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Process Based Stochastic Modeling of Deep Marine Reservoirs

Petter Abrahamsen, Bjørn Fjellvoll, and Ragnar Hauge
Norwegian Computing Center

John Howell, Tor Even Aas
University of Bergen

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What is a turbidite?

- The sand rich parts of a deep marine deposit
- A turbulent flow of water and sediment
- Happens at continental shelf
- Can move 10's of km
- Moves fast ~ 20km/h
- Erodes and deposits
- Comes to rest at ocean floor

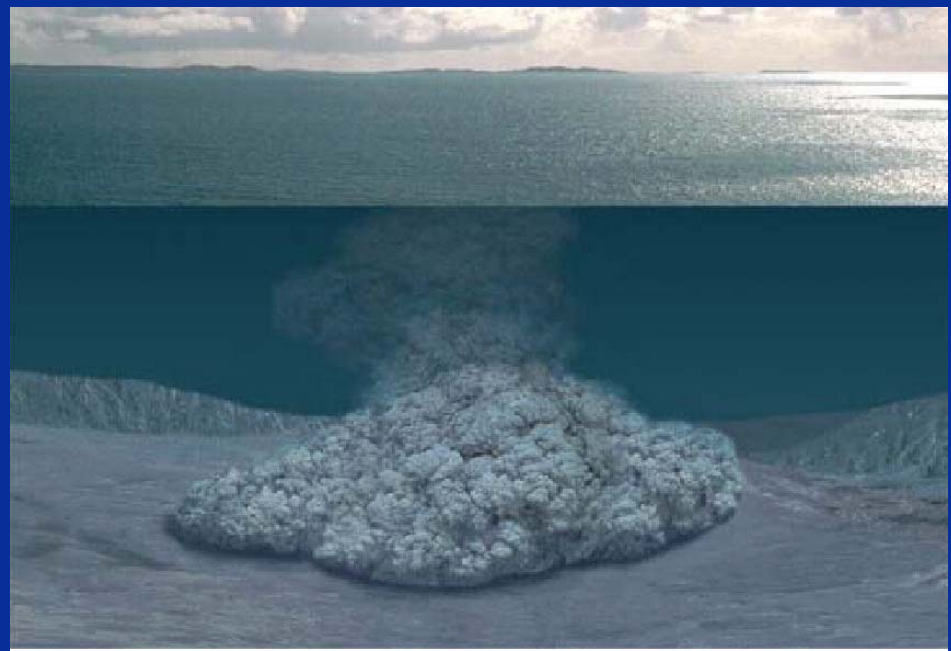
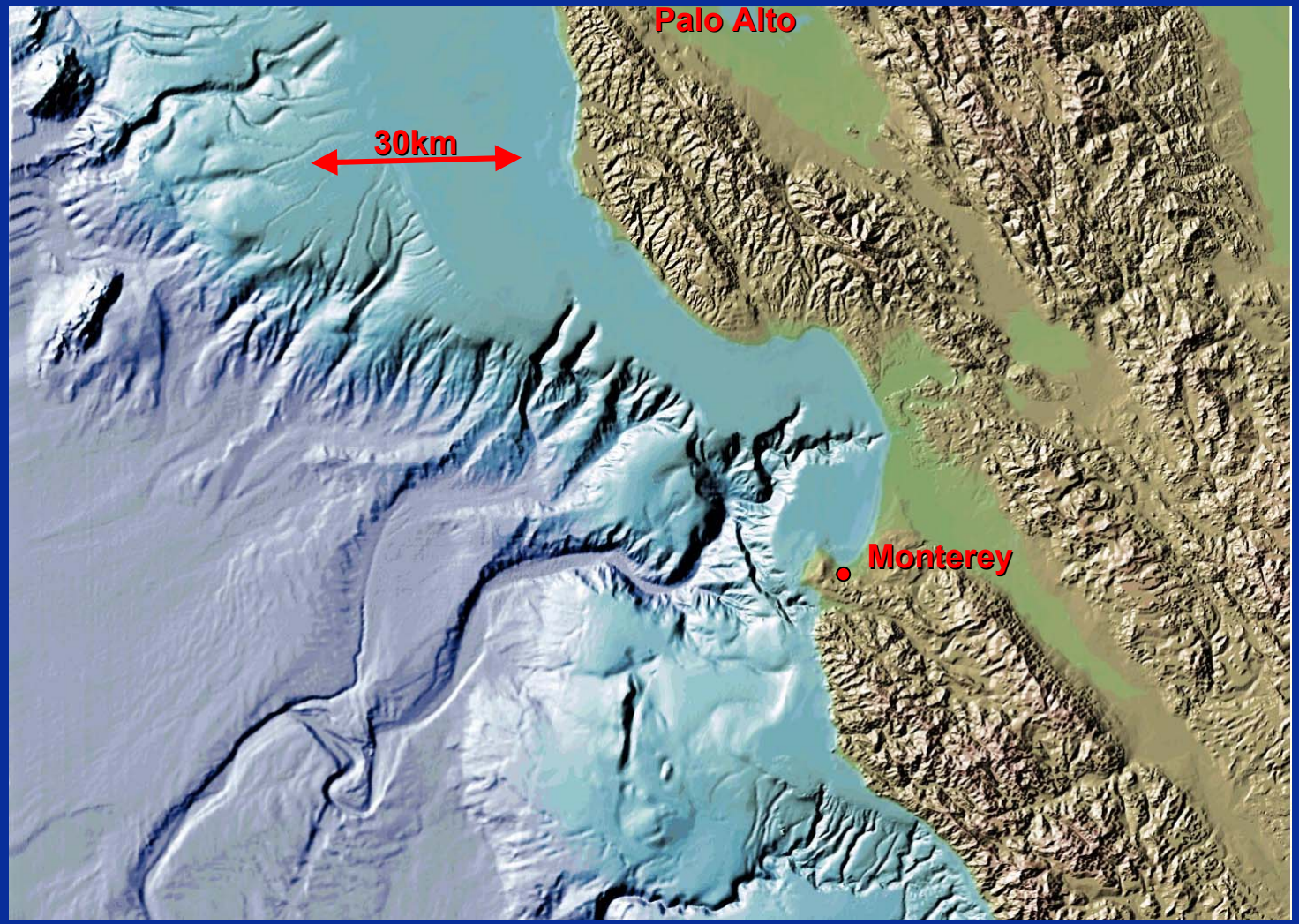


Image courtesy of the Open University

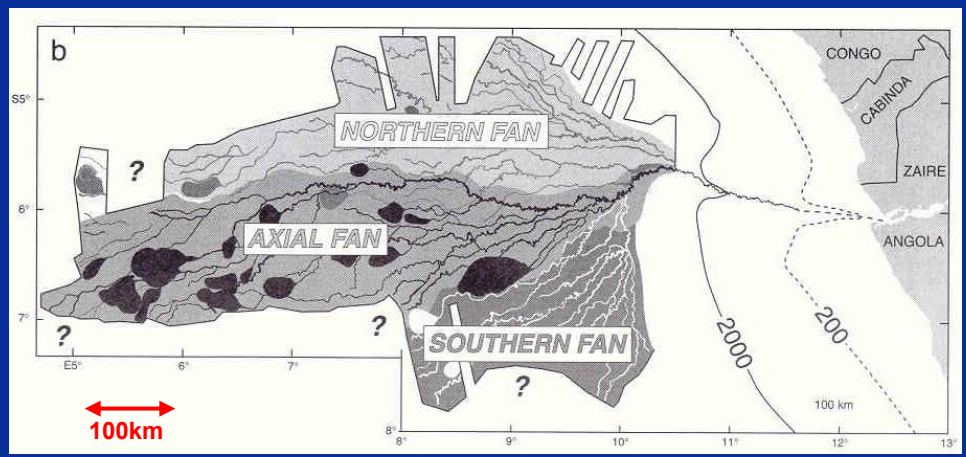
The Monterey Channel



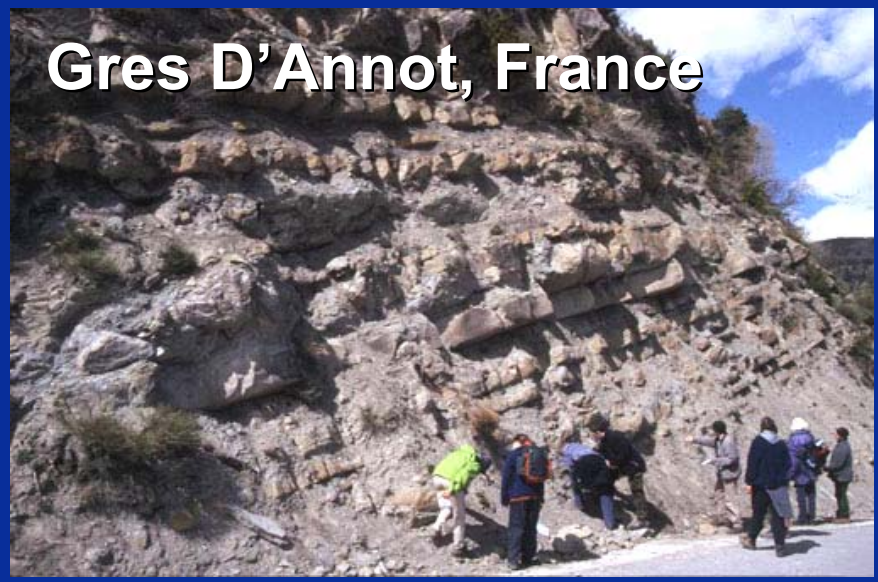
What is a deep marine deposit?

- A stack of turbidite deposits with hemipelagic clay in between

The Zaire fan

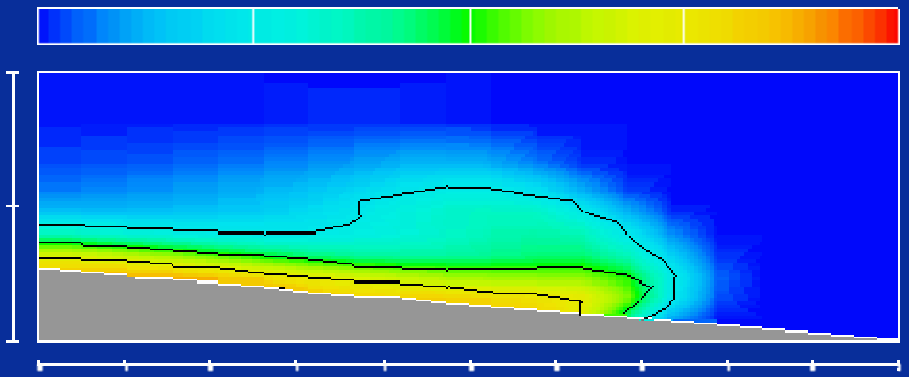


Gres D'Annot, France

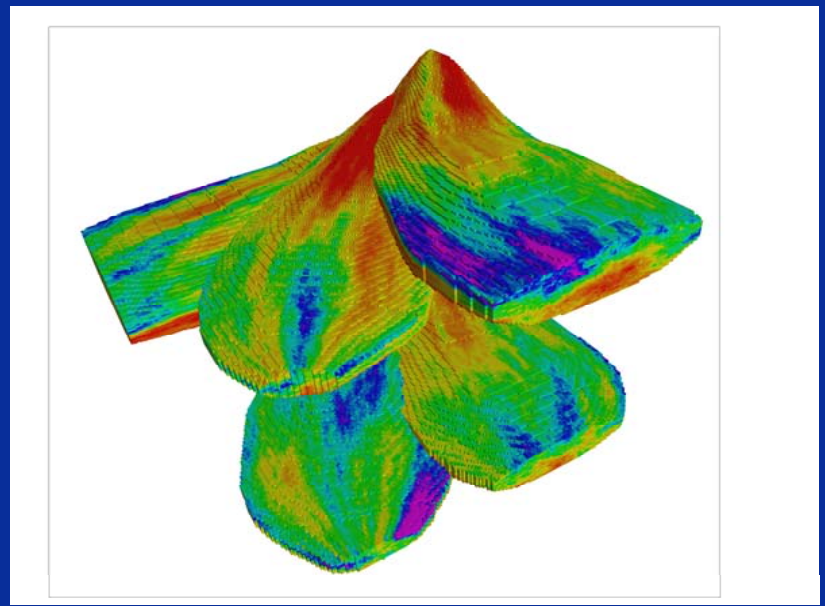


Why new approach?

- Process models
  - detailed physics
  - can not use well and seismic data
  - slow

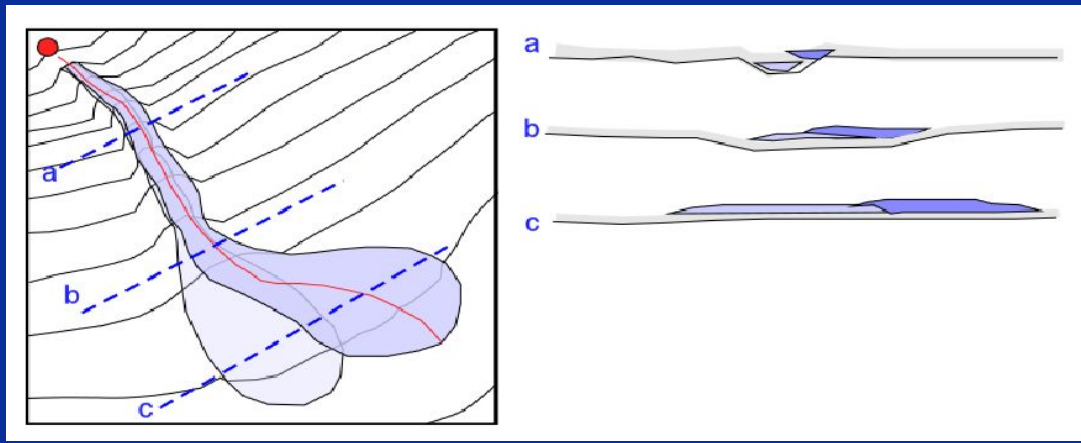


- Object models
  - simplistic geometry
  - wrong interaction between turbidite events
  - can condition on data



Basic ideas

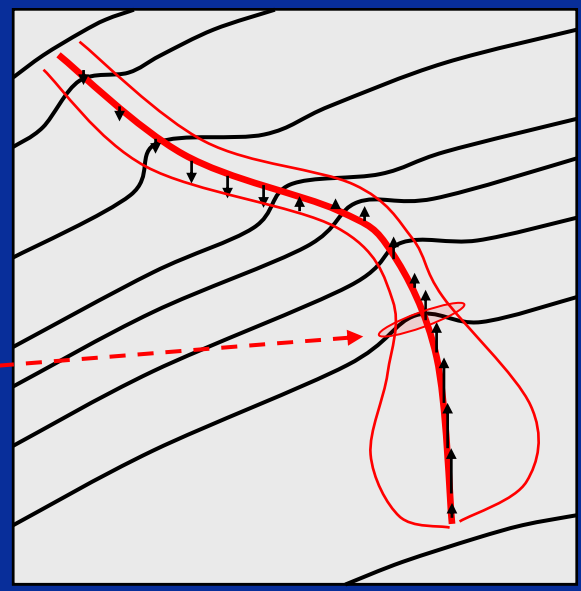
- Combine process model with stochastic elements
- Mimic the sequence of deposition
- Use simplified physical flow process to generate channel/lobe shapes fast



- Multiple events (10-1000?) flows generated chronological
- Minor stochastic element added to the physical process
  - Allows to honor data by intelligent trial and error

Generating one turbidite

1. Centre line
   - ► Run a single particle down the slope
2. Height
   - ► Find height using 1D model for erosion and deposition
   - ► Detect hydraulic jump
3. Width
   - ► Simplified particle model for side lines: repulsion from centre line
   - ► After hydraulic jump: change repulsion to attraction
4. Cross section shape
5. Adjust top and base using Gaussian random fields

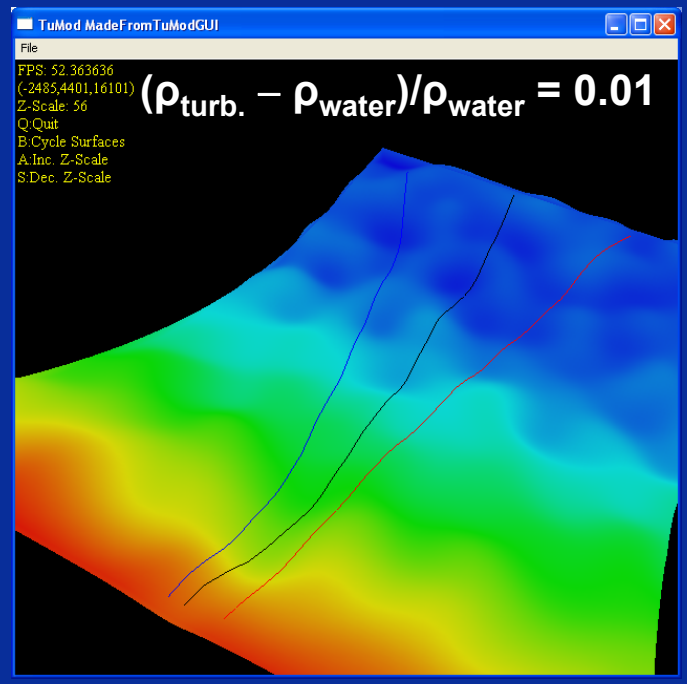


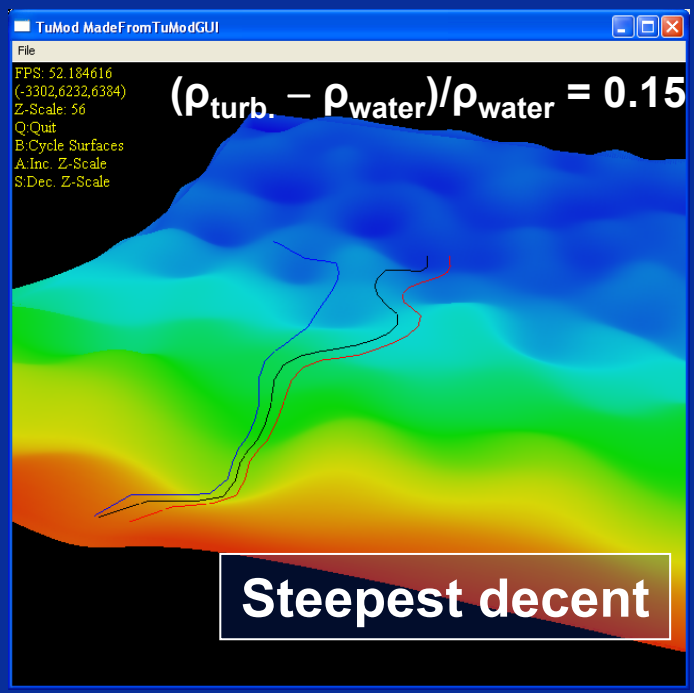
1. Centre line of turbidite

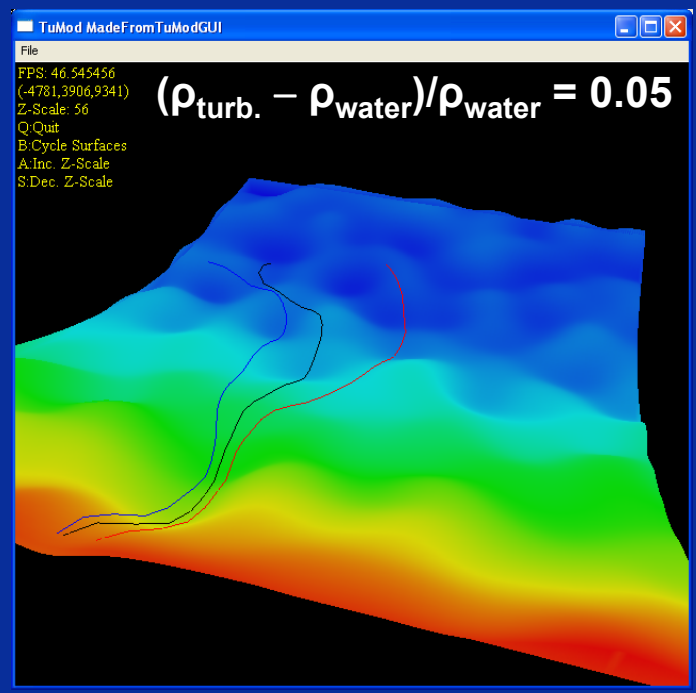
Main idea:
Track a particle sliding down the slope

- Main forces on a fluid particle:
  - Gravity
    - Force the particle downhill
    - Depend on the density
  - Friction
    - Surface friction – almost zero
    - Fluid friction – stops otherwise very fast flow
  - Random component
    - Seabed uncertainty
  - Attraction to and repulsion from well observations
- Minor forces:
  - Coriolis
  - Ocean currents

Density and velocity determines sensitivity to topography







2. Height: Deposition and erosion

- Using a method formulated by Leo C. van Rijn (Delft Hydraulics)
  - 1D calculation of erosion and depositional rate along centre line
  - Thickness gradient:

$$\partial h_2/\partial s = [1/(\gamma_2(1-c_2))][\gamma_1(1-c_2) - (1-c_2)(\tau_i+\tau_b) - 2\rho_2 u_2(W_i+W_b) - \gamma_3 \partial c_2/\partial s]$$

with:

$$\gamma_1=(\rho_s-\rho_w)h_2c_2\ g\ \sin\beta$$

$$\gamma_2=(\rho_s-\rho_w)h_2c_2\ g\ \cos\beta - \rho_2(u_2)^2=(\rho_s-\rho_w)h_2c_2\ g\ \cos\beta\ [1-(h_{2,cr}/h_2)^3]$$

$$\gamma_3=2\rho_2h_2(u_2)^2 + (\rho_s-\rho_w)\ (1-c_2)h_2(u_2)^2 + 0.5(\rho_s-\rho_w)(1-c_2)(h_2)^2\ g\ \cos\beta$$

mass balance for fluid in lower layer 2

$\partial(u_2h_2(1-c_2))/\partial s - W_i - W_b = 0$

mass balance for sediment in lower layer 2

$\partial(u_2c_2h_2)/\partial s - S_i - S_b = 0$

with :

h_1, h_2 = thickness of upper and lower layer ($h_1+h_2=h$=flow depth),

c_1, c_2 = depth-averaged volumetric suspended sediment concentration in upper layer 1and lower layer 2,

$u_1=q_1/h_1$, $u_2= q_2/h_2$ = velocity in upper layer 1 and lower layer 2,

W_i= exchange of fluid at the interface,

W_b = exchange of fluid at the bed,

S_i = exchange of sediment at the interface,

S_b = exchange of sediment at the bed,

ρ_2 = mixture density of lower layer,

ρ_w = fluid density (clear water in upper layer 1),

ρ_s = sediment density,

τ_i = shear stress at interface ($= \rho\ C_{di}\ u_2^2$),

τ_b = bed shear stress ($= \rho\ C_d\ u_2^2$),

C_d = bottom friction coefficient ($= g/C^2$), C = Chézy coefficient,

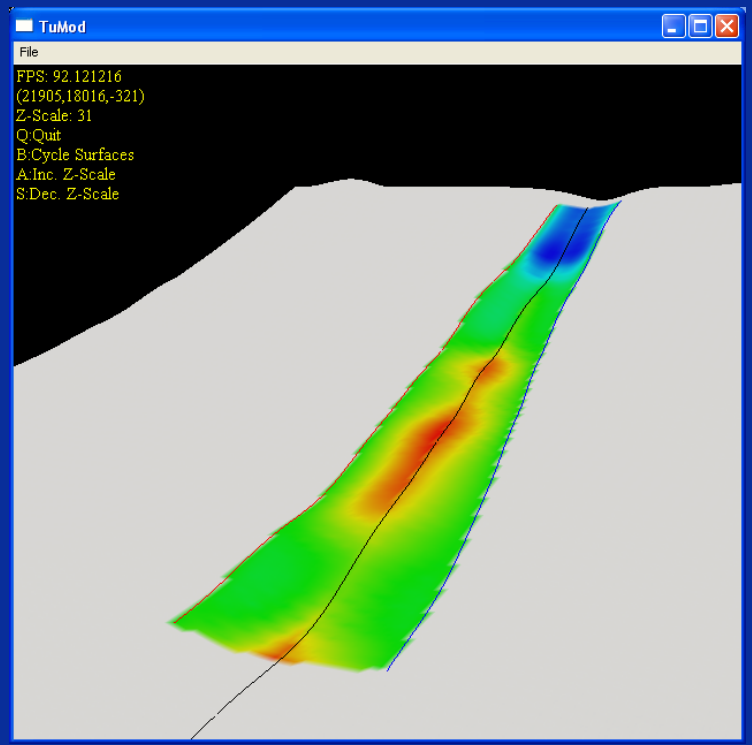
C_{di} = interface friction coeffcient,

β = angle of bed slope in s-direction,

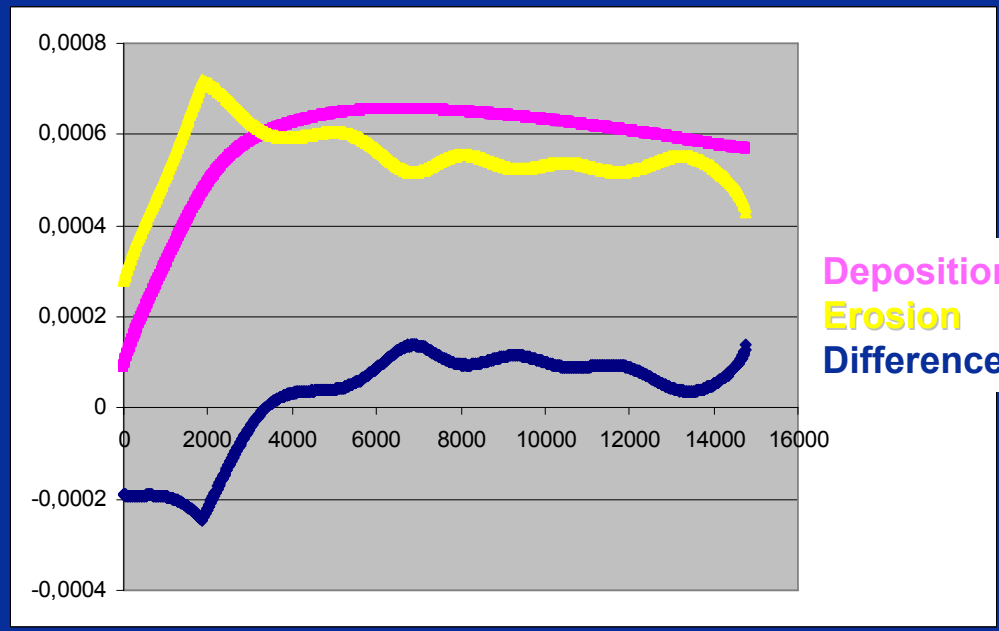
s = coordinate along bed slope.

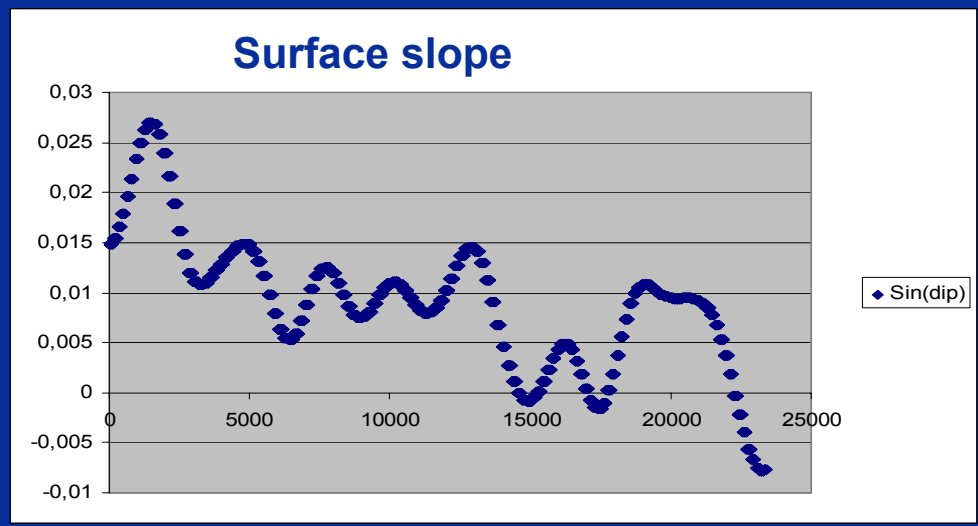
- Detects *hydraulic jump*
  - Caused by dilution of sediment and reduced speed at basin floor

Example

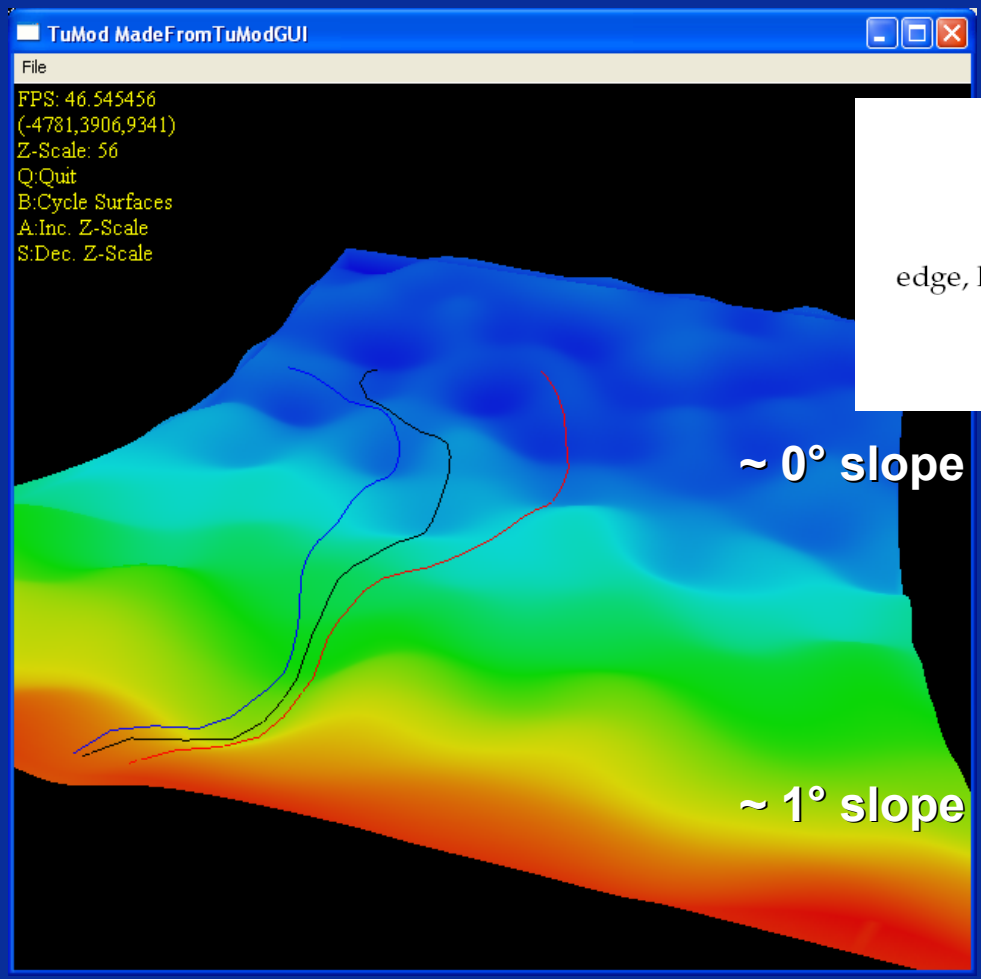


Blue is erosion
Red is deposition

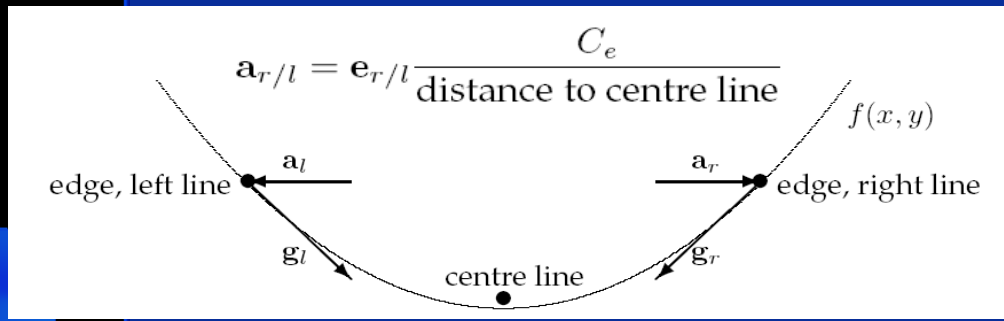




3. Width

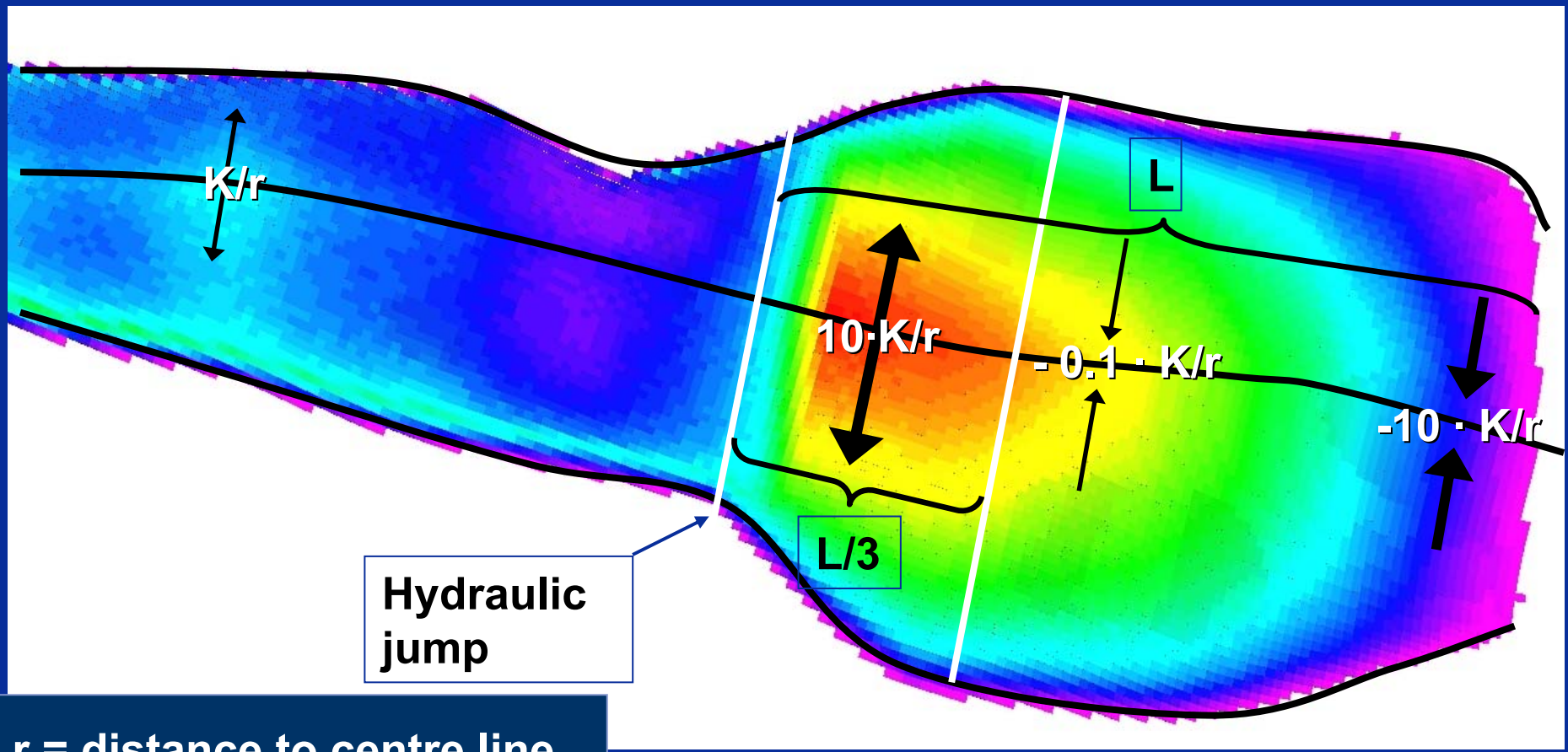


$$\mathbf{a}_{r/l} = \mathbf{e}_{r/l}\frac{C_e}{\text{distance to centre line}}$$



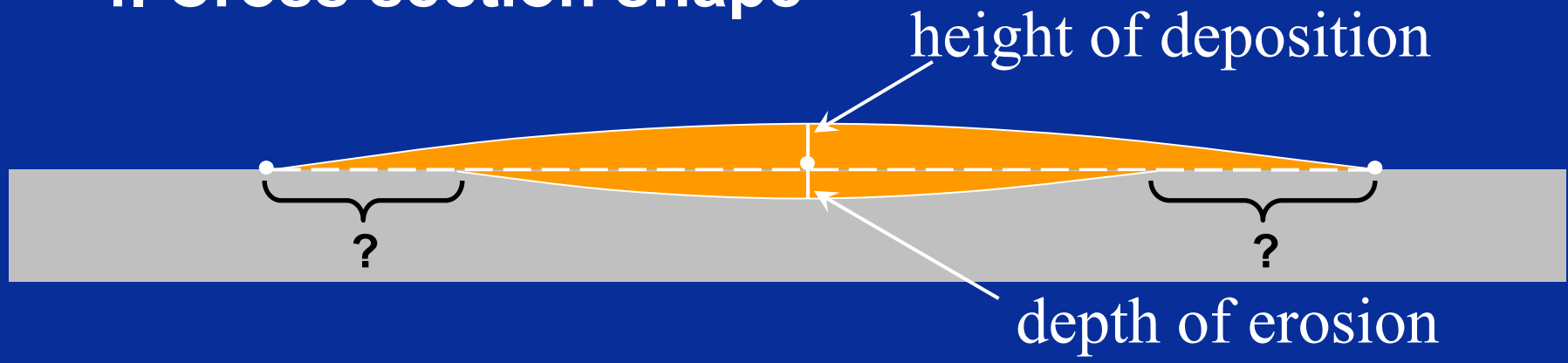
Closing the lobe

- Length, L, depend on mass at hydraulic jump

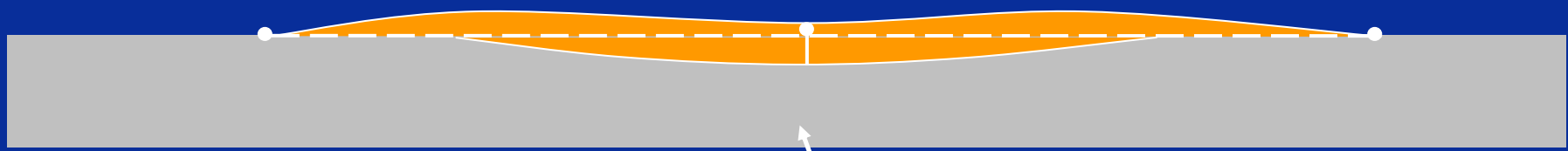


r = distance to centre line

4. Cross section shape

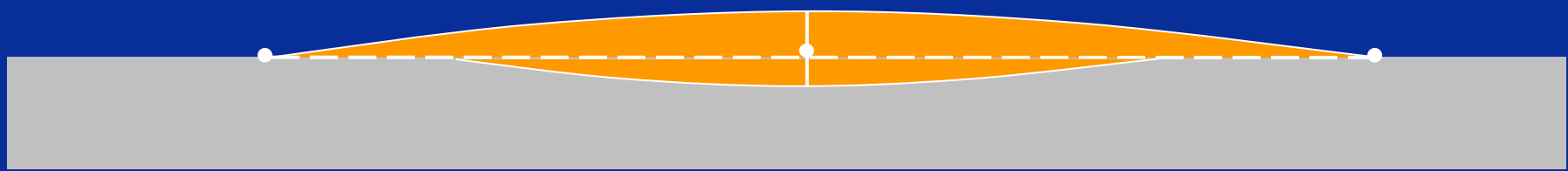


Draping deposit



Filling deposit

Mixing these extremes

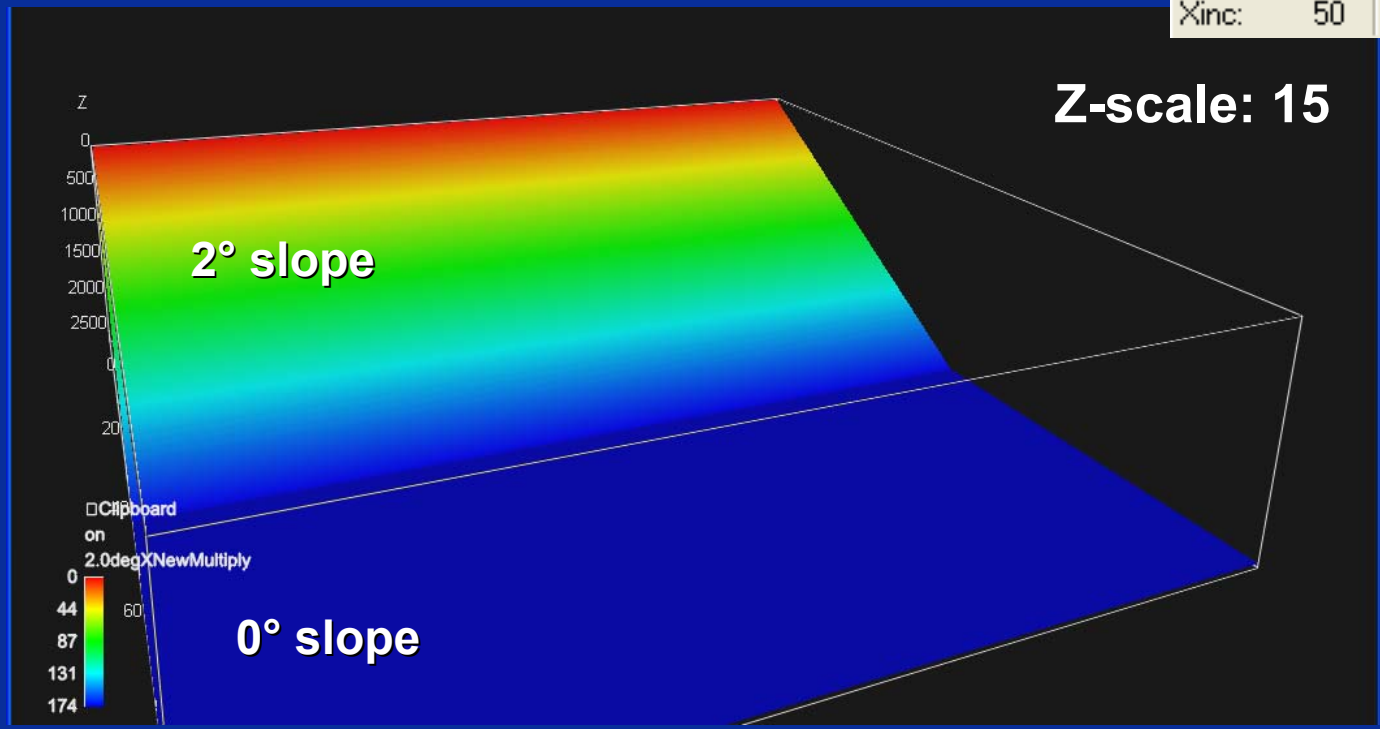


Physics is too stable!

- 2° dipping plane
- Dips in X-direction
- 20 Events

Xmin: 0.0 Xmax: 10000.0
Ymin: 0.0 Ymax: 10000.0
Zmin: 0 Zmax: 174

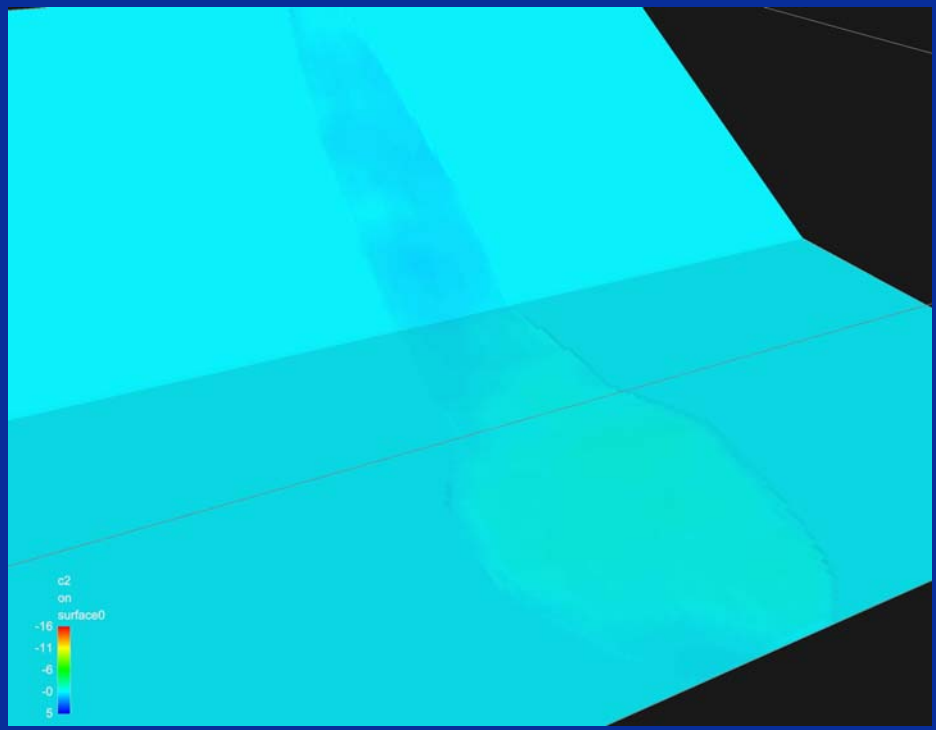
Surface grid size
Columns: 201 Rows: 201
Xinc: 50 Yinc: 50

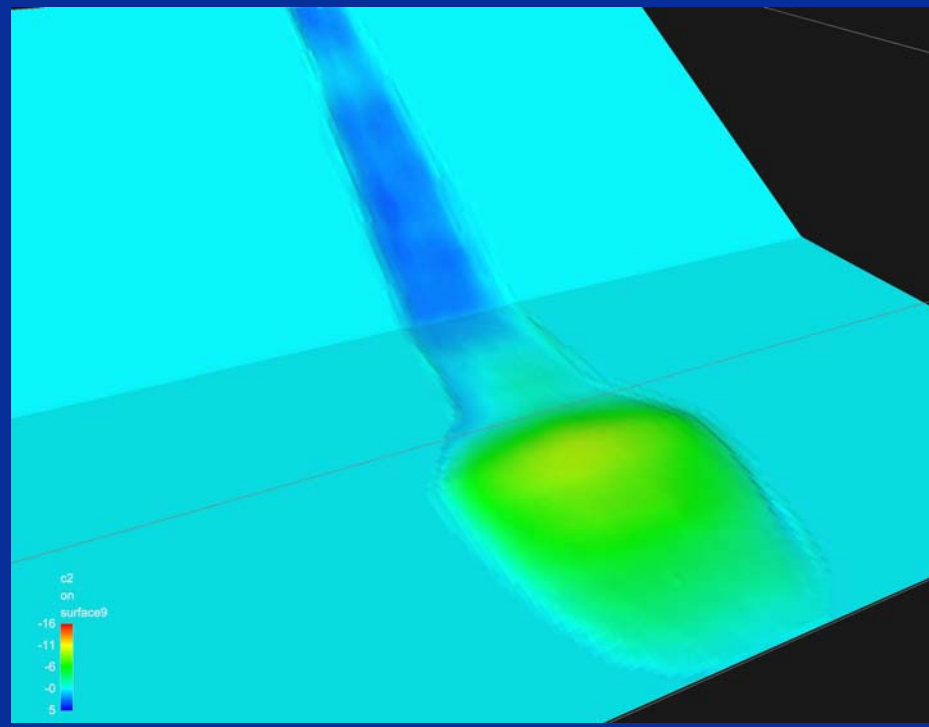


Results: Event: 1, 10

Red = net deposition

Blue = net erosion



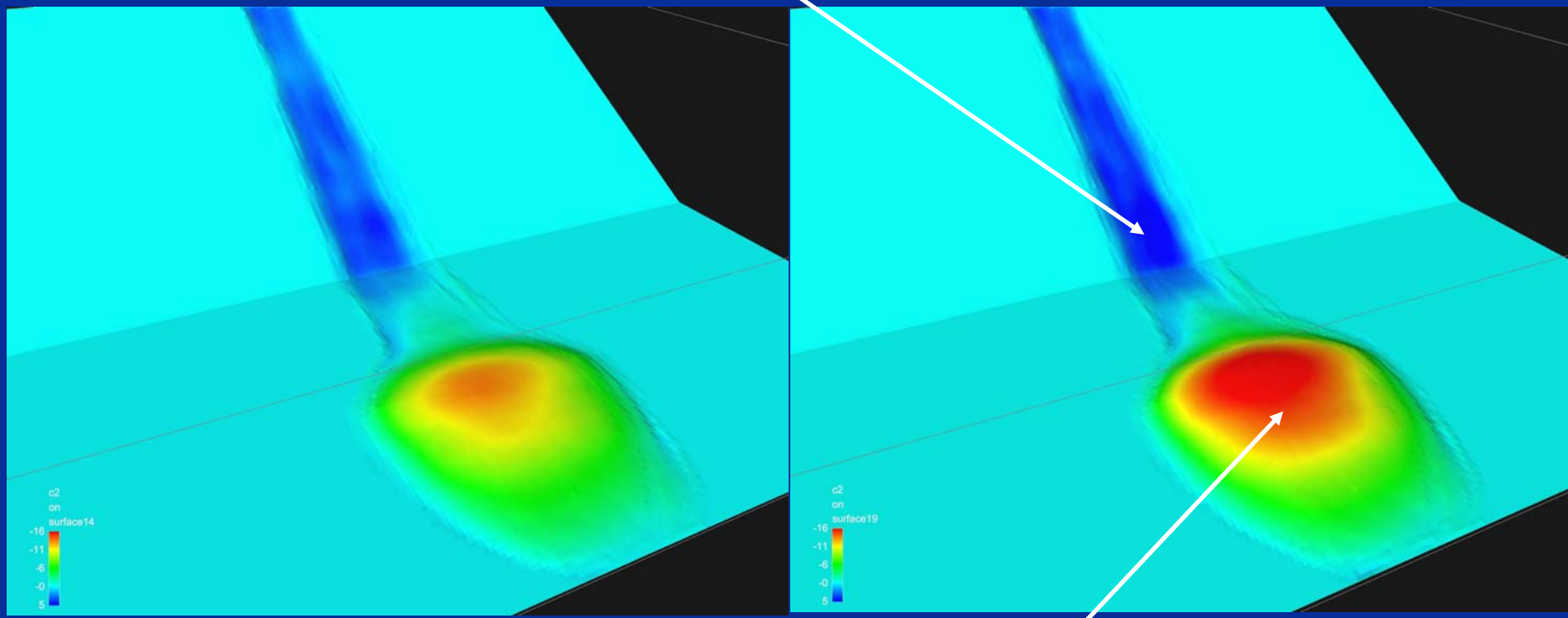


Results: Event: 15, 20

Red = net deposition

Blue = net erosion

Deep ditch



High pile

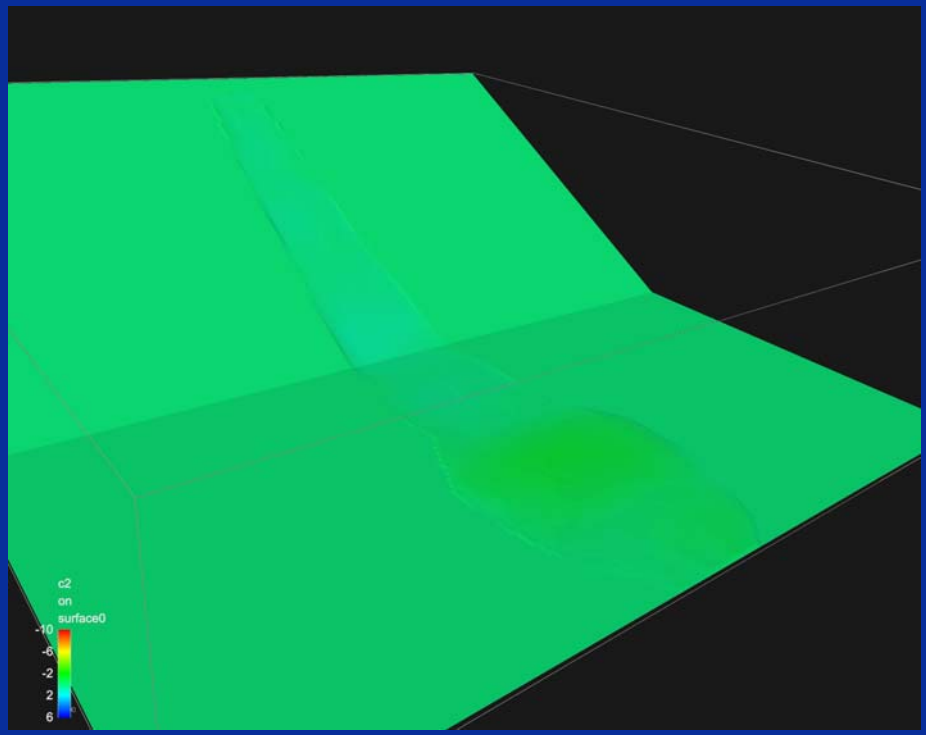
Problem and solution

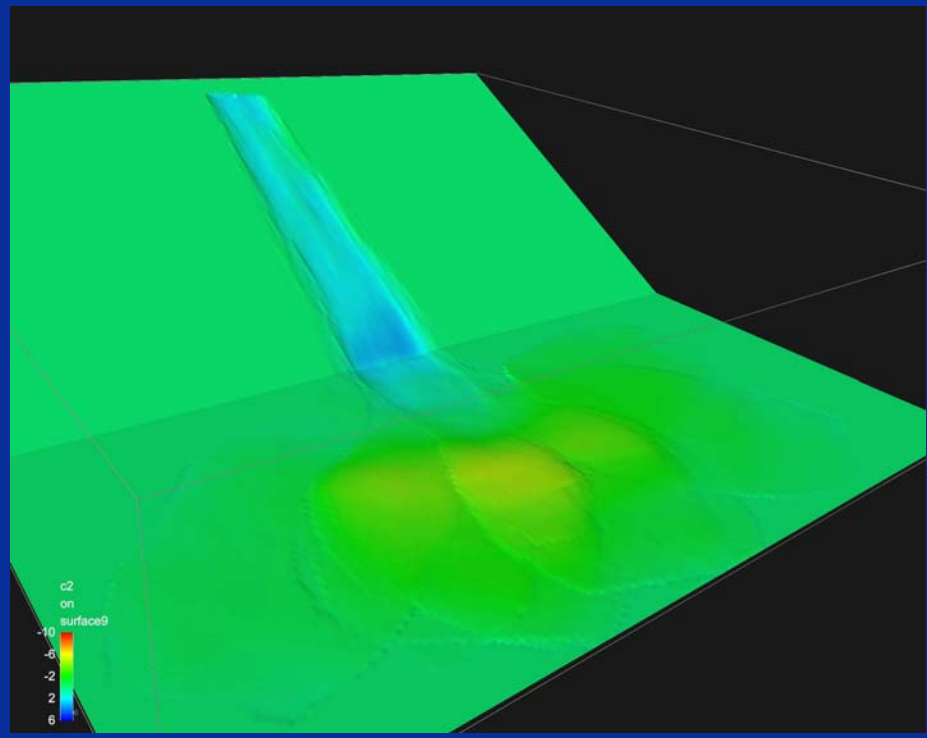
- Problem
  - Physics too stable
  - All events stack on top of each other
  - Sea floor is incredibly flat
- Solution
  - Add *antenna* to turbidite
  - Turbidity current sends shockwave forward to find easiest path.

New results: Event: 1, 10

Red = net deposition

Blue = net erosion

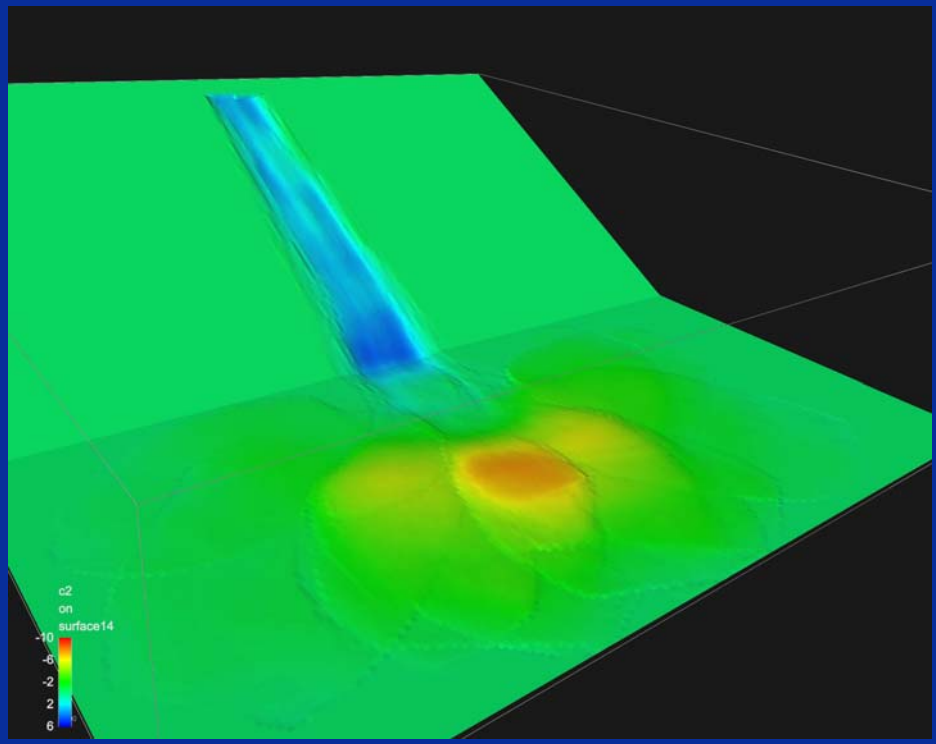


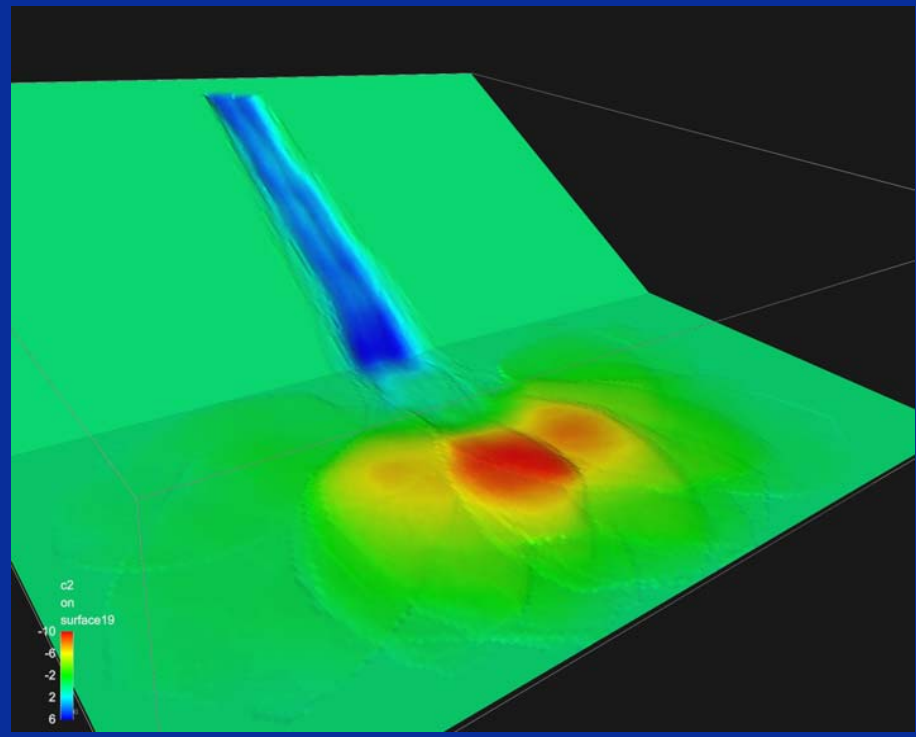


New results: Event: 15, 20

Red = net deposition

Blue = net erosion

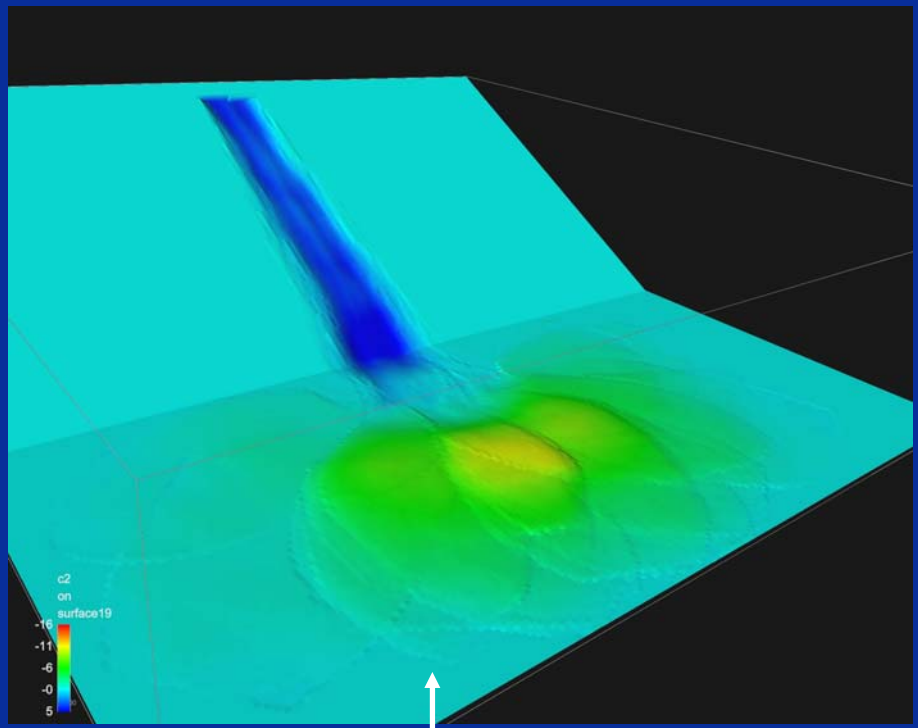




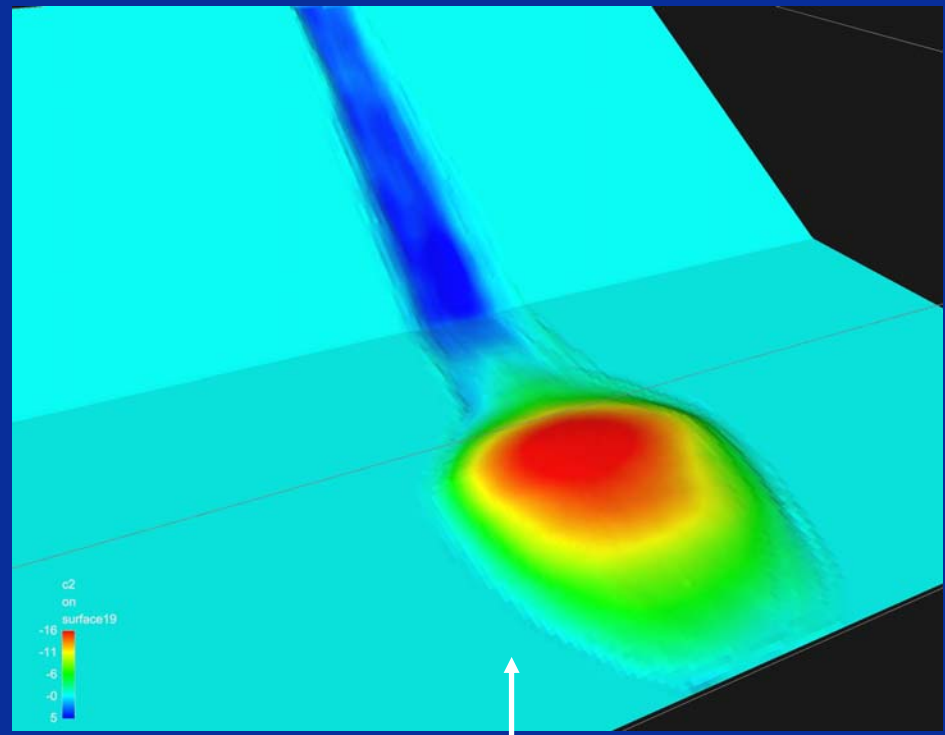
Comparing end results

Red = net deposition

Blue = net erosion

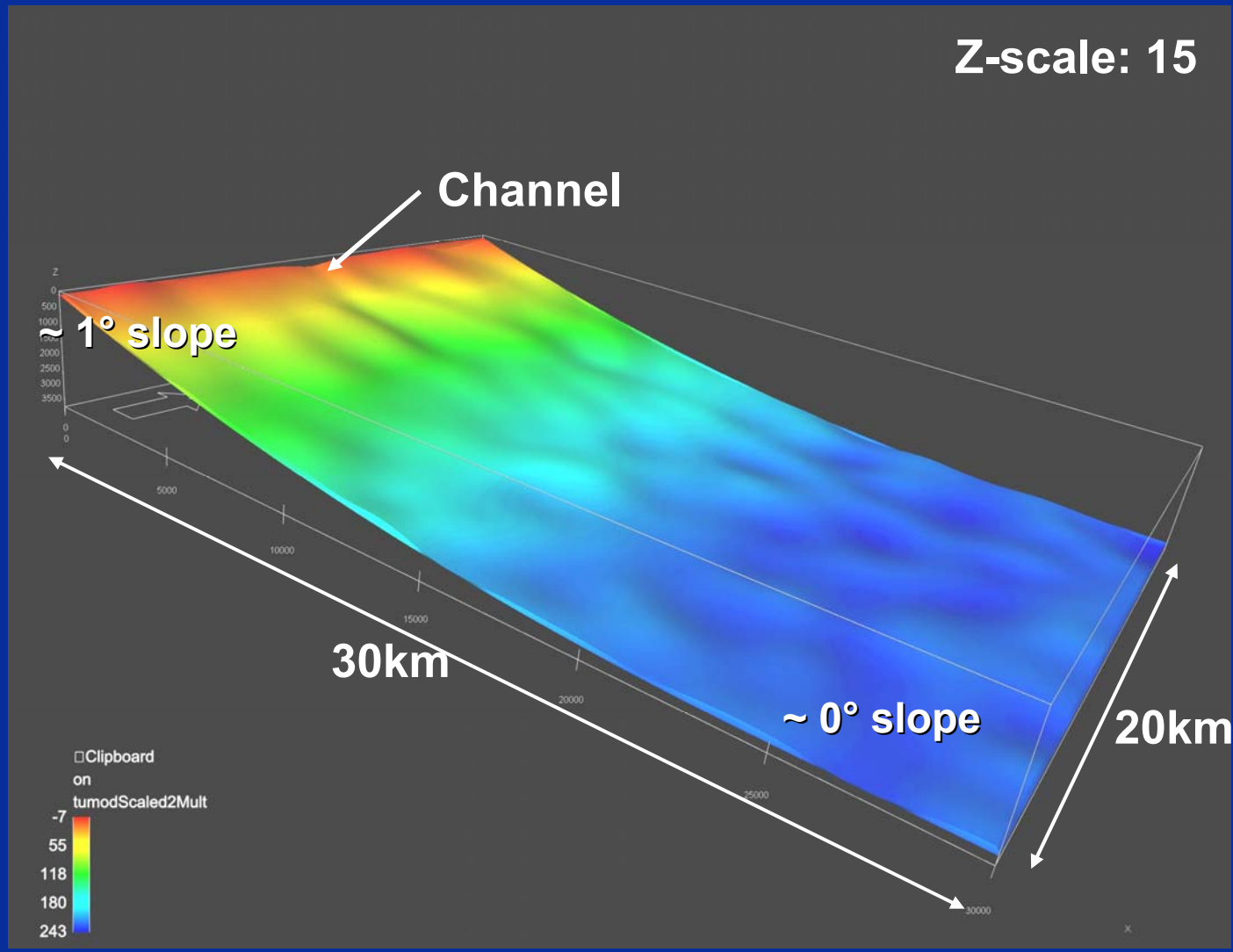


Looking forward:
On



Looking forward:
Off

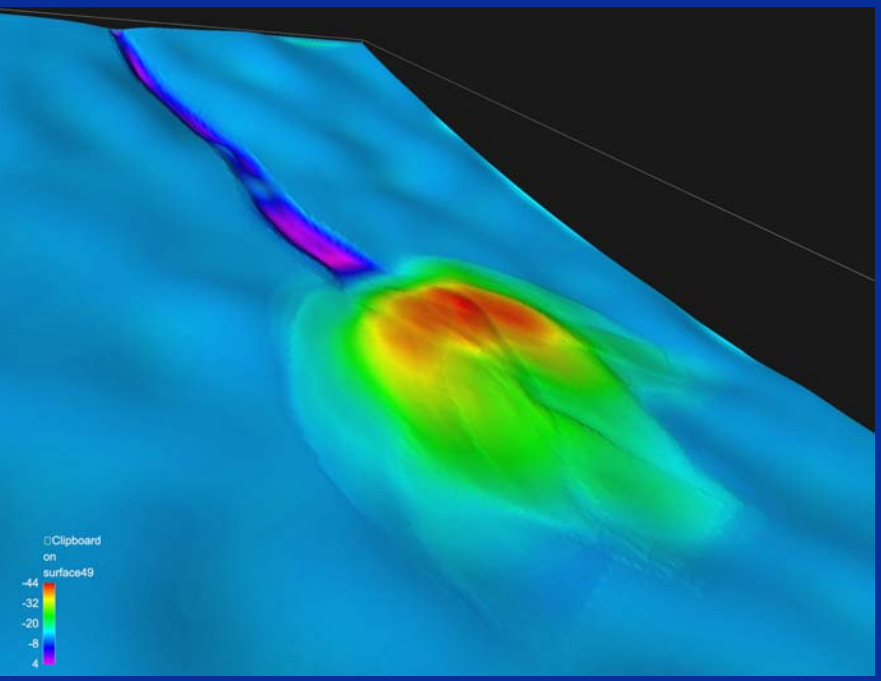
Another example

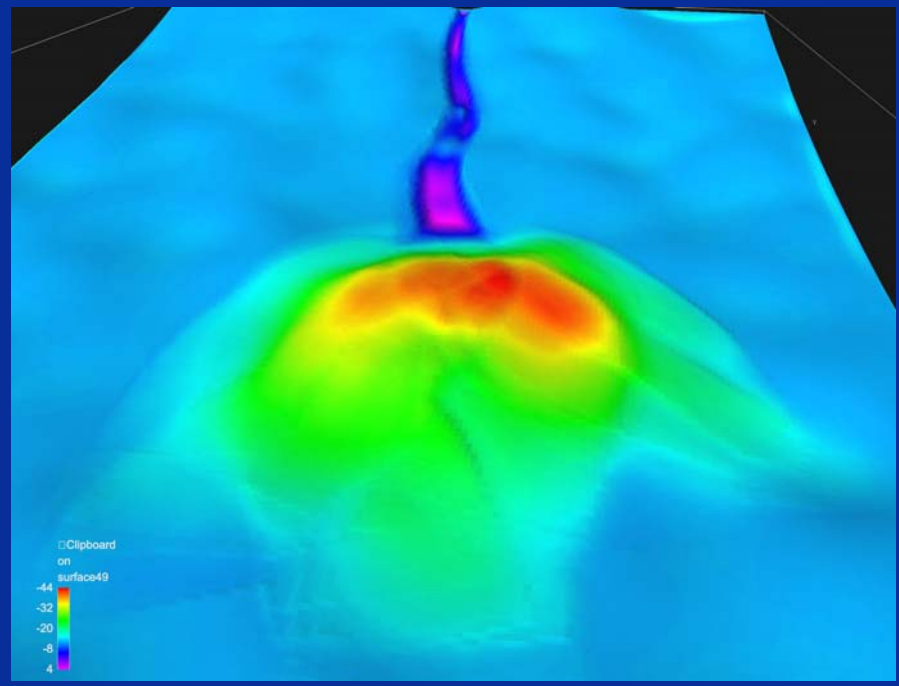


50 Events

Red = net deposition

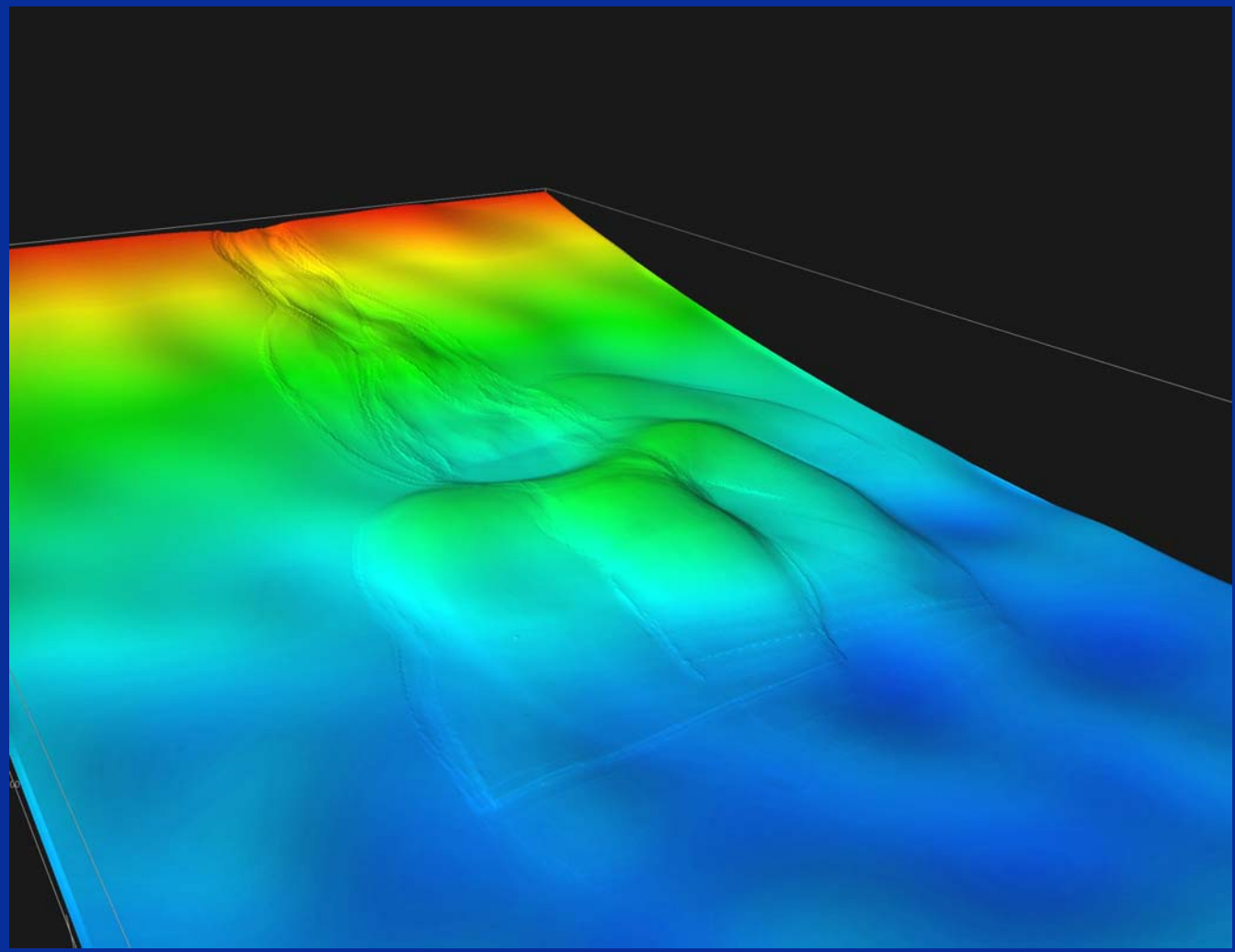
Blue = net erosion





Final realization

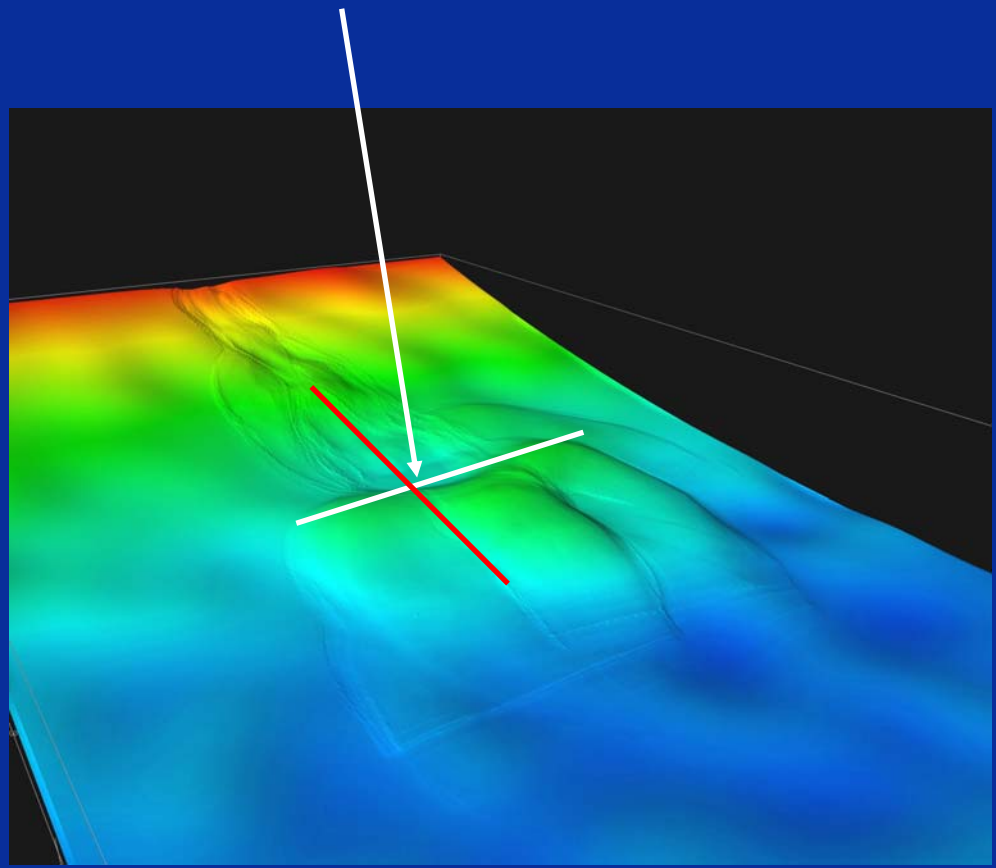
Similar example: 70 Events

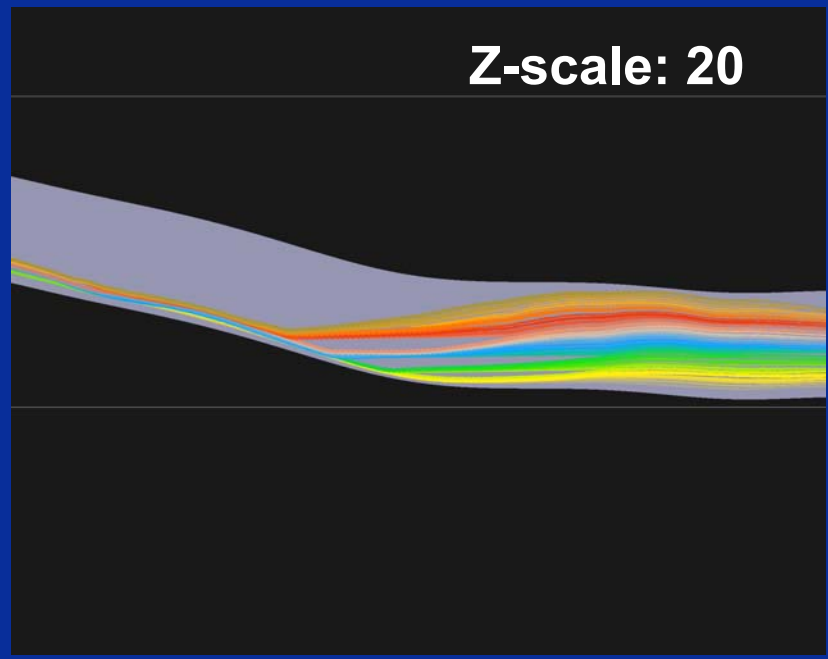


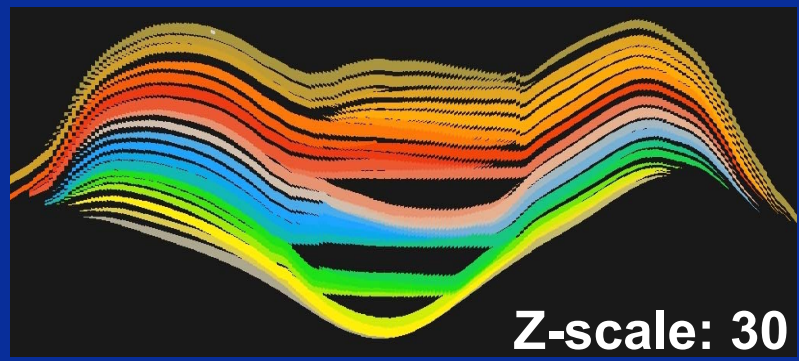
Continuous hemipelagic clay deposition between events

Filling

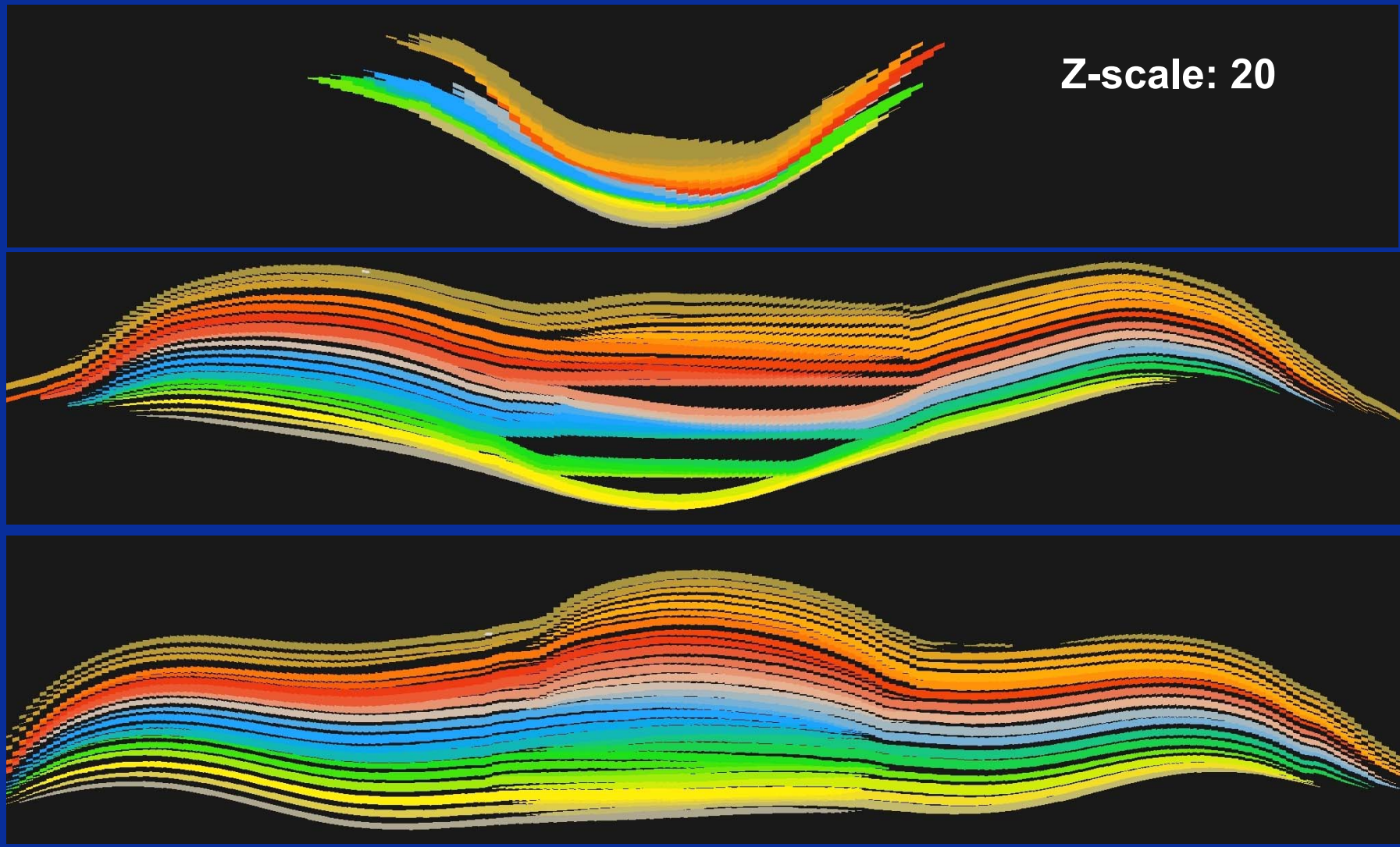
Filling accommodation space with shale up to spill-point



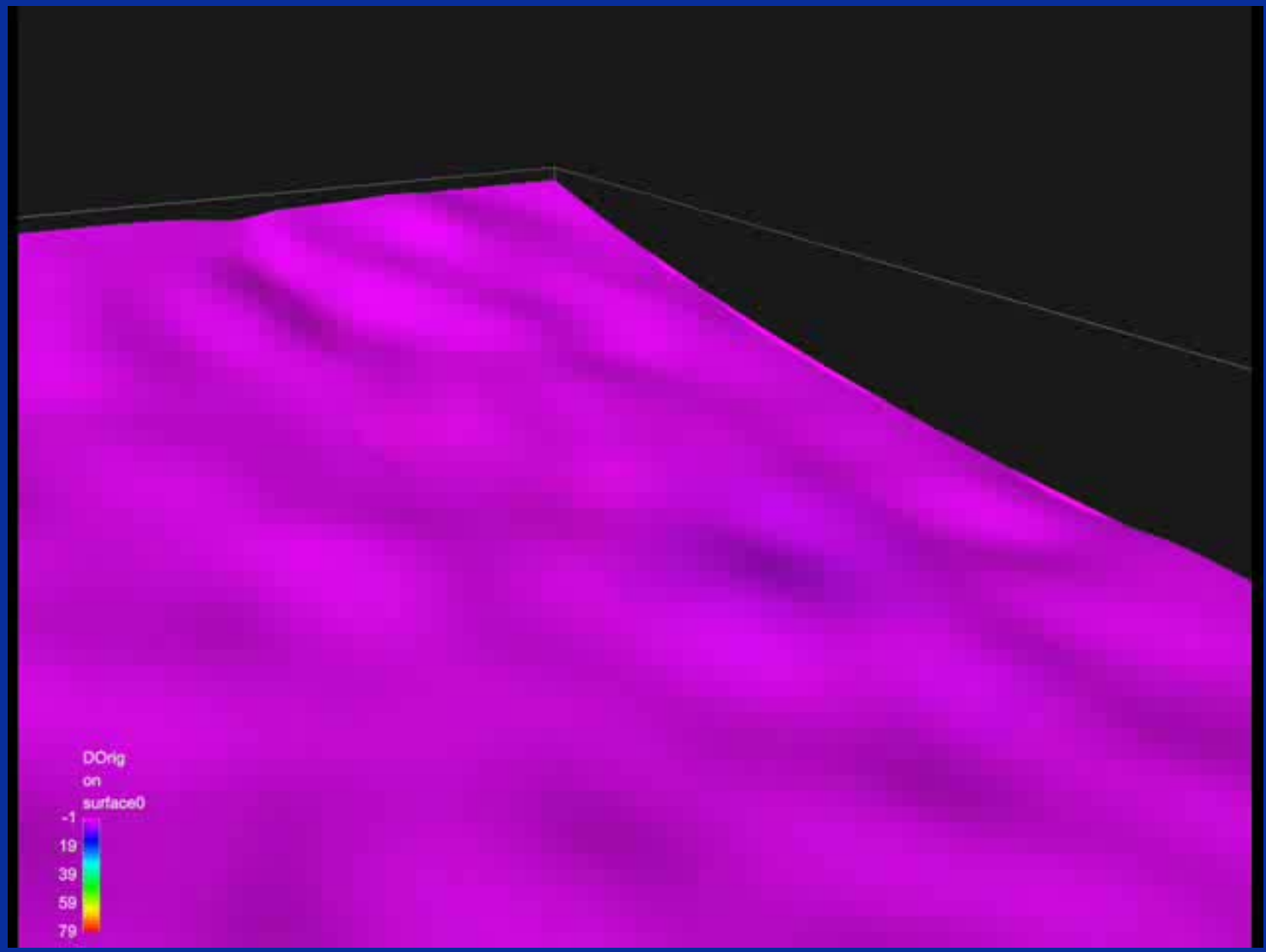




35 Events: Cross sections



70 Events cont.

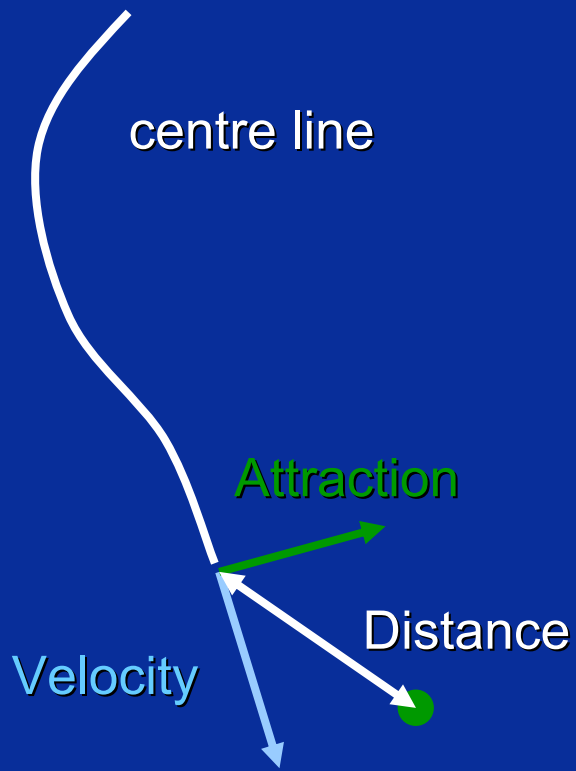


Well conditioning

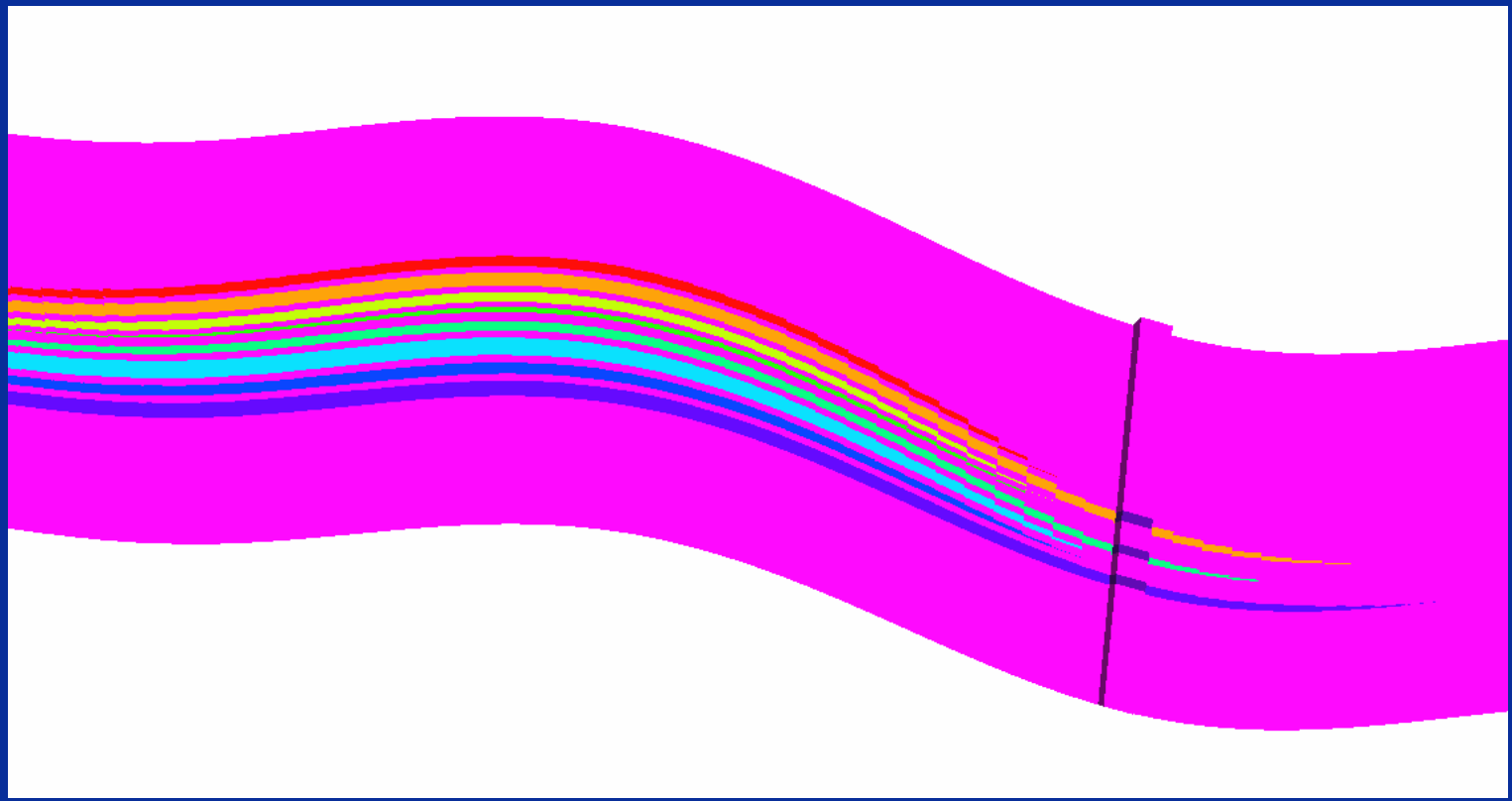
- Well conditioning in physics model
  - Sand observations are attractors
  - Shale observations are repulsors
- Additional conditioning with Gaussian fields
  - 1D field applied to left and right edge
  - 2D field applied to top and bottom

Physics conditioning – centre line

- Attracted to sand observations
- Shale observations give force in opposite direction



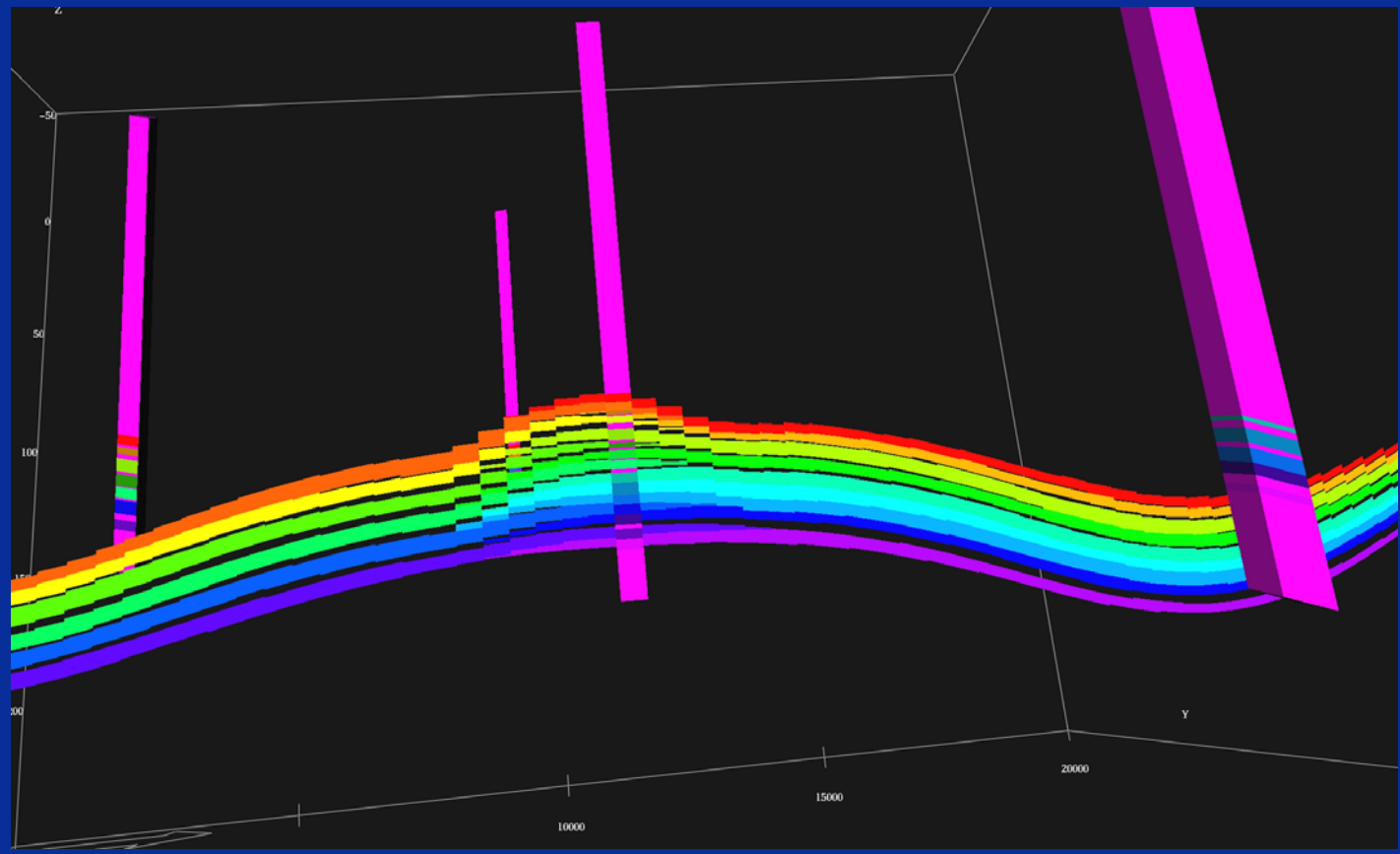
Well conditioning



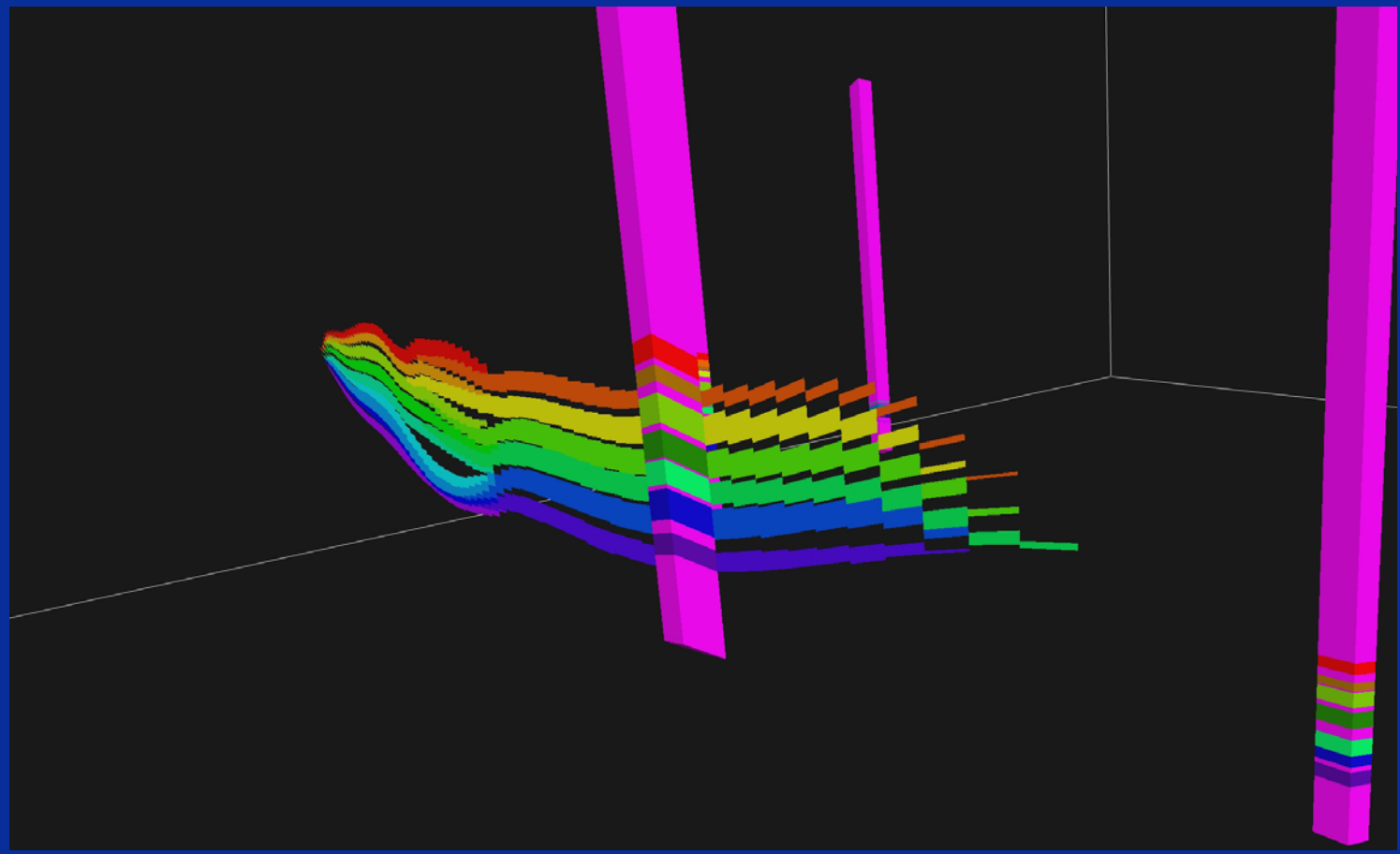
15 Events with wells

Well logs:

- Facies
  - Sand
  - Shale
- Body

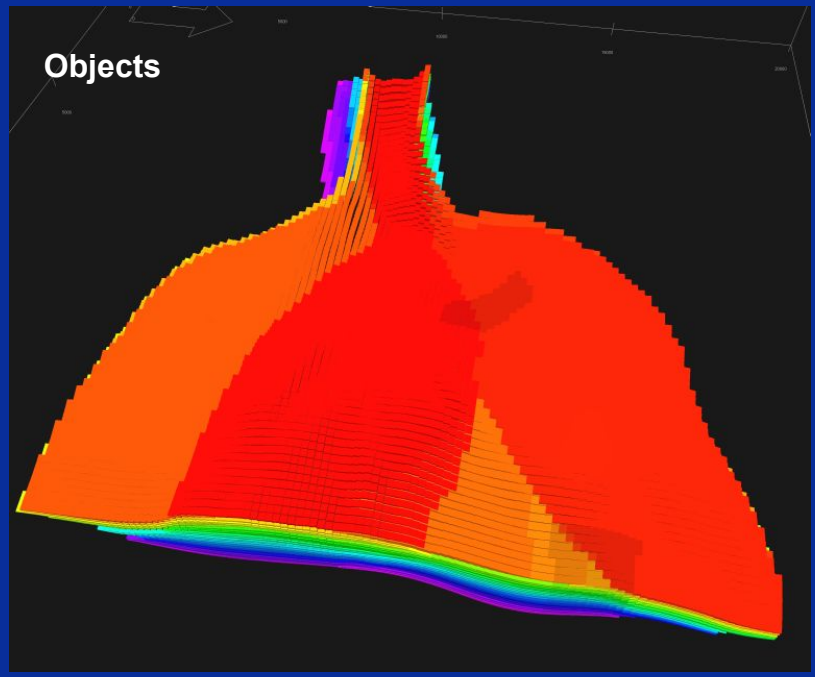


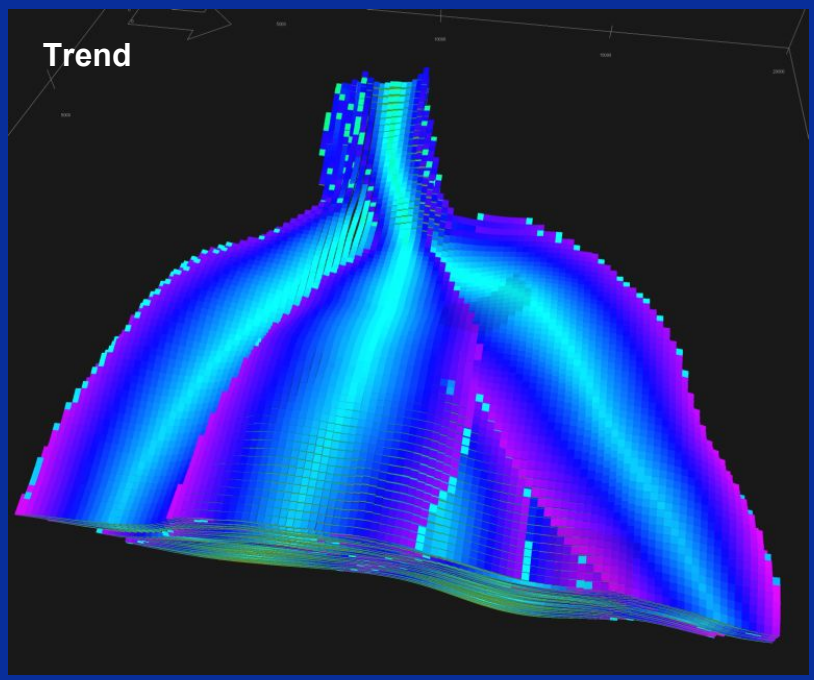
15 Events with wells cont.

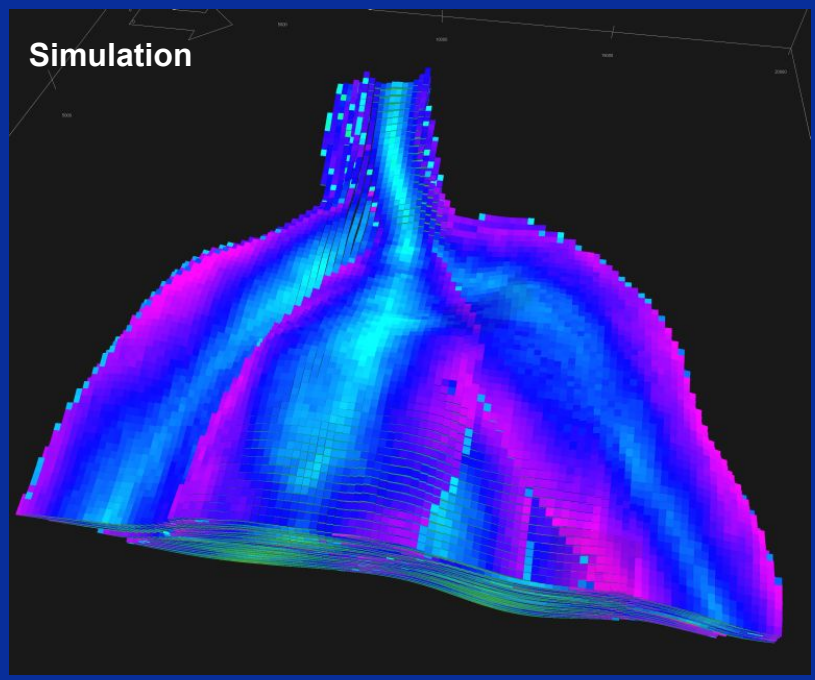


Petrophysics

- Standard approach for object models
  - Trends relative to object geometry
  - Anisotropy following objects

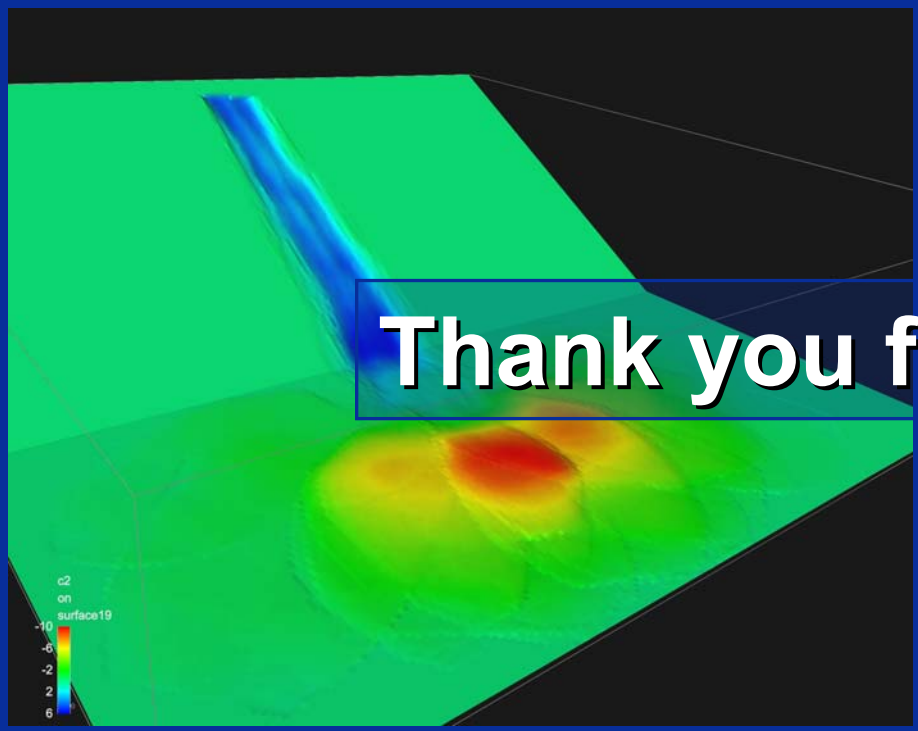


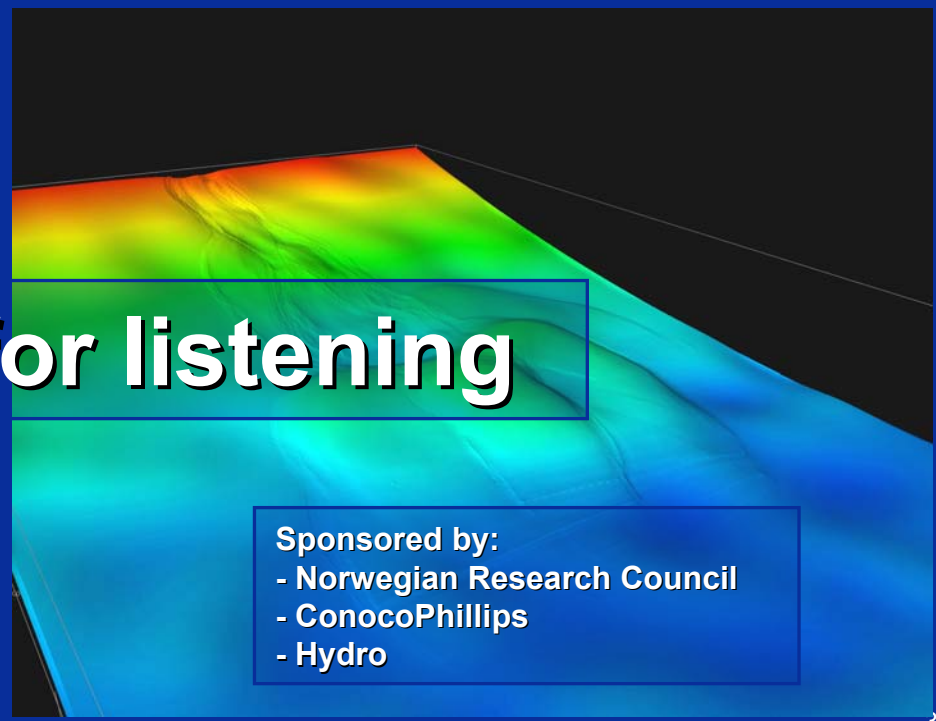




Closing remarks

- Realistic geometries
- Conditioning to well data (not perfect yet)
  - Rejection of bad proposals to be tested
- Complex model – a lot of parameters





Thank you for listening

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- Norwegian Research Council
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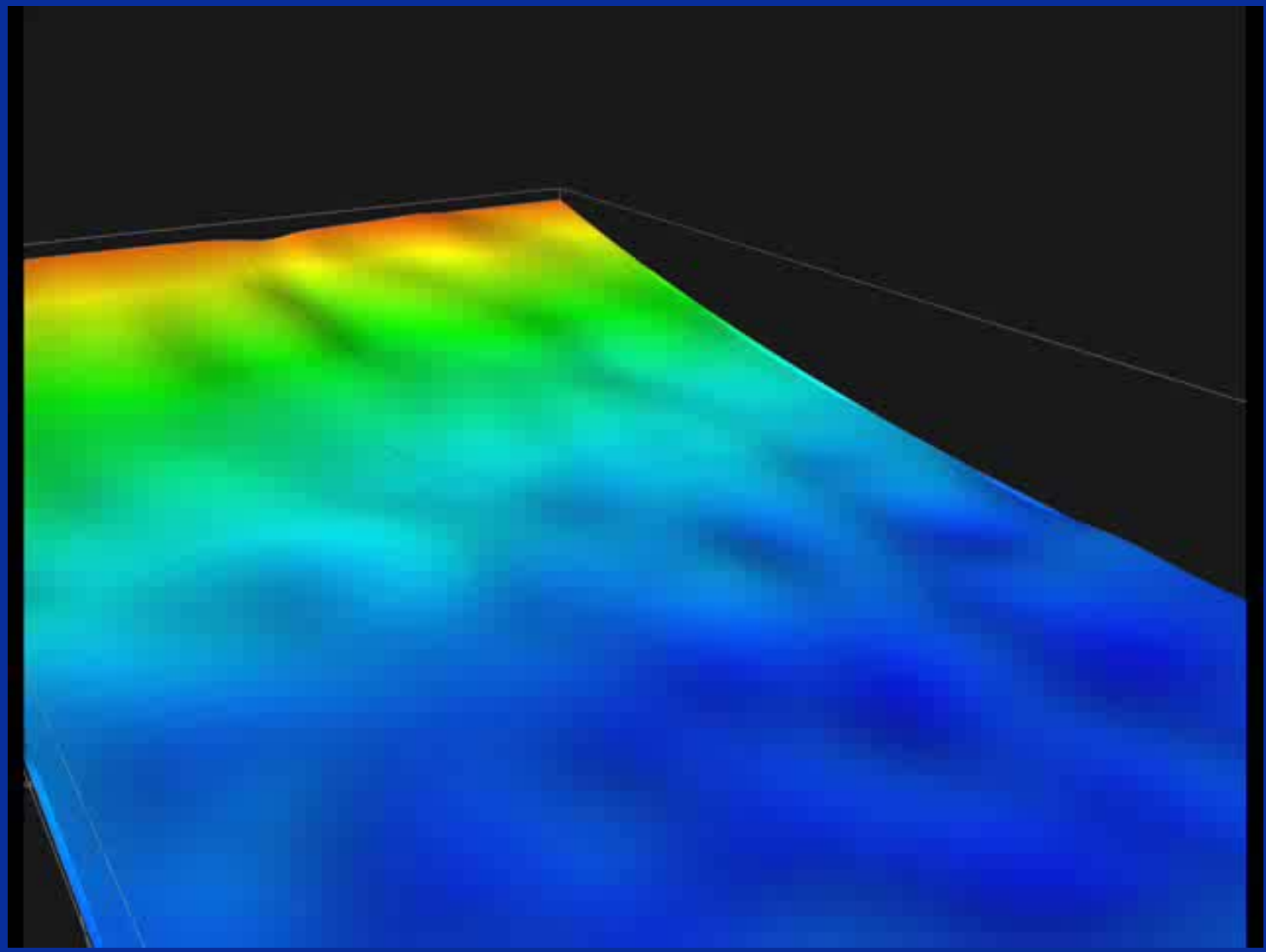
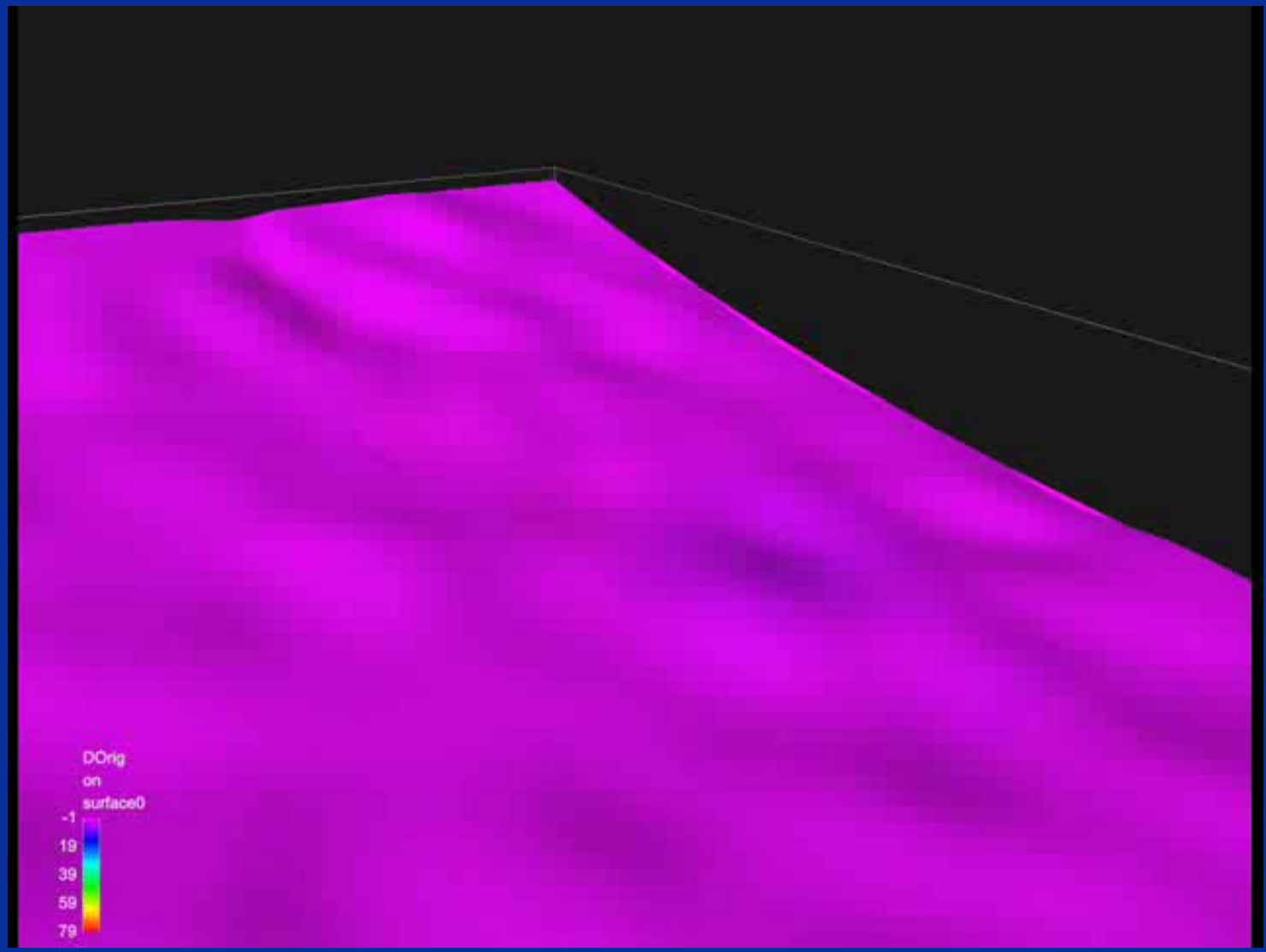
- Hydro

70 Events cont.

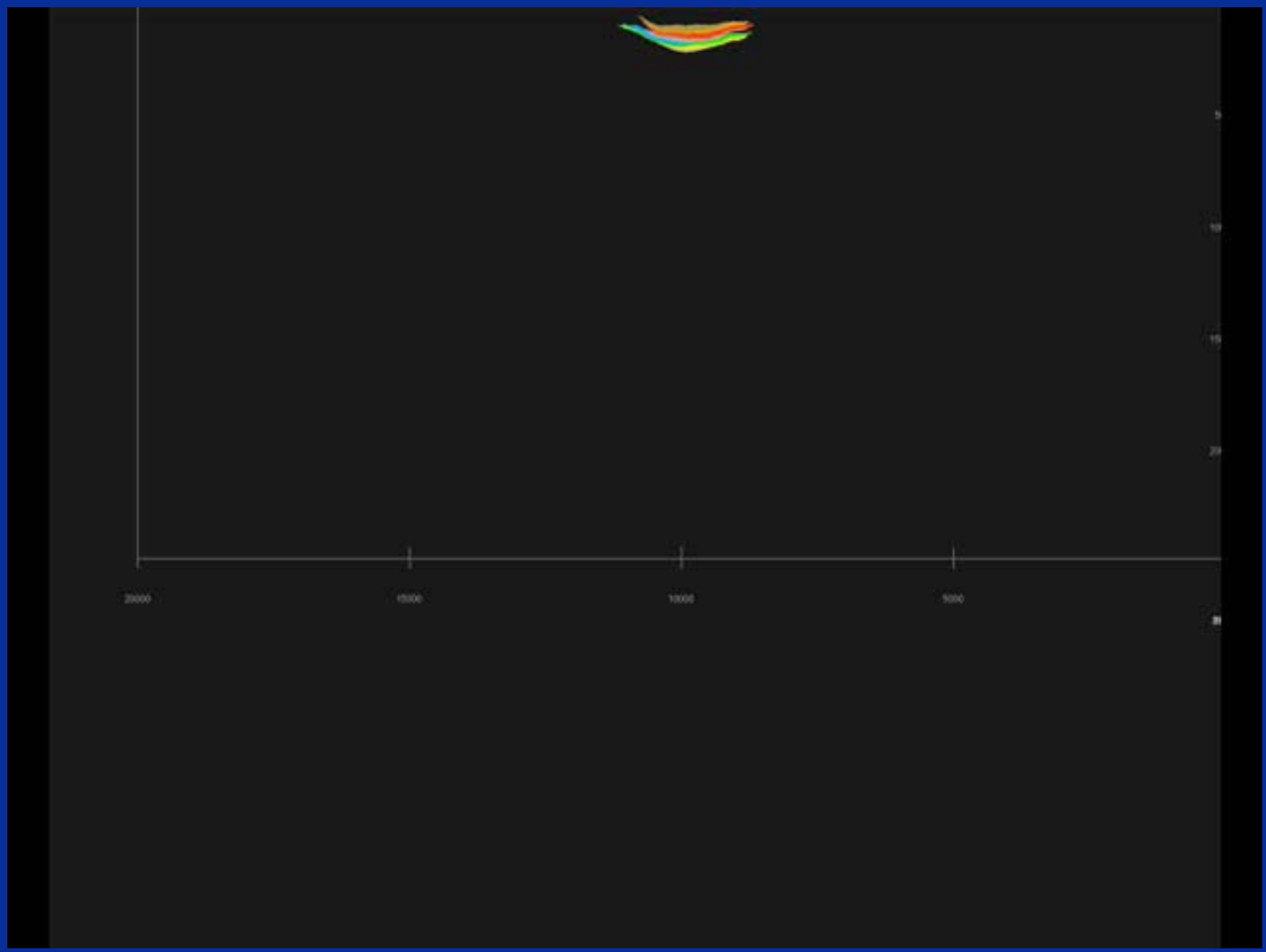


70 Events cont.



35 Events: Cross sections

From channel to abyssal plane



35 Events: Cross sections

Around hydraulic jump.