Meshing and Set Up Workflow

Problems and Challenges

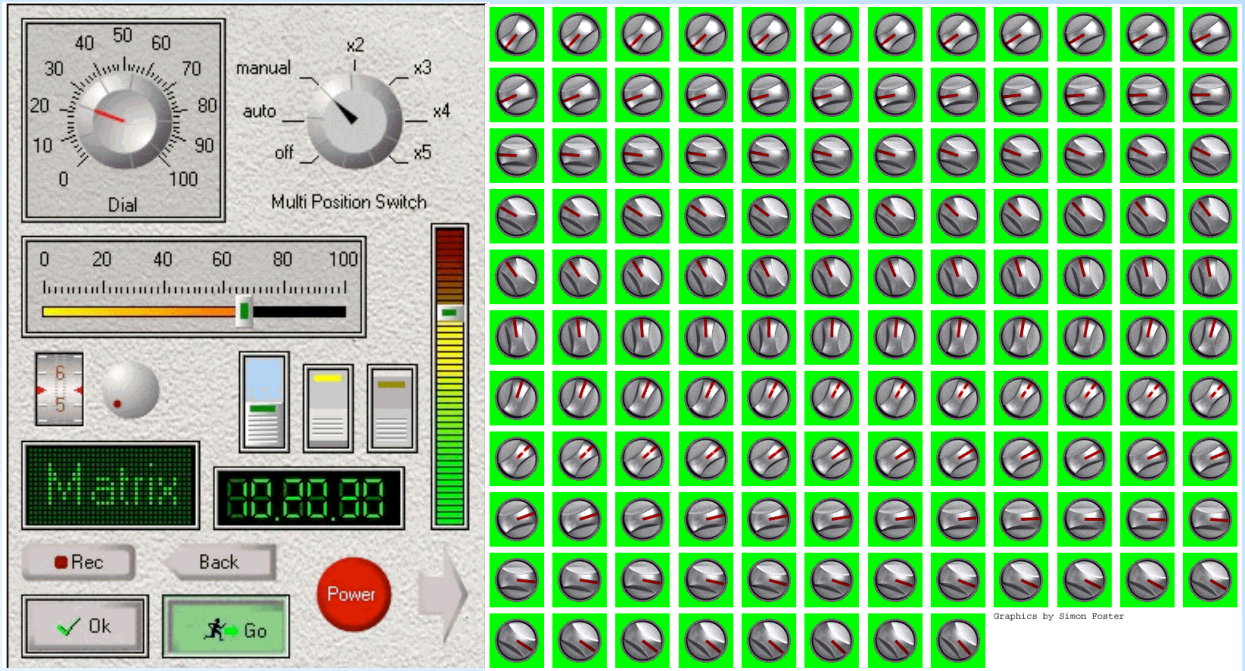
- Automated (but not automatic)

What users want.

Meshing and Set Up Workflow

Problems and Challenges

- Automated (but not automatic)

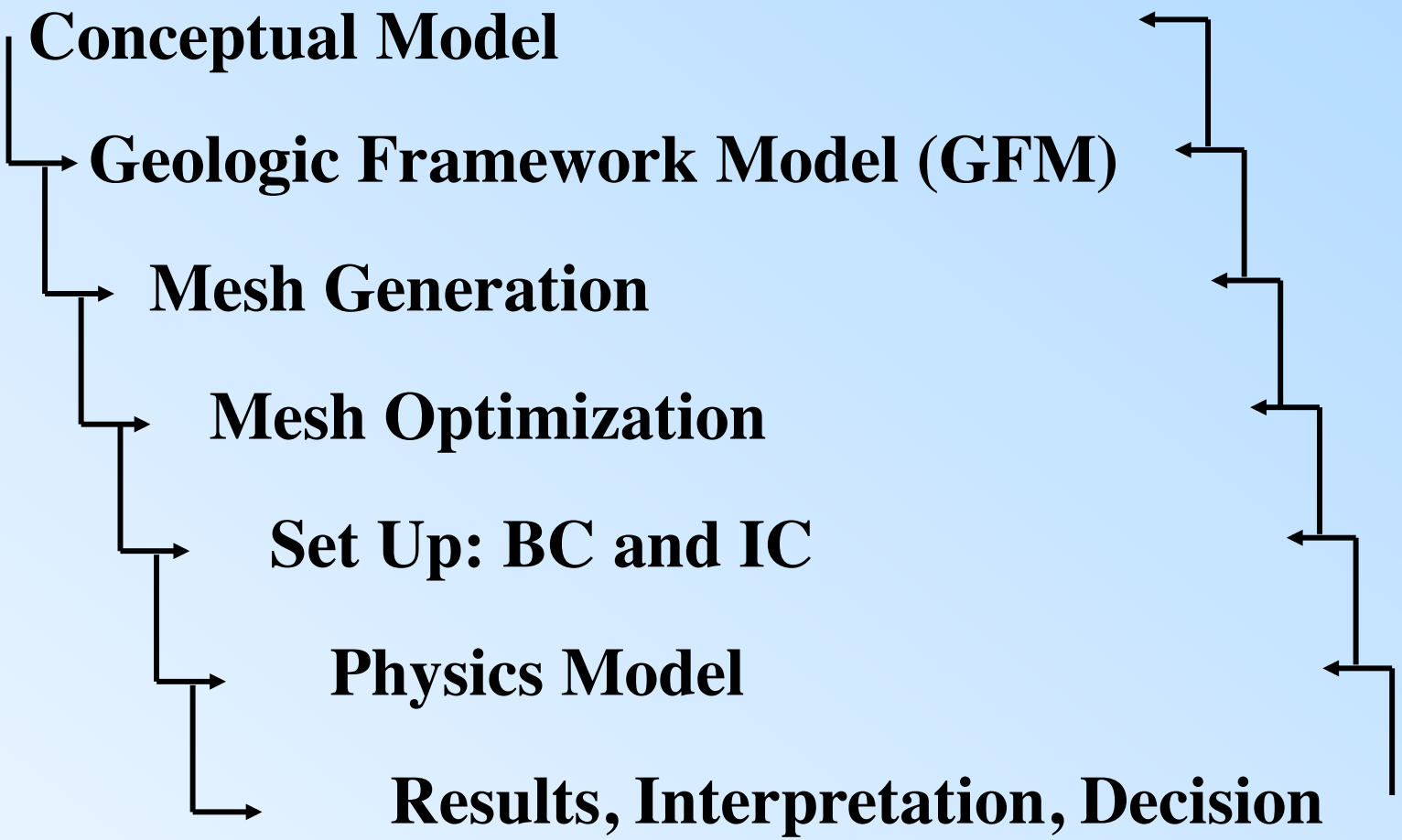


What users get.

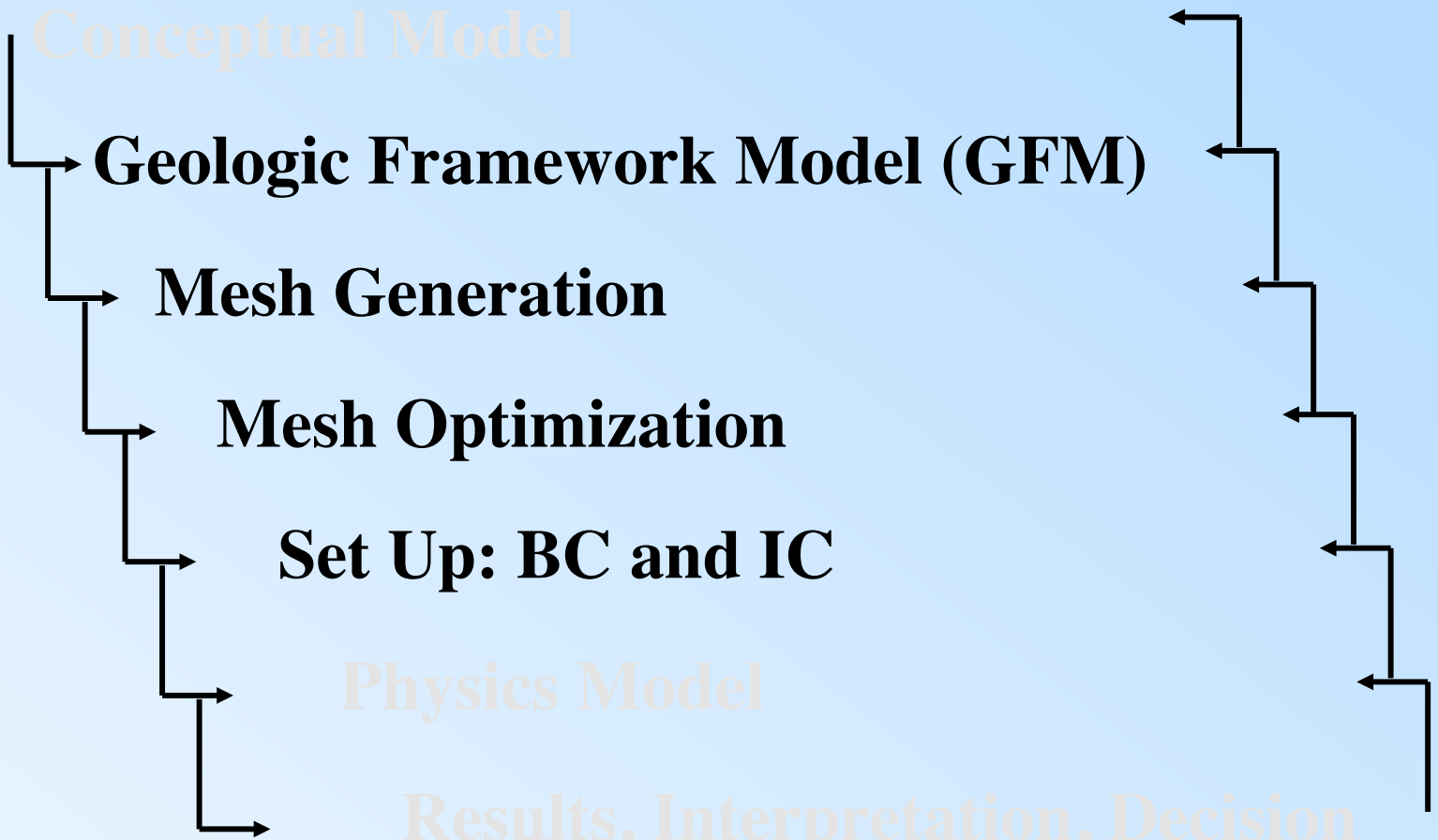
LaGriT Mesh Generation and Model Set Up

- LaGriT – Los Alamos Grid Toolkit
- General meshing and setup, pre & post processing package
- Present examples from various geological applications
- LaGriT Documentation: http://lagrit.lanl.gov
- Demos: http://meshing.lanl.gov
- Linux/MacOS/Solaris/SGI (not Windows)

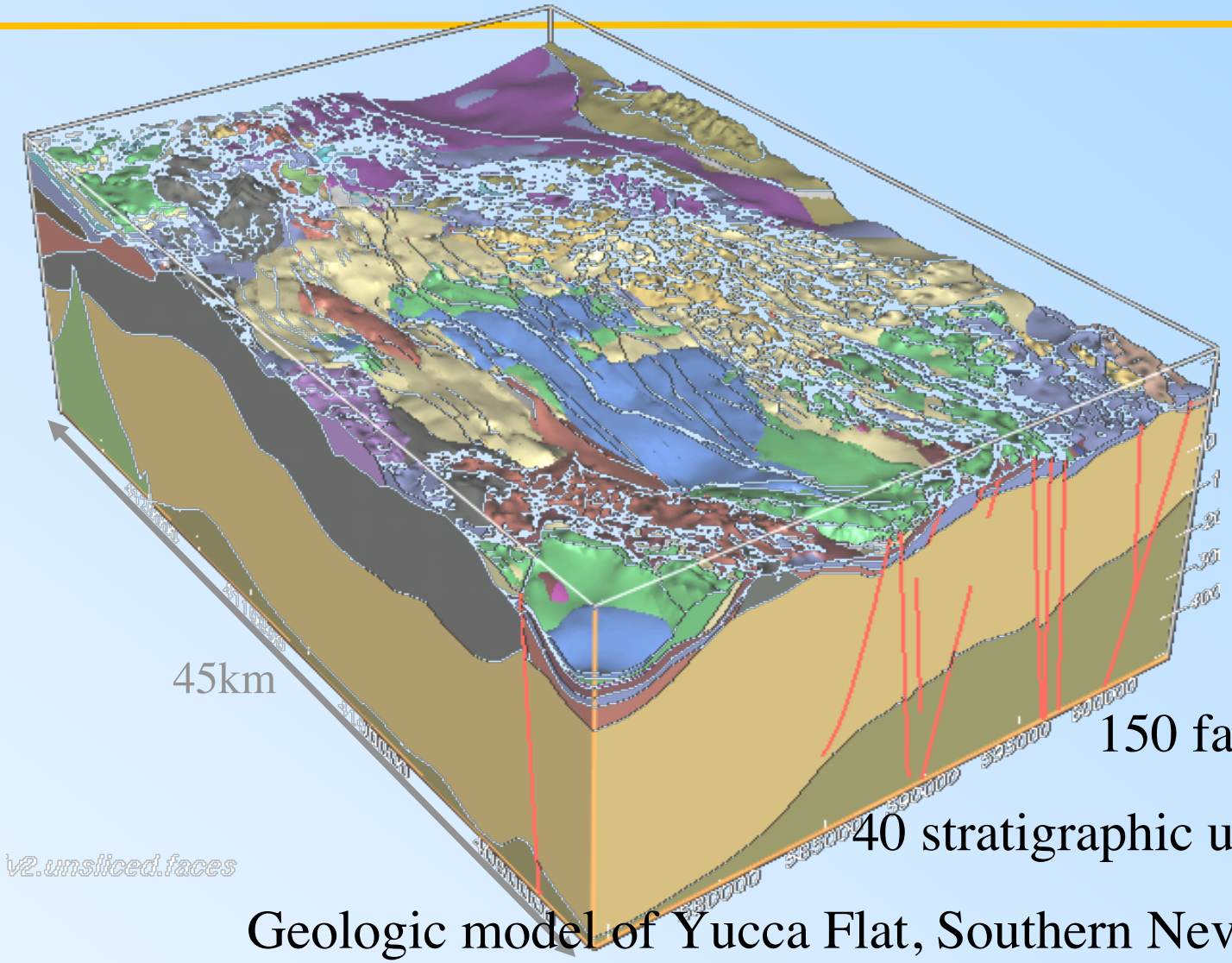
Geologic Modeling and Simulation Workflow



Geologic Modeling and Simulation Workflow



Geologic Framework Models (GFM) vs CAD

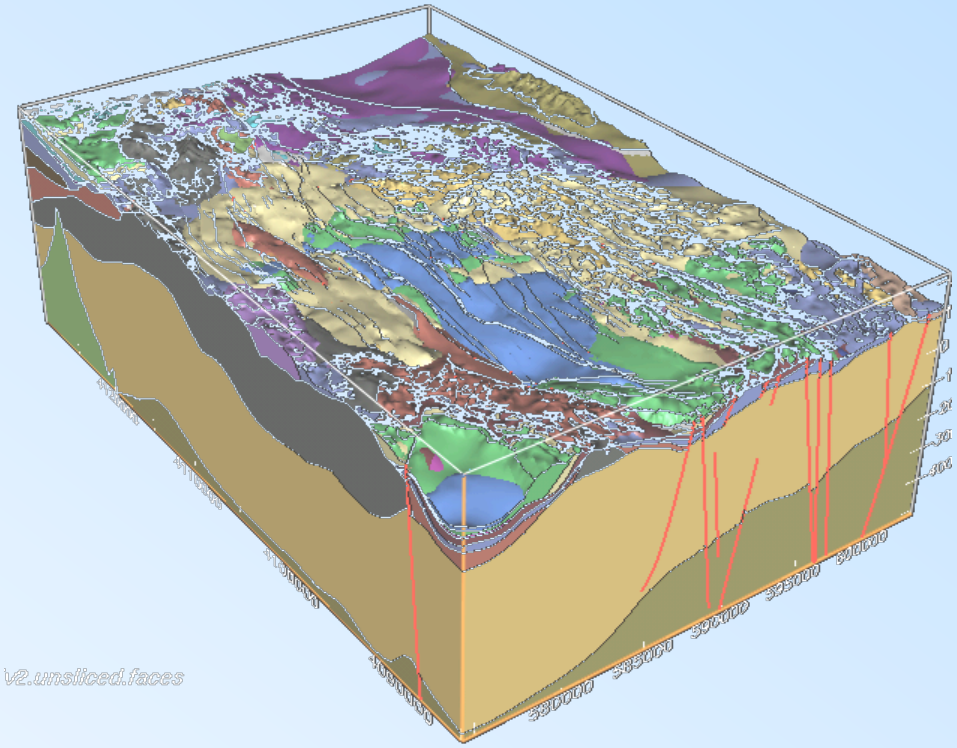


150 faults

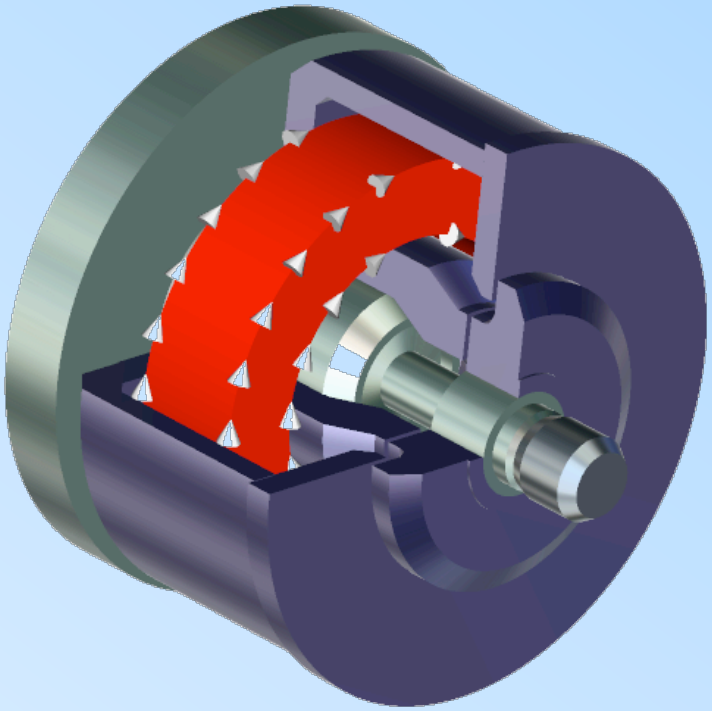
40 stratigraphic units

Geologic model of Yucca Flat, Southern Nevada

Geologic Framework Models (GFM) vs CAD



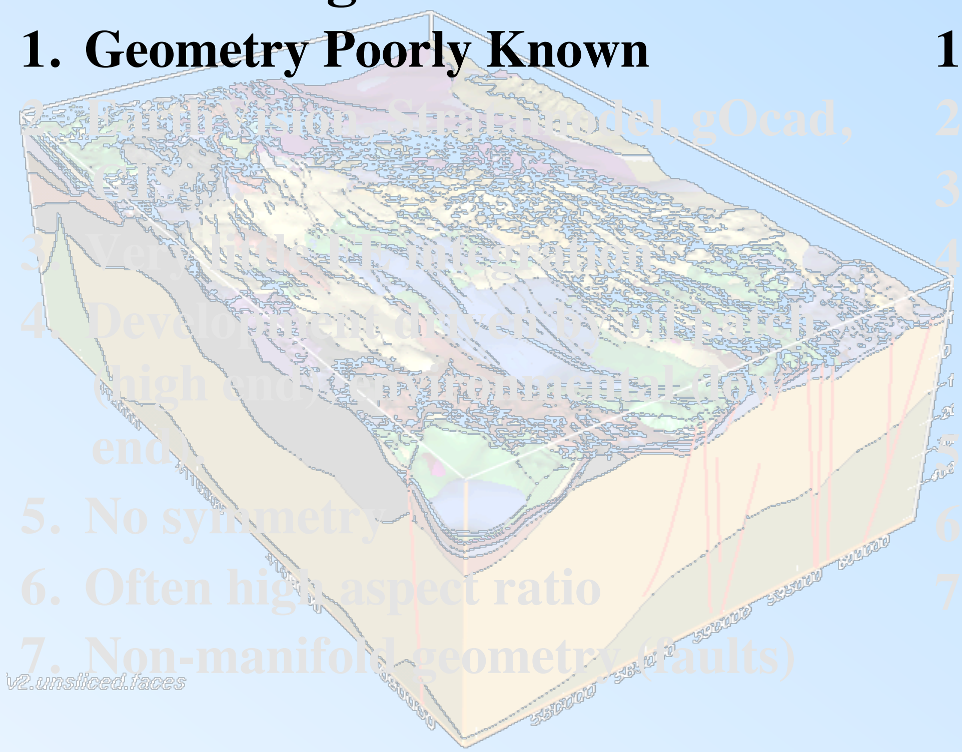
Geologic model of Yucca Flat



CAD Model

Comparison of GFM vs CAD

- **GFM Geologic**
  1. **Geometry Poorly Known**
  2. EarthVision, Stratamodel, gOcad, GIS
  3. Very little FE integration
  4. Development driven by oil patch (high end), environmental (low end)
  5. No symmetry
  6. Often high aspect ratio
  7. Non-manifold geometry (faults)



- **CAD Engineering**
  1. **Geometry Know to High Precision**
  2. CAD Model (ACIS, Pro/E, Autocad)
  3. FE application well integrated
  4. Development driven by automotive, aircraft, semiconductor, mechanical engineering, fluid dynamics
  5. Often symmetry
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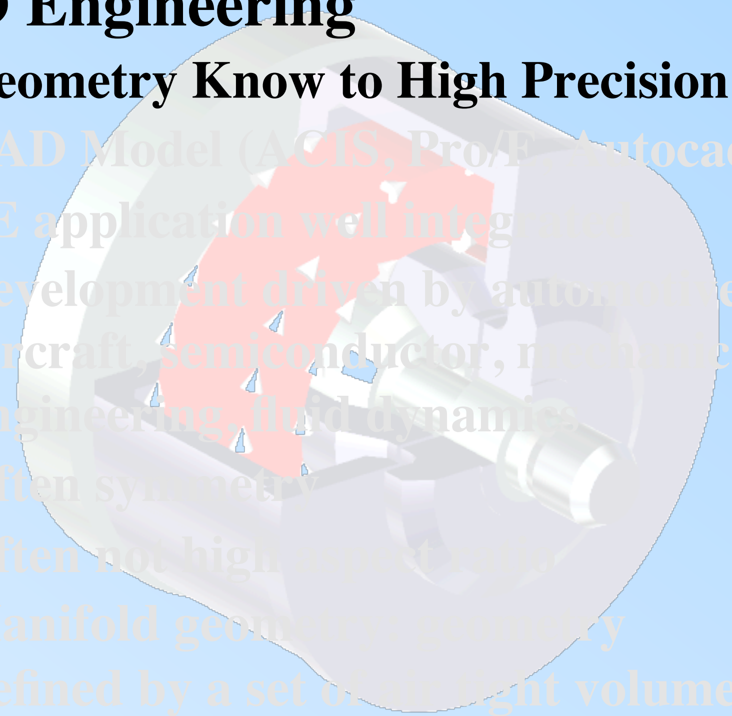
  7. Manifold geometry, geometry defined by a set of watertight volumes



Comparison of GFM vs CAD

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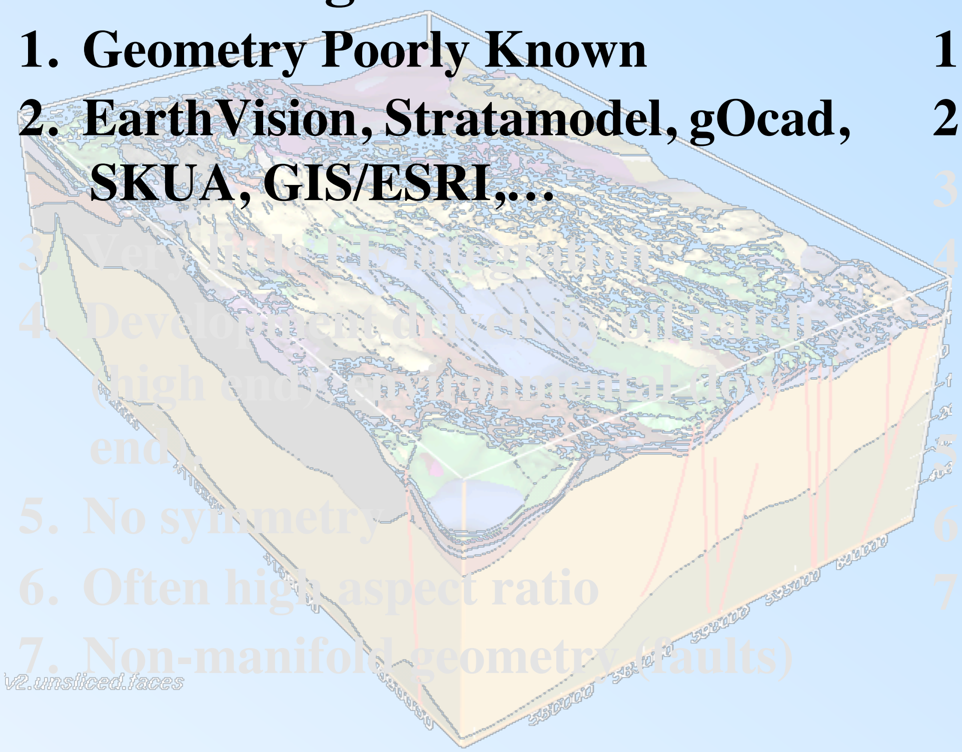

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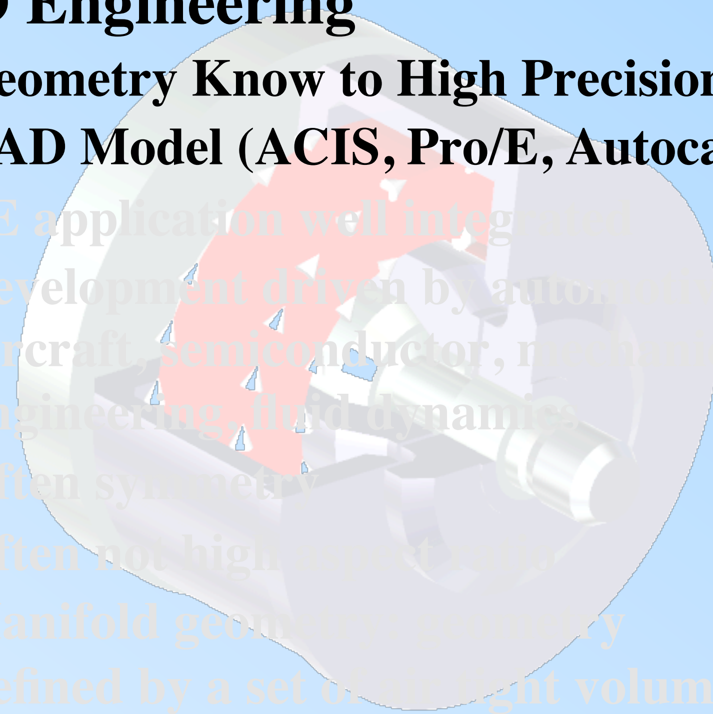

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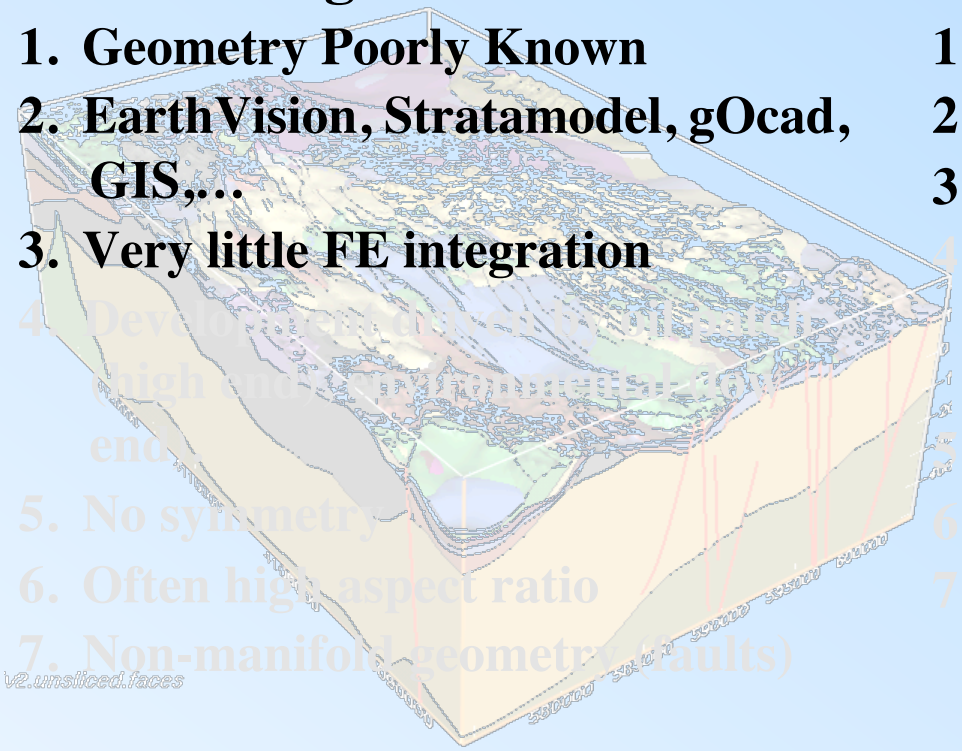

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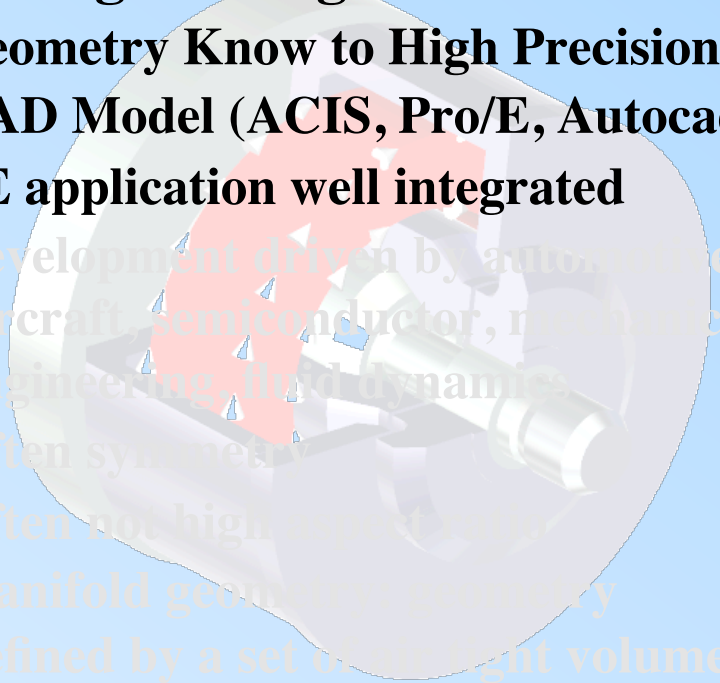

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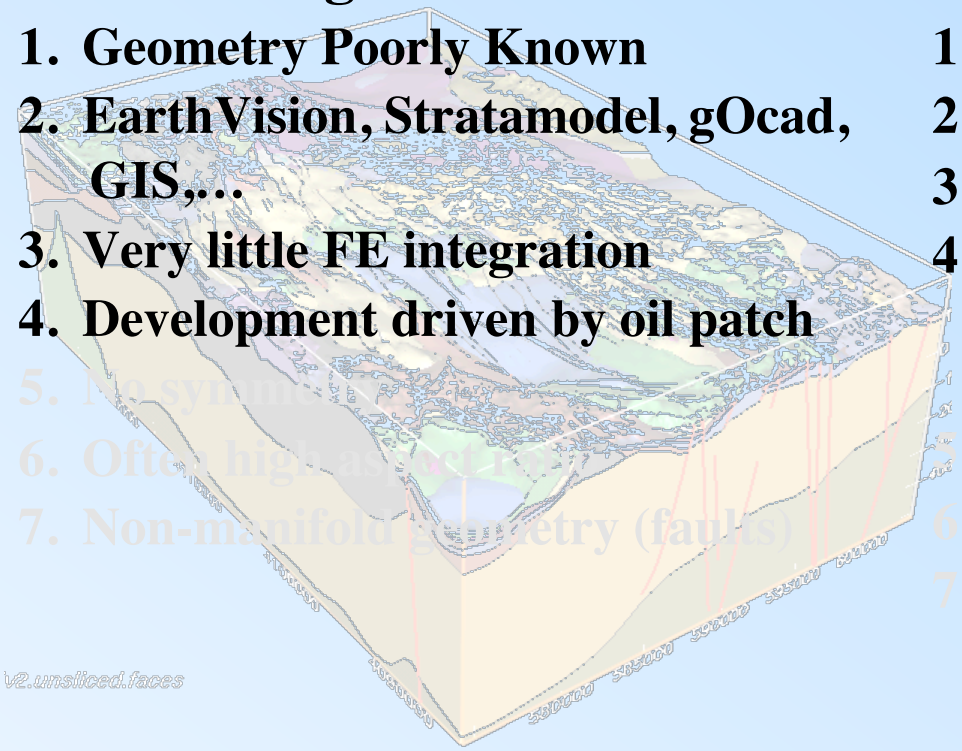

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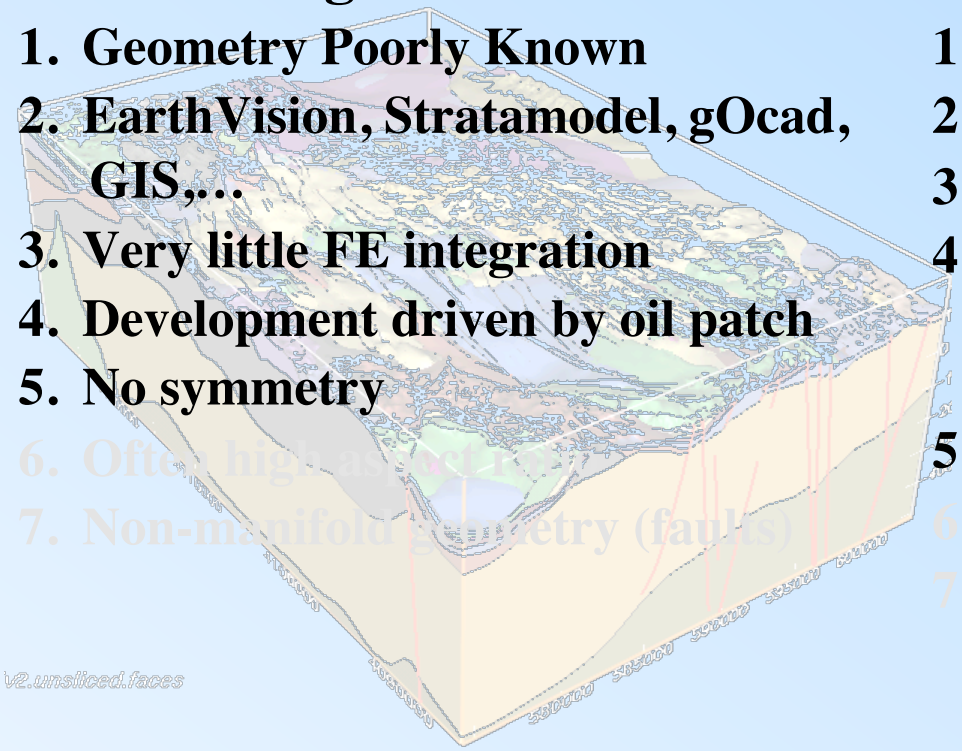

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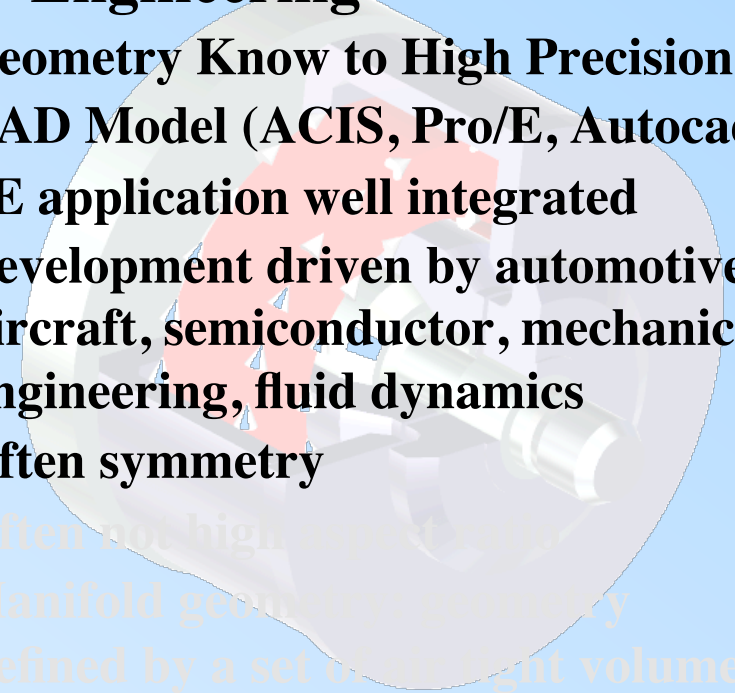

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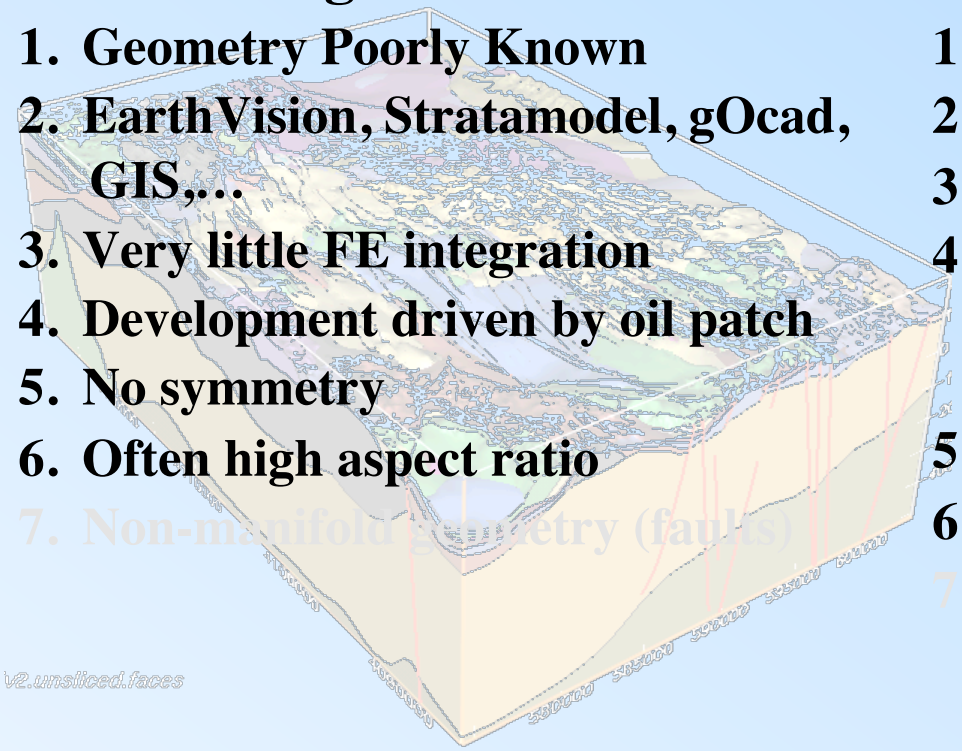

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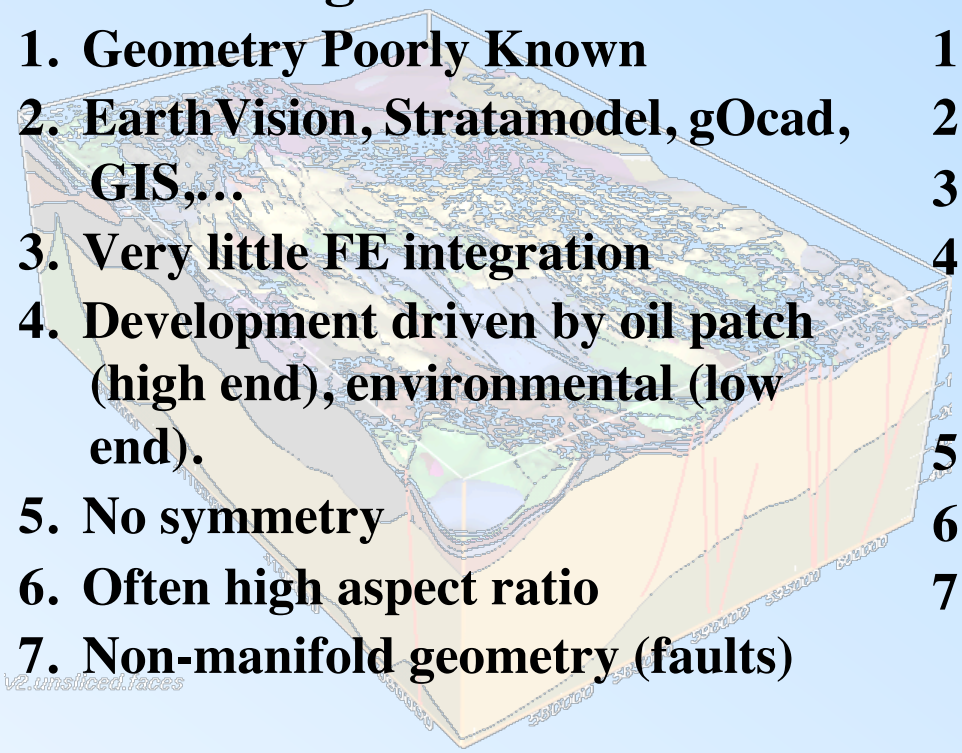

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  5. Often symmetry
  6. Often not high aspect ratio
  7. Manifold geometry: geometry defined by a set of air tight volumes

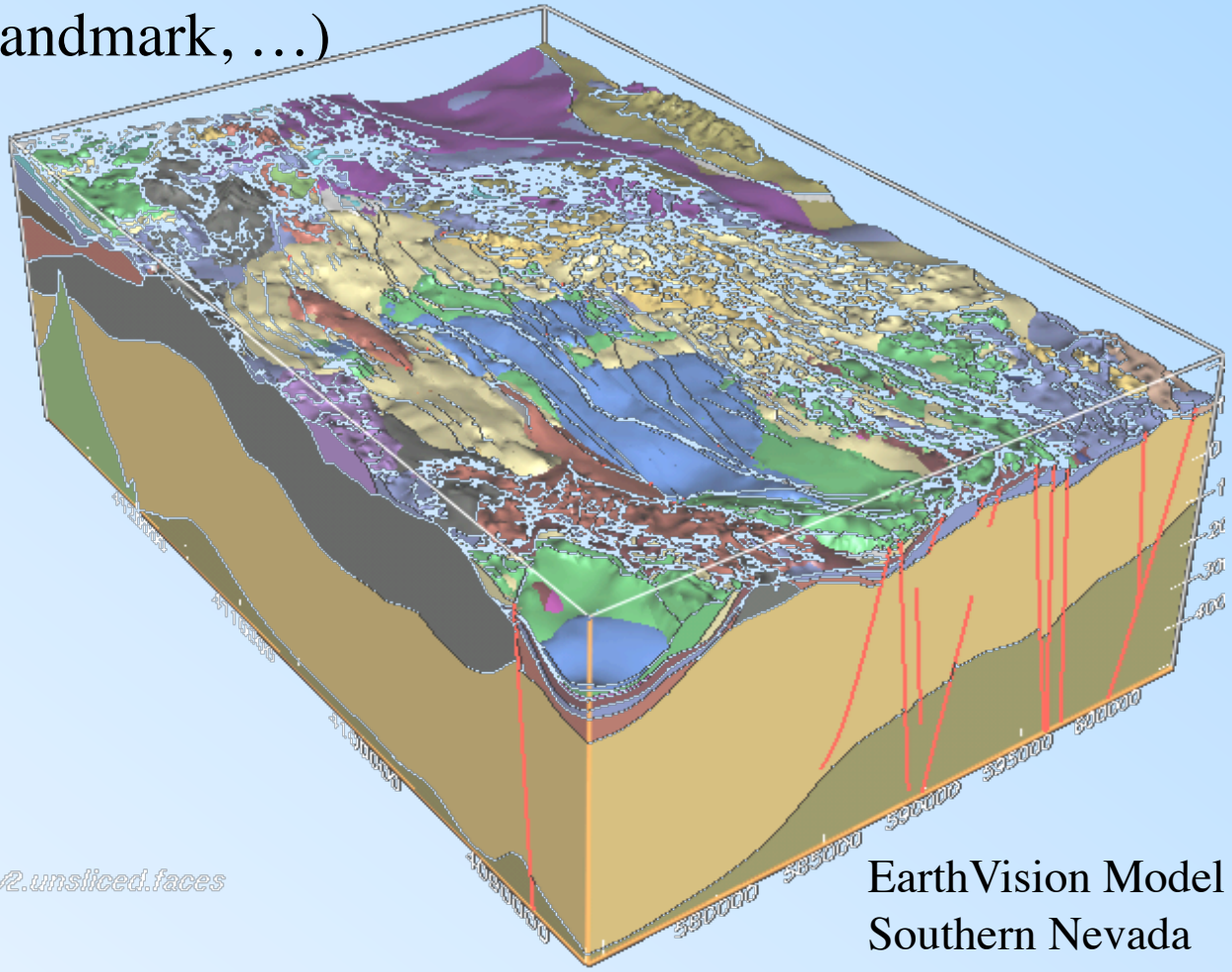
Forms of Geologic Framework Models (GFM)

Forms of Input to Meshing

- Picture
- Map
- Cross Section
- Collection of surfaces that bound volumes
- Non-manifold Geometry
- Cellular model of 2D or 3D space (triangle, quadrilateral, hexahedral, tetrahedral, prism, pyramid, polygon, polyhedral)
- CAD
- Geologic modeling software

Forms of GFMs

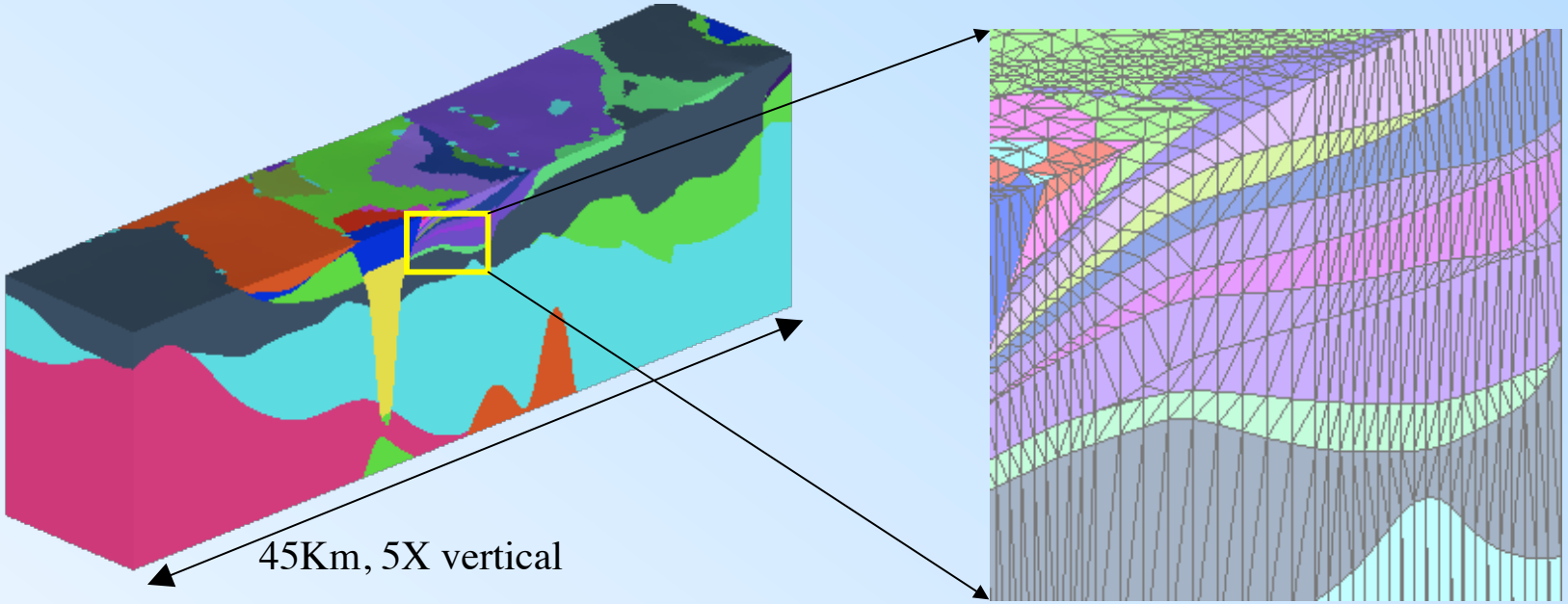
- Various Geologic Modeling Software Packages (EarthVision, gOcad/SKUA, Landmark, …)



EarthVision Model
Southern Nevada

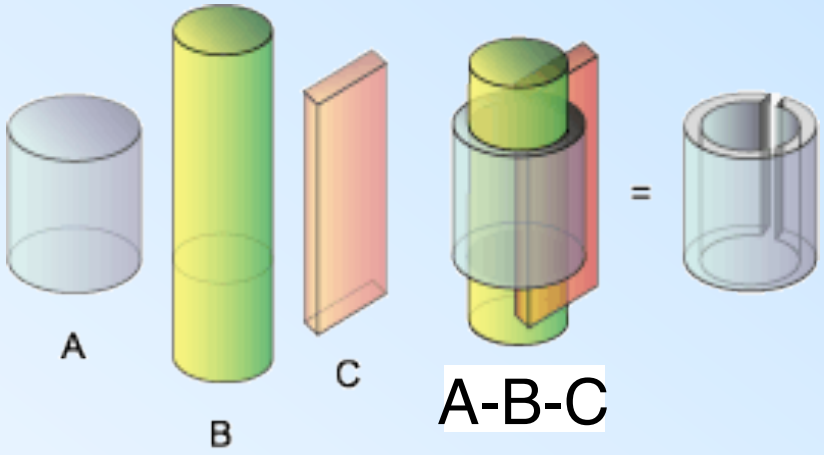
Forms of GFMs

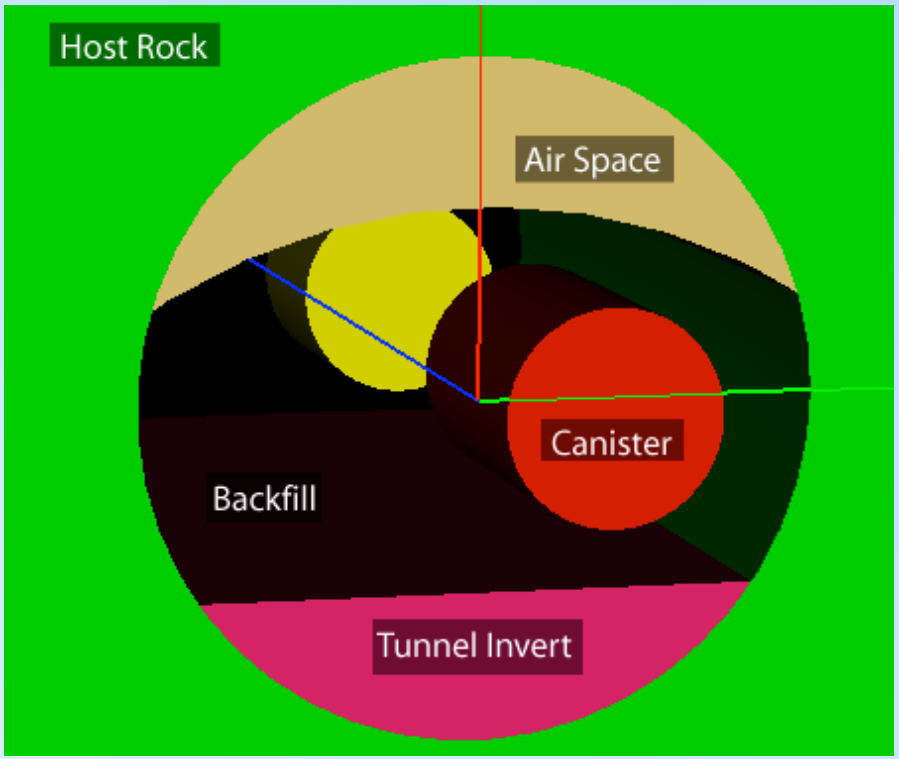
- Cellular model of 2D or 3D space (triangle, quadrilateral, hexahedral, tetrahedral, prism, pyramid, polygon, polyhedral)
- 3D geologic framework defined by tetrahedral elements



Forms of GFMs

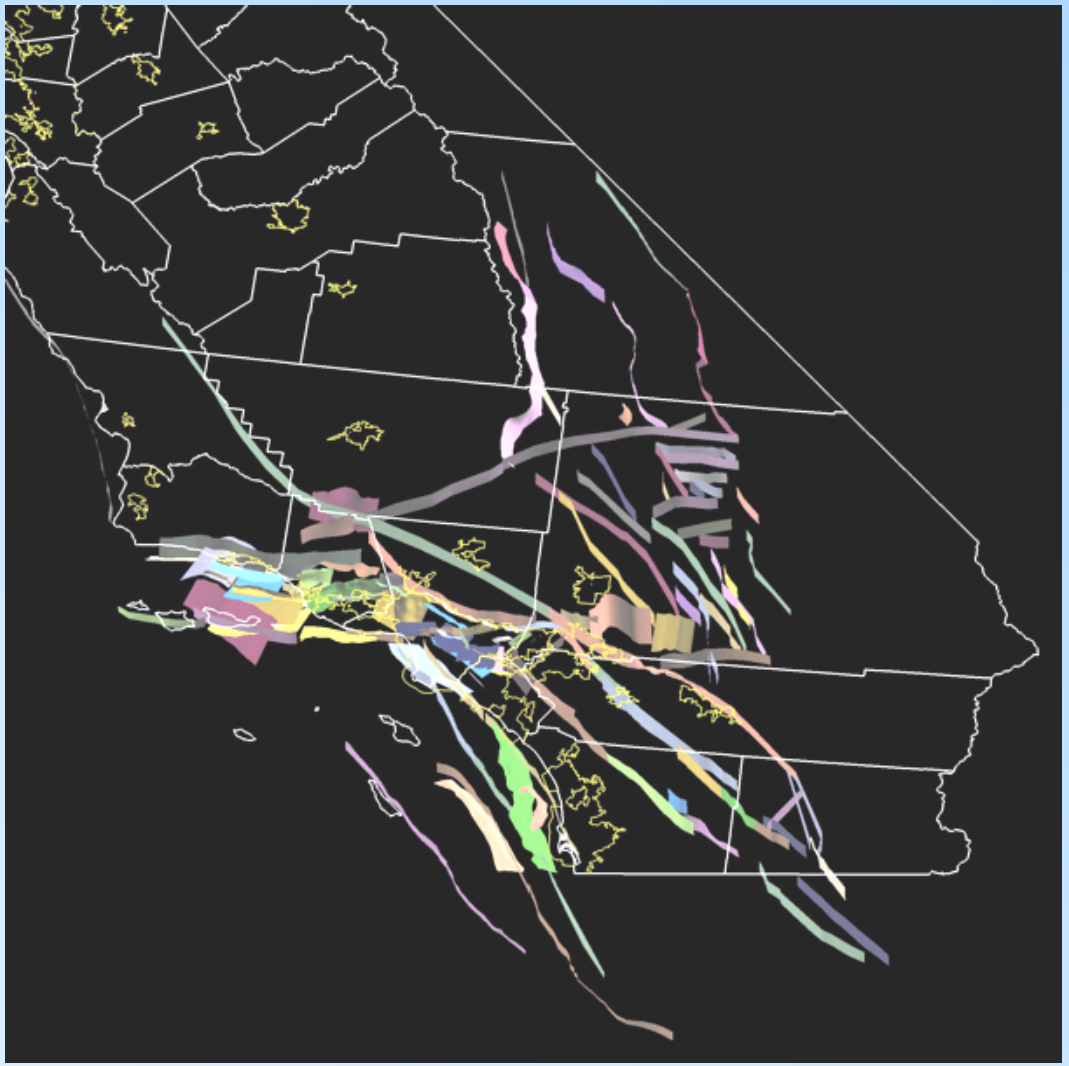
- **Constructive Solid Geometry**
- **Collection of surfaces that bound volumes**
- **Can be used to define geometry, topology and attributes**





Forms of GFMs

- Non-manifold Geometry
- Southern California Earthquake Center (SCEC) community fault model (CFM) of southern California
- Faults defined by triangulated surfaces
- Geometry of faults is well defined but topology is not defined



GFM Not in CAD Format

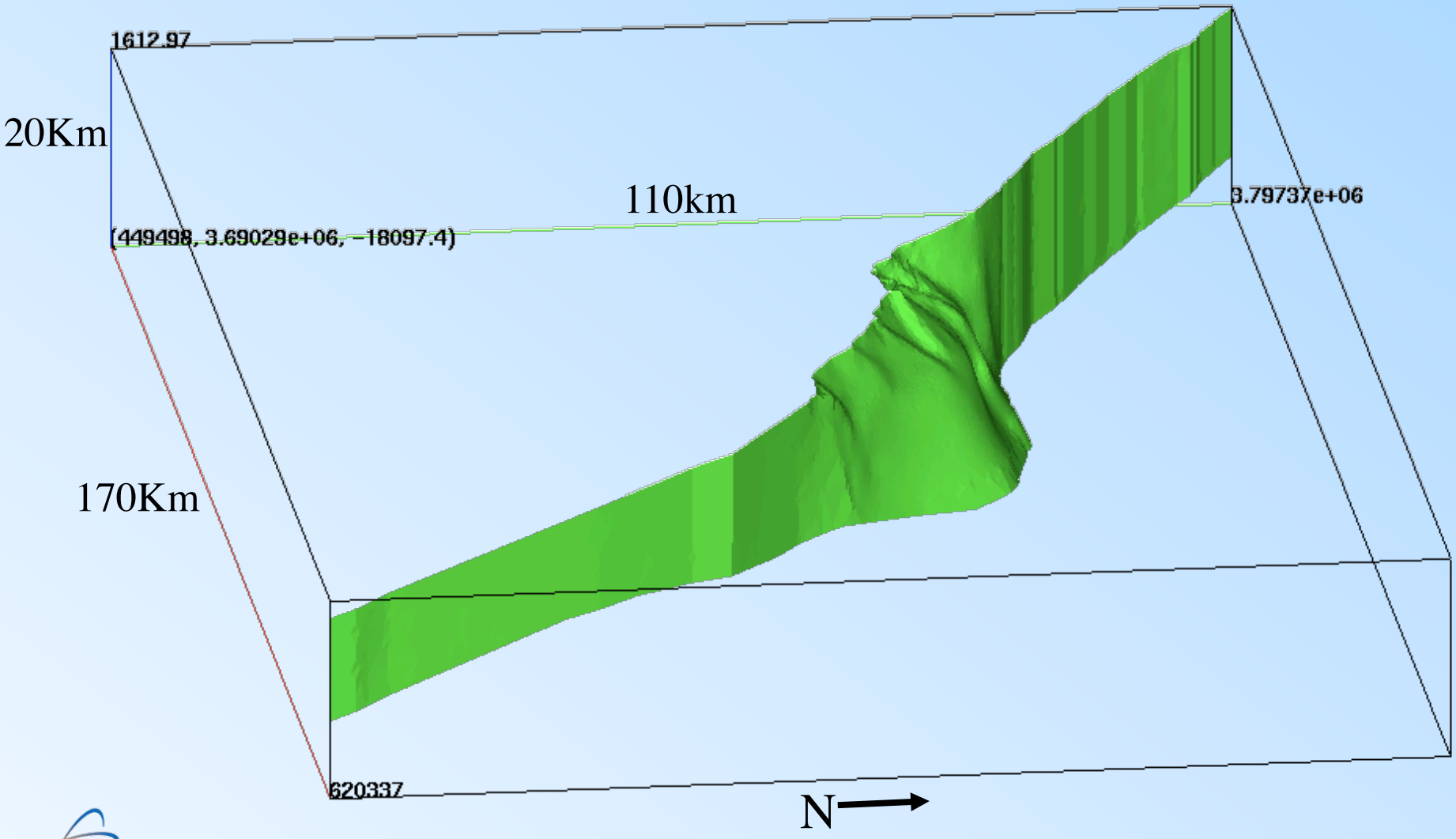
Option 1

1. **Derive CAD solid model (ACIS, Pro/E, etc.) from geologic model (EarthVision, gOcad, Stratamodel, …).**
2. **Use mesh generation tools that utilize CAD solid model input.**

Option 2

1. **Use mesh generation tools that do not require CAD solid model input.**

San Andreas Fault

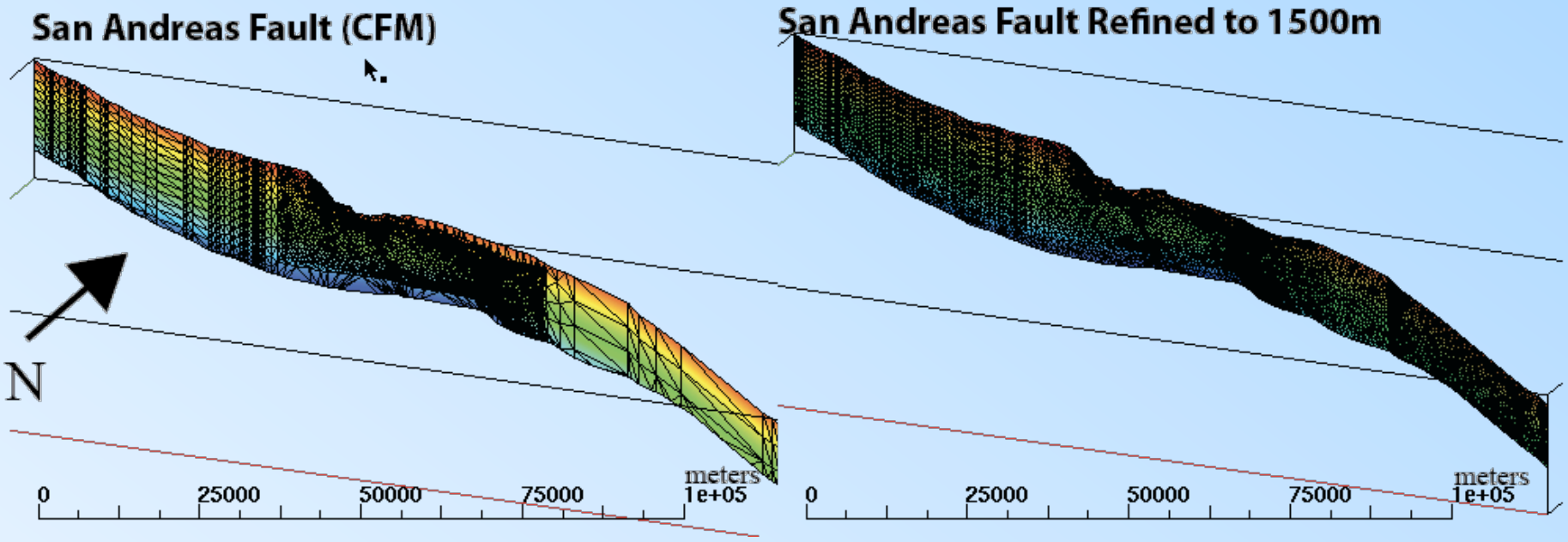


Los Alamos NATIONAL LABORATORY EST. 1943

http://lagrit.lanl.gov http://meshing.lanl.gov/proj

NNSA

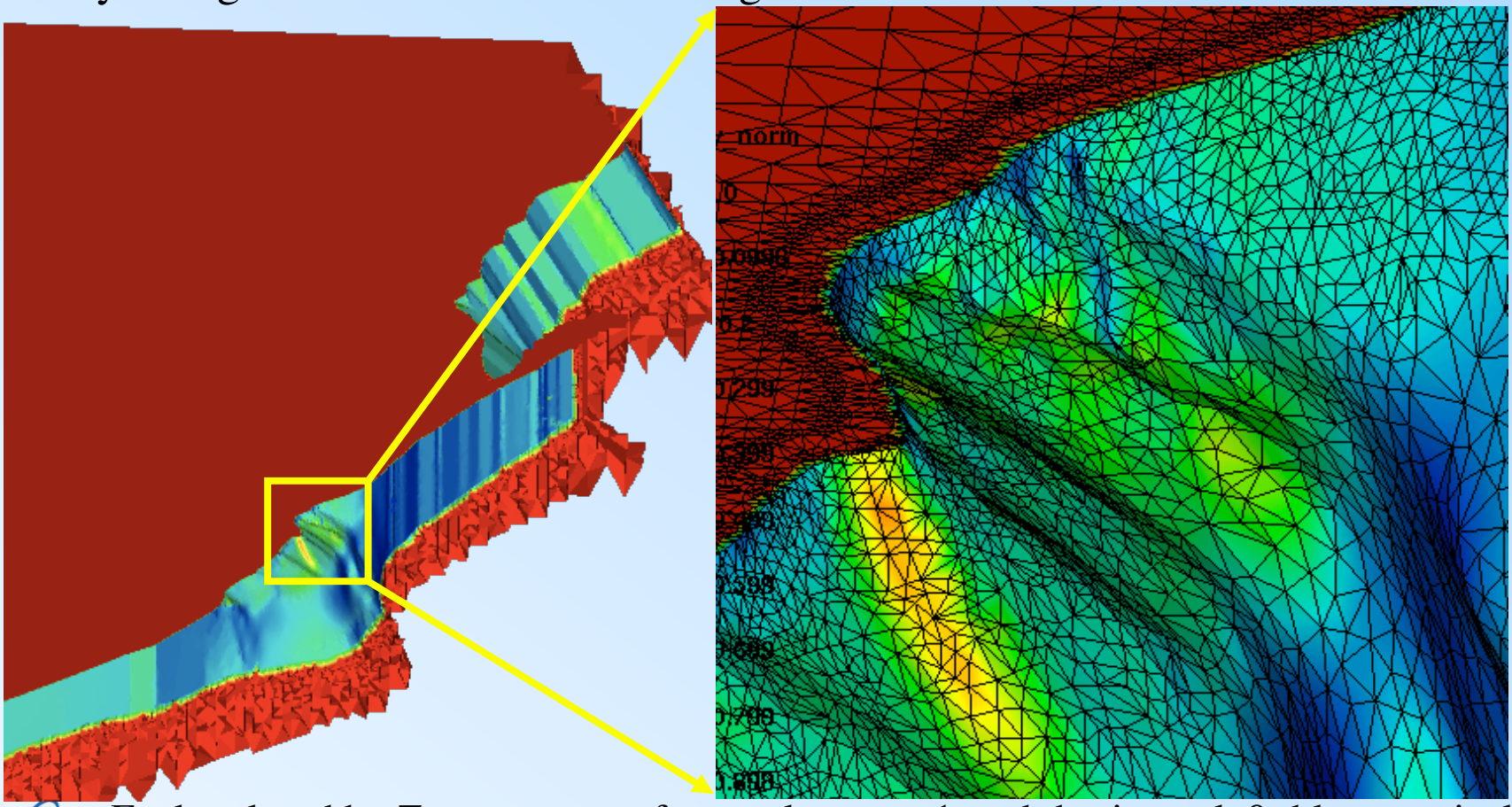
Non-Manifold Geometry



Goal: Build a 3D tetrahedral mesh with internal interface triangles that conform to the San Andreas Fault triangulation.

Non-Manifold Geometry

Insert fault triangulation into background mesh using properties of conforming Delaunay triangulation to insure fault triangulation is recovered in 3D tetrahedral mesh.

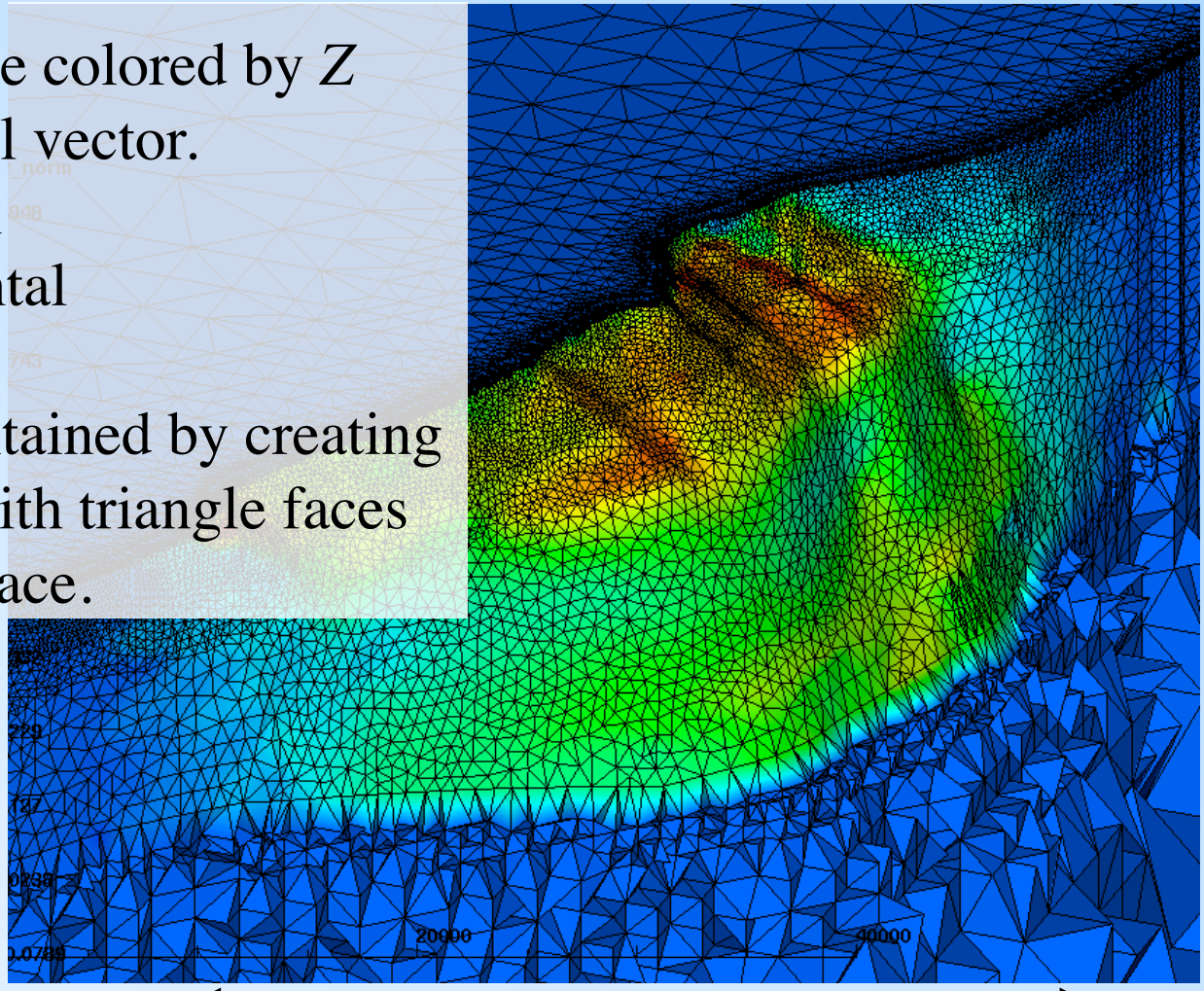


Fault colored by Z component of normal vector: 1=red=horizontal, 0=blue=vertical

San Andreas Fault

Fault surface attribute colored by *Z* component of normal vector.
Blue = 0 = vertical
Red = 1 = horizontal

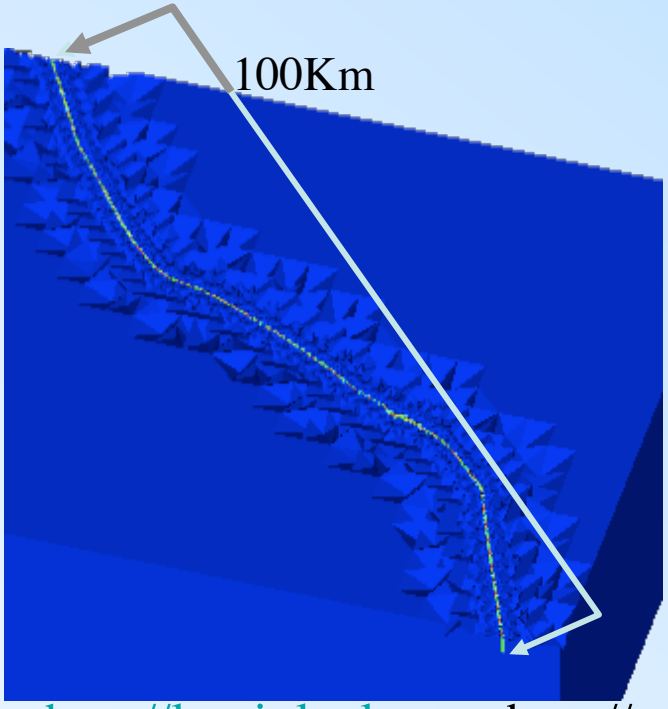
Fault surface is maintained by creating a tetrahedral mesh with triangle faces that follow fault surface.

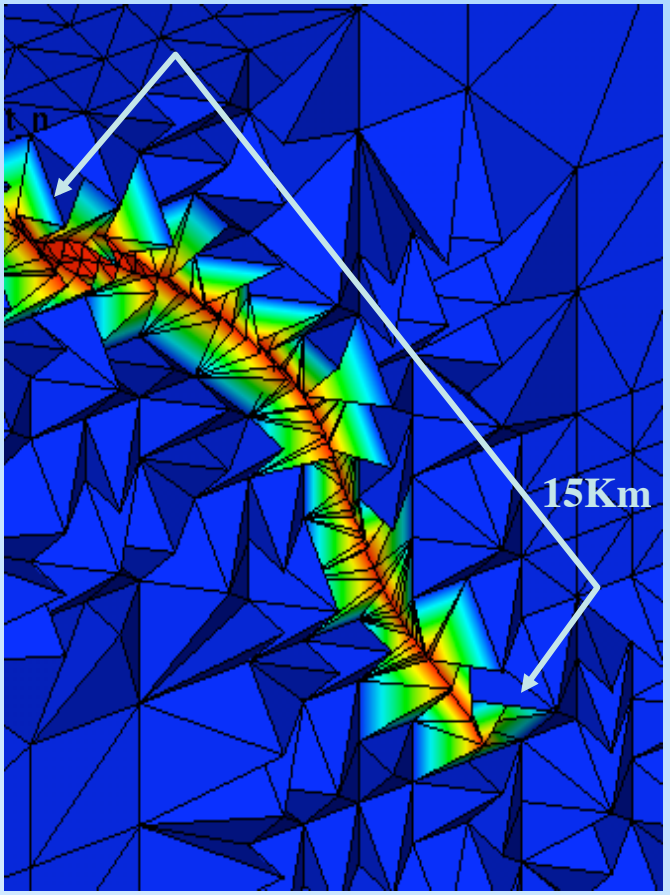


40Km

San Andreas Fault

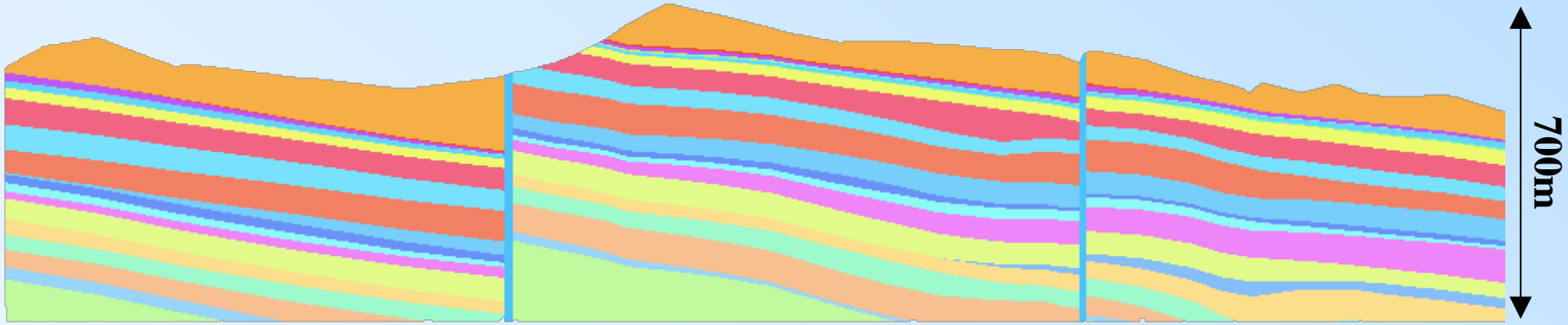
During mesh generation, GFM fault surface information such as distance from fault surface, surface orientation, desired mesh resolution, must be conveyed from GFM to meshing algorithms.





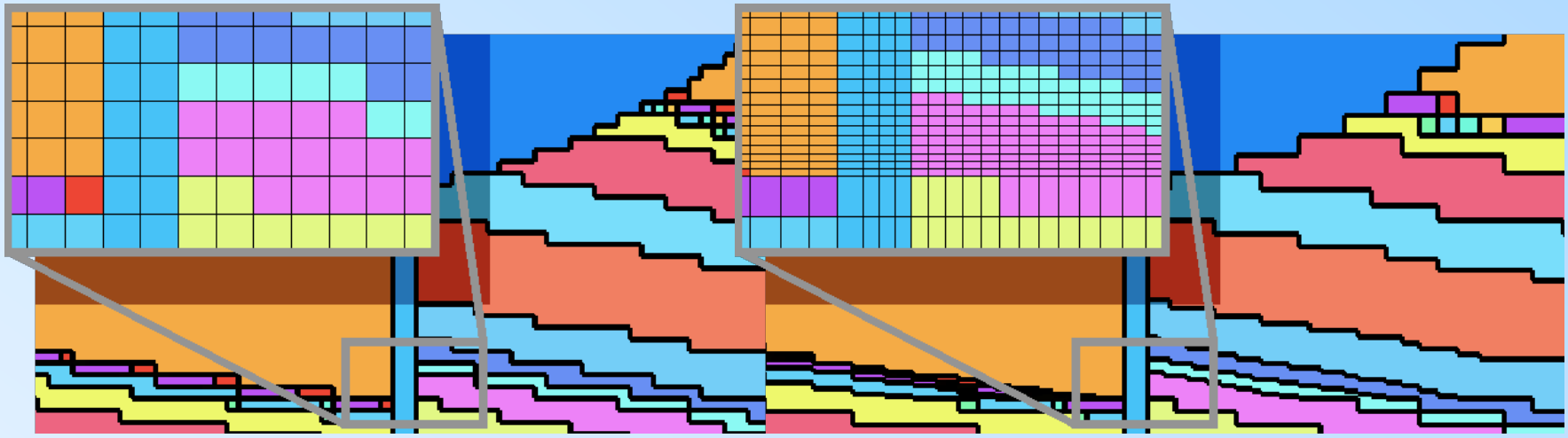
Mesh Generation Approach Depends on the Solver and Physics

- **Orthogonal Finite Difference, Logical Structured, Block Structured**
- **Quadtree, Octree**
- **2.5 D Unstructured (*e.g.* stacked triangles)**
- **Unstructured (quad, tri, hex, tet, prism, pyramid, polyhedral)**
- **Mesh quality (aspect ratio, volume variation, …)**



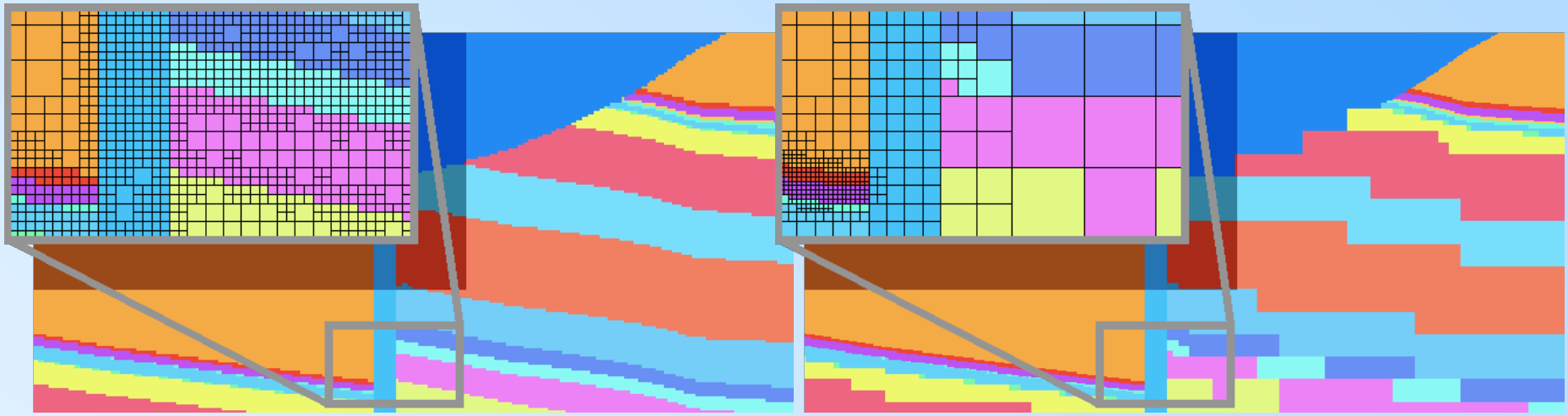
GFM, Yucca Mountain, Antler Ridge Cross Section

Mesh Generation: Orthogonal Finite Difference



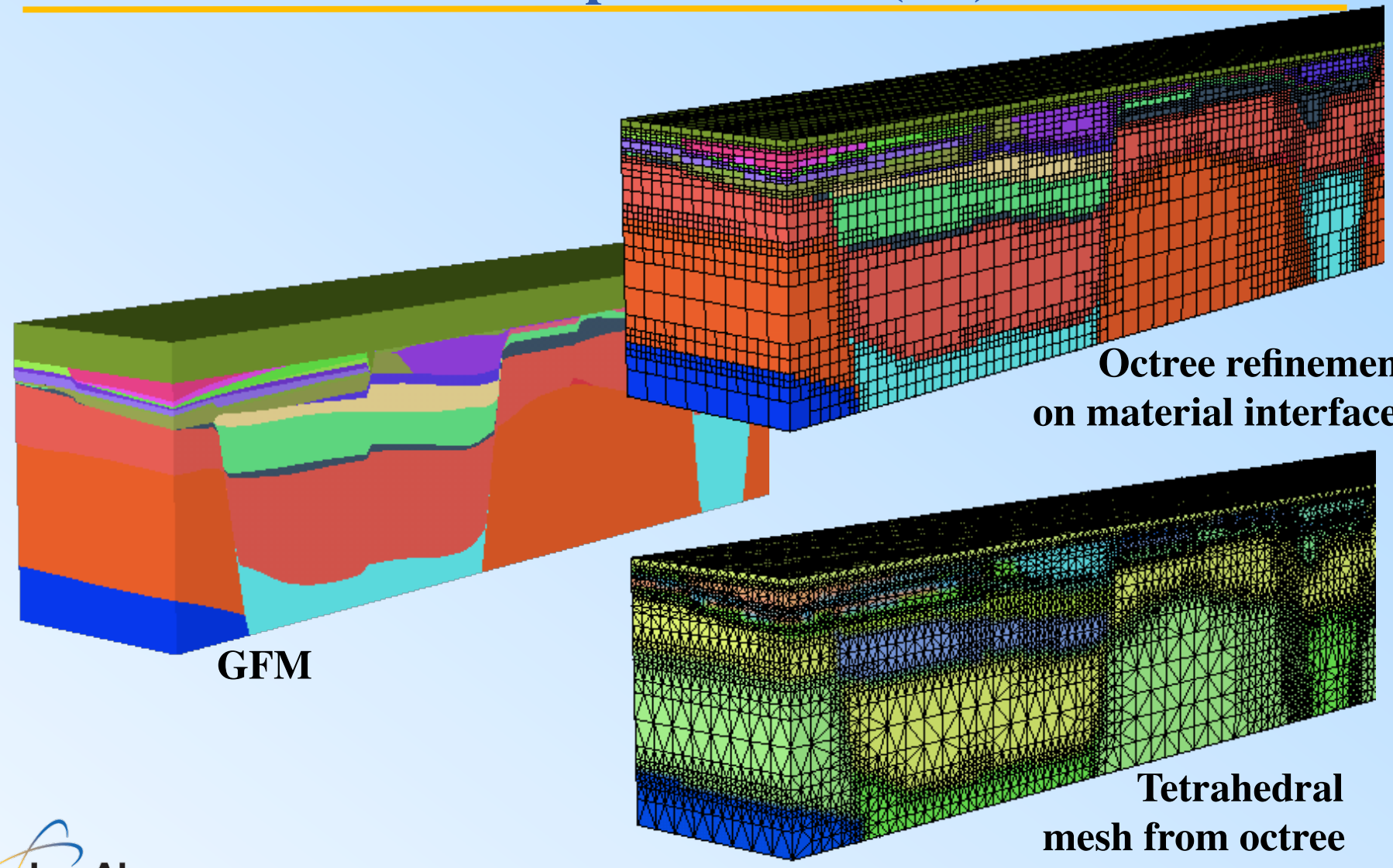
- **Mesh node and element attributes are assigned from GFM but mesh resolution is not informed by GFM details**

Mesh Generation: Adaptive Quadtree(2d)



- **Mesh node and element attributes are assigned from GFM**
- **Mesh refinement is informed by GFM geometry**

Mesh Generation: Adaptive Octree(3D)

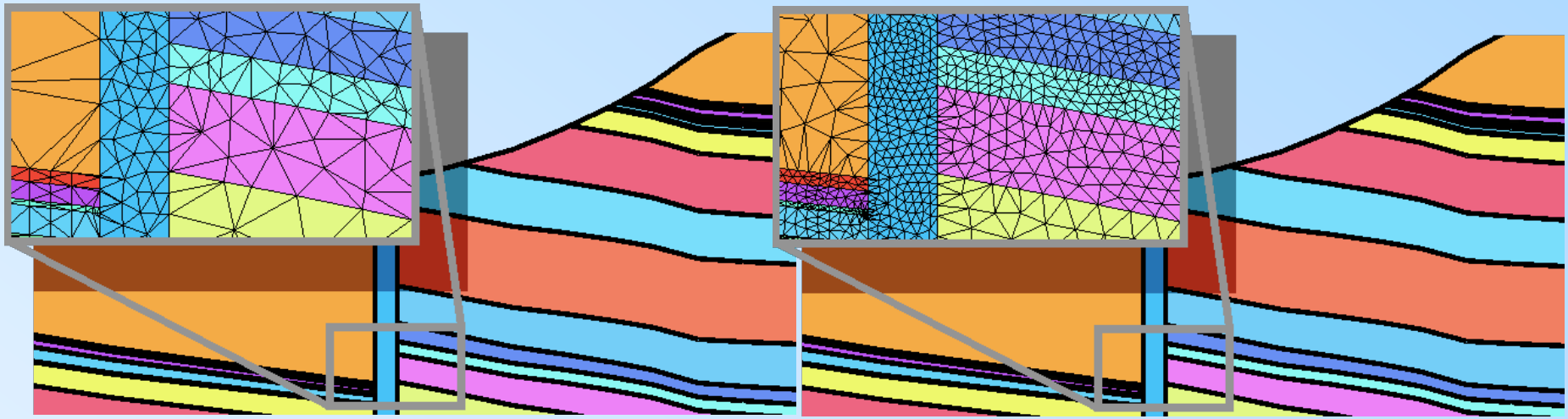


Los Alamos NATIONAL LABORATORY EST. 1943

http://lagrit.lanl.gov http://meshing.lanl.gov/proj

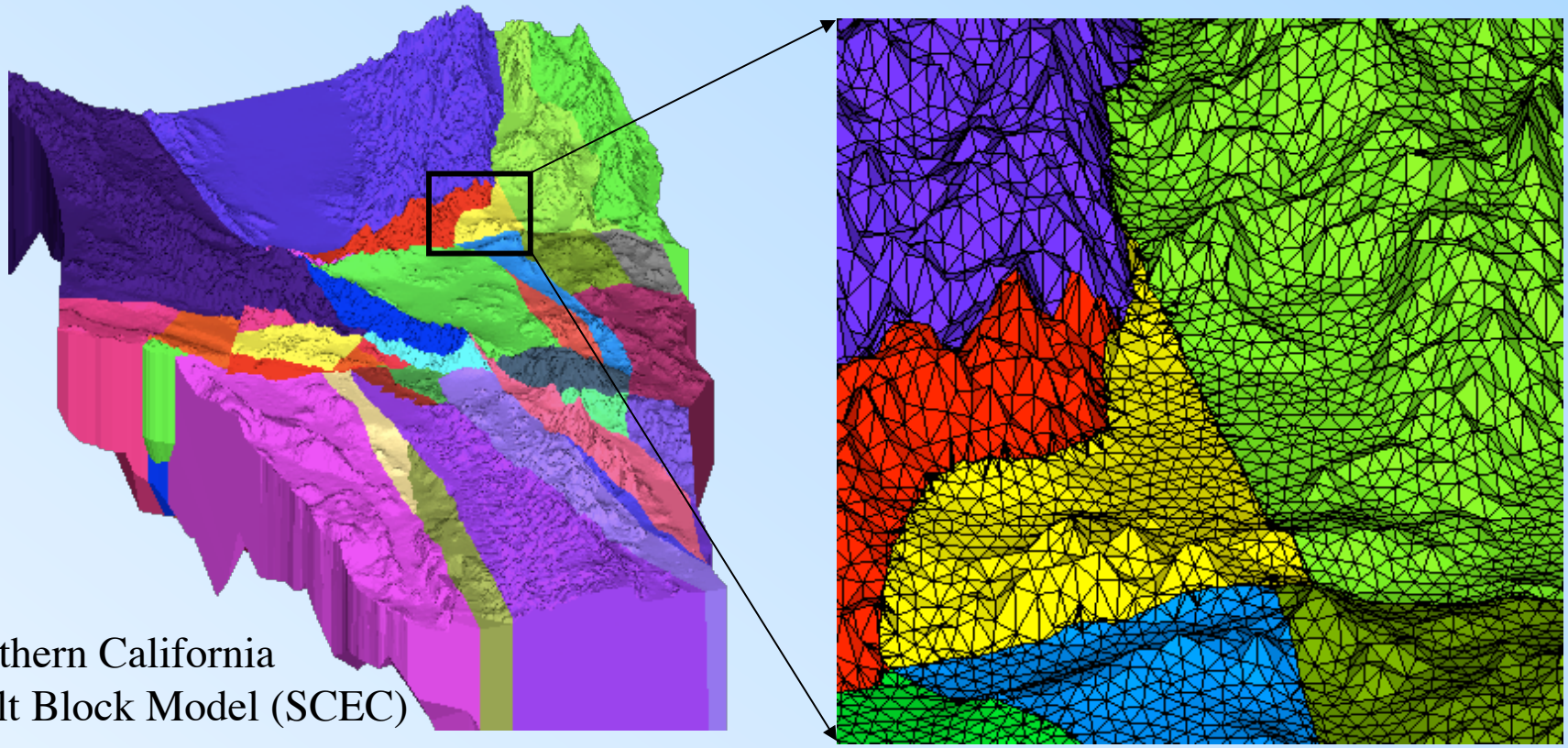
NNSA

Mesh Generation: Unstructured Triangle/Tetrahedral



- **Mesh node and element attributes are assigned from GFM**
- **Mesh reproduces geometry and topology of GFM**
- **Mesh resolution is informed by GFM**

Mesh Generation: Unstructured Tetrahedral (3D)



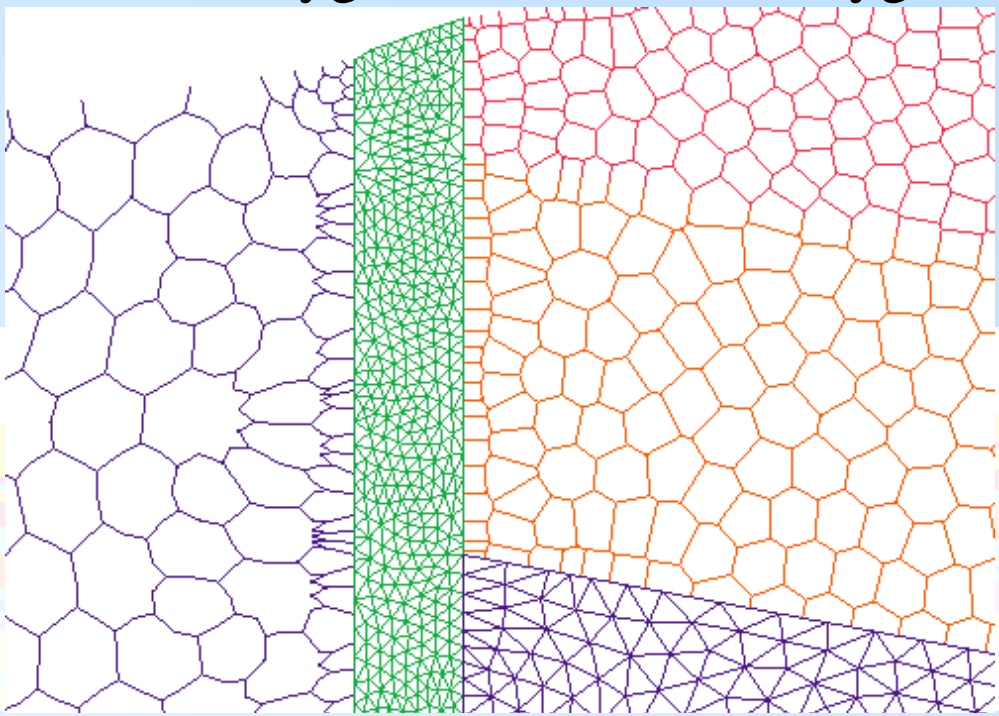
Southern California
Fault Block Model (SCEC)

- **Mesh node and element attributes are assigned from GFM**
- **Mesh reproduces geometry and topology of GFM**
- **Mesh resolution is informed by GFM**

Mesh Generation Depends on the Solver and Physics

- Unstructured polyhedra (control volume methods)

Median Polygon Voronoi Polygon

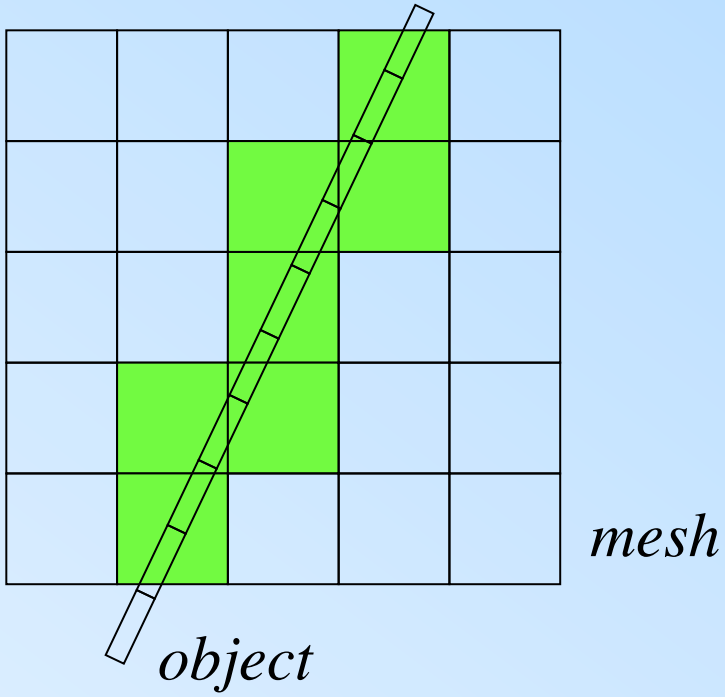


Model Setup: Attributes, Boundary and Initial Conditions

- **GFM to Mesh Interpolation**
  - **Set material properties to nodes and/or elements (*e.g.* density, permeability)**
  - **Set boundary conditions from GFM or another model (*e.g.* boundary flux)**
- **Upscale**
  - **Interpolate fine mesh properties onto a coarse mesh with various options for upscale function.**
- **Mesh-Object Intersections**
  - **Point (injection), line (well bore), surface (fault), volume (tunnel)**

Mesh-Object Intersection

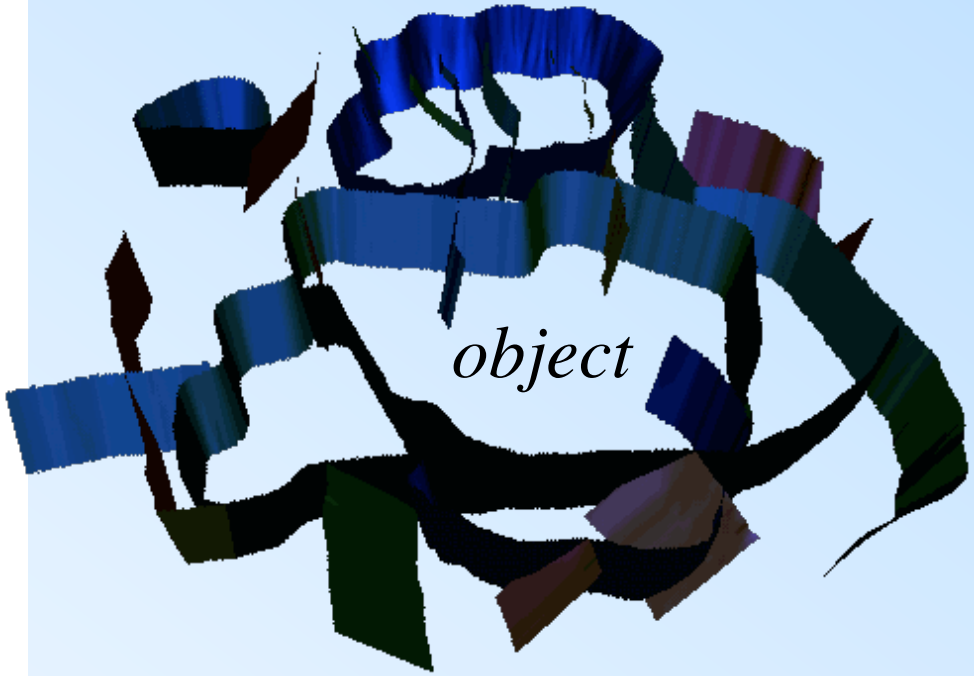
Compute intersection of *object* with *mesh*

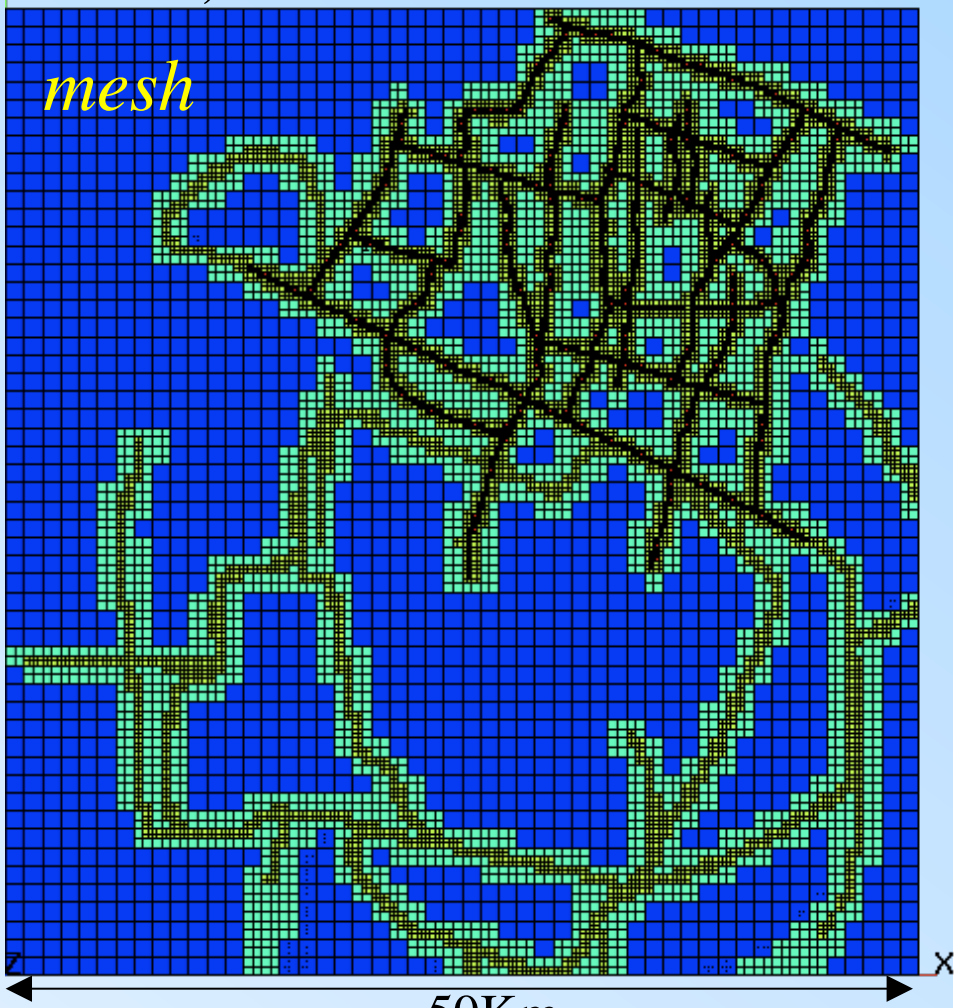


Mesh-Object Intersections: Point (injection), line (well bore), surface (fault, stratigraphic boundary), volume (tunnel, ore body, plume)

GFM Object - Computational Mesh Intersect/Refine

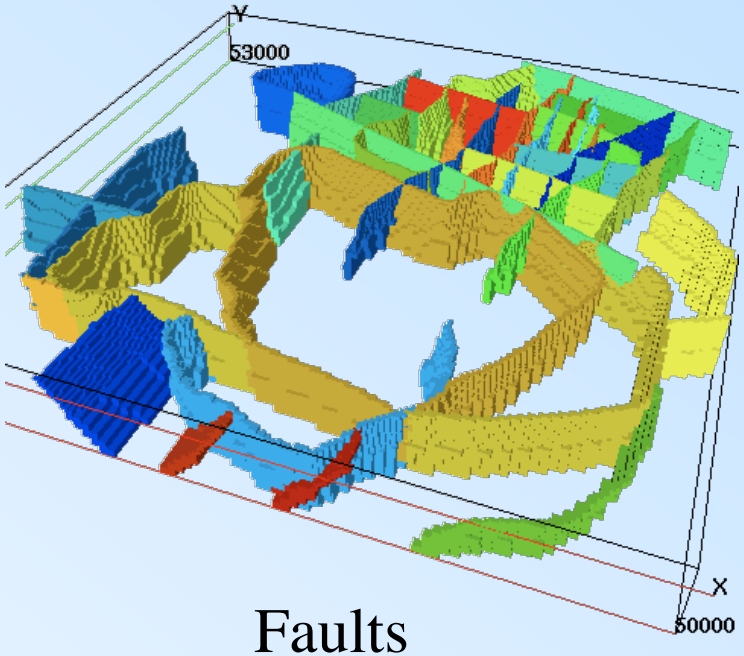
Compute intersection of *object* with *mesh*, refine mesh



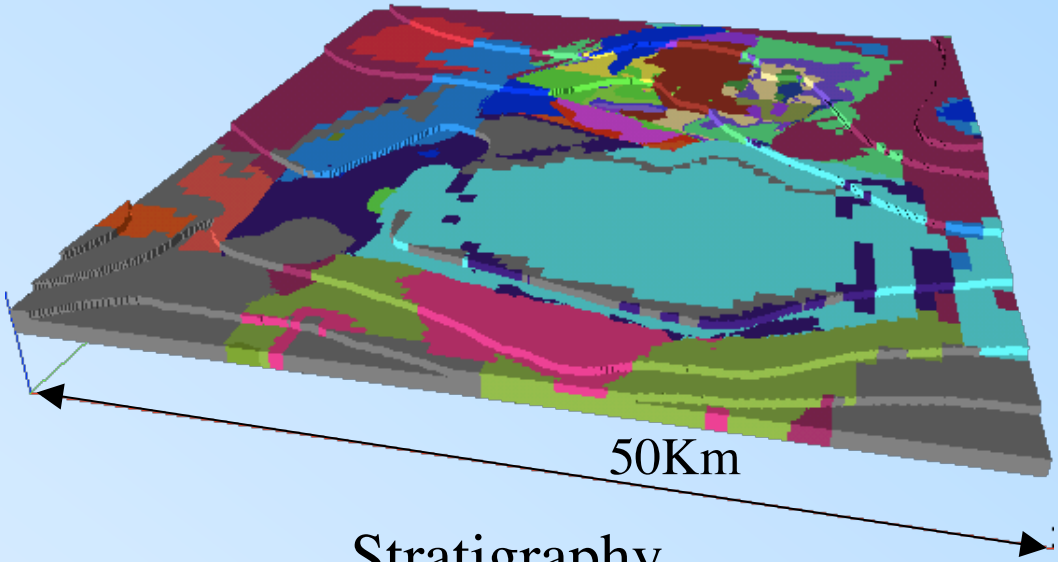


Intersect fault surfaces with mesh to select elements to be refined with quadtree type mesh refinement.

3D Octree Refined Mesh

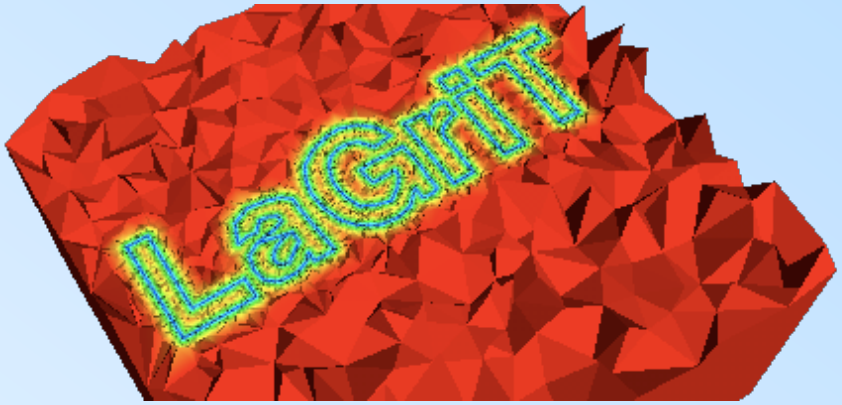


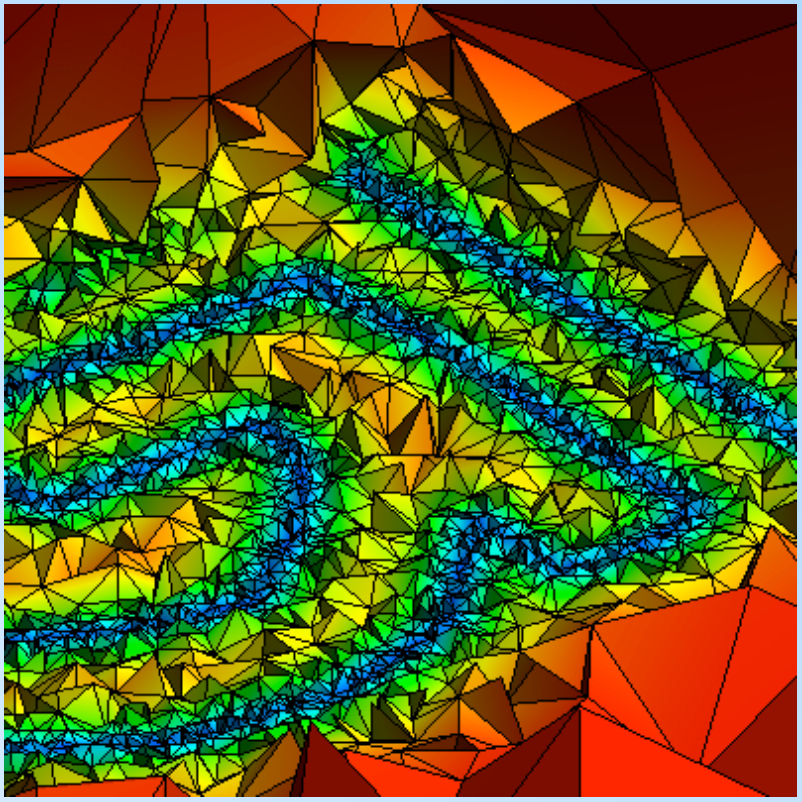
Faults



Stratigraphy

Mesh Optimization: Adaptive mesh refinement

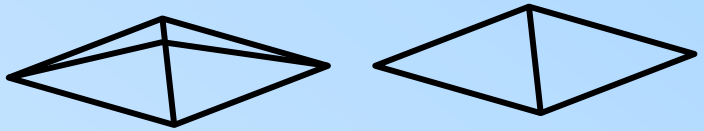


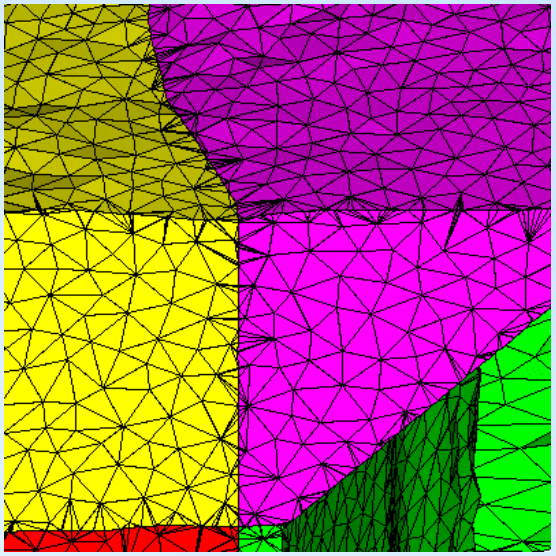


Mesh resolution depends on a field f($\underline{\mathbf{x}}$), such as distance from model feature. Requires calculation of distance field d=*dist*($\mathbf{q}$,p_i), where d denotes the minimum distance from a point q to the nearest point on object p_i.

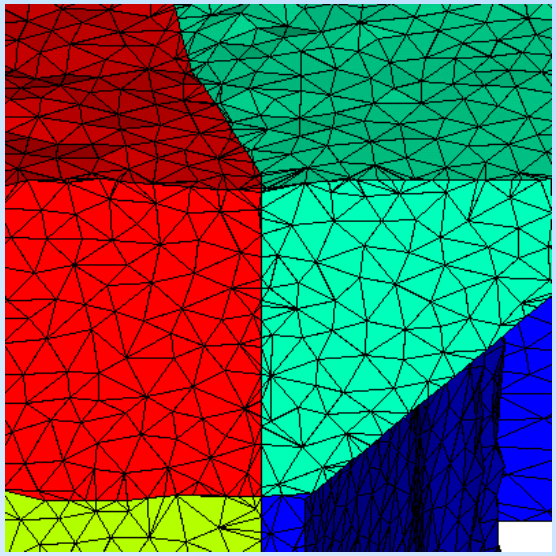
Mesh Optimization

- **Refine, Derefine, Smooth**
  - **edge length, volume, aspect**





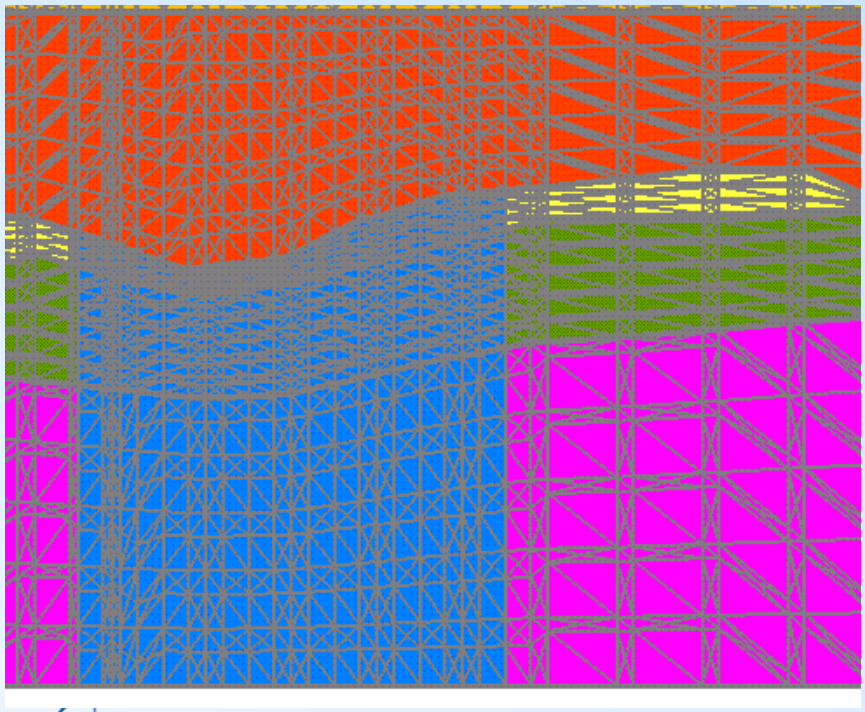
Original Elements

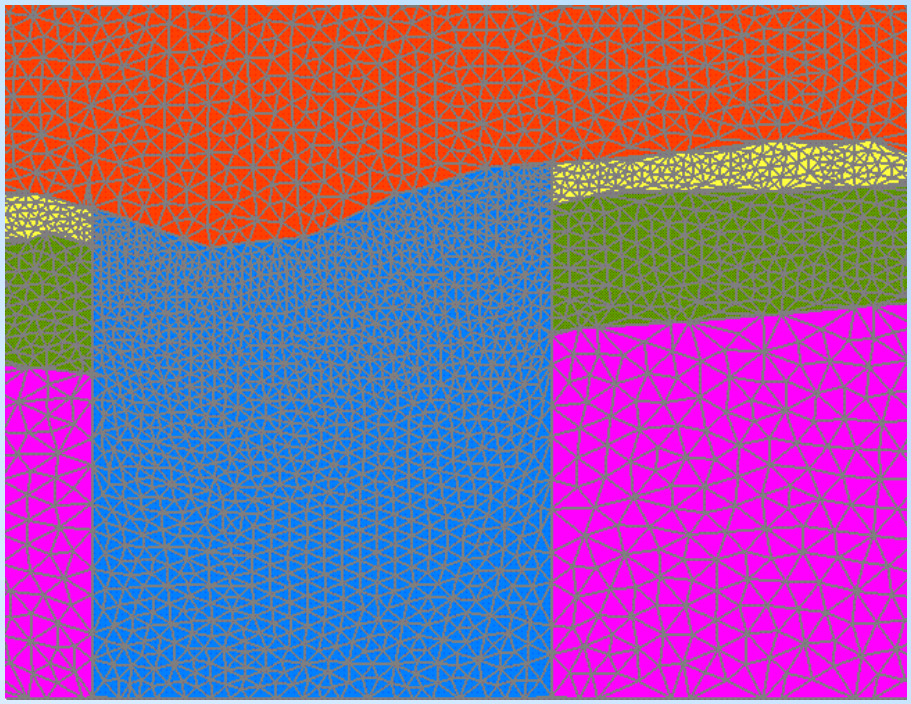


Remove small area/volume and high aspect ratio elements while maintaining geometry.

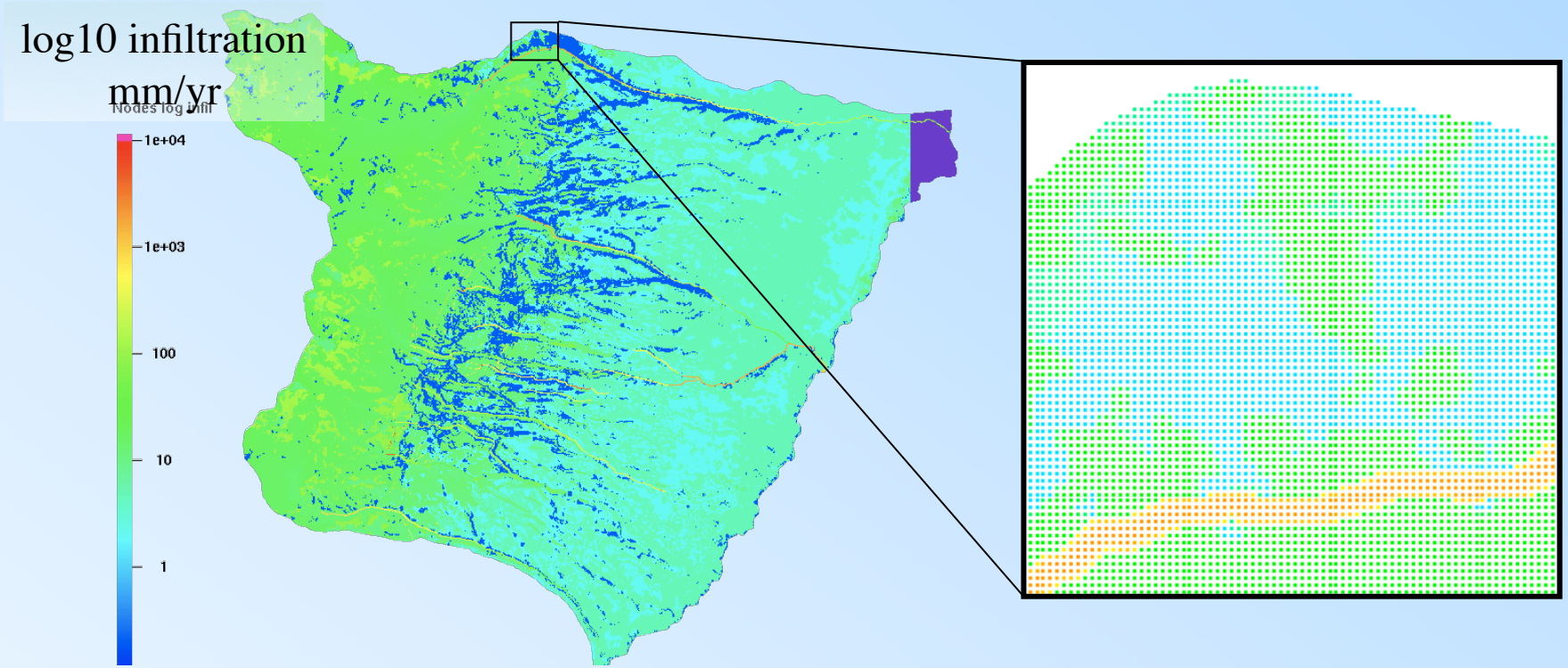
Mesh Smoothing

- **Smooth 2D and 3D**
  - **elliptic, laplace, aspect, …**



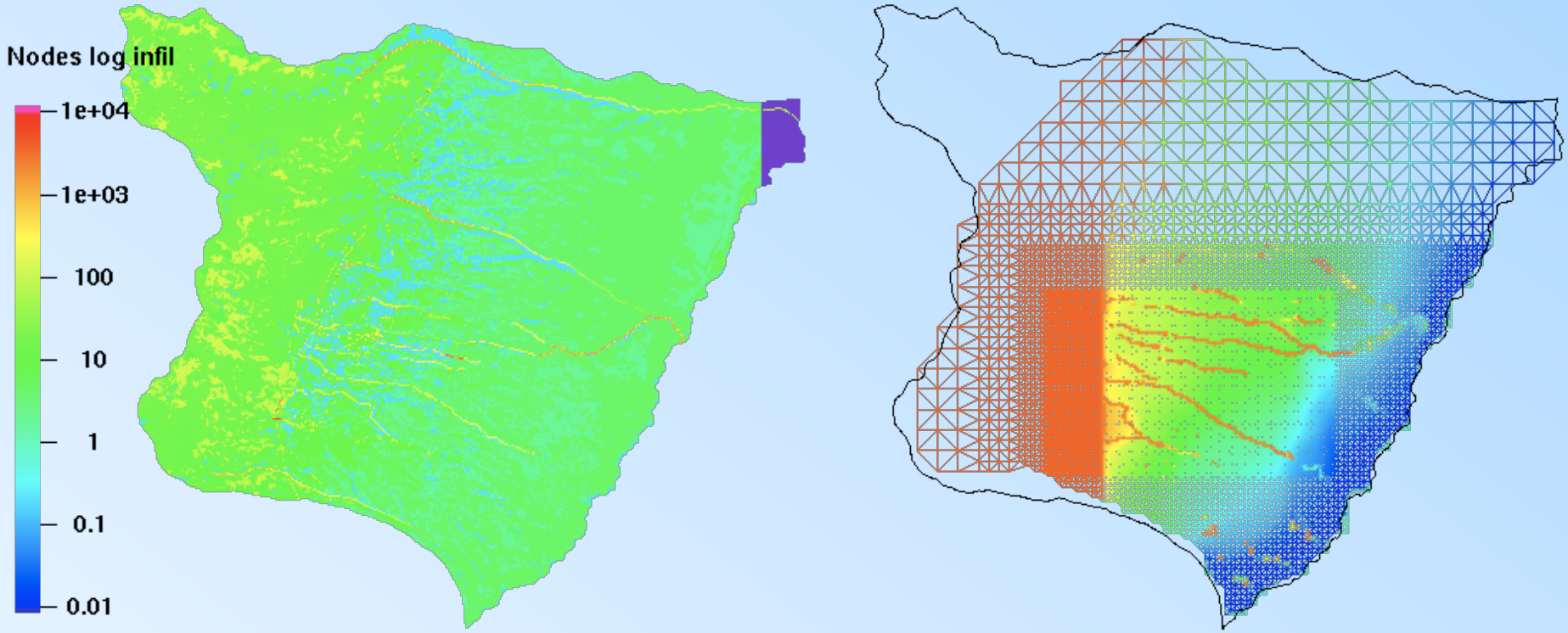


Mesh to Mesh Interpolation



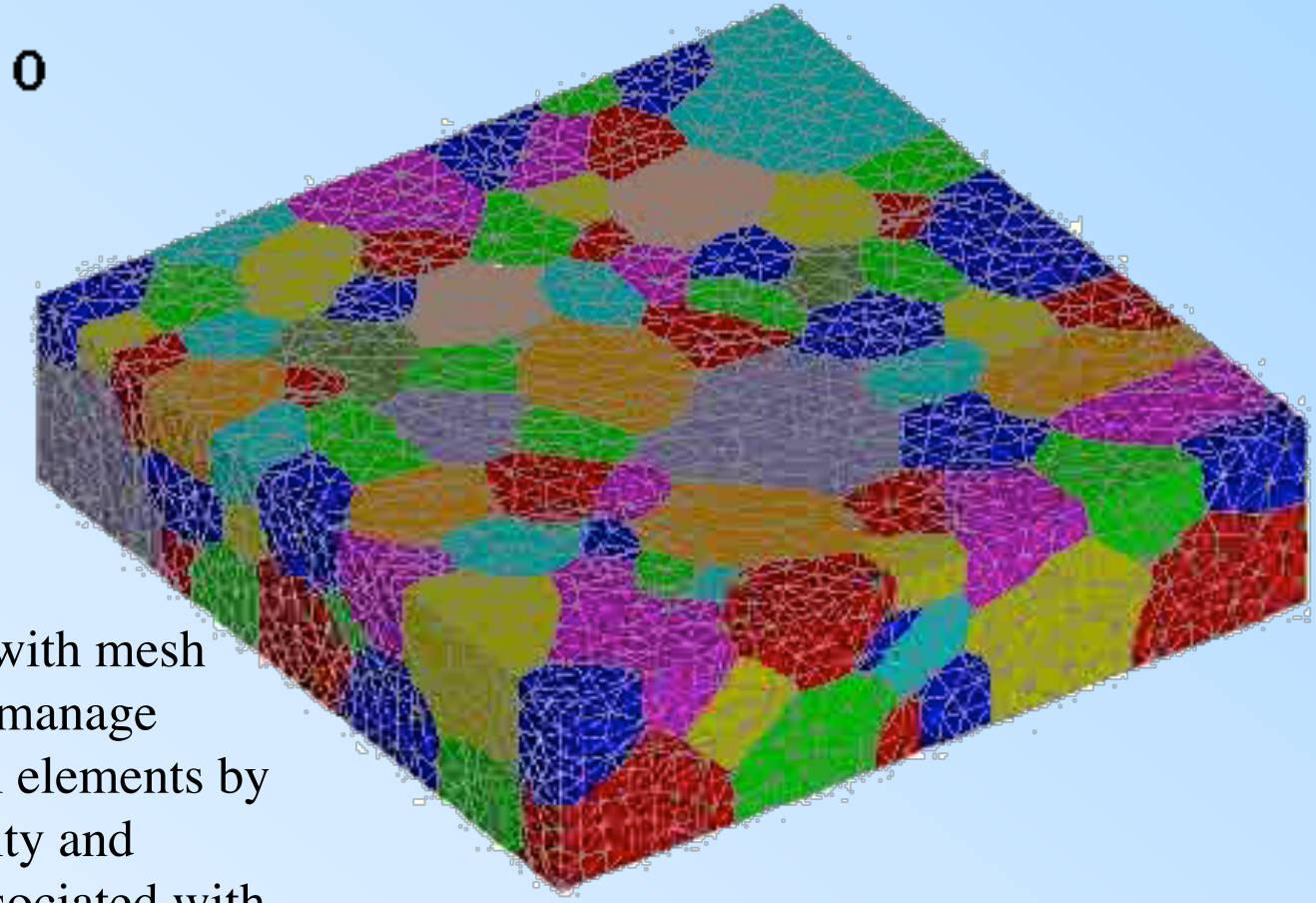
- Infiltration (mm/yr) map on regular mesh.

Mesh to Mesh Interpolation



- Infiltration boundary condition (right) based on mass conserving interpolation from a high resolution mesh to a lower resolution computational mesh for flow model.

Moving Finite Element Simulation of Thermally Driven Grain Growth

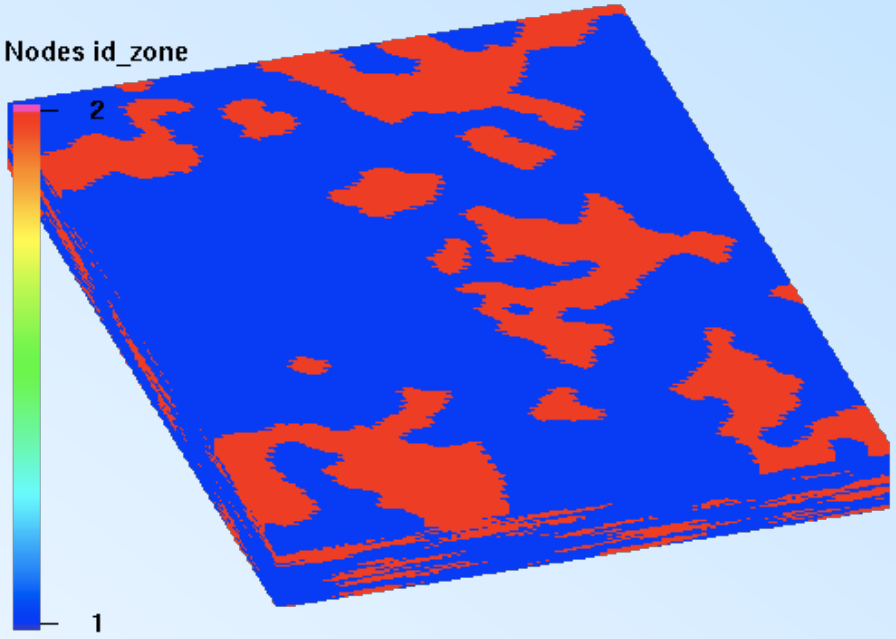


Physics code interacts with mesh generation software to manage evolution of tetrahedral elements by maintaining mesh quality and topological changes associated with elimination of grains.

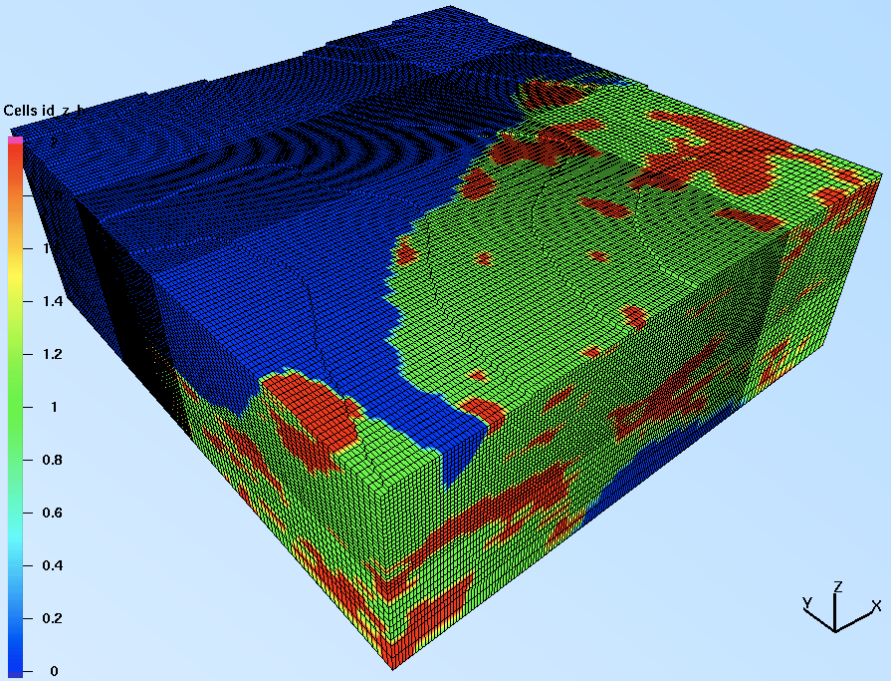
Calculation by Andrew Kuprat

Model Setup

•Interpolate scalar quantity (head, concentration, geostatistical property distribution) from one mesh to another



Source



Sink

LaGriT

- No GUI
- 3 Ways to Run LaGriT
  - Command line:
```
read / gmv / points.gmv / mo1
connect
dump / gmv / tets.gmv / mo1
```
  - Command File: `lagrit < input.lgi`
  - Call from C or Fortran Code:
```
string = 'read / gmv / points.gmv / mo1'
call dotask(string,error_flag)
```

LaGriT

Mesh Object: A data structure that contains geometry, topology and attributes

- Node geometry, x, y, z
- Mesh topology, connectivity of line, tri, quad, prism, pyramid, tet, hex elements
- Attributes (pressure, temperature, color): integer or real quantities on nodes or elements
- Point sets
- Element sets
- Neighbor Information
- Other book keeping…

LaGriT allows you to have many mesh objects simultaneously

LaGriT

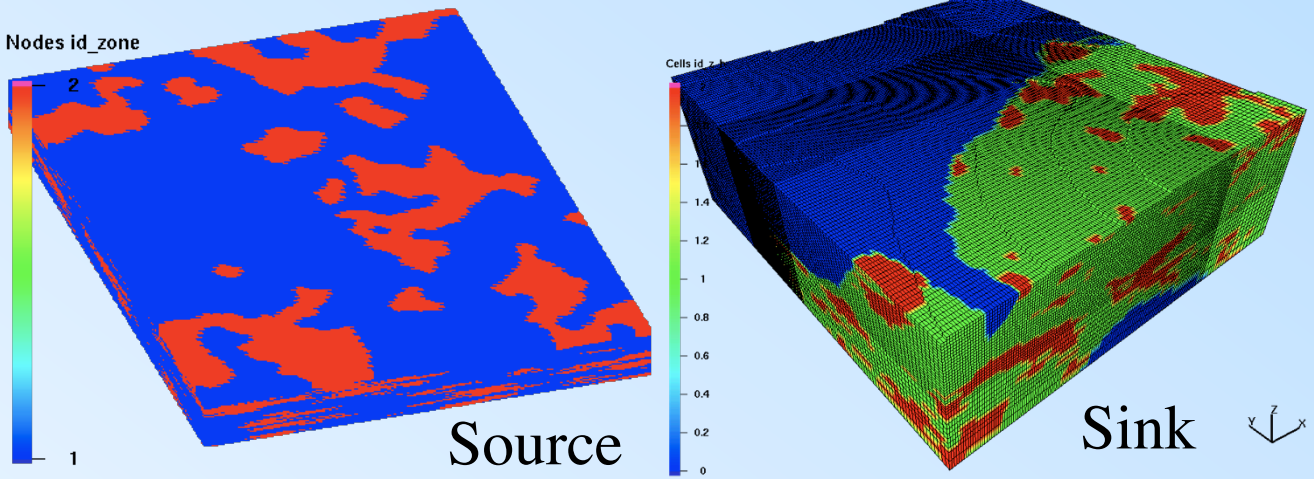
Command Line Syntax (http://lagrit.lanl.gov/docs/conventions.html)

- Lines are a maximum of 80 characters long
- Continuation lines are signaled by an "&" as the last character of a line to be continued. A command can be up to 1024 characters long.
- Delimiters are comma, slash, equal sign, or blank. (',' '/' '=" ').
- Commands should be typed in lower case, however names are case sensitive.
- To separate commands on the same line use a semicolon (;).
- Three coordinate systems are used, xyz, rtz, rtp.

Model Setup

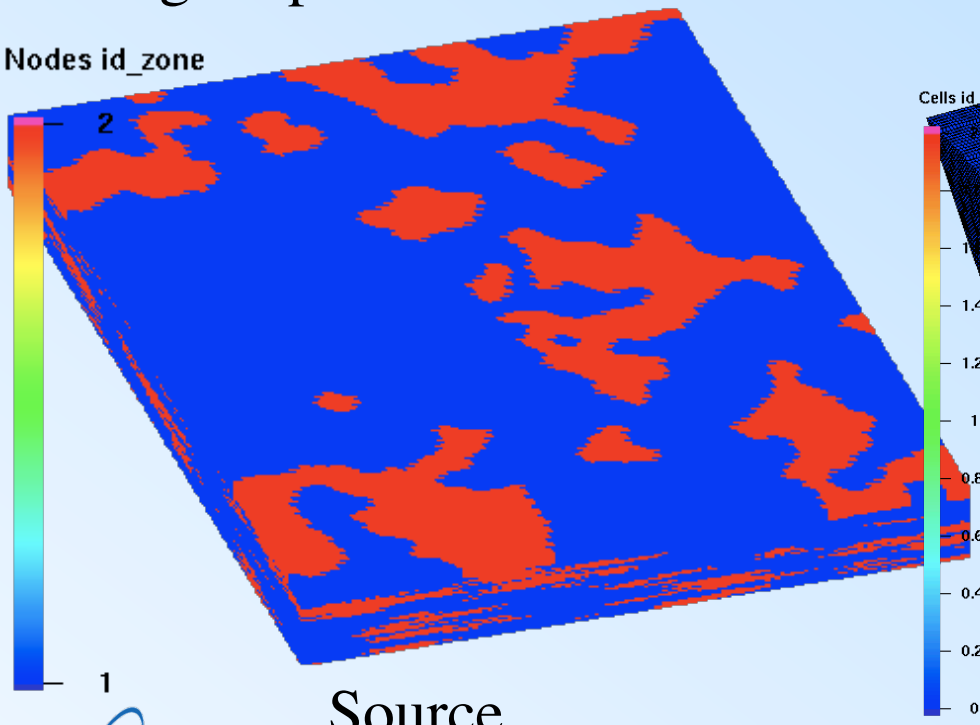
- Interpolate scalar quantity (head, concentration, geostatistical property distribution) from one mesh to another

```
cmo/readatt/source_mesh / xic yic zic id_zone id_elem /1,0,0 / file1
read / gmv / file2 / sink_mesh
pset /pinterp1/ attribute / imt / 1 0 0 / 10 / eq
interpolate / voronoi / sink_mesh / id_z_a / pset get pinterp1 /
source_mesh / id_zone
pset / pa_1 / attribute / id_z_a / 1 0 0 / 1 / eq
pset / pa_2 / attribute / id_z_a / 1 0 0 / 2 / eq
pset / pa_1 / zonn / outfile1.zonn / ascii
pset / pa_2 / zonn / outfile2.zonn / ascii
```

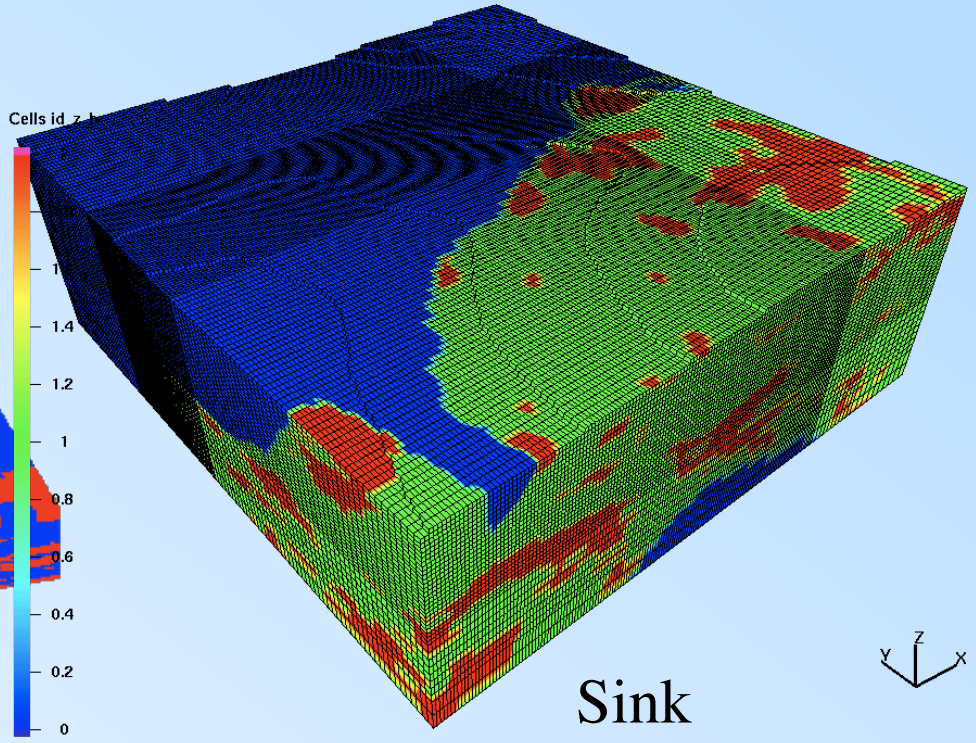


Model Setup

- Interpolate scalar quantity (head, concentration, geostatistical property distribution) from one mesh to another
- Accelerated implementation using a kd-tree search resulting in NlogM speed



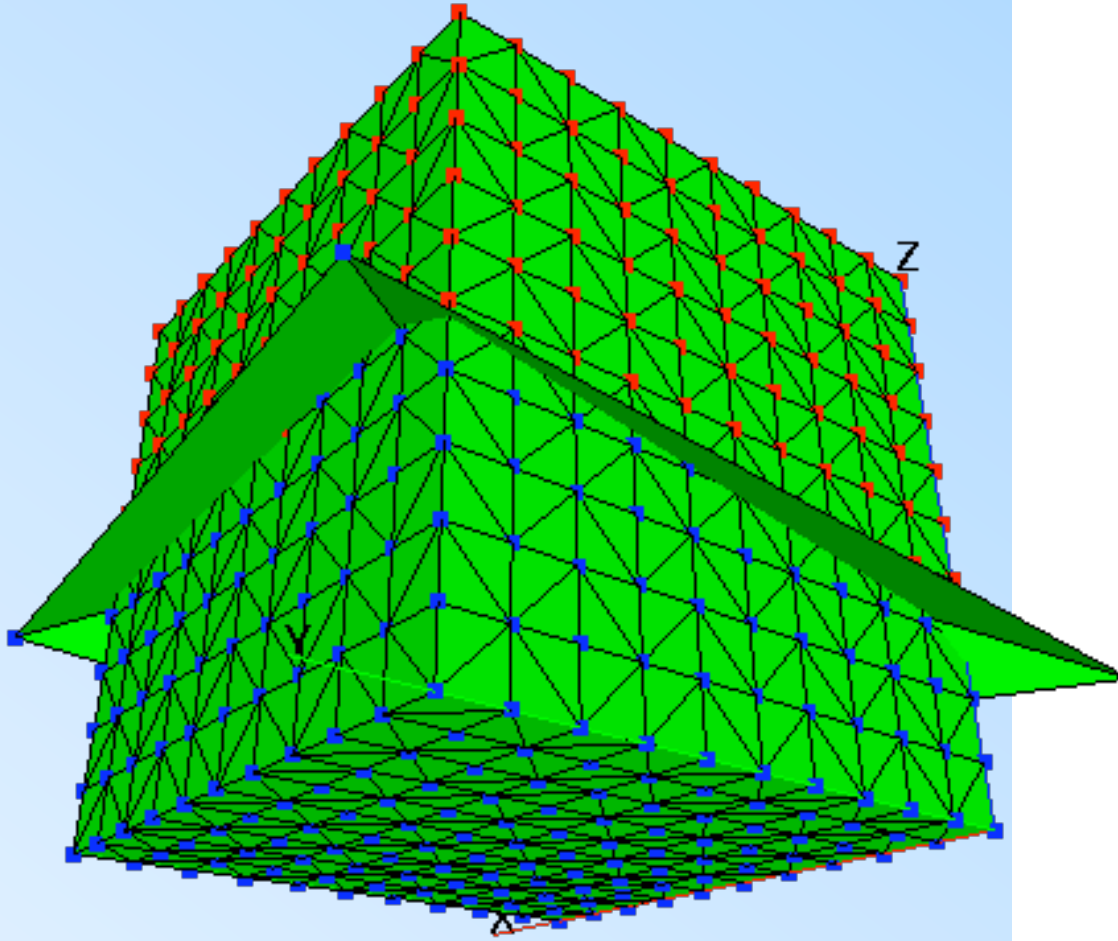
Source



Sink

Model Setup

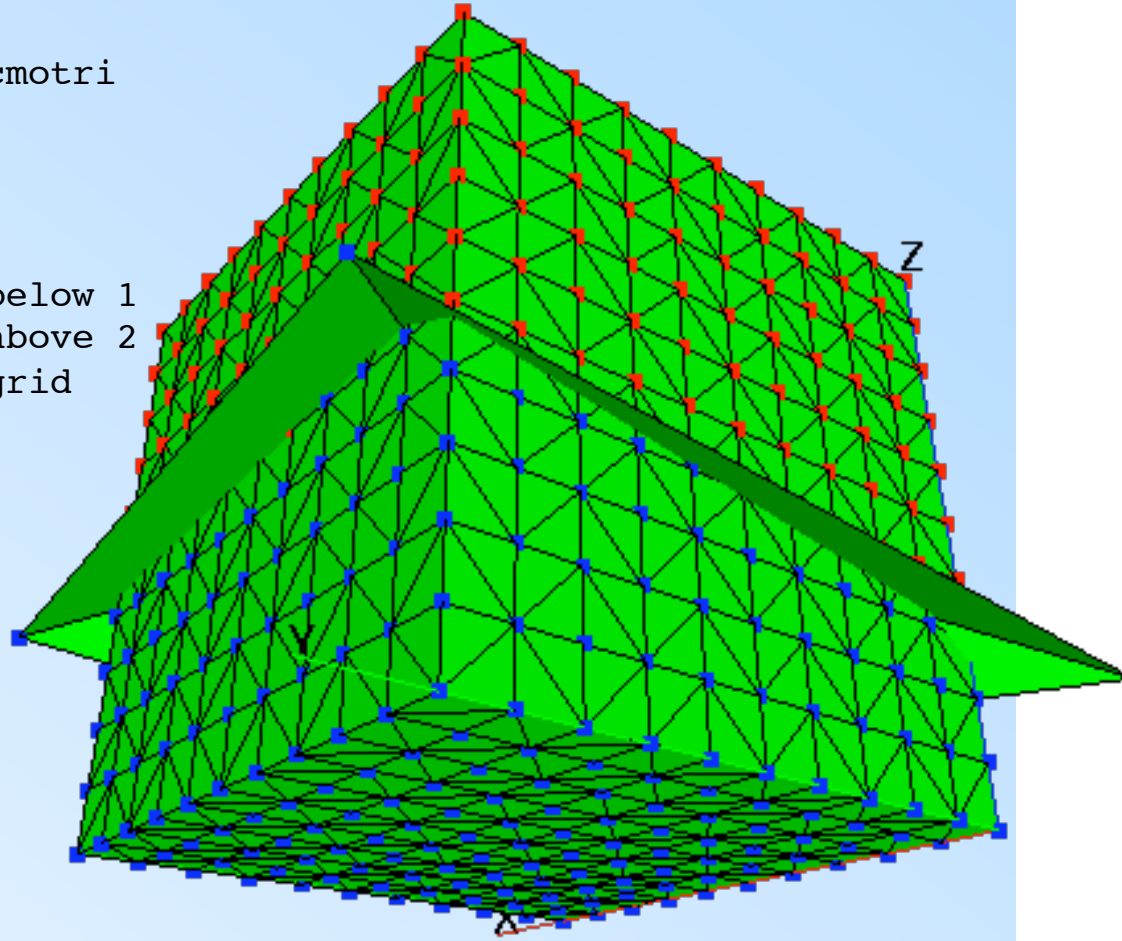
- Identify nodes above/below a surface (water table)



Model Setup

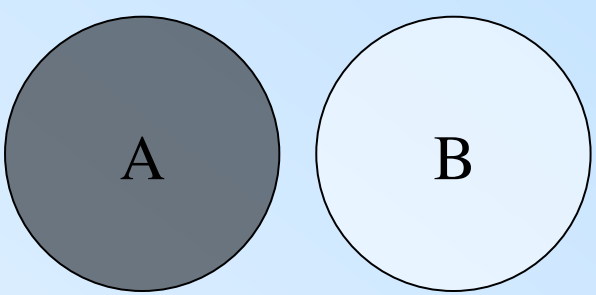
- Identify nodes above/below a surface (water table)

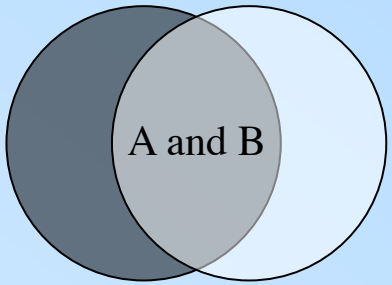
```
read / avs / WT_FILE / cmo_surf
read / avs / GRID_FILE / cmo_grid
surface / swt / reflect / sheet / cmotri
region / rwt / le swt
pset / pbelow / region rwt / 1 0 0
pset / pall / seq / 1 0 0
pset / pabove / not pall pbelow
cmo setatt cmo_grid imt pset get pbelow 1
cmo setatt cmo_grid imt pset get pabove 2
dump / zone_imt / ZONE_FILE / cmo_grid
```

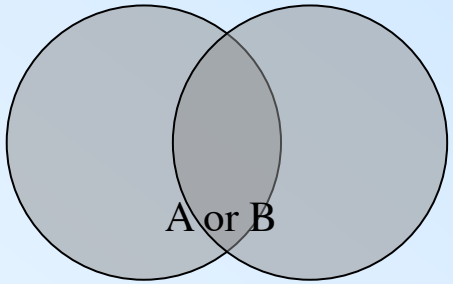


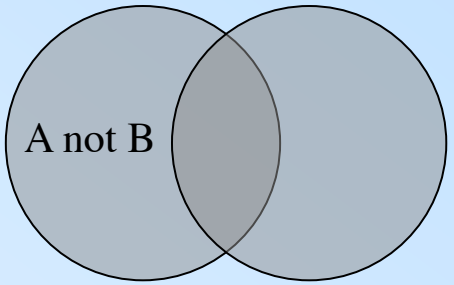
Model Setup

- Boolean operations on point sets (zone files)



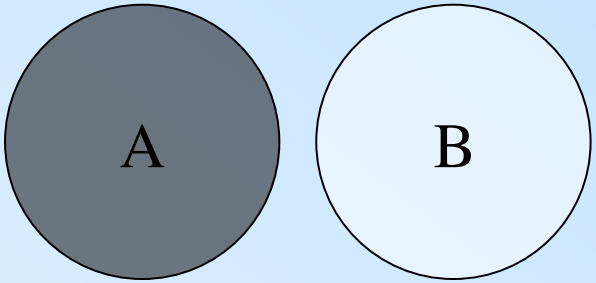




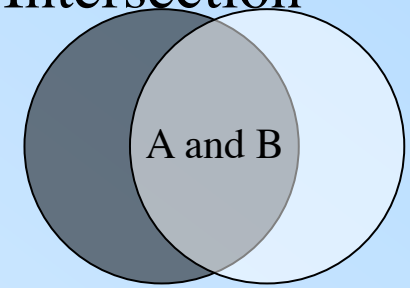


Model Setup

- Boolean operations on point sets (zone files)

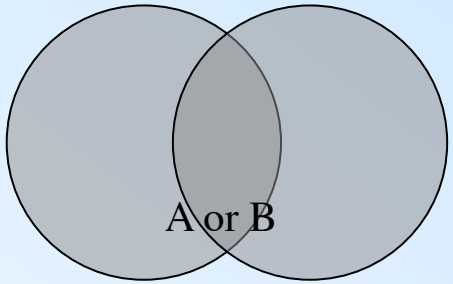


Intersection



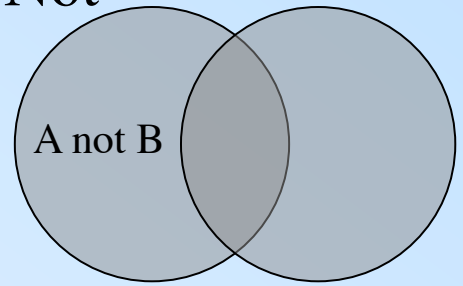

```
pset / p2 / inter / pa pb
```

Union




```
pset / p3 / union / pa pb
```

Not




```
pset / p4 / not pa pb
```

Model Setup

- Boolean operations on point sets (zone files)
- For Example:
  - Nodes that belong to material_4 and are below the water table and are within 5 km of fault_5
  - Nodes within 1 km of the topographic surface that are not within 1 km of a fault and are on the external boundary of the model

Meshing and Set Up Workflow

Problems and Challenges

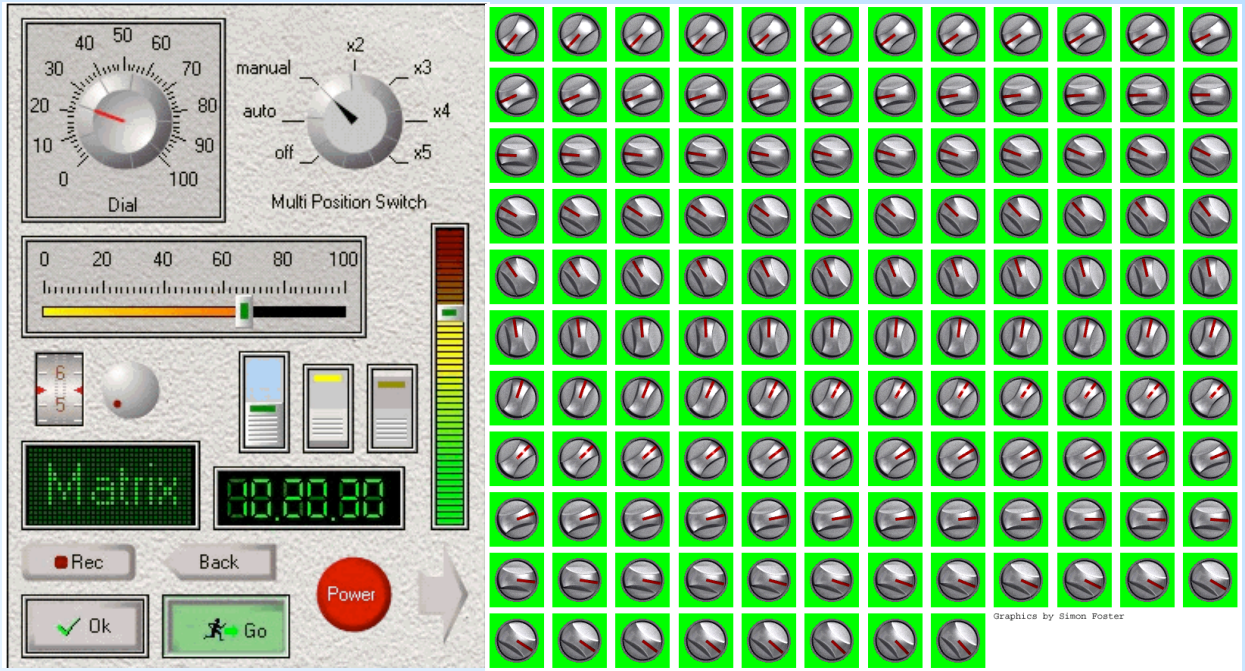
- Automated (but not automatic)

What users want.

Meshing and Set Up Workflow

Problems and Challenges

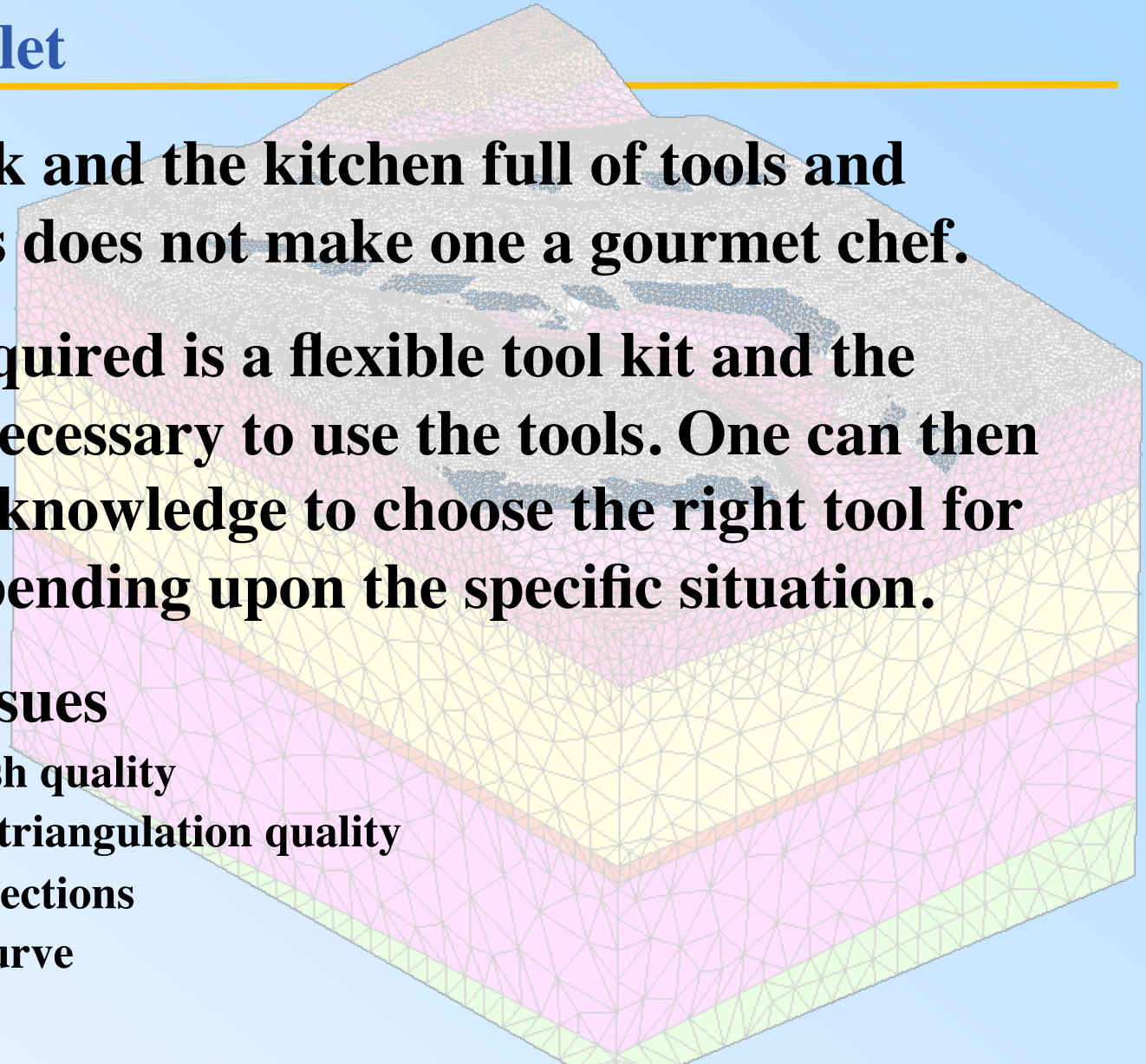
- Automated (but not automatic)



What users get.

No Silver Bullet

- **A cookbook and the kitchen full of tools and ingredients does not make one a gourmet chef.**
- **What is required is a flexible tool kit and the expertise necessary to use the tools. One can then use expert knowledge to choose the right tool for the job depending upon the specific situation.**
- **Ongoing issues**
  - **Output mesh quality**
  - **Input fault triangulation quality**
  - **Fault intersections**
  - **Learning curve**



Acknowledgements

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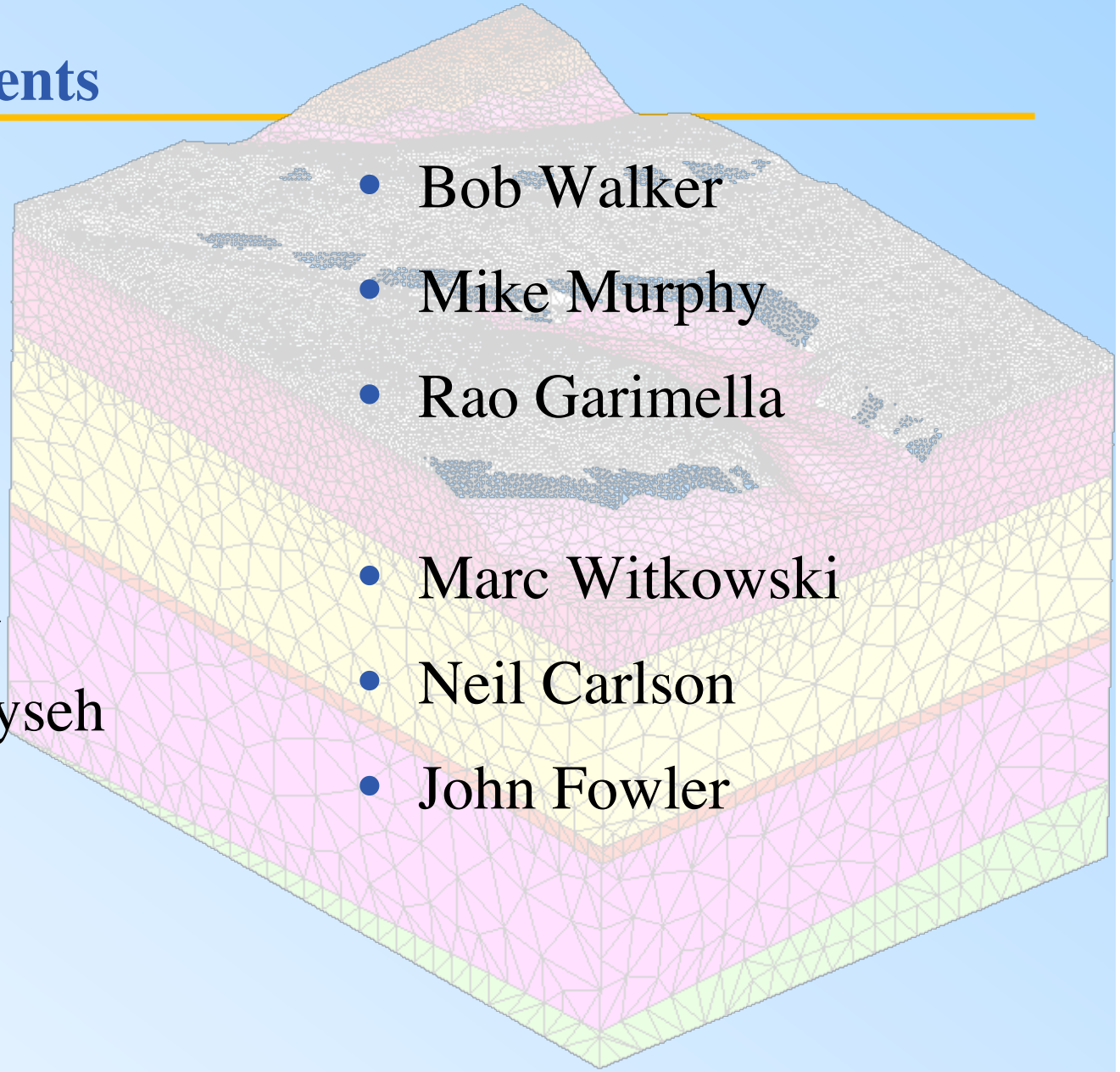
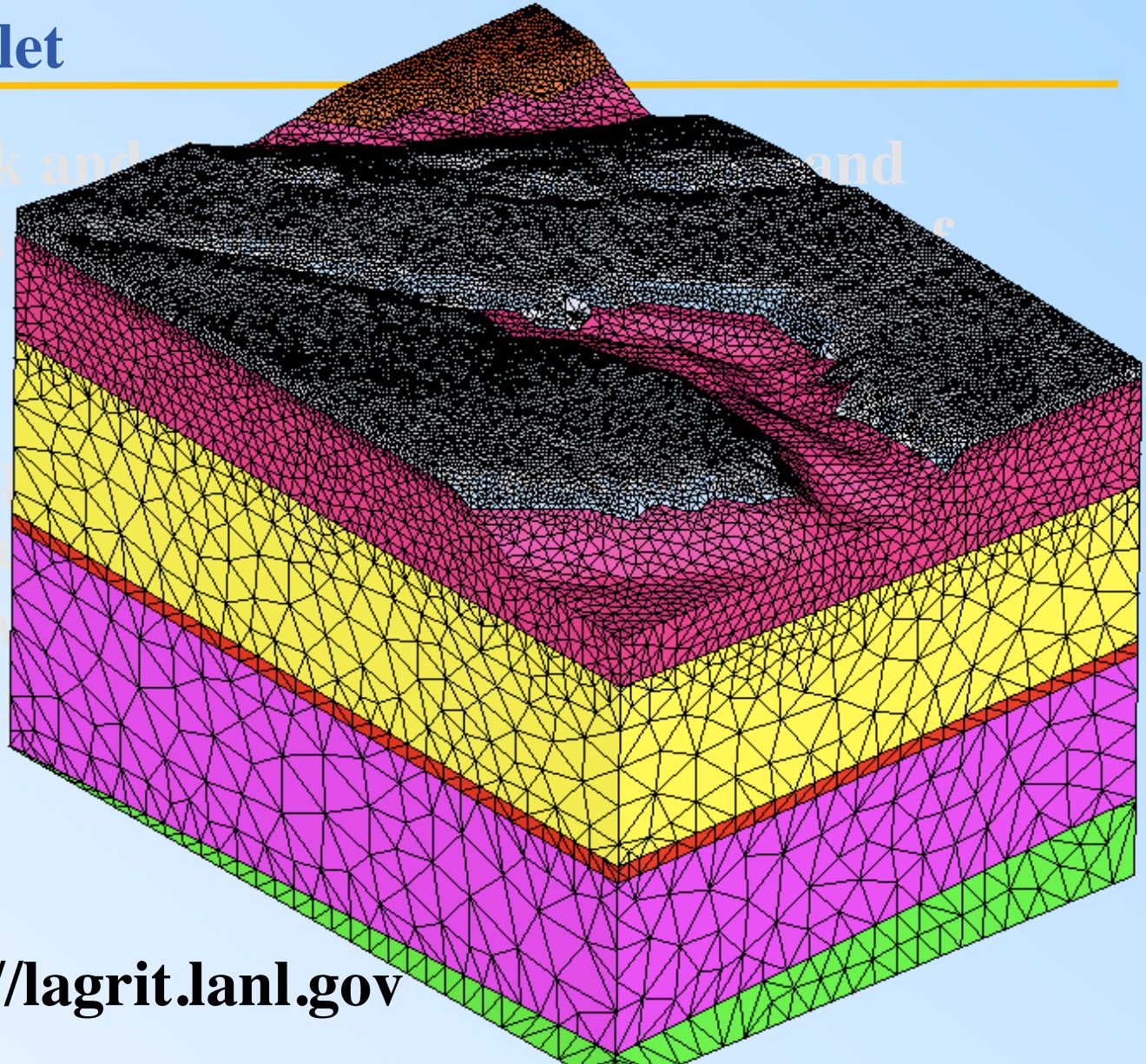
- Bob Walker
- Mike Murphy
- Rao Garimella
- Marc Witkowski
- Neil Carlson
- John Fowler



No Silver Bullet

- A cookbook and [illegible] and ingredients [illegible]
- What is req[illegible] expertise ne[illegible] expert know[illegible] job depend[illegible]



LaGriT – http://lagrit.lanl.gov

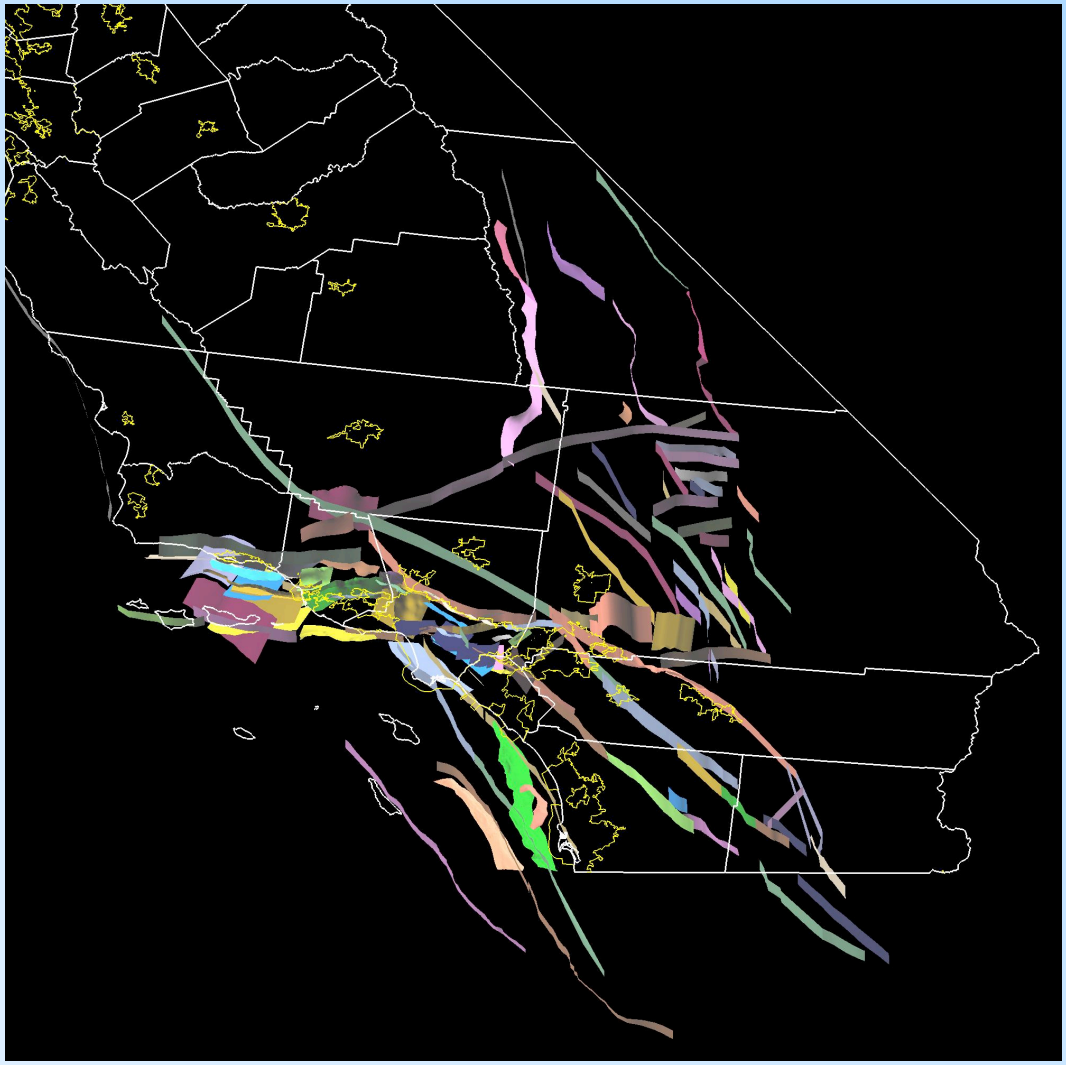
Los Alamos NATIONAL LABORATORY EST. 1943

http://lagrit.lanl.gov http://meshing.lanl.gov/proj

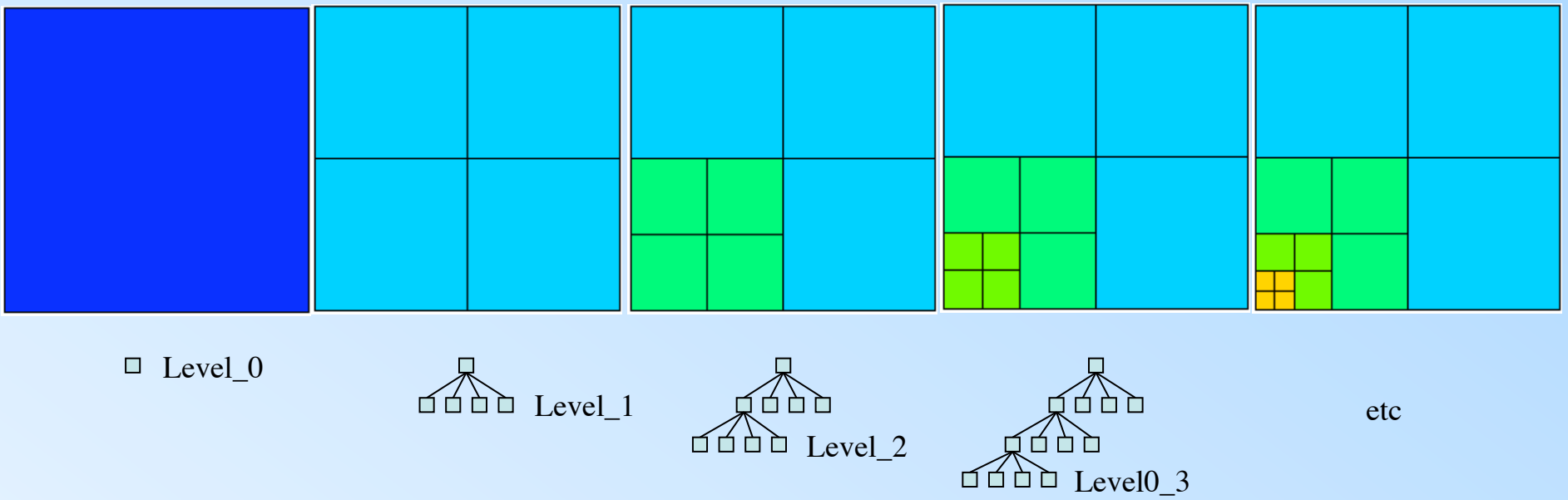
NNSA

Meshing Non-manifold geometry

- Southern California Earthquake Center (SCEC) fault model for southern California
- 145 Faults defined by triangulated surfaces
- Surfaces have well defined normal (above and below surface) but since topology is not defined by closed volumes, a question such as, “Given an arbitrary location x,y,z, what material am I in?”, is ill defined.



What is a 2D QUADTREE, 3D OCTREE mesh?



- Tree data structure, each branch has 4 leaves
- Balance tree = level n has neighbors of level n-1, n, n+1
- Octree is the 3D extension