Modeling Earth Surface Dynamics from Source to Sink

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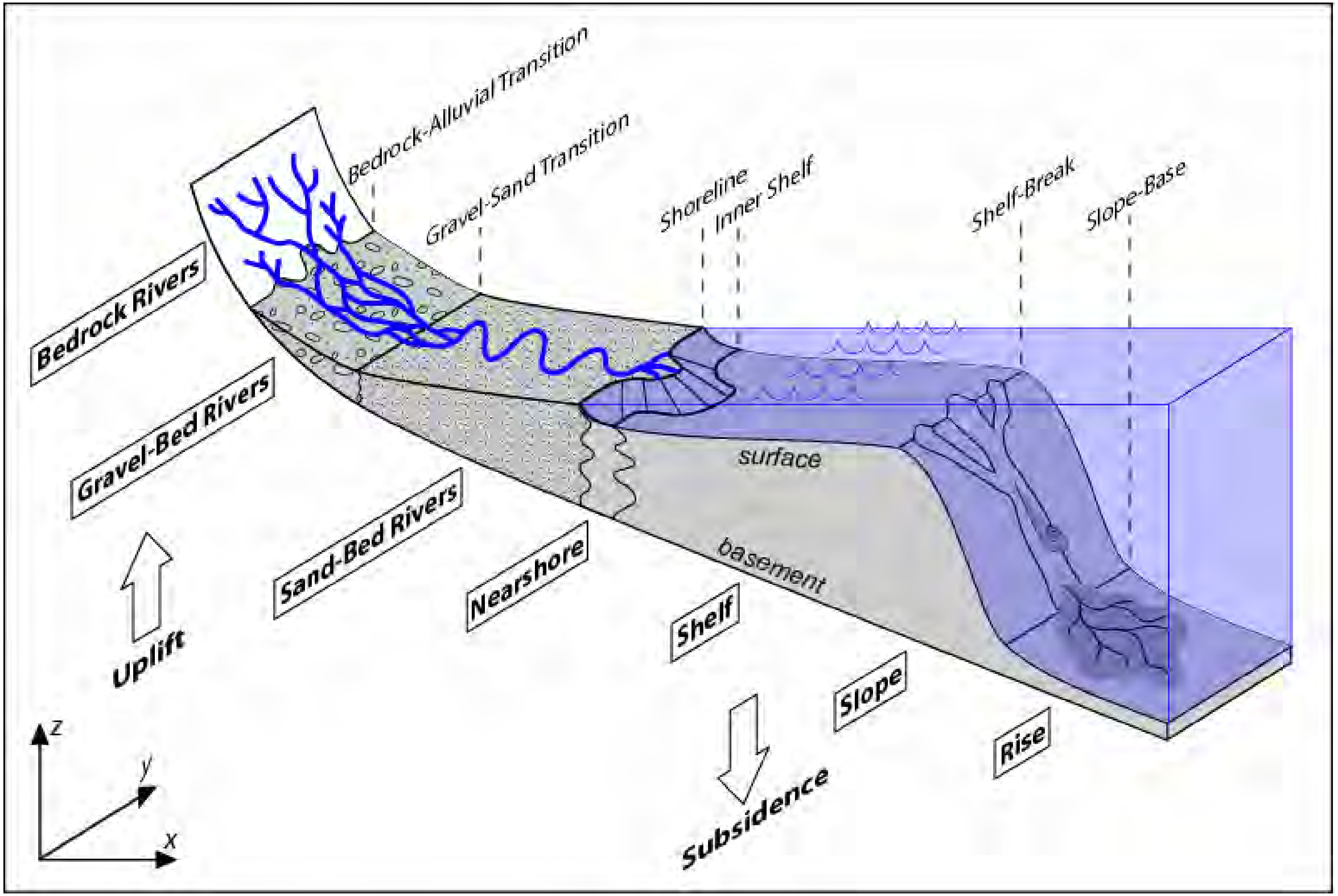
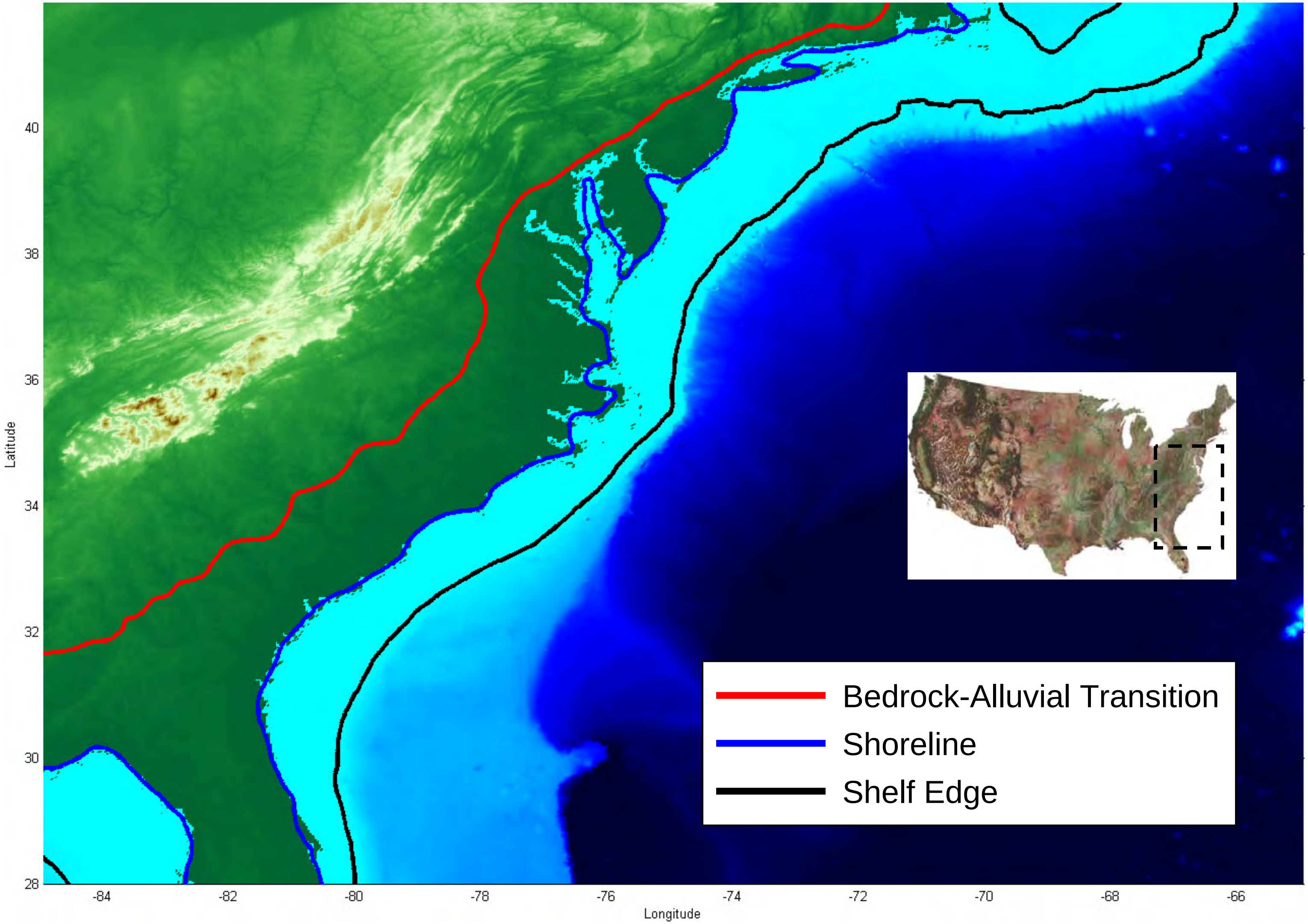
Introduction

- NCED studies the diverse channel systems that serve as the arterial network of Earth's “Critical Zone”
  - mountain streams, alluvial fans, river floodplains and deltas, submarine canyons and fans, …
- Over geologic time channel systems sculpt erosional landscapes and deposit sedimentary records of the past
- On continental scales linked channel systems transport sediment from high mountain source areas to deep marine sink areas

Processes, Environments, and Boundaries

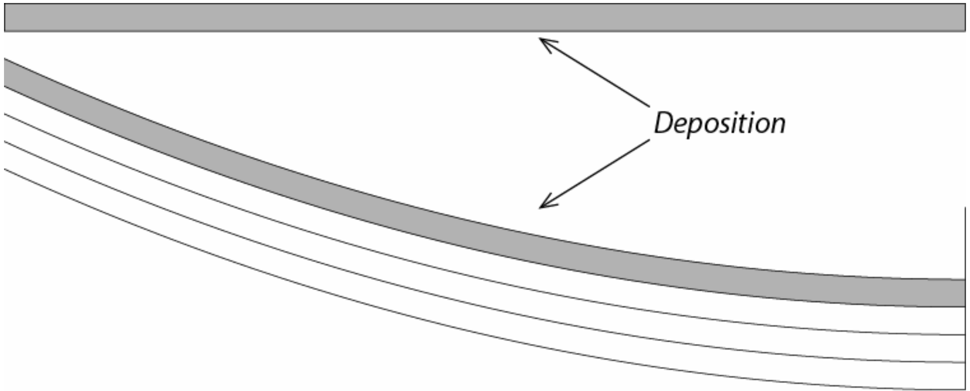


Processes, Environments, and Boundaries

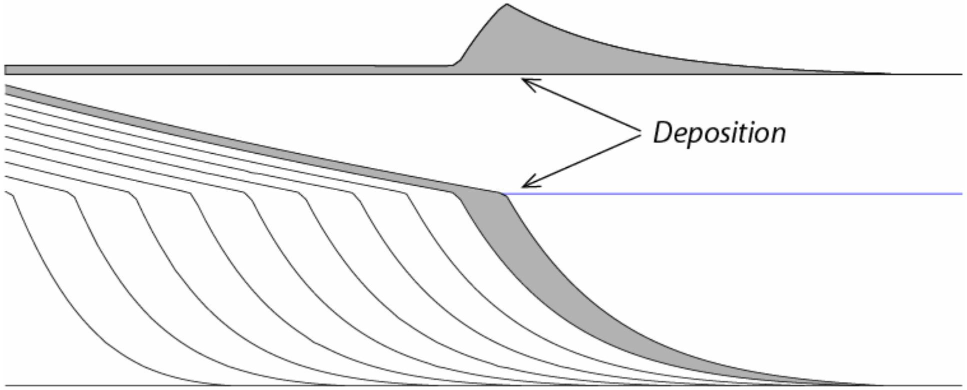


Sedimentary Processes and Boundary Coupling

Boundary coupling is as important as sedimentary processes in determining surface dynamics and stratigraphy!



Half-Graben (Graded Profile)



Prograding Delta (Dynamic Profile)

A unified framework to explore …

- Large-scale evolution of source to sink system
  - Coupled landscape, seascape, and stratigraphic evolution
  - signatures of paleo-environments and processes
- Medium-scale system evolution of sub-systems
  - migration of boundaries between sedimentary environments
  - propagation of “signals” upstream/downstream within environments
- Large-scale consequences of alternative process models and hypotheses developed by NCED research

Outline of Talk

1) Overview of modeling framework
    - Conservation of mass and momentum between flow and sediment
    - Generalized morphodynamic evolution equation

2) Prototype model
    - Simplified bedrock-alluvial-marine model
    - Response to sea level cycles

3) Alluvial Rivers
    - Gravel-sand transitions: Sharp vs diffuse
    - MATLAB Dynamic Stratigraphy Toolbox

4) Marine Turbidity Currents
    - Effect of wave climate on shelf morphology

Conservation of Sediment Mass

surface elevation =

sediment thickness + basement elevation

surface change =

deposition/erosion + uplift/subsidence

$$\boxed{\partial_t \eta = -\partial_x q - \sigma}$$ (Exner Equation)

$\eta =$ surface elevation , $q =$ sediment flux

$\sigma =$ subsidence

Sediment Flux Laws

Equilibrium Flux Laws

$$\boxed{q = f\left[\eta, S\right]}$$

bedload diffusion $q \sim S$

"Fast" equilibration between sediment flux and bed/flow conditions

"Slow" equilibration between sediment flux and bed/flow conditions

Non-Equilibrium Flux Laws

$$\boxed{\partial_x q = f\left[q, \eta, S\right]}$$

bedrock incision $\partial_x q \sim S$

passive settling $\partial_x q \sim q$

Morphodynamic Evolution Equation

- Exner + Flux Law → Advection-Diffusion-Reaction Equation

$$\boxed{\partial_t \eta + V \partial_x \eta = \partial_x \left(\kappa \partial_x \eta \right) + \Phi}$$

- Nonlinear coefficients (Velocity, Diffusivity, Source)

$$V = V\left[\eta, q, S\right], \kappa = \kappa\left[\eta, q, S\right], \Phi = \Phi\left[\eta, q\right]$$

- Conservation of (grain-size specific) sediment flux

$$\partial_x q_i = -\partial_t \eta_i$$

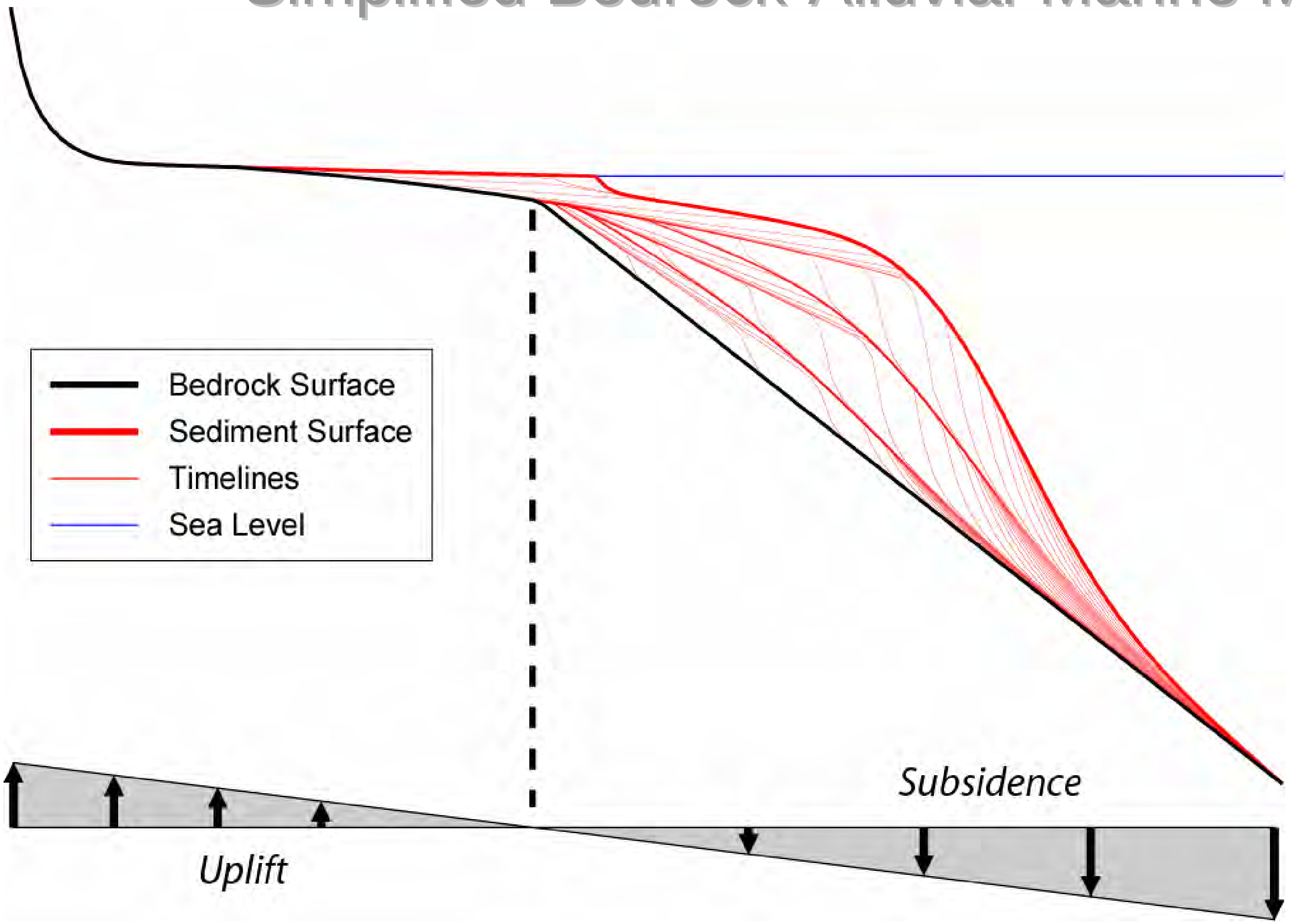
Simplified Bedrock-Alluvial-Marine Model

- Single grain size
- Lump marine processes into "diffusion"
- *Linear* coefficients + moving boundaries → *Nonlinear* system

Environment	V	κ	Φ	**Threshold**
Bedrock	$-V_0 x$	0	$-\sigma$	$h = 0 , q < q_a$
Alluvial	0	κ_a	$-\sigma$	$\eta > z_{SL}$
Marine	0	κ_m	$-\sigma$	$\eta < z_{SL}$

(Humphrey and Heller,1995; Jordan and Flemings, 1991)

Simplified Bedrock-Alluvial-Marine Model



Simplified Bedrock-Alluvial-Marine Model

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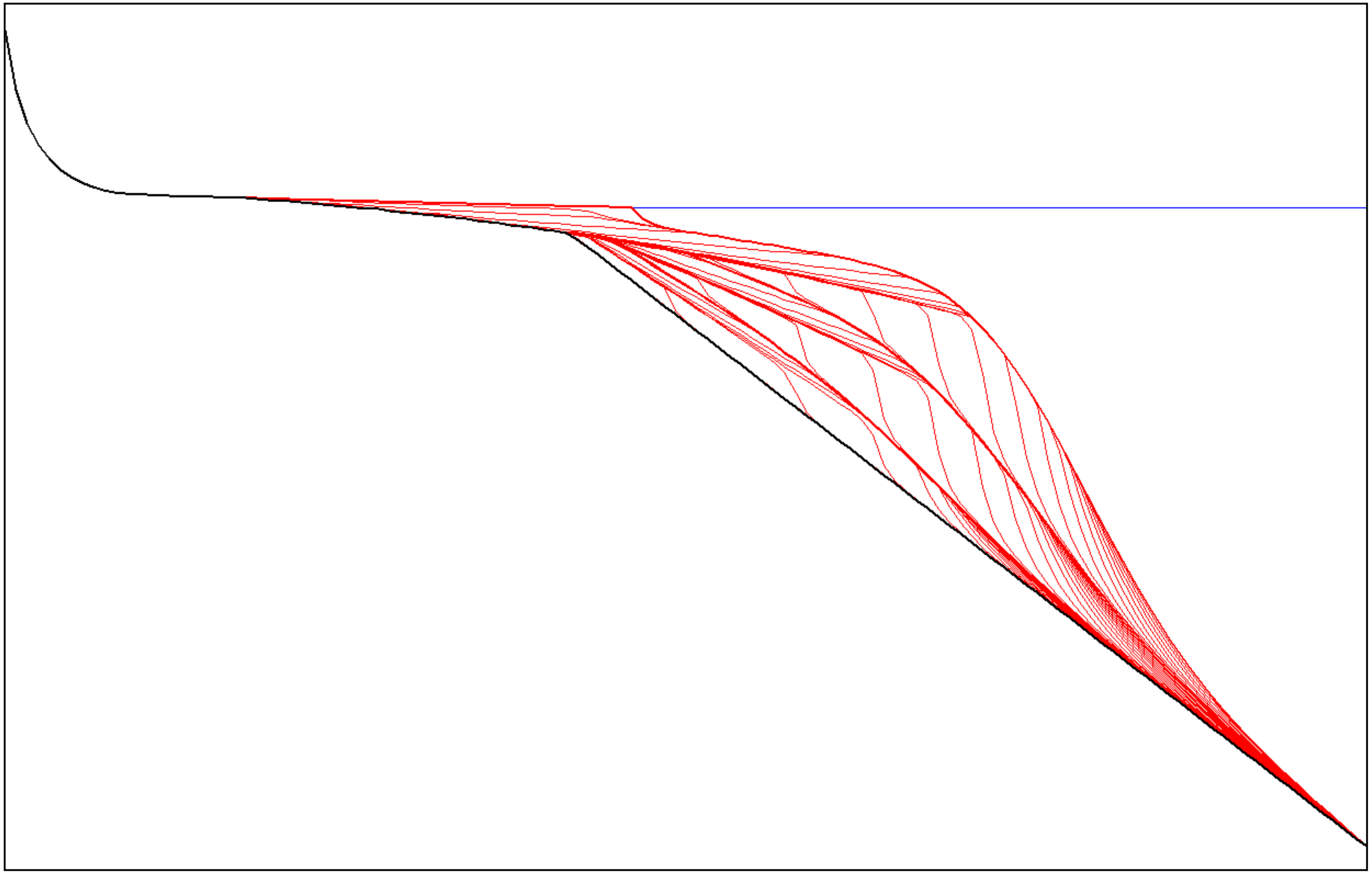
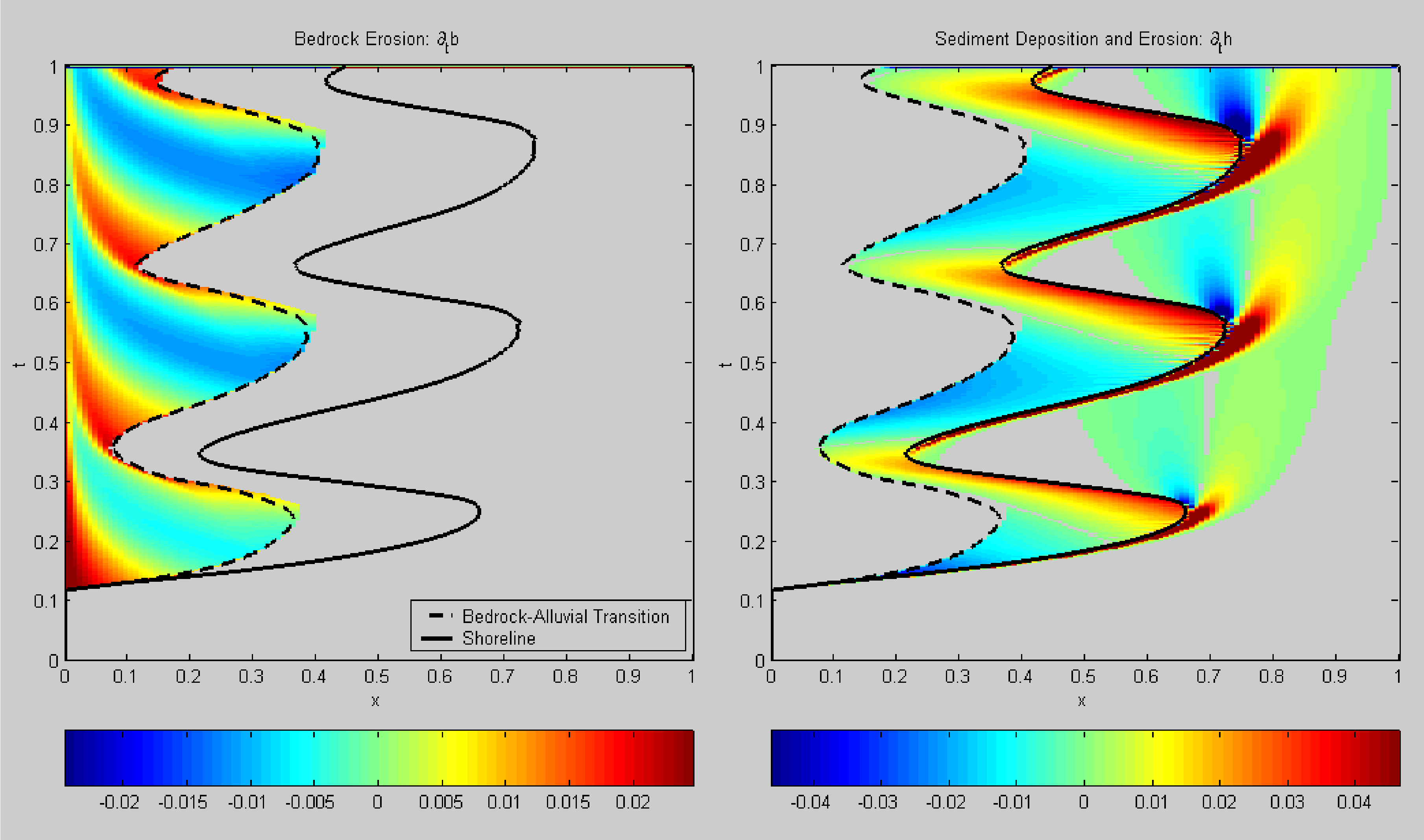


Simplified Bedrock-Alluvial-Marine Model

- Over long timescales source area corresponds to region of uplift, sink area corresponds to region of subsidence
- “Equilibrium” bedrock-alluvial transition = tectonic transition
- Sea level forcing causes shoreline migration, which forces migration of bedrock-alluvial transition
- Boundary migration triggers upstream waves of deposition and erosion, as seen by …

Depositional History and Moving Boundaries



Summary of Bedrock-Alluvial-Marine Model

- Large change (discontinuity) in deposition across shoreline, with strong localization of deposition (erosion) near shoreline

- Transgression triggers upstream waves of deposition in coastal plain (“upward tilt” to deposition contours)

- Sea level changes cause perturbations in relative uplift, preventing equilibrium bedrock channel profiles

- Perturbations in bedrock erosion rates “passively” advected upstream without decay (steady tectonics)

Gravel-Sand Transitions

- Typically downstream fining is relatively continuous within gravel-bed rivers and within sand-bed rivers

- However there is typically a rapid downstream transition in bed grain size and slope between these two river types

- Modeling formation and dynamics of gravel-sand transitions an essential component of the long profile model

- Two classes of models: explicit interface vs self-organized
  - Explicit interface models assume a sharp transition
  - Self-organized models allow for diffuse transitions

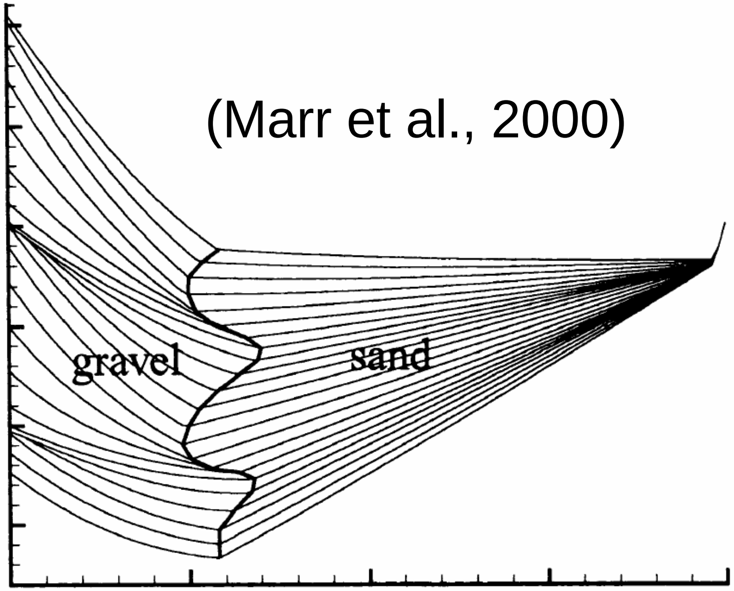
Explicit-Interface Gravel-Sand Models

Two grain sizes: gravel + sand

$$q = q_s + q_g$$

Aggregated diffusive flux law

$$\Phi = -\sigma\,, V = 0$$

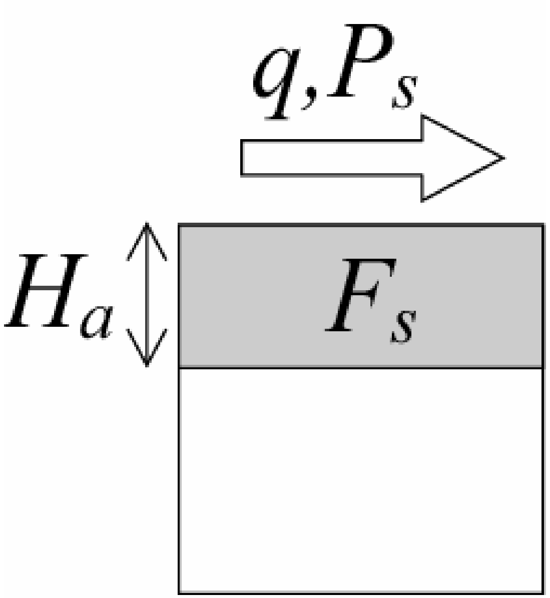


(Marr et al., 2000)

Environment	Threshold	κ	Deposition
Gravel	$q_g > 0$	κ_g	$\partial_x q_g$
Sand	$q_g = 0$	κ_s	$\partial_x q_s$

Self-Organized Gravel-Sand Models

Conservation of grain-size fractions (Hirano, 1971):



P_s = sand fraction in *transport*

F_s = sand fraction in *active layer*

H_a = active layer thickness

$$\boxed{H_a \partial_t F_s = \left(P_s - F_s\right) \partial_t \eta - q \partial_x P_s}$$

Mixed-Grain Bedload Flux

Grain-size specific (diffusive) flux laws

$$q_i = \left(Rg\right)^{-1} F_i W_i \tau^{3/2}$$

Quasi-static hydrodynamic momentum balance

$$\tau^{3/2} = \left(\sqrt{C_D}\, g\right) q_w S$$

Effective diffusivity averaged over bed composition

$$\kappa = \left\langle \kappa_i \right\rangle = F_s \kappa_s + F_g \kappa_g$$

Preferential Transport of Sand

Sand more mobile than gravel

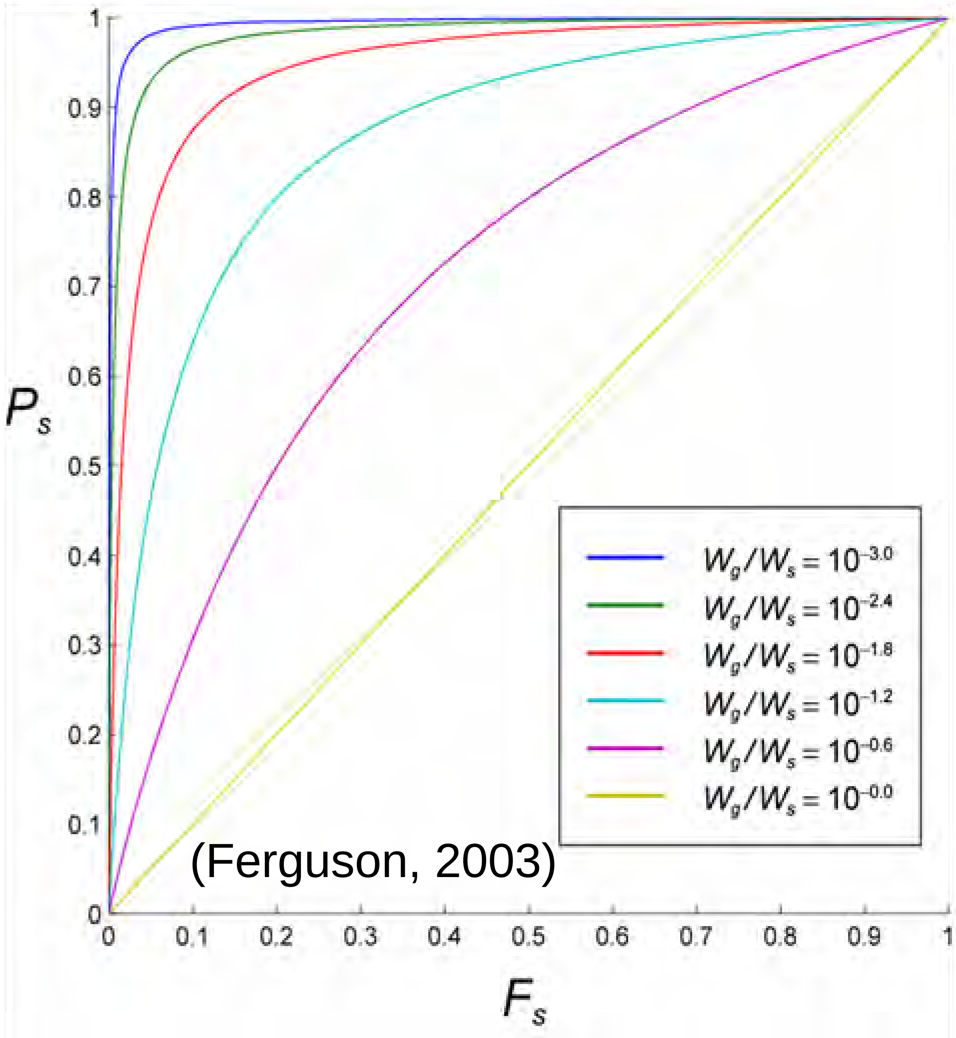
⇨

preferential sand transport

$$W_g = \varepsilon W_s$$

➡

$$\boxed{P_s = \frac{F_s}{\varepsilon + F_s\left(1-\varepsilon\right)}}$$



(Ferguson, 2003)

Transient Gravel-Sand Modeling

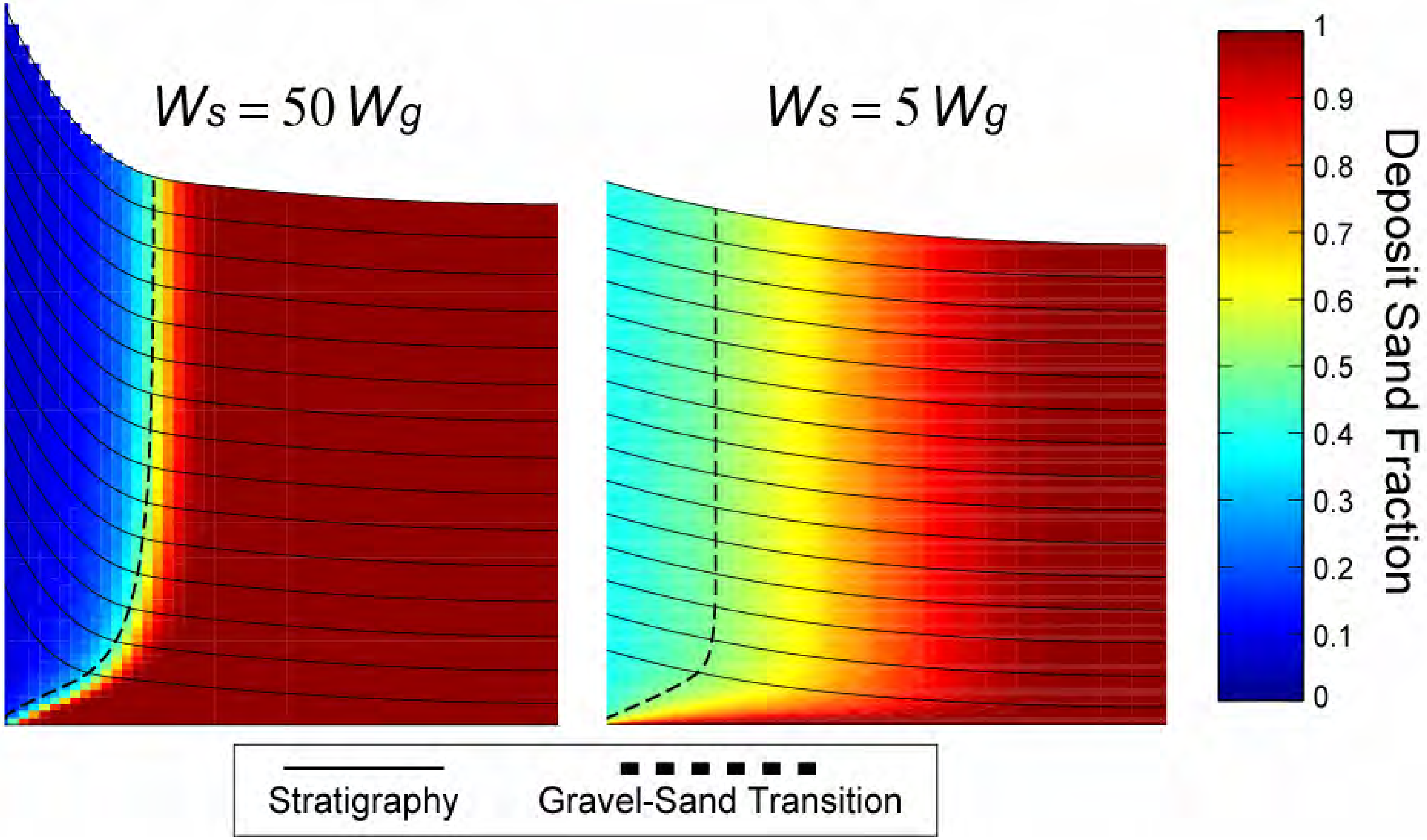
- Changes in external forcing → transient response
- Must solve transient Hirano with possibility of erosion
  - Must keep track of bed composition (i.e. stratigraphy)
  - Rarely able to solve transient Hirano analytically
- Stratigraphy is typically very dynamic
  - columns grow/shrink due to deposition/erosion
  - A difficult computational problem
- Use discrete data structure to efficiently store, access, and update stratigraphy … while hiding details from user

MATLAB Dynamic Stratigraphy Toolbox

$$\boxed{H_a \partial_t F_s = \left(P_s - F_s\right)\partial_t \eta - q \partial_x P_s}$$

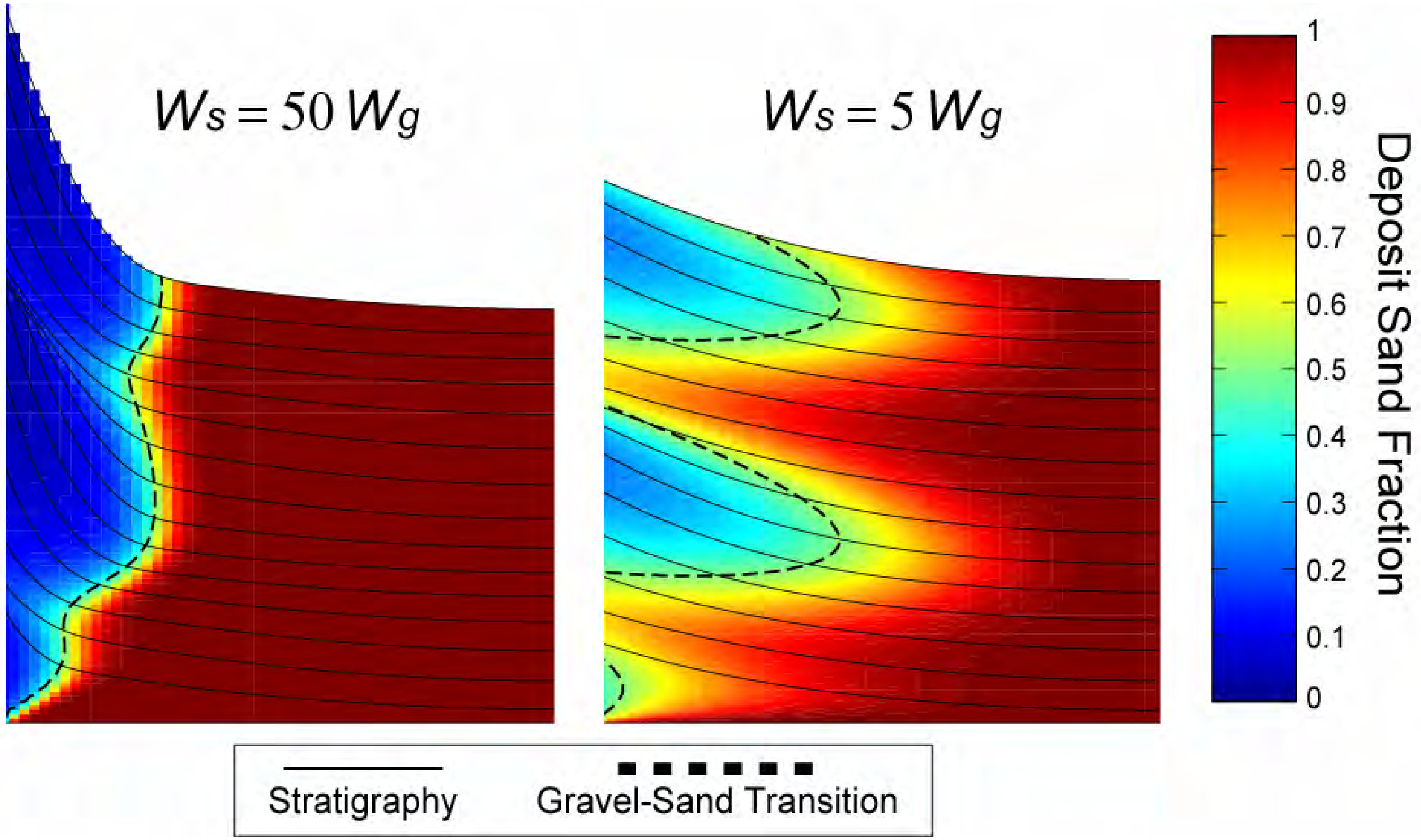
```
% SedLayer data structure
SedLayer = { dz,phi,tdep,F[Ngrain] }

% Matlab interface routines
StratPtr = InitStrat(eta0,Hactive,Ngrain)
  SrfLyr = GetSrfLyr(StratPtr,col)
    deta = ColUpdate(StratPtr,col,deta)
   Strat = GetStrat(StratPtr)
           FreeStrat(StratPtr)

% Matlab display routines
Zcont = ContourTime(Strat,Tcont)
        ShadeStrat(Strat,fname)
```

Transient Gravel-Sand Transition: Steady Forcing



Time to reach equilibrium appears to depend on two factors: 1) gravel diffusion time and 2) basin filling time

Transient Gravel-Sand Transition: Cyclic Forcing (P_{s0})



Sharp transition simulation has small fluctuations in interface position, but large fluctuations in slope (unconformities)

Example MATLAB Routine: Multi-Grain Diffusion

```
StratPtr=InitStrat(eta0,Hactive,Ngrain);
for i=1:nx-1
    % compute slope
    S=(eta(i)-eta(i+1))/dx;

    % compute diffusivities
    SrfLyr=GetSrfLyr(StratPtr,i);
    K=(SrfLyr.F).*W;

    % compute potential erosion/deposition
    dQ=Q-K*S; deta=dQ*dt/dx;

    % compute actual erosion/deposition
    deta=ColUpdate(StratPtr,i,deta);
    dQ=deta*dx/dt;

    % update surface and fluxes
    eta(i)=eta(i)+sum(deta); Q=Q-dQ;
end
Strat=GetStrat(StratPtr);
FreeStrat(StratPtr);
```

Sediment Density Currents: “Rivers of the Sea”

River Mechanics

Shear stress determined by slope and *water* flux …

Shear stress determines (equilibrium) sediment transport …

$$\boxed{Q_s \sim \tau \sim Q_w S}$$

Turbidity Current Mechanics

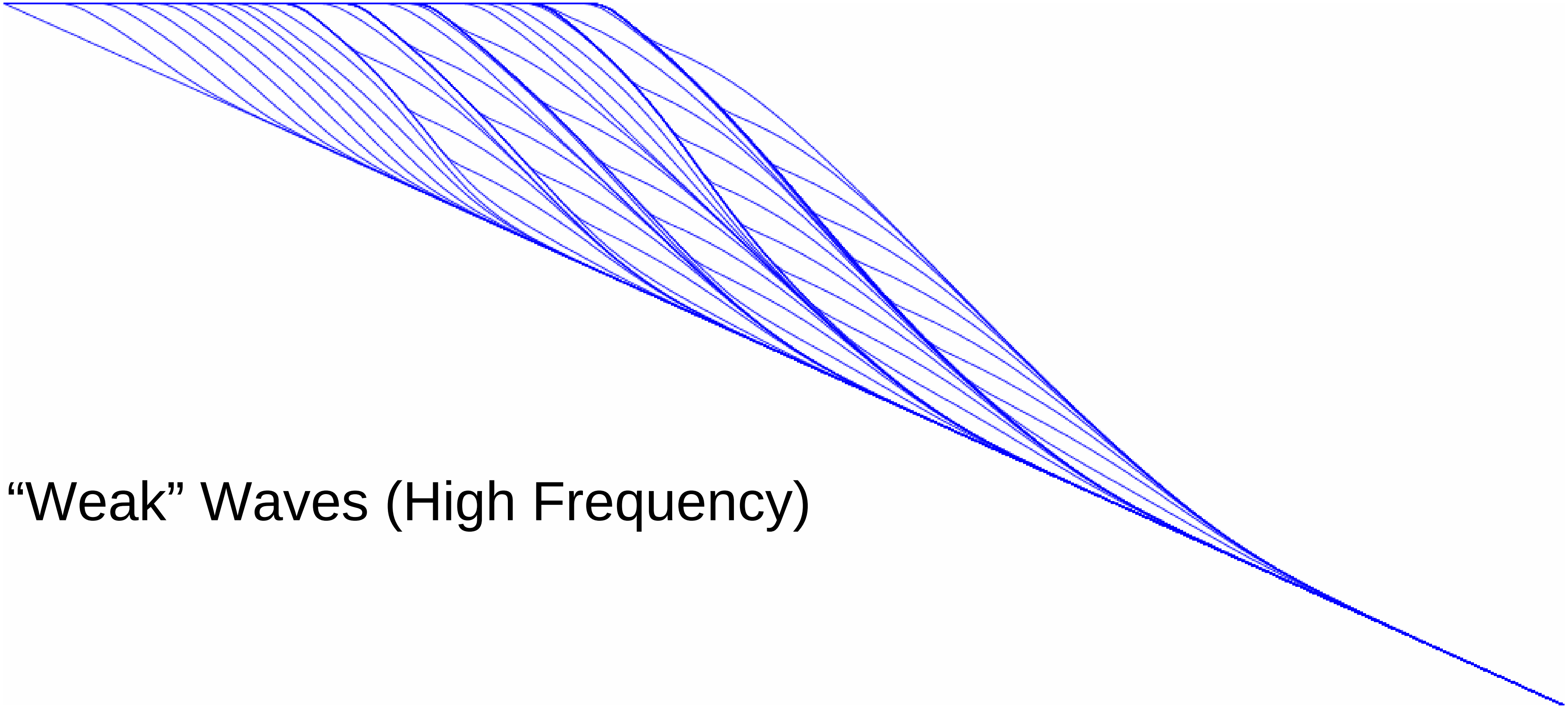
Shear stress determined by slope, *sediment* flux, and waves …

Stress determines (disequilibrium) sediment entrainment …

$$\boxed{\tau \sim Q_s S + u_w^2} \qquad \boxed{\partial_x Q_s \sim Q_s \left(1 - \tau / \tau_c\right)}$$

→ Sediment bypass occurs at critical shear stress

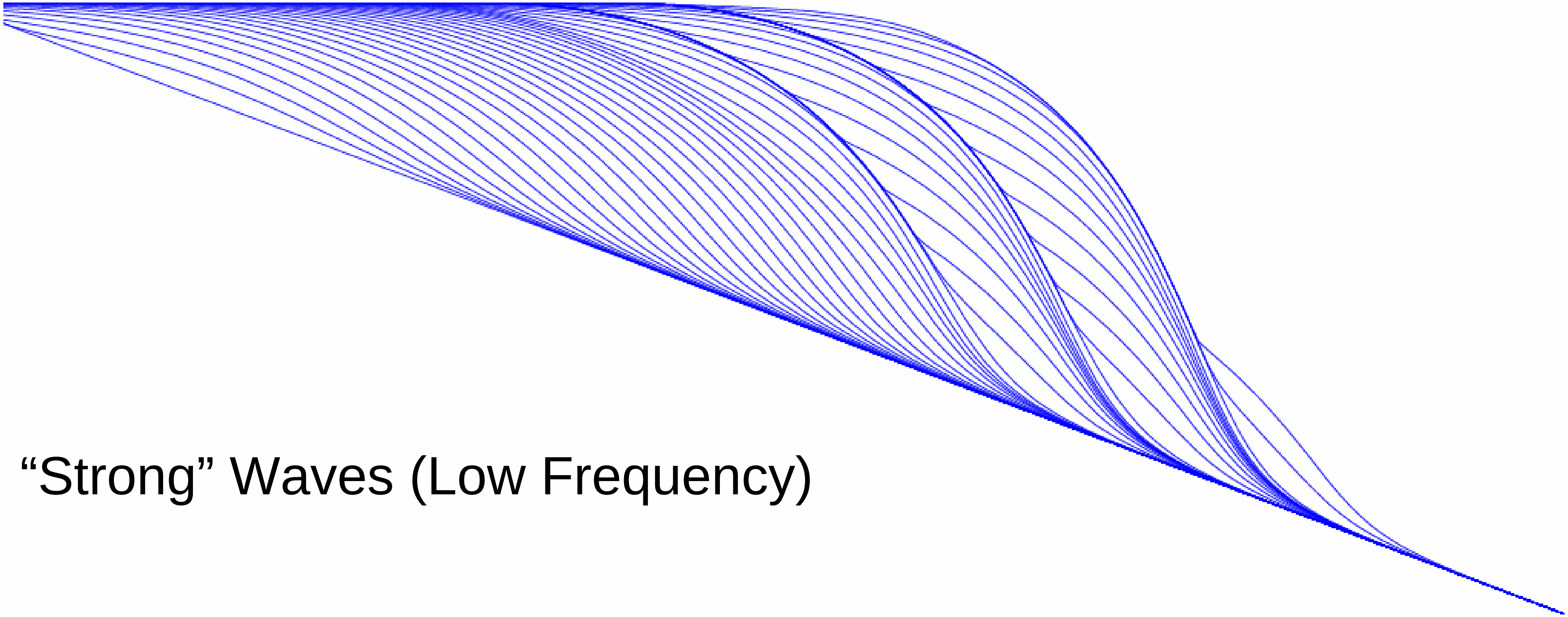
Marine Sedimentation: Example Simulation



“Weak” Waves (High Frequency)

Continental shelf is flat with sharp rollover, continental slope steepens until currents bypass, forming seafloor fans

Marine Sedimentation: Example Simulation



"Strong" Waves (Low Frequency)

Continental shelf is convex with gradual rollover

Future Work

- Complete alluvial component of long-profile model
  - Multiple grain sizes: gravel, sand, and mud
  - Quasi-2D Effects: floodplain deposition, valley incision

- Refine marine process models
  - Multiple grain sizes: sand and mud
  - Mixed mode transport: sand as bedload *and* suspended load

- Apply to natural systems
  - Waipaoa Sedimentary System (New Zealand), New Jersey Margin (NSF-MARGINS S2S)
  - Adriatic Margin (EUROSTRATAFORM)

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