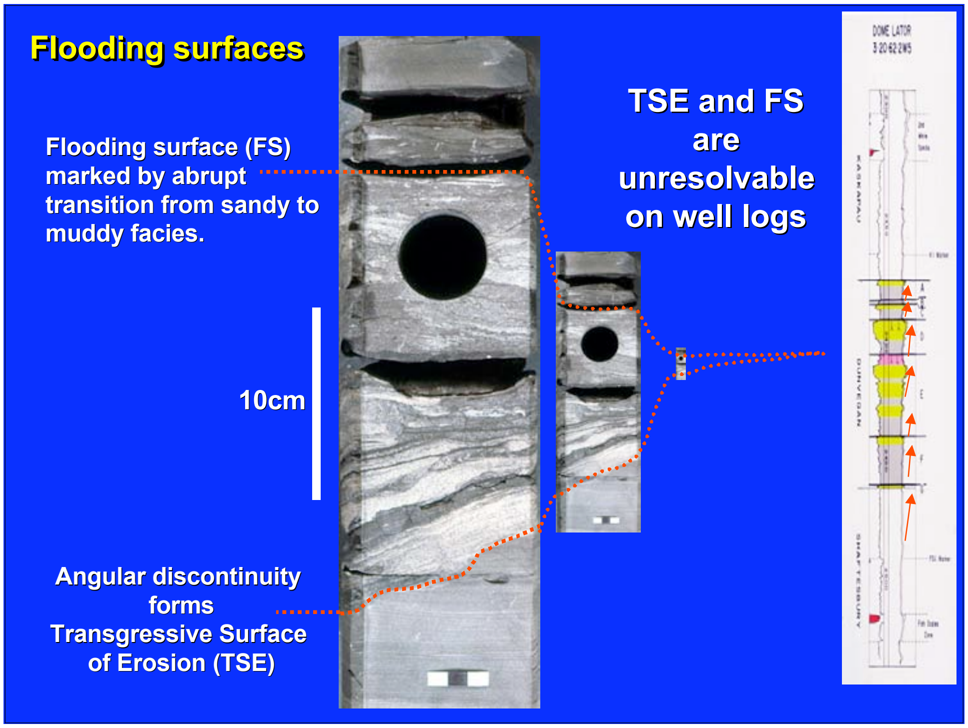
Flooding surfaces - Bounding discontinuities

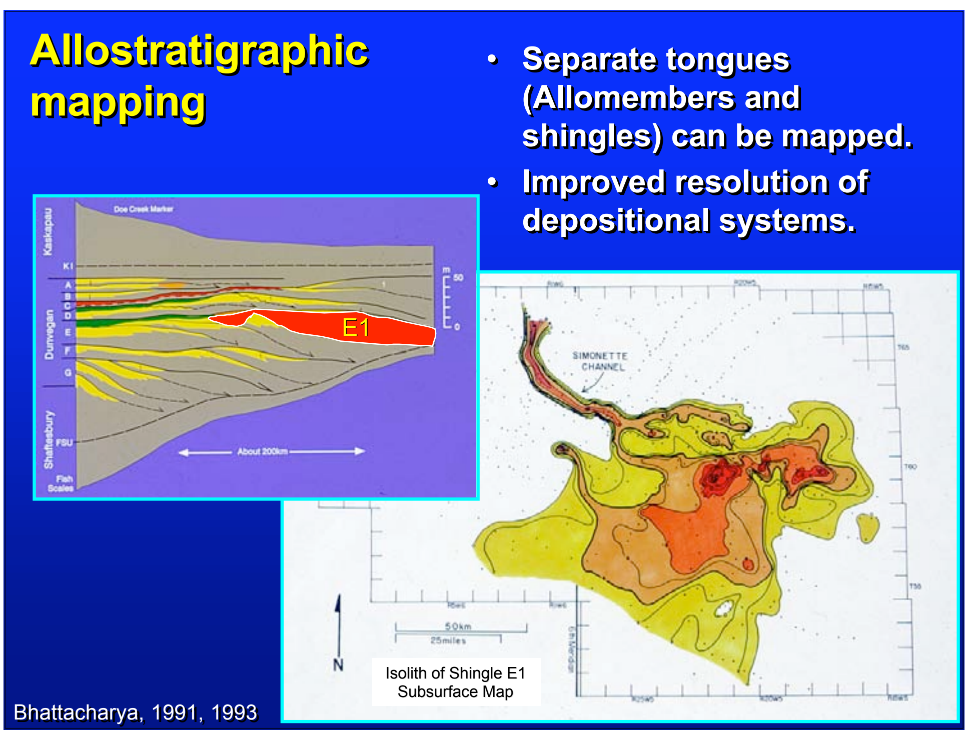
Razor sharp contact between shallow water sandstone and deeper water marine mudstones records deepening.

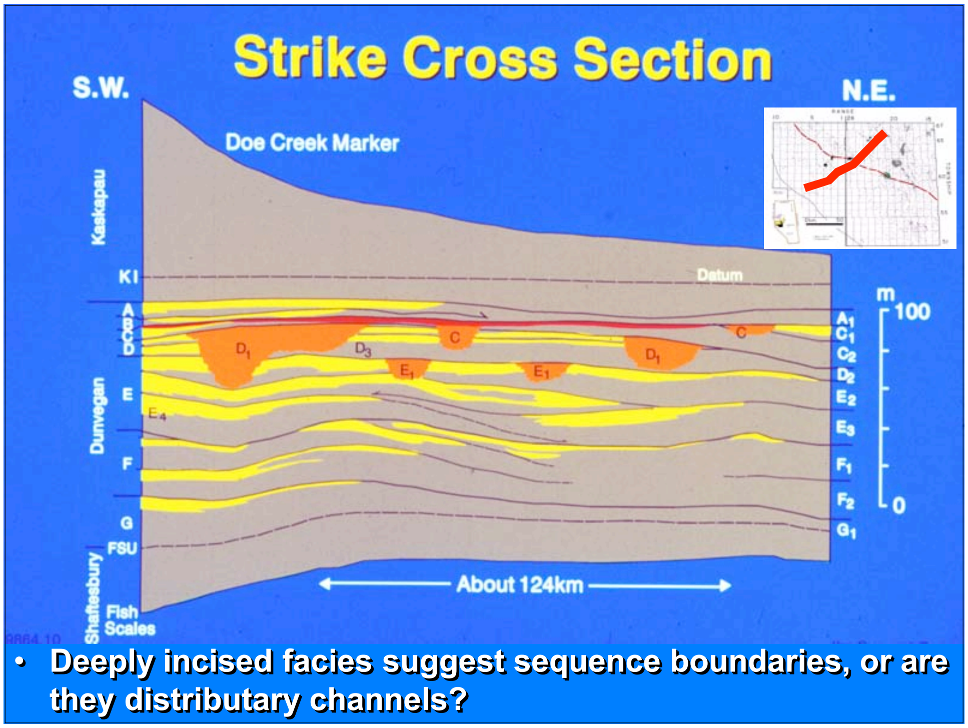
Bioturbation shows marine working of previously exposed surface.

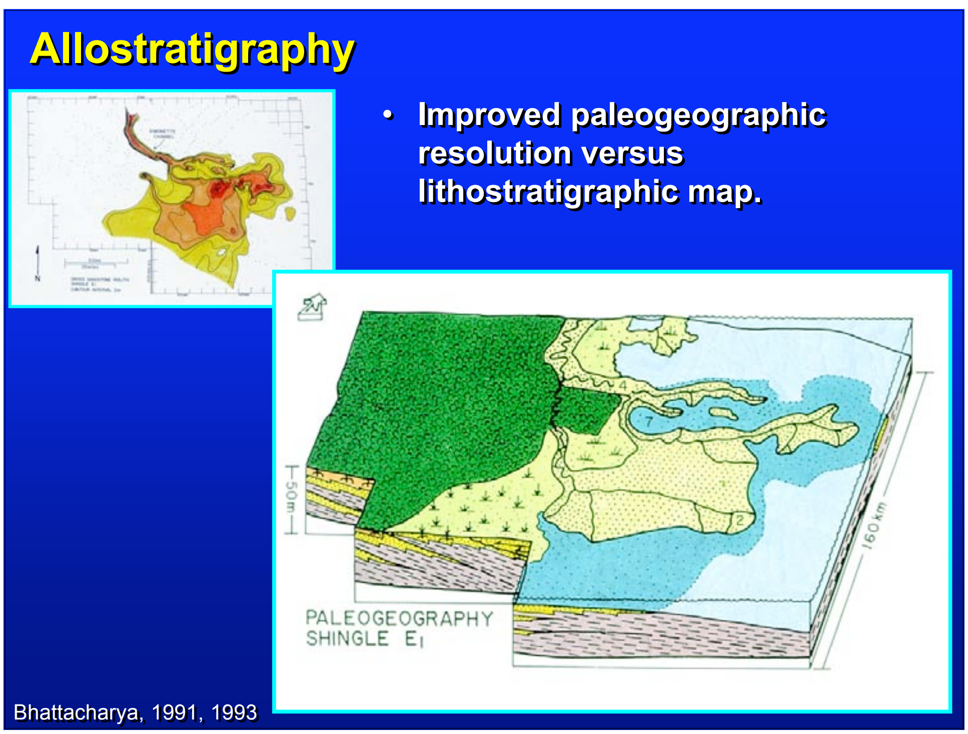
Roots record subaerial exposure.

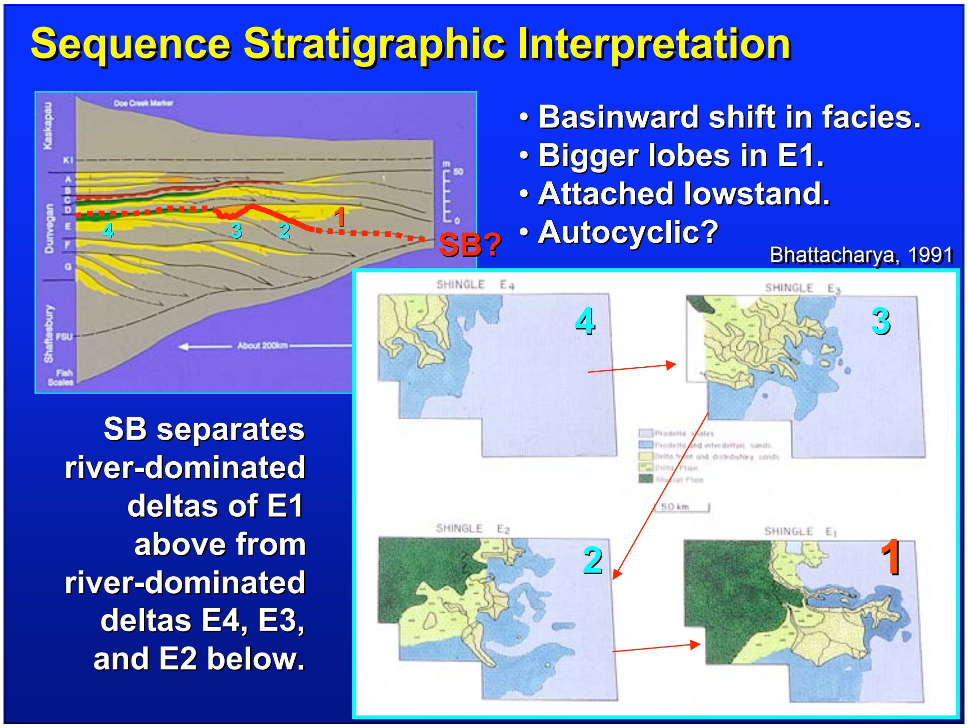


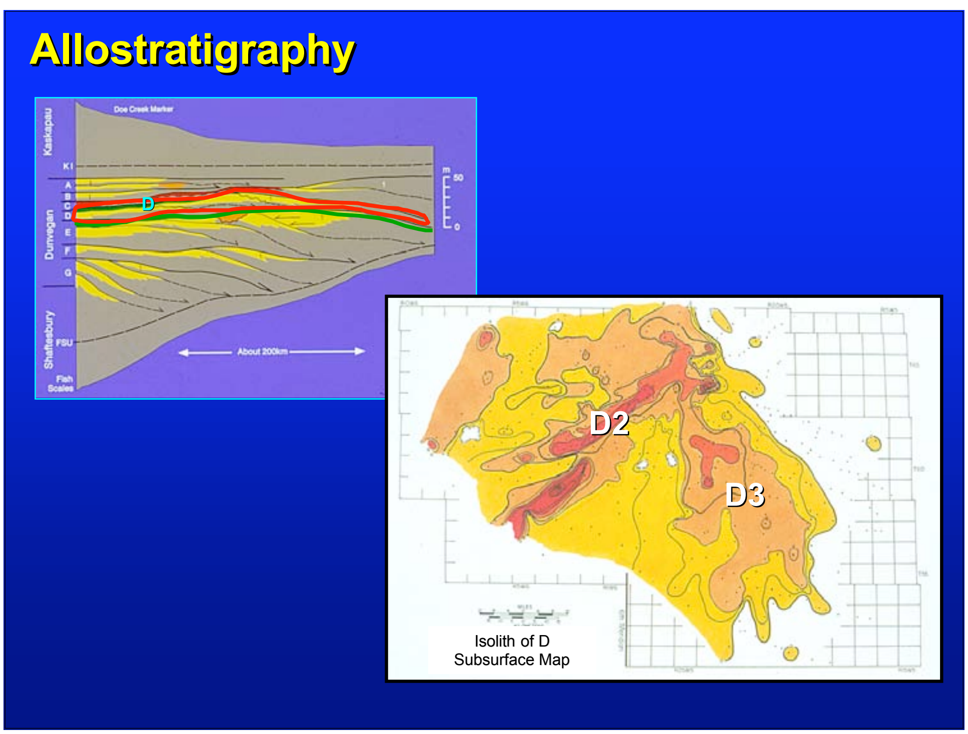

Flooding surfaces
Flooding surface (FS) marked by abrupt transition from sandy to muddy facies.
10cm
Angular discontinuity forms Transgressive Surface of Erosion (TSE)
TSE and FS are unresolvable on well logs


Allostratigraphic mapping
• Separate tongues (Allomembers and shingles) can be mapped.
• Improved resolution of depositional systems.
E1
Kaskapau
Dunvegan
Shaftesbury
About 200km
SIMONETTE CHANNEL
N
Isolith of Shingle E1
Subsurface Map
Bhattacharya, 1991, 1993

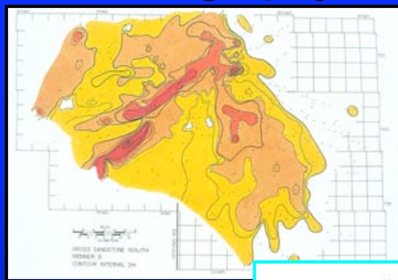

Strike Cross Section
S.W.
N.E.
Doe Creek Marker
Kaskapau
Dunvegan
Shaftesbury
KI
A
B
C
D
E
F
G
FSU
Fish Scales
Datum
m
100
0
About 124km
• Deeply incised facies suggest sequence boundaries, or are they distributary channels?


Allostratigraphy
• Improved paleogeographic resolution versus lithostratigraphic map.
PALEOGEOGRAPHY
SHINGLE E1
50m
160km
Bhattacharya, 1991, 1993

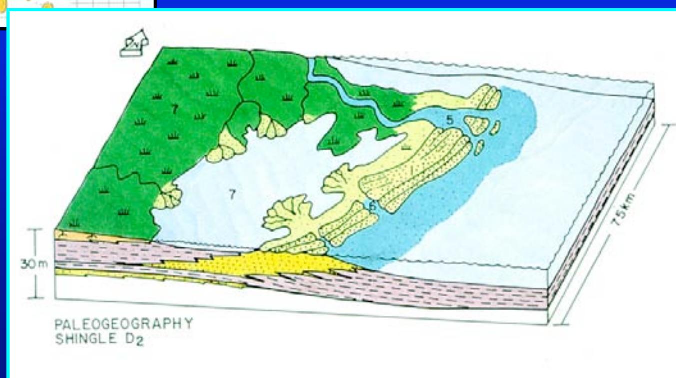

Sequence Stratigraphic Interpretation
• Basinward shift in facies.
• Bigger lobes in E1.
• Attached lowstand.
• Autocyclic?
Bhattacharya, 1991
SB?
SB separates river-dominated deltas of E1 above from river-dominated deltas E4, E3, and E2 below.
Doe Creek Marker
Kaskapau
Dunvegan
Shaftesbury
About 200km
SHINGLE E4
SHINGLE E3
SHINGLE E2
SHINGLE E1
4
3
2
1
50 km


Allostratigraphy
Doe Creek Marker
Kaskapau
Dunvegan
Shaftesbury
About 200km
D
D2
D3
Isolith of D
Subsurface Map

Allostratigraphy



Major paleogeographic reorganization occurs across allomember boundary from wave- versus river dominated depositional systems.



Conclusion

Allostratigraphy is an excellent framework for correlation within which sequence stratigraphy may be interpreted.

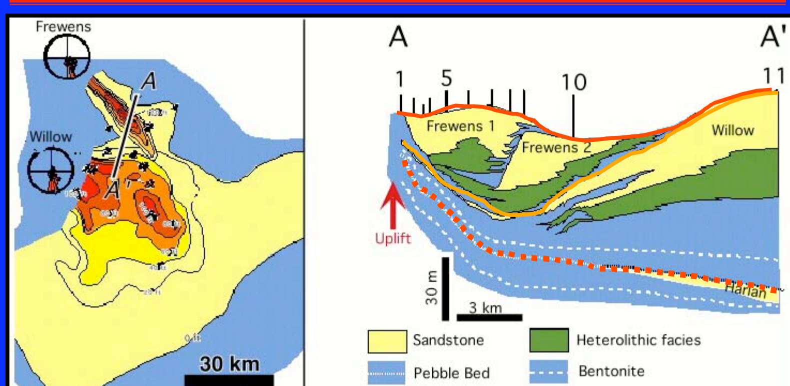
What is a Bounding Discontinuity?

- General Surfaces
  - Unconformity
  - Disconformity
  - Paraconformity
  - Omission Surface
  - Discontinuity Surface
  - Any traceable bed boundary?
- Sequence Stratigraphic Surfaces
  - Sequence Boundary
  - Transgressive Surface
  - Flooding Surface
  - Maximum Flooding Surface
  - Correlative Conformity

What is a Bounding Discontinuity?

- Any mappable or "pickable" stratal boundary.
- Most beds boundaries have some time missing and thus represent discontinuities (Derek Ager).
  - Missing time is not required to define discontinuity.
- Most beds represent a change in lithology and thus represent a facies discontinuity, even if no time is missing.
  - e.g. bentonite beds in Wyoming represent regionally traceable sharp change in lithology.
- It is the ability to map the discontinuity that is important not the interpretation of the origin of the discontinuity nor amount of time missing.

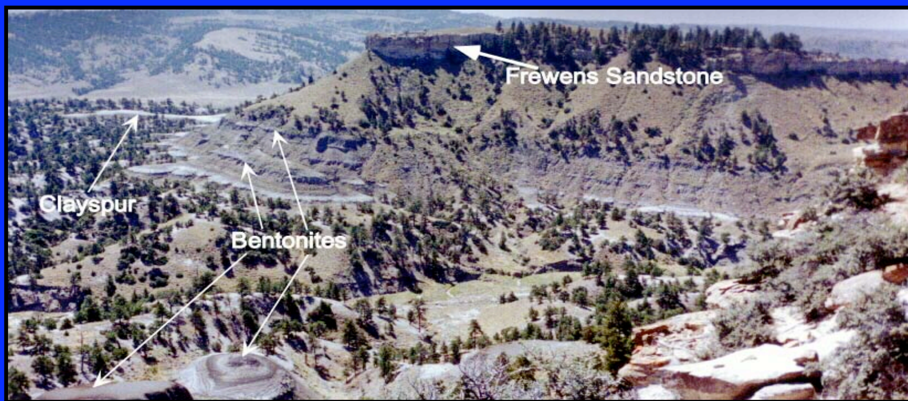
Allostratigraphy of Frontier Fm., Wyoming



Bhattacharya and Willis., 2001

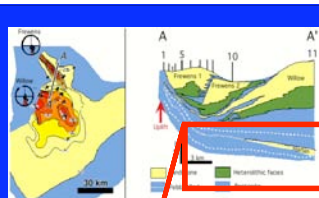
- Bentonites and pebble-capped ravinement surfaces used to define allomembers.

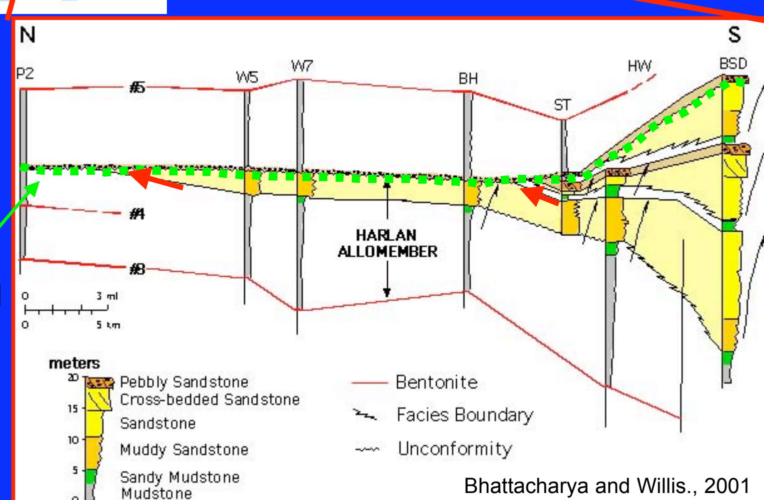
Bentonites of Frontier Fm.



- Bentonites and pebble-capped ravinement surfaces used to define allomembers.

Bounding discontinuities formed by marine erosion over subtle uplifts



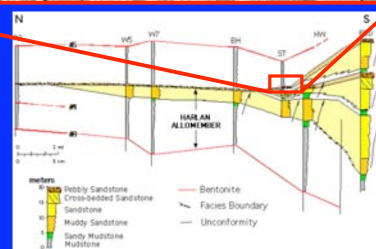


Bhattacharya and Willis., 2001

Marine erosion enhanced over high area

Lag Facies

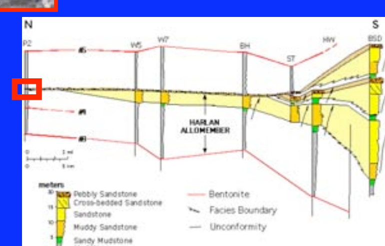
- Proximal expression
  - Pebble bed overlying delta front facies.



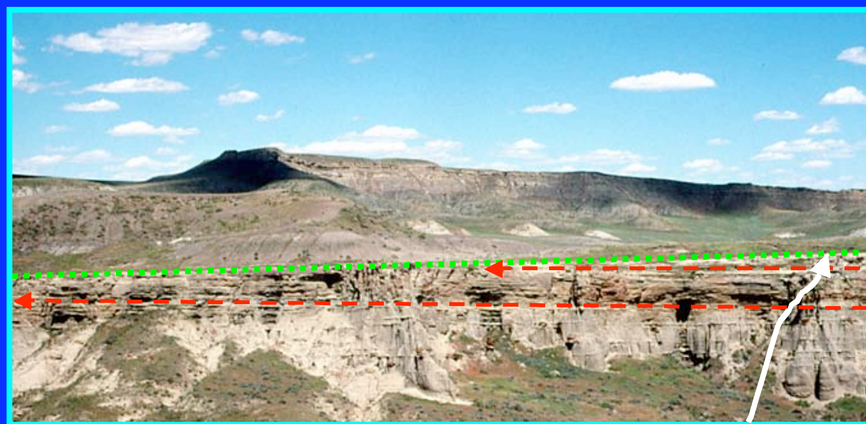
Lag Facies

- Distal expression
  - Thin pebble bed encased in marine mudstones.
  - Abundant shark's teeth

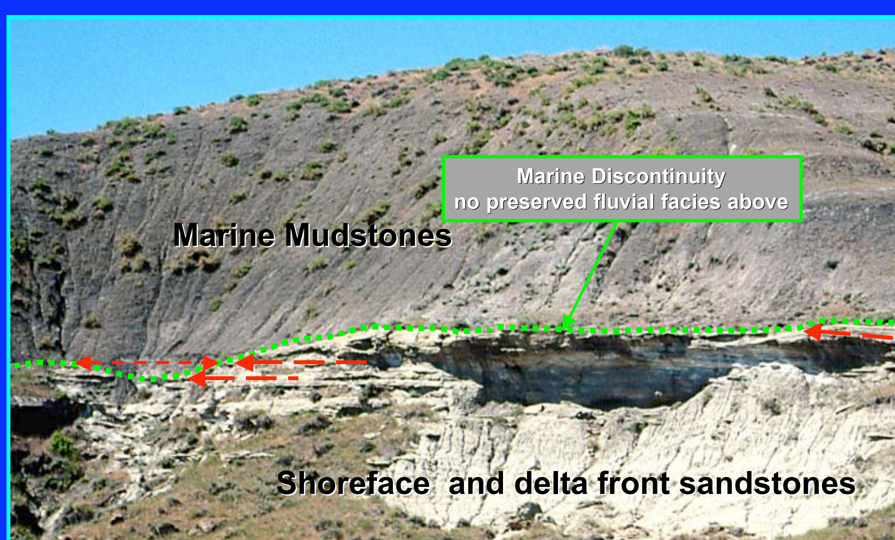
Big Pebbles in Mudstone

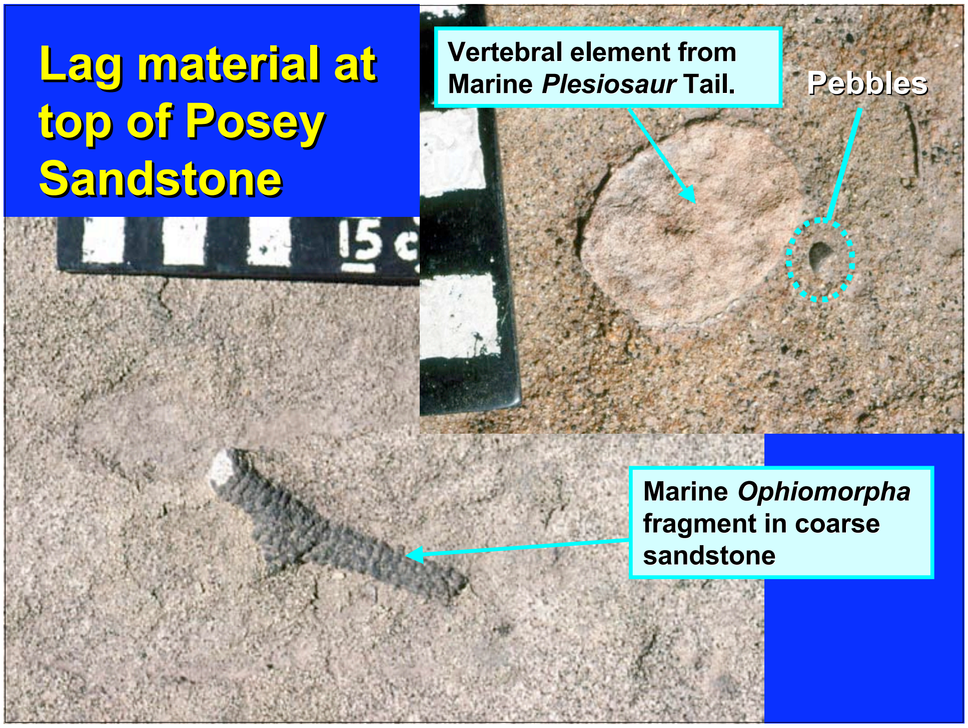


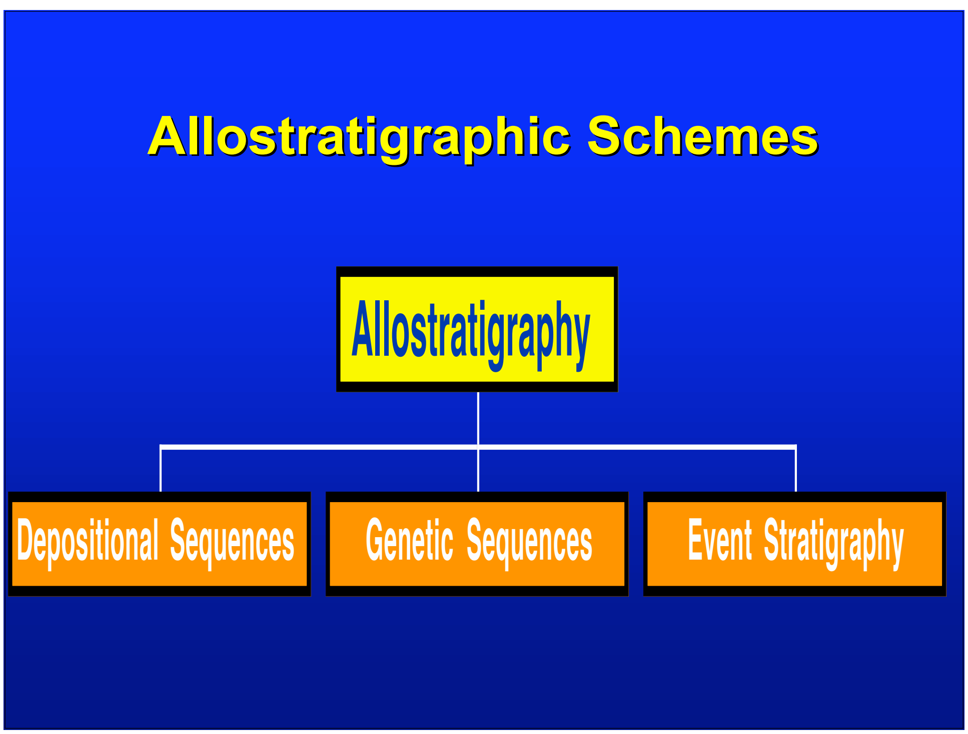
Posey Sandstone - Frontier Fm.



Posey Sandstone - Frontier Fm.




Lag material at top of Posey Sandstone
Vertebral element from Marine *Plesiosaur* Tail.
Pebbles
15 c
Marine *Ophiomorpha* fragment in coarse sandstone

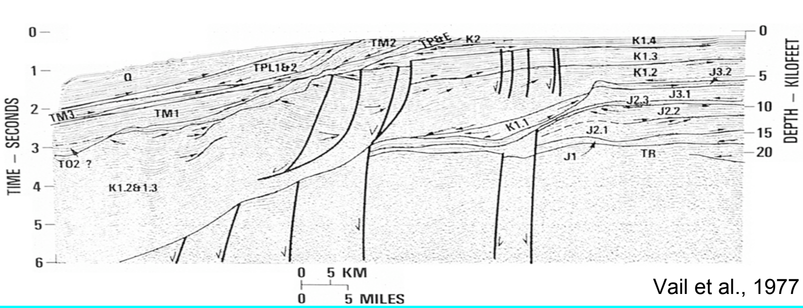

Allostratigraphic Schemes
Allostratigraphy
Depositional Sequences
Genetic Sequences
Event Stratigraphy

Sequence Stratigraphy

- Powerful way of interpreting allostratigraphic units in the context of cyclic changes in accommodation and accumulation.
- Stems from seismic stratigraphy.
- Defined by the “SEQUENCE BOUNDARY”

Seismic Stratigraphy

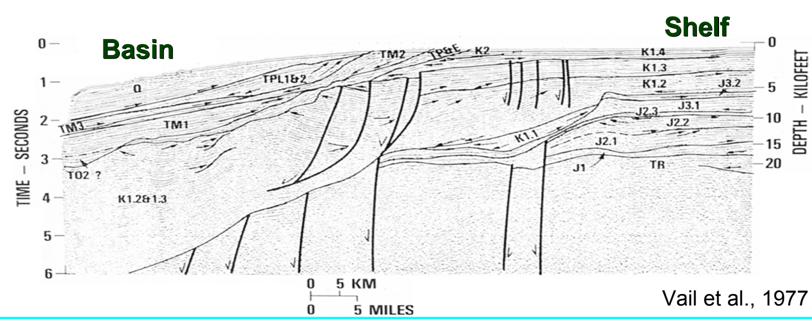
- Based on *observed* changes in reflection patterns at the basin-scale.
- Physical position of stratal packages (sequences, systems tracts) can be observed and mapped.
- Sequence bounding unconformities can be observed passing into correlative conformities because reflections are continuous.



Vail et al., 1977

Seismic Stratigraphy

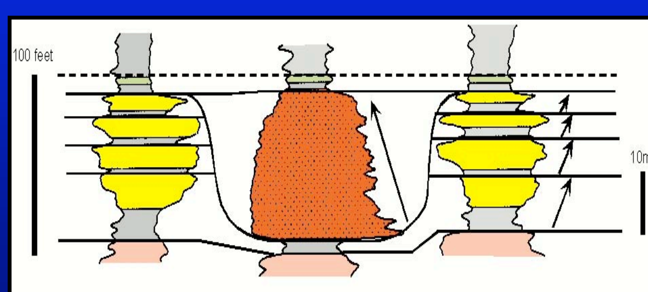
- Environments (shelf, slope, basin etc.) are easily distinguished.
- Lithologies are difficult to distinguish.
  - inferred rather than observed from stratal patterns.
  - Industry routinely loses tens of millions of dollars every year because of poor predictability of reservoir lithology.



Vail et al., 1977

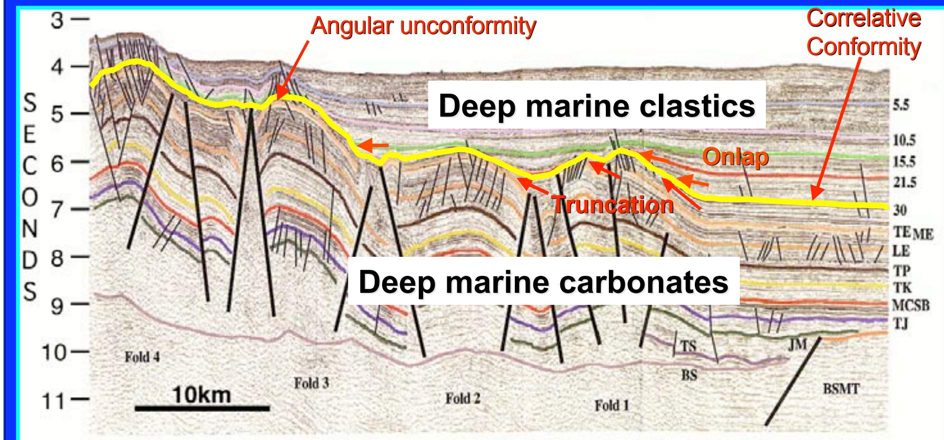
Sequence Boundary

- Sequence boundary originally defined as the unconformity and its correlative conformity (Mitchum, 1977).
- Redefined as an erosional surface that is ***subaerially exposed*** (Van Wagoner et al., 1990).



Incised Valley within Fall River Sandstone, (Willis, 1997)

Seismic Stratigraphy



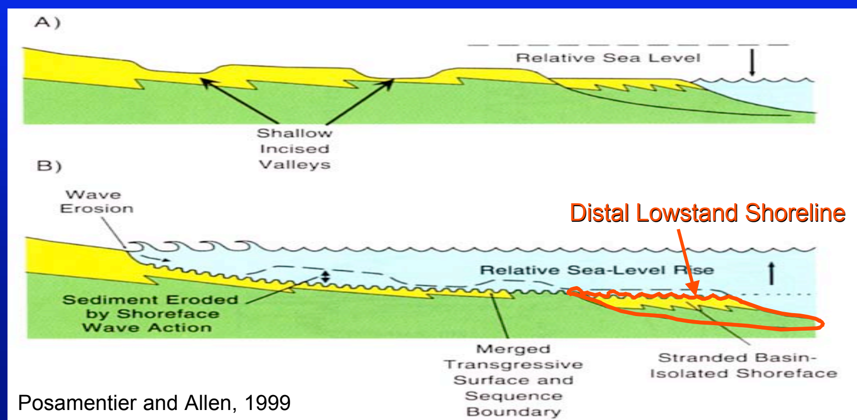
- Perdido fold belt, Gulf of Mexico (Fiduk et al., 1999)
- No subaerial exposure, totally marine erosion.
- Can this be a sequence boundary?

No Sequence or No Sense?

- Wholly marine unconformities, useful in allostratigraphy, *do not* satisfy the strict definition requiring subaerial exposure.
  - Deepwater unconformities like Perdido Fold belt.
  - Marine erosion surfaces like in Frontier Fm.
  - Other ravinement and flooding surfaces.
  - Deep tidal scours (Willis, this meeting).
- Angular Unconformities are not always sequence boundaries?
  - Sea-level and environmental facies bias in definition.

Lowstand System Tract

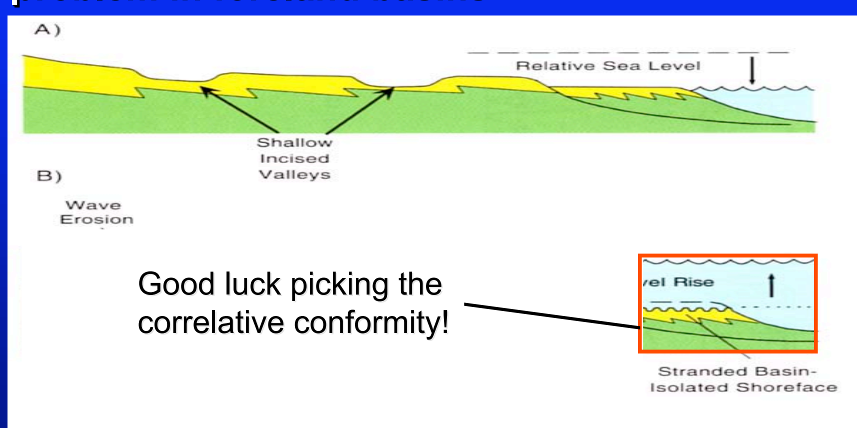
- **Definition**
  - The lowstand systems tract overlies the *"sequence boundary" (includes correlative conformity).*
- **Distal lowstands overlie correlative conformities.**



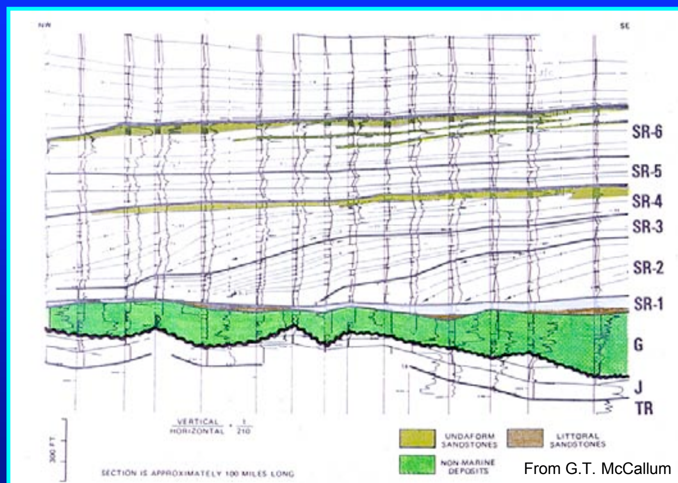
Posamentier and Allen, 1999

Correlative Conformities

Let's remove the proximal facies, a common problem in foreland basins

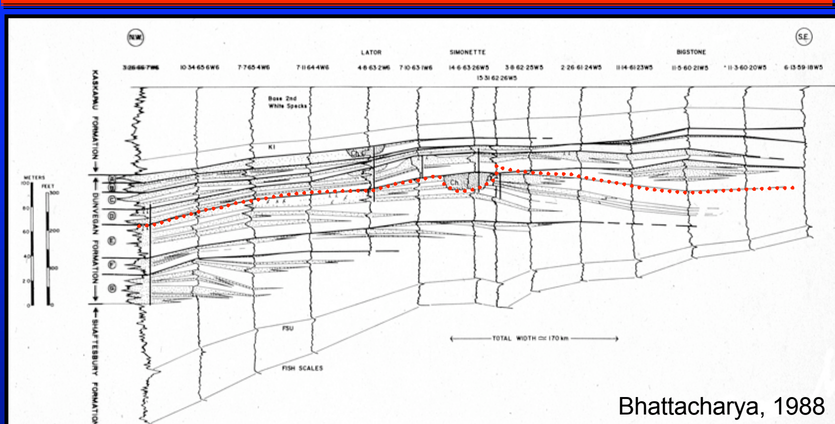


Well Log Sequence Stratigraphy



Mitchum et al., 1977

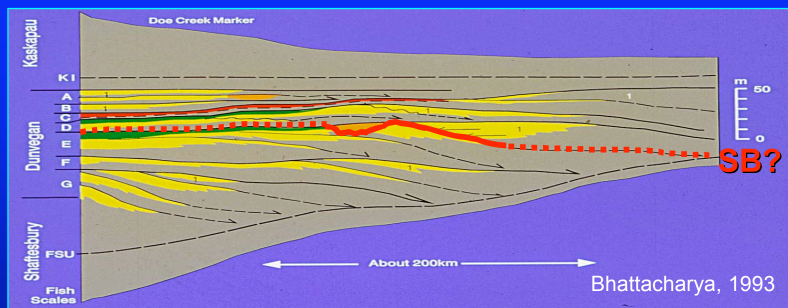
Limitations of outcrop, well log and core studies



Bhattacharya, 1988

- Surfaces have to be extrapolated between data points.

Limitations of outcrop, well log and core studies



- Sequence boundary can not be objectively picked where it is expressed as a correlative conformity.
- This makes it impossible to correctly identify the "sequences" in some (many?) cases.

Sequence Hierarchies

Impossible to use in most outcrop studies. Unwieldy in core studies. Good for measuring tidal bundles and tidal laminites

- EXXON School
  - Lamina
  - Laminaset
  - Bed
  - Bedset
  - Parasequence
  - Parasequence set
  - Sequence

- European/Texas School
  - Facies
  - Facies Association
  - Depositional System
  - Systems Tract
  - Sequence

Sequence Hierarchies

- Hierarchy of beds and bedsets is in a state of constant flux as we learn more about facies architecture.

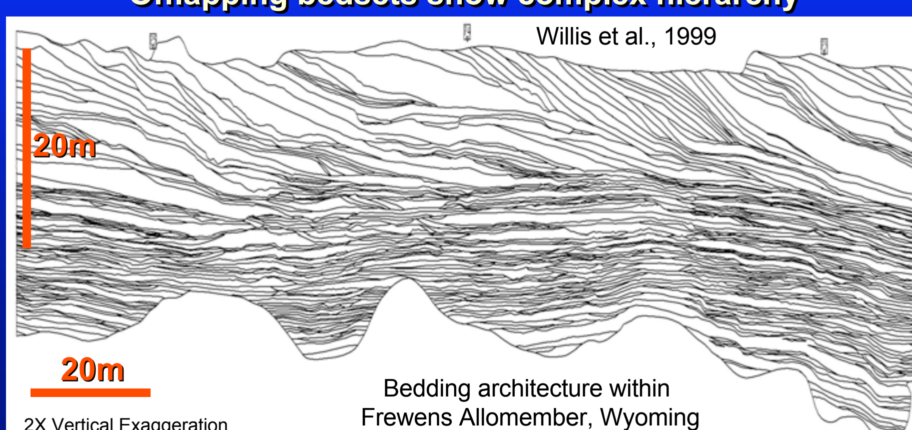
- Lamina
- Laminaset
- **Bed**
- **Bedset**
- Parasequence
- Parasequence set
- Sequence

- Facies
- Facies Association
- Depositional System
- Systems Tract
- Sequence

Sequence Hierarchies

- Numerous scales of bed and bedsets are common.
- Hierarchy changes if beds offlap or are cross stratified.

Offlapping bedsets show complex hierarchy



Sequence Hierarchies

- Standard facies nomenclature is much more flexible.
- Incorporation of facies architecture terms is a major challenge.

- Lamina
- Laminaset
- Bed
- Bedset
- Parasequence
- Parasequence set
- Sequence

- Facies
- Facies Association
- Depositional System
- Systems Tract
- Sequence

Terminology Problems

- Lack of consistency in definition and usage of sequence terms.
- May convey either positional or temporal concepts.
  - Despite claims that Systems Tracts are defined purely physically, most practitioners refer to ***early*** and ***late*** subdivision within systems tracts.
  - Use of time terms suggests that sequence stratigraphers fundamentally believe that a system tract represents a unit of time or a period of sea level change rather than a rock unit.

More Terminology Problems

- Practical problems in defining the correlative conformity.
- Difficult to define sequences where evidence for erosion is cryptic or absent.
- Bias towards subaerial exposure results in inability to label tectonically produced marine erosion surfaces as sequence boundaries (sensu Exxon).
- Marine erosion may remove evidence of prior subaerial exposure, which must then be inferred rather than observed.
- If I can't call erosion bounded units sequences what term do I use?
  – Allostratigraphy avoids genetic terminology

The Good News

- Sequence Stratigraphy
  – highly flexible tool for genetic ***interpretation***.
  – retain flexibility to add or delete categories as we better understand the complexity of the stratigraphic record.
    - Falling Stage Systems Tract in favor
    - Shelf Margin Systems Tract rarely used
    - Type 2 Sequence Boundary largely abandoned in most published examples.

Conclusions

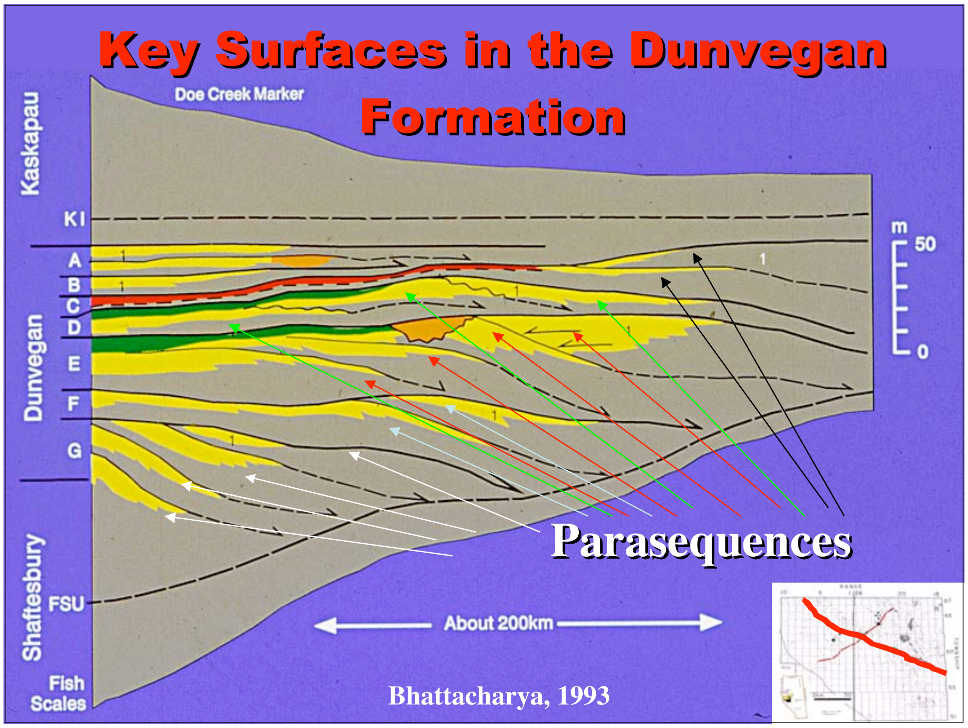
- Sequence terminology needs clarification.
  - Highly biased towards sea level changes through time.
  - Need to clarify temporal and genetic bias in terminology.
- Because of genetic nature of terminology, Sequence Stratigraphy is a less valuable scheme for formally naming rock units.
- Attempts to formalize sequence categories will likely not be successful.
  - Attempts to present formalized facies schemes have been moderately successful at best.

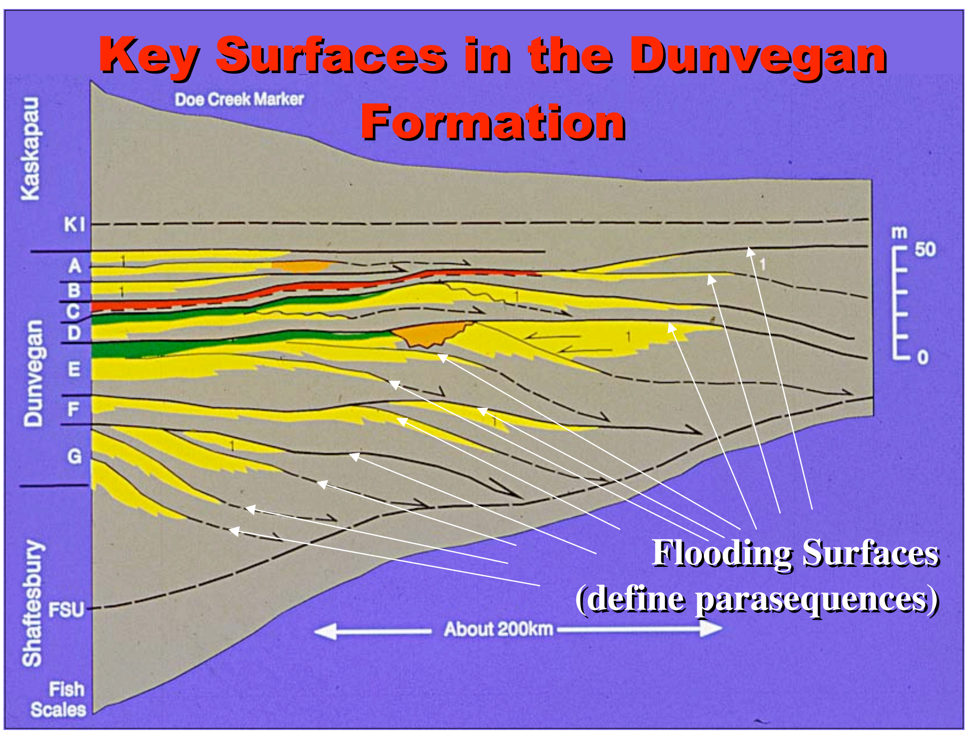
Conclusions

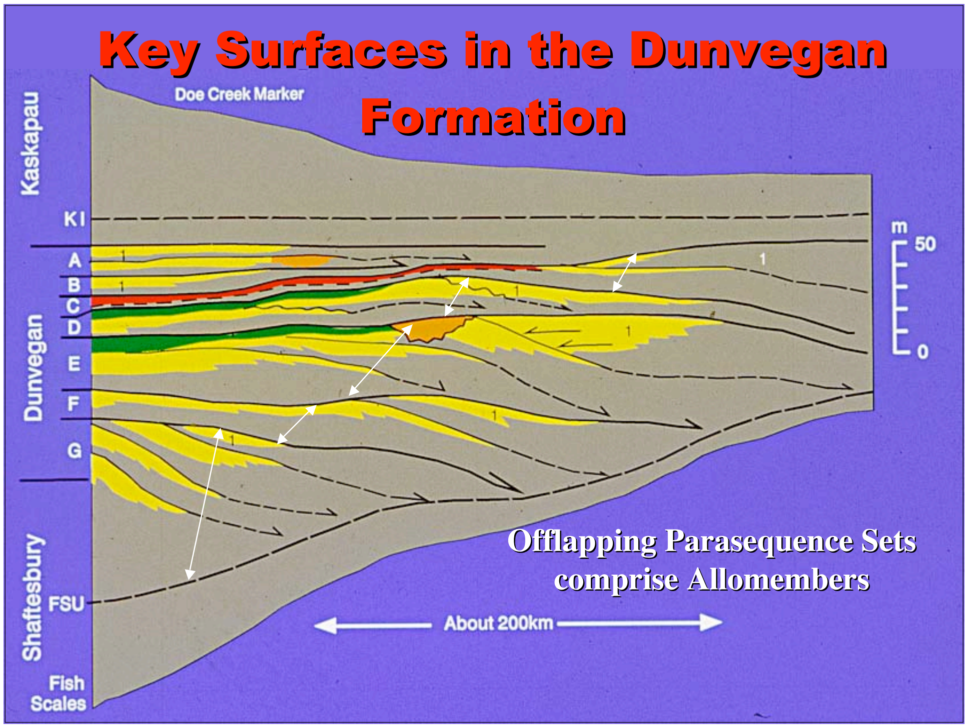
- Allostratigraphy is inherently less controversial in that it emphasizes mappable, observable discontinuities, rather than inferred exposure surfaces.
- Only available scheme for formal naming.
- Results should be reproducible.

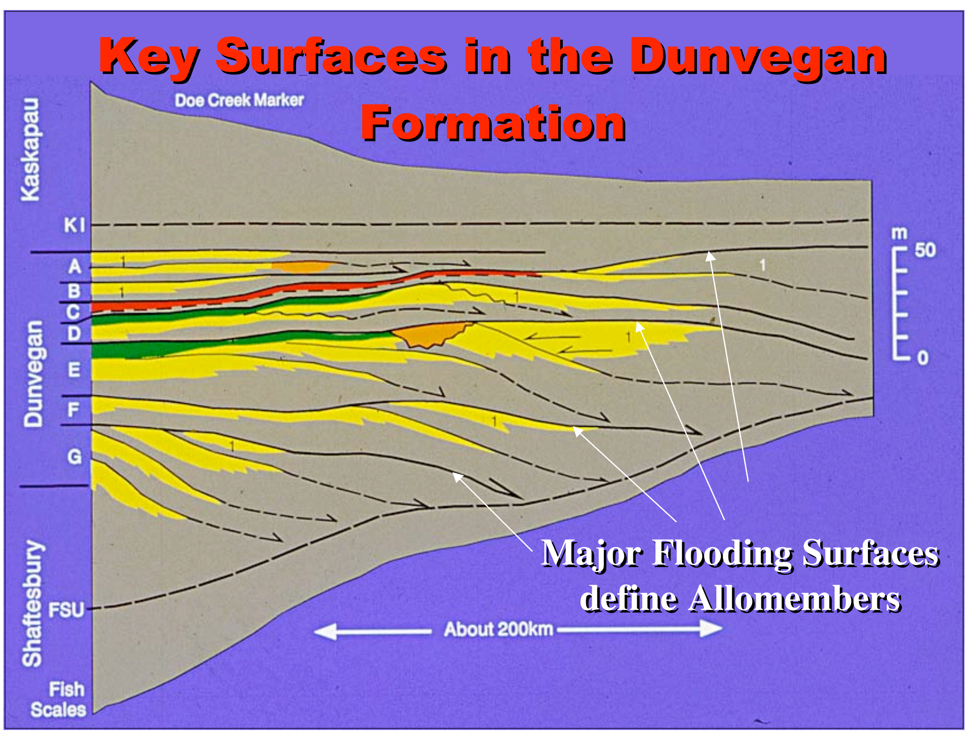
Conclusions

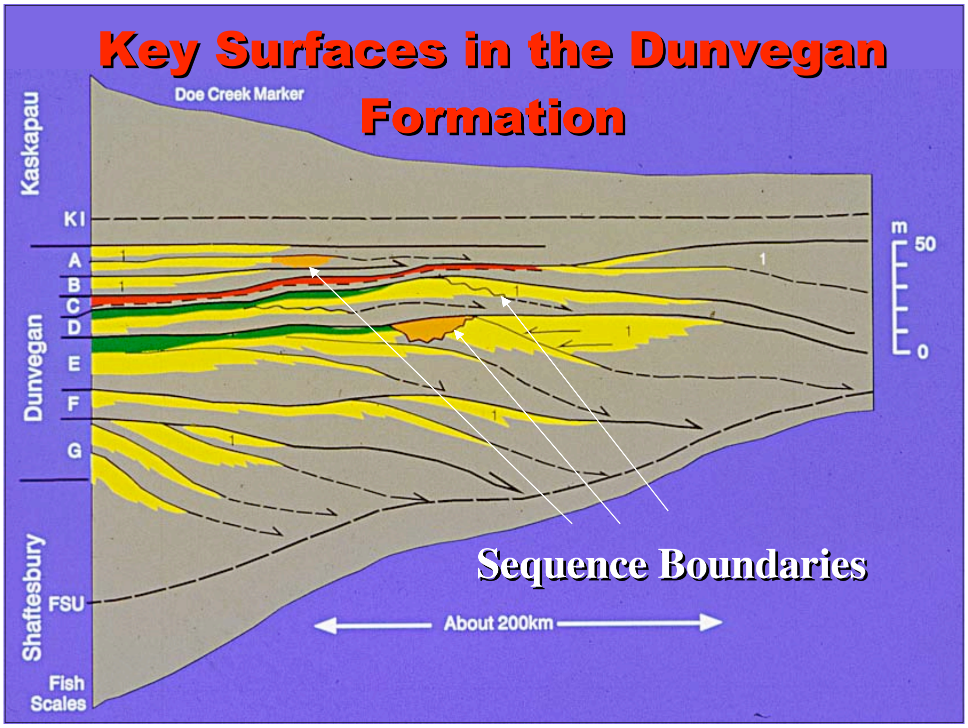
- Allostratigraphy lacks the theoretical intellectual framework for interpreting strata in the context of key surfaces formed by changes in accommodation and accumulation.
- Sequence interpretation is best built on a robust allostratigraphic framework.
  - Sequence Stratigraphic Interpretations may change.
  - Basic allostratigraphic definitions of mappable units should have a longer shelf life than ensuing interpretations.

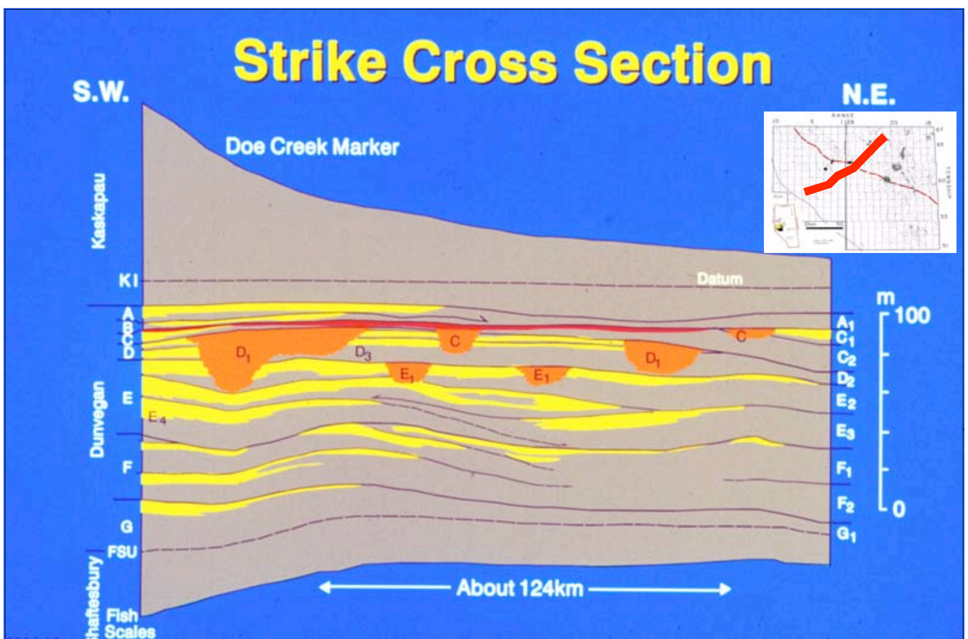

Key Surfaces in the Dunvegan Formation
Doe Creek Marker
Kaskapau
KI
A
B
C
D
E
F
G
Dunvegan
Shaftesbury
FSU
Fish Scales
m
50
0
Parasequences
About 200km
Bhattacharya, 1993


Key Surfaces in the Dunvegan Formation
Doe Creek Marker
Kaskapau
KI
A
B
C
D
E
F
G
Dunvegan
Shaftesbury
FSU
Fish Scales
m
50
0
Flooding Surfaces
(define parasequences)
About 200km

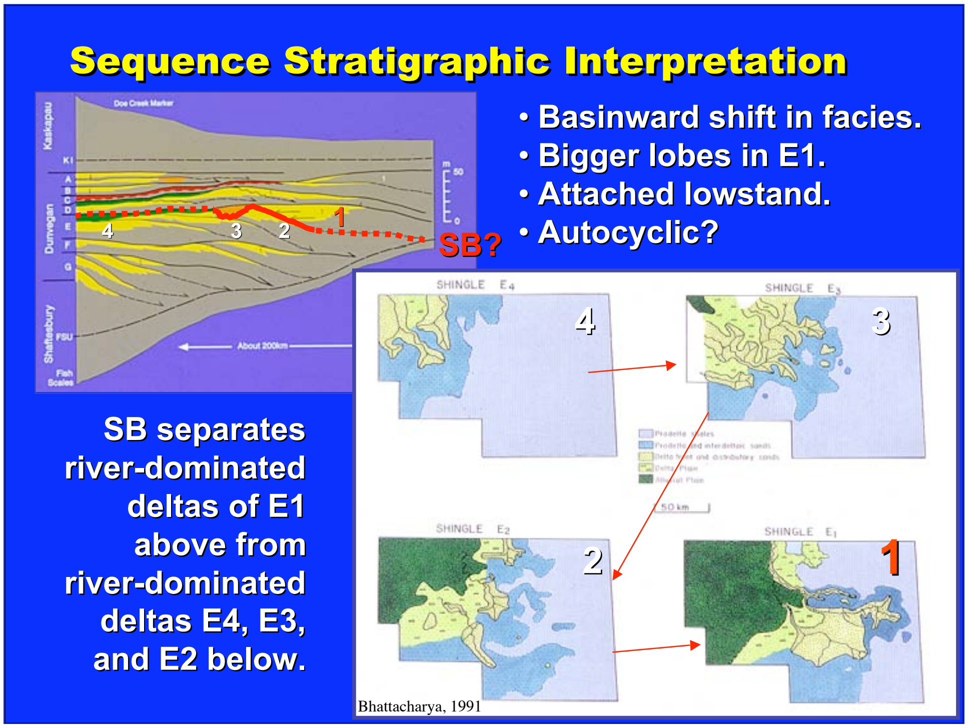

Key Surfaces in the Dunvegan Formation
Doe Creek Marker
Kaskapau
KI
A
B
C
D
E
F
G
Dunvegan
Shaftesbury
FSU
Fish Scales
m
50
0
Offlapping Parasequence Sets comprise Allomembers
About 200km

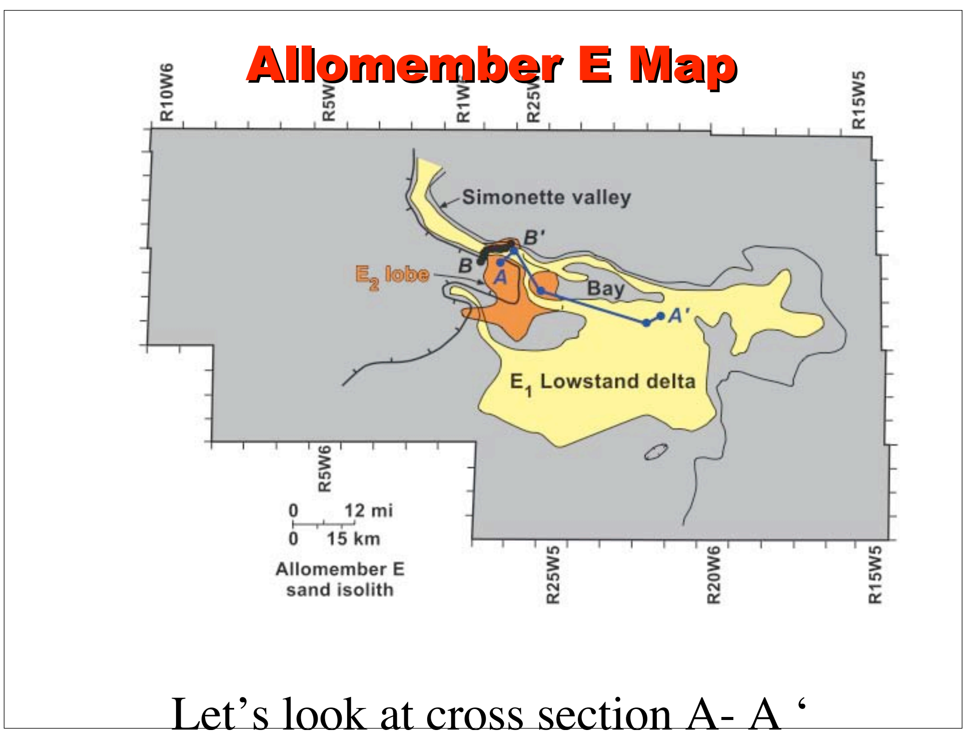

Key Surfaces in the Dunvegan Formation
Doe Creek Marker
Kaskapau
KI
A
B
C
D
E
F
G
Dunvegan
Shaftesbury
FSU
Fish Scales
m
50
0
Major Flooding Surfaces define Allomembers
About 200km

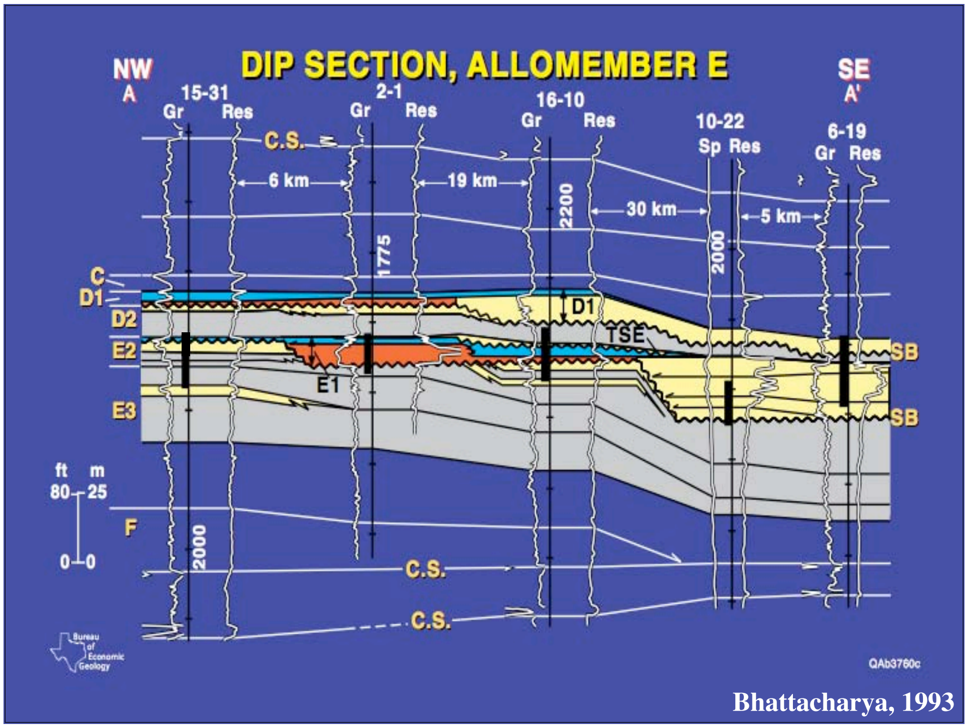




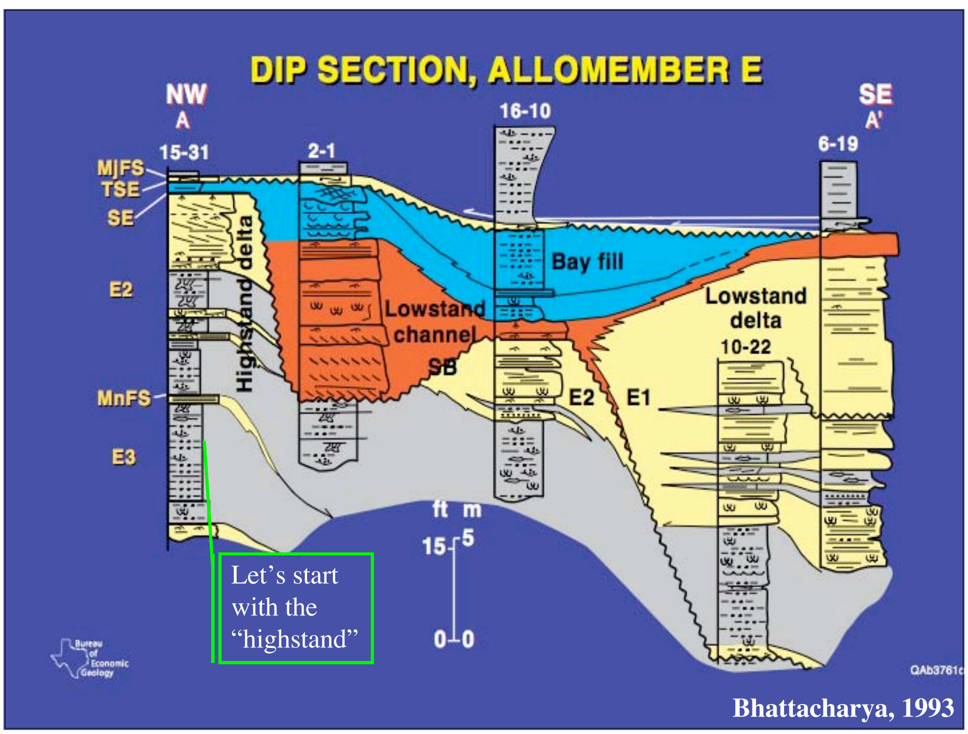
- Valleys and sequence boundaries much easier to identify in strike section.


Sequence Stratigraphic Interpretation
• Basinward shift in facies.
• Bigger lobes in E1.
• Attached lowstand.
• Autocyclic?
SB?
SB separates river-dominated deltas of E1 above from river-dominated deltas E4, E3, and E2 below.
SHINGLE E4
SHINGLE E3
SHINGLE E2
SHINGLE E1
Bhattacharya, 1991

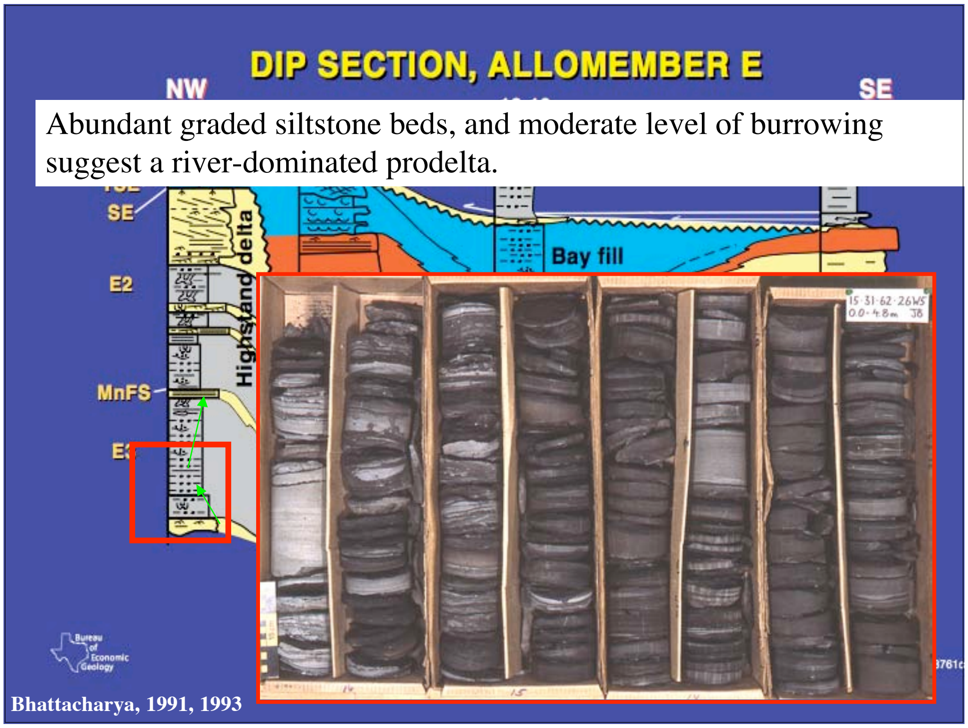

Allomember E Map
R10W6
R5W6
R1W6
R25W5
R15W5
Simonette valley
B'
B
E2 lobe
A
Bay
A'
E1 Lowstand delta
0 12 mi
0 15 km
Allomember E sand isolith
R20W6
Let's look at cross section A- A '

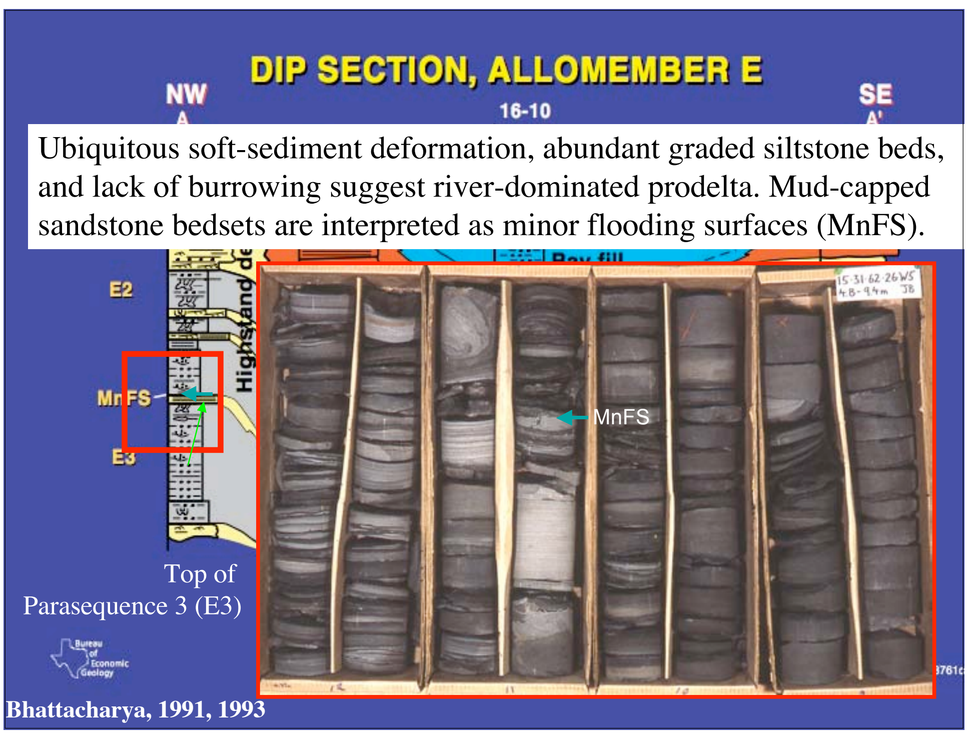


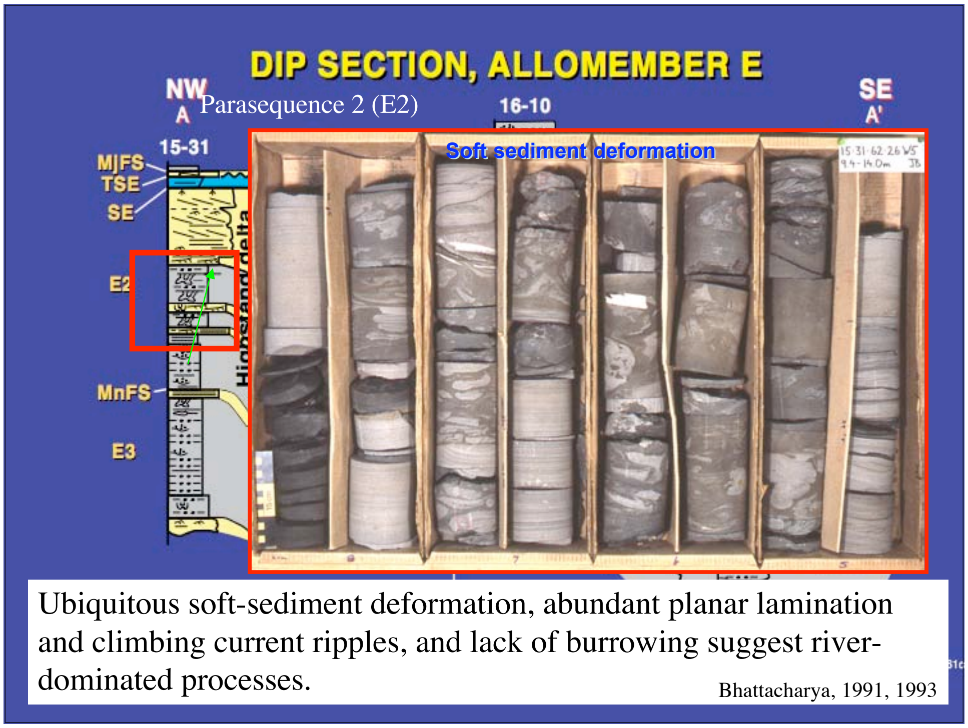
Bhattacharya, 1993

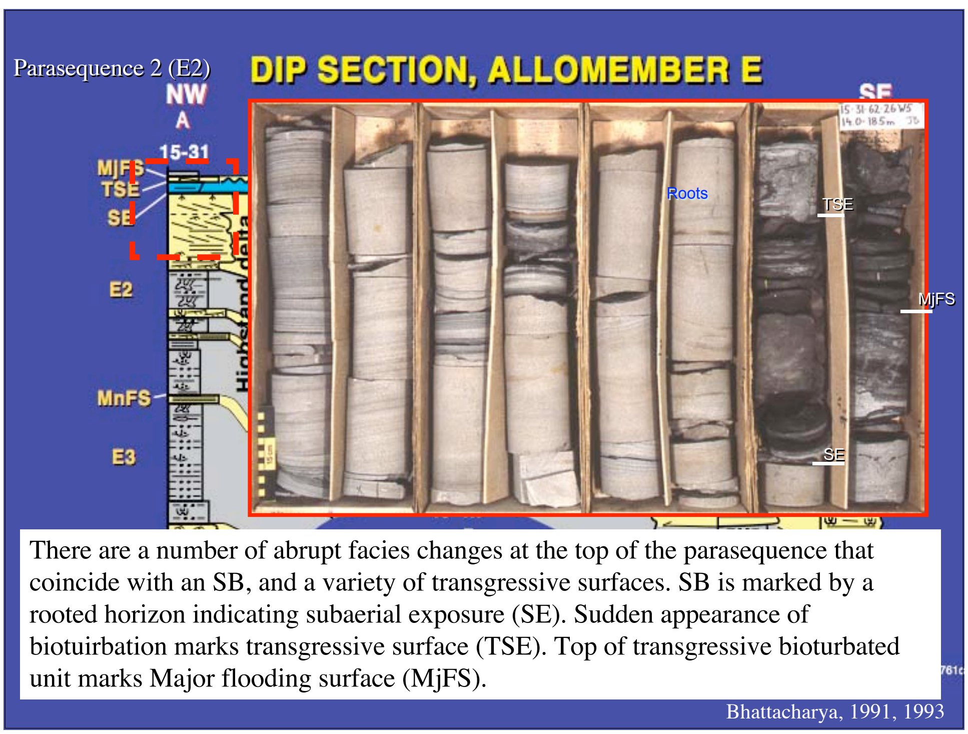


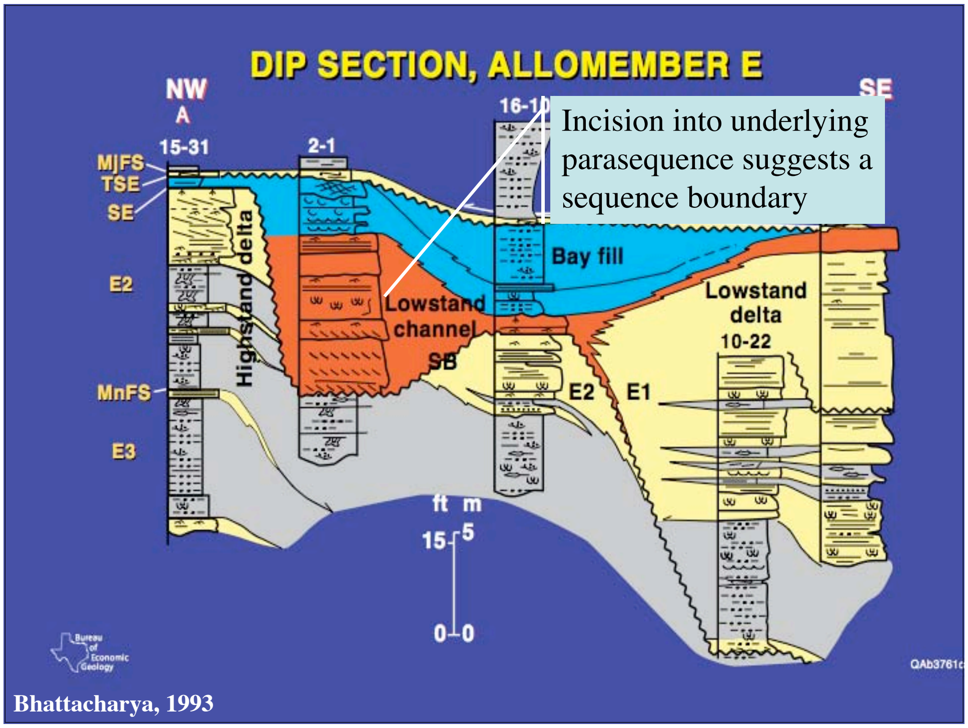
Bhattacharya, 1993

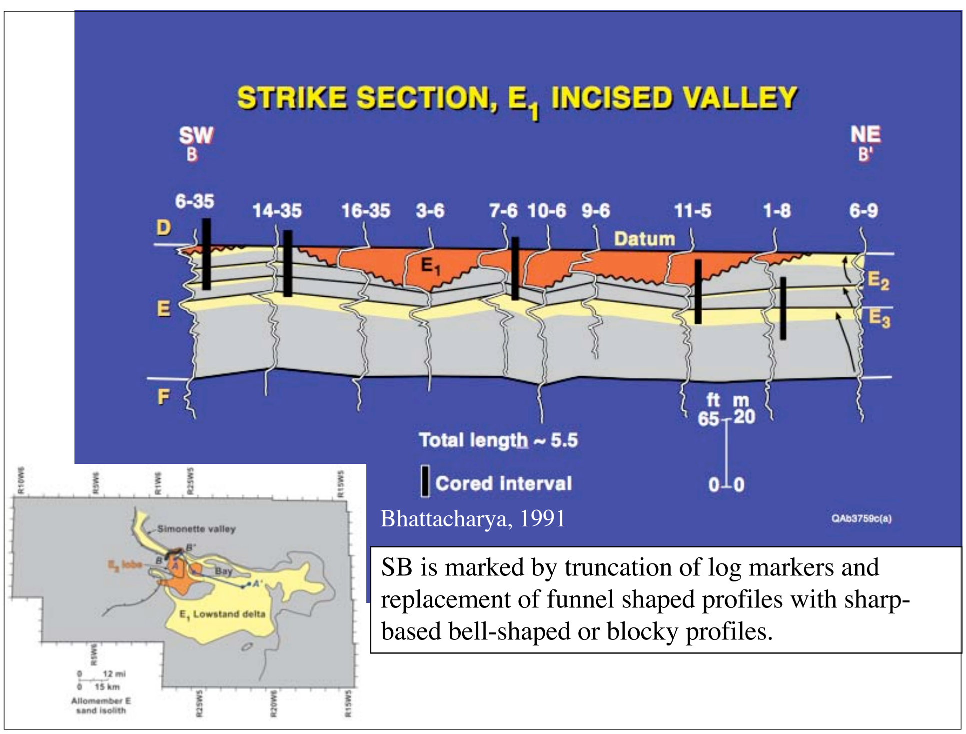

DIP SECTION, ALLOMEMBER E
NW
SE
Abundant graded siltstone beds, and moderate level of burrowing suggest a river-dominated prodelta.
SE
E2
MnFS
Highstand delta
Bay fill
Bhattacharya, 1991, 1993

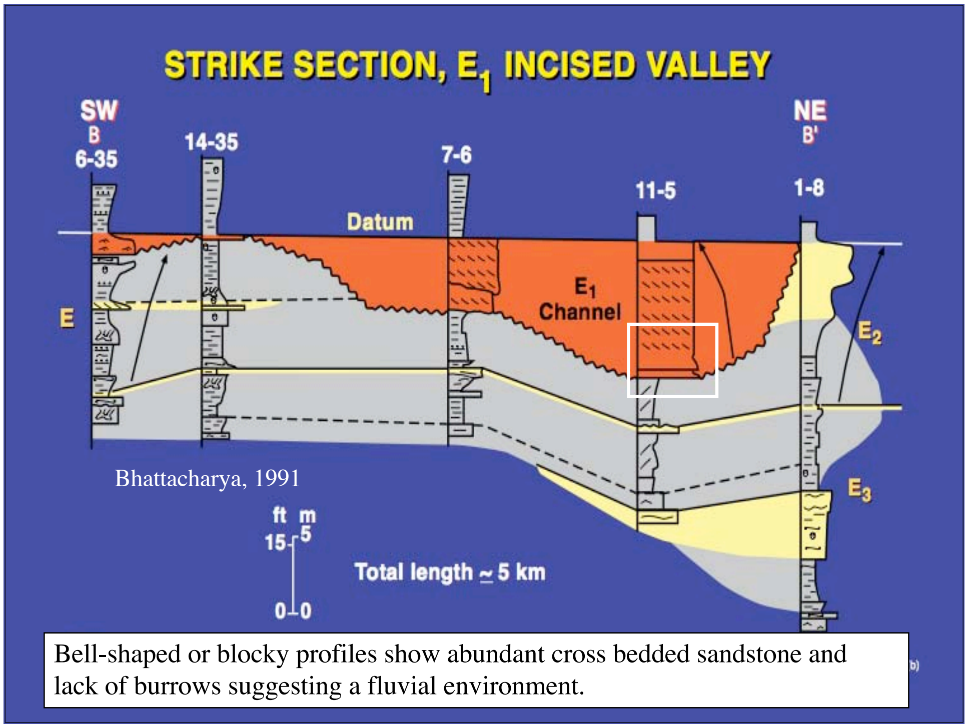

DIP SECTION, ALLOMEMBER E
NW
A
16-10
SE
A'
Ubiquitous soft-sediment deformation, abundant graded siltstone beds, and lack of burrowing suggest river-dominated prodelta. Mud-capped sandstone bedsets are interpreted as minor flooding surfaces (MnFS).
E2
MnFS
E3
Highstand
MnFS
Top of Parasequence 3 (E3)
Bhattacharya, 1991, 1993

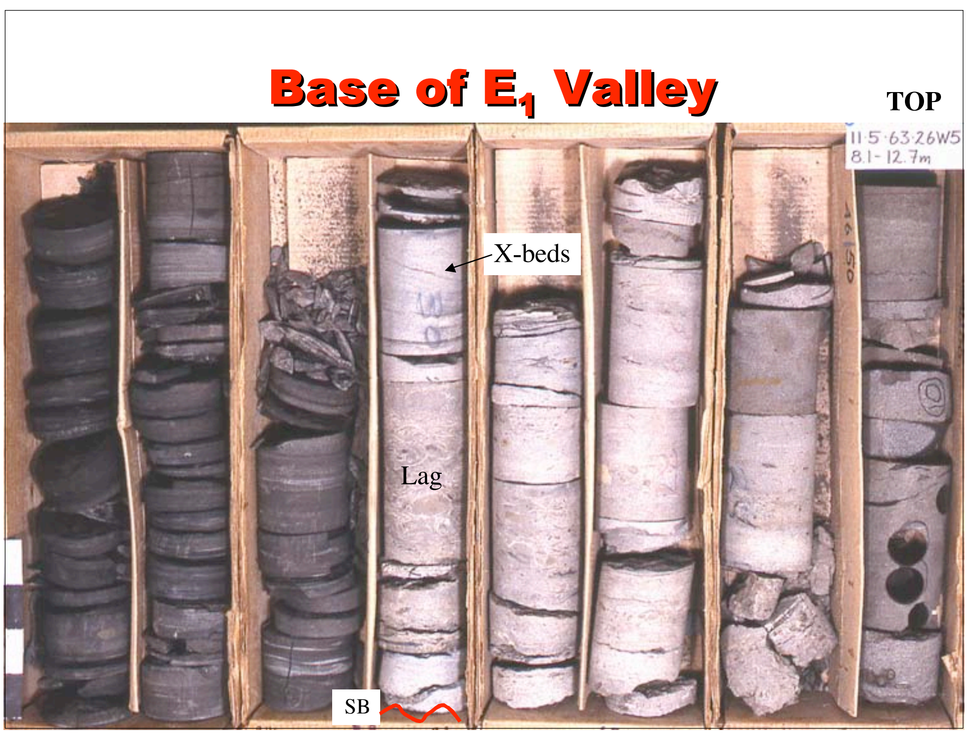

DIP SECTION, ALLOMEMBER E
NW
A
Parasequence 2 (E2)
16-10
SE
A'
15-31
MjFS
TSE
SE
E2
MnFS
E3
Highstand delta
Soft sediment deformation
Ubiquitous soft-sediment deformation, abundant planar lamination and climbing current ripples, and lack of burrowing suggest river-dominated processes.
Bhattacharya, 1991, 1993

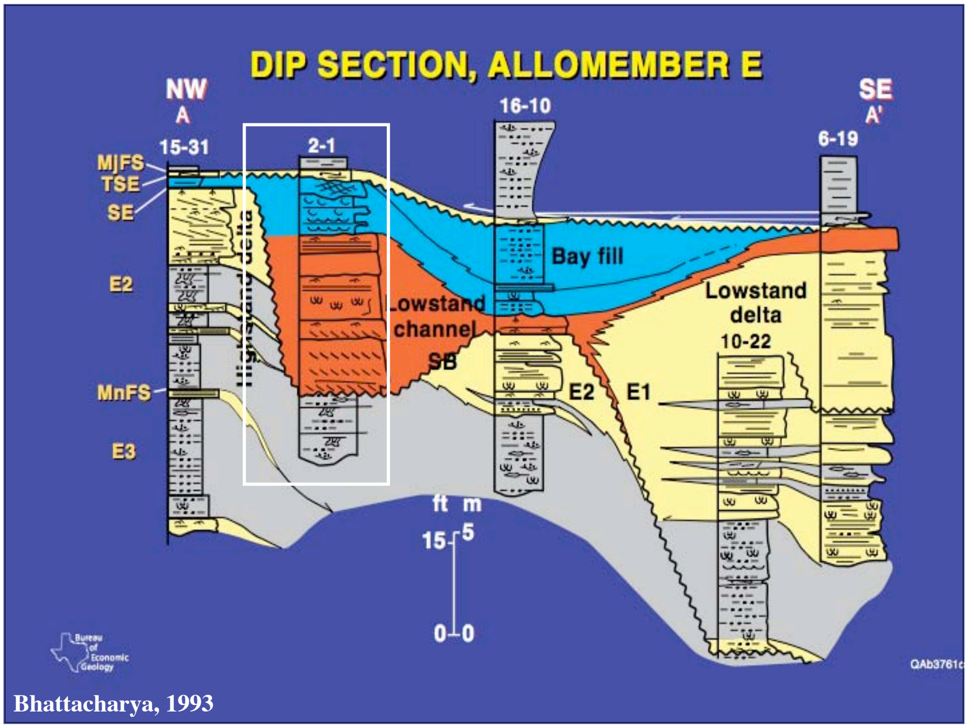

Parasequence 2 (E2)
DIP SECTION, ALLOMEMBER E
NW
A
15-31
MjFS
TSE
SE
E2
MnFS
E3
Highstand delta
Roots
TSE
MjFS
SE
There are a number of abrupt facies changes at the top of the parasequence that coincide with an SB, and a variety of transgressive surfaces. SB is marked by a rooted horizon indicating subaerial exposure (SE). Sudden appearance of biotuirbation marks transgressive surface (TSE). Top of transgressive bioturbated unit marks Major flooding surface (MjFS).
Bhattacharya, 1991, 1993


DIP SECTION, ALLOMEMBER E
NW
A
SE
15-31
2-1
16-10
Incision into underlying parasequence suggests a sequence boundary
MfFS
TSE
SE
E2
MnFS
E3
Highstand delta
Lowstand channel
SB
Bay fill
Lowstand delta
10-22
E2
E1
ft m
15 5
0 0
Bureau of Economic Geology
QAb3761c
Bhattacharya, 1993


STRIKE SECTION, E1 INCISED VALLEY
SW
B
NE
B'
6-35
14-35
16-35
3-6
7-6
10-6
9-6
11-5
1-8
6-9
Datum
D
E
F
E1
E2
E3
ft m
65 20
0 0
Total length ~ 5.5
Cored Interval
Bhattacharya, 1991
QAb3759c(a)
Simonette valley
E1 lobe
Bay
E1 Lowstand delta
0 12 mi
0 15 km
Allomember E sand isolith
SB is marked by truncation of log markers and replacement of funnel shaped profiles with sharp-based bell-shaped or blocky profiles.


STRIKE SECTION, E_1 INCISED VALLEY
SW
B
6-35
14-35
7-6
11-5
NE
B'
1-8
Datum
E_1
Channel
E
E_2
E_3
Bhattacharya, 1991
ft m
15 5
0 0
Total length ~ 5 km
Bell-shaped or blocky profiles show abundant cross bedded sandstone and lack of burrows suggesting a fluvial environment.

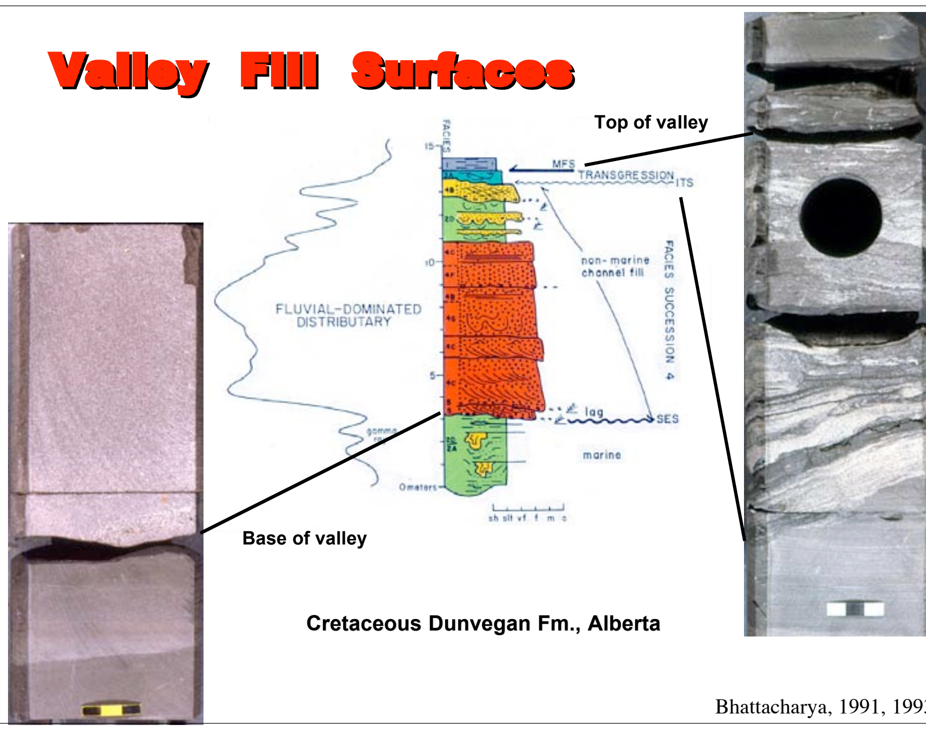

Base of E_1 Valley
TOP
11-5-63-26W5
8.1-12.7m
X-beds
Lag
SB


DIP SECTION, ALLOMEMBER E
NW
A
SE
A'
15-31
2-1
16-10
6-19
MJFS
TSE
SE
E2
MnFS
E3
Highstand delta
Bay fill
Lowstand channel
SB
Lowstand delta
10-22
E2
E1
ft m
15 5
0 0
Bureau of Economic Geology
QAb3761c
Bhattacharya, 1993


E1 Valley, Well 2-1
2-1-63-26W5
1.6 - 5.7m
TOP
SB
Fluvial
Prodelta

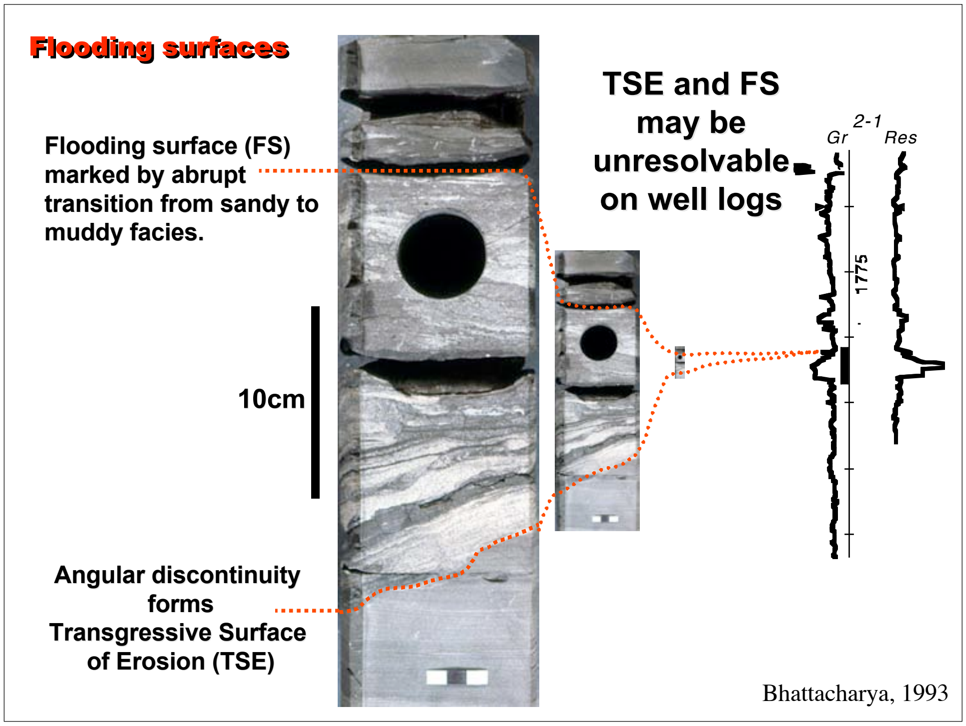
E1 Valley, Well 2-1

Valley Fill Surfaces

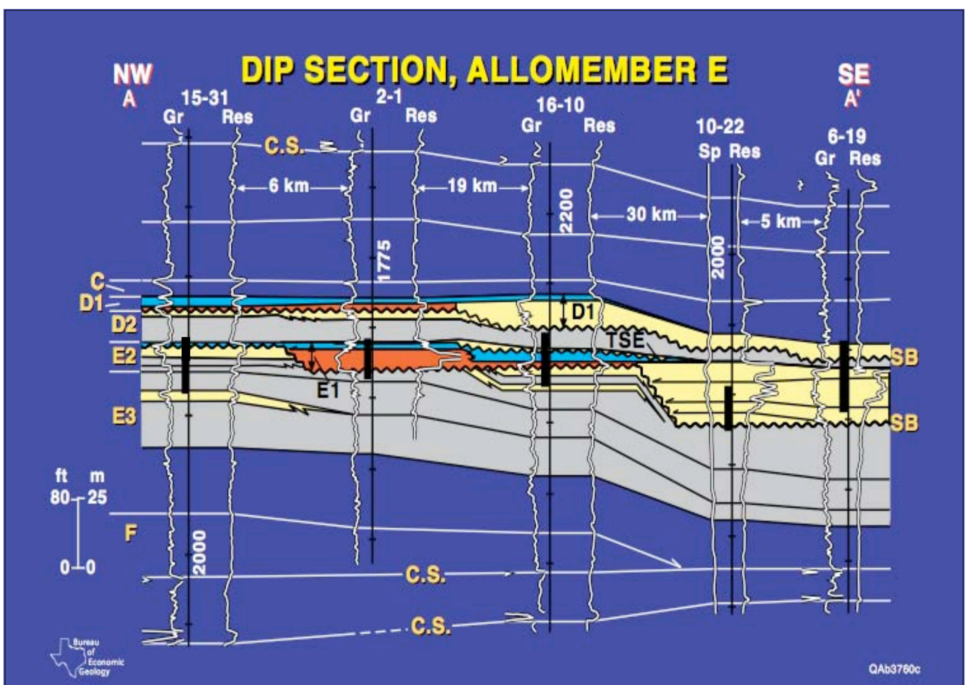


Cretaceous Dunvegan Fm., Alberta

Bhattacharya, 1991, 1993

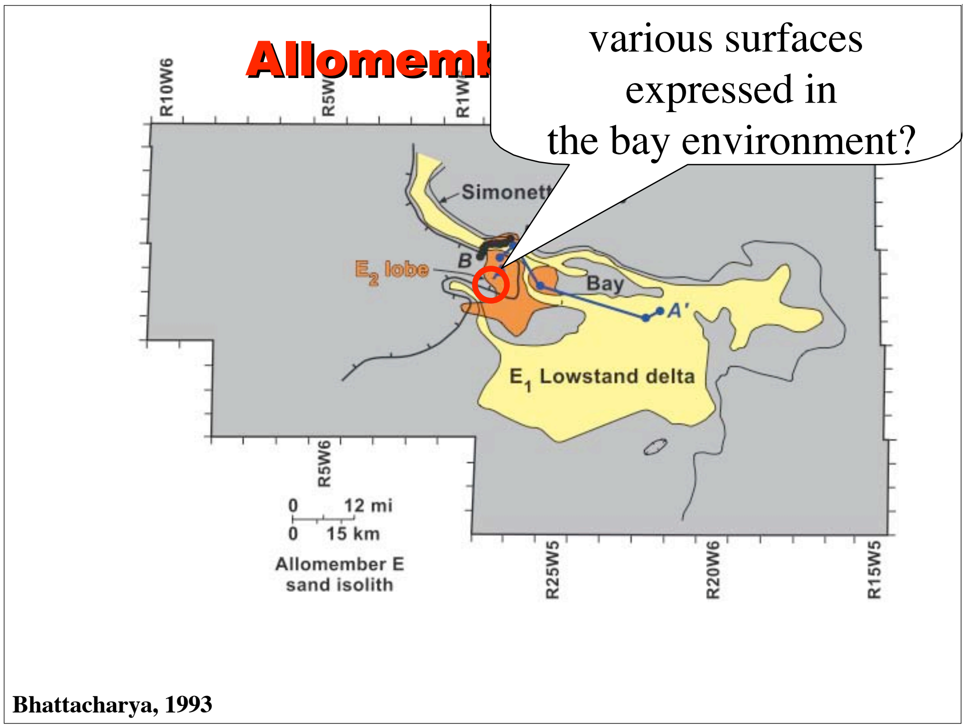


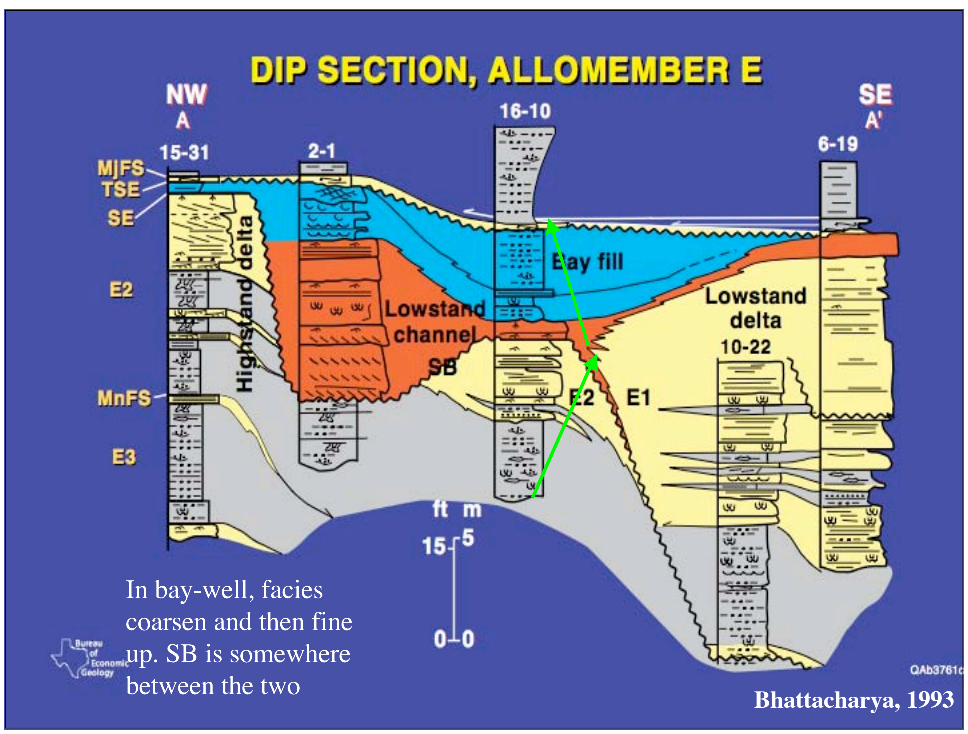
Bhattacharya, 1993

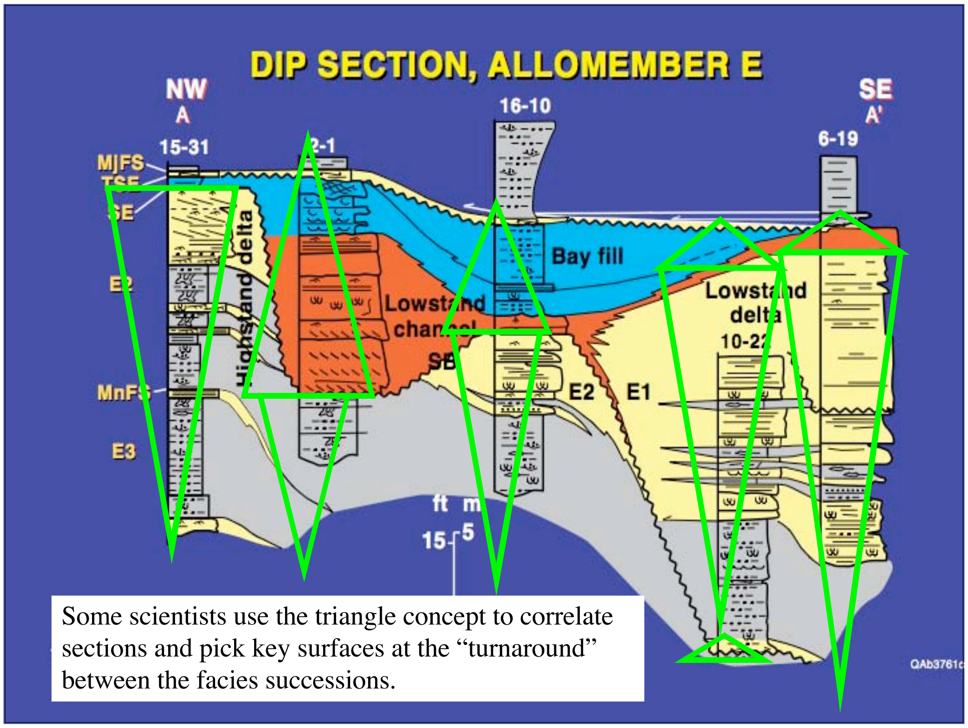


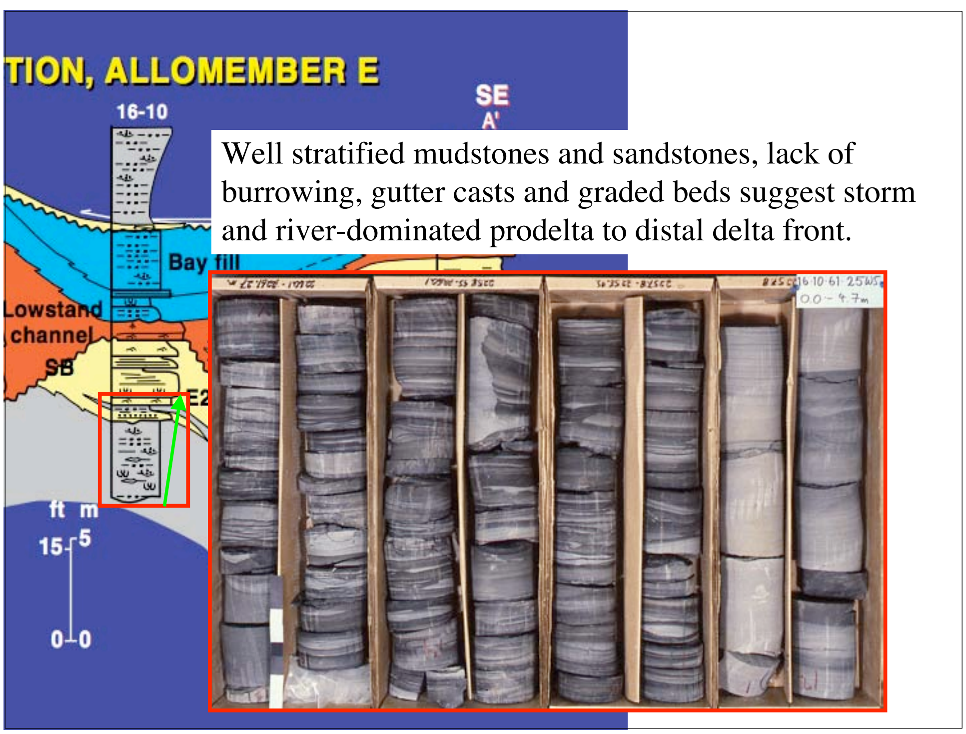
Bhattacharya, 1993

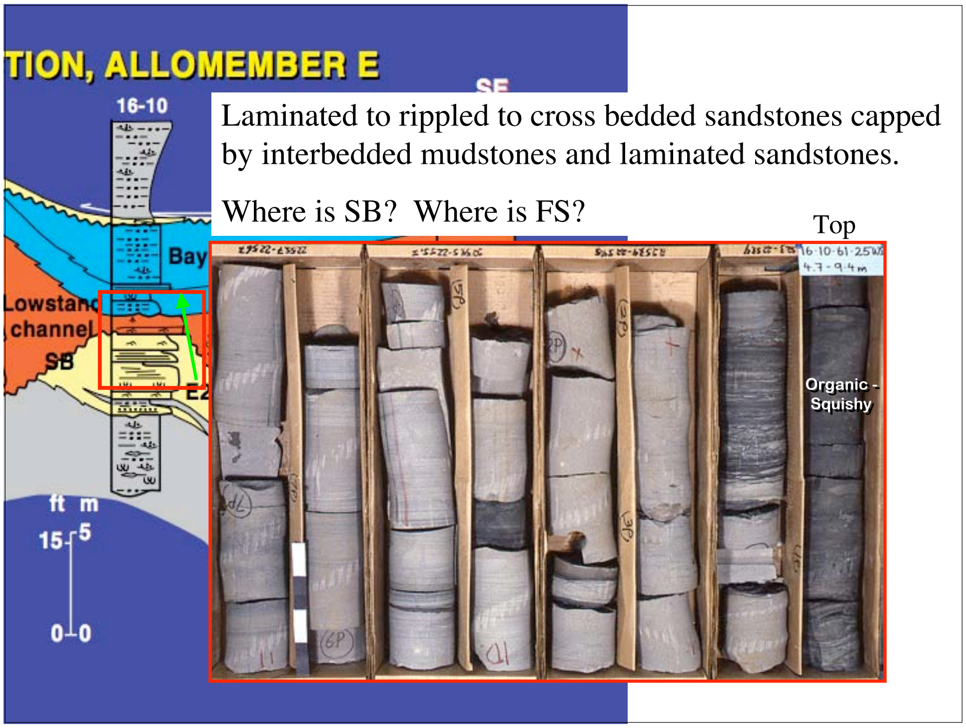
366

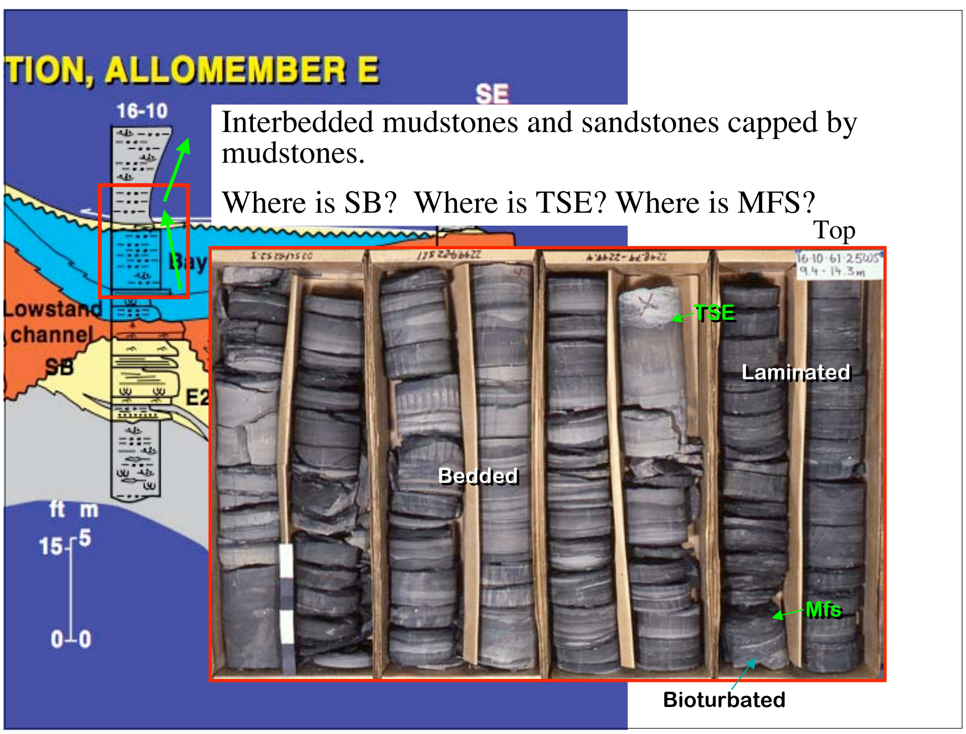

Allomemb
various surfaces expressed in the bay environment?
R10W6
R5W6
R1W6
Simonett
B
E2 lobe
Bay
A'
E1 Lowstand delta
R5W6
0 12 mi
0 15 km
Allomember E sand isolith
R25W5
R20W6
R15W5
Bhattacharya, 1993

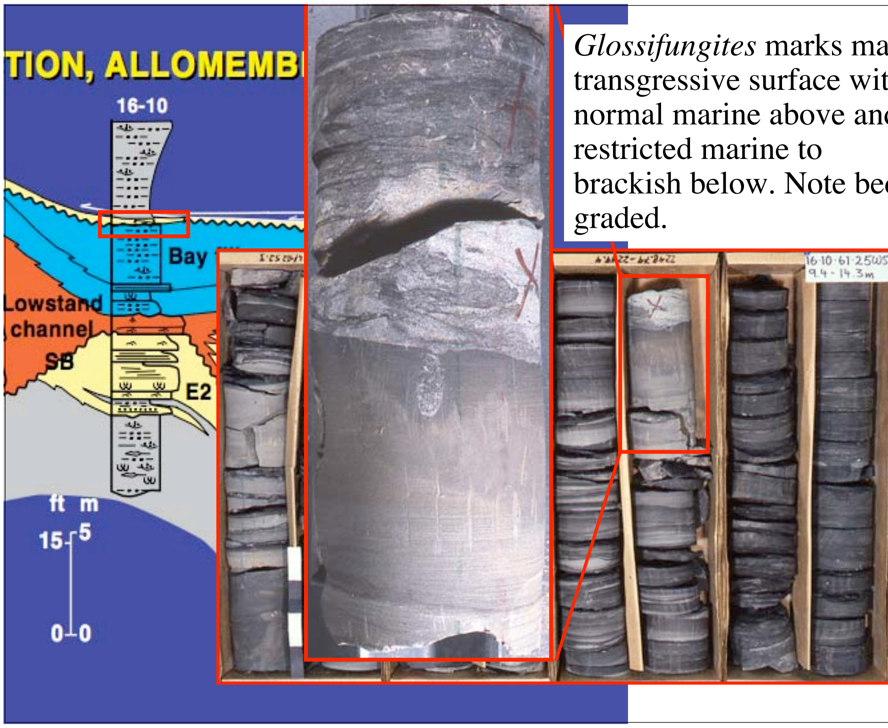

DIP SECTION, ALLOMEMBER E
NW
A
SE
A'
16-10
15-31
2-1
6-19
MfFS
TSE
SE
E2
MnFS
E3
Highstand delta
Lowstand channel
SB
Bay fill
Lowstand delta
10-22
E2
E1
ft m
15 5
0 0
In bay-well, facies coarsen and then fine up. SB is somewhere between the two
Bhattacharya, 1993


DIP SECTION, ALLOMEMBER E
NW
A
SE
A'
15-31
16-10
6-19
MJFS
TSE
SE
E2
MnFS
E3
Highstand delta
Lowstand channel
SB
Bay fill
E2
E1
Lowstand delta
10-22
ft m
15 5
Some scientists use the triangle concept to correlate sections and pick key surfaces at the "turnaround" between the facies successions.

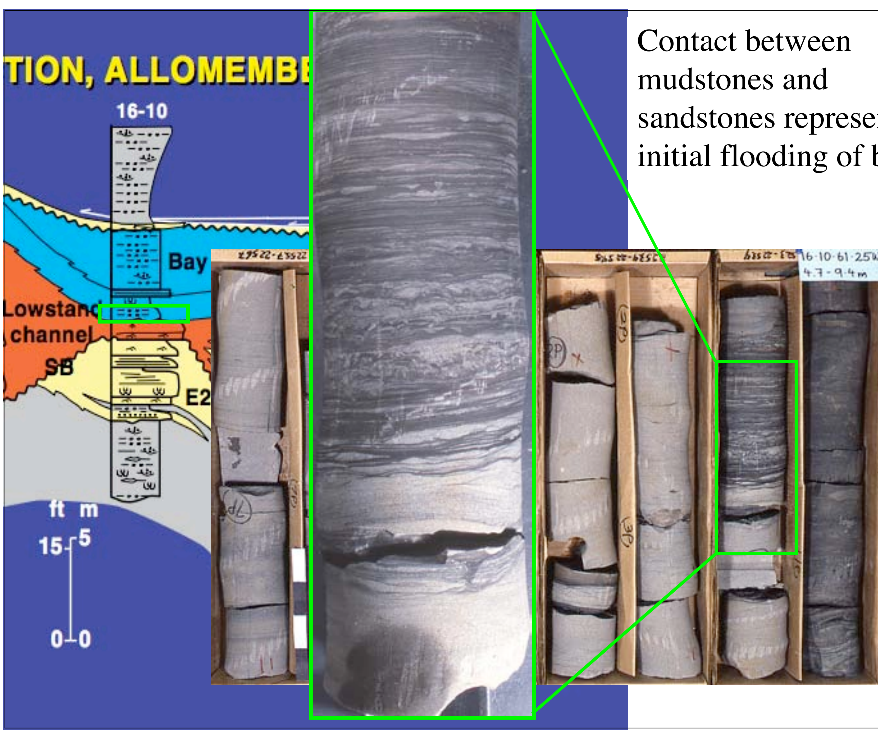

TION, ALLOMEMBER E
16-10
SE
A'
Bay fill
Lowstand channel
SB
ft m
15 5
0 0
Well stratified mudstones and sandstones, lack of burrowing, gutter casts and graded beds suggest storm and river-dominated prodelta to distal delta front.


TION, ALLOMEMBER E
16-10
Bay
Lowstand
channel
SB
E2
ft m
15 5
0 0
Laminated to rippled to cross bedded sandstones capped by interbedded mudstones and laminated sandstones.
Where is SB? Where is FS?
Top
Organic - Squishy

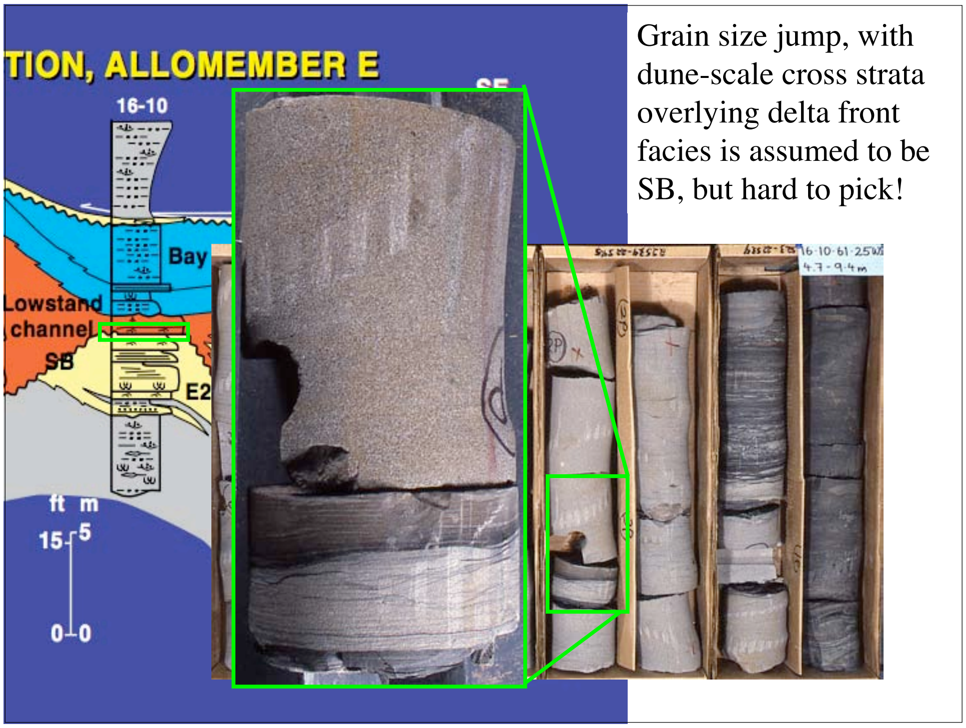

TION, ALLOMEMBER E
SE
16-10
Bay
Lowstand
channel
SB
E2
ft m
15 5
0 0
Interbedded mudstones and sandstones capped by mudstones.
Where is SB? Where is TSE? Where is MFS?
Top
TSE
Laminated
Bedded
Mfs
Bioturbated

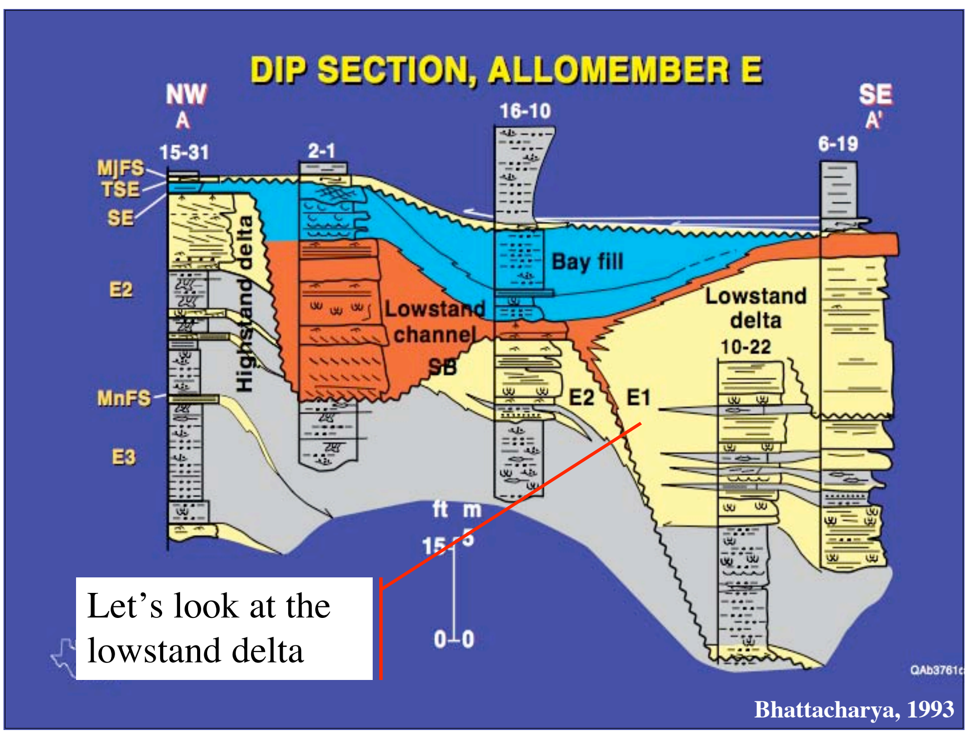


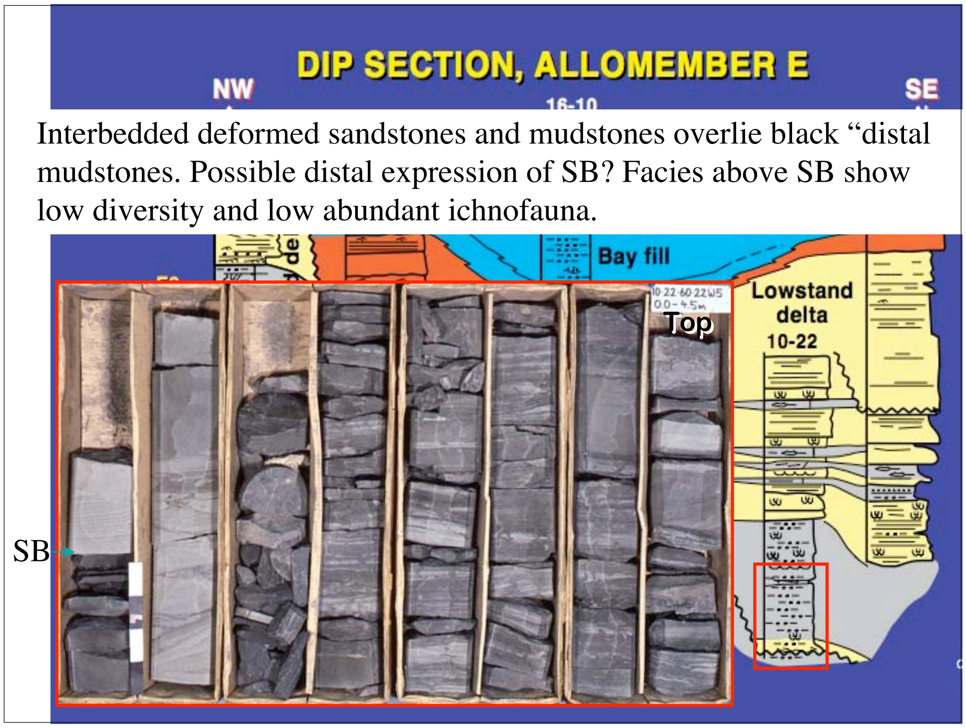
Glossifungites marks major transgressive surface with normal marine above and restricted marine to brackish below. Note bed is graded.

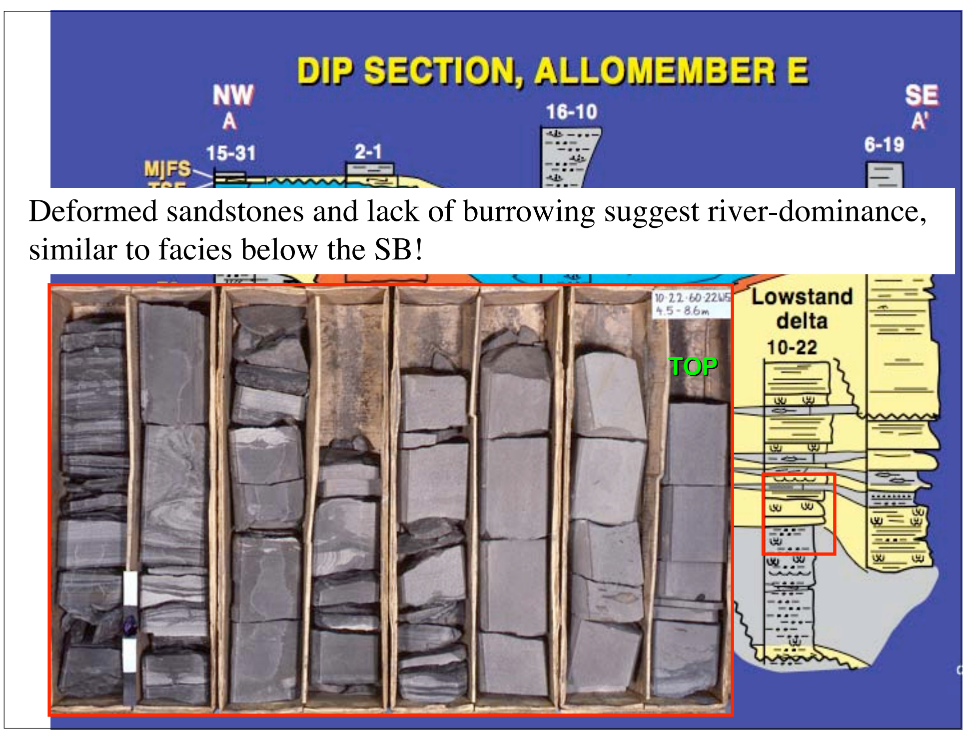


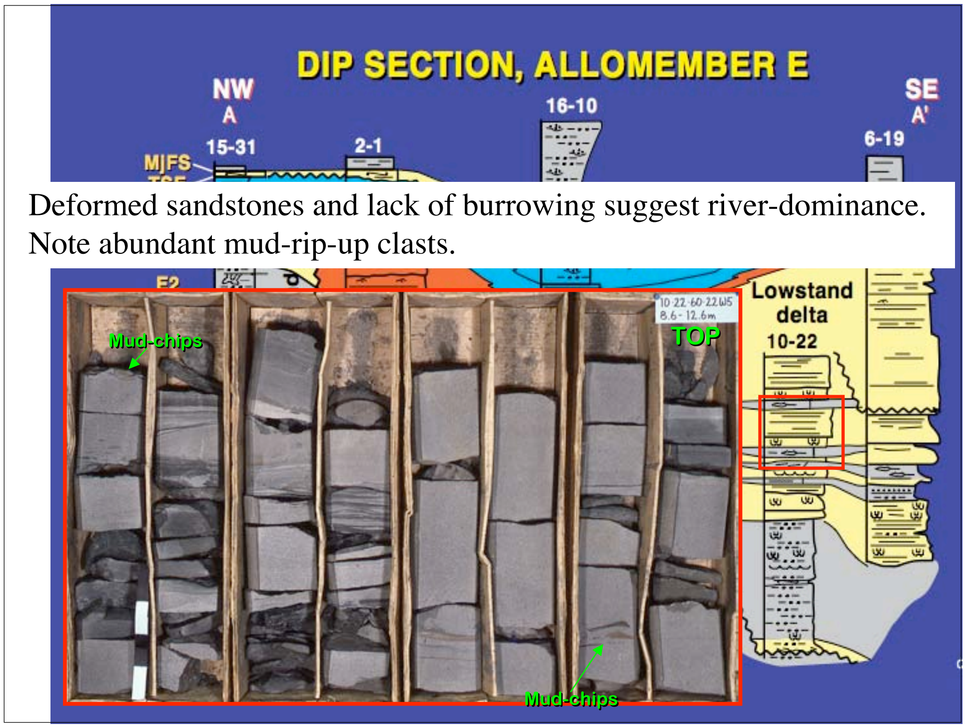
Contact between mudstones and sandstones represents initial flooding of bay.

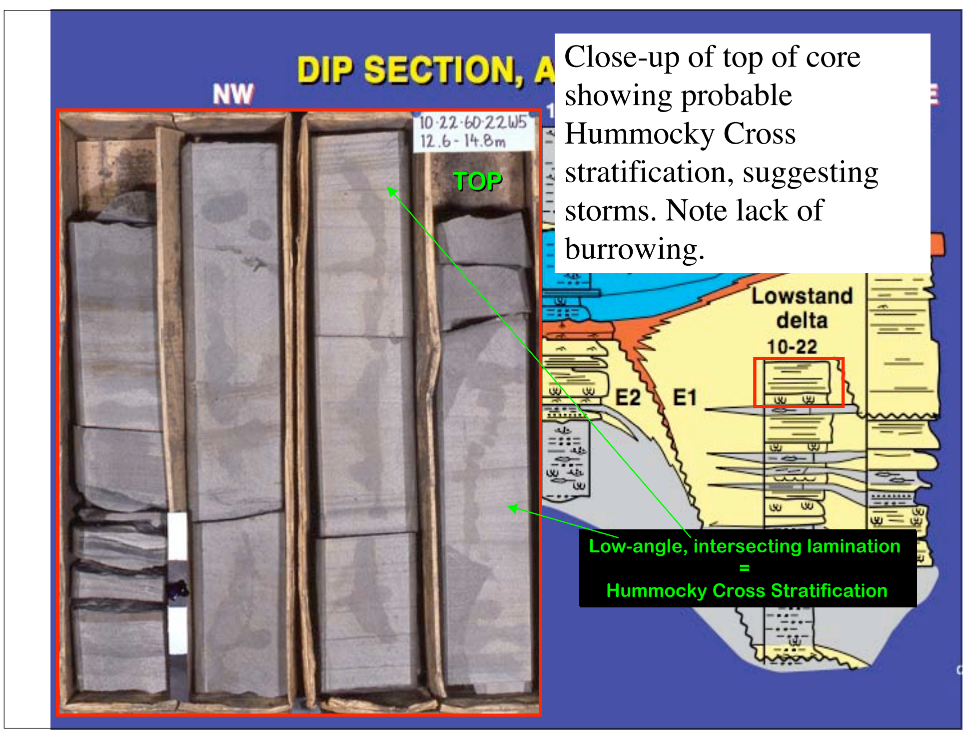

TION, ALLOMEMBER E
16-10
Bay
Lowstand
channel
SB
E2
ft m
15 5
0 0
Grain size jump, with dune-scale cross strata overlying delta front facies is assumed to be SB, but hard to pick!

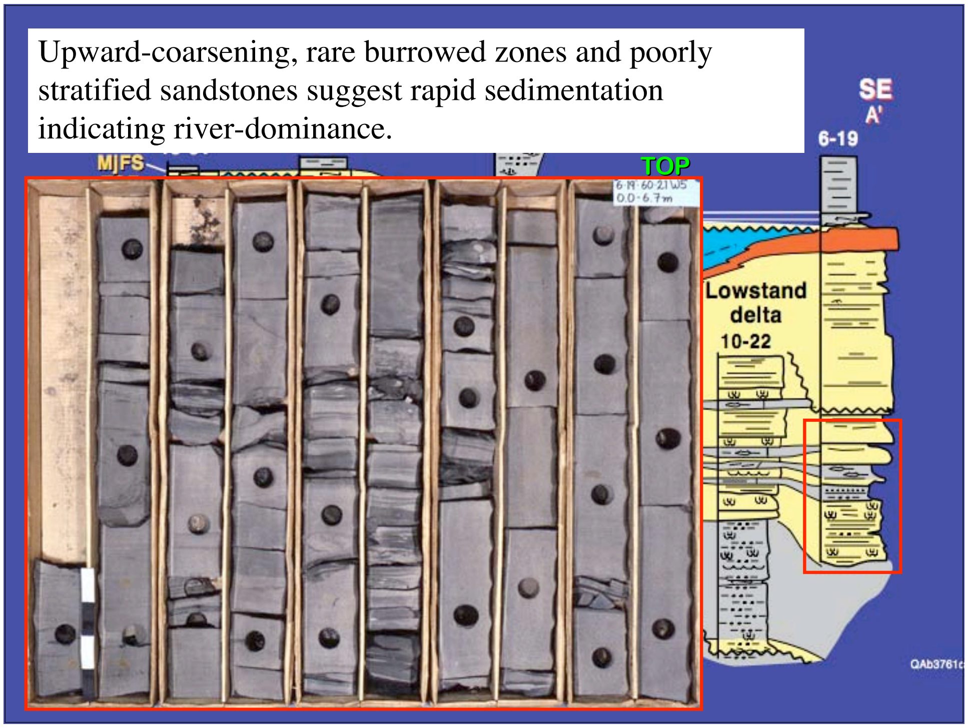

DIP SECTION, ALLOMEMBER E
NW
A
SE
A'
15-31
2-1
16-10
6-19
MJFS
TSE
SE
E2
MnFS
E3
Highstand delta
Bay fill
Lowstand
channel
SB
E2
E1
Lowstand
delta
10-22
ft m
15 5
0 0
Let's look at the lowstand delta
Bhattacharya, 1993

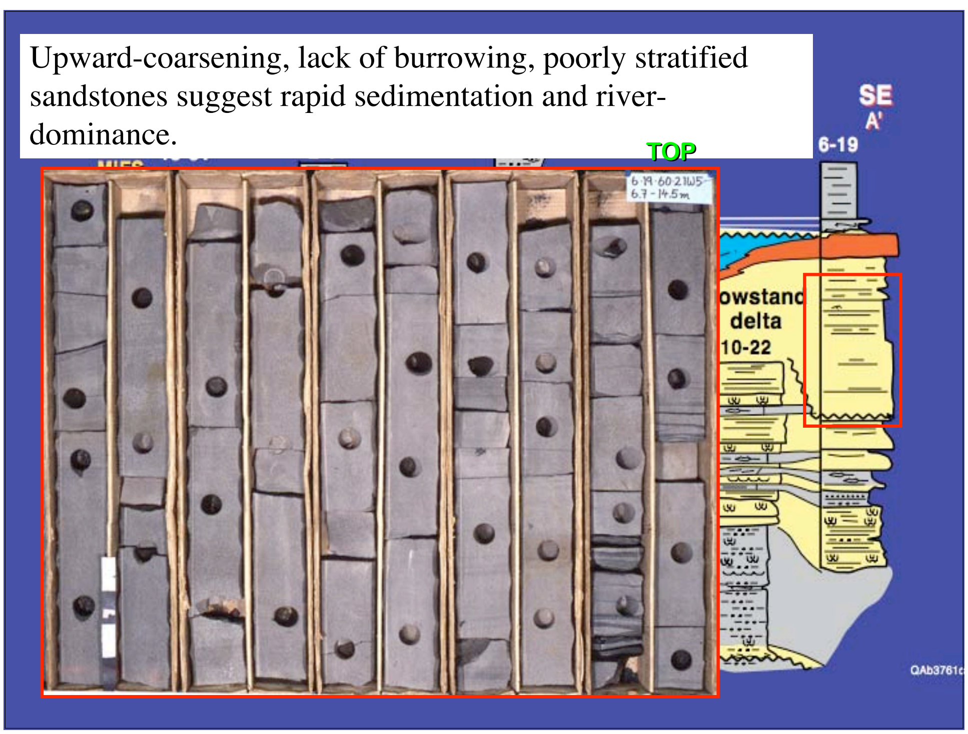

DIP SECTION, ALLOMEMBER E
NW
SE
Interbedded deformed sandstones and mudstones overlie black “distal mudstones. Possible distal expression of SB? Facies above SB show low diversity and low abundant ichnofauna.
Bay fill
Top
Lowstand delta
10-22
SB

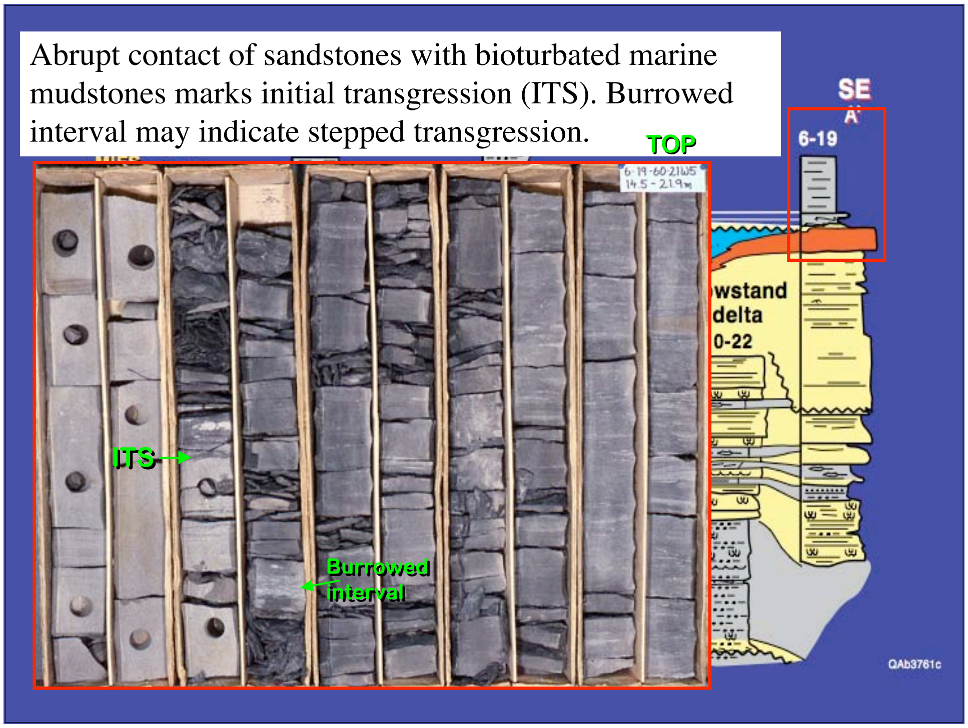

DIP SECTION, ALLOMEMBER E
NW
A
SE
A'
16-10
15-31
2-1
6-19
MJFS
Deformed sandstones and lack of burrowing suggest river-dominance, similar to facies below the SB!
TOP
Lowstand delta
10-22

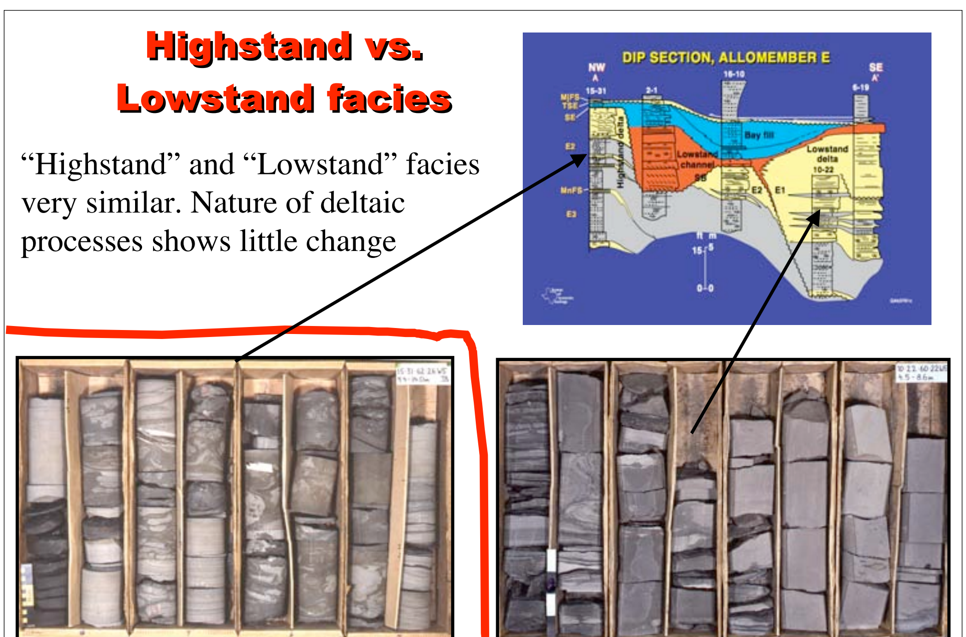

DIP SECTION, ALLOMEMBER E
NW
A
SE
A'
16-10
15-31
2-1
6-19
MJFS
Deformed sandstones and lack of burrowing suggest river-dominance. Note abundant mud-rip-up clasts.
E2
Mud-chips
10-22-60-22W5
8.6-12.6m
TOP
Lowstand
delta
10-22
Mud-chips


DIP SECTION, A
NW
Close-up of top of core showing probable Hummocky Cross stratification, suggesting storms. Note lack of burrowing.
10-22-60-22W5
12.6-14.8m
TOP
Lowstand
delta
10-22
E2
E1
Low-angle, intersecting lamination
=
Hummocky Cross Stratification


Upward-coarsening, rare burrowed zones and poorly stratified sandstones suggest rapid sedimentation indicating river-dominance.
MJFS
TOP
SE
A'
6-19
Lowstand
delta
10-22
QAb3761c


Upward-coarsening, lack of burrowing, poorly stratified sandstones suggest rapid sedimentation and river-dominance.
TOP
SE
A'
6-19
owstand
delta
10-22
QAb3761c

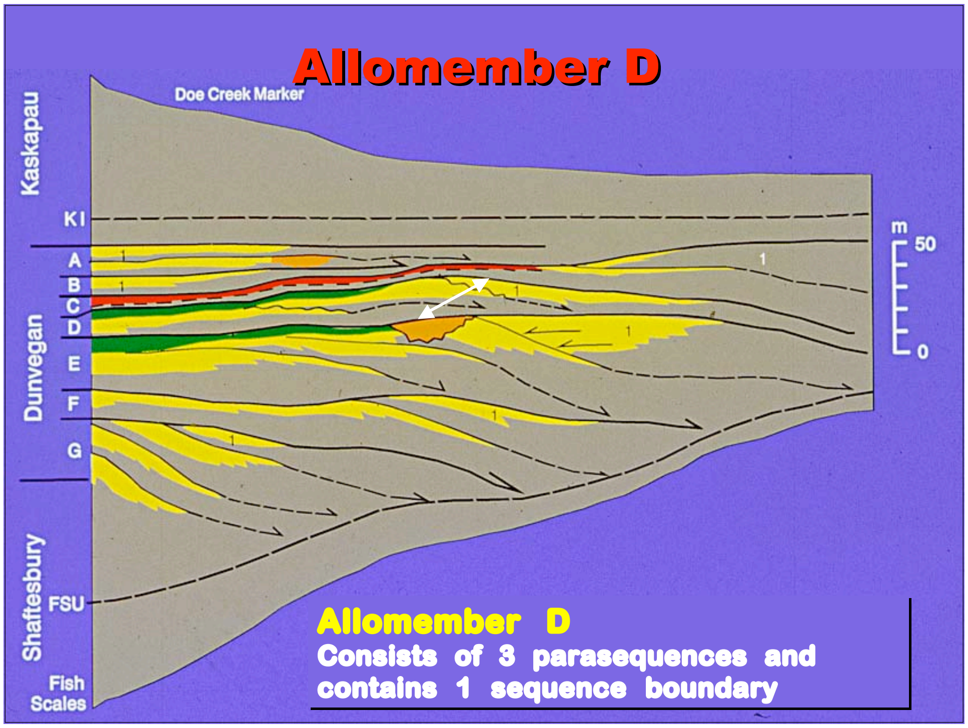


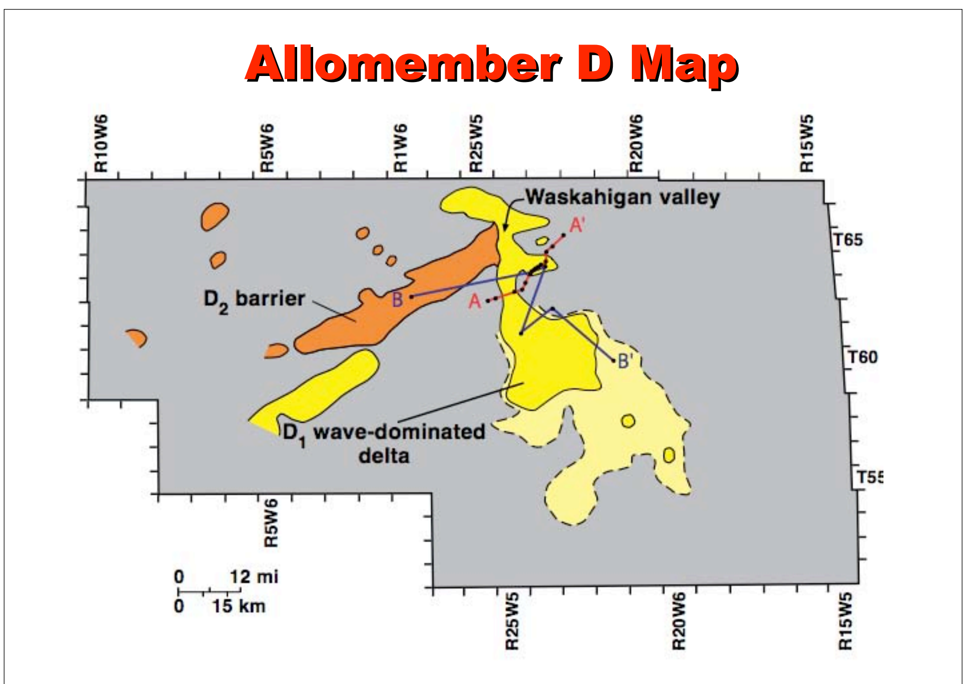


“Highstand” E2 delta

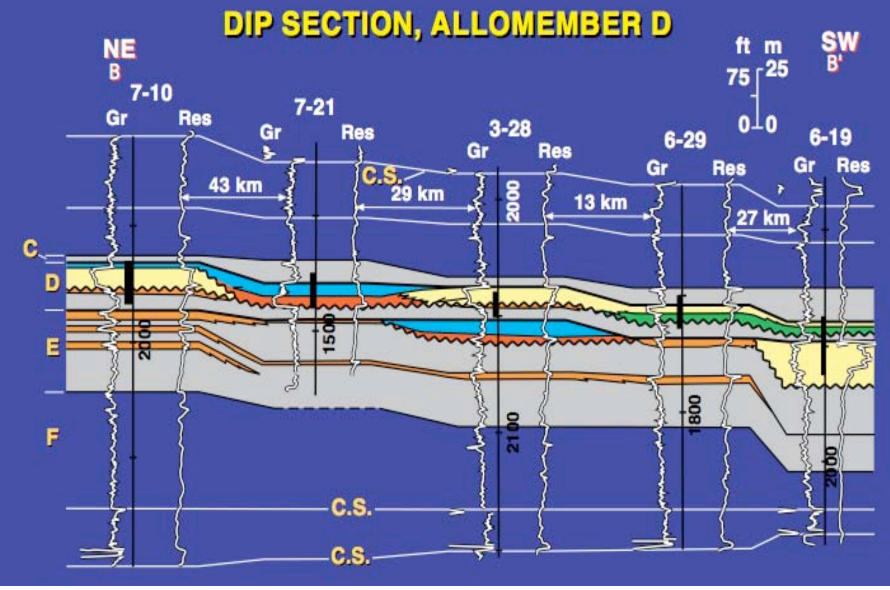
“Lowstand” E1 delta

375

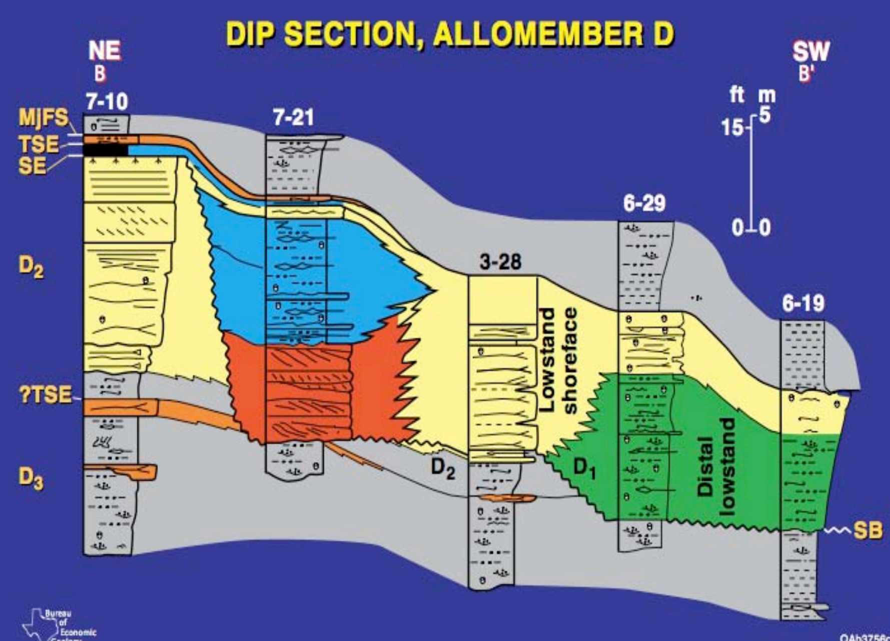




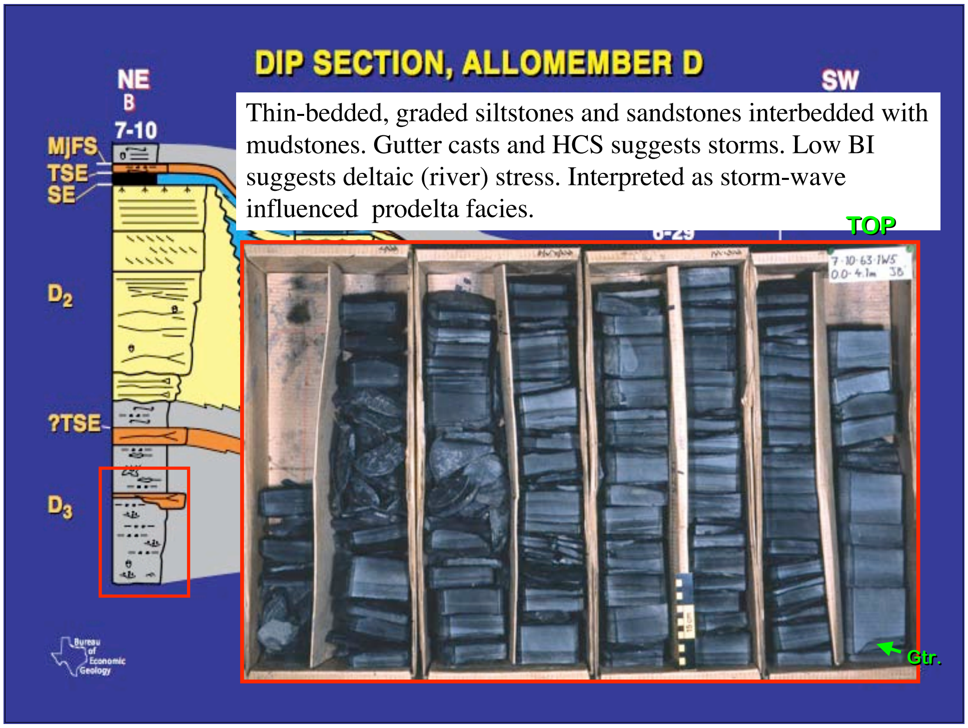
Bhattacharya, 1993

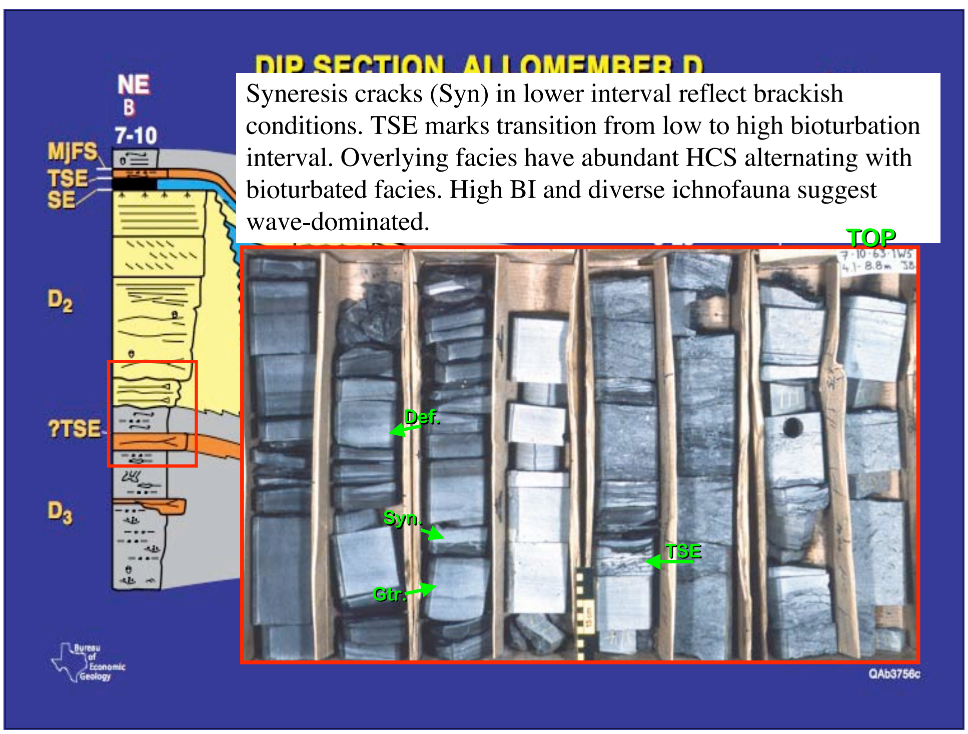


Allomember D show clear downstepping, when flattened on a lower datum. Top of D drops by 25 meters indicative of a forced regression during falling sea-level.

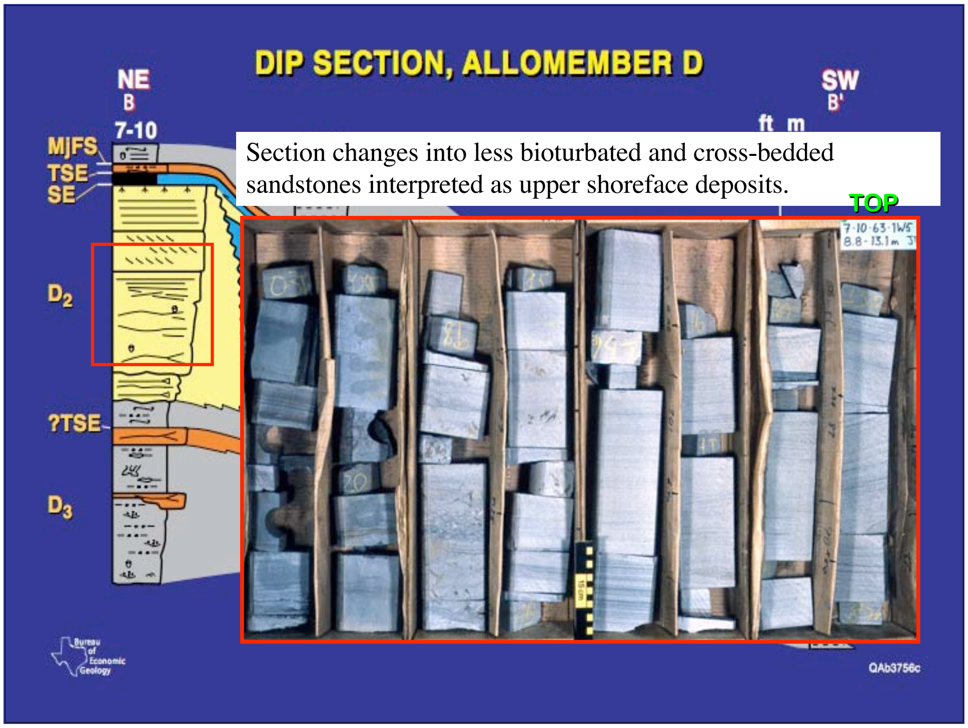


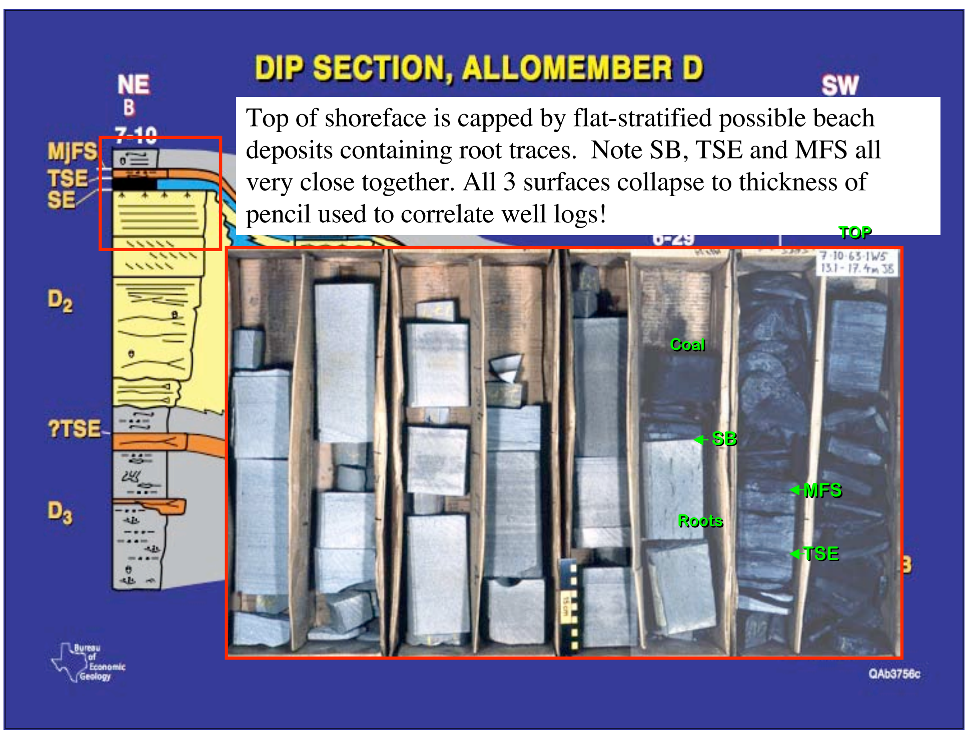
Bhattacharya, 1993

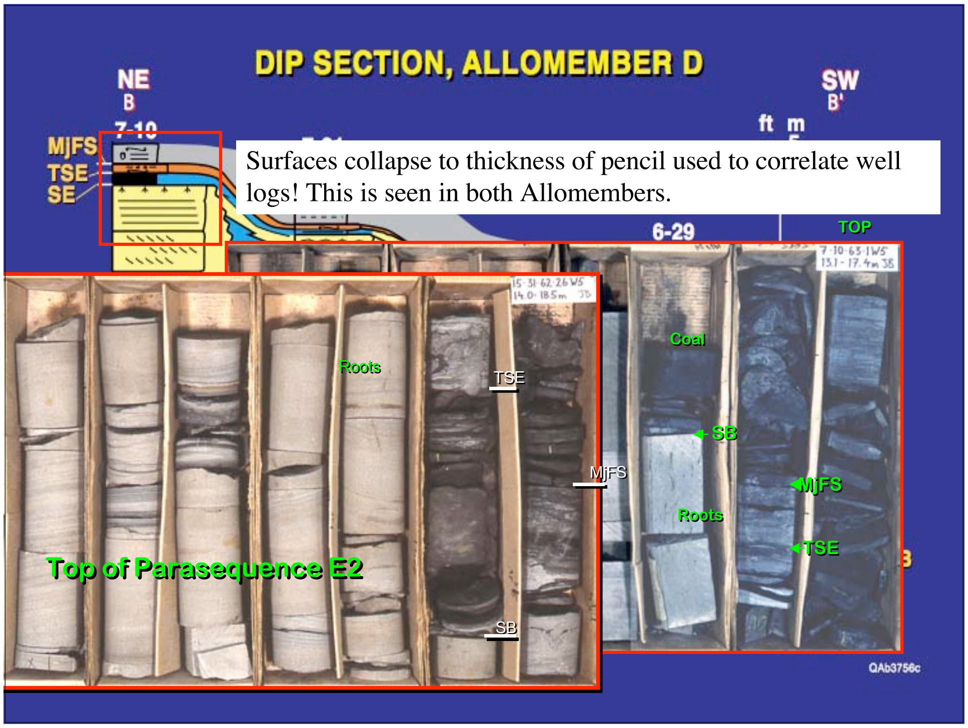

DIP SECTION, ALLOMEMBER D
NE
B
7-10
SW
MJFS
TSE
SE
D2
?TSE
D3
Thin-bedded, graded siltstones and sandstones interbedded with mudstones. Gutter casts and HCS suggests storms. Low BI suggests deltaic (river) stress. Interpreted as storm-wave influenced prodelta facies.
TOP
Gtr.
Bureau of Economic Geology

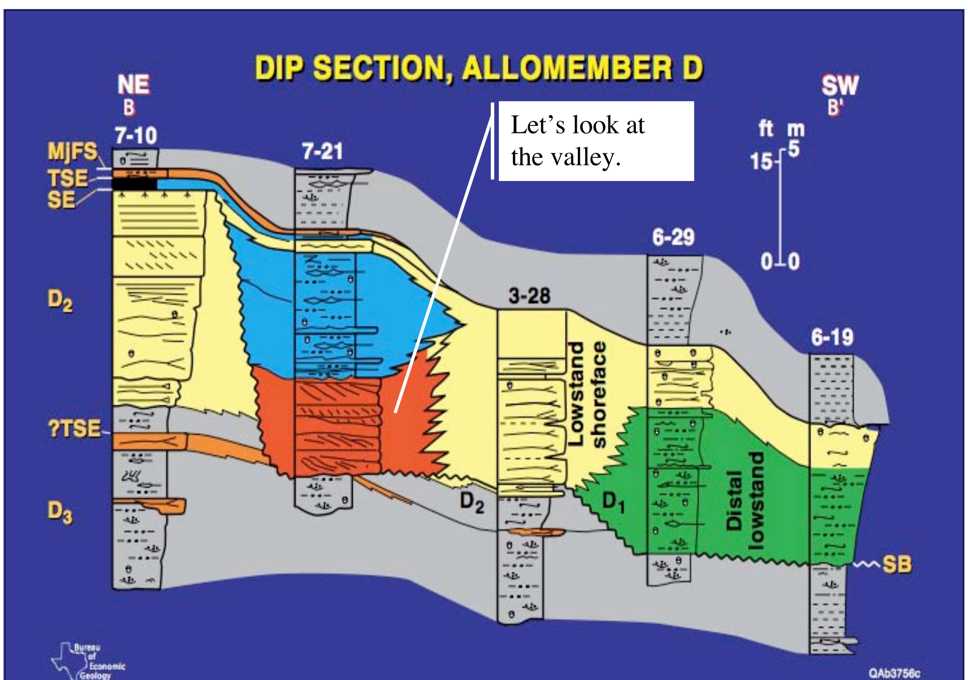

NE
B
7-10
MJFS
TSE
SE
D2
?TSE
D3
Syneresis cracks (Syn) in lower interval reflect brackish conditions. TSE marks transition from low to high bioturbation interval. Overlying facies have abundant HCS alternating with bioturbated facies. High BI and diverse ichnofauna suggest wave-dominated.
TOP
Def.
Syn.
Gtr.
TSE
Bureau of Economic Geology
QAb3756c

378


DIP SECTION, ALLOMEMBER D
NE
B
7-10
SW
B'
ft m
MJFS
TSE
SE
D2
?TSE
D3
Section changes into less bioturbated and cross-bedded sandstones interpreted as upper shoreface deposits.
TOP
Bureau of Economic Geology
QAb3756c

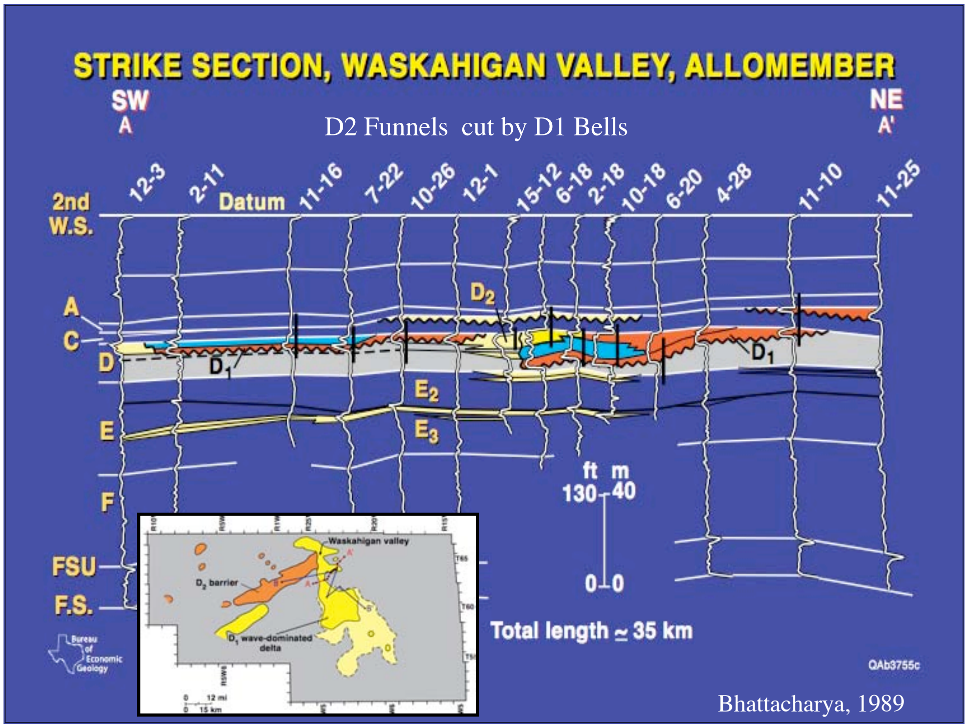

DIP SECTION, ALLOMEMBER D
NE
B
7-10
SW
MJFS
TSE
SE
D2
?TSE
D3
Top of shoreface is capped by flat-stratified possible beach deposits containing root traces. Note SB, TSE and MFS all very close together. All 3 surfaces collapse to thickness of pencil used to correlate well logs!
TOP
Coal
SB
MFS
Roots
TSE
Bureau of Economic Geology
QAb3756c

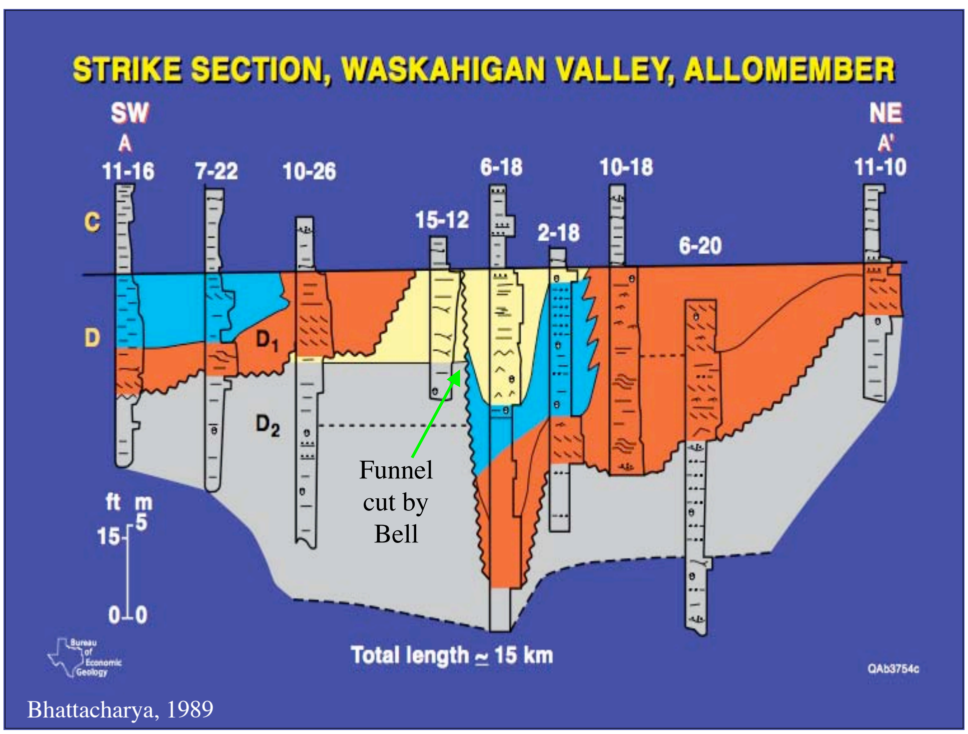


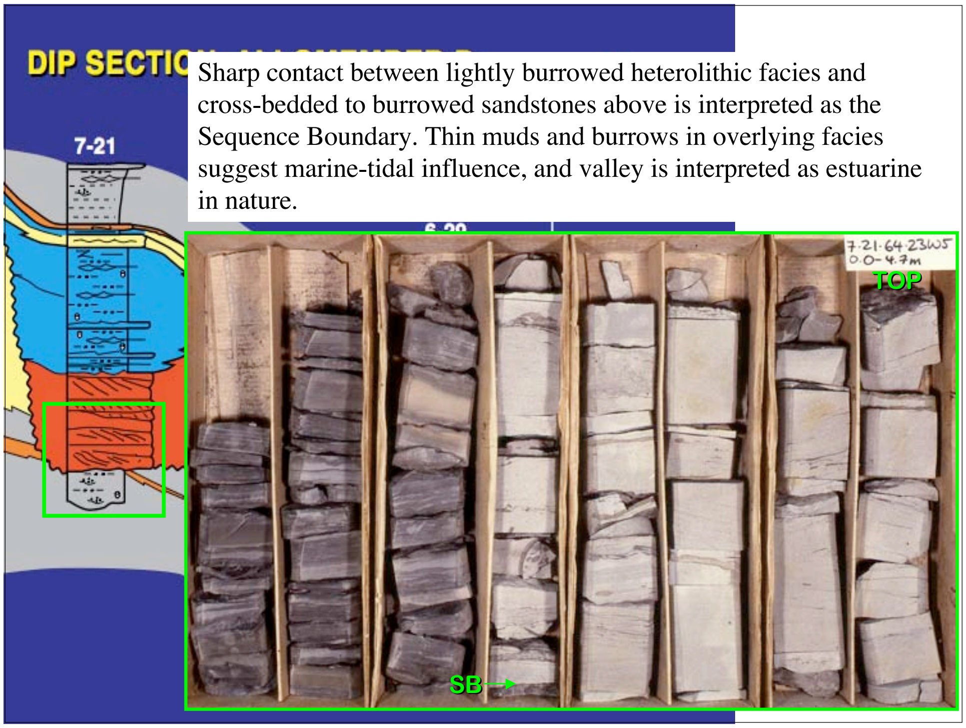


Bhattacharya, 1993

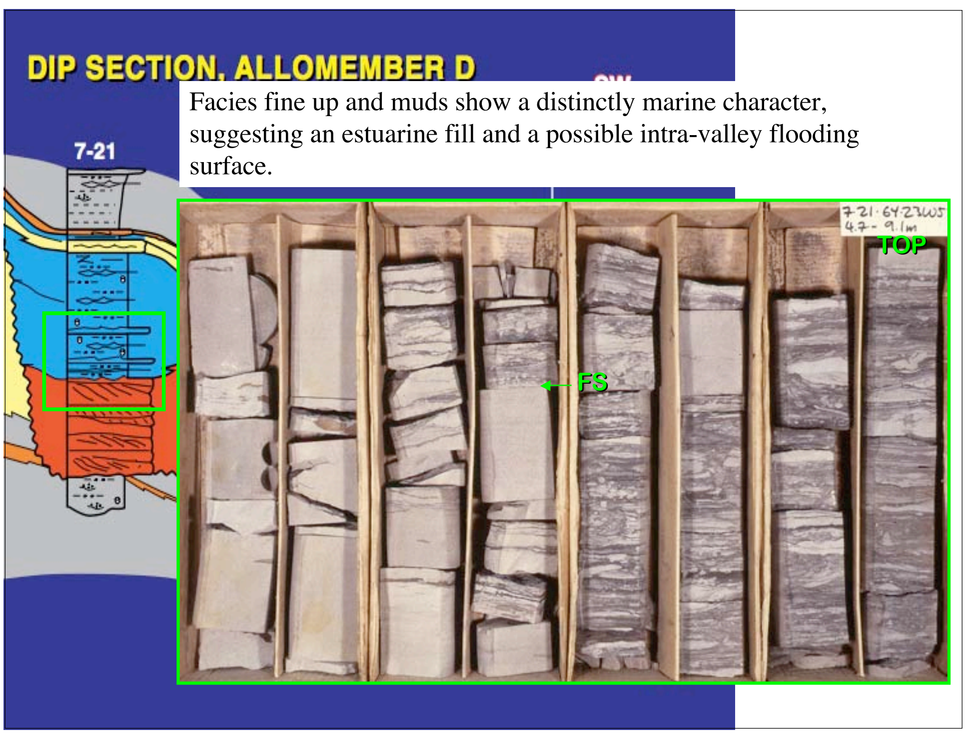
380


STRIKE SECTION, WASKAHIGAN VALLEY, ALLOMEMBER
SW
A
NE
A'
D2 Funnels cut by D1 Bells
2nd W.S.
Datum
12-3
2-11
11-16
7-22
10-26
12-1
15-12
6-18
2-18
10-18
6-20
4-28
11-10
11-25
A
C
D
E
F
FSU
F.S.
D_2
D_1
E_2
E_3
ft m
130 40
0 0
Total length ≃ 35 km
Waskahigan valley
D_2 barrier
D_1 wave-dominated delta
QAb3755c
Bhattacharya, 1989

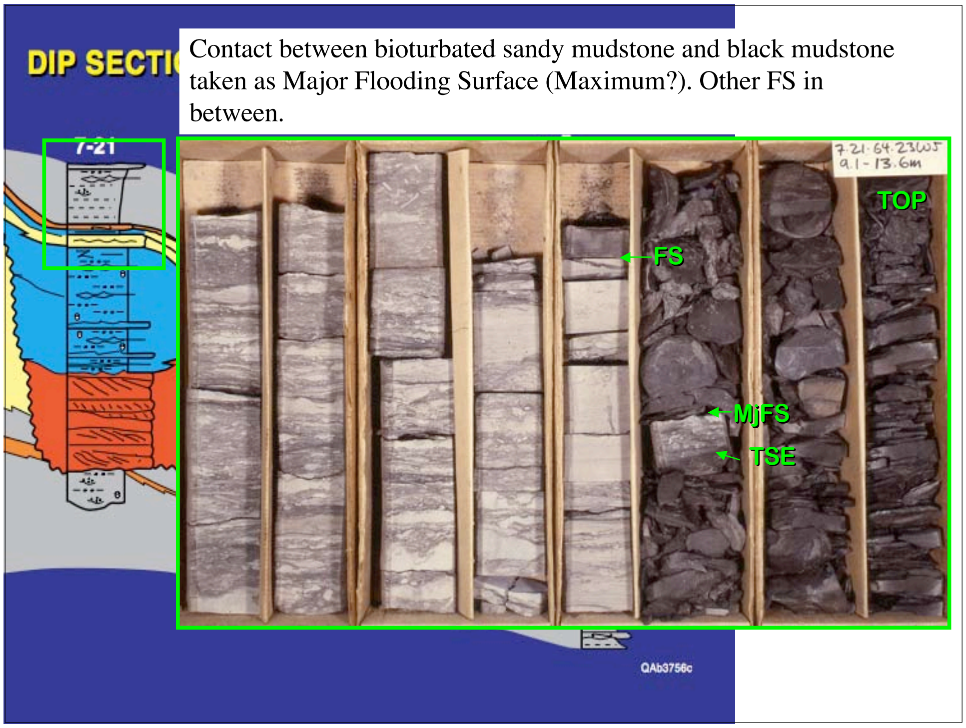

STRIKE SECTION, WASKAHIGAN VALLEY, ALLOMEMBER
SW
A
NE
A'
11-16
7-22
10-26
15-12
6-18
2-18
10-18
6-20
11-10
C
D
D_1
D_2
Funnel
cut by
Bell
ft m
15 5
0 0
Total length ≃ 15 km
QAb3754c
Bhattacharya, 1989

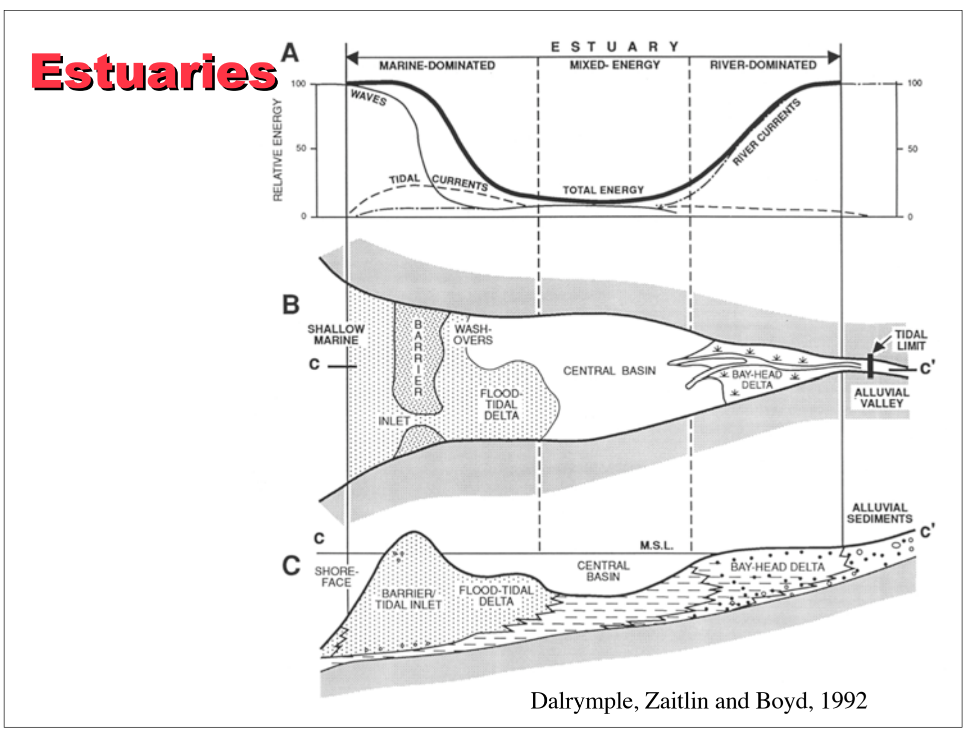


Sharp contact between lightly burrowed heterolithic facies and cross-bedded to burrowed sandstones above is interpreted as the Sequence Boundary. Thin muds and burrows in overlying facies suggest marine-tidal influence, and valley is interpreted as estuarine in nature.



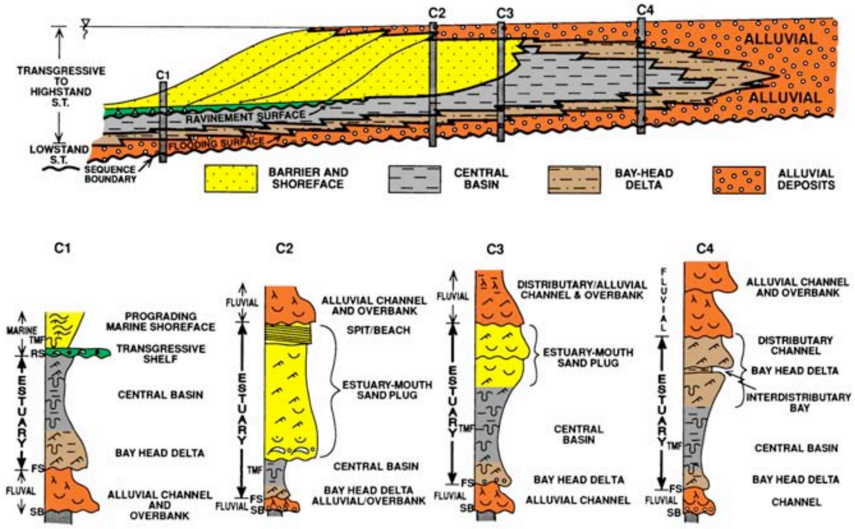
Facies fine up and muds show a distinctly marine character, suggesting an estuarine fill and a possible intra-valley flooding surface.


DIP SECTI
Contact between bioturbated sandy mudstone and black mudstone taken as Major Flooding Surface (Maximum?). Other FS in between.
7-21
7-21-64-23W5
9.1-13.6m
TOP
FS
MjFS
TSE
QAb3756c

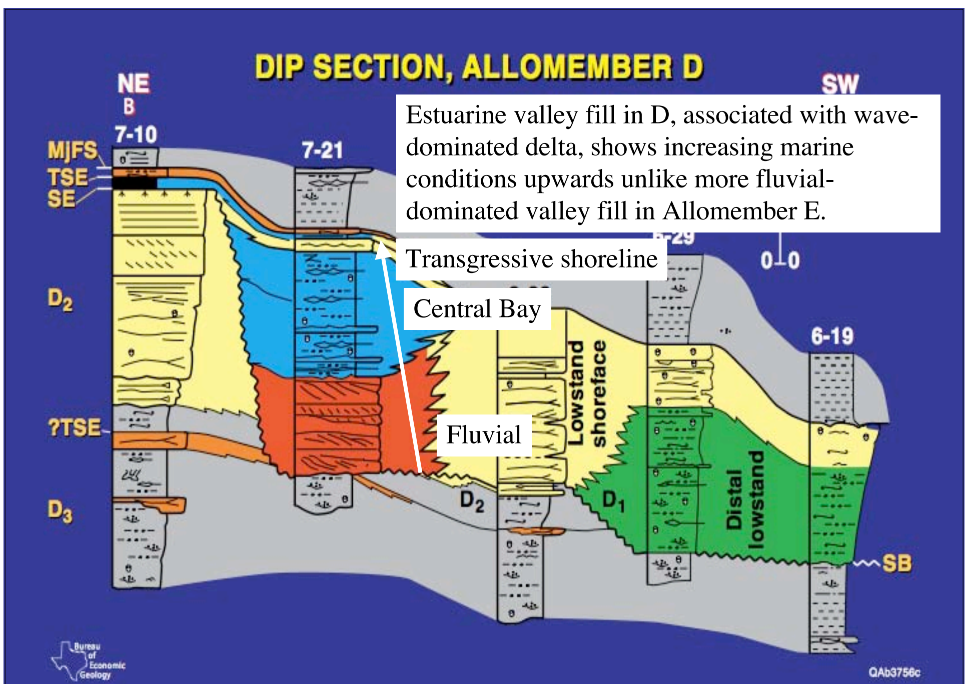

Estuaries
A
ESTUARY
MARINE-DOMINATED
MIXED- ENERGY
RIVER-DOMINATED
RELATIVE ENERGY
100
50
0
WAVES
TIDAL
CURRENTS
TOTAL ENERGY
RIVER CURRENTS
B
SHALLOW MARINE
BARRIER
WASH-OVERS
CENTRAL BASIN
FLOOD-TIDAL DELTA
INLET
BAY-HEAD DELTA
TIDAL LIMIT
ALLUVIAL VALLEY
C
C'
ALLUVIAL SEDIMENTS
M.S.L.
SHORE-FACE
BARRIER/ TIDAL INLET
FLOOD-TIDAL DELTA
CENTRAL BASIN
BAY-HEAD DELTA
Dalrymple, Zaitlin and Boyd, 1992

Estuaries

Commonly show tripartite transgressive fill (Alluvial, Central Bay capped by marine facies). Alluvial facies may not prograde back over marine facies in distal end.

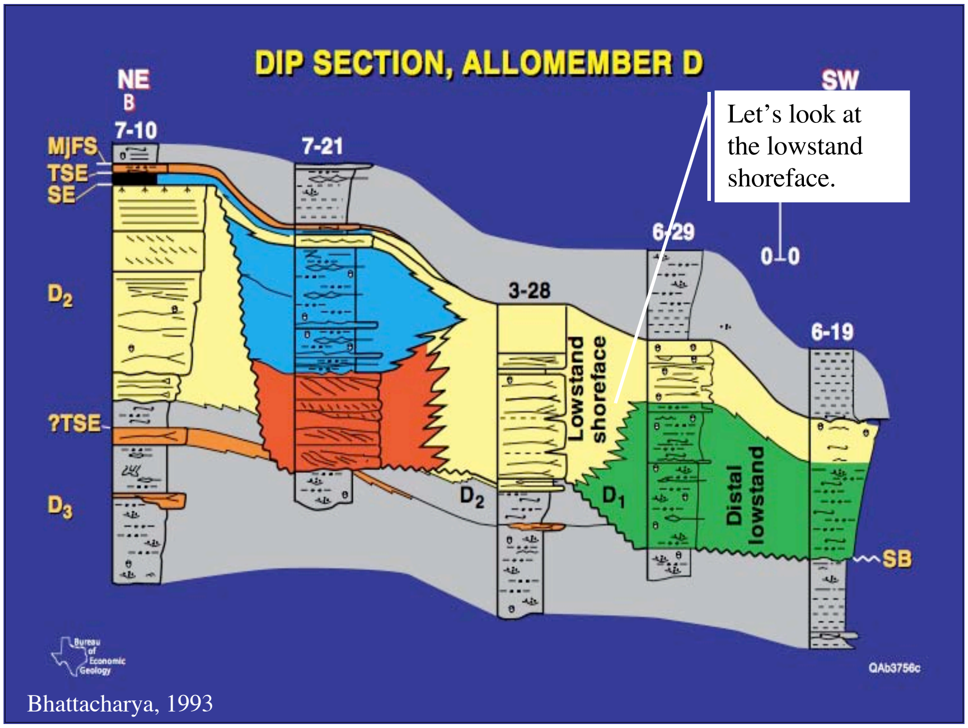


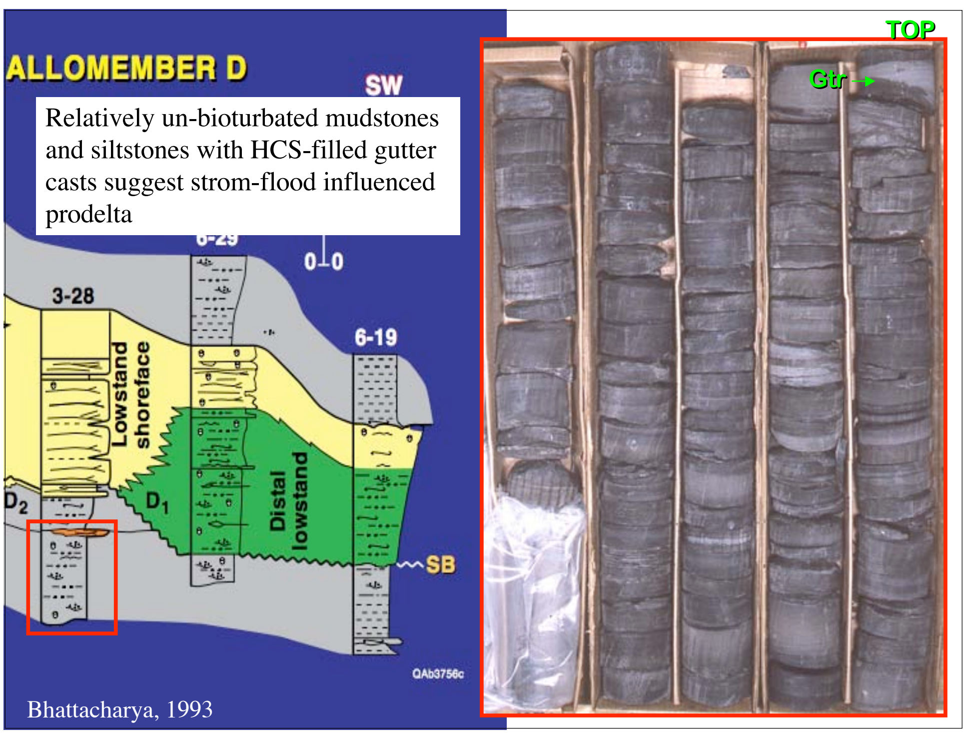
Dalrymple, Zaitlin and Boyd, 1992

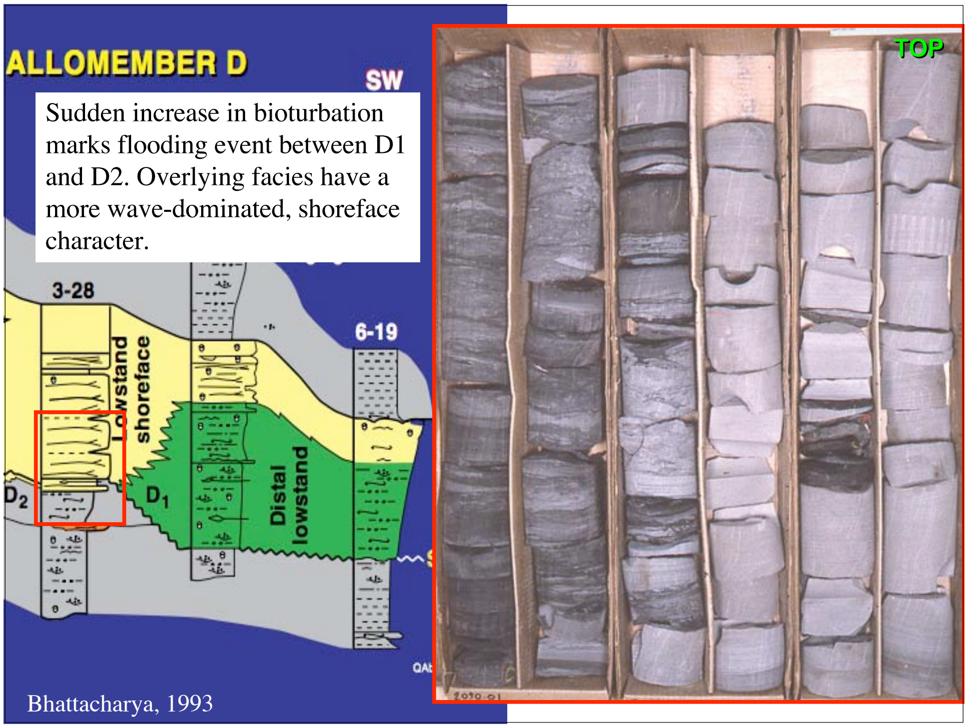


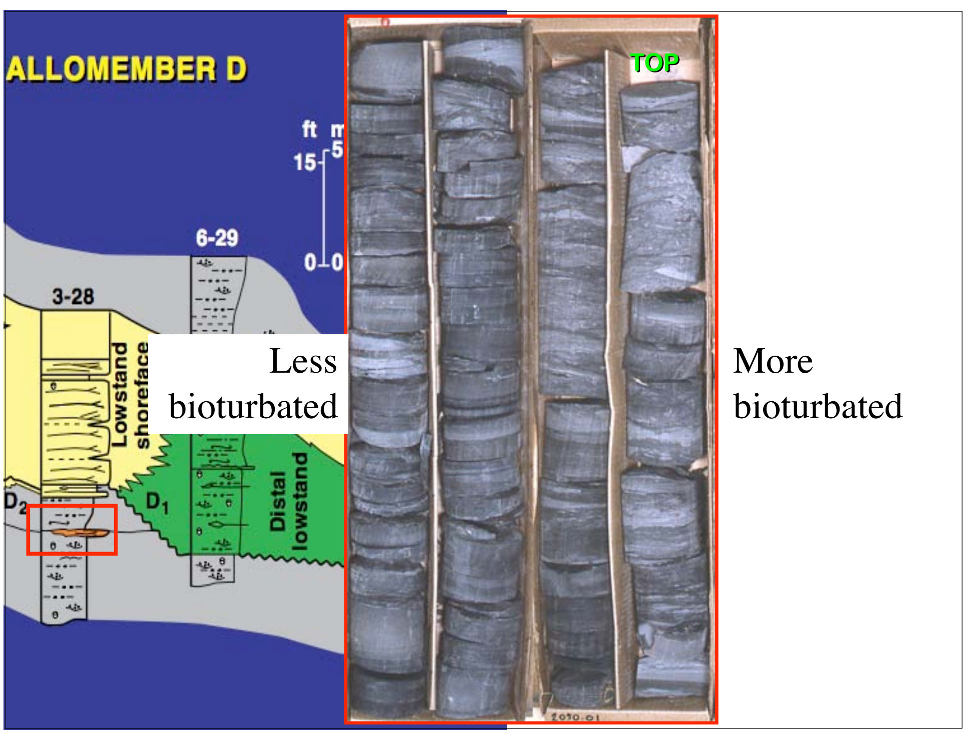
Bhattacharya, 1993

384

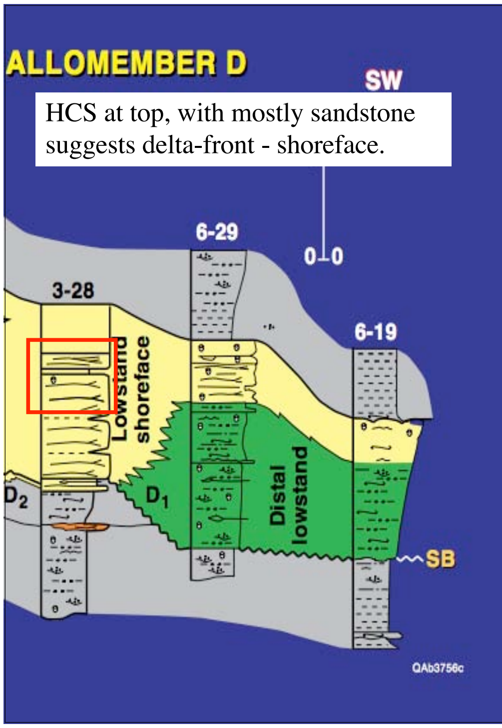

DIP SECTION, ALLOMEMBER D
NE
B
7-10
MJFS
TSE
SE
D2
?TSE
D3
7-21
3-28
Lowstand shoreface
D2
D1
6-29
Distal lowstand
SW
Let's look at the lowstand shoreface.
0-0
6-19
SB
QAb3756c
Bhattacharya, 1993


ALLOMEMBER D
SW
Relatively un-bioturbated mudstones and siltstones with HCS-filled gutter casts suggest strom-flood influenced prodelta
3-28
Lowstand shoreface
D2
D1
Distal lowstand
0-0
6-19
SB
QAb3756c
Bhattacharya, 1993
TOP
Gtr

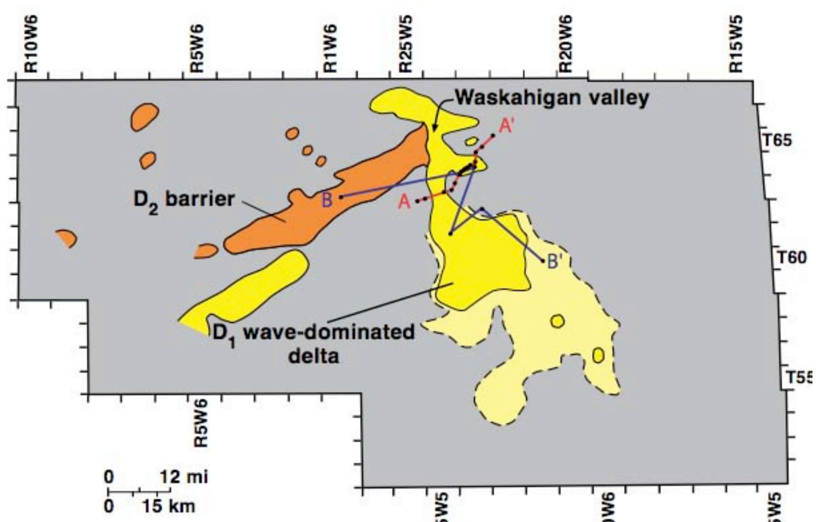

ALLOMEMBER D
SW
Sudden increase in bioturbation marks flooding event between D1 and D2. Overlying facies have a more wave-dominated, shoreface character.
3-28
Lowstand shoreface
6-19
D_2
D_1
Distal lowstand
TOP
Bhattacharya, 1993


ALLOMEMBER D
ft m
15 5
0 0
6-29
3-28
Lowstand shoreface
D_2
D_1
Distal lowstand
TOP
Less bioturbated
More bioturbated

386

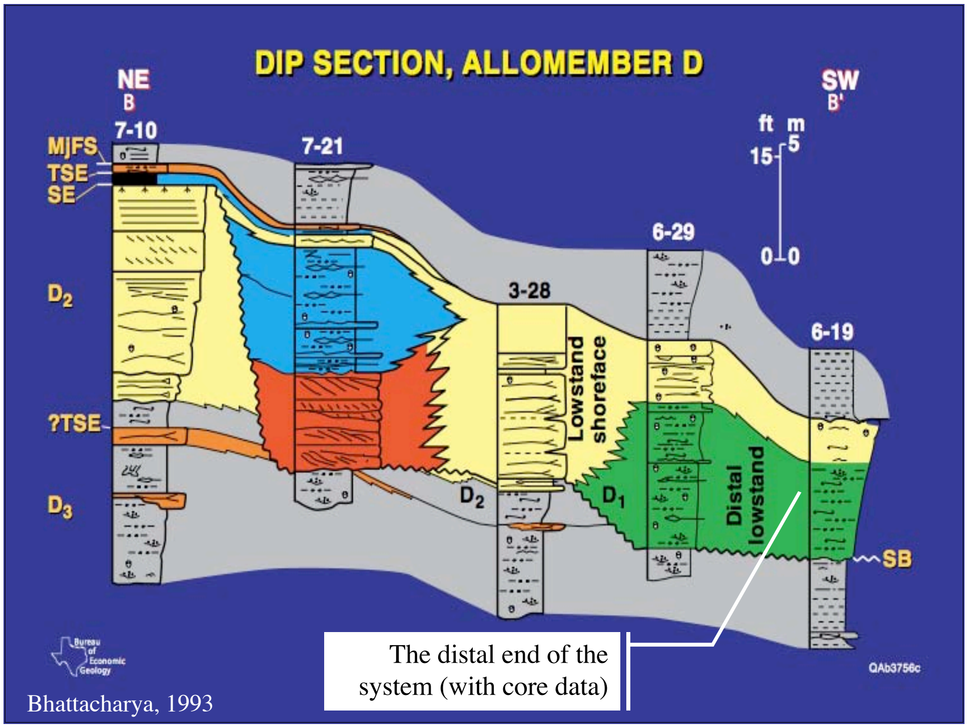


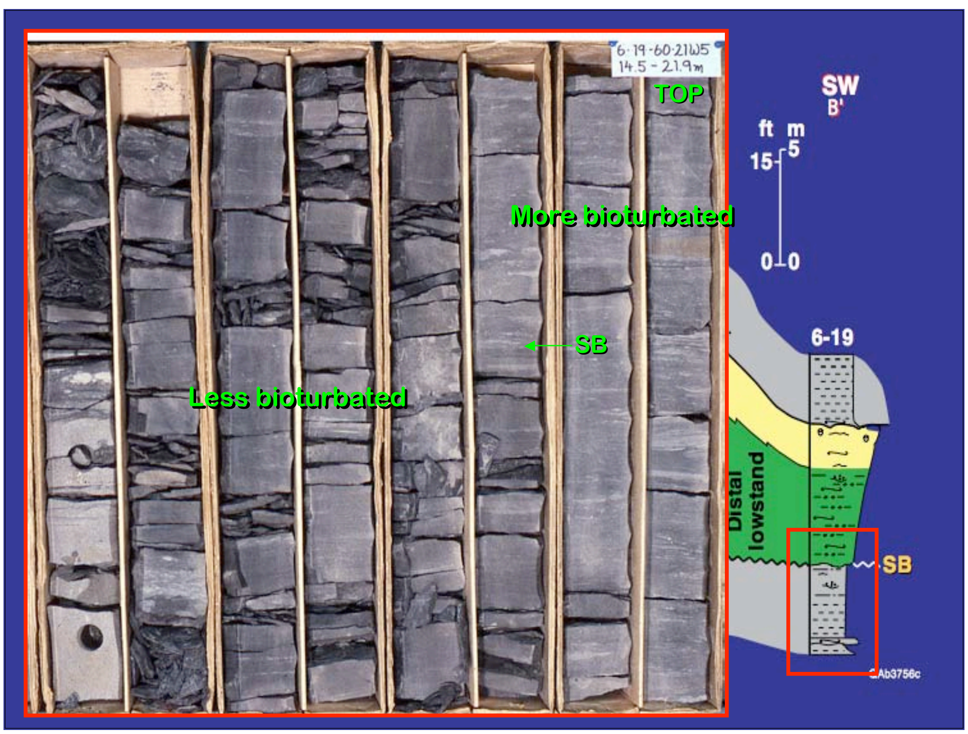
Allomember D Map

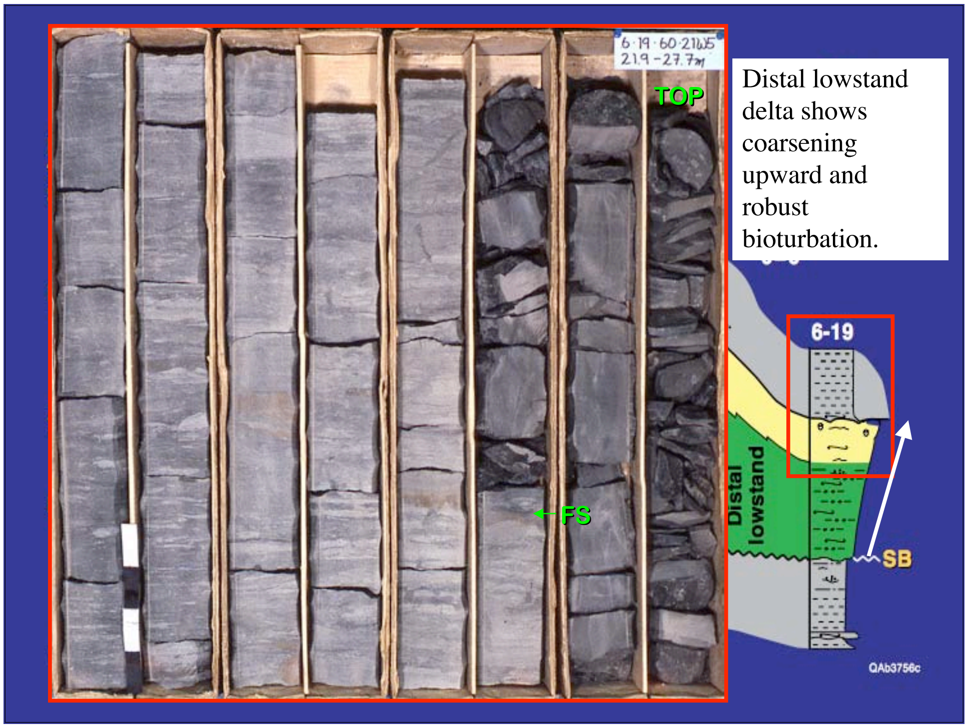


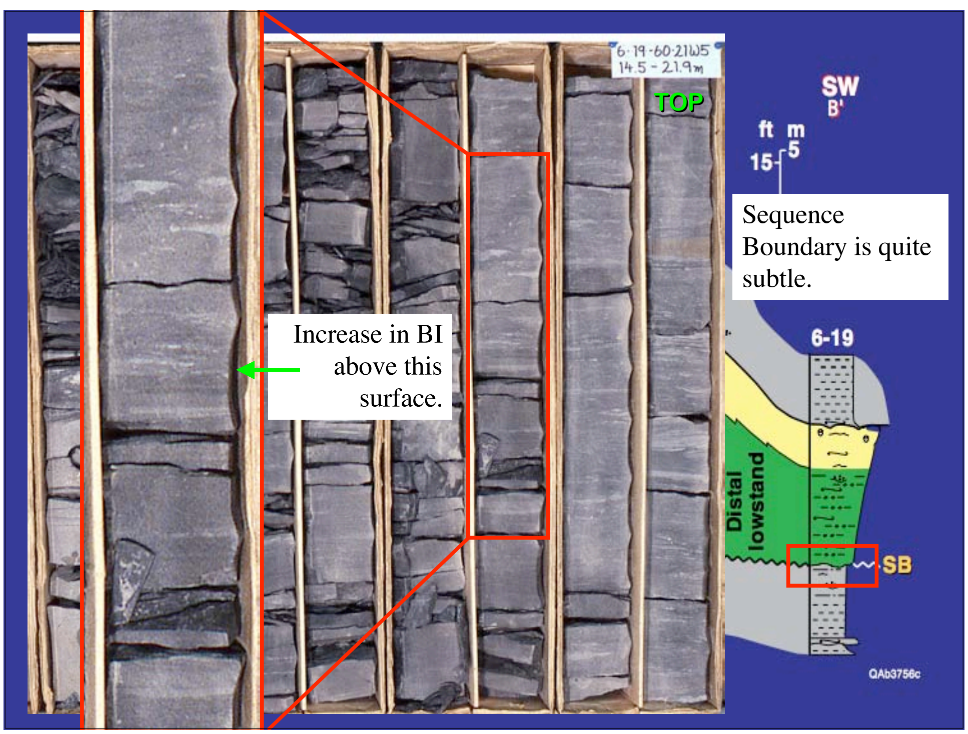
Cuspate, lobate sand body fed by Waskahigan valley indicates lowstand, wave-influenced delta

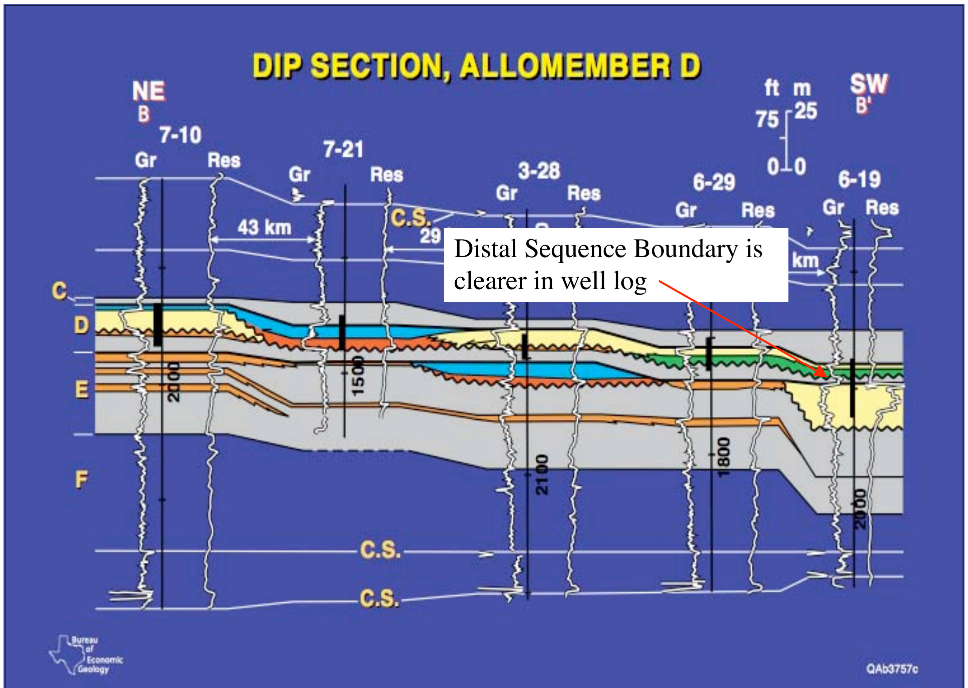
Bhattacharya, 1993


DIP SECTION, ALLOMEMBER D
NE
B
SW
B'
7-10
7-21
3-28
6-29
6-19
MJFS
TSE
SE
D2
?TSE
D3
D2
D1
Lowstand shoreface
Distal lowstand
SB
ft m
15 5
0 0
The distal end of the system (with core data)
Bhattacharya, 1993
QAb3756c


6-19-60-21W5
14.5 - 21.9m
TOP
More bioturbated
SB
Less bioturbated
SW
B'
ft m
15 5
0 0
6-19
Distal lowstand
SB
QAb3756c


6-19-60-21W5
21.9-27.7m
TOP
FS
Distal lowstand delta shows coarsening upward and robust bioturbation.
6-19
Distal lowstand
SB
QAb3756c

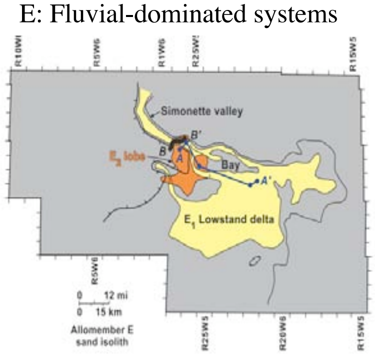

6-19-60-21W5
14.5-21.9m
TOP
SW
B'
ft
m
15
5
Sequence Boundary is quite subtle.
Increase in BI above this surface.
6-19
Distal lowstand
SB
QAb3756c



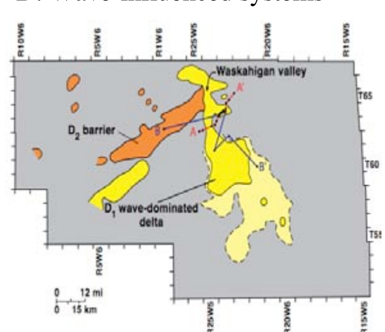
Bhattacharya, 1993

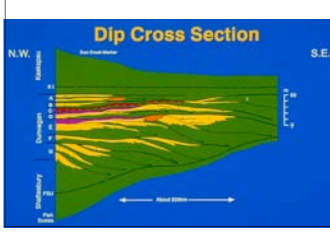
Conclusions

E: Fluvial-dominated systems

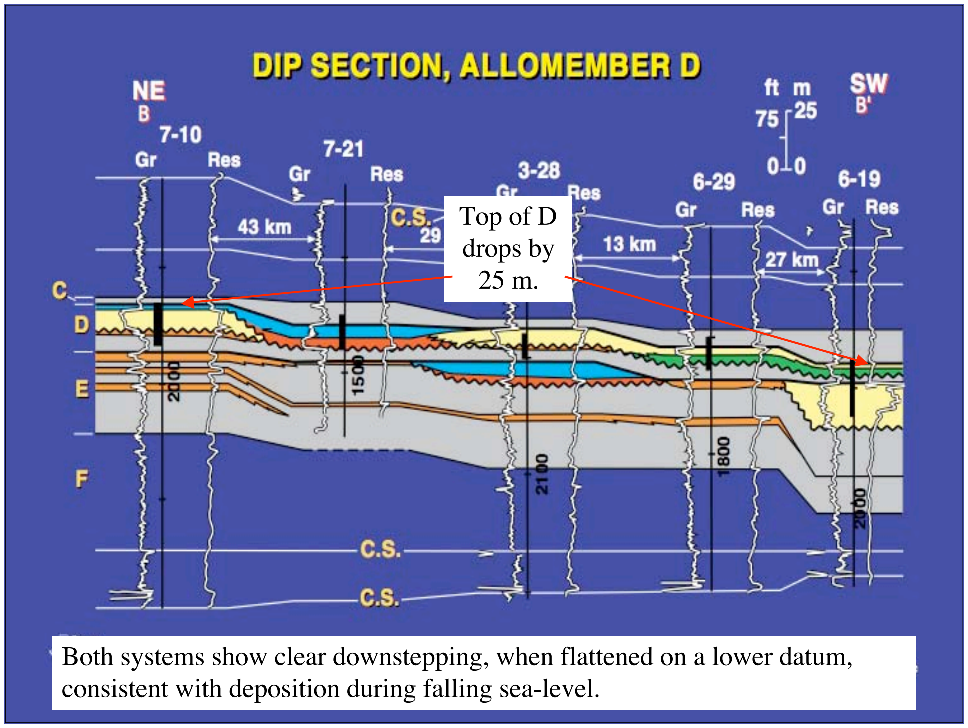


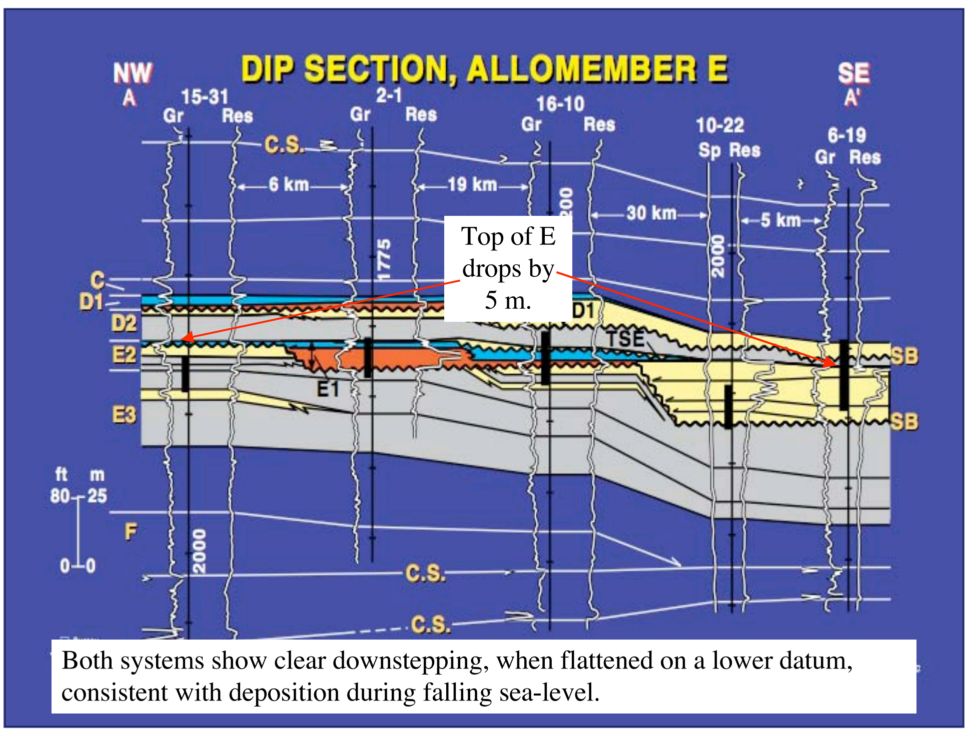
D: Wave-influenced systems





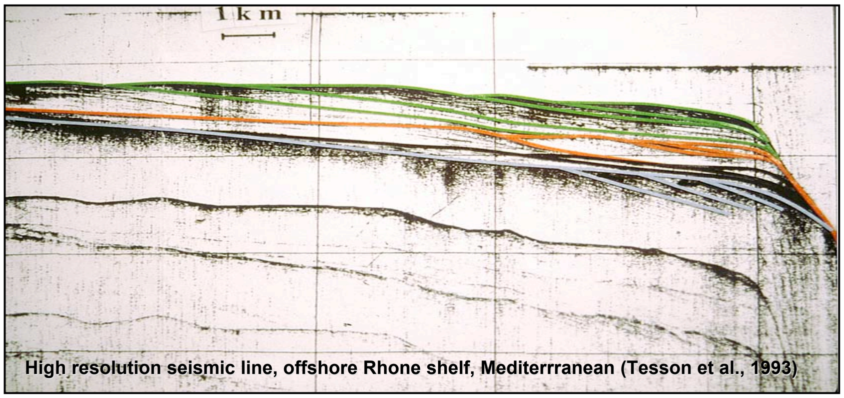
Study contrasts sequence stratigraphy and key surfaces of fluvial versus wave-dominated systems.


DIP SECTION, ALLOMEMBER D
NE
B
SW
B'
7-10
7-21
3-28
6-29
6-19
Gr
Res
43 km
13 km
27 km
C.S.
Top of D drops by 25 m.
C
D
E
F
ft m
75 25
0 0
2000
1500
2100
1800
2000
Both systems show clear downstepping, when flattened on a lower datum, consistent with deposition during falling sea-level.


DIP SECTION, ALLOMEMBER E
NW
A
SE
A'
15-31
2-1
16-10
10-22
6-19
Gr
Res
Sp
C.S.
6 km
19 km
30 km
5 km
Top of E drops by 5 m.
C
D1
D2
E2
E1
E3
F
TSE
SB
ft m
80 25
0 0
1775
2000
Both systems show clear downstepping, when flattened on a lower datum, consistent with deposition during falling sea-level.

Downstepping

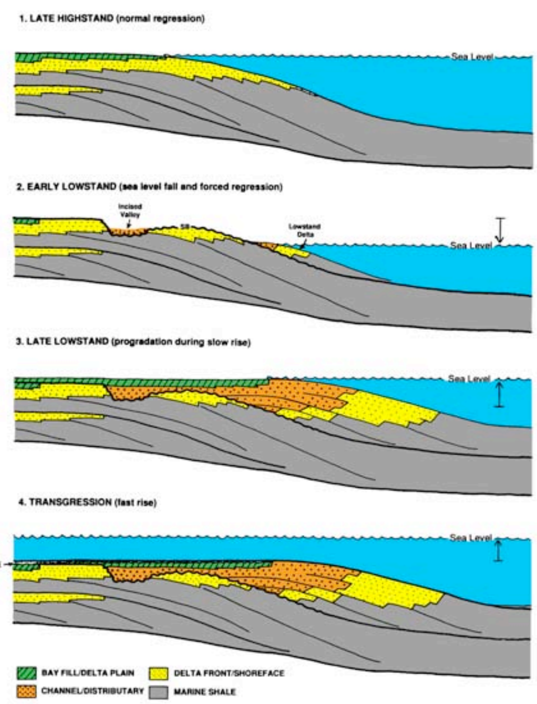
- Similar to that seen in Quaternary-aged forced regressive deltas, like the Rhone.



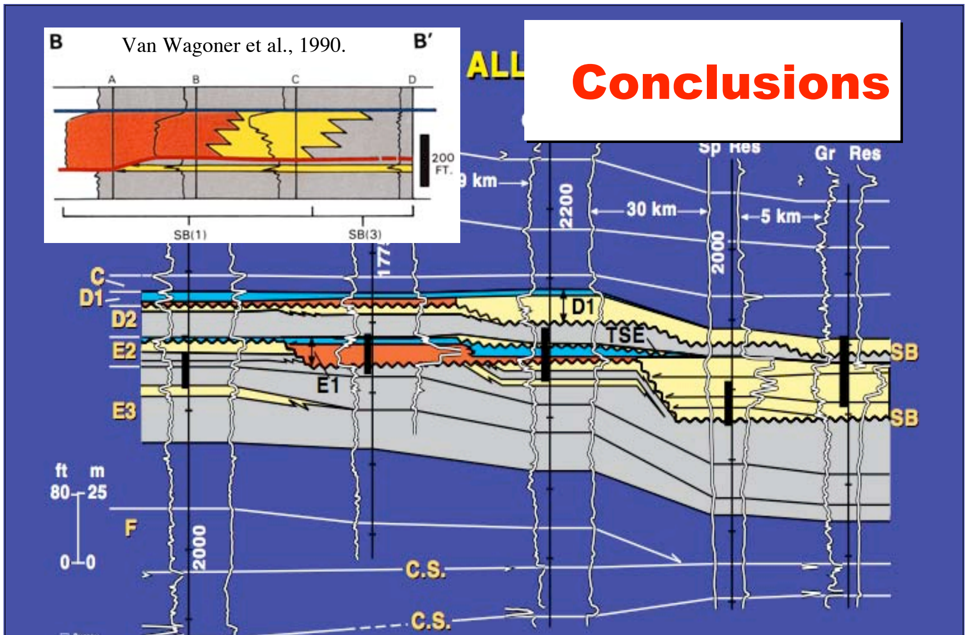
High resolution seismic line, offshore Rhone shelf, Mediterrranean (Tesson et al., 1993)

Evolution of Allomembers

- Allomembers show similar parasequence architecture, stacking and expression of key surfaces, despite contrasting environments of deposition.



Bhattacharya, 1993

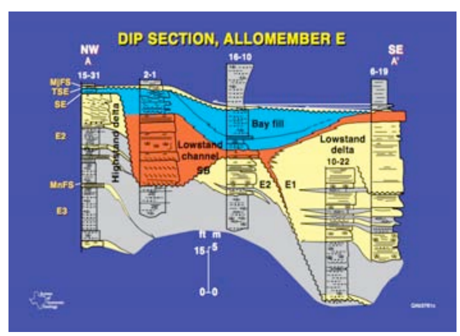


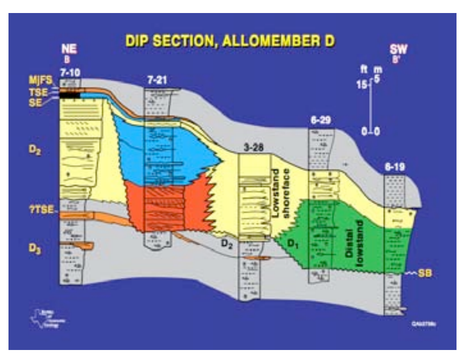
Conclusions

SB's at base of valleys can be tracked seaward, as suggested by Van Wagoner et al., 1990.

Conclusions

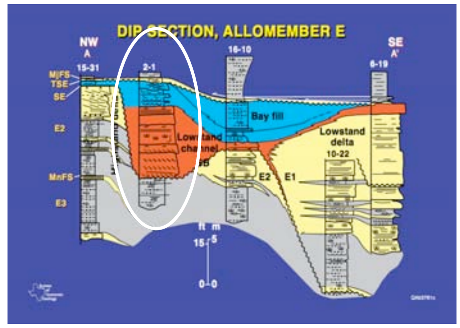
- Similarity of surfaces, despite differences in facies.
- Depositional systems above and below SB's are not hugely different and therefore hard (but not impossible) to pick.
- Major paleogeographic reorganization of facies and environments occurs across flooding surfaces, not SB's.

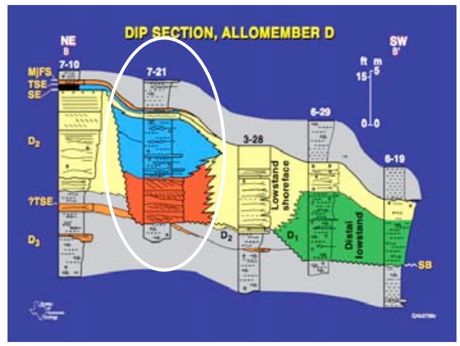




Conclusions

- Valley fills show markedly different internal facies reflecting difference in fluvial versus marine processes.
  - E is fluvial-dominated fill
  - D is marine-dominated





Conclusions

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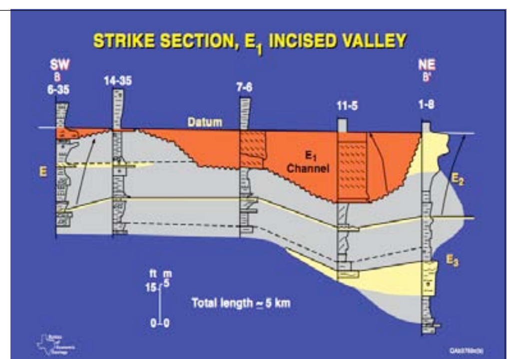

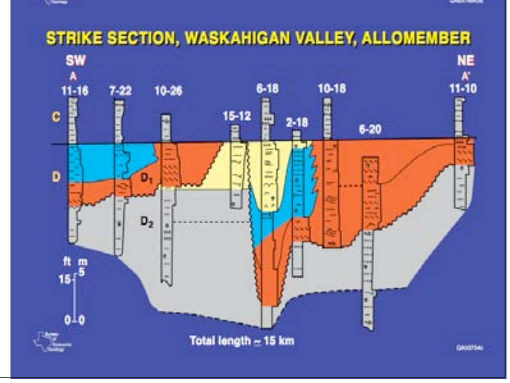

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