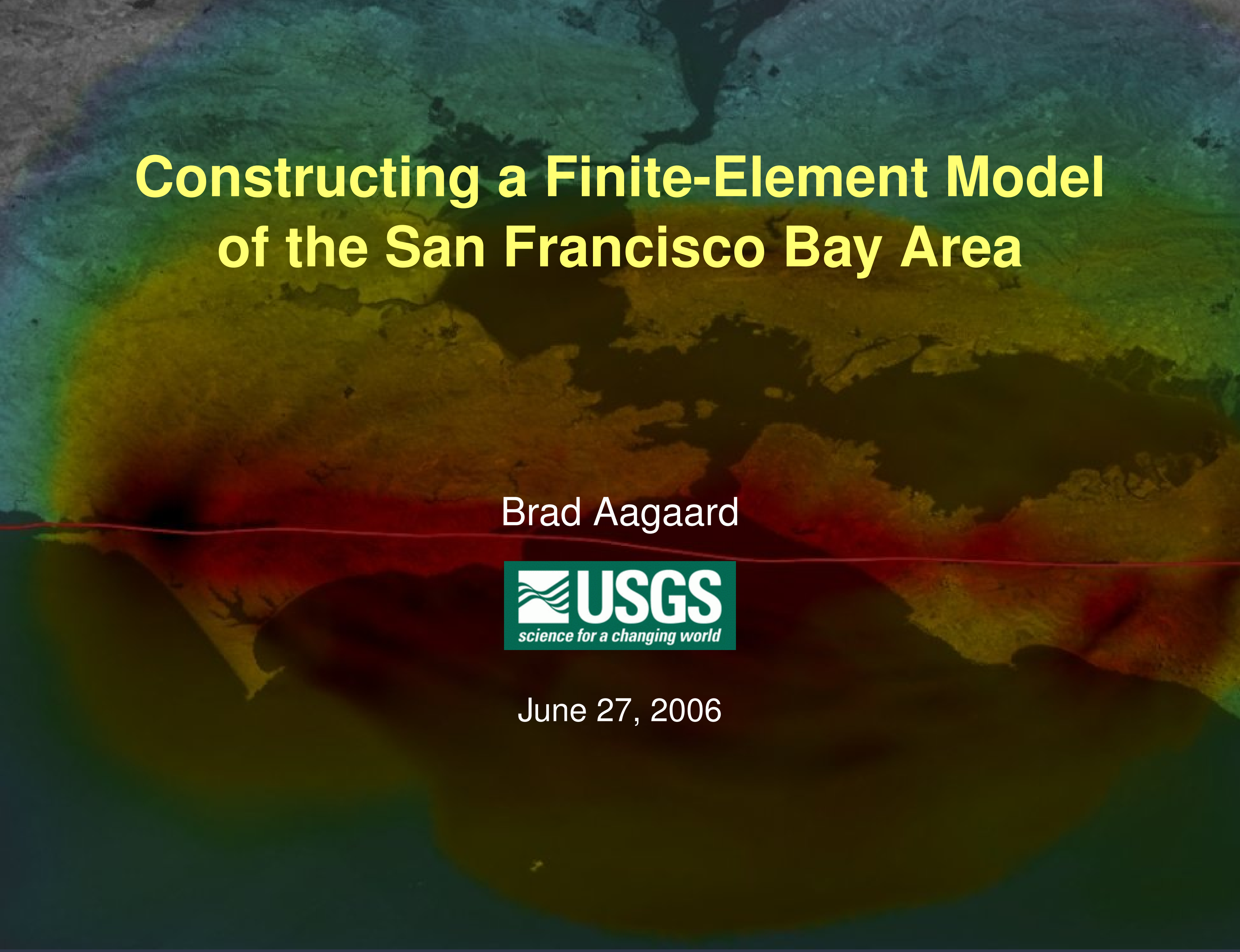

Constructing a Finite-Element Model of the San Francisco Bay Area

Brad Aagaard

USGS
science for a changing world

June 27, 2006

Overview

- Objective: Build finite-element mesh of the San Francisco Bay area
- Purpose: Ground motion simulations of the M7.9 San Francisco eq
- Mesh generator: LaGriT
  - Linear, tetrahedral finite elements
  - Complex geologic surfaces

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Model Ingredients

- 3-D geologic structure
  - Topography & bathymetry
  - Major fault surfaces
  - Include curvature of the Earth
- Discretization constraints
  - Fault implementation
    - Fault surfaces are part of solid model geometry $\Rightarrow$
    - Align element faces on fault surface
  - Want largest time step possible (computational efficiency)
    - Element edge length proportional to Vs
    - “Plump” elements

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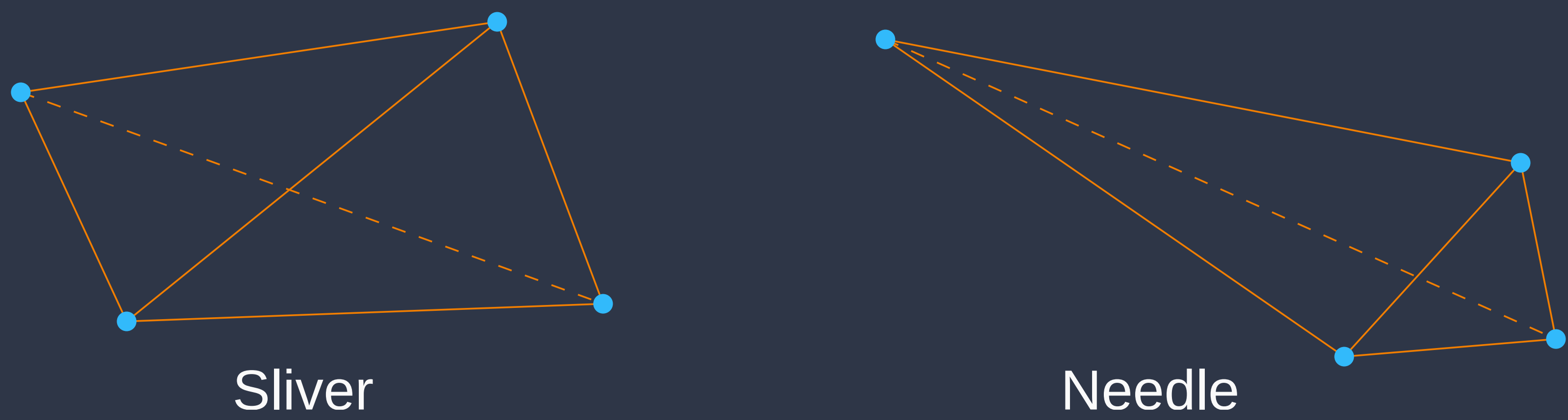
Why is element quality so important?

Distorted elements artificially increase the rigidity of the material

- Distorted elements have artificially high stresses
- Forces use of smaller time steps to maintain numerical stability



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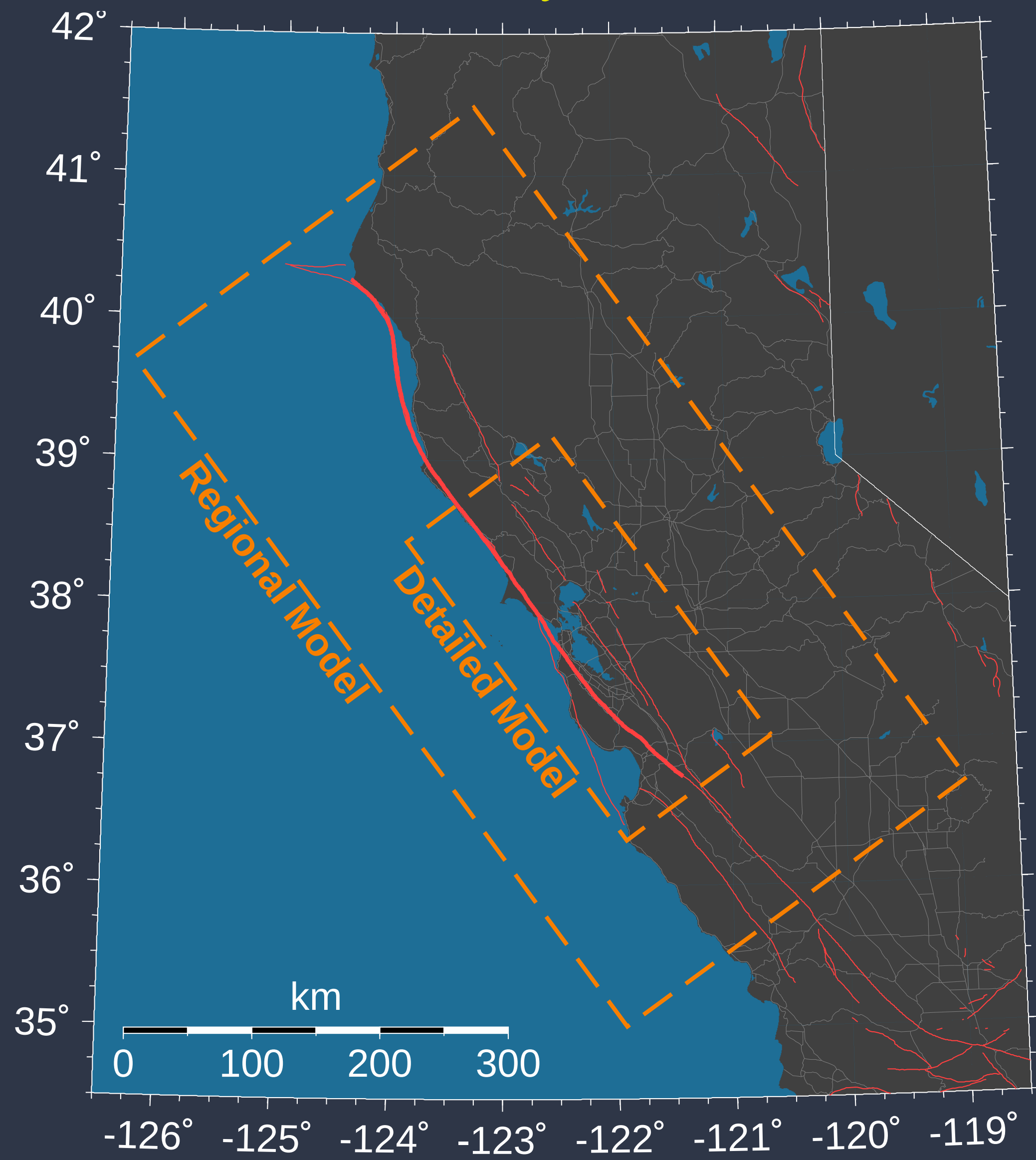
USGS Central California 3-D Geologic Model

Unified representation of fault surfaces and lithologies

- Fault surfaces and lithologic boundaries
  - Active and inactive faults
  - Depositional surfaces and unconformities
  - Topography & bathymetry
- Hierarchical structure (how to assemble blocks from surfaces)
  - Easy to refine/update model
  - Easy to extract subsets of features
- Constructed in Earth Vision (Dynamic Graphics)

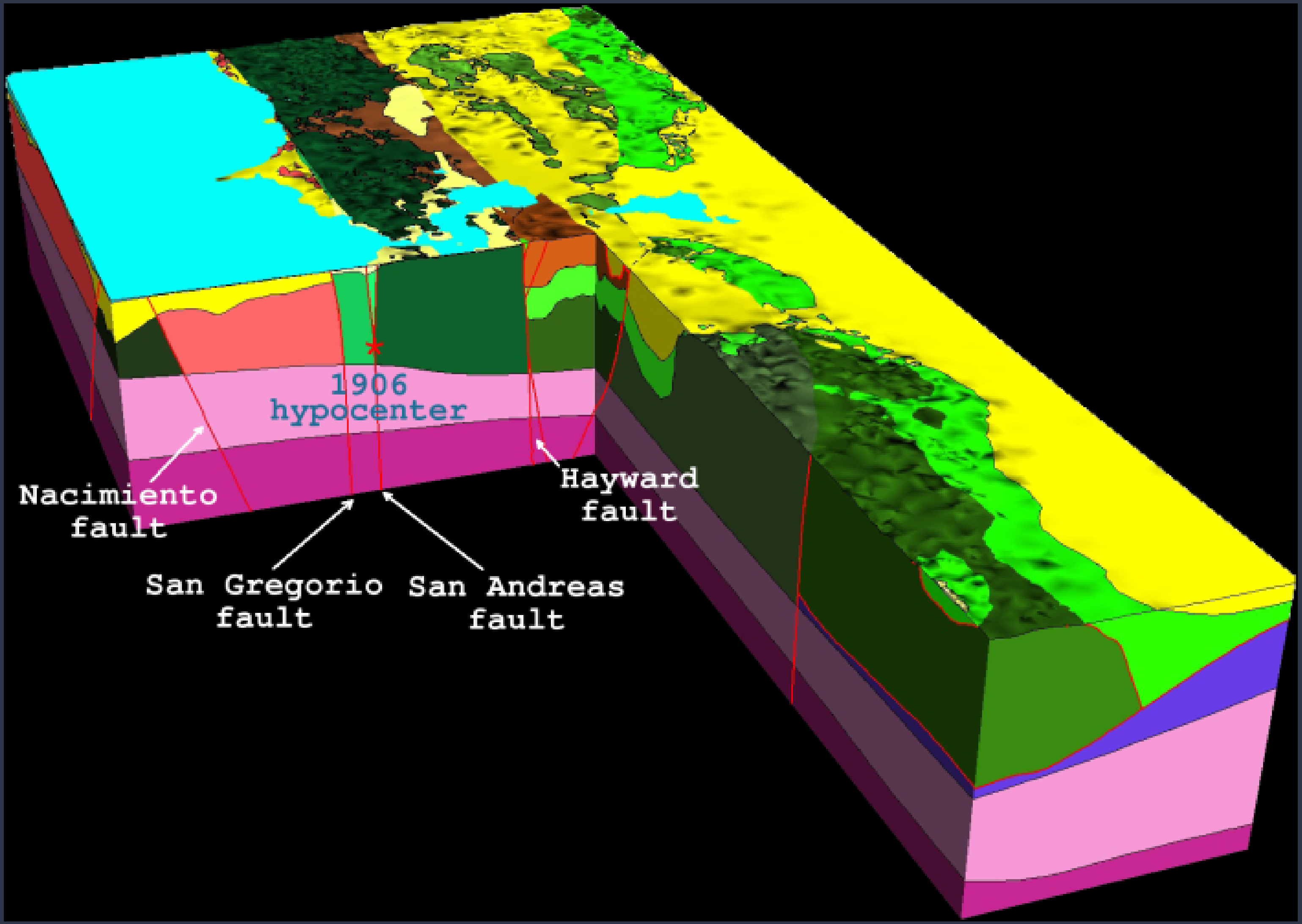
Geologic Model: Geographic Coverage

Detailed model is surrounded by low-resolution, simple model



Geologic Model: Perspective View

Model contains 26 blocks and 24 fault surfaces



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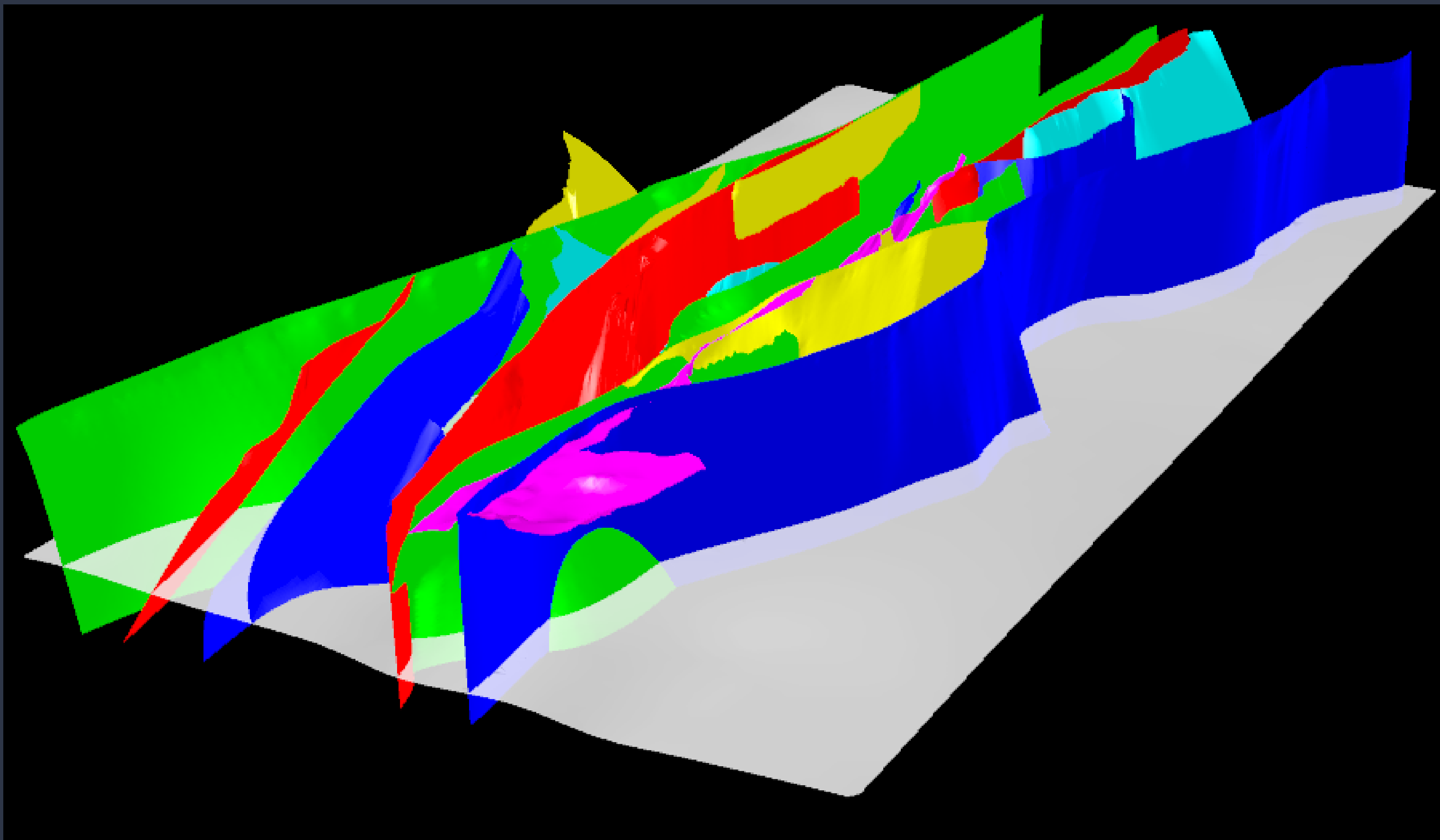
Geologic Model: Fault Surfaces

View of fault surfaces and mantle boundary from southeast



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Geologic Model: Dissemination

Distribute geometry via ASCII tsurf files

- Faults and lithologic boundary surfaces
  - Discretized using triangular facets
  - Exported as Gocad tsurf files (same as SCEC CFM)
- Hierarchical structure (how to assemble blocks from surfaces)
  - Diagram of block hierarchy
  - Rules defining hierarchy

USGS Central California 3-D Seismic Velocity Model

Create seismic velocity model from geologic model

- Assign material properties to lithologies in geologic model
  - Develop regressions based on variety of data
  - Check against tomographic models
- Given longitude/latitude/elevation return material properties
  - Vp
  - Vs
  - Density
  - Qp
  - Qs
  - Lithology & depth from free surface

Mesh generation with LaGriT

Overview of meshing procedure

1. Pick bounding box for modeling domain

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2. Import geometry from geologic model (few mins)

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3. Assemble geometry into blocks (few seconds)

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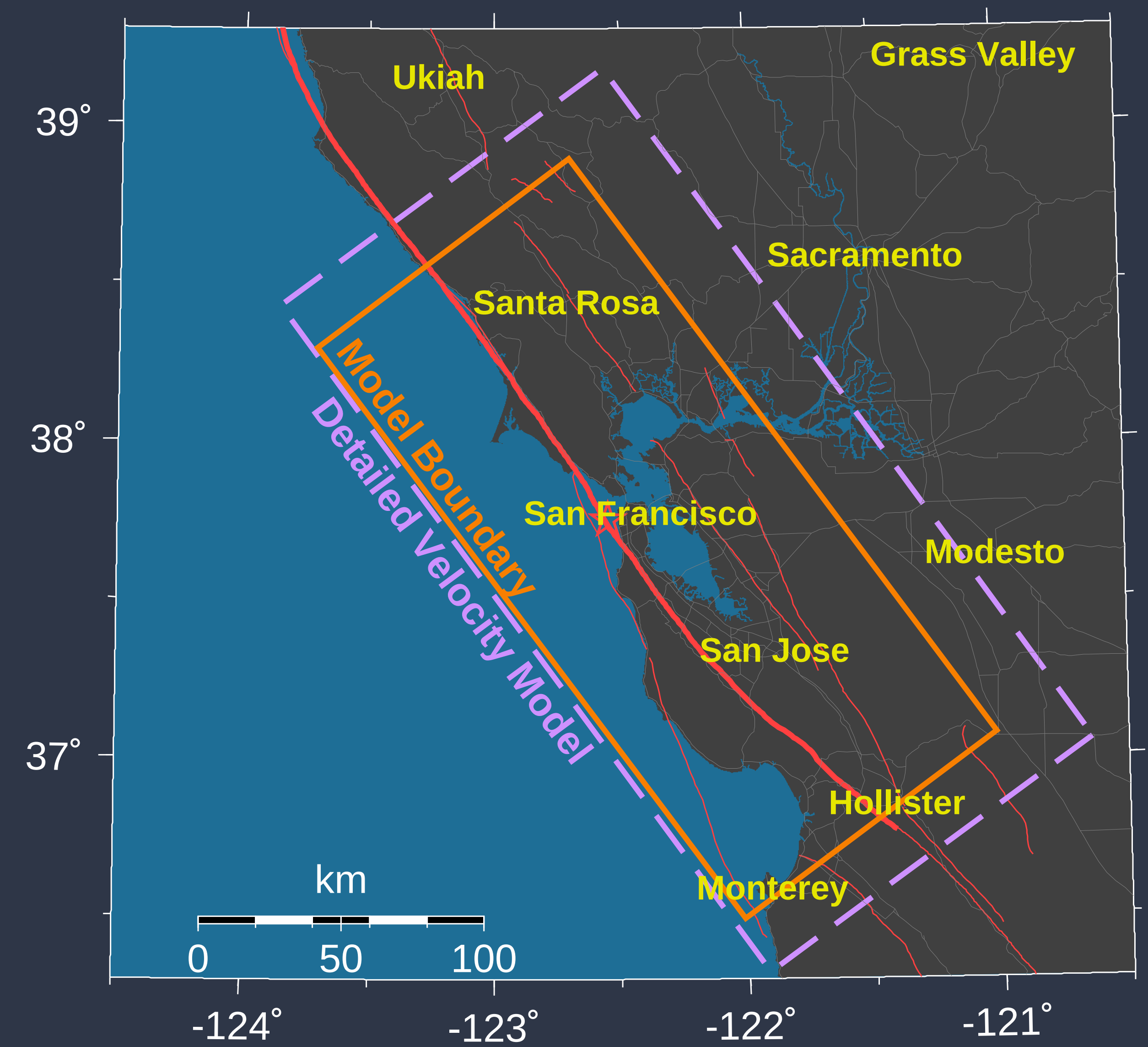
8. Apply 4x uniform refinement in parallel

Model domain

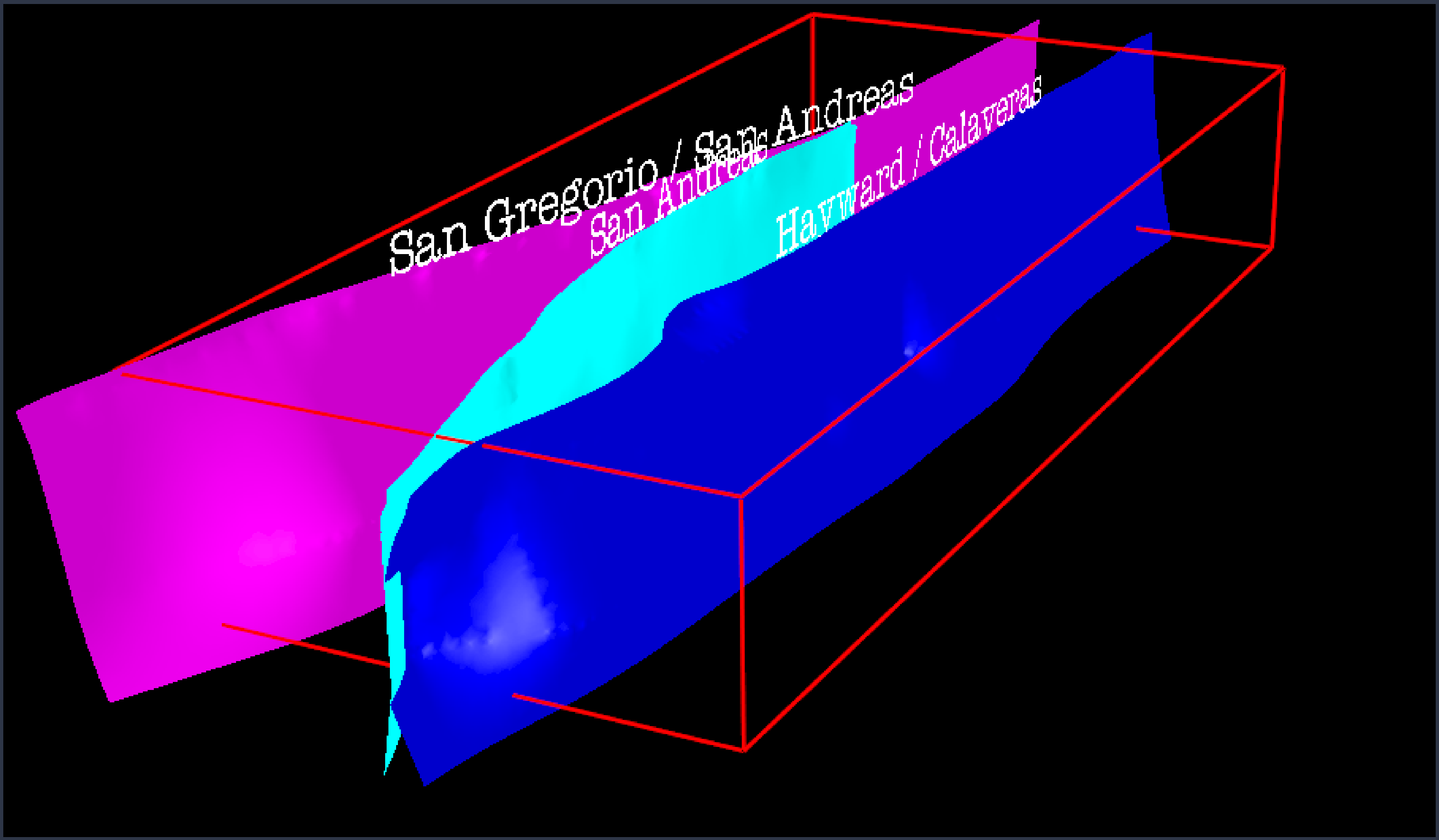
Domain is 250 km x 110 km x 40 km



Import geometry from geologic model

- Convert lon/lat/elev in tsurf files to local Cartesian system
- Import tsurf files containing surfaces
- Call `massage` for each surface
  - Change nominal resolution to about 3.5 km
  - Retain surface detail (damage is 5.0 m)

Import geometry from geologic model



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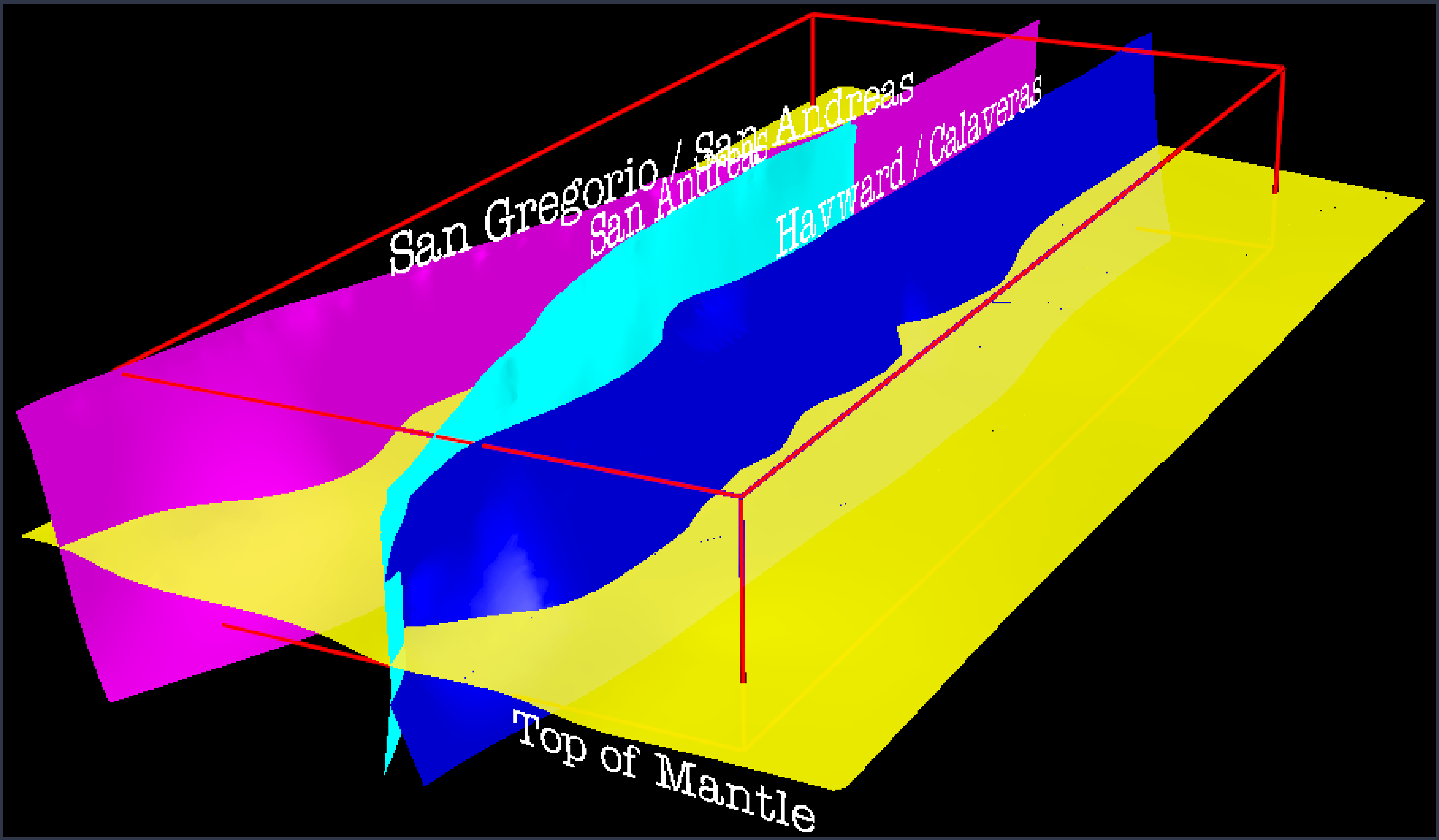

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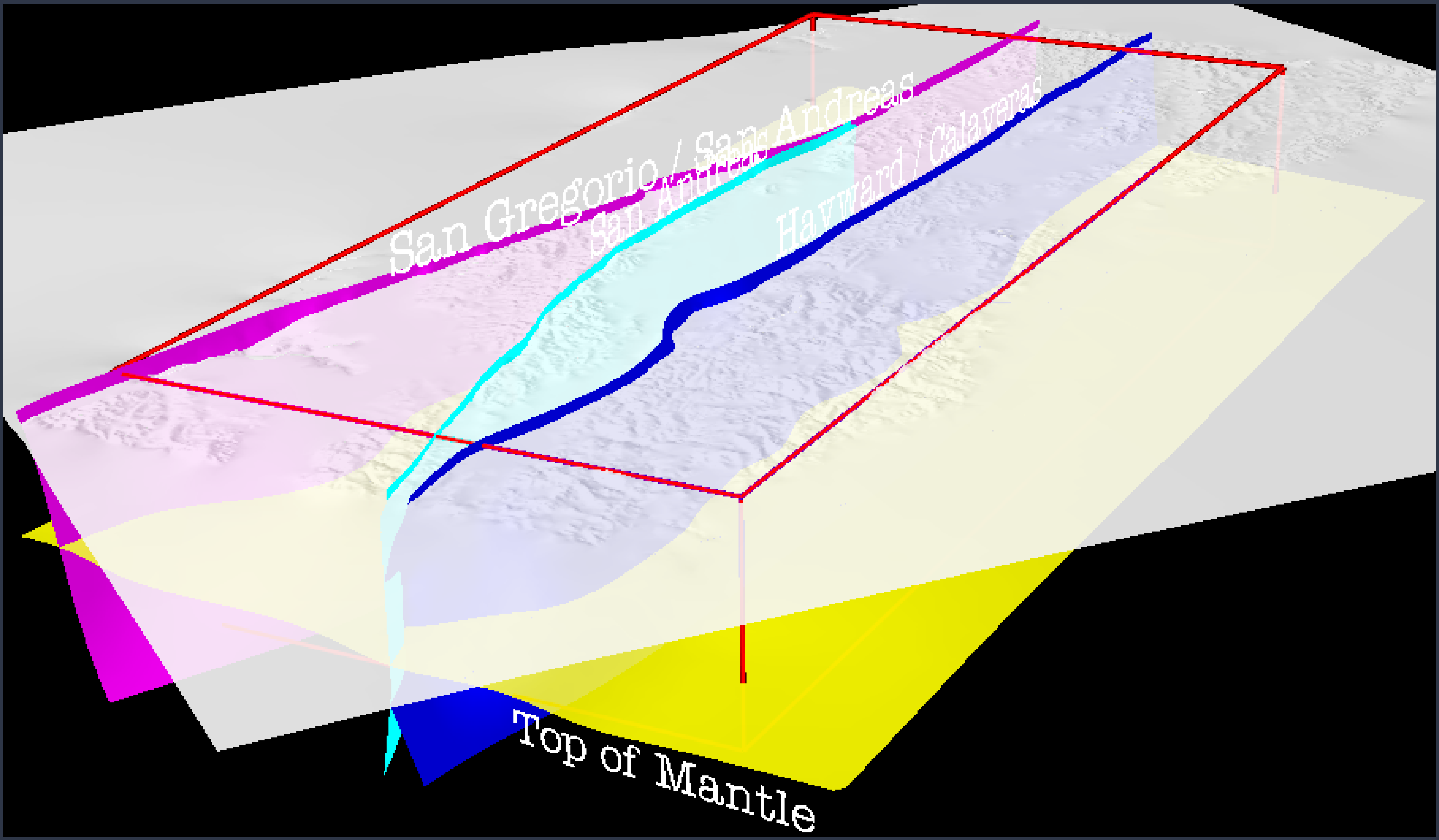

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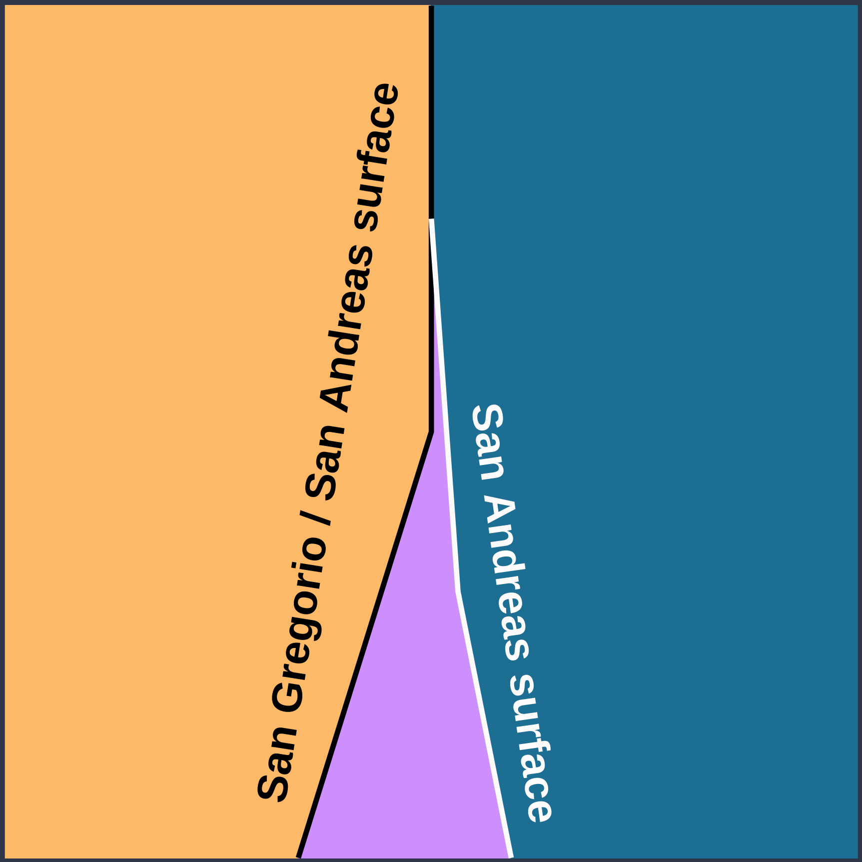
Assemble geometry into blocks

- Use rules associated with blocks in geologic model
- Add auxiliary surfaces to cleanup intersections with small angles



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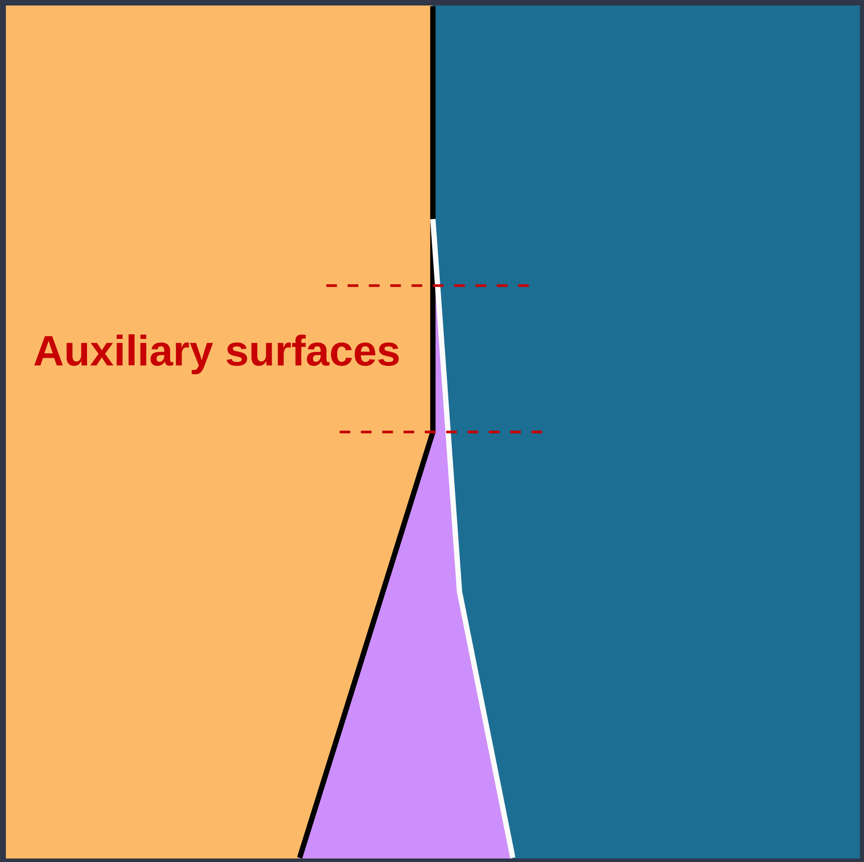

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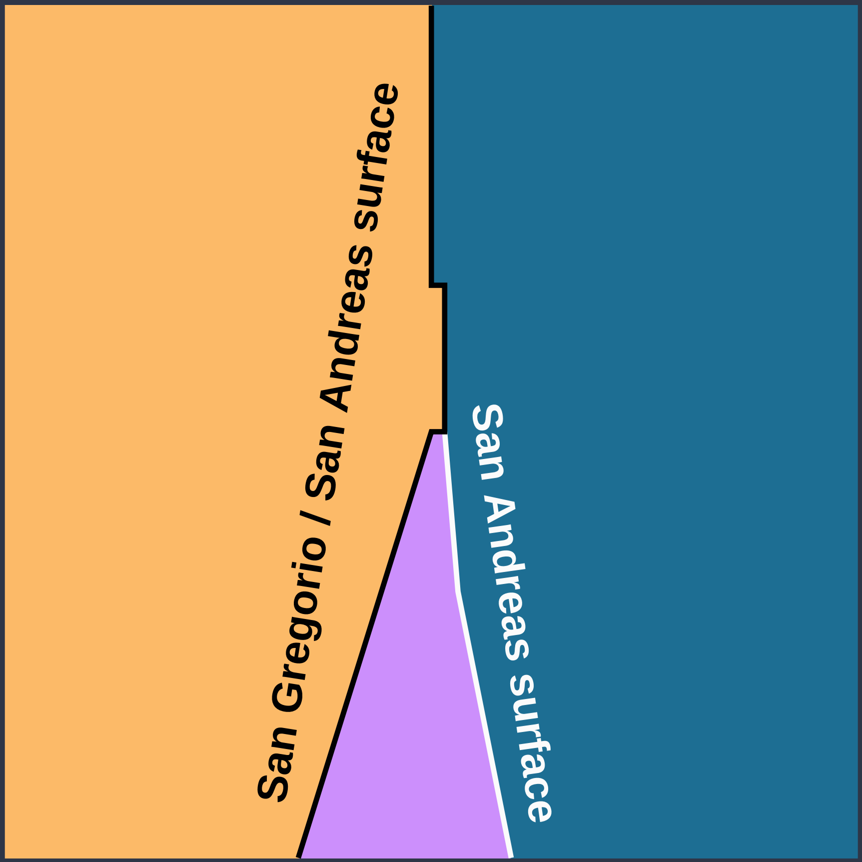

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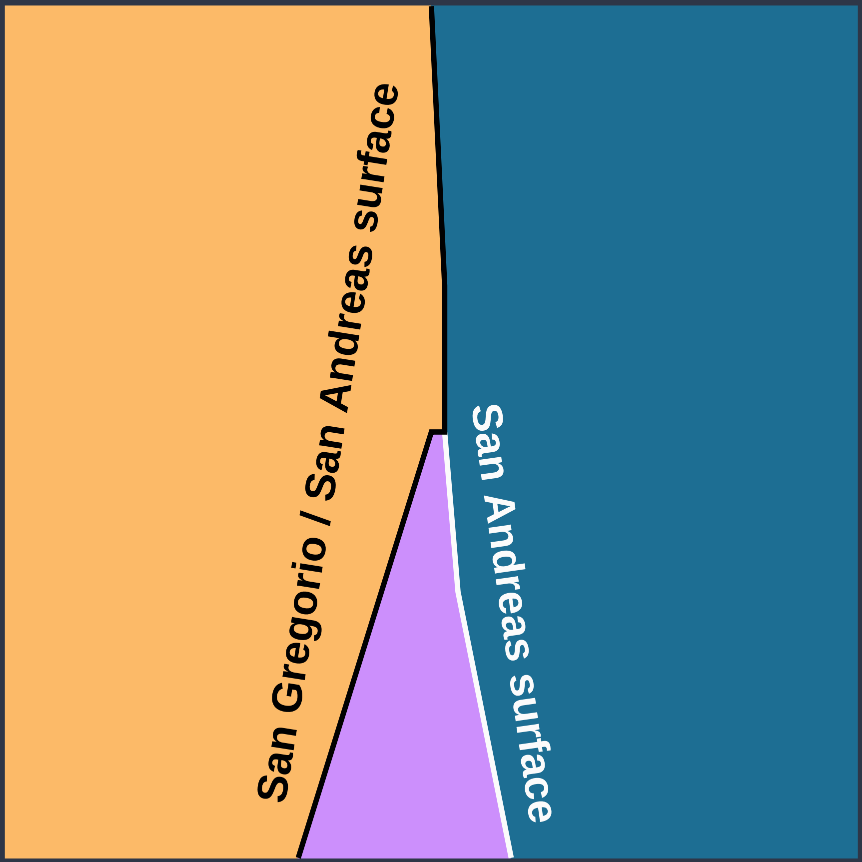
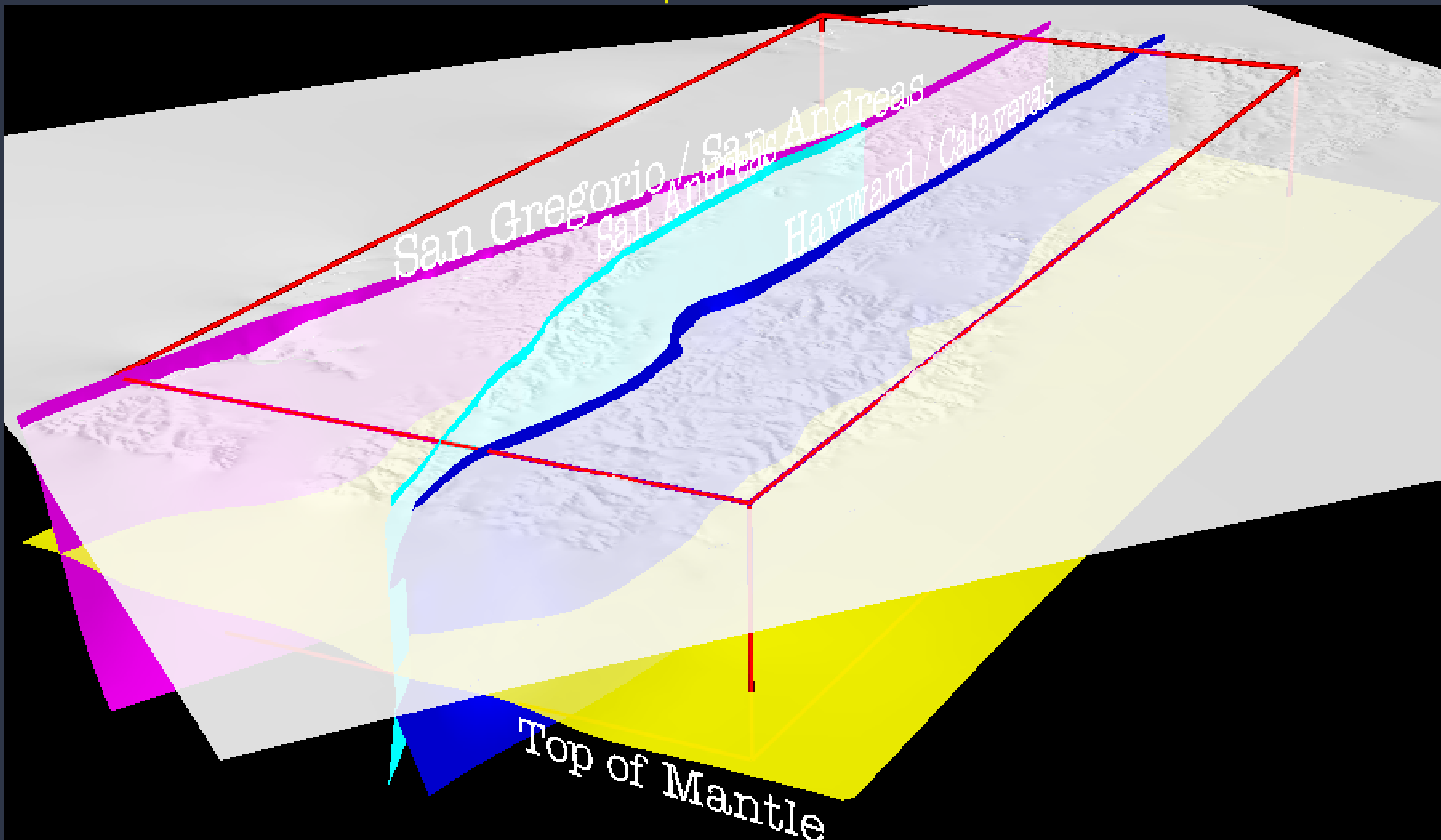


Assemble geometry into blocks

Create simplified block model



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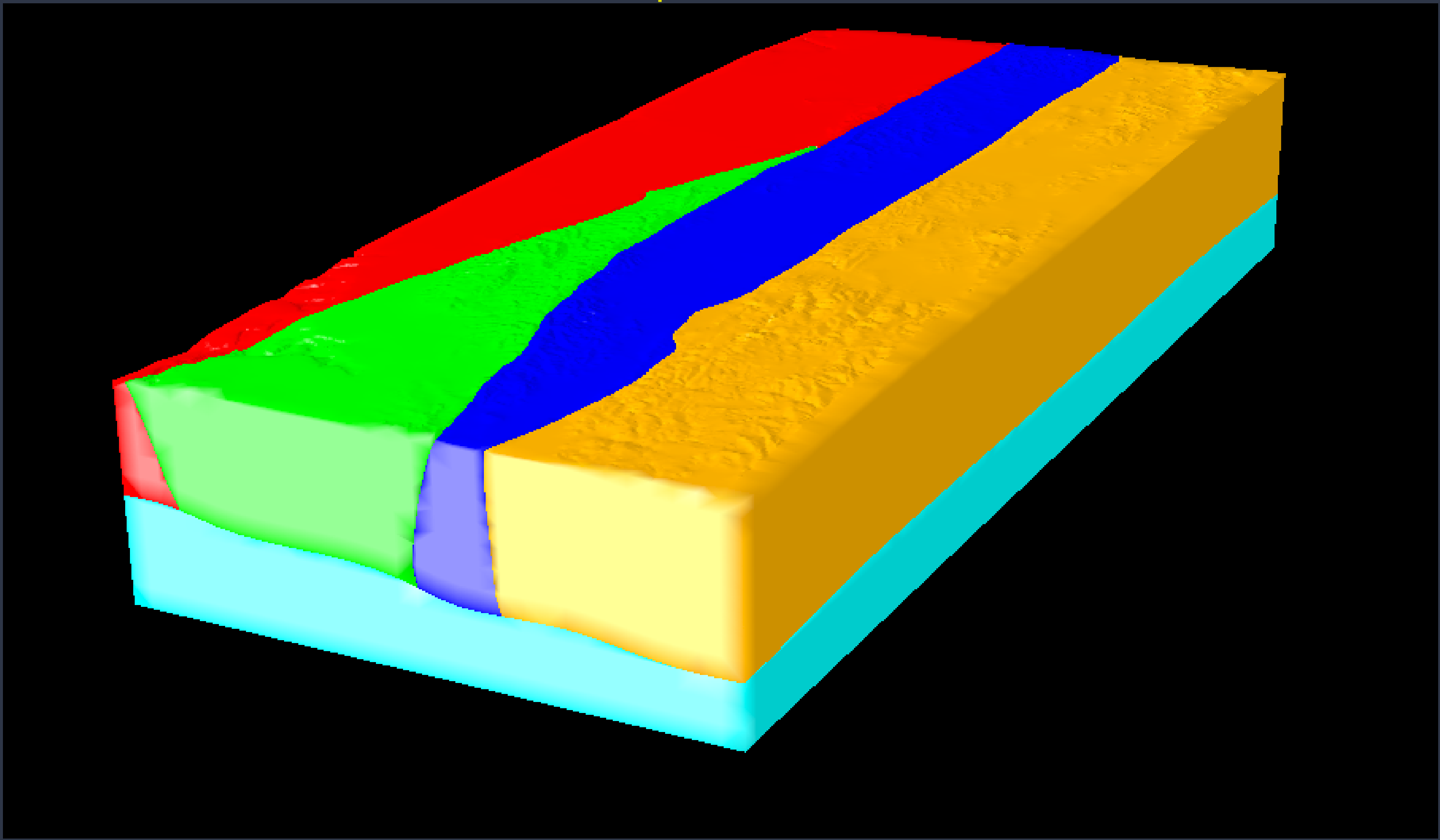

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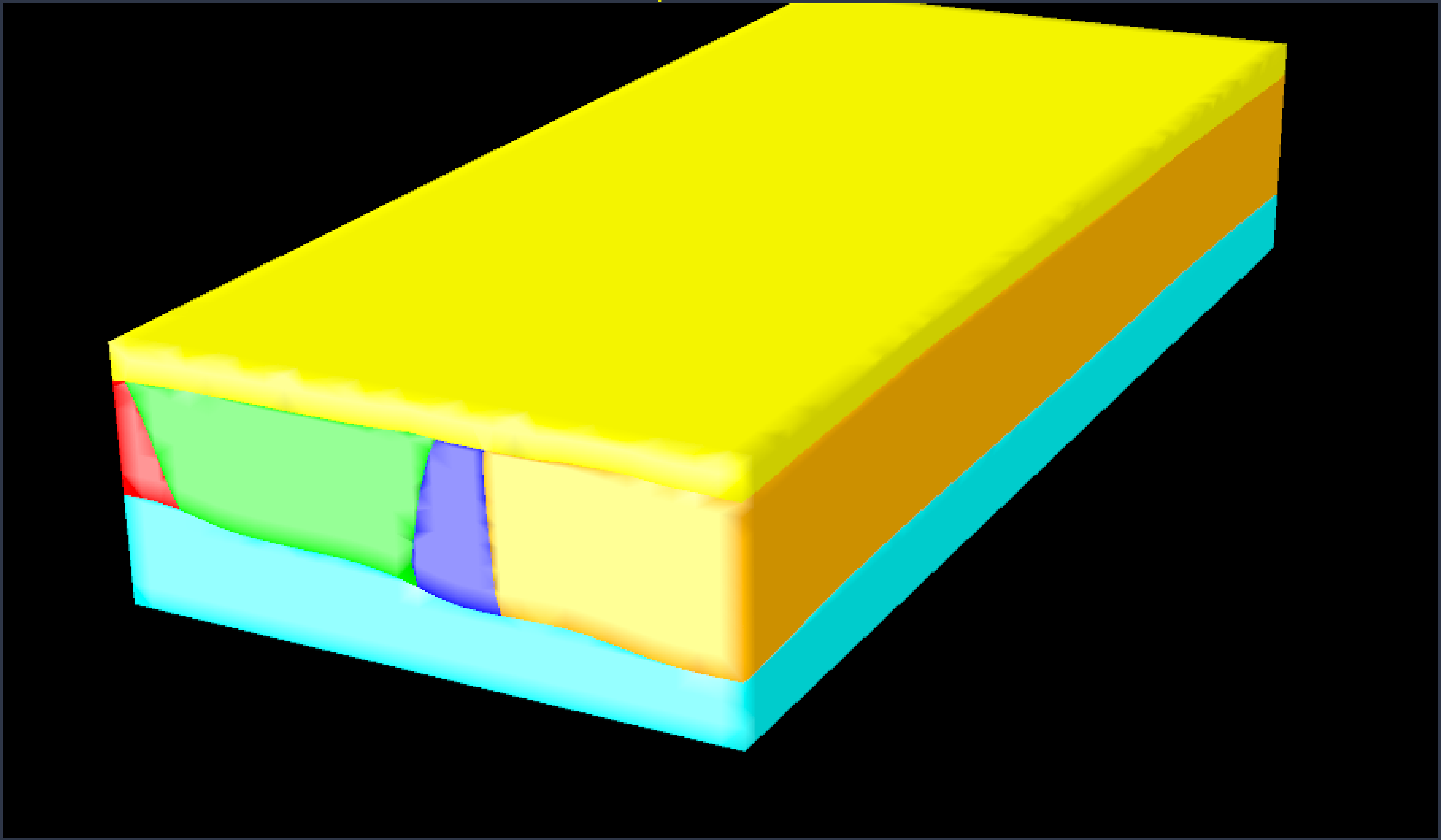
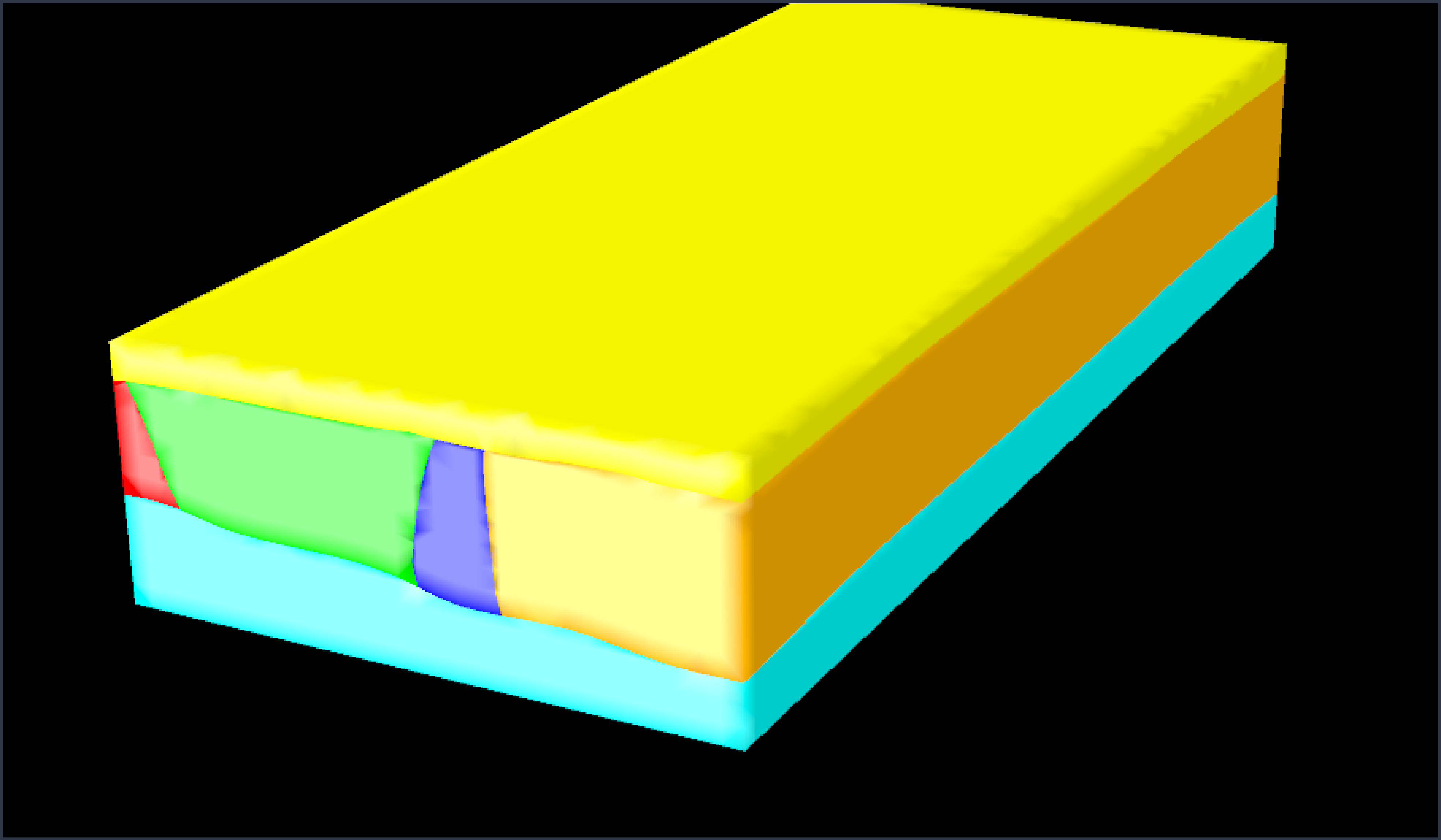


Construct uniform mesh

- Scatter points at uniform resolution (3680 m)
- Include points already on surfaces
- Connect points into elements (tetrahedra)
- Don’t worry about distorted elements (for now)

Construct uniform mesh



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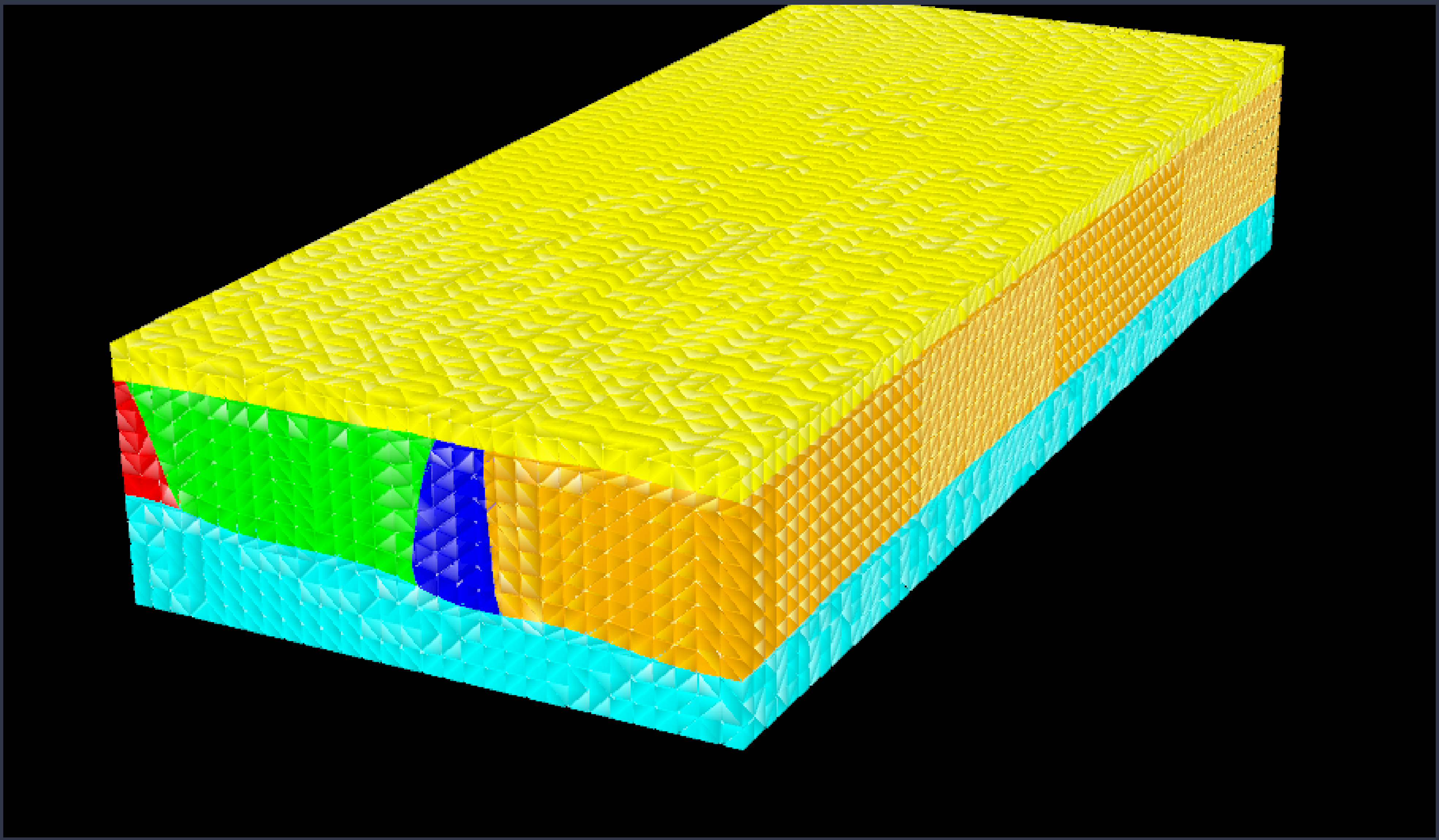

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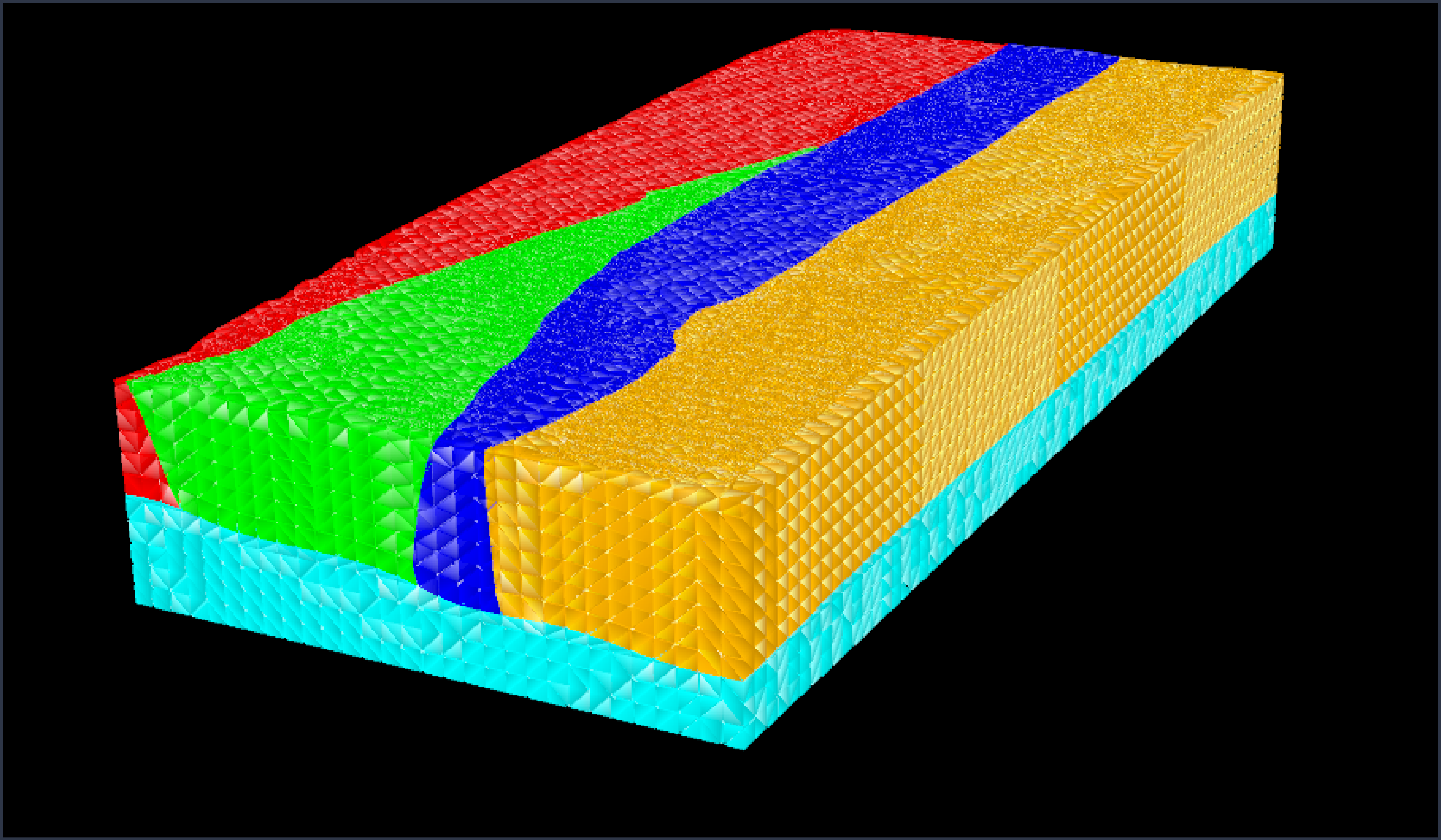

Adjust element size and improve mesh quality

Improving element quality is a complex, intricate process

1. Bin elements according to desired size
   - Call user-defined function to query velocity model and set element attribute to desired size

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   - Call `recon` to adjust element connectivities
   - Call `smooth` w/geometry option on most distorted elements

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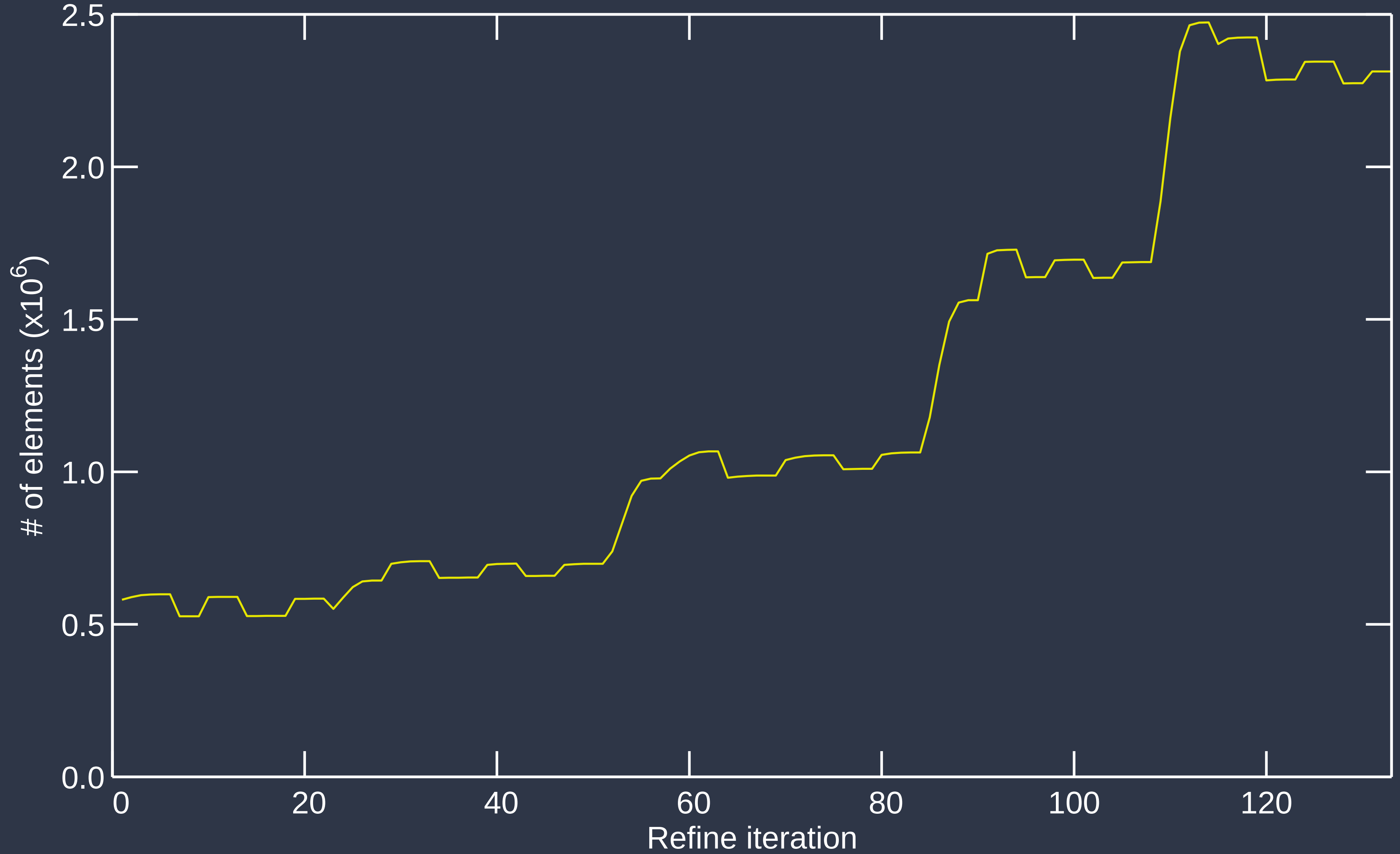
Adjust element size and improve mesh quality

Loop over bins (big → small) to limit memory and runtime



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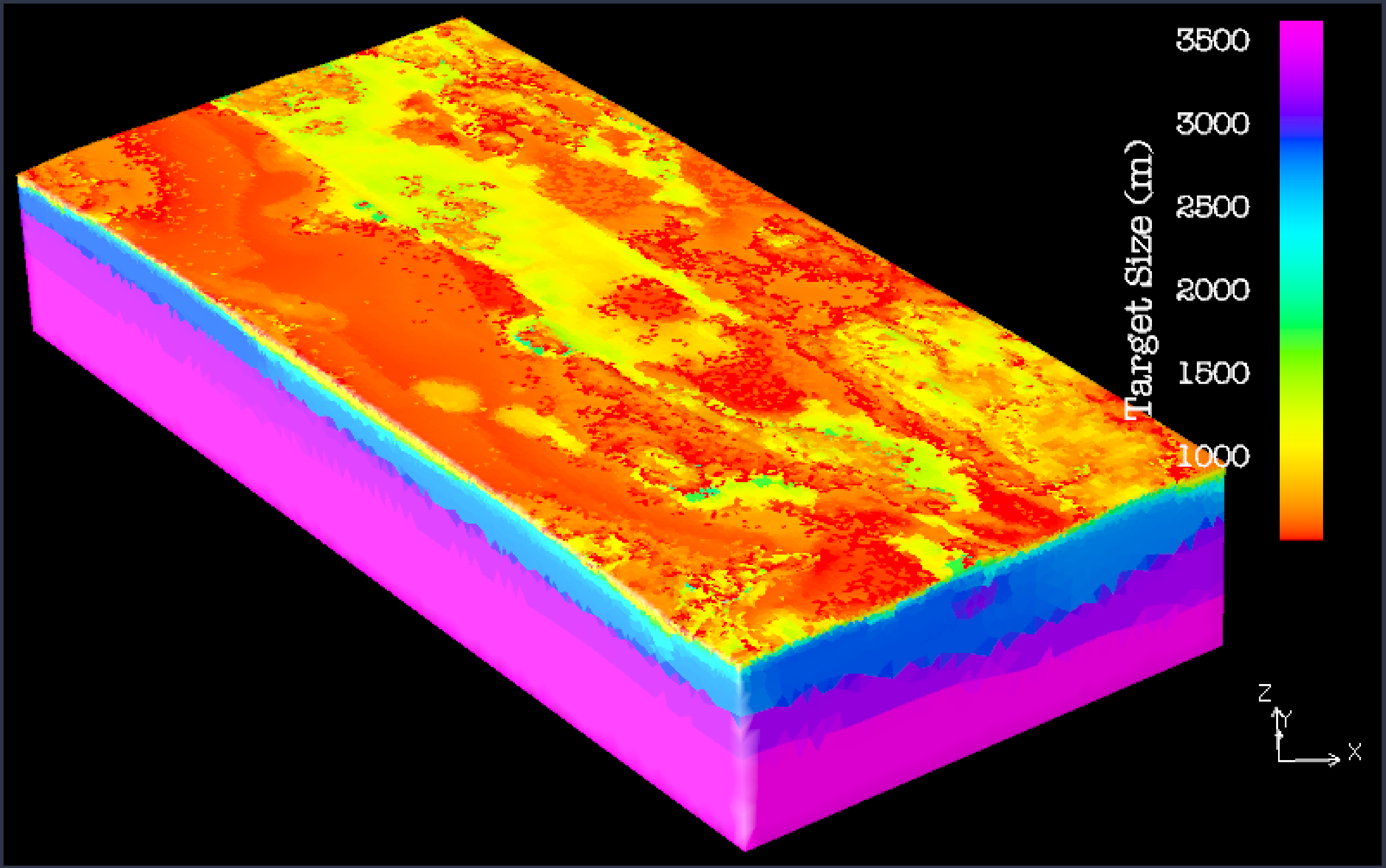

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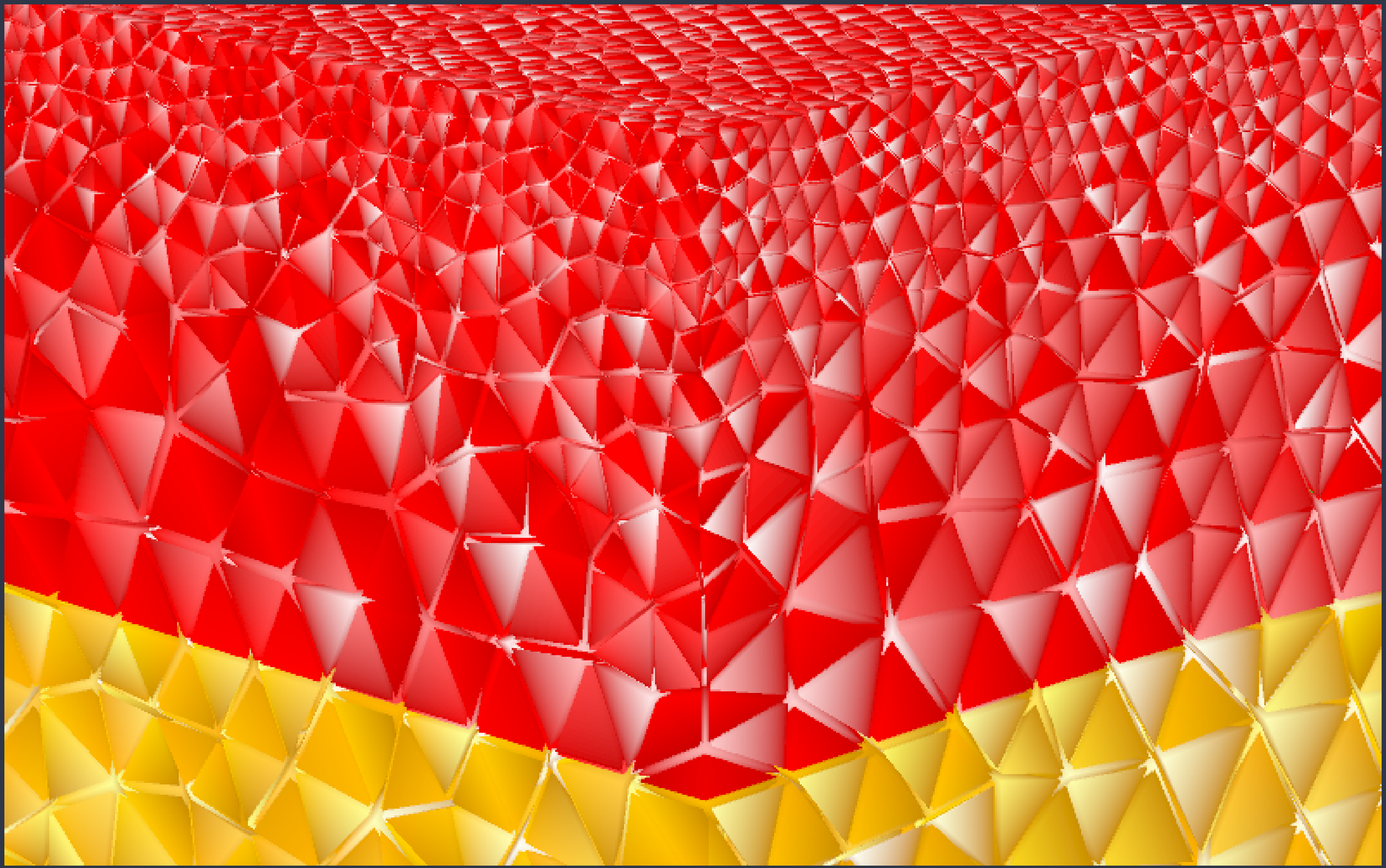


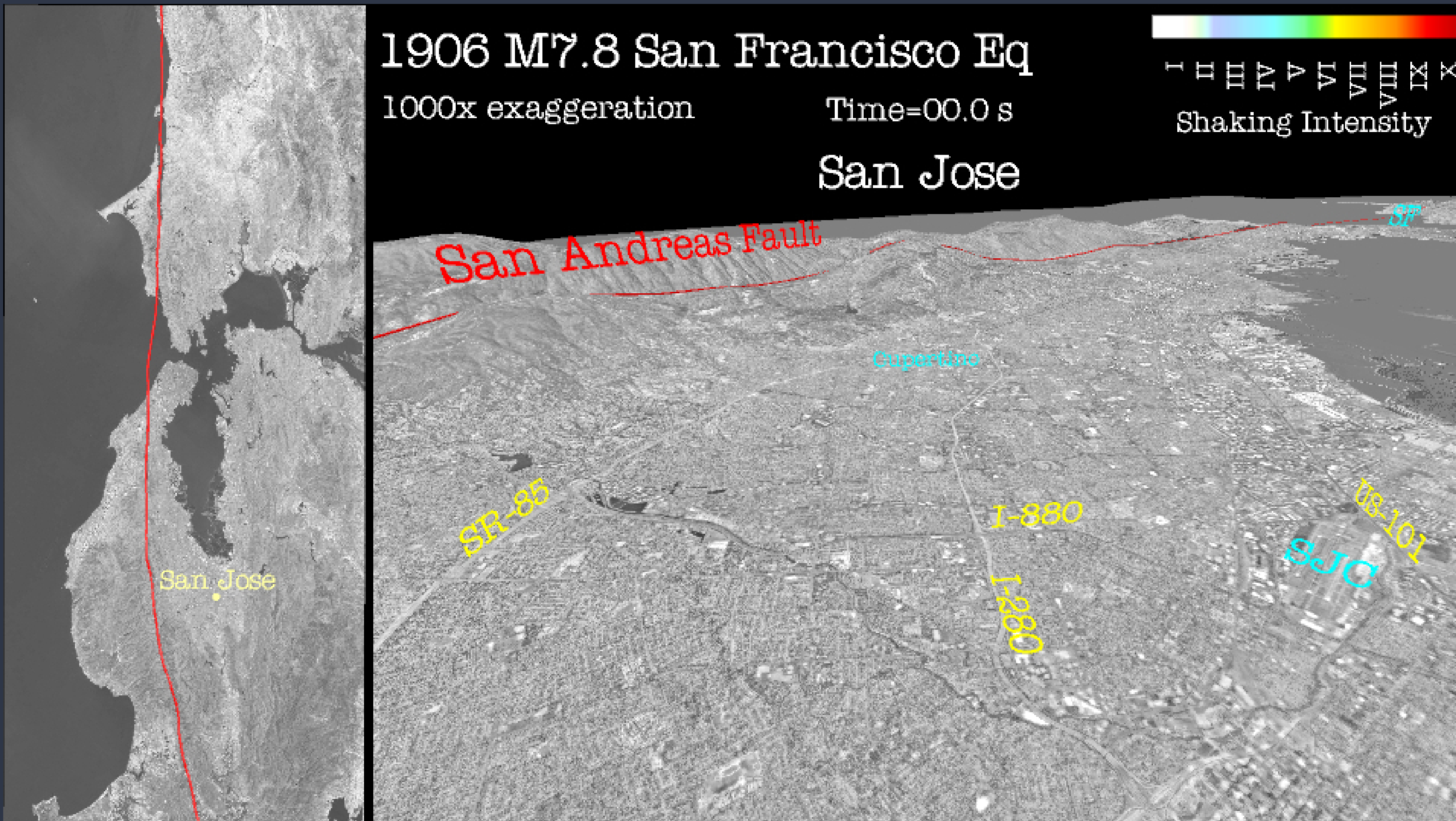
Do final cleanup by hand

- Some elements have all nodes on surfaces
- LaGriT doesn’t know how to move nodes on surface and retain shape
- Move 6–8 nodes by hand to achieve reasonable time step

Export mesh

- Remove coincident nodes associated with fault surfaces
- Remove lid (air) leaving ground surface as top surface
  - With lid: $\approx$ 2.2 million elements
  - Without lid: $\approx$ 1.4 million elements
- Create sets of nodes associated with boundaries & faults
- Write mesh to GMV file

Visualization of the end result . . .



Strategies that seem to work

Creating a mesh is easy, creating a *good* mesh is difficult!

- Start with uniform mesh
- Adjust size and improve quality simultaneously
  - Use variety of techniques to unlock & fix distorted elements
  - Don’t overshoot desired number of elements
  - Limit gradient in desired element size
- Start with simple test cases and gradually add complexity

Unresolved issues

- Is there a simple, robust solution for improving element quality?
- How large of a gradient in element size can I have without sacrificing element quality?
- How well do mesh generators support adaptive mesh refinement?
- Can mesh generation implementations be made more efficient?
  - Want to build larger meshes
  - Want to build similar sized meshes in less time
  - Is parallel mesh generation feasible?

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