Applying Deltaic and Shallow Marine Outcrop Analogs to the Subsurface

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Outline

• Problem
• Shorefaces versus Deltas
• Facies Architecture
• Subsurface Correlations
• Conclusions
Problem

• How to correlate regional or field-wide “deterministic” elements in subsurface data?
  – Well logs

• How do we capture effects of complex 3D Facies Architecture in reservoir models.
  – Reservoir modeling/Well Log Correlation

• How to interpret reservoir geometry in 3D Seismic data?
  – Seismic geomorphology
Solution

• Requires a conceptual framework for geological interpretation
  – Facies models
  – Sequence stratigraphy

• Need “training” data sets
  – Outcrops
  – High resolution seismic
    • e.g. Anderson and Fillon (2004)
  – Theoretical (numerical) models
    • e.g. Thorne et al. (1991)
Solution

- Requires a conceptual framework for geological interpretation
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Deltaic Facies Models

• Had their heyday in the late 70’s
  – Galloway Triangle

• 80’s and early 90’s research largely focused on regional-scale sequence stratigraphy.

• Late 90’s considered as non-essential (cloud-technology) by some major’s.
Deltaic Facies Models

- Deltaic reservoirs still important?
  - GOM Shelf; North Slope, Alaska; Offshore Trinidad; Nigeria; Angola; Venezuela; Alberta Basin; offshore Canada; Mackenzie Delta; Onshore USA; Siberia; Sakhalin and many others.

- Are existing facies models adequate to predict production and exploration of shelf reservoirs?
  - I am hearing a resounding NO!

(From N. Tyler 1988)
Delta Front Facies Models

- Deltas are fundamentally regressive and build upward-coarsening facies successions.

modified after Scruton, 1960
Most shoreface models require presence of Hummocky Cross Stratification (Walker and Plint, 1992).
Amalgammated hummocky beds with climbing wave-ripples and *Skolithos* burrows.

Low degree of burrowing in background mudstones
Ichnology can be used to distinguish Prodelta vs. Shelf Mudstones

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

**Deltaic**

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

**Non-deltaic**

Distinguishing fluvial influence

Wave-influenced deltaic

Below shoreface

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

More highly burrowed shelf mudstones, Cretaceous Dunvegan Formation, Alberta.
Shorefaces (wave-dominated) also show upward coarsening facies successions

- Shoreface-model is heavily biased towards the storm-dominated (HCS) examples in the Cretaceous Interior.
- Are these shorefaces, delta fronts, or both?
Shorefaces versus Storm Beaches

- The shoreface is a fairweather feature made by swell waves, not storm waves.
  - Seaward-dipping profile that forms in response to the asymmetry of shoaling waves.
  - HCS beds are interpreted to represent preservation below fairweather wave-base.

Walker and Plint, 1992
Shorefaces versus Storm Beaches

- Storms are destructive
  - tend to remove sediment from the shoreline
- Storms also cause river floods (hyperpycnal conditions).
- Why should any fairweather shoreface be also storm-dominated?

Walker and Plint, 1992
Delta Front Facies Successions

- Shorefaces and delta fronts supposedly have different sand-body geometries and different internal facies heterogeneties.
- Very different reservoir behavior.
- Can they be distinguished in ancient examples?
Outcrop Analogs

- Cretaceous Foreland Basin of North America hosts numerous superb exposures of prograding “shelf” sandstones.
- Natural laboratory for determining 3D vertical and lateral facies relationships (Facies Architecture).
Gallup Sandstone - New Mexico

- Stacked Upward coarsening faces at Parasequence Point, near Shiprock, NM.
- Historically interpreted as “classic” wave-dominated shorefaces.
Basal facies are heterolithic, largely unburrowed and show a fluvial stress.
Gallup Sandstone - New Mexico

- Sandstones show Bouma $T_{abc}$ sequences.
- Stressed ichnofauna.
- Indicate river-fed, delta front turbidites.
  - Possibly hyperpycnal flood deposits.
- Facies suggest a fluvial-influenced delta front, versus a wave-dominated shoreface.
Site 2. Gallup Sandstone - New Mexico

- Dipping clinoforms
Site 2. Gallup Sandstone - New Mexico
Gallup Sandstone - New Mexico

- What does delta correlate with?
- Where are “classic shorefaces”?
  - View along cliff shows that “heterolithic” sandstones dive under massive, cliff-forming sandstones.
  - Let’s look at these!
Gallup Sandstone - New Mexico

View of massive, cliff-forming sandstones.
These looks more like a classic upward-coarsening “shoreface”.
• basal heterolithics are pervasively bioturbated (commonly taken to imply wave-dominated).
Gallup Sandstone - New Mexico

- *Ophiomorpha* burrowed sandstones pass upward into cross bedded sandstones.
- HCS is not particularly dominant.
Let’s look at a facies model that links shorefaces and deltas.
Facies Model: Asymmetric Wave-Influenced Deltas

- Danube
- Brazos
- Guadiana (Iberia)
- Damietta Branch of Nile

Bhattacharya and Giosan, 2003
Possible Ancient Examples

• Gallup sandstone in New Mexico previously interpreted as a wave-dominated barrier-lagoon system (McCubbin, 1982).

• Asymmetry may suggest that barrier-lagoons are components of a larger asymmetric delta.

• This asymmetry is suggested in outcrops at Shiprock (Green Lifesaver).

McCubbin, 1982
Facies architecture of an asymmetric delta

- **Clean sands updrift**
  - Potentially sharp-based shoreface deposits.
- **Heterolithic facies downdrift**
  - May include river and wave successions

Bhattacharya and Giosan, 2003
Delta Front Facies Successions

- Our new model suggests how river and shoreface deposits are linked in major coastal prograding systems.
- Model has recently been applied to Book Cliffs successions in Utah (Hampson and Howell, *in press*).
- Looks applicable to Gallup sst. in New Mexico.

Could you see this in a seismic slice or horizon map?
Facies Architecture

- Applied to continuous outcrops (Bedding Diagrams).
- Hierarchy of architectural elements well established for fluvial systems.
  - Channel Belts
  - Channels
  - Bars (macroforms)
  - Bedforms
  - Shale elements
- Architectural element analysis also well established for deep water and aeolian systems.
- Very poorly elucidated for shallow marine and deltaic deposits.
- Key area of research that bridges gap between sequence stratigraphy and facies analysis.
- Emphasis on bounding surfaces.
- Critical for reservoir characterization.

Fig. 4.2. The scales of depositional elements in a fluvial system, showing the bounding-surface hierarchy (Table 4.2). Circled numbers indicate the ranks of the bounding surfaces. In (c), the two-letter codes are for architectural element types (Table 4.3). In (d), the sand flat is shown as being built up by migrating nations of these are shown internal cross-bedding that clarity

after Miall, 1985
Delta front Clinoforms

Cretaceous Wall Creek Sst, Wyoming

Pennsylvanian, Taos Trough, New Mexico

Cretaceous Frewens sst., Wyoming
GPR versus Photomosiac

Dipping delta front foresets visible in photo and GPR data
Delta Front Facies
Cretaceous Wall Creek member
Frontier Formation, Wyoming

In 1D, Wall Creek consists of vertically stacked upward-coarsening bedsets.

Delta front facies.

Heterolithic facies at base (prodelta)
Burrow in successive beds within bedset indicates very rapid sedimentation rates.
Graded beds indicate delta front turbidites.

Cretaceous Wall Creek sandstone, Wyoming.
GPR versus Photomosiac

3D reconstruction of foreset beds
Raptor Ridge Site:
Fluvial-Tide influenced delta front
Raptor Ridge data set

- 2D and 3D GPR grids
- 10 cores (porosity, permeability, gamma)
- 20 outcrop sections
- Photomosaics
Facies Succession
Channel Facies
Channel Facies

Sharp-based with mud chips
Landward accreting graded beds
Mouth Bar Facies

Seaward accreting tidally-modified mouth bars
Abundant mud drapes = Tidal Bundles
Tidal Bar Facies

Herringbone cross bedding = Tidal
• Tidally reworked mouth bars are associated with fluvially-derived frontal splays and possibly hyperpycnal channel deposits.
Flow Grid Description and Grid Selection

- **Cornerpoint flow grid**
  - The 14 radar interpreted stratigraphic surfaces construct a cornerpoint flow grid.
  - Stratigraphic surfaces are interpolated in accord with the geologic conceptual model.

Tang and White, 2005
SGBSIM Modeling Results

Concretion Geostatistical Modeling

Base case

No trend

1.5 times more concretion

Half range

Base case 3D

No trend and Half proportion 3D

Tang and White, 2005
Imposing the trend deforms the flow front and retards the breakthrough.

Tang and White, 2005
3D Flow Simulation

Designed Flow Simulation

- In three dimensions, only flow direction is highly significant.
  - Concretions have fewer significant effects on 3D flow than on 2D flow, especially for the factor ranges that appear reasonable at the Raptor Ridge locality.

Tang and White, 2005
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Bedding geometry in seismic data

- Quaternary Rhone deltas show seaward dipping bedding geometry.

Tesson et al., 1990
Delta front Clinoforms

Cretaceous Wall Creek Sst., Wyoming

Pennsylvanian, Taos Trough, New Mexico

Cretaceous Frewens sst., Wyoming
Delta front Clinoforms

Cretaceous Wall Creek Sst., Wyoming

Pennsylvanian, Taos Trough, New Mexico

Diachronous, “Shazam” boundary between sandy delta front and muddy prodelta facies

Cretaceous Frewens Sst., Wyoming
Layer-Cake facies in the Mekong

Ta et al. 2002
Re-correlation of Mekong Facies

Beds follow time lines.
Facies dislocate along beds.
Layer-Cake Facies of Mekong Delta

Ta et al., 2002
Re-correlation of Mekong Facies

Beds follow time lines.
Facies dislocate along beds.
Layer-Cake vs. Clinoform correlations in subsurface

- Sikrit Field, Thailand
- Ainsworth et al., 1999
How to correlate wells?

- Dip-section, Wilcoxin Sandstone, GOM
How to correlate wells?

- Lithostratigraphic Correlation
  - Simple intertonguing
  - No emphasis on key-surfaces
How to correlate wells?

- Sequence stratigraphic correlation

Diagram:
- Flow unit 1
- Flow unit 2
- Flow unit 3
- Flow unit 4a
- Flow unit 4b
- Flow unit 5
- Shale Barrier

Legend:
- FEET
- MILES 0 5
How to correlate wells?

- Lithostratigraphic Correlation
  - Simple intertonguing
  - No emphasis on key-surfaces
How to correlate wells?

- Sequence stratigraphic correlation

Datum disappears

Beds dip seaward
Romeo Equity Zone Stratigraphy

Lithostratigraphic Cross section across Prudhoe Bay Field, Alaska

Tye et al. (1999)
Well 09-35A Additional Recovery

09-35A

09-35

700 foot Slotted Liner

GR

SONIC

RILD

09-35 Conventional Completion

No Production in 09-35: 100% Production in 09-35A

09-35 & 09-35A Oil and Water Production (BBLs/Day)

Tye et al. (1999)
Conclusions

• Depositional environments and systems are not mutually exclusive!
• Deltas and shoreface deposits are linked in many major wave-influenced prograding coastal systems.
  – Looks applicable to ancient systems.
Conclusions

- Outcrop analogs help guide regional and field-scale correlations.
  - Get away from the layer-cake.
Conclusions

• 3D outcrop analogs useful in reservoir characterization.
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