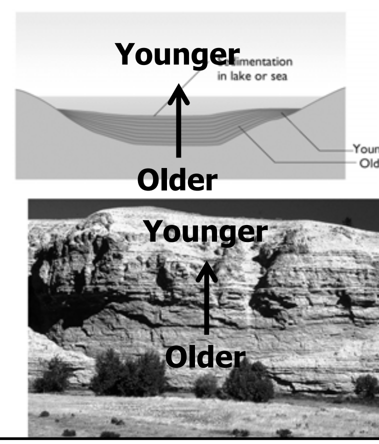
Concepts in Stratigraphy

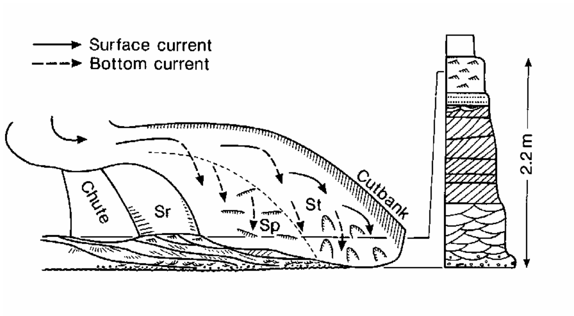
Stratigraphy
- Basic Concepts
- Lithostratigraphy
- Sequence Stratigraphy
  - Sea level and sediment supply
  - Consequences of changes in sea level
  - Types of sequences
- Biostratigraphy
- Other Types of Stratigraphy

Basic Principles
- Steno (1669)
- Principal of original horizontality
  - Sediments deposited as essentially horizontal beds
- Principal of superposition
  - Each layer of sedimentary rock (sediment) in a tectonically undisturbed sequence is younger than the one beneath it and older than the one above it

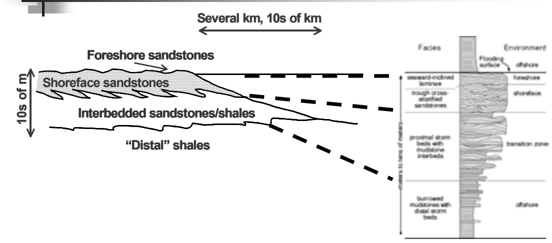


Basic Principles
- Hutton (1700s)
  - Principle of Uniformitarianism: The processes that shaped Earth throughout geologic time were the same as those observable today
  - "The present is the key to the past"
  - Sometimes there are environments/conditions that do not have good modern analogues

Basic Principles
- Walther (1884)
  - Walther's Law: Only those facies and facies-areas can be superimposed primarily which can be observed beside each other at the present time
    - Only applies to *conformable* successions – i.e., no major breaks in sedimentation
    - Vertical successions do not always reproduce horizontal sequence of environments



- "Shalier (fining) upward" succession



Lithostratigraphy

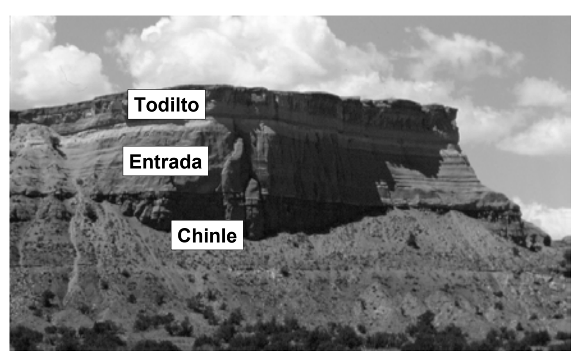
- **Formation**
  - **Fundamental unit of lithostratigraphic classification**
  - **A body of rock identified by lithic characteristics (composition, colour, sedimentary structures, fossils, etc) and stratigraphic position**

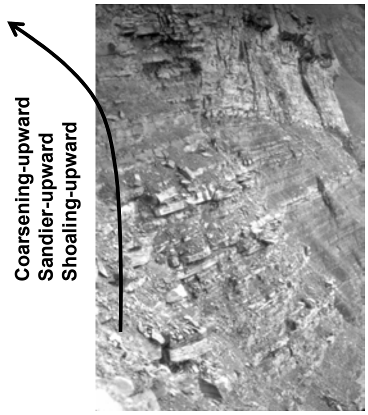
Lithostratigraphy

- **Formation**
  - **Generally considered to be tabular in geometry**
  - **Large enough to be mappable at the Earth's surface or traceable in the subsurface**
  - **Existing formations range from a few m to several 1000s of m thick**
  - **Traceable for a few km or several 1000 km**

Lithostratigraphy

- **Formation**
  - **Names (unfortunately…) may change at political boundaries or from one region to another**
  - **Names generally based on geographic locations**
  - **Contacts between formations established at obvious lithologic changes (sharp or gradational; lateral or vertical)**





Lithostratigraphy

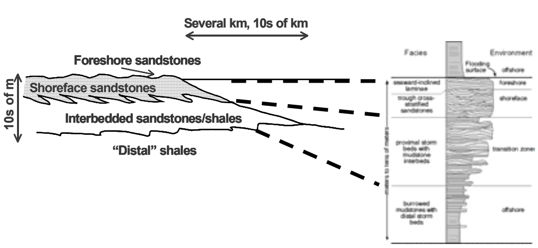
- **Members**
  - **Subdivisions of formations**
  - **Possess characteristics that distinguish it from other parts of the formation**
  - **Not all formations are subdivided into members**
- **Beds**
  - **Smallest formal lithostratigraphic unit**
  - **Used only if official designation is useful**

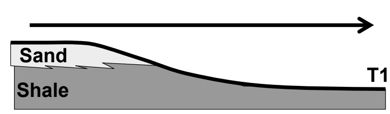
Lithostratigraphy

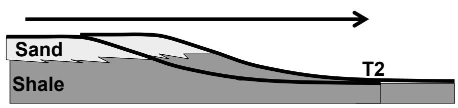
- **Groups**
  - **Two or more formations related lithologically**
  - **Component formations may change laterally (e.g., due to facies changes)**
- **Supergroups**
  - **Assemblage of related or superimposed groups**
  - **Sometimes useful for regional syntheses**

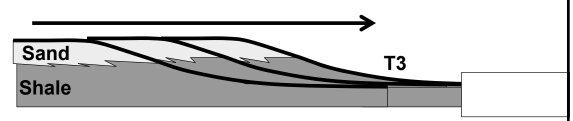
Lithostratigraphy

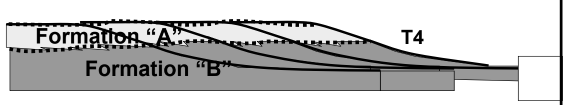
- **Units described at "type sections"**
  - **Outcrops, well logs**
- **Independent from inferred geologic history**
  - **Based on objective, identifiable characteristics**
  - **Interpretations of geologic history may change with time**
- **Diachronous to some extent**
  - **Produced by shifting depositional environments**











Problems with Lithostratigraphy

- Different facies represent different depositional environments
- As laterally contiguous environments shift with time, facies boundaries shift so that the facies of one environment lie above those of another environment
  - Walther's Law

Problems with Lithostratigraphy

- Timelines cross lithologic boundaries
- Obscures genetic relationships when we are reconstructing geologic history

Problems with Lithostratigraphy

- Quest: Find/define "timelines" that will permit depositional histories to be defined with precision
- Timelines: stratigraphic surfaces generated by the interplay of tectonics, eustacy (global sea level) and sediment supply
- Use links between sea level, sediment supply and other factors to develop predictive models

Sequence Stratigraphy

- **Definition:**

  The analysis of stratigraphic successions in terms of genetically related packages of strata, bounded by discontinuities

Sequence Stratigraphy

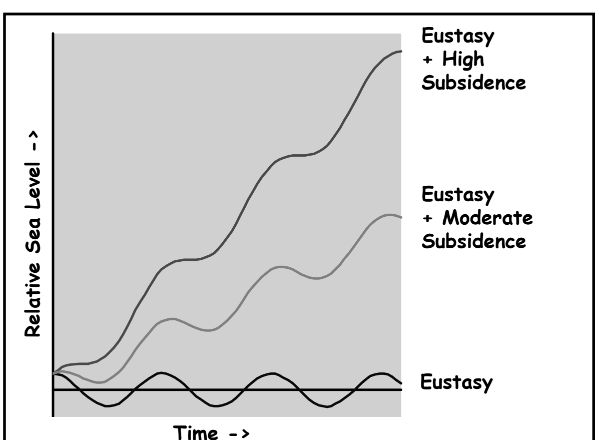
- **Key concepts:**
  - **"Genetically related strata" – different environments, deposited contemporaneously ("systems tracts")**
  - **"Bounding discontinuities" – 3 principal types of surfaces (unconformities, flooding surfaces, maximum flooding surfaces)**
  - **Relate sequence development to interplay of 3 first-order controls (global sea level, local tectonic movements, sediment supply)**

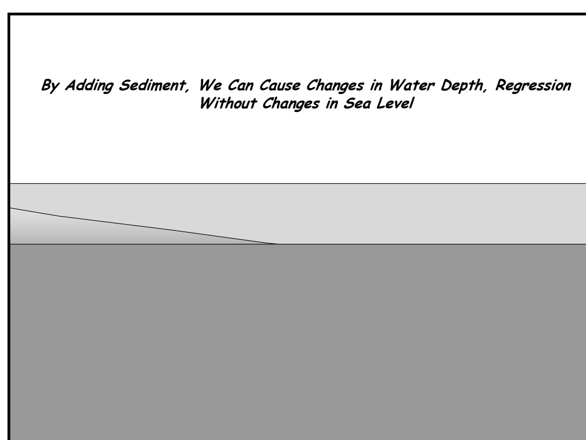
Sequence Stratigraphy

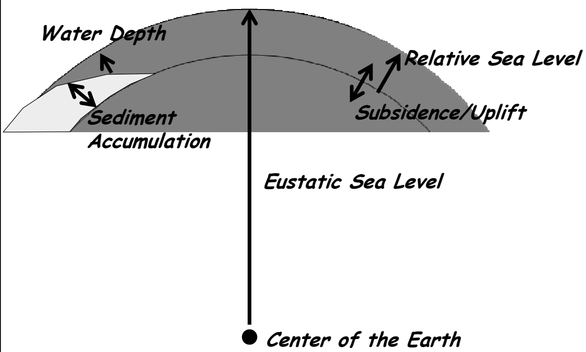
- **Problems:**
  - **Different schools of thought/competing approaches**
  - **"Gurus" and "dogma" in some groups**
  - **Tends to be "jargon intensive"**
- **Solution (this course):**
  - **"Generic approach"**
  - **Adapt (not *adopt*) EXXON terminology (most widely practiced form of sequence stratigraphy)**

Sea Level and Sediment Supply

- **In previous lectures we looked at how changes in global sea level and regional subsidence/uplift combine to create changes in relative sea level**
- **Now let's start adding sediment**







Cyclical Sedimentation

- Transgression
  - Landward movement of the shoreline
- Regression
  - Basinward movement of the shoreline
- Progradation
  - “Outbuilding” of shoreline (deposition)
- Retrogradation
  - “Backstepping” of shoreline (deposition)

Cyclical Sedimentation

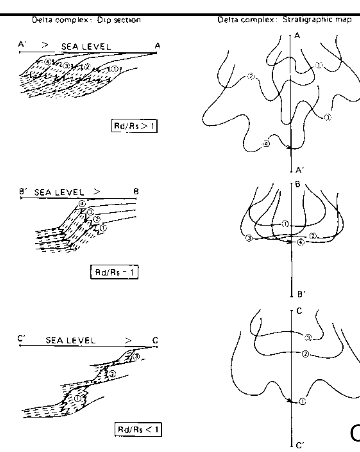
- Progradation is a type of regression
  - Not all regressions involve progradation
- Retrogradation occurs during transgression
  - Not all transgressions involve retrogradation

Cyclical Sedimentation

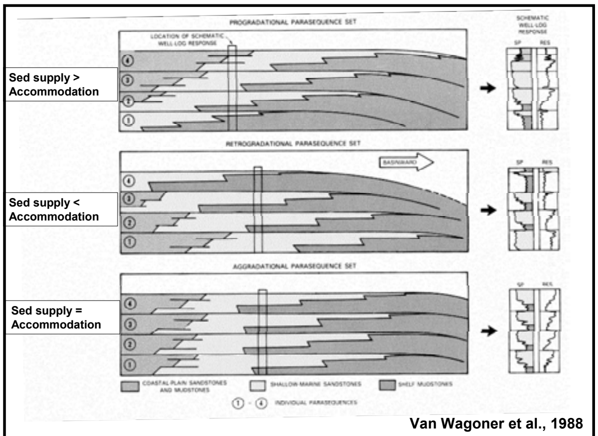
- Whether an area will see transgression or regression (progradation or retrogradation) depends upon the interplay of two factors:
  - Rate of sediment supply (clastic, carbonate)
  - Rate at which “accommodation space” is made available/removed

Cyclical Sedimentation

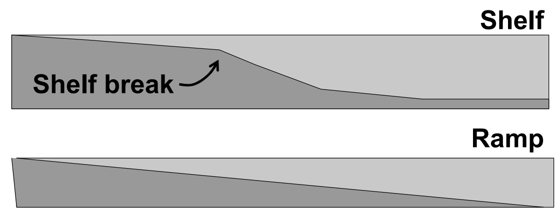
- Accommodation space: Space available for sediment to accumulate vertically
- Approximately equal to water depth in marine settings
  - Changes in relative sea level create/remove accomodation space
- Other types of accommodation (e.g., fluvial “base level”)



Curtis, 1970



Van Wagoner et al., 1988



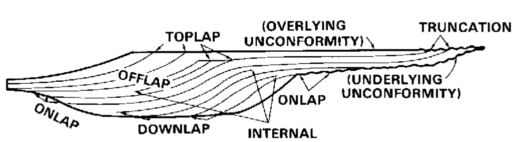
Lateral changes in accommodation vary from place to place – influenced by physiography

Consequences of Sea Level Change

- Based on Embry (2002)
- Changes in "depositional trend"
- Two main possibilities:
  1. Change from deposition to erosion and vice versa
  2. Change from shallowing upward trend to deepening upward trend and vice versa

Stratal terminations

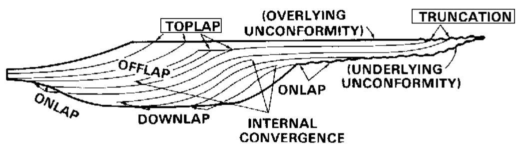
- Describe geometric relationships between a reflection/marker and the surface against which it terminates
- Lapout - lateral termination of a reflection ("bedding plane") at its depositional limit.
  - E.g., toplap, downlap, etc.
  - Based on *geometry* alone
- Truncation – implies surface originally extended further but was "cut"
  - E.g., erosional truncation, fault truncation
  - Can be based on *interpretation*



- Different types of stratal terminations may be identified on seismic sections or log cross-sections. They provide clues that may be used to define depositional histories.

Reflection terminations

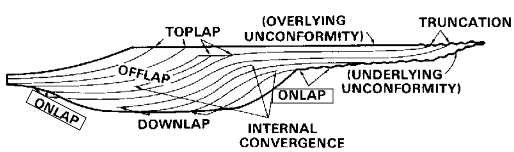
- Toplap – termination of inclined reflections against an overlying, lower angle surface
  - Assumes termination is original depositional limit
- Erosional truncation – termination of reflections against an overlying erosion surface
  - Erosion surface may be marine (e.g., submarine channel) or non-marine (fluvial channel)
- Distinction between toplap and erosional truncation sometimes involves interpretation



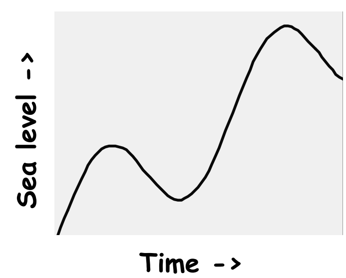
- Toplap and erosional truncation

Reflection terminations

- Baselap – lapout of reflections against an underlying seismic horizon
- Two types: downlap and onlap
  - Downlap – dip of the underlying horizon is less than that of the terminating reflections
  - Onlap – dip of the underlying horizon is greater than that of the terminating reflections
- Downlap almost always indicates a marine setting
- Onlap may be marine or non-marine



- Baselap

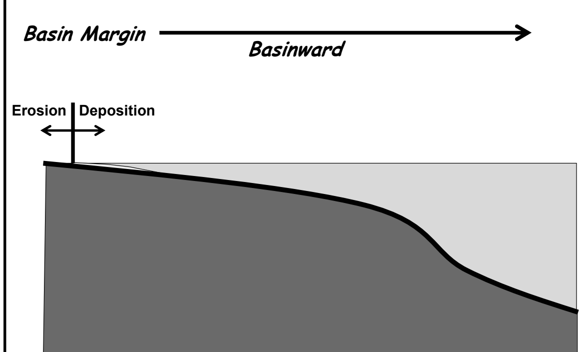


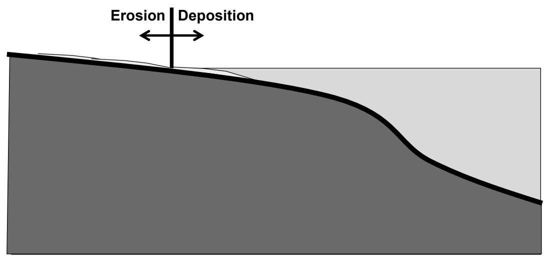
A relative sea level curve

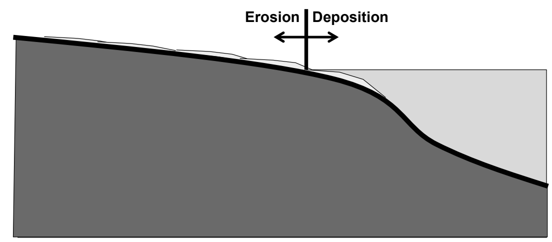
Let's walk through one cycle of fall/rise

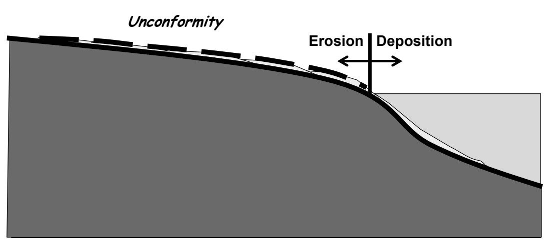
Consequences of Sea Level Change

- Base level fall:
  - Sediment accumulation ceases along basin margin, subaerial erosion surface expands basinward
  - Sea-floor erosion on inner shelf in advance of prograding shoreline









Unconformity

A surface separating younger from older strata along which there is evidence of subaerial erosion and truncation (and in some instances correlative submarine erosion) and subaerial exposure along which a significant hiatus is represented

Van Wagoner et al., 1988

Unconformity

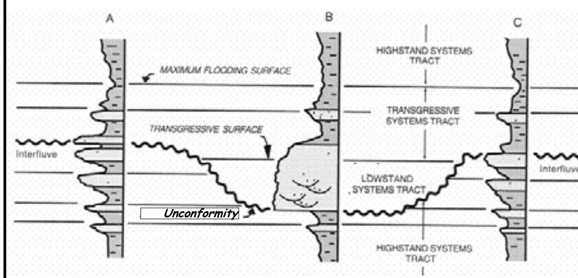
- Starts to form when base level falls
  - Earth's surface exposed to erosion to fluvial action and wind
- Expands basinward as sea level falls and the basin edge is progressively exposed
- All strata below a subaerial unconformity are older than all strata above it

Unconformity

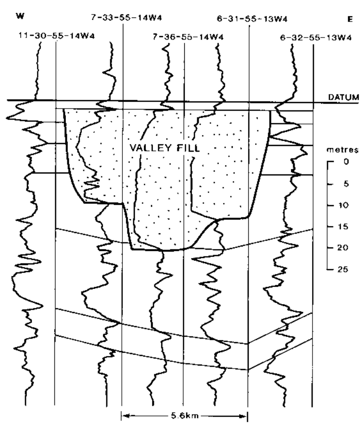
- "Bypass surface"
- Channel incision -> incised valley formation
- "Interfluves" -> soil horizons

Unconformity - Recognition

- Truncation of strata below
  - Seismic
  - Logs
- Onlap of strata above
  - Seismic
  - Logs



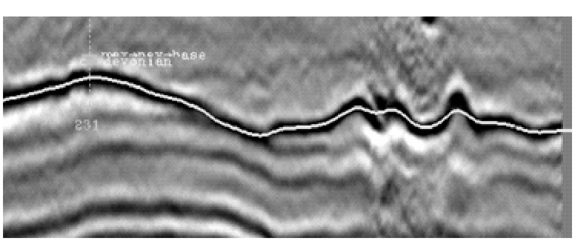
Posamentier and Allen



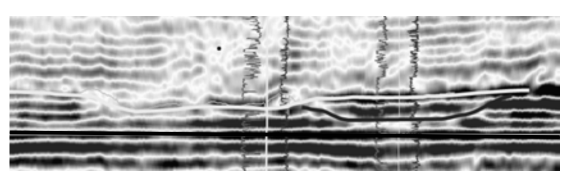
Cant, 1994

Seismic Stratigraphy

- Unconformities are produced by subaerial erosion associated with a drop of relative sea level. Different amounts of time may be associated with these surfaces. They are recognized by erosional truncation of underlying stratigraphy.



The image above shows a significant unconformity (yellow line) between Devonian carbonates and Lower Cretaceous clastics for an area of western North America. Approximately 250 million years is missing at the unconformity. Note the reflection truncations below the unconformity.



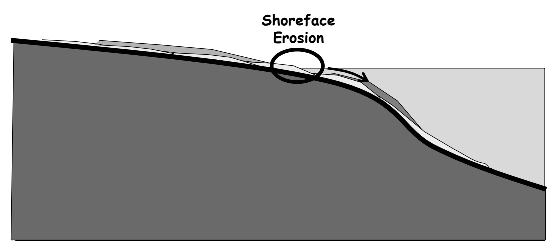
The image below shows two "nested" unconformities in a Lower Cretaceous offshore section. Each unconformity is probably associated with a fourth-order sequence superimposed on a third-order fall of relative sea level. The section has been flattened on an underlying horizon (green) for clarity.

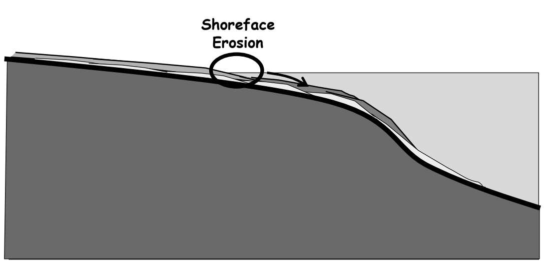
Unconformity - Recognition

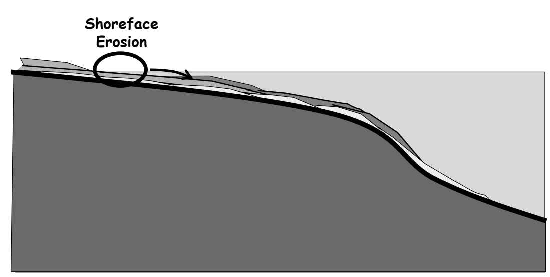
- Incised valleys/channels
  - Can we distinguish “significant incision” from localized channel scour?
  - Other factors can cause “significant incision”
    - Increase in fluvial discharge/power (climate?)
    - Decrease in sediment load
    - Tectonic uplift
- Soil development on interfluves
  - Not all soil horizons are at unconformities
- Changes in channel stacking patterns, sandstone amalgamation, etc.

Consequences of Sea Level Change

- Base level rise:
  - Accumulation of non-marine strata spreads in a landward direction above a subaerial erosion surface
    - Rising water table
  - Change from regressive trend to a transgressive trend in marine deposits
  - Deposition ceases at shoreline and erosion at shoreline starts
  - Change from transgressive trend to a regressive trend





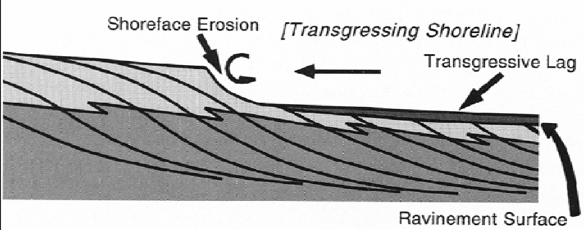


Flooding Surface

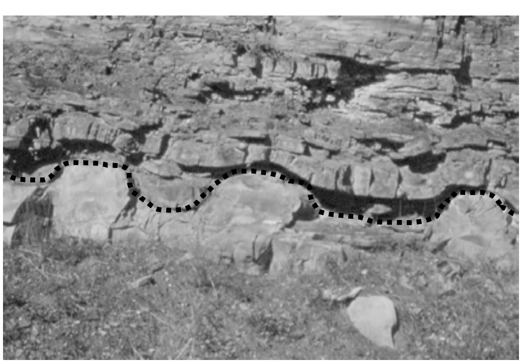
- Surface across which there is evidence of an abrupt deepening
- Formed during transgression
  - Shoreface erosion: “Ravinement surface”
  - Can remove 10-20 m of strata
  - Erosion may cut down through underlying unconformity
- Offshore: “abandonment”, marine erosion?

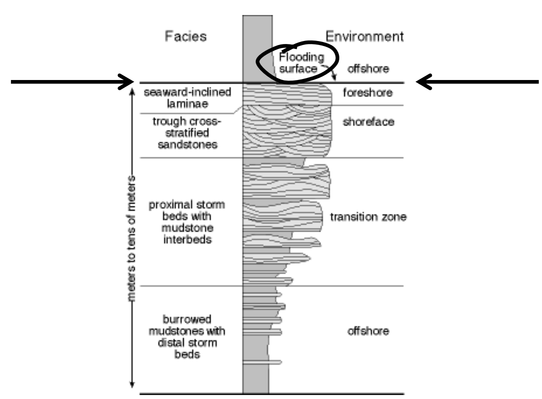
Flooding Surface

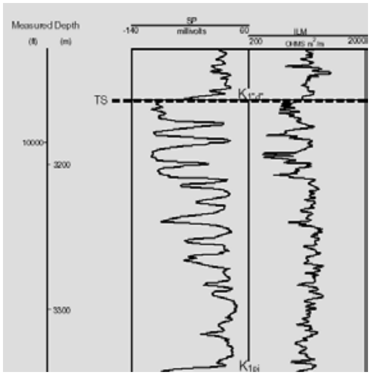
- Aka transgressive/transgression surfaces
- Shallowing upward cycles overlain by deepening upward cycles
- May be capped by transgressive lag
- Early diagenesis immediately below may be apparent



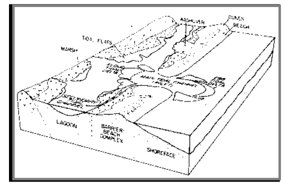
“Erosional shoreface retreat”



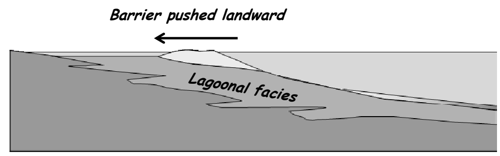


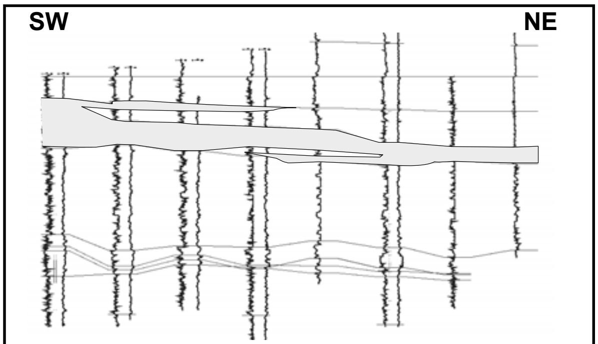


Simmons 'A' 1 well, Yazoo Co., MS

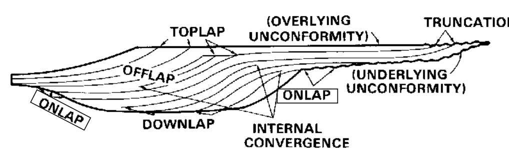


Barrier islands may form during transgression but are not always preserved in the stratigraphic record

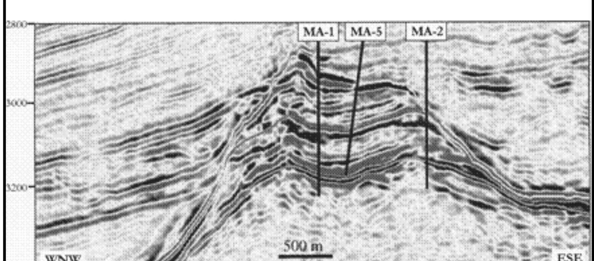




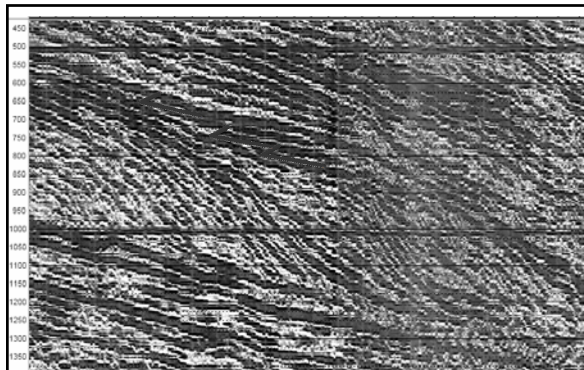
Cliff House Sandstone:
Preserved transgressive barrier complex
Note interfingering with over/underlying strata



- Baselap



Marine Onlap – Tertiary, S.E. Asia



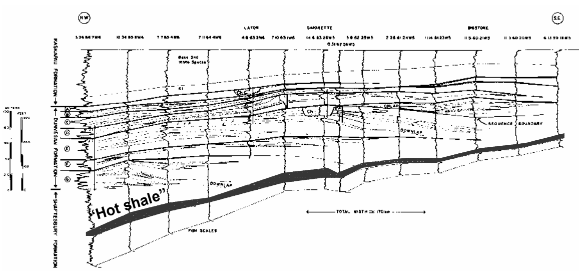
Coastal Onlap – Paleocene, Offshore N.S.

Maximum Flooding Surface

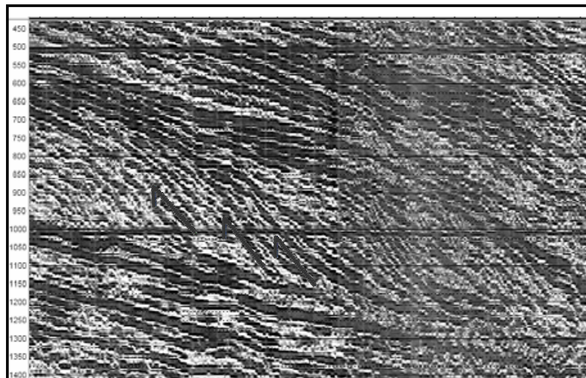
- End of transgression, start of regression
- Shallowing-upward trend overlying a deepening-upward trend
- May be a surface of non-deposition or marine erosion
- May be an interval of very slow deposition
  - "Condensed section" – not really a surface

Maximum Flooding Surface

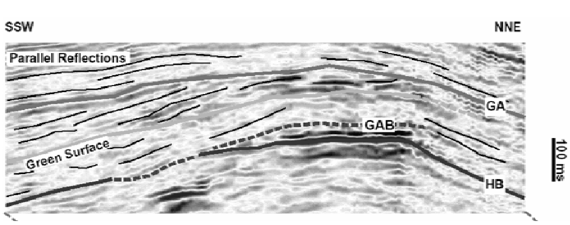
- Recognition
  - Downlap surface log cross-sections
  - Downlap surface seismic images
  - "Hot shales" on gamma ray logs



Bhattacharya and Walker, 1994



Downlap – Paleocene, Offshore N.S.



The image above shows a downlap surface ("Green Surface") separating two different deltaic lobes in a young lowstand deltaic setting. A shale horizon at the downlap surface acts as a vertical barrier to fluid flow, separating two stacked reservoir intervals.

Seismic Stratigraphy

- Downlap surfaces are present at the base of prograding packages. They are commonly associated with maximum flooding surfaces produced by a rise in relative sea level, but may be present elsewhere, such as in deltaic settings where they separate packages generated by autocyclic lobe switching.

Sequences

- The surfaces just described may be used to define "sequences"
  - Subaerial erosion surfaces
  - Flooding surfaces
    - Transgression surfaces/maximum regressive surfaces
  - Maximum flooding surfaces

Sequences

- The surfaces just described may be used to define "systems tracts"
  - Linkage of contemporaneous depositional environments
  - Form during specific portions of the relative sea level curve

Sequences

- Different "schools" of sequence stratigraphy define sequences in different ways
- We will look at two:
  - "Exxon school"
    - Use subaerial unconformity and "correlative conformity"
  - "Embry school"
    - Use subaerial unconformity and transgression surfaces (aka "maximum regressive surfaces")

Exxon School

- Sequence boundary defined using unconformity and its "correlative conformity"
- Can we recognize the unconformity?
  - Most people will agree
  - ?Some tendency to "over-interpret"
    - Not every channel base is a sequence boundary

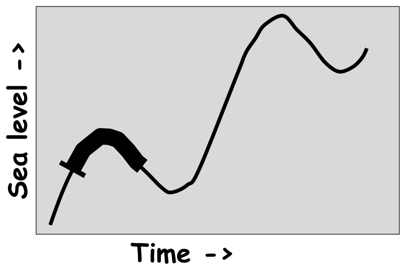
Exxon School

- What is the correlative conformity?
- Forms basinward of subaerial unconformity
- Deposition is continuous
- No consensus on what it is, how to recognize it, when it forms, etc.

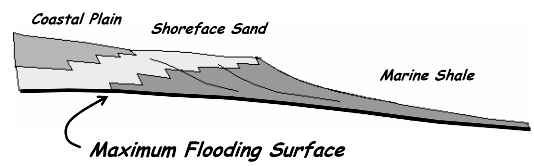
Key Surfaces

- Define "systems tracts" based on where strata are with respect to 3 key surfaces:
  - Highstand Systems Tract ("Progradational Systems Tract")
    - Between MFS & SB
  - Lowstand Systems Tract
    - Between SB & FS
  - Transgressive Systems Tract
    - Between FS & MFS

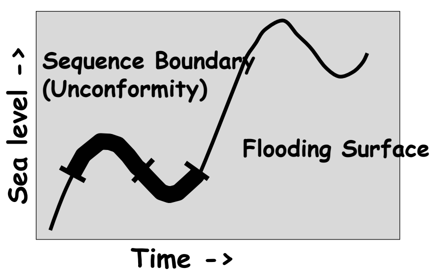
Sequence Stratigraphy
The Exxon Model



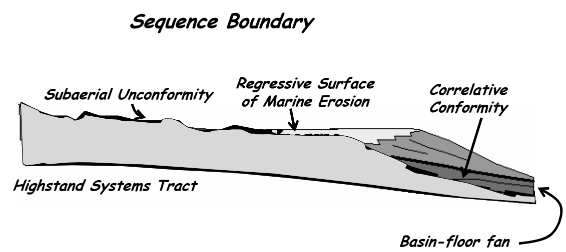
Highstand systems tract: progradation on shelf

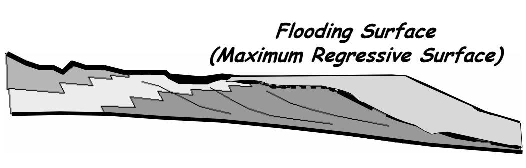


Sequence Stratigraphy
The Exxon Model

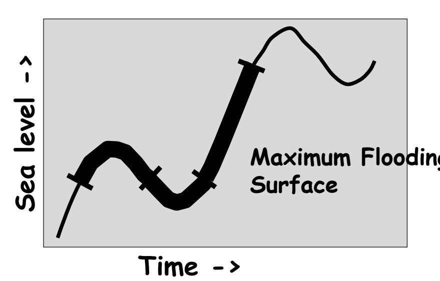


Lowstand systems tract: submarine fans, prograding wedges, bypass/erosion on shelf

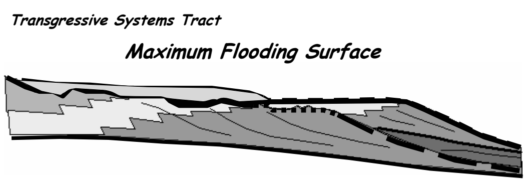




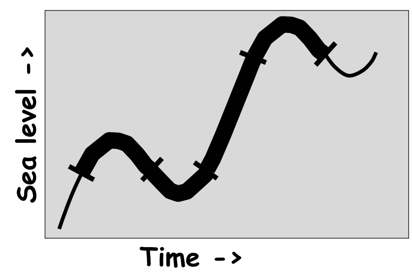
Sequence Stratigraphy
The Exxon Model



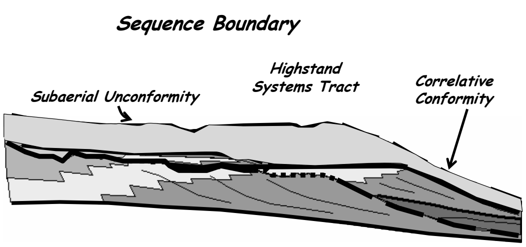
Transgressive systems tract: non-deposition, coastal plain aggradation, marine shale



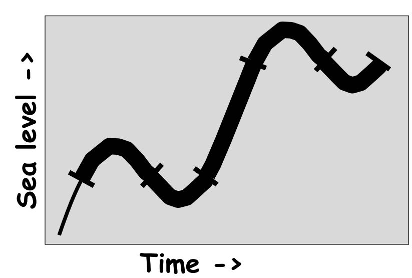
Sequence Stratigraphy
The Exxon Model



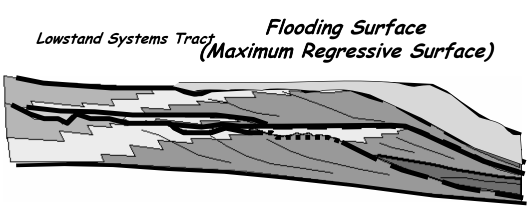
Cycle begins anew – Highstand systems tract



Sequence Stratigraphy
The Exxon Model

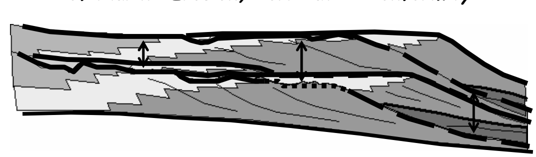


Lowstand systems tract



Depositional Sequence

Bounded by Subaerial Unconformity, Regressive Surface of Marine Erosion, Correlative Conformity

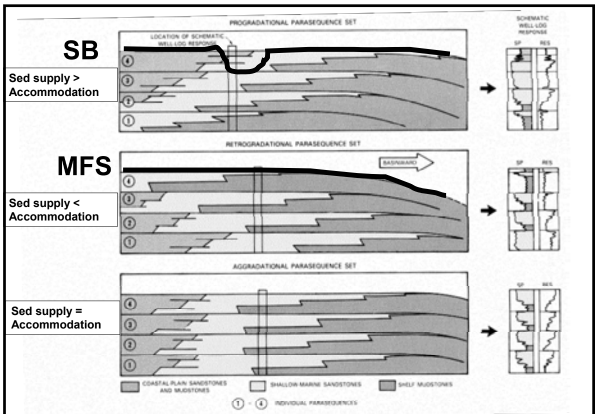


The Exxon Model
A (Shared) Personal Perspective

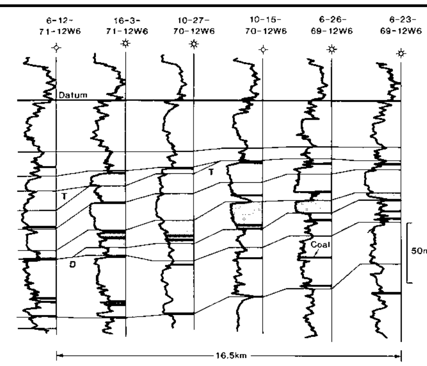
- The Exxon model is a useful tool for understanding the depositional history of a package of sedimentary rocks
- It is a useful starting point – do not accept it as “absolute truth”
  - Be flexible
- It is associated with a lot of complex terminology (“jargon”)
  - Focus on the concepts, rather than the terminology

Parasequences

- Shoaling-upward stratigraphic units bounded by flooding surfaces, or their correlative surfaces (Van Wagoner et al. 1990)
- Considered to be the building blocks of sequences
- Best defined in shallow-marine deposits
- Parasequence stacking patterns differ between systems tracts
  - *Progradational, aggradational, retrogradational*

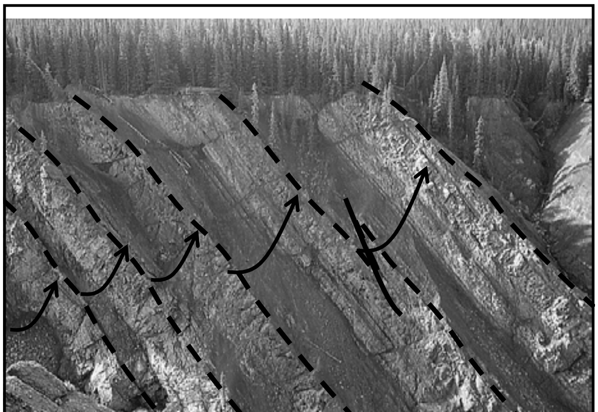


Van Wagoner et al., 1988



Correlation of flooding surfaces to define parasequences
Cretaceous clastics, Alberta

Cant, 1994



Parasequences

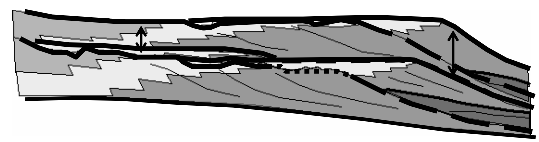
- May be formed during transgression or regression
- May be related to changes in sea level or “autocyclic” phenomena like lobe switching in a delta

Transgressive-Regressive Sequences

- Embry and Johannessen, Embry 2002
- Sequence boundary is subaerial unconformity on shelf
- Basinward sequence boundary corresponds to “maximum regressive surface”
  - Change from “shallowing up” to “deepening up” trend
  - Maximum regressive surface also known as “transgressive surface”

Transgressive-Regressive Sequence

Bounded by Subaerial Unconformity and Maximum Regressive Surfaces



Transgressive-Regressive Sequences

- Sequences divided up into two systems tracts:
  - Transgressive systems tract: between sequence boundary (base) and maximum flooding surface (top)
    - Deepening upward trend
  - Regressive systems tract: between maximum flooding surface (base) and sequence boundary (top)
    - Shallowing upward trend

Transgressive-Regressive Sequences

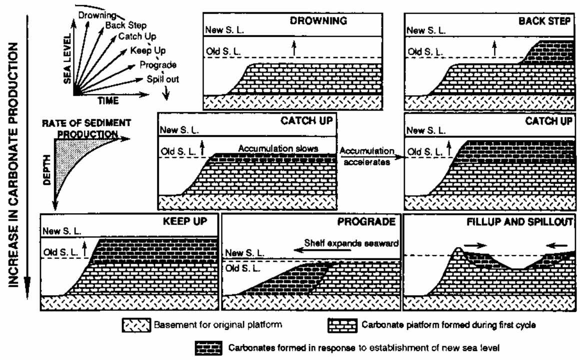
- Advantages:
  - Simple, less jargon (e.g., “forced regressive systems tract”)
  - Bounded by surfaces that can be objectively defined (subaerial unconformity, maximum regressive surface)
- Disadvantages:
  - Not widely used

Carbonate Sequence Stratigraphy

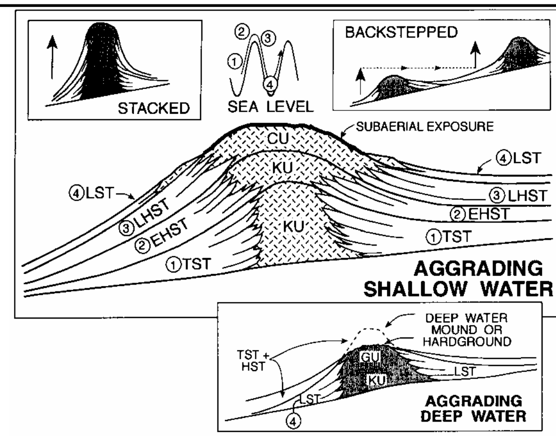
- **Many similarities to siliciclastic sequences**
- **BUT-> sediment typically produced locally**
- **Therefore need to consider relative rates of sediment *production* (not *supply*) and relative sea level**

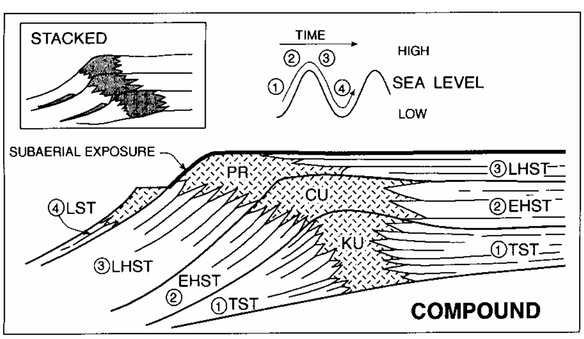
Carbonate Sequence Stratigraphy

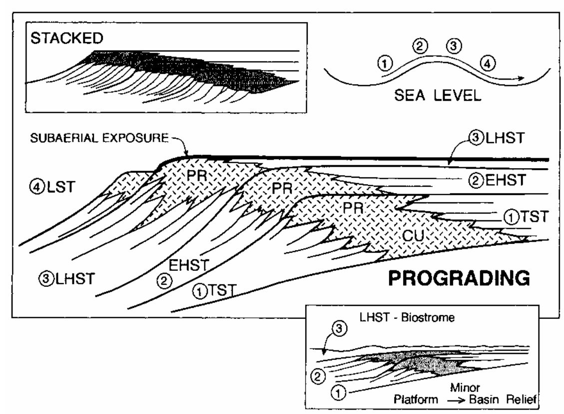
- **“Keep up”**
  - **Carbonate production able to keep up with rise in sea level – water never deepens**
- **“Catch up”**
  - **Sea level rises, water deepens then carbonate aggradation catches up to s.l.**
- **“Give up” (drowning)**
  - **Sea level rises, carbonate factory shut down – water stays deep**



Jones and Desrochers, Facies Models







Carbonate Sequence Stratigraphy

- **Karst surfaces develop when carbonate platforms are exposed**
  - **Dissolution of carbonates by acidic rain/surface water/groundwater**
  - **Small-scale -> large scale**
  - **Sinkholes, caves, valleys, etc.**

Sequence Stratigraphy

- **Traditionally 2 aspects:**
  - **Global sea level**
    - **less emphasized now**
    - **Problems with correlation and mechanisms above 2nd order cycles**
  - **<u>Methodology</u> for studying sedimentary rocks**
    - **Started with seismic, then logs and outcrops**
    - **Think about *relative* sea level**

Sequence Stratigraphy

- **Avoid using sequence stratigraphic models as "templates"**
  - **Don't "force-fit" observations**
- **Watch out for different approaches/jargon**
  - **e.g., "Depositional sequences" *vs* "Genetic sequences"**

Sequence Stratigraphy

- **Focus on principles**
  - **They are fairly simple**
- **Concepts applicable to carbonate/clastic, modern/ancient, small/large scales**

Summary

- **Traditional lithostratigraphy not ideal for understanding/defining earth history**
- **"Timelines" cross lithostratigraphic contacts**
- **Many stratigraphic successions show cyclicity**
- **Different scales of cyclicity may be present**

Summary

- **Stratigraphic record controlled by interplay between three main variables:**
  - **Global ("eustatic") sea level change**
  - **Local/regional subsidence/uplift**
  - **Sediment supply**
- **Eustatic sea level change and local tectonic movements produce relative sea level change**

Summary

- **Relative sea level change, sedimentation, and basin shape define accommodation space**
- **Three key surfaces: sequence boundaries, flooding surfaces, maximum flooding surfaces**
- **Key surfaces used to define systems tracts**

Summary

- **Carbonates show similar patterns to siliciclastic systems**
  - **"Keep-up", "Catch-up", "Give-up"**
- **Global sea level changes occur at a variety of magnitudes, rates**
  - **Many different processes responsible**
- **Use sequence stratigraphy as a guide, not a template**