Development and Application of Sedimentary Rules in Stratigraphic Prediction of Deepwater Reservoir Presence and Architecture*

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Abstract

Stratigraphy correlates and modulates sedimentary attributes used to characterize subsurface reservoirs. Important attributes include lithology, process facies, sedimentation units, sedimentary bodies and sedimentation regions. These sedimentary responses are hierarchical and scale to parameters, like slope stability and flow confinement, describing different frequency and magnitude processes. Attributes from many examples provide a temporal and spatial framework used to establish differences in initial boundary conditions for parameters associated with general deepwater system responses. These parameters represent the surface and sediment forces governing the energy and architecture of sedimentary systems. Surface forces preserve, shape and confine, while sediment forces modify, modulate and transform sedimentary response. Gradient and turbidite event magnitude govern mass dispersion and form the principal components used to group multiple parameters describing surface and sediment forces in deepwater systems.

The principal components are formulated into three sedimentary rules combining co-varying parameters and hierarchical attributes to account for non-uniform and unsteady changes in system energy. Sedimentary systems are not self-similar or fractal because different boundary conditions control the formation of similar features, like ripples and dunes. Consequently, grain size limiting ripple formation cannot predict dunes scaling to turbulent boundary layers. Though scaling to different parameters, these sedimentary attributes do correlate to fluid properties in multipartite turbidity currents dependent on the down-flow gradient, the effect of turbidite event magnitude on the cross-flow gradient, and longer-term longitudinal gradient adjustments to deposition and deformation.
Sedimentary rules correlate scalar parameters to attributes generated from observation, comparison, and verification of consistently classified outcrop examples recording known differences in initial conditions. Rule application enables larger scale patterns to be correlated to smaller scale features, or the inverse (e.g., use channel stacking pattern to predict the presence of channel-base drapes). Rule-based sedimentological detection and stratigraphic modulation of pattern variation utilizes principle components to predict complex system responses to the multiple co-varying parameters governing reservoir presence and multiple scales of heterogeneity.

References


Presenter’s Notes: There is a rich literature on the technology requirements for successful deepwater exploration and development. Therefore this talk will focus on the geologic considerations of deepwater depositional systems that impact and will drive technology development. The added constraint of operational water depth suggests future deepwater exploration and field development will follow a different path than shown by the more mature extraction history from onshore basins.
MOTIVATION

Prediction of Deepwater Reservoir Presence and Architecture

Explain variations in:

- Reservoir Type
- Reservoir Quality
- Heterogeneity at Multiple Scales

Based on Limited Data or information
Empirical Observation from Outcrop Studies in the Geological Analogs and Information Archive (GAIA) Project—“the Gardner World Tour”

Consistently Classify Sedimentary Architecture from the Best and Most Complete Outcrop Examples—“we don’t claim to be right, but we will be consistently wrong or may differ from the classification you may internally deploy”

Data Classified with over 400 Geological Metadata Terms Spanning Many Spatial and Temporal Scales and 500 Additional Terms for the Data Types and Sources

Search the Data using Multiple Methods to Mine Data Requiring Development of Database Software and Search Apps to Identify Common Patterns

- TOADAL (Heritage)
- GAIA (Under development)
Develop *Response-Process* Algorithms, or Rules, Based on Empirical Data that Attempt to Explain Similarity and Dissimilarity in Sedimentary Architecture

**Important disclaimer:** I am not a mathematician, nor a programmer, but rather a lowly field geologist (making this an inverse problem)

Started with over 30 rules distilled to one in the past year—the subject of this talk
PREMISE

- Deepwater Reservoirs are Generated by Complex Systems
- Systems Approach based on Identifying the Principle Components of Deepwater Systems
- Principle Components are used to Group Multiple Process Parameters to Simplify Complex Systems
PREMISE

Principle Components Define Sedimentary System Energy by *Interaction* of:

- Gradient ($G_{5}$)
- Sedimentation Event ($S_{E}$)
- Mass Dispersion ($M_{D}$)

Prediction—Stratigraphic (time and space) Correlation of System Energy

- **Sedimentary Pattern Rule** $M_{D} = \frac{(G_{5} \cdot S_{E})}{dt}$
Intellectual Leashes or Assumptions

Turbidity currents are multipartite flows—in other words, a single event contains different regions that exhibit both Newtonian (turbulent) and non-Newtonian (high viscosity) behavior in different parts of the flow.

Turbidity currents are open systems that can add sediment through erosion and remove sediment by deposition.

Turbidity currents interact with a cumulative gradient that operates over different time scales.

Presenter’s Notes: Reflecting the geomorphic terrains they generate, all sedimentary systems are governed by site-specific processes that determine deposition and preservation. The challenge is separating these local processes, which can be unique to a place and time, from the more general system response and behavior. The list of parameters in Slide 47 is considered inclusive and fundamental to the generation of deep-water sedimentary architecture. This list of formative process parameters is also applicable to other environments of deposition on Earth. (notes continued on next slide)
These parameters combine to describe sedimentary system behavior. For example, it is well known that shelfal accommodation is a composite response to eustatic, tectonic, and sediment supply controls on shallow marine sedimentation on the shelf (Mitchum, 1985; Jervey, 1988; Vail, 1987). In this well-studied shallow water example, no single parameter, i.e. eustasy, controls shelfal accommodation. This example also illustrates how the composite effect that results from combining different parameters generates variations in sedimentary architecture.

Because a common set of deepwater analog patterns emerge from the multiple outcrop and subsurface examples now documented in the GAIA project, it is likely that a common set of formative processes are responsible for this repetition. If this is true, then these patterns can be defined and described by their formative parameters. This is the idea behind formulating logic statements (rules) from formative parameters to define the sedimentary architecture of a pattern.

Geologic rules are generated through observation, parameter correlation, and verification. Rule development uses a family of deterministic outcrop and subsurface datasets to extract and describe the most common sedimentation patterns. The rules are logic statements that define how parameter trends combine to produce different deepwater sedimentation patterns (Slide 44). Rules and their associated parameters are cross-tested against various datasets to capture the range of variations for a particular sedimentation pattern.

A geological rule utilizes physical laws to describe repeatable outcrop-derived empirical relationships defined by two or more parameters (system inputs) for probability-based, subsurface geologic prediction of sedimentary architecture.
Cumulative Gradient \((G_5)\) Affecting Sedimentation and Preservation

Cumulative gradient sums five gradients operating at different scales illustrated in diagram of deepwater system. They bridge the gap between tectonic orders of deformation and the hierarchy of stratigraphic cycles modulating sedimentary responses to the following gradients:
Definition of Cumulative Gradient

1. **equilibrium profile gradient** from basin margin to low point in basin.
2. **deformational adjustment of the basin/shelf margin** commonly associated with depositional outbuilding of continental margin.
3. **depositional topography** from aggradation of localized sediment thick changes gradient and body stacking patterns.
4. **instantaneous cross-flow gradient** affects lateral flow expansion and changes turbidity current height.
5. **instantaneous down-flow gradient** affects turbidity current momentum and turbulent suppression promoting transformation.
Quantitative Expression of Cumulative Gradient

1. **equilibrium profile gradient** from basin margin to low point in basin.
2. **deformational adjustment of the basin/shelf margin** commonly associated with depositional outbuilding of continental margin.
3. **depositional topography** from aggradation of localized sediment thick changes gradient and body stacking patterns.
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5. **instantaneous down-flow gradient** affects turbidity current momentum and turbulent suppression promoting transformation.

\[
\begin{align*}
\int 10^6 \frac{\partial x_1}{\partial z_1} \, dt + \int 10^5 \frac{\partial x_2}{\partial z_2} \, dt + \int 10^3 \frac{\partial x_3}{\partial z_3} \, dt + \int 10^{-2} \frac{\partial x_4}{\partial z_4} \, dt + \int 10^{-2} \frac{\partial x_5}{\partial y_1} \, dt
\end{align*}
\]

- \( x = \) down-profile distance
- \( \partial x = \) change in down-profile distance
- \( y = \) cross-profile distance
- \( \partial y = \) change in cross-profile distance
- \( z = \) elevation
- \( \partial z = \) change in elevation
Significantly, this approach emphasizes the interaction of turbidity current momentum and cumulative gradient; it does not require the static precursor creation of accommodation space for sedimentation. Accommodation space is a stratigraphic concept and simplification derived from geometric forward models. Unfortunately, accommodation space cannot be empirically measured (Muto and Steel, 2000). Quantified using a static energy measure like force displacement (Newton-meter), accommodation space fails to describe how momentum interacts with gradient (Gardner et al., 2004). Dynamic interaction of the cumulative gradient and turbidity current momentum does not require the creation of precursor accommodation space. Geometric models based on accommodation space reproduce cycle stacking patterns, but not the hierarchy of sedimentary structures or bodies that change within these cycles (Cross and Lessenger, 1998). 

*notes continued on next slide*
Formative deep-water parameters are grouped into three categories that can be directly related to the dimensionless accommodation/sediment supply (A/S) ratio. The A/S ratio correlates fourth-order through sixth-order cycle sediment volumes and their stacking patterns to sedimentary architecture. Independent of these categories, the parameters can be linked into logic statements (Slide 48) that describe co-varying, process-response rules, or action-reaction pairs, that relate formative sedimentation processes to the most likely depositional response. These rules are embedded in the deep-water sedimentation patterns framed in SSEM diagram (Slide 44). System energy is correlated to formative deep-water parameters, grouped into three categories, to describe the balance between surface and sedimentation forces responsible for sedimentary architecture. The objective is to explicitly infuse sedimentation patterns within SSEMs with the formative processes that describe them at the varying temporal and spatial scales represented in stratigraphy.

Multiple co-varying parameters can be estimated from subsurface proxies (e.g., channel stacking pattern can be used to infer the preservation of fine-grained channel-base drape), to help validate the interpretation. The ability to measure the formative parameters for a particular pattern from a specific set of observational attributes helps establish the uncertainty in the geologic interpretation. Changes in the accommodation-sediment supply ratio, which is a lower resolution proxy for system energy, result from changes in a varying number of finite parameters that combine to produce discrete sedimentation patterns.

Because changes in system energy generate differences in sedimentary architecture, and because system energy can be defined by a finite set of parameters, these parameters can be formulated into logic statements to predict sedimentary architecture. The application of geologic rules for the prediction of reservoir architecture represents a new interpretation tool, but an old idea, whose origin can be traced to fundamental principles like Walther’s Law. Nonetheless, the application of geologic rules may be unfamiliar to many experienced subsurface geoscientists.

Rules are embedded in sedimentation patterns depicted in all depositional models—they simply aren’t explicitly stated or used to help validate the interpretation. We rarely rank the certainty of Walther’s Law in subsurface interpretation of sedimentary architecture. The requirements for Walther’s Law are either implicit, and self-evident in the interpretation, or the answer requires specialized and high-level information beyond the experience level of the subsurface interpreter.

Embedding rules in sedimentary patterns in the matrix (Slides 43-45) provides a structured process that is more transparent and accessible to a broader spectrum of geoscientists and engineers. Because numerical data have been consistently classified, they can also be used to verify geologic rules.

The basic assumption is that geologic rules can be formulated to predict repeatable (outcrop-derived) sedimentary patterns from two or more parameters (system inputs). Rules must be reproducible, globally applicable, and describe fundamental process-response behavior. Rules can be tested against numerous examples of the same system recording known differences in system inputs, e.g. change in grain size. Demonstrating repetitive patterns from multiple examples helps validate and identify rule limits. These different sedimentary architectures, or patterns, reflect some unique combination in a repetitive set of input parameters, like grain size and gradient. These combine in predictable relationships that describe the physical processes of sediment erosion, transport, and deposition that generate sedimentary architecture. In this view, an ancient sedimentary system is defined by the system energy requirements for sedimentation to generate a geomorphology and accommodation space to preserve it.
Sediment Continuity Equation

- Unit volume conserves mass
- Simplify multipartite to “bi-partite flow”
- Addition or removal of sediment measured by change in two regions:
  - Granular layer
  - Suspended layer
y = high concentration granular layer thickness Non-newtonian

\( dx \) = area of unit volume width and length parallel to flow

\( \phi \) = porosity (pore space)

\( C \) = sediment concentration > 9% by volume

\( h \) = thickness of suspension cloud \((h-y)\)

\( dq_s \) = difference in sediment flux across unit volume \(((q_s)2 - (q_s)1)\) Newtonian

\( dy \) = change in layer thickness from deposition and/or erosion in unit volume
Sediment Continuity in Bi-partite Turbidity Current

1. \( \frac{dy}{dx} = -\frac{1}{1-\varnothing} (dq_s) \frac{dt}{dx} \)  
   Sediment thickness and porosity change across flow volume

2. \( \frac{dy}{dx} = -\frac{1}{1-\varnothing} (h \frac{dC}{dx}) \frac{dx}{dx} \)  
   Accounts for concentration change

3. \( \frac{dy}{dt} = -\frac{1}{1-\varnothing} \left( \frac{dq_s}{dx} + h \frac{dC}{dt} \right) \frac{8 \sin a}{f_0 + f_i} \)  
   Bed elevation change over time

8 \sin a = Chezy modified gradient  
\( f_o \) = friction at base of flow  
\( f_i \) = friction at top of flow
Turbidity Current Momentum

\[
dqs = T_m \quad \text{Turbidite momentum}
\]

\[
(T_m)_1 \pm dy = (T_m)_2
\]
Multpartite Turbidity Current Conserves Mass and Momentum in Open System

\[(T_m)_1 \pm dy = (T_m)_2\]

- \(y\) = high concentration granular layer thickness
- Non-newtonian
- \(dx\) = area of unit volume width and length parallel to flow
- \(\varnothing\) = porosity (pore space)
- \(C\) = sediment concentration > 9% by volume
- \(h\) = thickness of suspension cloud \((h-y)\)
- \(dq_s\) = difference in sediment flux across unit volume \(((q_s)_2 - (q_s)_1)\) Newtonian
- \(dy\) = change in layer thickness from deposition and/or erosion in unit volume

1. \(\frac{dy}{dx} = -\frac{1}{1-\varnothing} \left(\frac{dq_s}{dt}\right)\) Sediment thickness and porosity change across flow volume
2. \(\frac{dy}{dx} = -\frac{1}{1-\varnothing} (h \frac{dC}{dx})\) Accounts for concentration change
3. \(\frac{dy}{dt} = -\frac{1}{1-\varnothing} \left(\frac{dq_s}{dx} + h \frac{dC}{dt}\right) \frac{8 \sin a}{f_0 + f_i}\) Bed elevation change over time

8 \(\sin a\) = Chezy modified gradient
\(f_0\) = friction at base of flow
\(f_i\) = friction at top of flow
Multipartite Turbidity Current Conserves Mass and Momentum in Open System

\( (T_m)_1 \pm dy = (T_m)_2 \)

\( \sin a \)

\( y = \) high concentration granular layer thickness Non-newtonian
\( dx = \) area of unit volume width and length parallel to flow
\( \phi = \) porosity (pore space)
\( C = \) sediment concentration > 9% by volume
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\( dq_s = \) difference in sediment flux across unit volume \(((q_s)_2-(q_s)_1)\) Newtonian
\( dy = \) change in layer thickness from deposition and/or erosion in unit volume

1. \( \frac{dy}{dx} = -\frac{1}{1-\phi} (dq_s) \frac{dt}{dt} \) Sediment thickness and porosity change across flow volume
2. \( \frac{dy}{dx} = -\frac{1}{1-\phi} (h \frac{dC}{dx}) \) Accounts for concentration change
3. \( \frac{dy}{dt} = -\frac{1}{1-\phi} \left( \frac{dq_s}{dx} + h \frac{dC}{dt} \right) \frac{8 \sin a}{f_0 + f_i} \)
   - Bed elevation change over time
   - \( 8 \sin a = \) Chezy modified gradient
   - \( f_0 = \) friction at base of flow
   - \( f_i = \) friction at top of flow
Cumulative Gradient Interacts with Turbidite Momentum to Generate Mass Dispersion

A. Sediment Continuity Equation for Multipartite Turbidity Current ($S_e$)

1. $\frac{dy}{dx} = -\frac{1}{1-\phi} \frac{d(q_s)}{dt}$
   - Sediment thickness and porosity change across flow volume
   - $y =$ sedimentation layer thickness from seafloor
   - $d_y =$ high concentration granular layer thickness
   - $dx = $ area of unit volume width and length parallel to flow
   - $\phi = $ porosity (pore space)
   - $C = $ sediment concentration $> 9\%$ by volume

2. $\frac{dy}{dx} = -\frac{1}{1-\phi} \frac{dC}{dx} \frac{dy}{dt}$
   - Accounts for concentration change
   - $h = $ thickness of suspension cloud ($h_y$
   - $d(q_s) = $ difference in sediment flux across unit volume

3. $\frac{dy}{dt} = -\frac{1}{1-\phi} \left( \frac{d(q_s)}{dx} + h \frac{dC}{dt} \right) \frac{8 \sin \alpha}{f_0 + f_f}$
   - bed elevation change over time
   - $8 \sin \alpha = $ Chezy modified gradient
   - $f_f = $ friction at base of flow
   - $f_f = $ friction at top of flow

B. Cumulative Gradient ($G_5$)

Cumulative gradient sums five gradients operating at different scales illustrated in diagram of deepwater system. They bridge the gap between tectonic orders of deformation and the hierarchy of stratigraphic cycles modulating sedimentary responses to the following gradients:

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5. **instantaneous down-flow gradient** affects turbidity current momentum and turbulent suppression promoting transformation.

$$\int_{10^6}^{10^3} \frac{\partial x_1}{\partial t} dt + \int_{10^5}^{10^2} \frac{\partial x_2}{\partial t} dt + \int_{10^3}^{10^1} \frac{\partial x_3}{\partial t} dt + \int_{10^2}^{10^4} \frac{\partial x_4}{\partial t} dt + \int_{10^2}^{10^4} \frac{\partial x_5}{\partial t} dt$$

- $x = $ down-profile distance
- $\delta x = $ change in down-profile distance
- $y = $ cross-profile distance
- $\delta y = $ change in cross-profile distance
- $z = $ elevation
- $\delta z = $ change in elevation

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*Source: [Nature](https://www.nature.com)*
Sedimentary Pattern Rule

\[ MD = \frac{G_5 \cdot S_e}{dt} \]

Cumulative gradient and turbidite momentum account for energy and mass and are principle components of mass dispersion in deepwater systems.

Scale-invariant principle components predict across scale, while honoring scalar limits of process-response relationship described by parameters limited by scale.

So What-How does this or will it impact the bottom line?
Presenter’s Notes: Different contributions from the same parameters produce different sedimentation patterns. These pattern and process changes reflect the modulation of system energy that can be categorized in a SSEM. The sedimentary system energy matrix (SSEM) summarizes the paleogeographic (gradient) and stratigraphic (AIGR) controls on deep-water sedimentary architecture as illustrated with examples from the sandstone-rich Brushy Canyon Formation. The axes of the matrix show temporal and spatial changes in system (notes continued on next slide).
energy defined by grain size and erosion. The energy conditions recorded at a particular profile and gradient position during a specific energy phase generates variations in sedimentary architecture depicted in the matrix and normalized to a channel fairway position.

Because the patterns in the SSEM are embedded with predictive rules (e.g., gradient rule in Slide 48), and the rules with parameters (Slide 47), the SSEM forms the starting point for detailed interrogation of a set of subsurface observations leading to interpretation and prediction. Together these energy matrices describe changes occurring across a range of scales that span a single sedimentation event to the creation of an entire submarine fan.
Pattern Rule Emphasizes Scales of Sedimentary Attributes Required for Stratigraphic Prediction

**Increasing dimension and composition of sedimentary attributes**

**Process Facies**

- Turbidite Bowna Divisions:
  - Te
  - Td
  - Tc
  - Tb
  - Ta

- Energy conditions at deposition:
  - Grain size
  - Fabric
  - Primary structures
  - Texture
  - Bounding surfaces

- Estimate flow size as proxy for:
  - Event magnitude
  - Event duration
  - Longitudinal flow structure
  - Process facies duration in bedform stability field

**Sedimentation Units** (facies succession)

- Channelform
  - 100 x 300 x 15 m
  - 5 x 10
  - 5 x 10 x 10

- Wedgeform
  - 60 x 200 x 5 m

- Lobiform
  - 300 x 800 x 5 m

- Drape
  - km x km x 2 m

**Sedimentary Bodies**

- 1D — facies association
- 2D — shape
- 3D — macroform

**Stratigraphic modulation**

- Threefold hierarchy is minimum requirement for deconvolution of stratigraphic amplitude created by different frequency cycles

- Sedimentary system energy derived from many Earth surface processes combine to create depositional episodes

**Response**

- Sedimentary bodies (architectural elements) reflect state of confinement:
  - Type
  - Stacking pattern
  - Trajectory
  - Placement
  - Neighbors
  - Fill

- Sedimentary attributes in sedimentary pattern:
  - Process facies
  - Sedimentation unit
  - Sedimentary body
Presenter’s Notes: The SSEMt can be filtered into component architectural element plots that feature and emphasize changes in the dominant sedimentary bodies. In the case of deep-water systems, channelforms and lobeforms are the two most common sedimentary body types. By highlighting the channel and lobe elements in each body pattern in the matrix, the dominant formative processes are more directly related to the sedimentation pattern. These SSEMs can also be used to predict facies distributions. The elemental sedimentary system energy matrix summarizes the paleogeographic (gradient) and stratigraphic (AIGR/BCFS) controls on submarine channel and distributary channel and lobe and ponded sandstones that stack to form continuous sheet-like architectures. The combination of energy conditions recorded at a particular profile and gradient position determine different channel and sheet architectures.
Impediments to Stratigraphic Prediction

• Correlation is not causality, but causality required for prediction
• Spatial limits to correlation of sedimentary attributes because sedimentation in neither constant nor continuous—*material and non-material representation of linear geologic time*
• Complex feedback responses and buffers—*generate co-variance among sedimentary attributes*
• Non-unique and non-linear process variation impedes deconvolving composite energy signal into independent variables—*one process can generate multiple responses, and multiple processes can generate similar response*
• Definition of initial boundary conditions—*creates pattern variation*
• Deposition and preservation contribute to preserved sedimentary response—*limiting sedimentological prediction*
• Incomplete representation of sedimentary system—*fragmented outcrops rarely preserve source to sink components*
• Geologic time preserves order of magnitude differences in sedimentary process—*problem with comparison of modern and ancient systems*
Presenter’s Notes: Reflecting the geomorphic terrains they generate, all sedimentary systems are governed by site-specific processes that determine deposition and preservation. The challenge is separating these local processes, which can be unique to a place and time, from the more general system response and behavior. The list of parameters in Slide 47 is considered inclusive and fundamental to the generation of deep-water sedimentary architecture. This list of formative process parameters is also applicable to other environments of deposition on Earth. (notes continued on next slide)
These parameters combine to describe sedimentary system behavior. For example, it is well known that shelfal accommodation is a composite response to eustatic, tectonic, and sediment supply controls on shallow marine sedimentation on the shelf (Mitchum, 1985; Jervey, 1988; Vail, 1987). In this well-studied shallow water example, no single parameter, i.e. eustasy, controls shelfal accommodation. This example also illustrates how the composite effect that results from combining different parameters generates variations in sedimentary architecture.

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Geologic rules are generated through observation, parameter correlation, and verification. Rule development uses a family of deterministic outcrop and subsurface datasets to extract and describe the most common sedimentation patterns. The rules are logic statements that define how parameter trends combine to produce different deepwater sedimentation patterns (Slide 44). Rules and their associated parameters are cross-tested against various datasets to capture the range of variations for a particular sedimentation pattern.

A geological rule utilizes physical laws to describe repeatable outcrop-derived empirical relationships defined by two or more parameters (system inputs) for probability-based, subsurface geologic prediction of sedimentary architecture.
Presenter’s Notes: Hemipelagic mudstone: Lower values in ash material as Kaolinite, Montmorillonite, Muscovite, and Zeolite. Higher values in high specific gravity minerals like: zircon, hornblende, dolomite, K-feldspar, and biotite. Clay fabrics controlled by flocculation processes that generate disorganized structures recognized at scales smaller than 10 microns. Shear velocity within the turbiditic flow allows transport of suspended grains with a higher specific gravity. (notes continued on next slide)
Pelagic mudstone: Higher values in ash material as Kaolinite, Montmorillonite, Muscovite, and Zeolite. Lower values in high specific gravity minerals like: zircon, hornblende, dolomite, K-feldspar, and biotite. Clay fabrics are controlled by dispersion processes that generate organized structures recognized at scales smaller than 10 microns. Setting velocity dominates within the pelagic mud deposition, suspension fallout is mainly controlled by dispersion forces due to the high polar activity of the clay minerals and low shear velocities that suppress transport of suspended grains with a high specific gravity.
Sedimentation Response to Local Gradient Developed by Seafloor Deformation

- W. Africa seismic architecture reflects LOCAL gradient change
- Adjustment defines stratigraphic changes in architecture & orientation

Presenter’s Notes: Comparison of deep-water profile across simple longitudinal profile of recent Amazon Fan and stratigraphic evolution of seismic architecture related to development of local topography and gradient associated with deformational outbuilding of West African continental margin. (notes continued on next slide)
Individual Amazon channel-levee systems tend to stack laterally and/or vertically into larger complexes (Flood et al. 1991; Piper and Normark, 2001). The modern Amazon Fan and BCE sixth-order elements show comparable durations, similar stacking patterns, body types and areal distributions. Differences are related to the higher sedimentation rates in the Amazon fan system. The consistent lobe-channel-levee seismic architecture observed within the modern Amazon and Zaire Fans and West African subsurface datasets reflects a common pattern. Evolving seabed topography and gradients are related to the combined effect of basin-margin adjustment/deformation and sediment deposition. This produces long-term patterns of lobe and channel-levee distributions that record a progressive increase in local topographic relief and gradient related to the basinward migration of compressional fold belts.
Statistical Analysis of Turbidite Events, middle Sites Mbr. at Cache Creek

- Red = SU thickens up
- Blue = SU thins up
- Gray = no change in thickness

Stratigraphic Modulation of Turbidite Bed Thickness (delta), middle Sites Mbr. at Cache Creek

Murray (1992)
Stratigraphic Modulation of Turbidite Bed Thickness (delta), from lower Sites Mbr. at Cache Creek

Murray (1992)
Stratigraphic Modulation of Turbidite Bed Thickness (delta), Lower Sites Mbr. at Cache Creek

Chester (1993)
Auto-correlation of increasing-decreasing energy trends as measured by turbidite bed thickness (delta)

- $\Delta$ Average $\sim 0$
- For every increase/decrease, there is an equal and opposite delta:
  - Majority of the time immediately afterward
  - Interpreted by Murray/Chester as ‘noise’
Presenter’s Notes: Reflecting the geomorphic terrains they generate, all sedimentary systems are governed by site-specific processes that determine deposition and preservation. The challenge is separating these local processes, which can be unique to a place and time, from the more general system response and behavior. The list of parameters in Slide 47 is considered inclusive and fundamental to the generation of deep-water sedimentary architecture. This list of formative process parameters is also applicable to other environments of deposition on Earth. (notes continued on next slide)
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_A geological rule utilizes physical laws to describe repeatable outcrop-derived empirical relationships defined by two or more parameters (system inputs) for probability-based, subsurface geologic prediction of sedimentary architecture._
Complications and Challenges

- Correlation is not causality, but causality required for prediction
- Spatial limits to correlation of sedimentary attributes because sedimentation in neither constant nor continuous over time — material and non-material representation of linear geologic time
- Complex feedback responses and buffers generate co-variance among sedimentary attributes
- Non-unique and non-linear process variation impedes deconvolving composite energy signal into independent principle components—one process can generate multiple responses, and multiple processes can generate similar response
- Initial boundary conditions create pattern variation
- Deposition and preservation contribute to preserved sedimentary response limiting sedimentological prediction
- Geologic time preserves order of magnitude differences in sedimentary process

Presenter’s Notes: Reflecting the geomorphic terrains they generate, all sedimentary systems are governed by site-specific processes that determine deposition and preservation. The challenge is separating these local processes, which can be unique to a place and time, from the more general system response and behavior. The list of parameters in Slide 47 is considered inclusive and fundamental to the generation of deep-water sedimentary architecture. This list of formative process parameters is also applicable to other environments of deposition on Earth. (notes continued on next slide)
These parameters combine to describe sedimentary system behavior. For example, it is well known that shelfal accommodation is a composite response to eustatic, tectonic, and sediment supply controls on shallow marine sedimentation on the shelf (Mitchum, 1985; Jervey, 1988; Vail, 1987). In this well-studied shallow water example, no single parameter, i.e. eustasy, controls shelfal accommodation. This example also illustrates how the composite effect that results from combining different parameters generates variations in sedimentary architecture.

Because a common set of deepwater analog patterns emerge from the multiple outcrop and subsurface examples now documented in the GAIA project, it is likely that a common set of formative processes are responsible for this repetition. If this is true, then these patterns can be defined and described by their formative parameters. This is the idea behind formulating logic statements (rules) from formative parameters to define the sedimentary architecture of a pattern.

Geologic rules are generated through observation, parameter correlation, and verification. Rule development uses a family of deterministic outcrop and subsurface datasets to extract and describe the most common sedimentation patterns. The rules are logic statements that define how parameter trends combine to produce different deepwater sedimentation patterns (Slide 44). Rules and their associated parameters are cross-tested against various datasets to capture the range of variations for a particular sedimentation pattern.

A geological rule utilizes physical laws to describe repeatable outcrop-derived empirical relationships defined by two or more parameters (system inputs) for probability-based, subsurface geologic prediction of sedimentary architecture.