MORPHODYNAMICS OF RIVERS AND TURBIDITY CURRENTS:

AN ELEGANT CONVERSATION BETWEEN WATER AND SEDIMENT

APS physics

National Center for Earth-surface Dynamics

Image courtesy A. Alabyan

Gary Parker
Dept. of Civil & Environmental Engineering, Dept. of Geology
University of Illinois

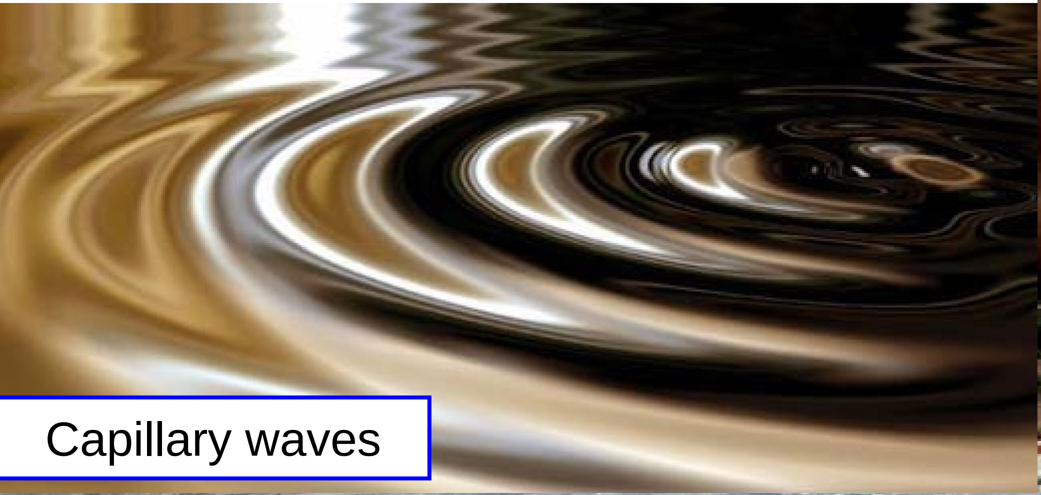
APS physics dfD

A CIVIL ENGINEER/GEOLOGIST GIVING AN INVITED TALK AT THE AMERICAN PHYSICAL SOCIETY

IS LIKE A COUNTRY PRIEST GRANTED AN AUDIENCE WITH THE POPE

http://www.broughtonhousegallery.co.uk/raverat/058-prodigal-son.jpg

“PURE FLUID MECHANICS”


Capillary waves


Haboob dust storm

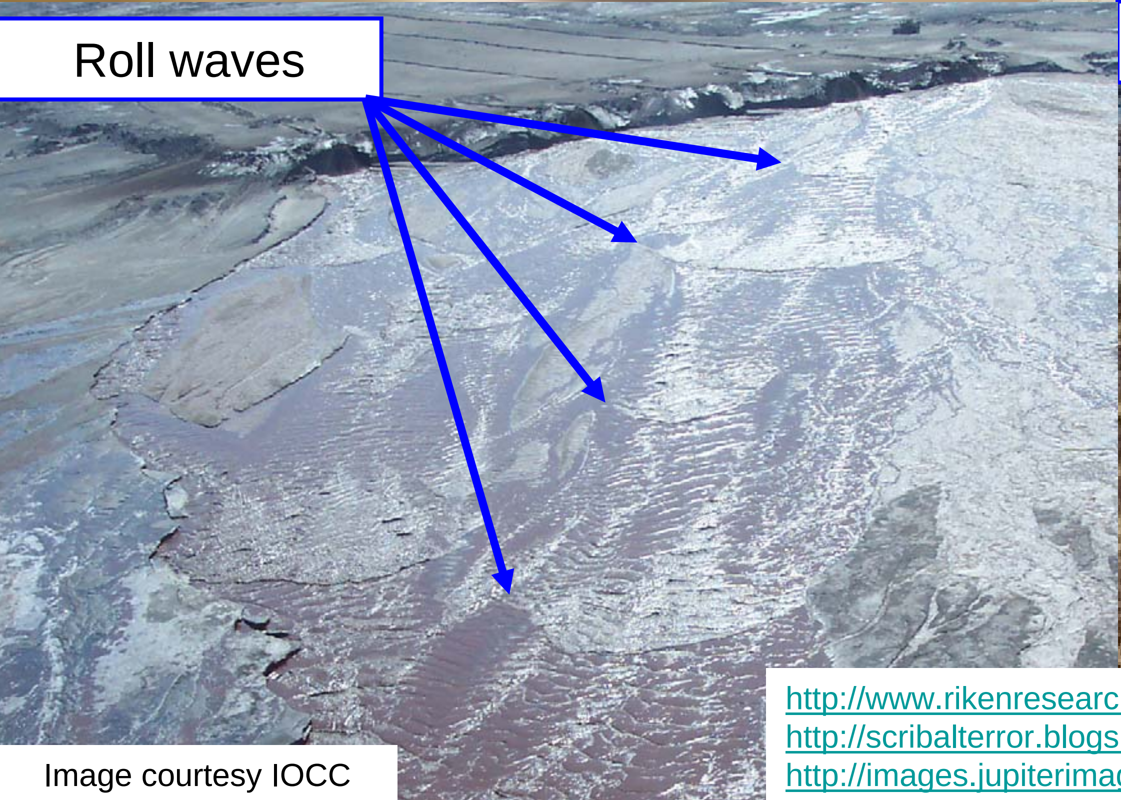

Roll waves

Image courtesy IOCC

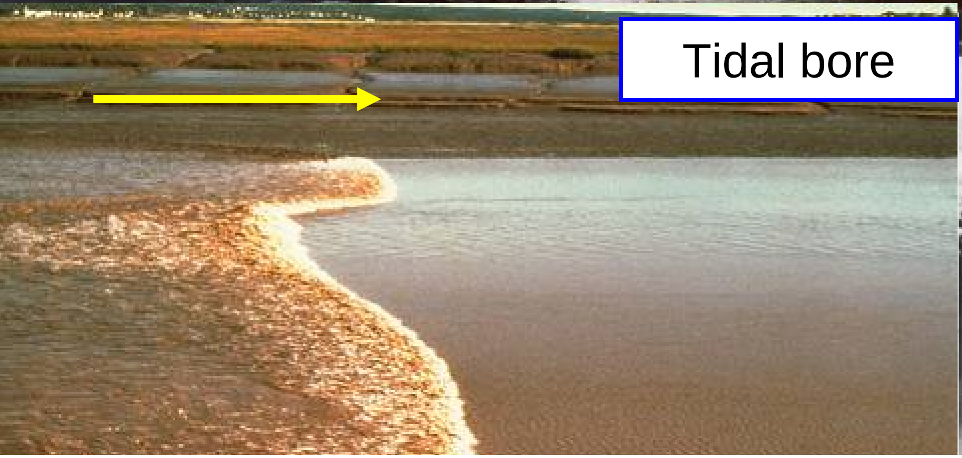

Wind ripples

http://www.rikenresearch.riken.jp/research/223/images/2234070426115631.jpg
http://scribalterror.blogs.com/scribal_terror/images/2007/05/02/dust_2.jpg
http://images.jupiterimages.com/common/detail/66/41/23354166.jpg

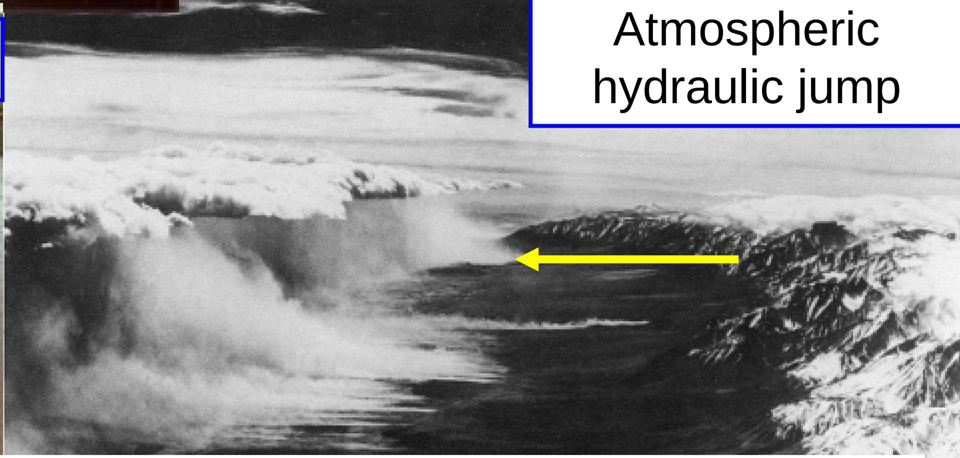
HYDRAULIC JUMPS AND BORES

Jump in mountain river

Circular jump in kitchen sink



Tidal bore



Atmospheric hydraulic jump

http://pasternack.ucdavis.edu/falls/aircontent/images/firstthreat.jpg
http://upload.wikimedia.org/wikipedia/commons/thumb/f/f4/Hydraulic_jump_in_sink.jpg/391px-Hydraulic_jump_in_sink.jpg
http://www.gomoncton.com/ENSite/Motorcoach/images/ImageBank/low/TidalBore_Web.jpg
http://imgi.uibk.ac.at/mmetgroup/trex/webstyle/sierrawave.png

NON-SEDIMENT FLUID-BOUNDARY INTERACTION: MEANDERING CHANNELS IN ICE

http://people.whitman.edu/~carsonrj/researchpics/MendenhallAK2.jpg
http://crevassezone.org/Photos/Graphics/3054L-(Meander).jpg

THE EFFECT OF INCREASING THE WIDTH-DEPTH RATIO B/H

Flume with flow off

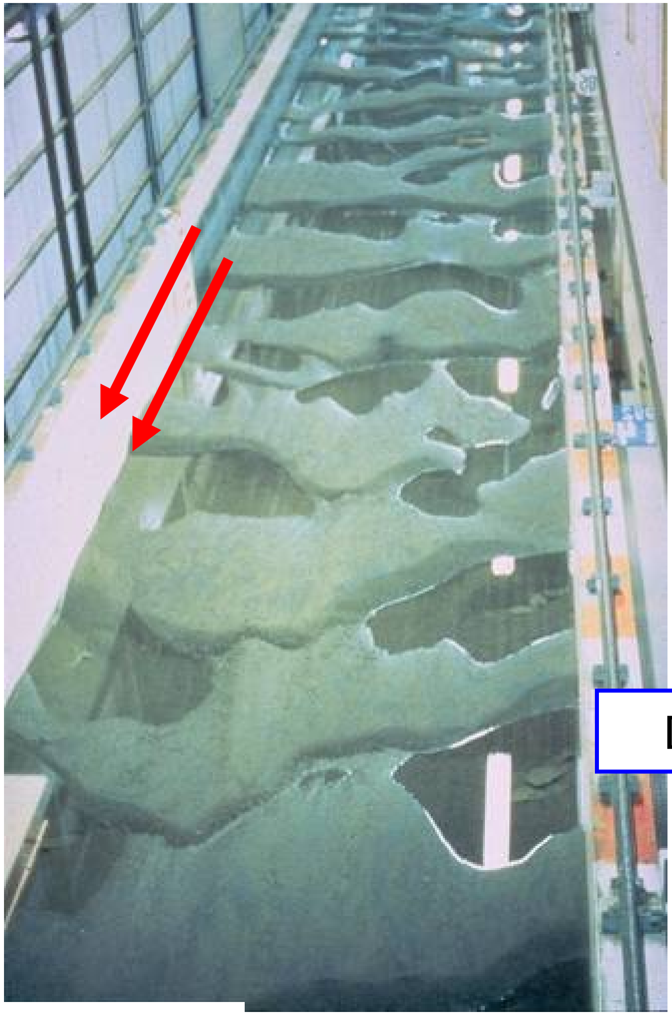


Image courtesy H. Ikeda

Tributary of Amazon River

Courtesy National Geographic

Dunes

Flume with flow off

B/H → UP

Rhine River, Switzerland

Single-row alternate bars

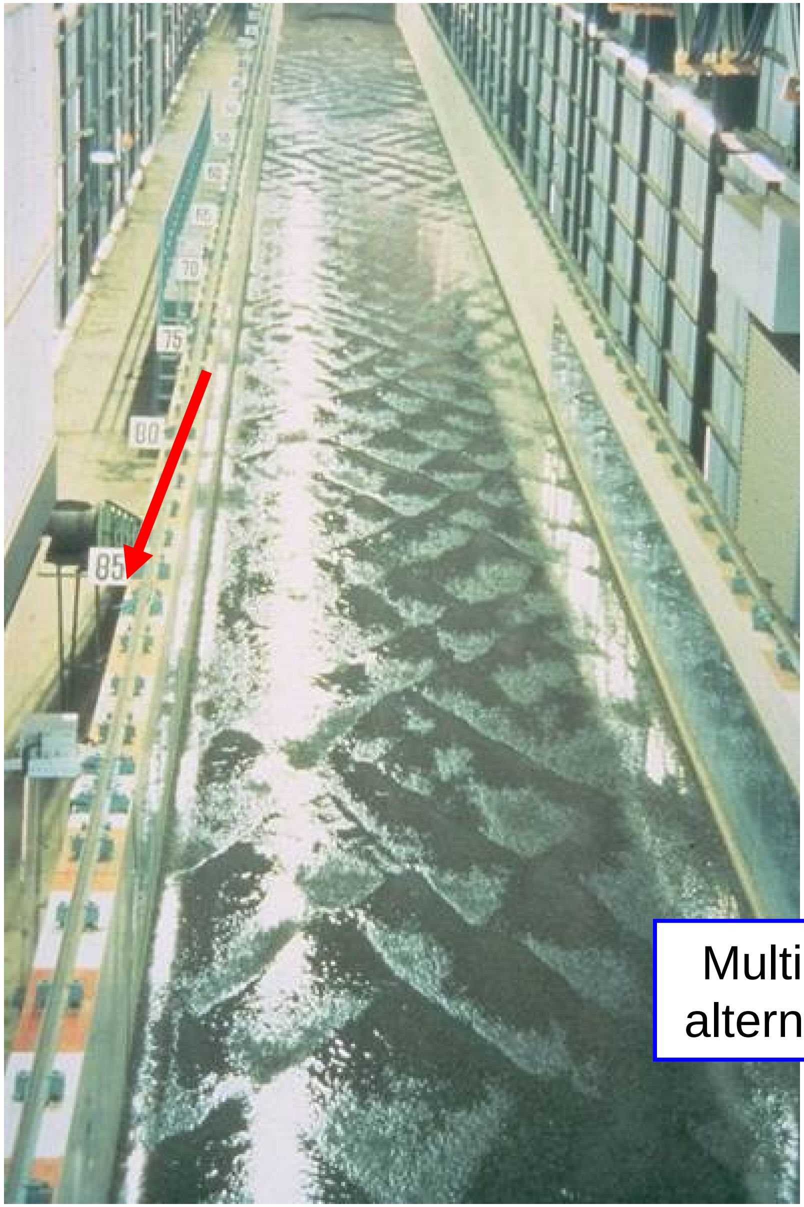
Courtesy H. Ikeda

Courtesy M. Jaeggi

Flume with flow off

B/H → UP

Fuefuki River, Japan



Multiple-row alternate bars

Courtesy H. Ikeda

Courtesy S. Ikeda

B/H → UP

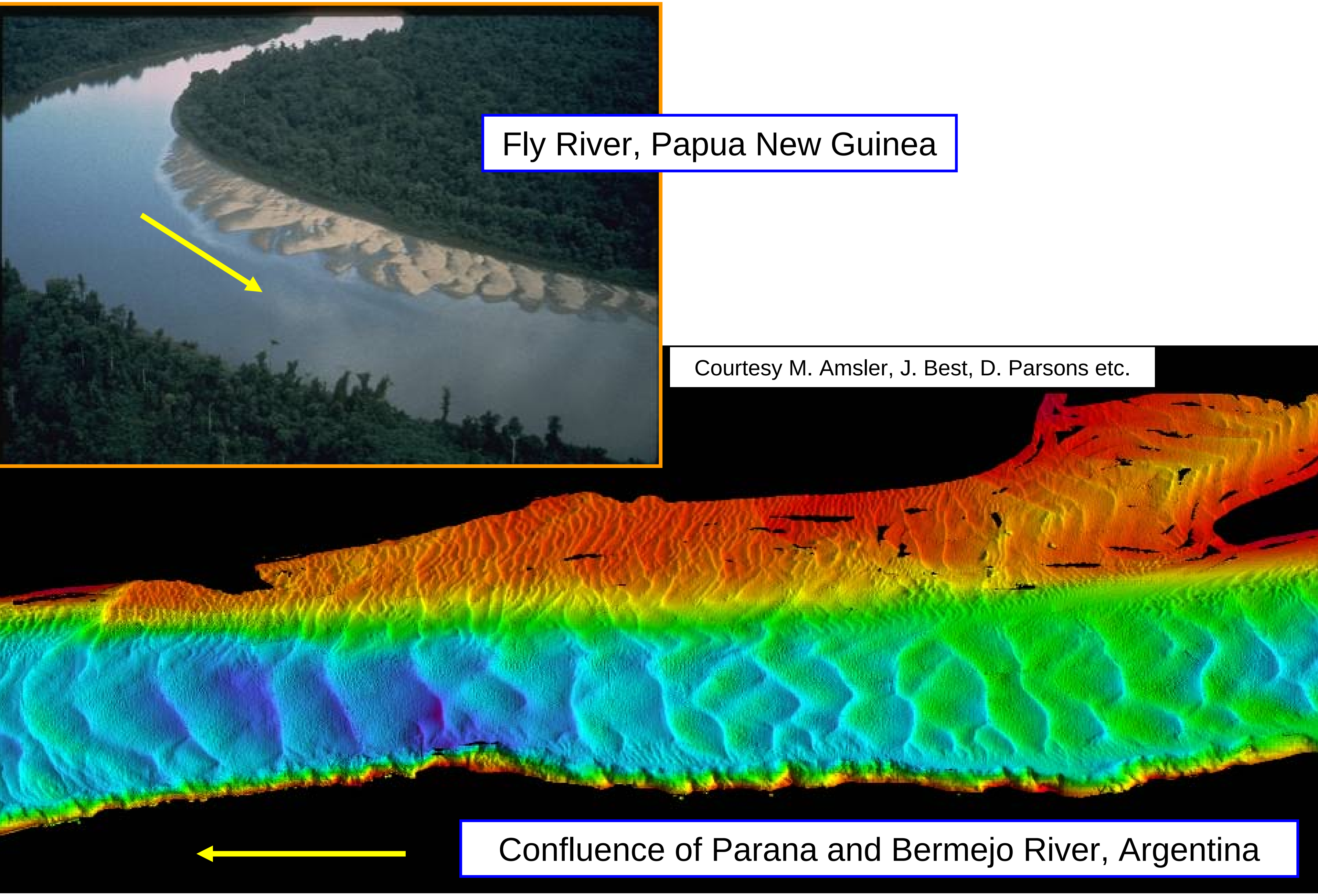
Flume with flow off

Courtesy H. Ikeda

Braiding

Ohau River, New Zealand

RIVER DUNES



Fly River, Papua New Guinea

Courtesy M. Amsler, J. Best, D. Parsons etc.

Confluence of Parana and Bermejo River, Argentina

DUNES IN THE RHINE DELTA, THE NETHERLANDS

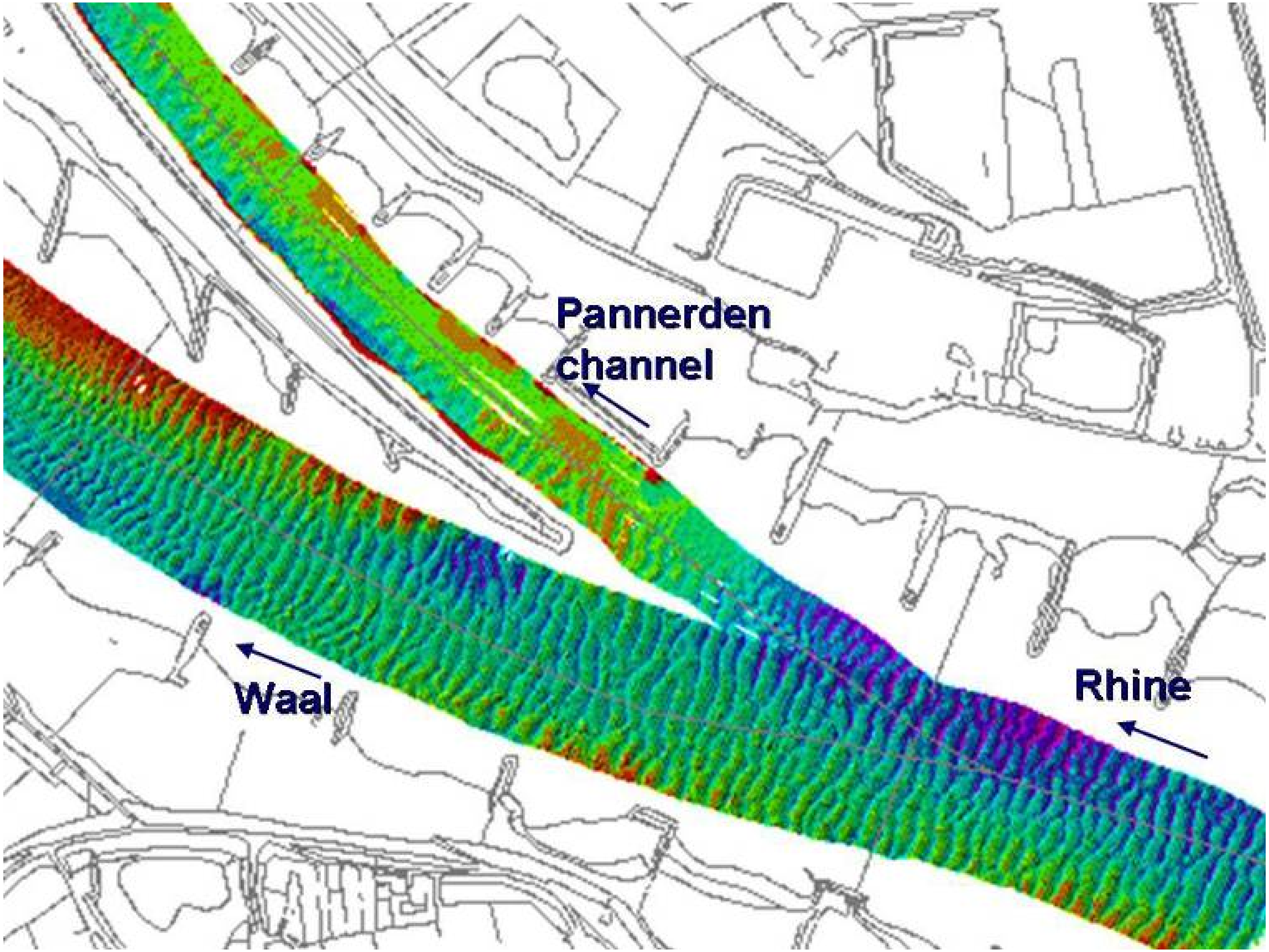
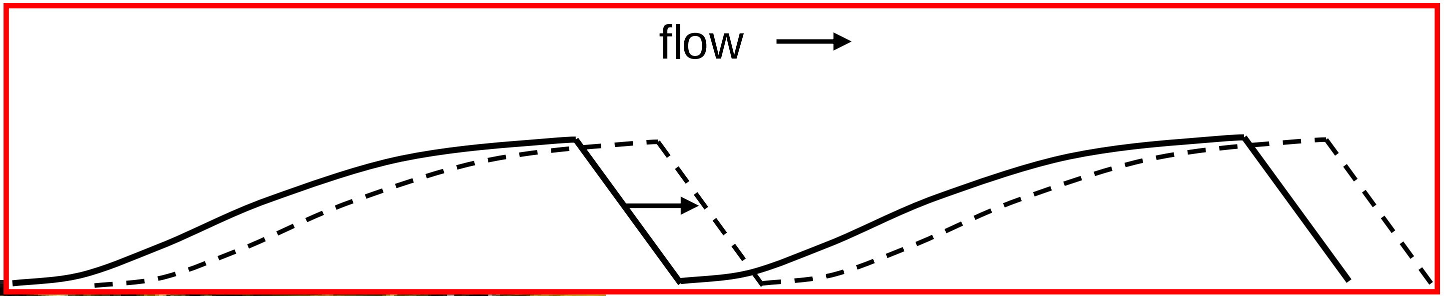
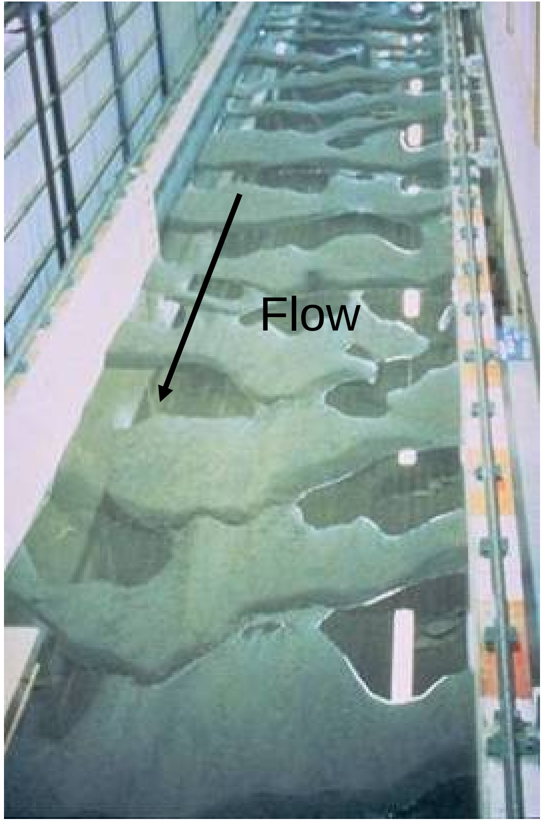


Image courtesy A. Wilbers and A. Blom

DUNE ASYMMETRY



Dunes in a channel at St. Anthony Falls Laboratory, University of Minnesota, USA



Dunes in a channel at Tsukuba University, Japan.
Image courtesy H. Ikeda.

FELIX EXNER: FATHER OF RIVER MORPHODYNAMICS

Exner’s Question (1920, 1925): *Why Are Dunes Asymmetric?*

The parameters:

x = streamwise distance [L]

t = time [T]

η = bed elevation [L]

q_t = volume total sediment transport rate per unit stream width [L^2/T]

$\xi = H + \eta$ = water surface elevation [L]

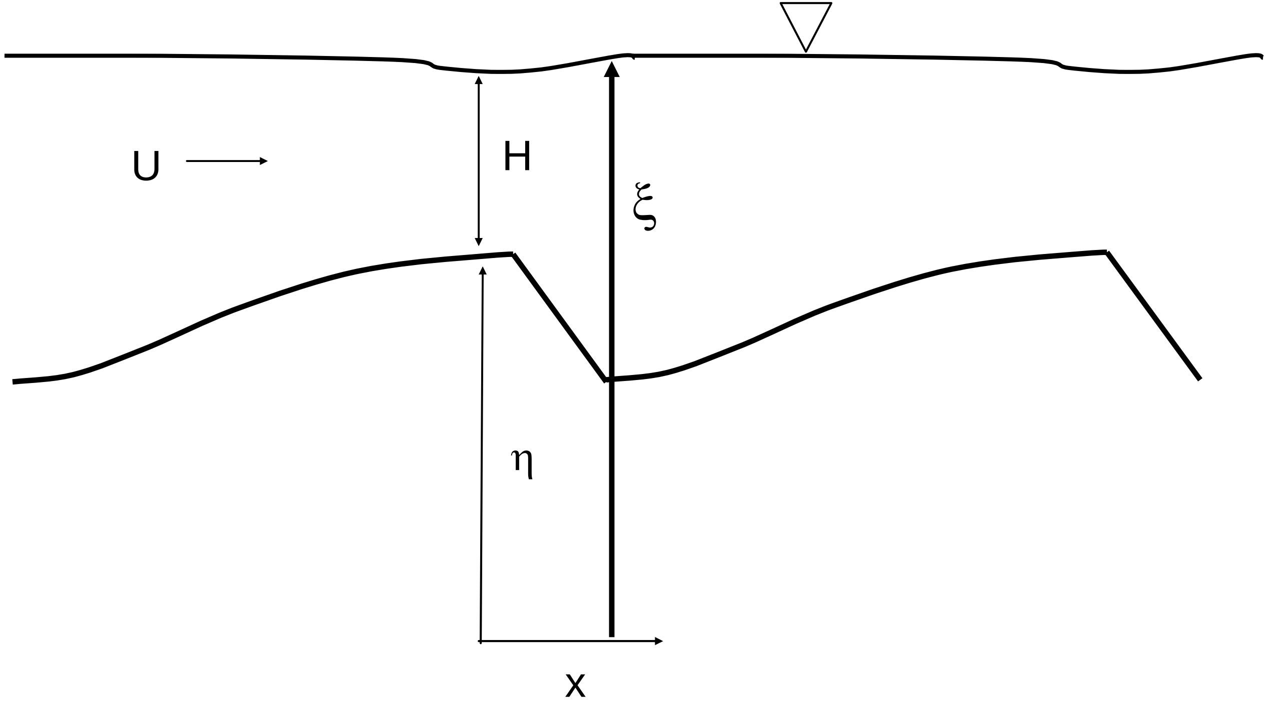
λ_p = bed porosity [1]

g = acceleration of gravity [L/T^2]

H = flow depth [L]

U = depth-averaged flow velocity [L/T]

$q_w = UH$ = water discharge per unit stream width [L^2/T]



OCCAM'S RAZOR: THE MIMINAL FORMULATION TO ANSWER THE QUESTION

Shallow-water inviscid equations of mass and momentum balance

$$\boxed{\begin{aligned} &\cancel{\frac{\partial H}{\partial t}} + \frac{\partial UH}{\partial x} = 0 \quad \rightarrow \quad UH = q_w = \mathrm{constant} \\ &\cancel{\frac{\partial UH}{\partial t}} + \frac{\partial U^2 H}{\partial x} = -\frac{1}{2} gH \frac{\partial H}{\partial x} - \frac{1}{2} gH \frac{\partial \eta}{\partial x} \end{aligned}}$$

Quasi-steady assumption: $q_t/q_w << 1$

Exner's equation of conservation of bed sediment:

$$\boxed{(1-\lambda_p)\frac{\partial \eta}{\partial t} = -\frac{\partial q_t}{\partial x}}$$

Exner's seminal contribution: if more sediment enters a reach than leaves, the bed elevation in the reach increases.

Relation between sediment transport rate and flow hydraulics:

$$\boxed{q_t = q_t(U) = \alpha U^n \quad , \quad n > 0}$$

The phenomenon of sediment transport was poorly known in Exner's time. Exner guessed that a higher velocity caused a higher sediment transport rate.

REDUCTION

$$\boxed{UH = q_w \quad \text{and} \quad H = \xi - \eta \quad \rightarrow \quad U = \frac{q_w}{\xi - \eta}}$$

$$\frac{\partial U^2 H}{\partial x} = -\frac{1}{2} gH \frac{\partial H}{\partial x} - \frac{1}{2} gH \frac{\partial \eta}{\partial x} \quad \text{and} \quad H = \xi - \eta \quad \text{and} \quad U = \frac{q_w}{\xi - \eta}$$

$\rightarrow$

$$\frac{\partial H}{\partial x} = -\frac{1}{(1 - \mathbf{Fr}^2)} \frac{\partial \eta}{\partial x} \quad \text{and} \quad \frac{\partial \xi}{\partial x} = -\frac{\mathbf{Fr}^2}{(1 - \mathbf{Fr}^2)} \frac{\partial \eta}{\partial x}$$

where

$$\mathbf{Fr} = \frac{U}{\sqrt{gH}} = \text{Froude number}$$

Range for dunes: low Froude number: $\mathbf{Fr}^2 << 1$

$$\boxed{\frac{\partial \xi}{\partial x} = -\frac{\mathbf{Fr}^2}{(1 - \mathbf{Fr}^2)} \frac{\partial \eta}{\partial x} \cong 0 \quad \therefore}$$

Constant water surface elevation

MORE REDUCTION

$$U = \frac{q_w}{\xi - \eta} \quad \text{and} \quad q_t = \alpha U^n \quad \text{and} \quad \frac{\partial H}{\partial x} = -\frac{1}{1 - \mathbf{Fr}^2}\frac{\partial \eta}{\partial x}$$
$$\text{and} \quad \mathbf{Fr}^2 << 1 \quad \text{and} \quad \xi = \text{constant}$$

substituted into

$$(1 - \lambda_p)\frac{\partial \eta}{\partial t} = -\frac{\partial q_t}{\partial x}$$

yields

$$\frac{\partial \eta}{\partial t} + c(\eta)\frac{\partial \eta}{\partial x} = 0$$

$$c(\eta) = \alpha q_w^n (\xi - \eta)^{-(n+1)}$$

Since ξ = constant. q_w = constant and n > 0,

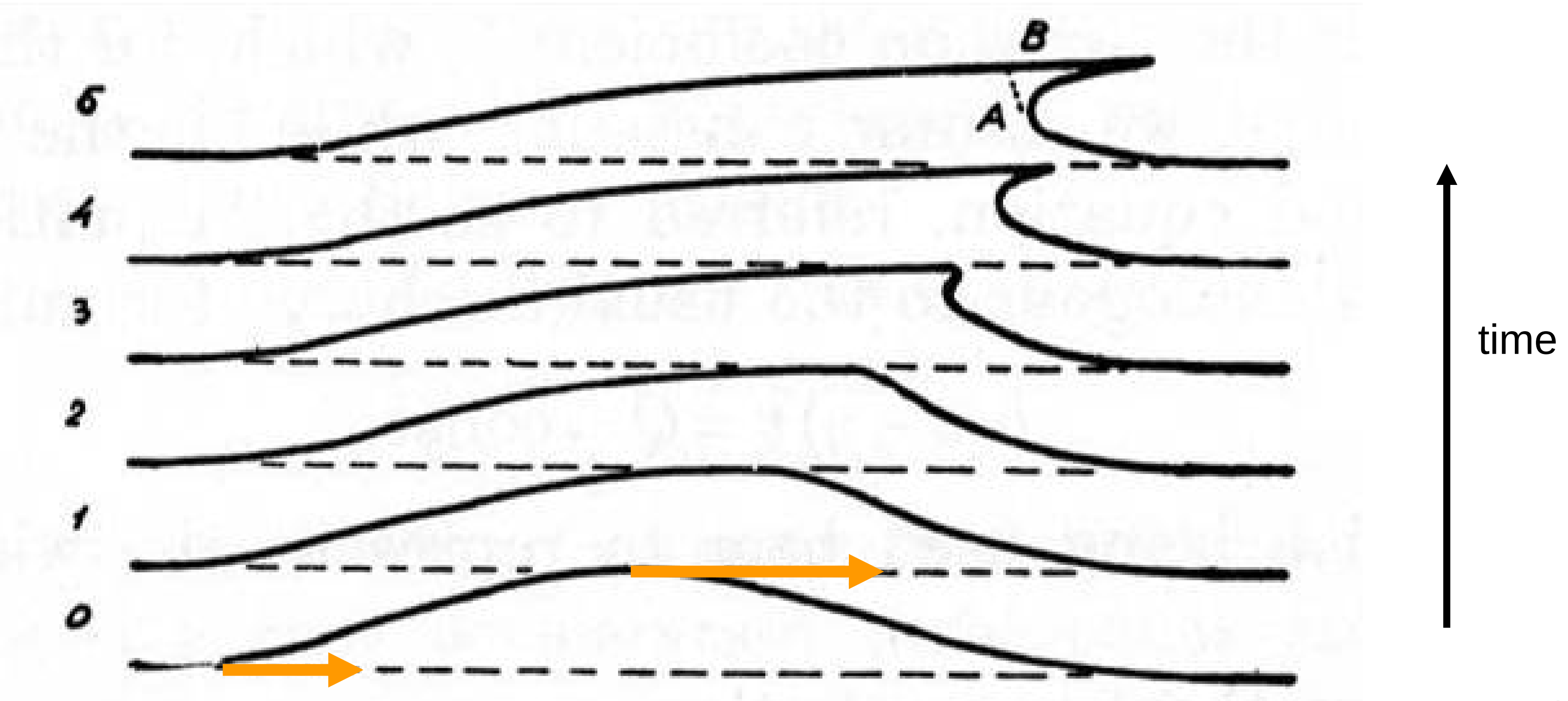
c > 0 is an increasing function of η!

THE RESULT

Dunes migrate downstream, and migration speed increases with bed elevation

$$\boxed{\frac{\partial \eta}{\partial t} + c(\eta)\frac{\partial \eta}{\partial x} = 0}$$

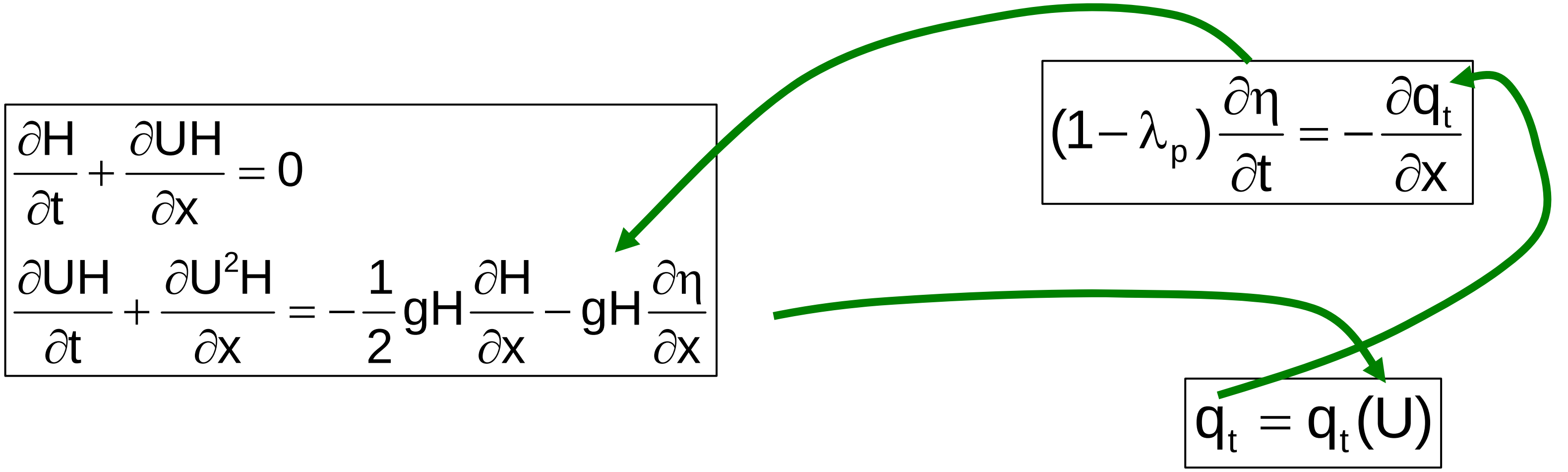
And thus the asymmetry!



Exner's original sketch

THE FLOW AND THE BED TALK TO EACH OTHER

The field of **sediment morphodynamics** consists of the class of problems for which the flow over a bed interacts strongly with the shape of the bed, both of which evolve in time.



$$\frac{\partial H}{\partial t} + \frac{\partial UH}{\partial x} = 0$$

$$\frac{\partial UH}{\partial t} + \frac{\partial U^2 H}{\partial x} = -\frac{1}{2} gH \frac{\partial H}{\partial x} - gH \frac{\partial \eta}{\partial x}$$

$$(1-\lambda_p)\frac{\partial \eta}{\partial t} = -\frac{\partial q_t}{\partial x}$$

$$q_t = q_t(U)$$

Quasi-steady assumption:
The flow naturally talks fast, but can also talk slow.
The bed naturally talks slow.
The only part of the flow's talk that the bed hears is the slow part.
(Quasi-steady assumption: $q_t/q_w << 1$)

THE CONVERSATION

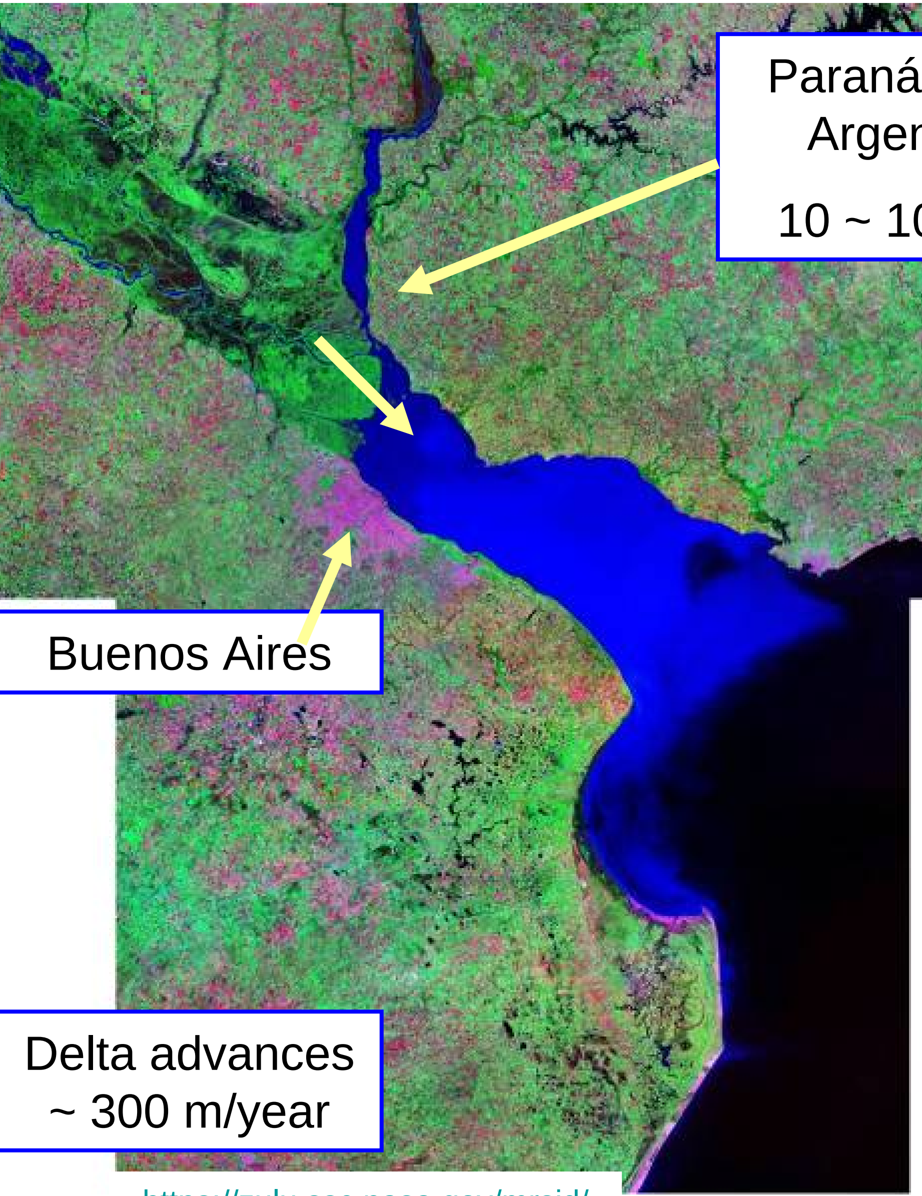
BLAH*blah*BLAH *blah*BLAH…

Could you slow down a bit, I'm having a bit of trouble trying to get the gist of it all.

http://people.debian.org/~neal/FOSDEM-2005/03-Marcus-IPC-0/03-Marcus-IPC-0.src/conversation.jpg

Courtesy IOCC

SCALES



Paraná delta,
Argentina

10 ~ 100 km

Buenos Aires

Delta advances
~ 300 m/year

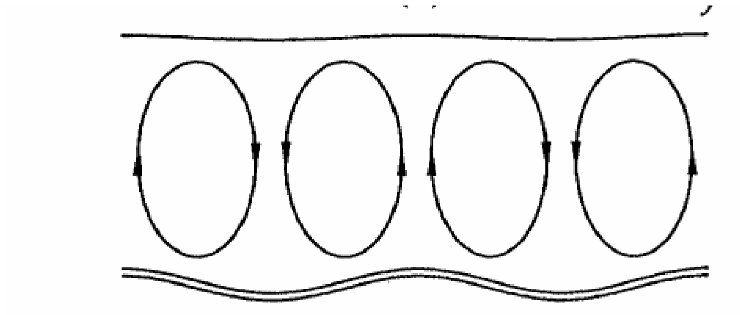
https://zulu.ssc.nasa.gov/mrsid/

Current ripples:

~ 20 cm
wavelength

http://www.ux1.eiu.edu/~cfjps/1300/ripples.jpg

LONGITUDINAL STREAKS



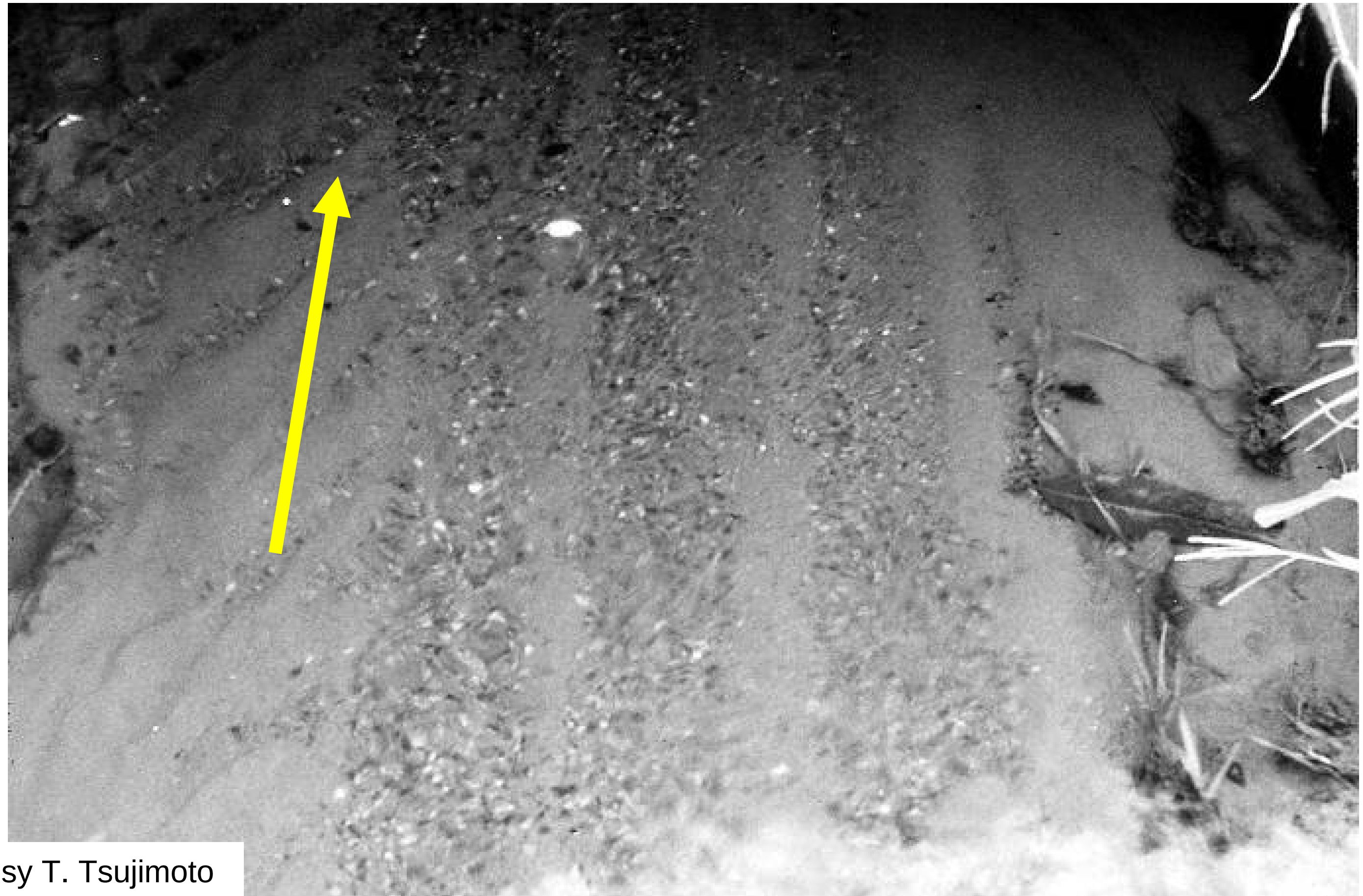
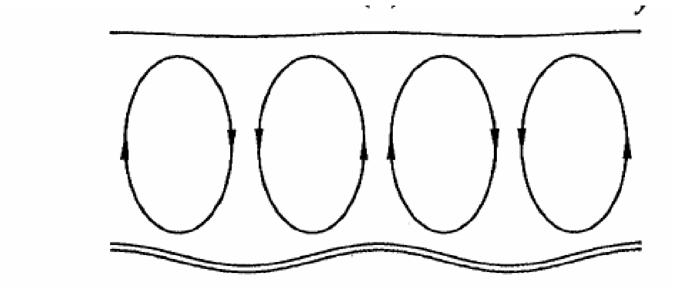
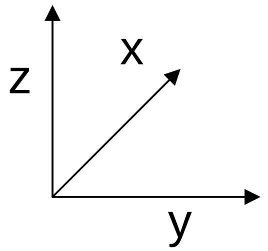


Image courtesy T. Tsujimoto

LONGITUDINAL STREAKS: LINEAR STABILITY ANALYSIS





$$\boxed{(1-\lambda_p)\frac{\partial\eta}{\partial t}=-\frac{\partial q_{tx}}{\partial x}-\frac{\partial q_{tz}}{\partial z}}$$

$$V\frac{\partial U}{\partial y}+W\frac{\partial U}{\partial z}=1+\frac{\partial\tau_{xy}}{\partial y}+\frac{\partial\tau_{xz}}{\partial z},$$

$$V\frac{\partial V}{\partial y}+W\frac{\partial V}{\partial z}=-\frac{\partial P}{\partial y}+\frac{\partial\tau_{yy}}{\partial y}+\frac{\partial\tau_{yz}}{\partial z},$$

$$V\frac{\partial W}{\partial y}+W\frac{\partial W}{\partial z}=-\frac{\partial P}{\partial z}+\frac{\partial\tau_{yz}}{\partial y}+\frac{\partial\tau_{zz}}{\partial z},$$

$$\frac{\partial V}{\partial y}+\frac{\partial W}{\partial z}=0,$$

3D non-isotropic closure for Reynolds-averaged Navier-Stokes equations: Speziale.

Closure for sediment transport rates q_x and q_z in terms of bed shear stress and slope vectors.

$$\tau_{ij}=-\tfrac{2}{3}k\delta_{ij}+2\nu_t D_{ij}+C_D l^2\left(D_{im}D_{mj}-\tfrac{1}{3}D_{mn}D_{mn}\delta_{ij}\right)+C_E l^2\left(\widehat{D}_{ij}-\tfrac{1}{3}\widehat{D}_{mm}\delta_{ij}\right).$$

Here D_{ij} is the mean rate of strain tensor, $\nu_t=\tfrac{1}{2}k^{1/2}l$ is the eddy viscosity and

$$\widehat{D}_{ij}=\frac{\mathrm{D}D_{ij}}{\mathrm{D}t}-\frac{\partial U_i}{\partial x_k}D_{kj}-\frac{\partial U_j}{\partial x_k}D_{ki}$$

DUNES, ANTIDUNES

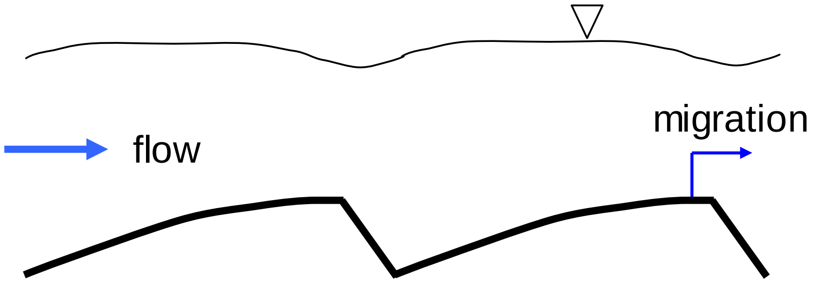
Image courtesy D. Mohrig

Dunes: Middle Loup River, Nebraska

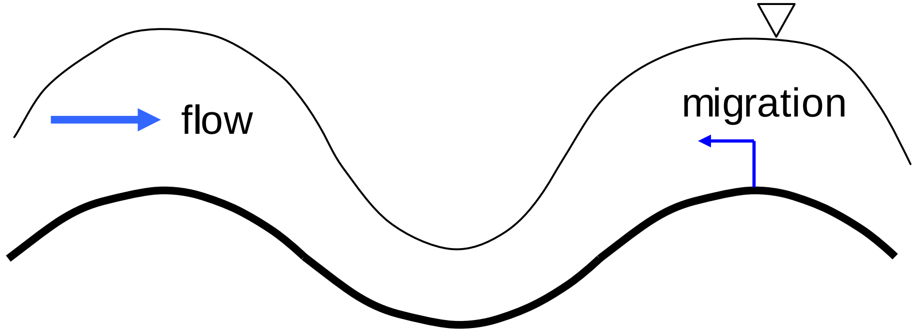
Antidunes, Brittany, France

DEFINITION OF DUNES AND ANTIDUNES

Dunes are 1D (or quasi-1D) bedforms for which the water surface fluctuations are approximately *out of phase* with the bed fluctuations. That is, the water surface is high where the bed is low and vice versa. As is shown below dunes migrate downstream.

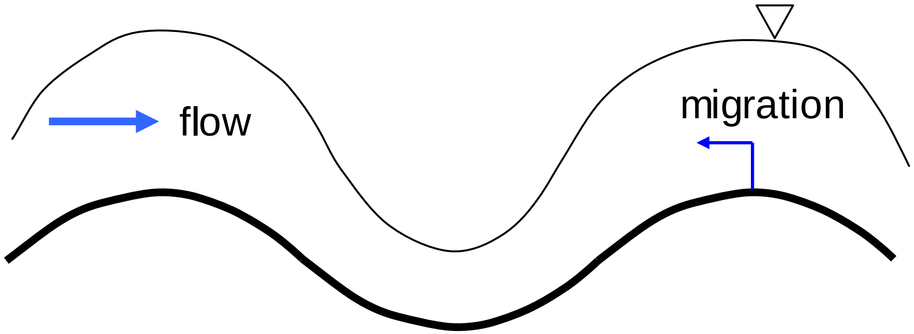


Antidunes are 1D (or quasi-1D) bedforms for which the water surface fluctuations are approximately *in phase* with the bed fluctuations. That is, the water surface is high where the bed is high and vice versa. As shown below, most antidunes migrate upstream, but there is a regime within which they can migrate downstream.



REGIME DIAGRAM: POTENTIAL FLOW OVER A WAVY BED

x = streamwise direction
y = vertical direction
u = streamwise velocity
v = vertical velocity
p = pressure
g = gravitational acceleration



$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}-g\frac{\partial \eta}{\partial x}$$

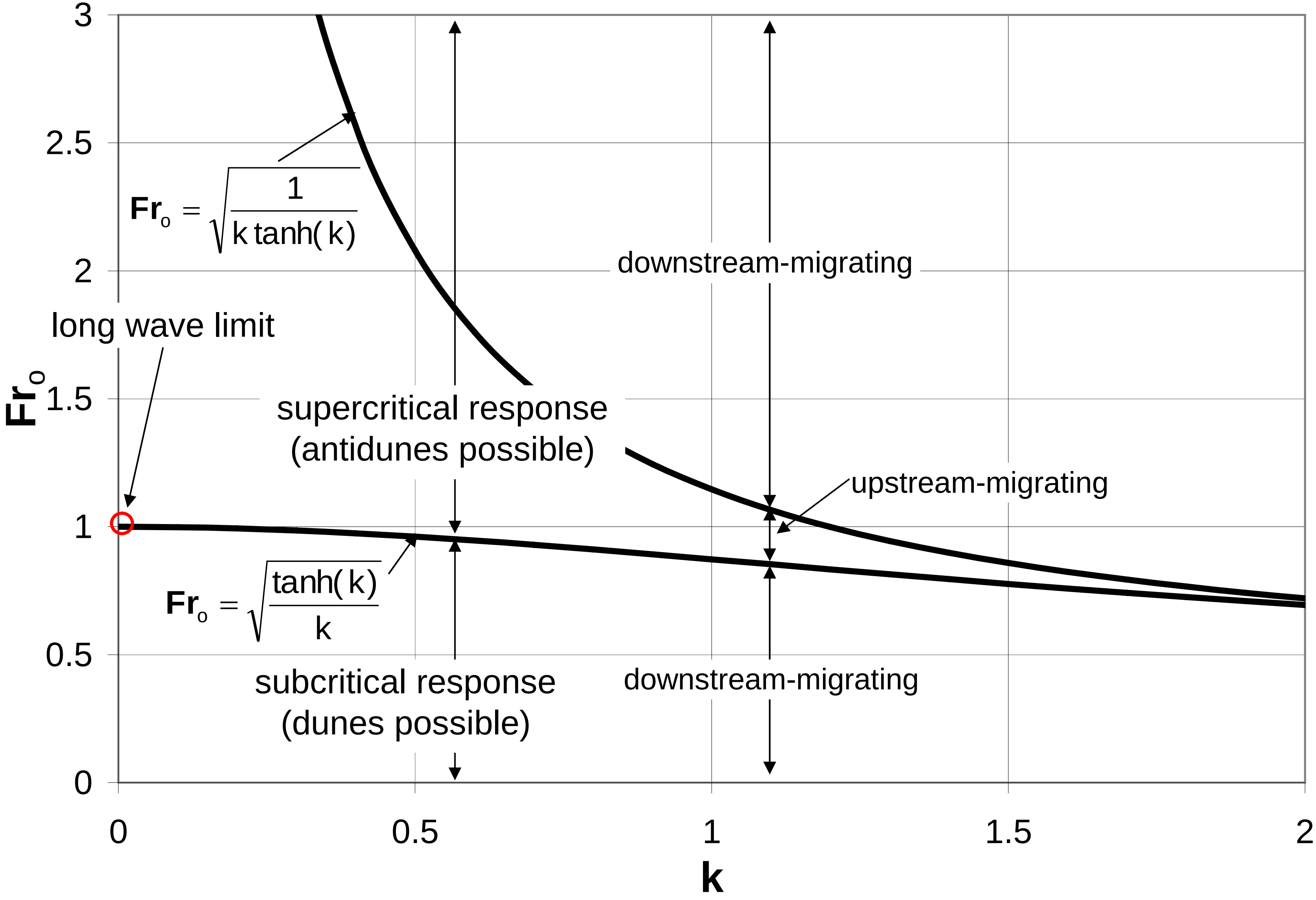
$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial v}-g$$

$$\eta=\eta_o\sin(kx)\quad,\quad k=\frac{2\pi H_o}{\lambda}$$

η_o = amplitude of bed perturbation
H_o = unperturbed depth

Linearized potential flow analysis is sufficient to explain existence regimes, but not formation (gives neutral stability)

PHASE DIAGRAM FOR DUNES AND ANTIDUNES BASED ON LINEAR POTENTIAL THEORY OVER A WAVY BED



FLOW IN THE DUNE REGIME

$\mathbf{Fr}_o < [\tanh(k)/k]^{1/2}$ $k = 2\pi H/\lambda$ H = depth, λ = wavelength

Water surface is out of phase with the bed.

Depth variation is out of phase with the bed

Flow accelerates from trough to crest.

Sediment transport increases from trough to crest.

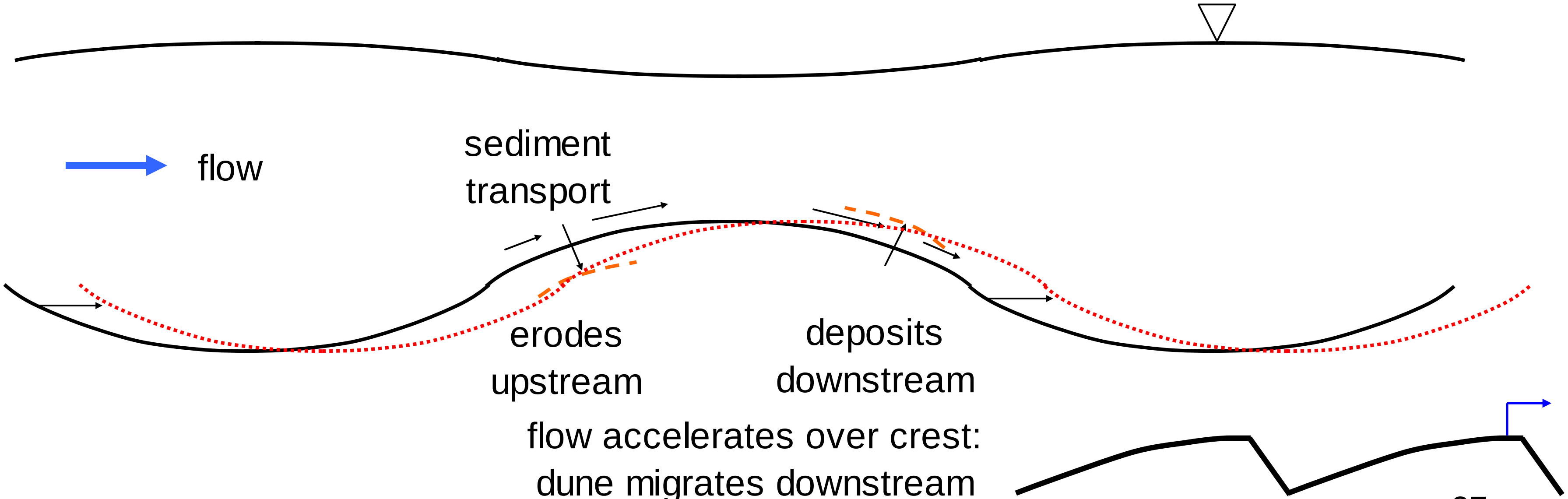
Bedform migrates downstream.

Bedform becomes asymmetric.

$k \to 0$ (shallow water)

$$\frac{\partial H}{\partial x} = -\frac{1}{(1-\mathbf{Fr}^2)}\frac{\partial \eta}{\partial x}$$

$$\frac{\partial \xi}{\partial x} = -\frac{\mathbf{Fr}^2}{(1-\mathbf{Fr}^2)}\frac{\partial \eta}{\partial x}$$



flow accelerates over crest:
dune migrates downstream

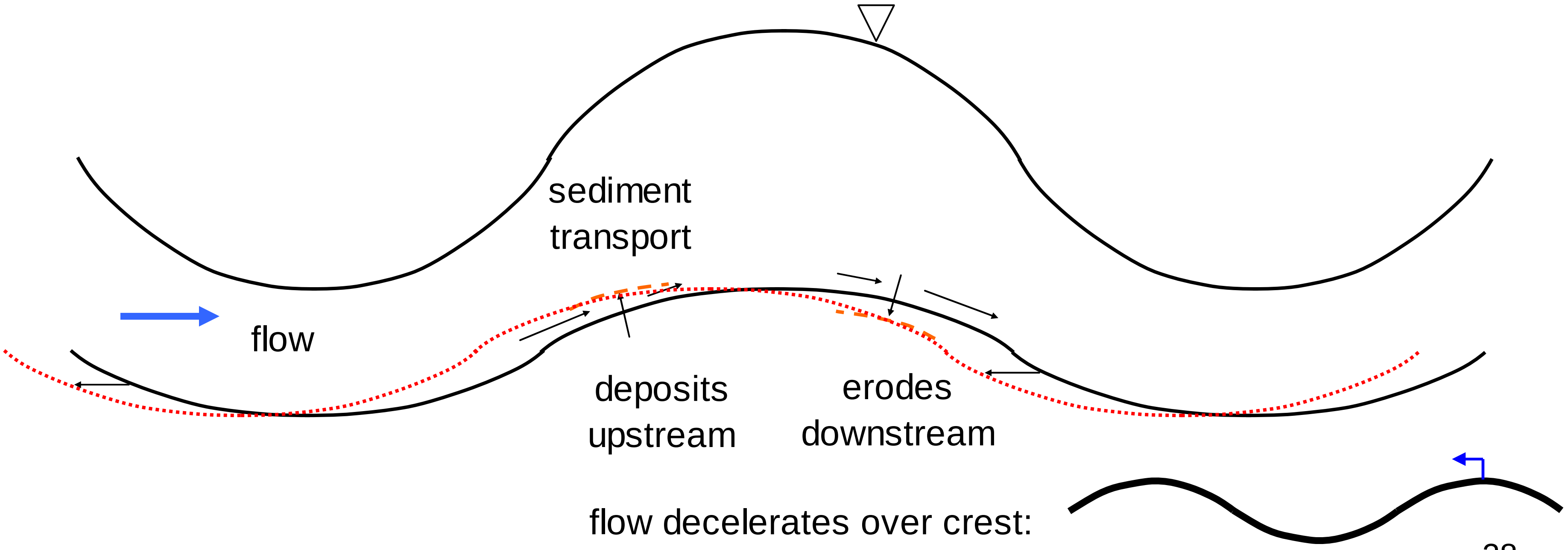
FLOW IN THE UPSTREAM-MIGRATING ANTIDUNE REGIME

$[\tanh(k)/k]^{1/2} < \mathbf{Fr}_o < [k \tanh(k)]^{-1/2}$
Water surface is in phase with the bed.
Depth variation is in phase with the bed
Flow decelerates from trough to crest.
Sediment transport decreases from trough to crest.
Bedform migrates upstream (or hardly at all).
Bedform stays symmetric.

$k \to 0$ (shallow water)

$$\frac{\partial H}{\partial x} = -\frac{1}{(1-\mathbf{Fr}^2)}\frac{\partial \eta}{\partial x}$$

$$\frac{\partial \xi}{\partial x} = -\frac{\mathbf{Fr}^2}{(1-\mathbf{Fr}^2)}\frac{\partial \eta}{\partial x}$$

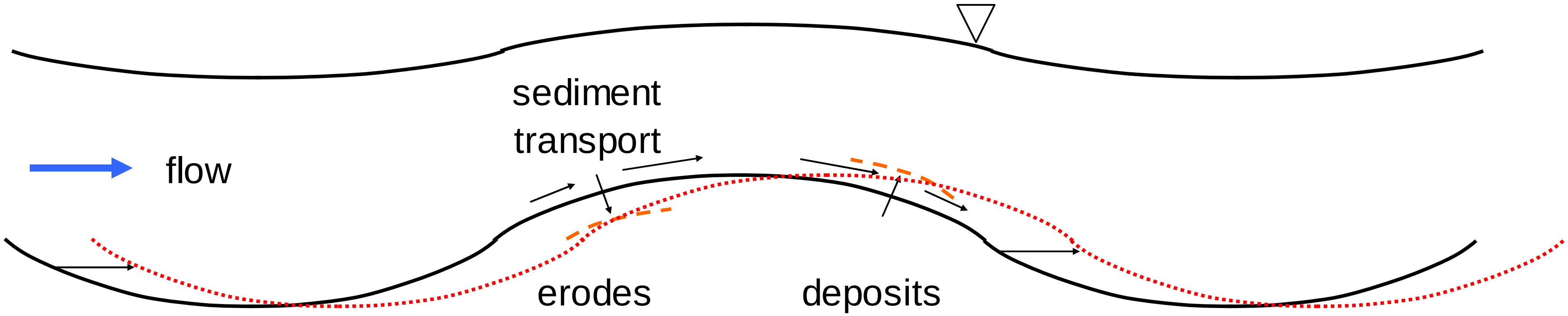


flow decelerates over crest:
antidune migrates upstream

FLOW IN THE DOWNSTREAM-MIGRATING ANTIDUNE REGIME

$[k \tanh(k)]^{-1/2} < \mathbf{Fr}_o$
Water surface is in phase with the bed.
Depth variation is out of phase with the bed.
Flow accelerates from trough to crest.
Sediment transport increases from trough to crest.
Bedform migrates downstream.
Bedform becomes asymmetric.
These are antidunes that look like dunes: not too common, but they are observed.

No shallow-water limit as $k \to 0$.

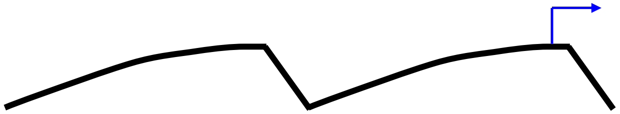


sediment transport

flow

erodes upstream

deposits downstream



flow accelerates over crest:
antidune migrates downstream

STABILITY ANALYSIS FOR DUNES AND ANTIDUNE FORMATION: OCCAM'S RAZOR

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}-g\frac{\partial \eta}{\partial x}+\frac{\partial}{\partial x}\left(\nu_t\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial x}\left(\nu_t\frac{\partial u}{\partial y}\right)-g\frac{\partial \eta}{\partial x}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial v}-g+\frac{\partial}{\partial x}\left(\nu_t\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial x}\left(\nu_t\frac{\partial v}{\partial y}\right)-g\frac{\partial \eta}{\partial x}$$

$$\eta=\eta_o e^{\alpha t}\sin(kx)\quad,\quad k=\frac{2\pi H_o}{\lambda}$$

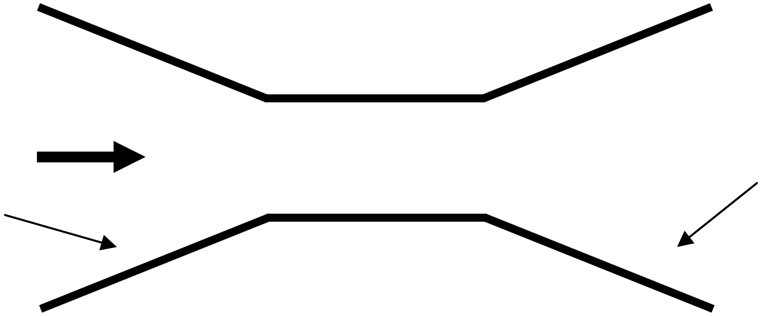
Closure for ν_t: a constant value that gives a result close to the logarithmic law

$$\boxed{(1-\lambda_p)\frac{\partial \eta}{\partial t}=-\frac{\partial q_t}{\partial x}}\qquad\qquad\boxed{q_t=f(\tau_b,\frac{\partial \eta}{\partial x})}$$

In sediment transport law, τ_b = bed shear stress

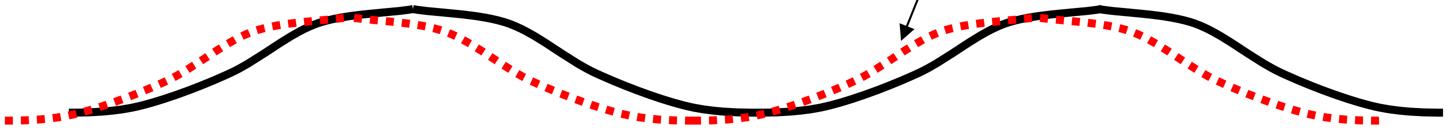
INSTABILITY MECHANISM FOR DUNES

Consider flow into a Venturi contraction.
The favorable pressure gradient on the upstream side intensifies the bed shear stress.
The adverse pressure gradient on the downstream side suppresses shear stress.



Wall shear stress τ_b intensified

Wall shear stress τ_b suppressed



Bed perturbation: black solid

Shear stress perturbation → sediment transport rate perturbation: red dashed

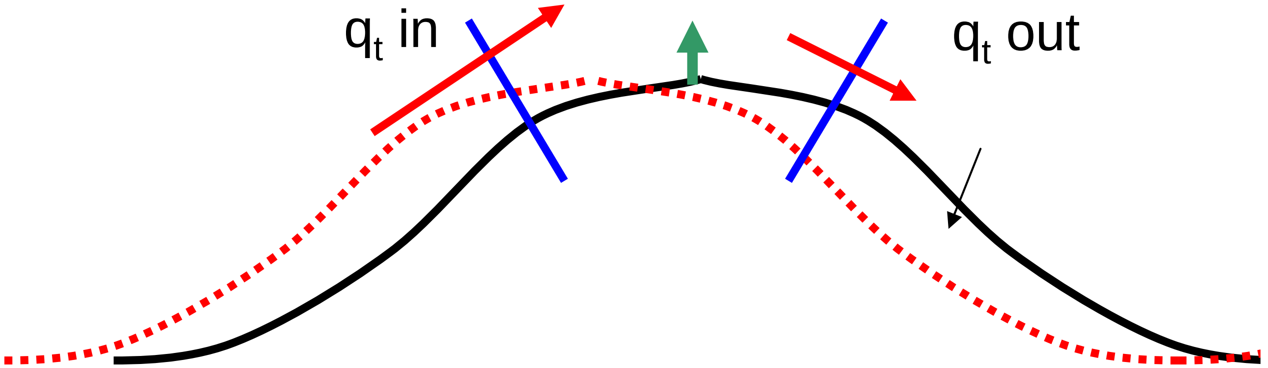
Sediment transport rate peaks a little before the bed perturbation peak

NET DEPOSITION AT APEX: LINEAR MODEL

The bed shear stress perturbation, and thus the sediment transport rate perturbation, lead the bed elevation perturbation.

There is thus net deposition at the apex (and net erosion at the trough), and so amplitude increases in time.

A nonlinear analysis including flow separation on the lee side of dunes is necessary to explain nonlinear equilibrium: numerical, e.g. k-ε



Bed perturbation:
black solid

sediment transport rate
perturbation: red dashed

NONLINEAR PHENOMENON OF ANTIDUNES

SINGLE-ROW AND MULTIPLE-ROW ALTERNATE BARS

Occam's razor minimal analysis:
2D shallow water equations +
2D sediment transport formulation

Controlling parameter: width-depth ratio B/H
No bars → single-row bars →multiple-row bars

Hii River, Japan

Image courtesy H. Takebayashi

Naka River, Japan

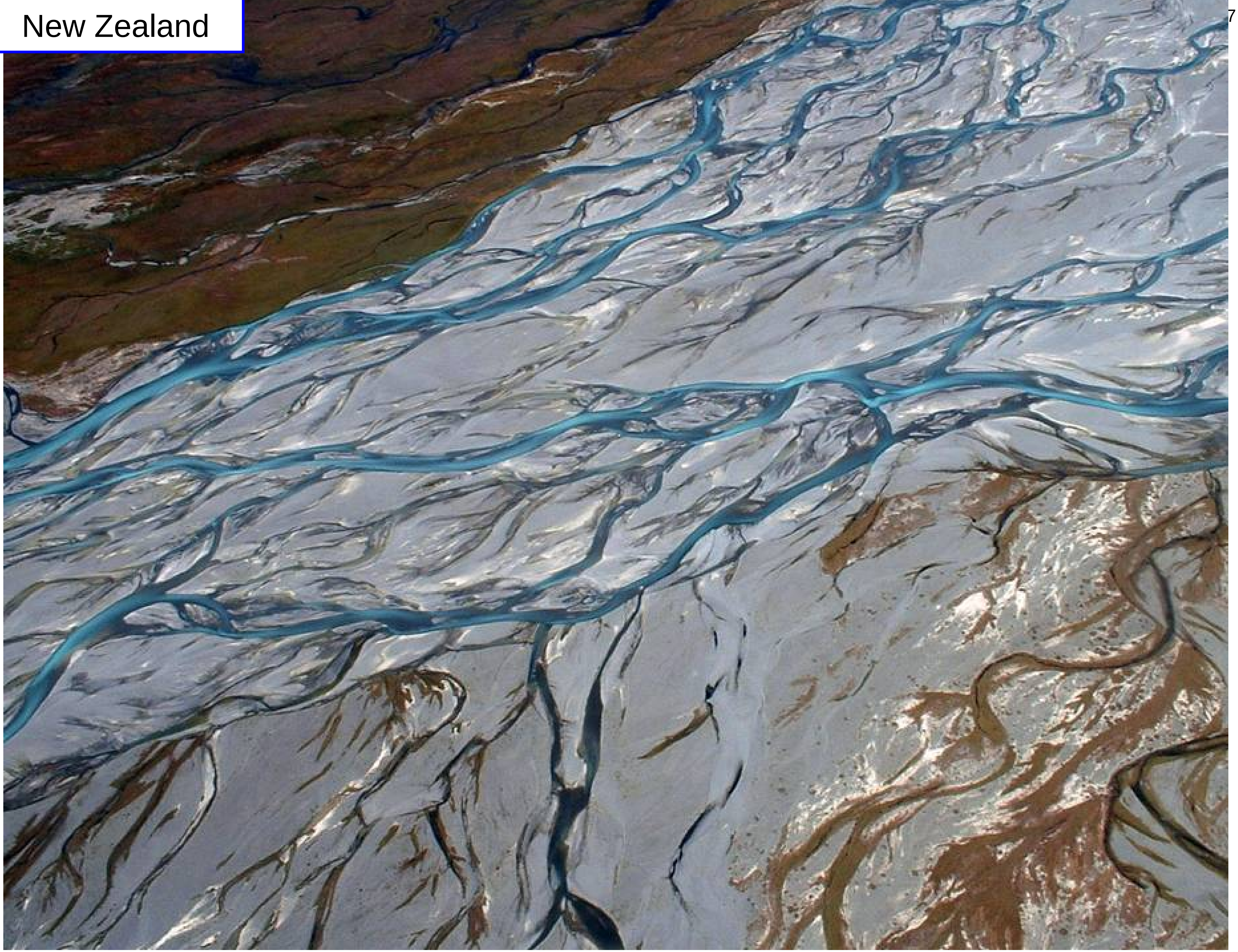
Image courtesy S. Ikeda

New Zealand

BRAIDING

New Zealand

New Zealand



William River Canada

http://www.athabascalake.com/ecoexped/william_river_braided.jpg

BRAIDING MECHANISM: CONFLUENCES

Skeithara Sandur, Iceland

Image courtesy H. Johannesson

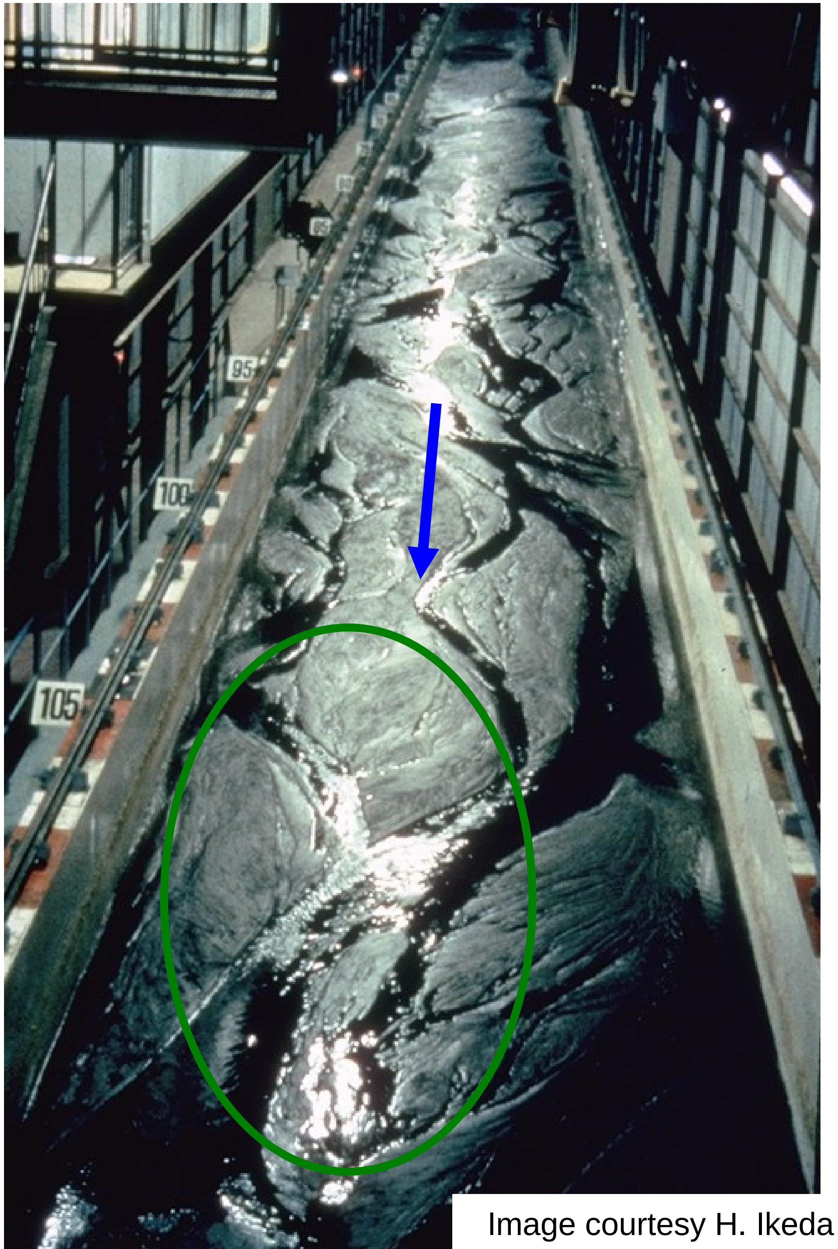


Image courtesy H. Ikeda

NONLINEAR INTENSIFICATION OF SEDIMENT TRANSPORT RATE AT CONFLUENCES: SCOUR

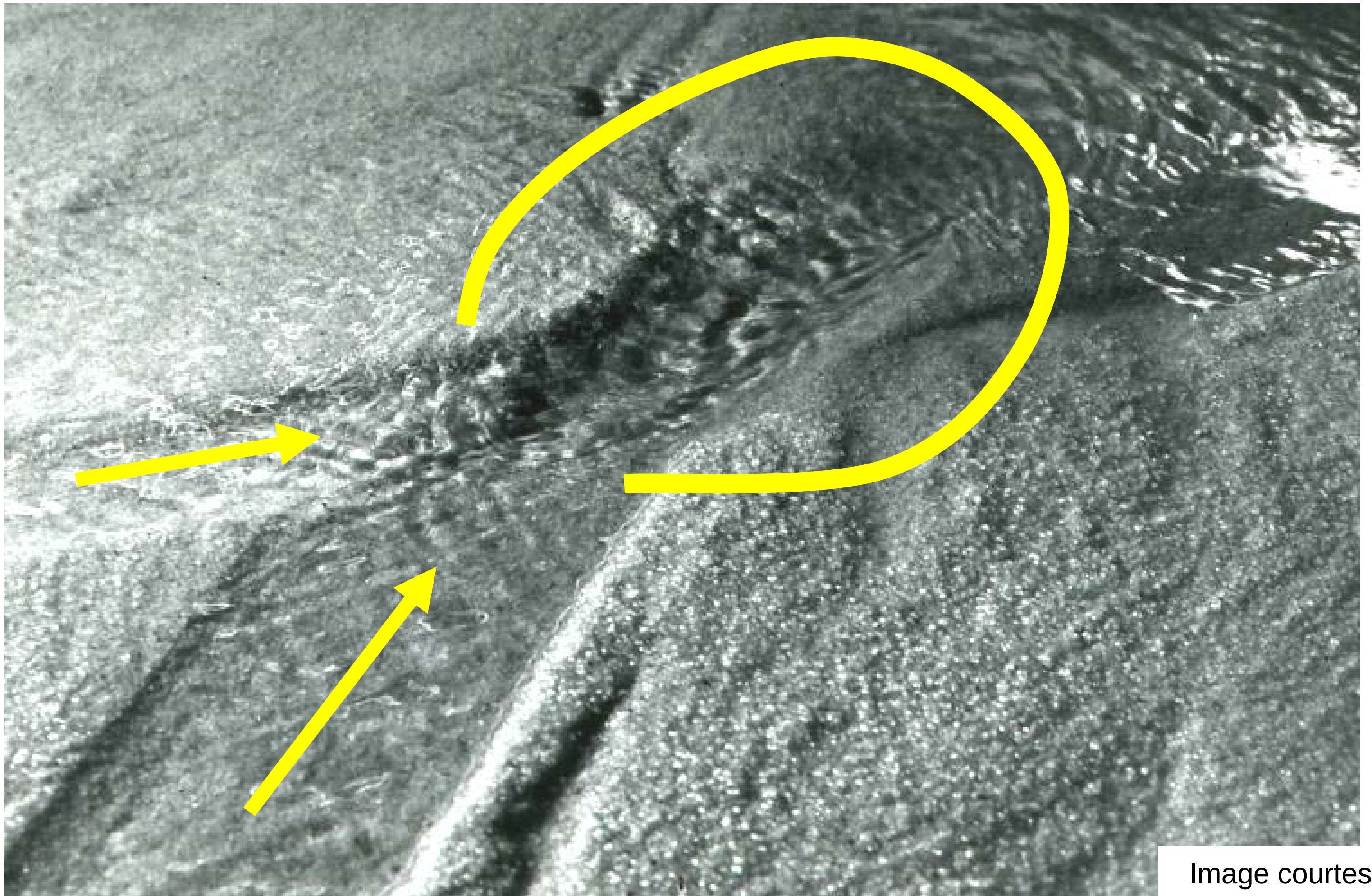


Image courtesy P. Ashmore

DOWNSTREAM, THE FLOW EXPANDS AND DEPOSITS A MINI-FAN

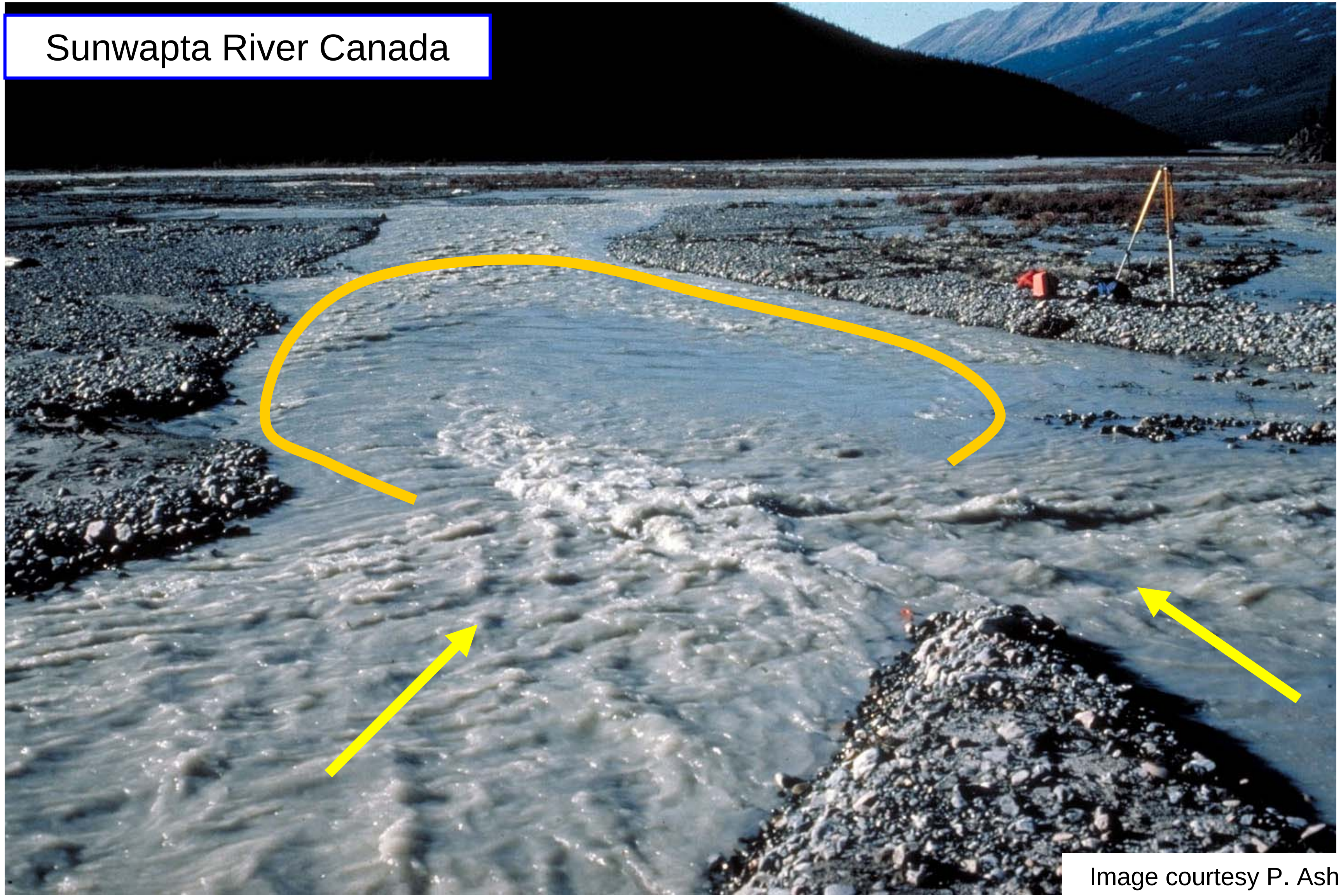
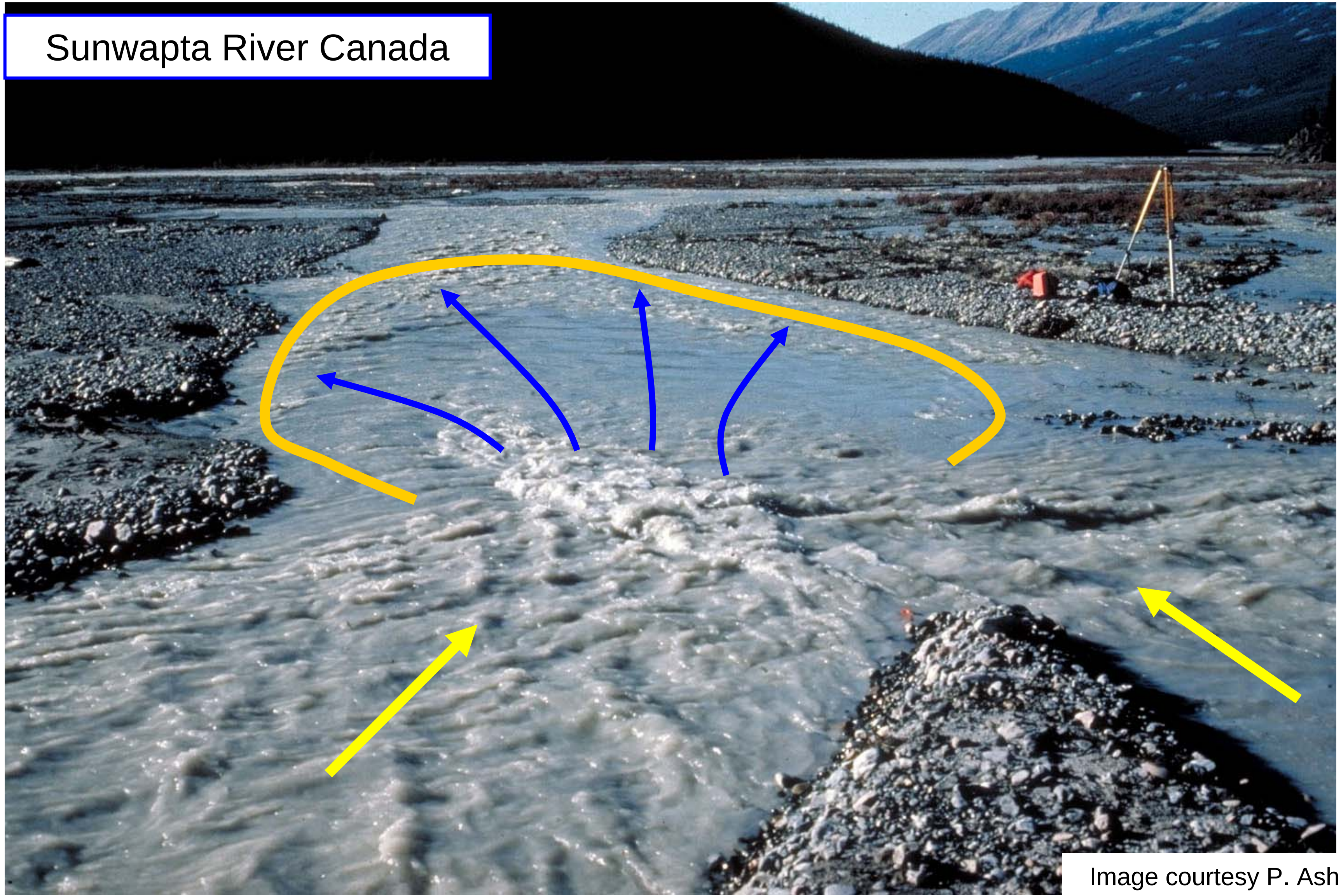


Image courtesy P. Ashmore

DOWNSTREAM, THE FLOW EXPANDS AND DEPOSITS A MINI-FAN

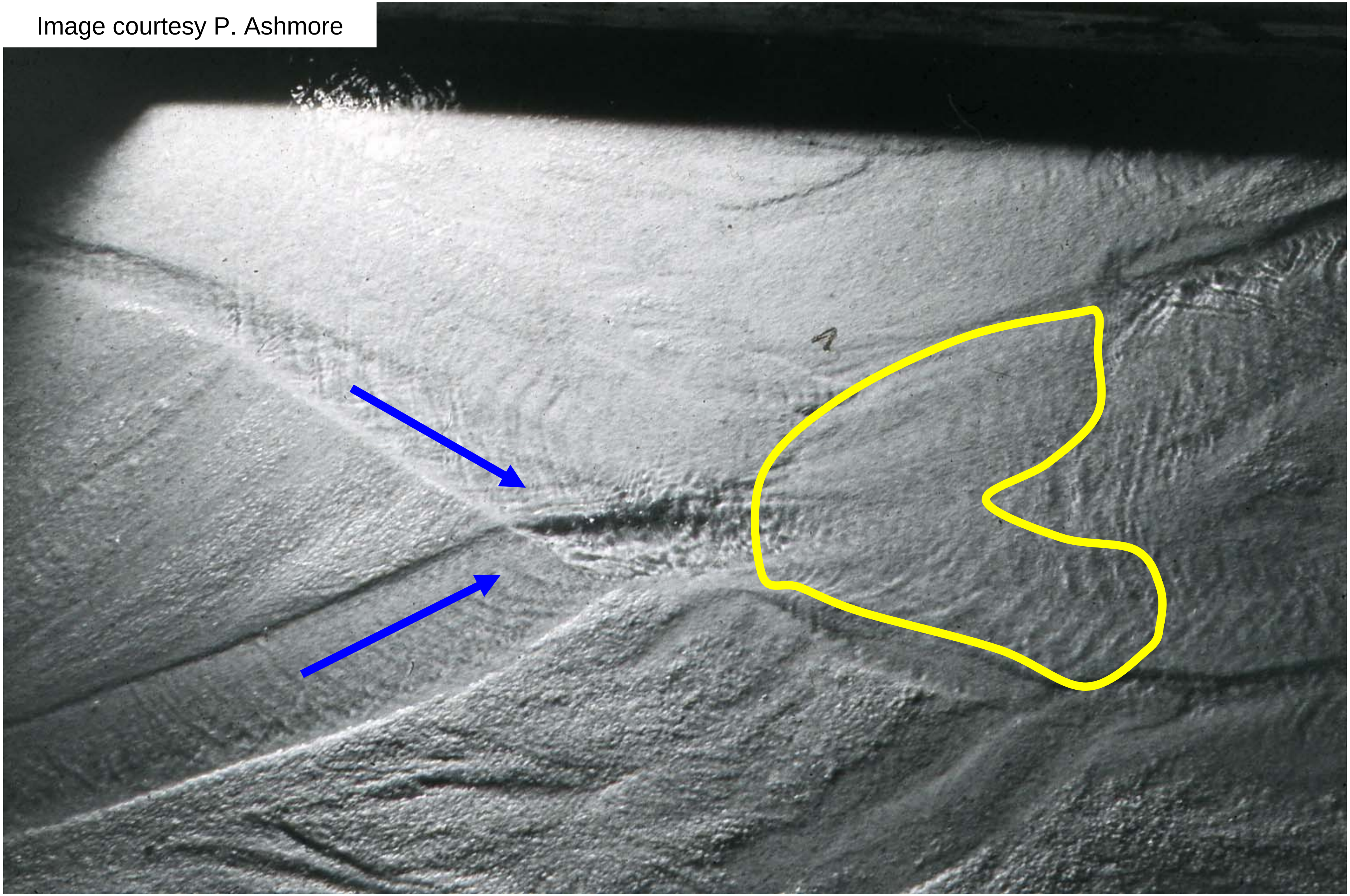


Sunwapta River Canada

Image courtesy P. Ashmore

AS THE FLOW GETS WIDER AND SHALLOWER, IT BECOMES UNSTABLE AND BIFURCATES INTO ONE OR MORE CHANNELS

Image courtesy P. Ashmore



AS THE FLOW GETS WIDER AND SHALLOWER, IT BECOMES UNSTABLE AND BIFURCATES INTO ONE OR MORE CHANNELS

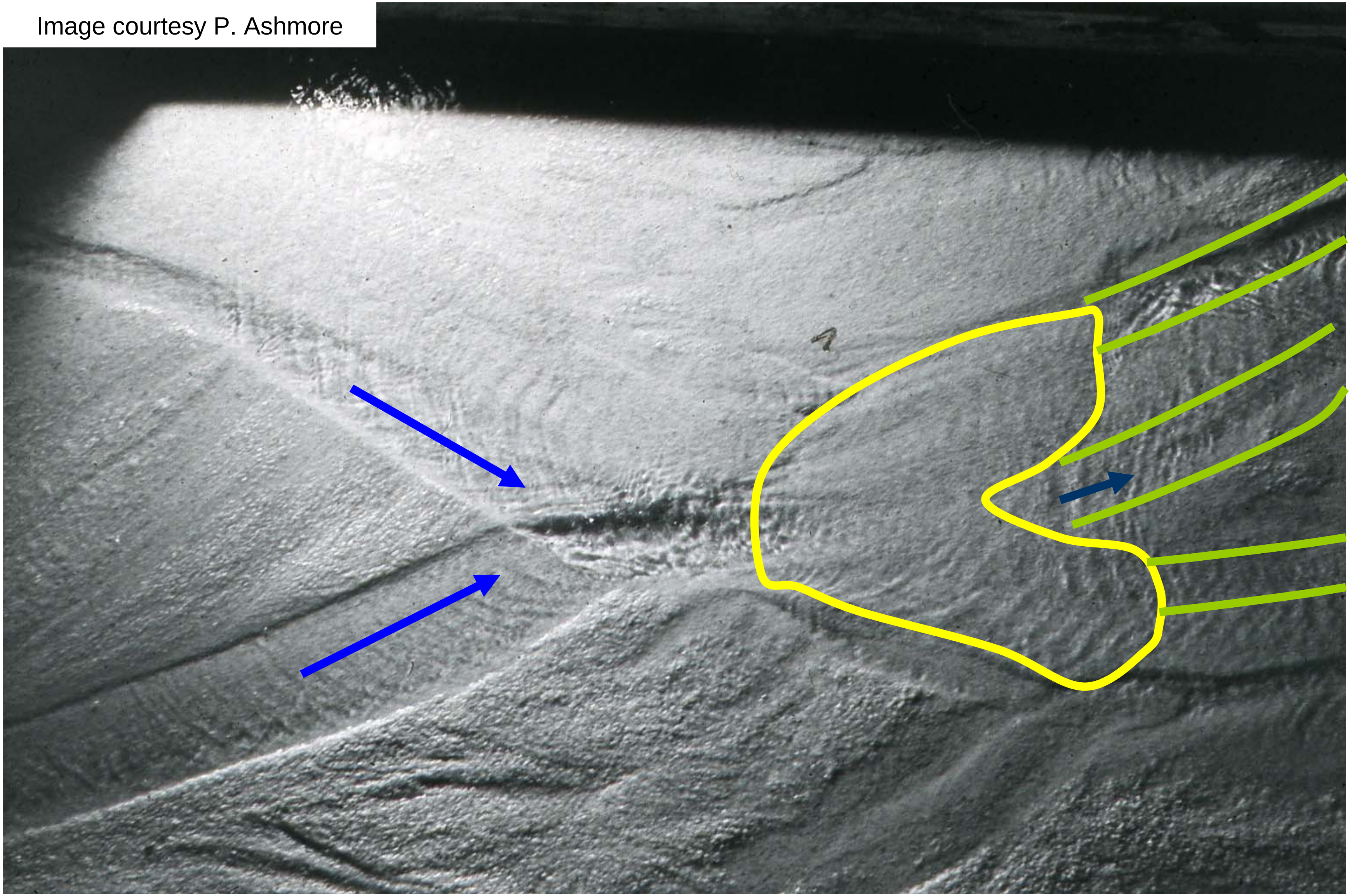


Image courtesy P. Ashmore

Copyright G. Parker, 2007

MEANDERING

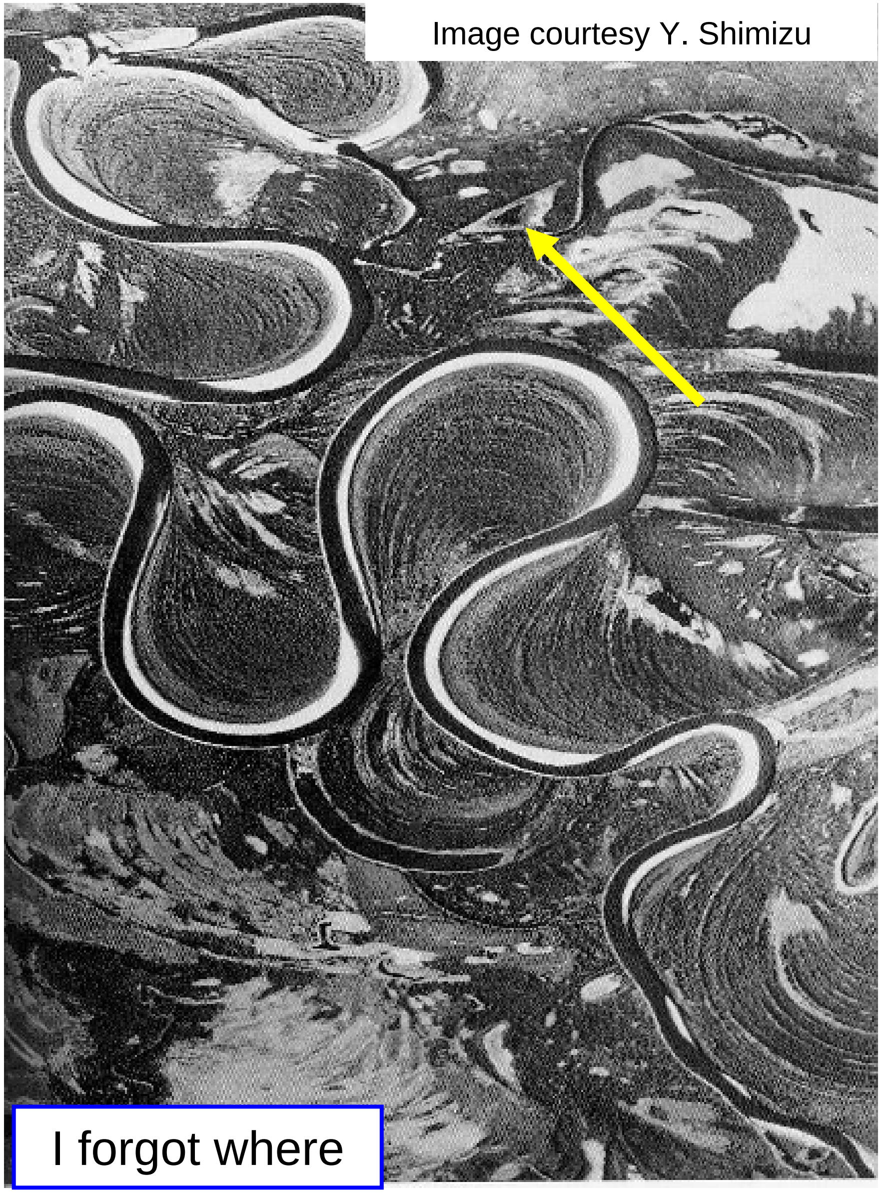


Image courtesy Y. Shimizu

I forgot where

Mississippi River, USA

From maps of H. Fisk

MEANDERING MECHANISM

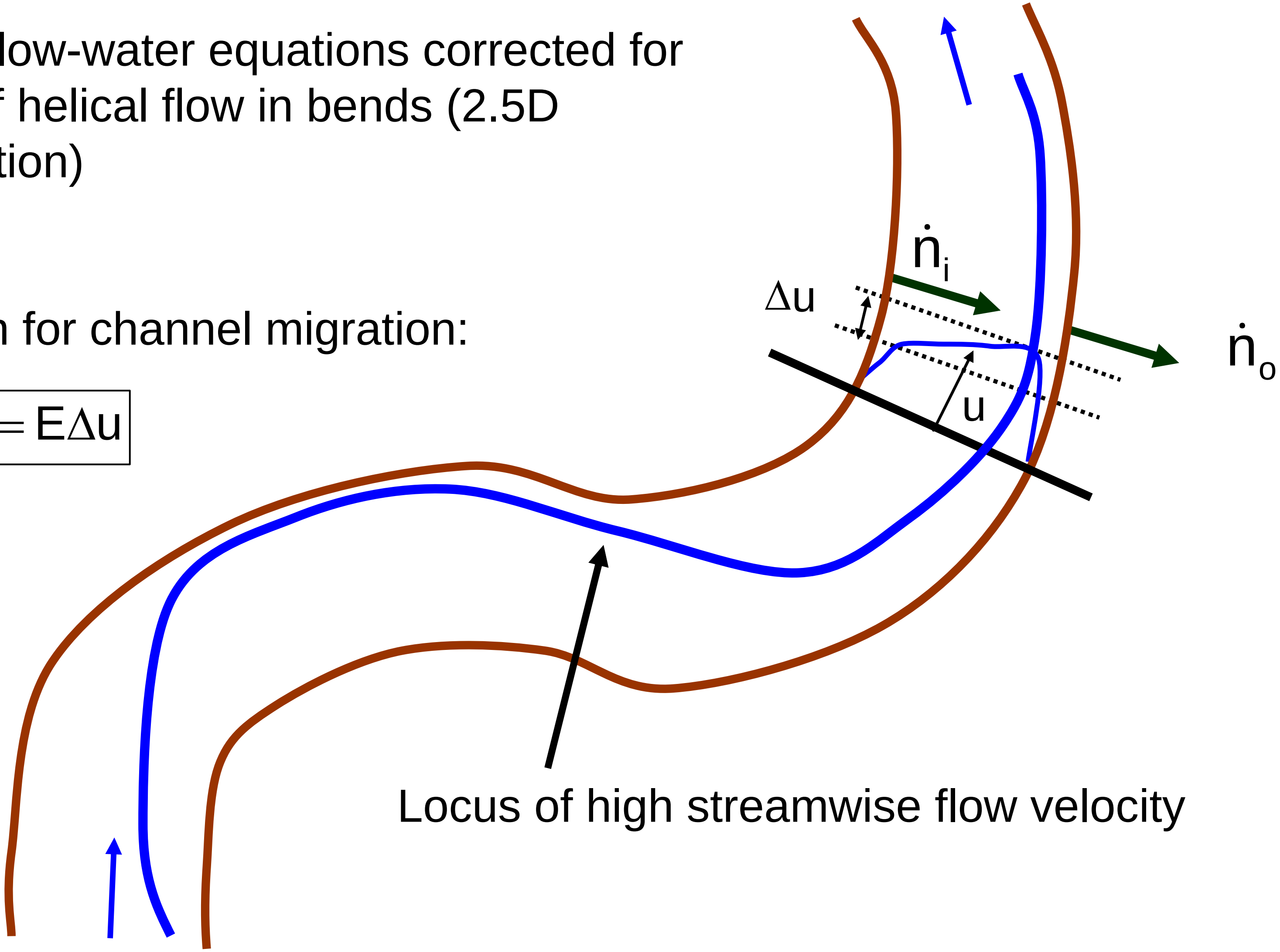
Occam's razor first analysis:

2D shallow-water equations corrected for effect of helical flow in bends (2.5D formulation)

+

Relation for channel migration:

$$\boxed{\dot{n}_o = E \Delta u}$$



Locus of high streamwise flow velocity

ONLY BRAIDING IS POSSIBLE IN THE ABSENCE OF BANK STABILIZATION

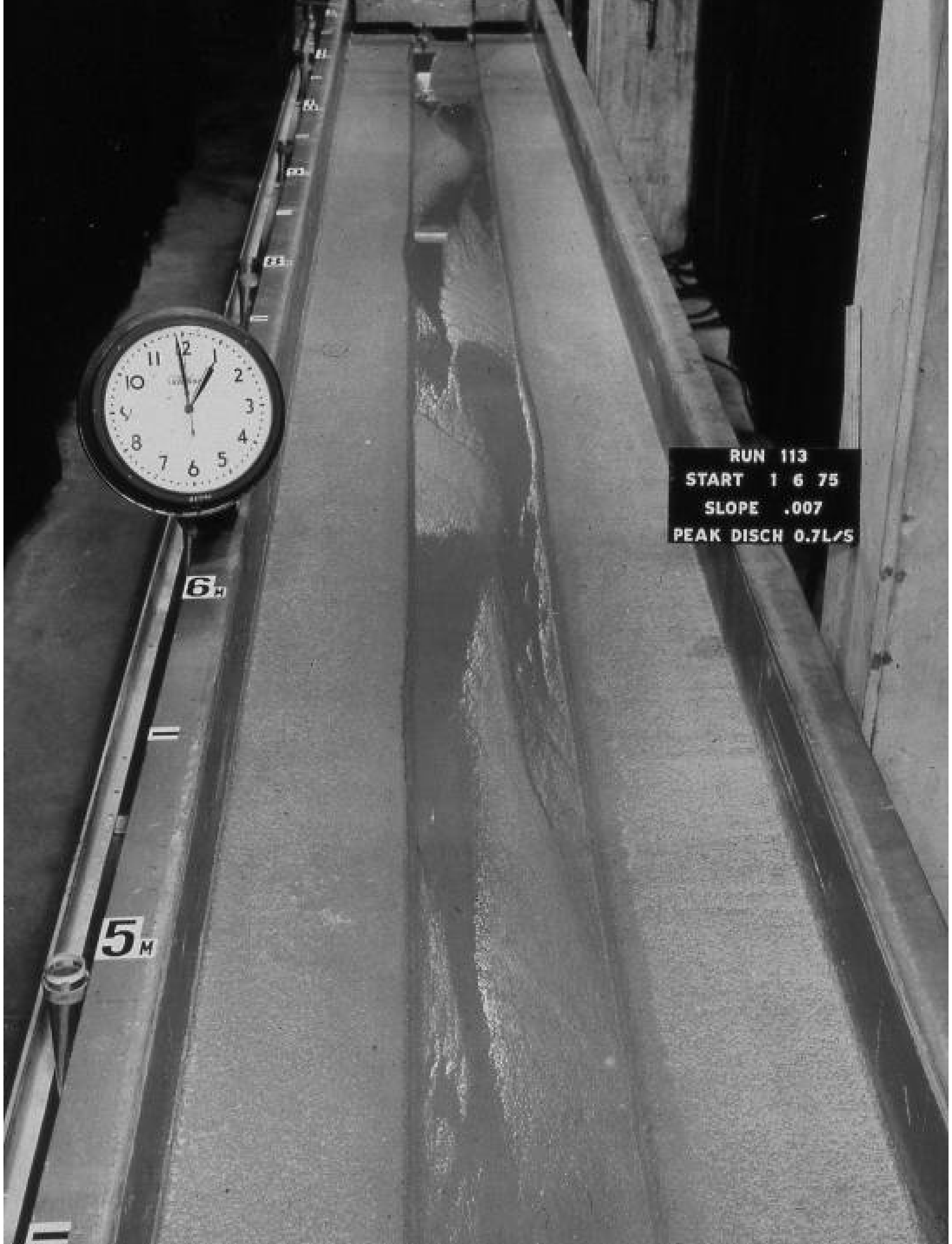
Image courtesy B. Murray

Braided stream on the North Slope, Brooks Range, Alaska

SWEET LITTLE LIES

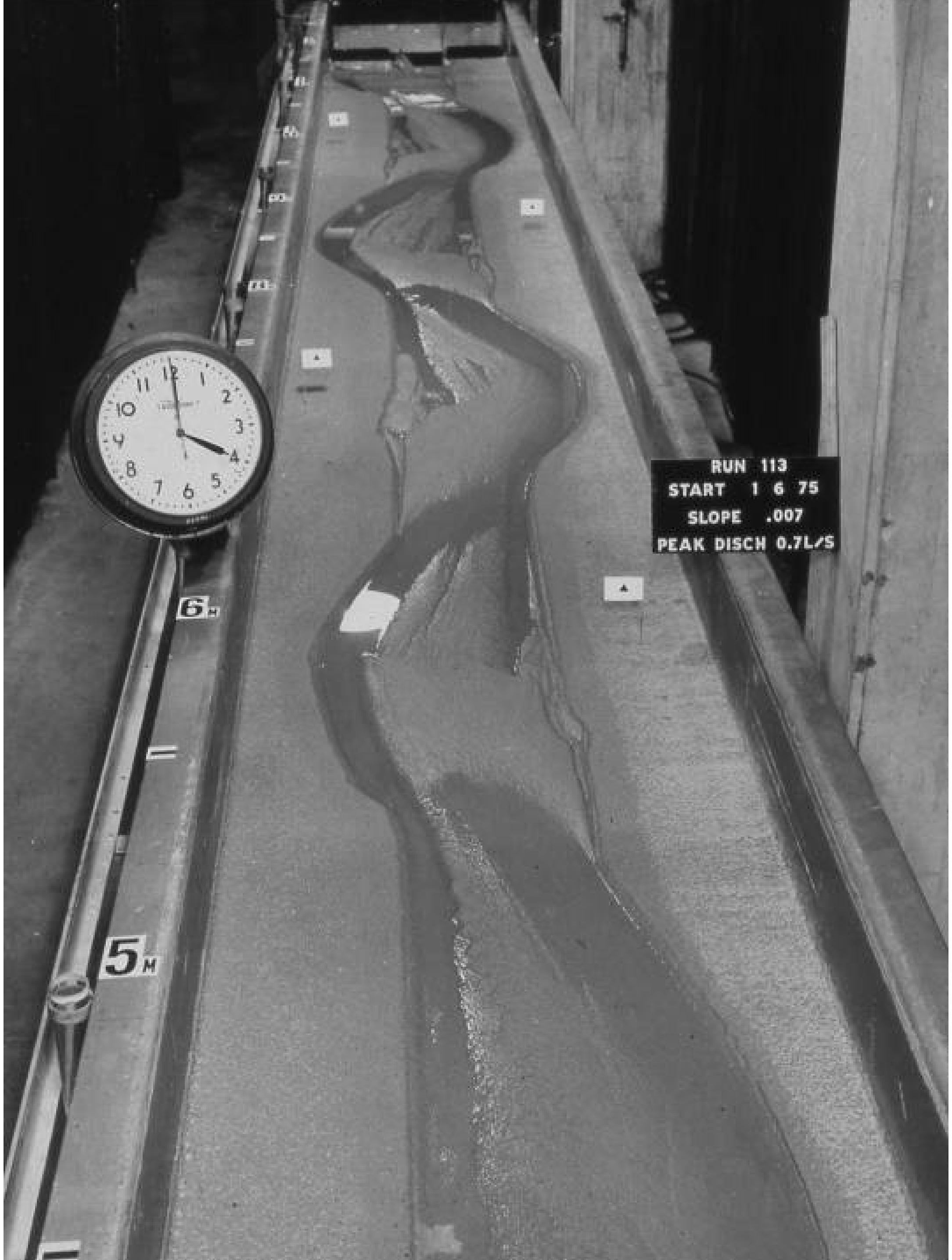
Yes, honey, I’m with you.

http://images.google.com/imgres?imgurl=http://jeroenarendsen.nl/pics/Conversation-Icelanders-pianist.gif&imgrefurl=http://jeroenarendsen.nl/category/countries/&h=327&w=387&sz=94&hl=en&start=14&um=1&tbnid=4OxlA6BGtduRcM:&tbnh=104&tbnw=123&prev=/images%3Fq%3Dconversation%26ndsp%3D21%26svnum%3D10%26um%3D1%26hl%3Den%26client%3Dfirefox-a%26rls%3Dorg.mozilla:en-US:official%26sa%3DN



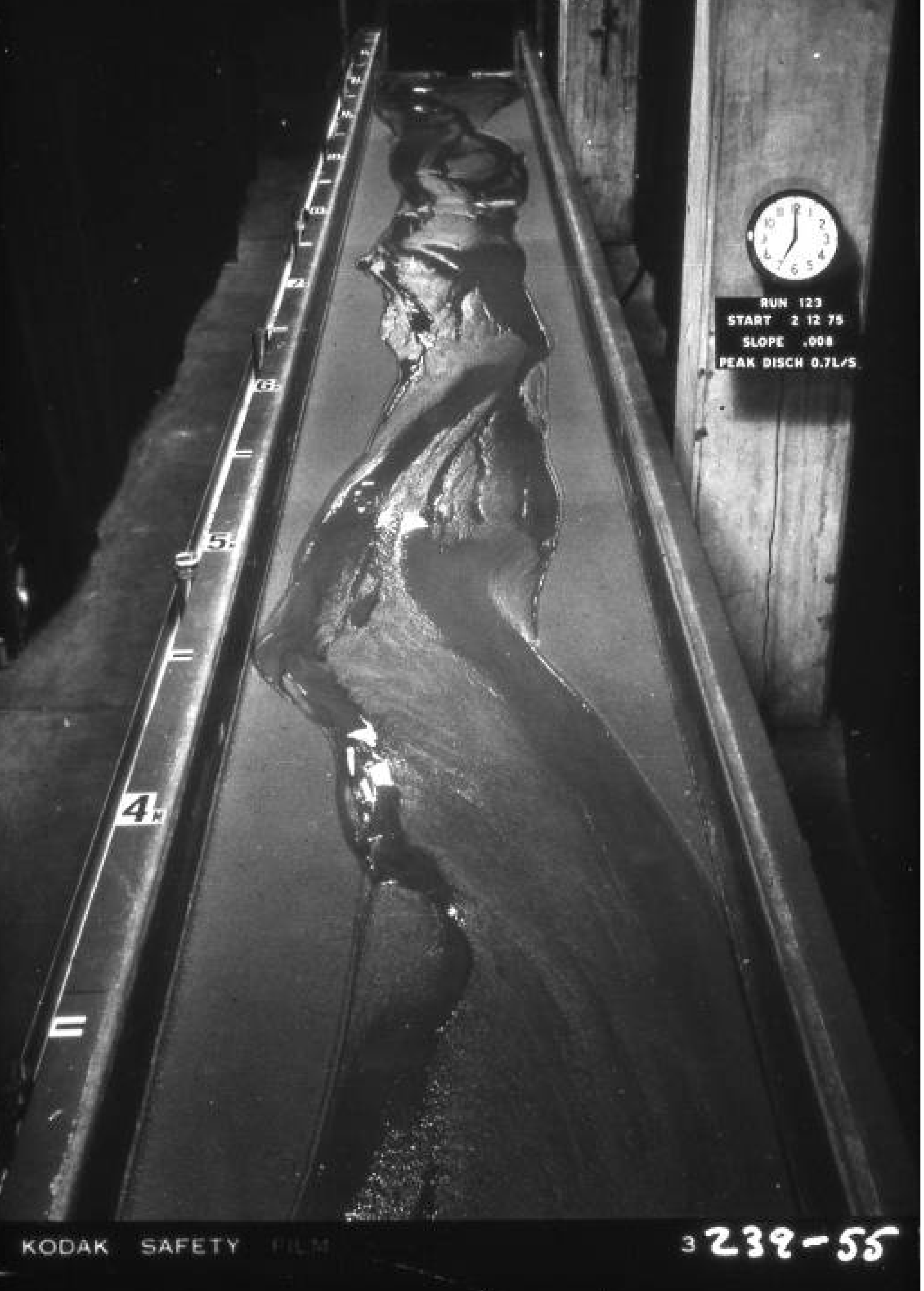
Inside bank to outside bank:

“Yes, I’m following you.”



Inside bank to outside bank:

"Yes, I'm following you."



Yeah, while you were pretending to listen, ***look at the mess we got ourselves into!***

Image courtesy H. Johannesson

BEND SKEWING: SUBCRITICAL BIFURCATION OF NONLINEAR STABILITY ANALYSIS

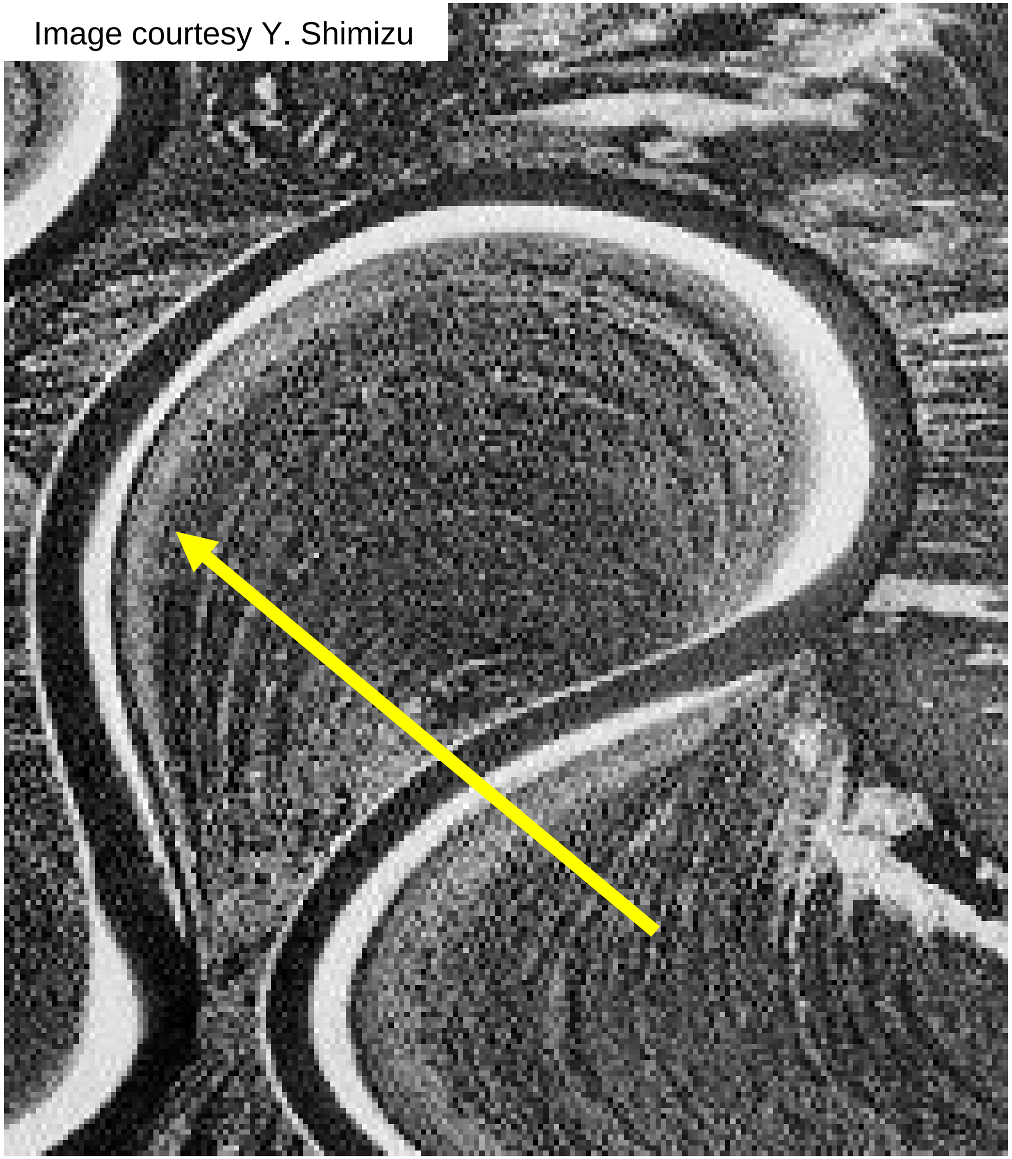


Image courtesy Y. Shimizu

Bends grow until cutoff:
There is no nonlinear
stable state

Old oxbow lake due
to cutoff

Image courtesy W. Dietrich

SLUMPING ON OUTSIDE SLOWS DOWN EROSION SO TRAPPING OF SEDIMENT BY VEGETATION ON INSIDE CAN KEEP UP

Vermilion River, USA

I slump

Do we talk to each other?

I trap

Vermilion River, USA

NOW FOR A TOUR OF MORPHODYNAMIC PHENOMENA WITHOUT DETAIL AS TO HOW THEY ARE SOLVED

Yes, they are tractable to various degrees

SCROLL BARS

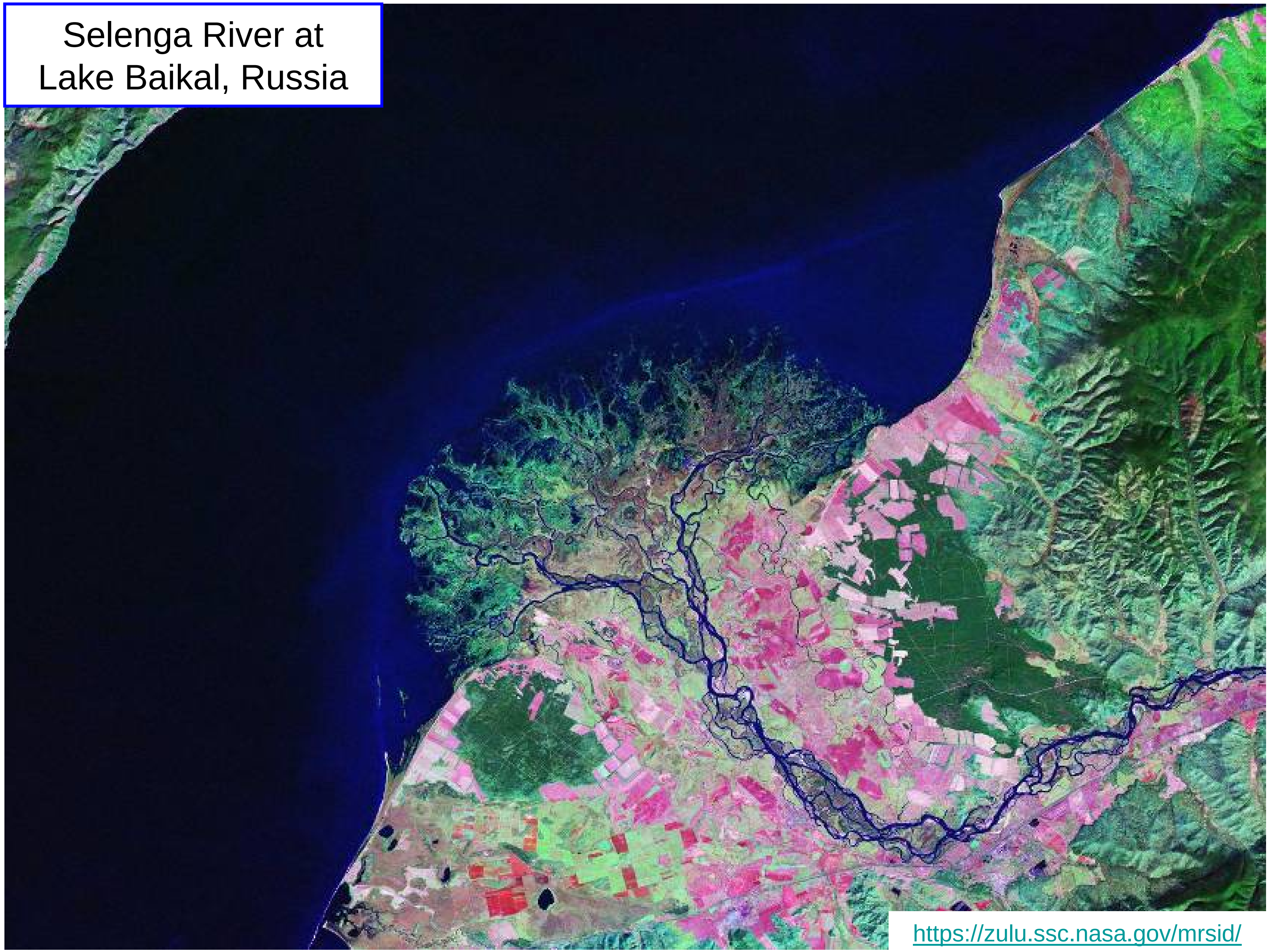
Image courtesy Y. Shimizu

I still can't remember

Image courtesy W. Dietrich

Strickland River, Papua New Guinea

ALLUVIAL FANS AND FAN-DELTAS

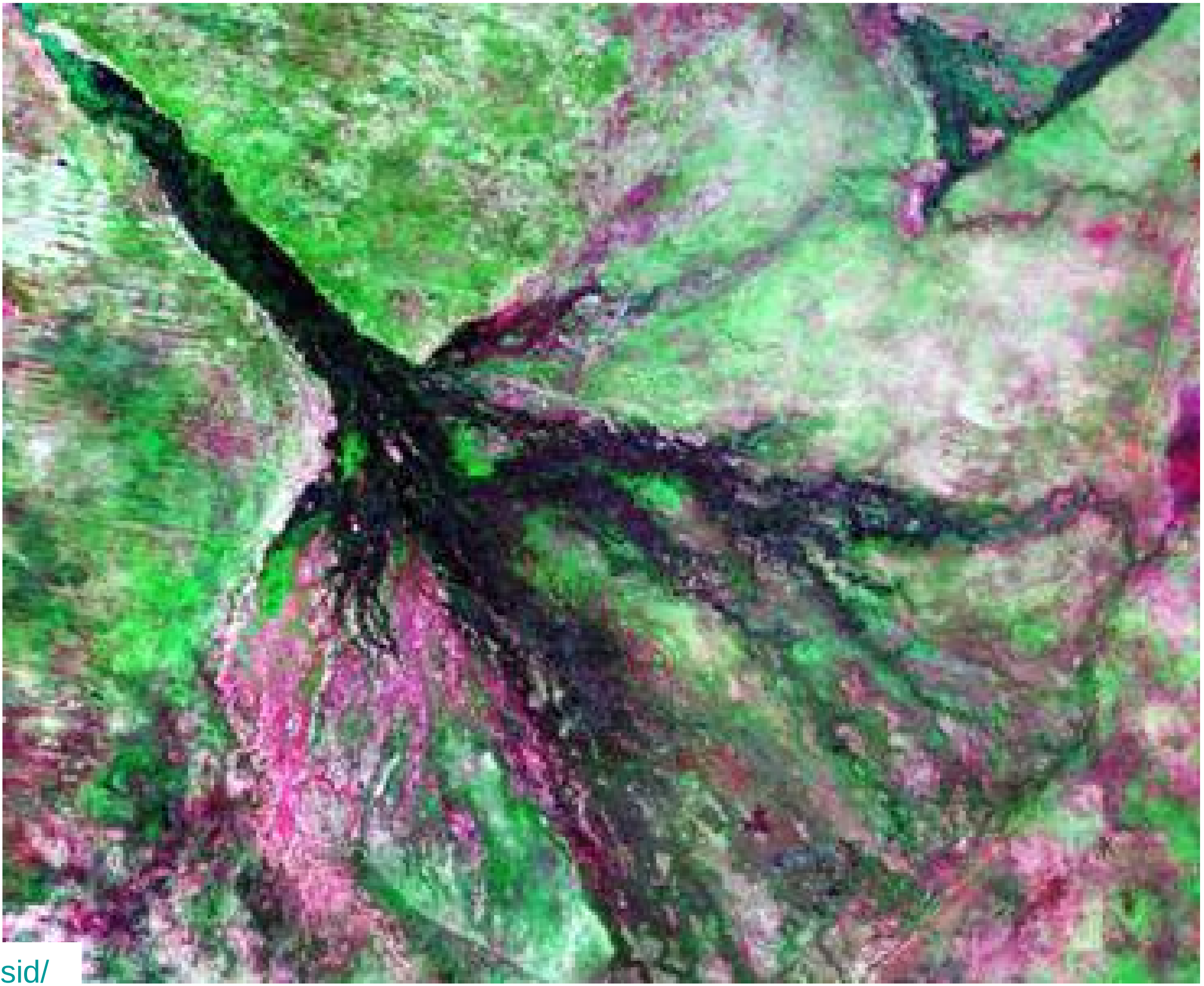


Selenga River at
Lake Baikal, Russia

https://zulu.ssc.nasa.gov/mrsid/

THE OKAVANGO INLAND FAN, BOTSWANA, AFRICA

Graben: subsidence



https://zulu.ssc.nasa.gov/mrsid/

THE FAN-DELTA OF THE KUROBE RIVER, JAPAN

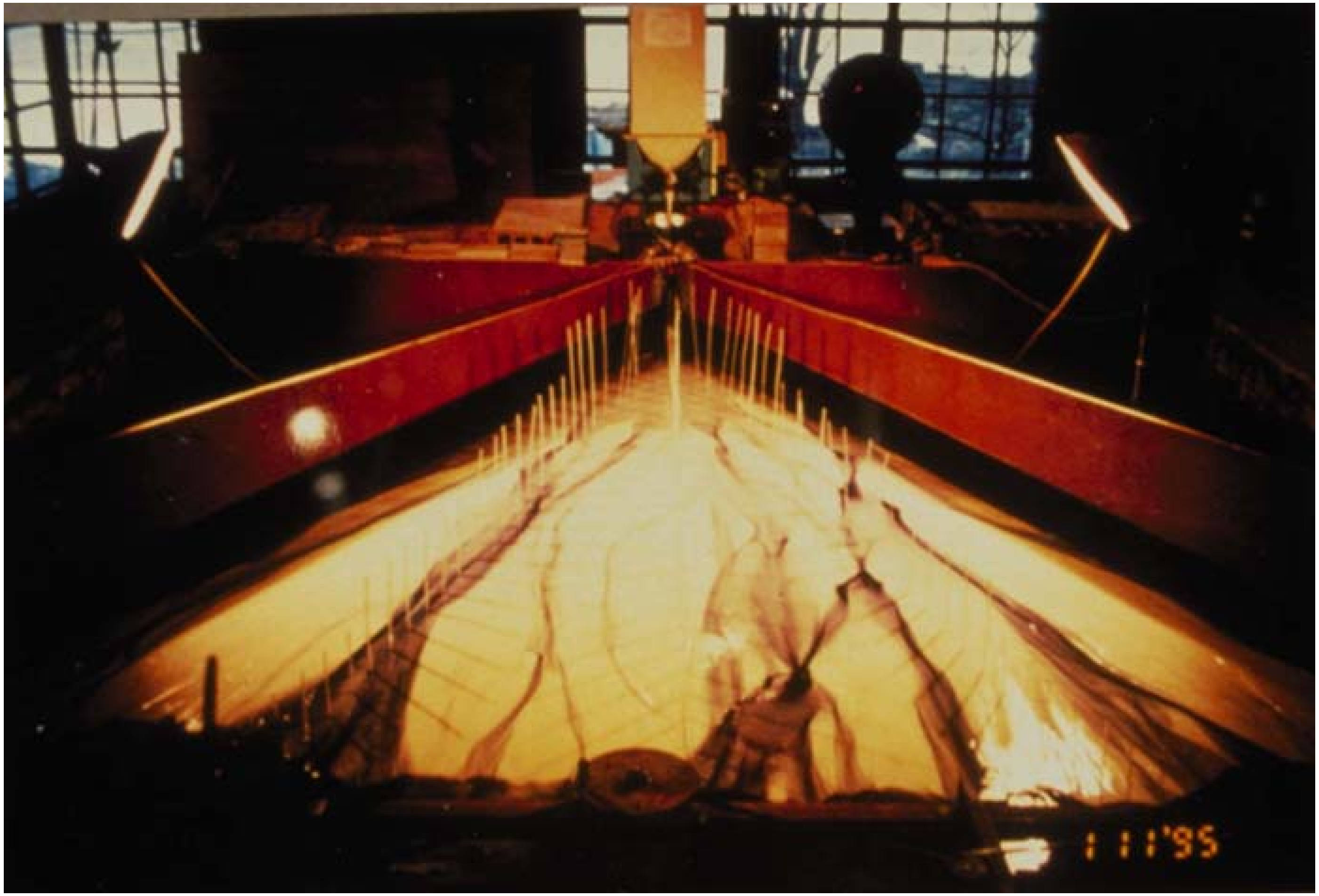
https://zulu.ssc.nasa.gov/mrsid/

THE FAN-DELTA OF THE IOCC IRON MINE, LABRADOR, CANADA

THE FAN IN THE DELTA

http://wakamononoh.logoz.
org/images/toimg3.jpg

FANS AND FAN-DELTAS AT VARIOUS SCALES



Laboratory fan-delta, ~ 3 m.

Image taken at St. Anthony Falls Laboratory, University of Minnesota USA.

FANS AND FAN-DELTAS AT VARIOUS SCALES contd.

Fan created by runoff from cultivated field; ~ 6 m.
Image taken by author near Pigeon Point, California.

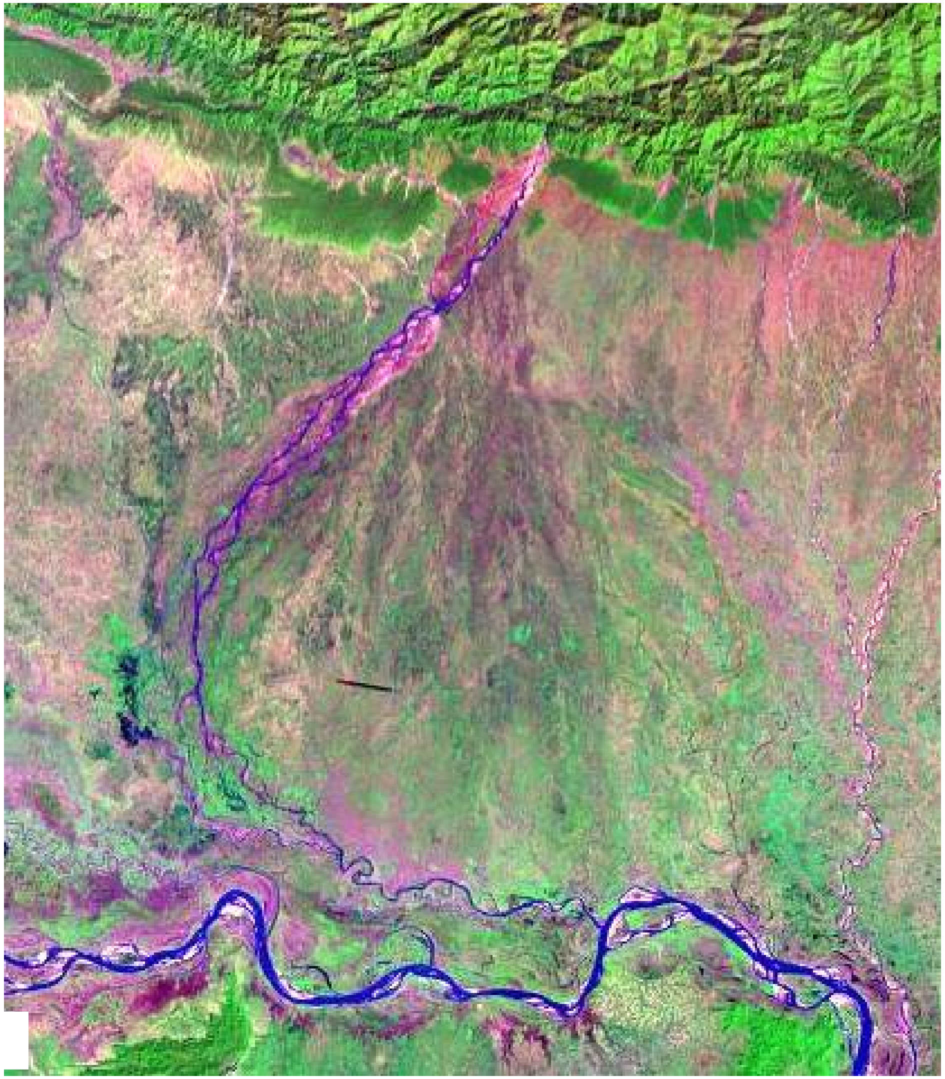
FANS AND FAN-DELTAS AT VARIOUS SCALES contd.

Fan in Idaho, USA created by runoff from burned hillside, ~ 50 m.

FANS AND FAN-DELTAS AT VARIOUS SCALES contd.

Copper Creek Fan, Death Valley, USA; ~ 10 km.
Image courtesy Roger Hooke.

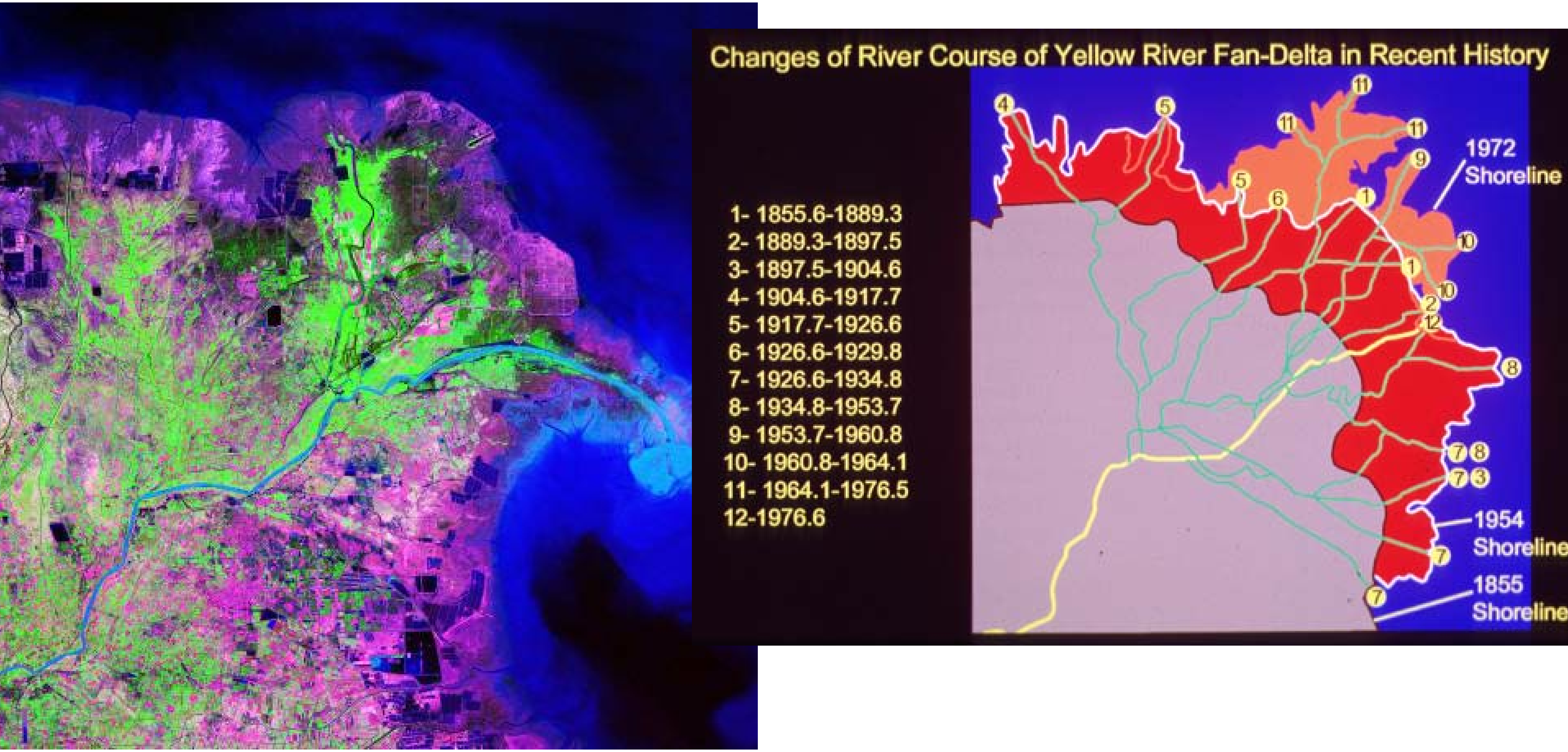
FANS AND FAN-DELTAS AT VARIOUS SCALES contd.



https://zulu.ssc.nasa.gov/mrsid/

Kosi River Fan, India; ~ 125 km.

RIVER MIGRATION AND AVULSION MAKES FANS



https://zulu.ssc.nasa.gov/mrsid/

Yellow River Fan-delta, China

CONCAVE BANK BENCHES

Image courtesy OTML

Fly River, Papua New Guinea

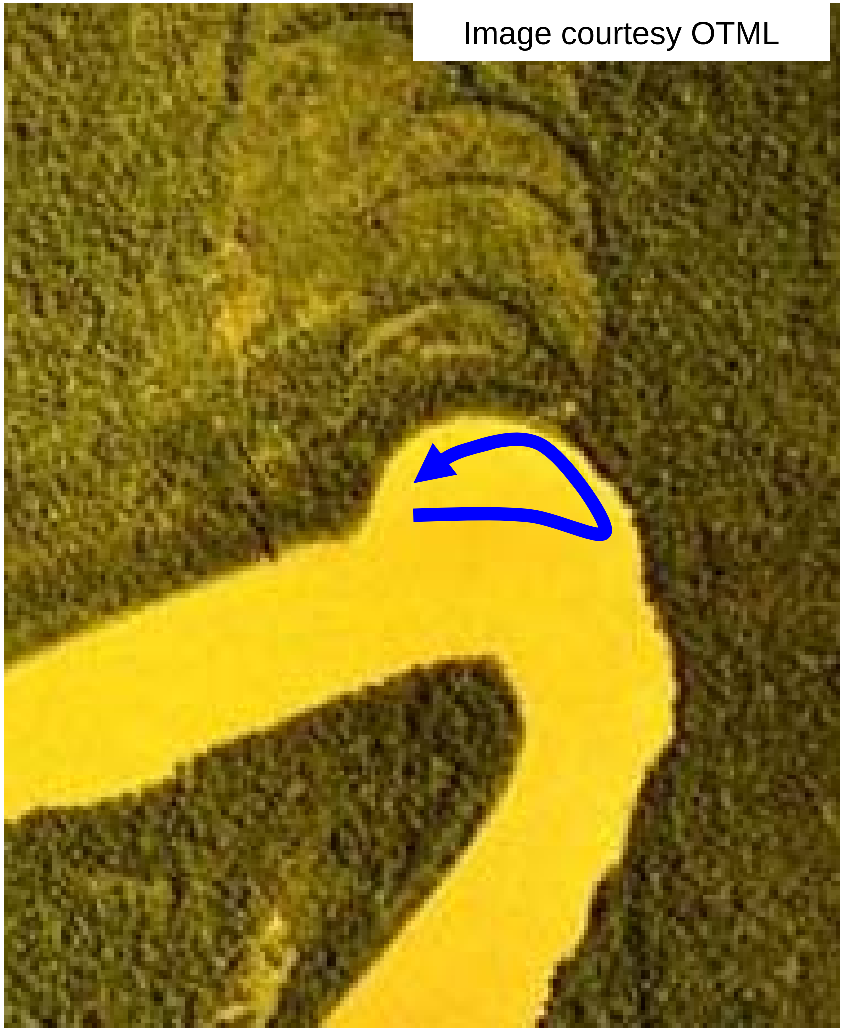


Image courtesy OTML

SELF-CHANNELIZATION: NATURAL LEVEES

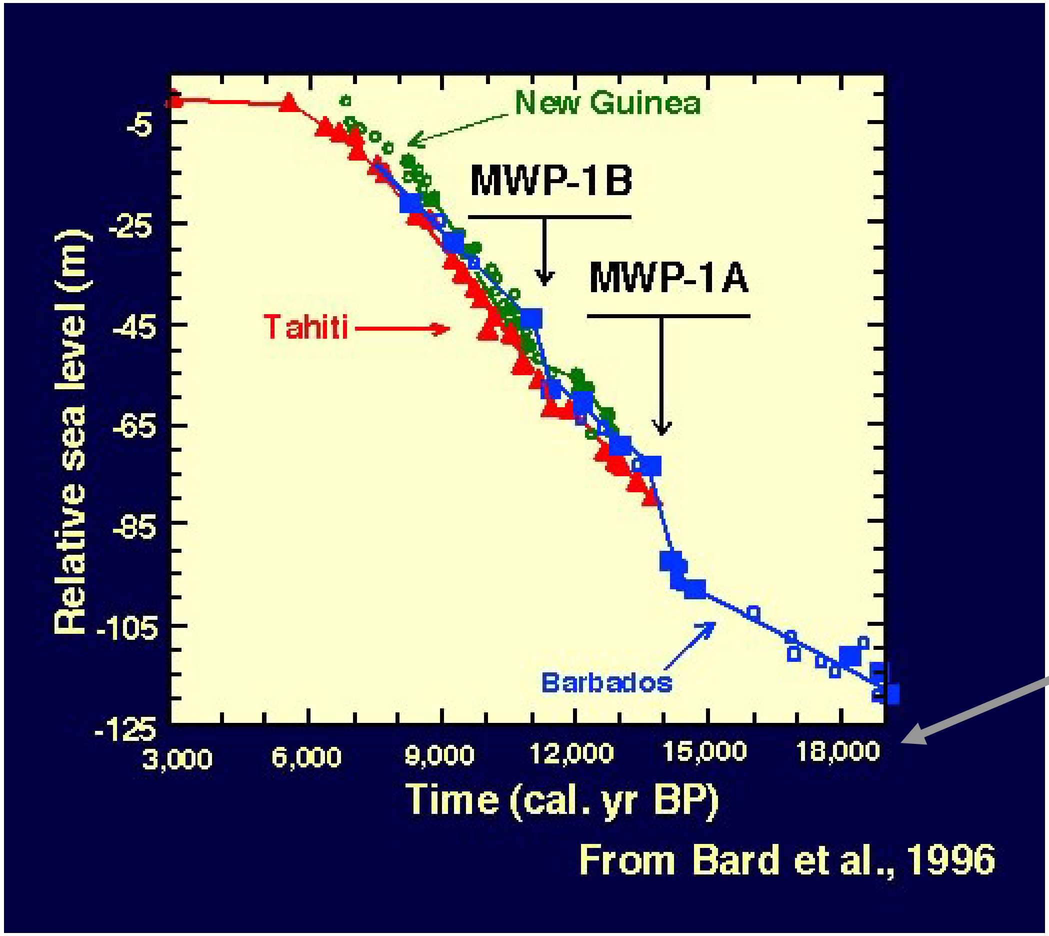
Image courtesy National Geographic

Gilgal Abey River, Ethiopia

https://zulu.ssc.nasa.gov/mrsid/

Missisippi River, USA

SEA LEVEL ROSE SOME 120 M SINCE THE END OF THE LAST GLACIATION



From Bard et al., 1996

Years before present

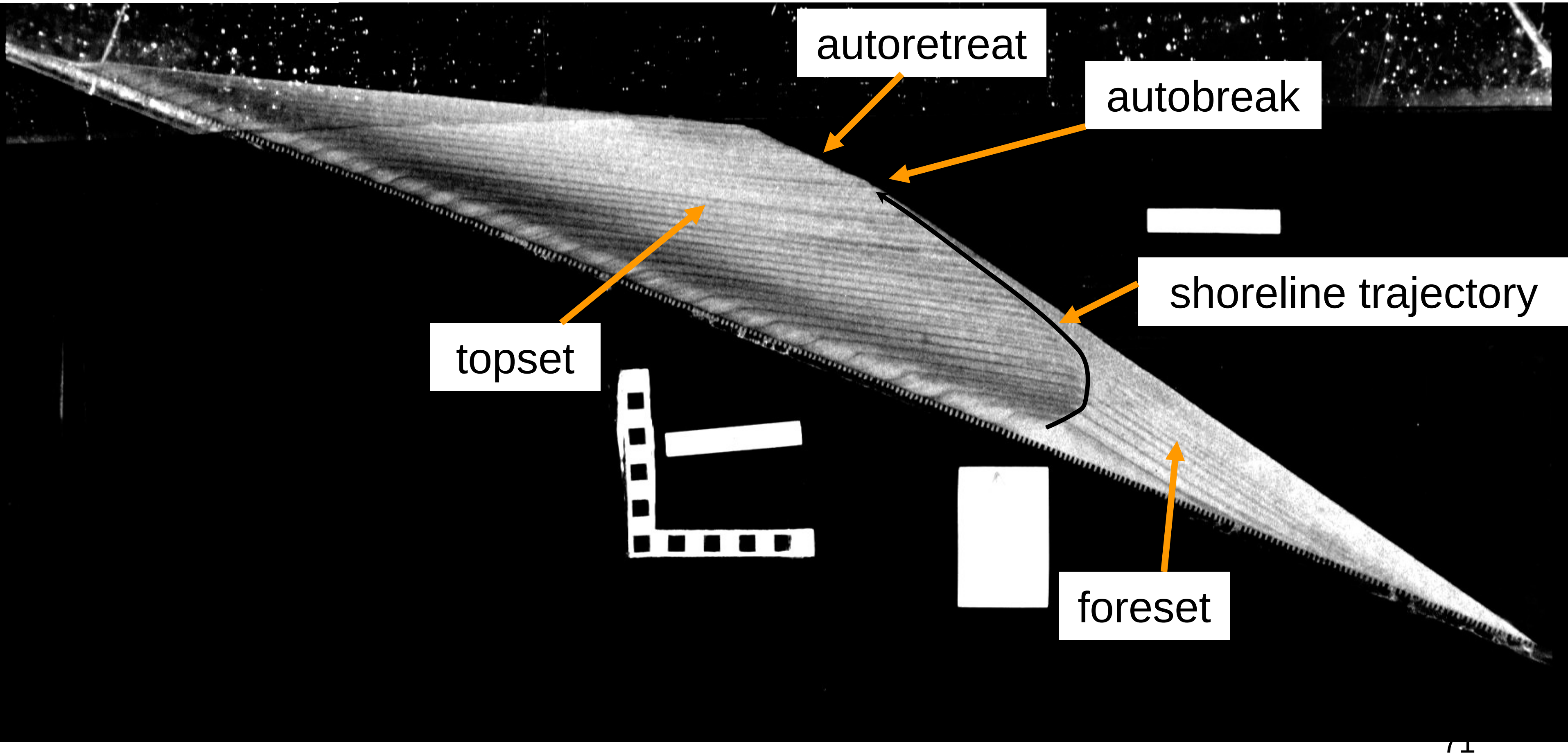
How does a river mouth respond to sea level rise?

- Does a delta continue to prograde into the ocean?
- Or does the sea drown the delta and invade the river valley (transgression)?

DELTAS AND SEA LEVEL RISE

Experiment on effect of base level rise on delta

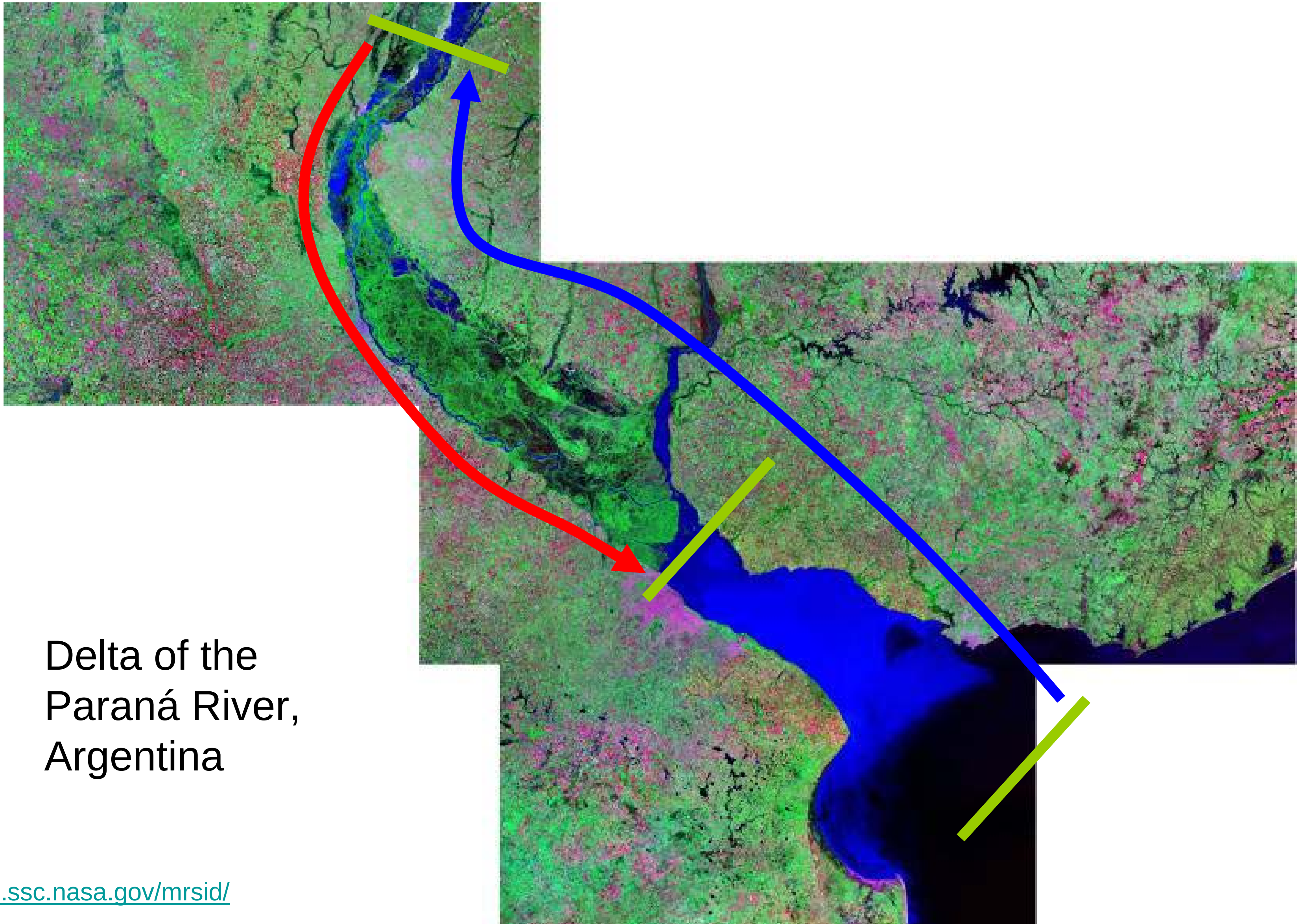
Image courtesy T. Muto



Clip courtesy T. Muto

AUTORETREAT

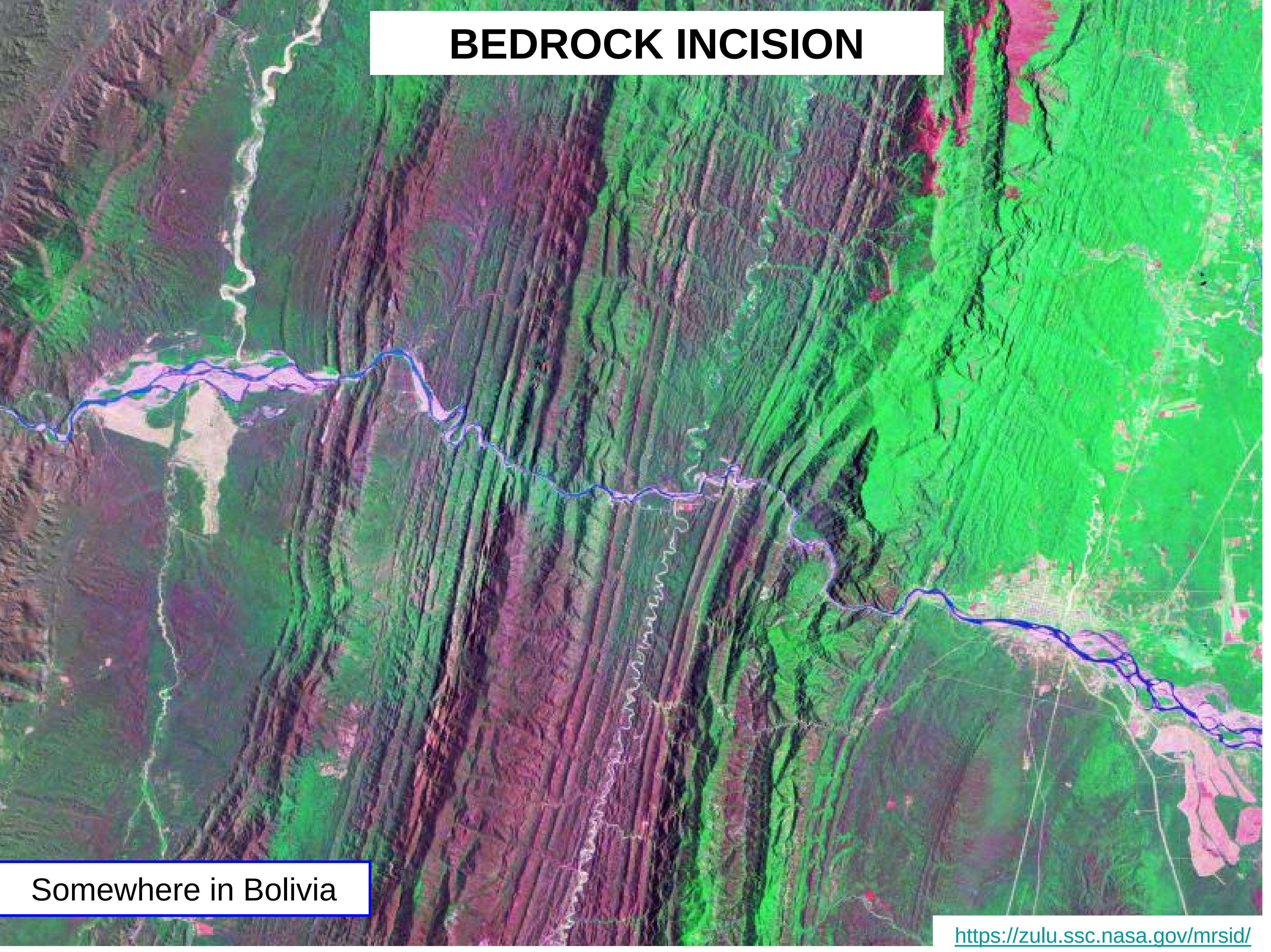
HOW DID THE DELTAS OF MAJOR RIVERS RESPOND?



Delta of the
Paraná River,
Argentina

https://zulu.ssc.nasa.gov/mrsid/

BEDROCK INCISION

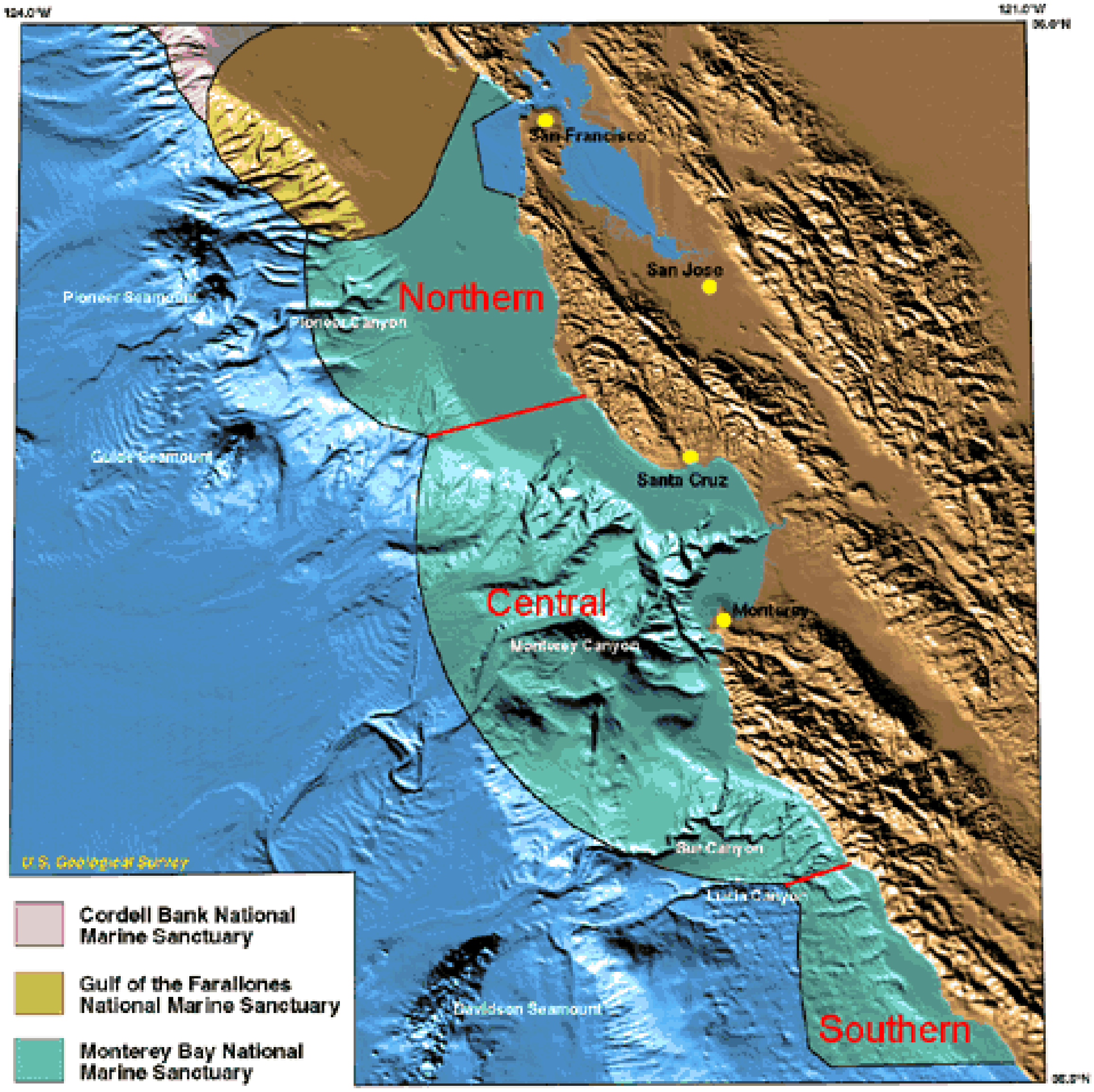


Somewhere in Bolivia

https://zulu.ssc.nasa.gov/mrsid/

Hirose River, Japan

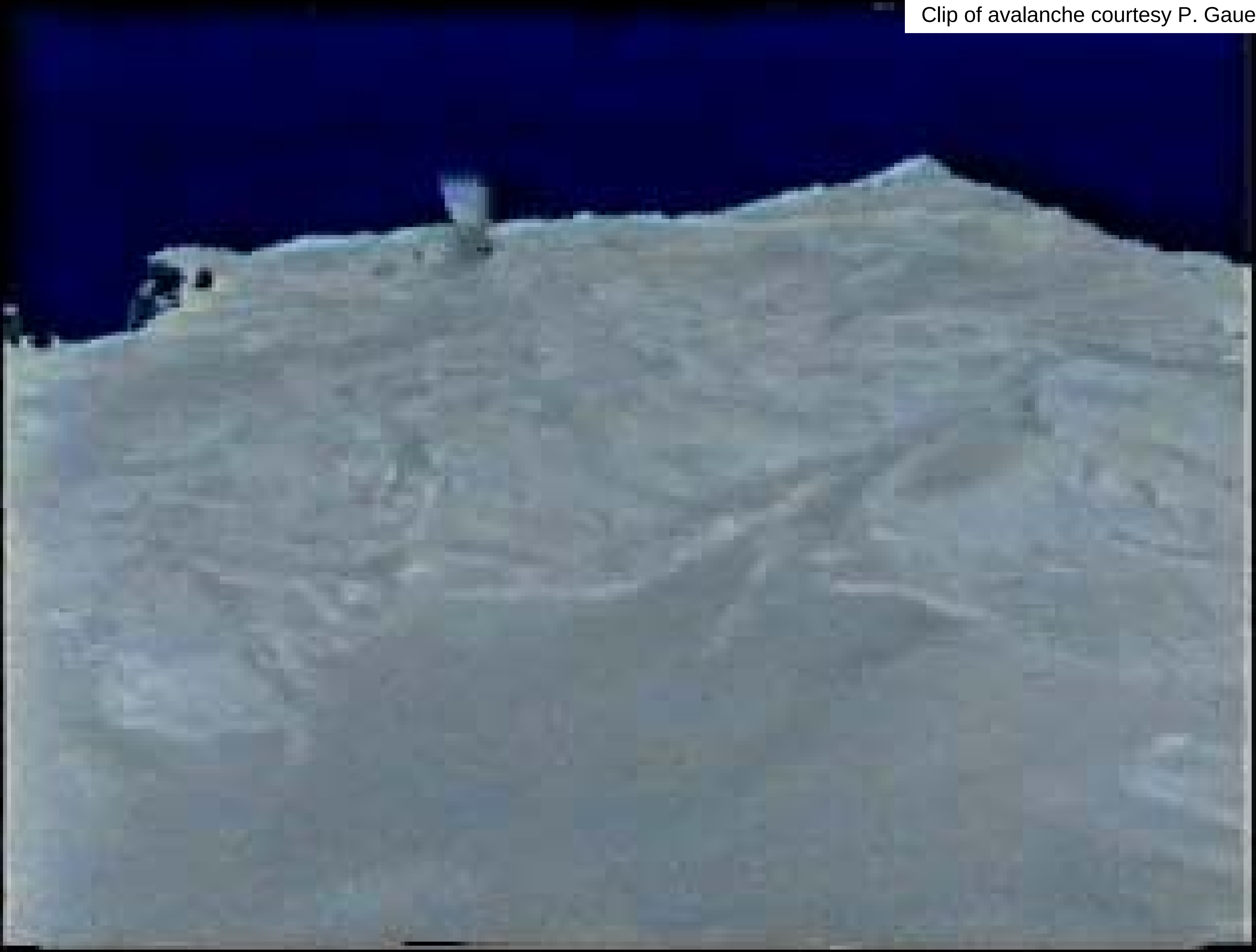
SUBMARINE MORPHODYNAMICS DUE TO TURBIDITY CURRENTS



Computer generated image of the topograhy onshore (brown) and offshore (blue) Central California.
Prepared by Norman M. Maher and Robert K. Hall.

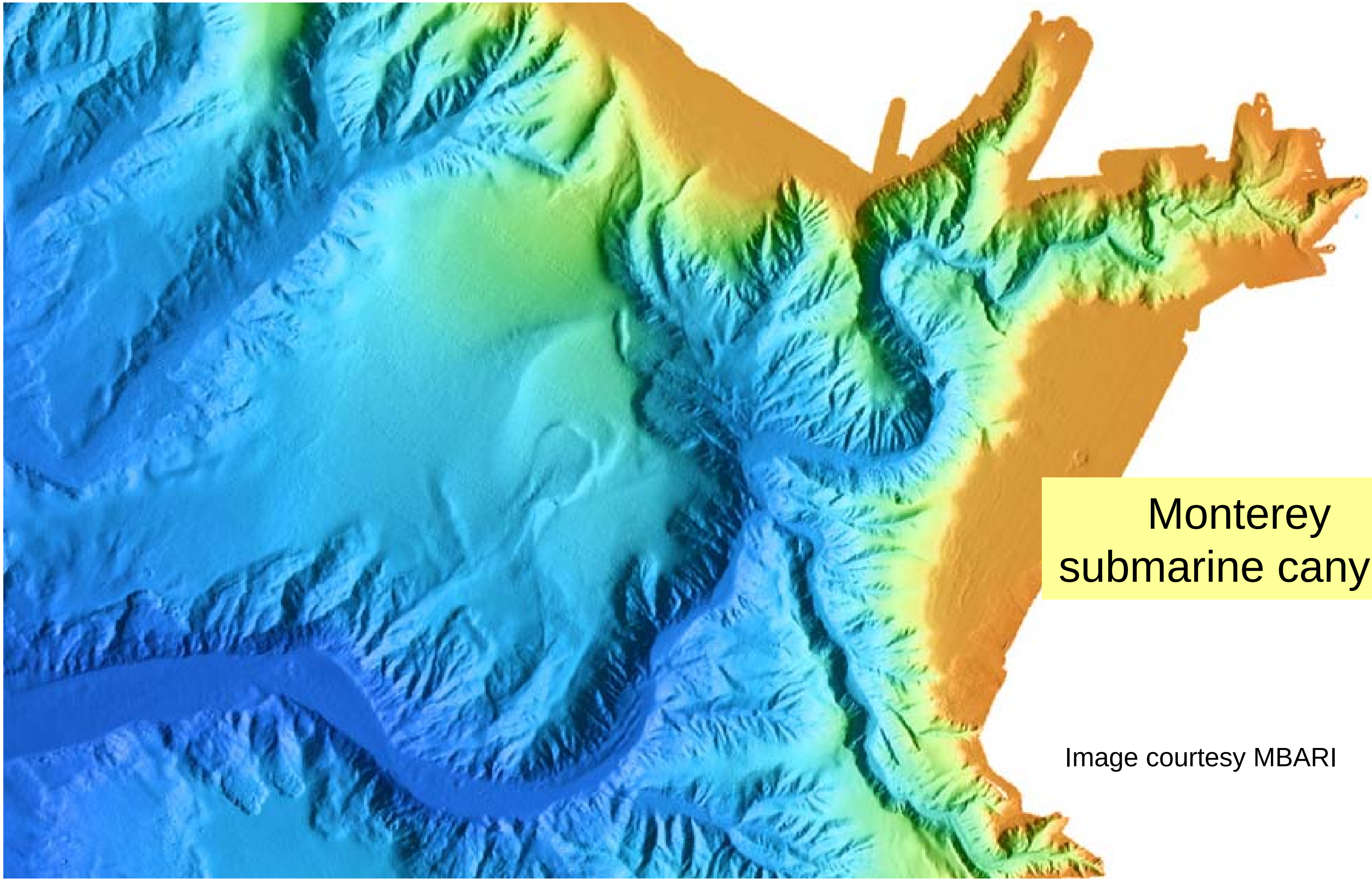
California Margin

Image courtesy MBARI



Clip of avalanche courtesy P. Gauer

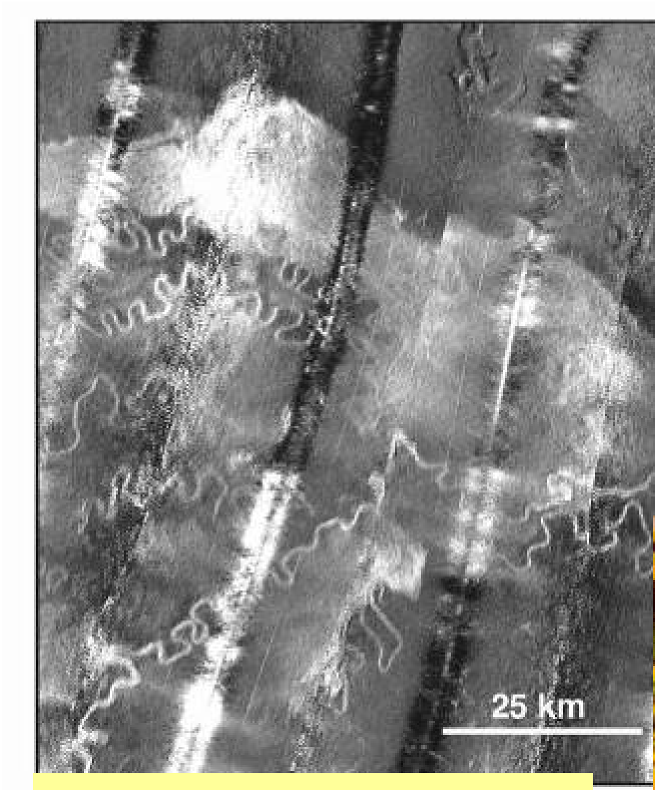
CANYON EXCAVATION



Monterey
submarine canyon

Image courtesy MBARI

MEANDERING OF SUBMARINE CHANNELS

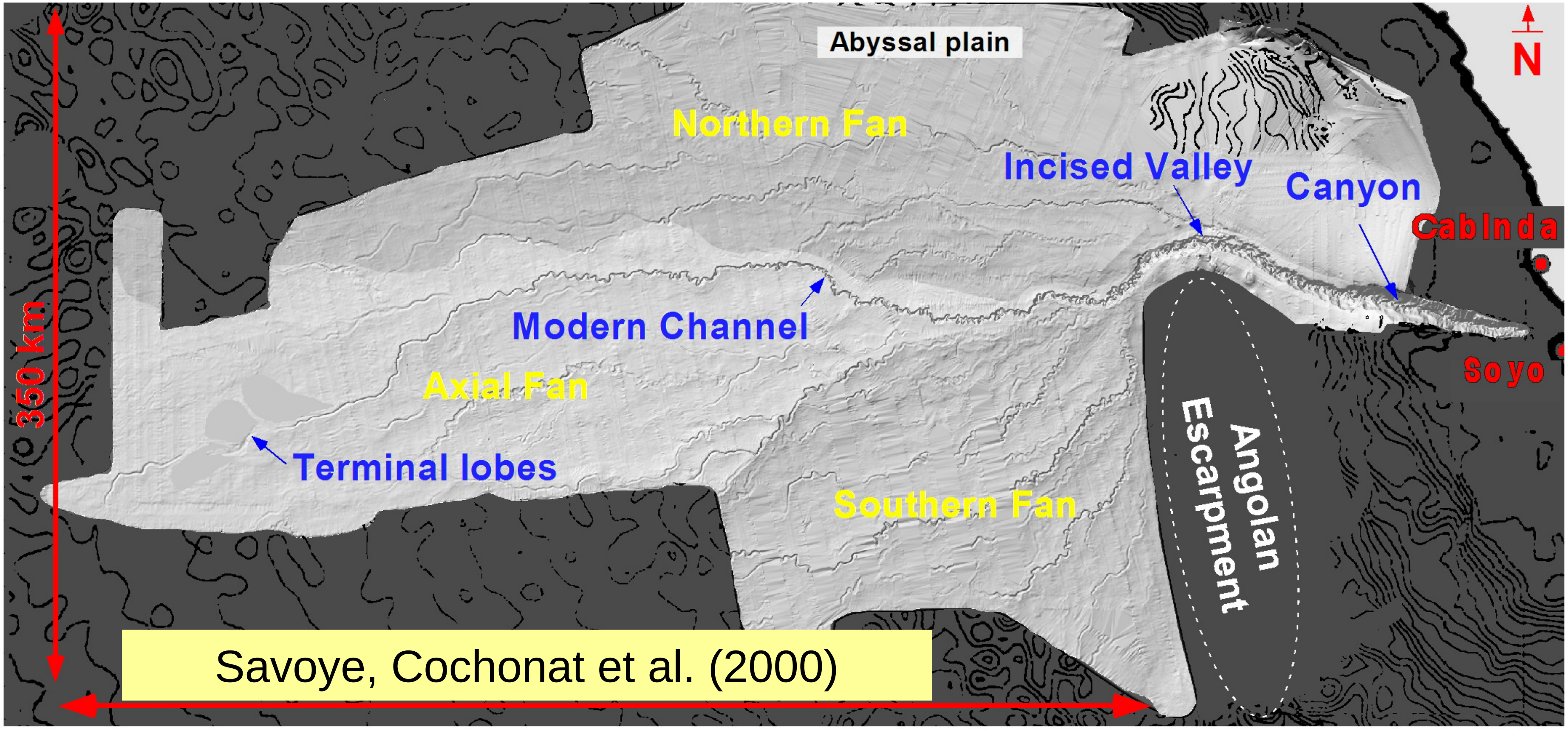


Indus Submarine Fan (Kenyon et al., 1995)

Mississippi Submarine Fan (Weimer, 1991).

Amazon Submarine Fan (Pirmez, 1995)

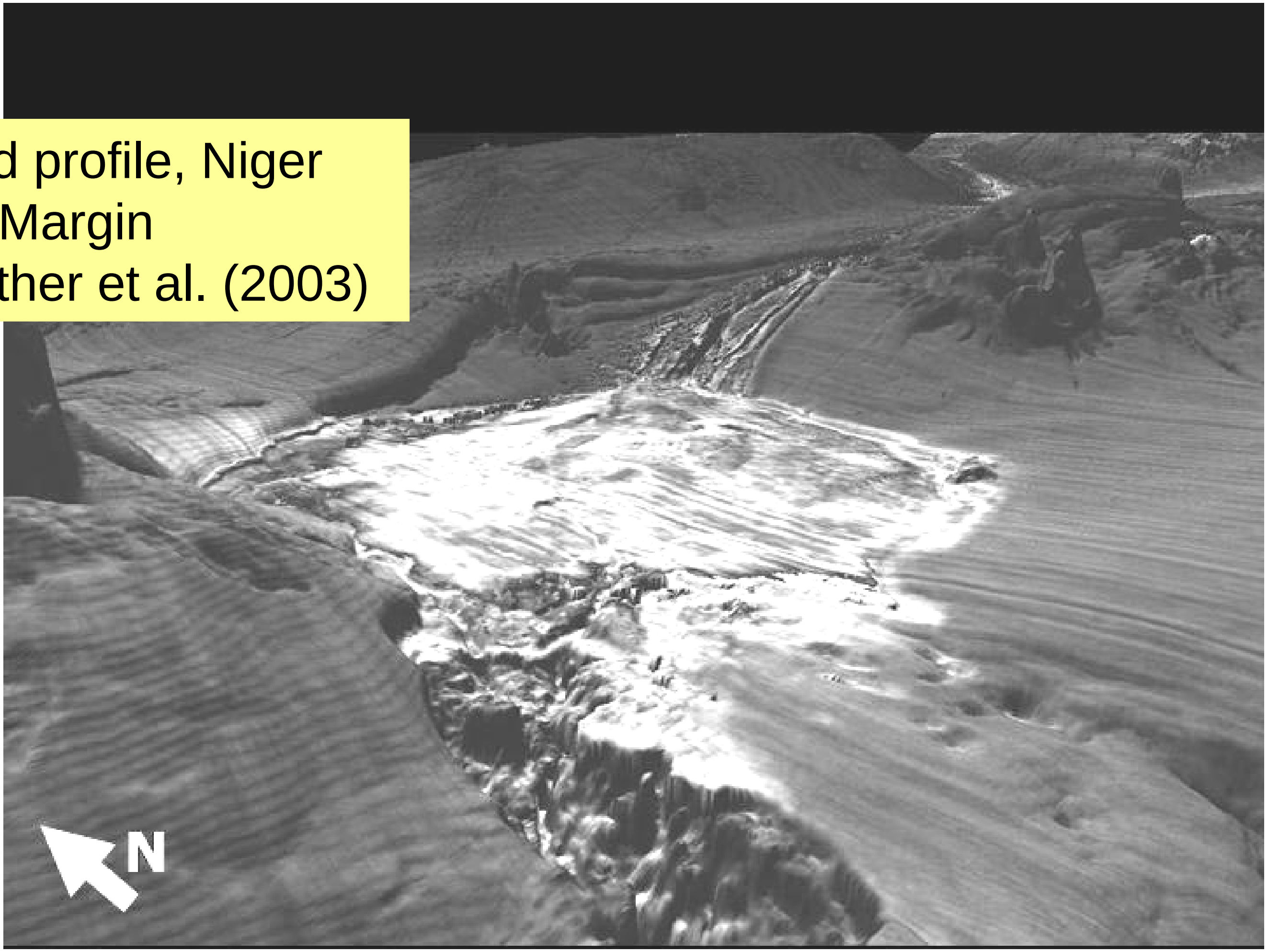
CONGO DEEP-SEA FAN



Savoye, Cochonat et al. (2000)

EM12 Bathymetry of the Pleistocene to Present Zaire Deep-Sea Fan.

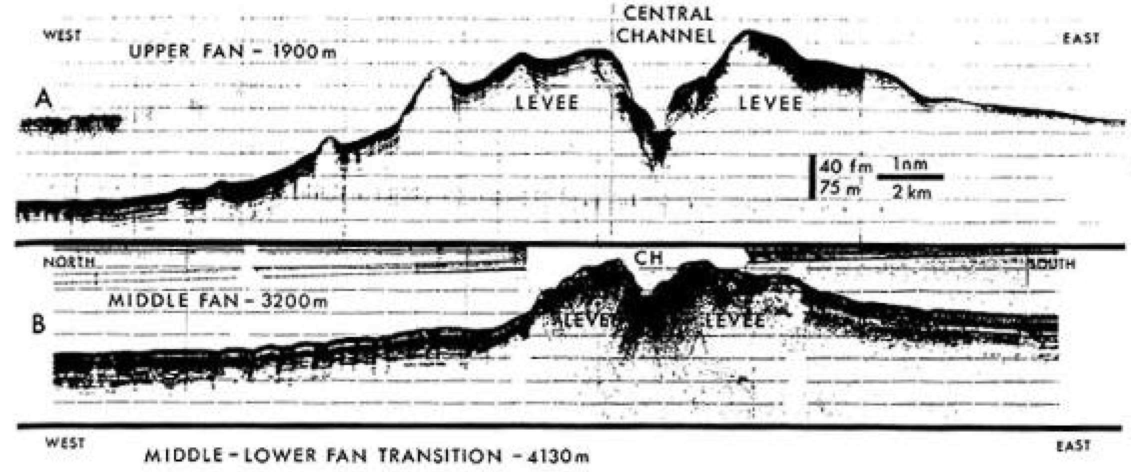
FANS AND CANYONS: STEPPED PROFILES



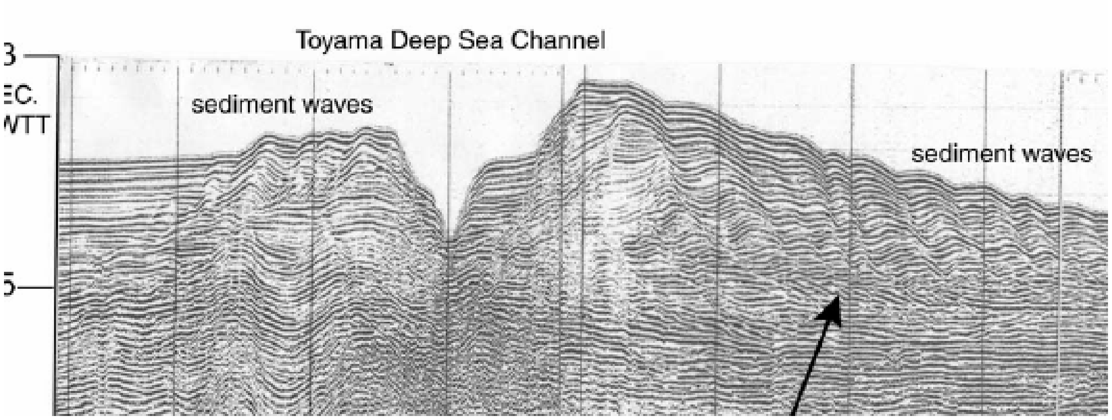
Stepped profile, Niger Margin
From Prather et al. (2003)

SELF-CONFINEMENT AND LEVEE CONSTRUCTION

Turbidity currents are adept at confining themselves between levees.



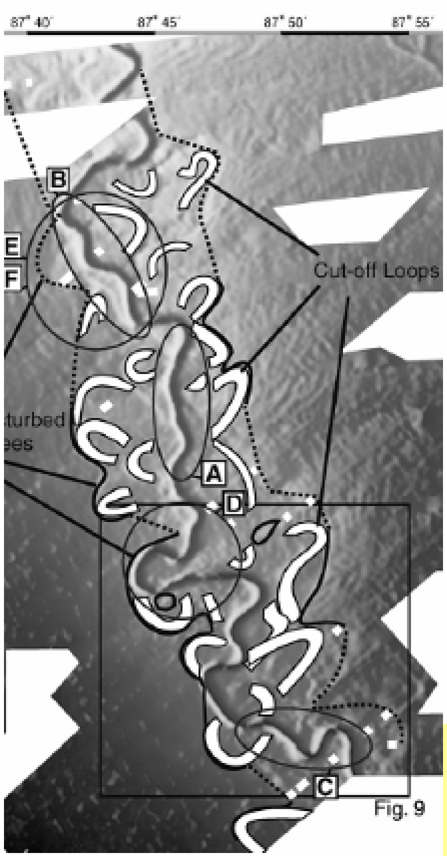
Channel on Amazon
Submarine Fan
Damuth and Flood (1985)

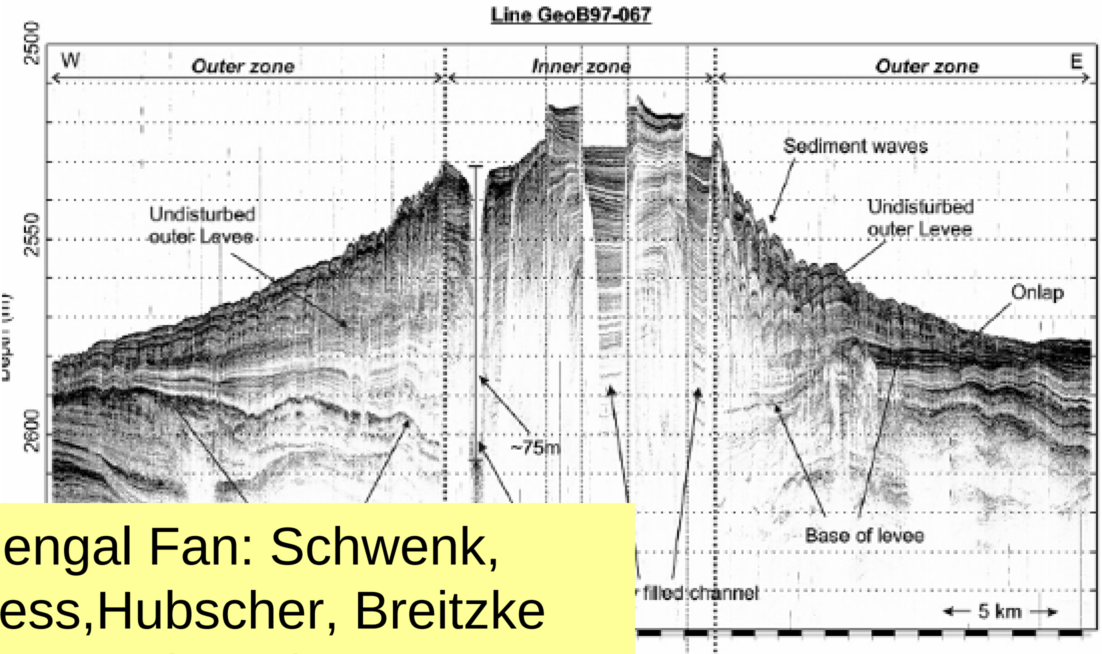


Toyama Submarine Channel
Kubo and Nakajima (2002)

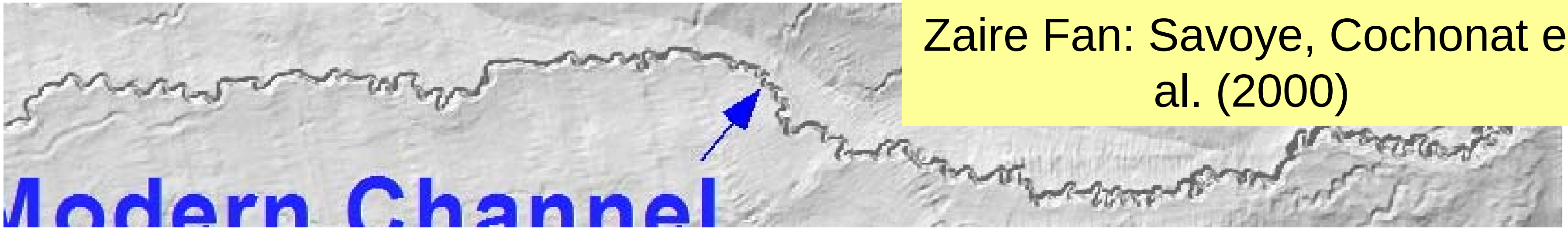
SELF-CONTAINMENT

Submarine meandering channels contain themselves between levees over 100’s ~ 1000’s of km and scores ~ 100’s of bends.



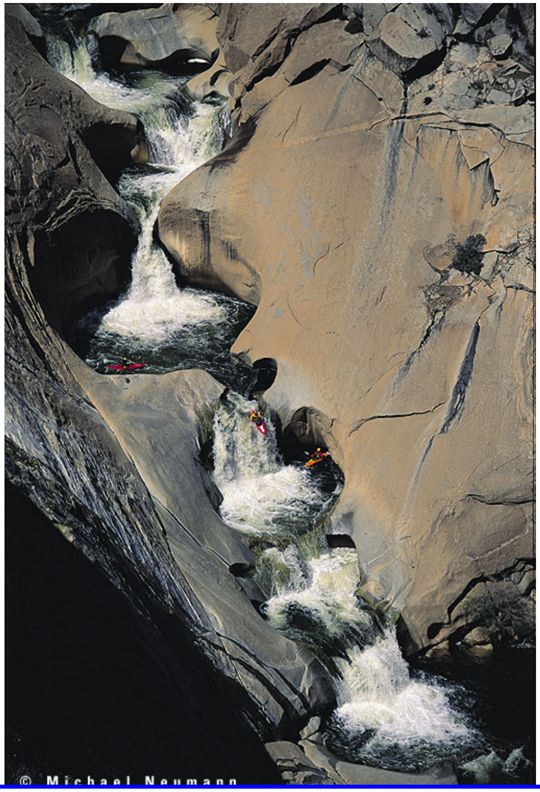


Bengal Fan: Schwenk, Spiess,Hubscher, Breitzke (2003)



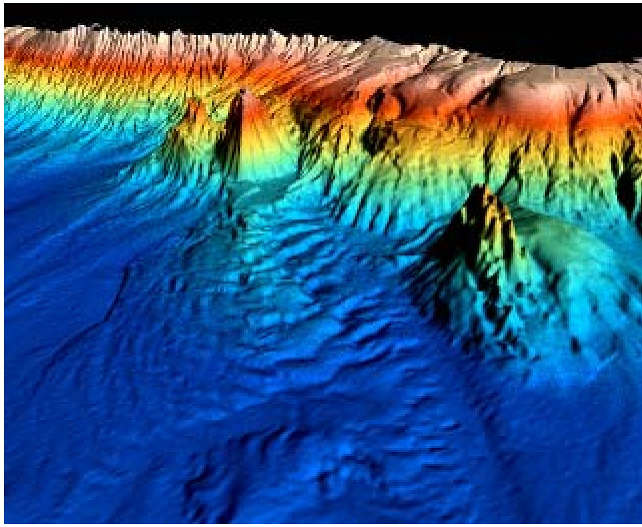
Zaire Fan: Savoye, Cochonat et al. (2000)

CYCLIC STEPS: A UNIVERSAL BEDFORM OF FROUDE-SUPERCRITICAL FLOW IN RIVERS AND TURBIDITY CURRENTS FLOWING OVER ERODIBLE BEDS



Dry Meadow Creek, USA

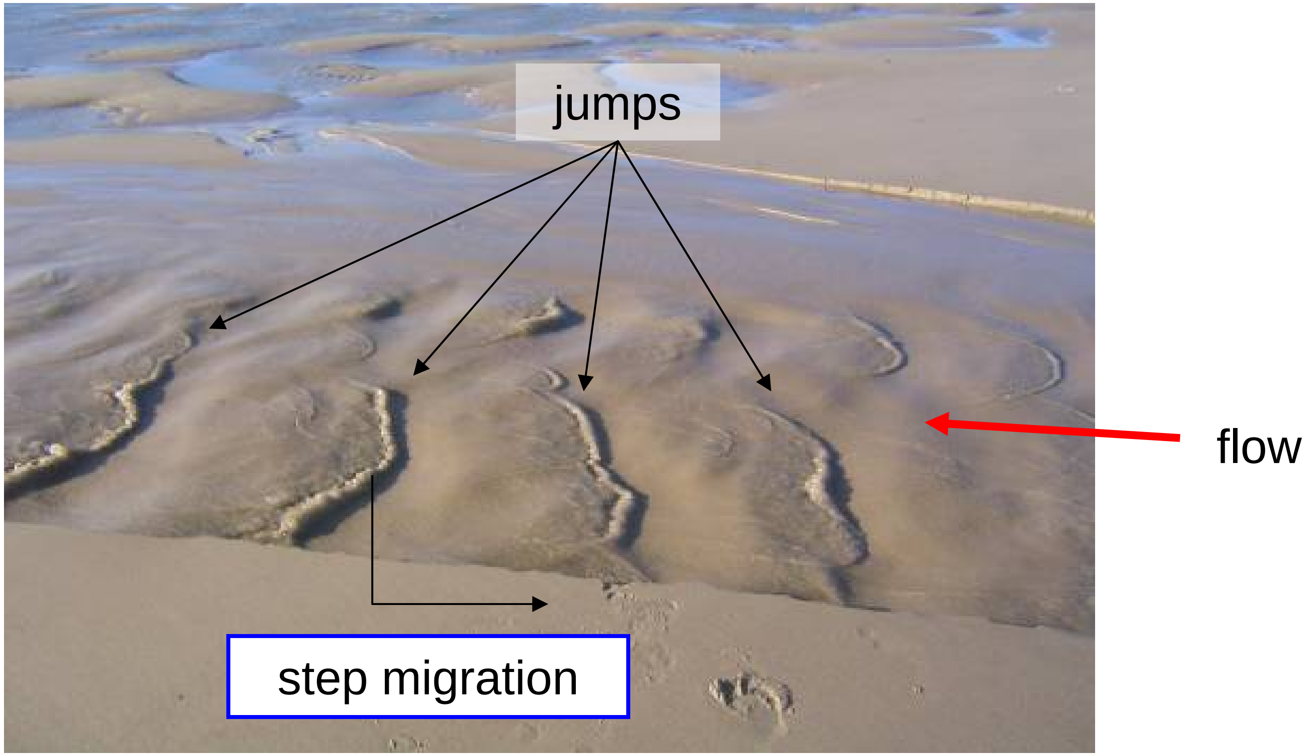
Small stream near Calais, France



Deep sea offshore of California, USA

Images courtesy M. Neumann, H. Capart and L. Pratson

TRAIN OF HYDRAULIC JUMPS



Trains of cyclic steps in a coastal outflow channel on a beach in Calais, France. Image courtesy H. Capart.

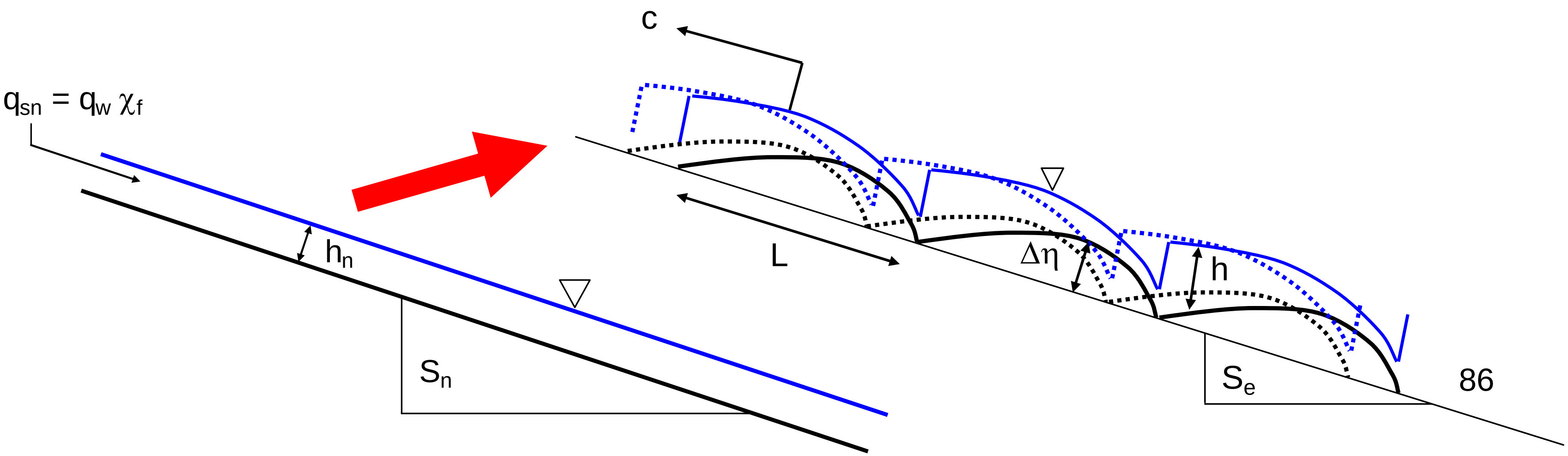
The steps move upstream

THE IDEA

Steady, uniform (normal) Froude-supercritical flow ($Fr_n > 1$) over a freely-erodible bed of sand might be unstable,

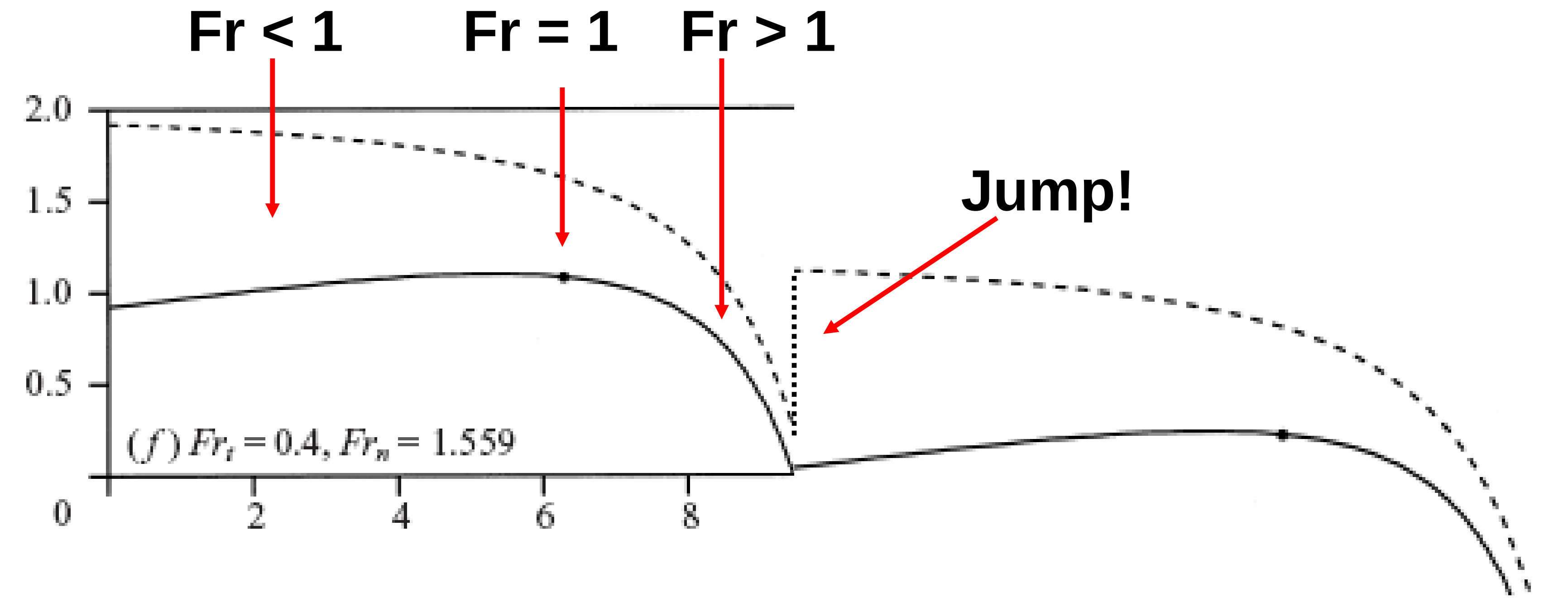
and within an appropriate range might not devolve to ephemeral, short-wave (L/h ~ 1) antidunes, but instead would devolve to

orderly, sustained trains trains of long-wave (L/h << 1) cyclic steps, with regions of subcritical and supercritical flow bounded by hydraulic jumps

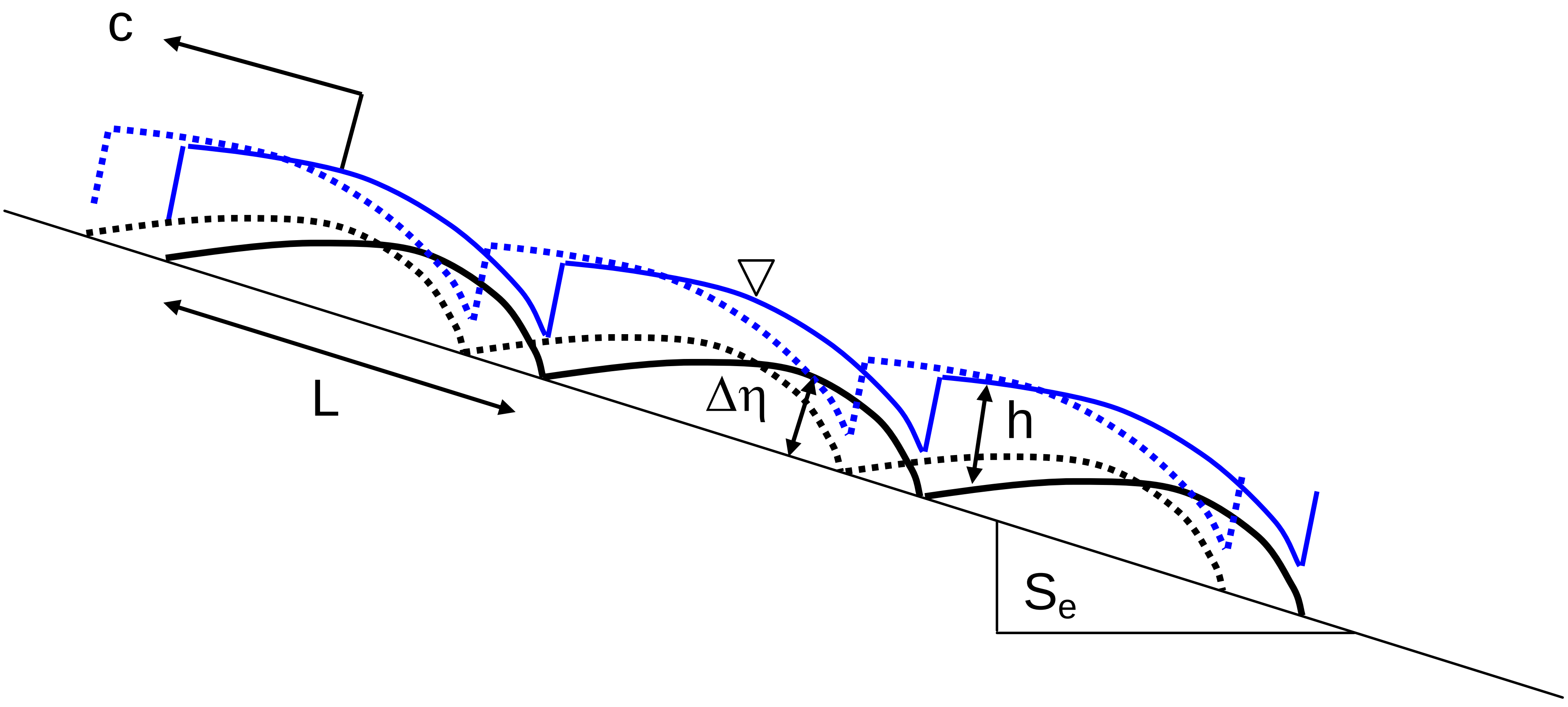


FULLY NONLINEAR PERIODIC SOLUTION OF PERMANENT FORM WITH CONSTANT UPSTREAM MIGRATION

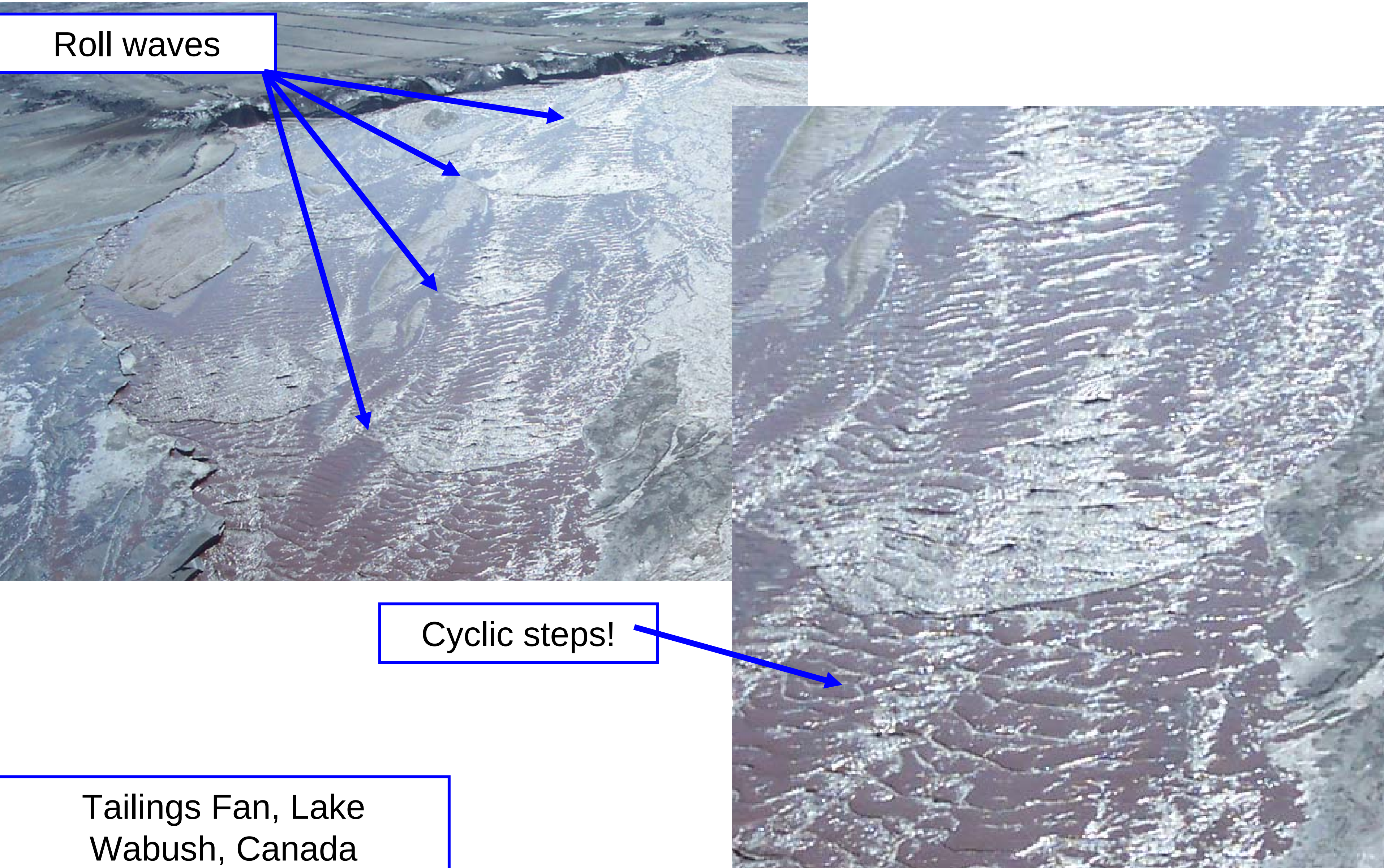
Sufficiently supercritical flow over a plane bed is subject to a *long-wave* instability that devolves into upstream-migrating supercritical and subcritical regions bounded by hydraulic jumps.



LIKE THIS



LET’S LOOK AT THIS IMAGE AGAIN

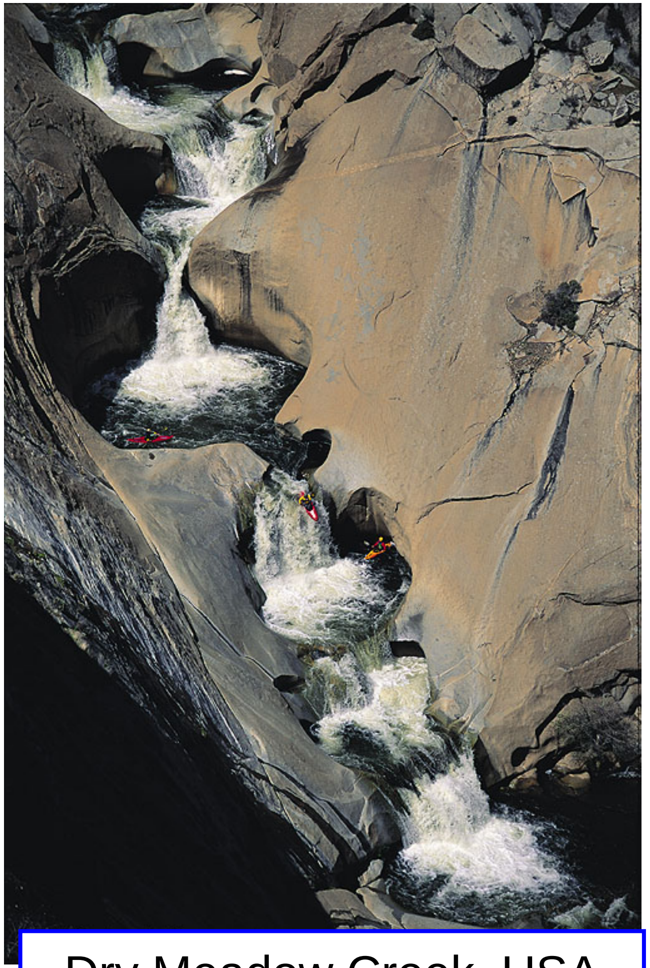


Roll waves

Cyclic steps!

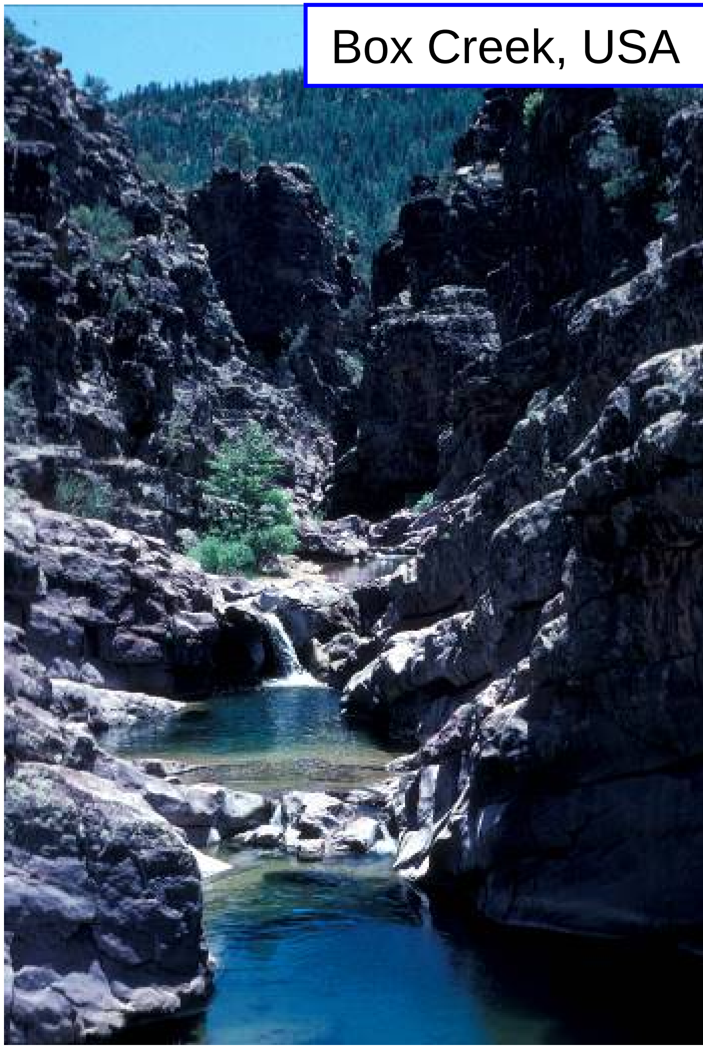
Tailings Fan, Lake Wabush, Canada

THE SAME CYCLIC STEP INSTABILITY IS FOUND IN INCISING BEDROCK STREAMS



Dry Meadow Creek, USA

Gough Island



Box Creek, USA

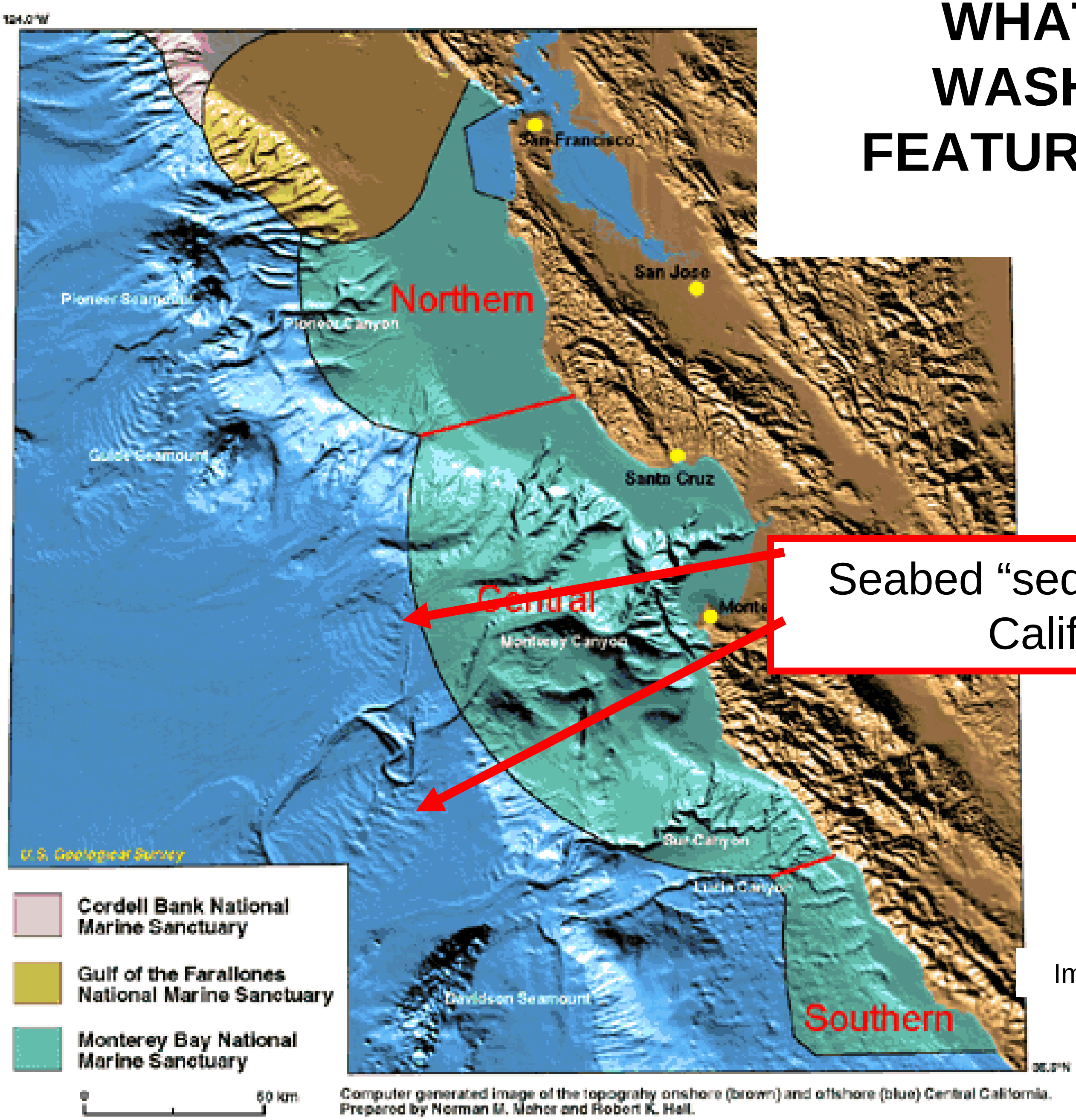
Images courtesy Michael Neumann, Gough Island Weather Station and Ellen Wohl

Image courtesy H. Ikeda

CYCLIC STEPS IN BEDROCK: *This one is too beautiful not to show*

Ojiro River, Japan

WHAT ARE THESE WASHBOARD-LIKE FEATURES IN THE DEEP SEA?



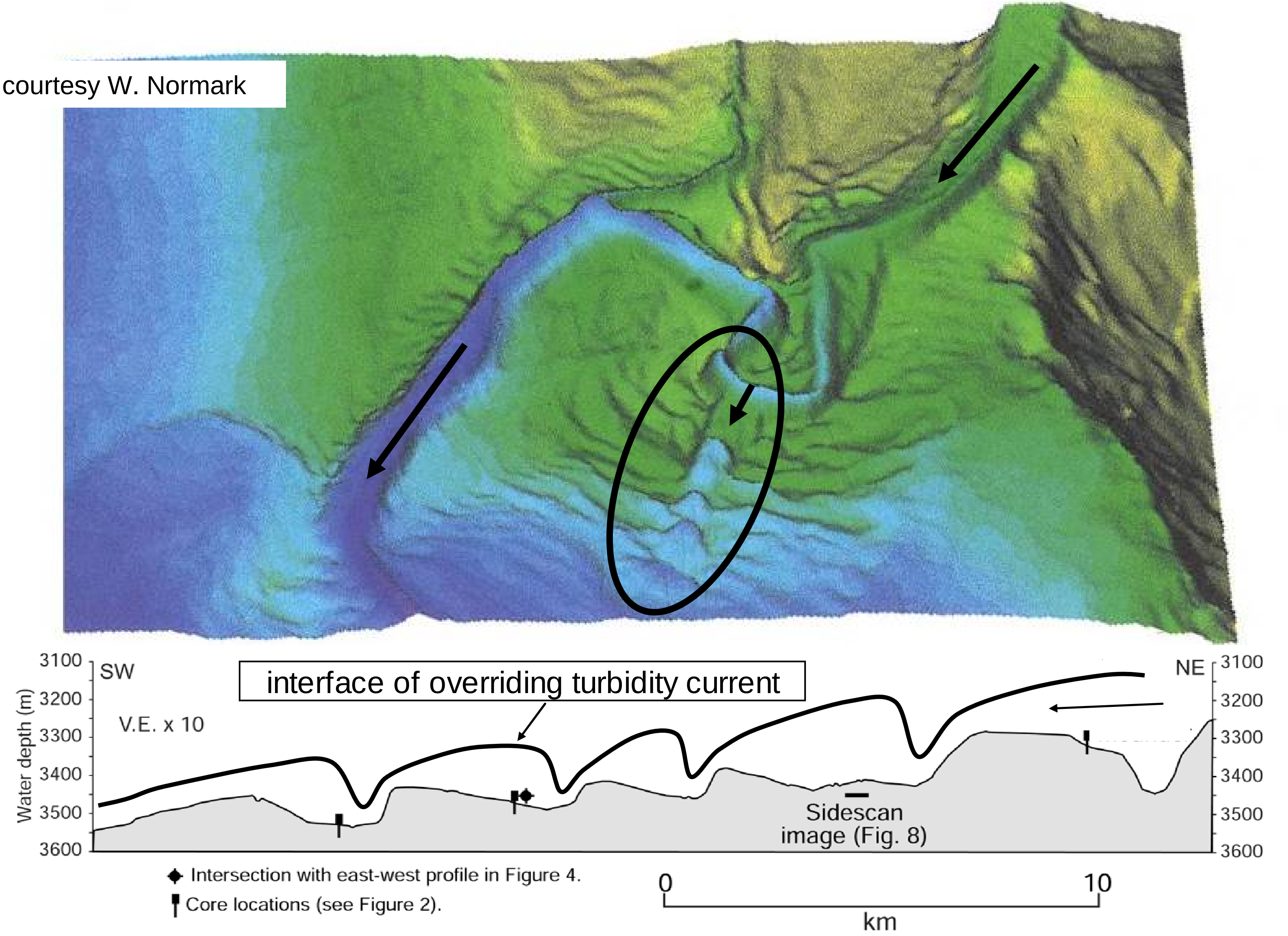
Computer generated image of the topograhy onshore (brown) and offshore (blue) Central California. Prepared by Norman M. Maher and Robert K. Hall.

Seabed “sediment waves” off the California margin

Image courtesy MBARI

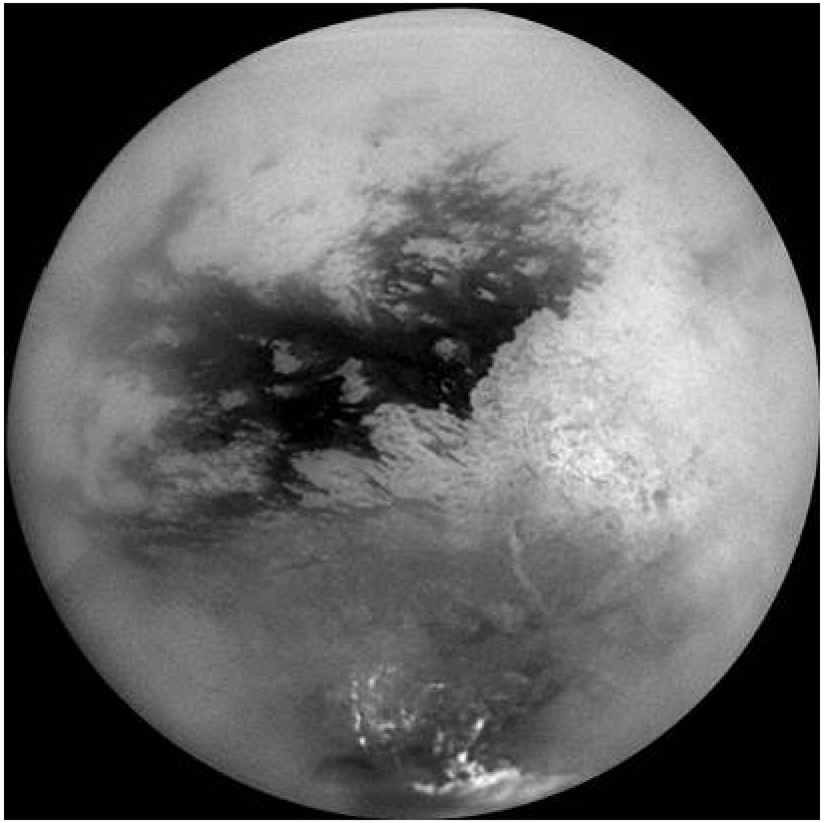
SUBAQUEOUS DEPOSITIONAL AND EROSIONAL CYCLIC STEPS

Image courtesy W. Normark



interface of overriding turbidity current

EARTH → TITAN

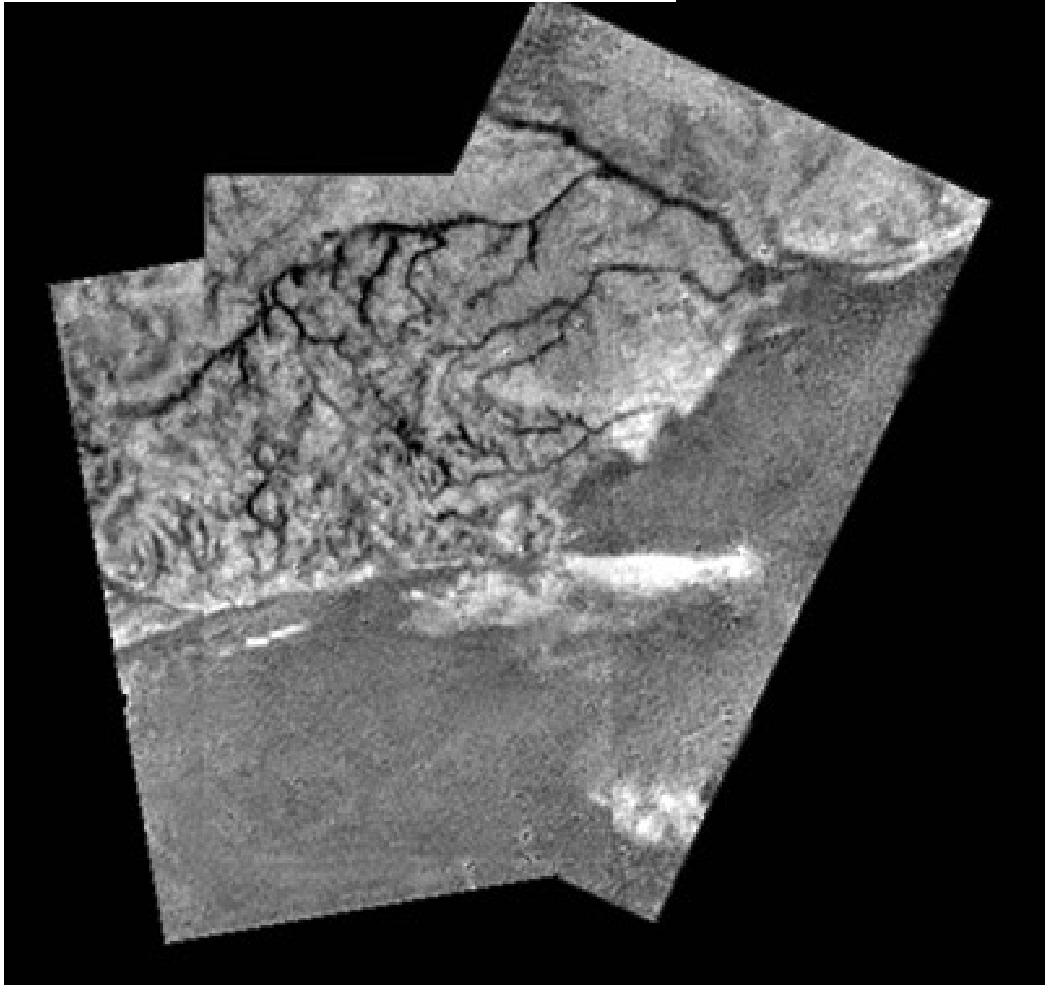


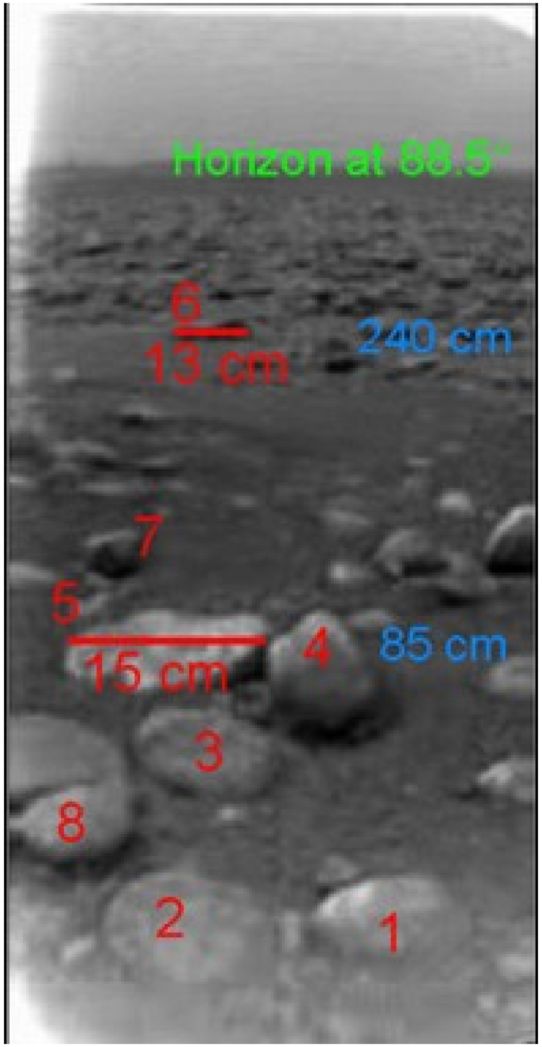
European Space Agency

Water → liquid methane
Granitic rock → ice as a “rock”

ALLUVIAL GRAVEL-BED RIVERS ON TITAN?

Images courtesy European Space Agency





The evidence suggests that at least near where Huygens touched down, there is a **plethora of alluvium in the gravel and sand sizes**. The **gravel** presumably consists of **water ice** and appears to be **fluvially rounded**.

AN EXCITING FUTURE WAITS