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]

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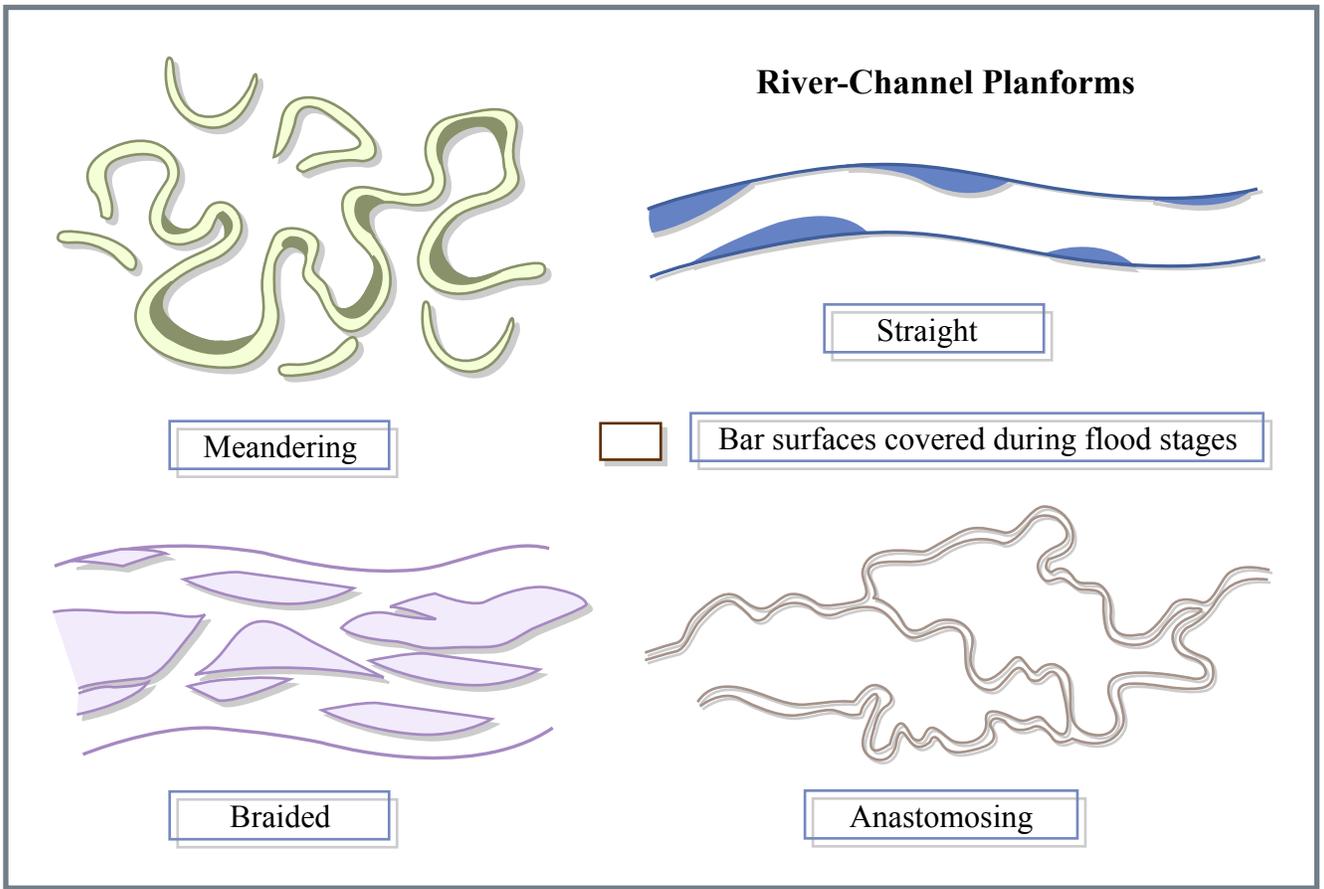

Sandy alluvial fan (3km in length) Hibbing, MN

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.

(Bars+Dunes, aerial view)   20m
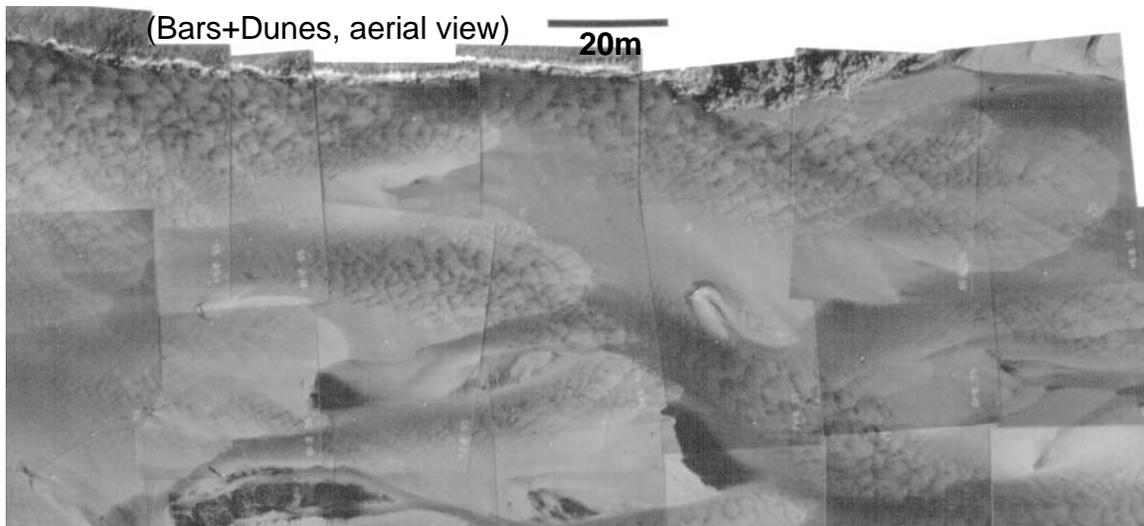
Width-to-Depth Closure for River Channels (*notes are modified from Gary Parker E-book:* **1D SEDIMENT TRANSPORT MORPHODYNAMICS with applications to RIVERS AND TURBIDITY CURRENTS**)

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

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

Example:
If stress rises above given value, it induces bank erosion that widens the flow.
Widening reduces flow depth, reduces bed 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.
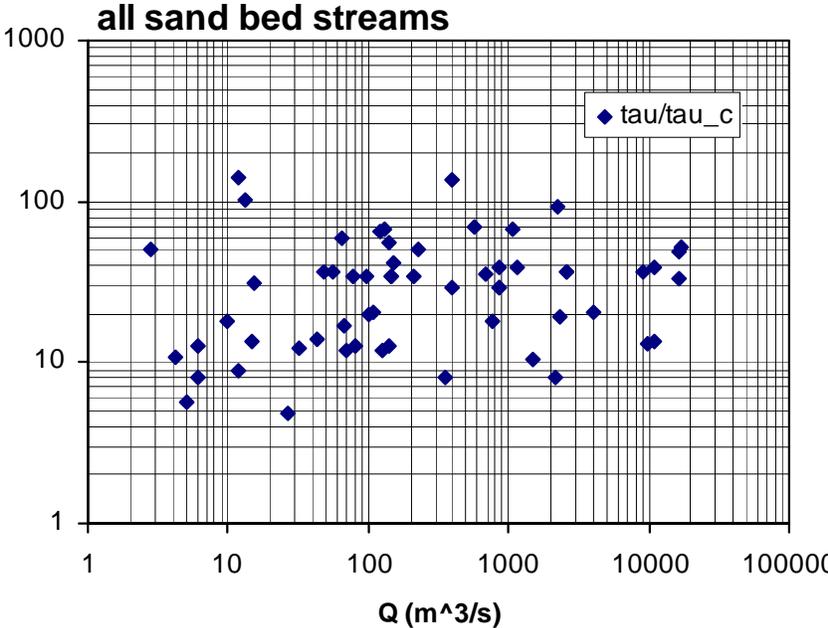
Paola et al. (1992) were the first to propose the assumption of constant bankfull bed stress in modeling the morphodynamics of streams. The general form of their analysis is used in the following material.

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

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

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

$\tau_{form}{}^*$ = *channel-formative bed stress*

$$\tau_{bf\,50}^* = \frac{H_{bf} S}{R D_{50}} = const. = \tau_{form}^*$$

Definitions:
Q_{bf} = bankfull discharge [L³/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 [L²/T]
$R = (\rho_s/\rho - 1)$ = sediment submerged specific gravity (~ 1.65 for natural sediment) [1]
g = gravitational acceleration [L/T²]

bed material transport

$$Q_{tbf} = B_{bf} q_{tbf} = B_{bf} \sqrt{RgD}\, D\, \alpha_t \left[\varphi_s \tau_{bf\,50}^* - \tau_c^*\right]^{n_t}$$

Equations from notes on bedload physics

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

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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).

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

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Example of control of water and sediment discharge on slope.

Images removed due to copyright concerns.

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

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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]

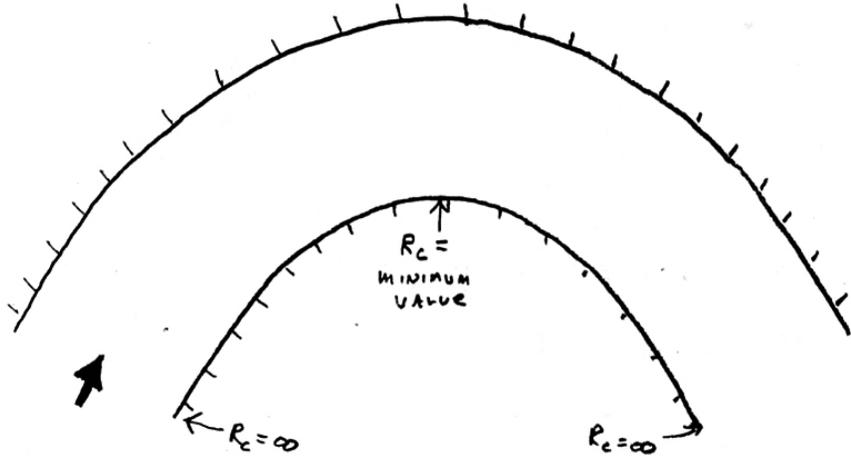Image Courtesy of Prof. Paul Heller, University of Wyomimg. Used with permission.

(Niobrara River, NE, sandy braided river, aerial view from USDA 1993)
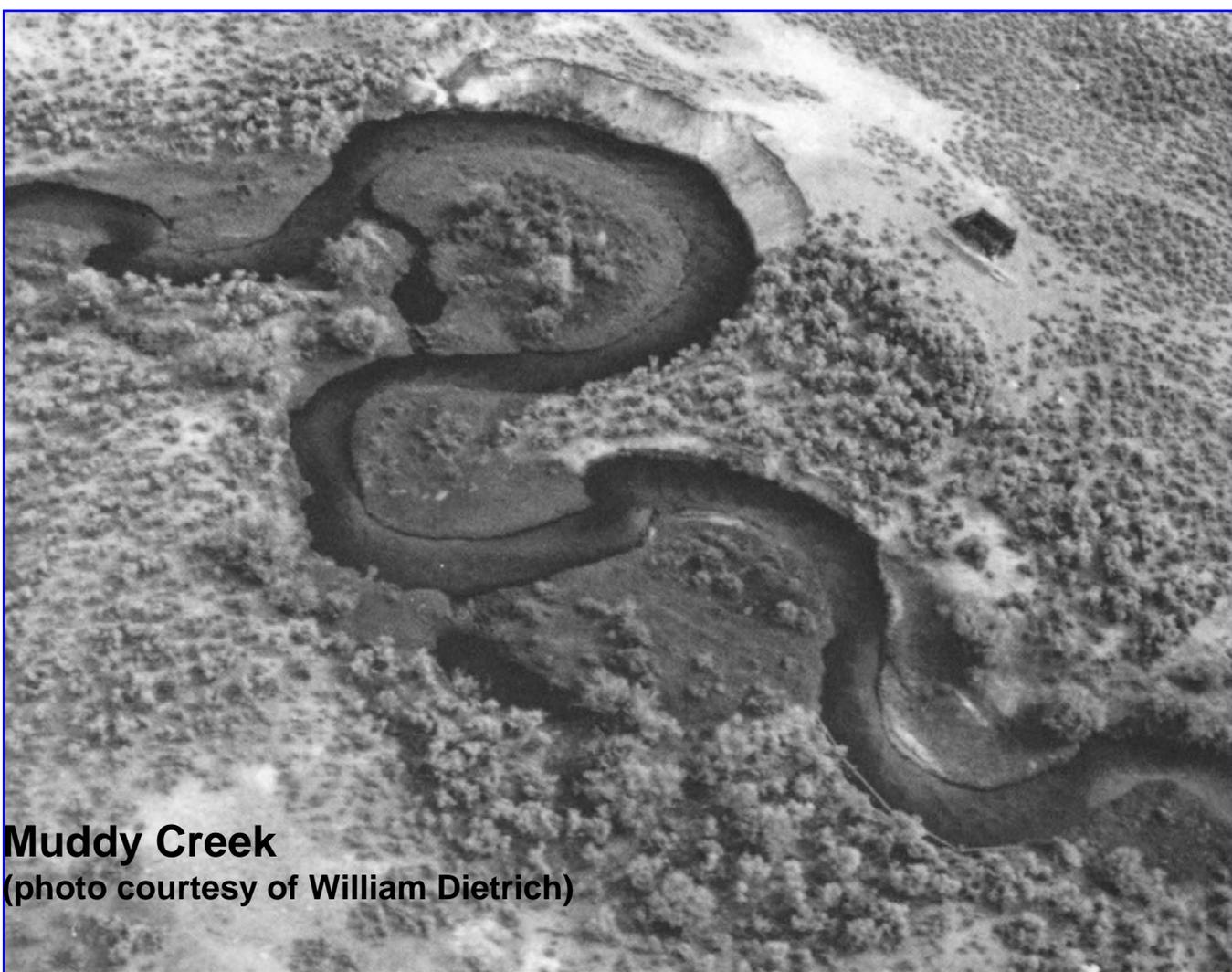
Muddy Creek
(photo courtesy of William Dietrich)

Flow and sediment transport in a bend

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

Centrifugal acceleration associated with particle following a curved path

$R_c =$ MINIMUM VALUE

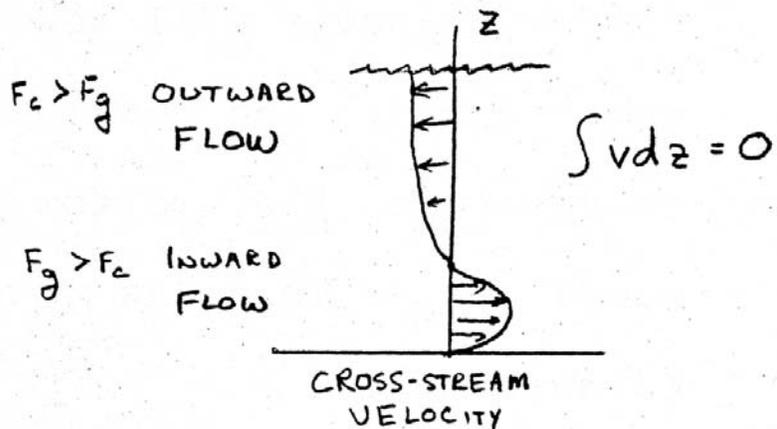$R_c = \infty$ $R_c = \infty$

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.
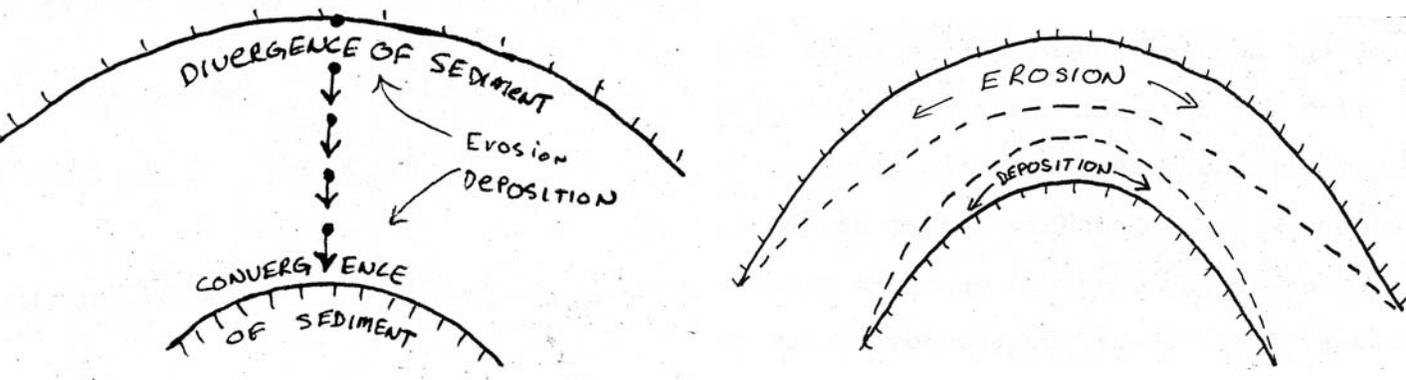

F_g = pressure force

F_c F_g
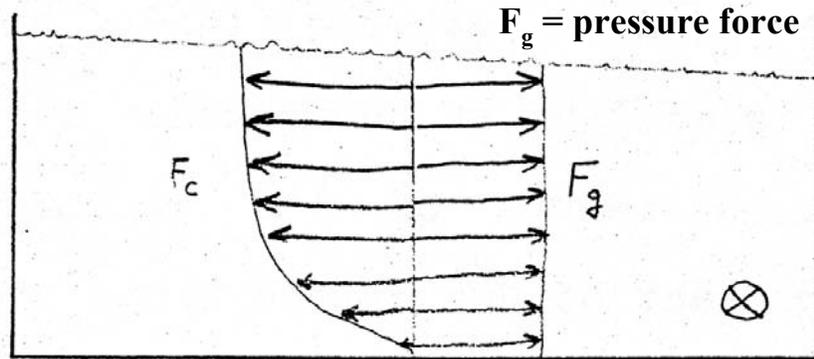
Setup of helical circulation. Force associated with surface slope is constant, centrifugal force varies with depth.

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

$F_c > F_g$ OUTWARD FLOW

$F_g > F_c$ INWARD FLOW

$\int v \, dz = 0$

CROSS-STREAM VELOCITY

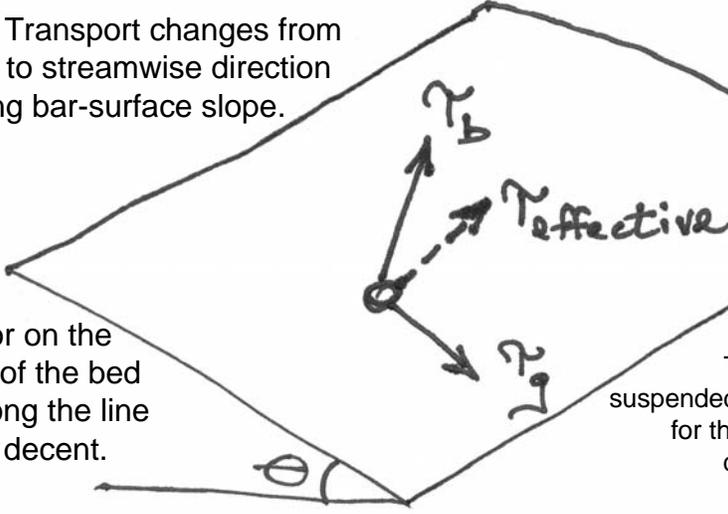[drawings courtesy of Jonathan Nelson]

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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.

Lateral Migration