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 synthesis

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

Interbedded sandstones/shales

“Distal” shales

Shoreface sandstones

Foreshore sandstones

Several km, 10s of km

10s of m
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.

- **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)

**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)

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**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.

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*By Adding Sediment, We Can Cause Changes in Water Depth, Regression Without Changes in Sea Level*
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 accommodation space
- Other types of accommodation (e.g., fluvial “base level”)

Curtis, 1970
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

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

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

- 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

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

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.

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.
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”
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

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.

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.

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.
Sequences

• The surfaces just described may be used to define “sequences”
  – Subaerial erosion surfaces
  – Flooding surfaces
    • Transgression surfaces/maximum regressive surfaces
  – Maximum flooding surfaces

• 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

- **Coastal Plain**
- **Shoreface Sand**
- **Marine Shale**
- **Maximum Flooding Surface**

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

- **Sequence Boundary**
- **Subaerial Unconformity**
- **Regressive Surface of Marine Erosion**
- **Correlative Conformity**
- **Basin-floor fan**

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

- **Flooding Surface**
- **(Maximum Regressive Surface)**
- **Lowstand Systems Tract**
- **Maximum Flooding Surface**
Maximum Flooding Surface

Transgressive Systems Tract

Sequence Boundary

Subaerial Unconformity

Highstand Systems Tract

Correlative Conformity

Sequence Stratigraphy
The Exxon Model

Sea level ->

Cycle begins anew - Highstand systems tract

Lowstand Systems Tract

Flooding Surface (Maximum Regressive Surface)

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

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 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
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
- Methodology 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”

**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

**Sequence Stratigraphy**

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

**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