Click to view movie. (10.7 MB)

Secondary Flow in Meandering Channels on Submarine Fans: Implications for Channel Morphodynamics and Architecture*

Jorge D. Abad[1], Octavio Sequeiros[2], Benoit Spinewine[3], Carlos Pirmez, Marcelo Garcia[1], and Gary Parker[1]

Search and Discovery Article #40480 (2010)
Posted February 12, 2010

*Adapted from oral presentation at AAPG Annual Convention and Exhibition, Denver, Colorado, June 7-10, 2009.

*Please refer to the companion article, Search and Discovery Article #40516 (2010) entitled "Controls on gravel Deposits in Deep-Water Reservoirs: Bedload Transport and Bedforms Associated with Turbidity Currents."

[1]Civil & Environmental Engineering, University of Illinois Urbana-Champaign, Urbana, IL (parker@illinois.edu)
[2]Shell International Exploration and Production, Rijswijk, Netherlands
[3]Universite Catholique de Louvain, Louvain-la-Neuve, Belgium

Abstract

It has recently been suggested by some authors that the direction of secondary flow of turbidity currents in meandering channels should be reversed compared to rivers. Were this to be the case, the planform geometry of submarine meanders would likely be markedly different from that of rivers. More specifically, the ratio of wavelength to channel width would likely be markedly larger. Yet this ratio has been found to be quite similar for both rivers and channels on submarine fans. The argument for reversed secondary flow is based on the premise that the elevation at which peak streamwise velocity is attained is very low compared to the thickness of the flow. Here it is demonstrated that the position of this peak is strongly dependent upon the densimetric Froude number Frd of the flow. Supercritical Froude numbers (Frd > 1) favor a low elevation of peak velocity. Subcritical Froude numbers (Frd > 1) favor a high elevation of peak velocity. Reconstructions of channel-formative flows on the Amazon Submarine Fan indicate that the flows should have been well into the subcritical range over most of the channel length. The implication is that the sense of the secondary flows should likely have been the same as those of rivers. The magnitude of these secondary flows, however, should have been somewhat weaker than rivers. This conclusion is in concordance with the observed similarity between the planforms of rivers and meandering channels on submarine fans. The conclusion is supported with experimental, theoretical and field data.

Selected References

Abad, J.D. and M.H. Garcia, 2009, Experiments in a high-amplitude Kinoshita meandering channel: 1. Implications of bend orientation on mean and turbulent flow structure: Water Resources Research, AGU, v. 45, p. W02401. doi:10.1029/2008WR007016.

Abad, J.D. and M.H. Garcia, 2008, Experiments in a high-amplitude kinoshita meandering channel: 2. Implications of bend orientation on bed morphodynamics: Water Resources Research, AGU, v. 45, p. W02402. doi:10.1029/ 2008WR007017

Abad, J.D., G.C. Buscaglia, M.H. Garcia, and H. Marcelo, 2008, 2D stream hydrodynamic, sediment transport and bed morphology model for engineering applications: Hydrological Processes, v. 22/10, p. 1443-1459.

Abad, J.D. and M.H. García, 2006, RVR Meander: A toolbox for re-meandering of channelized streams: Computers & Geosciences, v. 32, p. 92-101.

Abreu, V., M. Sullivan, C. Pirmez, and D. Mohrig, 2003, Lateral accretion packages (LAPs); an important reservoir element in deep water sinuous channels: Marine and Petroleum Geology, v. 20/6-8, p. 631-648.

Babonneau, N., B. Savoye, M. Cremer, and B. Klein, 2002, Morphology and architecture of the present canyon and channel system of the Zaire deep-sea fan: Marine and Petroleum Geology, v. 19/4, p. 445-467.

Corney, R.K.T., J. Peakall, D.R. Parsons, et. al., 2008, The orientation of helical flow in curved channels; reply: Sedimentology, v. 55/1, p. 241-247.

Corney, R.K.T., J. Peakall, D.R. Parsons, et. al., 2006, The orientation of helical flow in curved channels: Sedimentology, v. 53/2, p. 249-257.

Hay, A.E., 1987, Turbidity currents and submarine channel formation in Rupert Inlet, British Columbia; 2, The roles of continuous and surge-type flow: Journal of Geophysical Research, v. 92/C3, p. 2883-2900.

Hay, A.E., 1987, Turbidity currents and submarine channel formation in Rupert Inlet, British Columbia; 1, Surge observations: Journal of Geophysical Research, v. 92/C3, Pages: 2875-2881.

Imran, J. and M.A. Islam, 2008, Helical Flow in Sinuous Submarine Channels: Search and Discovery Article #90078 (2008), Web accessed 5 November 2009. http://www.searchanddiscovery.net/abstracts/html/2008/annual/abstracts/414439.htm

Keevil, G.M., J, Peakall, and J.L. Best, 2007, The influence of scale, slope and channel geometry on the flow dynamics of submarine channels: Marine and Petroleum Geology, v. 24/6-9, p. 487-503. Doi:10.1016/j.marpetgeo.2007.01.009

Keevil, G., J. Peakall, J.L. Best, and K.J. Amos, 2006, Flow structure in sinuous submarine channels; velocity and turbulence structure of an experimental submarine channel: Marine Geology, v. 229/3-4, p. 241-257.

Kenyon, N.H., A. Amir, and A. Cramp, 1995, Geometry of the younger sediment bodies of the Indus Fan, *in* K.T. Pickering, R.N. Hiscott, N.H. Kenyon, F.R. Lucchi, and R.D.A. Smith, (eds.), Atlas of Deep-water Environments: Architectural Styles in Turbidite Systems: Chapman and Hall, London, p. 89-93

Kikkawa, H., S. Ikeda, and A. Kitagawa, 1976, Flow and bed topography in curved open channels: Journal of the Hydraulics Division of the American Society of Civil Engineers, v. 102/HY9, p. 1327-1342.

Pirmez, C. and J. Imran, 2003, Reconstruction of turbidity currents in Amazon Channel: Marine and Petroleum Geology, v. 20/6-8, p. 823-849.

Pirmez, C. and R.D. Flood, 1995, Morphology and structure of Amazon Channel: Proceedings of the Ocean Drilling Program, Part A Initial Reports, v. 155, p.23-45.

Schwenk, T., V. Spiess, C. Huebscher, and M. Breitzke, 2003, Frequent channel avulsions within the active channel-levee system of the middle Bengal Fan; an exceptional channel-levee development derived from Parasound and Hydrosweep data: Deep Sea Research, Part II Topical Studies in Oceanography, v. 50/5, p. 1023-1045.

Sequeiros, O.E., B. Spinewine, M.H. Garcia, R.T. Beaubouef, T. Sun, and G. Parker, 2009, Experiments on wedge-shaped deep sea sedimentary deposits in minibasins and/or on channel levees emplaced by turbidity currents; Part I, Documentation of the flow: Journal of Sedimentary Research, v. 79/8, p. 593-607.

Weimer, P., 1991, Seismic facies, characteristics, and variations in channel evolution, Mississippi Fan (Plio-Pleistocene), Gulf of Mexico, *in* P. Weimer and M.H. Link, (eds.), Seismic facies and sedimentary processes of submarine fans and turbidite systems, p. 323-347.

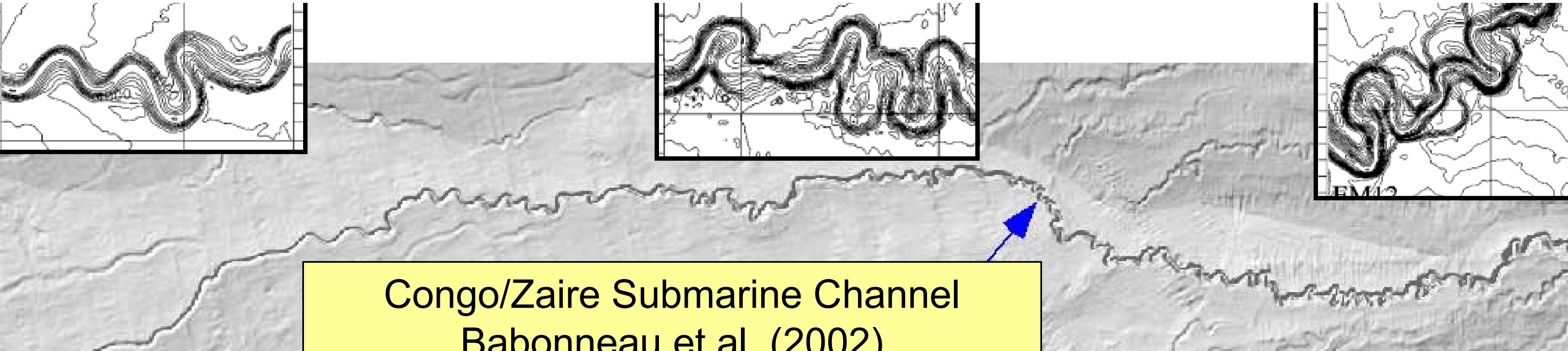
Weimer, P., 1991, Sequence stratigraphy of the Mississippi Fan related to oxygen isotope sea level index; discussion: AAPG Bulletin, v. 75/9, p. 1500-1507.

Wynn, T.C. and J.F. Read, 2007, Carbon-oxygen isotope signal of Mississippian slope carbonates, Appalachians, USA; a complex response to climate-driven fourth-order glacio-eustasy: Palaeogeography Palaeoclimatology Palaeoecology, v. 256/3-4, p. 254-272.

Xu, J.P., Noble, M.A., Rosenfeld, L.K., 2004. In-situ measurements of velocity structure within turbidity currents. Geophysical Research Letters, v. 31, p. 1029–1033.

NATIONAL CENTER FOR EARTH-SURFACE DYNAMICS

A NATIONAL SCIENCE FOUNDATION SCIENCE & TECHNOLOGY CENTER



Congo/Zaire Submarine Channel
Babonneau et al. (2002)

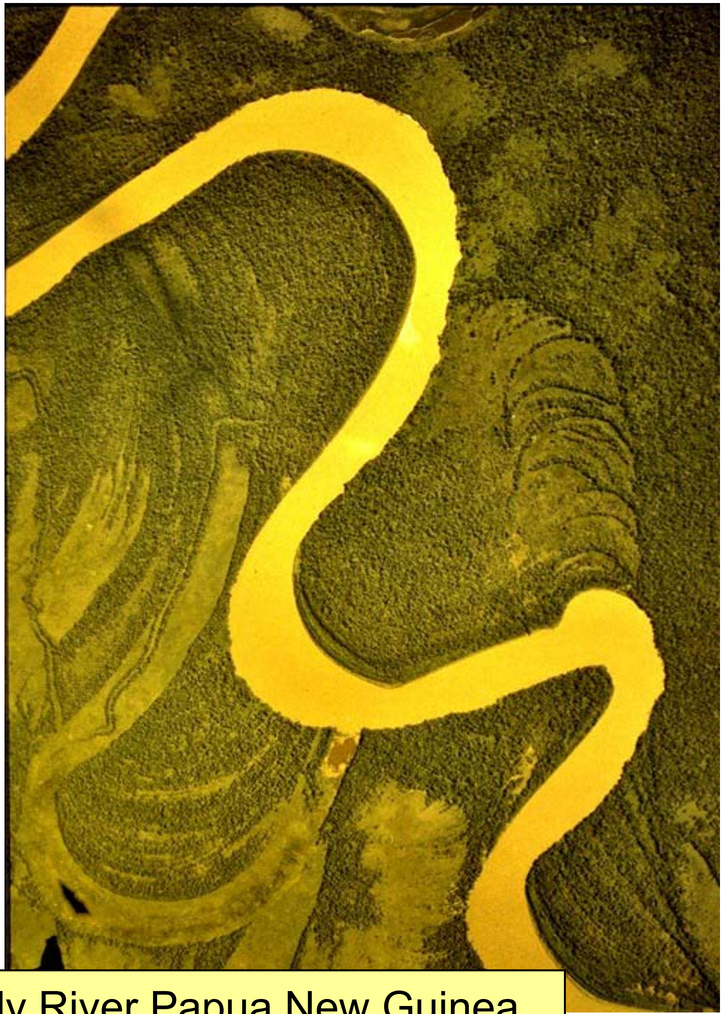
Secondary Flow in Meandering Channels on Submarine Fans: Implications for Channel Morphodynamics and Architecture

Jorge Abad*, Octavio Sequeiros, Benoit Spinewine, Carlos Pirmez, Marcelo Garcia*, Gary Parker*
*Depts. of Civil & Environmental Engineering and Geology
University of Illinois Urbana, USA

June 9, 2009

AAPG Annual Convention & Exhibition

MANY RIVERS SHOW BEAUTIFUL PATTERNS OF MEANDERING

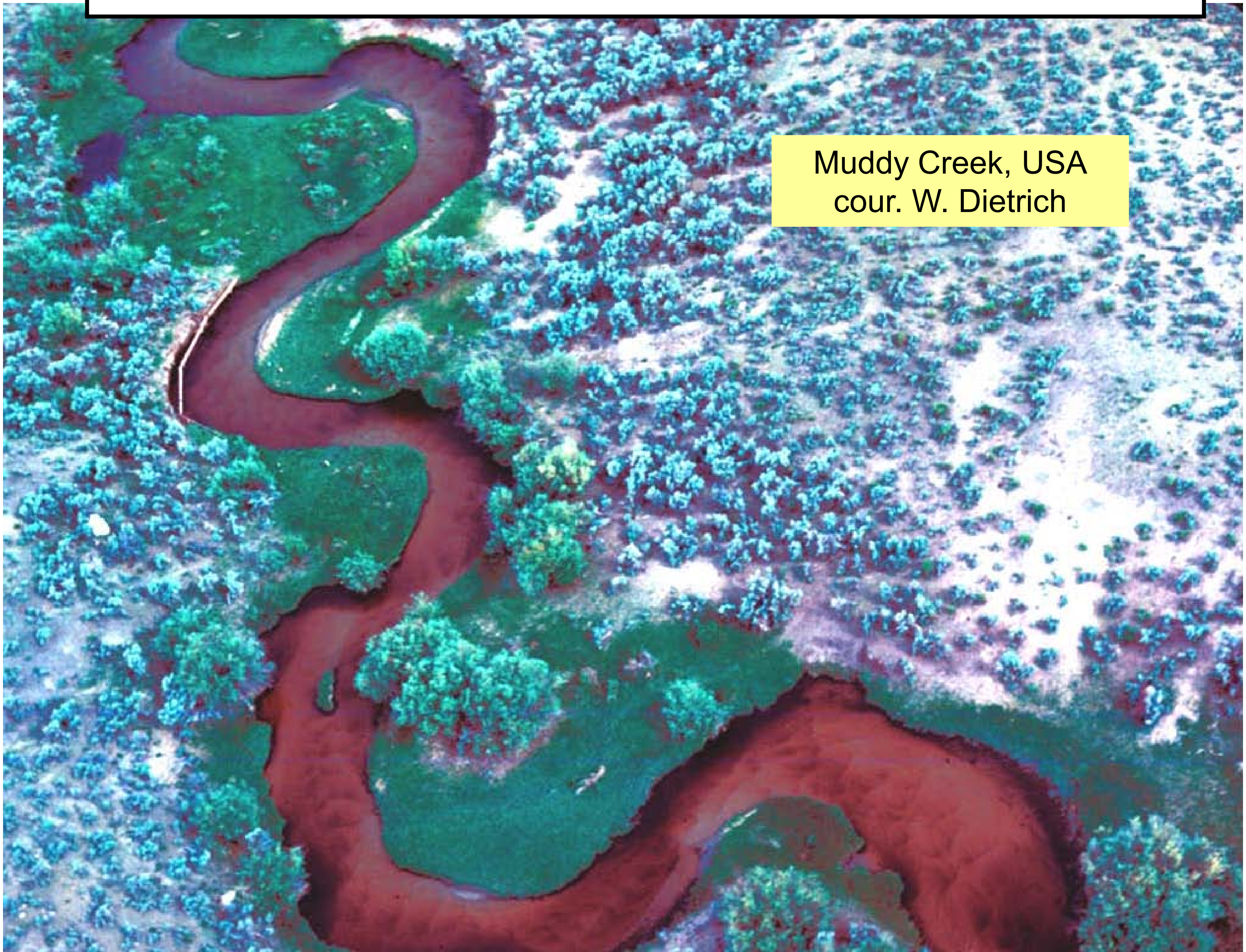


Fly River Papua New Guinea

Nameless Siberian River

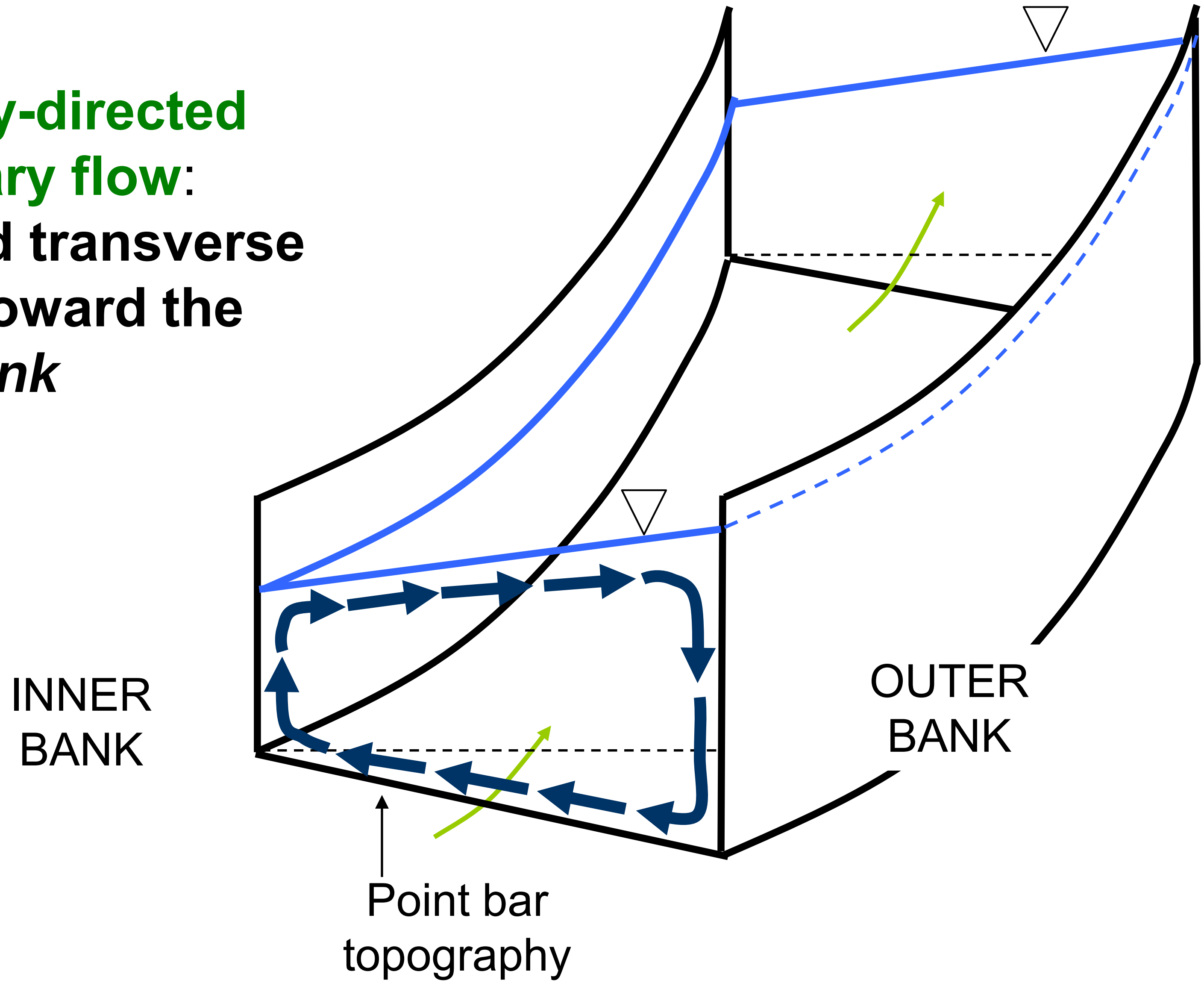
Maple River USA

CHANNEL MORPHOLOGY, POINT BAR CONSTRUCTION AND MIGRATION



ARE AT LEAST PARTIALLY CONTROLLED BY SECONDARY FLOW

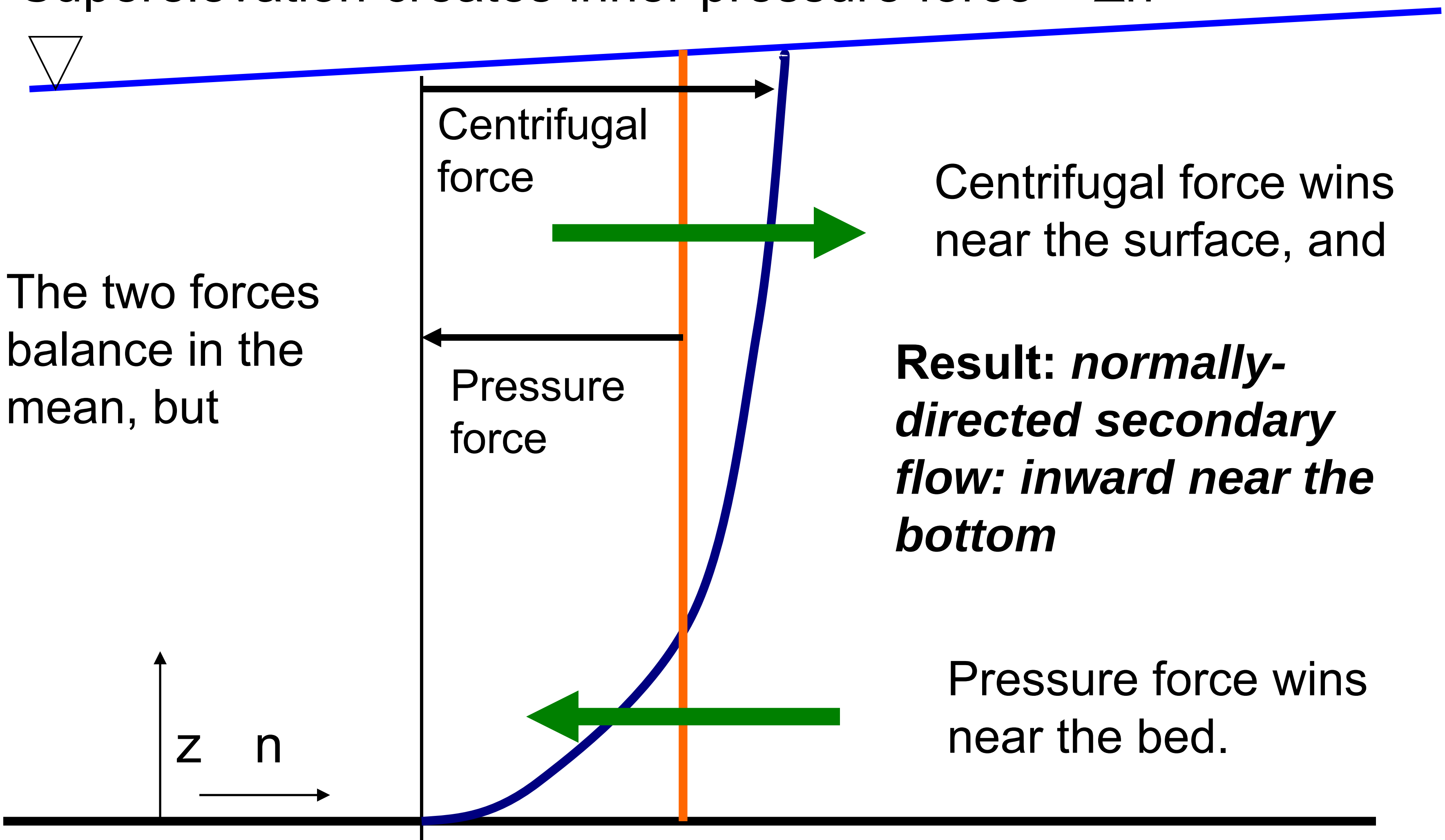
Normally-directed secondary flow: **near-bed transverse flow is toward the *inner bank***



THE BASIC PRINCIPLES OF SECONDARY FLOW

Streamwise velocity $u_s(z)$ creates outer centrifugal force $\sim u_s^2$

Superelevation creates inner pressure force $\sim \Delta h$



The two forces balance in the mean, but

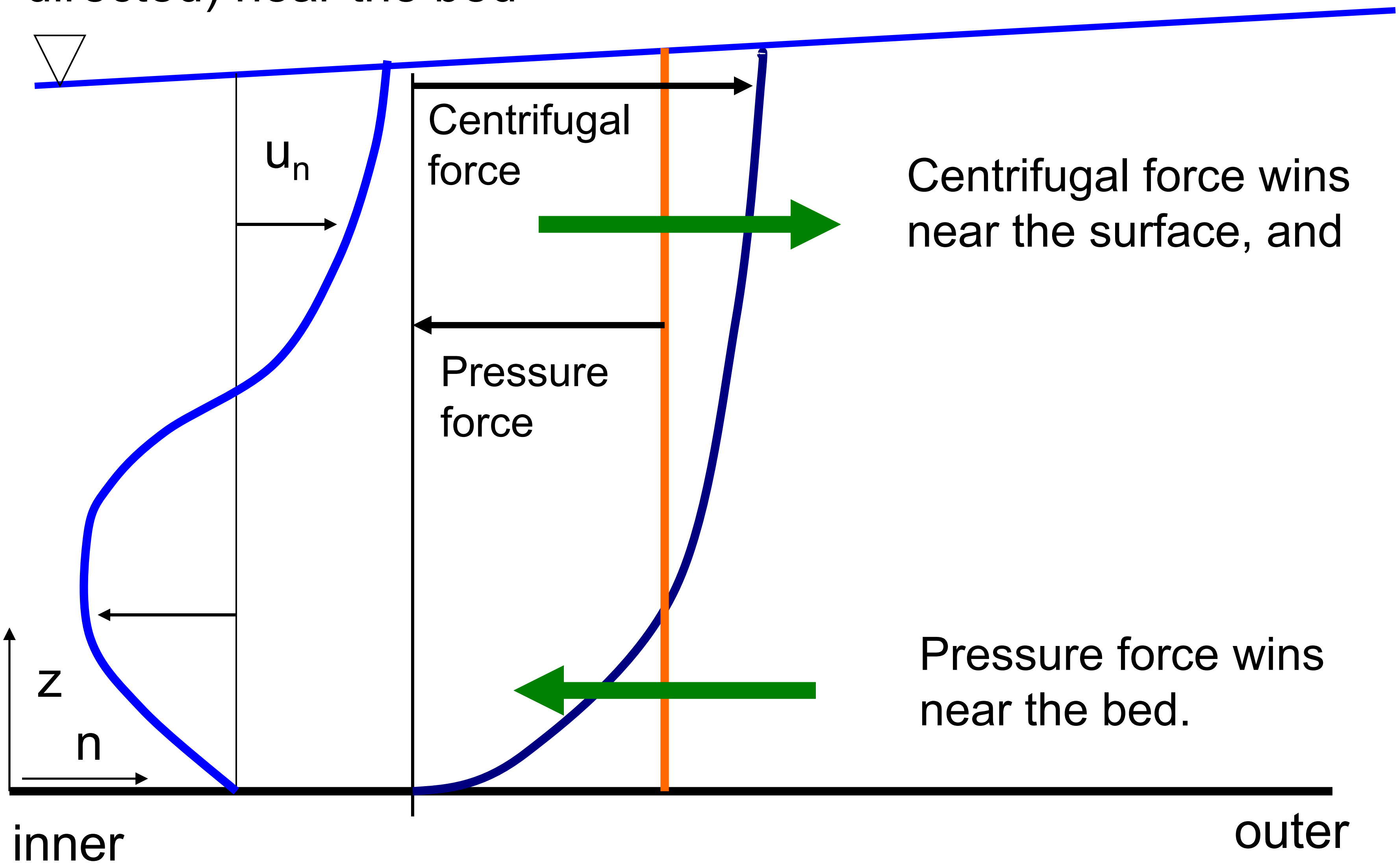
Centrifugal force wins near the surface, and

Pressure force wins near the bed.

Result: ***normally-directed secondary flow: inward near the bottom***

THE BASIC PRINCIPLES OF SECONDARY FLOW

As a result, the secondary flow velocity $u_n(z) < 0$ (is inward-directed) near the bed



Centrifugal force wins near the surface, and

Pressure force wins near the bed.

WHAT ABOUT MEANDERING SUBMARINE CHANNELS?

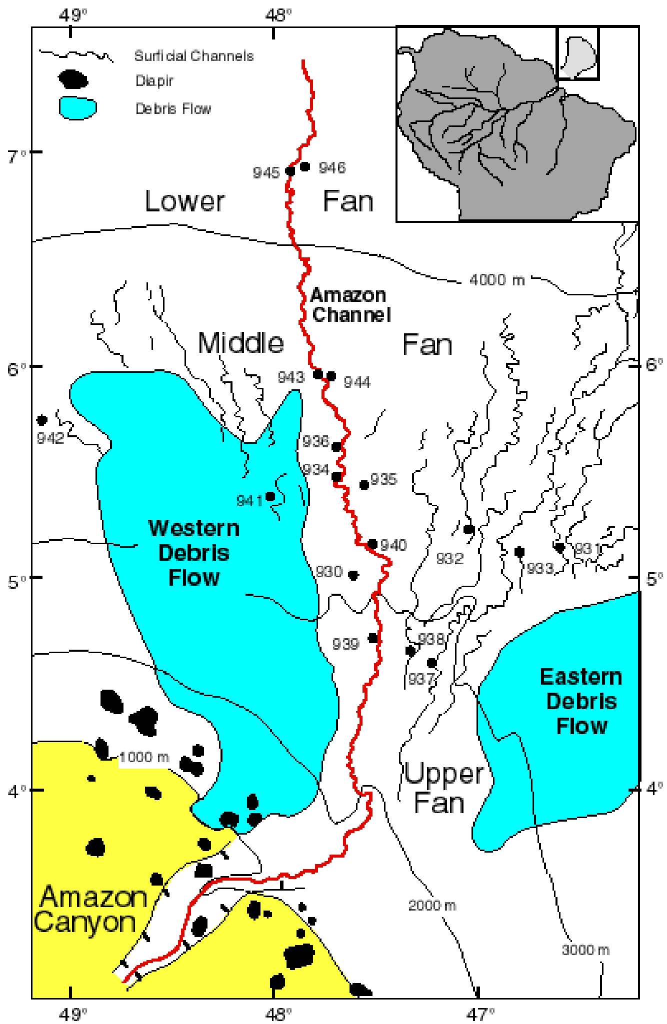
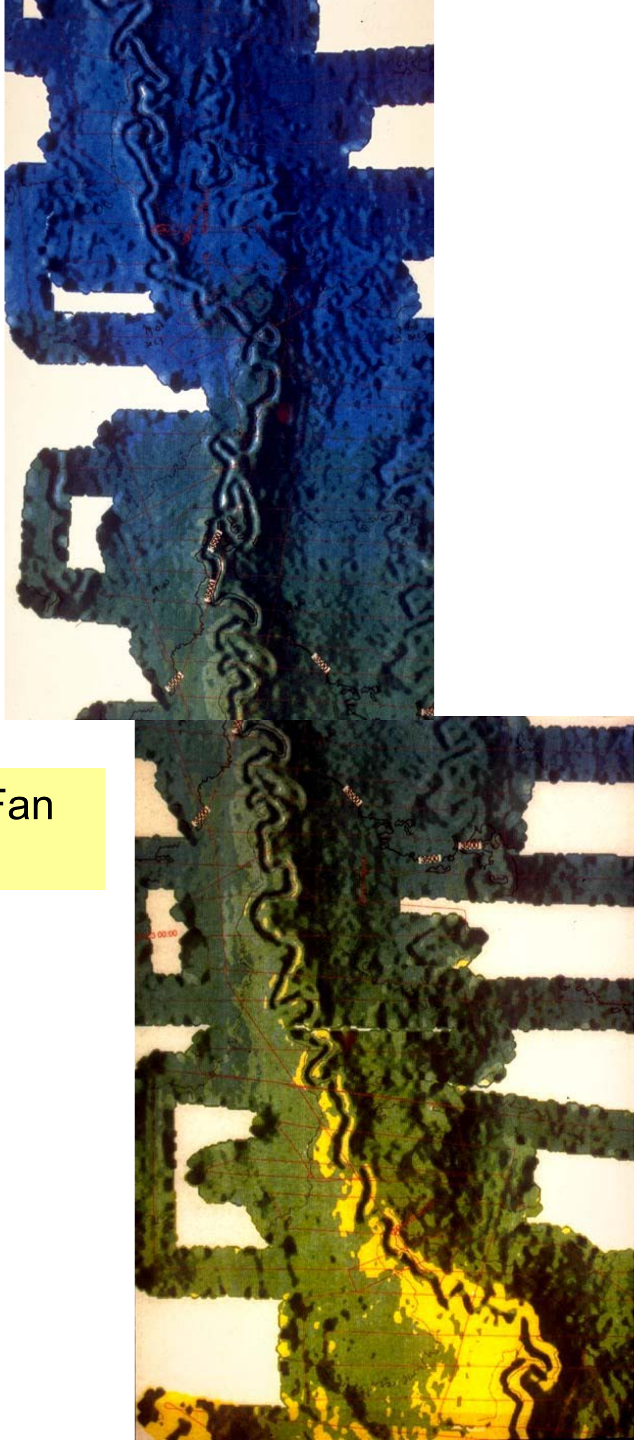
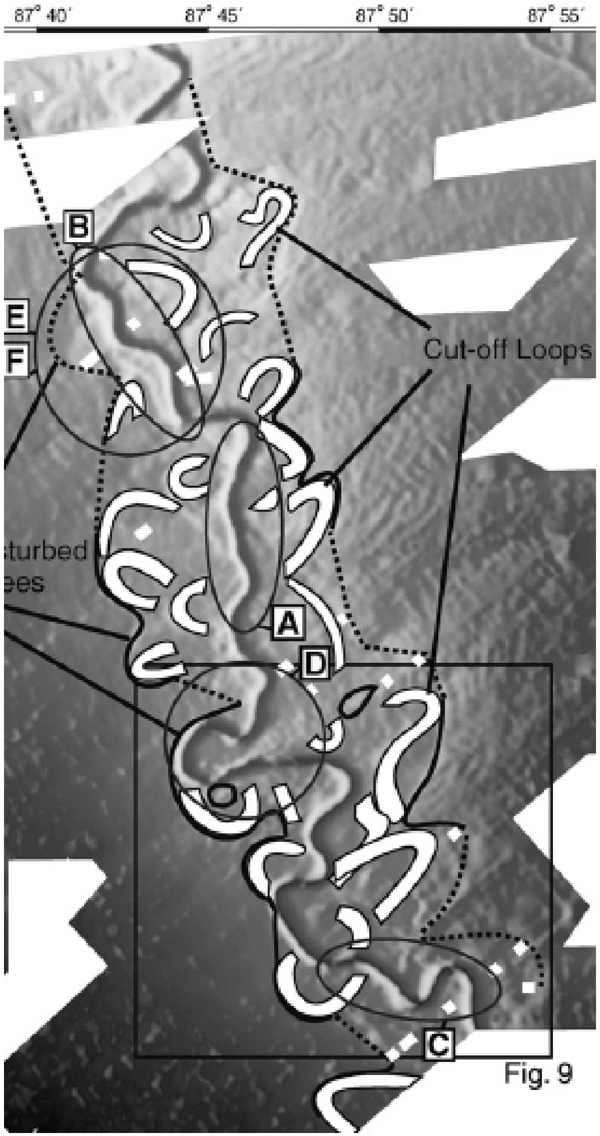


Figure 1. Surface features of Amazon Fan. Thick (red) line indicates the path of the most recently active channel system, Amazon Channel.

Amazon Submarine Fan (Pirmez, 1995)

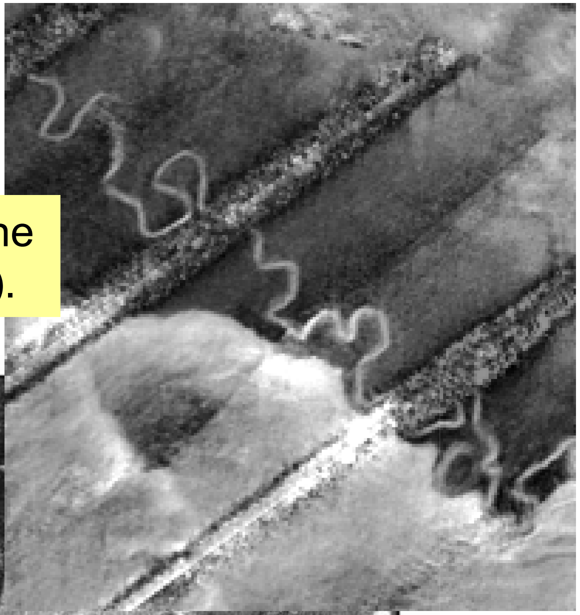


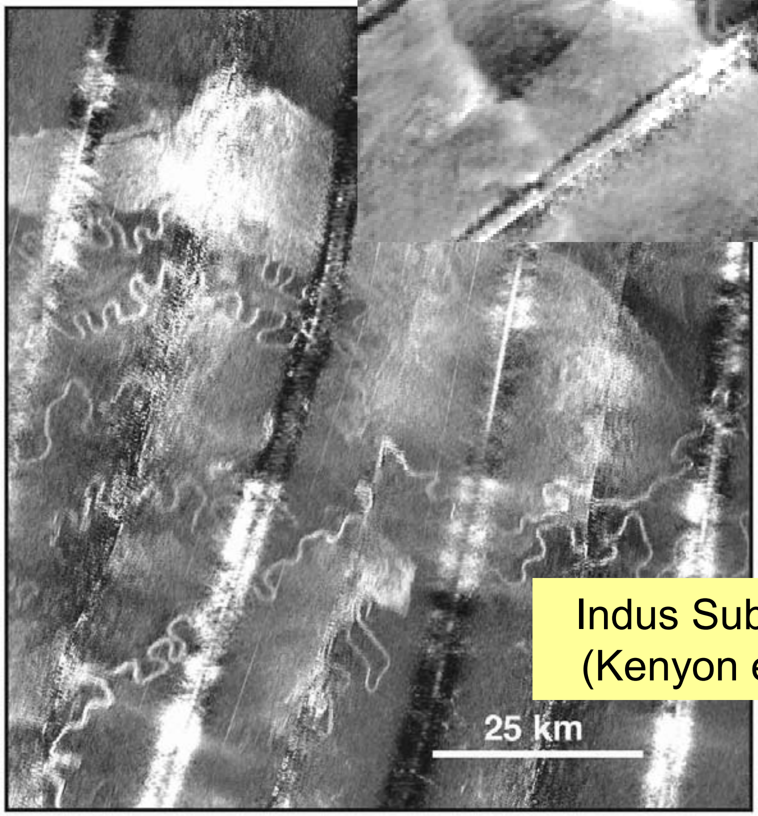
THERE ARE LOTS OF SUCH MEANDERING CHANNELS



Bengal Fan: Schwenk et al. (2003)

Mississippi Submarine Fan (Weimer, 1991).



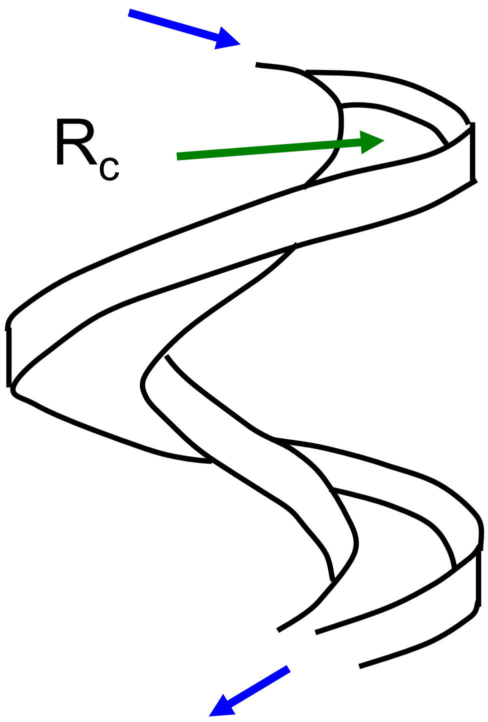


Indus Submarine Fan (Kenyon et al., 1995)

GLORIA side-scan sonar mosaic of the Indus submarine fan (Kenyon et al., 1995)

RECENTLY THE THEORY OF SECONDARY FLOW IN SPIRAL CHANNELS

R_c = centerline radius of curvature = constant

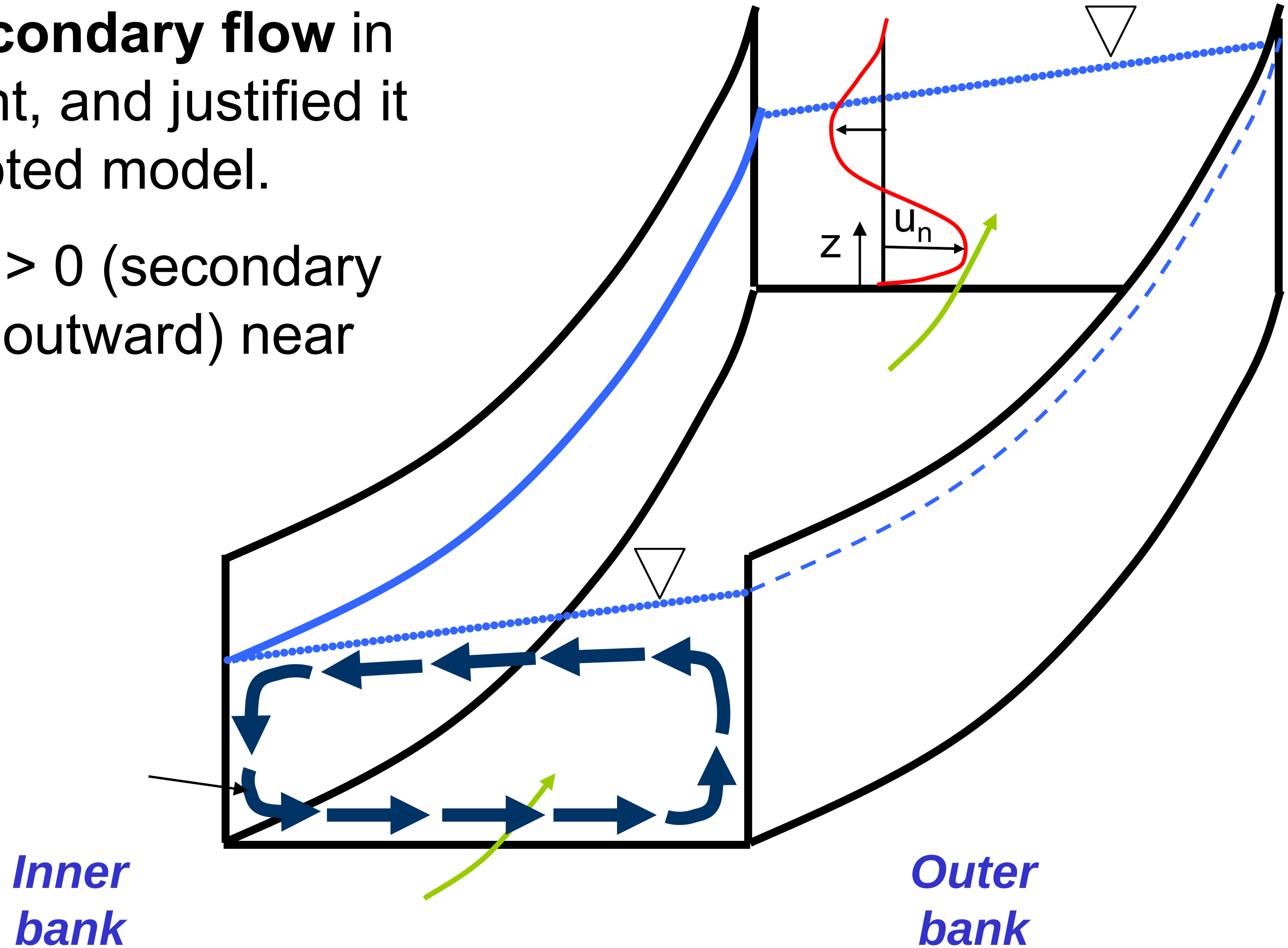


I.e. the classical Rozovskiian formulation, as applied by Kikkawa, Ikeda and Kikkawa (1976)

HAS BEEN ADAPTED TO THE SUBMARINE CASE

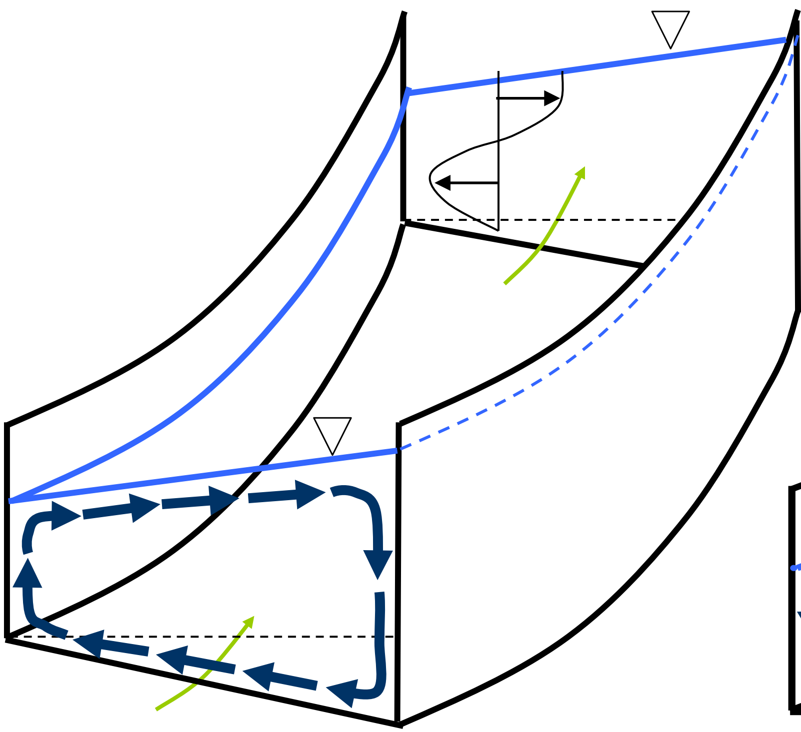
Corney et al. (2006) and Keevil et al. (2006) obtained **reversed secondary flow** in an experiment, and justified it with the adapted model.

That is, $u_n(z) > 0$ (secondary flow directed outward) near the bed

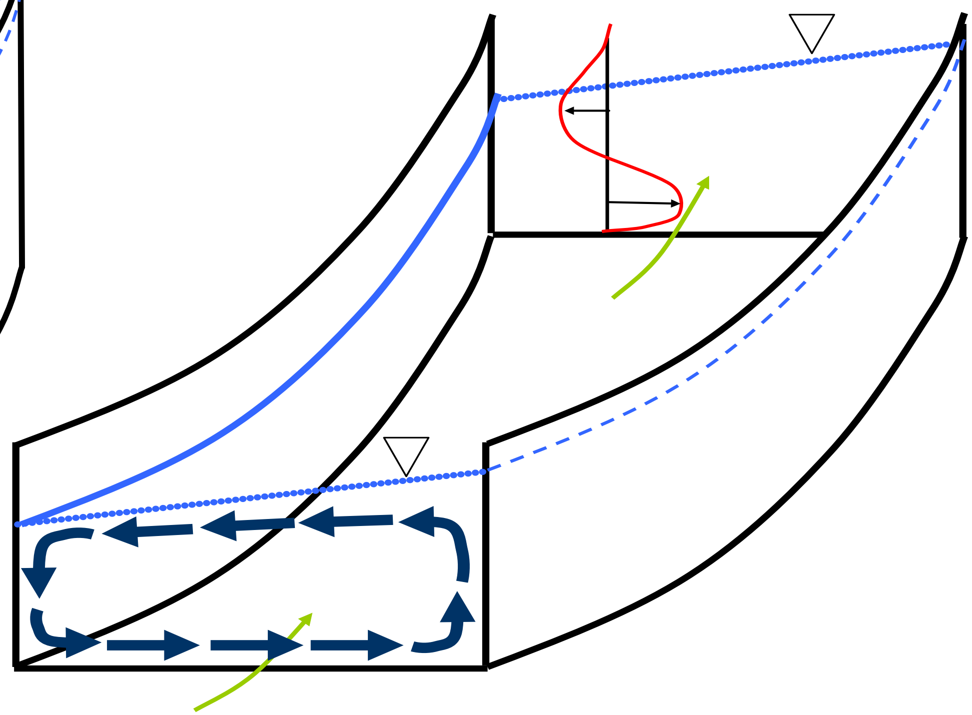


BASED ON THESE RESULTS, IT HAS BEEN SAID THAT SECONDARY FLOW SHOULD GENERALLY BE REVERSED IN SUBMARINE MEANDERING CHANNELS

Subaerial: near-bed inward



Submarine: near-bed outward?



THE BASIS FOR THE CLAIM

Wynn et al. (2007) state as follows.

“The position of the velocity maximum in natural channelised turbidity flows…, continuous input laboratory currents…, and numerical simulations of natural-sized flows… [is] in the range of 0.1 - 0.2 of the flow depth.

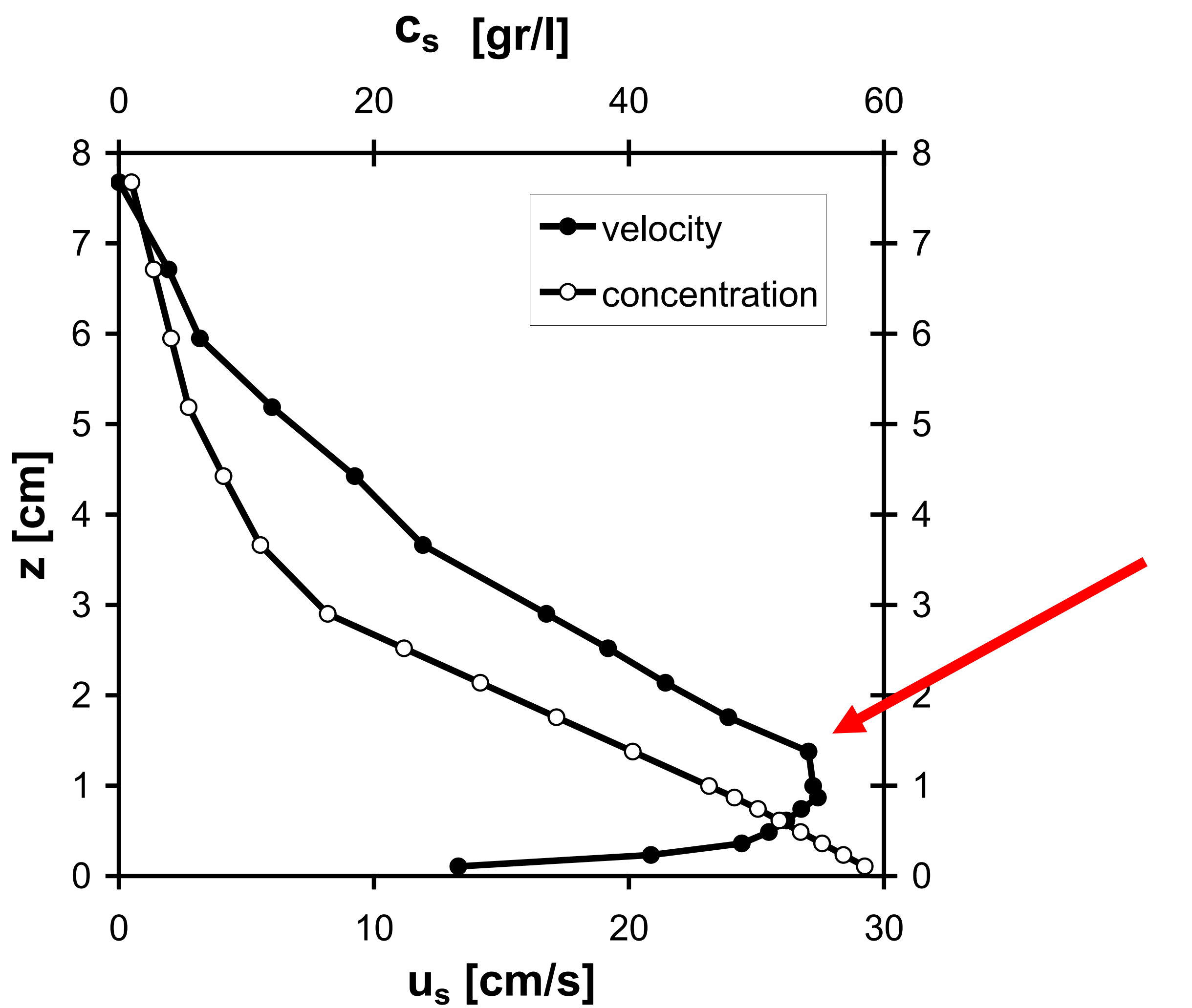
Consequently, the data suggest that **submarine channel flows will predominantly show a reversed secondary circulation relative to rivers**…”

“The position of the velocity maximum… [is] in the range of 0.1 - 0.2 of the flow depth. “

THIS MEANS THAT THE PEAK VELOCITY u_s OF THE STREAMWISE FLOW HUGS THE BED

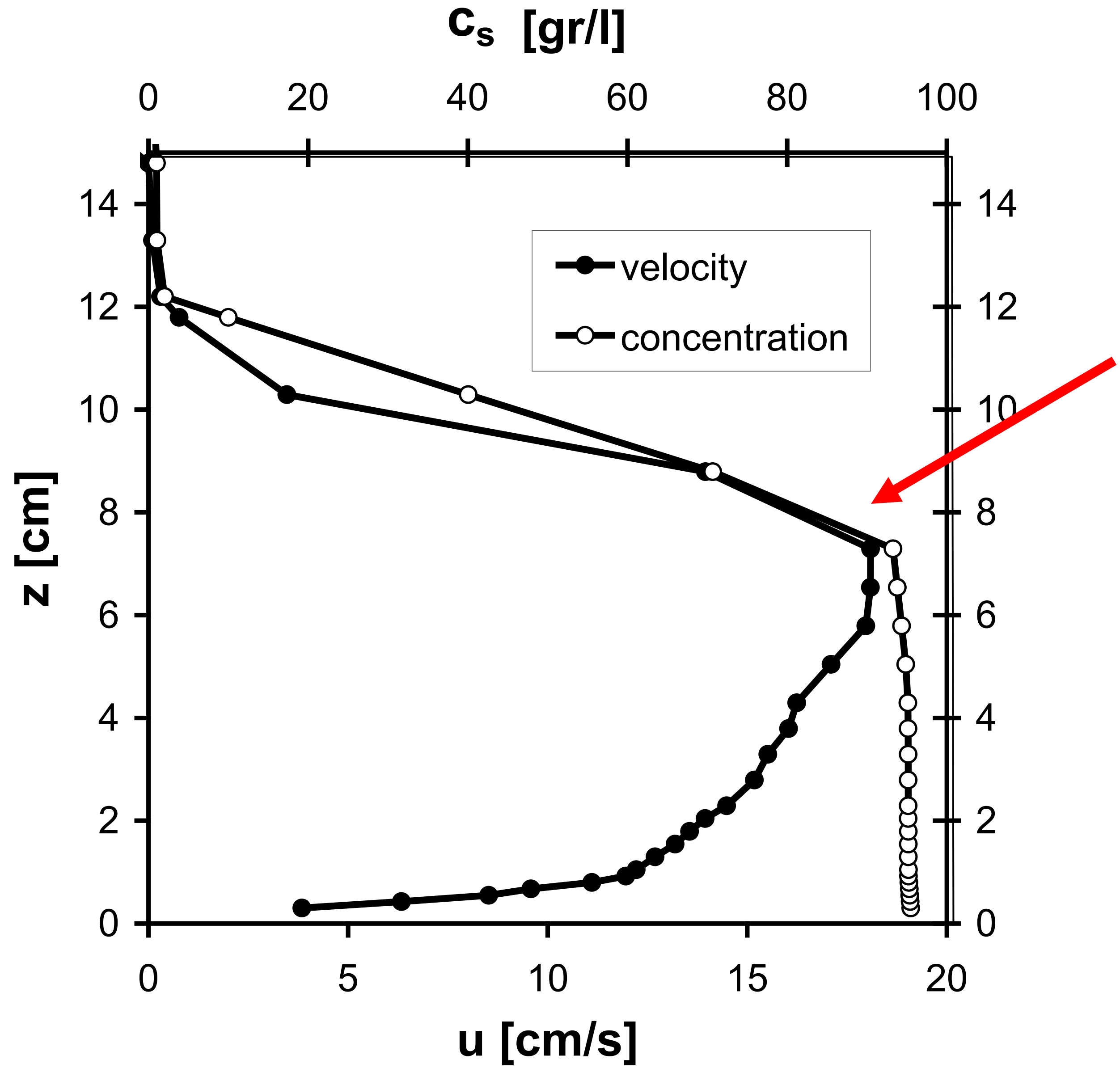
Densimetric Froude Number

Fr_d = 1.87

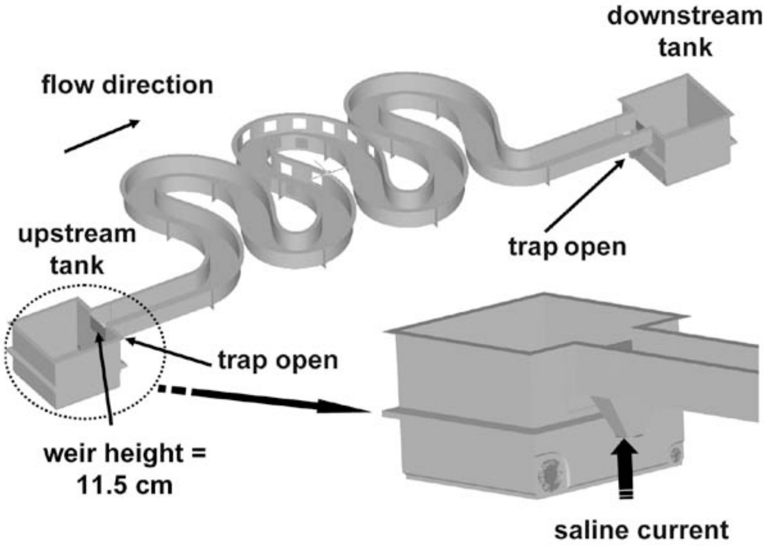


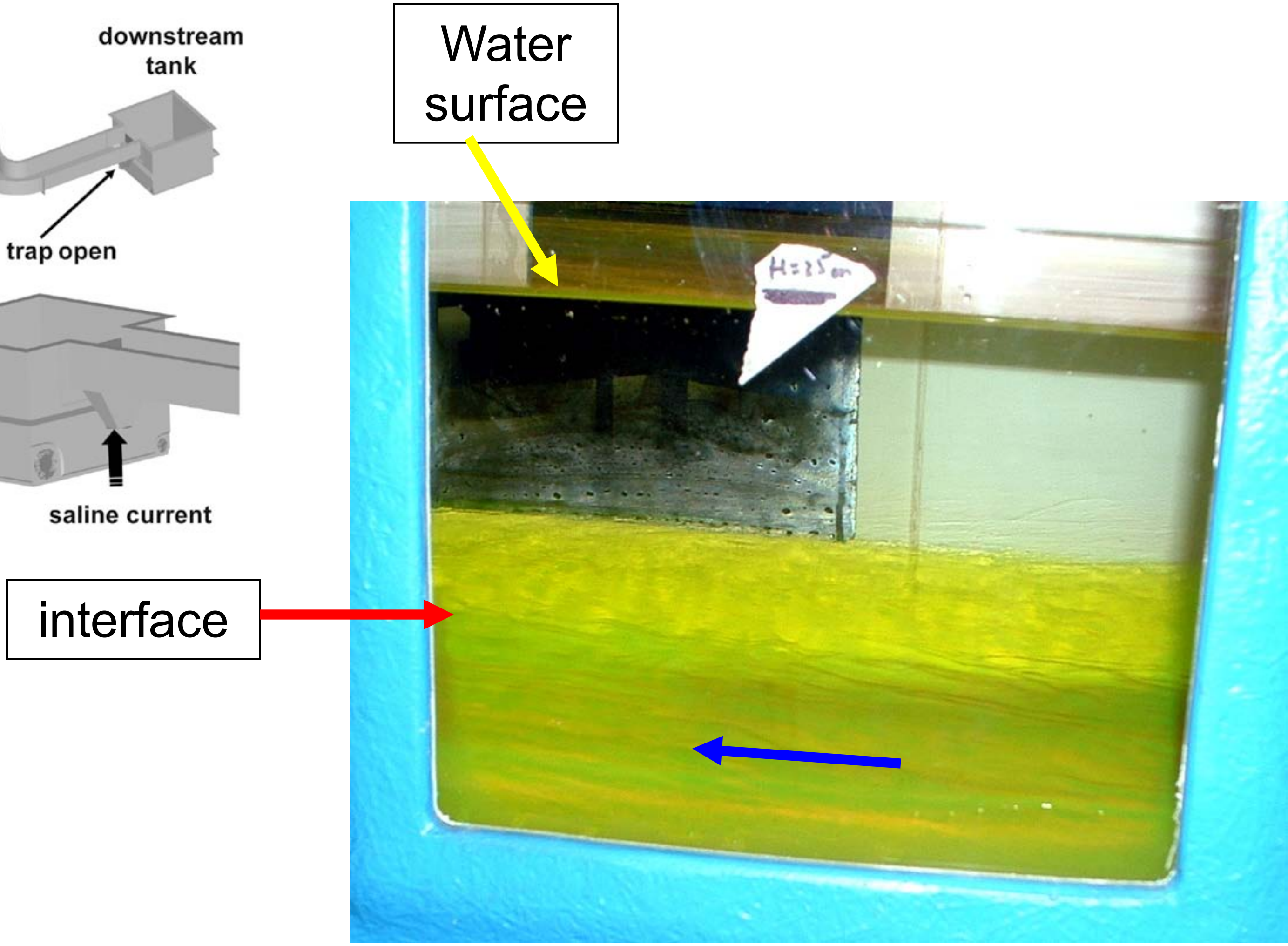
BUT IS IT ALWAYS TRUE?

Densimetric
Froude Number
$\mathbf{Fr}_d = 0.61$



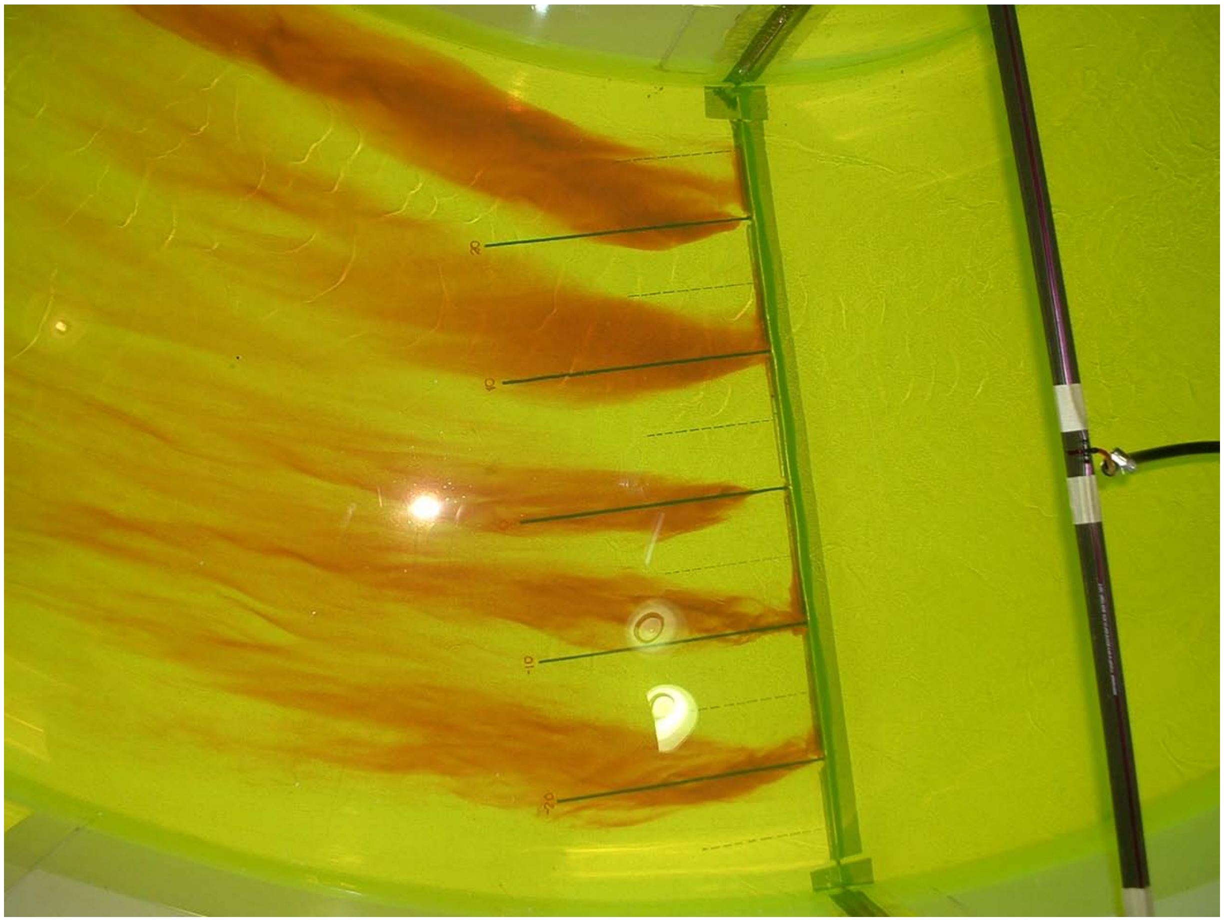
OTHER RESEARCHERS HAVE STUDIED SECONDARY FLOWS IN MODEL SUBMARINE CHANNELS



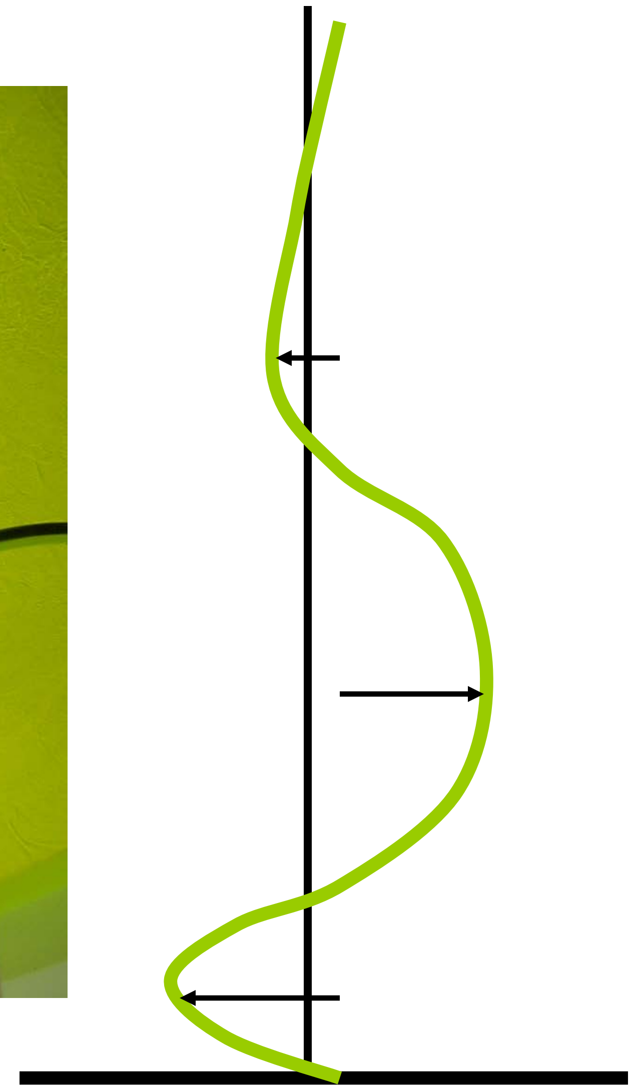


AND OBTAINED NORMALLY-DIRECTED SECONDARY FLOW

inner



outer



SALINE UNDERFLOW IN A HIGHLY MEANDERING CHANNEL

Abad, J. D., Garcia, M. H., and Parker, G.

Click to View Movie

From Upstream of S13

8%

December 2006

WHAT GIVES?

SOME PARAMETERS

z	=	vertical coordinate
n	=	transverse coordinate
$u_s(z)$	=	streamwise velocity
$u_n(z)$	=	transverse (secondary) velocity
$\delta(z)$	=	fractional excess density (due to sediment or salt)
ρ	=	ambient water density
τ_b	=	bed shear stress
R_c	=	centerline radius of curvature

h	=	layer thickness
U	=	layer-averaged streamwise velocity
Δ	=	layer-averaged fractional excess density

$$Uh = \int_0^\infty u_s dz \quad , \quad U^2 h = \int_0^\infty u_s^2 dz \quad , \quad U\Delta h = \int_0^\infty u_s \delta dz$$

SOME MORE PARAMETERS

Densimetric Froude Number

$$\mathbf{Fr}_d = \frac{U}{\sqrt{g\Delta h}}$$

Bed Friction Coefficient

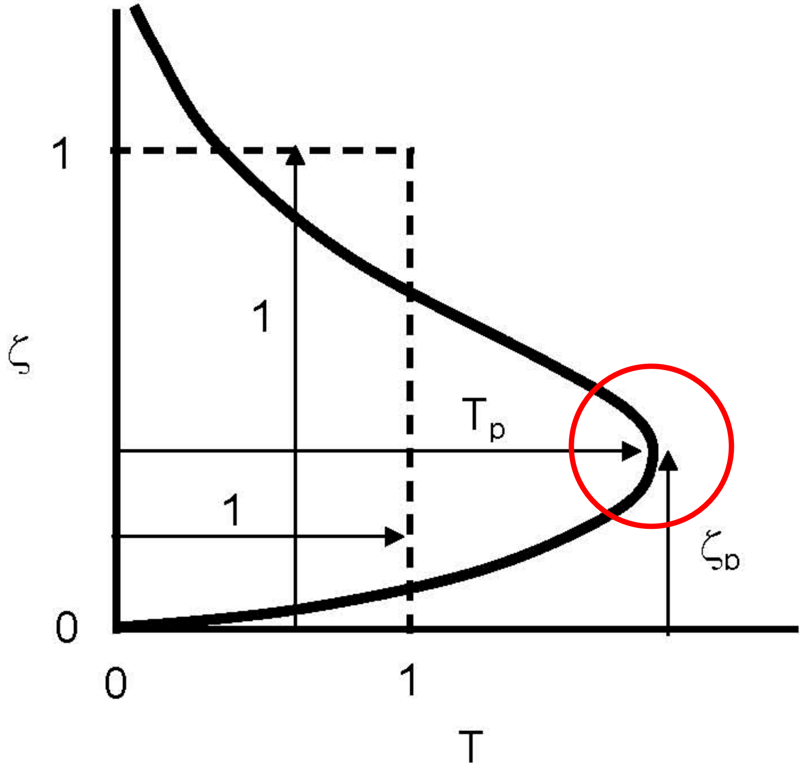
$$C_f = \frac{\tau_b}{\rho U^2}$$

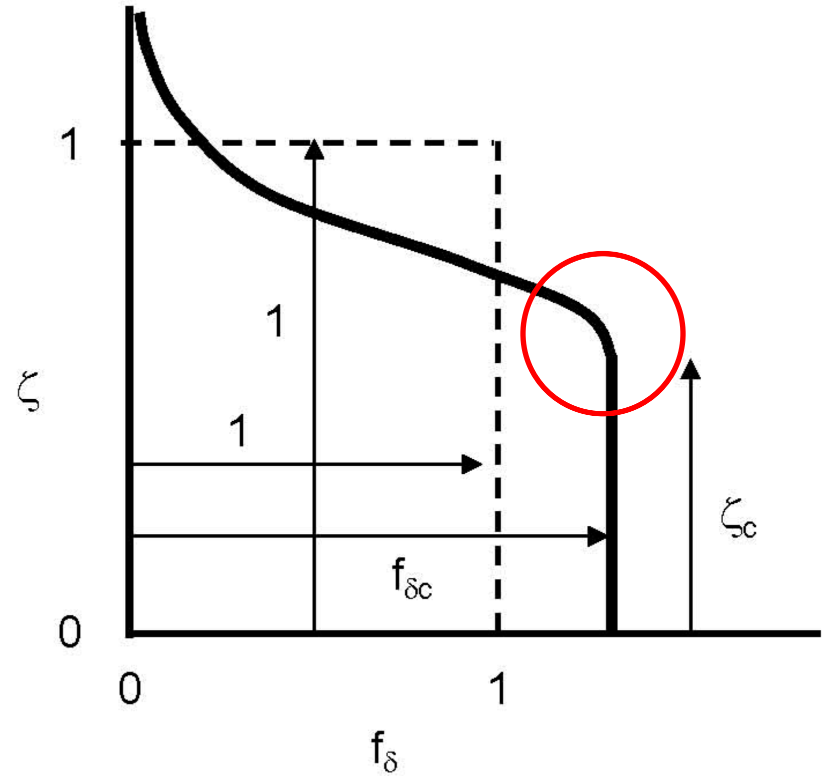
Chezy Bed Friction Coefficient

$$Cz = \frac{1}{\sqrt{C_f}}$$

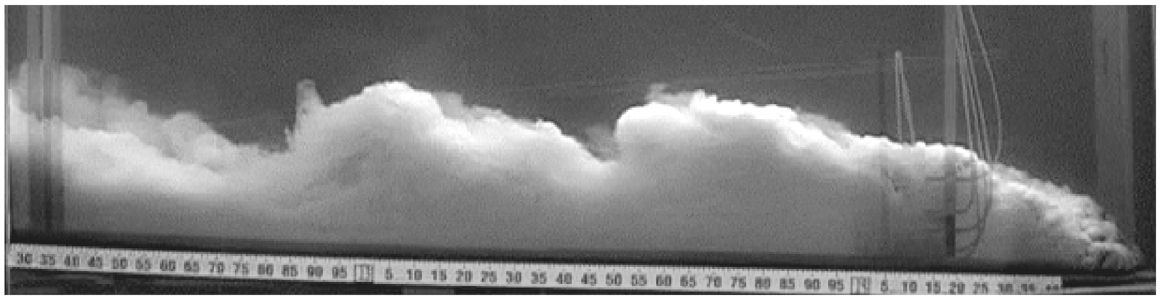
NORMALIZED VELOCITY, EXCESS DENSITY FUNCTIONS OF THE *PRIMARY (STREAMWISE)* FLOW

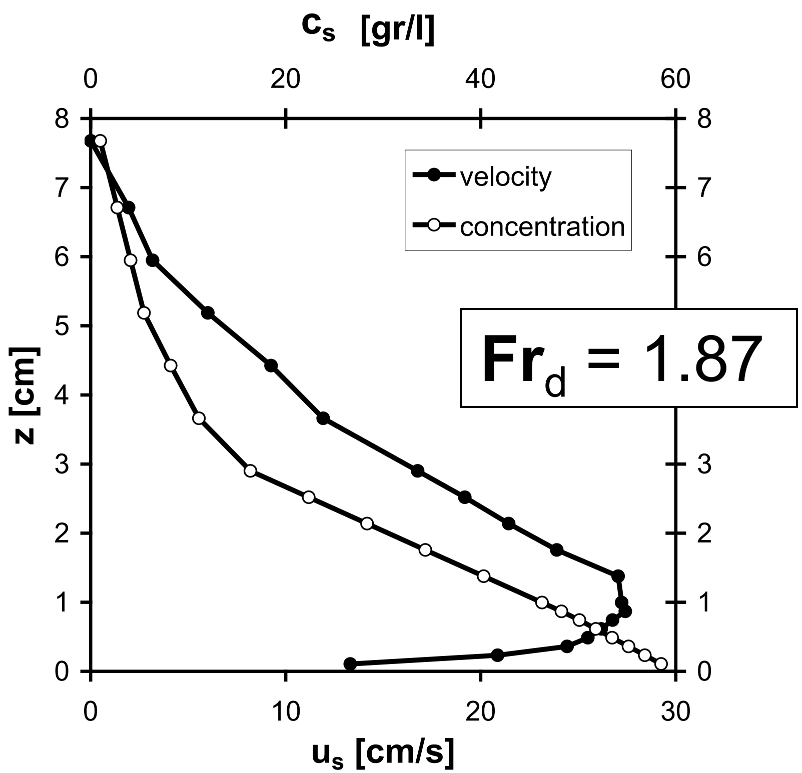
ζ	=	z/h = normalized vertical coordinate
T	=	u_s/U = normalized streamwise velocity profile
f_δ	=	δ/Δ = normalized excess density profile
ζ_p	=	point at which T reaches its peak value
ζ_c	=	point below which f_δ ~ constant

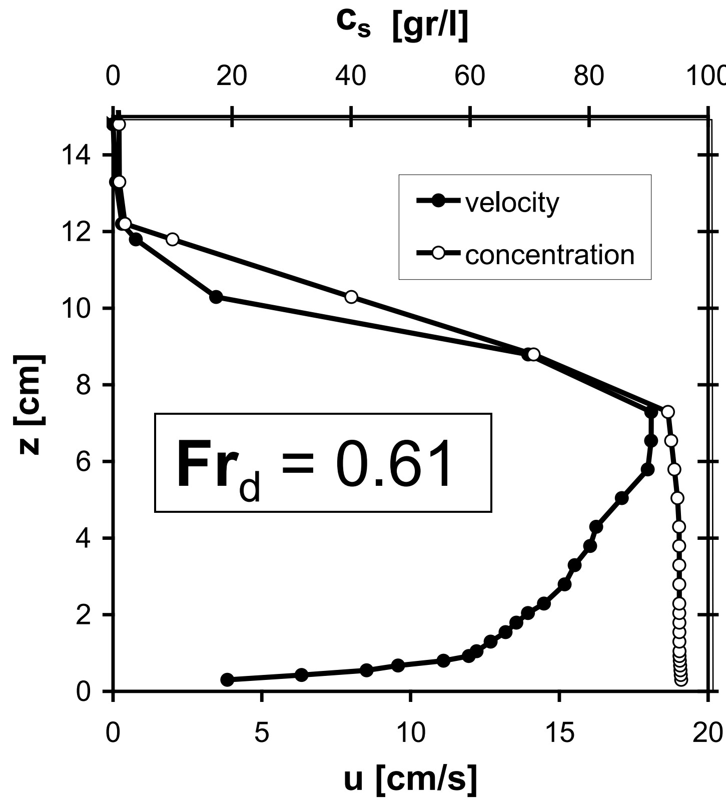




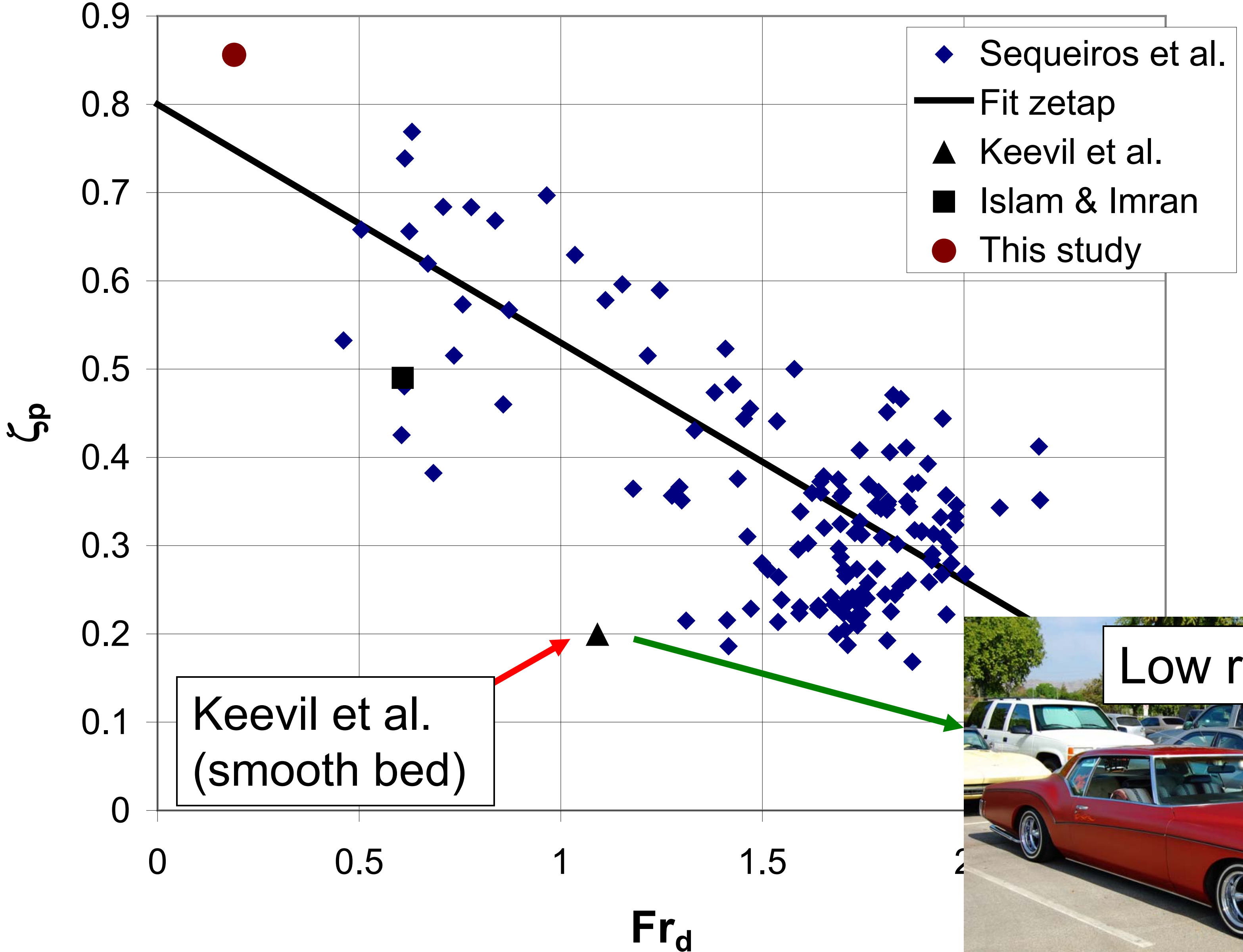
THE RECENT EXPERIMENTS OF SEQUEIROS ET AL. ALLOWED DETERMINATION OF THESE STRUCTURE FUNCTIONS IN A STRAIGHT CHANNEL



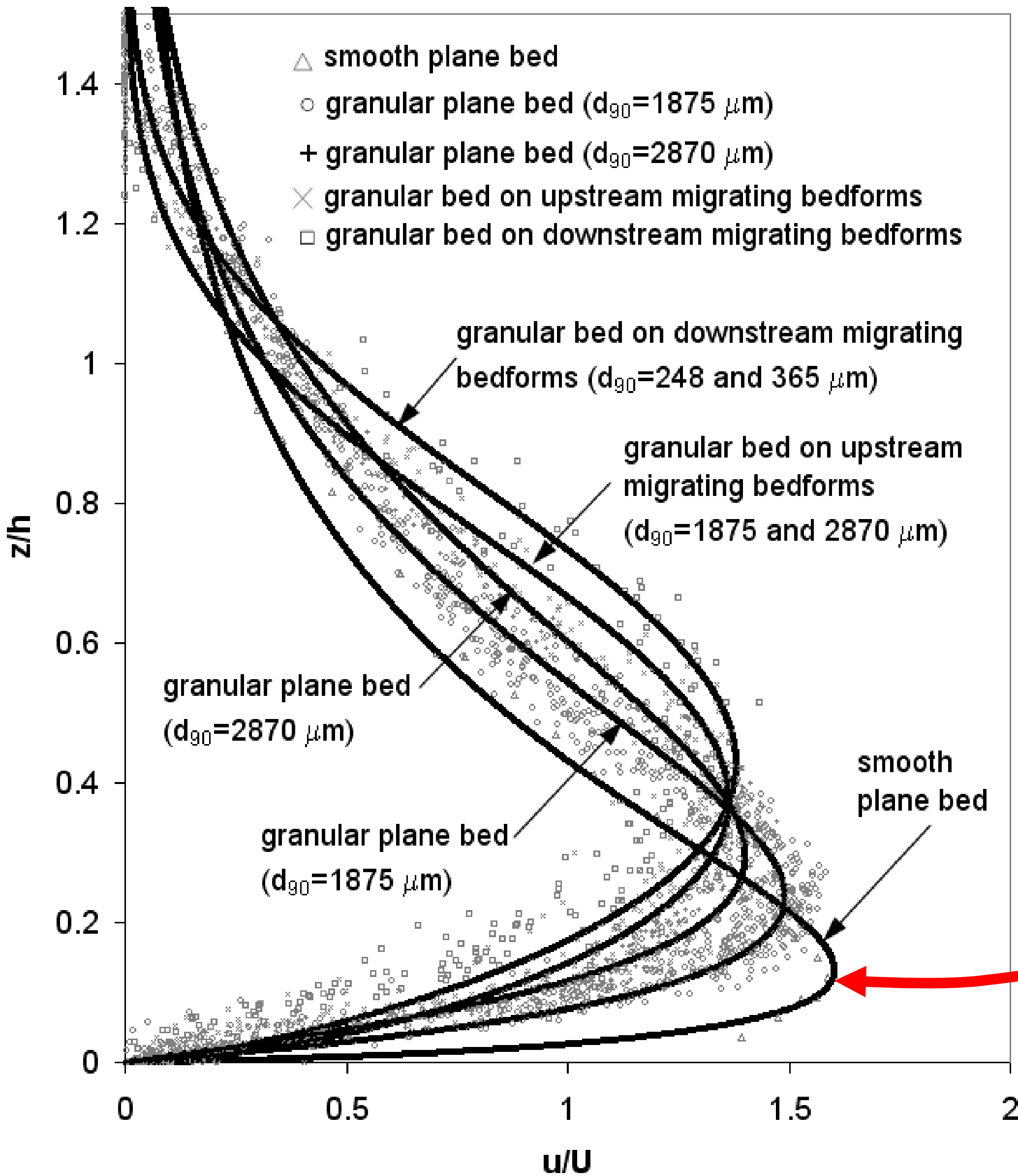




FIT FOR ζ_p FROM SEQUEIROS ET AL. DATA

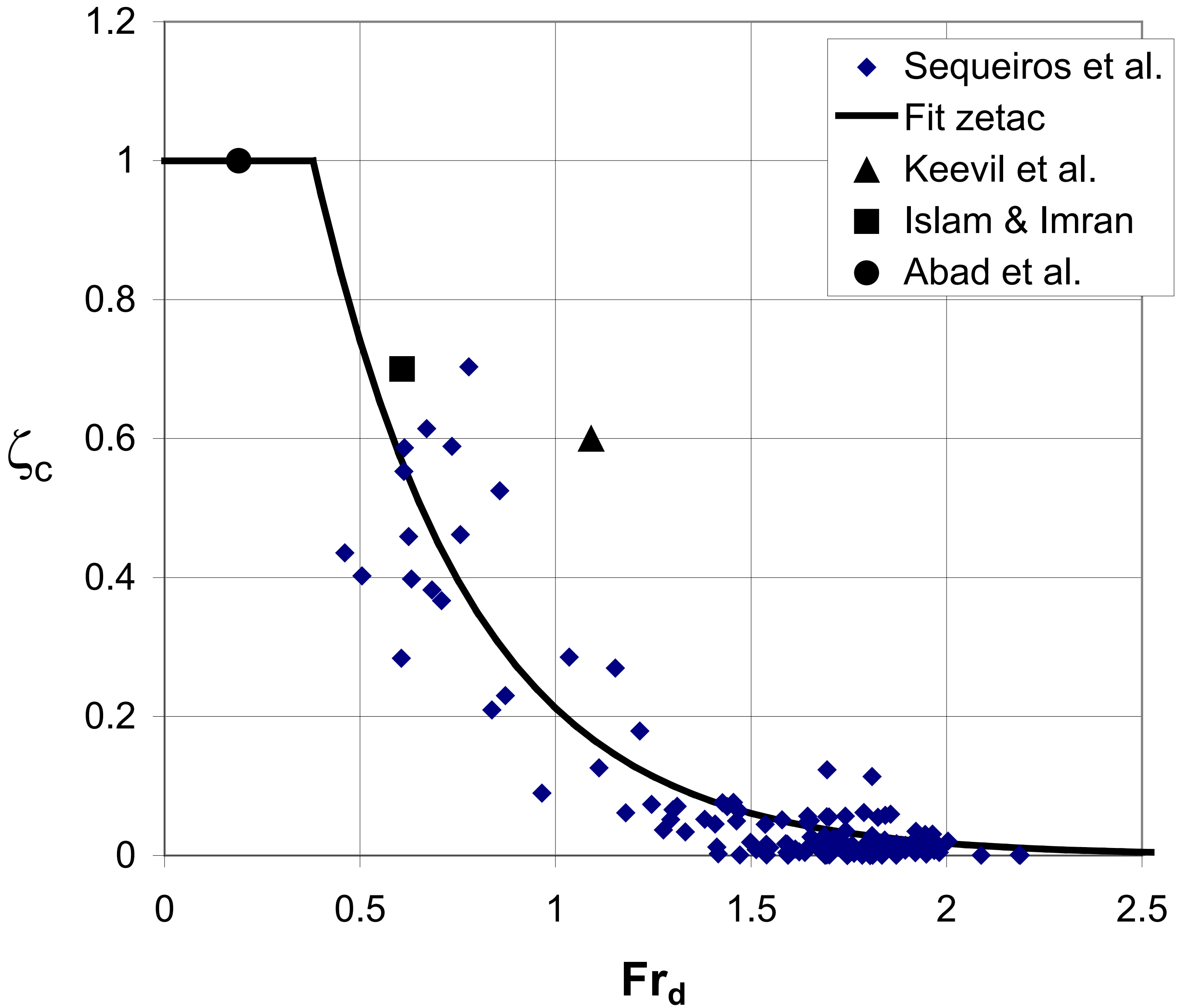


EXPERIMENT OF CORNEY ET AL. AND KEEVIL ET AL. WERE PERFORMED USING A SMOOTH BED



All the experiments Sequeiros et al. except one of were performed over granular beds. In the single exception, over a smooth, nonerodible bed, ζ_p was anomalously low.

FIT FOR ζ_c FROM SEQUEIROS ET AL. DATA



A CORRECTED FORMULATION OF SECONDARY FLOW WAS DEVELOPED TO INCLUDE THE EFFECTS OF DENSITY STRATIFICATION THROUGH ζ_p AND ζ_c

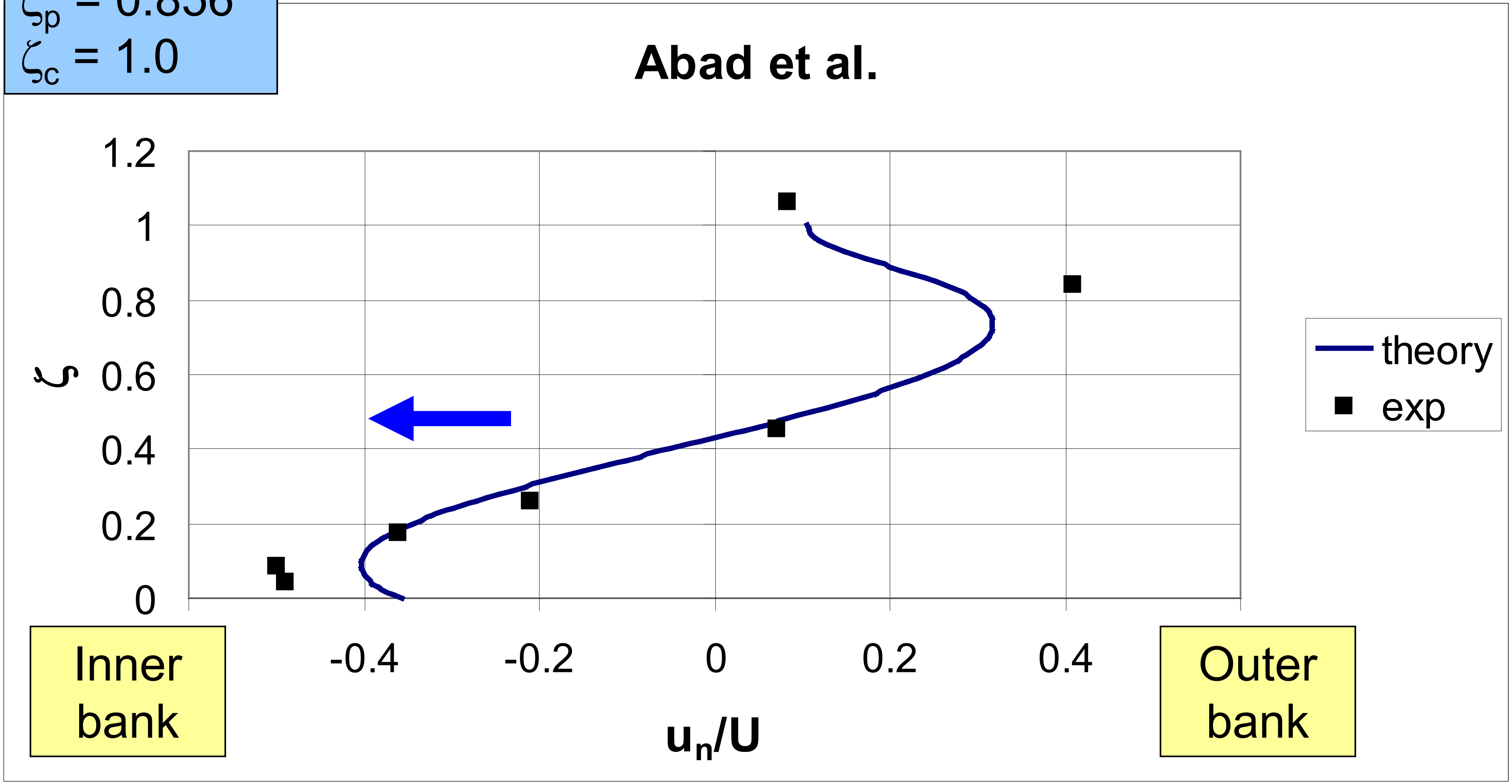
Our formulation:

1. Modified Engelund slip velocity formulation for $T(\zeta)$ with specified value of ζ_p.
2. Constant-linear formulation for $f_\delta(\zeta)$ with specified value for ζ_c.

Corney et al. considered the effect of ζ_p, but **did not include the effect of ζ_c, which strongly effects the transverse pressure gradient and thus the secondary flow.**

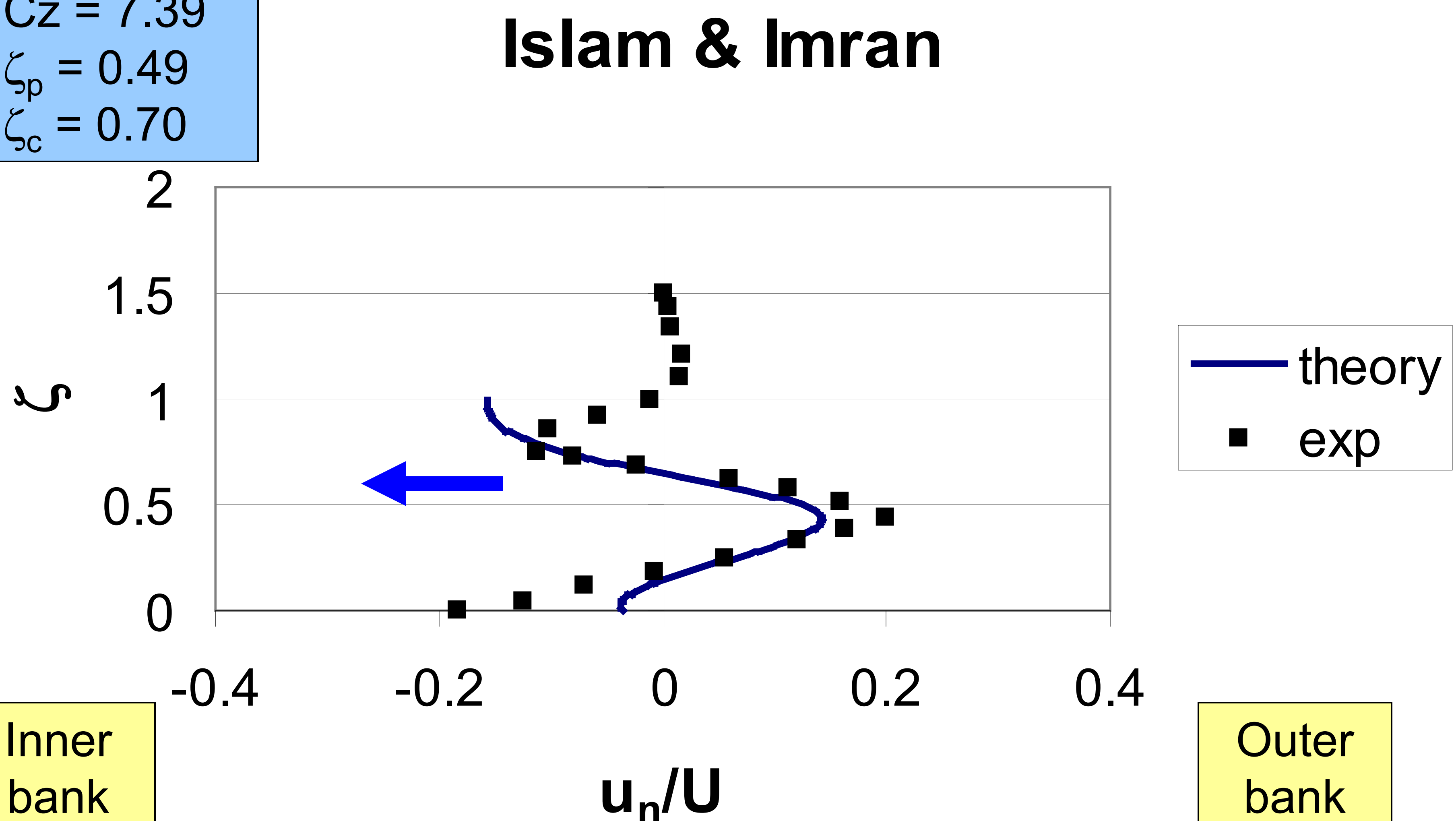
THEORY CORRECTLY PREDICTS NORMALLY-DIRECTED SECONDARY FLOW FOR OUR EXPERIMENT (ABAD ET AL.)

$Fr_d = 0.189$
$Cz = 8.59$
$\zeta_p = 0.856$
$\zeta_c = 1.0$



THEORY CORRECTLY PREDICTS NORMALLY-DIRECTED SECONDARY FLOW FOR EXPERIMENT OF ISLAM AND IMRAN (2008)

Fr_d = 0.608
Cz = 7.39
ζ_p = 0.49
ζ_c = 0.70



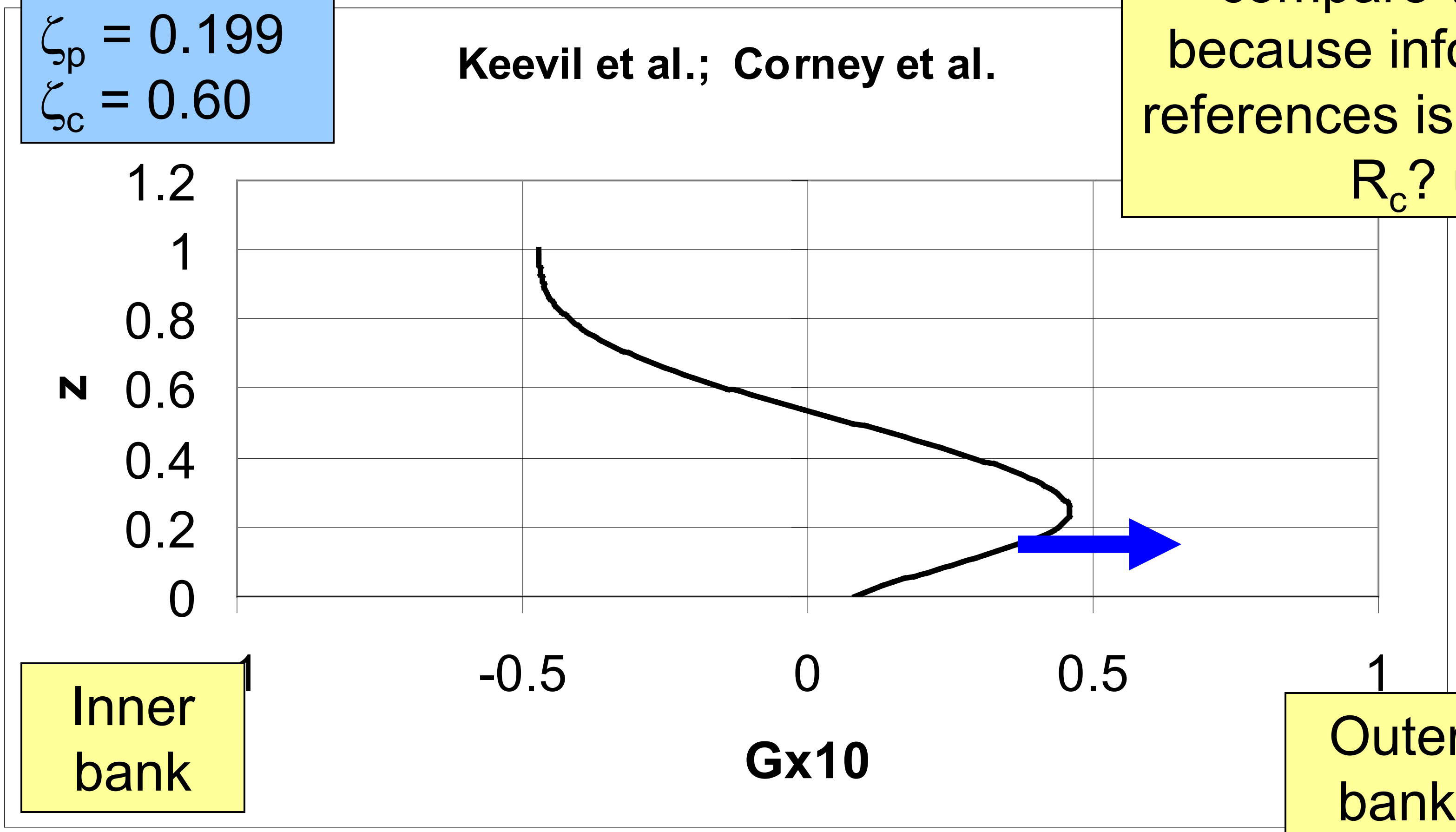
Inner bank

Outer bank

THEORY PREDICTS REVERSED SECONDARY FLOW FOR EXPERIMENT OF CORNEY ET AL. (2008); KEEVIL ET AL. (2008)

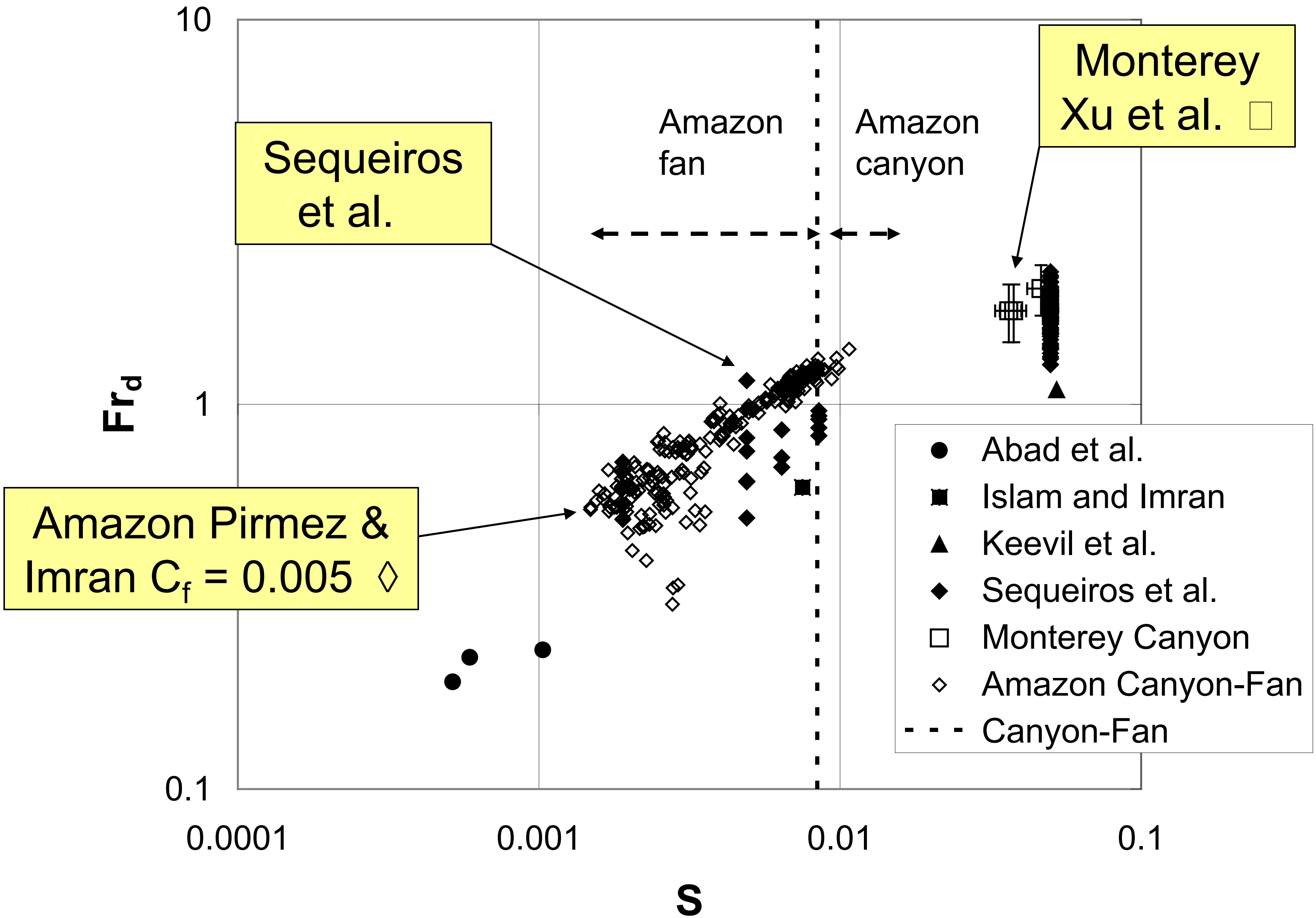
$Fr_d = 1.09$
$Cz = 5.05$
$\zeta_p = 0.199$
$\zeta_c = 0.60$

Note: not possible to compare with data because information in references is insufficient: R_c? u_n?

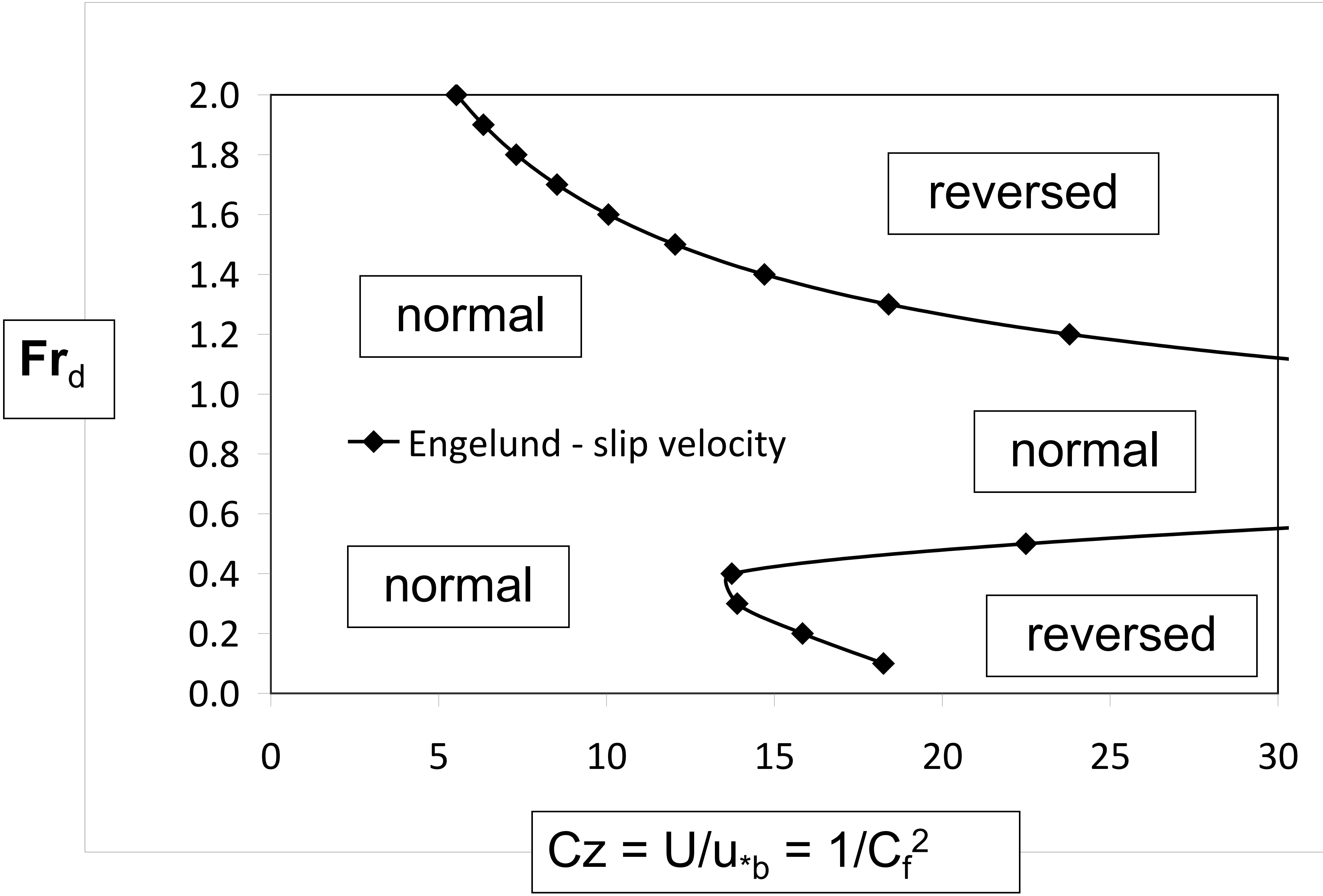


$$G = \frac{0.077}{Cz}\frac{R_c}{h}\frac{u_n}{U}$$

CAN OUR STRUCTURE FUNCTIONS $\zeta_p(Fr_d)$ and $\zeta_c(Fr_d)$ BE APPLIED AT FIELD SCALE?

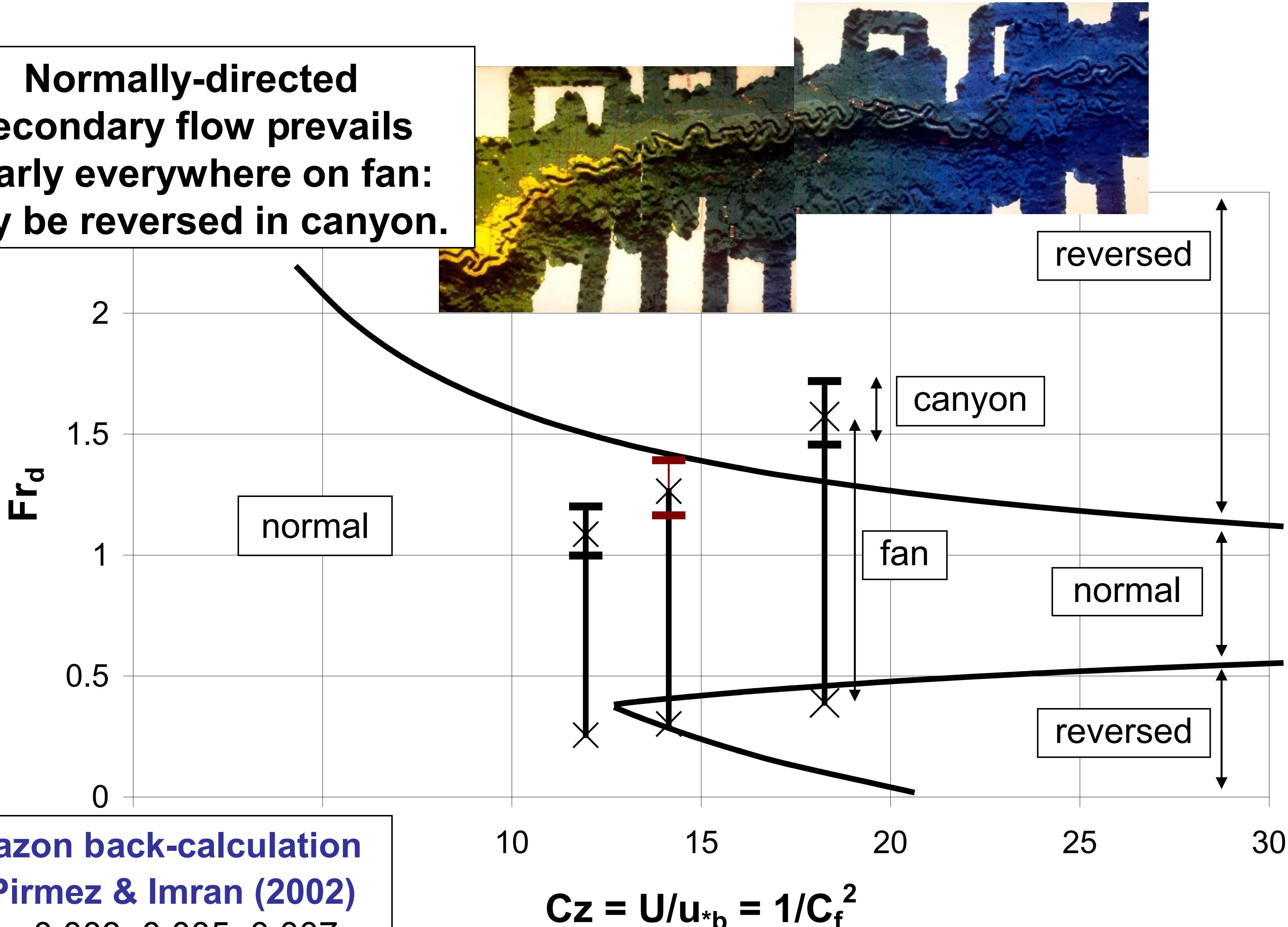


PHASE DIAGRAM FOR NORMAL VERSUS REVERSED SUBMARINE SECONDARY FLOW



APPLICATION TO THE AMAZON CANYON-FAN SYSTEM

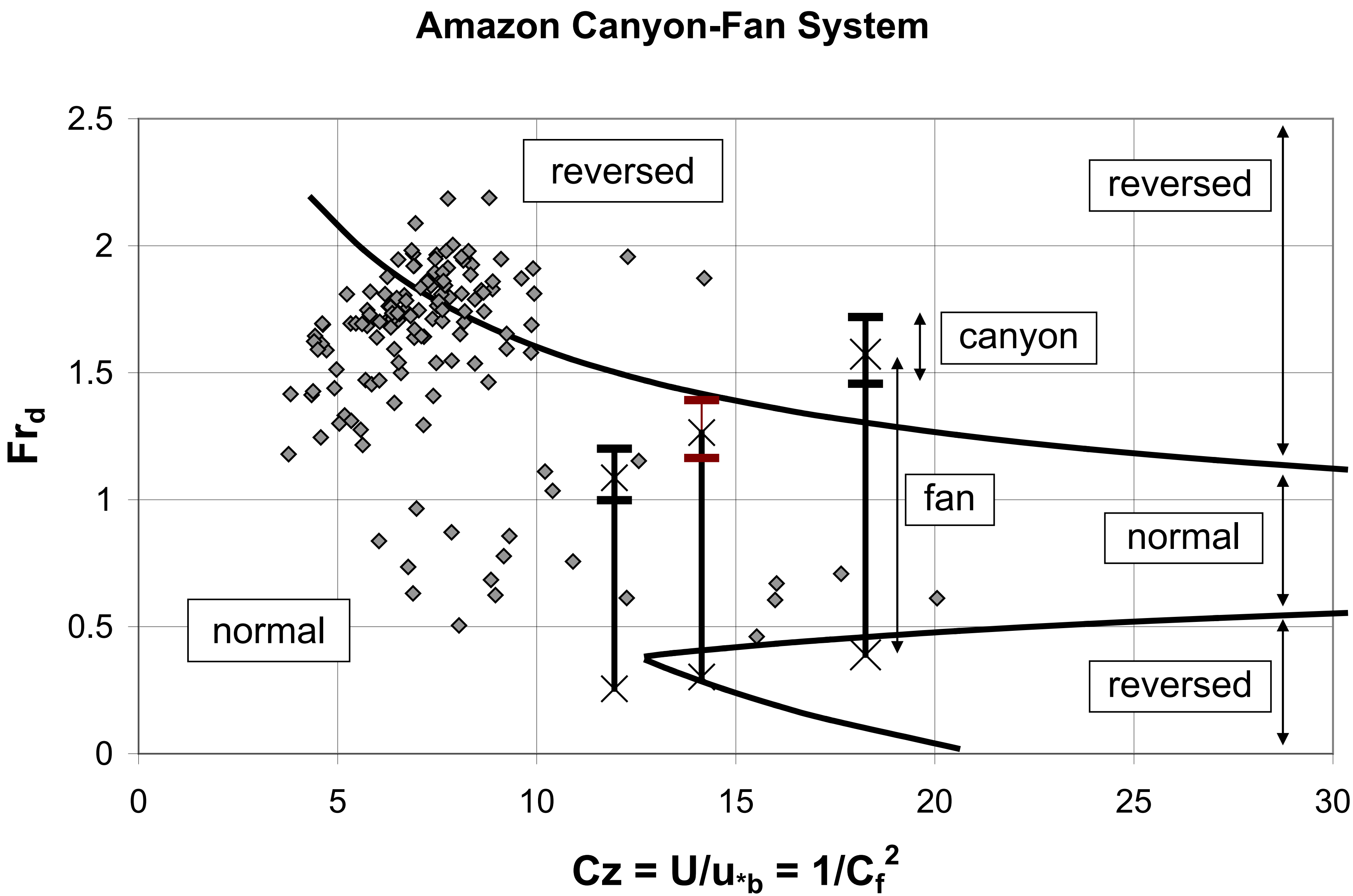
Normally-directed secondary flow prevails nearly everywhere on fan: may be reversed in canyon.



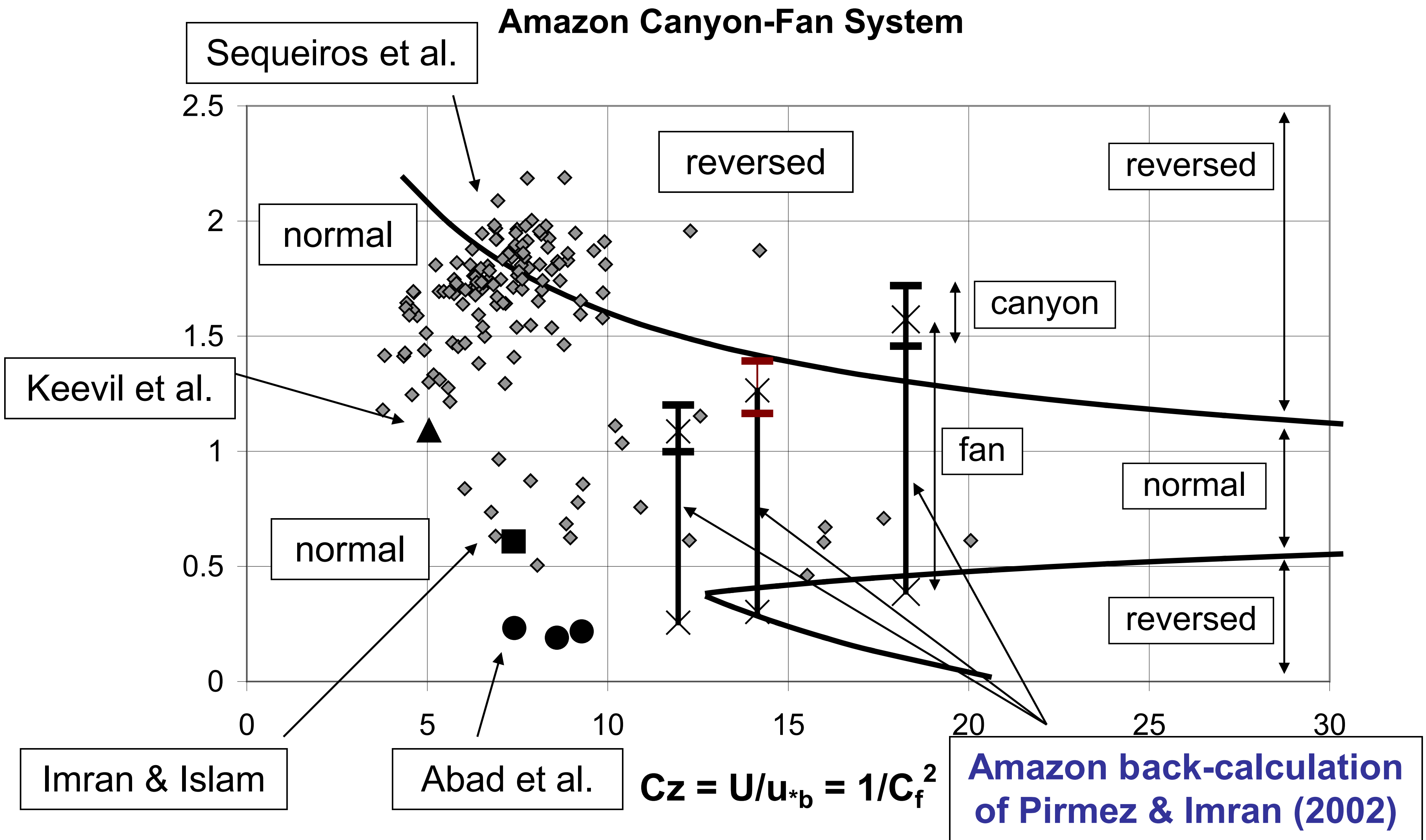
Amazon back-calculation of Pirmez & Imran (2002)

C_f = 0.003, 0.005, 0.007

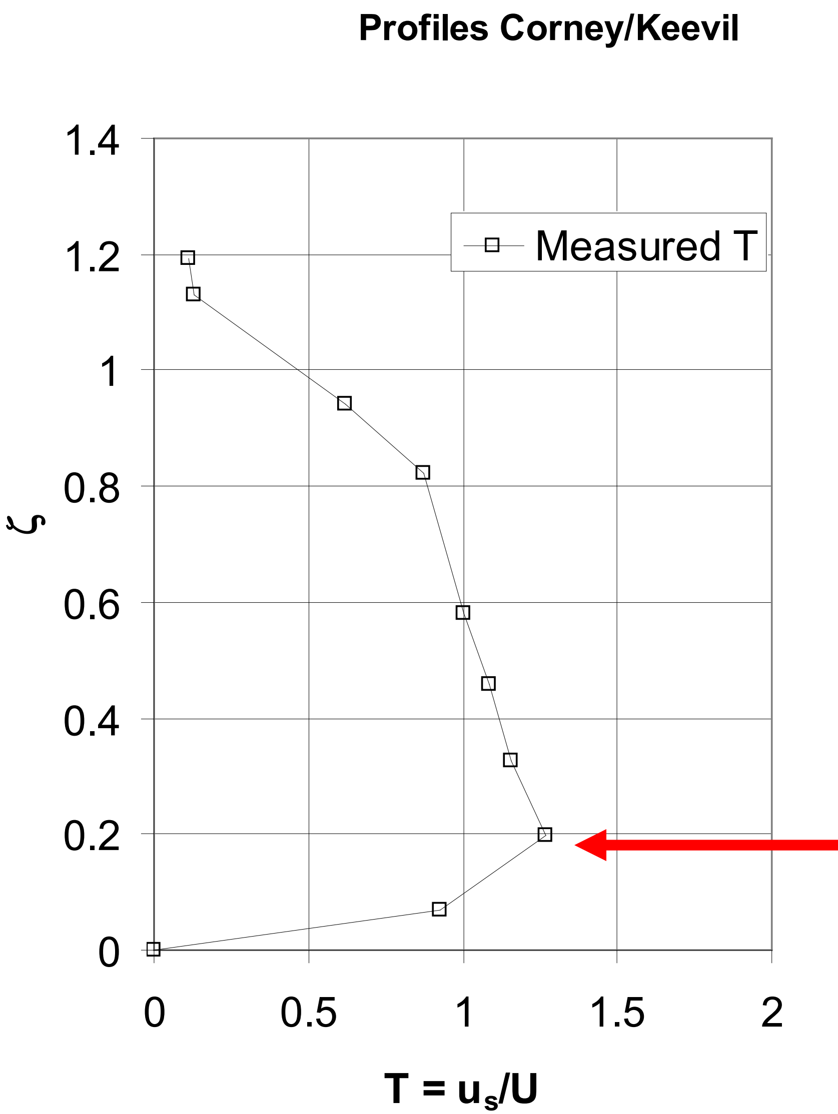
FURTHER JUSTIFICATION FOR USING THE SEQUEIROS ET AL. DATA AT FIELD SCALE



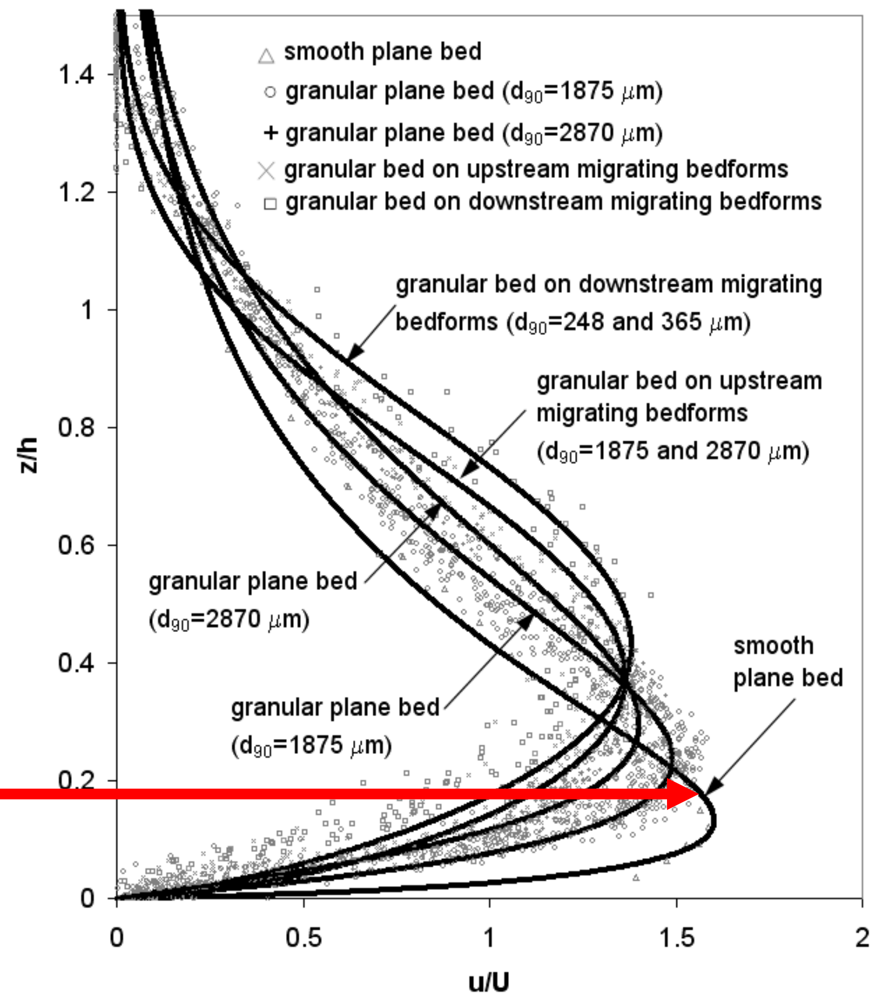
AND WHEN WE INCLUDE THE LABORATORY DATA, THE RESULTS FALL INTO THE RIGHT REGIME EXCEPT FOR CORNEY/KEEVIL



BECAUSE THE VALUE FOR ζ_p OF CORNEY/KEEVIL IS ANOMALOUSLY LOW

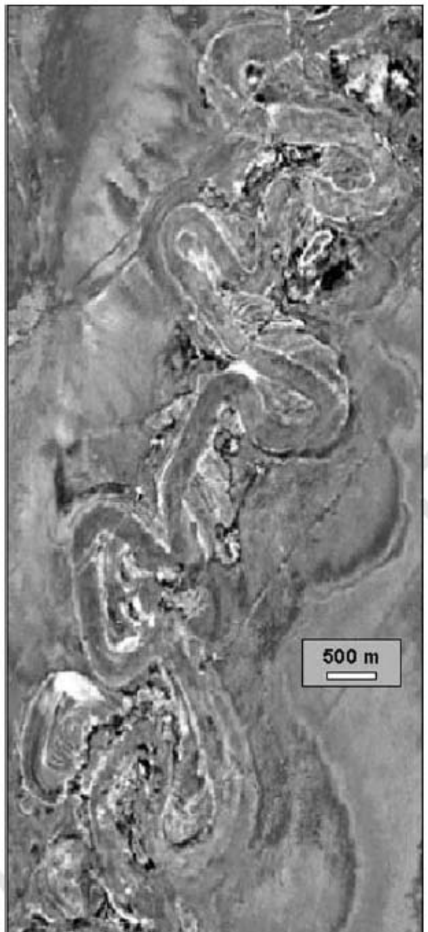


Sequeiros et al.

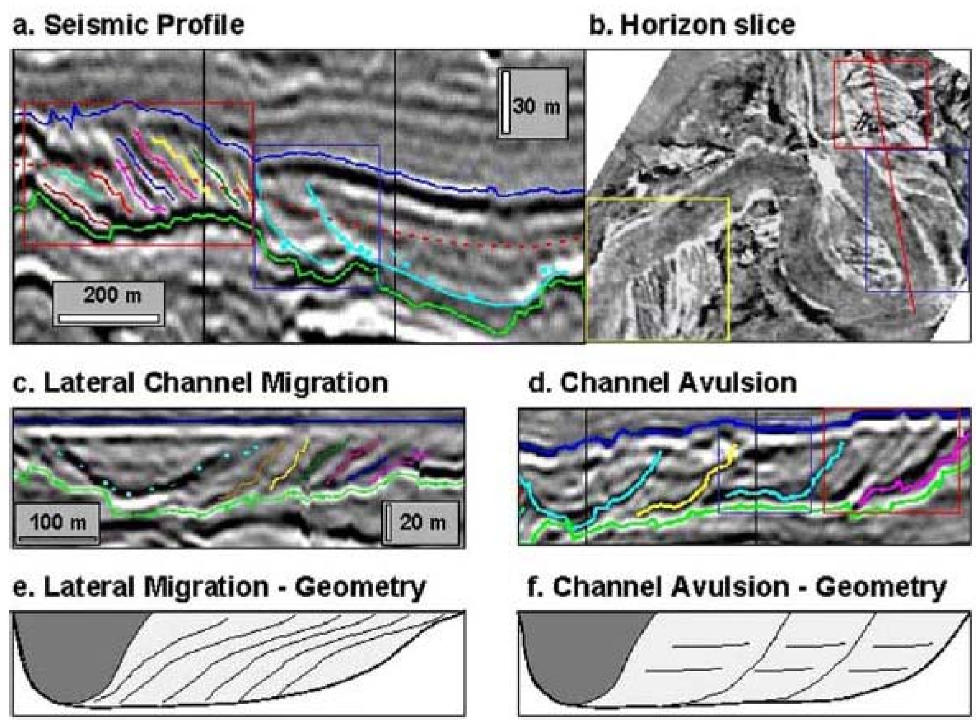


IMPLICATIONS FOR CHANNEL EVOLUTION

Meandering submarine channels must at some point go through a stage of migration and sinuosity increase. Normally-directed secondary flow helps promote this.



Lateral Accretion Packages:
Abreu et al. (2003)



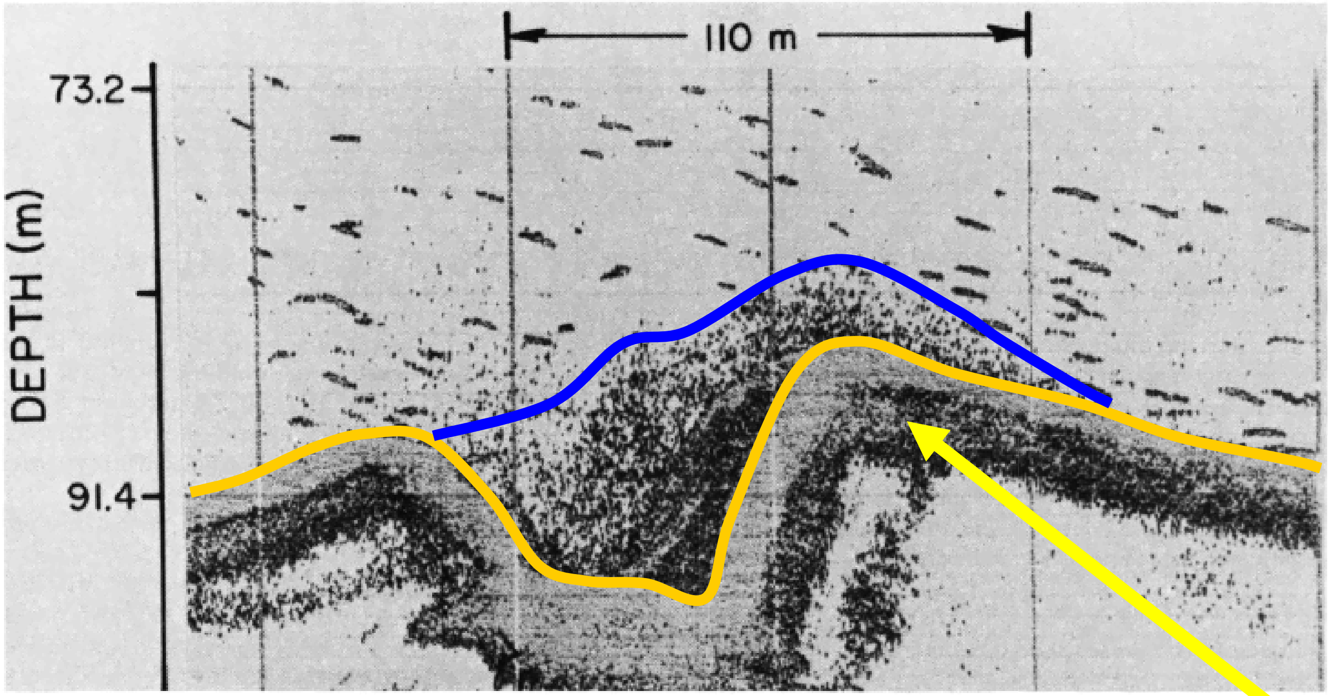
CONCLUSIONS

1. The analysis suggests that secondary flows in meandering channels on fans like the Amazon Submarine Fan should be normally-directed near the bed, as in rivers.

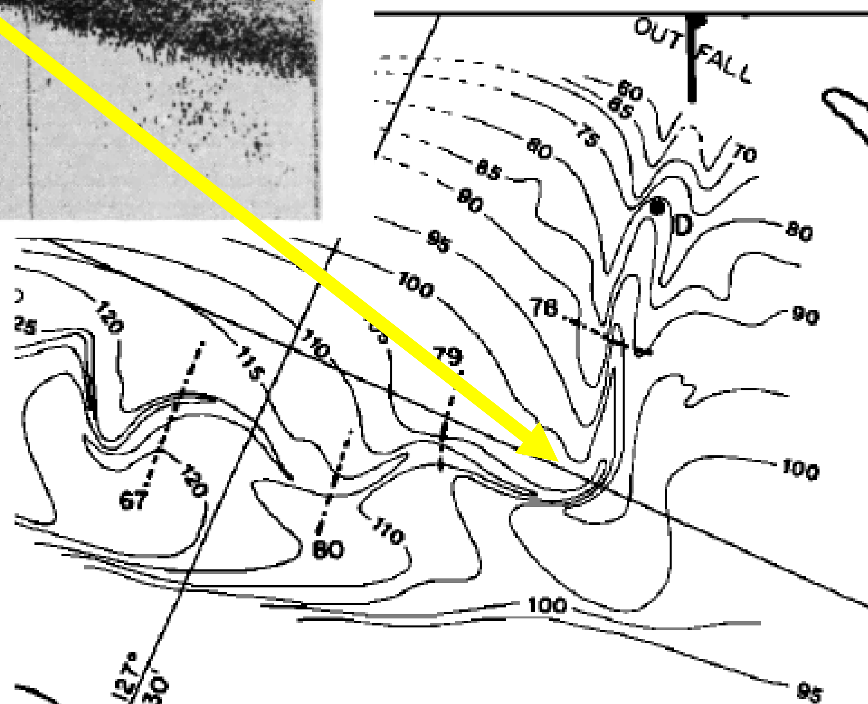
2. The same analysis suggests that the secondary flow may be reversed in some meandering submarine canyons.

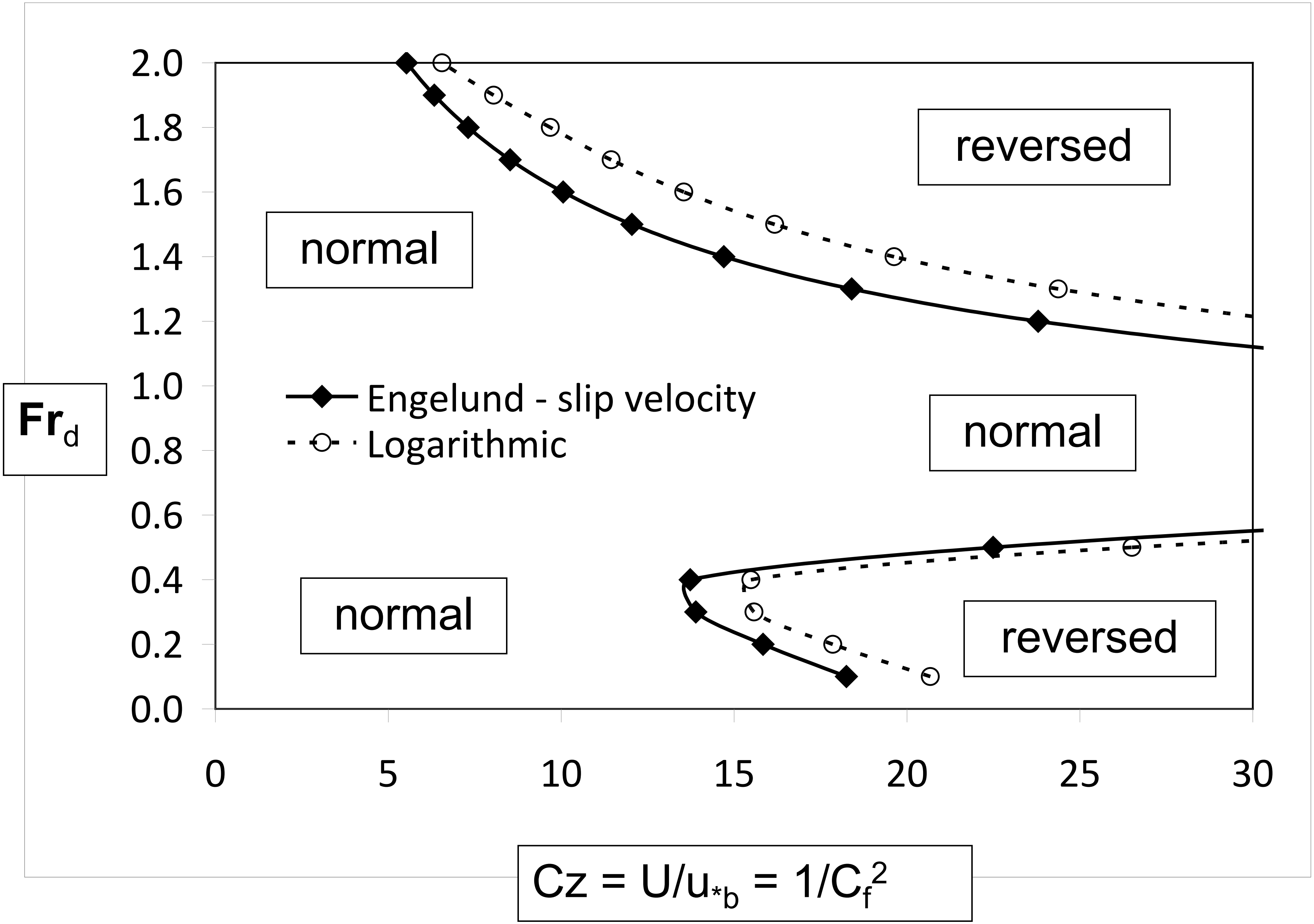
3. These conclusions are based on
   a) extensive laboratory experiments on the structure of streamwise velocity and density profiles in density underflows,
   b) Five experiments on density flows in meandering channels, and
   c) correction of the formulation of Keevil et al. to include the effect of stratification on the pressure term.

THANK YOU FOR LISTENING!



From Hay (1987b)





Fr_d
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
reversed
normal
normal
normal
reversed
Engelund - slip velocity
Logarithmic
Cz = U/u*b = 1/Cf2