# Earth-surface Dynamics Modeling & Model Coupling

## *A short course*

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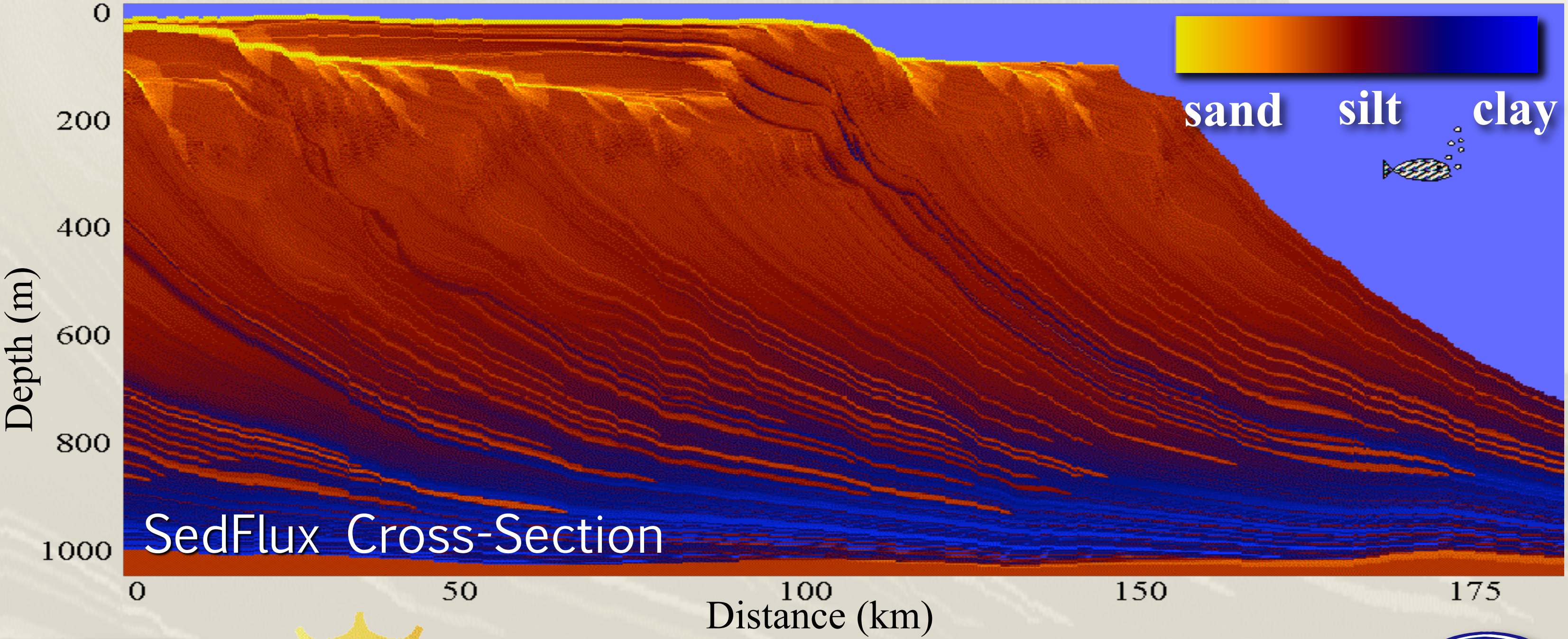
With special thanks to Irina Overeem, Mike Steckler, Lincoln Pratson, Dan Tetzlaff, John Swenson, Chris Paola, Cecelia Deluca, Olaf David



COMMUNITY SURFACE DYNAMICS MODELING SYSTEM

# Module 7: Source to Sink Numerical Modeling Approaches

ref: Syvitski, J.P.M. et al., 2007. Prediction of margin stratigraphy. In: C.A. Nittrouer, et al. (Eds.) Continental-Margin Sedimentation: From Sediment Transport to Sequence Stratigraphy. IAS Spec. Publ. No. 37: 459-530.

The S2S Modeling Challenge (1)

Linked Analytical Models (4)

e.g. *SEQUENCE4*

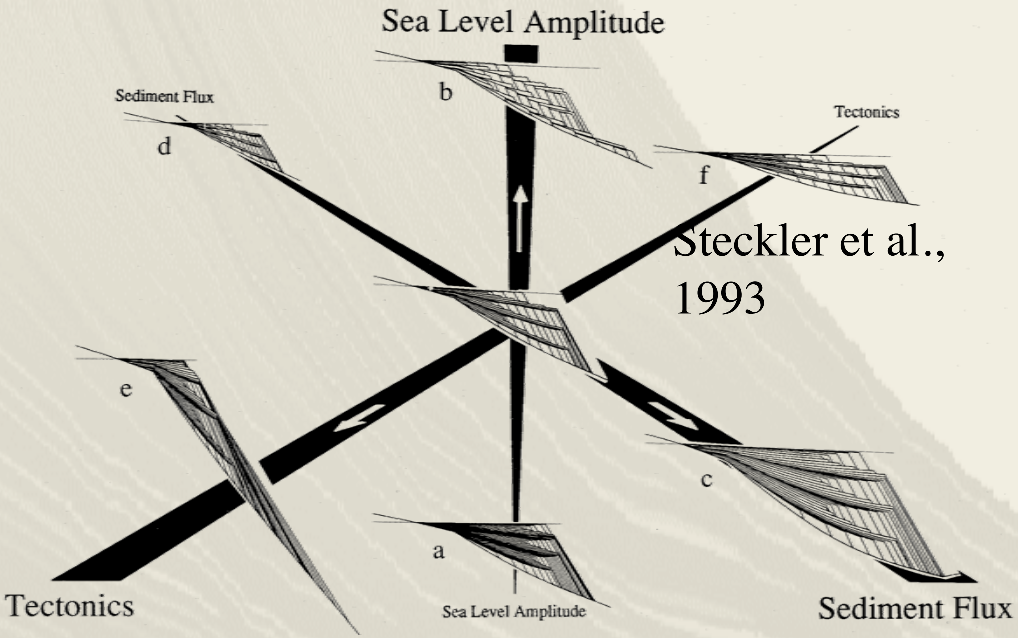
Linked Modular Numerical Models (9)

*e.g. TopoFlow, HydroTrend, CHILD, SedSim, SedFlux*

Computation Architecture (4)

e.g. *CSDMS, ESMF, OMS*

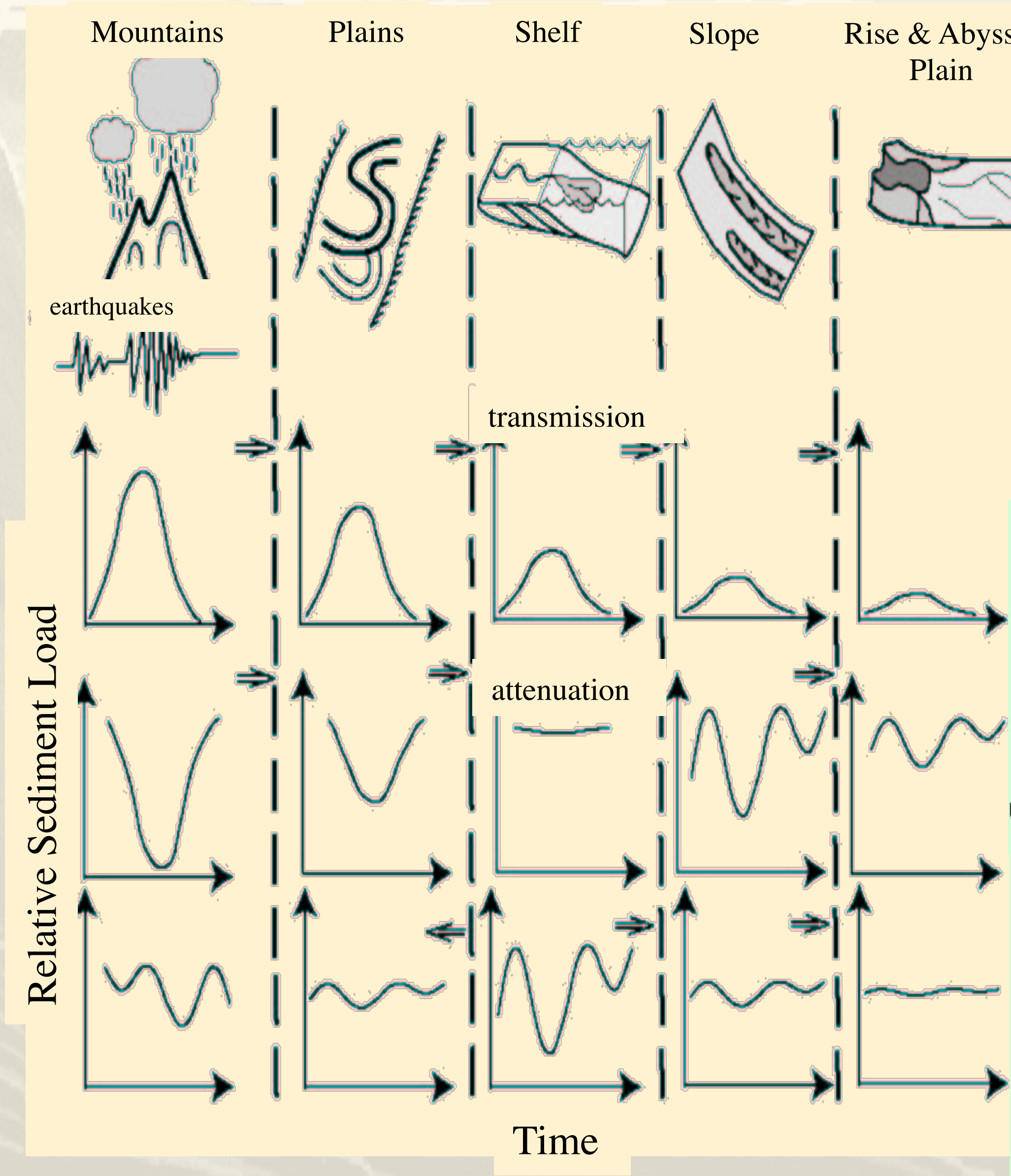
Summary (1)

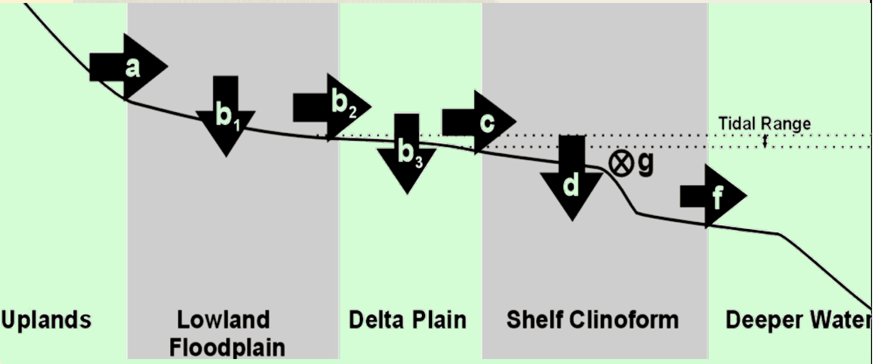


Steckler et al., 1993

# The S2S Modeling Challenge

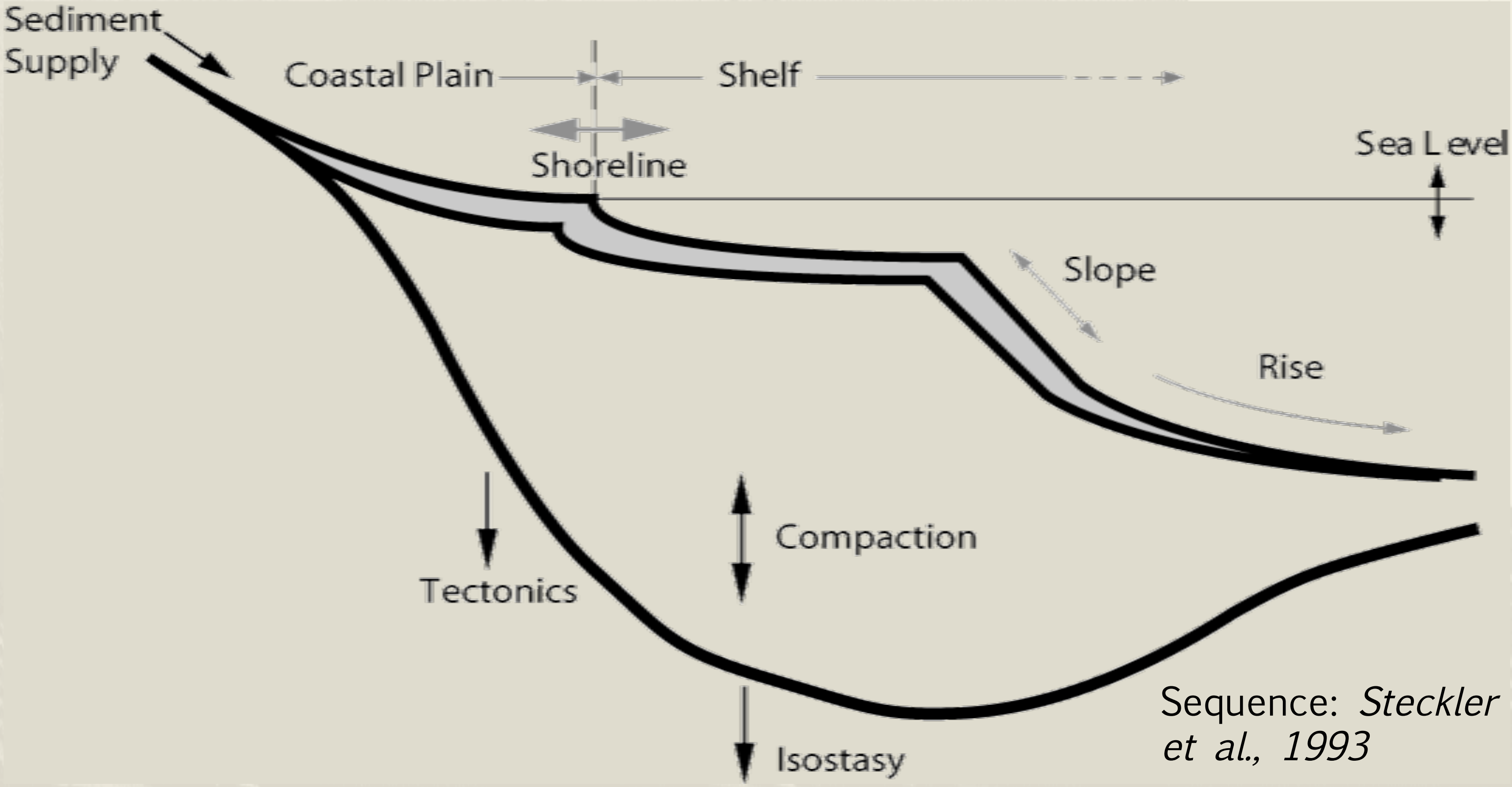
Quantitative prediction of material fluxes from source to sink





- Morphodynamics: production, transport, sequestration
- Signal tracing (transmission, attenuation)
- Marine/terrestrial coherency

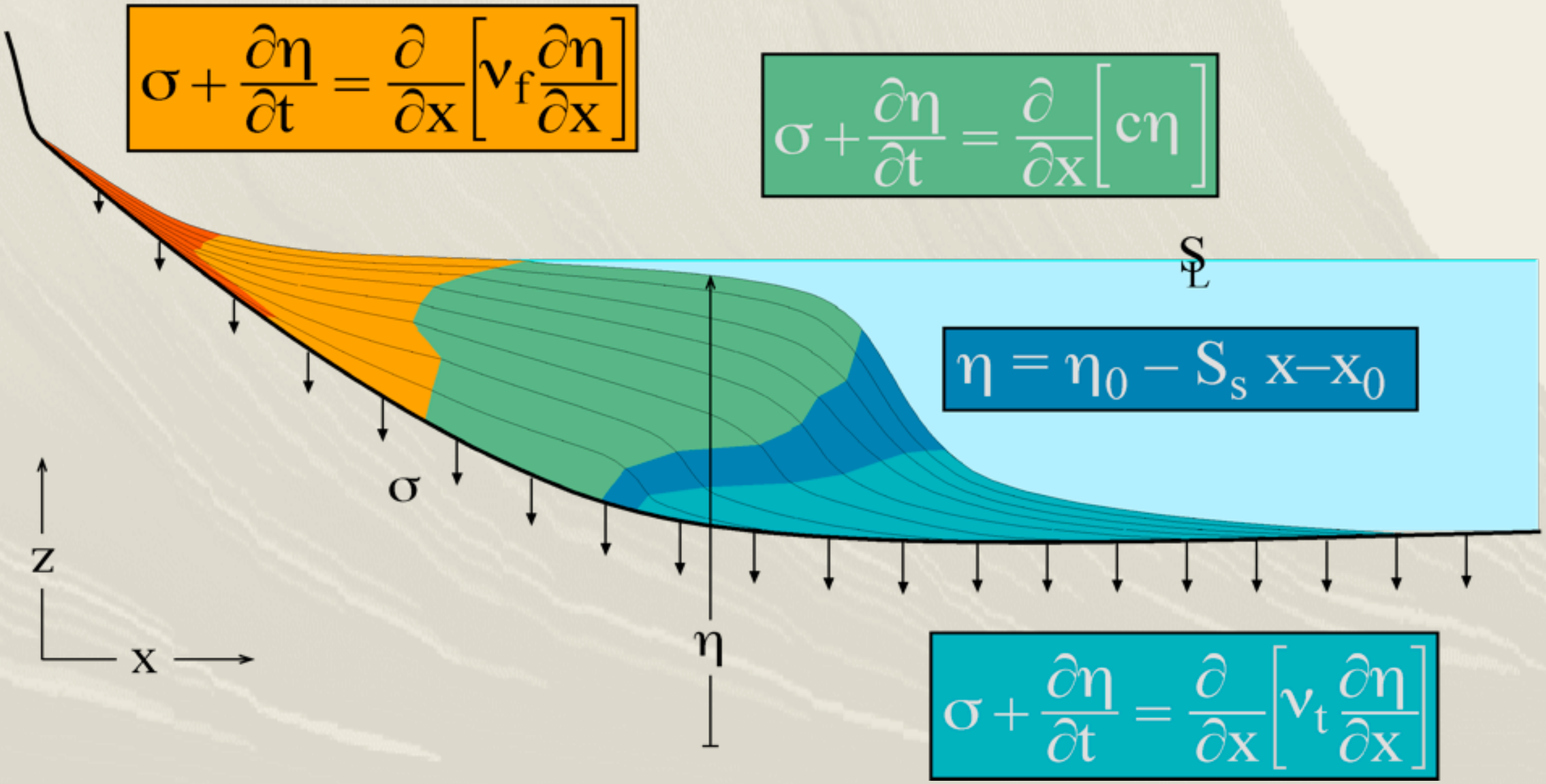
**Linked Analytical Models:** Key surface dynamics (e.g. sea level, sediment supply, compaction, & tectonics) and their moving boundaries are identified.



Sequence: *Steckler et al., 1993*

**Linked Analytical Models:** Expressions representing these surface dynamics are linked to conserve mass. Empirical coefficients are employed. E.g. Sequence (M Steckler & J Swenson & C Paola)

# An Integrated Margin Model

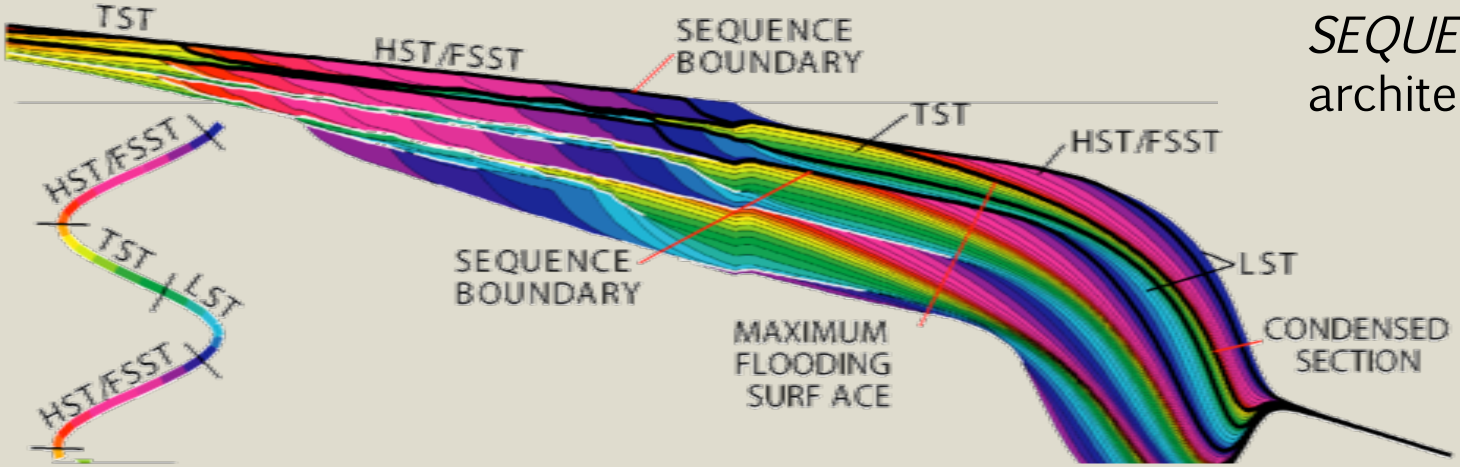


$$\sigma + \frac{\partial \eta}{\partial t} = \frac{\partial}{\partial x}\left[\nu_f \frac{\partial \eta}{\partial x}\right]$$

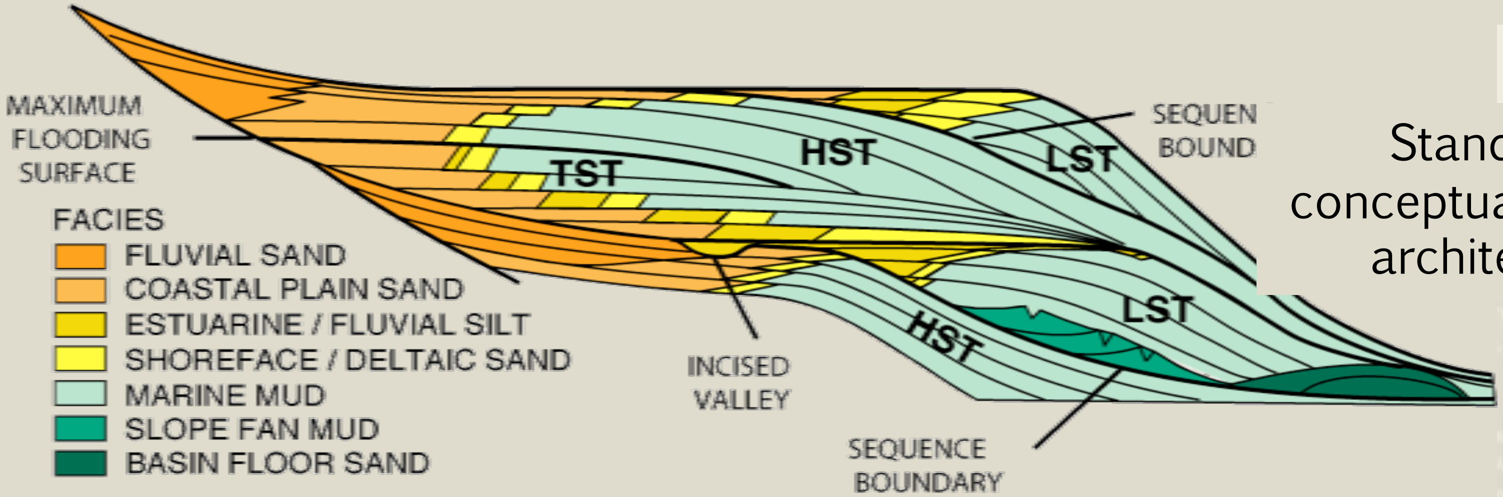
$$\sigma + \frac{\partial \eta}{\partial t} = \frac{\partial}{\partial x}\left[c\eta\right]$$

$$\eta = \eta_0 - S_s\ x - x_0$$

$$\sigma + \frac{\partial \eta}{\partial t} = \frac{\partial}{\partial x}\left[\nu_t \frac{\partial \eta}{\partial x}\right]$$



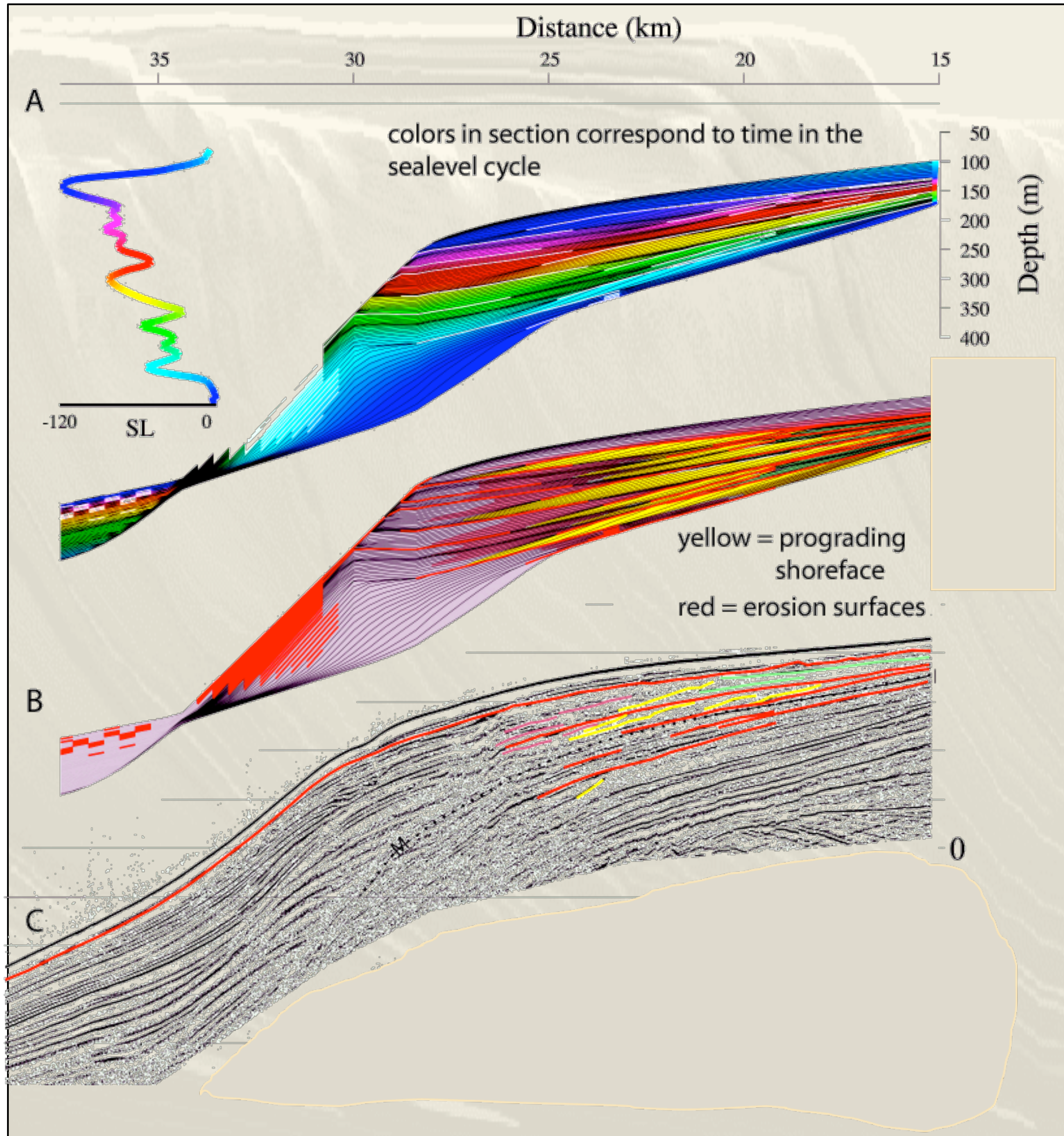
*SEQUENCE*
architecture



Standard
conceptual model
architecture

*SEQUENCE* simulation of the evolving systems tracts (defined as a package of sediment deposited within a sea-level cycle) uses bounding surfaces different than the standard model. *SEQUENCE* unconformities are time transgressive.

c/o M Steckler



SEQUENCE simulation of the Eel River margin for the last 125kyr showing
(A)Age distribution
(B)Sedimentary environment
(C)Interpreted seismic image

c/o M Steckler

In Syvitski et al., 2007

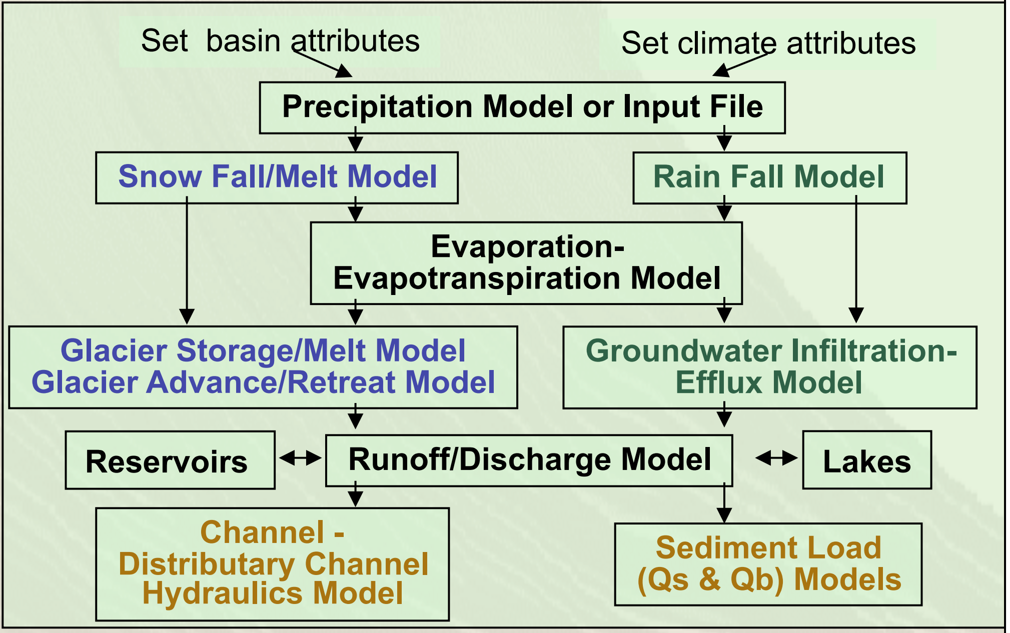
# Linked Modular Numerical Model:

1)Multiple fluid or geo dynamic modules to cover the S2S range,
2)Numerical Solutions (e.g. finite difference, implicit scheme)
3)Uber approach of high complexity, written in a single computer language,
4)Modules employ different levels of sophistication and resolution.

## *TopoFlow*

- Snowmelt (Degree-Day; Energy Balance)
- Precipitation (Uniform; varying in space and time)
- Evapotranspiration (Priestley-Taylor; Energy Balance)
- Infiltration (Green-Ampt; Smith-Parlange; Richards' eqn with 3 layers)
- Channel/overland flow (Kinematic; Diffusive; Dynamic Wave with Manning's formula or Law of Wall)
- Shallow subsurface flow (Darcian, multiple uniform layers)
- Flow diversions (sources, sinks and canals)

## *HydroTrend*



Set basin attributes
Set climate attributes
**Precipitation Model or Input File**
**Snow Fall/Melt Model**
**Rain Fall Model**
**Evaporation-Evapotranspiration Model**
**Glacier Storage/Melt Model**
**Glacier Advance/Retreat Model**
**Groundwater Infiltration-Efflux Model**
**Reservoirs**
**Runoff/Discharge Model**
**Lakes**
**Channel - Distributary Channel Hydraulics Model**
**Sediment Load (Qs & Qb) Models**

# CHILD after G. Tucker et al.

### 1. CONTINUITY LAWS

*Sediment:* $$\frac{\partial z}{\partial t} = U - \nabla \tilde{q}_s$$

*Water:* $$-\nabla \tilde{q} = R(x, y, t)$$

### 2. CLIMATE & HYDROLOGY

Stochastic, event-based storm sequence

Steady infiltration-excess or saturation-excess runoff

### 3. SOIL CREEP & VEGETATION

*Creep:* $$\tilde{q}_{cr} = -K_d \nabla z$$

Optional vegetation dynamics module

### 4. SHALLOW LANDSLIDING

(1) Nonlinear diffusion:

$$\frac{\partial z}{\partial t} = \frac{\partial}{\partial t}\left(-\kappa(z_x, t)\frac{\partial z}{\partial x}\right)$$

(2) Event-based approach

$$\tilde{q}_{ls} = \frac{K_d \nabla z}{1 - (|\nabla z| / S_c)^2}$$

### 5. FLUVIAL TRANSPORT & EROSION / DEPOSITION

$$\tilde{q}_f = f(q, S, D_{50}, q_s)$$

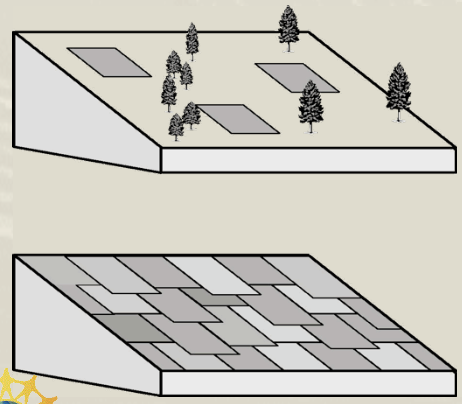
6 alternative transport laws

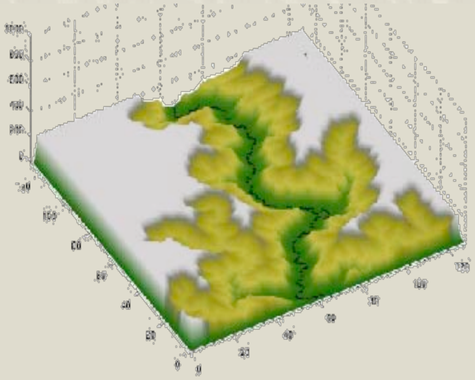
4 detachment-transport laws

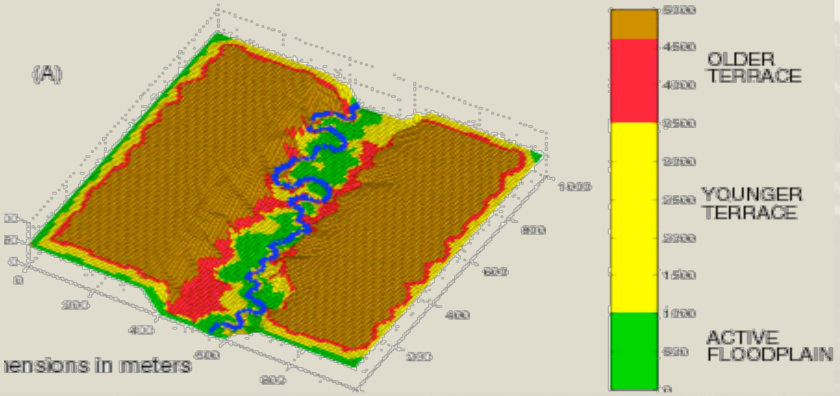
### 6. GRIDDING & NUMERICS

*Space:* irregular discretization using Delaunay triangulation; finite-volume solution scheme

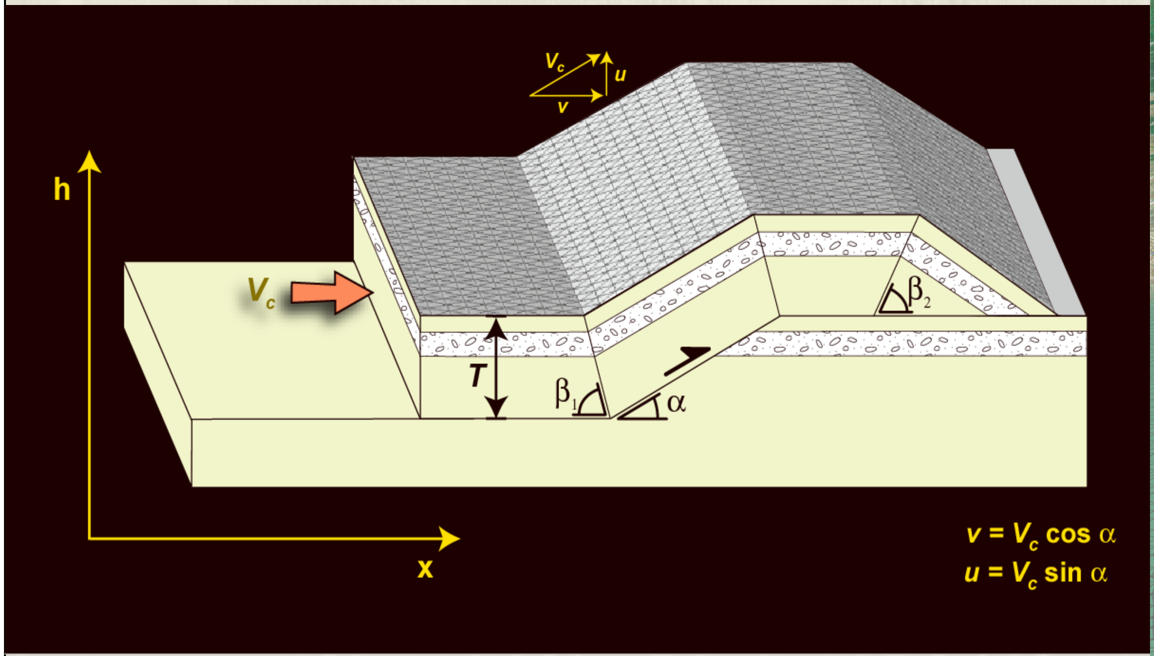
*Time:* event-based with adaptive time-stepping

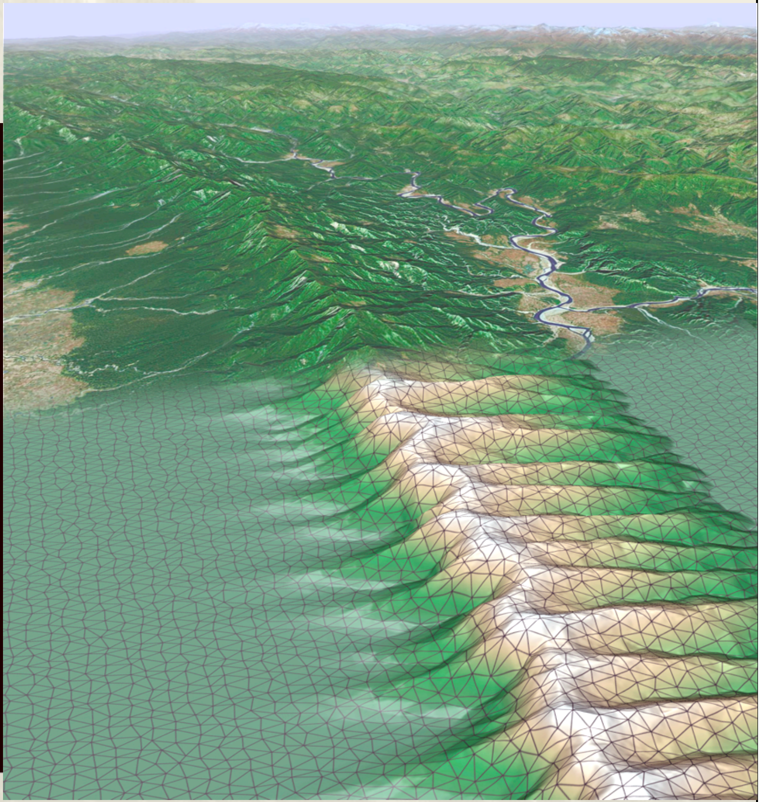






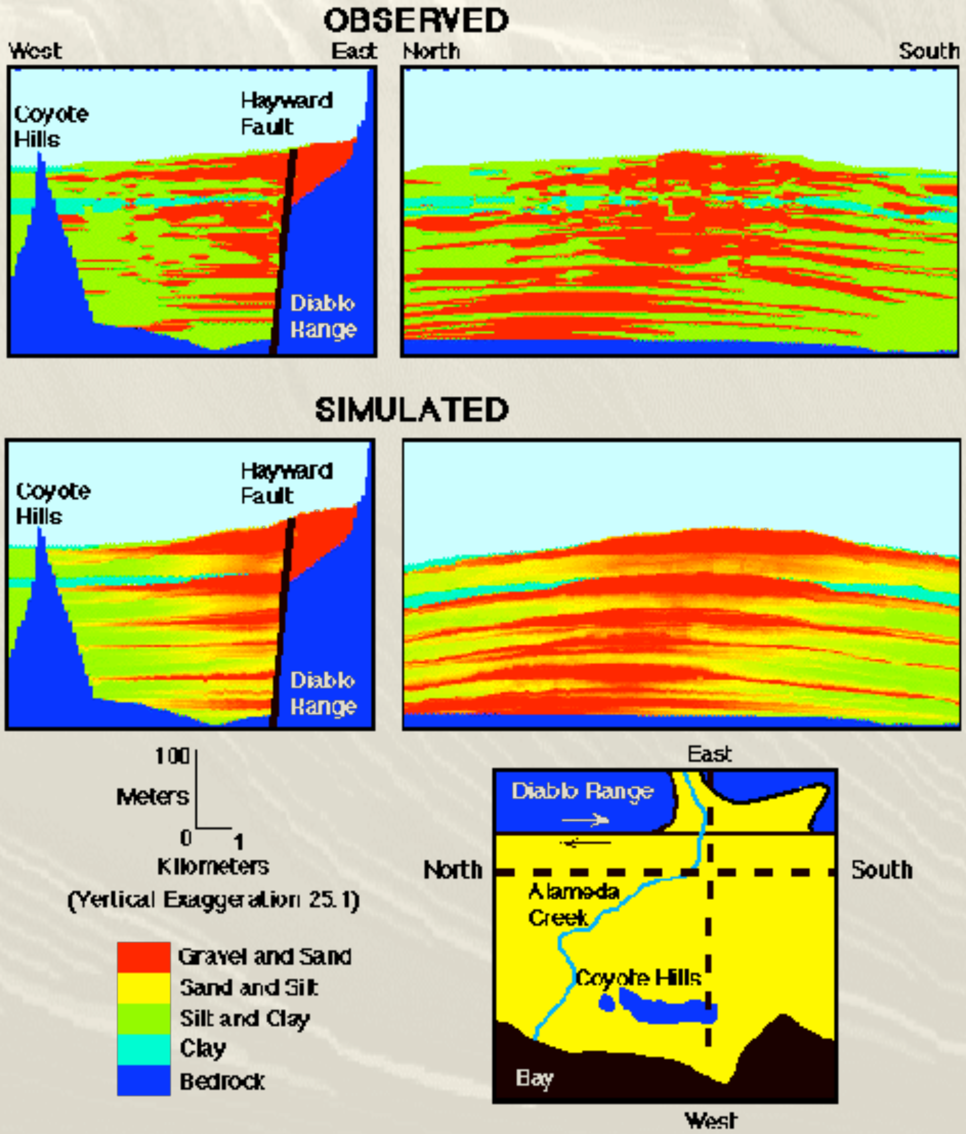
# CHILD + Lateral Advection (after R Slingerland)





$$\frac{\partial h^*}{\partial t^*} = u^* - v^* \frac{\partial h^*}{\partial x^*} + \frac{k_d}{TV_c}\left(\frac{\partial^2 h^*}{\partial x^{*2}} + \frac{\partial^2 h^*}{\partial y^{*2}}\right) + \frac{KT}{V_c}\left[A^*\left(\frac{\partial h^*}{\partial x^*}\right)\right]$$

# SEDSIM (after Dan Tetzlaff)

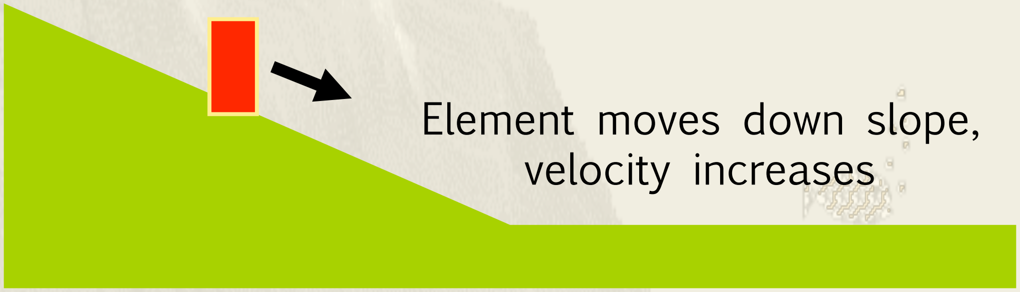


- Led by John Harbaugh (Stanford)
- Uses 'marker-in-cell' method
- Mixed Eulerian-Lagrangian
- Development largely closed

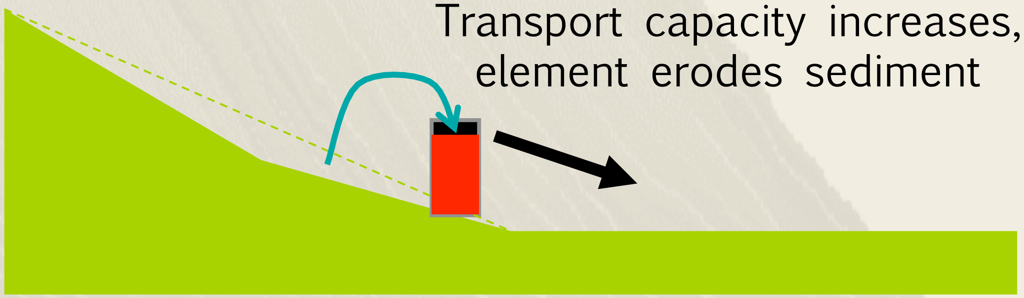
Kolterman & Gorelick (1992)

# Simplified Fluid Element Mechanism

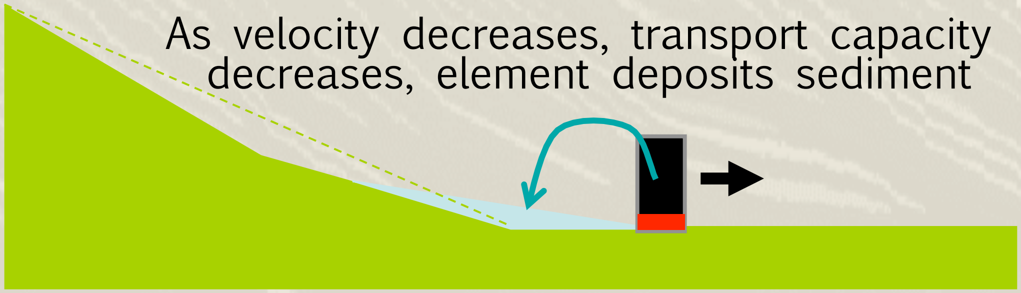
- 2D flow simulation (2D flow + depth)
- 3D sedimentary deposits
- Multiple sediment types, continuous mix
- Particle-in-cell method:
  - Uses particles or “fluid elements” moving on a grid
  - Facilitates modeling of highly unsteady flow
  - Prevents numerical dispersion for sediment transport



Element moves down slope, velocity increases

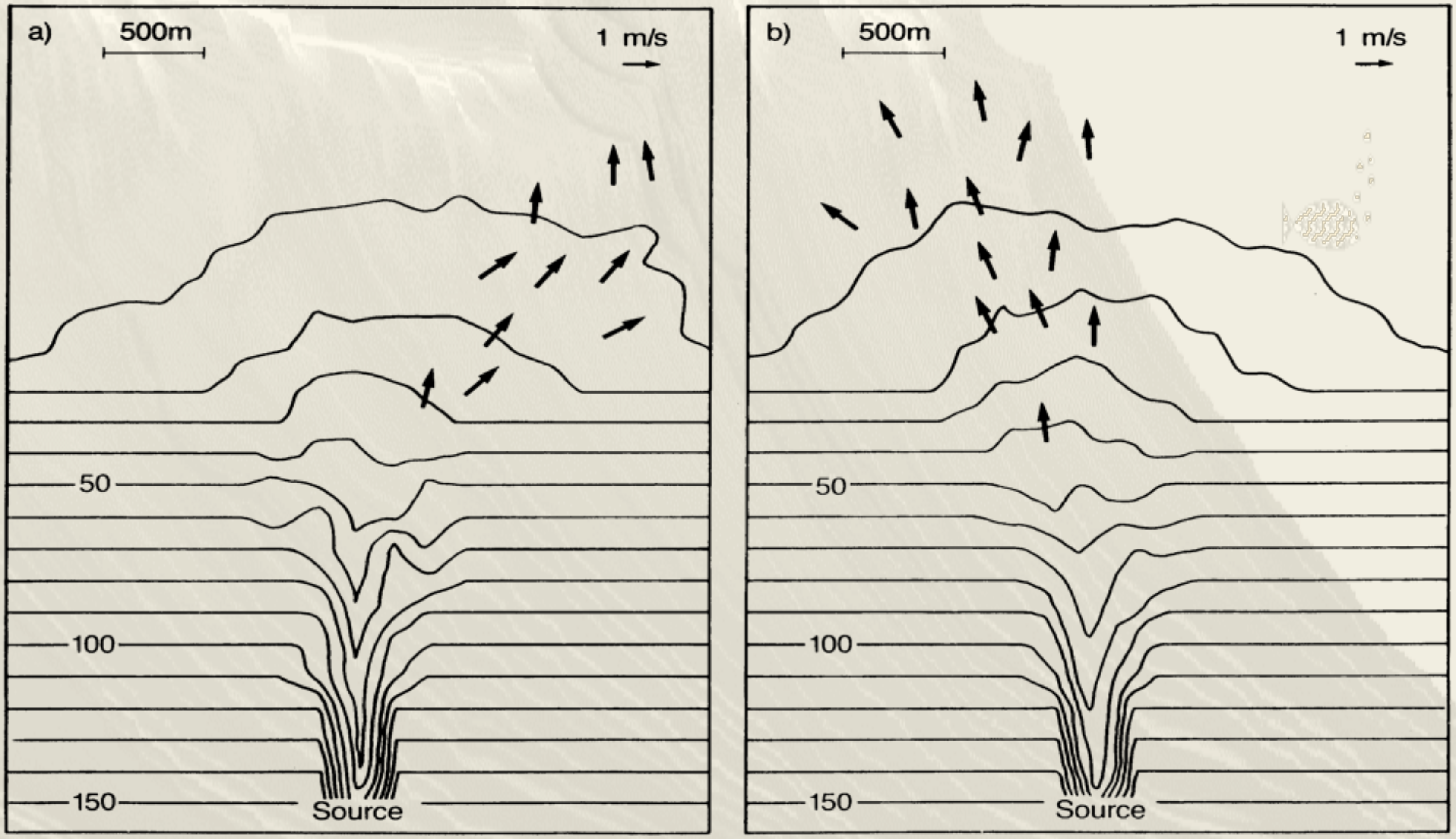


Transport capacity increases, element erodes sediment



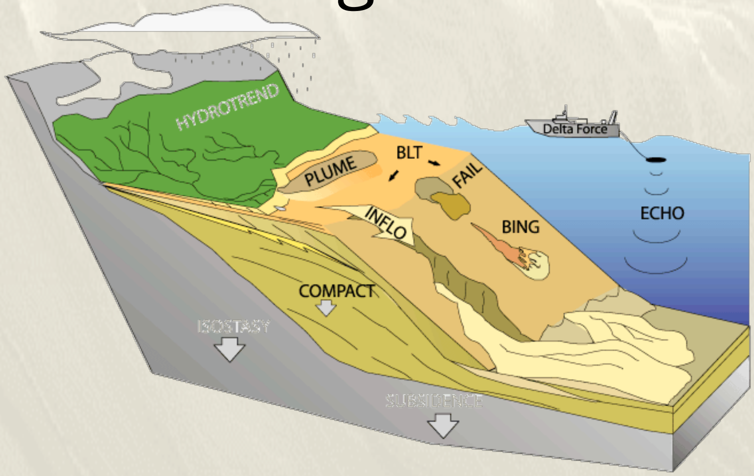
As velocity decreases, transport capacity decreases, element deposits sediment

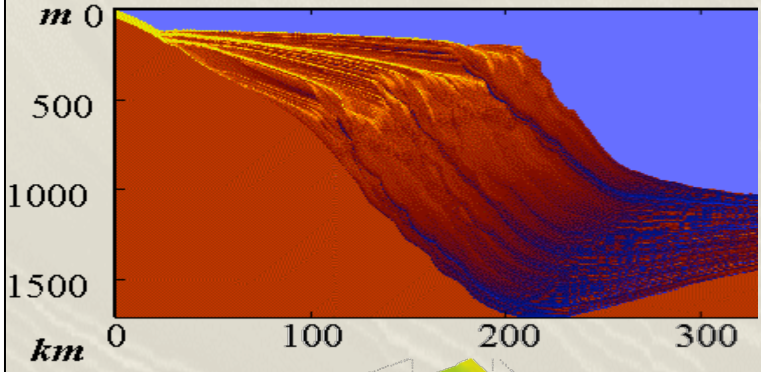
# Chaotic Behavior in SEDSIM

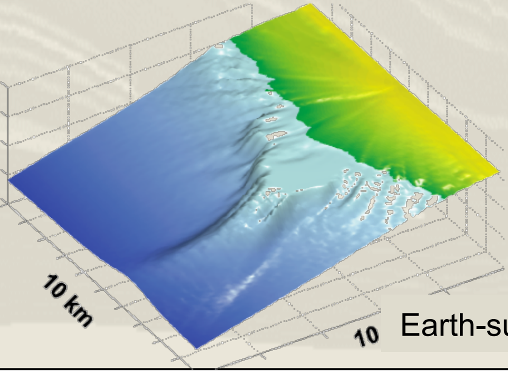


After simulating several high-density turbidity currents, the model settles into a pattern that is neither cyclic nor totally disordered. Extremely small changes in input (left vs. right figure) will cause the flow to exit in different directions.

# SedFlux Modular Modeling Scheme







## Hydrological Data or Model (e.g. HydroTrend)

daily Q, Qs, Q, Cs, grain size, river velocity, river channel size

+

## Ocean State:

sea level, waves, tides, currents, sea temperature & salinity

## Delta Models:

distributary channel dynamics, channel hydraulics, bedload dynamics
longshore transport, tidal dynamics

## River Plume Models:

hypopycnal plume dynamics, hyperpycnal plume dynamics

## Shelf Transport Models:

bottom boundary layer dynamics (wave, current interactions)
fluid muds, upwelling, downwelling

erosion, deposition, seafloor properties, stratigraphy

## Geotechnical Models:

compaction, porosity, permeability,
excess pore pressure, plasticity, sediment viscosity

## Slope Stability Models:

sediment strength, potential failure planes
earthquake loading, sediment loading

Failure volume and properties

## Gravity Flow Models:

Turbidity Current dynamics, Debris flow dynamics

erosion, deposition, seafloor properties, stratigraphy

## Geophysical Models:

tectonics (folding, faulting), isostasy, flexural response

## Acoustic Models:

sound scattering and attenuation

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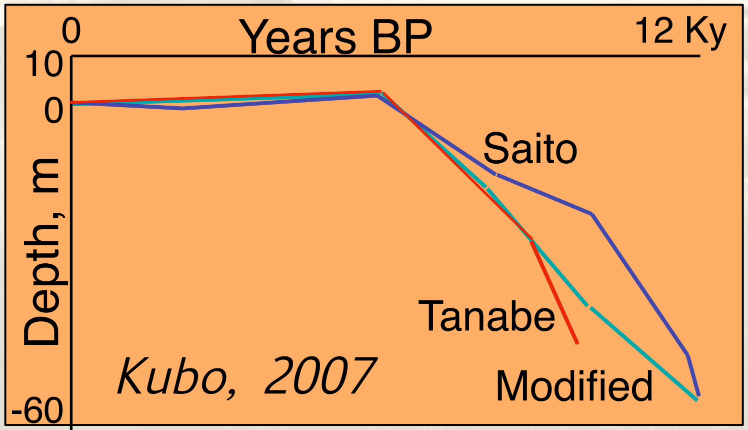
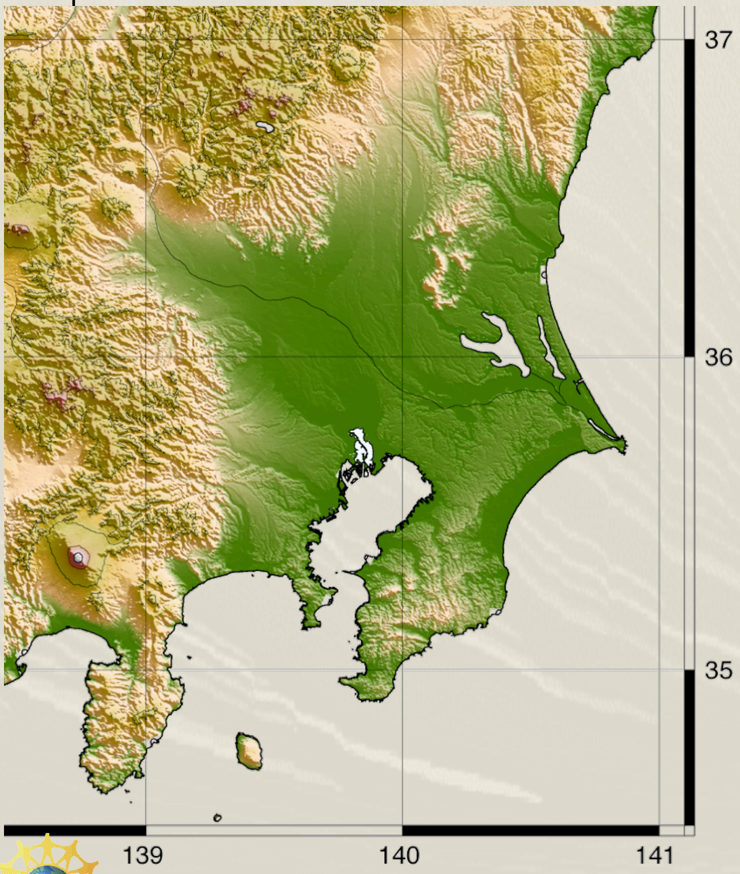
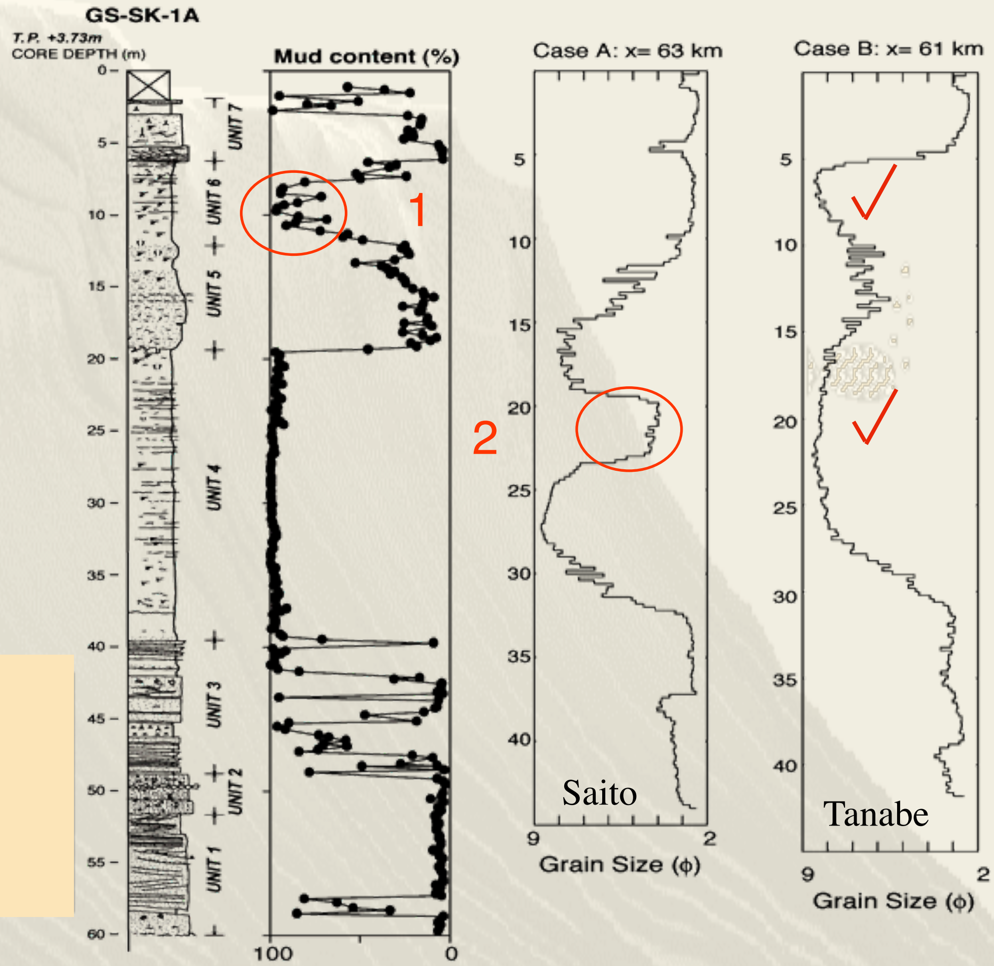
# *SedFlux Contributors 1985-2008*

- Bernie Boudreau – Oceanography
- Carl Friedrichs - Oceanography
- Chris Reed - Aerospace Engineering
- Damian O'Grady – Geological Sciences
- Dave Bahr - Geophysics
- Elizabeth Calabrese – Computer Science
- Eric Hutton - Engineering Physics
- Gary Parker - Civil Engineering
- Homa Lee - Geotechnical Engineering
- Irina Overeem – Geological Sciences
- Jacques Locat - Geological Engineering
- James Syvitski - Oceanography
- Jane Alcott - Geological Engineering
- Chris Paola - Geoscientist
- Jasim Imran - Civil Engineering
- Jeff Wong – Geotechnical Engineering
- John Smith – Chemistry
- Ken Skene – Oceanography
- Lincoln Pratson - Geophysics
- Mark Morehead - Geophysics
- Mike Steckler - Geophysics
- Patricia Wiberg - Sedimentology
- Rick Sarg – Geological Sciences
- Scott Peckham -Geophysics
- Scott Stewart - Aerospace Engineering
- Steve Daughney – Chemical Engineering
- Thierry Mulder – Geotech. Engineering
- Yu'suke Kubo - Geoscientist

*SedFlux* Master: Eric W.H. Hutton

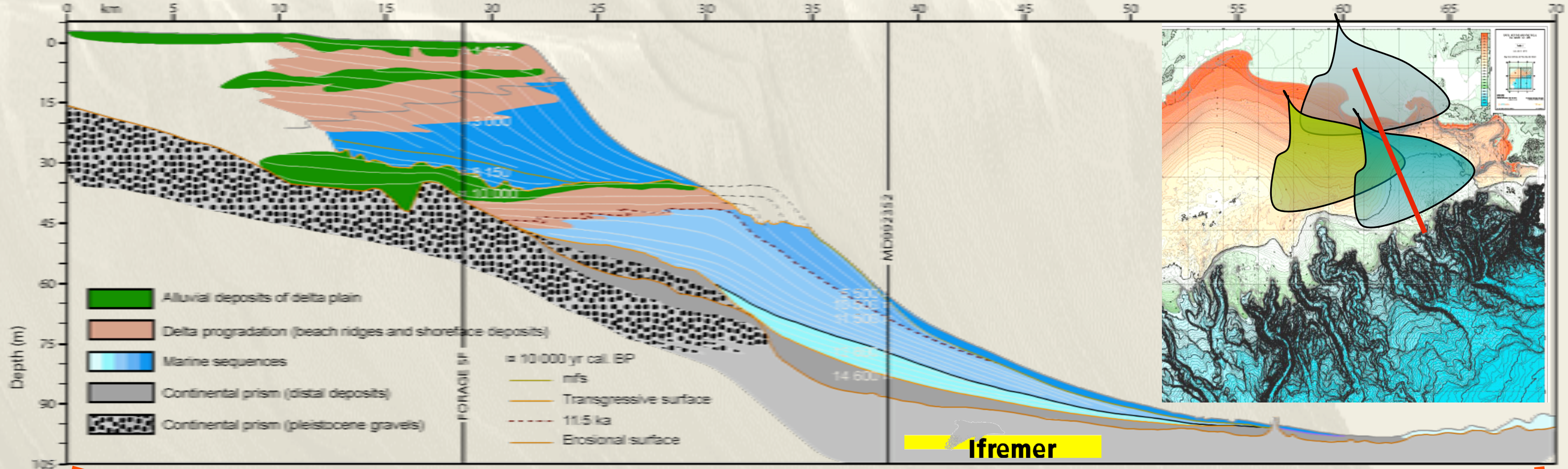


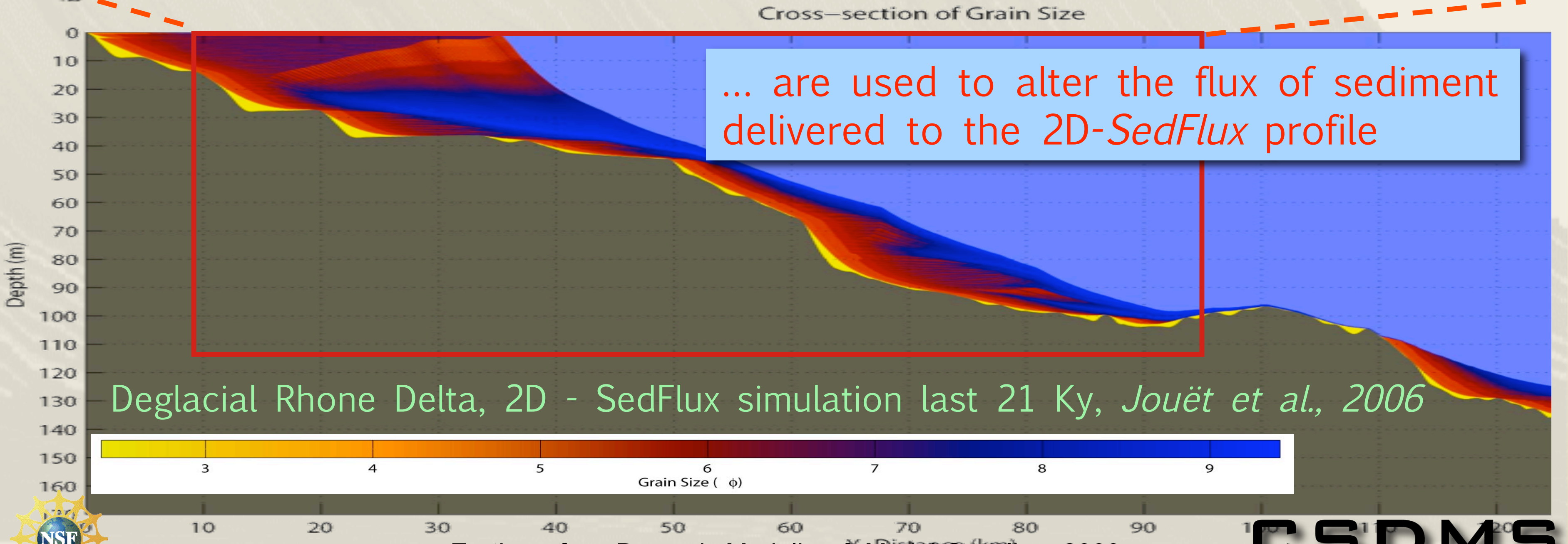




Using local sea level data (Tanabe) can substantively improve *SedFlux* predictions over inputs from outside the basin (Saito).

# Autocyclic details such as distances off profile of lobes …





… are used to alter the flux of sediment delivered to the 2D-*SedFlux* profile

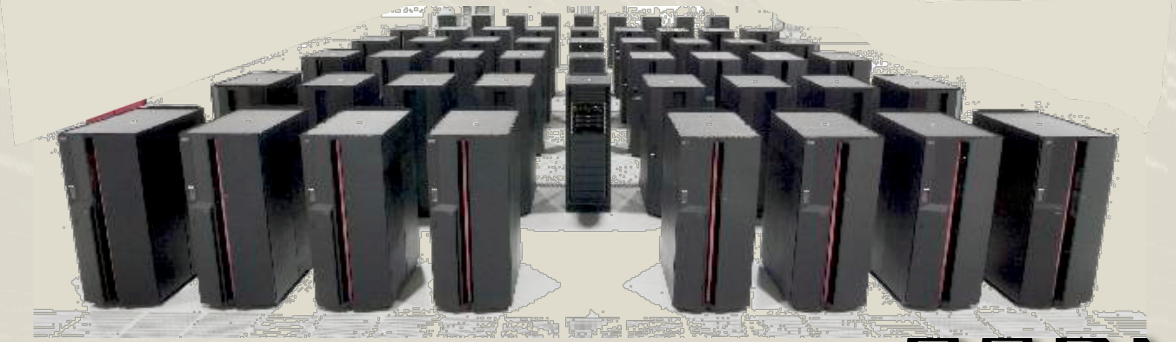
Deglacial Rhone Delta, 2D - SedFlux simulation last 21 Ky, *Jouët et al., 2006*

# Computational Framework and Architecture

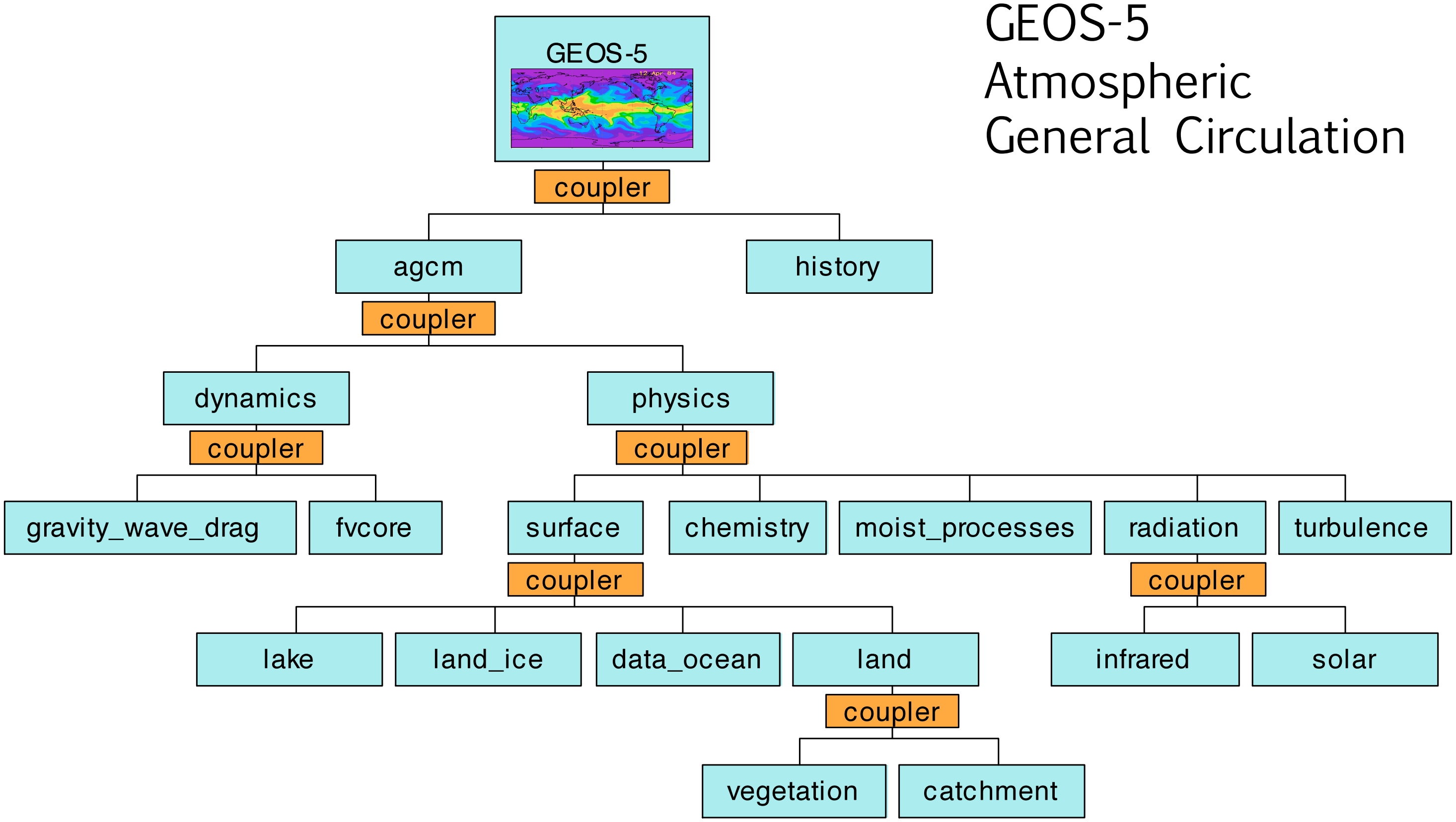
Modelers follow simple community-developed protocols that allow S2S component models to be linked.

Geological problems are matched with appropriate modules from a library of open-source code, with due consideration of the appropriate time & space resolution requirements.

The Community Surface Dynamic Modeling System (CSDMS) involving contributions from ≈300 scientists is perhaps the best coordinated effort working on Earth-surface problems with >100models, providing platform independence, and when required, massively-parallel or high performance computers. Other examples include the ESMF (climate-ocean applications), OpenMI (hydrological applications), and OMS (landuse applications).



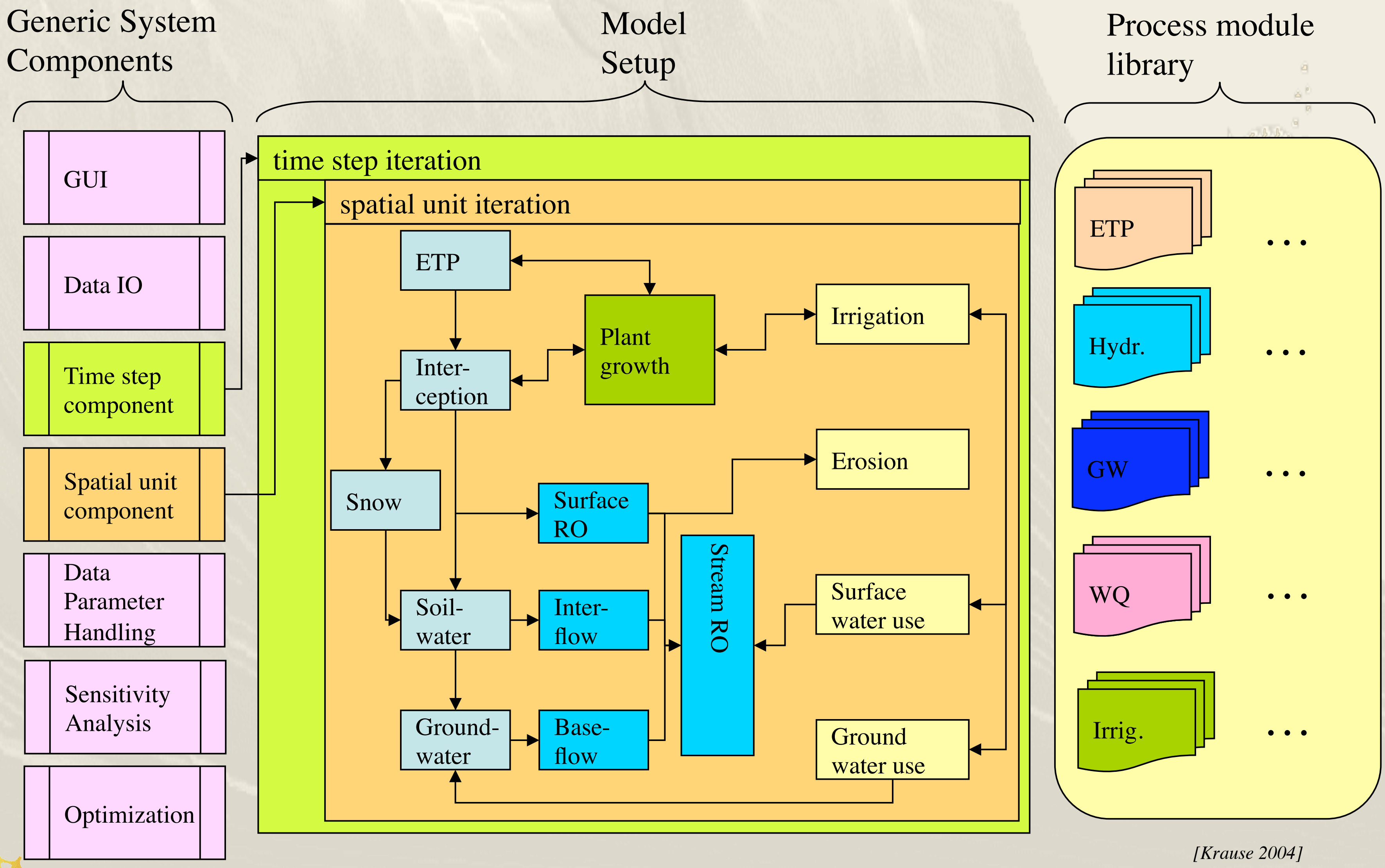
# ESMF Application Example



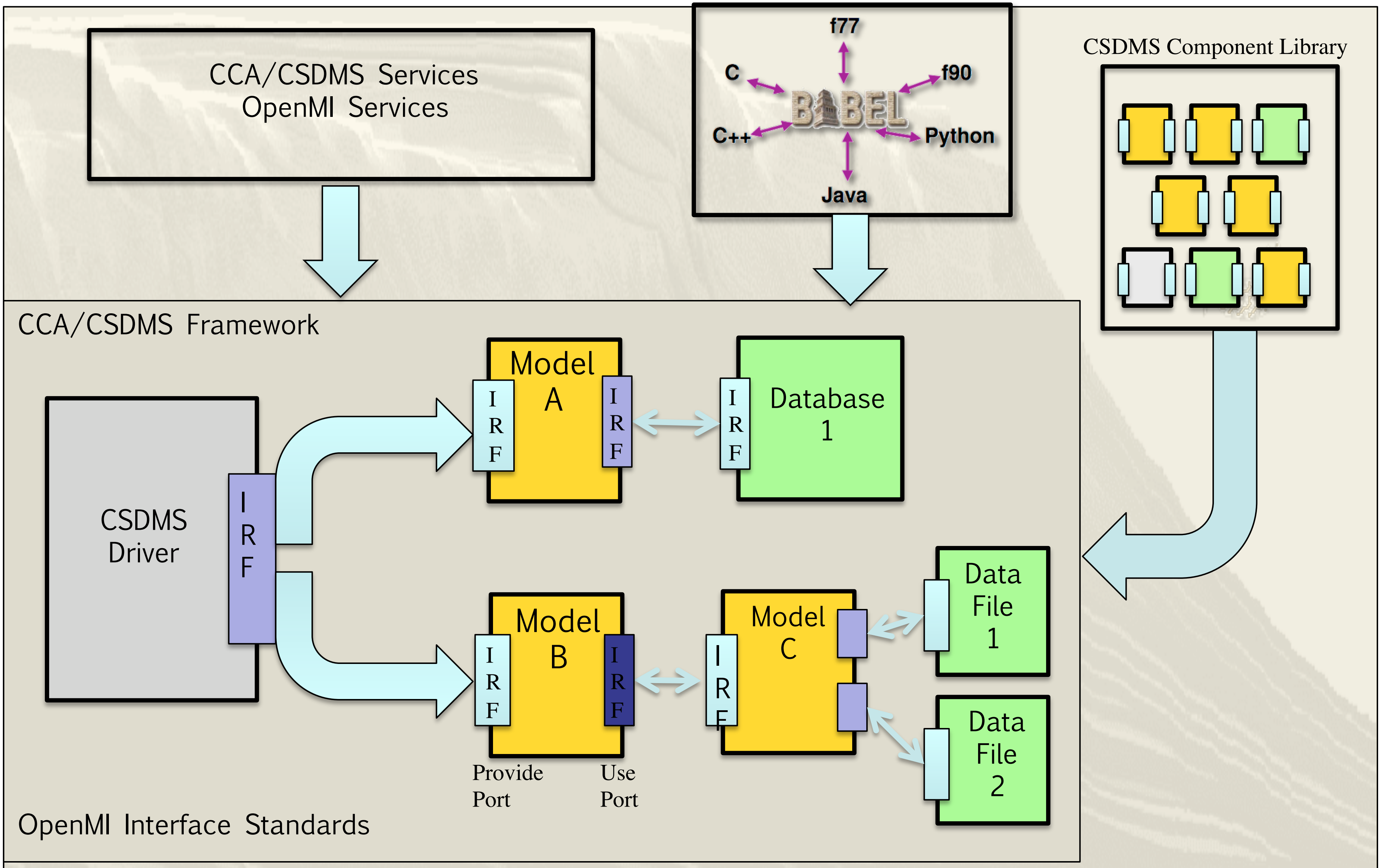
GEOS-5
Atmospheric
General Circulation

- Each box is an ESMF component
- Every component has a standard interface to facilitate exchanges
- Hierarchical architecture enables the systematic assembly of many different systems

# OMS Principle Modelling System Structure



*[Krause 2004]*



CCA/CSDMS Services
OpenMI Services

f77
C
f90
BABEL
C++
Python
Java

CSDMS Component Library

CCA/CSDMS Framework

CSDMS Driver

IRF

Model A

IRF

IRF

Database 1

Model B

IRF

IRF

Model C

IRF

Data File 1

Data File 2

Provide Port

Use Port

OpenMI Interface Standards

Earth-surface Dynamic Modeling & Model Coupling, 2009

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# Summary S2S Modeling Challenge

## Linked Analytical Equation Models

- big picture insight into main S2S basin controls
- computationally fast, few input requirements,
- parameter-tuning to local conditions necessary
- mass conservation

## Linked Modular Numerical Models

- Giant models requiring a “Master of the Code” & long term $
- computationally demanding, input requirements greater
- more capable & realistic (reservoir property) S2S simulations
- mass & momentum conservation

## Computation Architecture

- major community involvement, software engineers required
- computational simplicity & capabilities (e.g. languages, HPC)
- avoids duplication of effort, better vetted code
- state-of-the-art and enduring