Submarine Levees: Form, Process and Reservoir Prediction*

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Search and Discovery Article #50707 (2012)**
Posted August 31, 2012

*Adapted from oral presentation at AAPG Annual Convention and Exhibition, Long Beach, California, April 22-25, 2012

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Abstract

Submarine channel levees commonly show a regular decay in thickness away from their parent channel. The form of this decay (power-law or exponential) is governed by the flow processes over the levee(1), in particular by the rate of entrainment of ambient seawater, which is a function of the flow Richardson number. This in turn depends on the local slope on which the levees are built(2). Using characteristic scaling parameters(3,4) it is possible to generalize the form of the levee independently of its size. Calibrating with field data from an ancient slope channel system(5) one can deduce the exponent in the thickness scaling law, which is theoretically dependent only on the grain-size of the sediment.

The shape of the levee reflects the mean shape of the individual beds within it, which decay away from the channel; however, since mud and sand respond differently to the flow, the proportion of sand to mud in individual beds (and resulting net-to-gross) also decreases away from the channel. A similar scaling and calibration procedure using outcrop data can be applied to net-to-gross decay across the levee, in order to derive the exponent in the net-to-gross scaling law. This approach can be used to reduce substantially the uncertainty in reservoir prediction in levees.

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With thanks to Ian Kane, Takeshi Nakajima, Mason Dykstra, Daisy Pataki, Phil Thompson and Brendon Hall

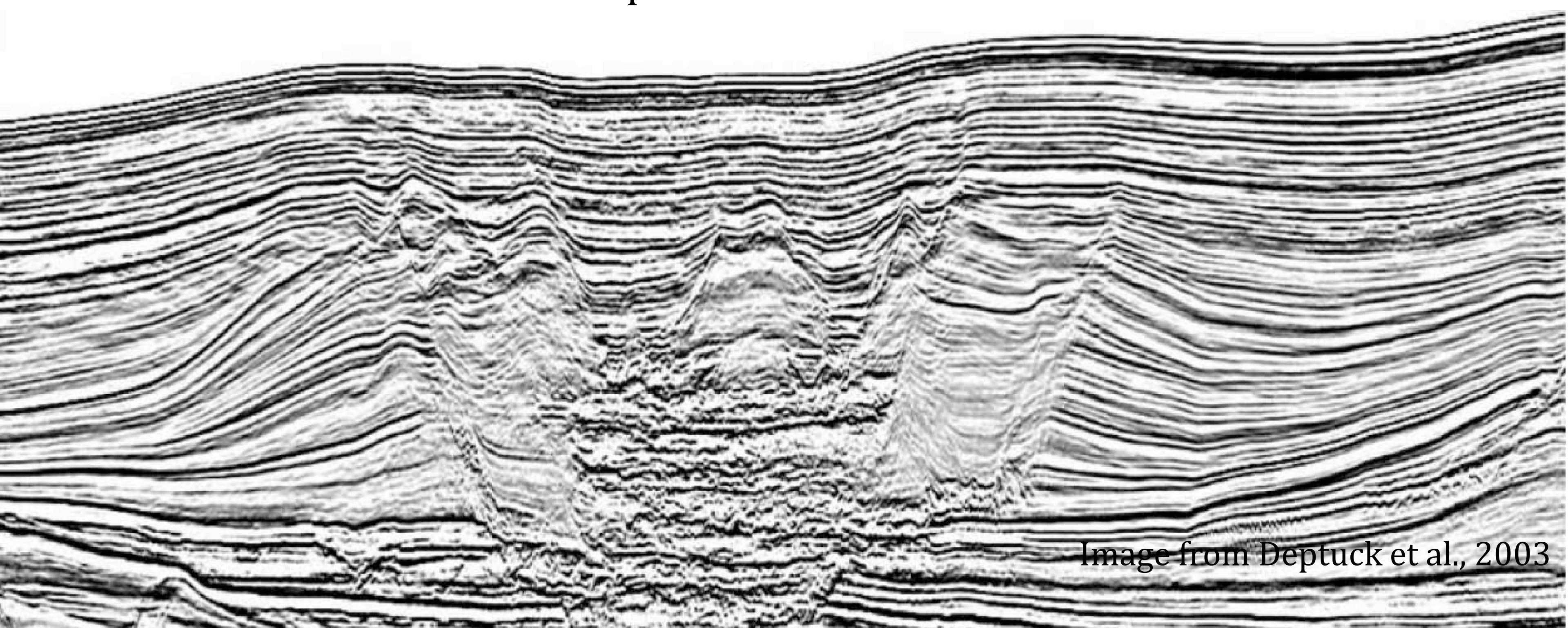
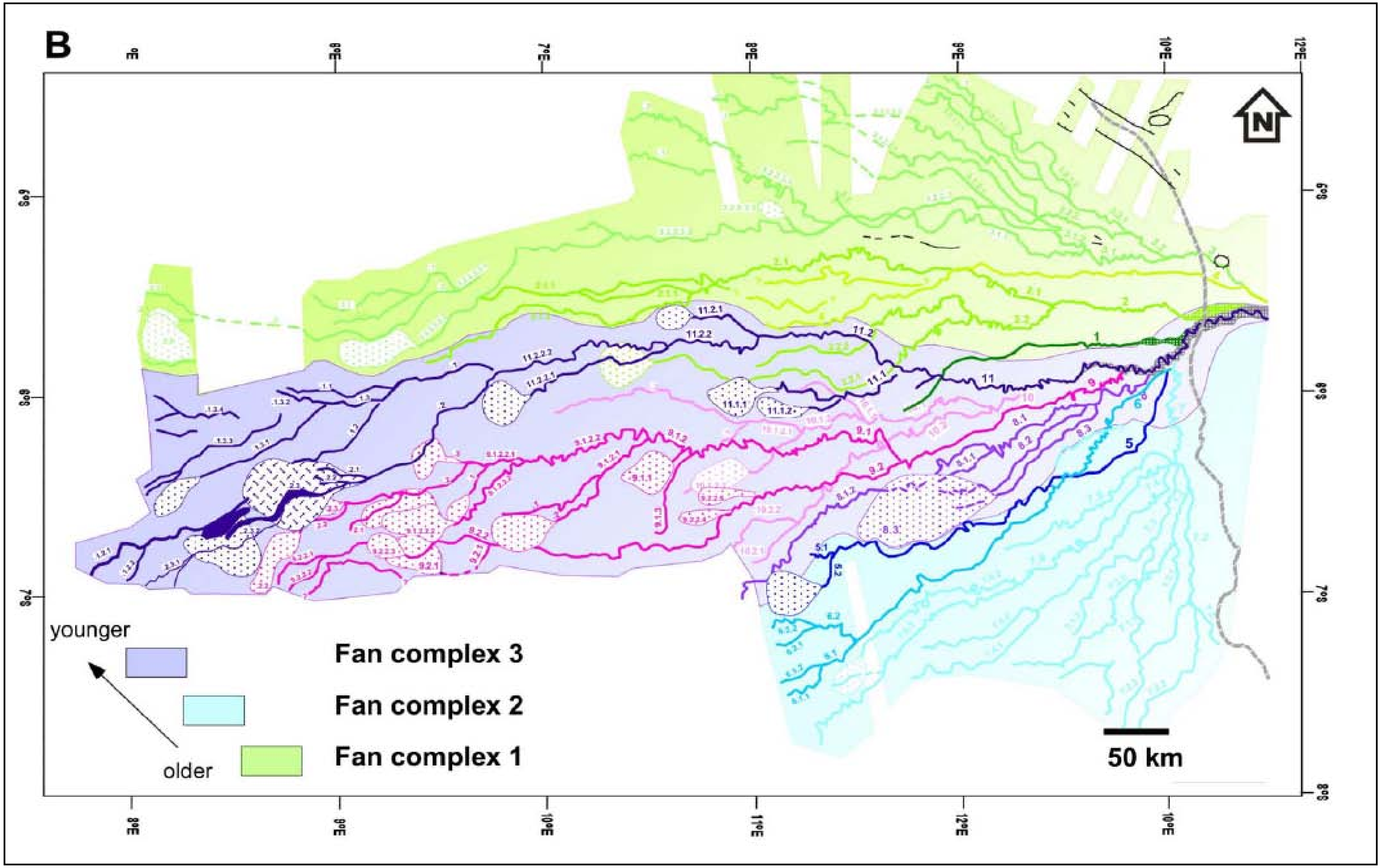


Image from Deptuck et al., 2003

Outline

- General characteristics of levees
- Assumptions – how levees build
- Importance of flow stratification
- Significance of water entrainment
- Geometrical and lithological characterization
- Reservoir prediction – general models?

Levees make up a large part of the continental slope and rise



Congo Fan. Vittori et al., 2000

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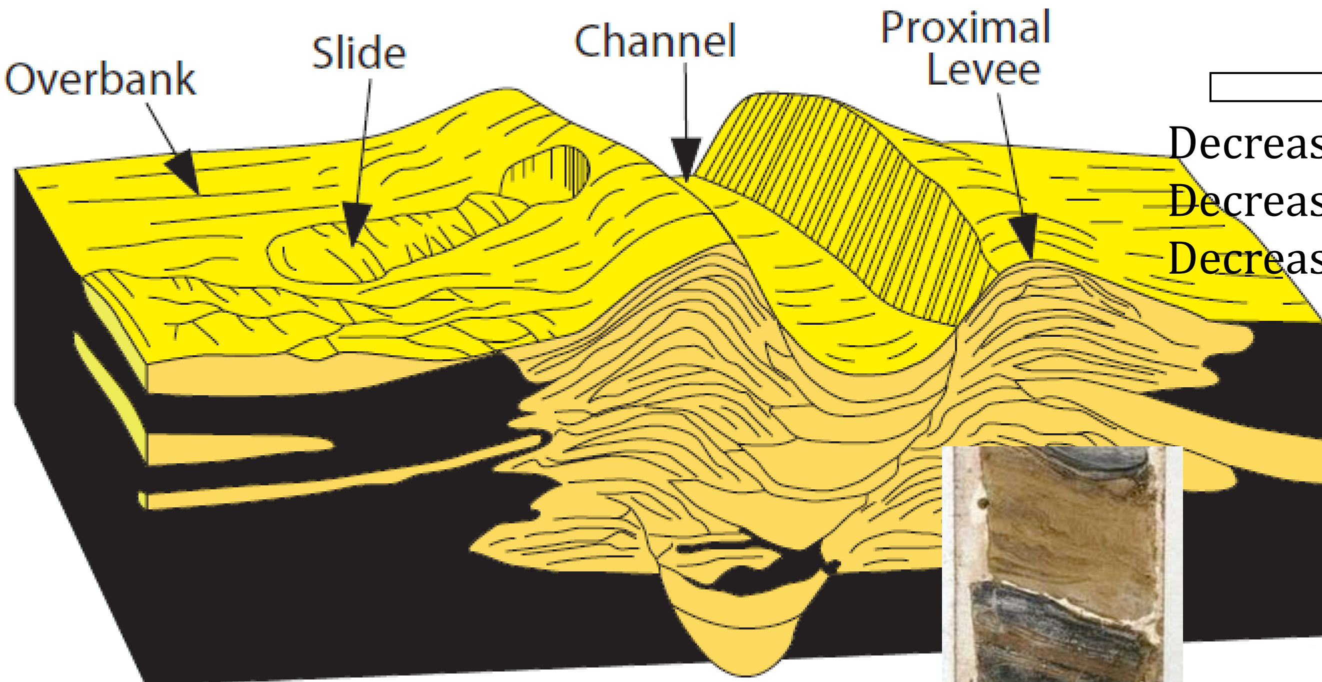
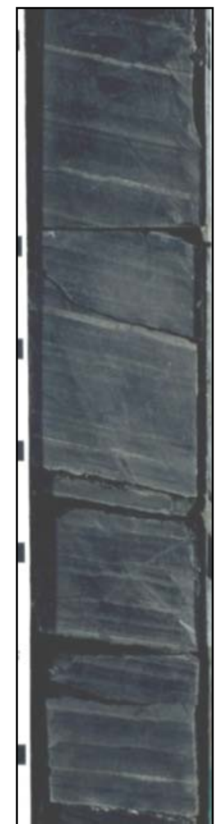
Stratigraphic Development of Slope Systems

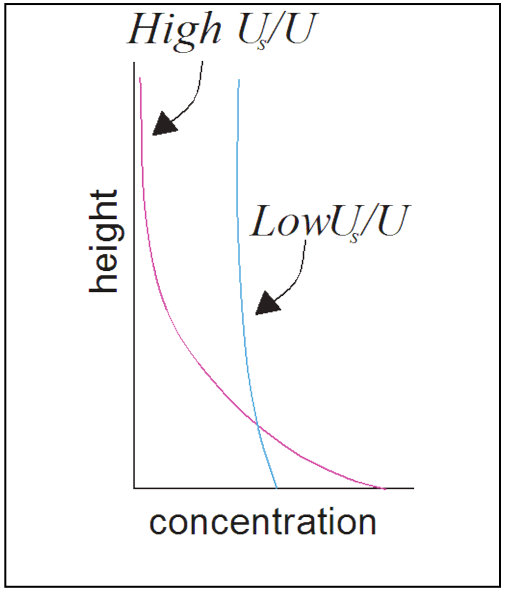


Decreasing grain-size
Decreasing bed thickness
Decreasing N/G



Modified from Roberts and Compani (1996)

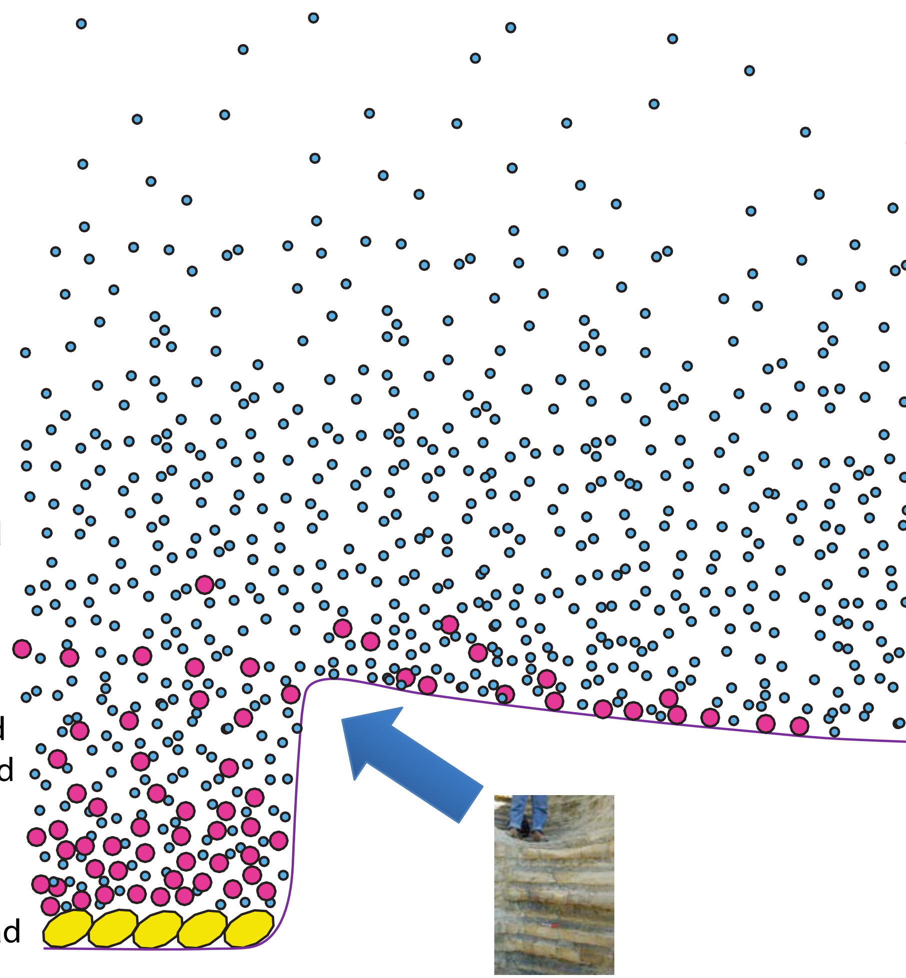
Grain size and density stratification of turbidity currents: consequences for overbank flow



Finer-grained suspended load overbanks

Coarse-grained suspended load confined to channel

Bedload



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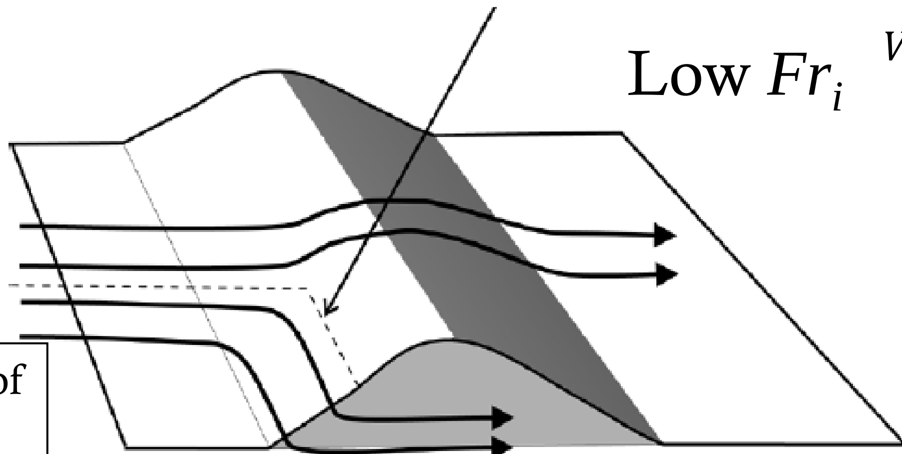
Interaction of stratified flows with topography: internal Froude number

Dividing stream-line

Low Fr_i



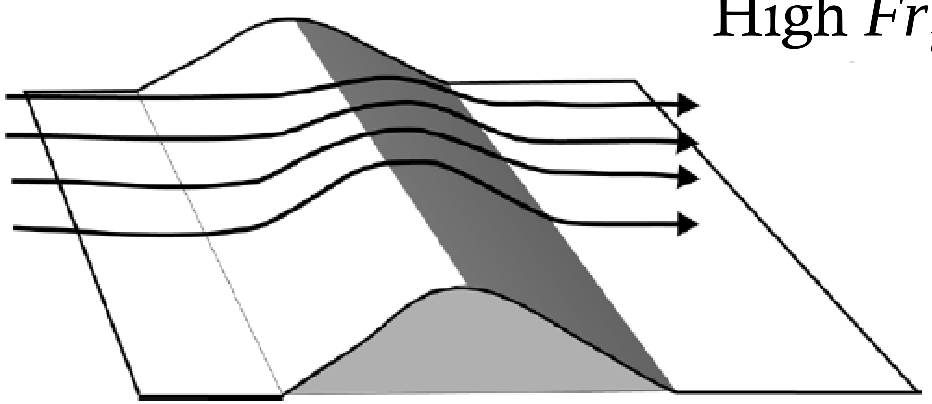
Vertical density gradient

$$Fr_i = \frac{\bar{U}}{H\left(\frac{\partial\rho / \partial z}{\rho_a}\right)^{0.5}}$$

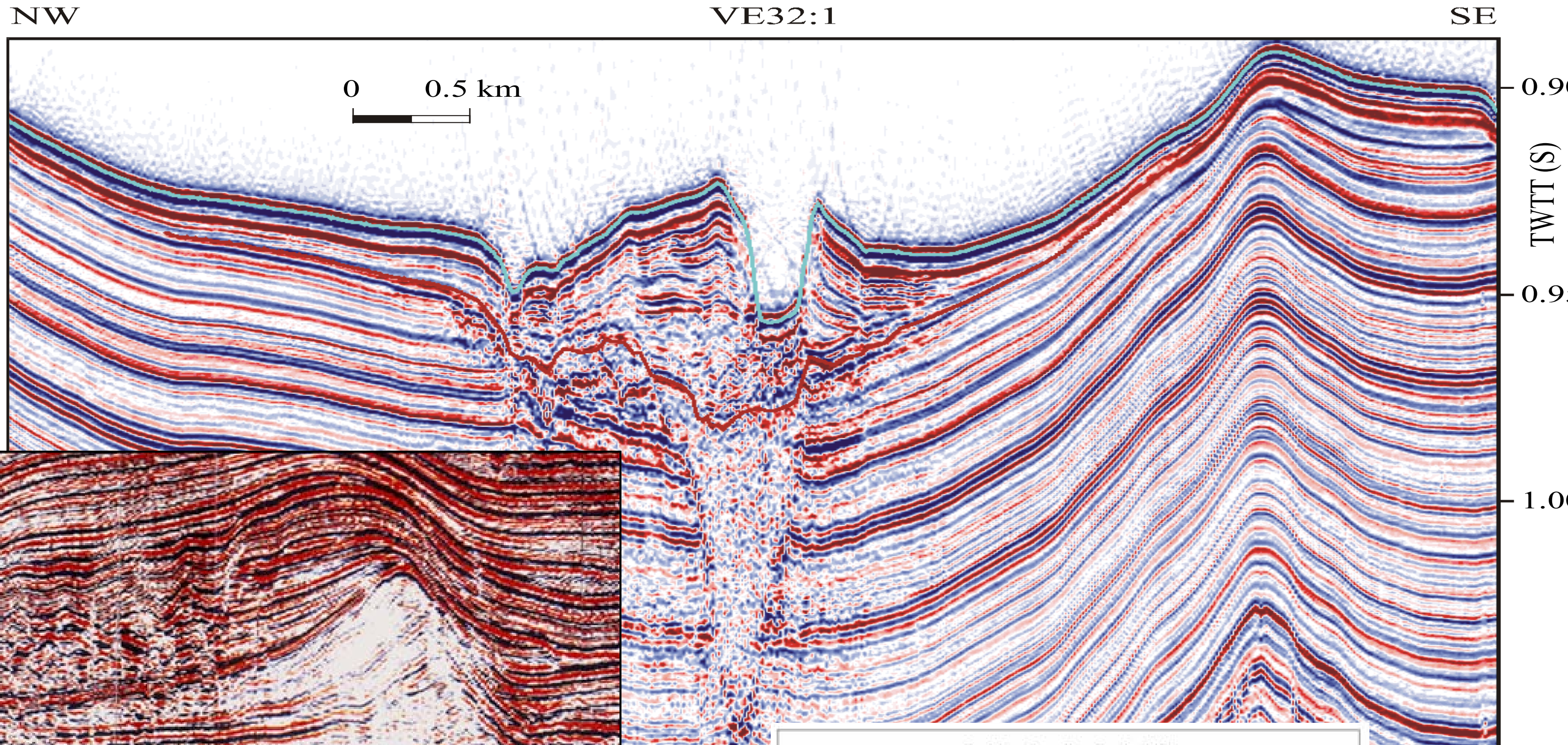
Deflection of lower parts of well stratified flows

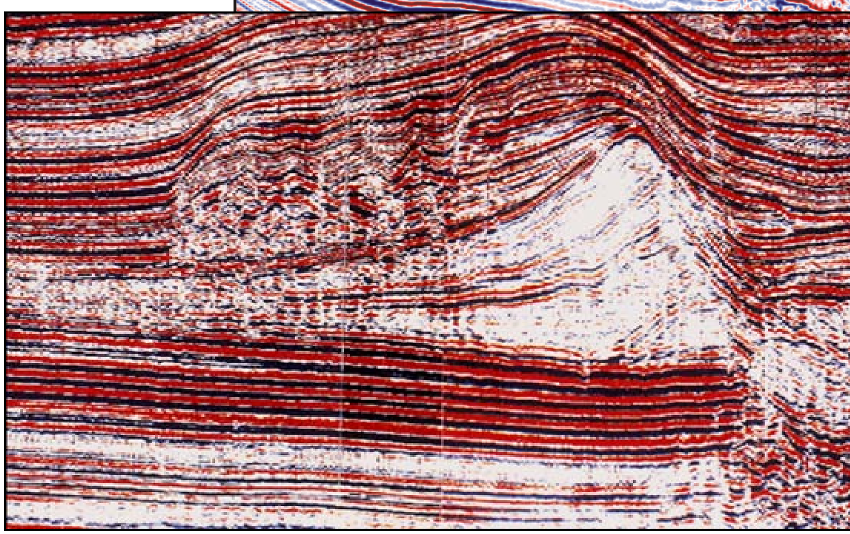
Height of dividing streamline ≈ $H\ (1 - 2Fr_i)$

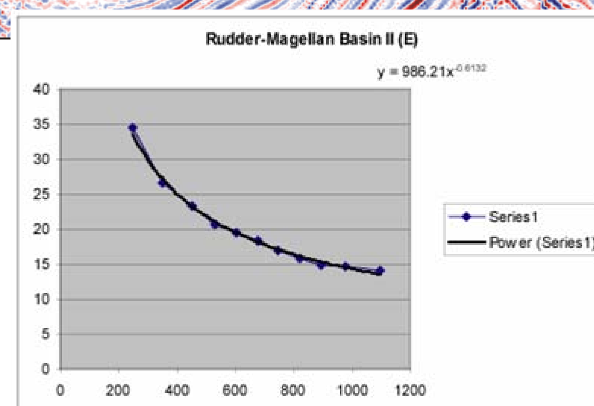
High Fr_i



Prediction in levees: mathematical characterization







Hackbarth Shew, 1994; Badalini et al., 2000 and unpub.
Data courtesy of Shell

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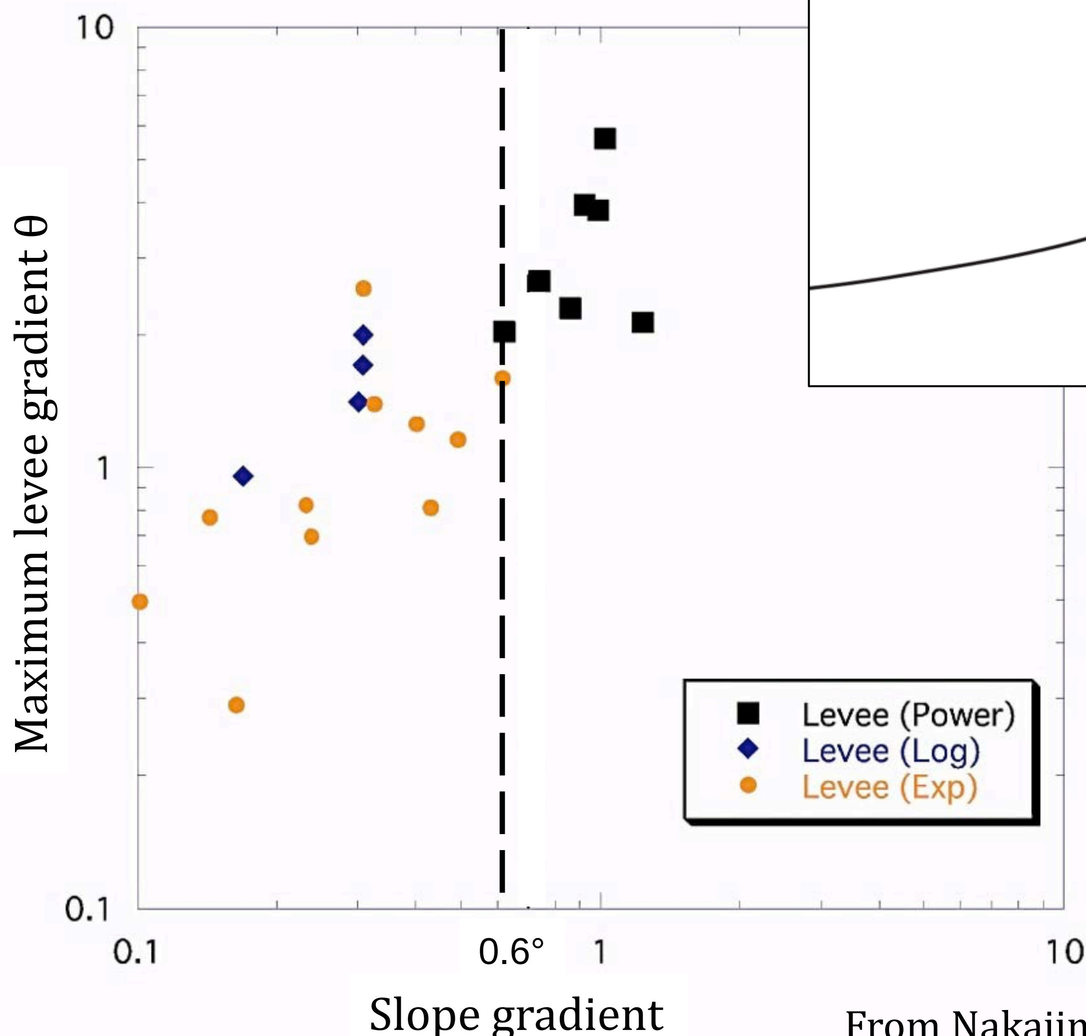
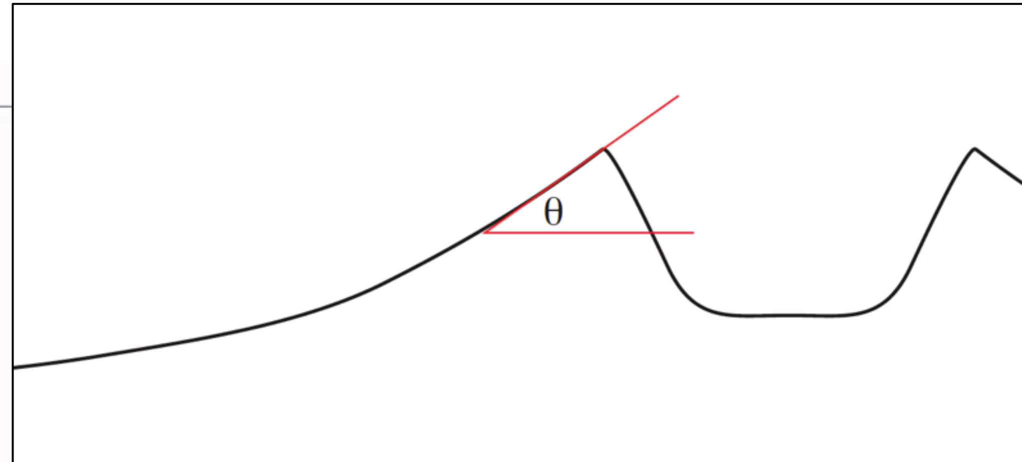
Relationship between slope gradient and maximum levee gradient, θ





- Gradients on levee scale with regional slope
- Type of decay depends on regional slope

From Nakajima and Kneller (in press)

What explains the difference between power law and exponential decay?

$$T_x = \mathrm{f}\left(\varphi_0 e^{-(u_s/uh)x}\right)$$

No entrainment of ambient water ➔ exponential decay

$$T_x = \mathrm{f}\left(\varphi_x^{\frac{u_s + E_0}{E_0}}\right)$$

Constant entrainment of ambient water ➔ power law decay

- u_s = settling velocity of particles
- ϕ = suspended sediment concentration
- uh = discharge per unit width
- x = horizontal coordinate
- E_0 = entrainment rate of ambient water

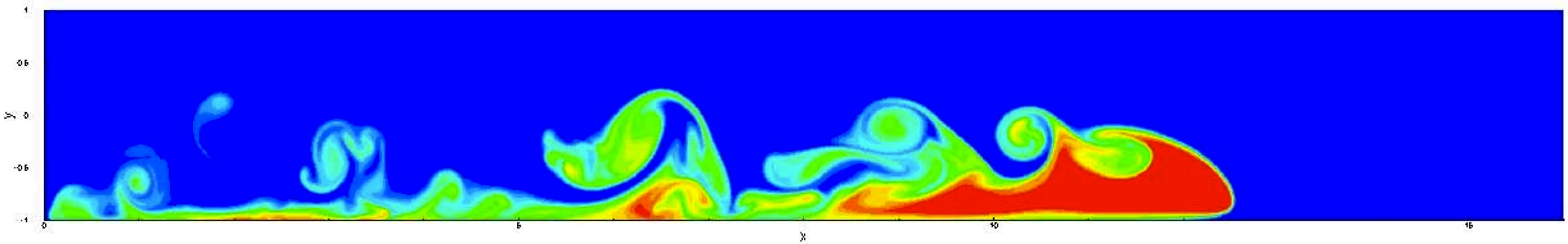
From Birman, Meiburg and Kneller, 2009

Entrainment occurs when flow stratification is unstable: $Ri_g < 0.25$

$$Ri_g = \frac{\left(g \frac{\partial \rho / \partial z}{\rho_a} \right)}{\left(\partial u / \partial z \right)^2}$$

Vertical density gradient ($\partial \rho / \partial z$)

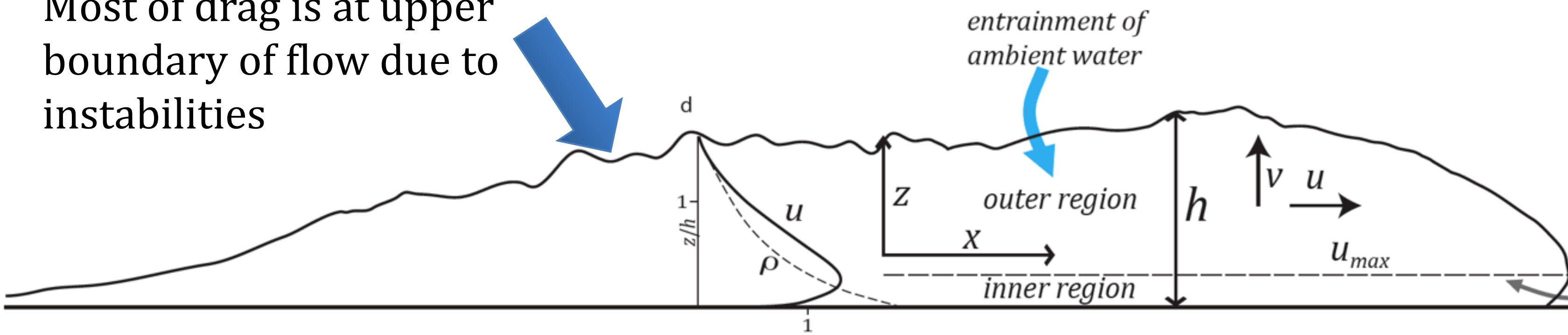
Vertical velocity gradient ($\partial u / \partial z$)



2D large eddy simulation of turbidity current, courtesy Brendon Hall, UCSB

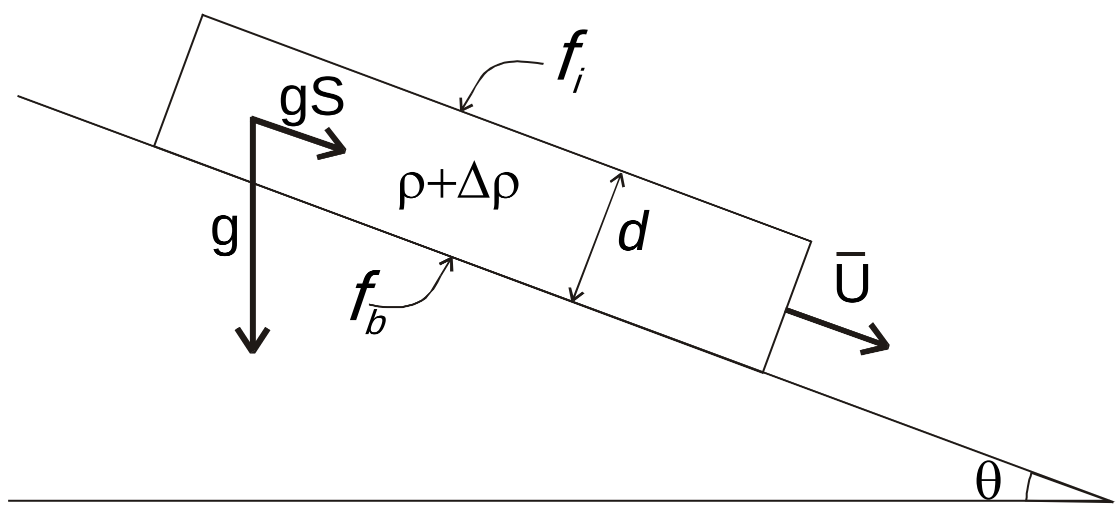
Entrainment **rate** depends on flow Richardson number, thus on slope

Most of drag is at upper boundary of flow due to instabilities



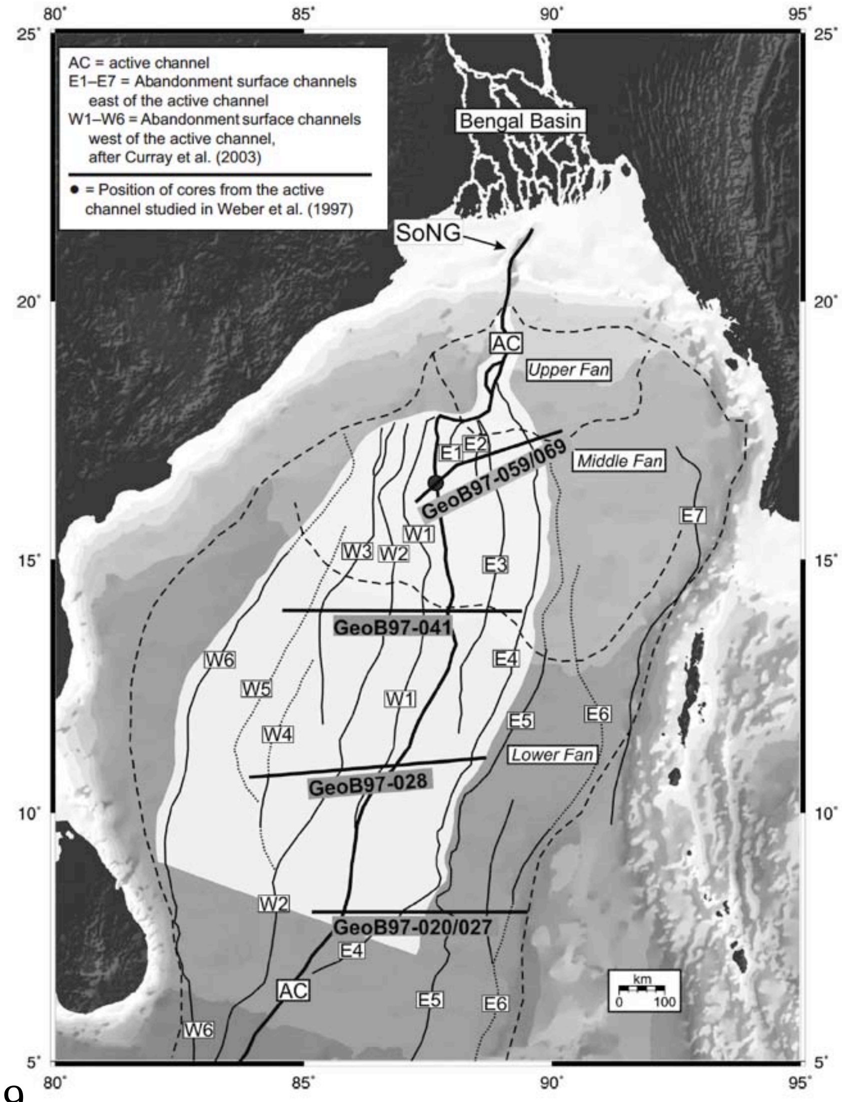
$$E \approx \frac{1}{Ri}$$

$$Ri_0 = \frac{g'h\cos\theta}{U^2}$$



…which helps explain the 'unreasonable' persistence of flows on low slopes

- Little drag
- Little entrainment



From Schwenk & Spieß, 2009

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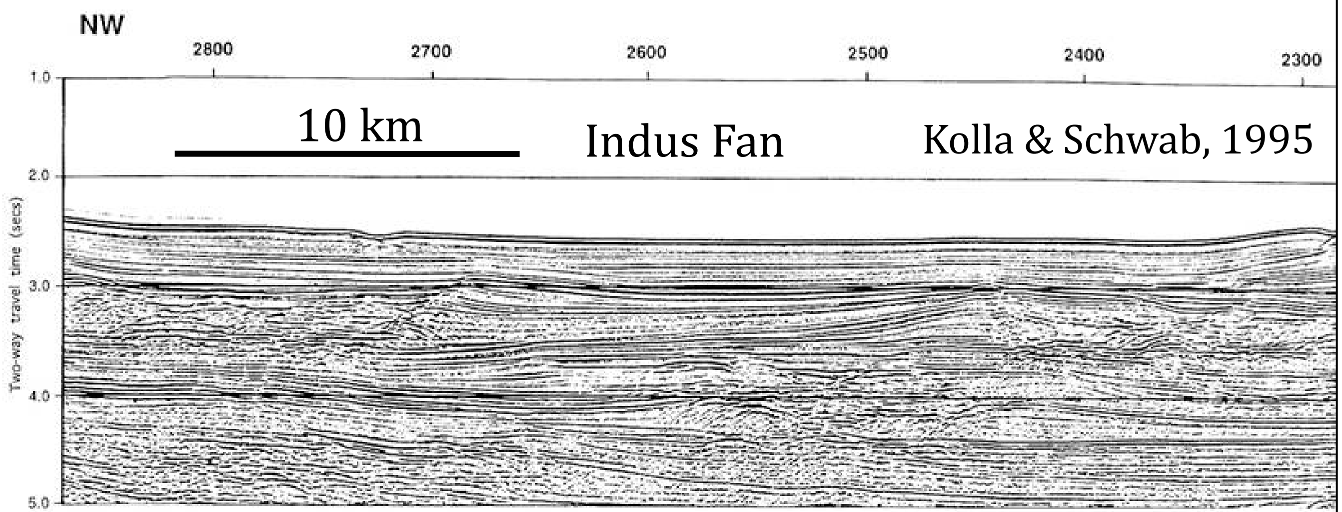
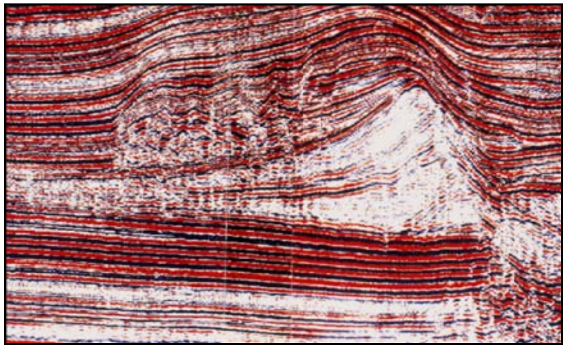
Generalizing geometry: approaches to scaling



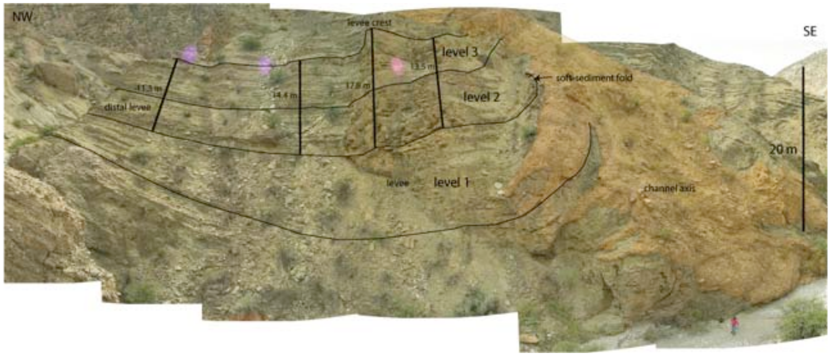
1 km



Gulf of Mexico Slope

Hackbarth Shew, 1994

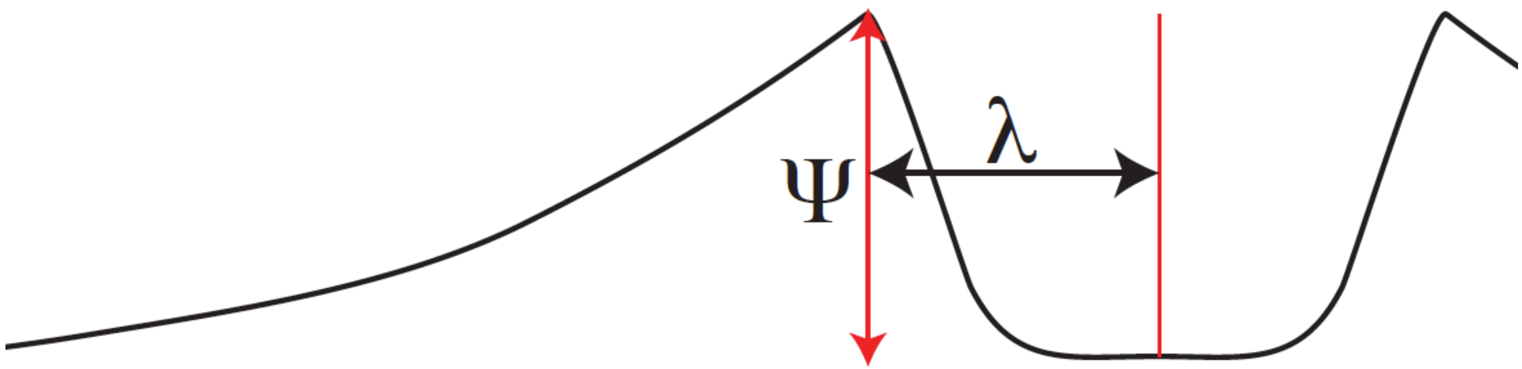
100 m



Outcrop

Dykstra et al., 2011

Characteristic scales for normalisation



λ = horizontal length scale

Ψ = value of dependent variable at levee crest (maximum)

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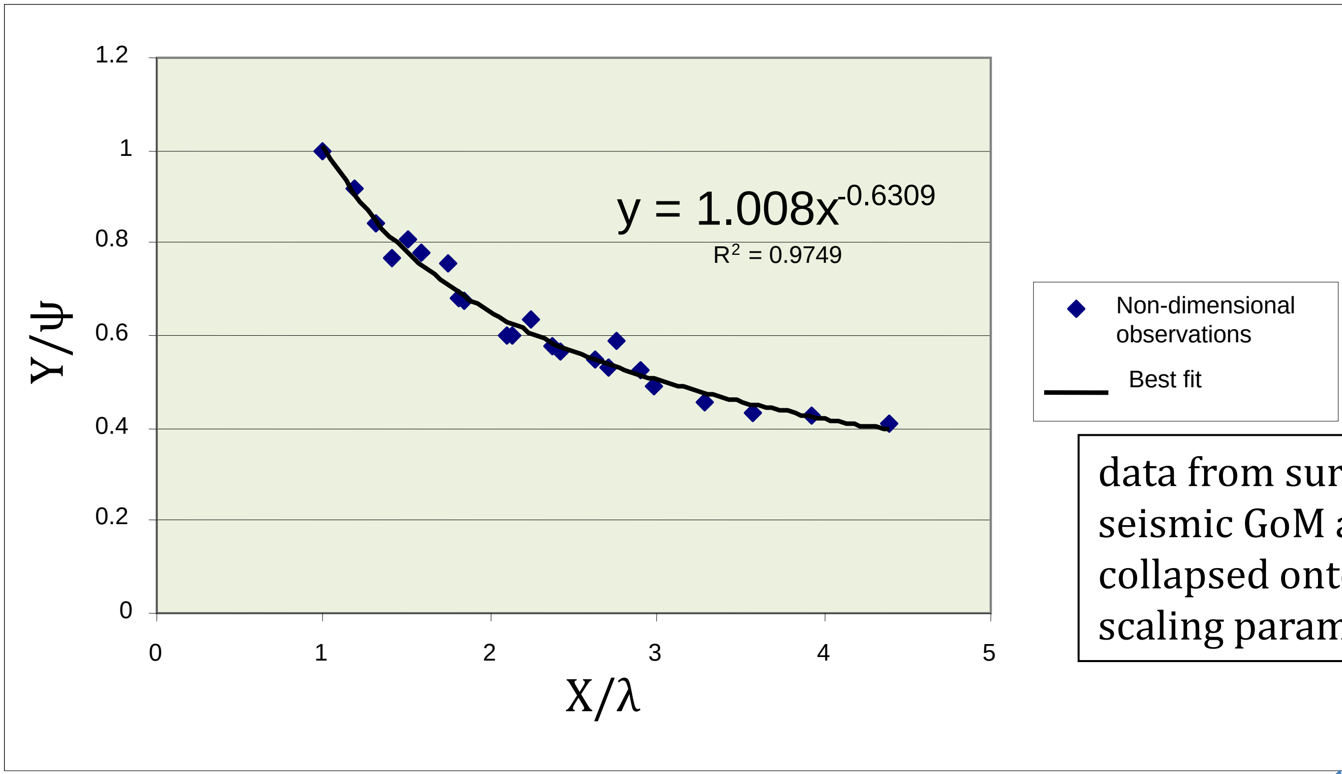
Non-dimensional thickness decay: slope channel levees



data from surface and shallow seismic GoM and outcrop, collapsed onto single curve using scaling parameters

General expression for thickness decay: $Y = \psi\,(X/\lambda)^{-0.63}$

Should be grain-size dependent

Ψ is vertical scaling parameter (thickness at levee crest)

λ is horizontal scaling parameter (channel centre to levee crest)

Data from Dykstra, Kneller & Milana, 2012

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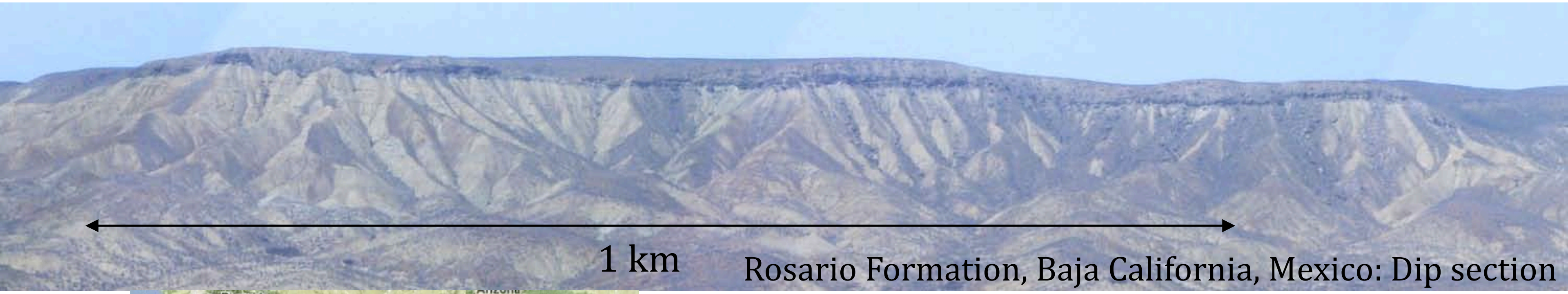
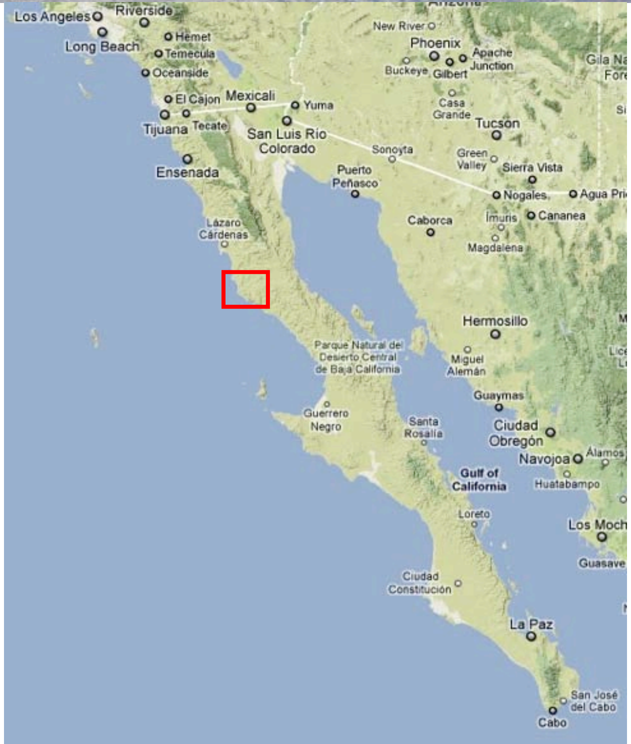
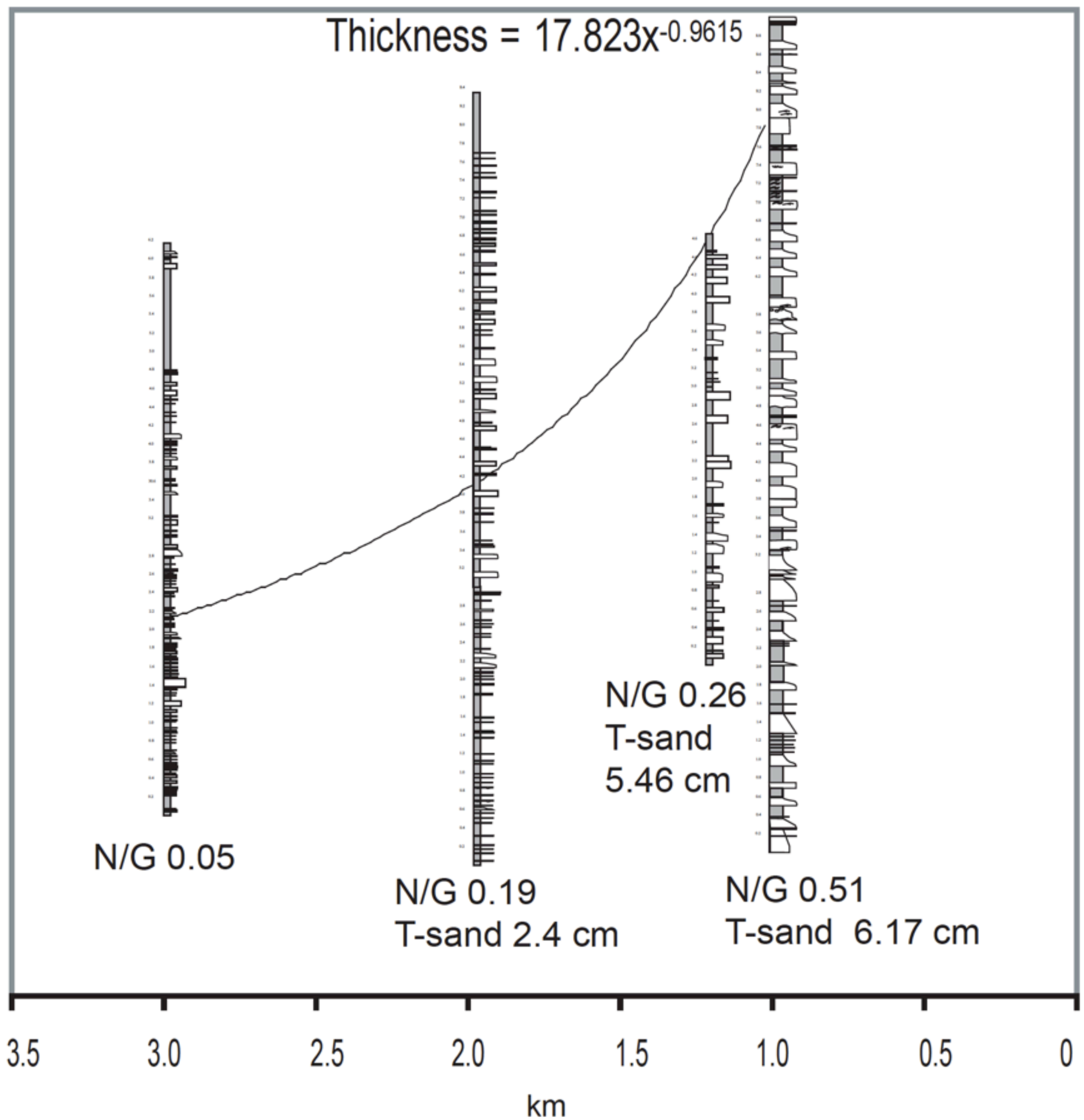
Conditioning to outcrop



Rosario Formation, Baja California, Mexico: Dip section

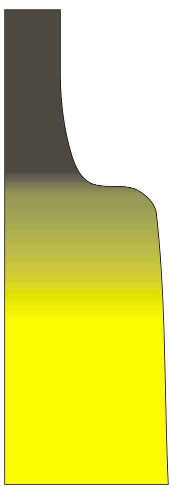


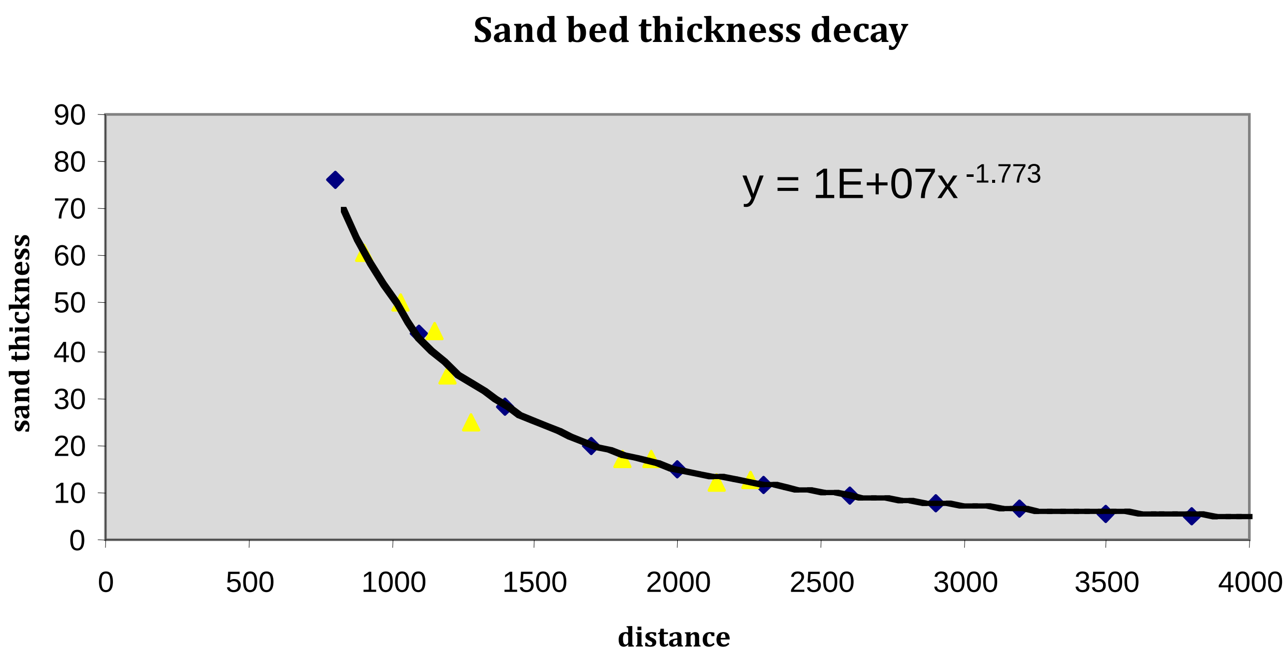
Composite levee profile from outcrop



Rosario Formation, Cretaceous, Baja California

Decay in sand thickness per bed, fit to outcrop data





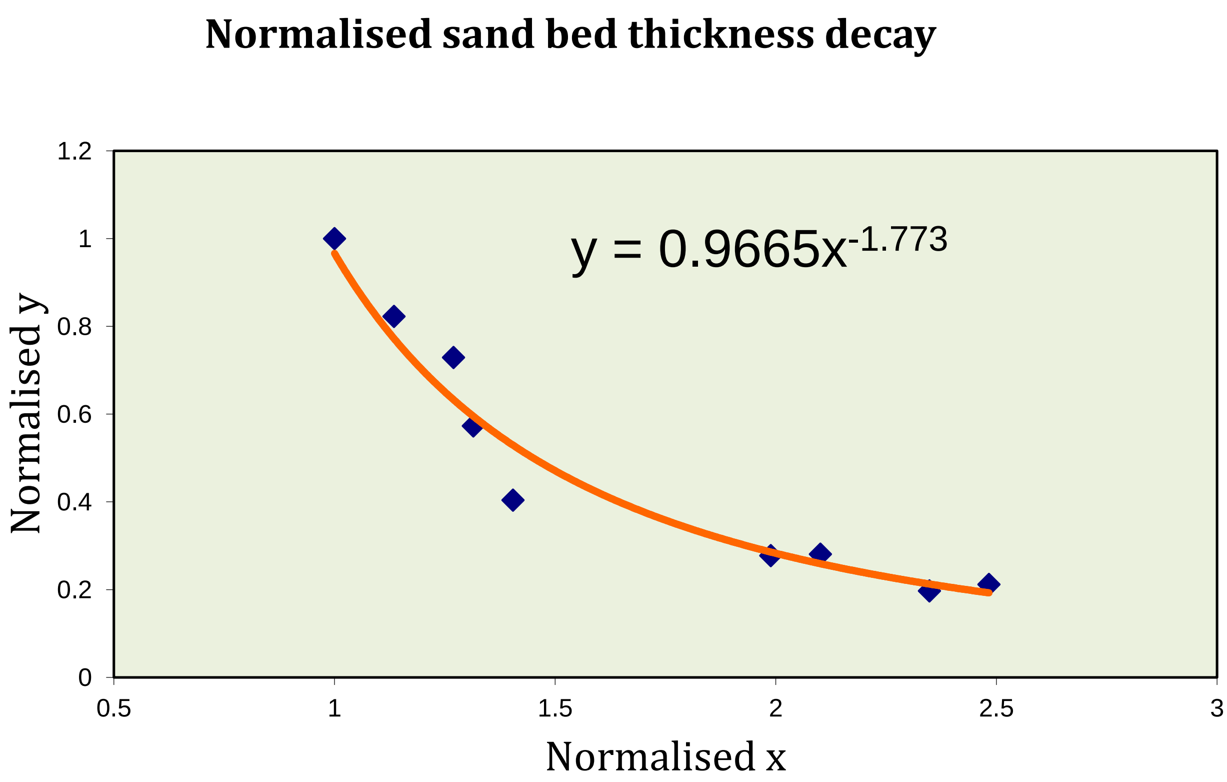
General expression for sand thickness decay: $t_s = \varphi\,(X/\lambda)^{-1.773}$

φ is vertical scaling parameter (sand thickness at levee crest)

λ is horizontal scaling parameter (channel center to levee crest)

Data from Kane, Kneller, Dykstra, Kassem, & McCaffrey, 2007

Normalised decay in sand thickness per bed



Data from Kane, Kneller, Dykstra, Kassem, & McCaffrey, 2007

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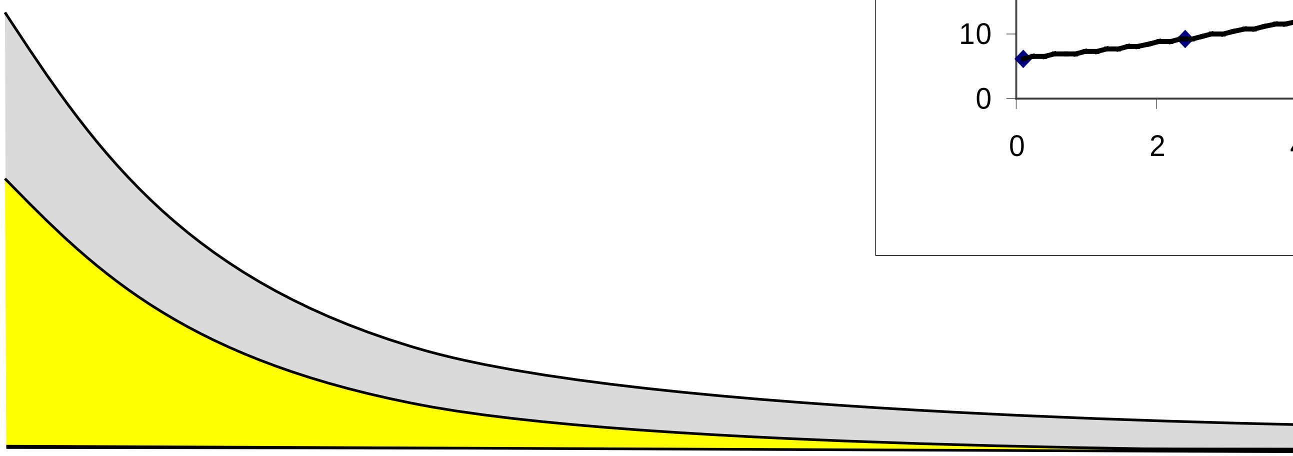
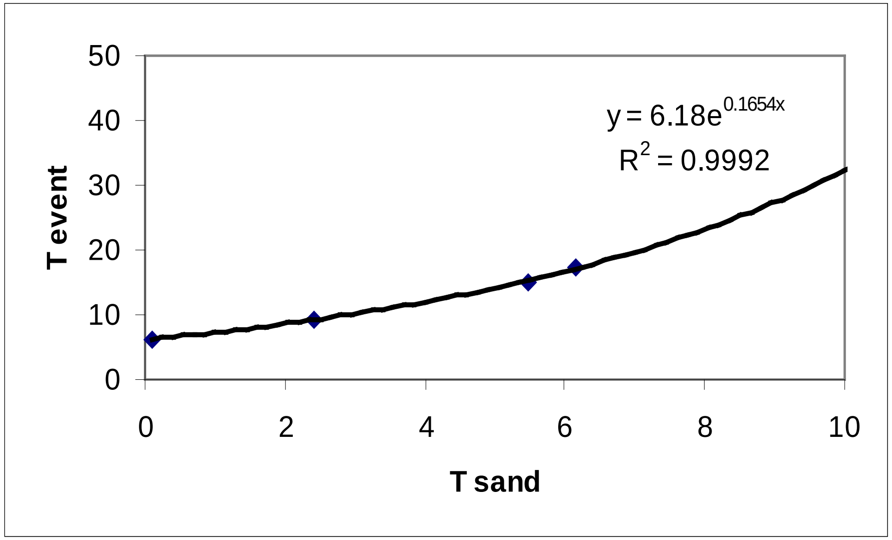
Decay in net-to-gross

$$T_x = \mathrm{f}\left(\varphi_x^{\frac{u_s+E_0}{E_0}}\right)$$





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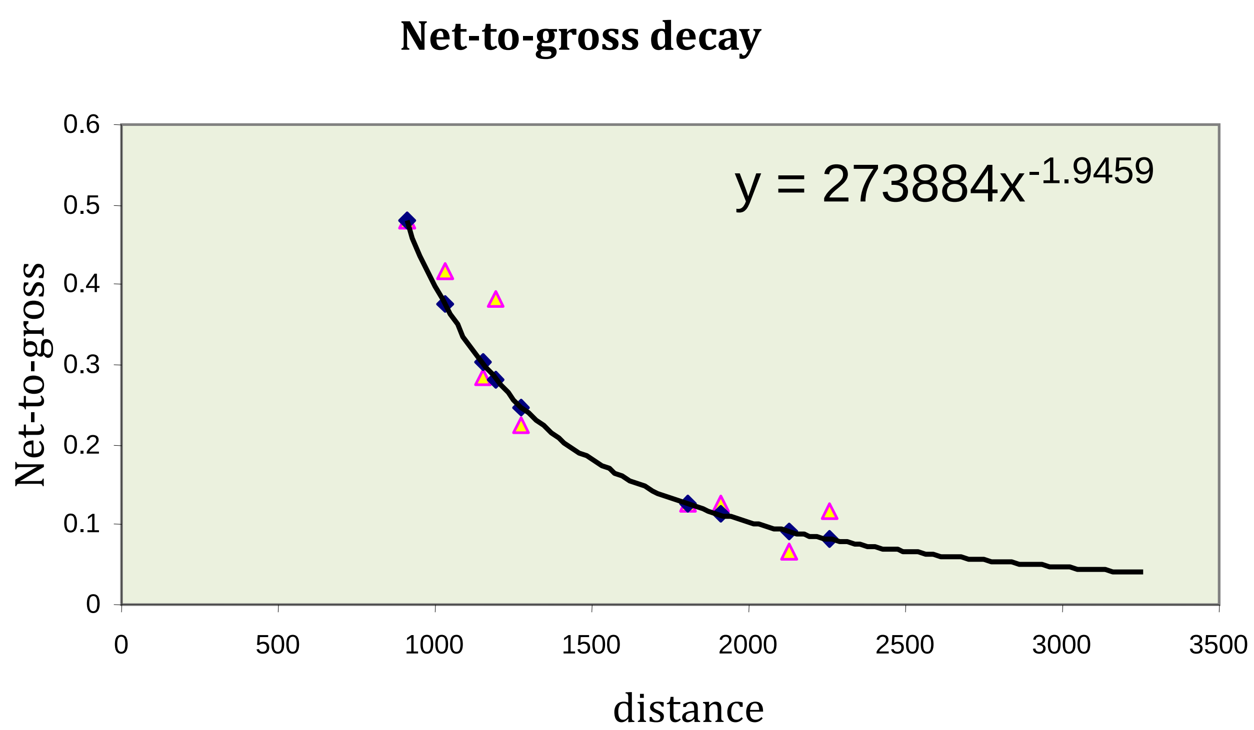
Decay in net-to-gross, fit to outcrop data



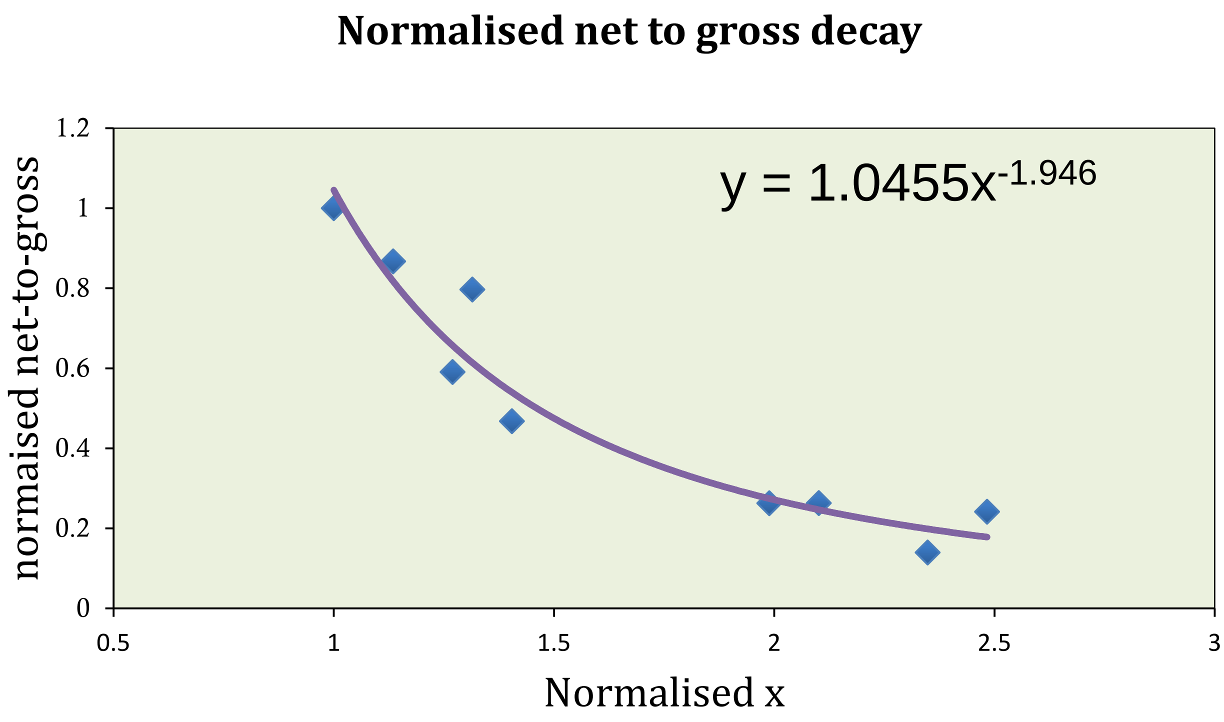
General expression for net-to-gross decay: $NTG = \nu\,(X/\lambda)^{-1.946}$

ν is vertical scaling parameter (NTG at levee crest)

λ is horizontal scaling parameter (channel center to levee crest)

Data from Kane, Kneller, Dykstra, Kassem, & McCaffrey, 2007

Decay in net-to-gross: a general model?



$$\hat{N} \approx \hat{X}^{-2}$$

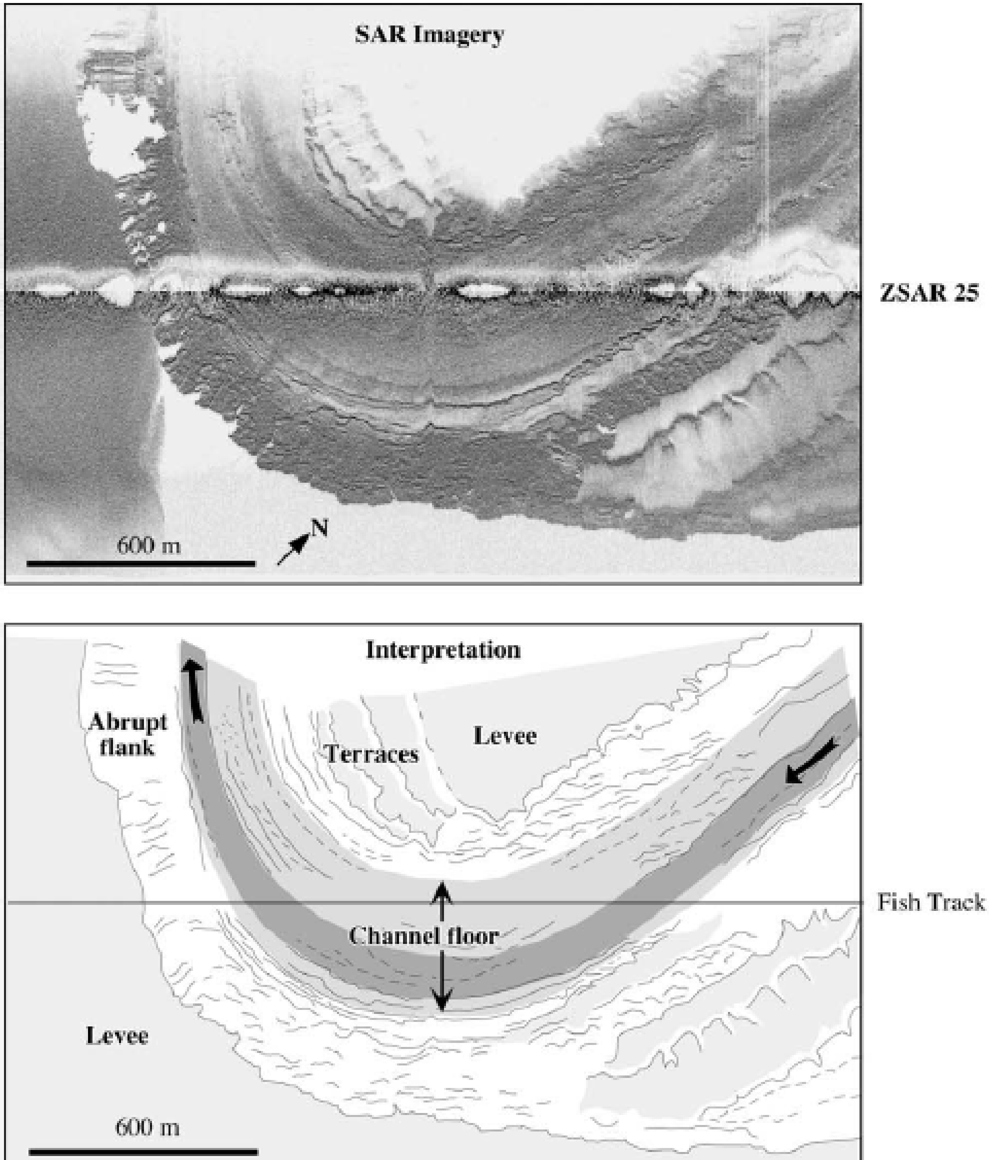
Data from Kane, Kneller, Dykstra, Kassem, & McCaffrey, 2007

Summary

- Levees are volumetrically highly significant sediment bodies
- They reveal much about characteristics of flows in channels
- Flow stratification is central to the behaviour of channelized flows and the formation of levees
- Fluid entrainment is key to levee geometry
- They commonly have predictable properties
- …which allows reservoir characterization

Thank you!

Not all channel-associated thin beds are levee



Congo Fan. From Babonneau et al., 2002

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Forming levees and terraces