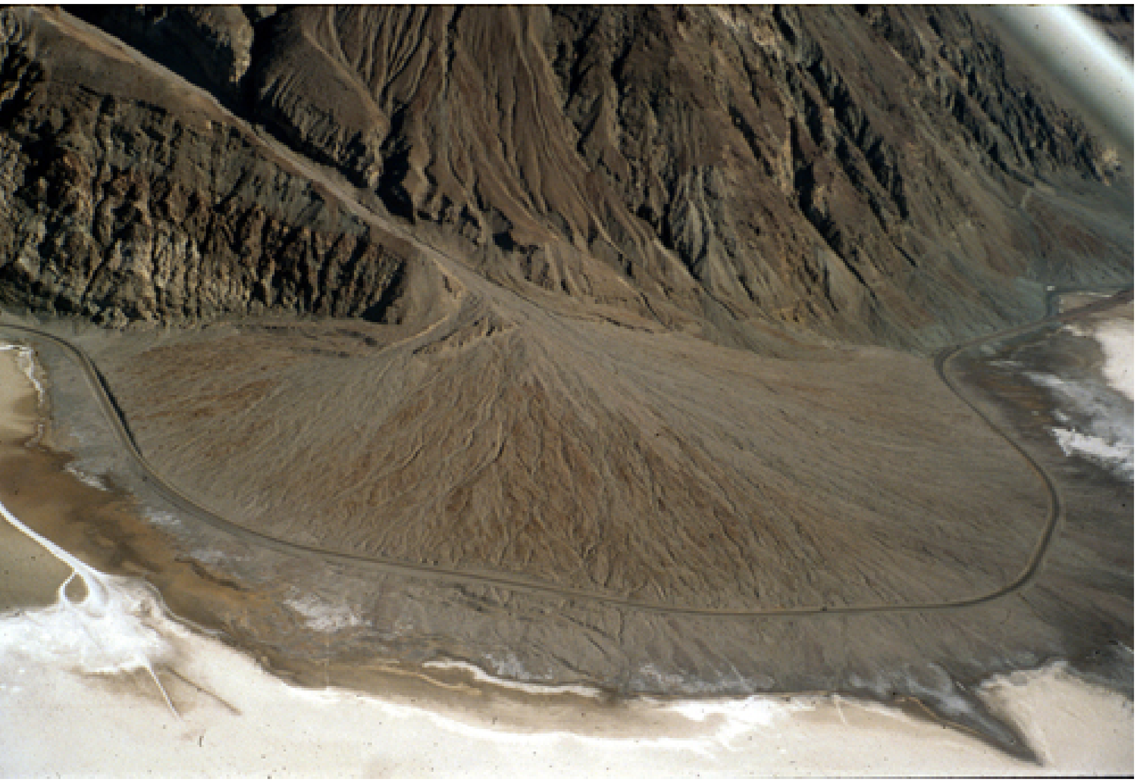
Alluvial Fans

Role of flow expansion - as flow becomes less restricted coming out of a canyon, it widens, promoting deposition.

What controls the extent of this widening?



Gravelly alluvial fan. Road encircling fan provides scale. **Badwater Fan, Death Valley, CA** [photo courtesy of Paul Heller]

Sandy alluvial fan (3km in length) Hibbing, MN

Images Courtesy of Prof. Paul Heller, University of Wyomimg. Used with permission.

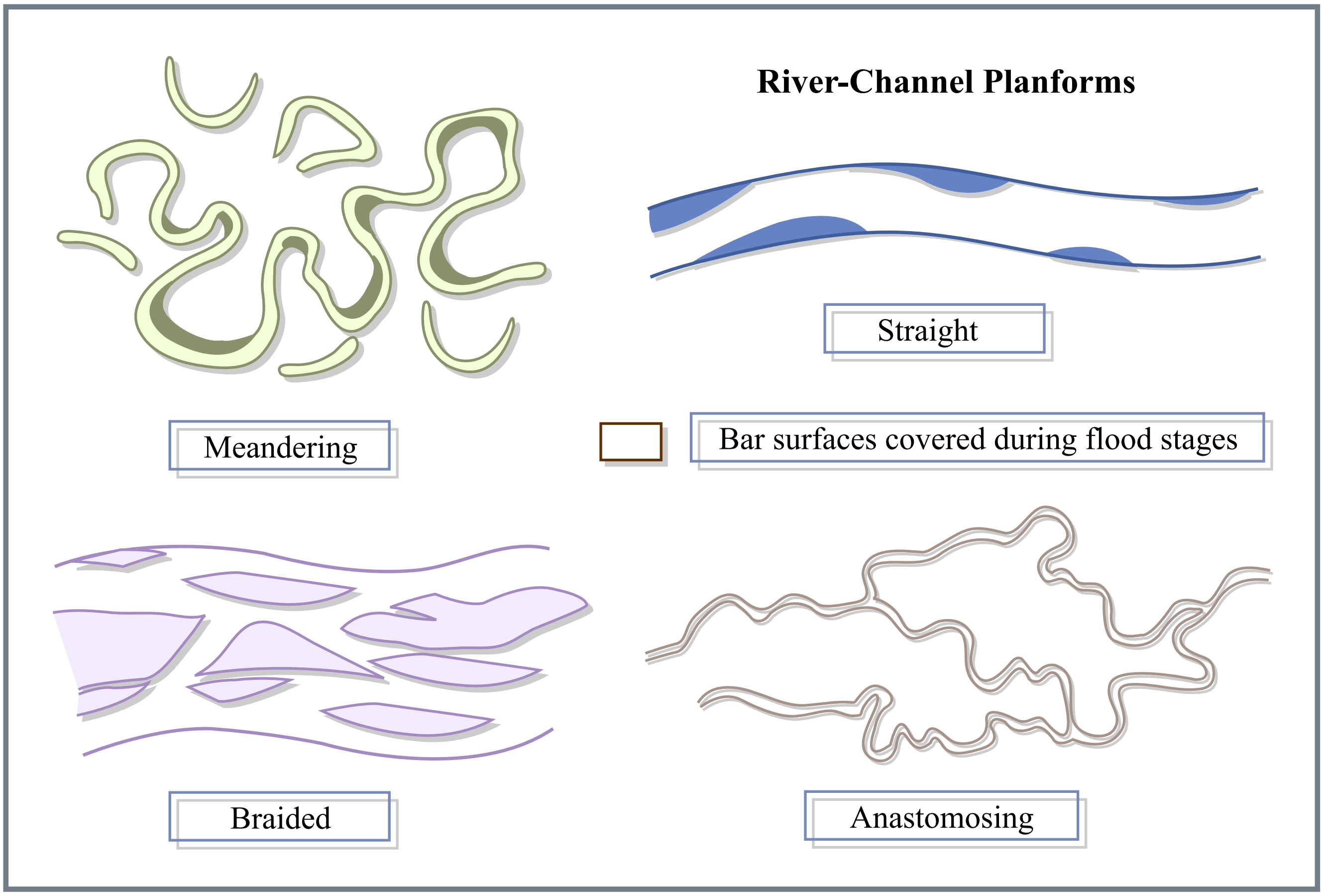


Figure by MIT OCW.

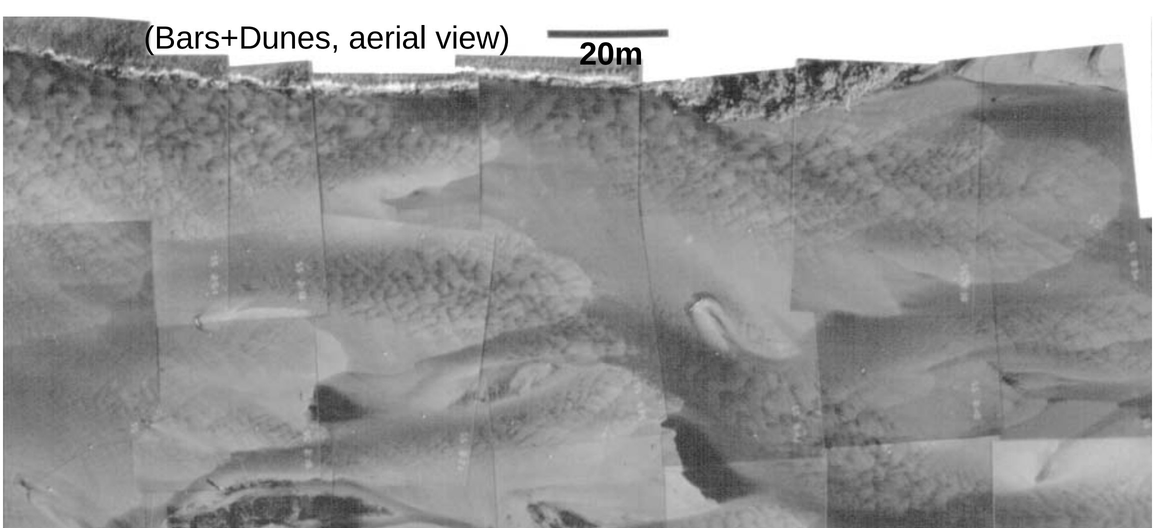
Transport of sediment typically results in the spontaneous development of trains of repetitive bed topography at a number of scales. The two basic types are: 1) bedforms; and 2) bar forms.

Bedforms:

Develop in response to variation in the vertical structure of the streamwise velocity field (i.e., arise because of spatial change in the ***x-z*** plane). *Scale of topography*: Bedforms are limited in scale to a fraction of the flow depth.

Bar forms:

Develop in response to variation in horizontal structure of the flow field (i.e., these structures arise because of spatial change in the flow field in the ***x-y*** plane). *Scale of topography*: Bar forms can grow to the water surface and have lengths that are scaled by channel width.



Width-to-Depth Closure for River Channels (*notes are modified from Gary Parker E-book:* **1D SEDIMENT TRANSPORT MORPHODYNAMICS with applications to RIVERS AND TURBIDITY CURRENTS**)

Rivers establish their **bankfull width and depth** through the co-evolution of the river channel and its substrate (commonly floodplain).

Gravel-Bed Rivers:

$$\tau_b = (1+\varepsilon)\tau_{cr}$$

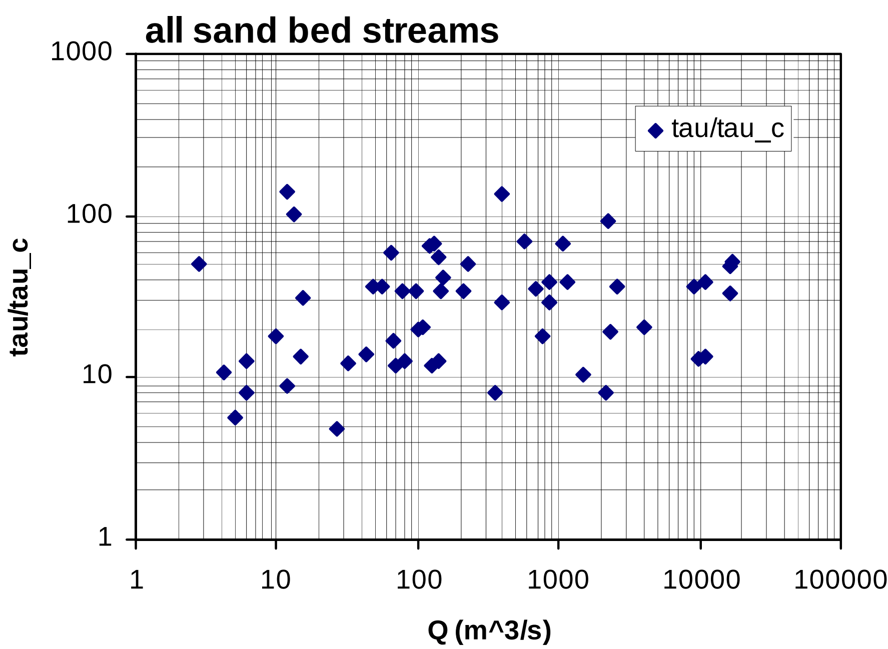
Theoretical:
ε = 0.2 (Parker, G., 1978, J. Fluid Mechanics, 89, 127-146)
Empirical:
ε = 0.4 (Paola & Mohrig, 1996, Basin Research, 8, 243-254)

Example:
If stress rises above given value, it induces bank erosion that widens the flow.
Widening reduces flow depth, reduces bed stress.

ε captures the difference between total boundary shear stress and skin friction shear stress.

Church & Rood (1983) data, with T (transport stage) plotted as function of water discharge.

Church, M., and Rood, K., 1983, Catalogue of Alluvial River Channel Regime Data: University of British Columbia, Dept. of Geography, Vancouver, B.C.



The considerable scatter in the data is probably due to

a) differing fractions of wash load versus bed material load in the various rivers,

b) differing amounts and types of floodplain vegetation, which encourages floodplain deposition, and

c) different hydrologic regimes.

Paola et al. (1992) were the first to propose the assumption of constant bankfull bed stress in modeling the morphodynamics of streams. The general form of their analysis is used in the following material.

Paola, C., Heller, P.L., and Angevine, C.L., 1992, The large-scale dynamics of grain size variation in alluvial basins, 1: theory: Basin Research, v. 4, p. 73-90.

SIMPLE THEORY FOR BANKFULL CHARACTERISTICS OF RIVERS

The formulation given here is based on three relations:

- a resistance relation describing quasi-normal bankfull flow;
- an example sediment transport relation describing transport of bed material load at quasi-normal bankfull flow;
- a specified bankfull bed stress criterion.

While varying degrees of complexity are possible in the analysis, here the problem is simplified by assuming a constant friction coefficient C_f and a sediment transport relation of generic form (with assumed constant φ_s, α_t and n_t). Where the subscript "bf" denotes bankfull flow, the governing equations are

momentum balance

$$\rho g h S = \tau_b = \rho u_*^2 = \rho c_f \left\langle u \right\rangle^2$$

$$g H_{bf} S = C_f \frac{Q_{bf}^2}{B_{bf}^2 H_{bf}^2}$$

τ_{form}* = *channel-formative bed stress*

$$\tau^*_{bf50} = \frac{H_{bf} S}{R D_{50}} = const. = \tau^*_{form}$$

Definitions:

Q_{bf} = bankfull discharge [L^3/T]
B_{bf} = bankfull width [L]
H_{bf} = bankfull depth [L]
S = bed slope [1]
D_{50} = median surface grain size [L]
ν = kinematic viscosity of water [L^2/T]
R = $(\rho_s/\rho - 1)$ = sediment submerged specific gravity (~ 1.65 for natural sediment) [1]
g = gravitational acceleration [L/T^2]

bed material transport

$$Q_{tbf} = B_{bf} q_{tbf} = B_{bf} \sqrt{RgD}\, D \alpha_t \left[\varphi_s \tau^*_{bf50} - \tau^*_c\right]^{n_t}$$

Equations from notes on bedload physics

$$\phi = \gamma [\, \tau_* - \tau_{*(cr)} \,]^{3/2} \qquad \phi = \frac{q_b}{[(\rho_s / \rho_f - 1) g\, d_{50}^3]^{1/2}}$$

The equations above provide three constraints for five parameters; bankfull discharge Q_{bf}, bankfull volume bed material load Q_{tbf}, bankfull width B_{bf}, bankfull depth H_{bf} and bed slope S.

Thus if any two of the five (Q_{bf}, Q_{tbf}, B_{bf}, H_{bf} and S are specified the other three can be computed.

WHAT THE RELATIONS SAY

Slope: doubling the water discharge halves the slope; doubling the bed material load doubles the slope.

$$S = \frac{(\tau^*_{form})^{3/2} R}{\alpha_t \left[\varphi_s \tau^*_{form} - \tau^*_c\right]^{n_t} \sqrt{C_f}} \frac{Q_{tbf}}{Q_{bf}}$$

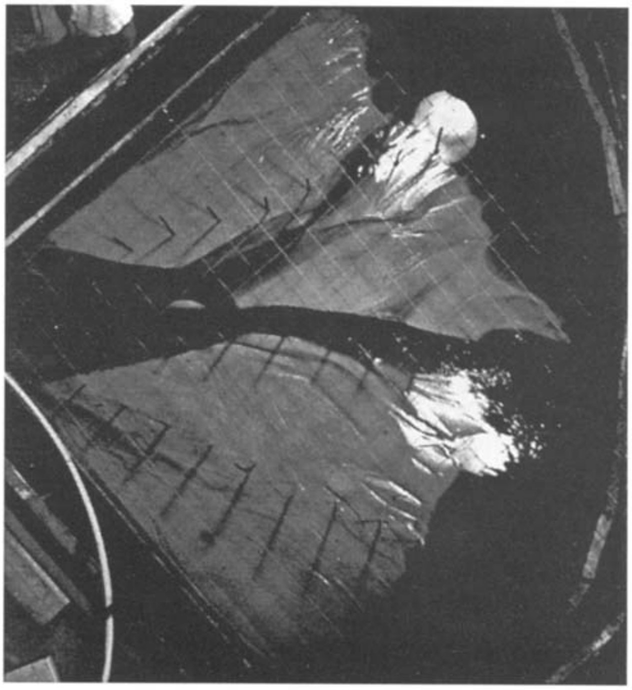
Width: doubling the bed material load doubles the width; doubling the water discharge without changing the bed material load does not change width (but slope drops and depth increases instead).

$$B_{bf} = \frac{1}{\sqrt{RgD}\, D\, \alpha_t \left[\varphi_s \tau^*_{form} - \tau^*_c\right]^{n_t}} Q_{tbf}$$

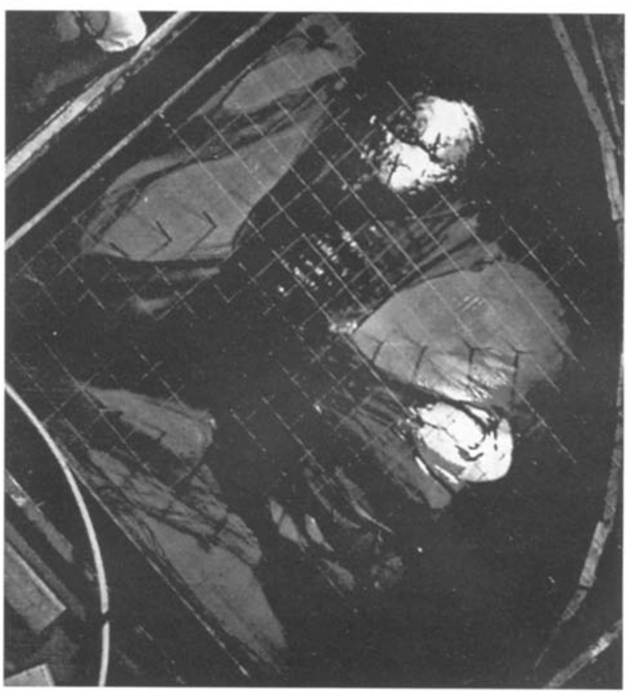
Depth: doubling the water discharge doubles the depth; doubling the bed material load halves the depth (but channel gets wider and steeper).

$$H_{bf} = \frac{D_{50} \alpha_t \left[\varphi_s \tau^*_{bf50} - \tau^*_c\right]^{n_t} \sqrt{C_f}}{\sqrt{\tau^*_{form}}} \frac{Q_{bf}}{Q_{tbf}}$$

Example of control of water and sediment discharge on slope.



A



B

Figure 3. Photographs of typical channel-lobe couplets in flow configuration taken 30 min apart during run S9. Glare is from reflection of overhead lights. *A*. Flow configuration at runtime 1:55. *B*. Flow configuration at runtime 2:20.

Whipple, K.X., Parker, G., Paola, C., and Mohrig, D., 1998, Channel dynamics, sediment transport, and the slope of alluvial fans: Experimental study: The Journal of Geology, v. 106, p. 677-693.

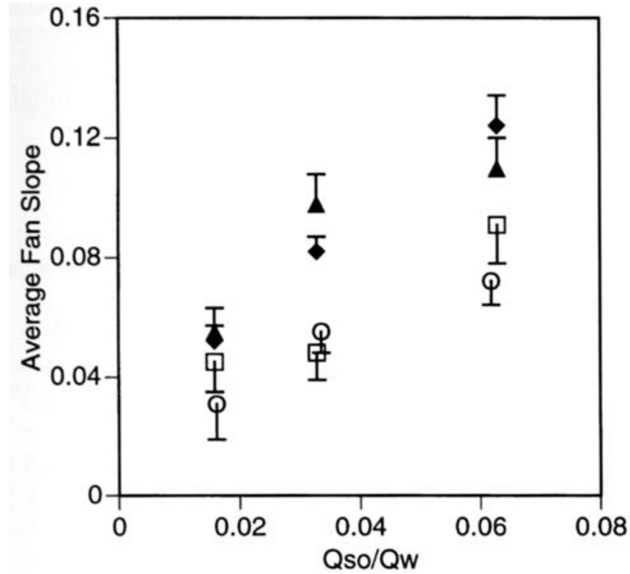


Figure 7. Reproducibility of measured fan slopes in the small basin (2.1 m) for the suspension-dominated fans. Symbols for data series: 70 µm, run S4 (open squares); 70 µm, run S8 (open circles); 160 µm, run S2 (solid triangles); 160 µm, run S7 (solid diamonds). Only half-error bars are plotted for readability. These data represent a "worst case" scenario because spatial and temporal variations in fan slope were strongest in the suspension-dominated experiments, and least constrained in the small basin (see table 1).

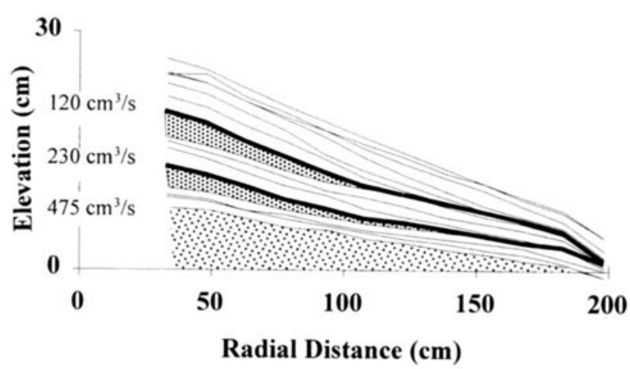
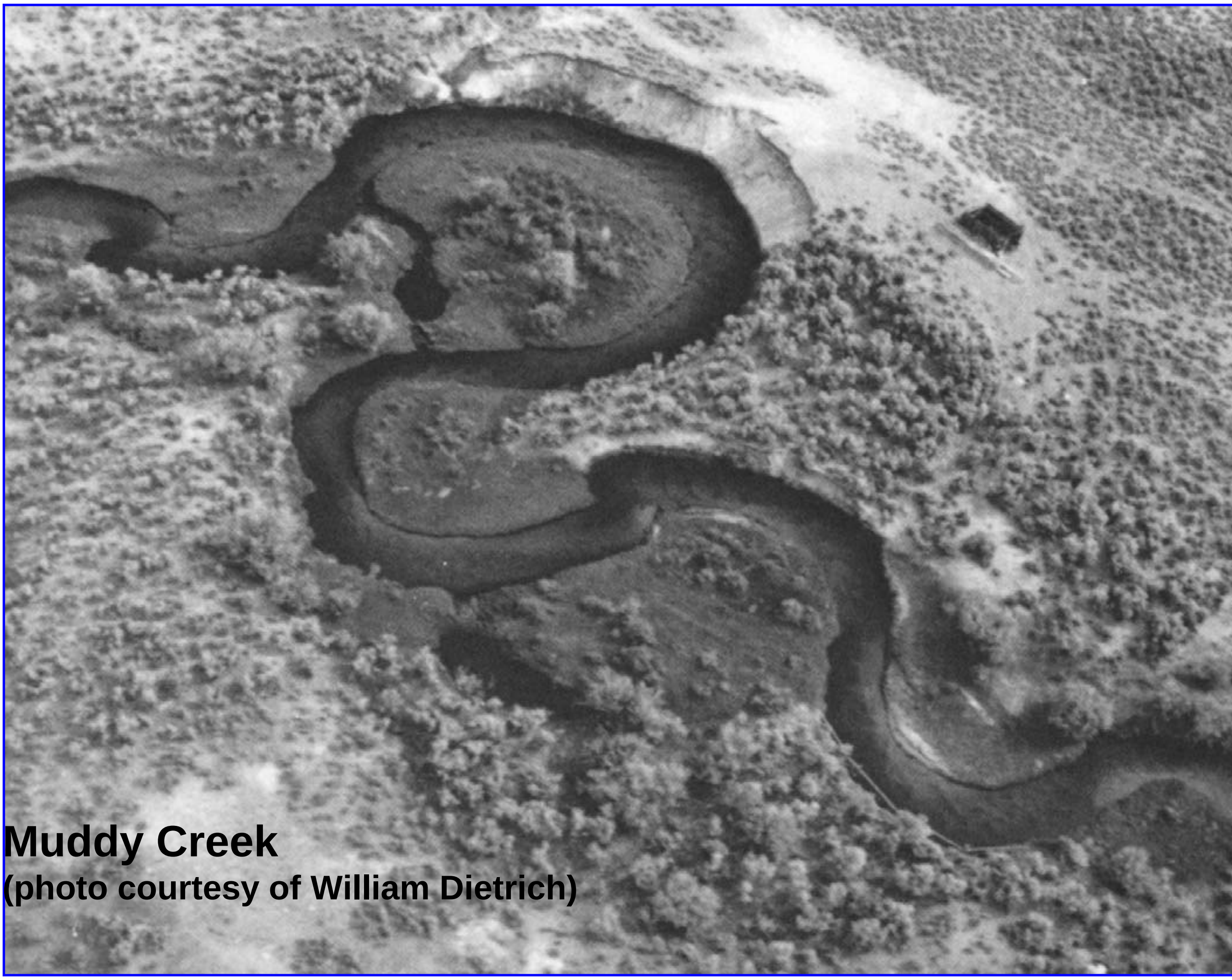


Figure 2. Pattern of fan-wedge progradation. Initial fan wedge (light dots) progrades with constant base level. Timelines (thin lines) show development of steady-state aggradation. Heavy lines indicate timelines immediately after a step decrease in water discharge (indicated on figure). Medium dot patterns highlight fan wedges produced by this change in discharge.

This insight plus relationship between flow depth and width and bar number provides pieces for investigating controls on channel form. See Fukuoka (1989).
Small channel width/channel depth – suppresses bar development
Large channel width/channel depth – multiple trains of bars (braided)
Intermediate value – single thread channels

Toutle River, WA, gravelly braided stream- During low flow primarily one channel is active, which happens to be, here, at the topographically highest position to the left of Chris Paola. [photo courtesy of Paul Heller]

(Niobrara River, NE, sandy braided river, aerial view from USDA 1993)

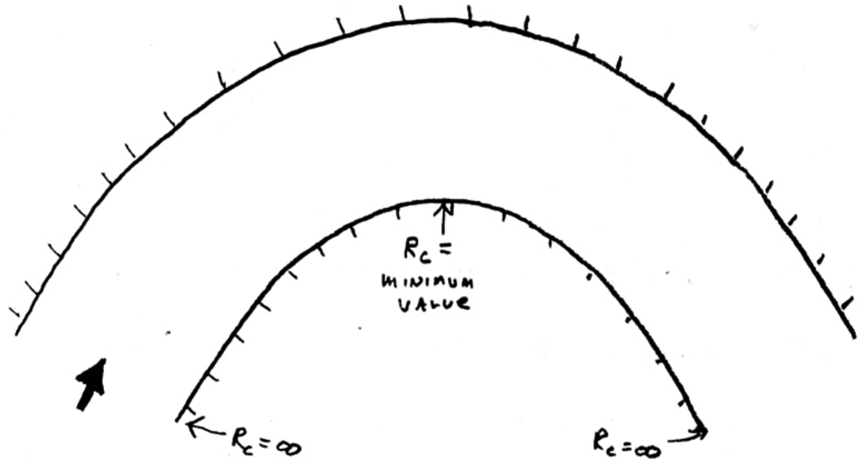


Muddy Creek
(photo courtesy of William Dietrich)

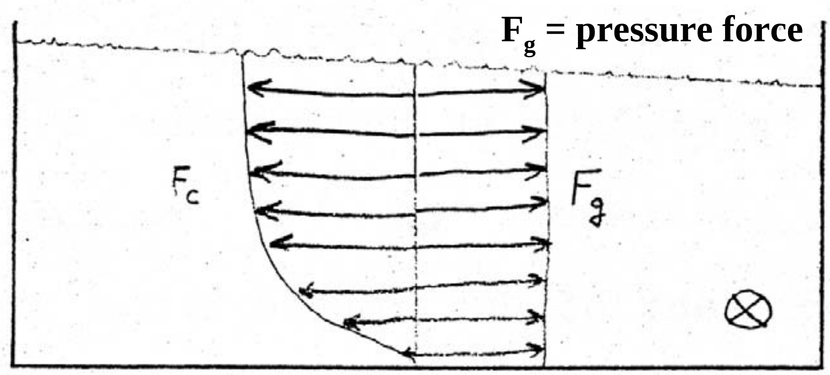
Flow and sediment transport in a bend

$$F_c = \rho \frac{u^2}{r}$$

Centrifugal acceleration associated with particle following a curved path

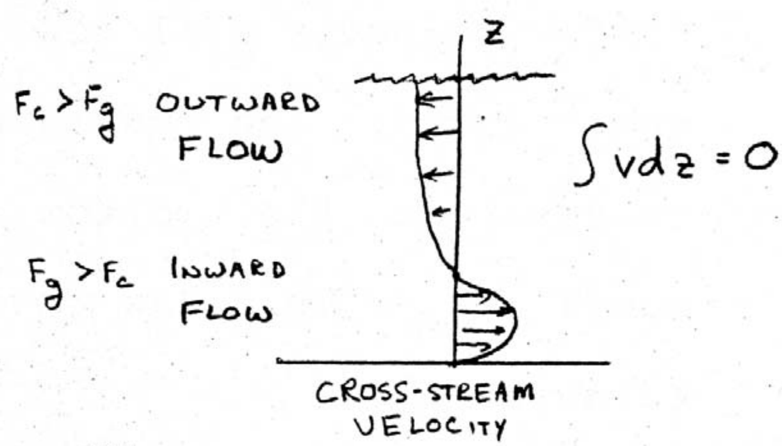


Acceleration of the fluid toward the outside bend produces a 'piling up' of fluid. This produces a cross stream slope, giving rise to a force toward the inner bank.



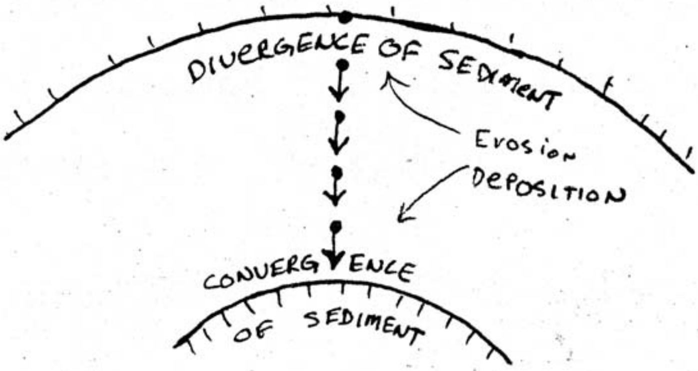
<u>Setup of helical circulation</u>. Force associated with surface slope is constant, centrifugal force varies with depth.

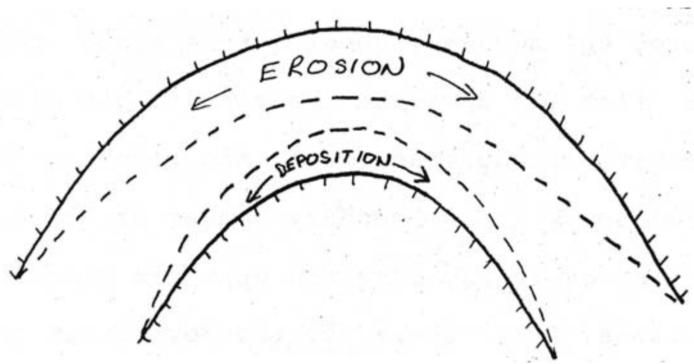
$$u = \frac{u_*}{\kappa} \ln \frac{z}{z_0}$$



[drawings courtesy of Jonathan Nelson]

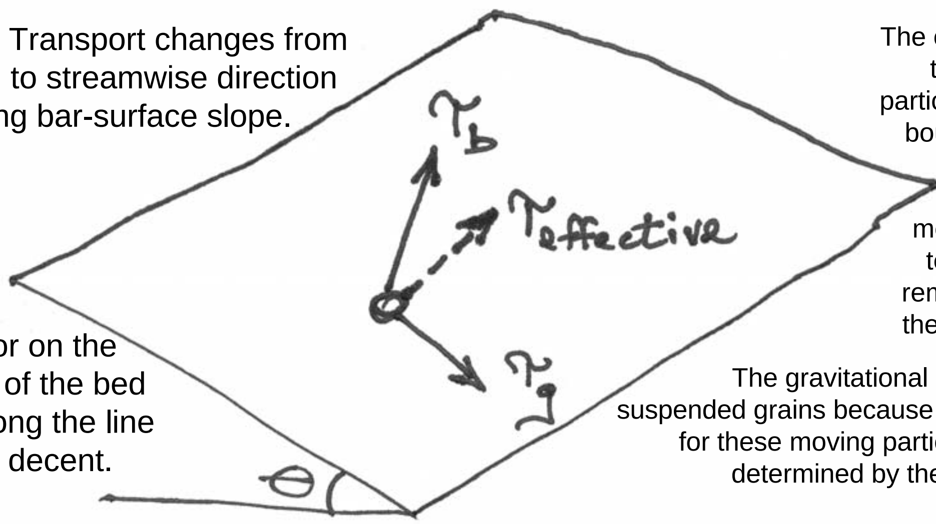
Development of point bar





Developing slope of the bar surface results in deflection of particle trajectories.

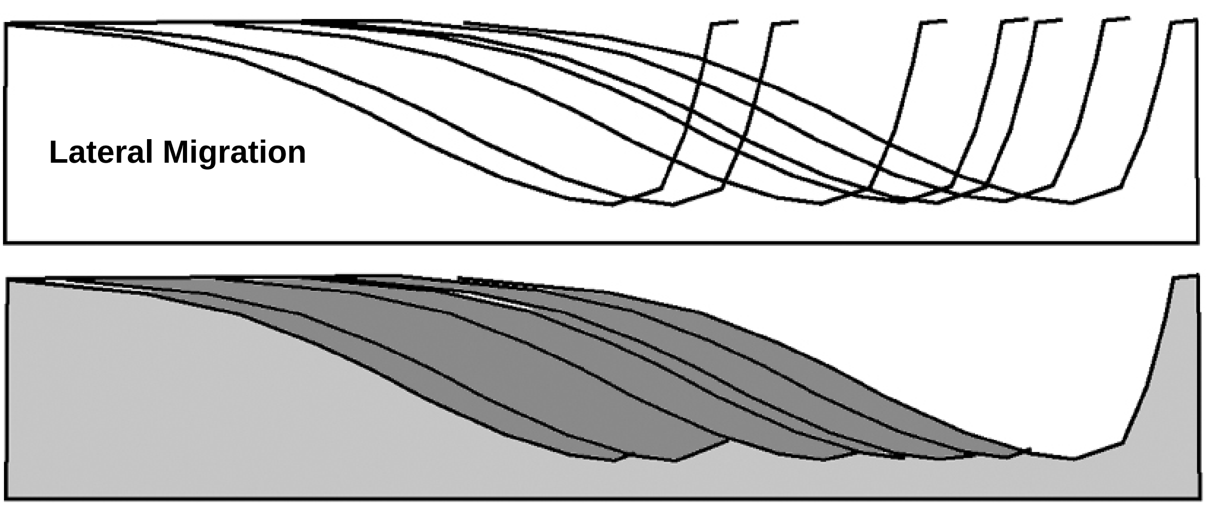
Transport changes from cross-stream to streamwise direction with increasing bar-surface slope.



τ_g = a vector on the local plane of the bed directed along the line of steepest decent.

The control of slope on the transport direction of a particle is largest when the boundary shear stress is just above the critical shear stress for initial motion and the particles tend to roll and saltate, remaining in contact with the bed most of the time.

The gravitational correction is small for suspended grains because the direction of travel for these moving particles is almost entirely determined by the direction of the flow.



DOWNSTREAM SORTING OF SEDIMENT (additional control on channel width, depth and slope)

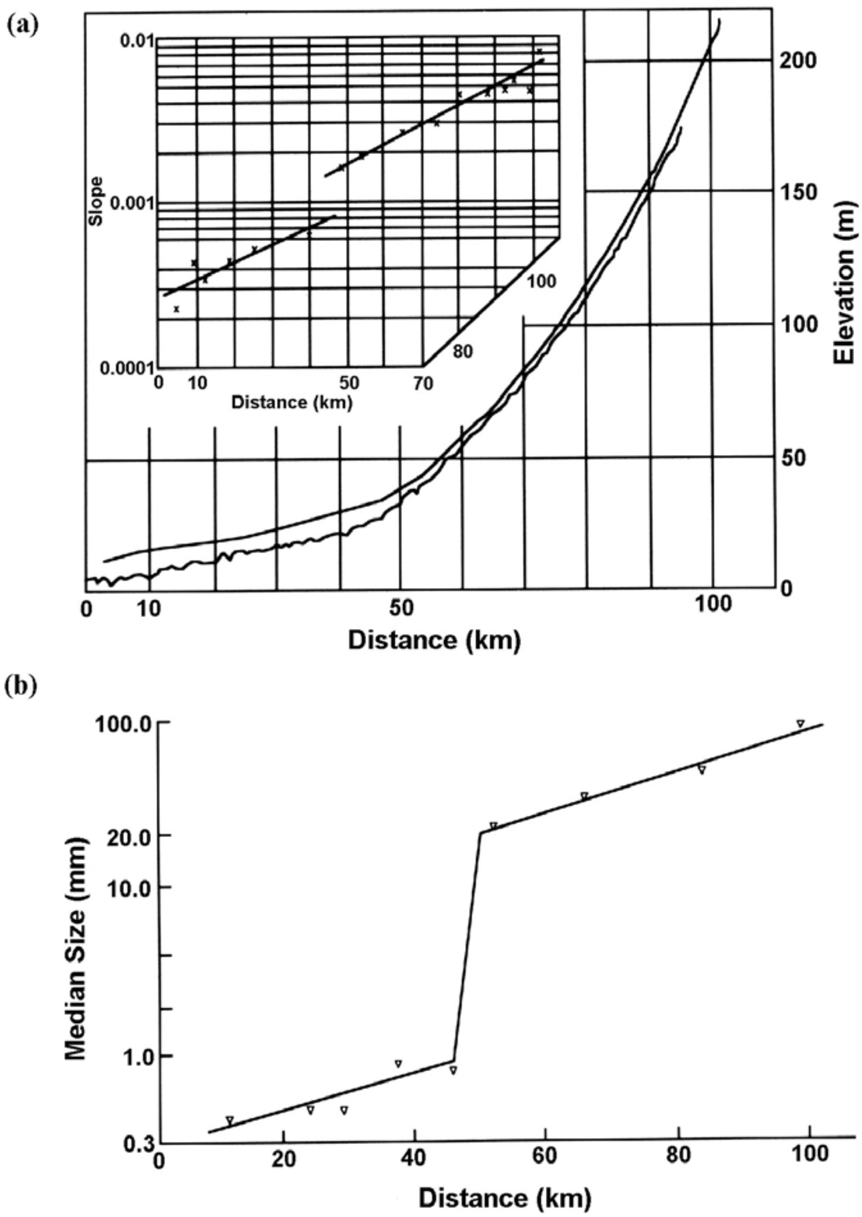


Image from Gary Parker E-book: [Yatsu (1955), Parker and Cui (1998)].

As the gravel gets finer, it is transported at lower slopes. The result is tendency to strengthen the upward concavity of a river profile.

The image shows a) the long profile of the Kinu River, Japan and b) the profile of median grain size in the same river. The river undergoes a sudden transition from gravel-bed to sand-bed before reaching the sea.

Fluvial gravels and conglomerates

Development of bedforms is suppressed by small values of flow depth/grain size.
(Toutle River, WA) [photo P. Heller]

Stratification often defines bar topography.

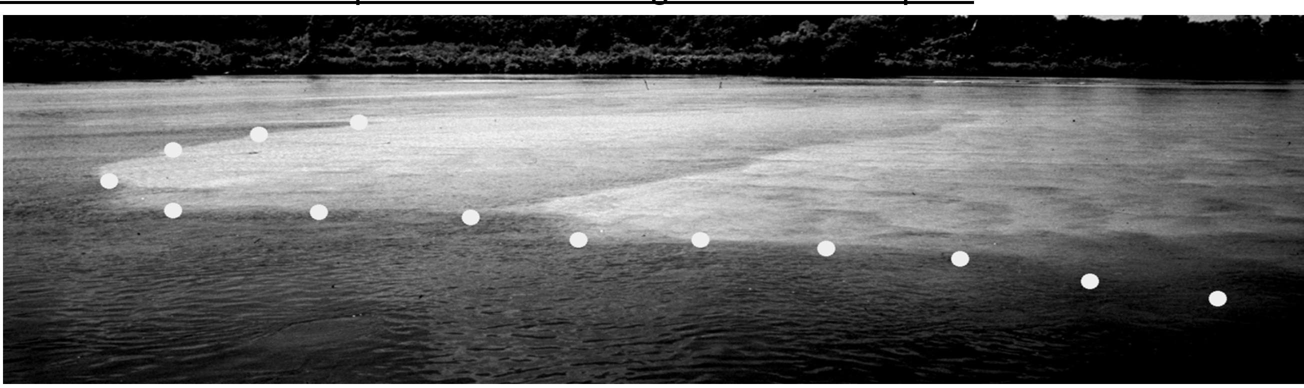
Images Courtesy of Prof. Paul Heller, University of Wyomimg. Used with permission.

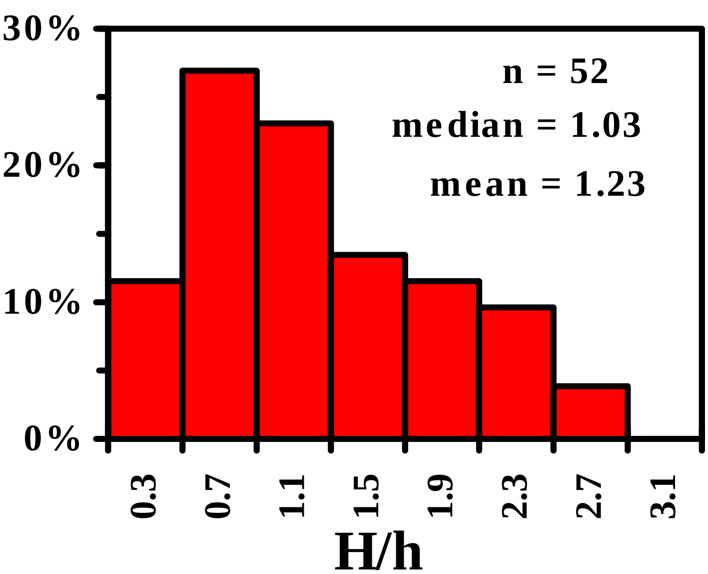
The shingled arrangement of adjacent particles is called **imbrication** and is most easily seen in gravelly deposits. Studies of clast imbrication can be used to constrain paleocurrent directions.

Do not be fooled: Many contacts between adjacent particles may not be observed in a 2D cut through the grain framework.

Image Courtesy of Prof. Paul Heller, University of Wyomimg. Used with permission.

What is the relationship between bar height and flow depth?





(upper) Mid-channel bar in the North Loup River, NE. White dots mark locations where bar height was measured

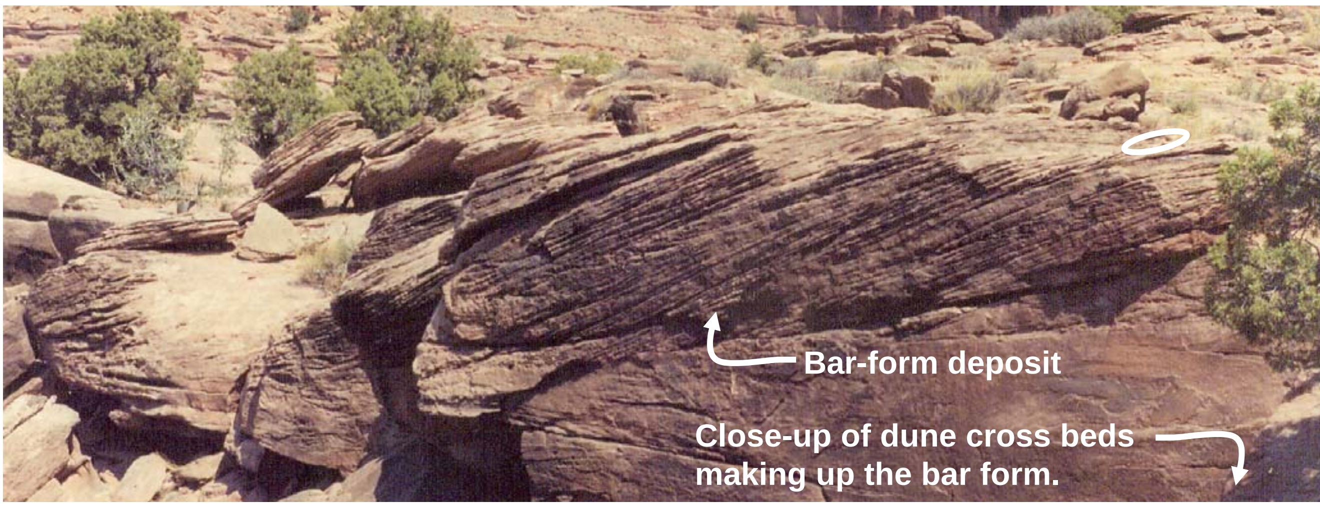
(left) Histogram of Local Bar Height (H) relative to Reach-Averaged Flow Depth (h) for Four Bars.

Values of H/h as high as 5 are commonly observed in river channels.

Image Courtesy of GSA Bulletin. Used with permission.

<u>Examples of compound bedding</u>:
Bars built out of dune sediment.

Bar-form deposit (person for scale)

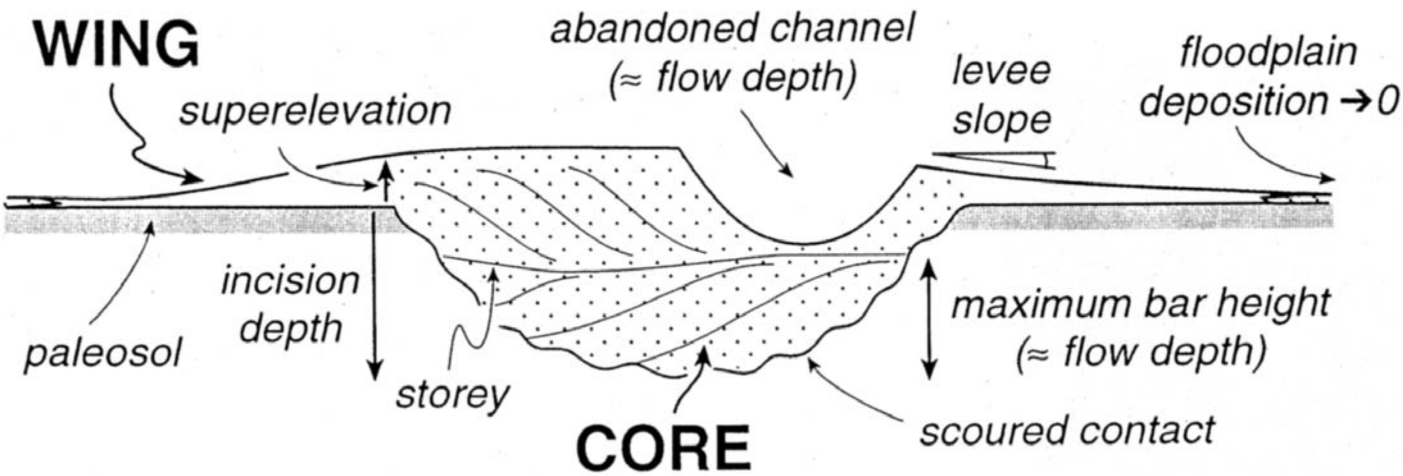


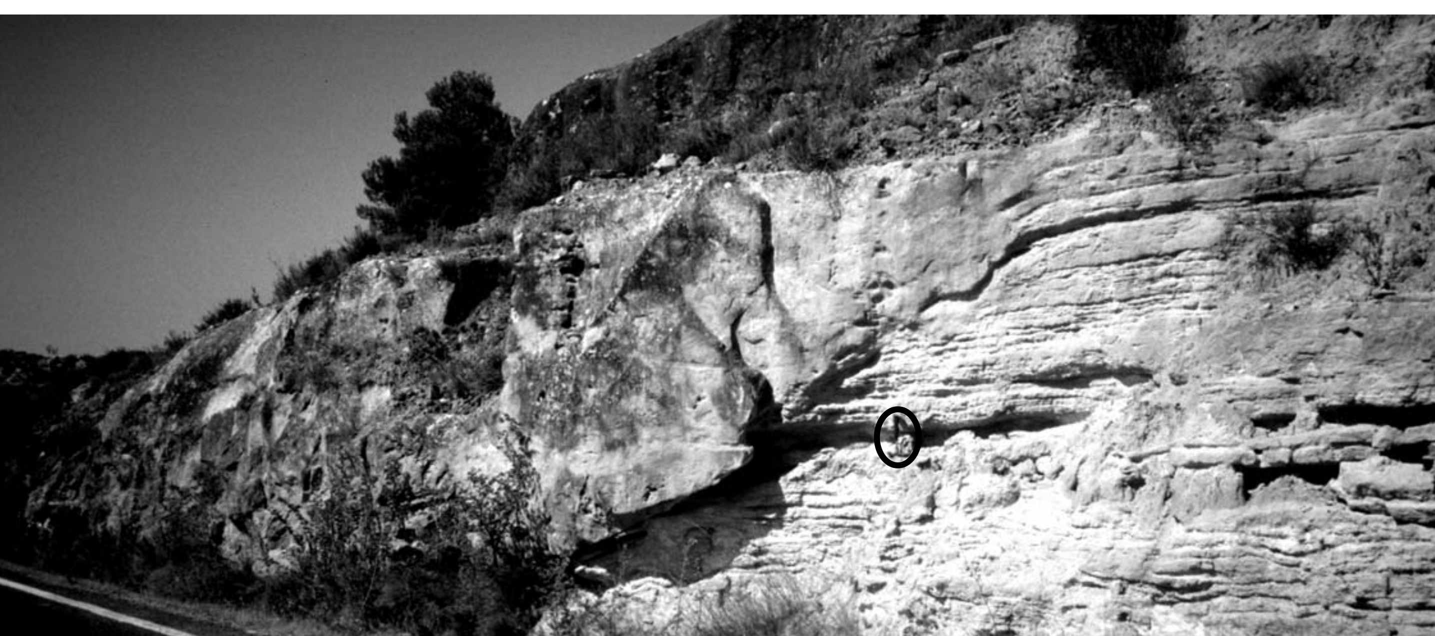
Overbank sedimentation

Rates of overbank sedimentation are greatest near channel margins, producing natural levees.

New overbank sand from the 1993 flood on upper Mississippi River, at Slim Island, MO, at mile 267. River flow is to the right. Photo by R.H. Meade, USGS.

Crevasse splay sand from levee break at Bryants Creek MO crossing floodplain of upper Mississippi River near mile 260. Photo by R.H. Meade, USGS





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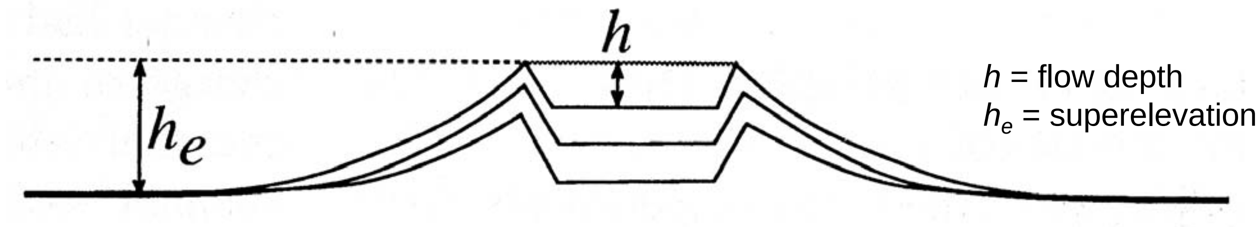
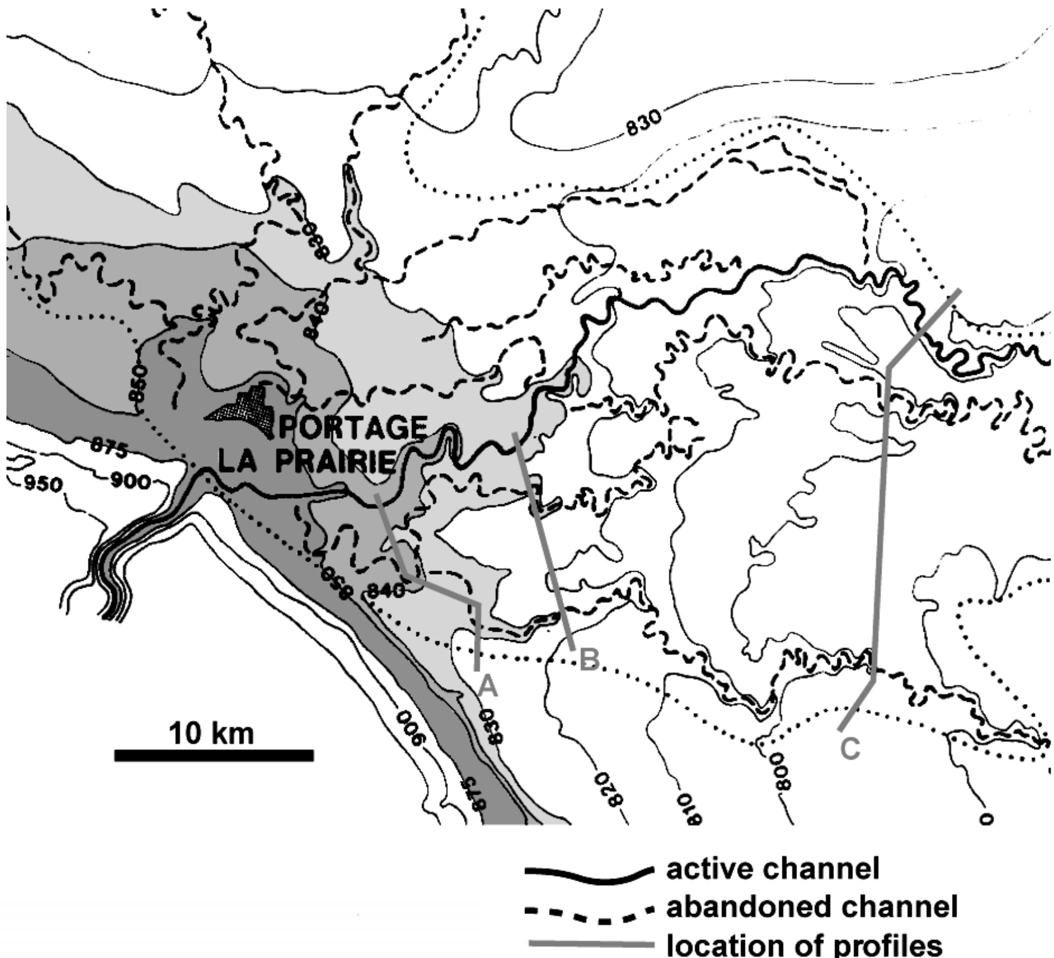
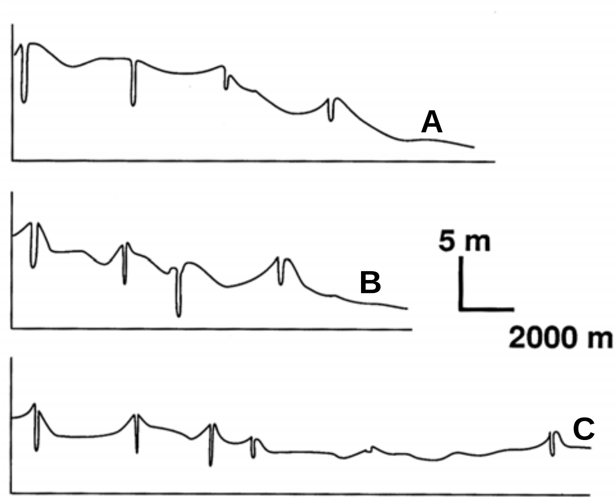
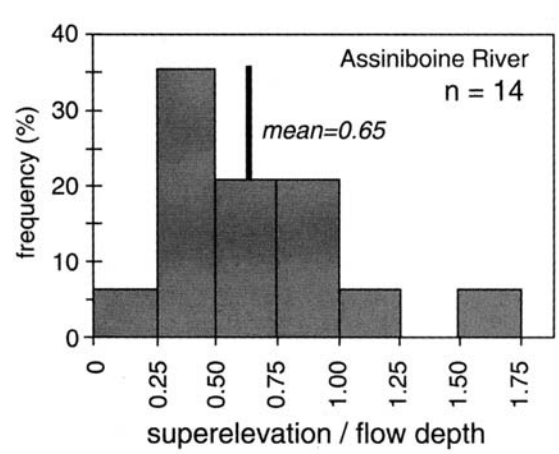
Focused sedimentation near channels results in their superelevation relative to the surrounding floodplain.









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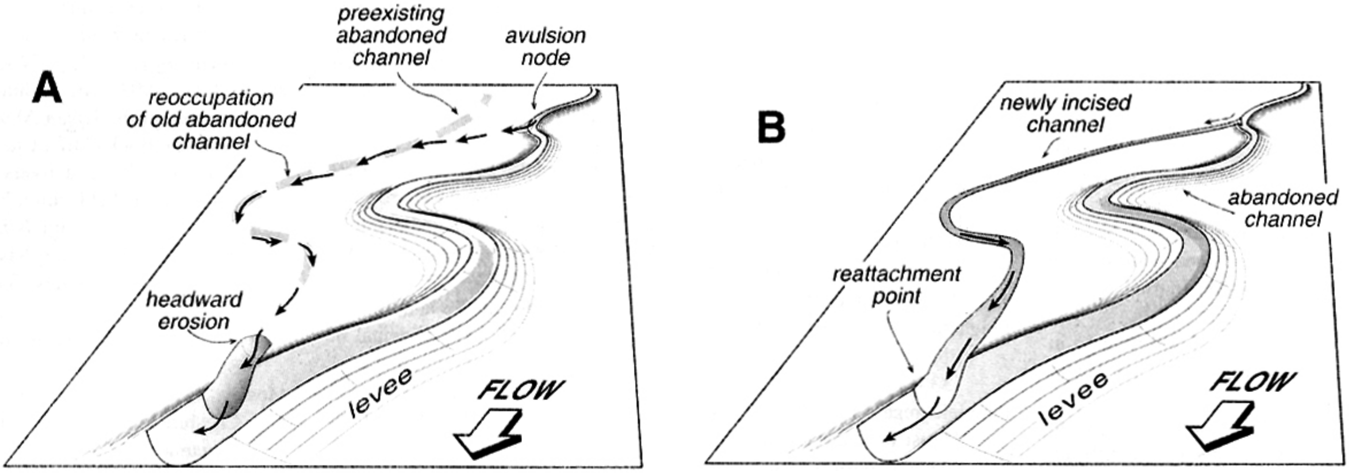
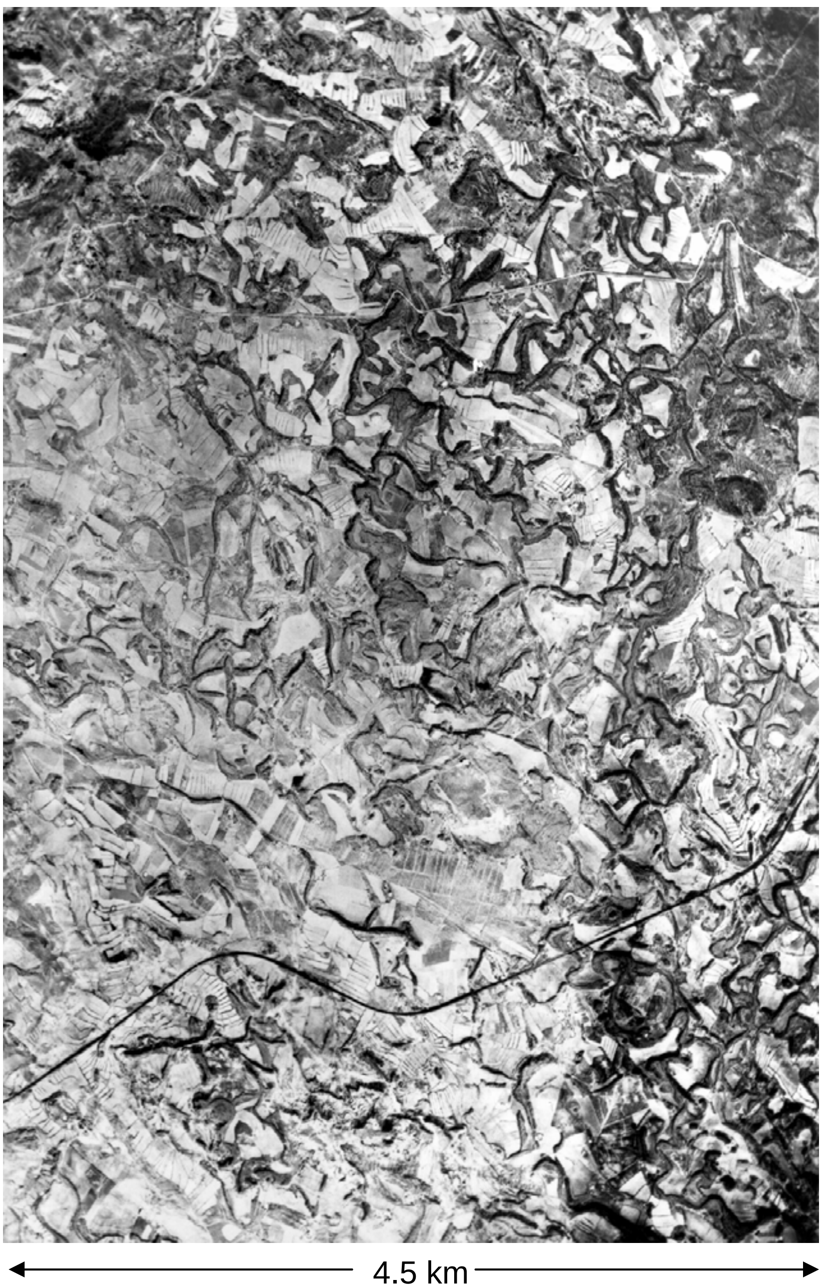
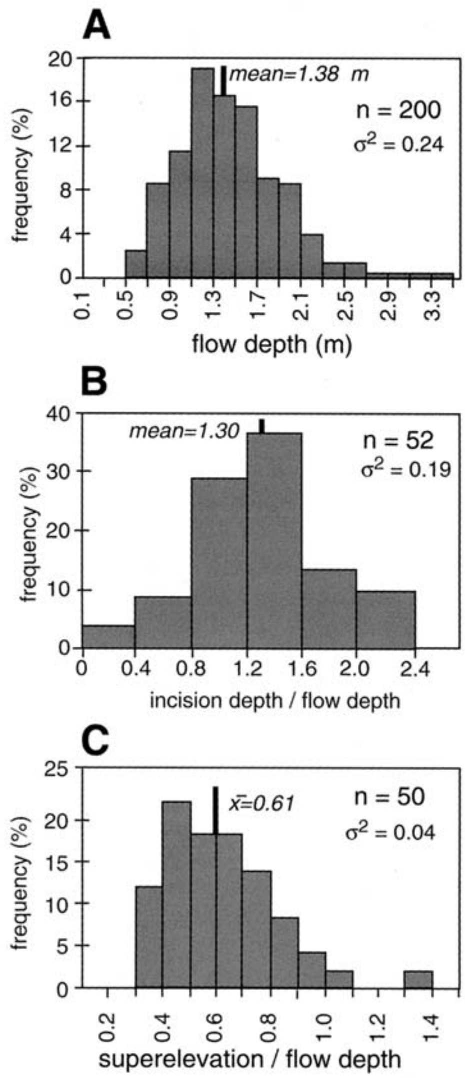
Influence of channel avulsion on stratigraphy





Aerial Photo of Ribbon Channel Sand Bodies Exposed near Caspe, Spain (Chattian)

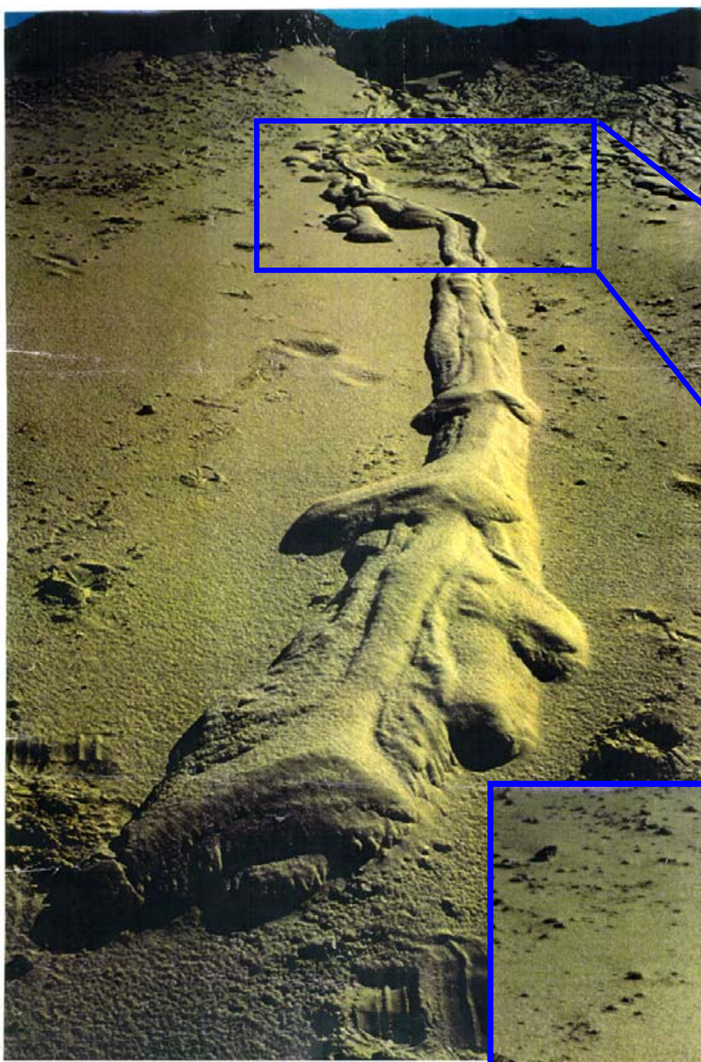


<u>Debris Flows:</u> A class of flows containing so much sediment that the particles are nearly touching. Their water component is interstitial and behaves as a pore fluid.

<u>Debris flow mobility can be facilitated by</u>:
1. Elastic collisions causing grains to vibrate enough for particles can move past each other. Inertial effect – typically associated with large surface slopes (i.e., grain flows)

2. Mixture of fine-grained sediment suspended in the water increases the viscosity of the fluid. Viscous effect – hinders motion of fluid around grains and effectively combines sediment +water so that for some period of time they move down slope as approximately a single phase.

3. Densification of the sediment framework by shear strain, transferring part of the vertical normal stress onto the pore fluid. High pore pressures – promote liquefaction of mixtures.



The Herschel-Bulkley constitutive equation is commonly used to describe the steady and uniform flow of debris flows.

$$\tau_{zx} = \tau_y + k\left(\frac{\partial u}{\partial z}\right)^n \qquad \tau_{zx} \geq \tau_y$$

$$\left(\frac{\partial u}{\partial z}\right) = 0 \qquad \tau_{zx} \leq \tau_y$$

where τ_{zx} is shear stress; *du/dz* is shear strain rate, and *k* and *n* are fluid index parameters. τ_y is the fluid yield stress.

Levees provide evidence of this flow possessing an effective yield strength.