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

Ole J. Martinsen[1]

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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 km^3 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

Boyd et al., 2008 Boyd, R.K.J. Ronald, I.D. Goodwin, M. Sandstrom, and C. Schroder-Adams: Highstand transport of coastal sand to the deep ocean: A case study from Fraser Island, Southeast Australia: Geology, v. 36, p. 15-18.

Castellort, S., and J.V.D. Driessche, 2003, How plausible are high-frequency sediment supply-driven cycles in the stratigraphic record?: Sedimentary Geology, v. 157, p. 3–13.

Gjelberg, J.G., T. Enoksen, P. Kjarnes, G. Mangerud, O.J. Martinsen, E. Roe, and E. Vagnes, 2001, The Maastrichtian and Danian depositional setting, along the eastern margin of the MØre Basin (mid-Norwegian Shelf): Implications for reservoir development of the Ormen Lange field, *in* O.J. Martinsen and T. Dreyer, eds., Sedimentary Environments Offshore Norway—Paleozoic to Recent: Norwegian Petroleum Society Special Publication 10, p. 421−440.

Jackson, C.A.L., G.P. Barber, and O.J. Martinsen, 2008, Submarine slope morphology as a control on the development of sand-rich turbidite depositional systems: 3D seismic analysis of the Kyrre Fm (Upper Cretaceous), Maloy Slope, offshore Norway: Marine and Petroleum Geology, v. 25, p. 663-680.

Kuenen, Ph. H., and C.I. Migliorini, 1950, Turbidity currents as a cause of graded bedding: Journal of Geology, v. 58, p. 91–127.

Leturmy, P. F. Lucazeau, and F. Brigaud, 2003**,** Dynamic interactions between the Gulf of Guinea passive margin and the Congo River drainage: Journal of Geophysical Research, v. 108 (B8), p. 2383-2395.

Lidmar-Bergstrom, K., and J.O. Näslund, 2002, Landforms and uplift in Scandinavia: Geological Society, London, Special Publications, no. 196, p. 103 - 116.

Martinsen, O.J., 1994: Mass movements, *in* A. Maltman, ed., The Geological Deformation of Sediments: Chapman & Hall, p. 127-165.

Martinsen, O.J., H.C. Fonneland, T. Lien, and J.G. Gjelberg, 2002, On latest Cretaceous−Paleocene drainage and deep-water sedimentary systems on-and offshore Norway, *in* T. Thorsnes, ed., Onshore-Offshore Relationships on North Atlantic Margins: Norwegian Geological Society Abstracts and Proceedings, v.2, p. 123−124.

Nemec, W., 1990, Aspects of sediment movement on steep delta slopes, *in* A. Colella and D.B. Prior, eds., Coarse-Grained Deltas: IAS Special Publications no. 10, p. 29-73.

Piper, D.J.W., 2005, Late Cenozoic evolution of the continental margin of eastern Canada: Norwegian: Journal of Geology, v. 85, p. 305–318.

Prather, B.E., 2003, Controls on reservoir distribution, architecture and stratigraphic trapping in slope settings: Marine and Petroleum Geology, v. 20, p. 529−545.

Reading, H.G., and M. Richards, 1994, Turbidite systems in deep-water basin margins classified by grain size and feeder system: AAPG Bulletin, v. 78, p. 792−822.

Sømme, T.O., O.J. Martinsen, and J.B. Thurmond, 2009, Reconstructing morphological and depositional characteristics in subsurface sedimentary systems: An example from the Maastrichtian−Danian Ormen Lange system, Møre Basin, Norwegian Sea: AAPG Bulletin, v. 93, p. 1347-1377.

Somme, T.O., W. Helland-Hansen, and O.J. Martinsen, and J.B. Thurmond, 2009, Predicting morphological relationships and sediment partitioning in source-to-sink systems: Basin Research, v. 21, p. 361−387.

Walker, R.G., 1992, Facies, facies models and modern stratigraphic concepts, *in* R.G. Walker and N.P. James, eds., Facies Models, Response to Sea-Level Change: Geological Association of Canada, p. 1-14.

Wetzel, A., 1993, The transfer of river load to deep-sea fans—A quantitative approach: AAPG Bulletin, v. 77, p. 1679−1692.

Websites

Lamont-Doherty Earth Observatory, www.ldeo.columbia.edu (accessed May 10, 2010).

University of Wisconsin, Stevens Point, http://www.uwsp.edu, http://www.uwsp.edu/geo/faculty/ritter/geog101/textbook/fluvial_systems/drainage_patterns.html (accessed May 10, 2010).

Education

Distinguished Lecture Program

Statoil

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

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- Processes and external controls
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- The Complete Context and Method
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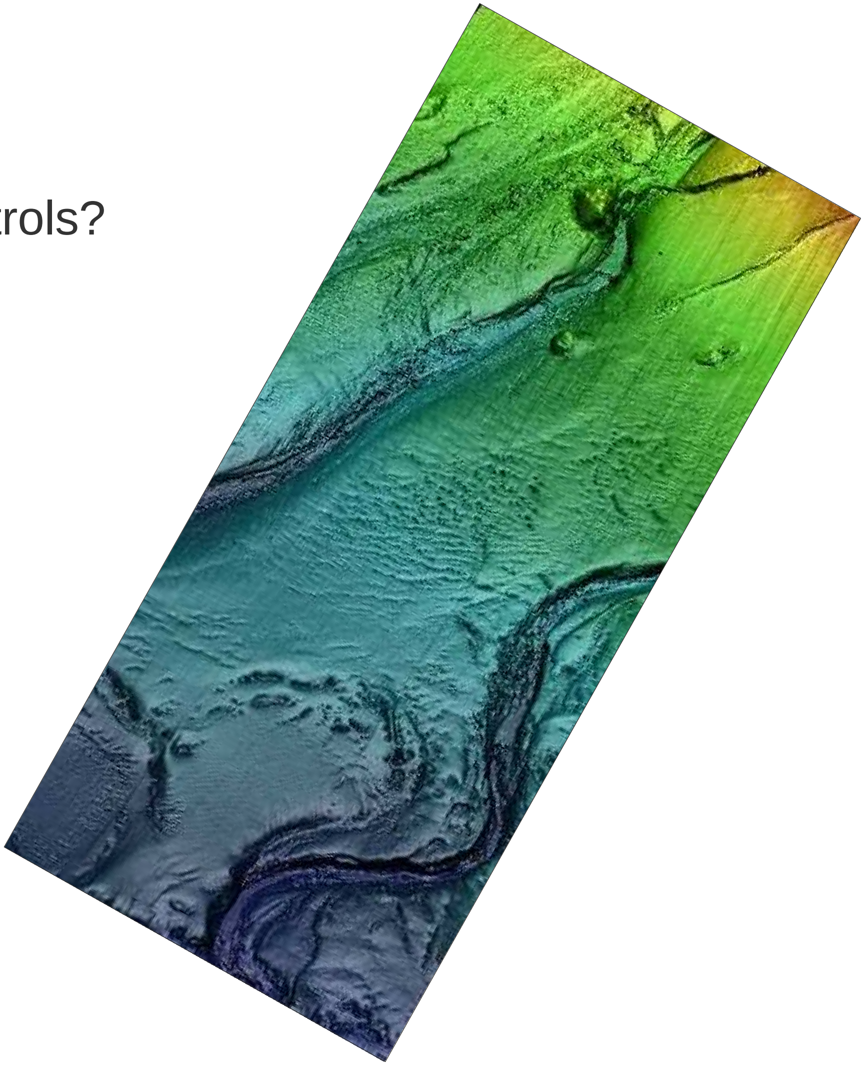
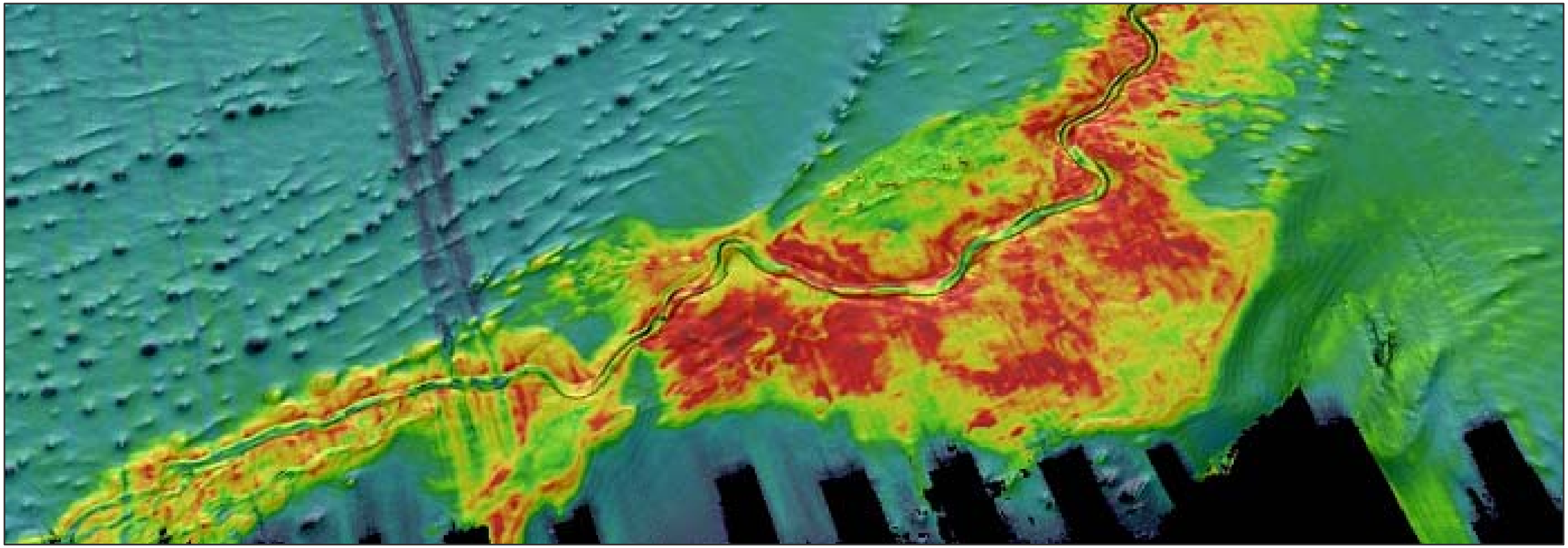
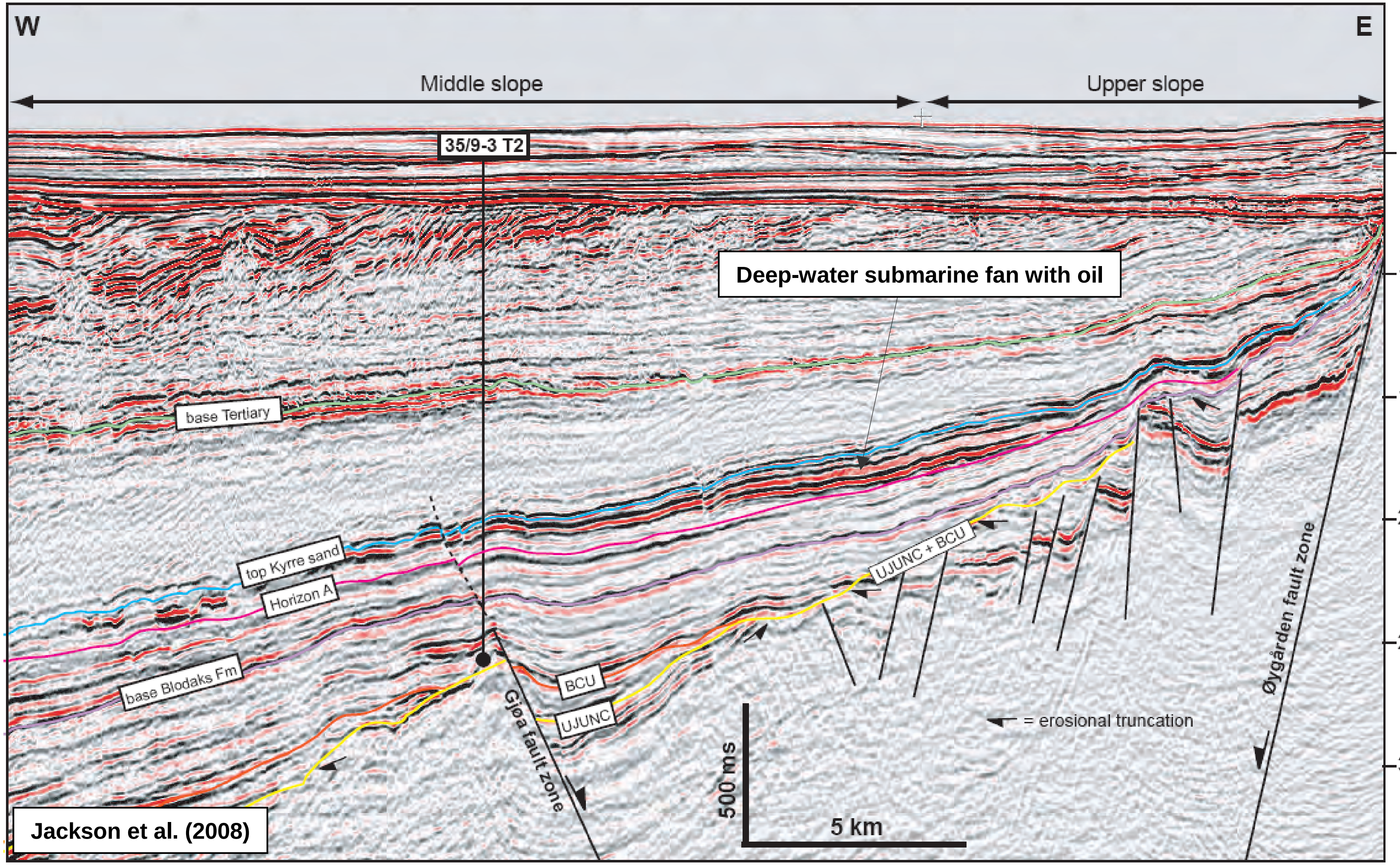


The challenge: why worry about external controls?

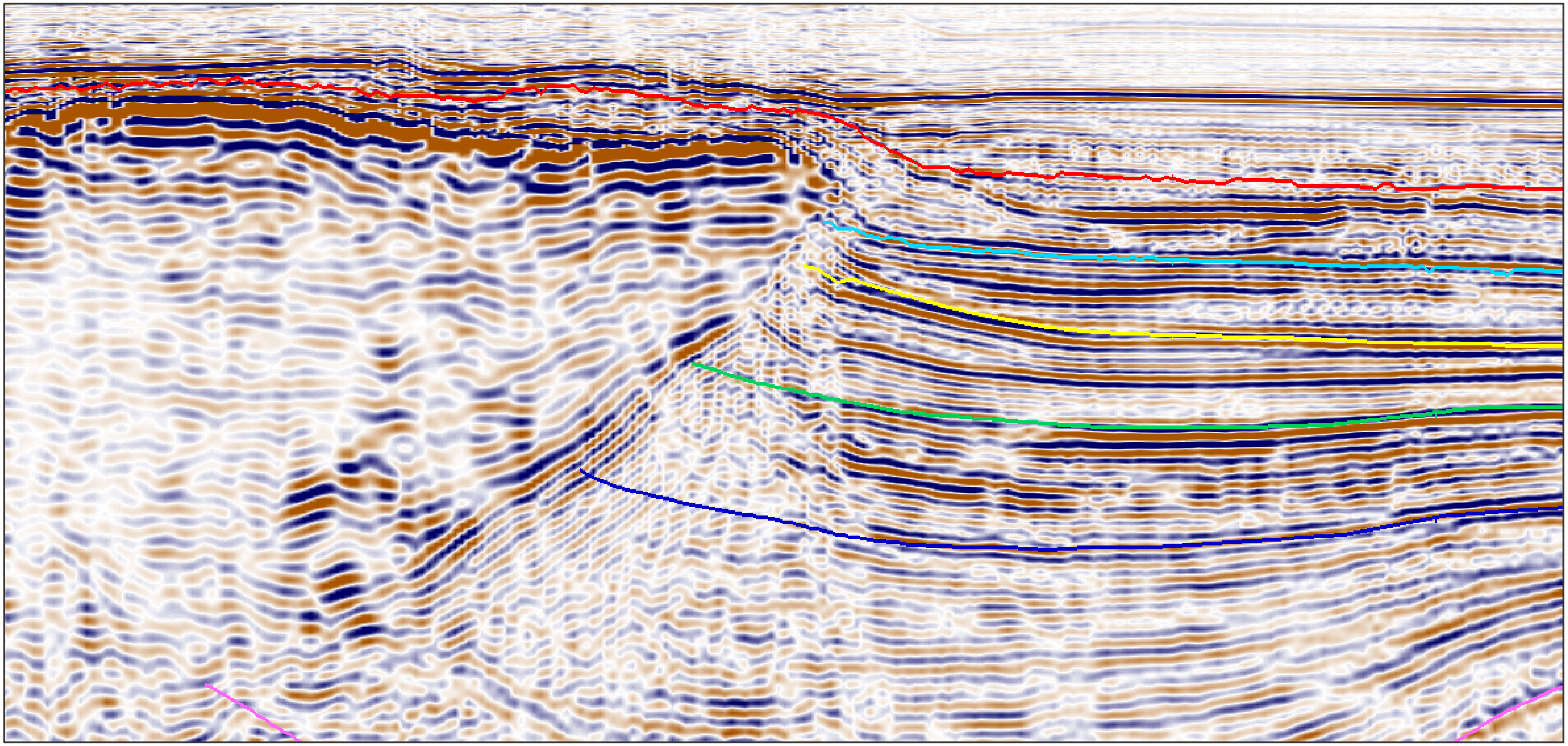
- Deep-water sedimentary systems are exceptionally sensitive to changes in sediment supply driven by hinterland controls



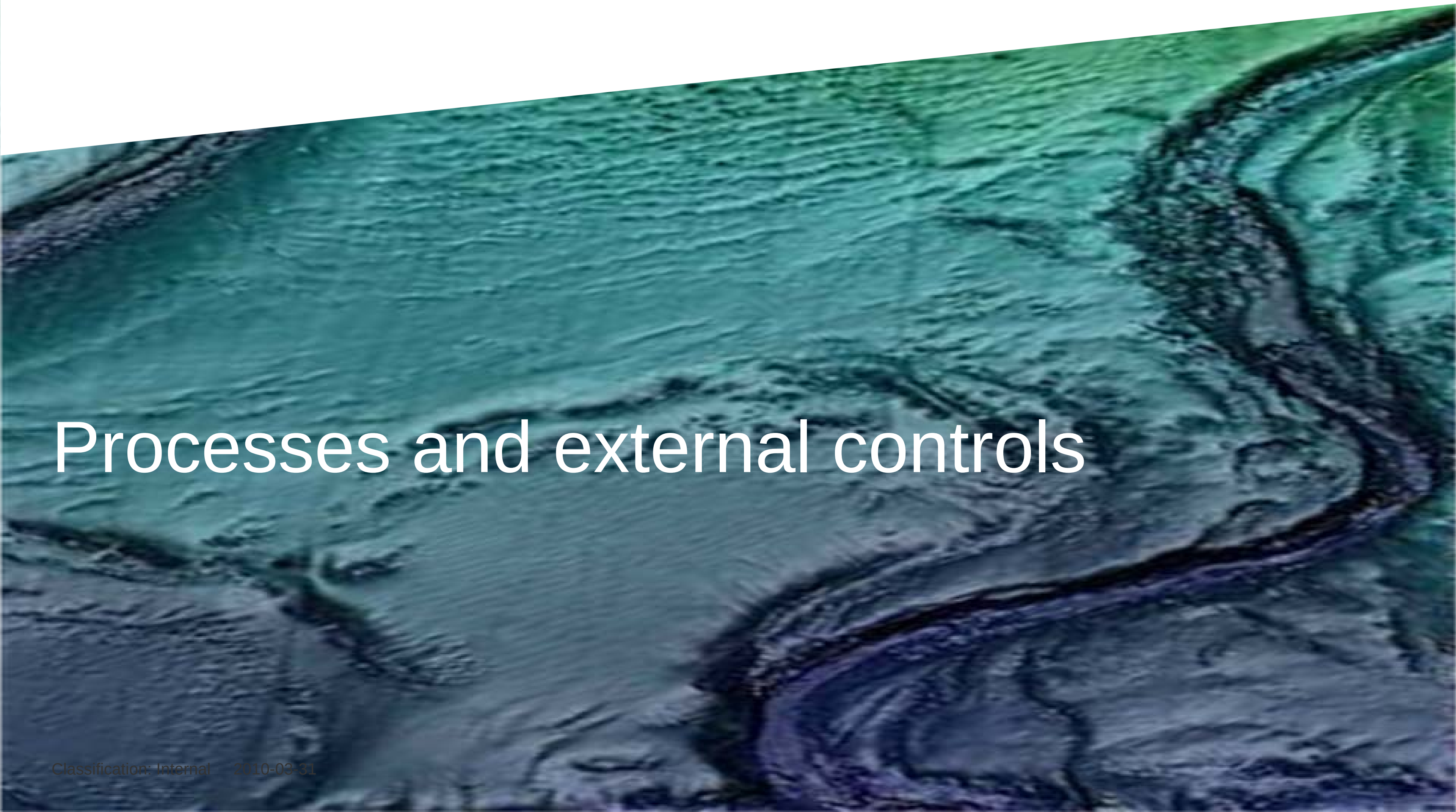
Prediction for subsurface success, but challenge of incomplete systems



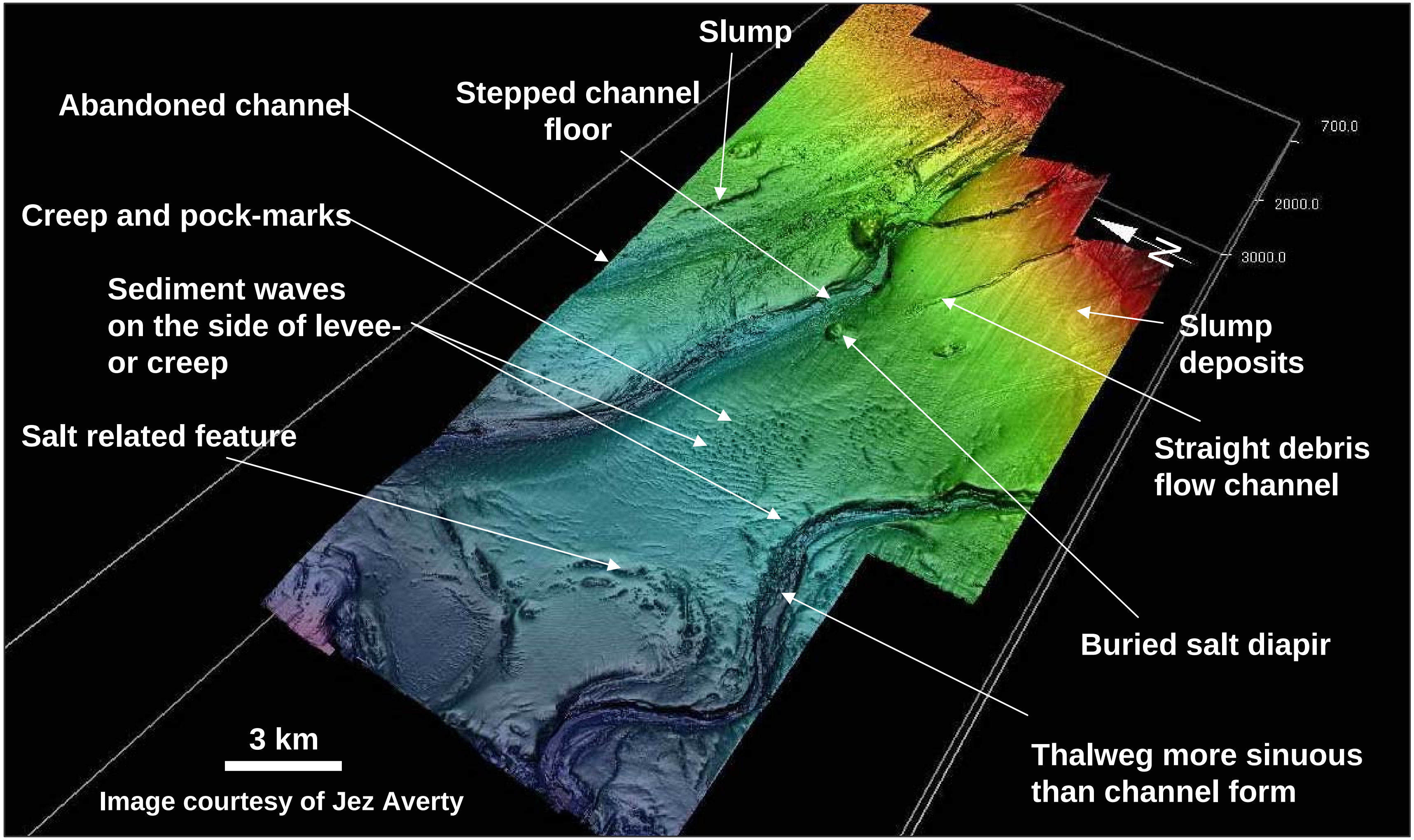
Technology significance:
Refine seismic for best imaging



Processes and external controls

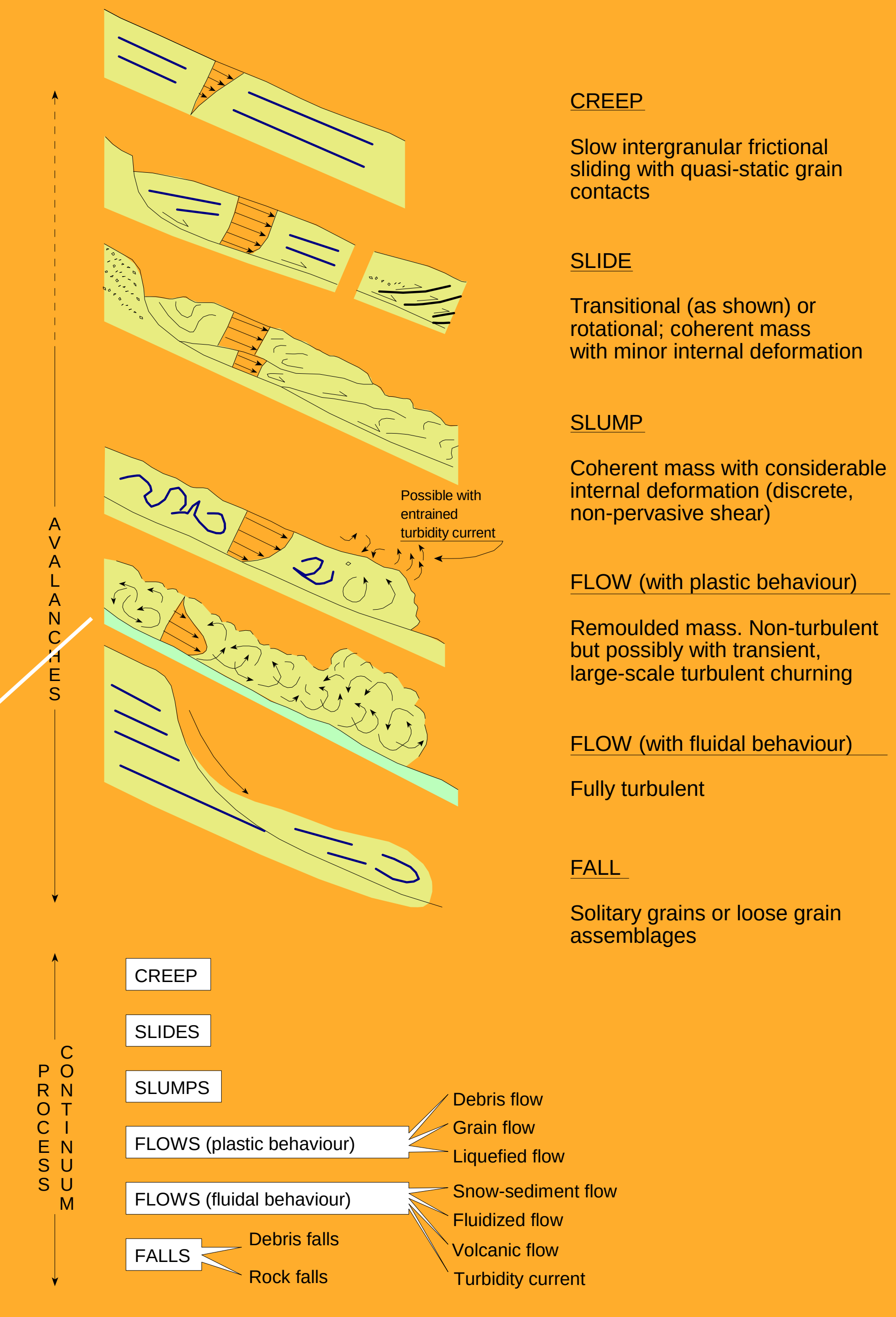


Sea-floor processes



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

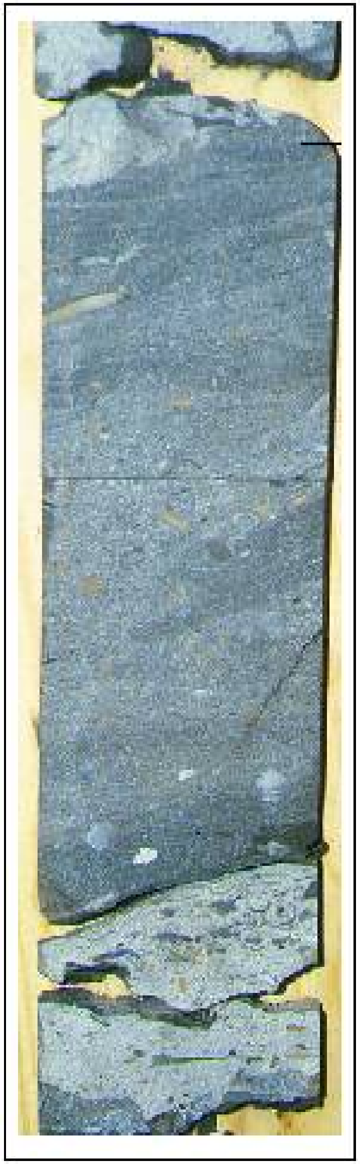
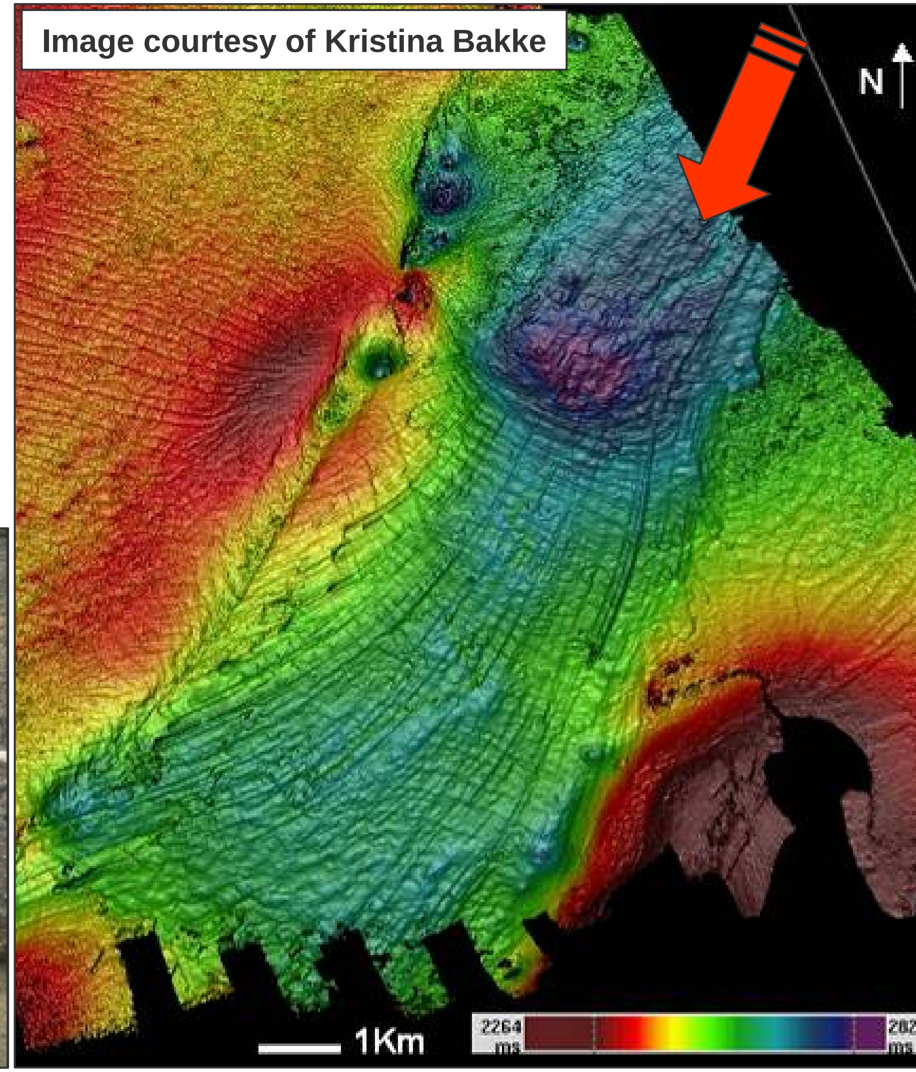


Photo by R. Walker
Cretaceous, North Sea

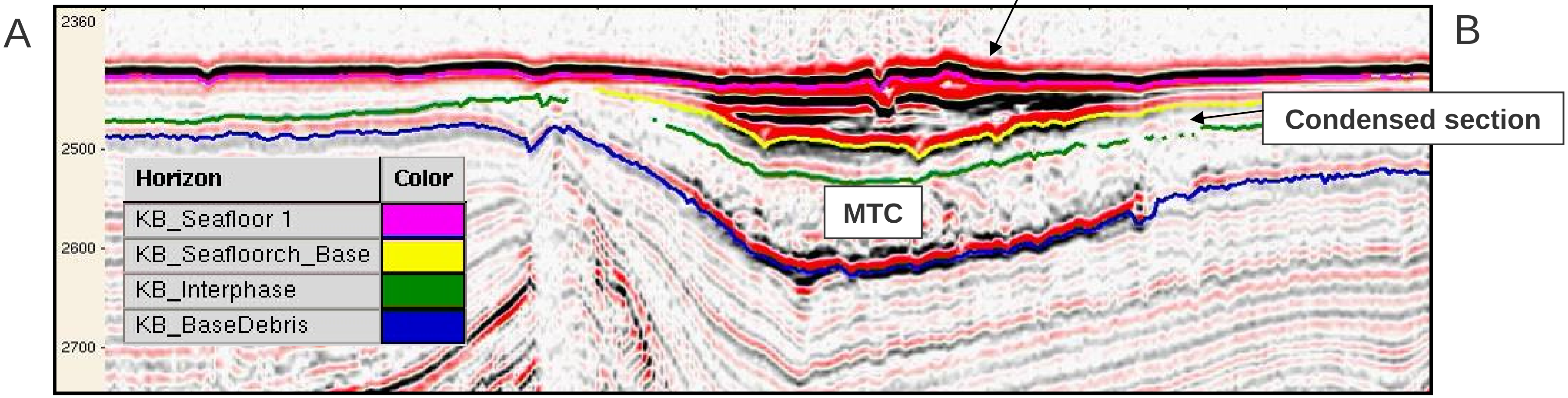
Outcrop expression of debris flow

Seismic expression

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



Near Sea Floor, West Africa



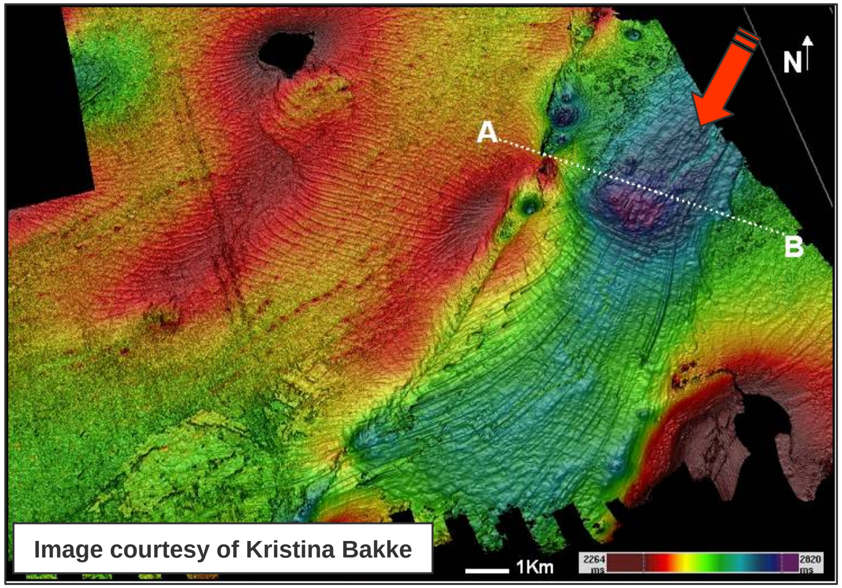


Image courtesy of Kristina Bakke

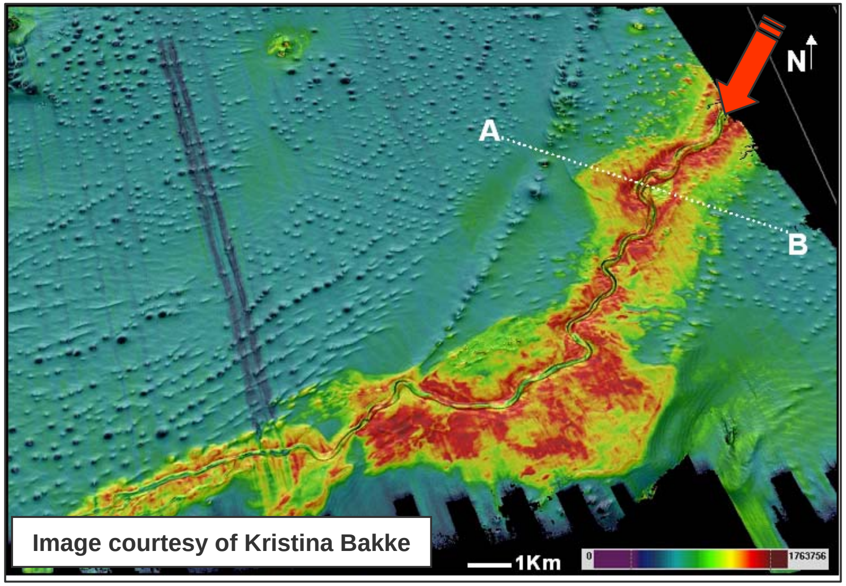
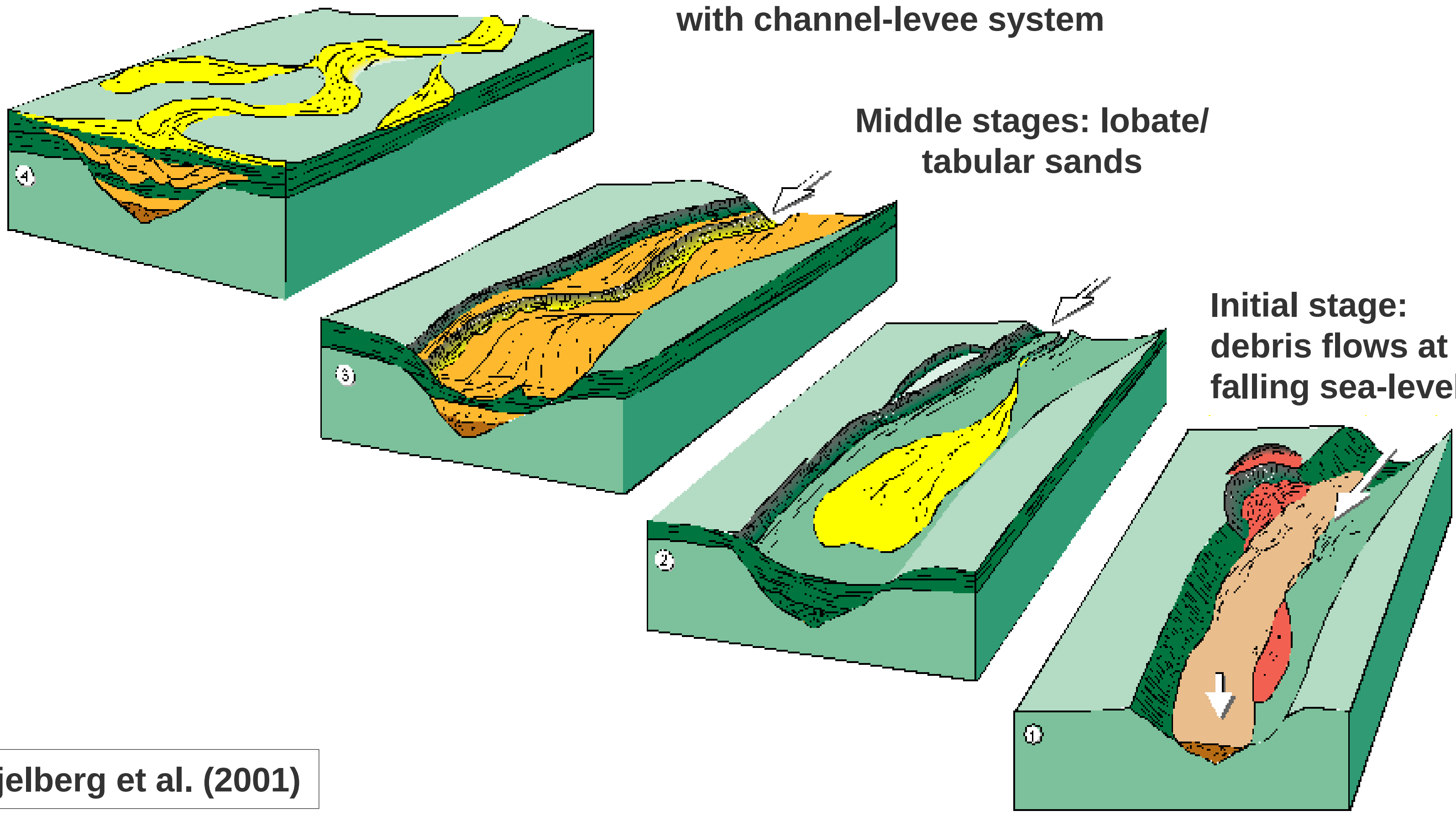


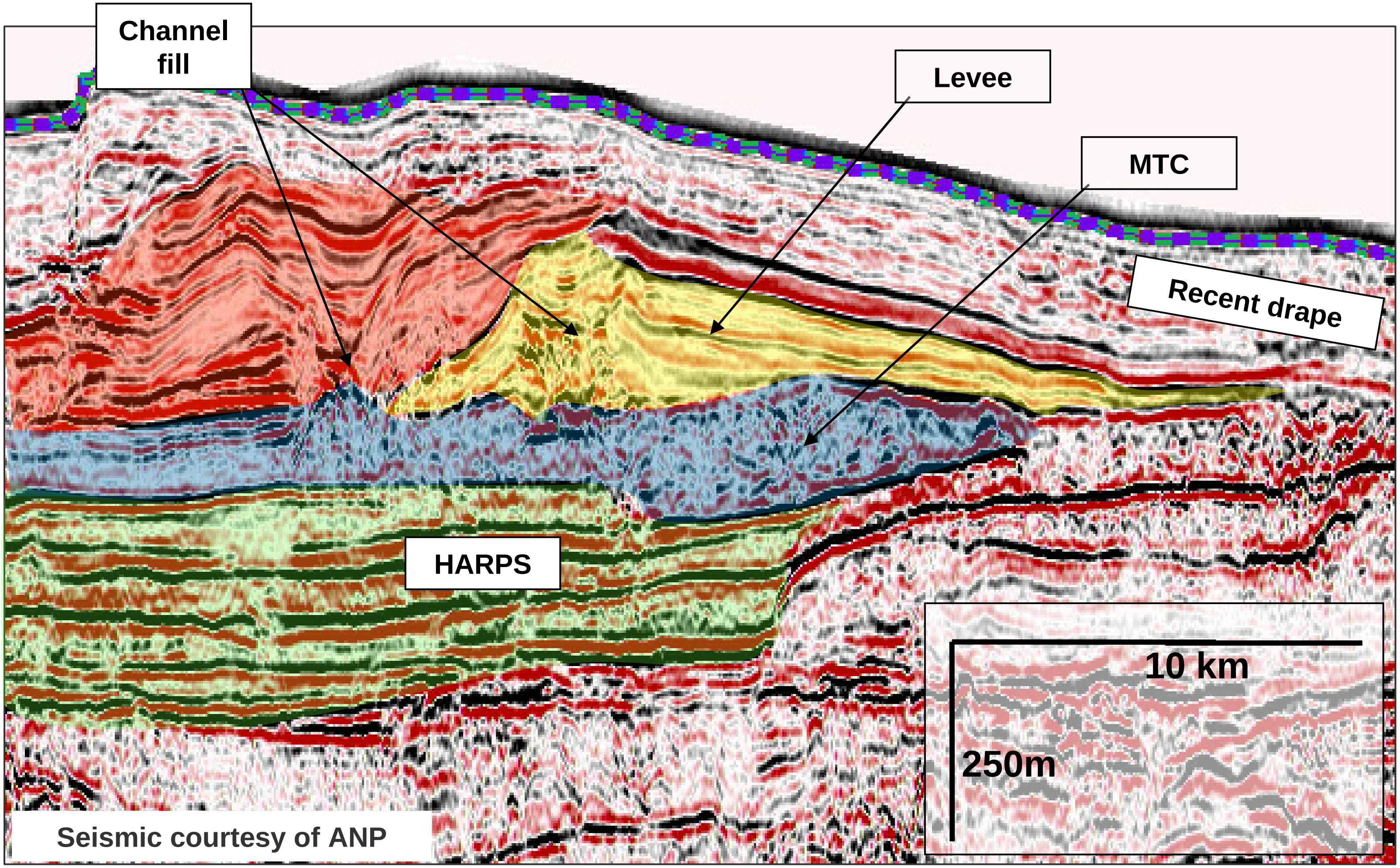
Image courtesy of Kristina Bakke

Active sedimentation at low sea level

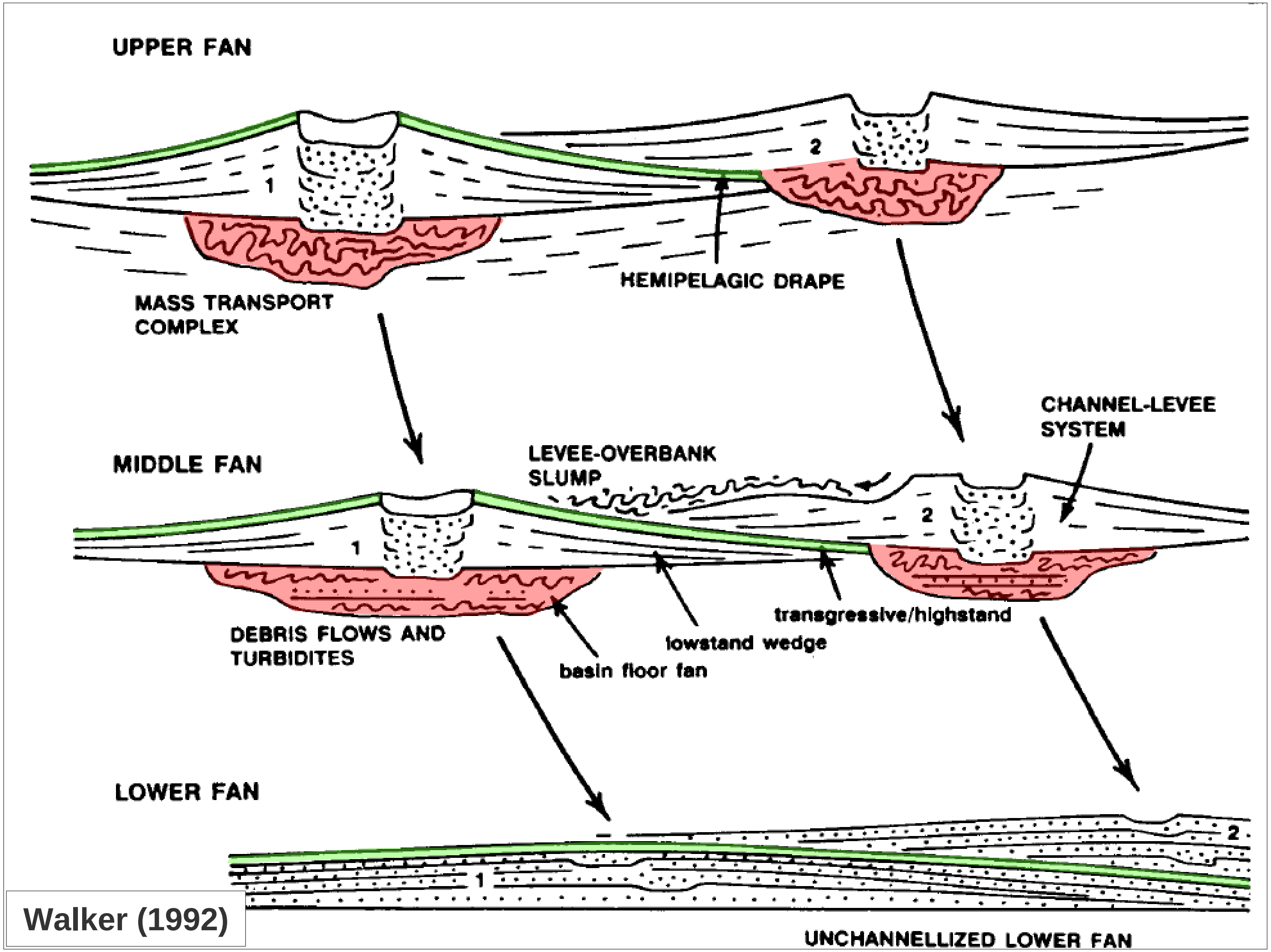


Gjelberg et al. (2001)

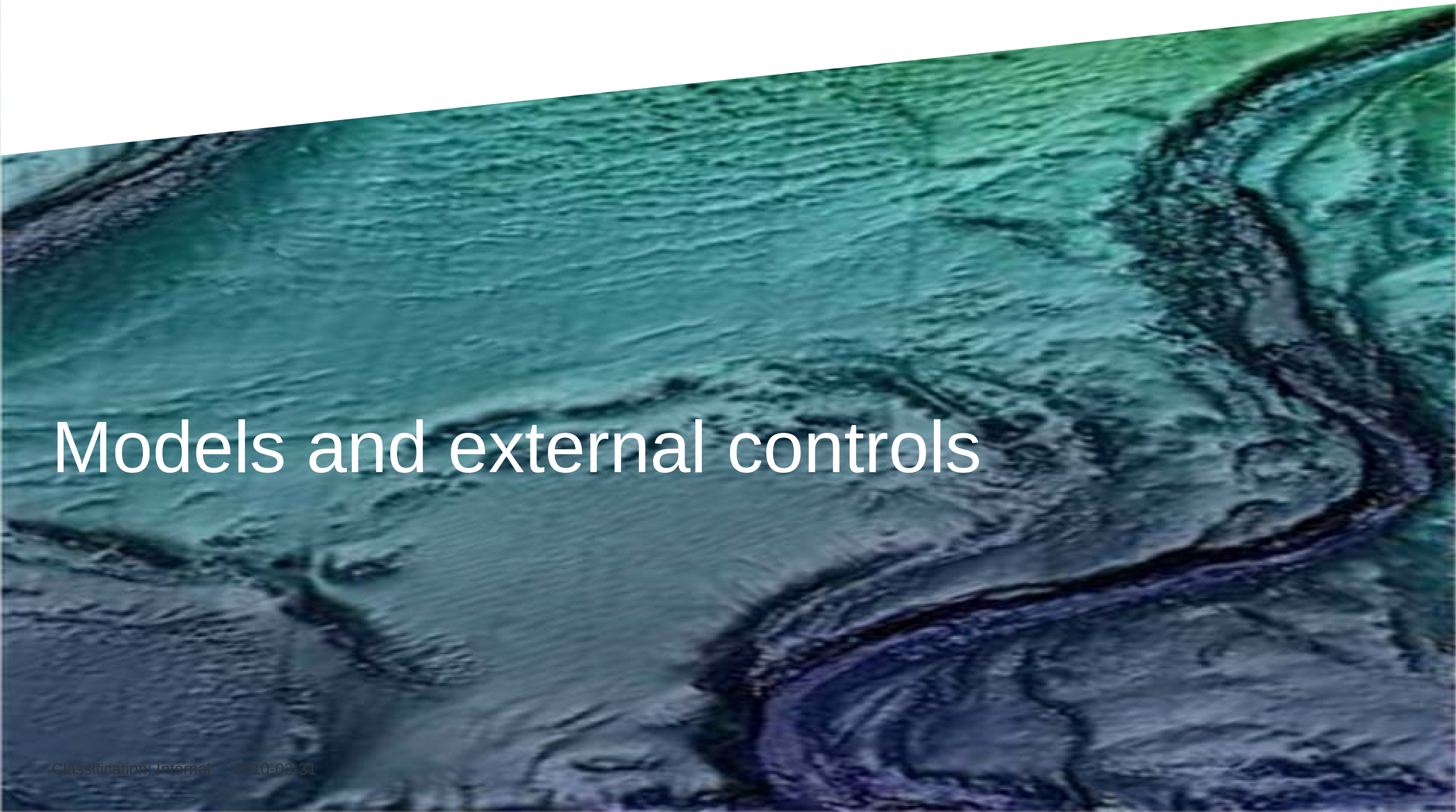
Amazon Fan Pleistocene Cyclicity



General model: but beware of local controls!



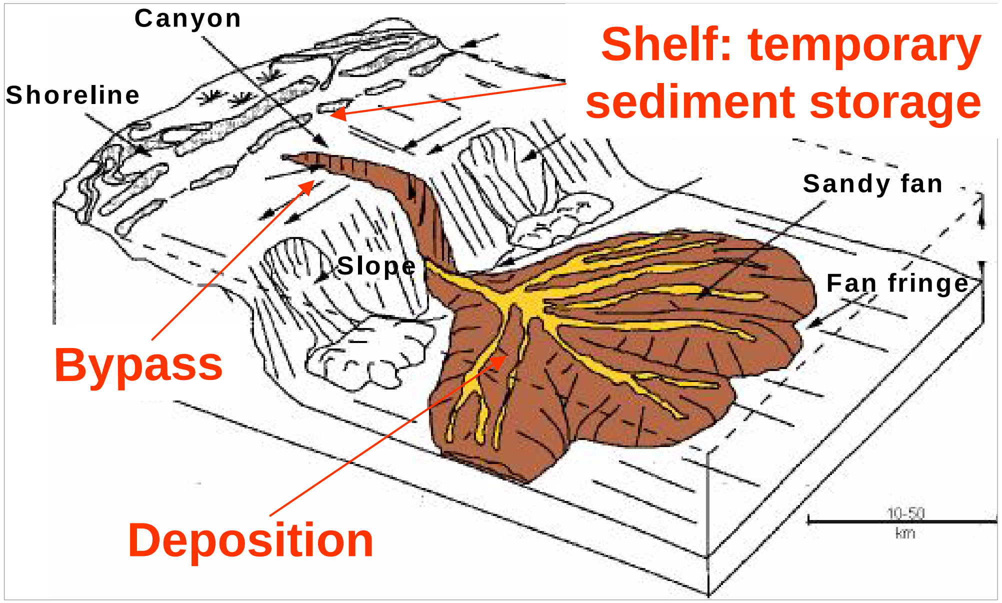
Walker (1992)



Models and external controls

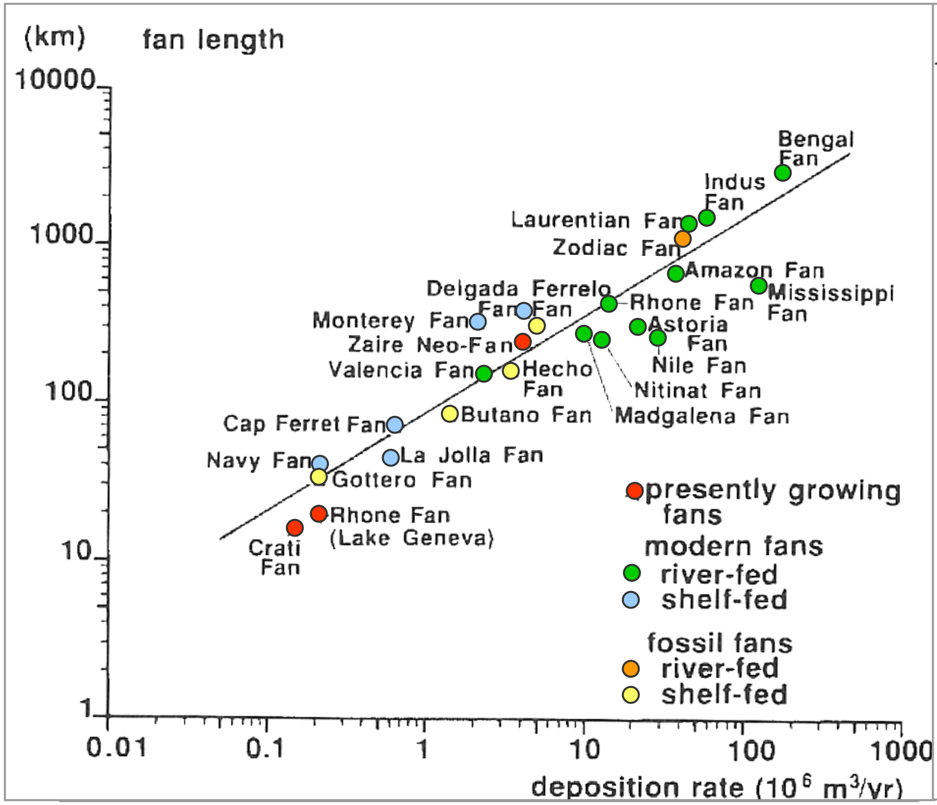
Previous templates for external controls

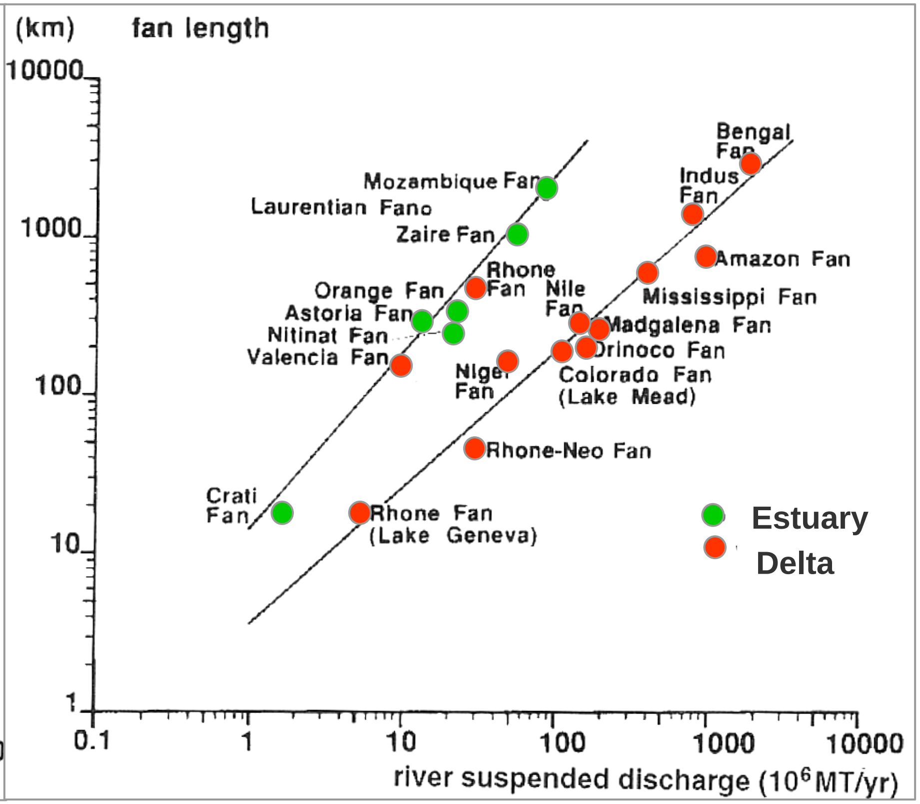
- Previous templates focused on only few critical factors for deep-water deposition
- On each margin, only a few factors dominate
  - Vary in time and space from basin to basin
- Are deep-water systems models useful at all?
- Need to consider using different and more complete templates



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)

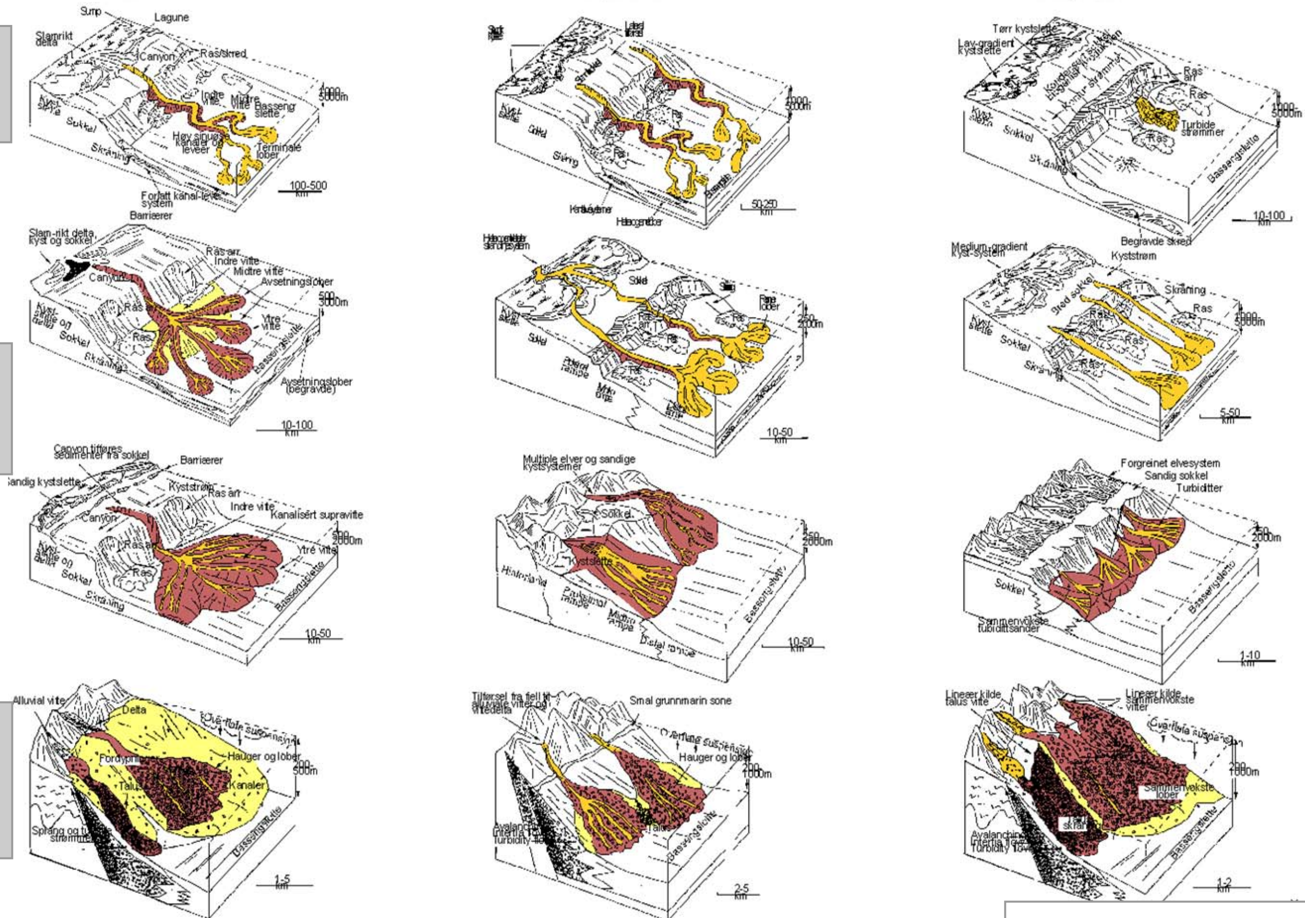
Template 2: Grain Size Vs. Feeder System

Type of feeder system

Point ← - - - **Ramp** - - - → **Line**

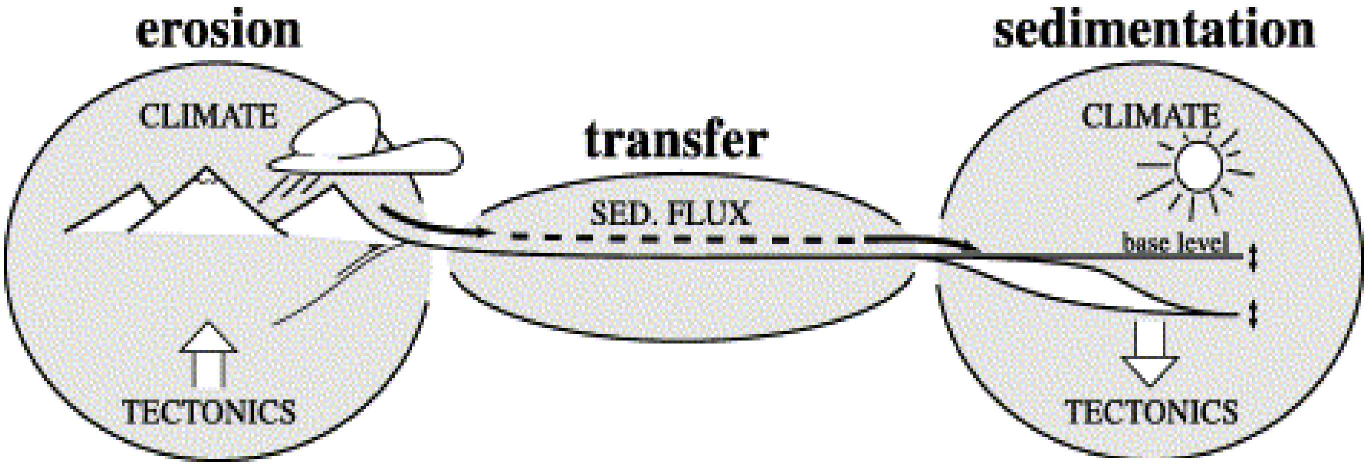
Sediment caliber

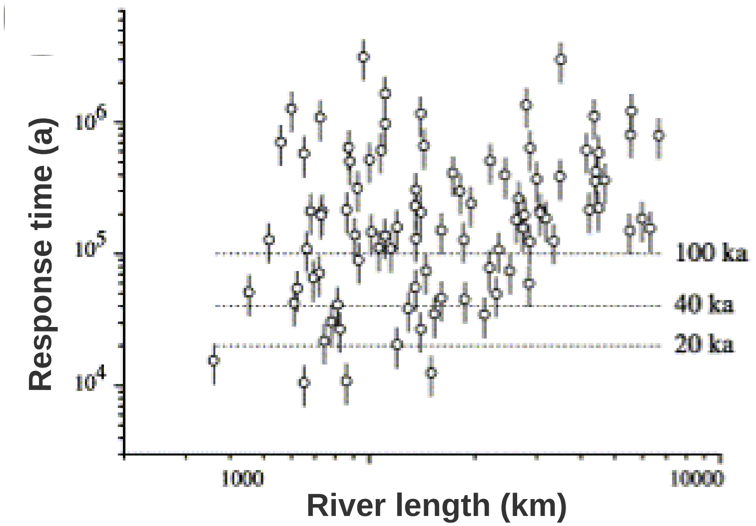
Mud ↑ **Sand** ↓ **Gravel**



Modified from Reading and Richards (1994)

Template 3: climatic controls

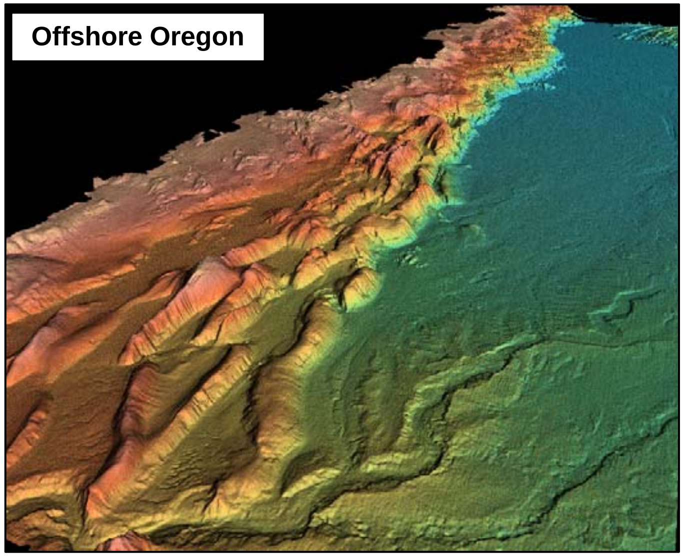


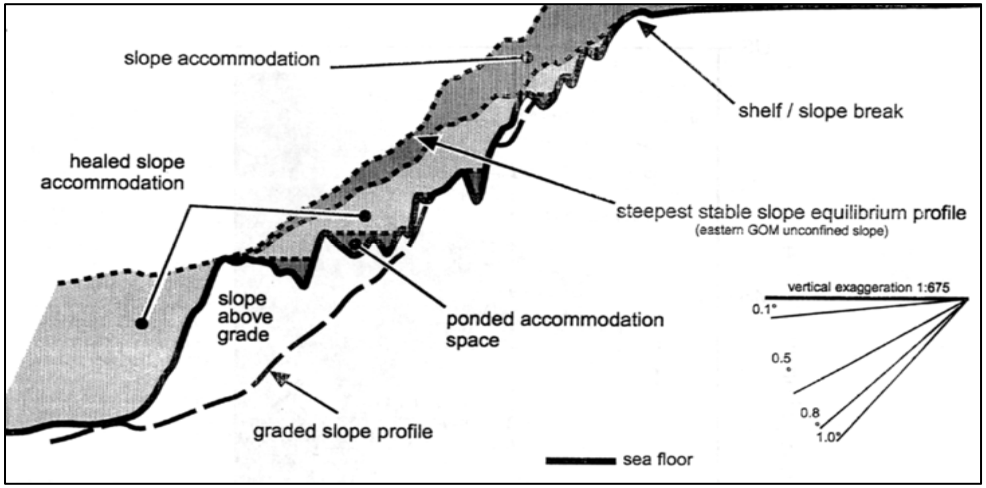


From Castellort et al. (2003)

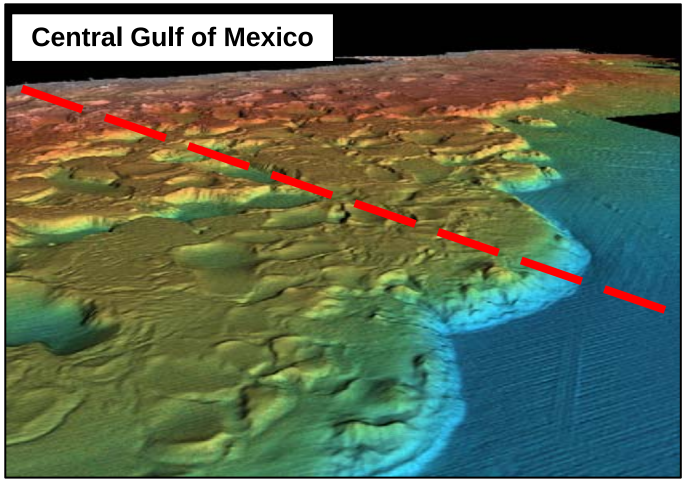
Template 4: Slope accommodation

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



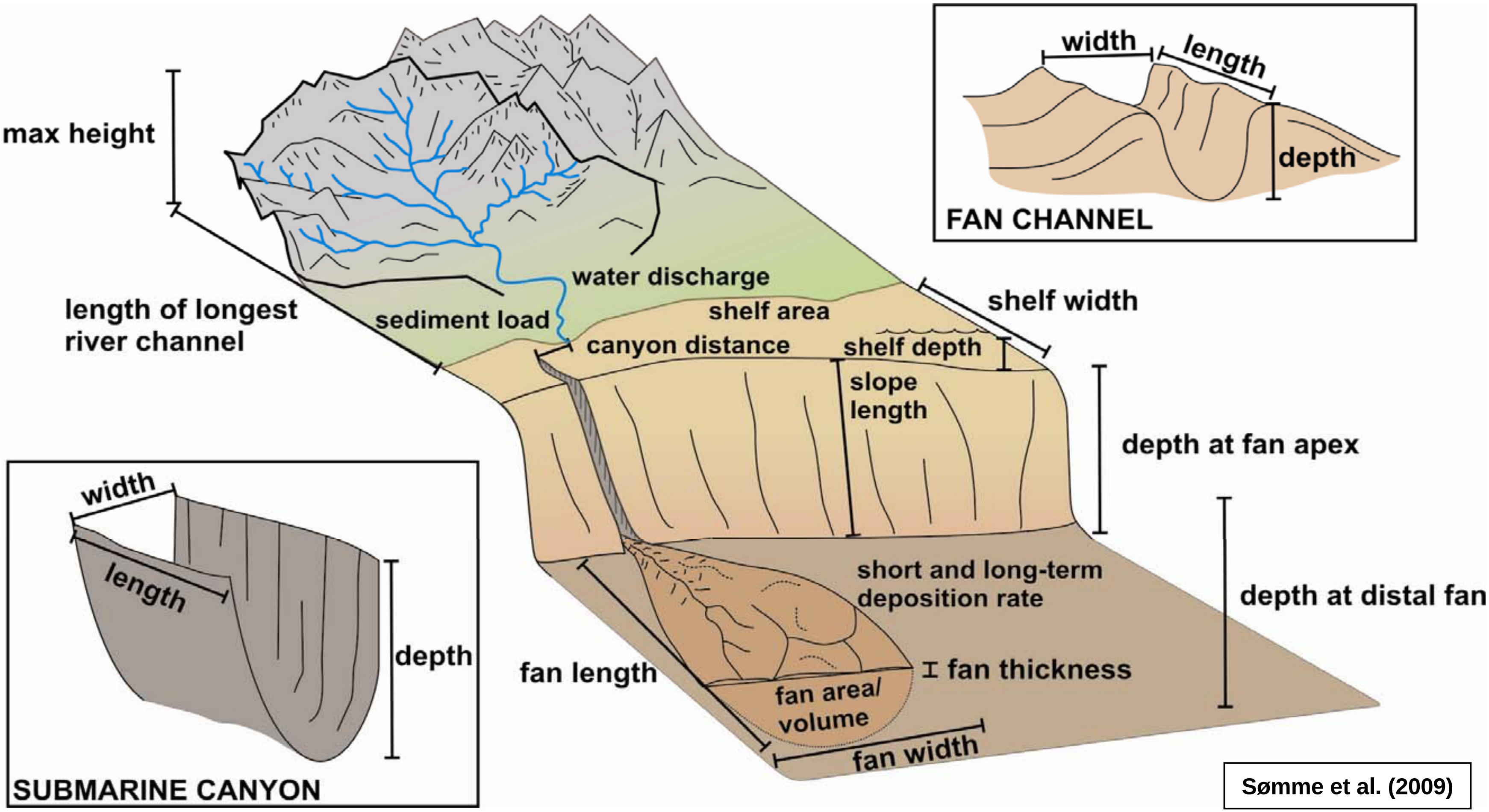


From Prather (2003)



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

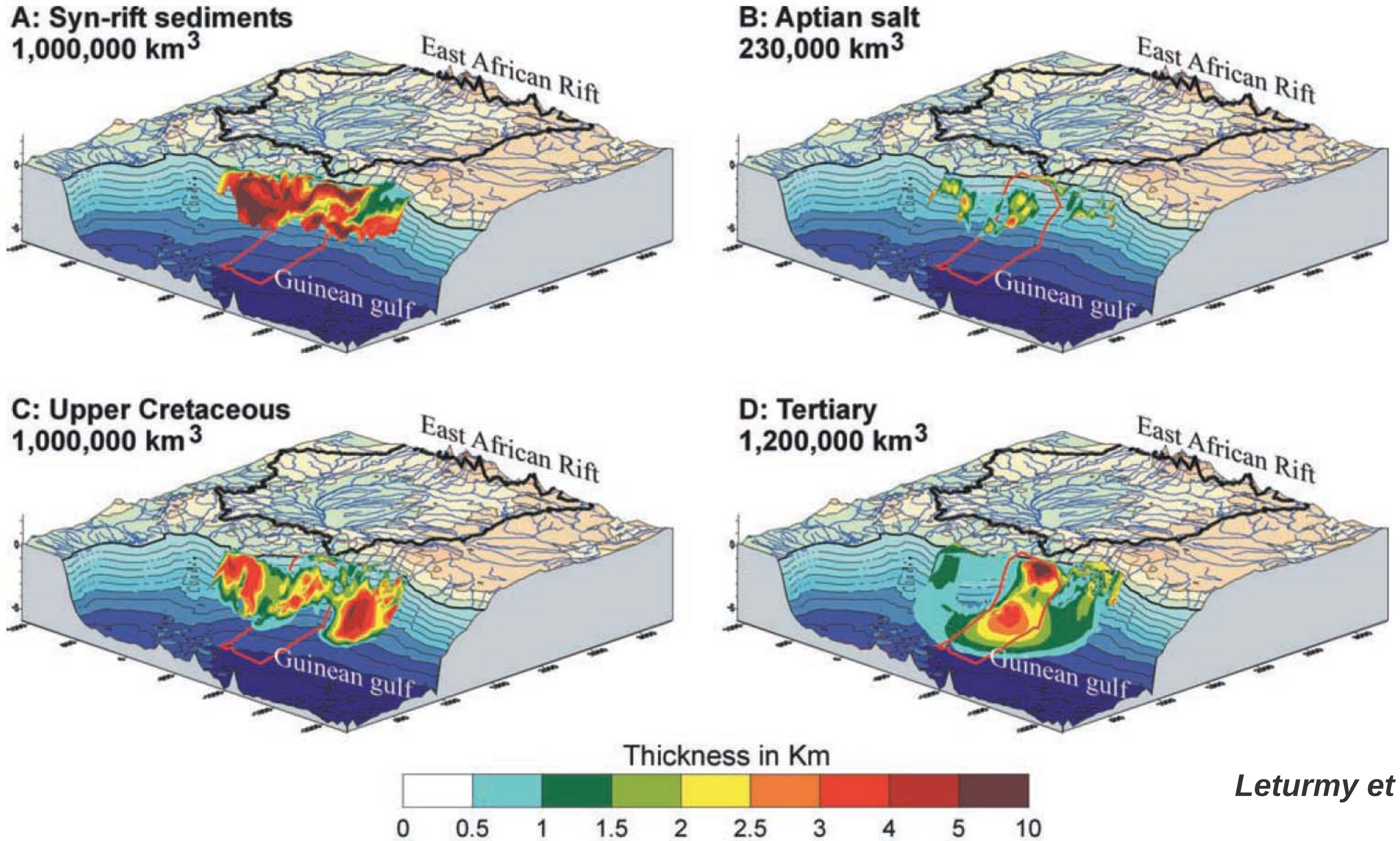
Complete source-to-sink approach



Sømme et al. (2009)

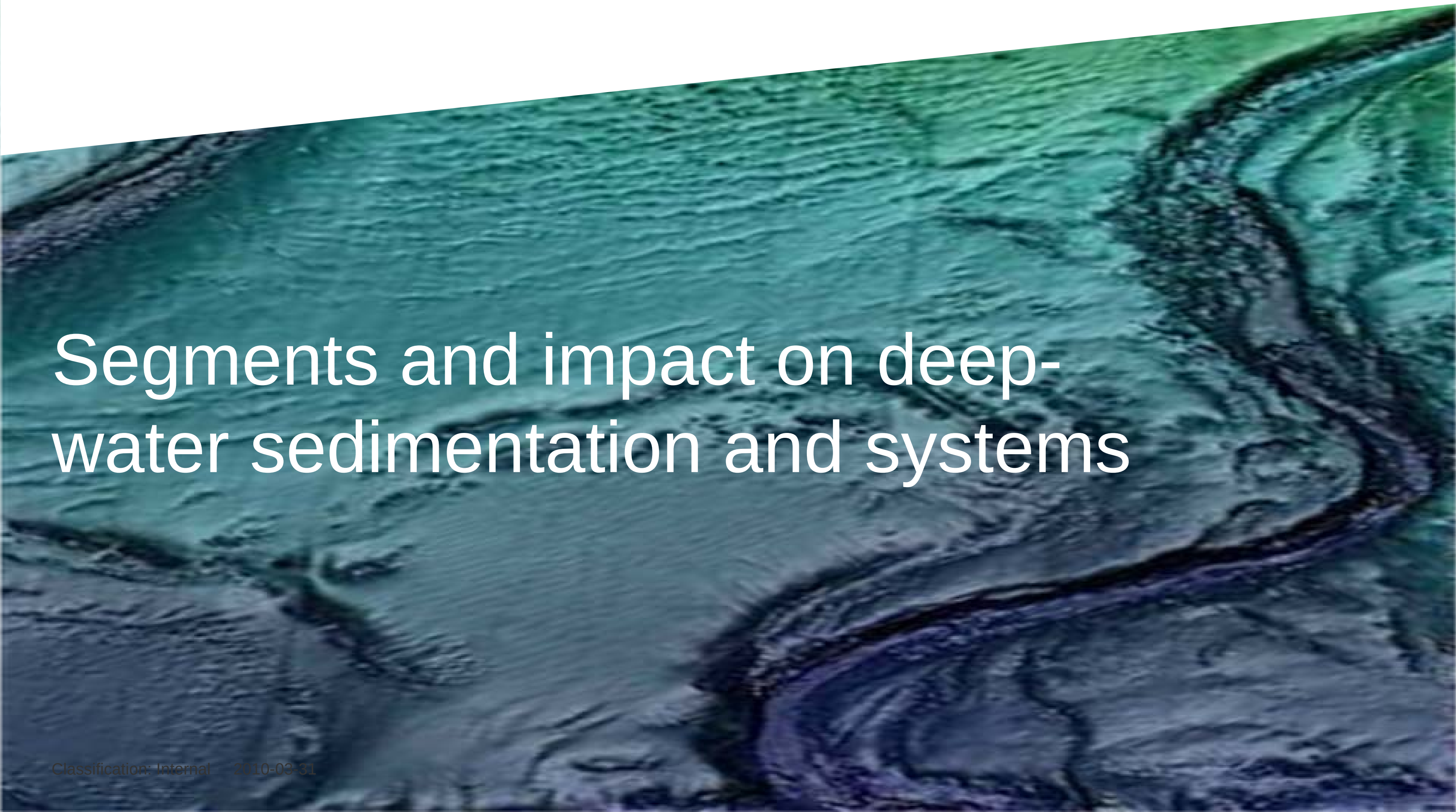
Congo River drainage and Gulf of Guinea example

Total sediment accumulation



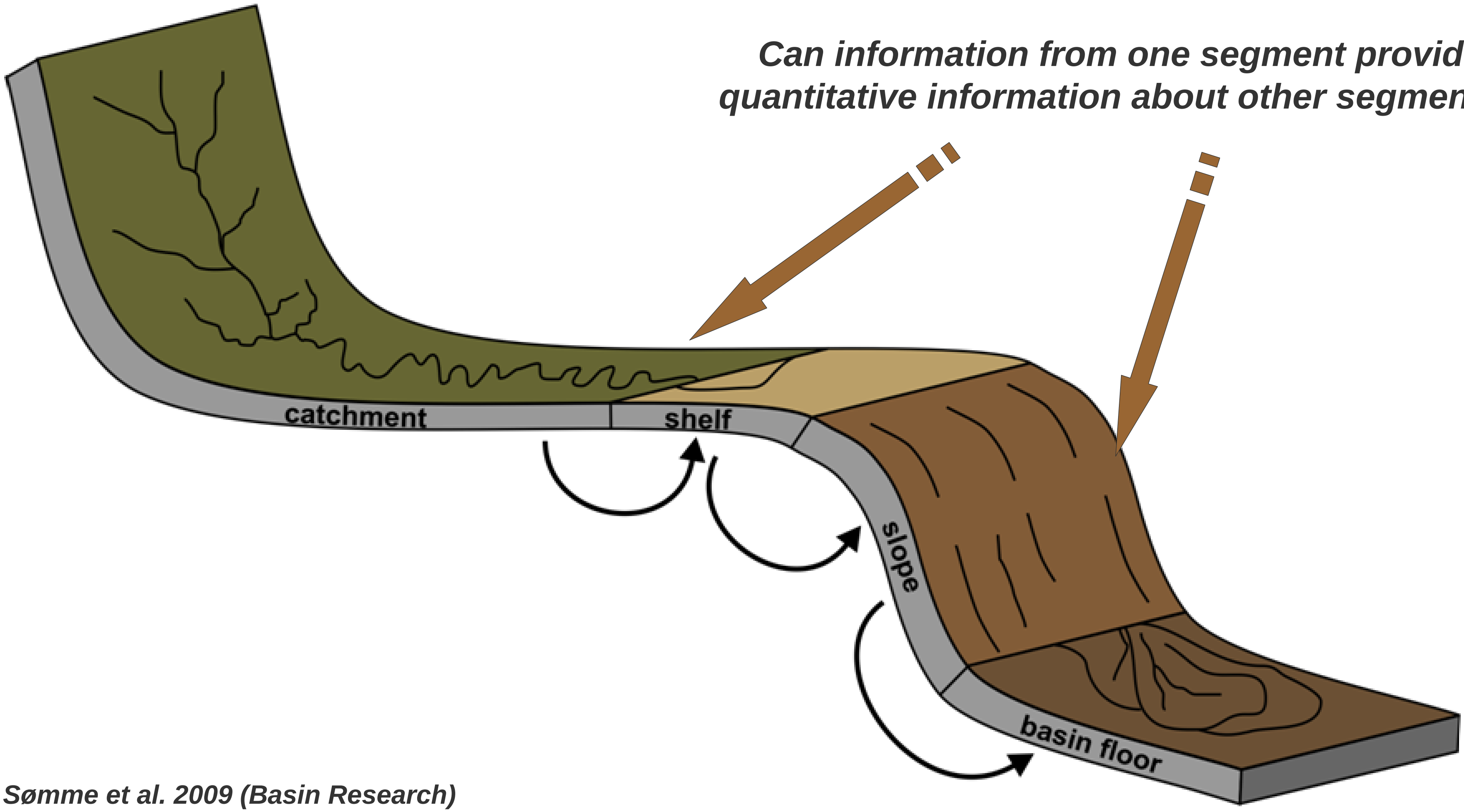
Leturmy et al. (2003)

Segments and impact on deep-water sedimentation and systems



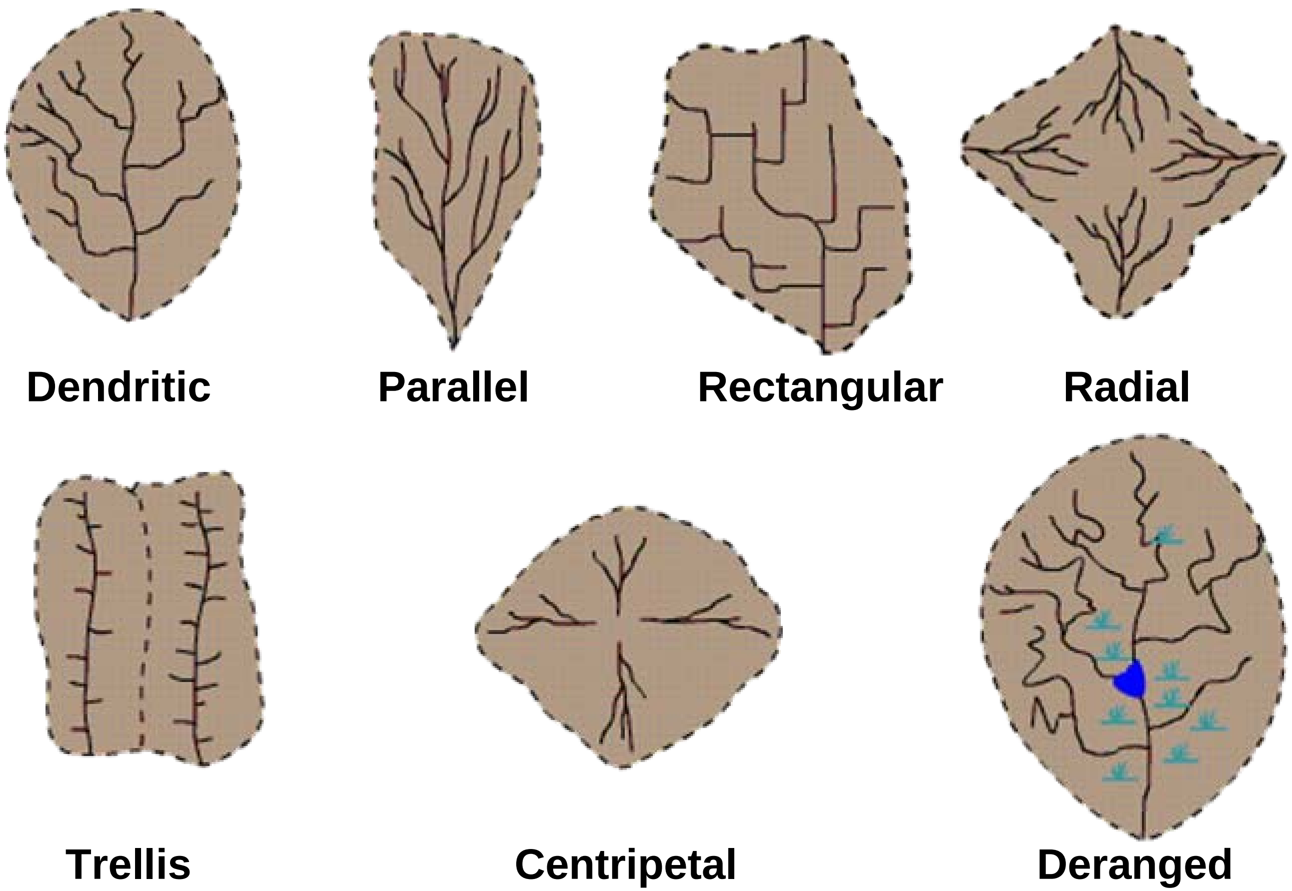
Morphological approach: linked segments

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



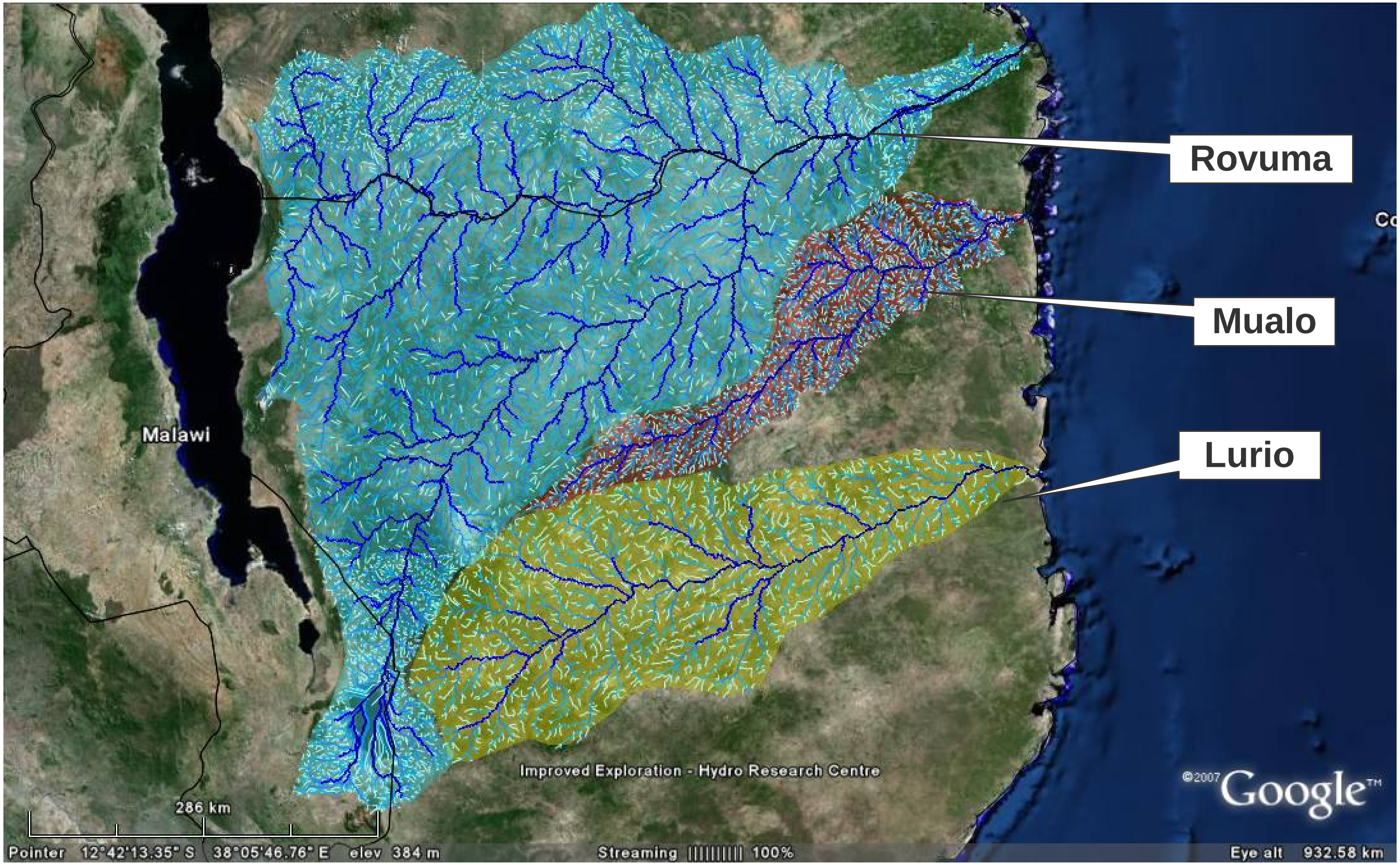
Sømme et al. 2009 (Basin Research)

Source/drainage systems: useful for deep-water exploration?



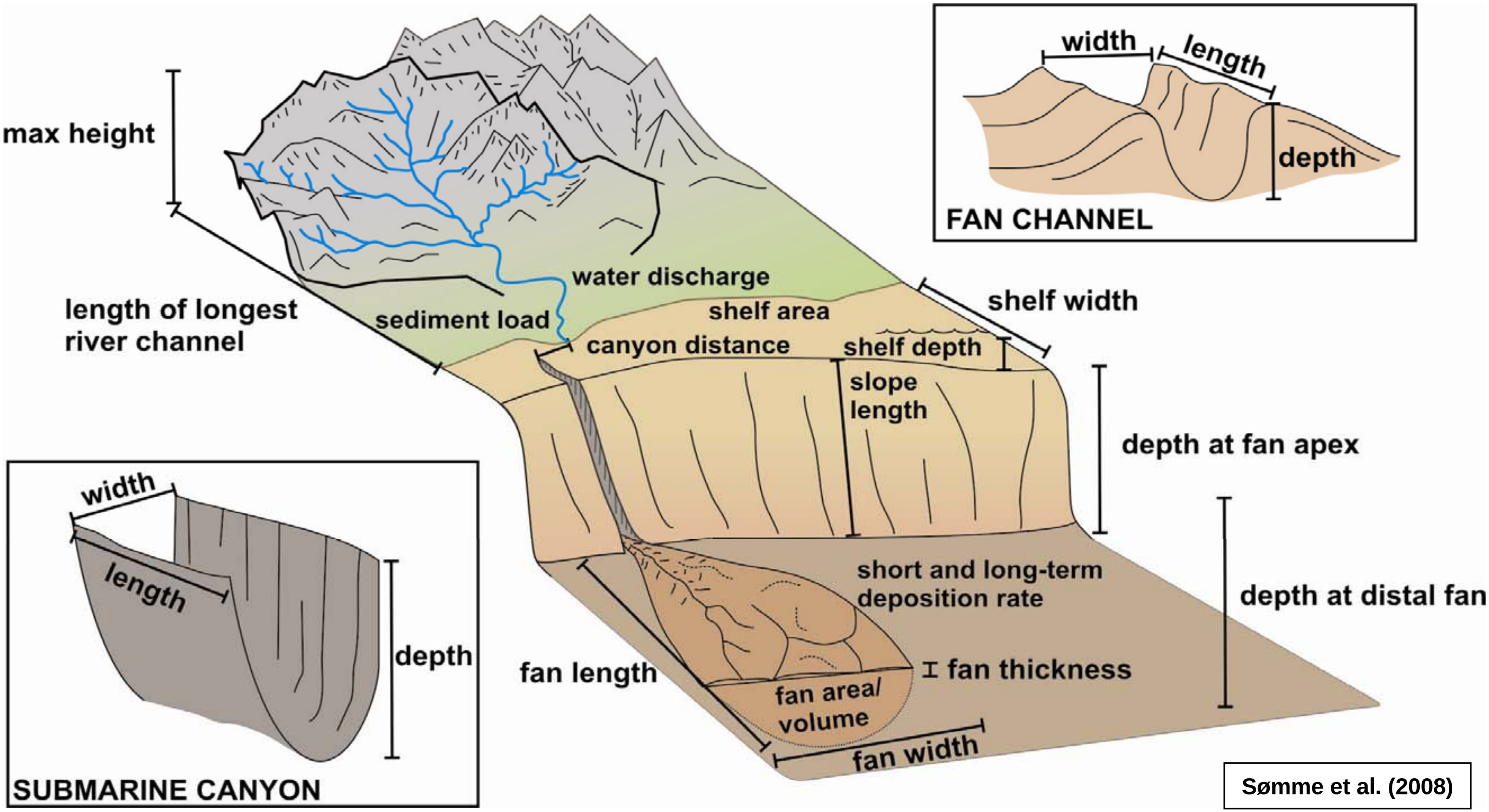
http://www.uwsp.edu/geo/faculty/ritter/geog101/textbook/fluvial_systems/drainage_patterns.html

East African drainage systems



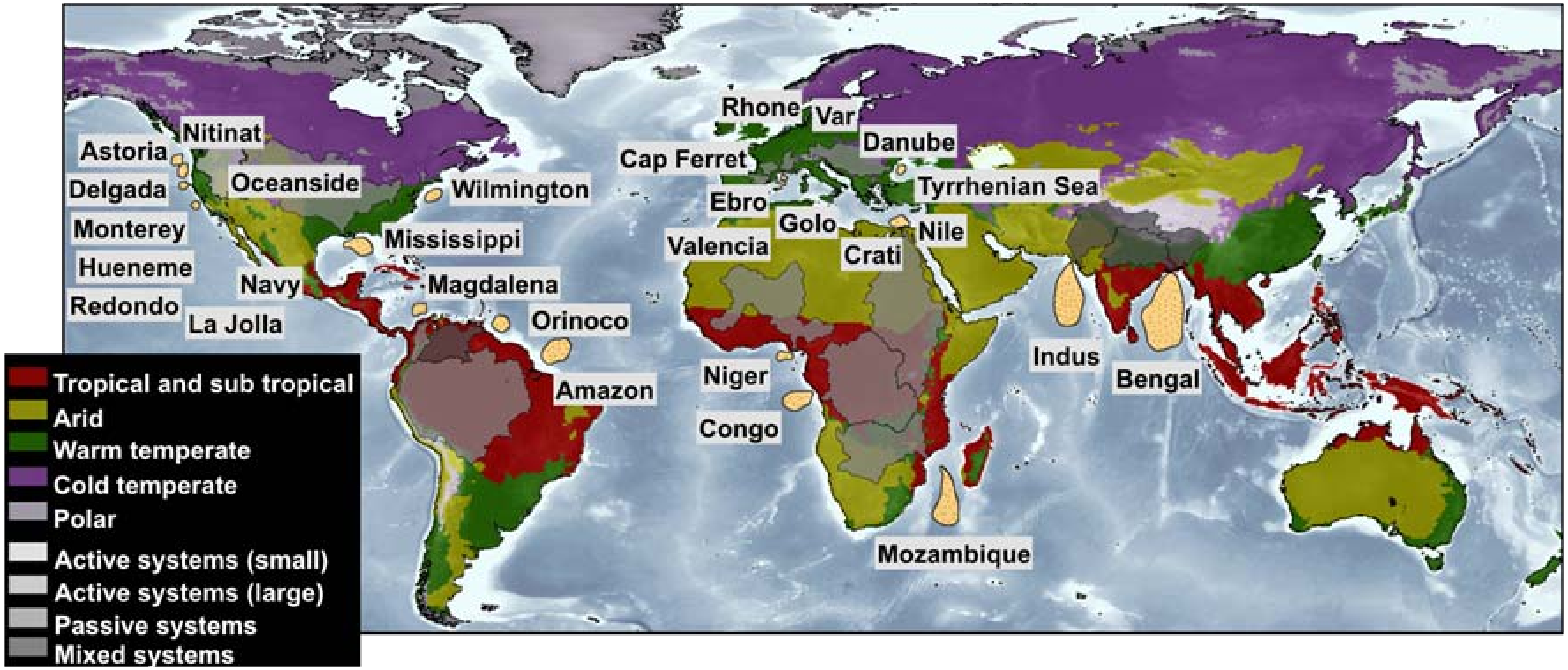
Courtesy of John Thurmond

Role of shelf in geological time



Sømme et al. (2008)

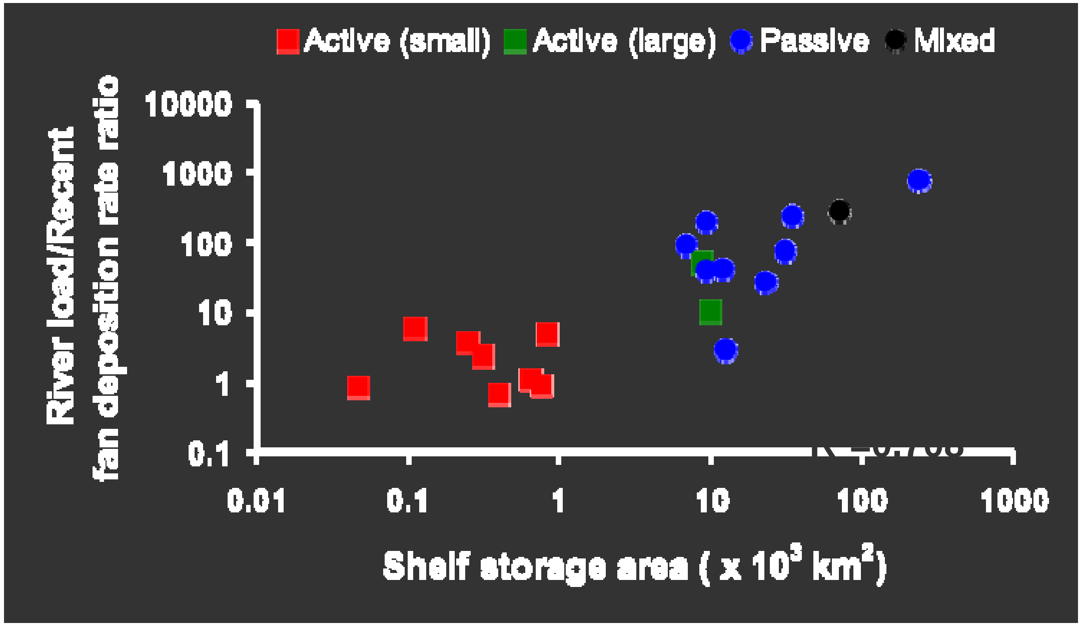
Are modern (Plio-Pleistocene) shelf environments analogues for ancient systems?



Sømme et al. (2009)

Shelf storage

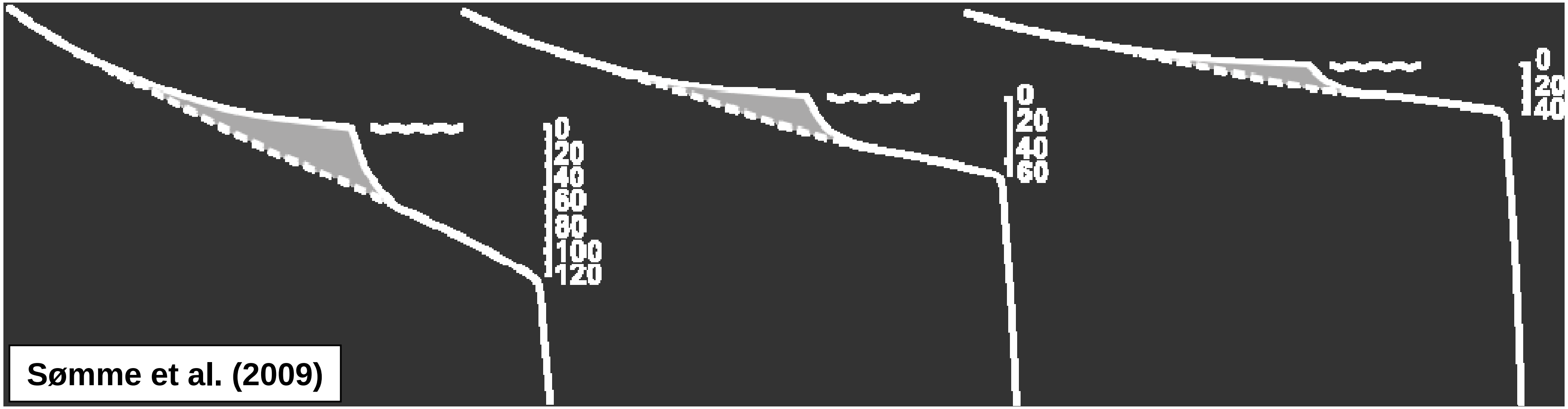
- **Shelf storage increases with system size**
- **Submarine canyons efficiently bypass sediment**



Sømme et al. (2009)

Shelf accommodation and icehouse-greenhouse times

Plio-Pleistocene **Eocene-Oligocene** **Late Cretaceous-Paleocene**

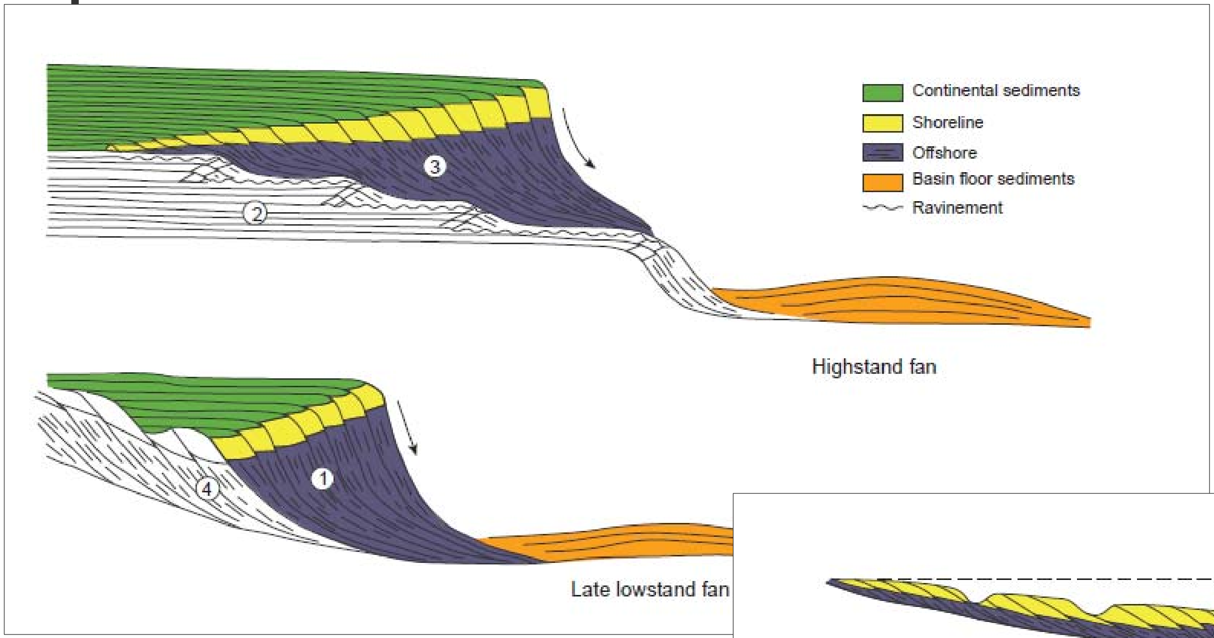


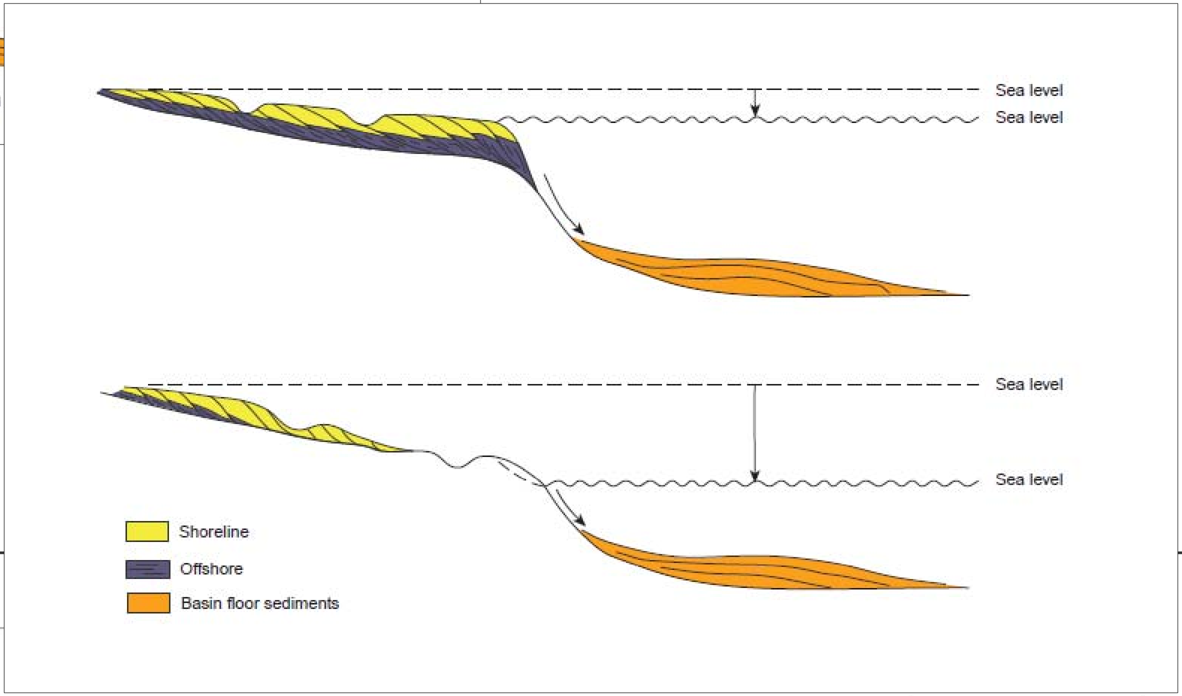
- **Decreasing eustatic amplitudes result in:**
  - **shallower shelf platform**
  - **lower shelf accommodation and more rapid transit times**
  - **higher possibility for highstand shelf edge deltas**
  - **higher impact of tectonics and sediment supply**

Shelf width, morphology and timing of sediment transport to deep-water

National Geographic Map

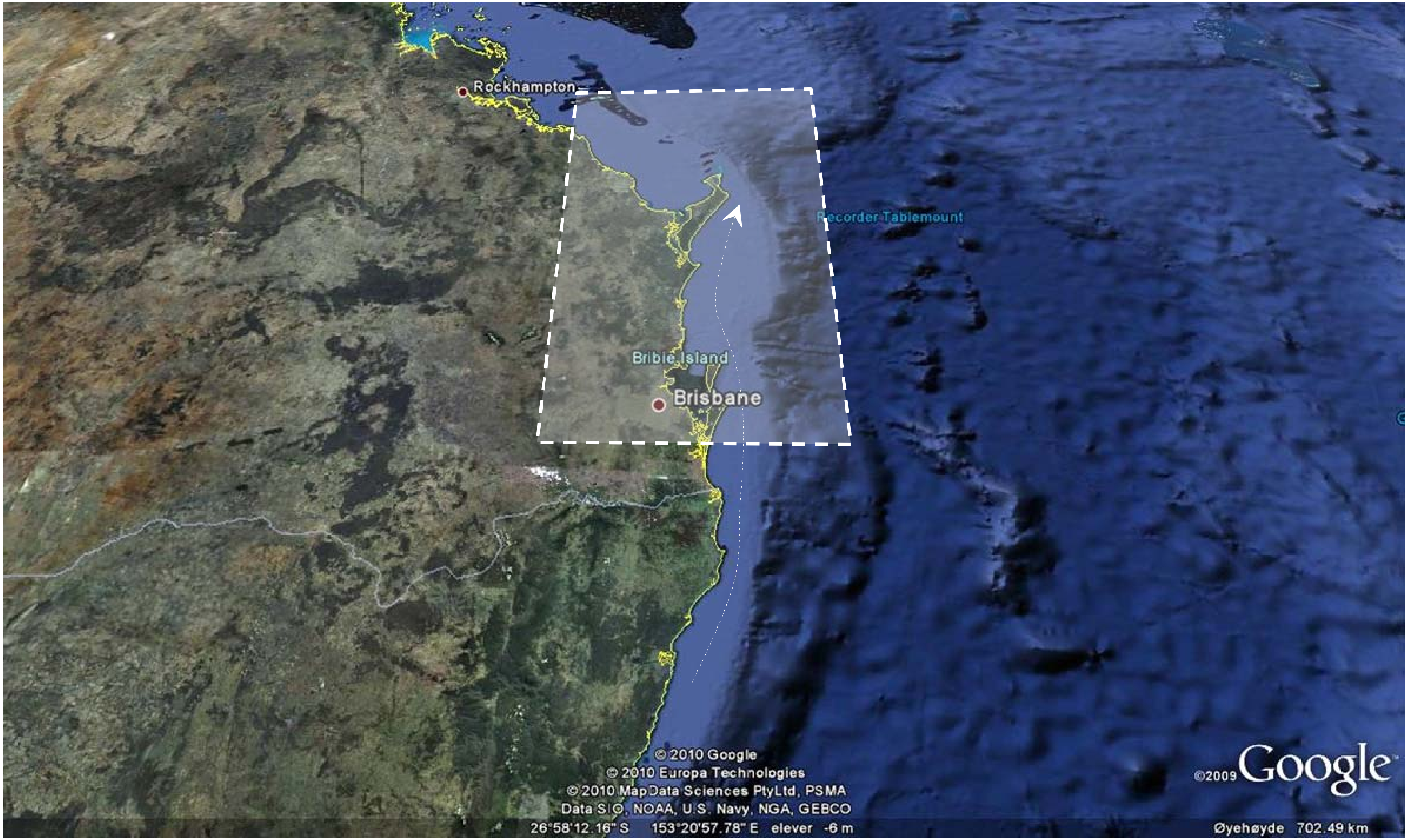
Timing and spatial partitioning of deep-water processes, sediments and surfaces



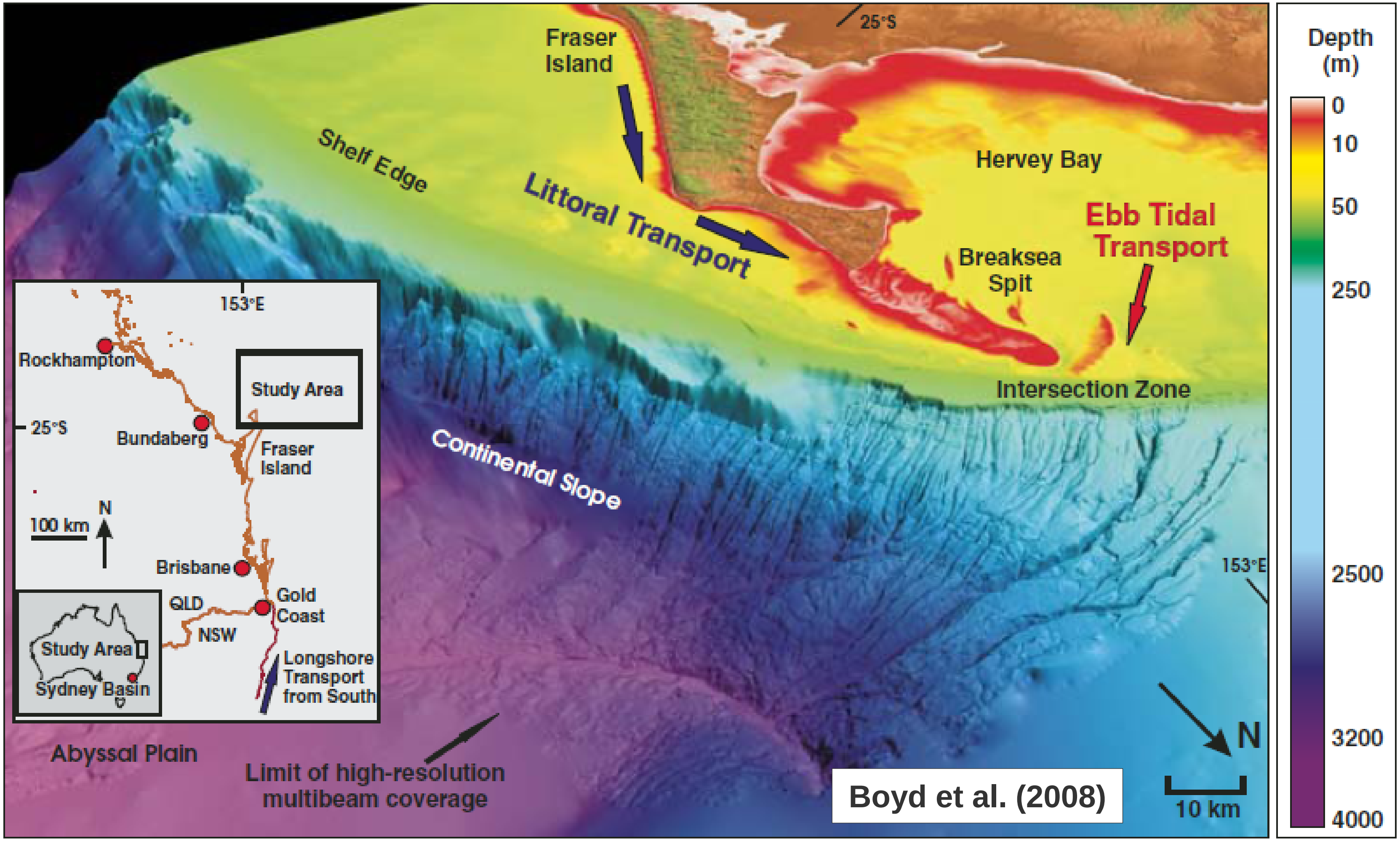


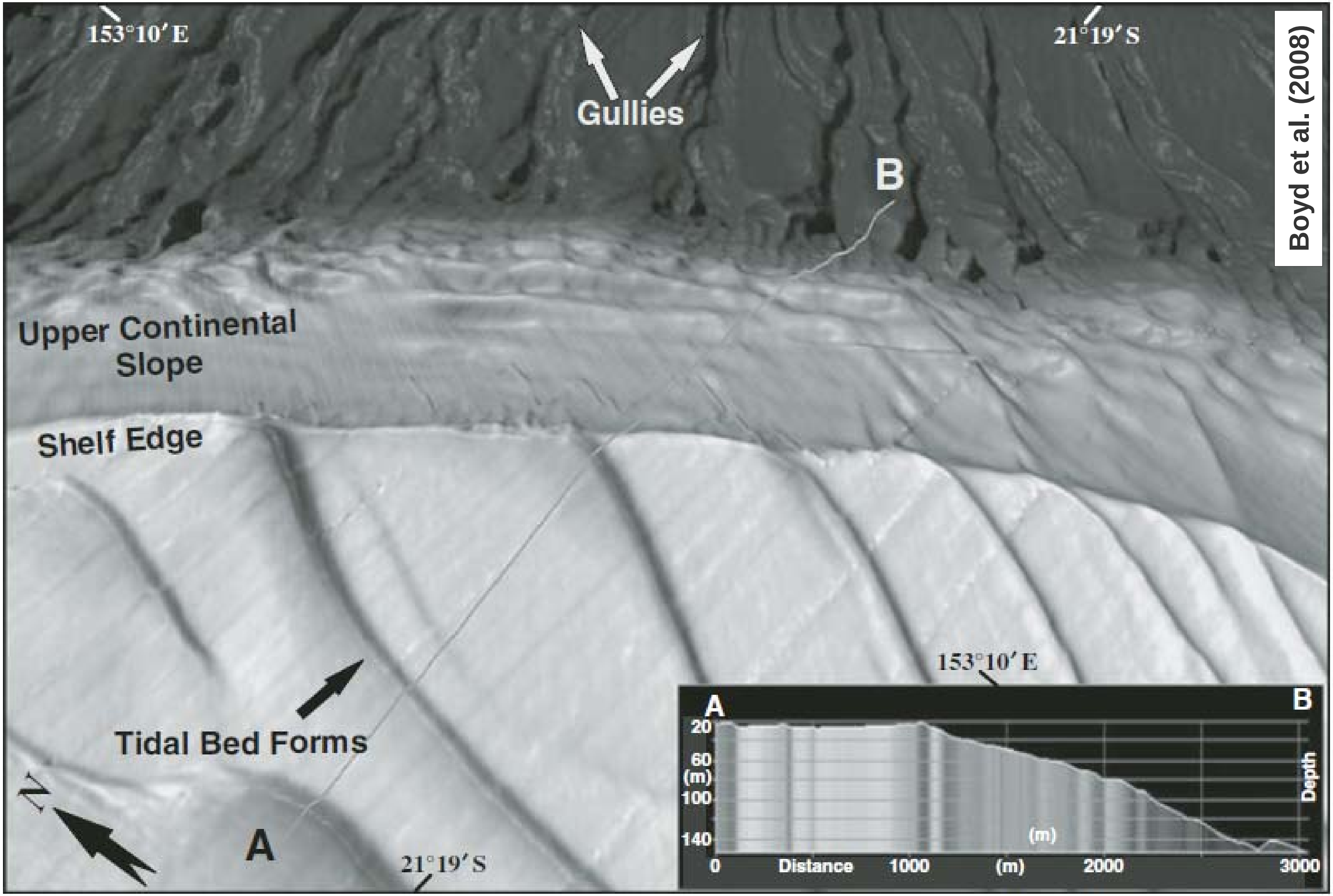
Courtesy of W. Helland-Hansen

Shelf morphology and transport

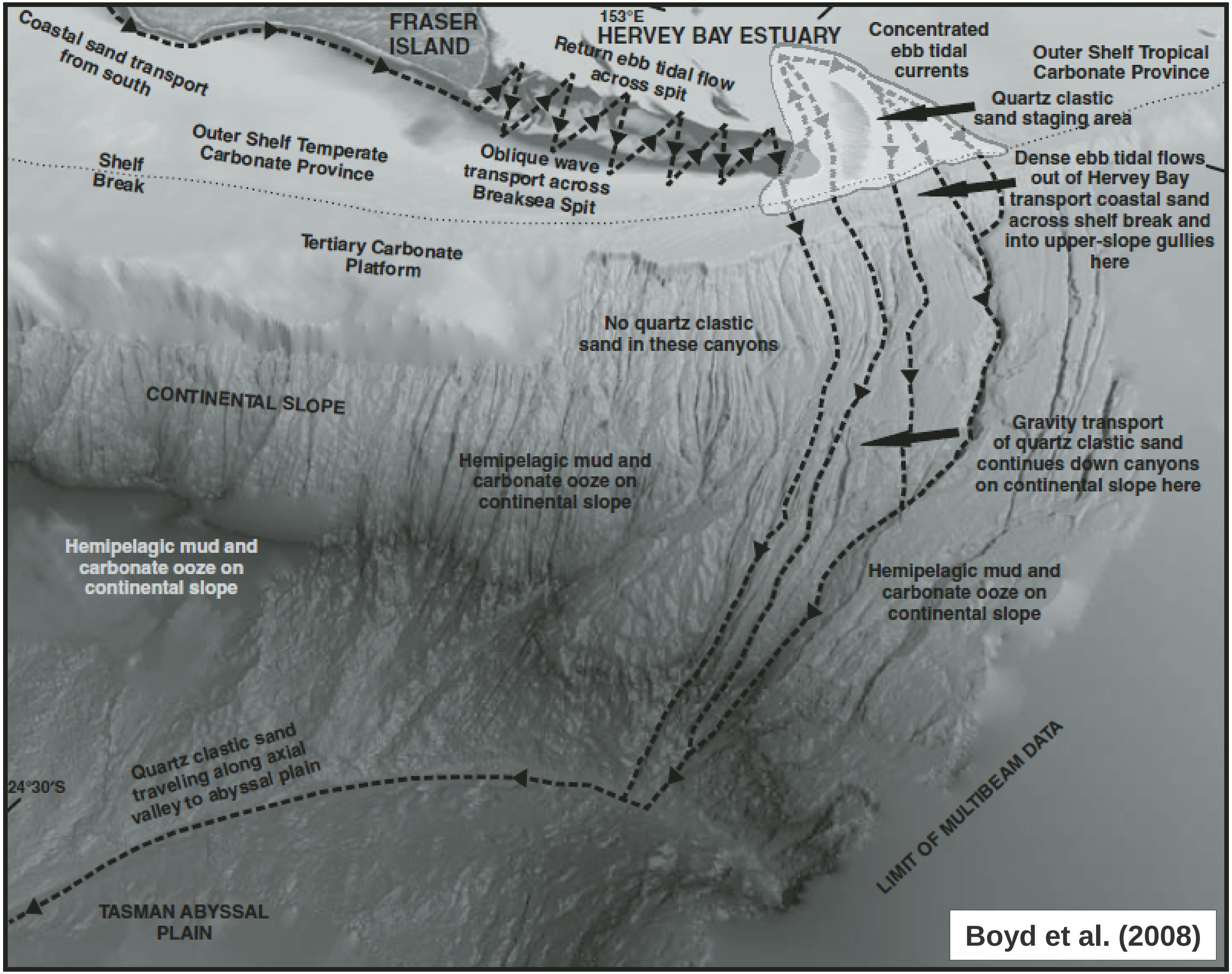


Shelf morphology, processes, deep-water supply at highstand



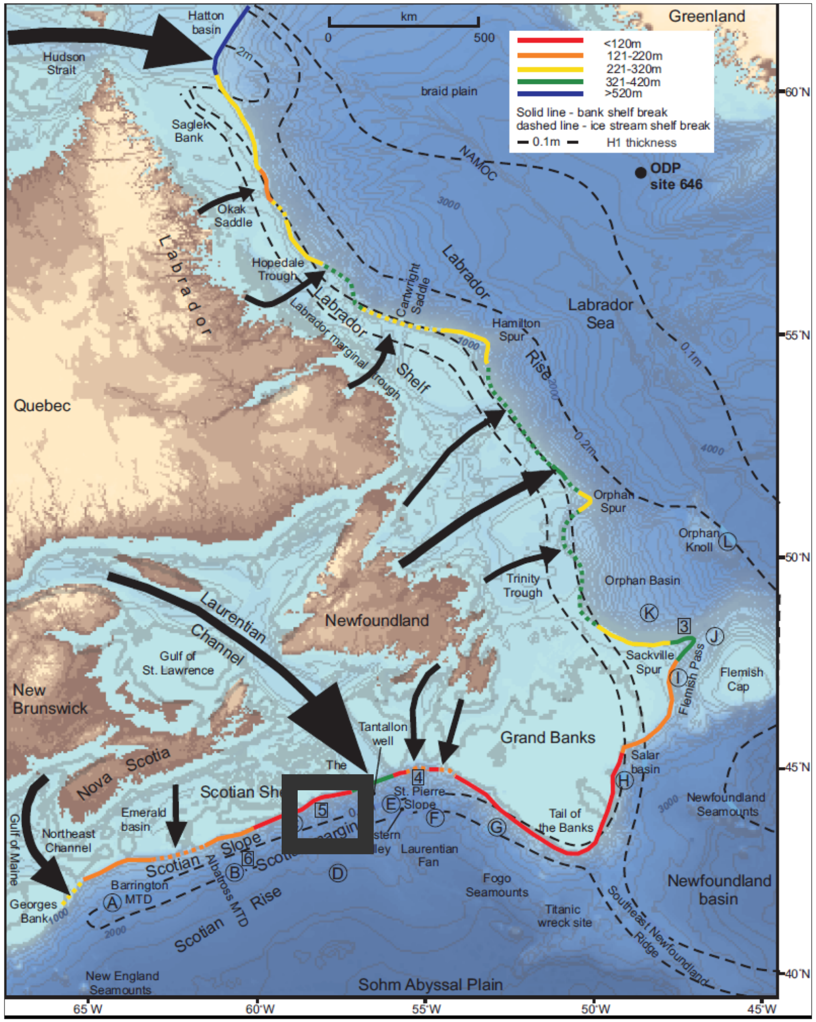


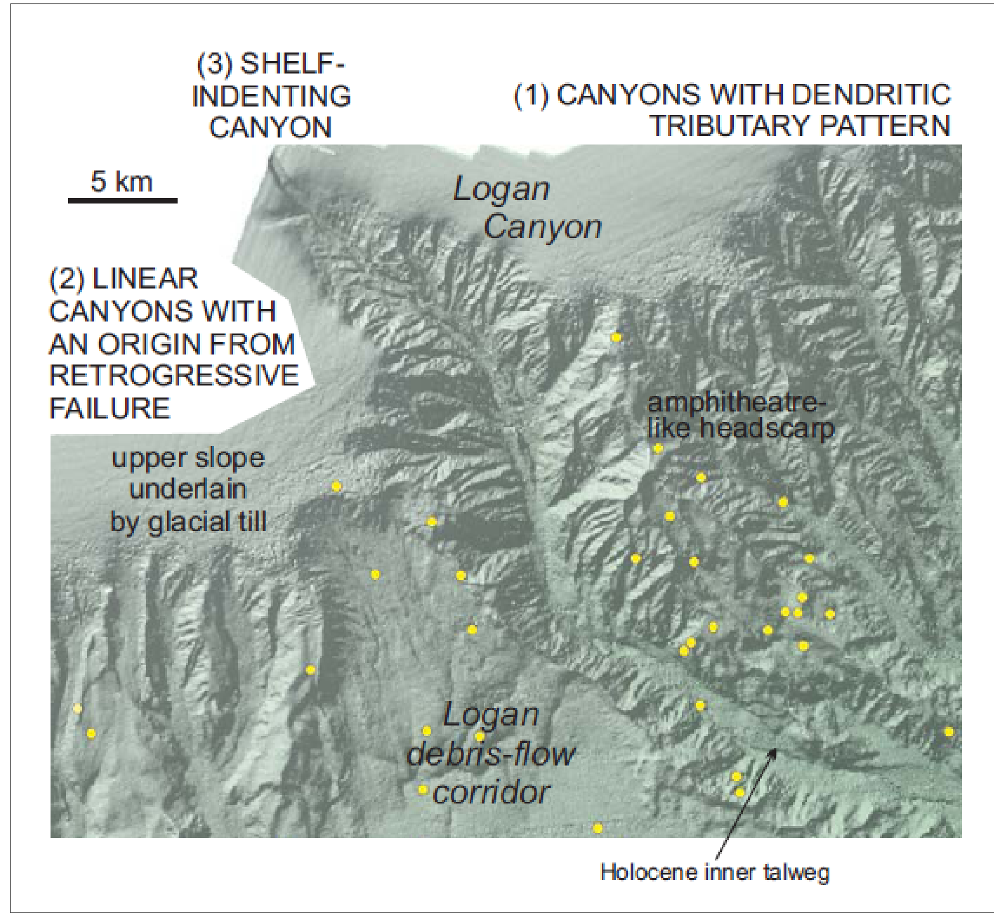
153°10′E
21°19′S
Gullies
Boyd et al. (2008)
B
Upper Continental Slope
Shelf Edge
Tidal Bed Forms
N
A
21°19′S
153°10′E
A
B
20
60
(m)
100
140
Depth
(m)
0
Distance
1000
(m)
2000
3000



Coastal sand transport from south
FRASER ISLAND
153°E
HERVEY BAY ESTUARY
Concentrated ebb tidal currents
Outer Shelf Tropical Carbonate Province
Return ebb tidal flow across spit
Quartz clastic sand staging area
Outer Shelf Temperate Carbonate Province
Shelf Break
Oblique wave transport across Breaksea Spit
Dense ebb tidal flows out of Hervey Bay transport coastal sand across shelf break and into upper-slope gullies here
Tertiary Carbonate Platform
No quartz clastic sand in these canyons
CONTINENTAL SLOPE
Gravity transport of quartz clastic sand continues down canyons on continental slope here
Hemipelagic mud and carbonate ooze on continental slope
Hemipelagic mud and carbonate ooze on continental slope
Hemipelagic mud and carbonate ooze on continental slope
24°30′S
Quartz clastic sand traveling along axial valley to abyssal plain
LIMIT OF MULTIBEAM DATA
TASMAN ABYSSAL PLAIN
Boyd et al. (2008)

Canyon variability: role of shelf incision

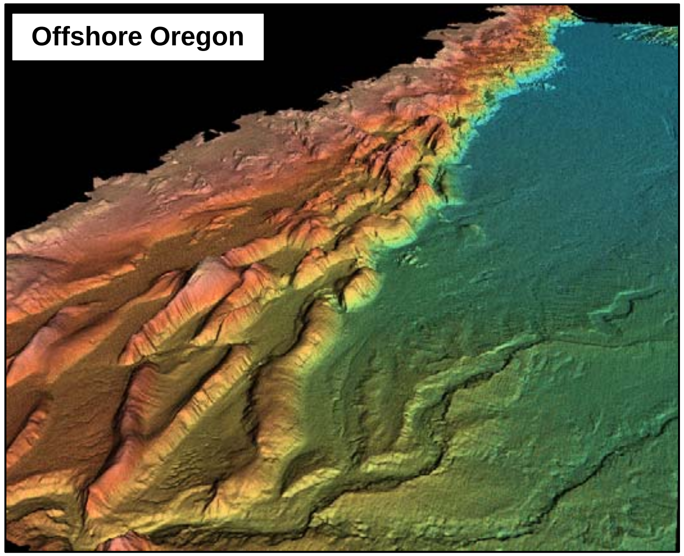


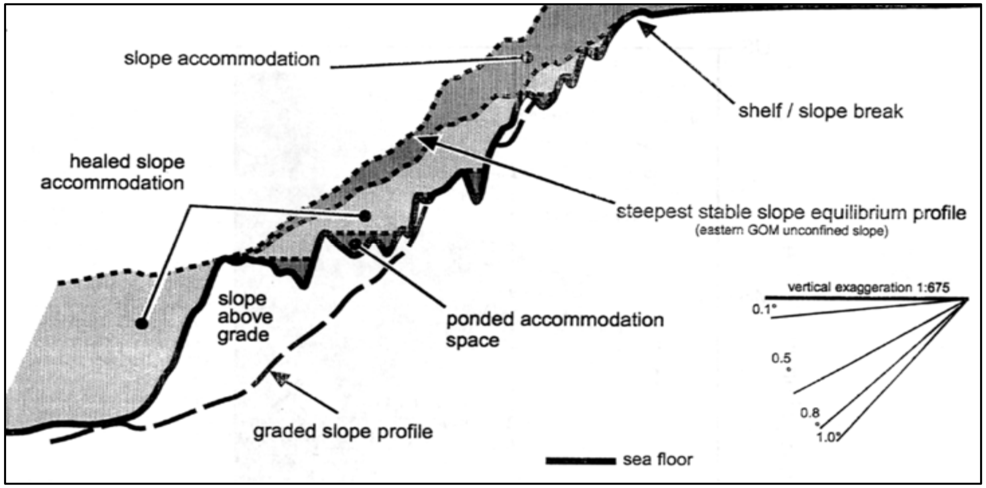


Piper (2006)

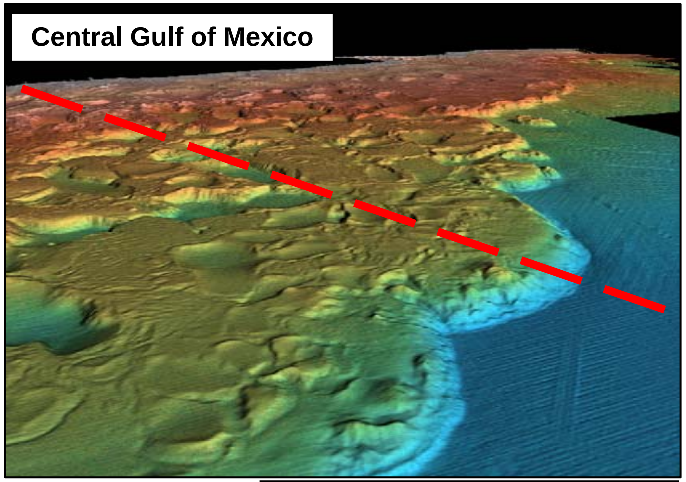
Slope accommodation

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



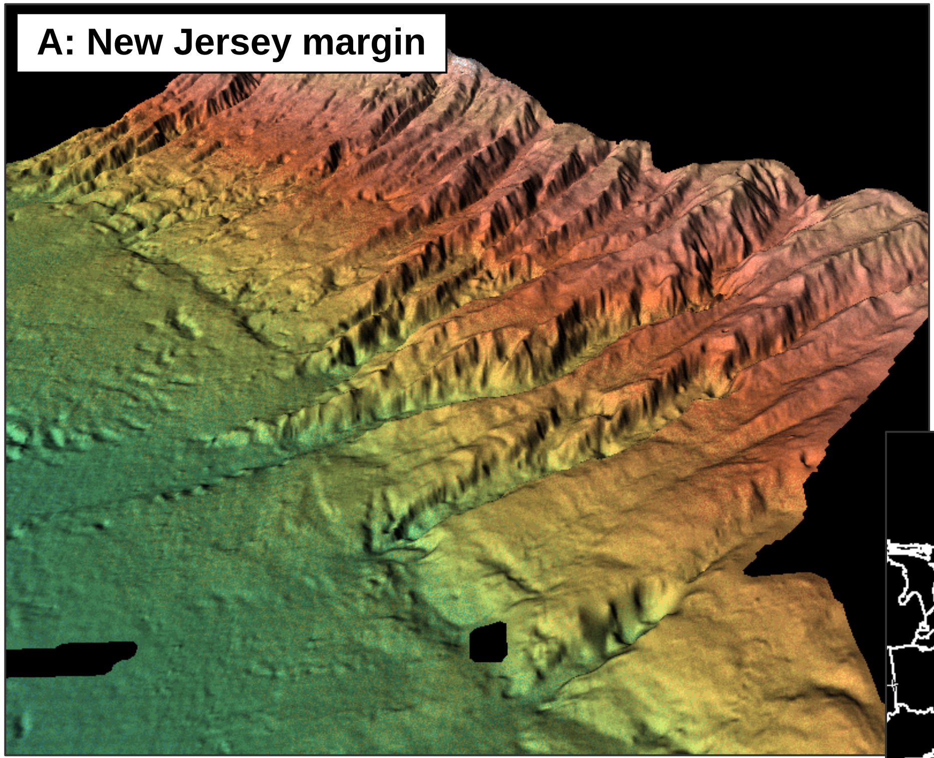


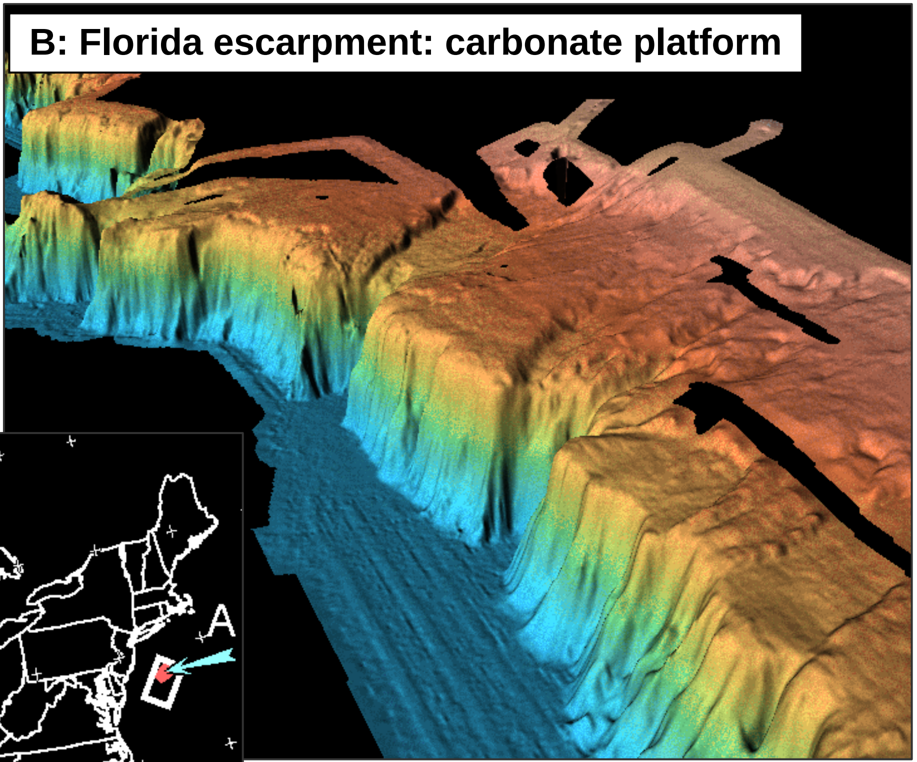
From Prather (2003)

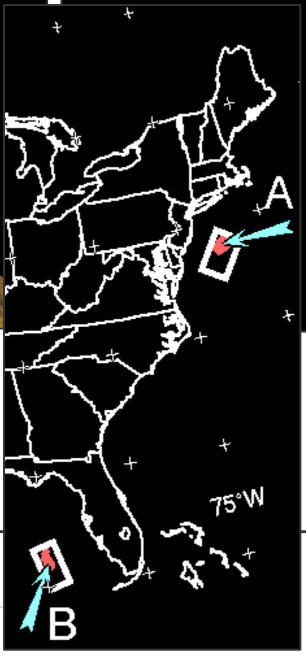


Images from:
http://www.ldeo.columbia.edu

Modern slope morphology (1)



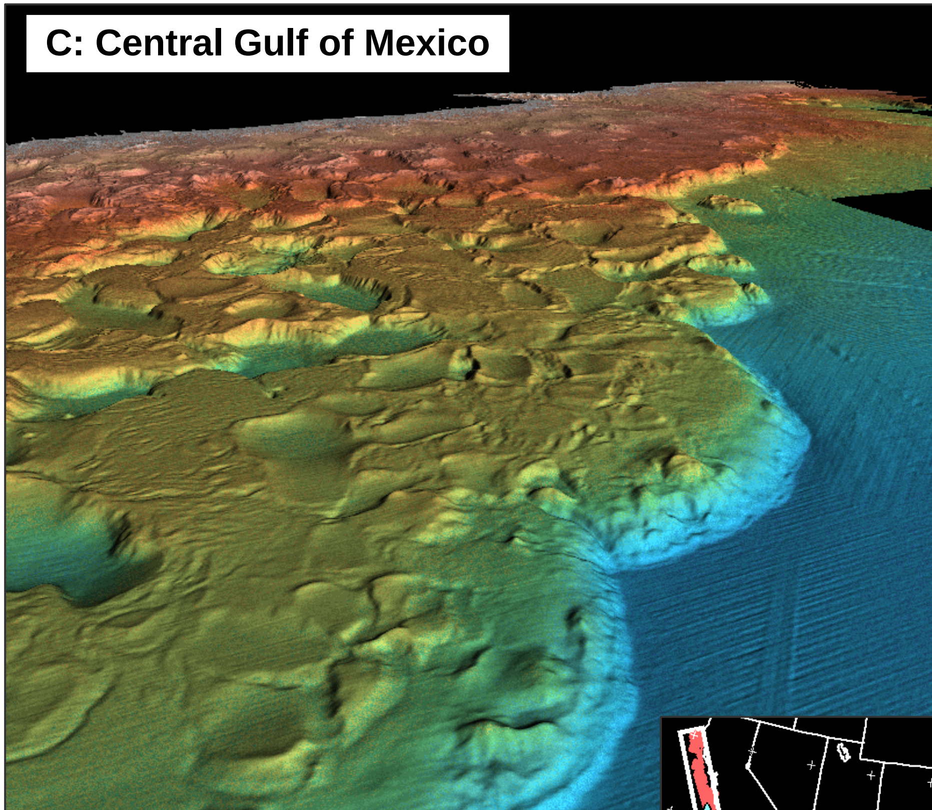


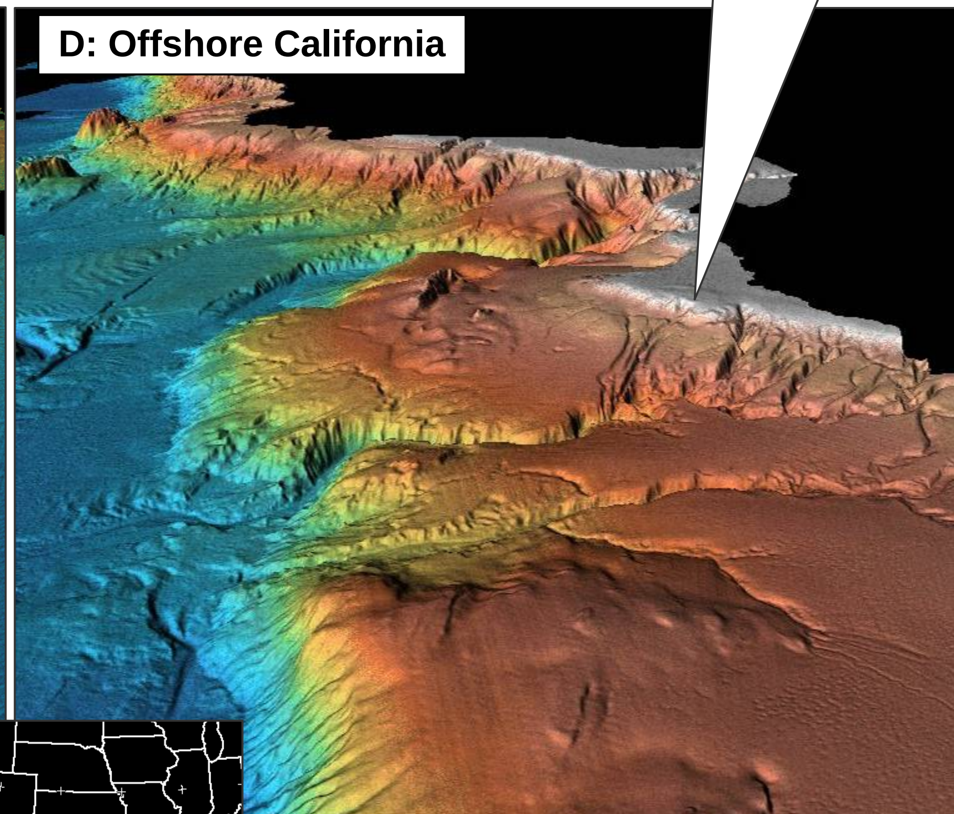


Images from:
http://www.ldeo.columbia.edu

Modern slope morphology (2)

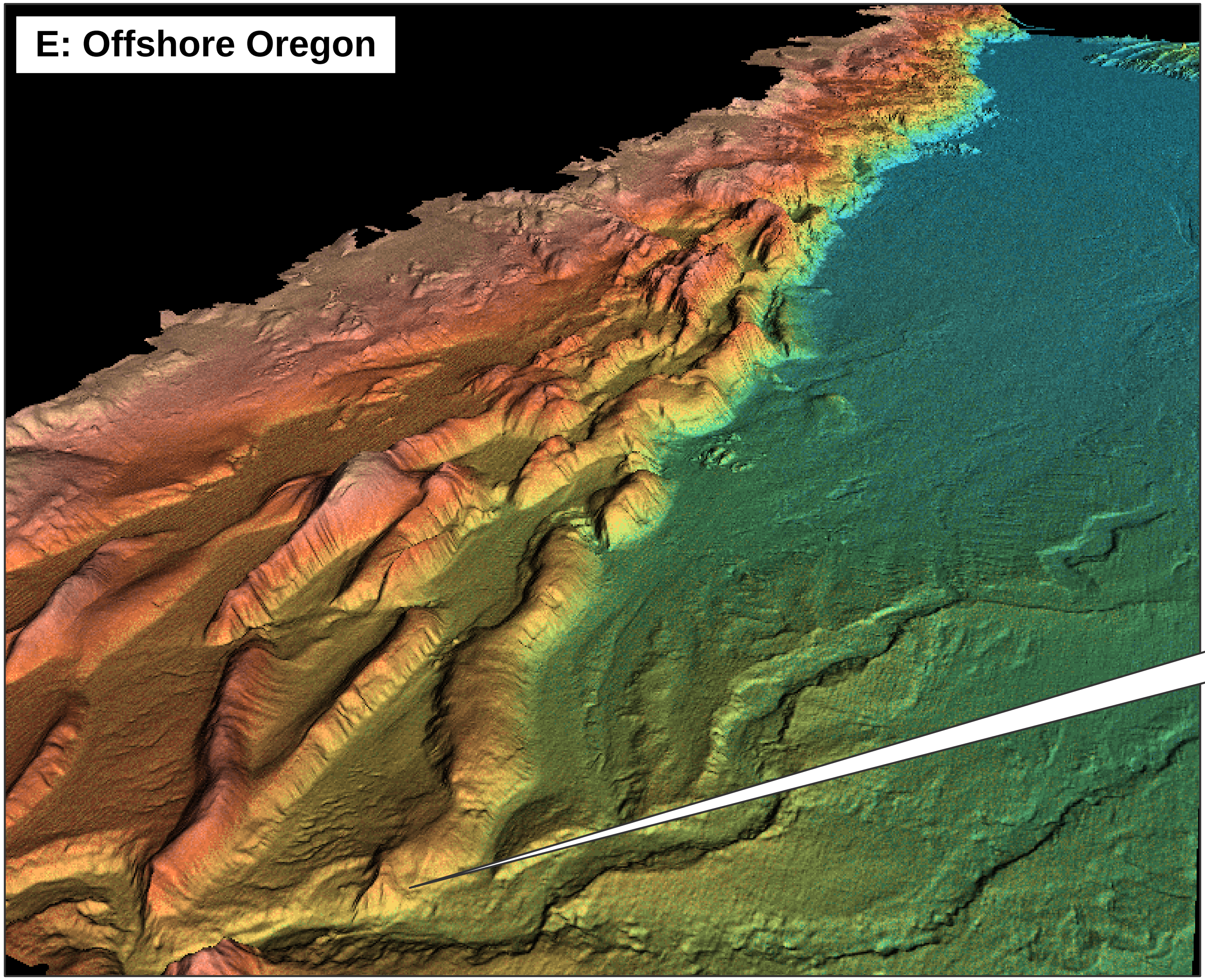
Sediment transfer from shelf to slope at highstand (narrow shelf)





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

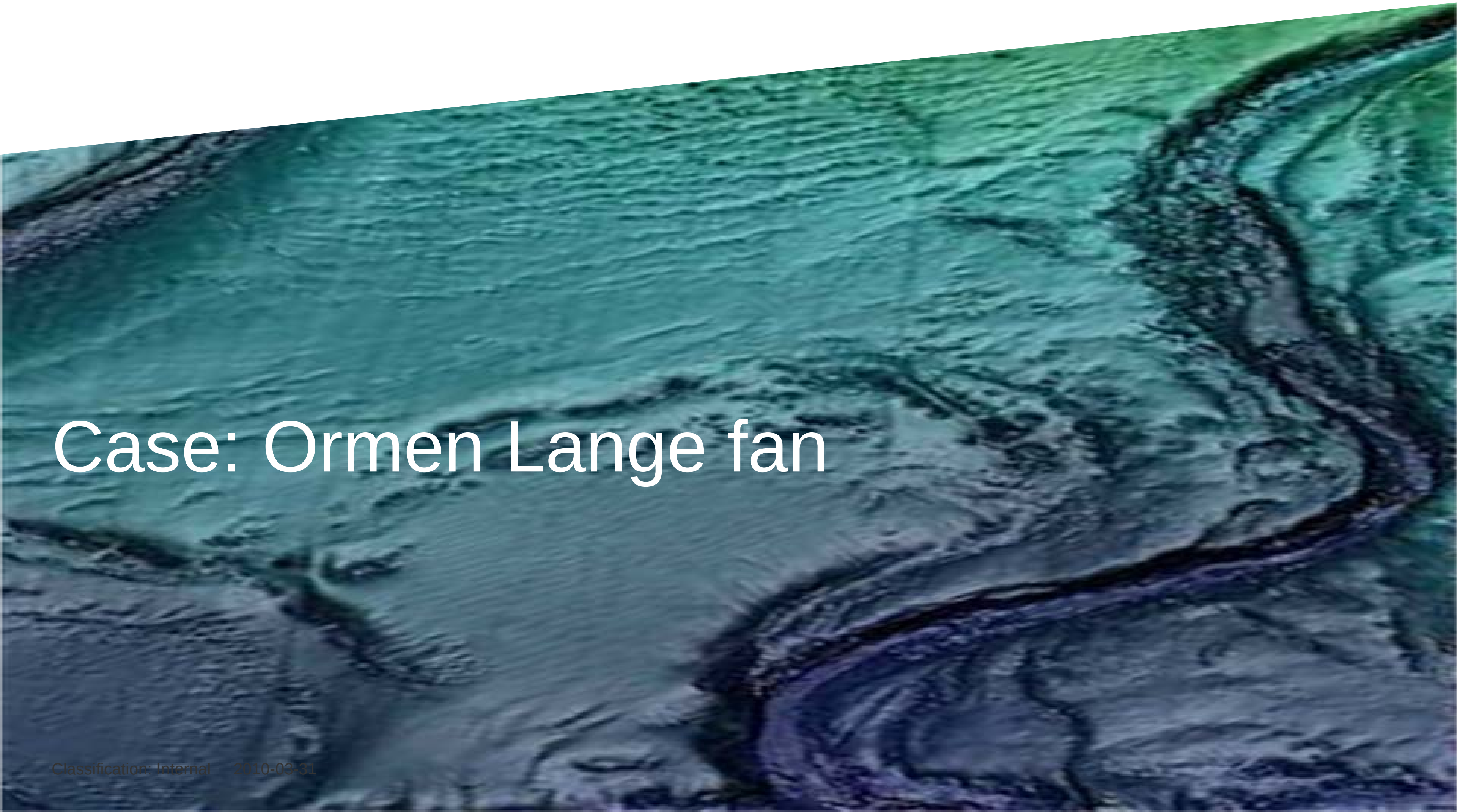
Modern slope morphology (3)



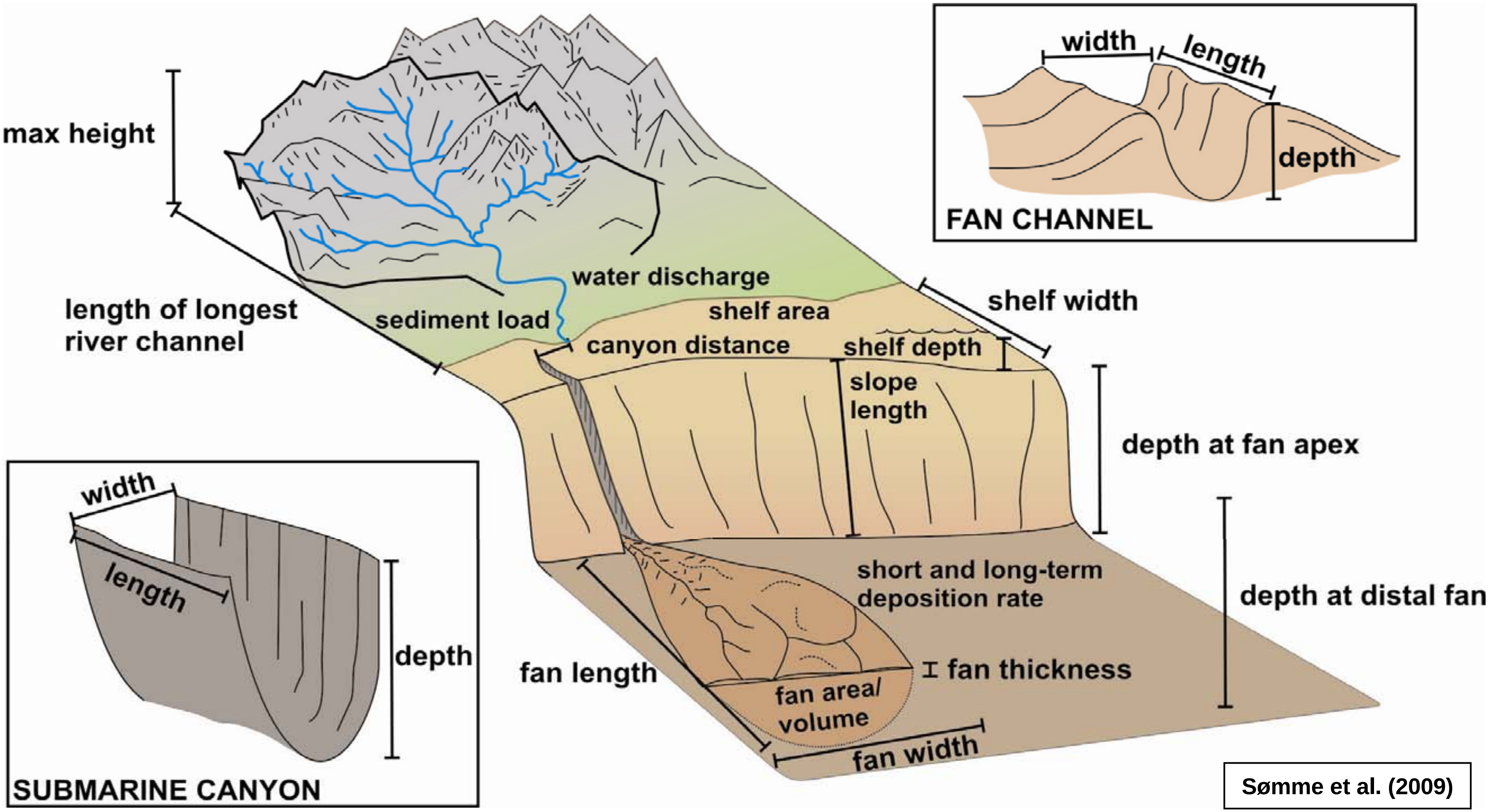
Sediment transfer through slopes?

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

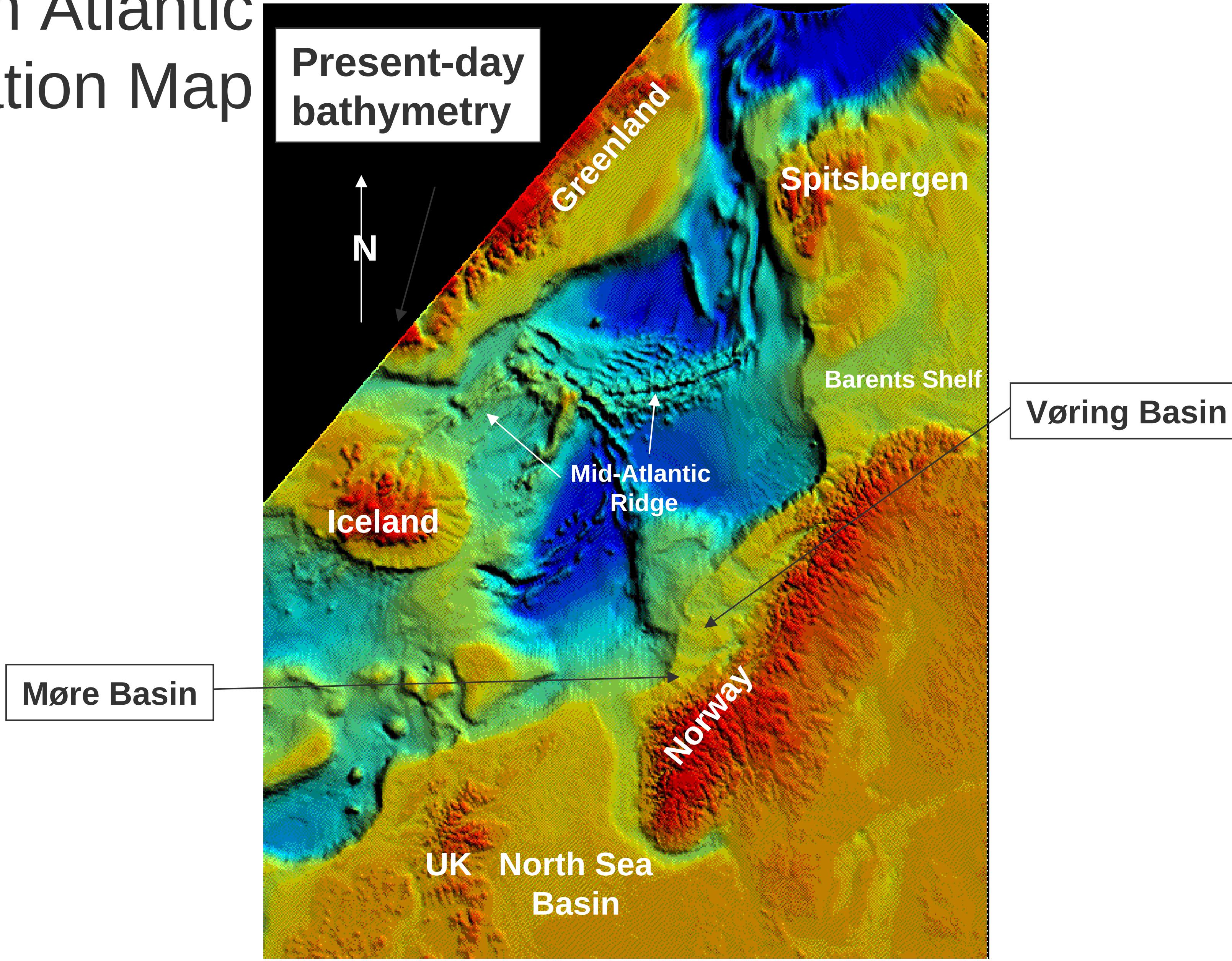
Case: Ormen Lange fan



Complete source-to-sink approach

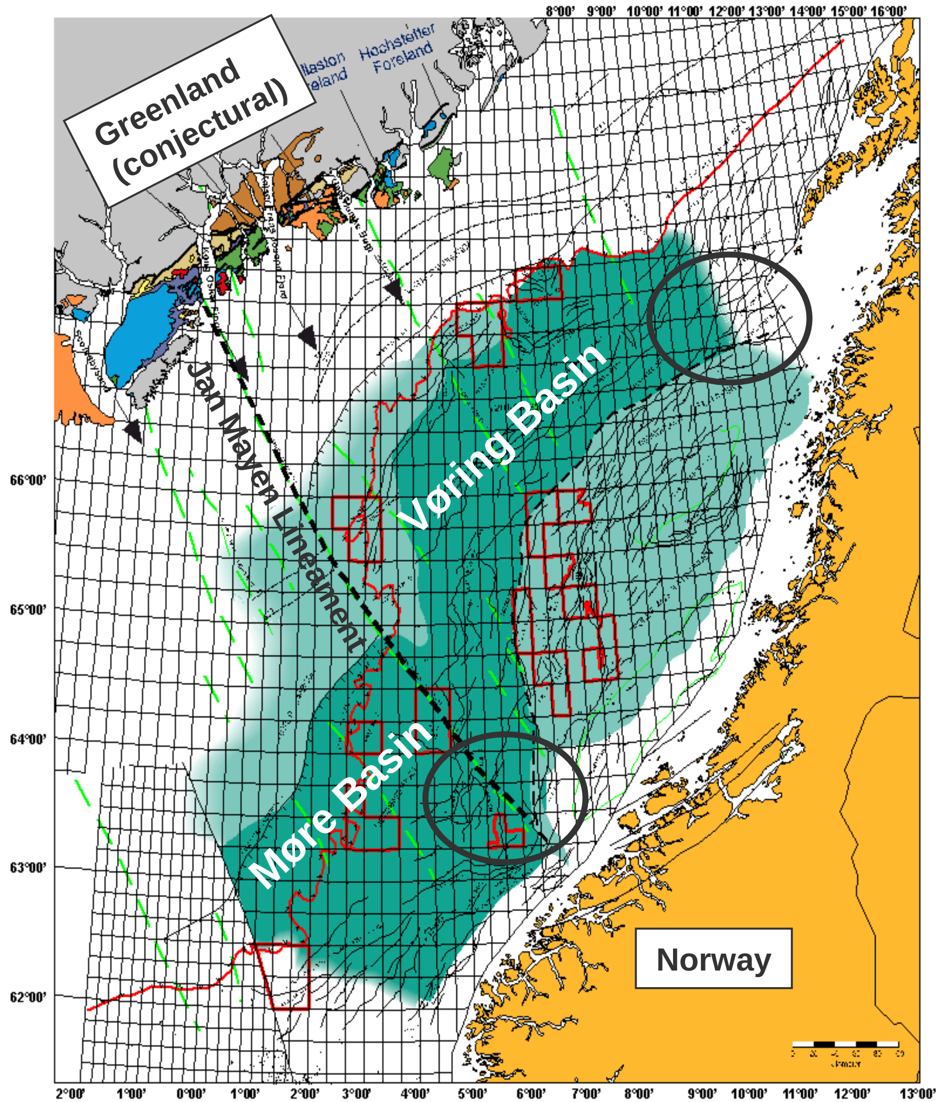


North Atlantic Location Map

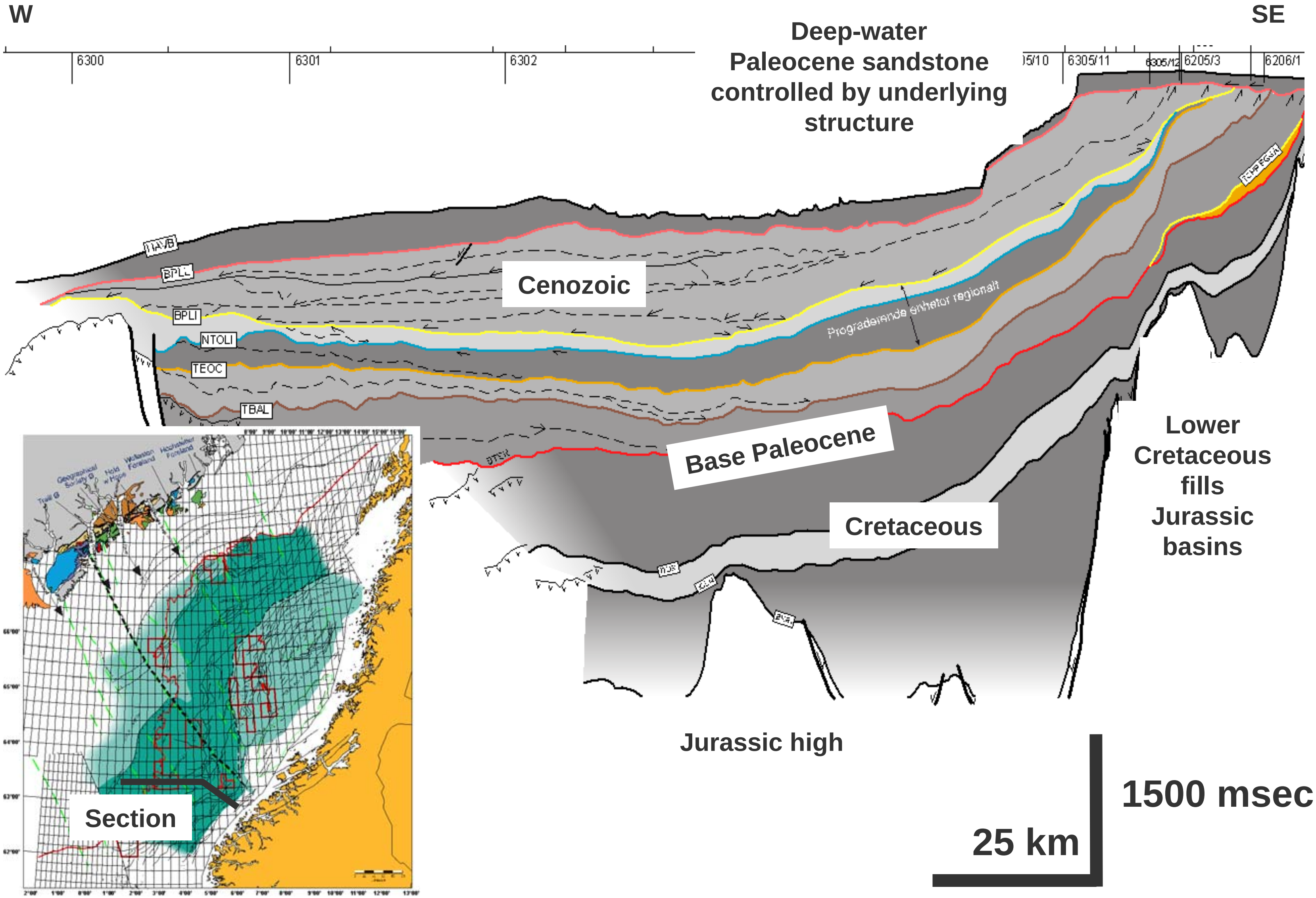


Geological Setting

- 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

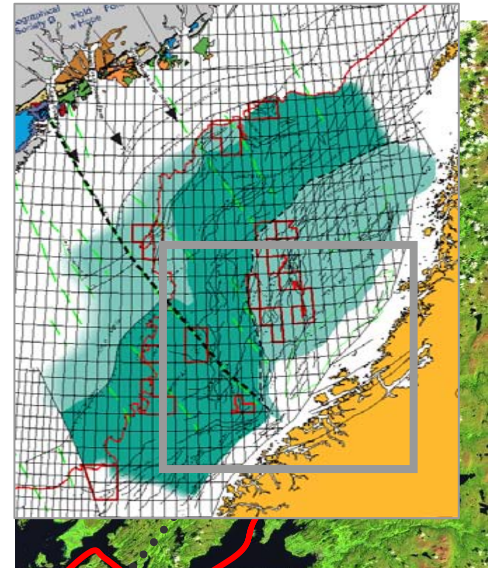


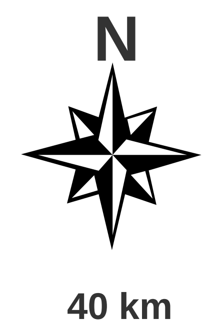
Paleocene Offshore Mid-Norway

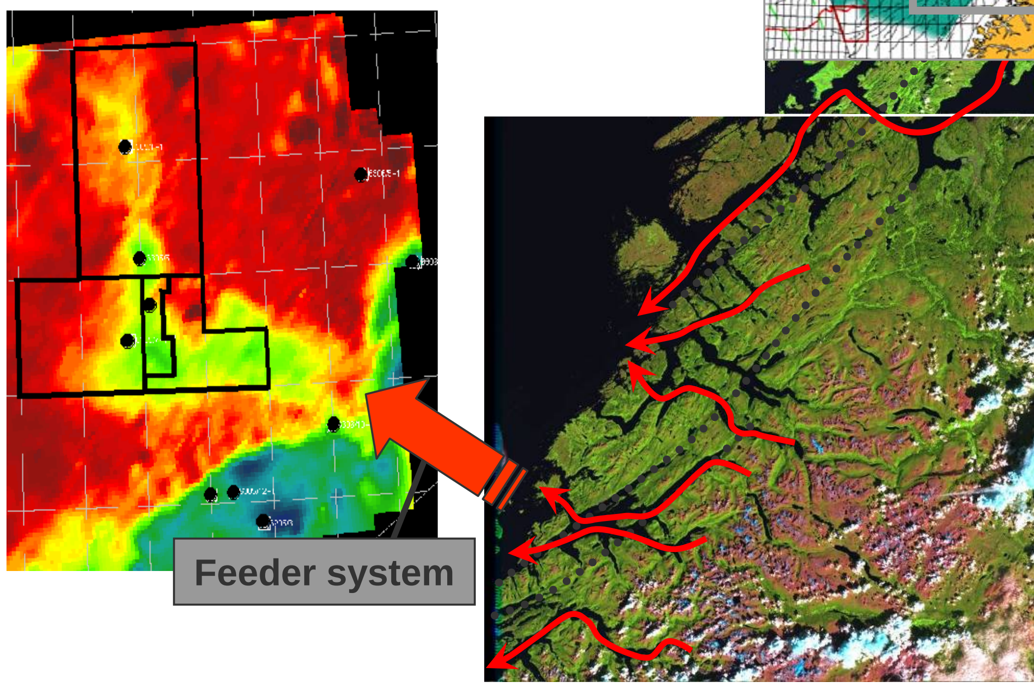


Paleocene Offshore Mid-Norway

- 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

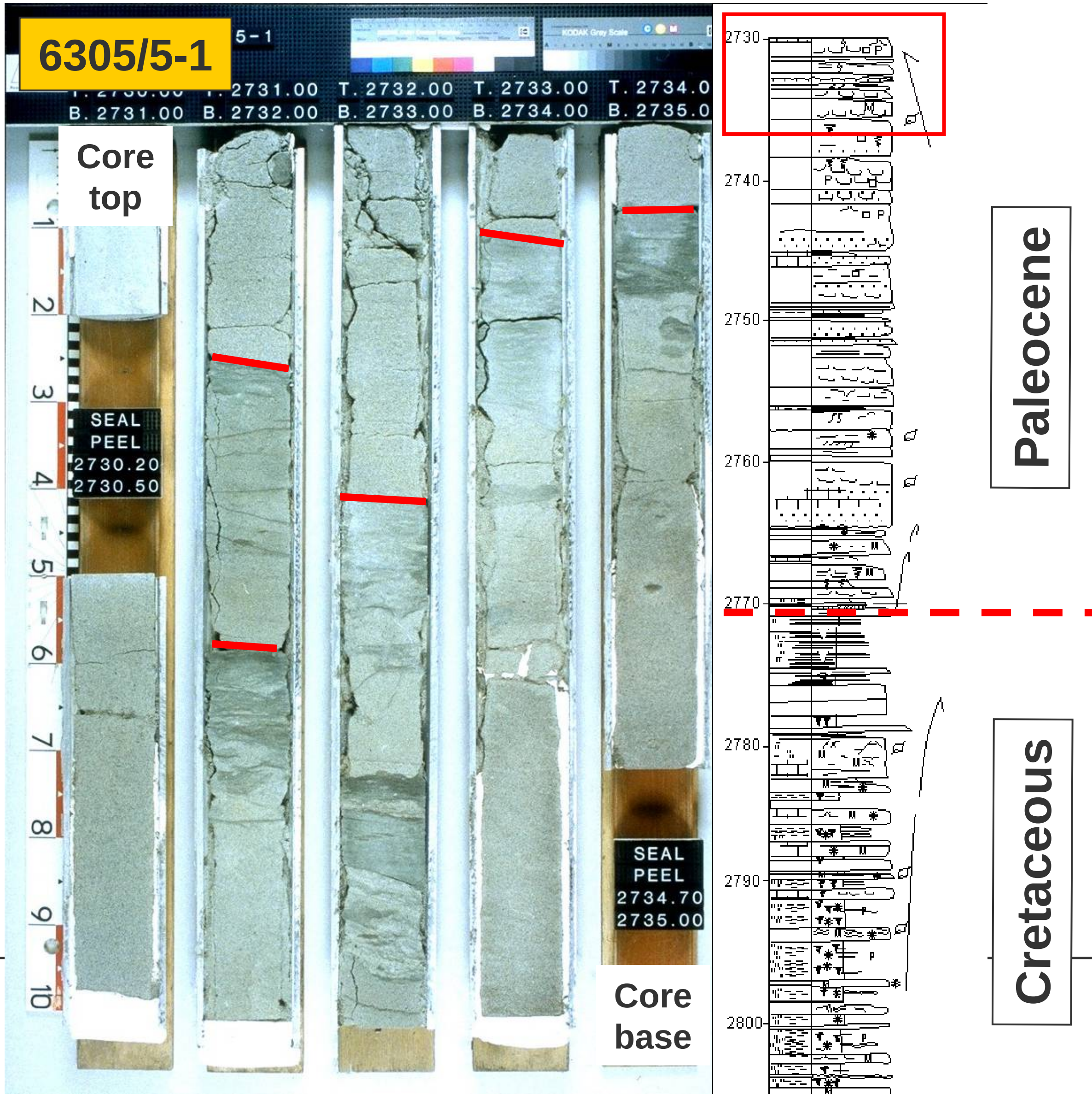






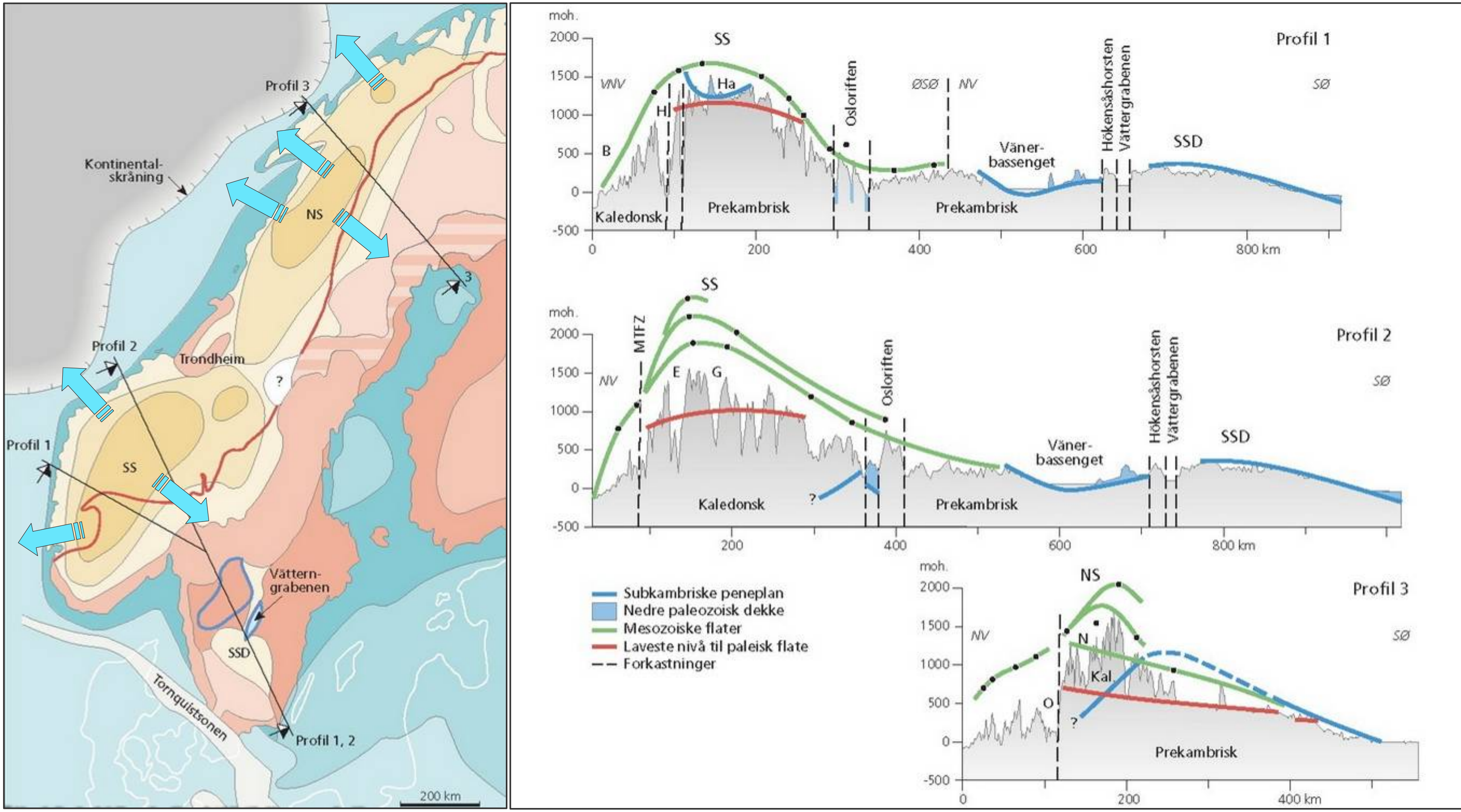
Martinsen et al. (2002)

Ormen Lange: Basin Floor

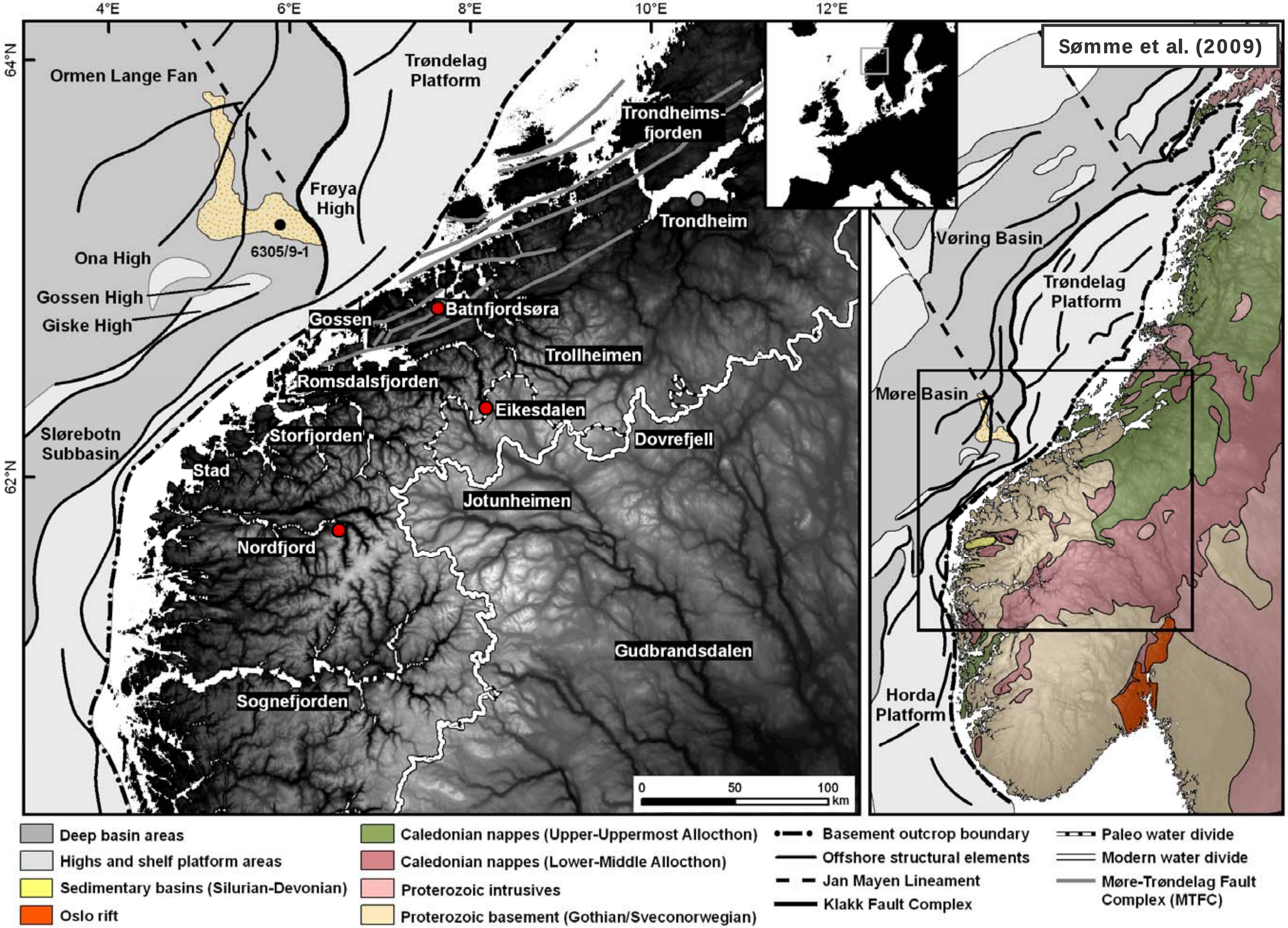


- Continuous sandier-upward succession from Cretaceous to Paleocene
- Older than basin margin deposits
- Sheet- and channelized turbidites in a sand-rich fan
- Beds <1.5 m in thickness

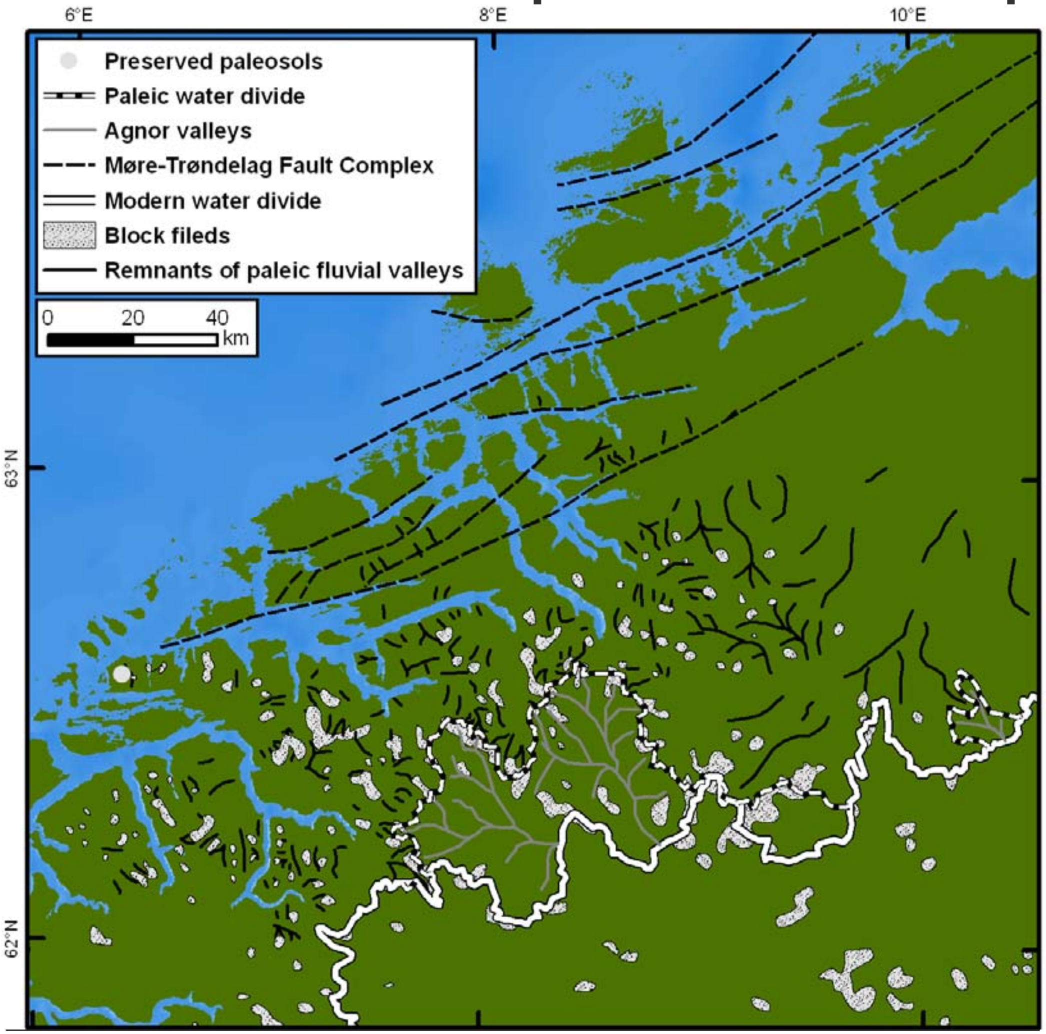
1st order topography: age and role?

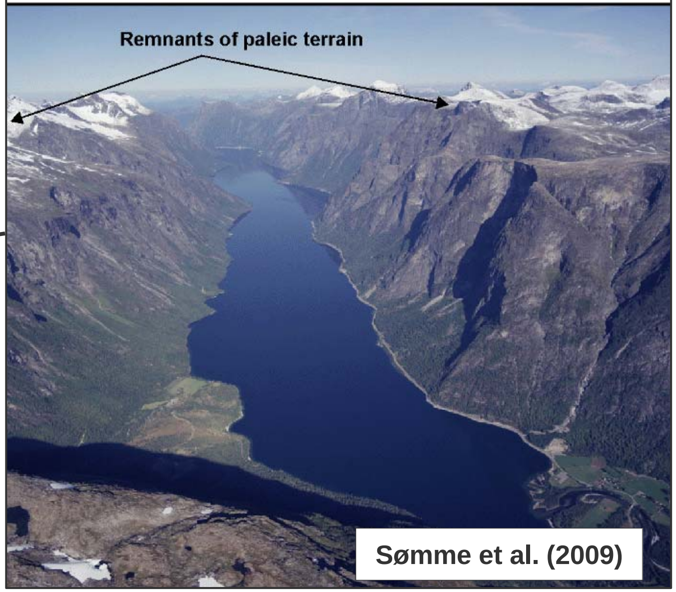


Modified from Lidmar-Bergstrøm & Näslund (2002)


Sømme et al. (2009)
4°E
6°E
8°E
10°E
12°E
64°N
62°N
Ormen Lange Fan
Trøndelag Platform
Trondheims-fjorden
Frøya High
Trondheim
6305/9-1
Ona High
Gossen High
Giske High
Gossen
Batnfjordsøra
Trollheimen
Romsdalsfjorden
Eikesdalen
Slørebotn Subbasin
Storfjorden
Dovrefjell
Stad
Jotunheimen
Nordfjord
Gudbrandsdalen
Sognefjorden
0
50
100
km
Vøring Basin
Trøndelag Platform
Møre Basin
Horda Platform
Deep basin areas
Highs and shelf platform areas
Sedimentary basins (Silurian-Devonian)
Oslo rift
Caledonian nappes (Upper-Uppermost Allocthon)
Caledonian nappes (Lower-Middle Allocthon)
Proterozoic intrusives
Proterozoic basement (Gothian/Sveconorwegian)
Basement outcrop boundary
Offshore structural elements
Jan Mayen Lineament
Klakk Fault Complex
Paleo water divide
Modern water divide
Møre-Trøndelag Fault Complex (MTFC)

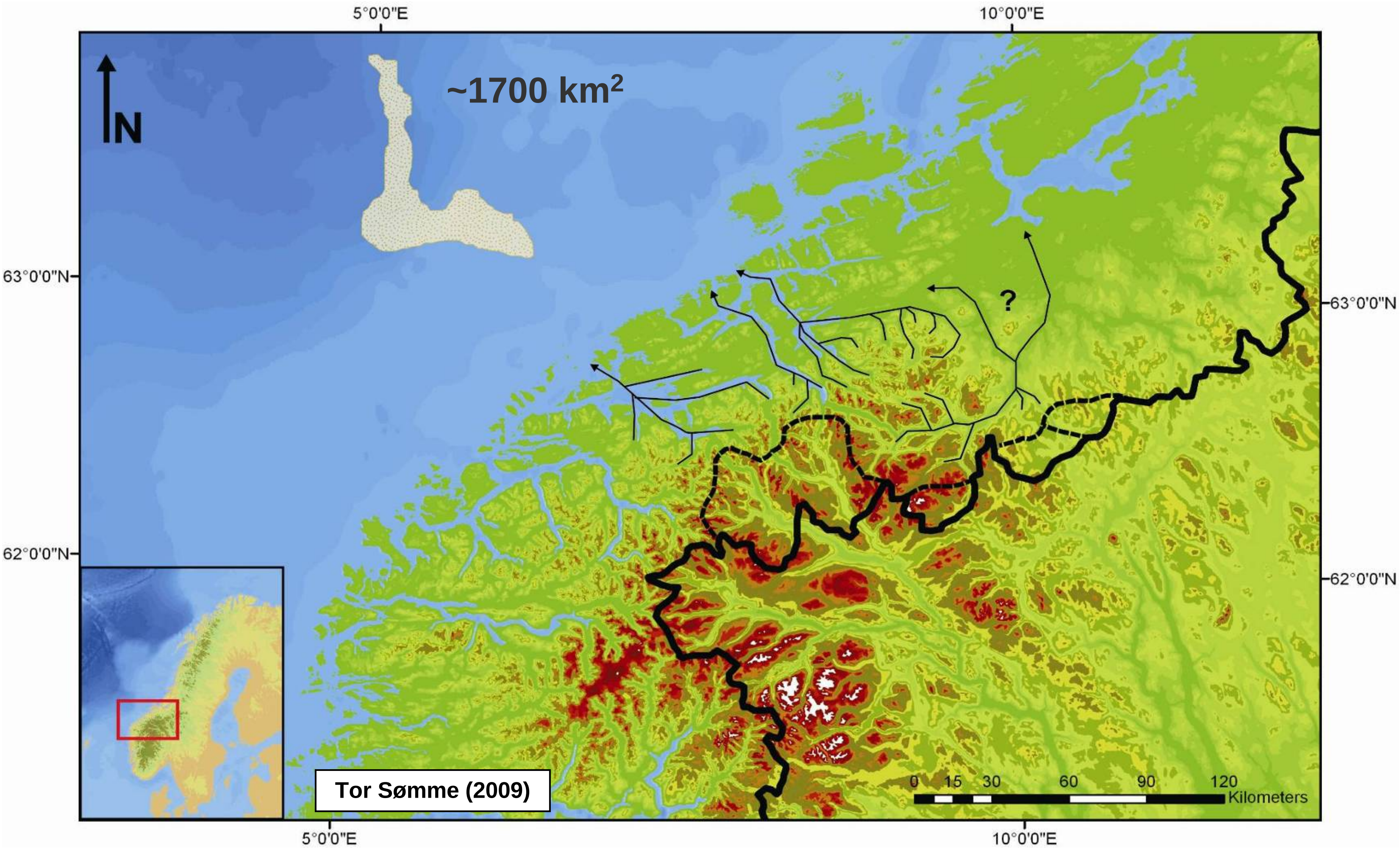
Source area: preserved topographic elements



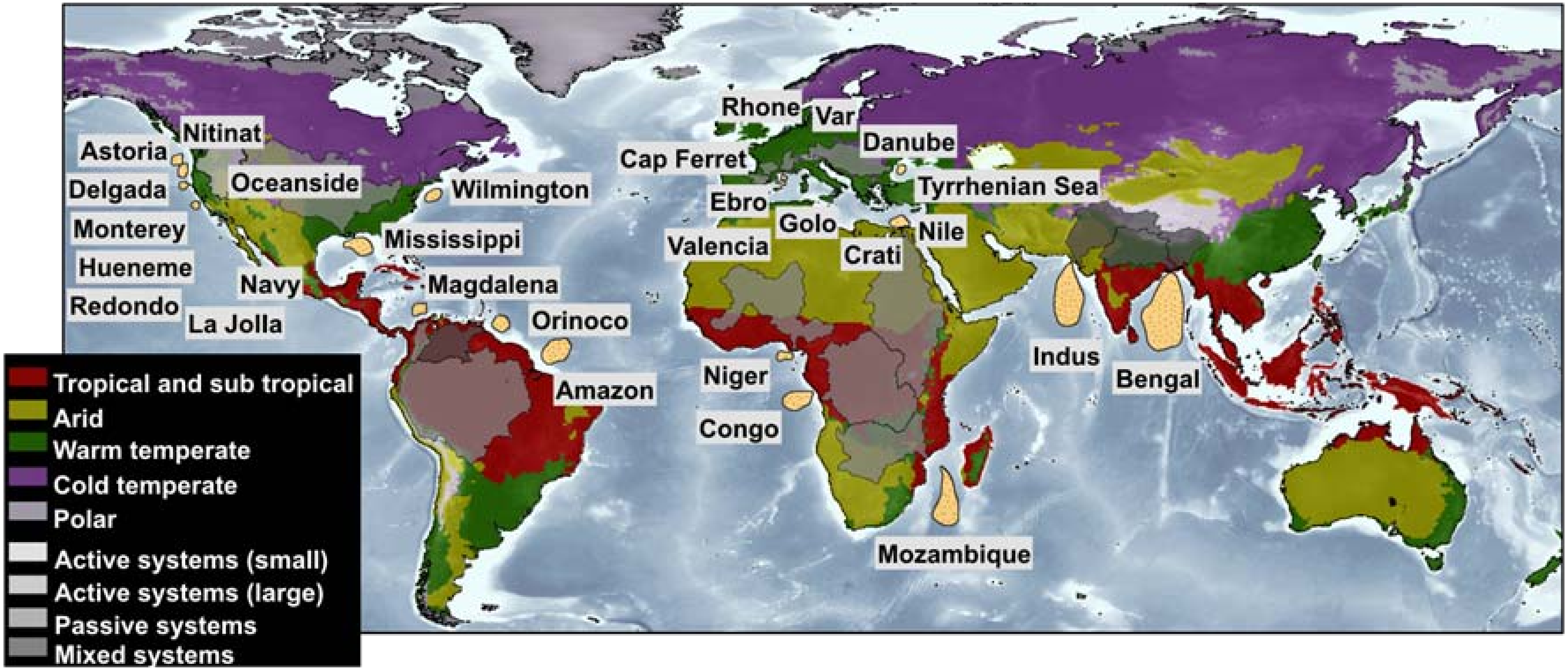


Sømme et al. (2009)

Drainage area and fan size: inversion



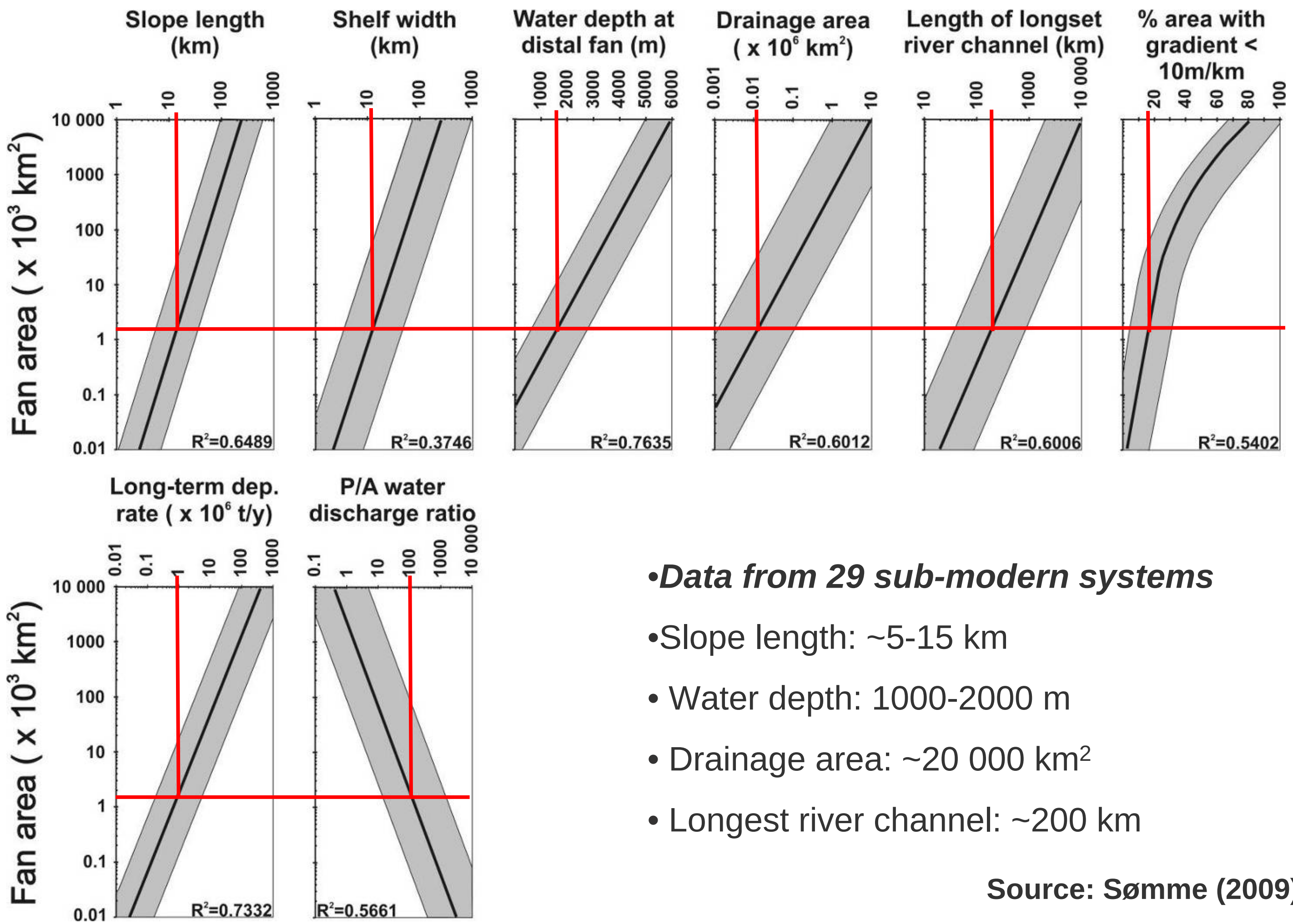
Database



Sømme et al. 2009 (Basin Research)

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

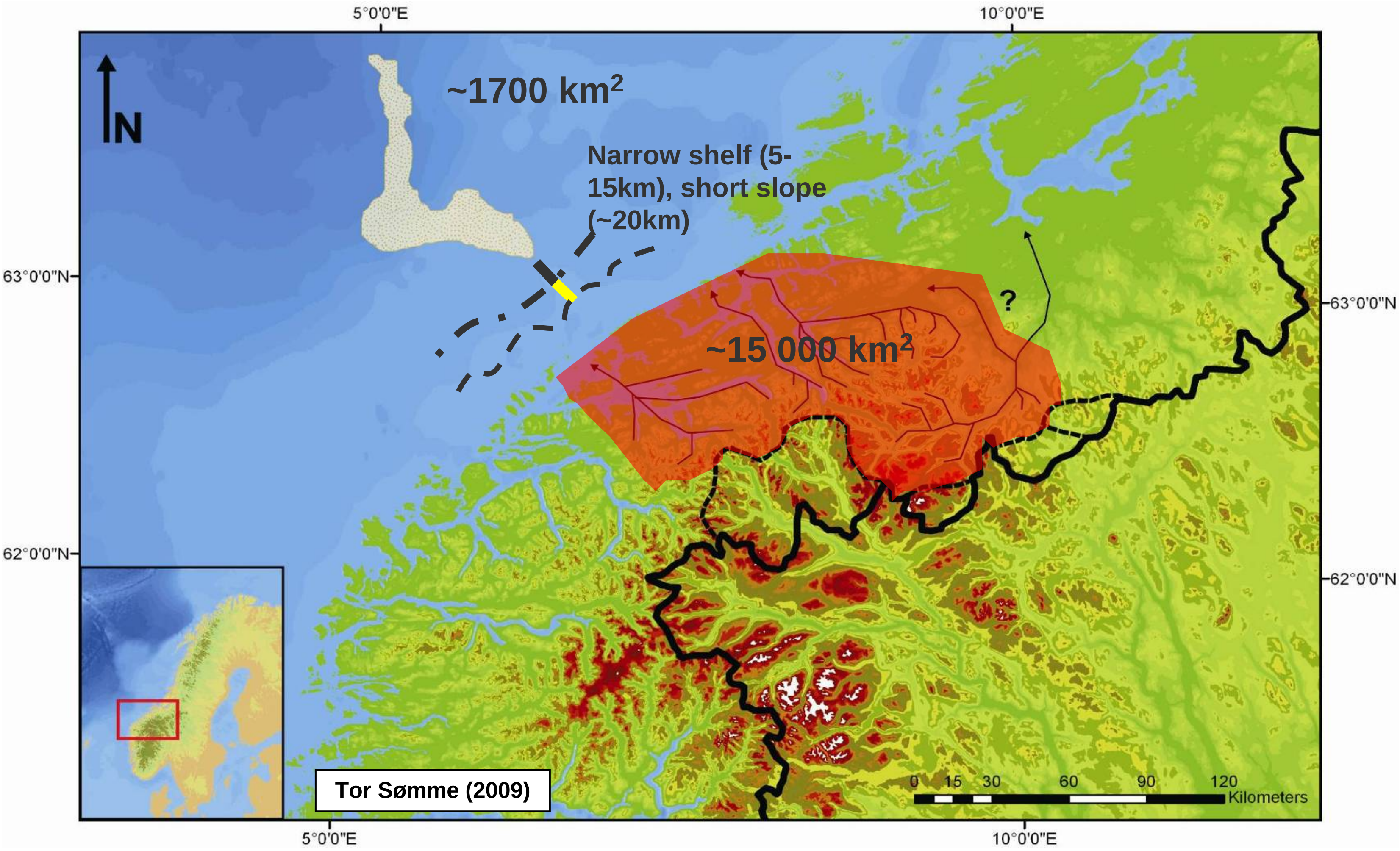
Analysis from global data



- ***Data from 29 sub-modern systems***
- Slope length: ~5-15 km
- Water depth: 1000-2000 m
- Drainage area: ~20 000 km^2
- Longest river channel: ~200 km

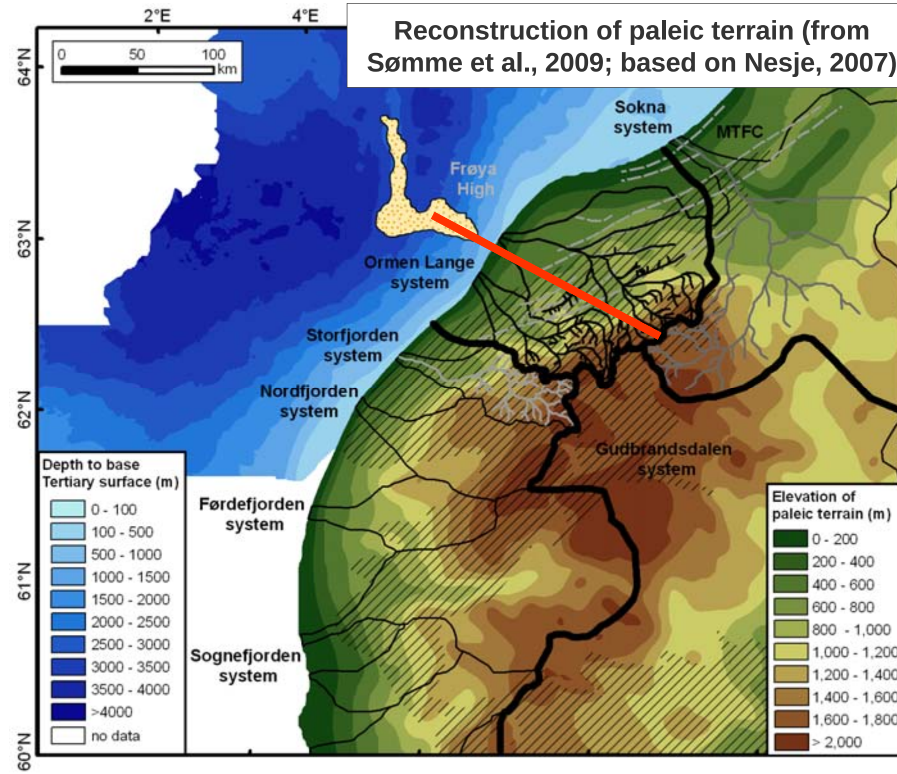
Source: Sømme (2009)

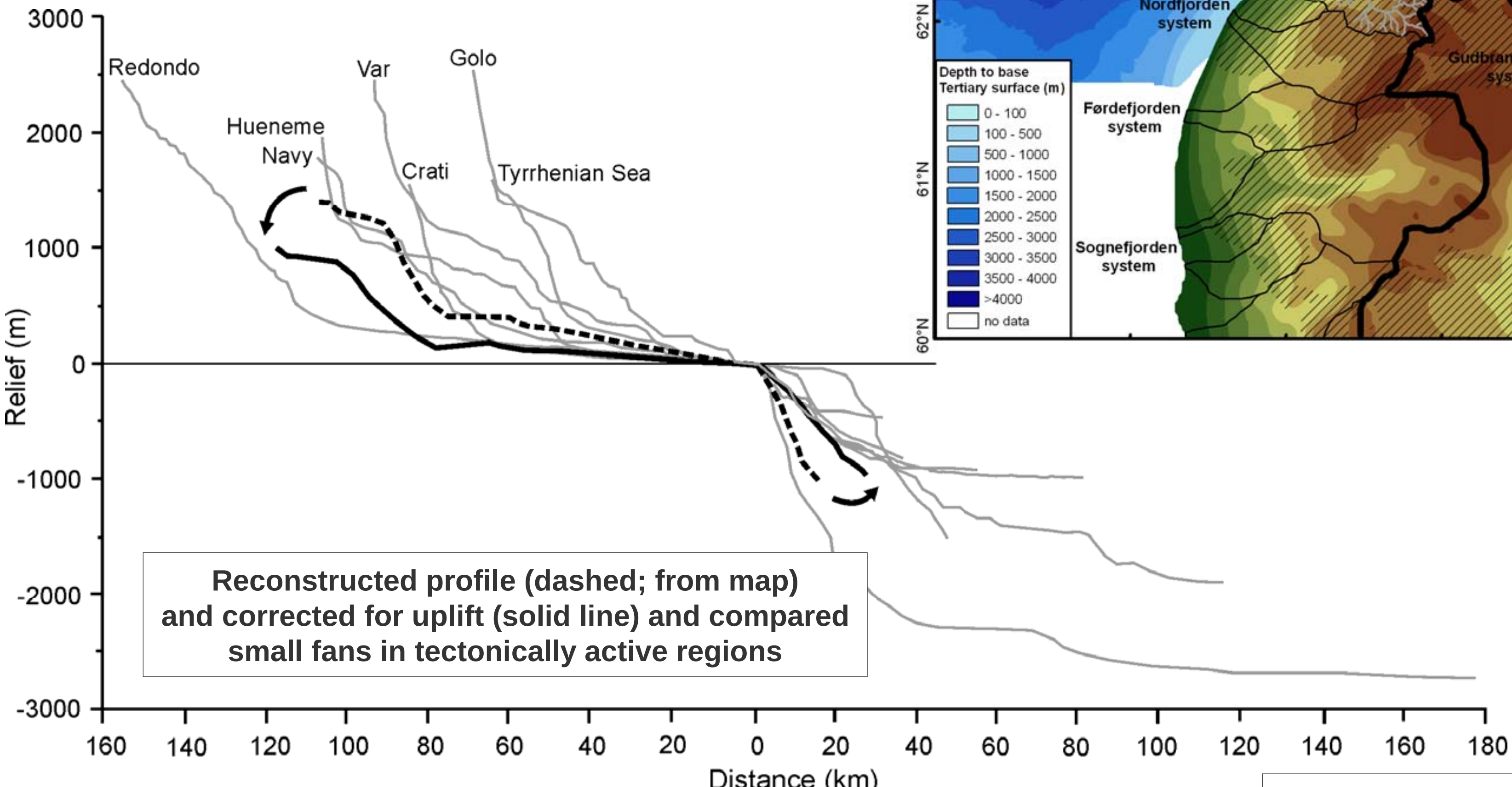
Inversion: results



Paleo-topography reconstruction from local & global data

Reconstruction of paleic terrain (from Sømme et al., 2009; based on Nesje, 2007)



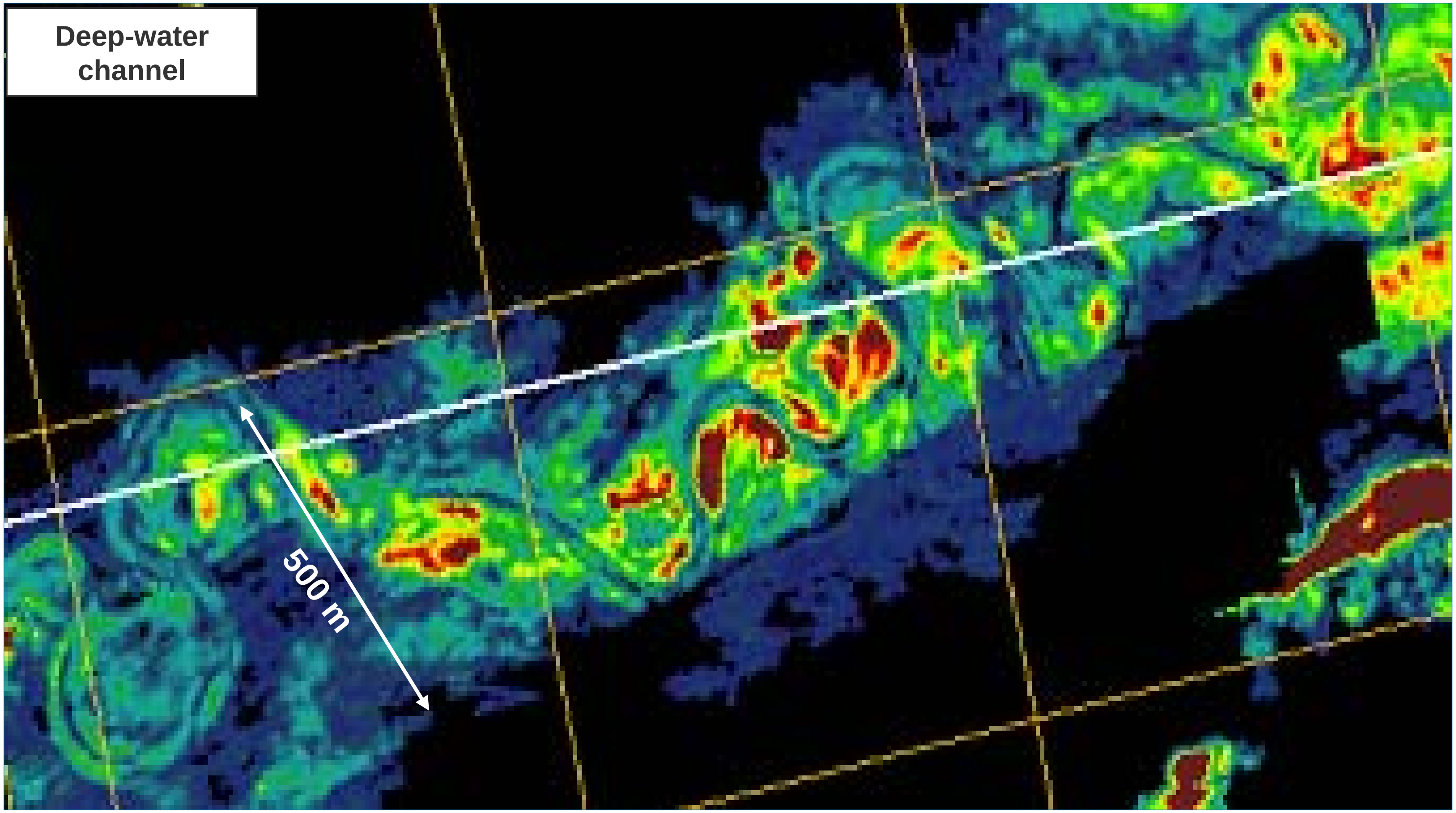


Reconstructed profile (dashed; from map) and corrected for uplift (solid line) and compared small fans in tectonically active regions

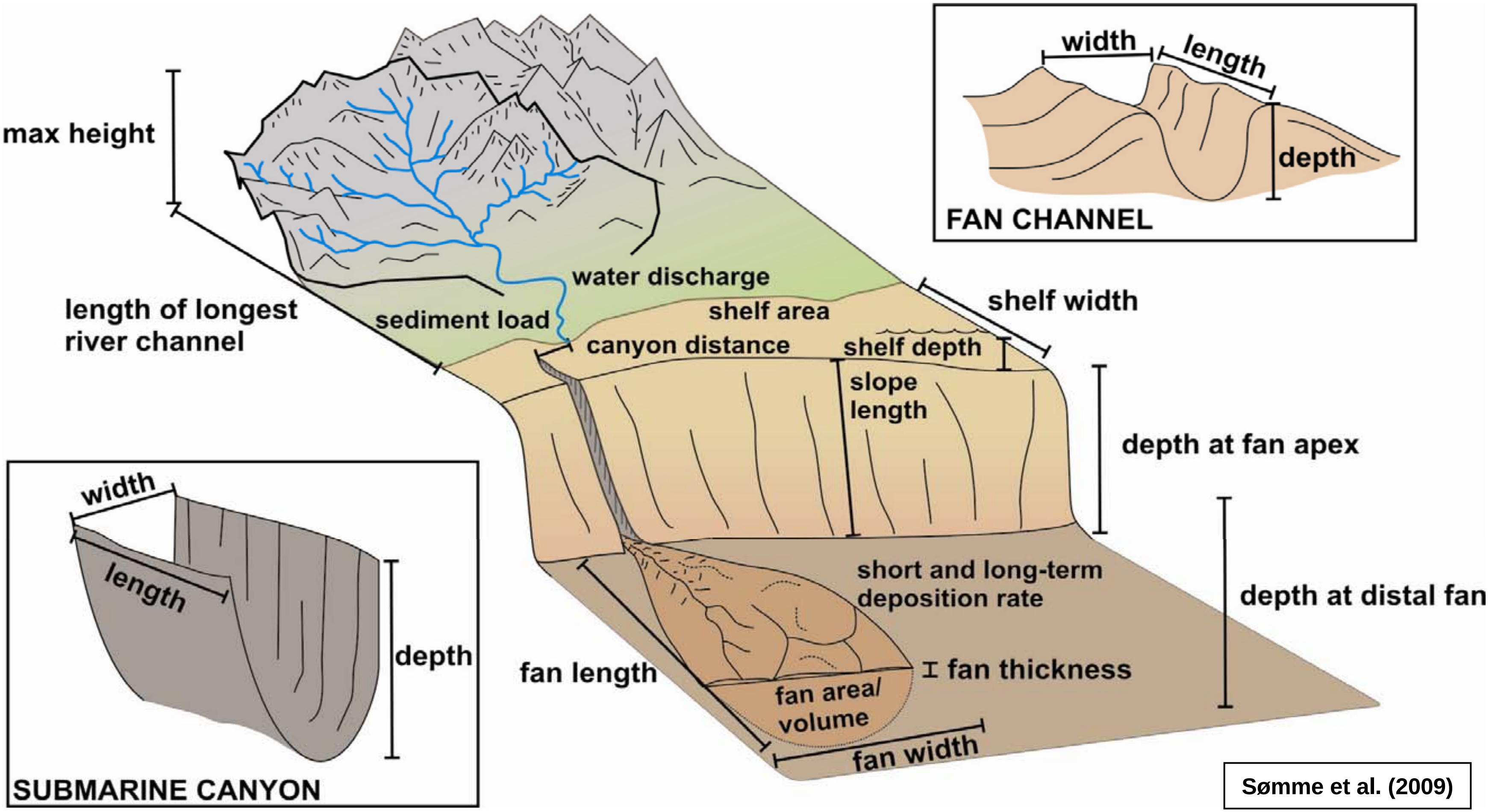
Sømme et al. (2009)

Applications and conclusions

Prediction of reservoir presence and quality



Complete systems



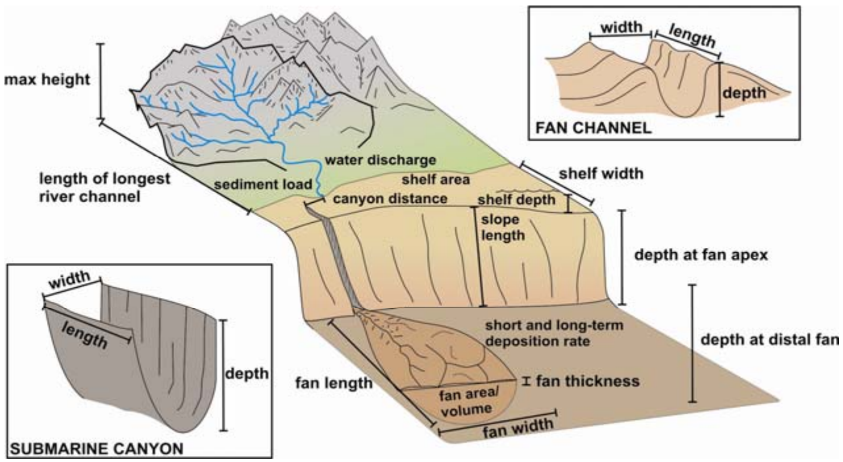
Sømme et al. (2009)

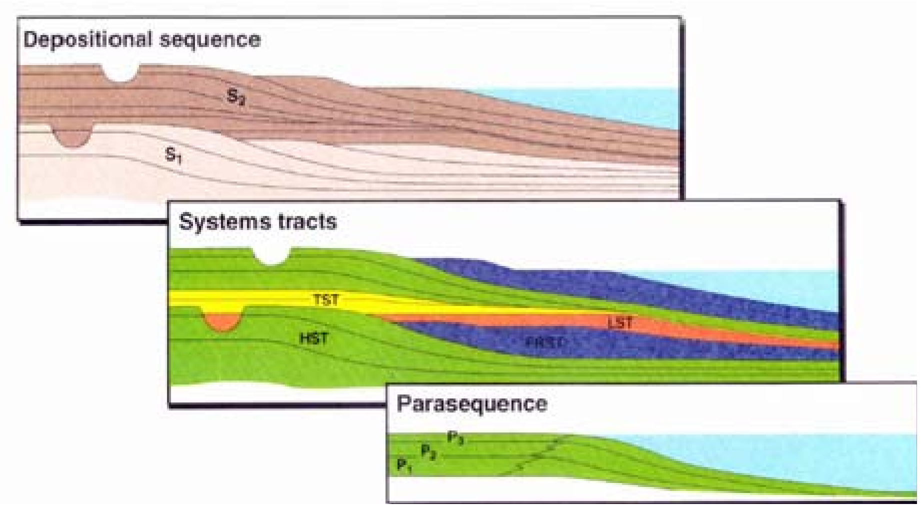
Source-to-Sink vs. Sequence Stratigraphy

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**

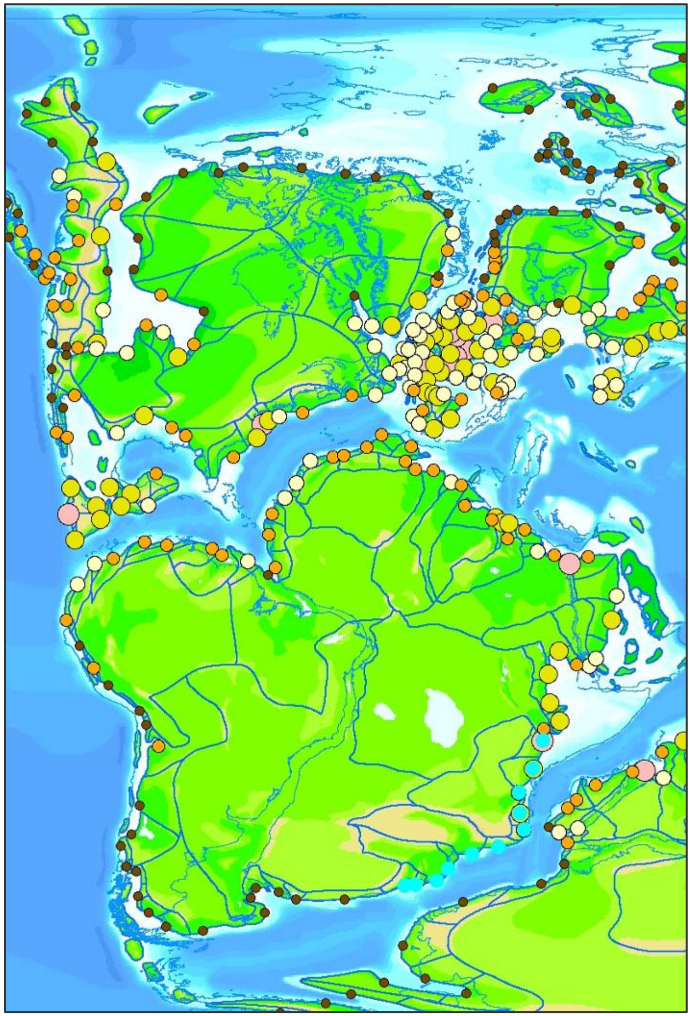




Dave Hunt, unpublished

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)