Deep-water Sedimentary Processes and Systems: The Role of Internal vs. External Controls on Lithology Distribution and Stratigraphy*

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Abstract

The understanding of deep-water sedimentary processes and systems has developed considerably since Kuenen and Migliorini’s (1950) first publication on the origin of turbidity currents. Still, their primary methods of investigation, flume studies and outcrop work in the Apennines, are still very valid methods today, although new technology has allowed for more accurate assessment of flow parameters, resulting sedimentary architecture and the role of external controls on deposits. Not the least have 3D seismic and the study of modern and sub-modern deep-water sedimentary systems with shallow seismic and side-scan sonar been instrumental in capturing new data and insight to allow for a better understanding.

A debate that is still highly active today is the relative role of intrinsic/autocyclic vs. extrinsic/allocyclic mechanisms on flows and sedimentary architecture. Flow processes vary from dilute, bottom-hugging currents through “normal” turbidity currents to huge mass-transport events several 1000s of km³ in scale. Even though the effects of these processes may be considered intrinsic to the deep-water sedimentary system, the causes of such events are usually extrinsic. In such a respect deep-water sedimentary systems are different from most other sedimentary systems because their deposits are dominated by events representing relatively short time periods. In most other sedimentary environments, the deposits record longer time intervals.

Although the range of external controls, such as sea level change, climate and various types of tectonics, is relatively clear, their relative roles in time and space are uncertain, even in many modern and sub-modern systems. Across small areas, the relative roles of external factors may vary significantly, and it is of utmost importance to analyse each system independently. While previously there was a bias towards understanding deep-water sedimentary systems based on local factors, recent insight into sub-modern and modern systems has shown that changes even at process level in deep-water sedimentary systems are driven by extrinsic factors in the ultimate onshore sediment source area. A complete understanding of deep-water sedimentary systems must involve analysis of updip onshore drainage and the adjacent shallow-marine and slope systems. This complicates analysis of deep-water sedimentary systems at outcrop and ancient systems, where commonly
only system remnants are preserved. In addition, another complication involves the question of uniformitarianism: how analogous are current and sub-modern deep-water sedimentary systems to ancient systems?

References


**Websites**


Deepwater Sedimentary Processes and Systems:

The Role of Internal vs. External Controls on Lithology Distribution and Stratigraphy

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Roy M. Huffington International Distinguished Lecturer 2009-2010
Contents

• Challenge: why worry about external controls?
• Processes and external controls
• Previous models
• The Complete Context and Method
  – Source-to-Sink
• Case studies
  – Testing the Method
• Applications
The challenge: why worry about external controls?

• Deep-water sedimentary systems are exceptionally sensitive to changes in sediment supply driven by hinterland controls.
Prediction for subsurface success, but challenge of incomplete systems

Deep-water submarine fan with oil

Jackson et al. (2008)
Technology significance:
Refine seismic for best imaging
Processes and external controls
Sea-floor processes

- Abandoned channel
- Creep and pock-marks
- Sediment waves on the side of levee or creep
- Salt related feature
- Stepped channel floor
- Slump
- Slump deposits
- Straight debris flow channel
- Buried salt diapir
- Thalweg more sinuous than channel form

Image courtesy of Jez Averty
Depositional processes and external controls

Outcrop work is essential to understand subsurface processes and architecture

Martinsen (1994), originally from Nemec (1990)
Subsurface expression of debris flow

Photo by R. Walker
Cretaceous, North Sea
Outcrop expression of debris flow

Eocene, S. Llorenç del Munt, Spain
Seismic expression

- Grooved bases
- Low sinuosity channels
- Matrix-supported texture
- Long run-out distances?
- Hummocky topography

Image courtesy of Kristina Bakke
Near Sea Floor, West Africa

Channel-levee system

Condensed section

Image courtesy of Kristina Bakke

MTC

Horizon | Color
---|---
KB_Seafloor 1 | Purple
KB_Seafloor_Base | Yellow
KB_Interphase | Green
KB_BaseDebris | Blue

Image courtesy of Kristina Bakke

Education
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Image courtesy of Kristina Bakke

1Km

Image courtesy of Kristina Bakke

1Km

Statoil
Active sedimentation at low sea level

Abandonment and reoccupation

Late stage: low or rising sea level with channel-levee system

Middle stages: lobate/tabular sands

Initial stage: debris flows at falling sea-level

Gjelberg et al. (2001)
Amazon Fan Pleistocene Cyclicity

Channel fill
Levee
MTC
Recent drape
HARPS
Seismic courtesy of ANP
General model: but beware of local controls!

Walker (1992)
Models and external controls
Previous templates for external controls

- Previous templates focused on only few critical factors for deep-water deposition
- On each margin, only a few factors dominate
  - Vary in time and space from basin to basin
- Are deep-water systems models useful at all?
- Need to consider using different and more complete templates

Modified from Reading and Richards (1994)
Template 1:
Submarine Fan Length Vs. Deposition Rate

Fan size vs. deposition rate
(proxy for sediment supply
and source area size)

Deltaic vs. estuarine-canyon source

Modified from Wetzel (1993)
Template 2: Grain Size Vs. Feeder System

Type of feeder system

Point  Ramp  Line

Sediment caliber

Mud  Sand  Gravel

Modified from Reading and Richards (1994)
Template 3: climatic controls

From Castellort et al. (2003)
Template 4: Slope accommodation

- Smooth slopes (no topography)
- Slopes with topography
  - Continuous or discontinuous

Images from: http://www.ldeo.columbia.edu
Complete source-to-sink approach

Sømme et al. (2009)
Congo River drainage and Gulf of Guinea example

Total sediment accumulation

Leturmy et al. (2003)
Segments and impact on deep-water sedimentation and systems
Morphological approach: linked segments

Can information from one segment provide quantitative information about other segments?

Sømme et al. 2009 (Basin Research)
Source/drainage systems: useful for deep-water exploration?

Dendritic  Parallel  Rectangular  Radial
Trellis  Centripetal  Deranged

http://www.uwsp.edu/geo/faculty/ritter/geog101/textbook/fluvial_systems/drainage_patterns.html
East African drainage systems

Rovuma
Mualo
Lurio

Courtesy of John Thurmond
Role of shelf in geological time

Sømme et al. (2008)
Are modern (Plio-Pleistocene) shelf environments analogues for ancient systems?

Sømme et al. (2009)
Shelf storage

- Shelf storage increases with system size
- Submarine canyons efficiently bypass sediment

Sømme et al. (2009)
Shelf accommodation and icehouse-greenhouse times

- Decreasing eustatic amplitudes result in:
  - shallower shelf platform
  - lower shelf accommodation and more rapid transit times
  - higher possibility for highstand shelf edge deltas
  - higher impact of tectonics and sediment supply

Sømme et al. (2009)
Shelf width, morphology and timing of sediment transport to deep-water

National Geographic Map

Education
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Timing and spatial partitioning of deep-water processes, sediments and surfaces

Courtesy of W. Helland-Hansen
Shelf morphology and transport
Shelf morphology, processes, deep-water supply at highstand

Boyd et al. (2008)
Canyon variability: role of shelf incision

Piper (2006)
Slope accommodation

• Smooth slopes (no topography)
• Slopes with topography
  – Continuous or discontinuous

From Prather (2003)

Images from: http://www.ldeo.columbia.edu
Modern slope morphology (1)

A: New Jersey margin

B: Florida escarpment: carbonate platform

Images from: http://www.ldeo.columbia.edu
Modern slope morphology (2)

C: Central Gulf of Mexico
D: Offshore California

Images from: http://www.ldeo.columbia.edu

Sediment transfer from shelf to slope at highstand (narrow shelf)
Modern slope morphology (3)

E: Offshore Oregon

Sediment transfer through slopes?

Image from: http://www.ldeo.columbia.edu
Case: Ormen Lange fan
Complete source-to-sink approach

Sømme et al. (2009)
North Atlantic Location Map

- Present-day bathymetry
- Greenland
- Spitsbergen
- Barents Shelf
- Vøring Basin
- Iceland
- Møre Basin
- Mid-Atlantic Ridge
- Norway
- UK North Sea Basin
Geological Setting

- Møre and Vøring Basins formed in early Cretaceous time on continental crust
- Present oceanic fracture zones line up with Greenland fjords
- Basin configuration influenced by Jurassic and older extensional structures
  - Wide vs. narrow shelf areas
- Jurassic structural relief caused influence on Palaeocene sedimentation because of compaction of generally fine-grained Cretaceous sediments
- Focus on narrow paleoshelf areas
Paleocene Offshore Mid-Norway

Deep-water Paleocene sandstone controlled by underlying structure

Cenozoic

Base Paleocene

Cretaceous

Lower Cretaceous fills Jurassic basins

Jurassic high

Section

25 km

1500 msec

Paleocene sandstone fills Jurassic basins controlled by underlying structure.
Paleocene Offshore Mid-Norway

- Small drainage systems controlled by Paleozoic basement structures
- Narrow shelf inherited from Jurassic
- Intraslope basins controlled by differential subsidence between draped Jurassic highs
- Sand-rich, small turbidite system

Martinsen et al. (2002)
Ormen Lange: Basin Floor

- Continuous sandier-upward succession from Cretaceous to Paleocene
- Older than basin margin deposits
- Sheet- and channelized turbidites in a sand-rich fan
- Beds <1.5 m in thickness
1st order topography: age and role?

Modified from Lidmar-Bergstrøm & Näslund (2002)
Source area: preserved topographic elements

Martinsen & Nøttvedt (2006)
Sømme et al. (2009)
Drainage area and fan size: inversion

~1700 km²

Tor Sømme (2009)
Database

- 29 modern or sub-modern systems
- Varying margin types in varying climatic zones (non-glacial)

Sømme et al. 2009 (Basin Research)
Analysis from global data

- Data from 29 sub-modern systems
  - Slope length: ~5-15 km
  - Water depth: 1000-2000 m
  - Drainage area: ~20 000 km²
  - Longest river channel: ~200 km

Source: Sømme (2009)
Inversion: results

~1700 km²
Narrow shelf (5-15km), short slope (~20km)

~15 000 km²
Paleo-topography reconstruction from local & global data

Reconstructed profile (dashed; from map) and corrected for uplift (solid line) and compared small fans in tectonically active regions

Reconstruction of paleic terrain (from Sømme et al., 2009; based on Nesje, 2007)
Applications and conclusions
Prediction of reservoir presence and quality
Complete systems

Sømme et al. (2009)
Source-to-Sink vs. Sequence Stratigraphy
Complementary approaches to predict sediment partitioning

- Holistic basin analysis
- Process-oriented
- Integration of earth processes
- Natural systems with inherent complexity
- Map-view and volumetric focus

- Stratigraphy-dominated
- Product-oriented
- Sink-focused
- Model-oriented 3D concepts, 2D practice
- Cross-sectional/depth focus

Dave Hunt, unpublished
Application to hydrocarbon exploration

- Prediction in frontier basins and of lithology
- Paleo - Digital Elevation Models and Earth Systems Modelling

Digital elevation model, reconstructed plates, drainage basins and sediment yield (circles)