3D Bedrock Channel Evolution with Smoothed Particle Hydrodynamics Coupled to a Finite Element Earth

3rd DualSPHysics Users Workshop

Università degli Studi di Parma

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Phaedra UPTON, GNS Science (New Zealand)

Our Road Map

- Where have we been?
  - Introduction: why are Earth Scientists excited by SPH?
  - Background: review established bedrock channel incision models
    - Problem: a great deal of information is missing
- Where are we now?
  - Finite Element Earth
  - Coupling of FEA with SPH
- Where are we going?
  - Current Limitations
  - Future Work

Applying SPH to Bedrock Incision: Why Should We Bother?

Bedrock channels

- "…transmit tectonic and/or climatic signals throughout the landscape" (Whipple & Tucker, 1999)
- "…set the boundary conditions for hillslope processes (e.g., soil creep and landslides) responsible for denudation of the land surface" (Whipple & Tucker, 1999)

GIF Credits: giphy.com

Dynamic Landscapes

- Our work examines the intersection of:
  - Geodynamics: forces associated with deep Earth processes
  - Geomorphology: shaping of Earth's surface

  …in dynamic environments with complex and competing interactions:

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Photo Credits: Graham Leonard (GNS)

Constructive and destructive forces acting on the landscape:

- Fluvial (river-generated)
- Topographic (slope and load)
- Glacial
- Tectonic
- Seismic
- …and more

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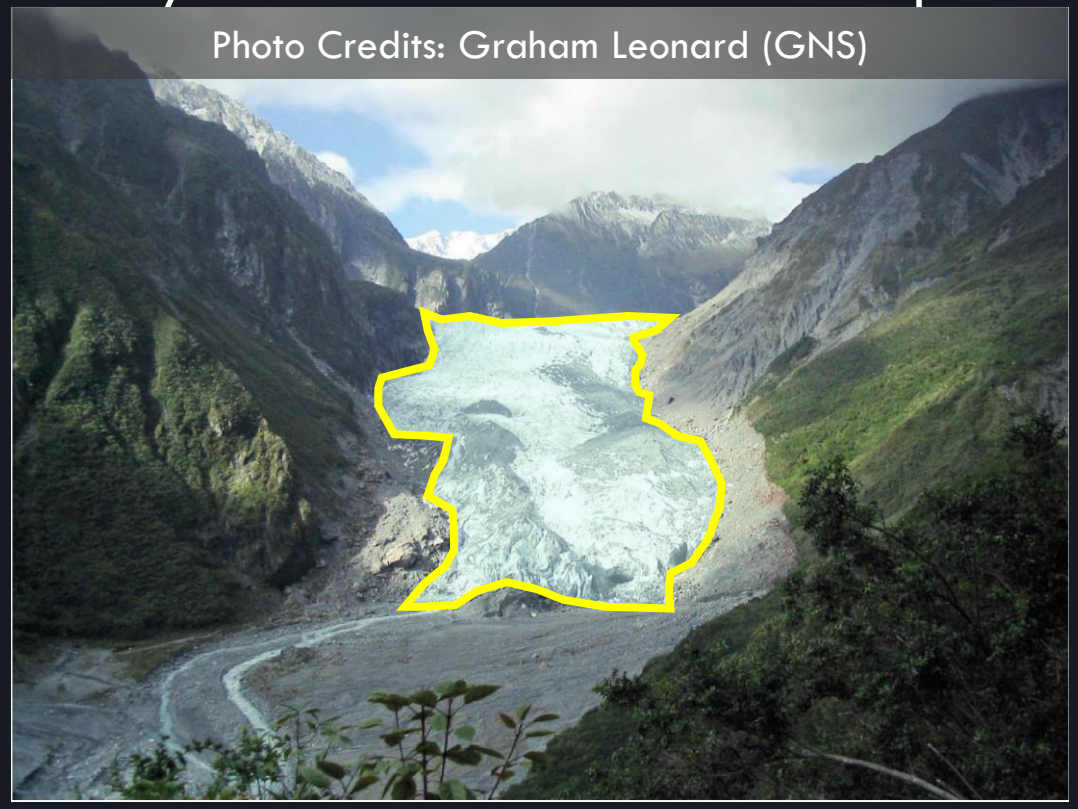

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The established bedrock incision paradigm considers "shear" stress:

Shear Stress Model

$$\frac{dz}{dt} = \mathrm{K}(\tau - \tau_c)$$

$\frac{dz}{dt}$ = rate of bedrock channel erosion

K = erodibility constant

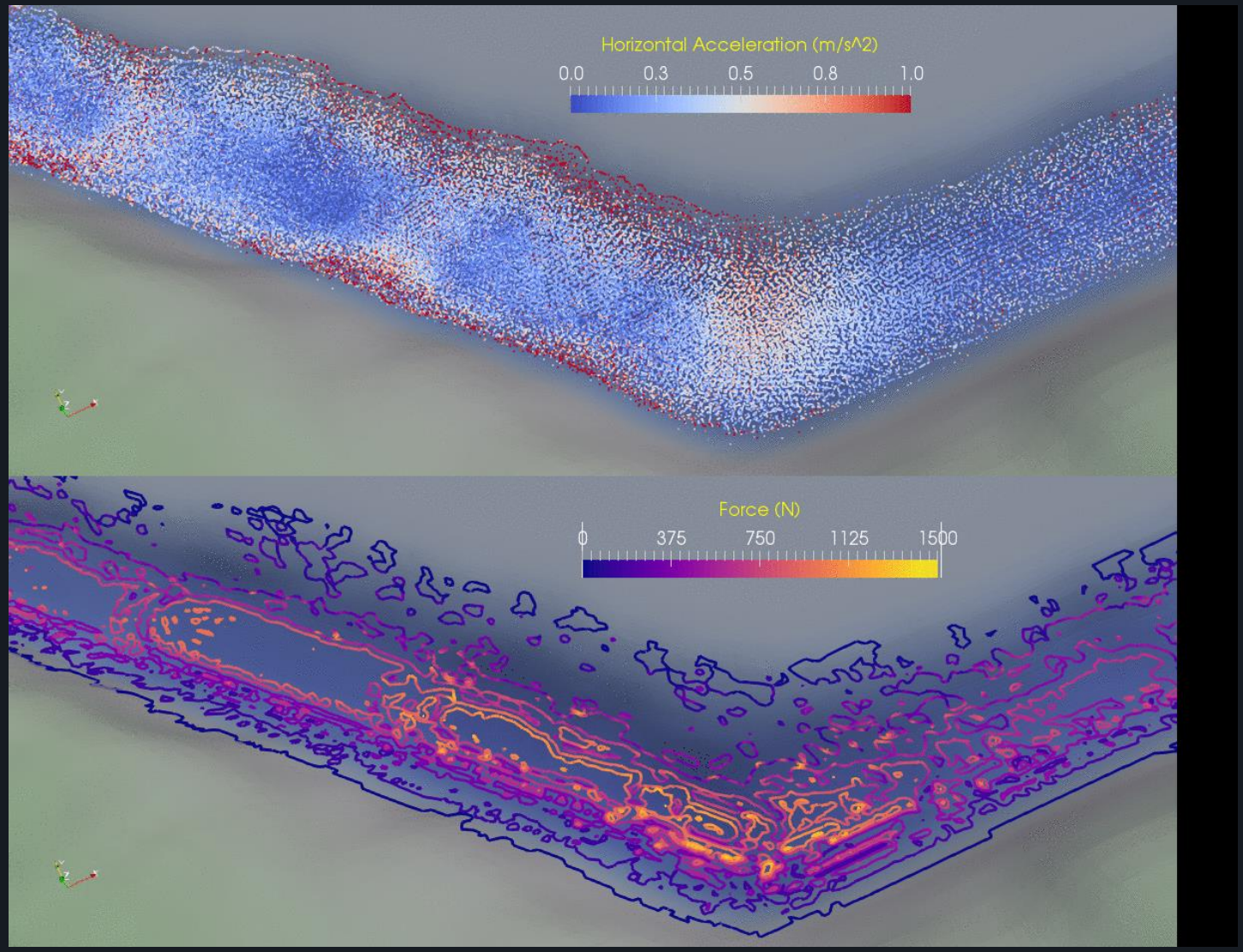
τ = shear stress imposed by the fluid

τ_c = critical shear stress

- Erodibility (***K***) represents the collective influence of climate, sediment supply, grain size, fracture spacing, and more

…but fails to capture the inertial term of Navier-Stokes (N-S)

The inertial term of N-S becomes very important in bedrock channels wherever there are steps, bends, or other causes for local accelerations



Hydraulic Forces with DualSPHysics

ComputeForces in DualSPHysics v4.0:

Finally, a tool to derive the fluvial contribution to the total stress state of dynamic landscapes

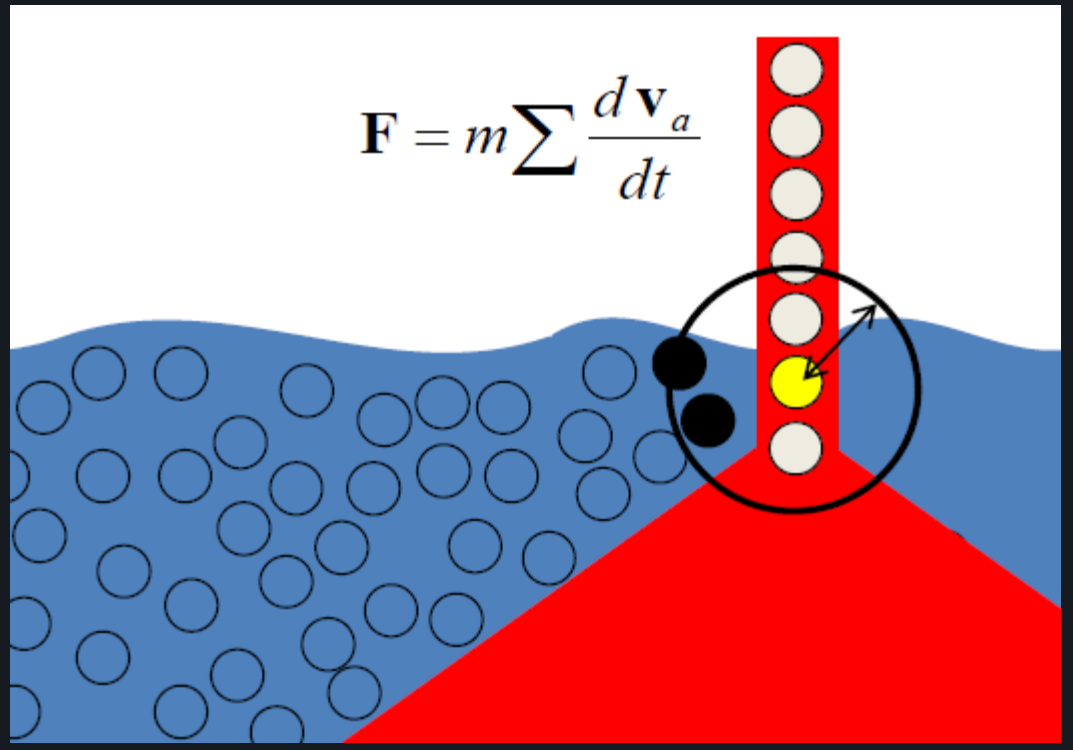


Image Credits: Crespo et al., 2015

COUPLED MODEL

Hydrodynamics + Failure Dynamics

+

Failure
Earth
Response
Model

(Koons and Upton, in prep)

The FERM Approach

Failure
Earth
Response
Model

(Koons and Upton, in prep)

Determining the *Total Stress* in the Landscape

Image Credits: Graham Leonard (GNS) & Peter Koons (UMaine)

$\Sigma = \sigma_{fluvial}$

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Determining the *Total Stress* in the Landscape

Image Credits: Graham Leonard (GNS) & Peter Koons (UMaine)

$$\Sigma = \sigma_{fluvial} + \sigma_{glacial}$$

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Response
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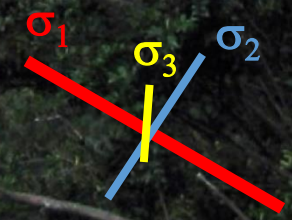

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Determining the *Total Stress* in the Landscape

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$$\Sigma = \sigma_{fluvial} + \sigma_{glacial} (+ \sigma_{coastal}) + \sigma_{slope}$$

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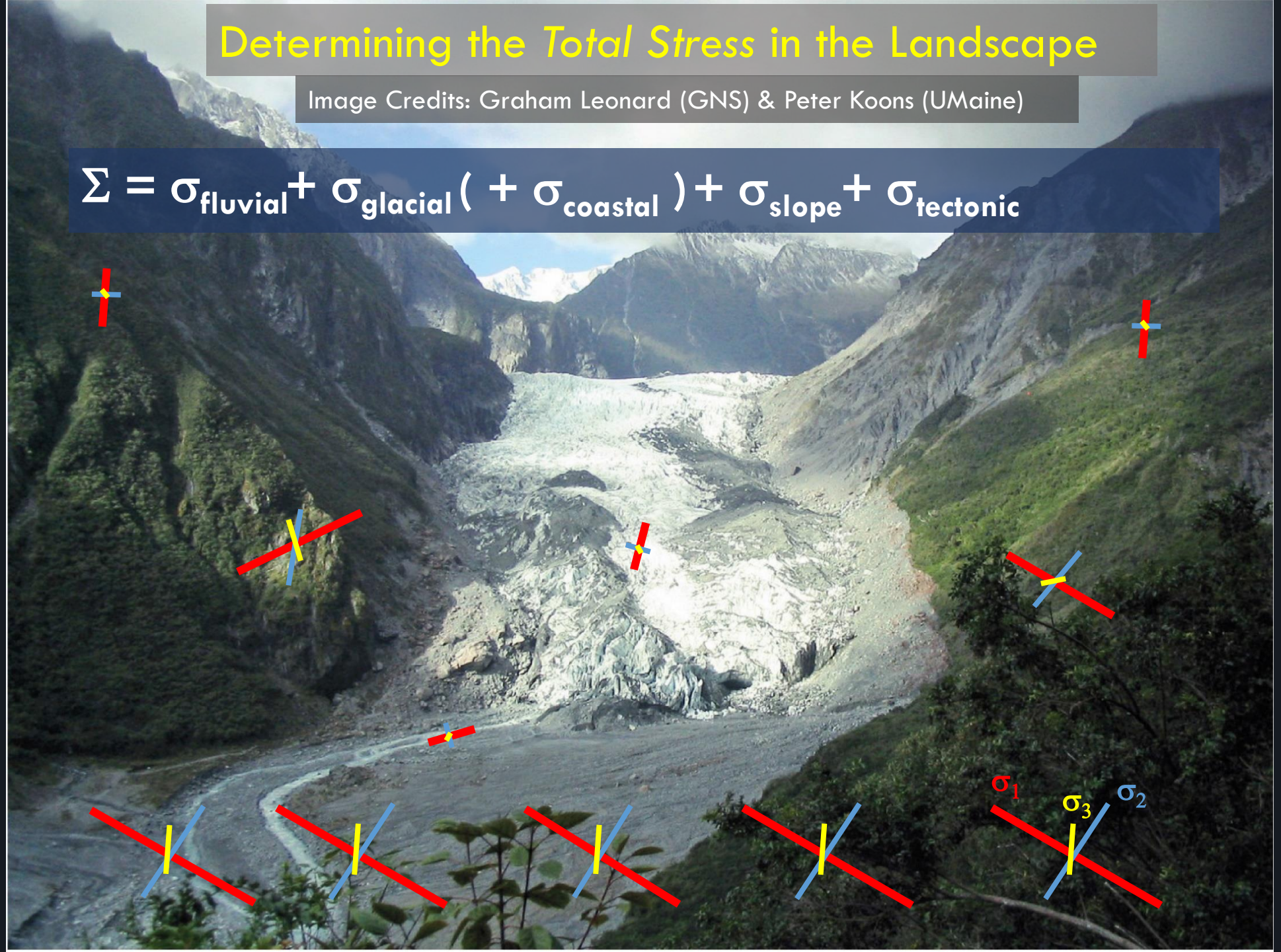

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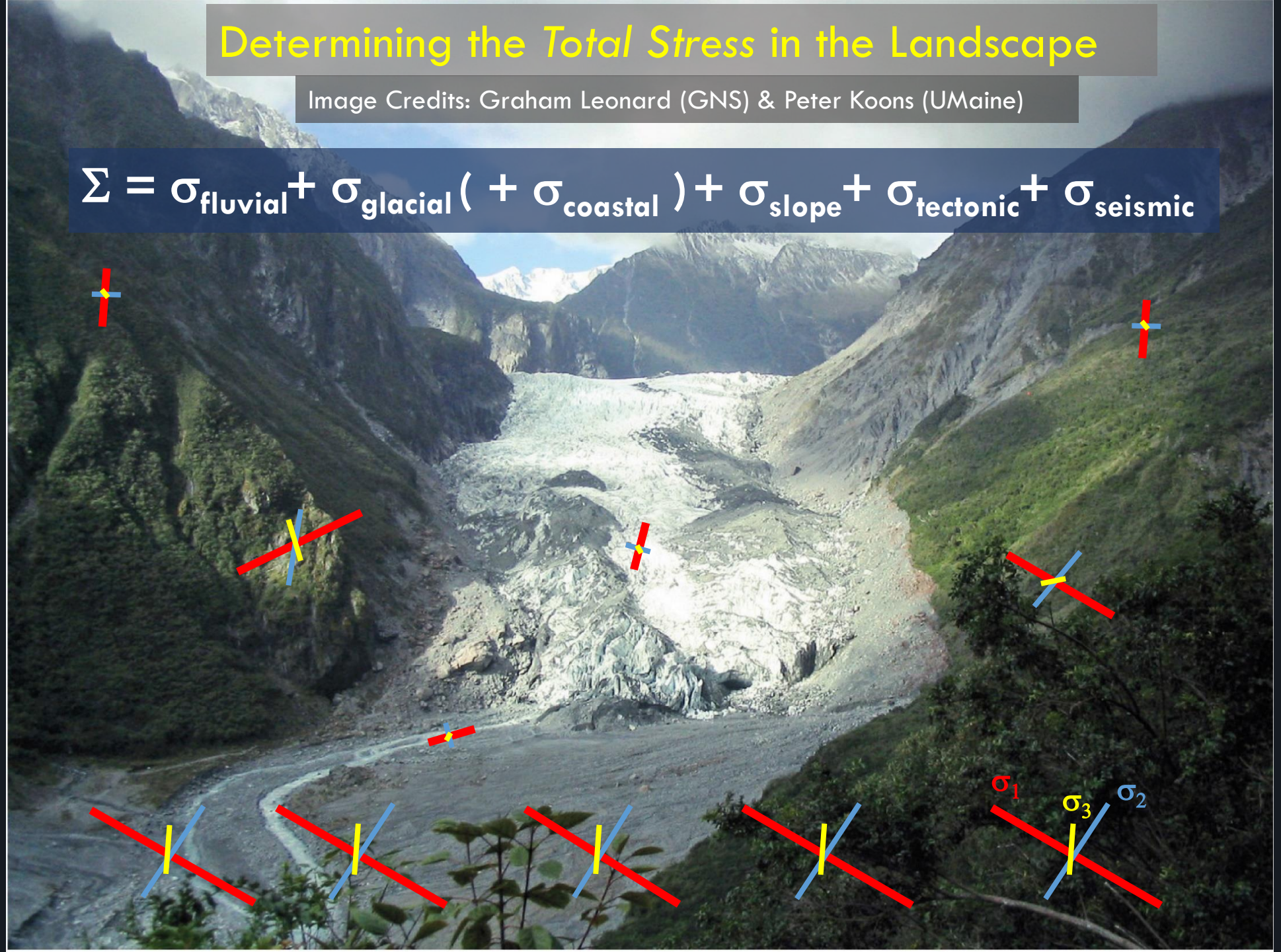

Bedrock Channel Erosion: The FERM Approach

- Now we can examine the three-dimensional stress state of any point in our domain and evaluate its failure potential based on measurements of:

Strength

- Cohesion
- Tensile Strength
- Pore Fluid Pressure
- Friction angle

Stress

- Fluvial
- Topography
- Glaciers
- Seismicity
- Any other quantifiable stress

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The strength components are measurable in the field, so we can predict failure as a function of observable, measurable phenomena

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Blocks are removed when:

$$C : \tau \leq 1$$

C = strength

τ = differential stress

An Example of Coupled FERM-DualSPHysics

Let's examine a simple synthetic example of a channel with a vertical drop akin to a fault scarp

Photo Credits: Kate Pedley, University of Canterbury

Above: fault scarp development following the 2016 Kaikoura earthquake (magnitude 7.8, South Island of New Zealand)

An Example of Coupled FERM-DualSPHysics

Let's examine a simple synthetic example of a channel with a vertical drop akin to a fault scarp

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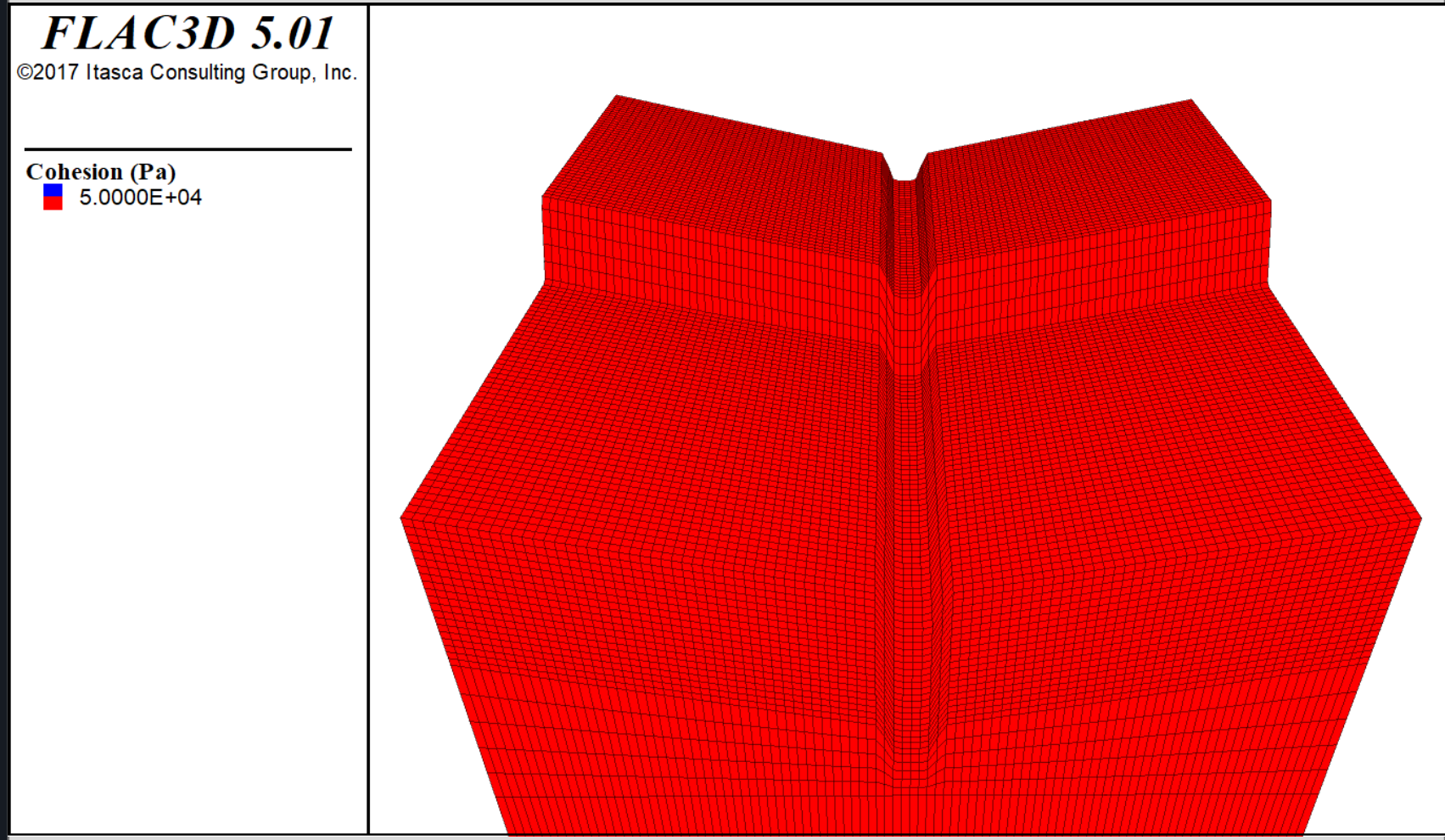
FEA Solution

- FERM is presently implemented in FLAC3D (Fast Lagrangian Analysis of Continua in 3 Dimensions), a commercial FEA solver traditionally used for geotechnical investigations



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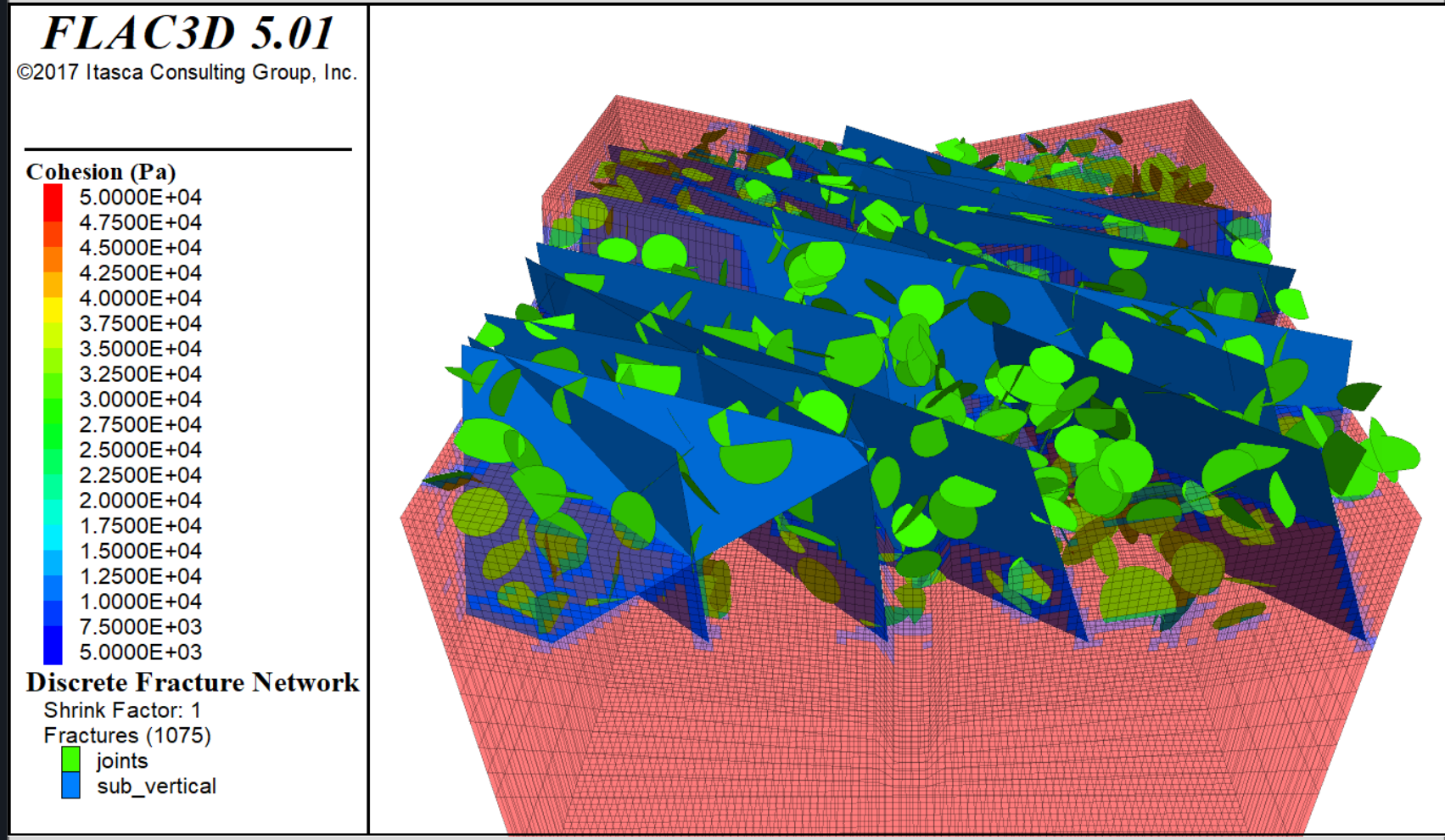
- Strength heterogeneities can be defined by fracture networks which interconnect weak zones



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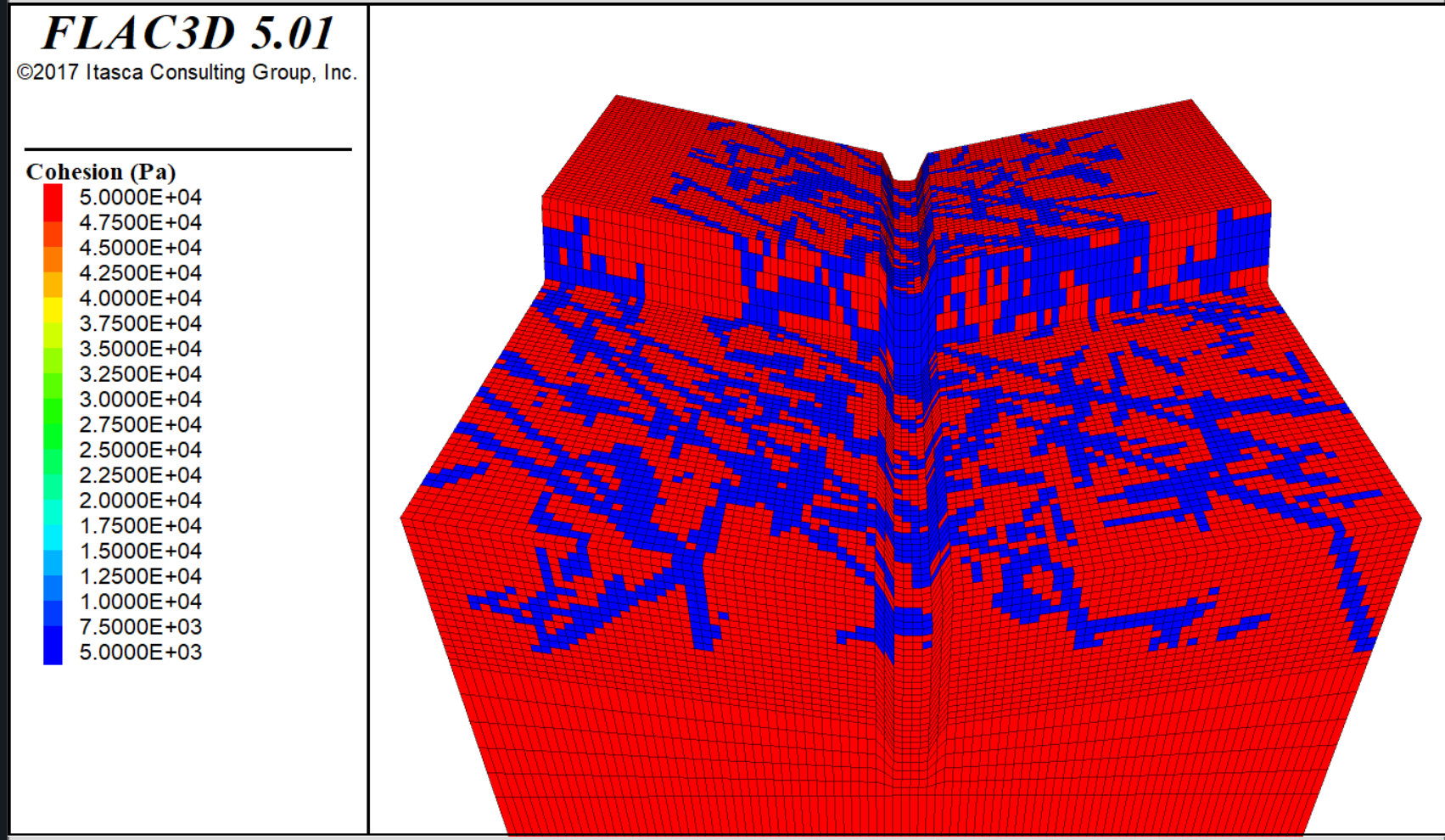


Channelized Flow in DualSPHysics

Constants, Parameters, etc.	
Domain Size	20 m (x), 20 m (y), 5.5 m (z)
dp (distance between particles)	0.1 m
Number of Particles (initial state)	112722 (bound=97115, fluid=15607)
Number of Particles (final erosion cycle)	145962 (bound=108500, fluid=37462)
Viscosity Scheme	Artificial
speed of sound coefficient (α)	20
Viscosity Value	0.1
ViscoBoundFactor (α_{fb})	10
Step Algorithm	Symplectic
Kernel	Wendland
Precision	Double
delta-SPH ($\delta\Phi$)	0.1
Time of Simulation	30 s
XPeriodicIncZ	2.5

Estimated as per:
Barreiro A, Domínguez JM, Crespo AJC, González-Jorge H, Roca D, et al. (2014) Integration of UAV Photogrammetry and SPH Modelling of Fluids to Study Runoff on Real Terrains. PLoS ONE 9(11): e111031.

An Example of Coupled FERM-DualSPHysics

Let's take a look at our fault scarp in GenCase

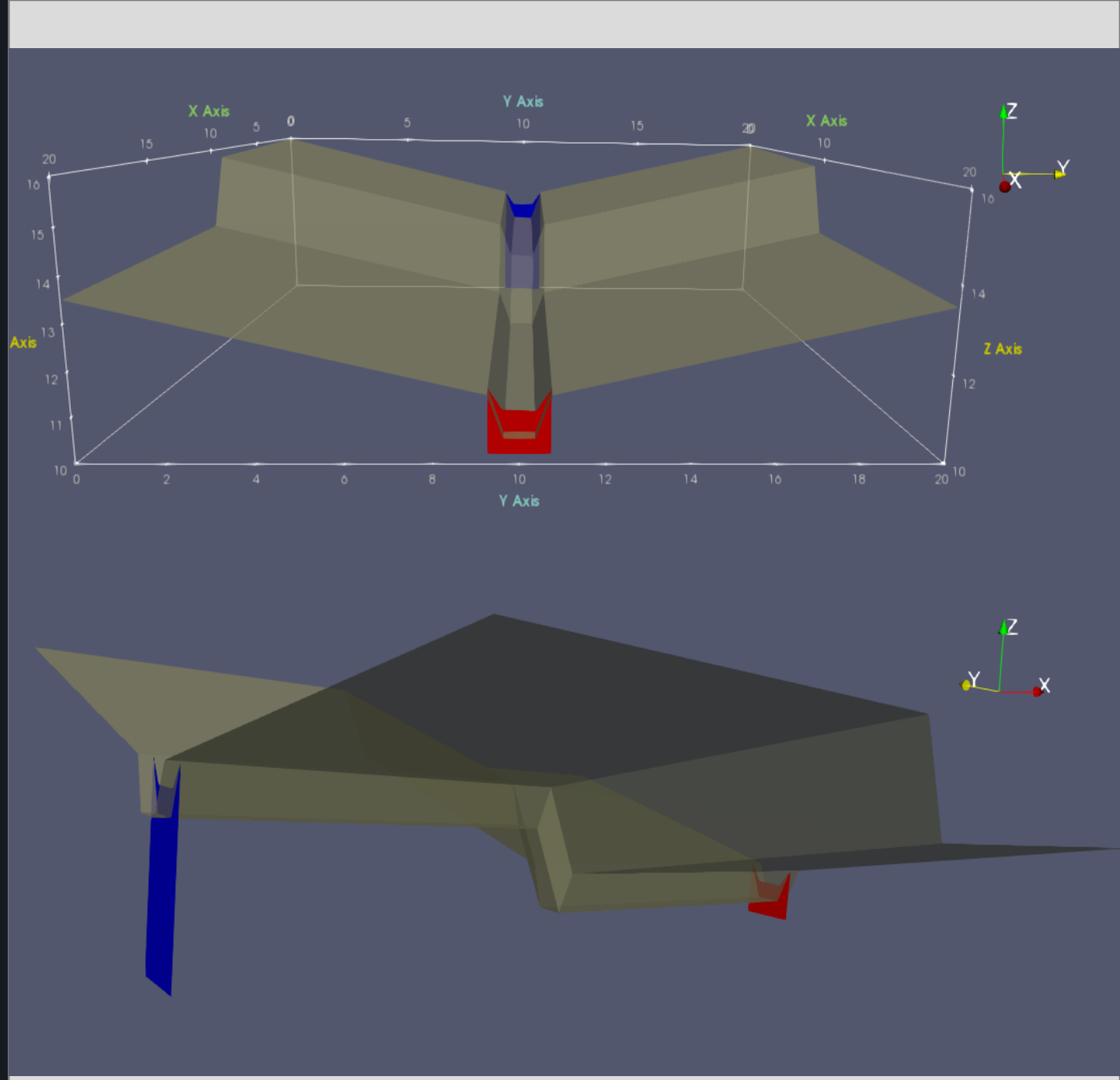
Photo Credits: Kate Pedley, University of Canterbury

Above: fault scarp development following the 2016 Kaikoura earthquake (magnitude 7.8, South Island of New Zealand)

Channelized Flow in DualSPHysics

Dimensions:

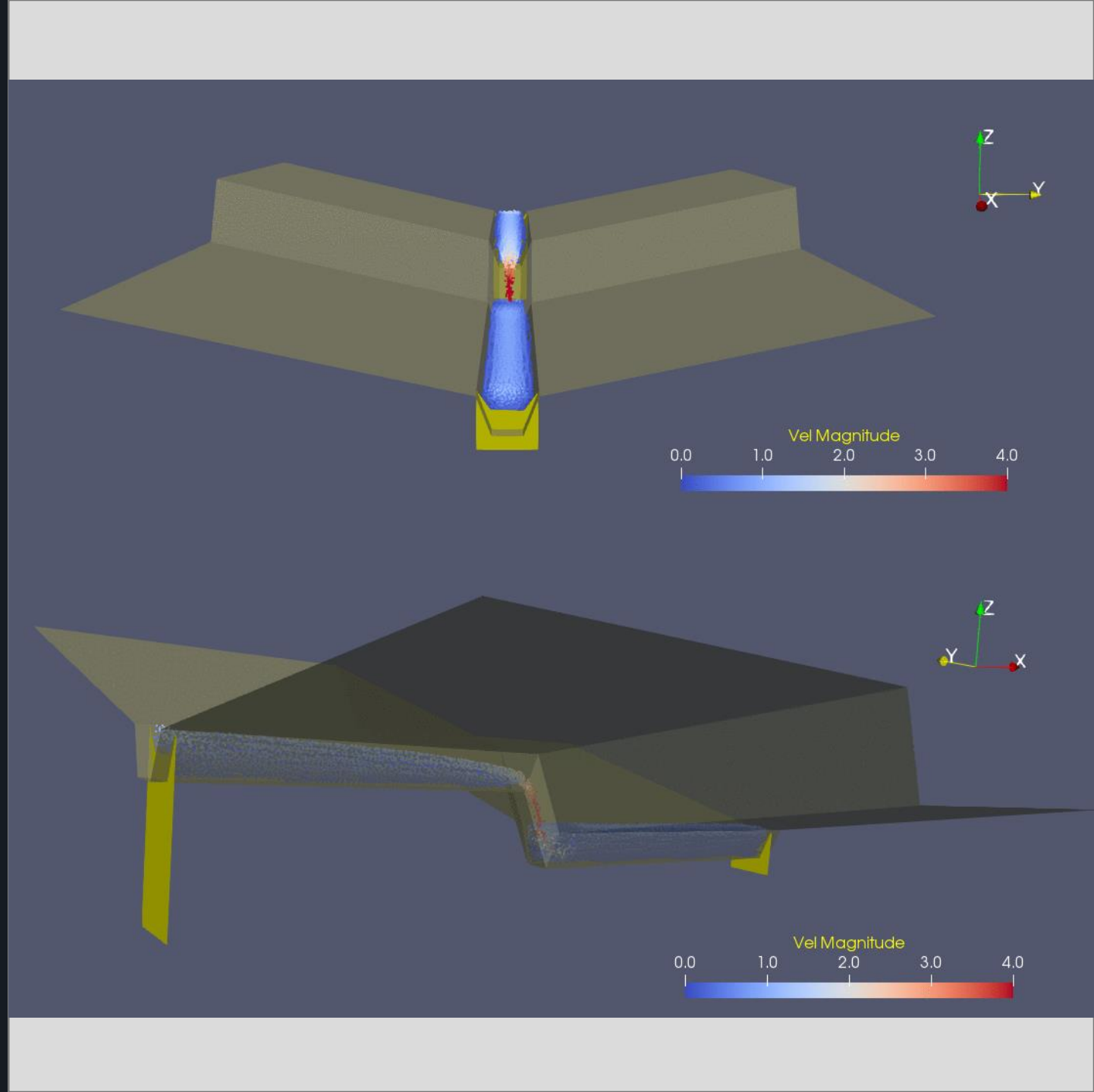
- 20m long (x)
- 20m wide (y)
- 2m drop at fault scarp
- Channel slope ≈1.5°
- Banks slope ≈12° towards channel
- Channel is 1.5m wide at top of banks, 0.75m wide at the channel bed



Channelized Flow in DualSPHysics

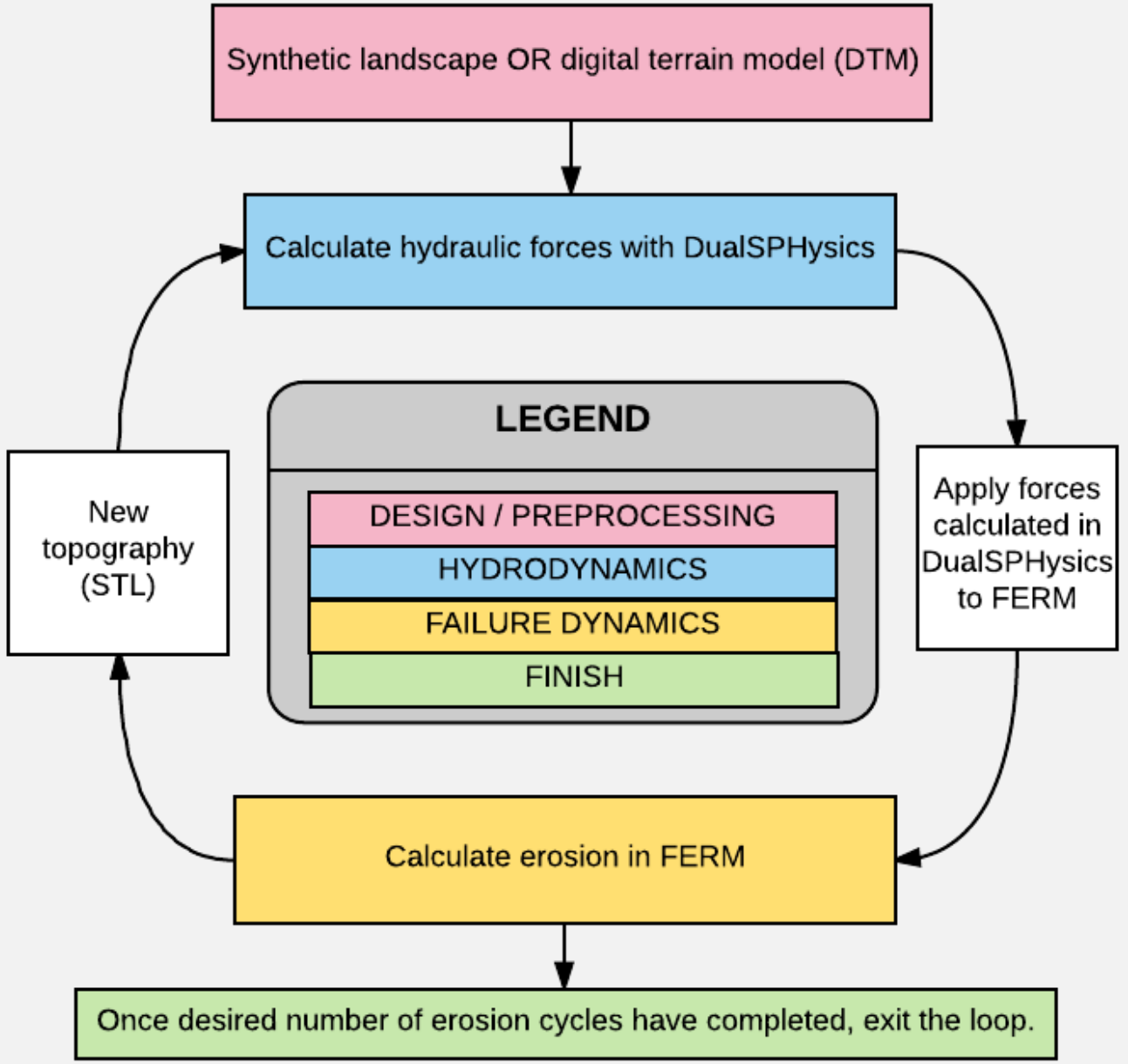
Boundary Conditions

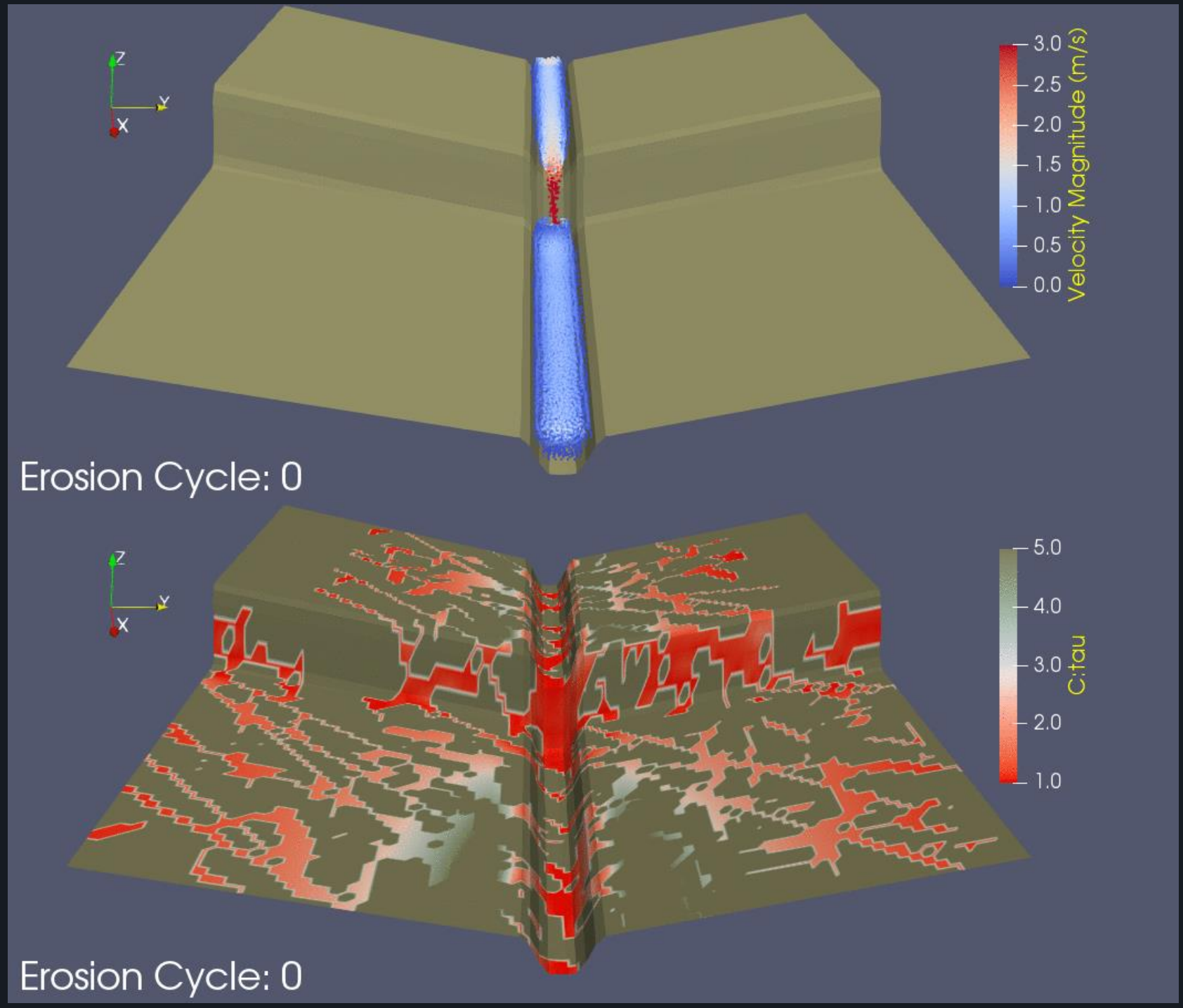
- Periodic Boundary Condition in the x-dimension
- Flow gates are used to control the discharge

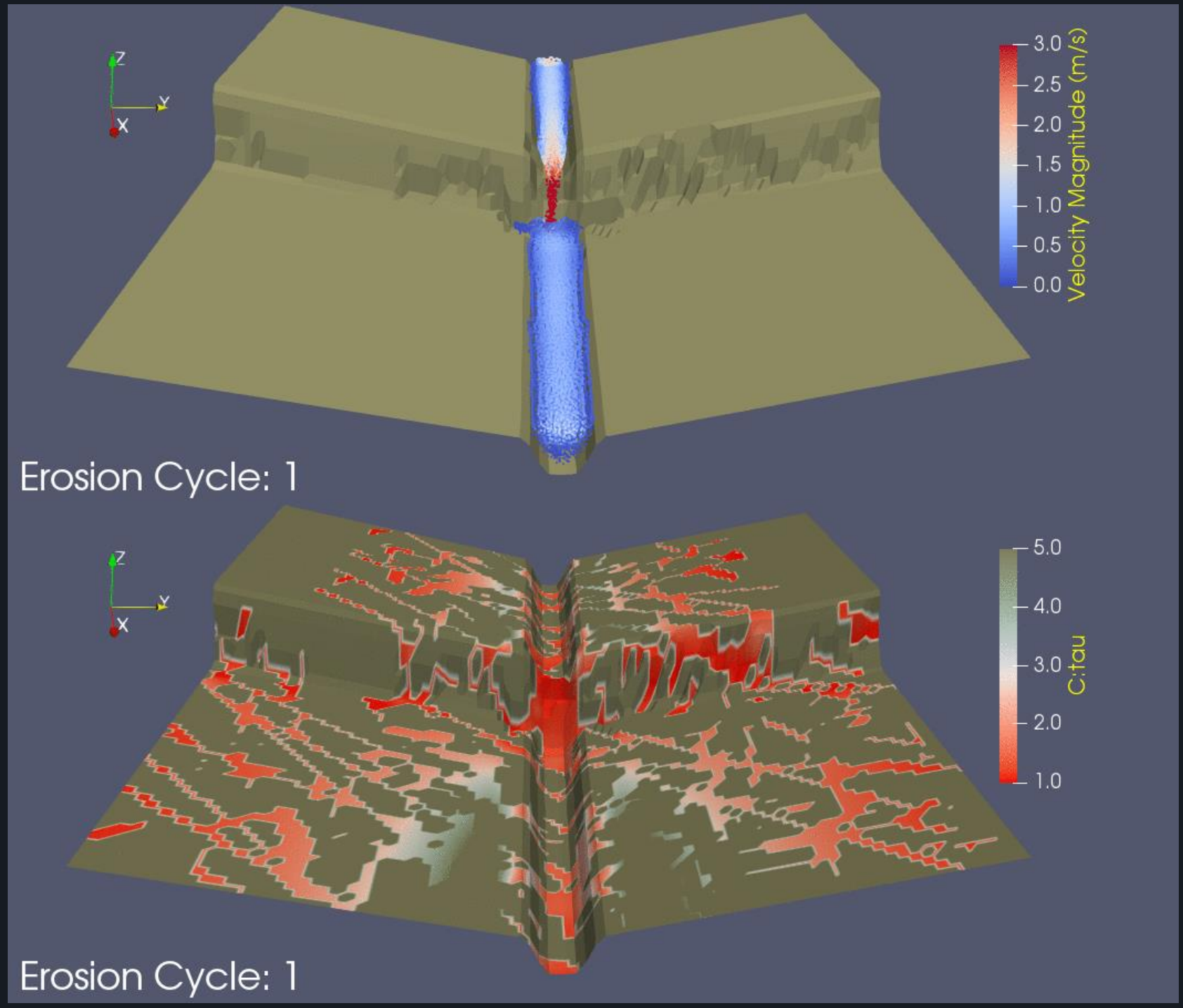


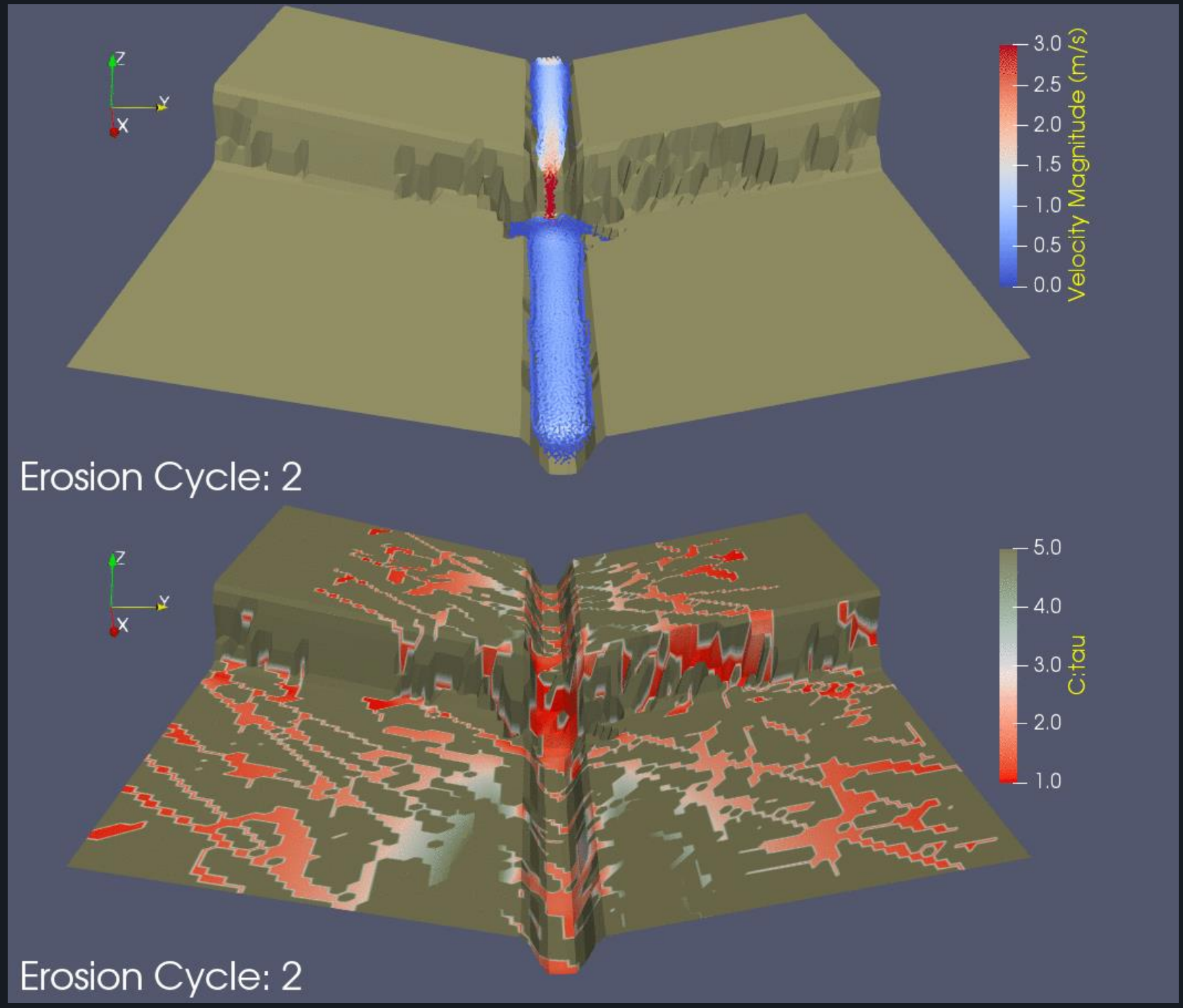
Coupling Methods

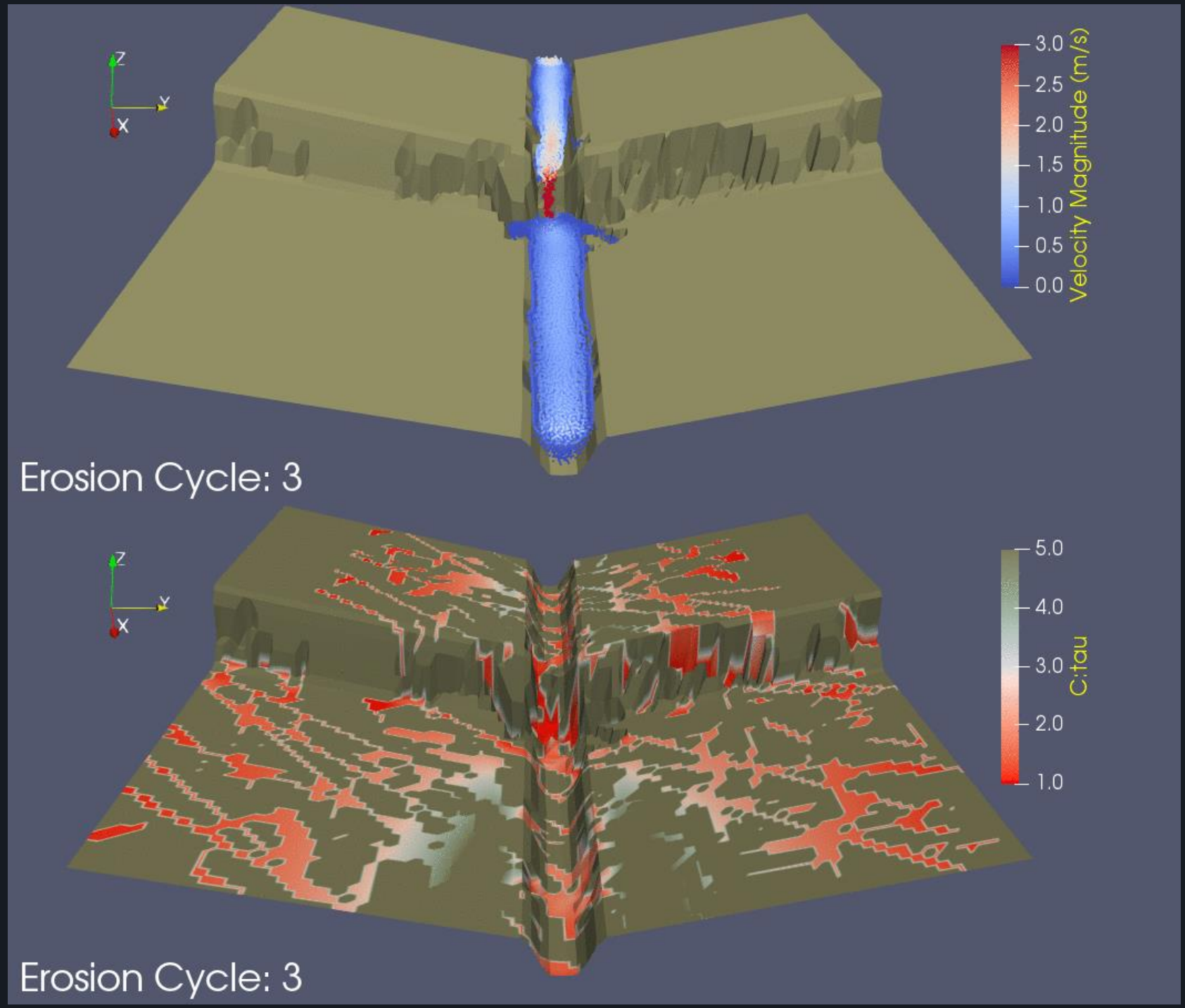
- Once the flow approaches a steady state, a “snapshot” of the forces (at t = 30s) is used as the force inputs into the failure solver

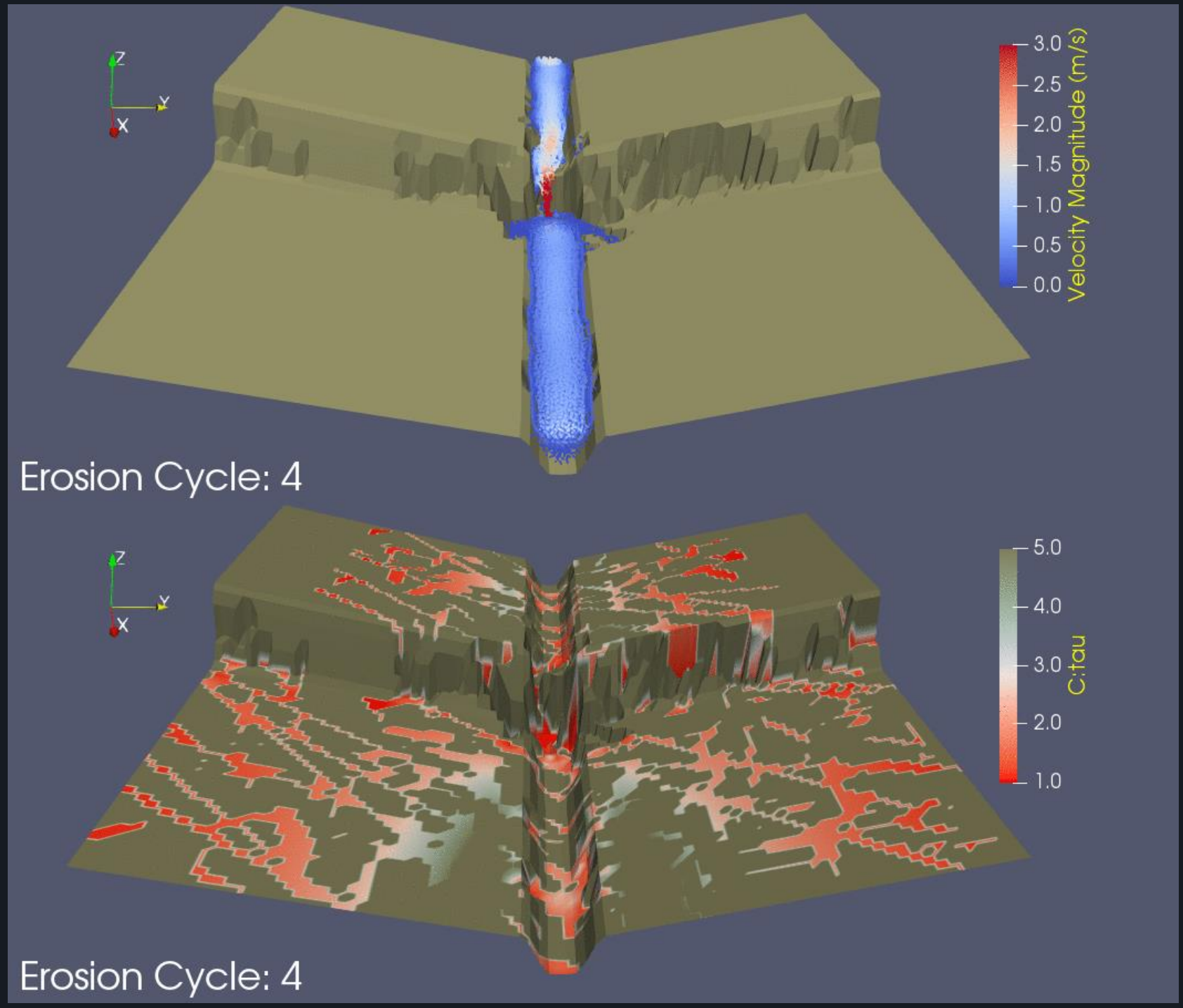


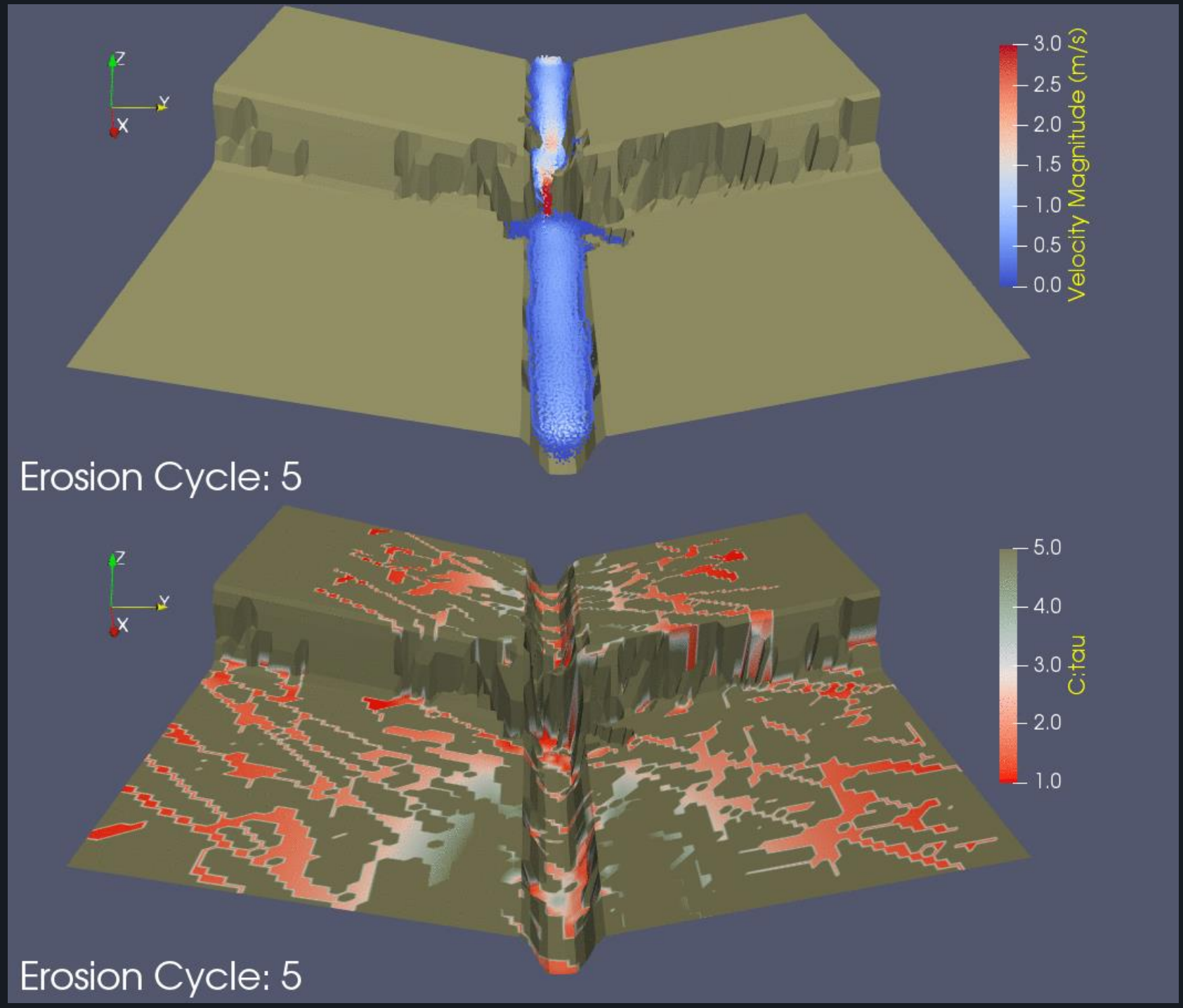

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 0
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 0

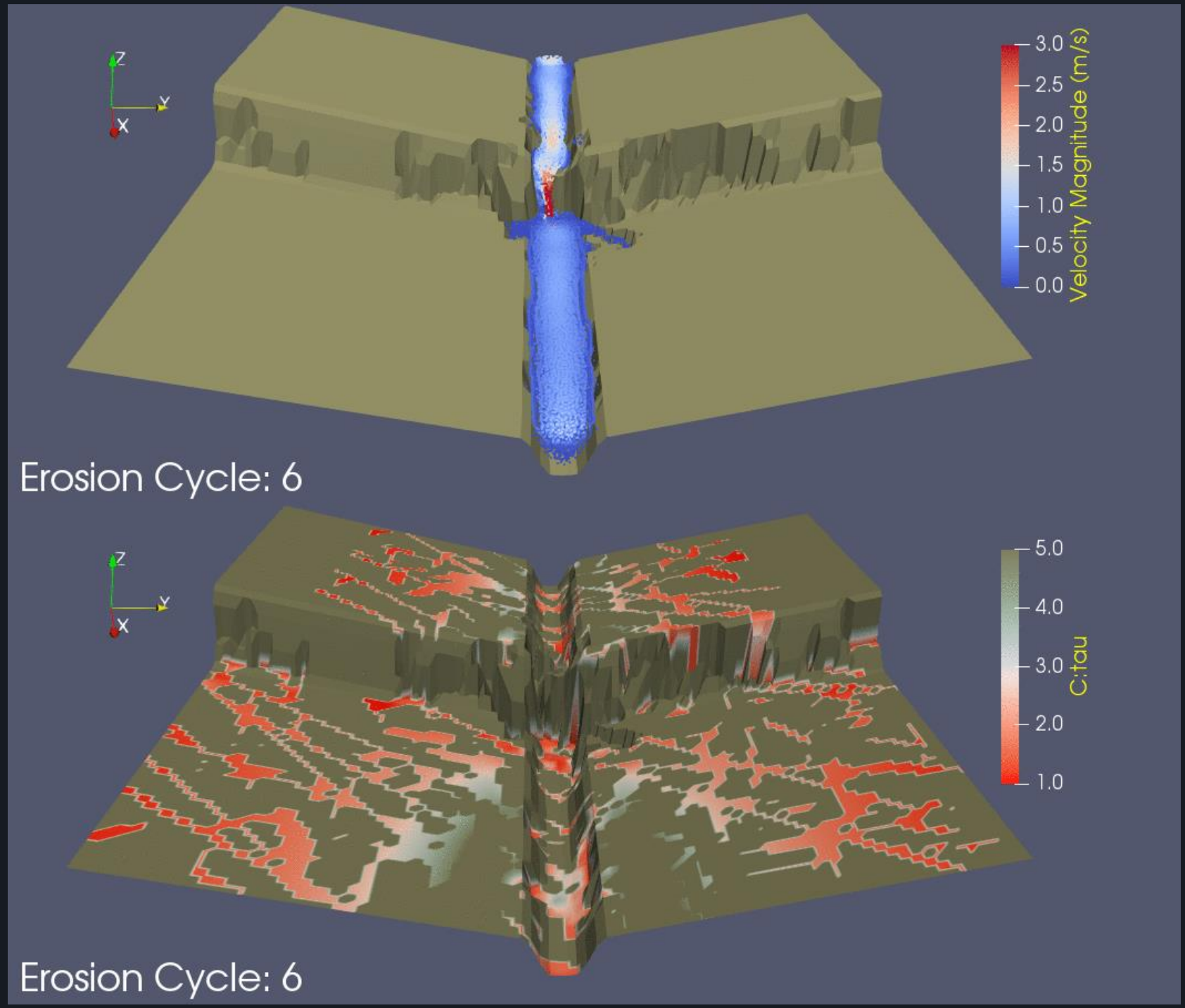

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 1
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 1

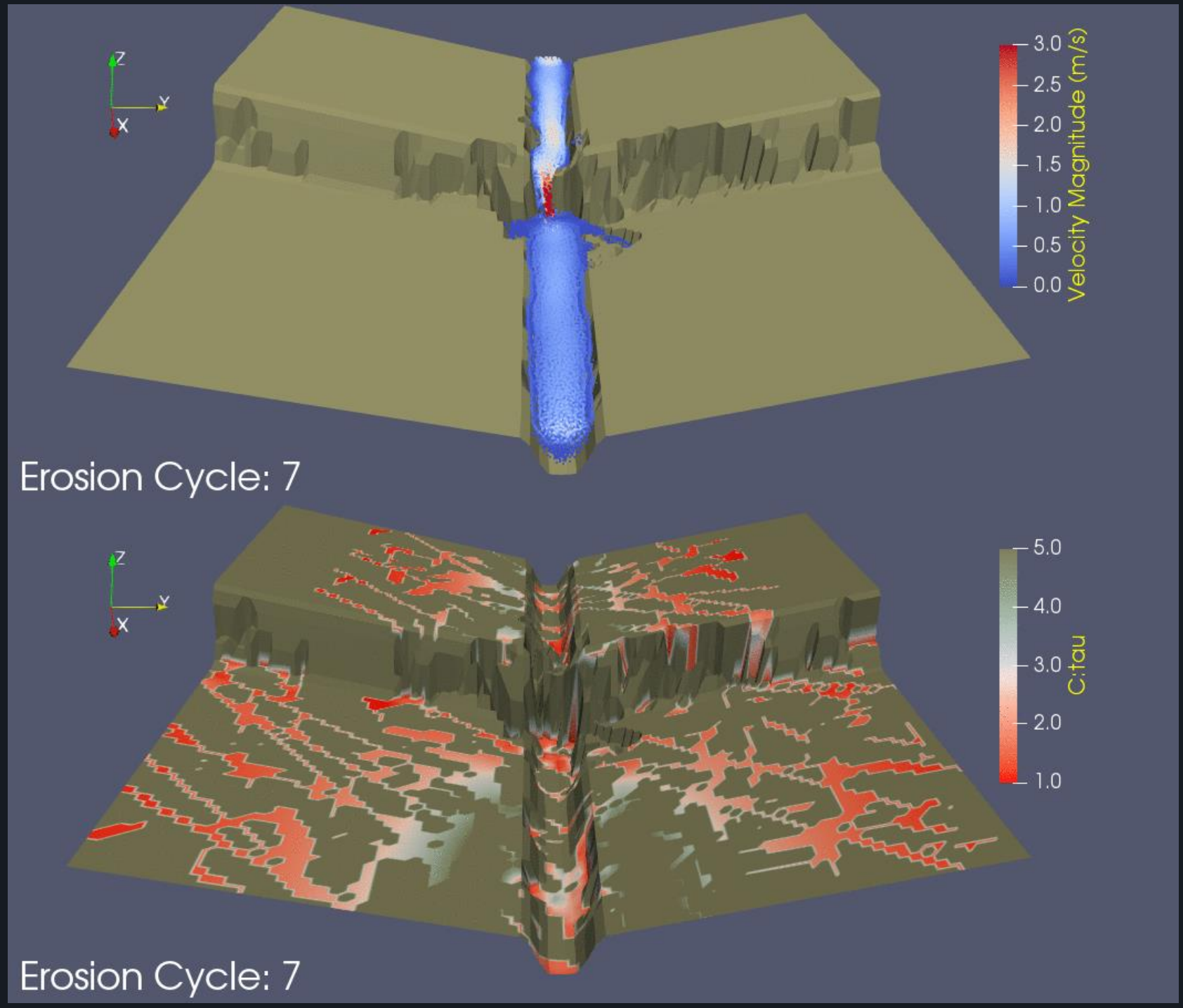

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 2
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 2

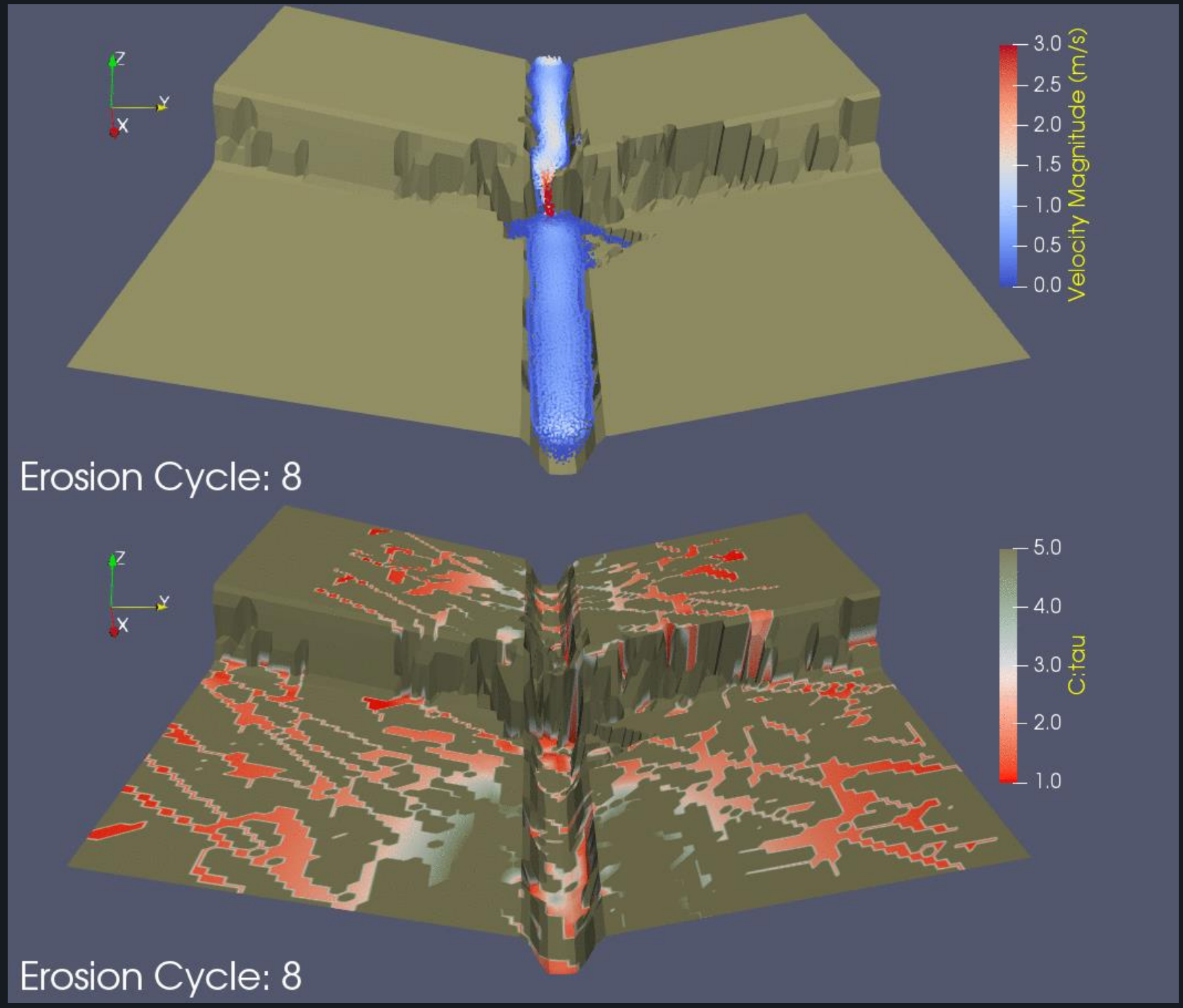

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 3
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 3

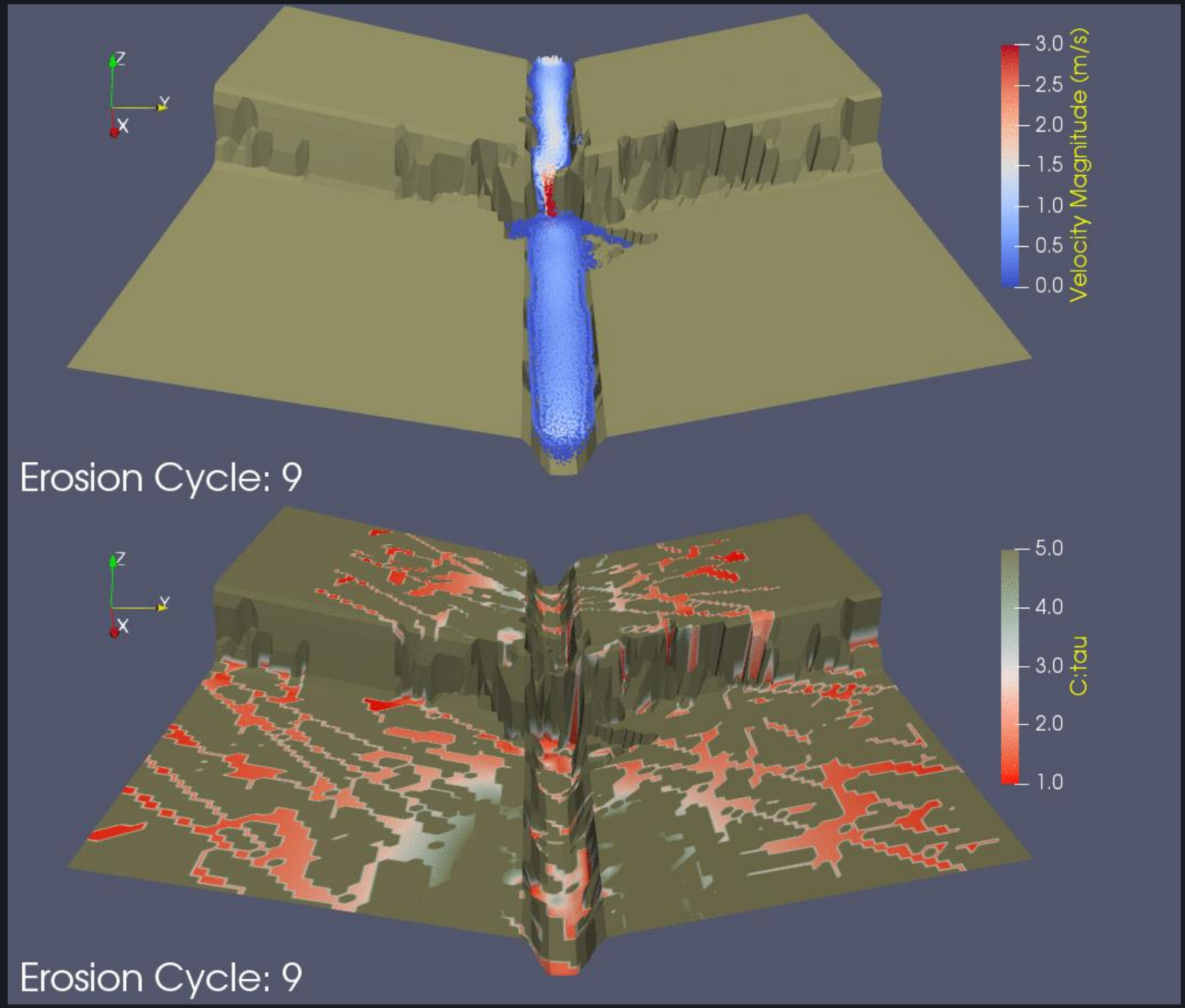

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 4
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 4

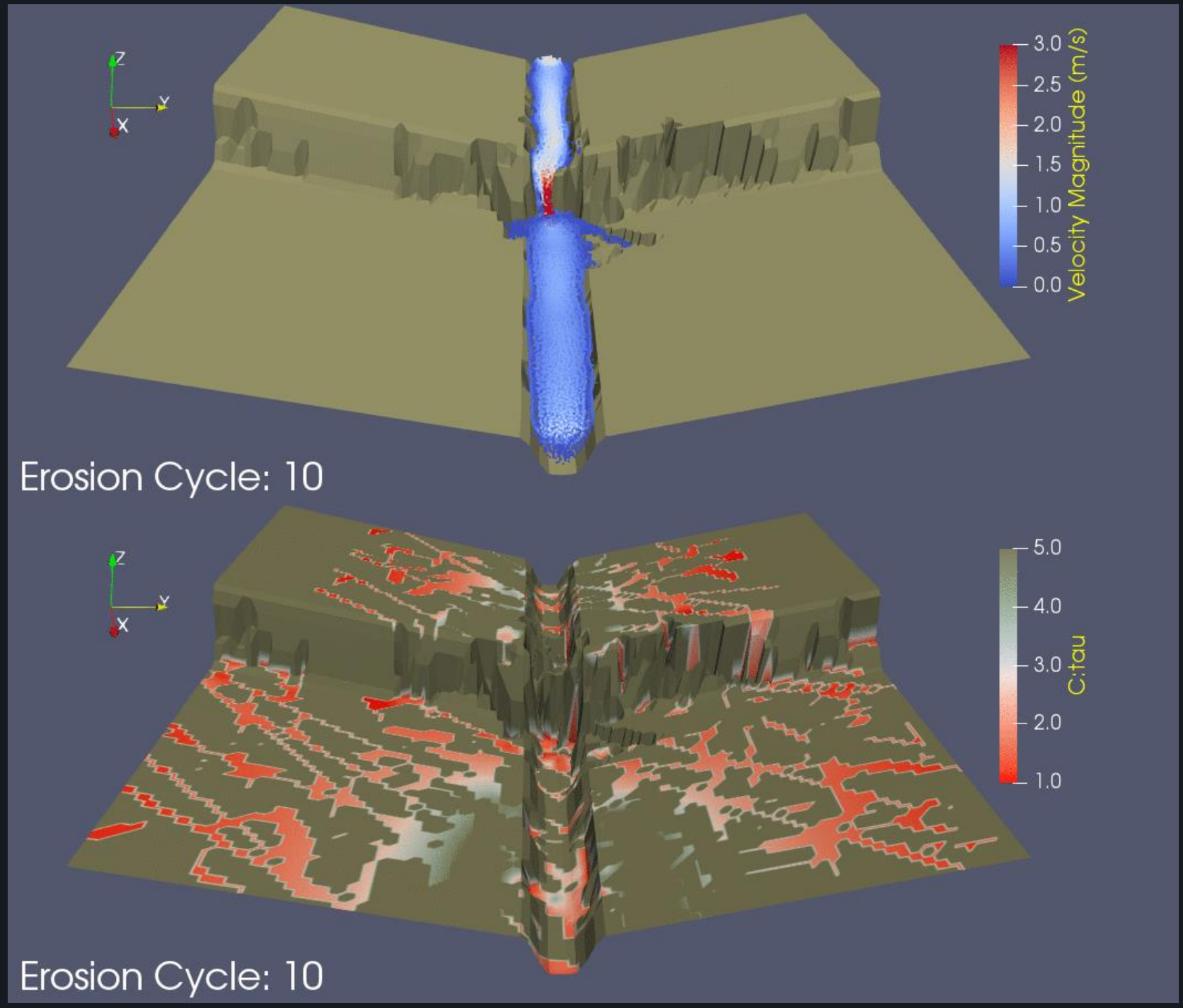

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 5
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 5

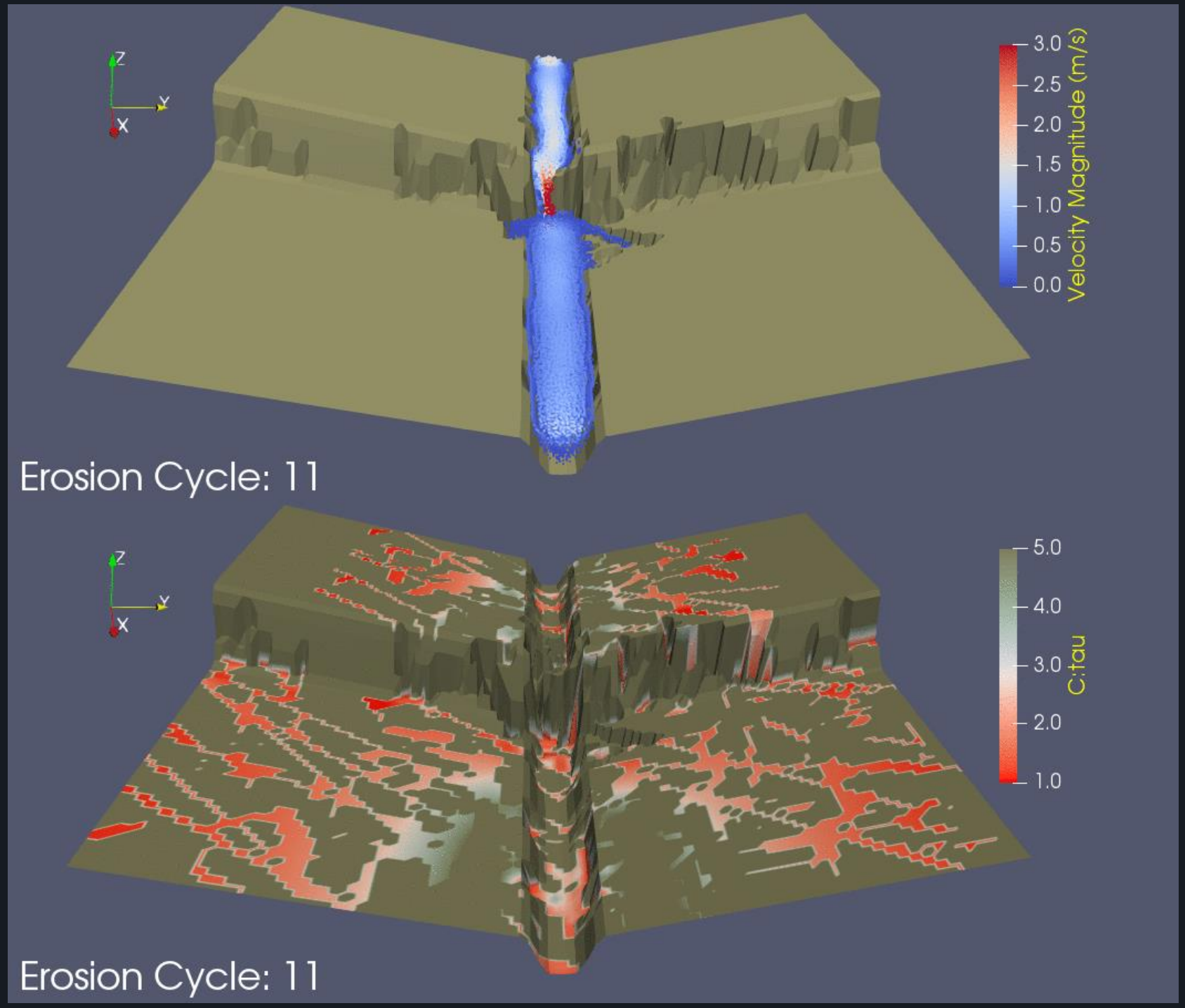

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 6
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 6

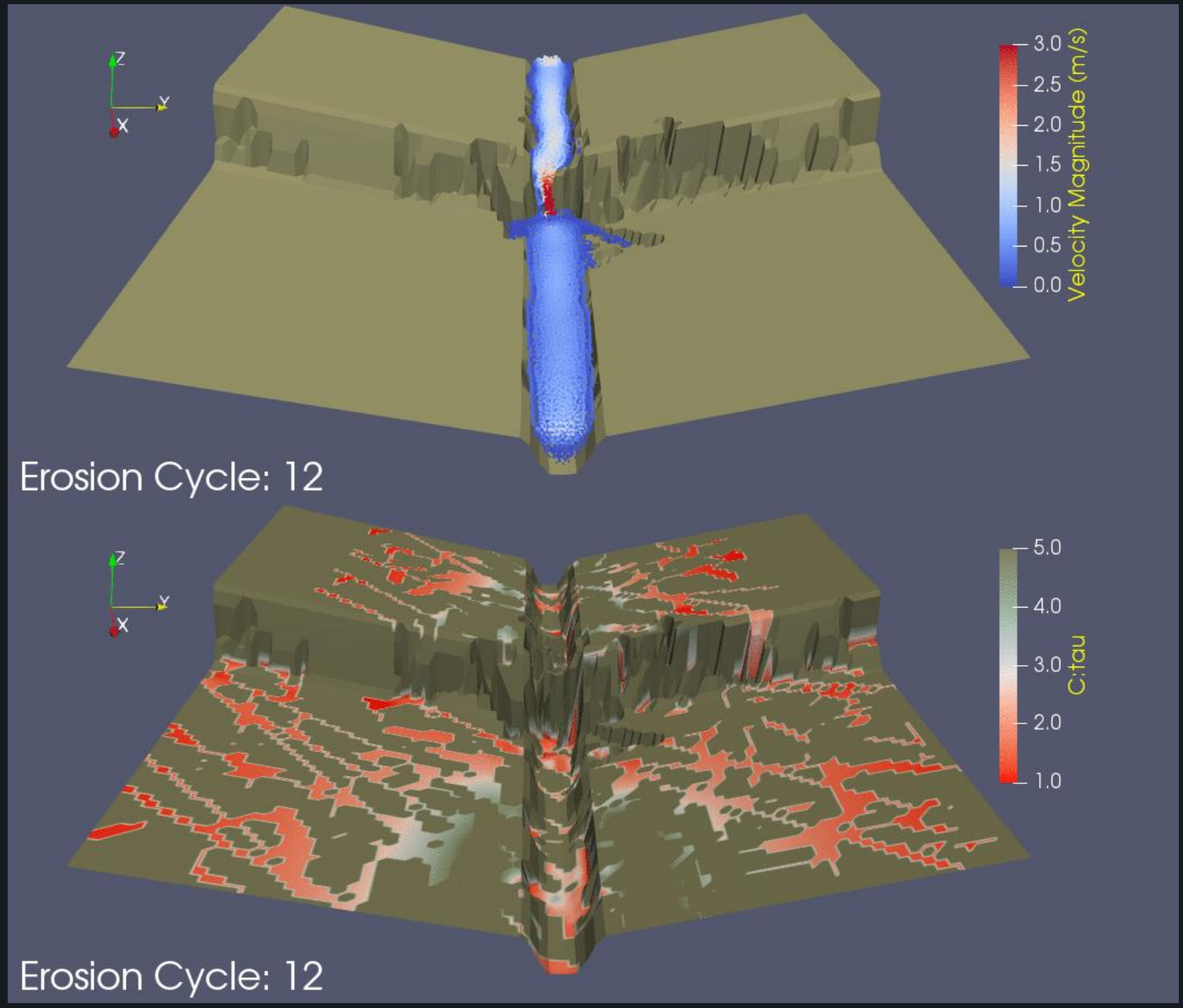

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 7
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 7

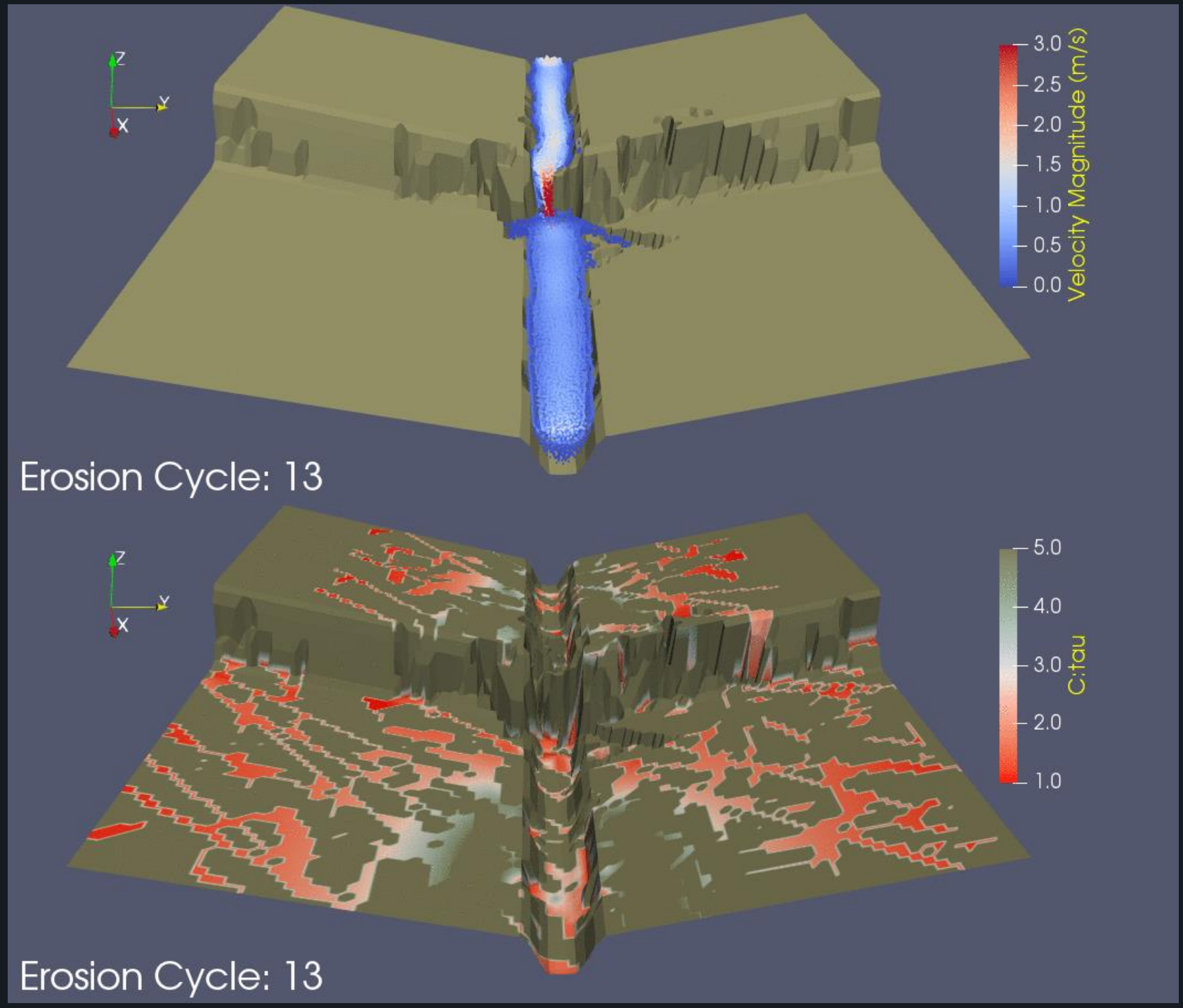

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 8
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 8

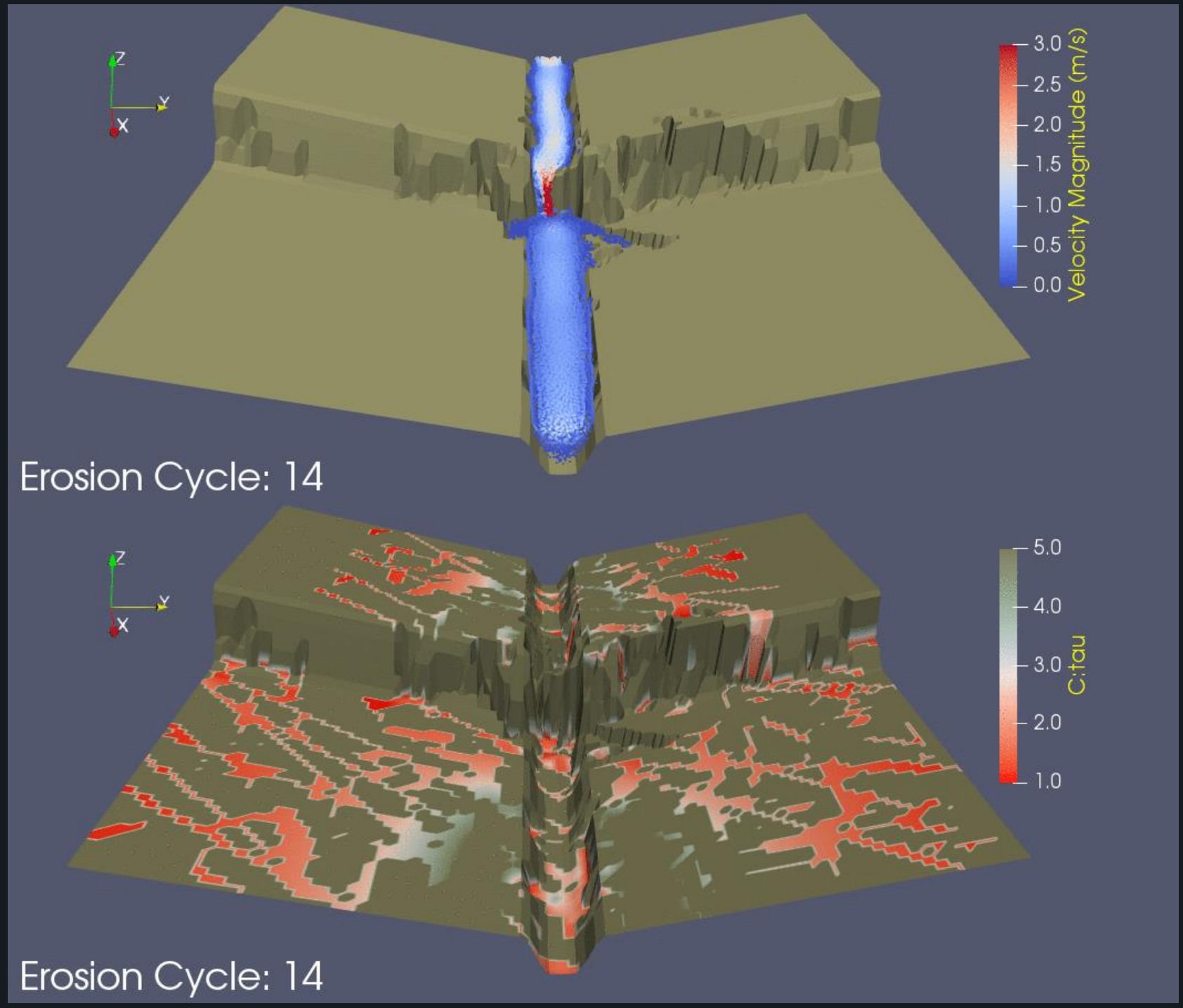

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 9
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 9

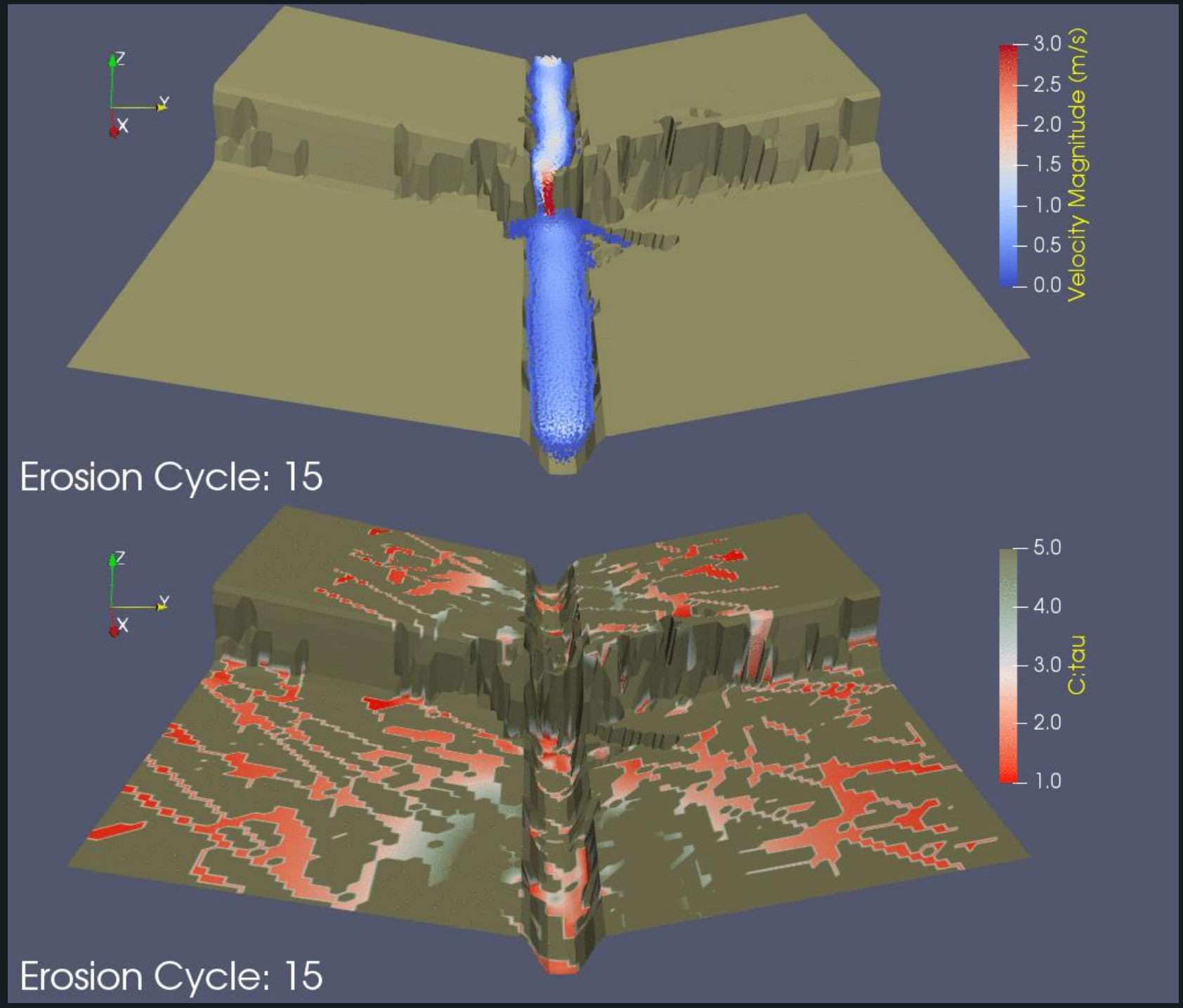

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 10
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 10

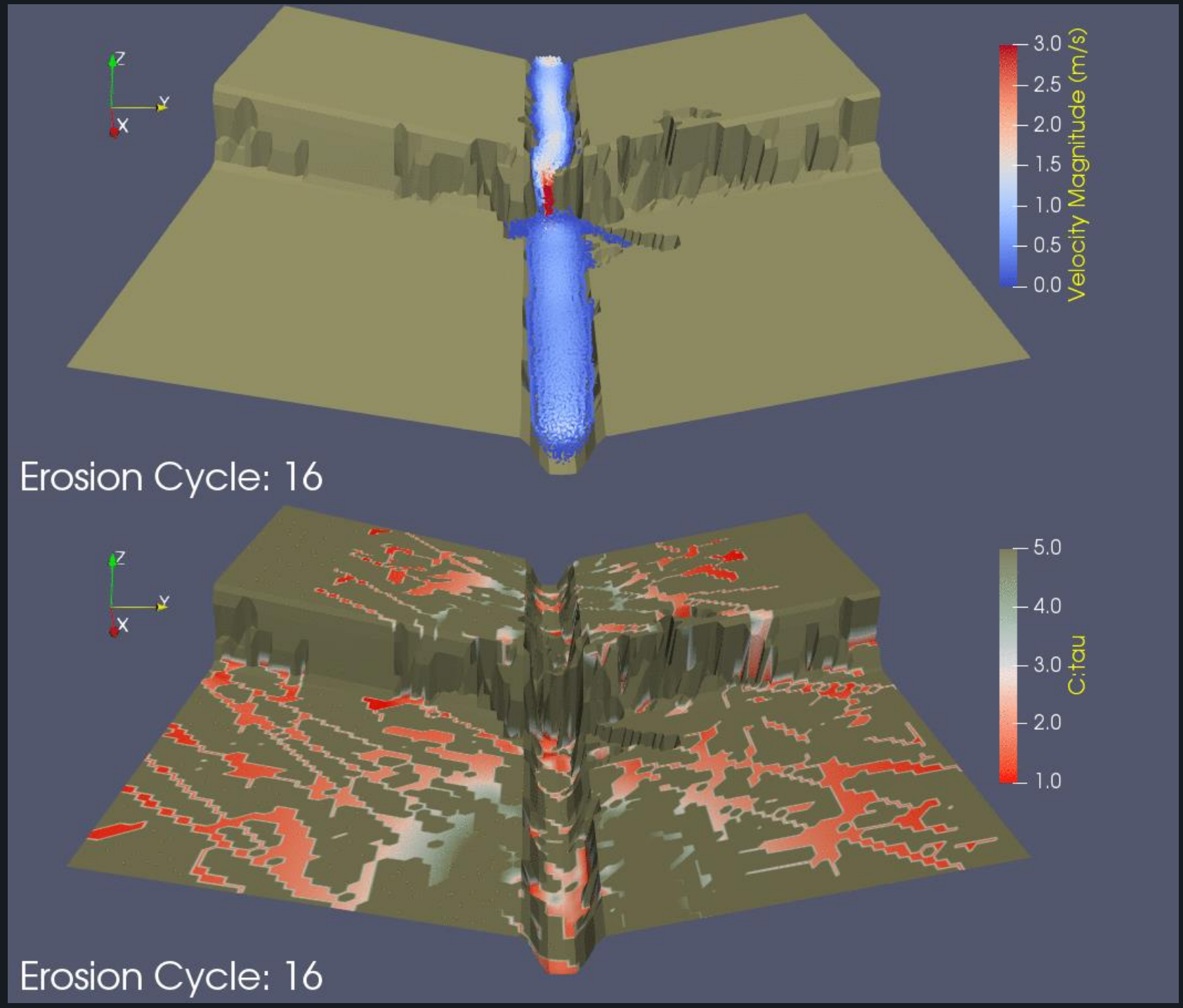

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 11
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 11

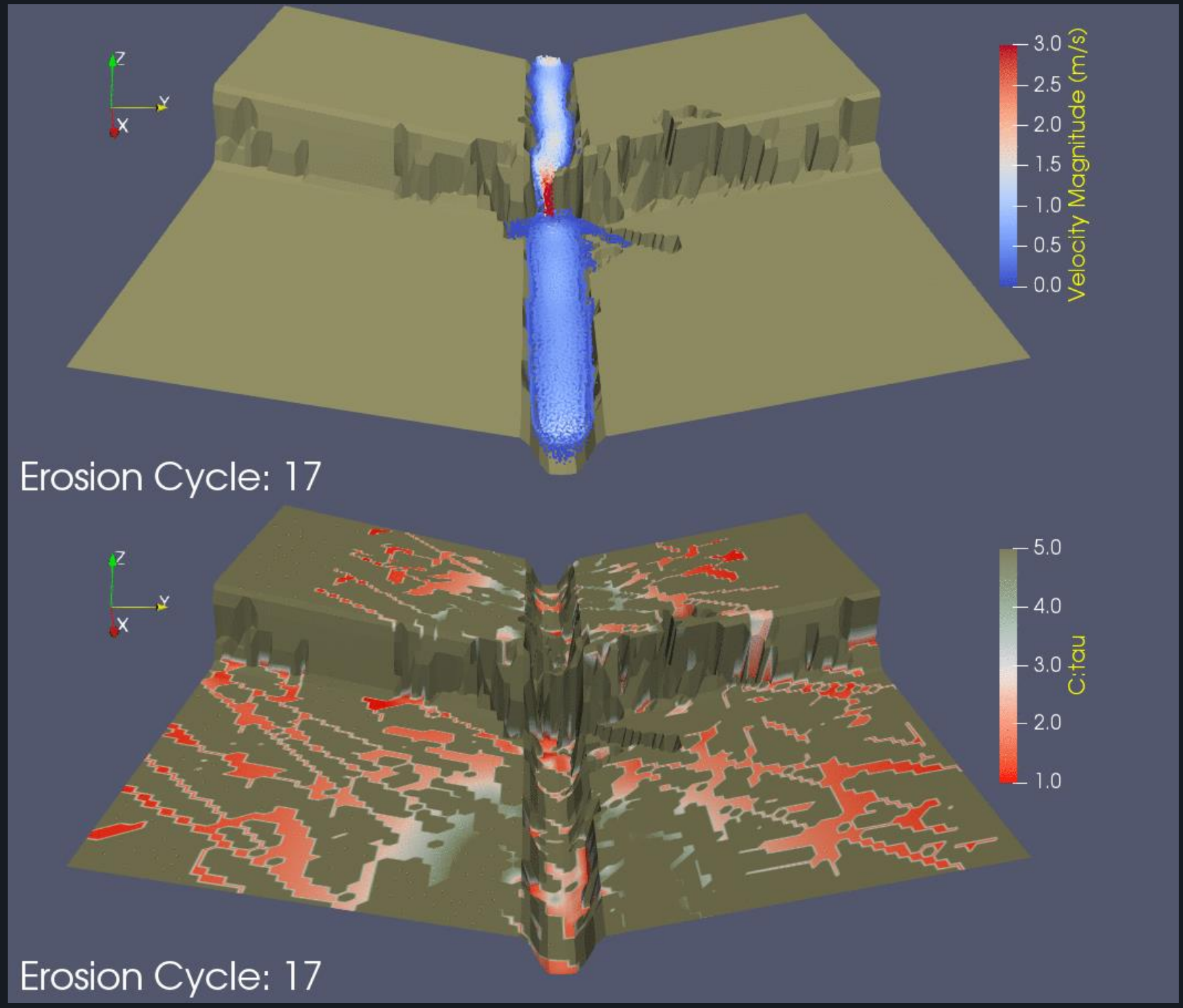

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 12
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 12

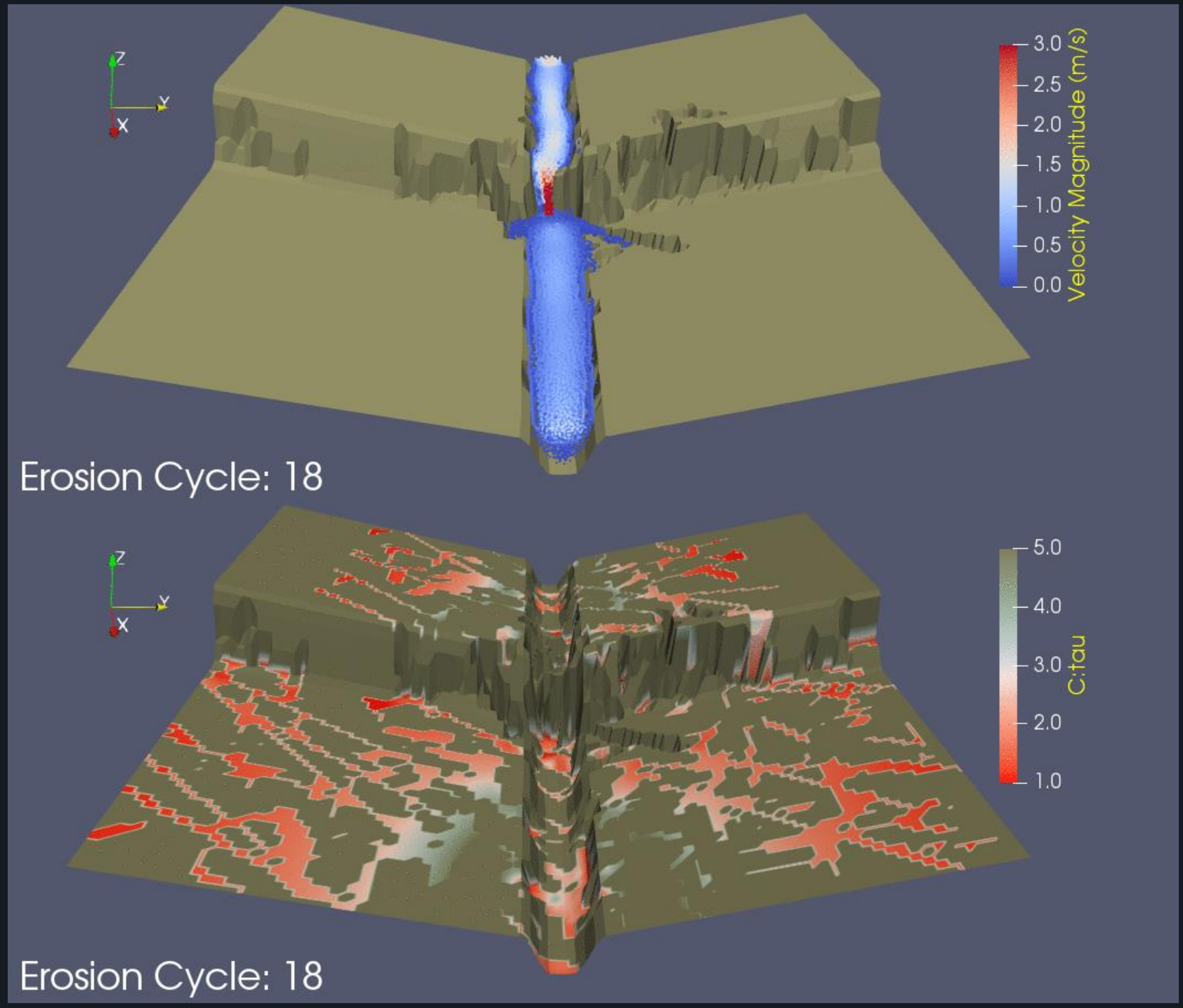

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 13
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 13

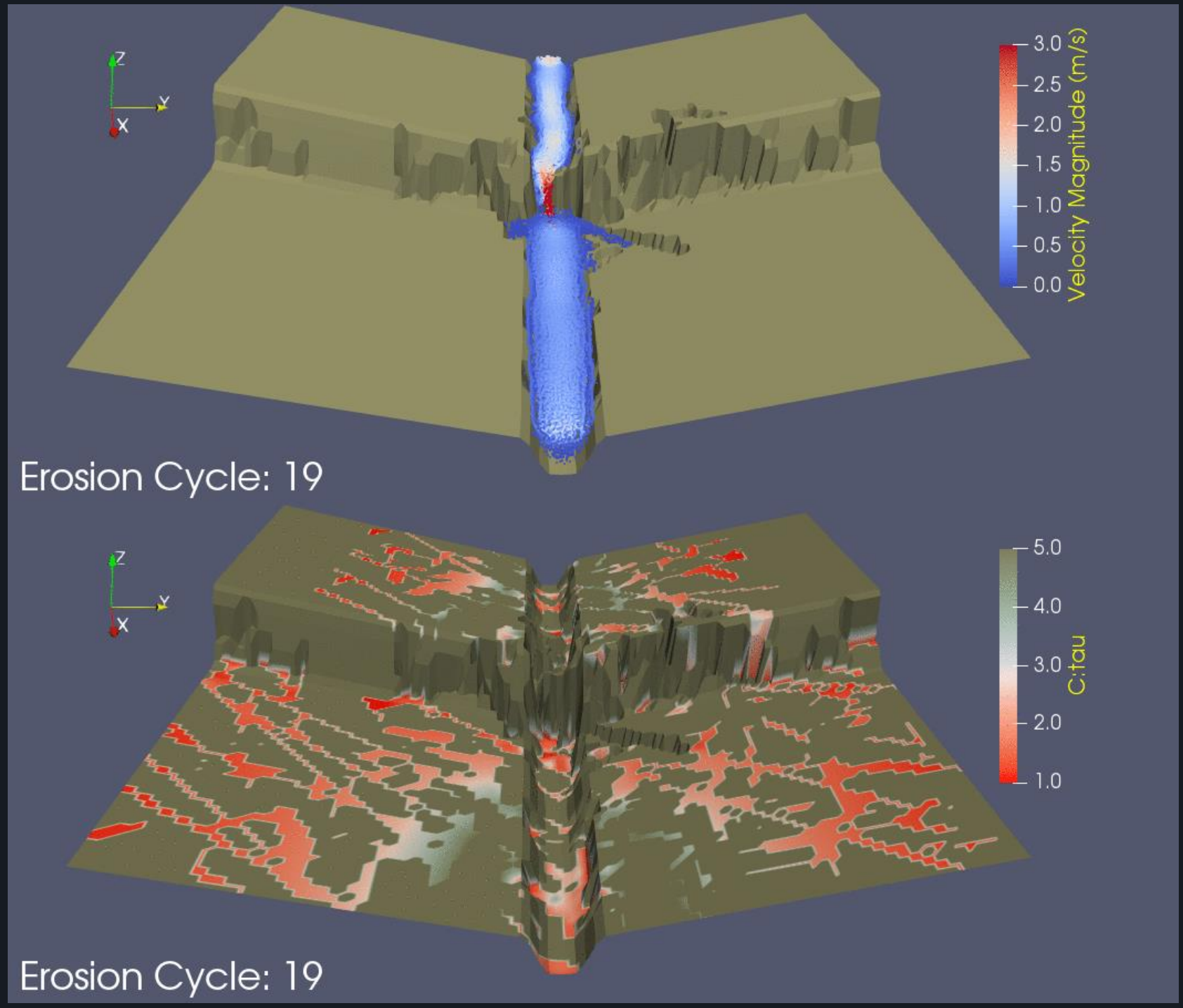

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 14
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 14

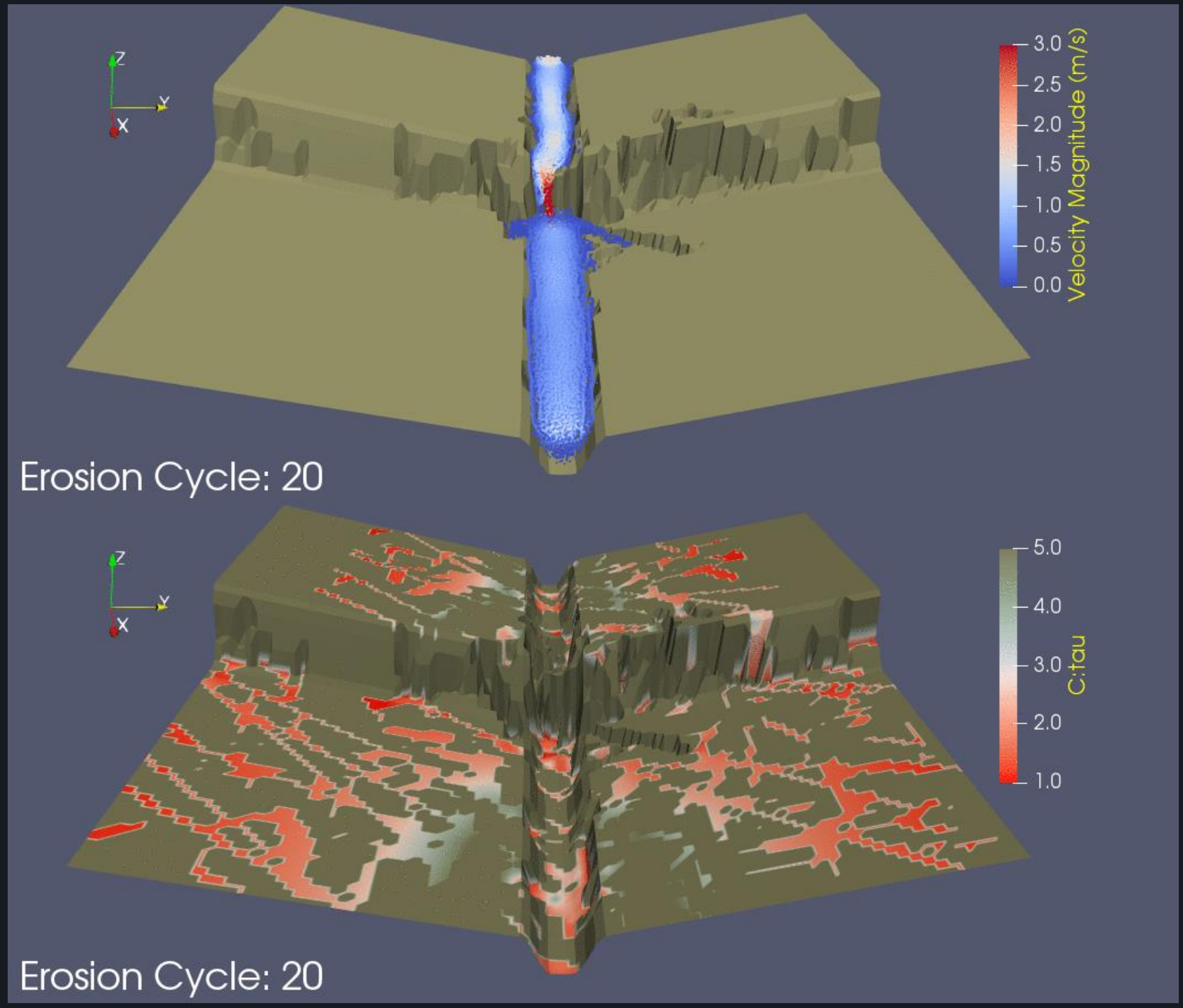

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 15
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 15


Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 16
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 16


Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 17
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 17

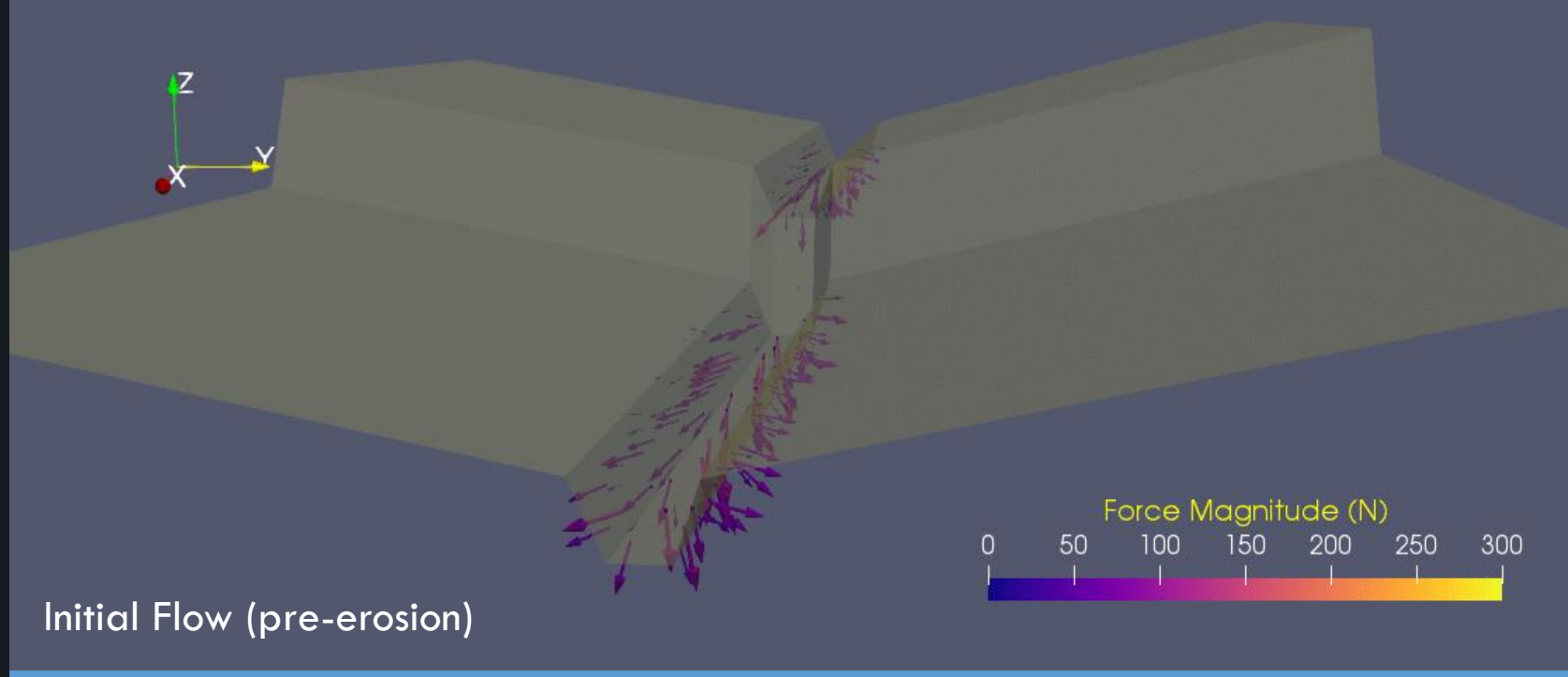

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 18
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 18


Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 19
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 19

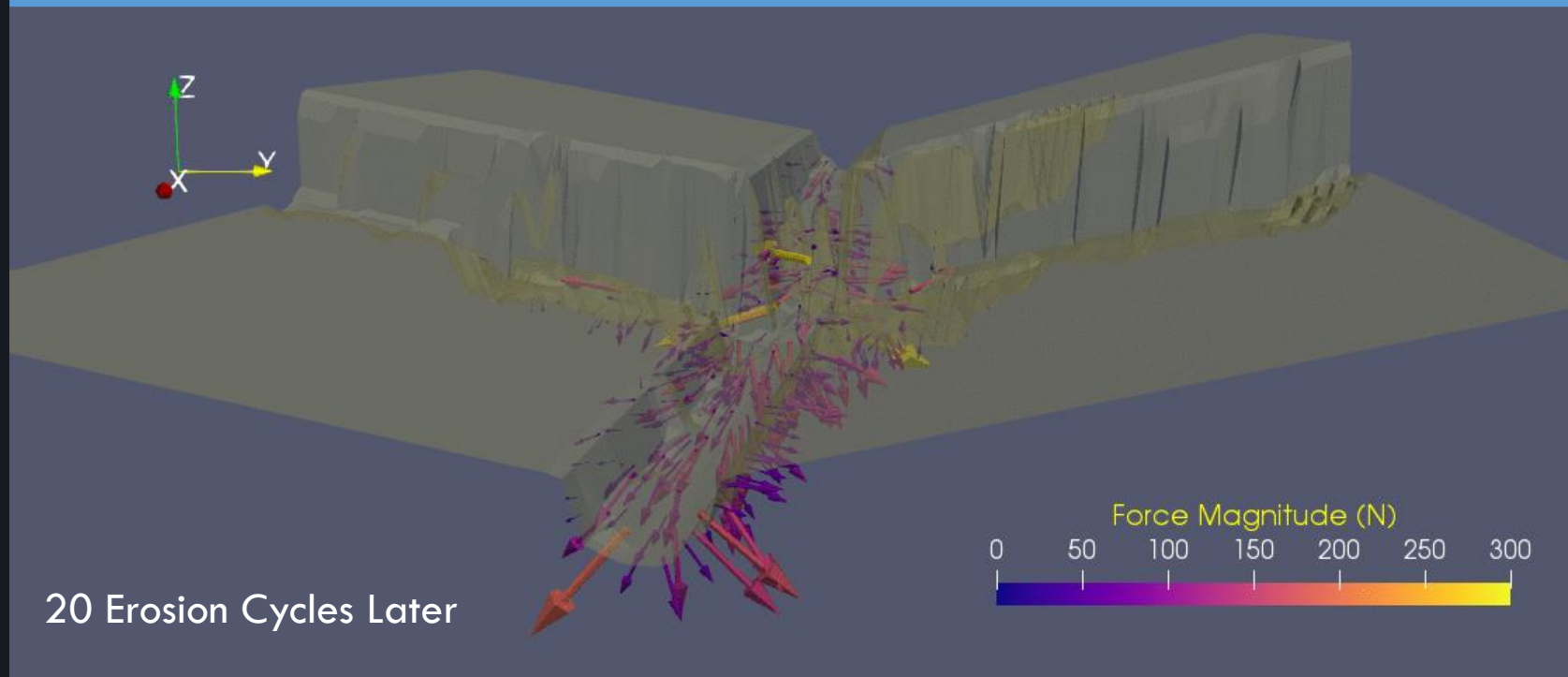

Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 20
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 20

Landscape Complexity

After cycles (here, 20 cycles) of SPH-FERM erosion, the magnitude and directional complexity of the hydraulic forces increases



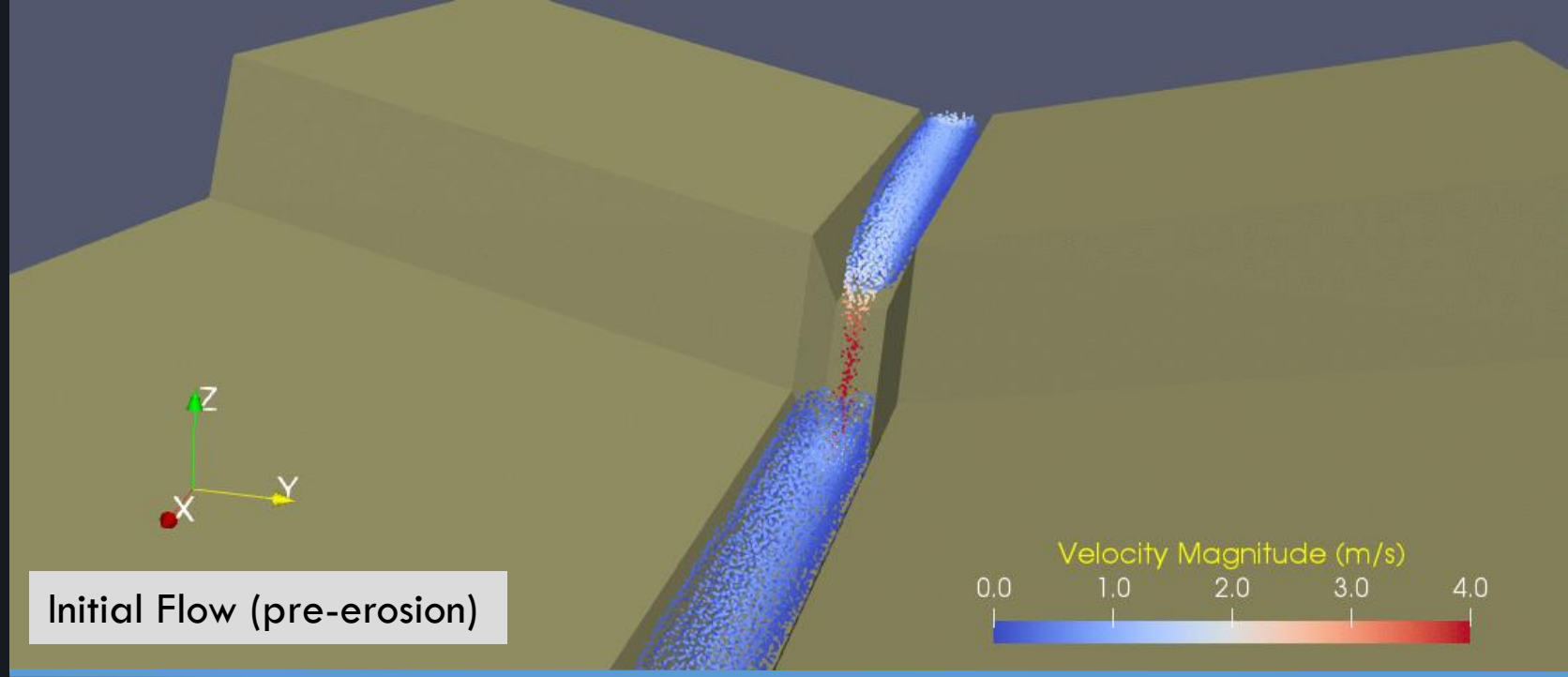
Initial Flow (pre-erosion)

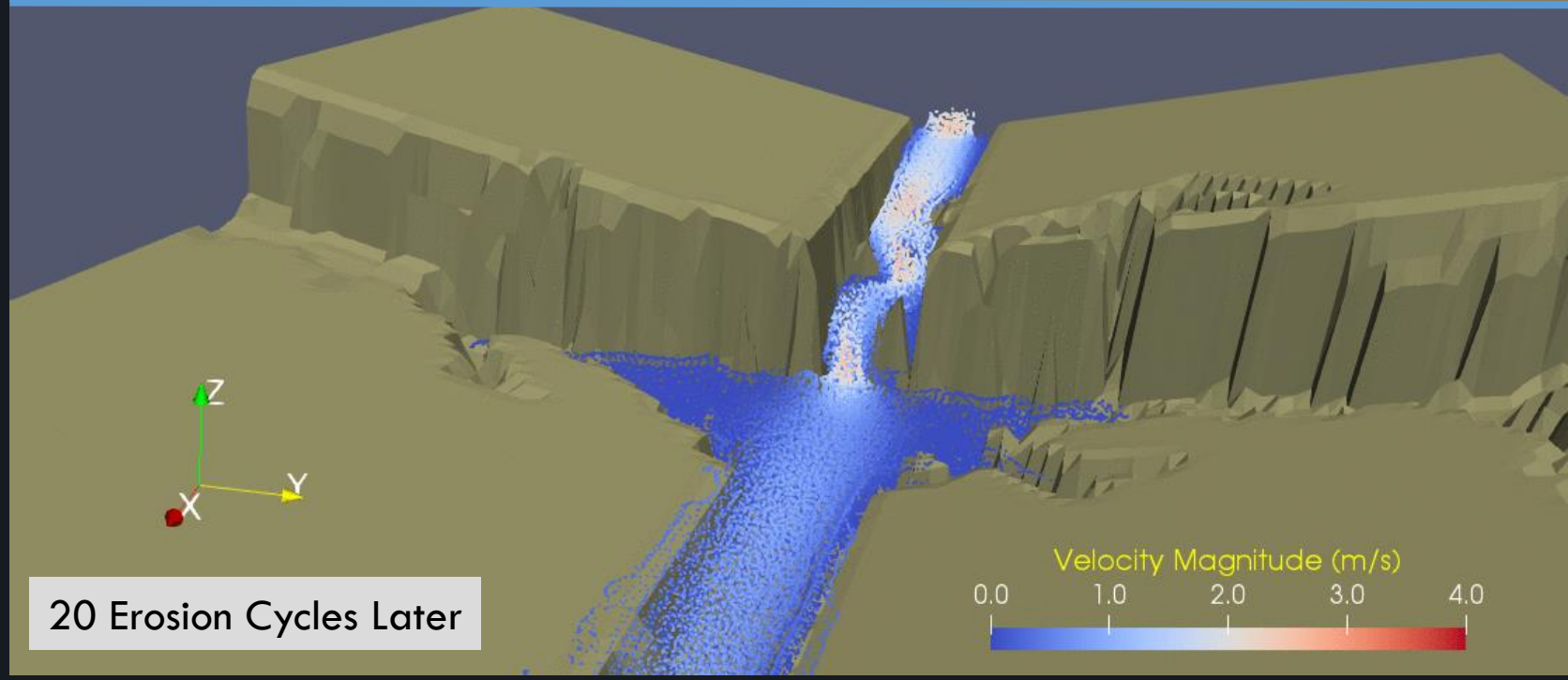


20 Erosion Cycles Later

Landscape Complexity

After cycles (here, 20 cycles) of SPH-FERM erosion, the magnitude and directional complexity of the hydraulic forces increases

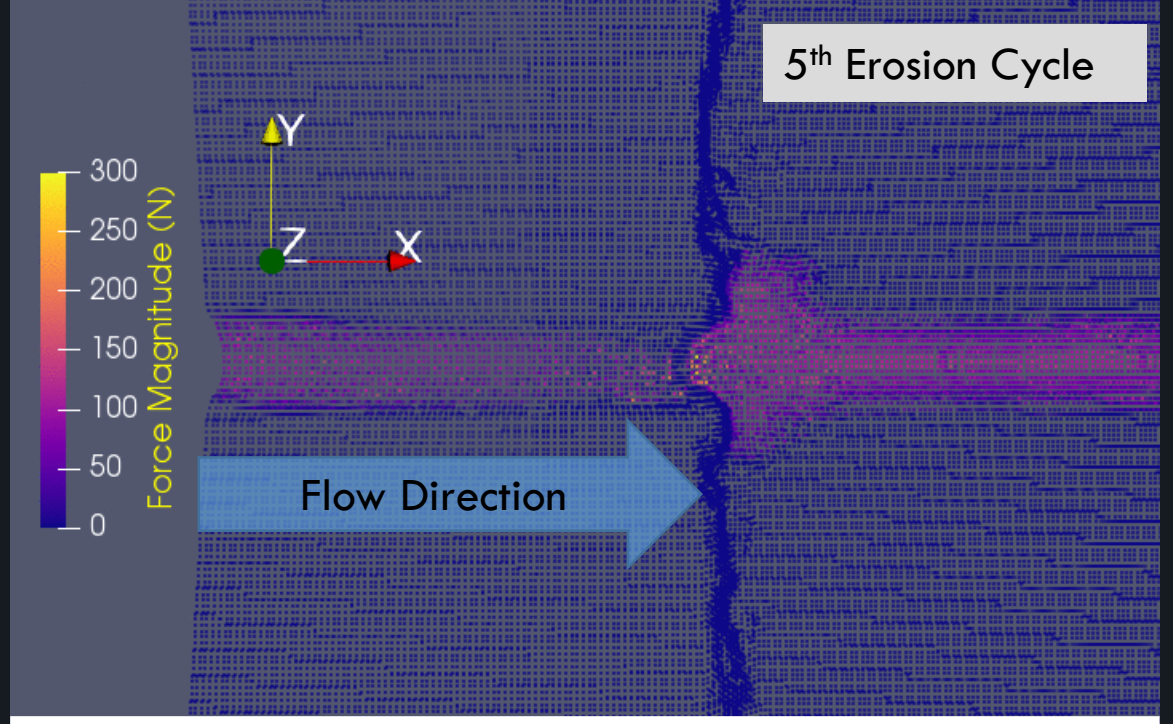


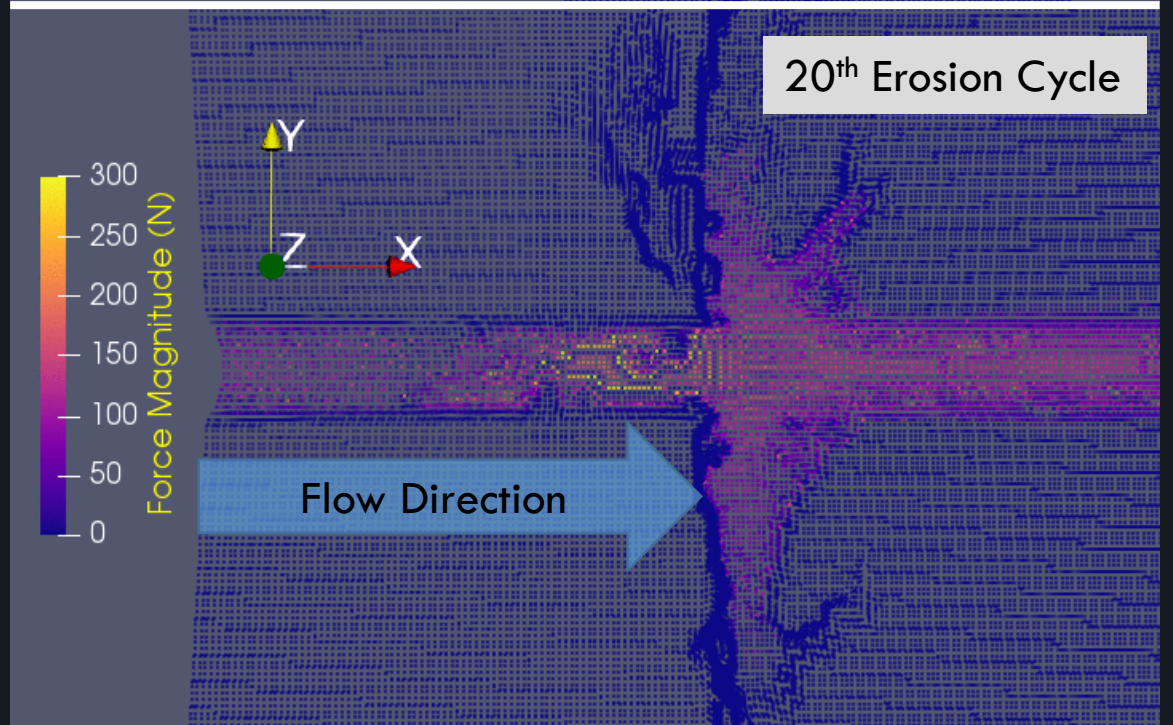


Changes in Force Distribution

Top frame: 5th erosion cycle

Bottom frame: 20th erosion cycle





Conclusion: What Do We Gain?

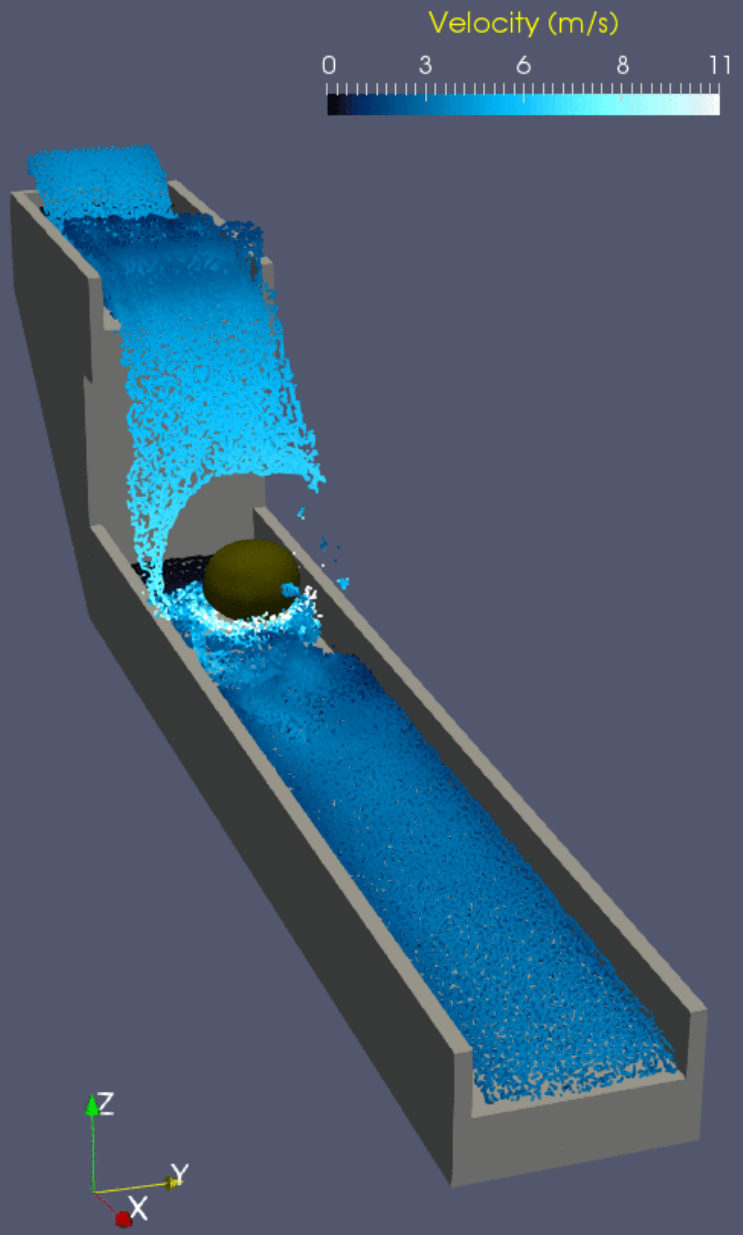
- Flexible, scalable, physics-based erosion
  - Physics-based way of studying the interaction of water with the earth
- Quantifiable stresses in changing geometries, especially at drops and bends (where most of the work is done)
- Model based on strength measurements that can be measured in the field by replacing non-physical approximations with engineering parameters
- Complex flows with deformable Earth → single way of describing the Earth (full stress tensor) → We can now look at coupled systems with a flow component

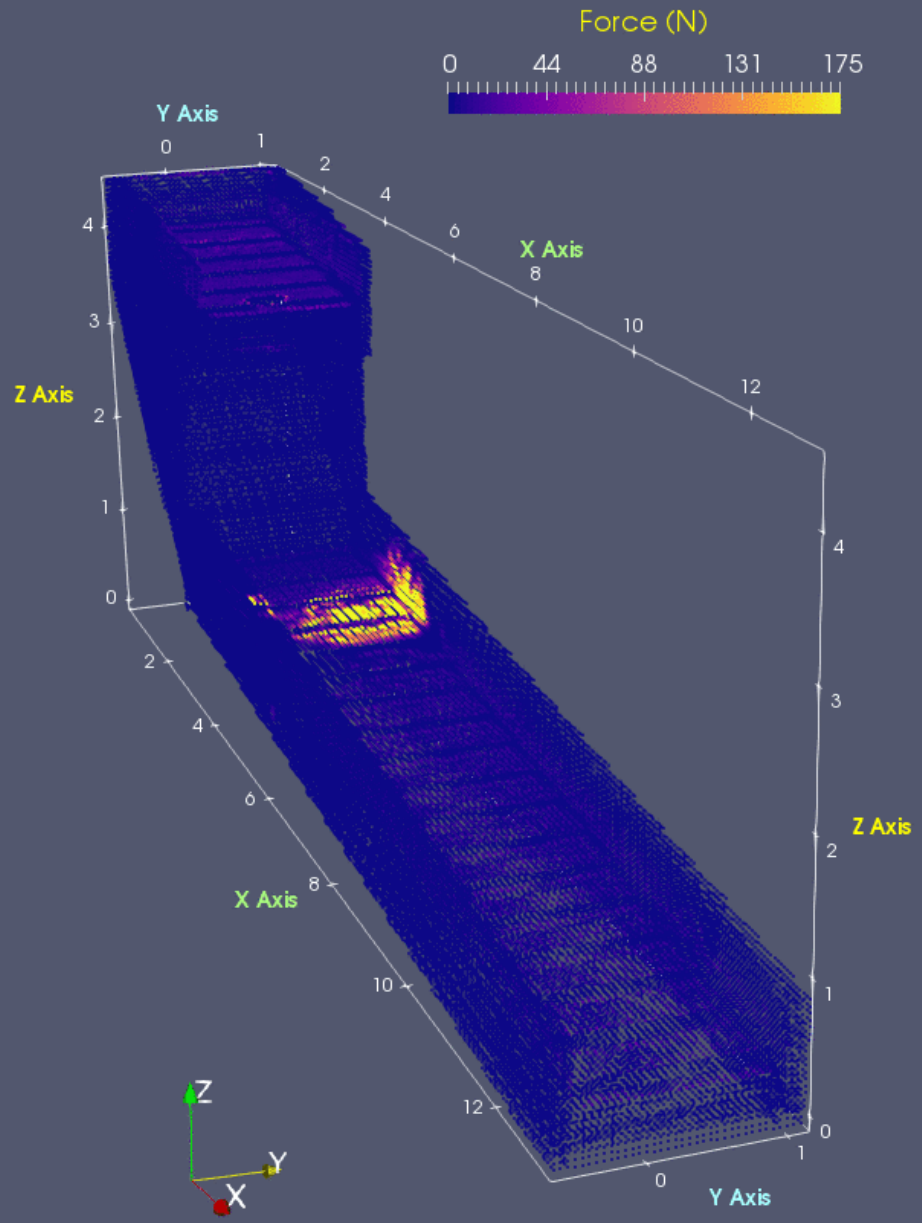
How to Improve

- More sophisticated surface process model
  - Rolling and sliding blocks with hillslope failure
    - Coupling with Project Chrono

Role of "Tools" in the Stress State of a Channel

- A cobble or boulder impacting the bed after a vertical fall produces stresses which are not being accounted for in the present model





How to Improve

- More sophisticated surface process model
  - Rolling and sliding blocks with hillslope failure
    - Coupling with Project Chrono
  - Sediment transport
    - Grain size heterogeneity (Coupling with Project Chrono)
    - Availability of more BCs in DualSPHysics Multiphase
- More powerful BCs for streams (inlet/outlet)
- Larger Domains
  - Multi-GPU support
  - Variable Resolution

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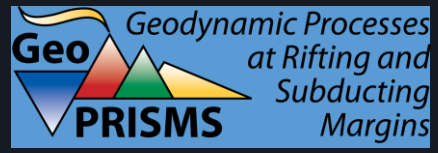

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