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SAND2010-0028C

Visualization of Complex, Real-World Fault and Fracture Geometry

Workshop on Ground Shock in Faulted Media

January 11-15, 2010

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Purpose of This Presentation

- We were asked to develop a few models of some faults and fractures “out there in the *“real world”*
  - This is partially in response to concerns by some folks that (necessary) downstream modeling approximations are ‘way too simplistic:
    - “smoothly” planar features
    - “infinite” extent

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- However: *caricatures are usually quite recognizable* – particularly if done well.

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- The idea is to illustrate real-world complexity on a scale from centimeters to kilometers, with major emphasis on the "meter scale" (1-10s m)

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  - *The upshot is that we see the same types of fault and fracture geometries on multiple scales and in many different environments*

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  - **Sagamore vein**
  - **Paymaster vein**

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  - **information drawn from both surface and underground workings, emphasizing multiple systems of faults and fractures**

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- **Miscellaneous**

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- ***The ESF provides an exceptional three-dimensional data set for visualization and quantitative study***

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The ESF Data Set

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  - Essentially, this "unrolls" the cylindrical tunnel form onto a flat sheet of paper
- These maps show "all fractures" that are greater than 1-m in length, or which were judged to have significant structural implications
  - Faults
  - Fractures
  - Fracture zones (breccia)

Available Data

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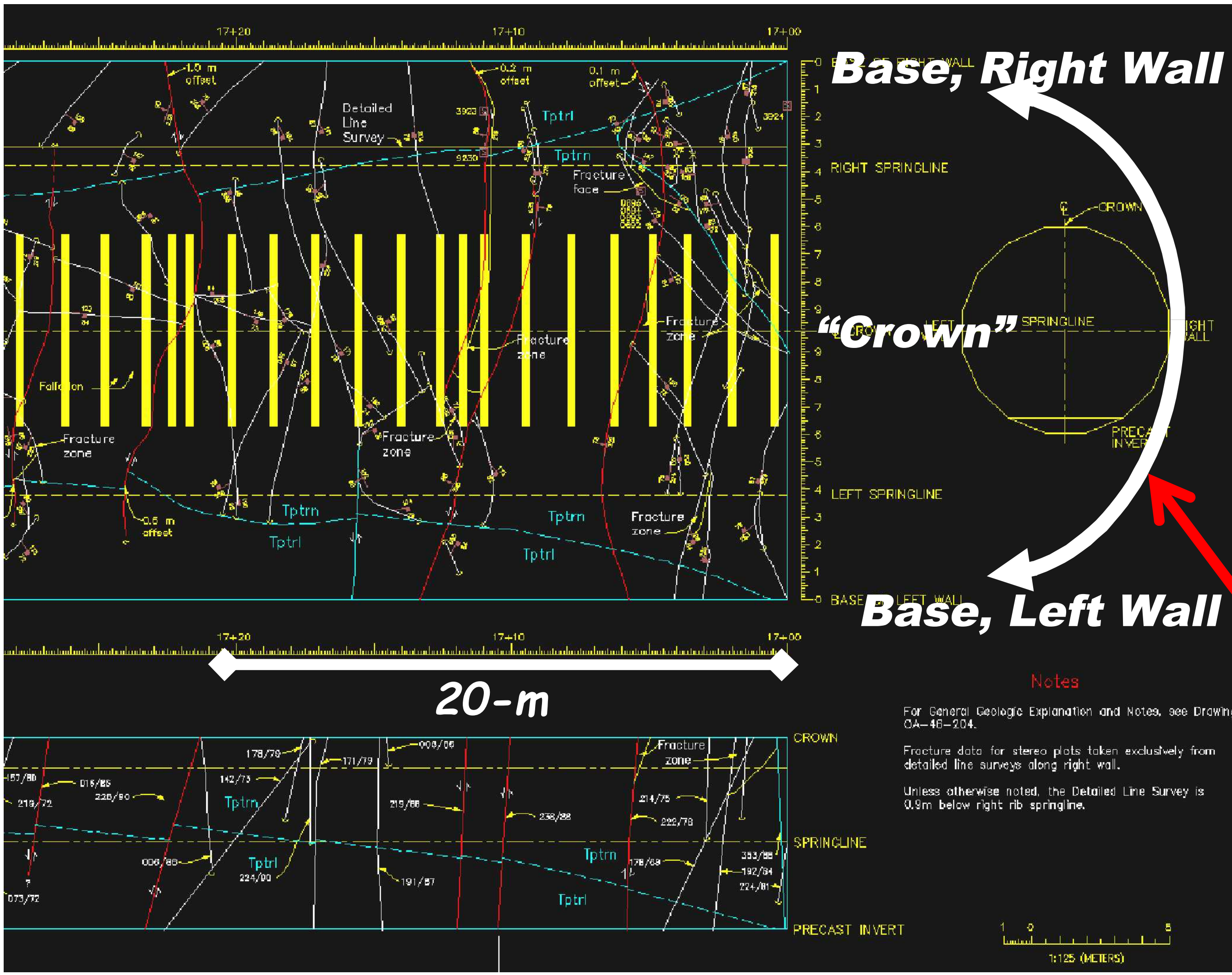
  - Attributes of feature surface were recorded
    - (there are many Excel files available with these fracture data)

ESF Full-Periphery Map



Example of detailed geologic mapping of the ESF:

The tunnel is "unrolled" from the bottom and presented as a flat map

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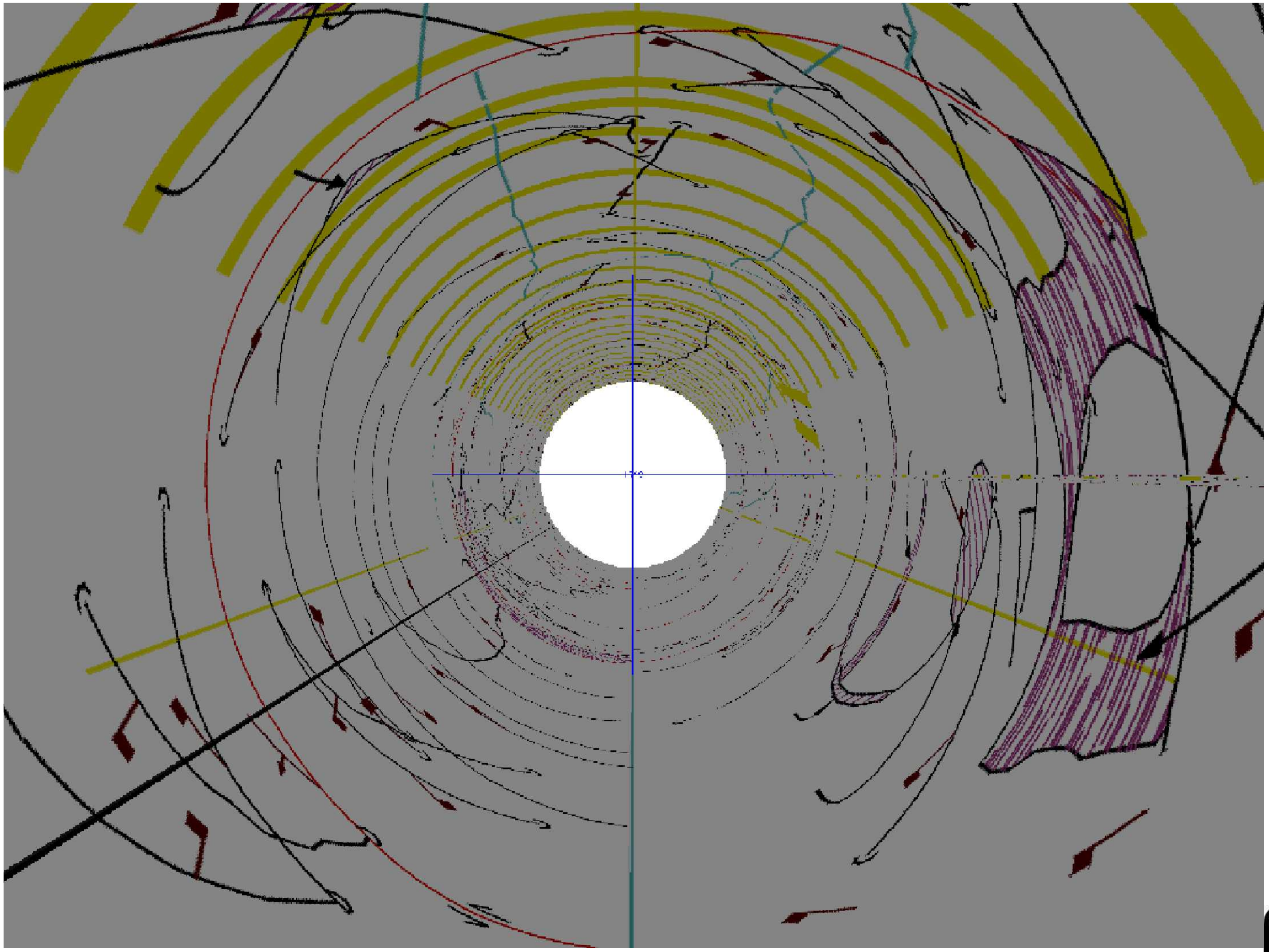
Key to Mapping in the Visualization



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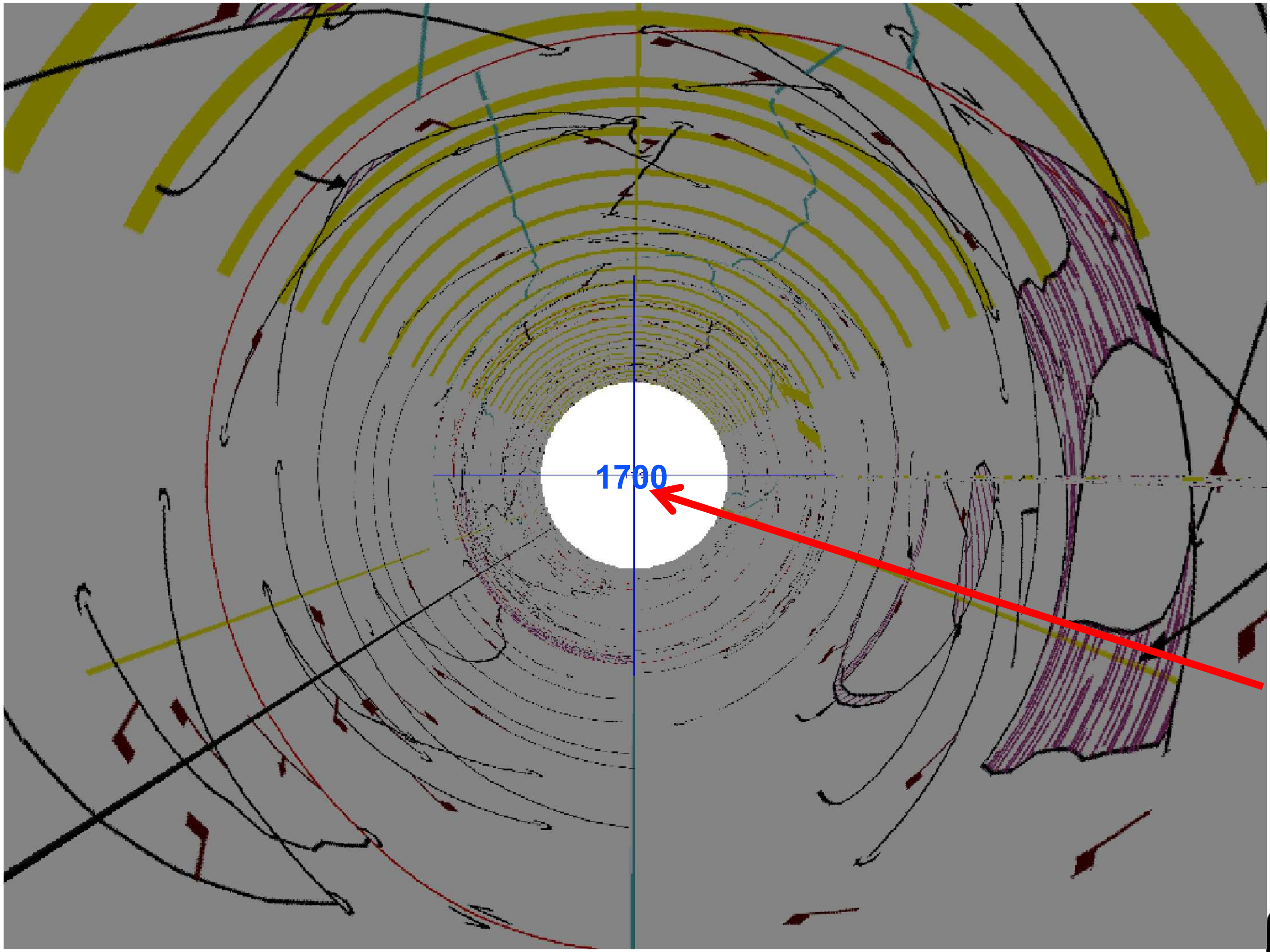
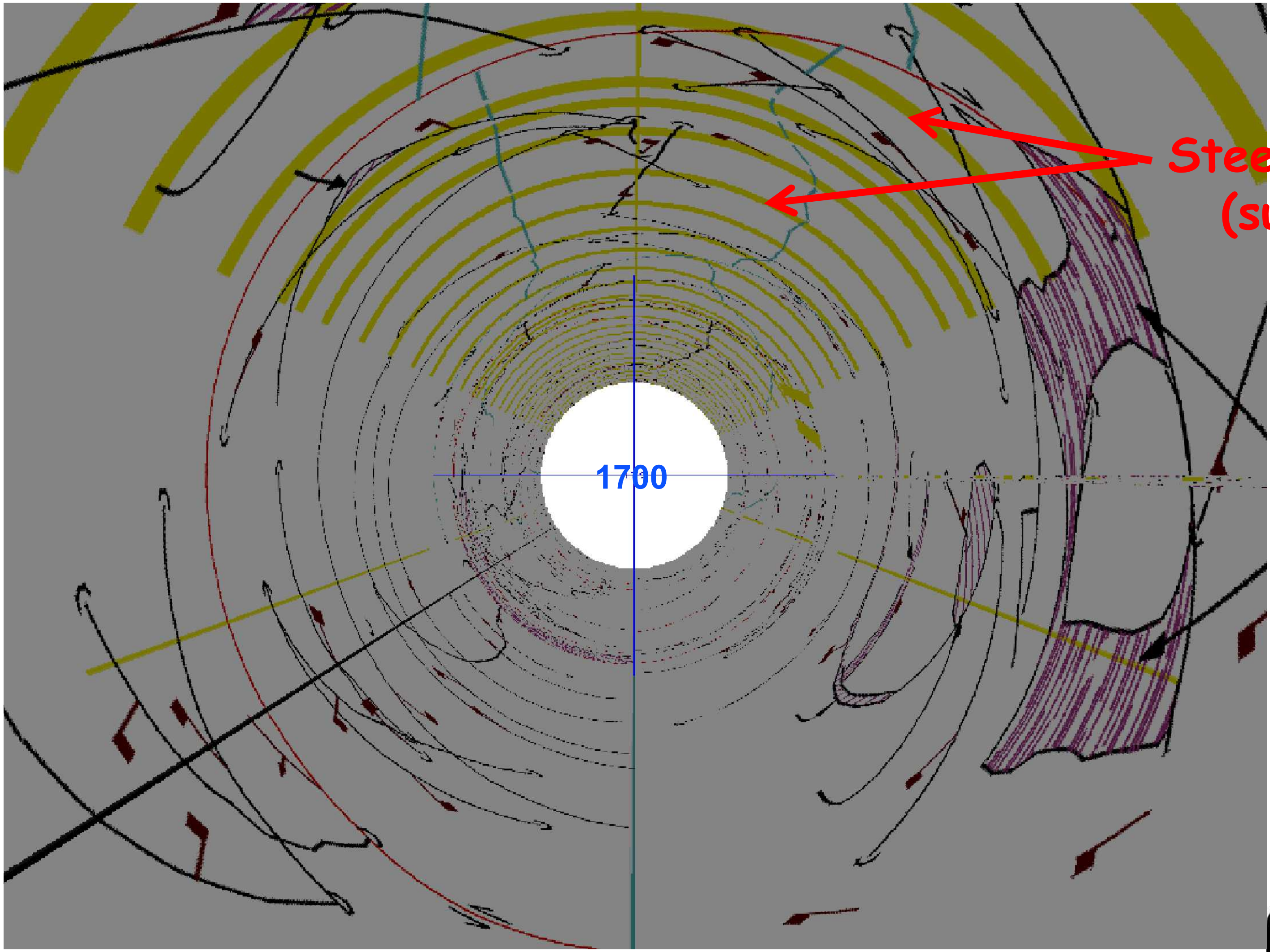


Distance Marker (meters)

Key to Mapping in the Visualization



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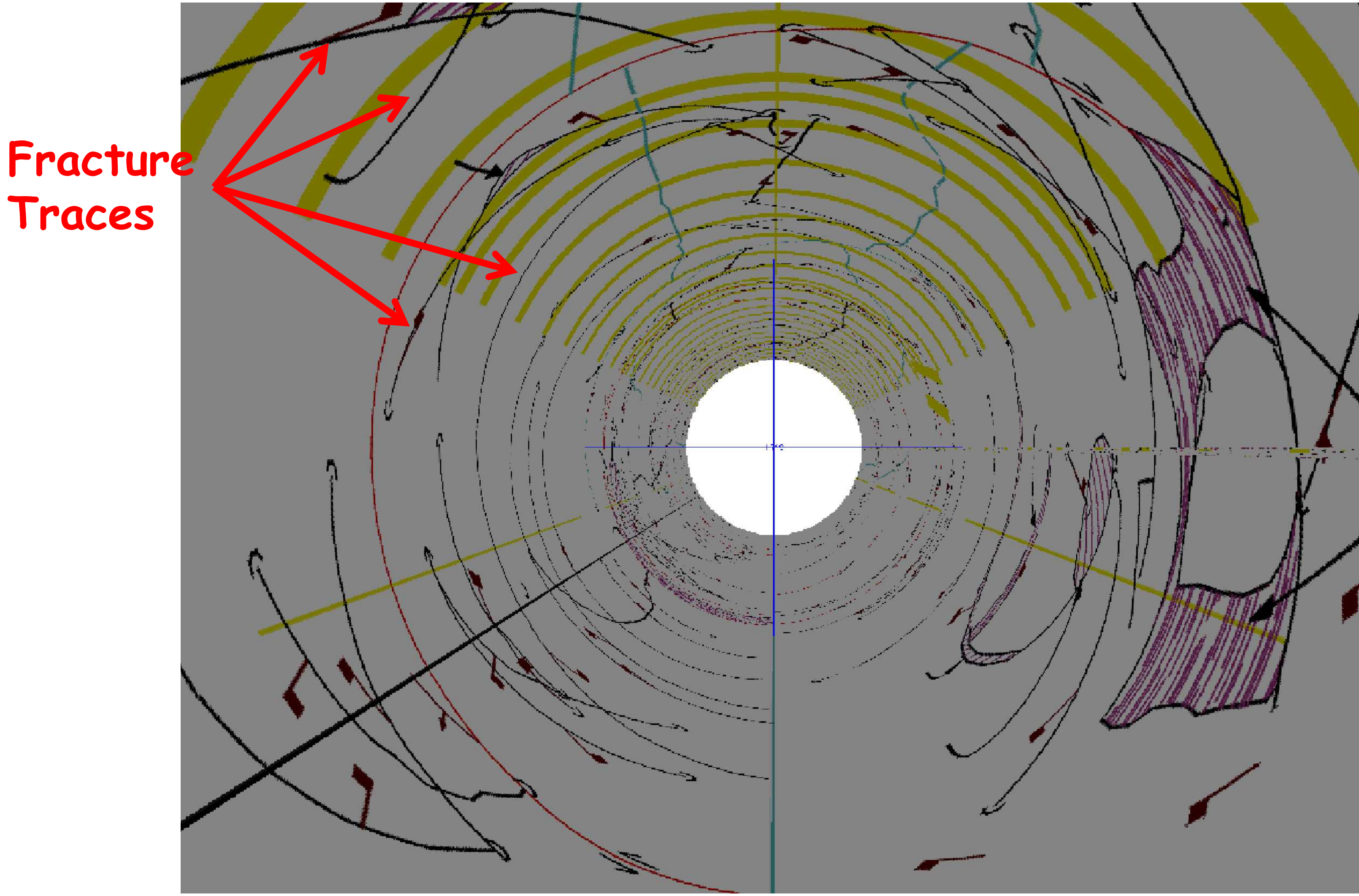

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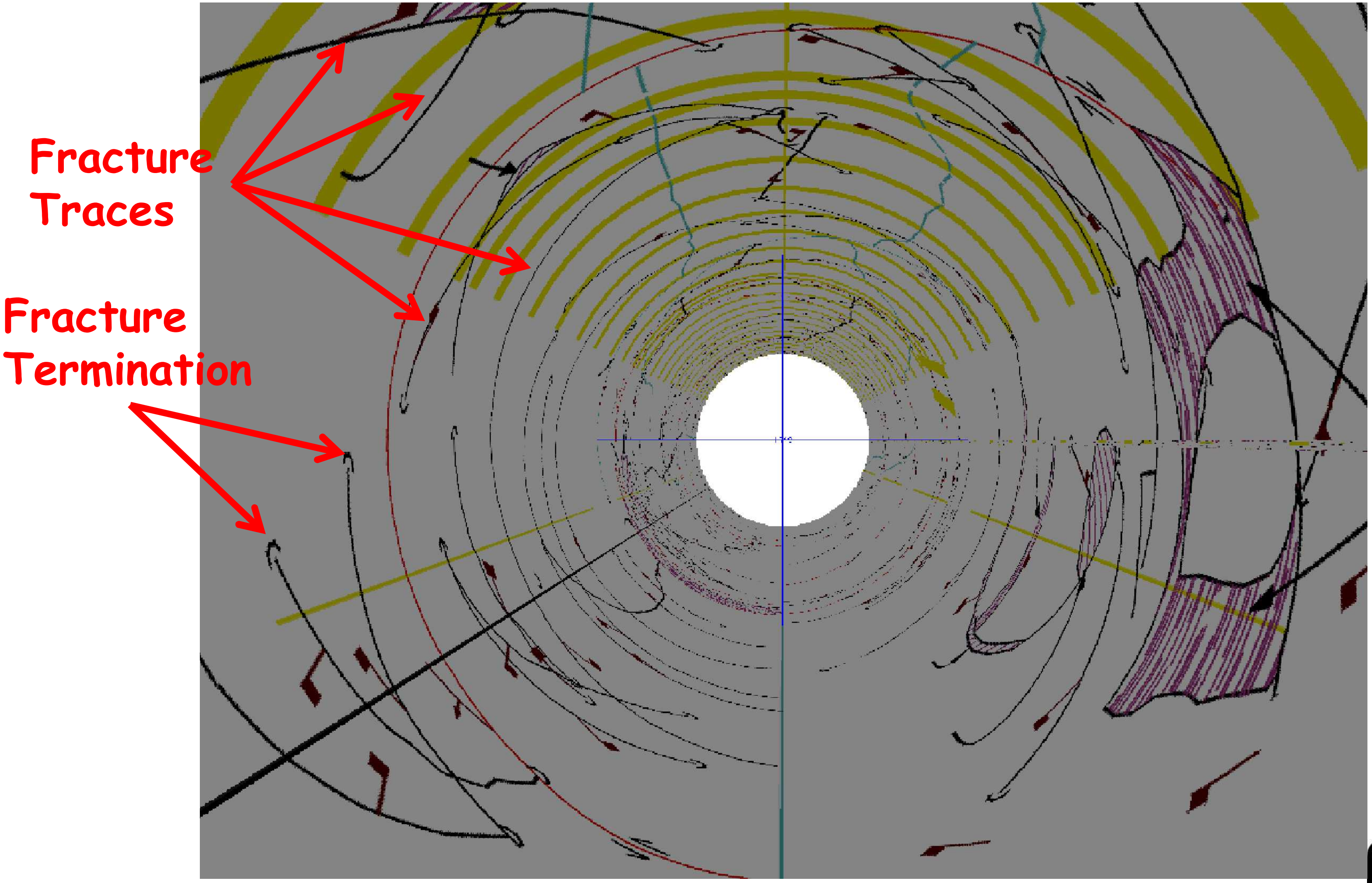

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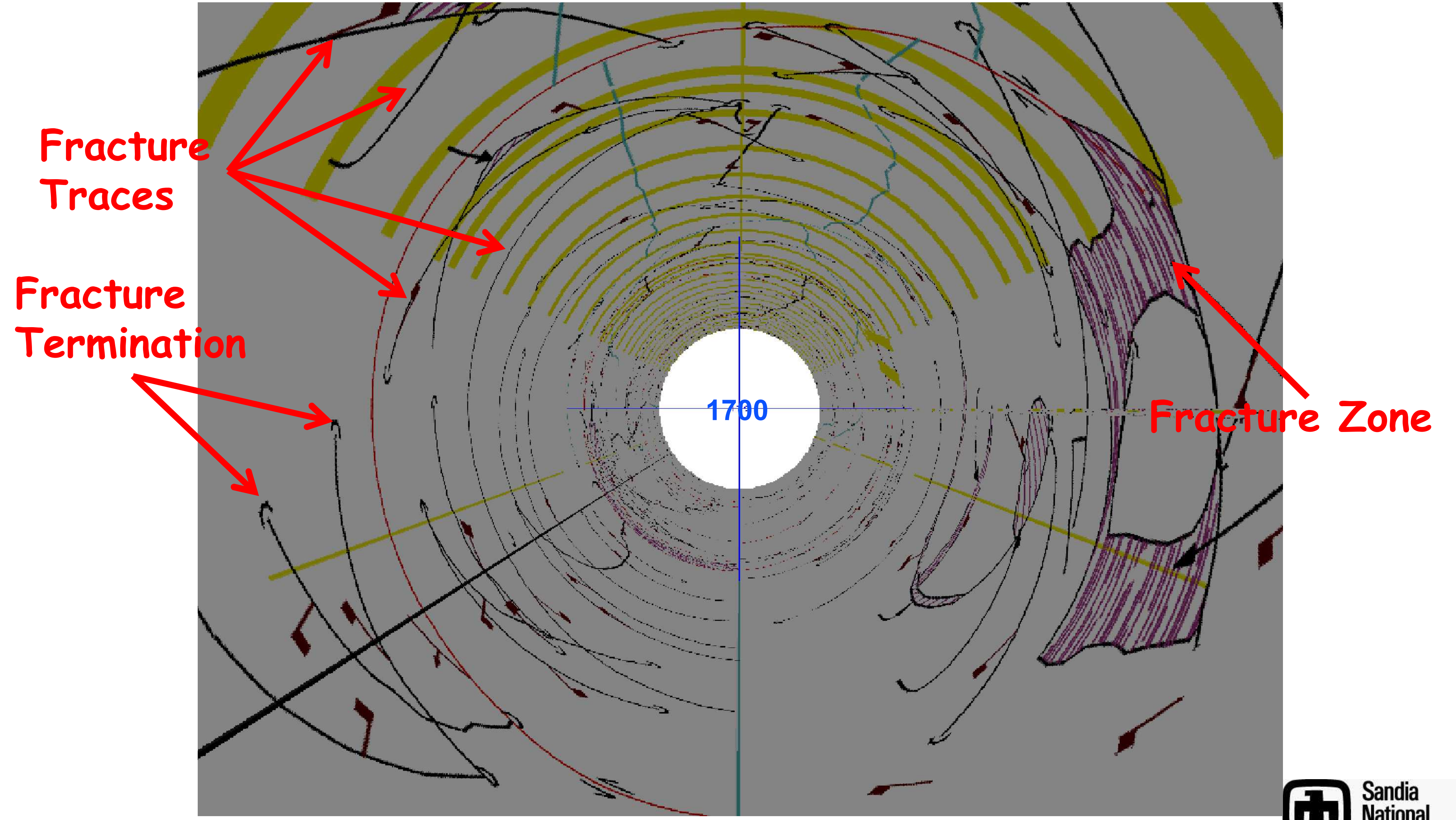

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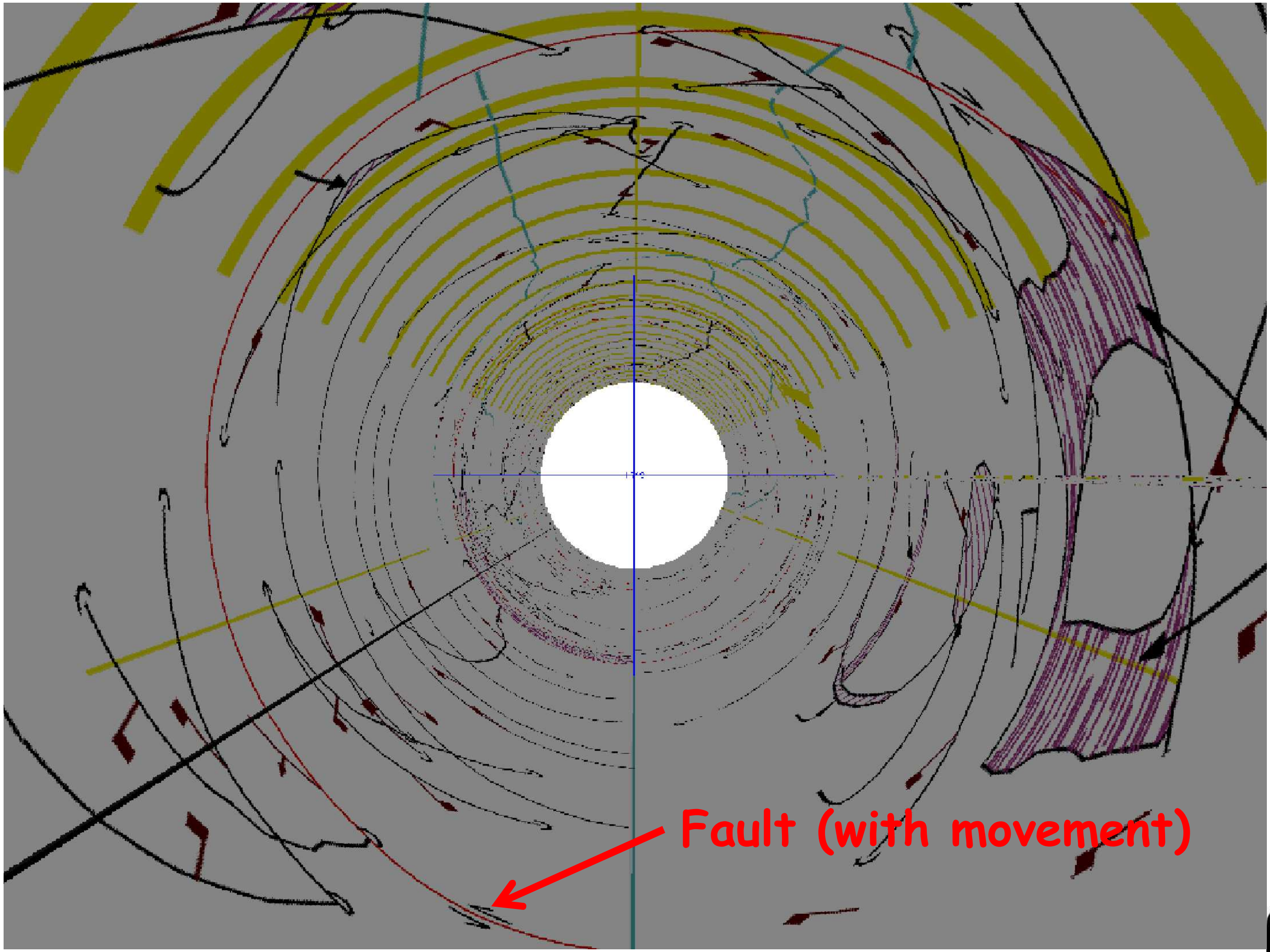

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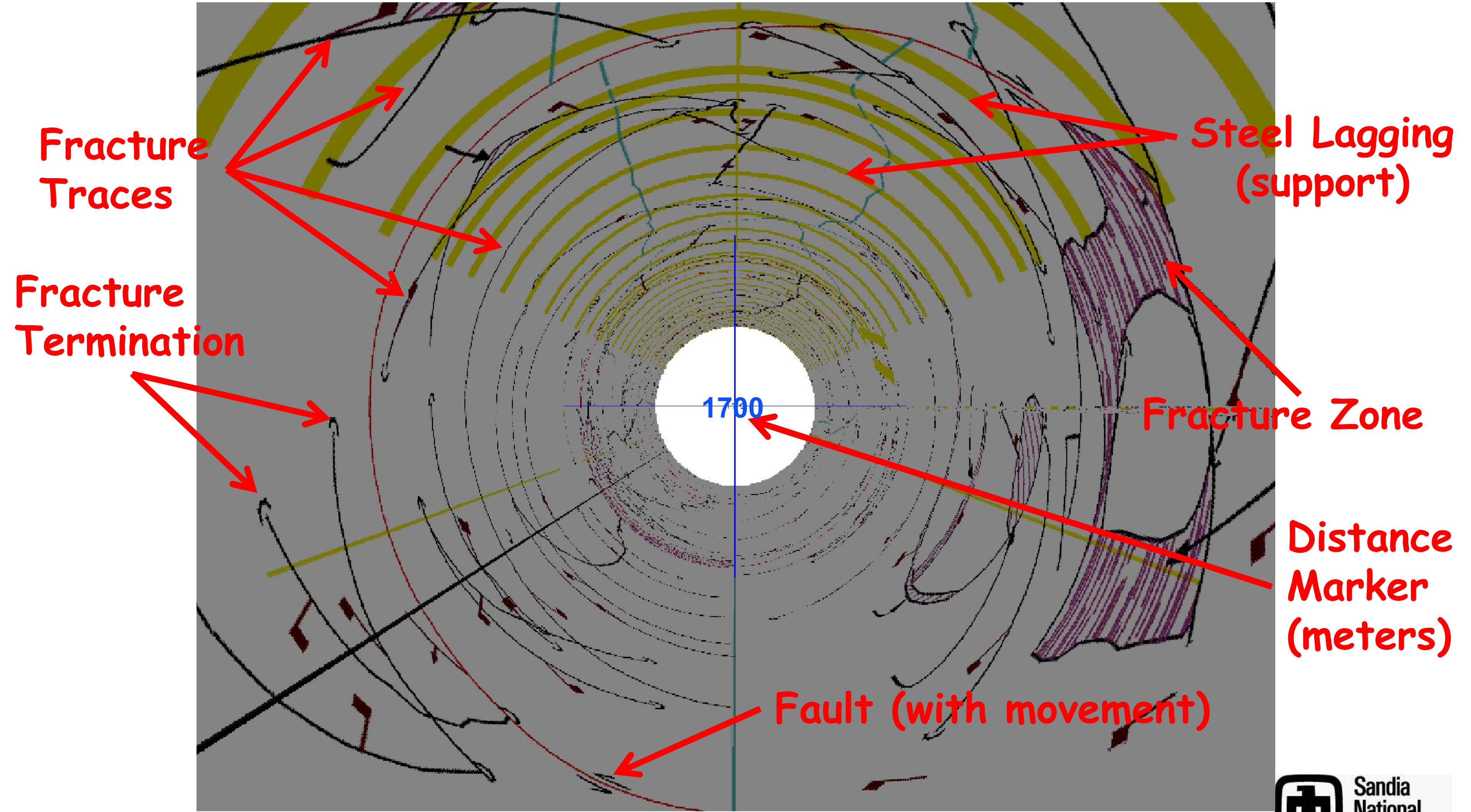
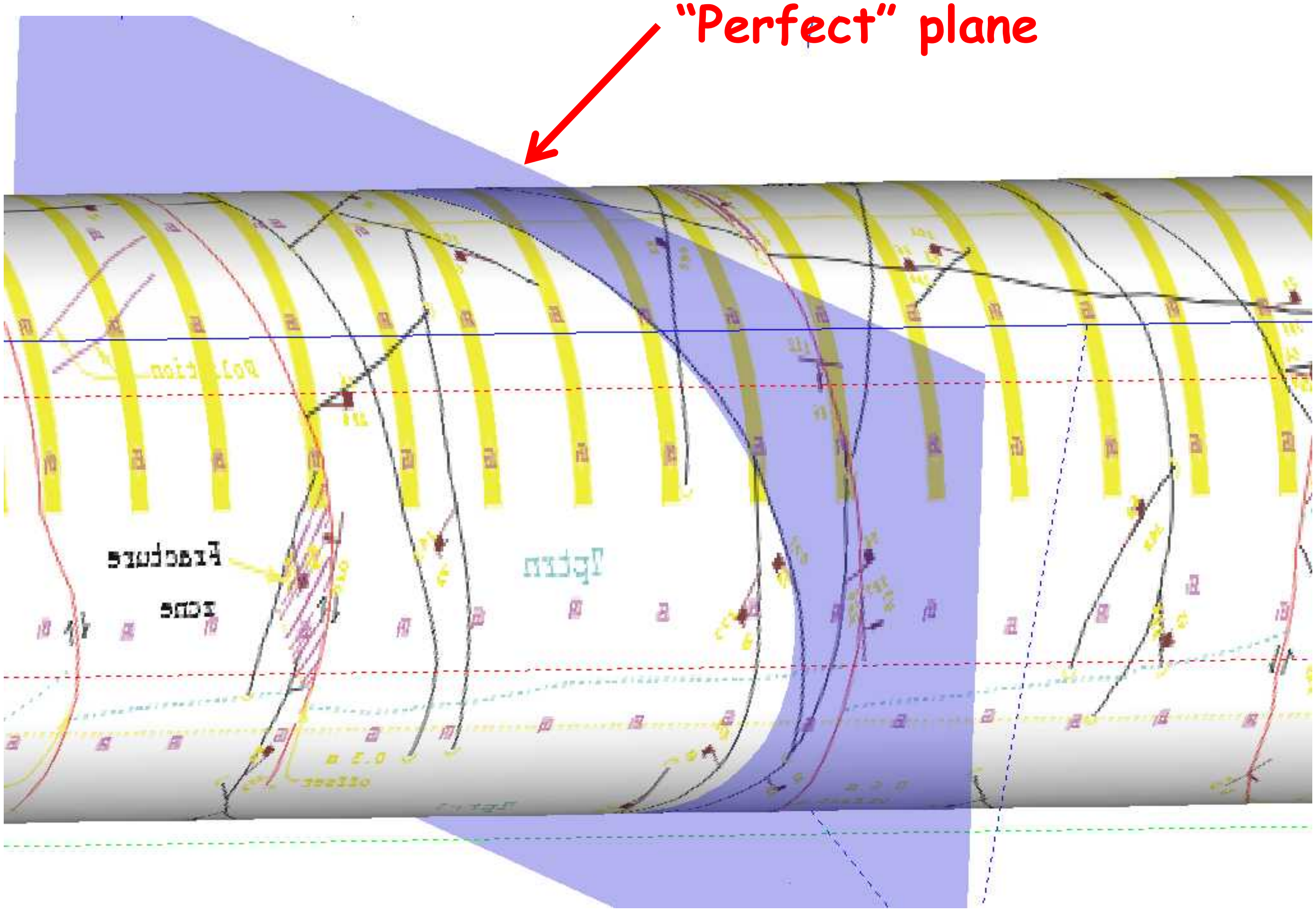


Fracture / Fault Intersections with a Cylinder

“Perfect” plane



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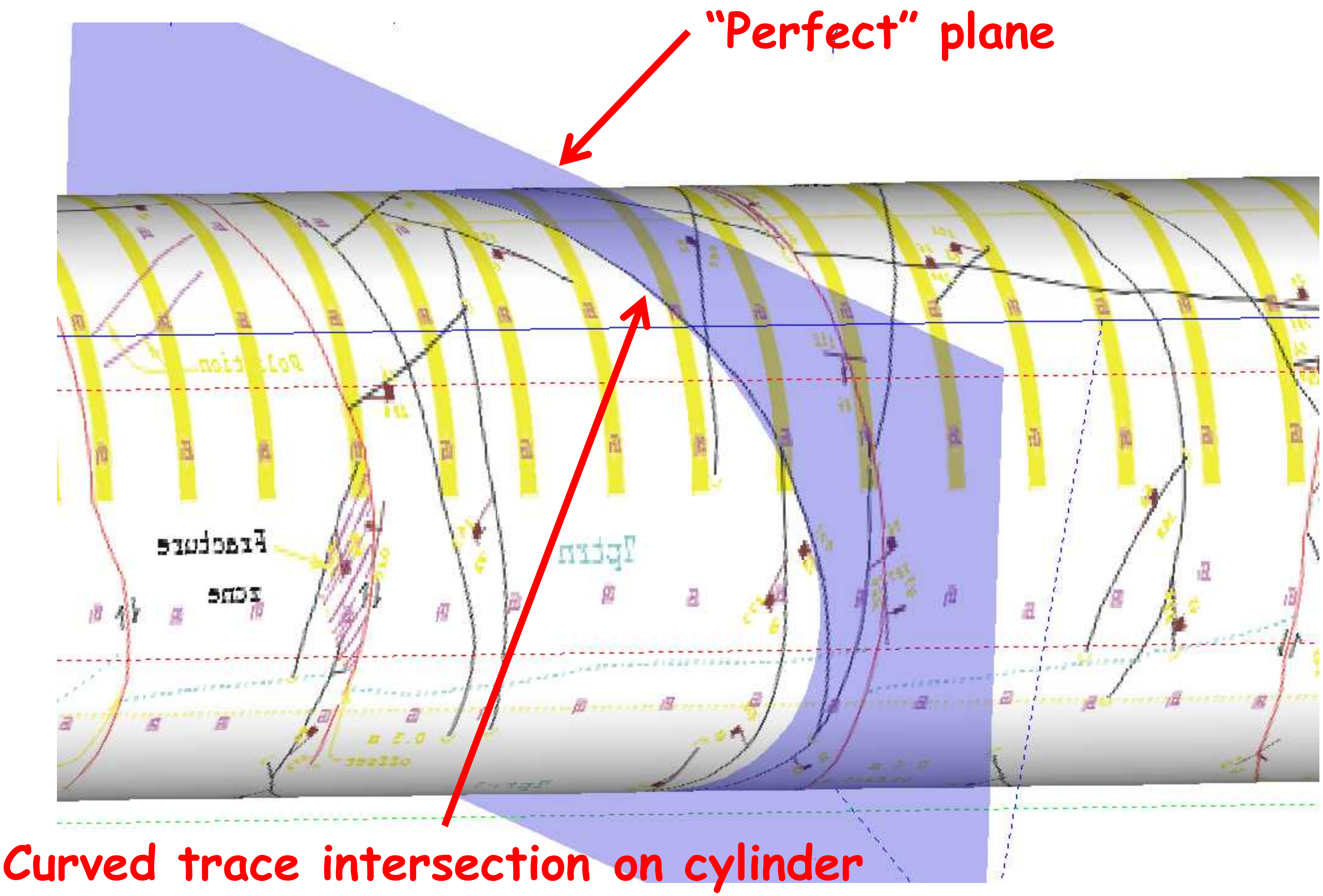

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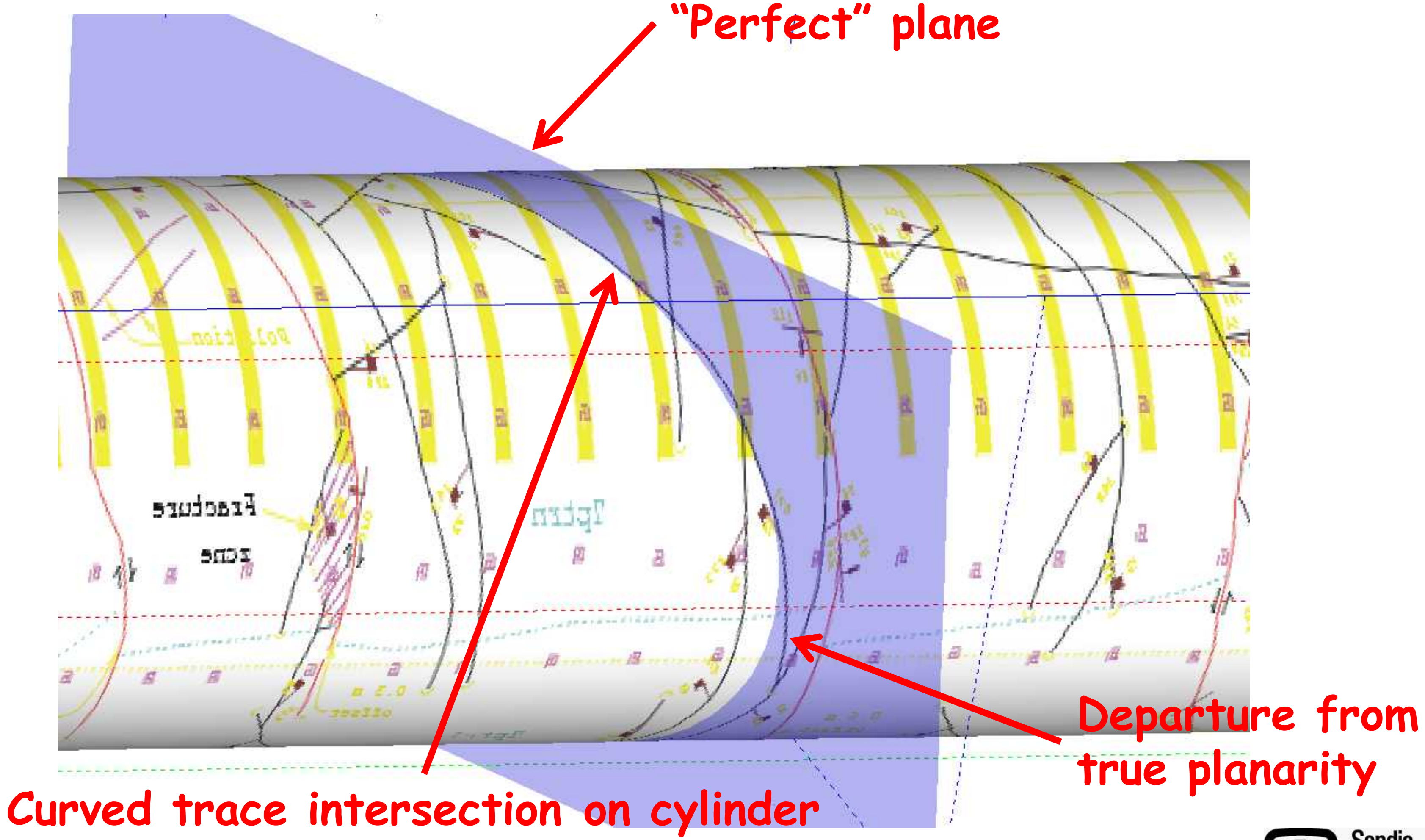
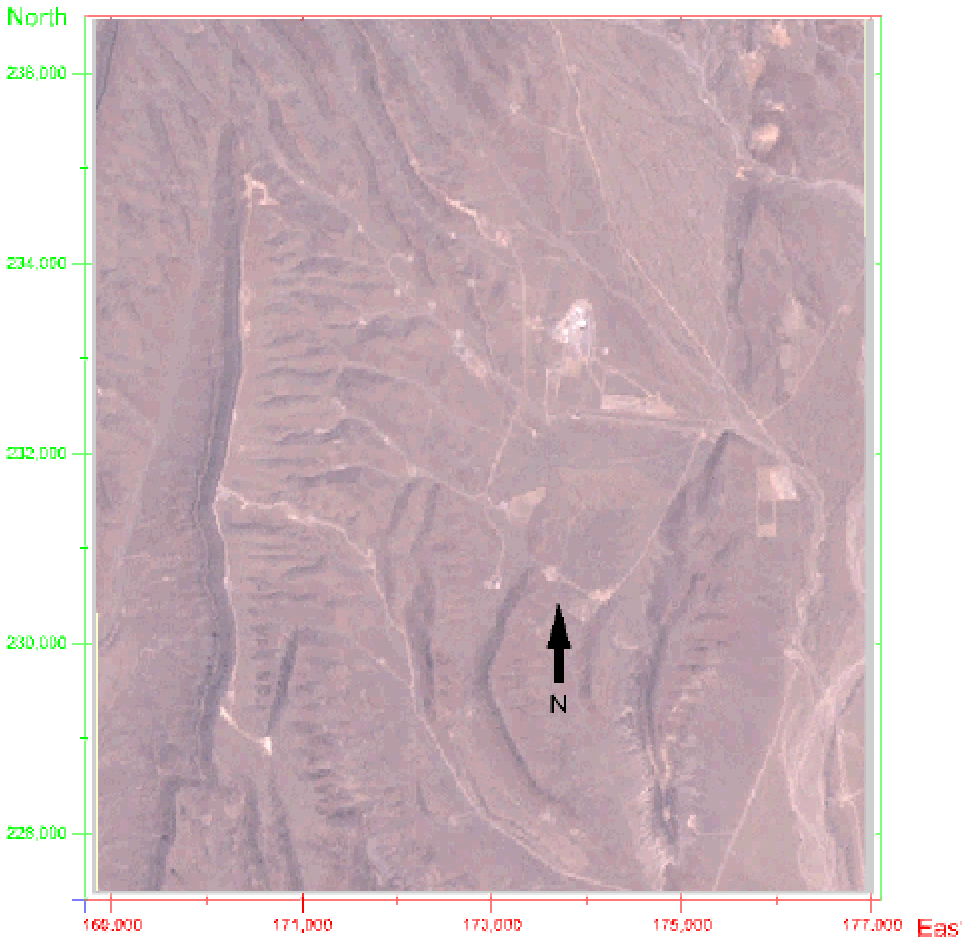


ESF Fly-Through



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- **Intensity of rock fracturing and fault varies spatially**
  - **local long intervals with no/minimal breaks**
  - **meter-scale fracture zones**

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Mountain City Copper Mine, Nev.

- Vein-type deposit located in Elko County, northeastern Nevada (Basin-and-Range province)
- Primary sulphide copper mineralization, with very significant secondary (oxide) enrichment
- Original mineralization formed pods within a shaly sedimentary unit (Paleozoic age)
- Mine active ~ 1932-1947

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- Mine active ~ 1932-1947
- **Developed by at least 7 major levels of drifting, over a vertical interval of > 800 ft**
- **Cut by numerous faults**

Available Data

- We have large-scale mine maps of each of seven levels vertically
  - Drifts are mapped
    - A first approximation of vein geometry
  - Open stopes allowed extensive examination of structures
  - Faults / major fractures were mapped, and in some cases projected between drifts on the same level
  - Dip directions are given for most features

Ridge, J.D., ed., 1968, *Ore deposits of the United States, 1933-1967, the Graton-Sales volume*, New York: Am. Inst. Mining, Metallurgical, and Petroleum Engineers, Inc., vol. 2, p. 1074-1101.

Model Construction

- The published mine maps were scanned, and the digital images were calibrated using distance information on the maps
  - Allows alignment among the levels
- Drifts digitized as polylines, with (x,y,z)
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- **Polylines mapped into 3-D model space for visualization**
  - **Rotation of model in 3-D allows visual identification of "most likely" assignment of individual mapped features to a particular fault (down-dip continuity)**
  - **Triangulated planes fitted to digitized points of polyline to represent fault planes**

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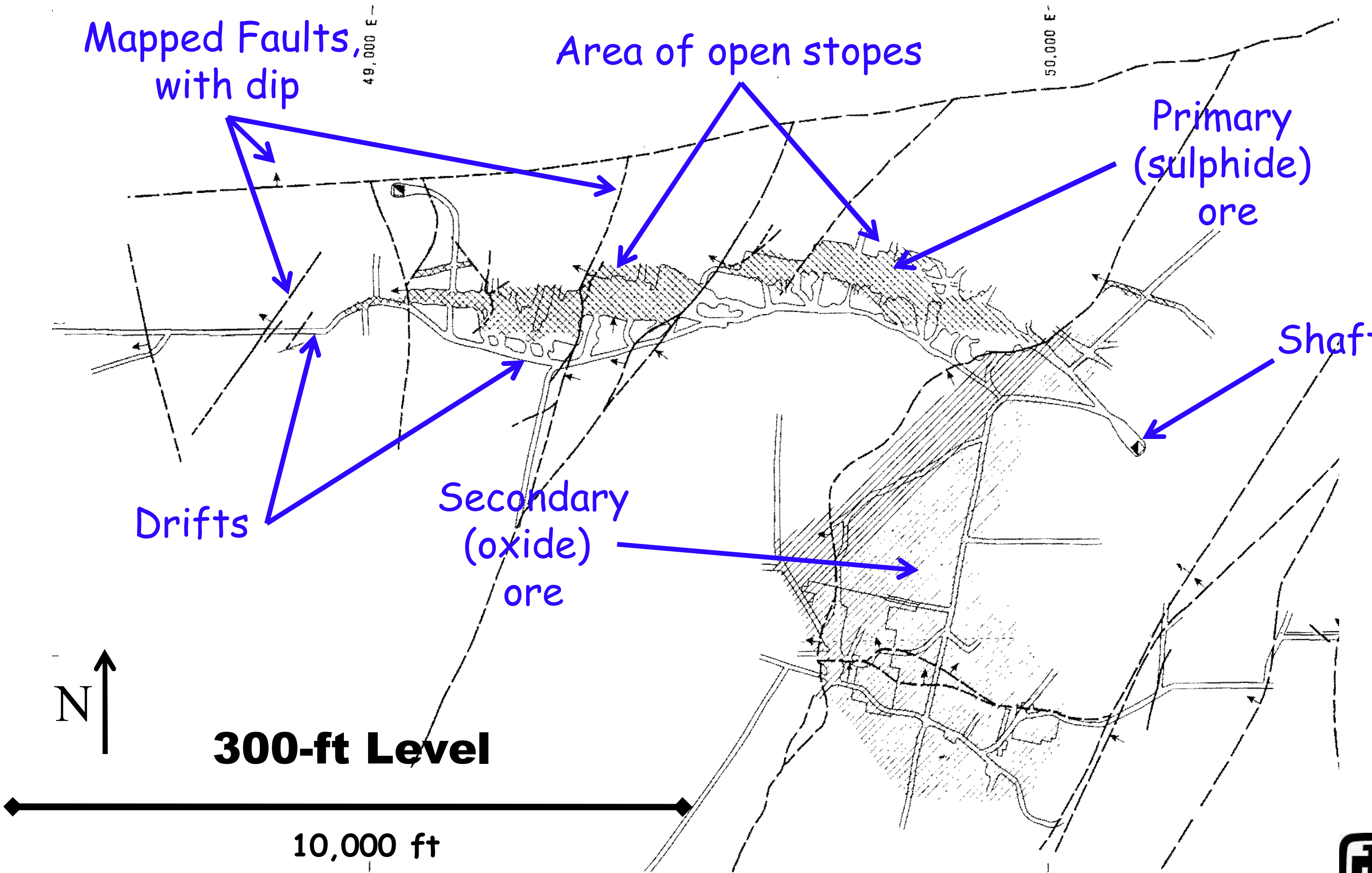
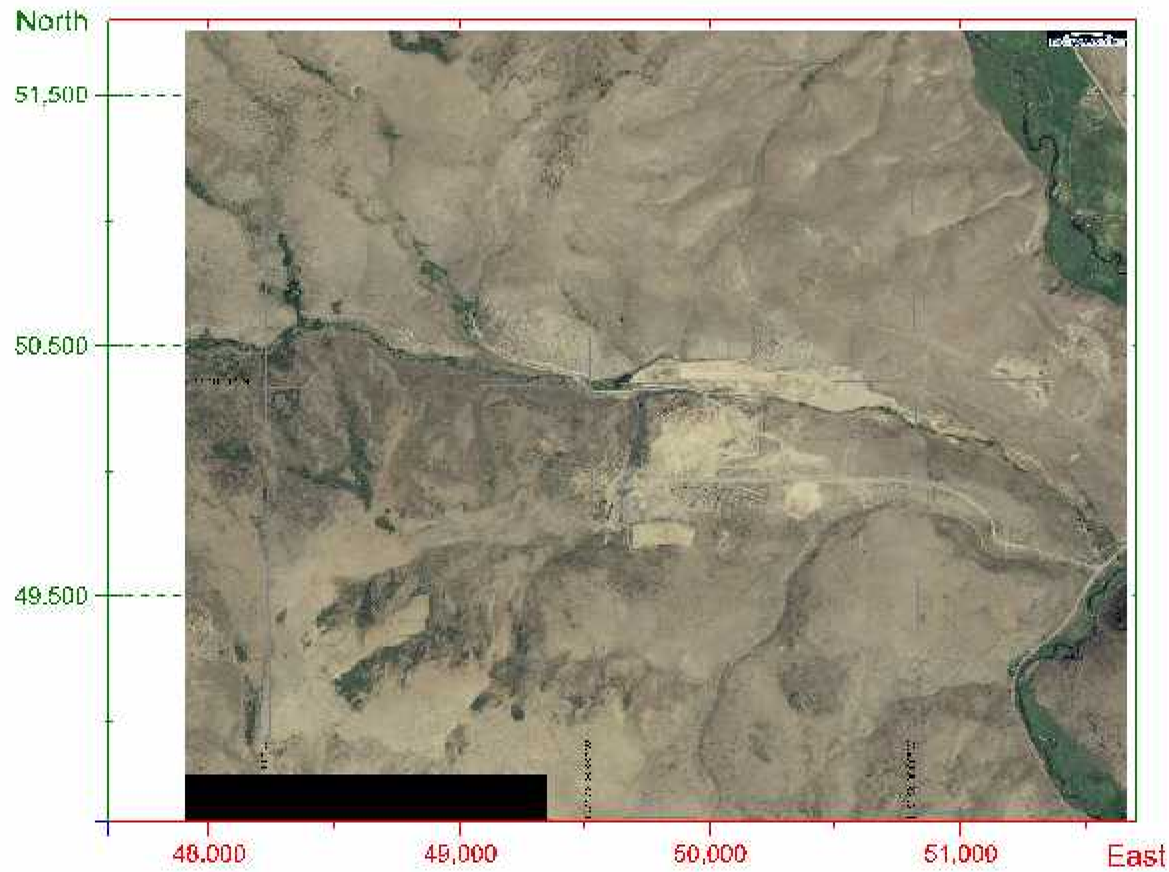
Example Mine Map



Mountain City Mine Model Construction



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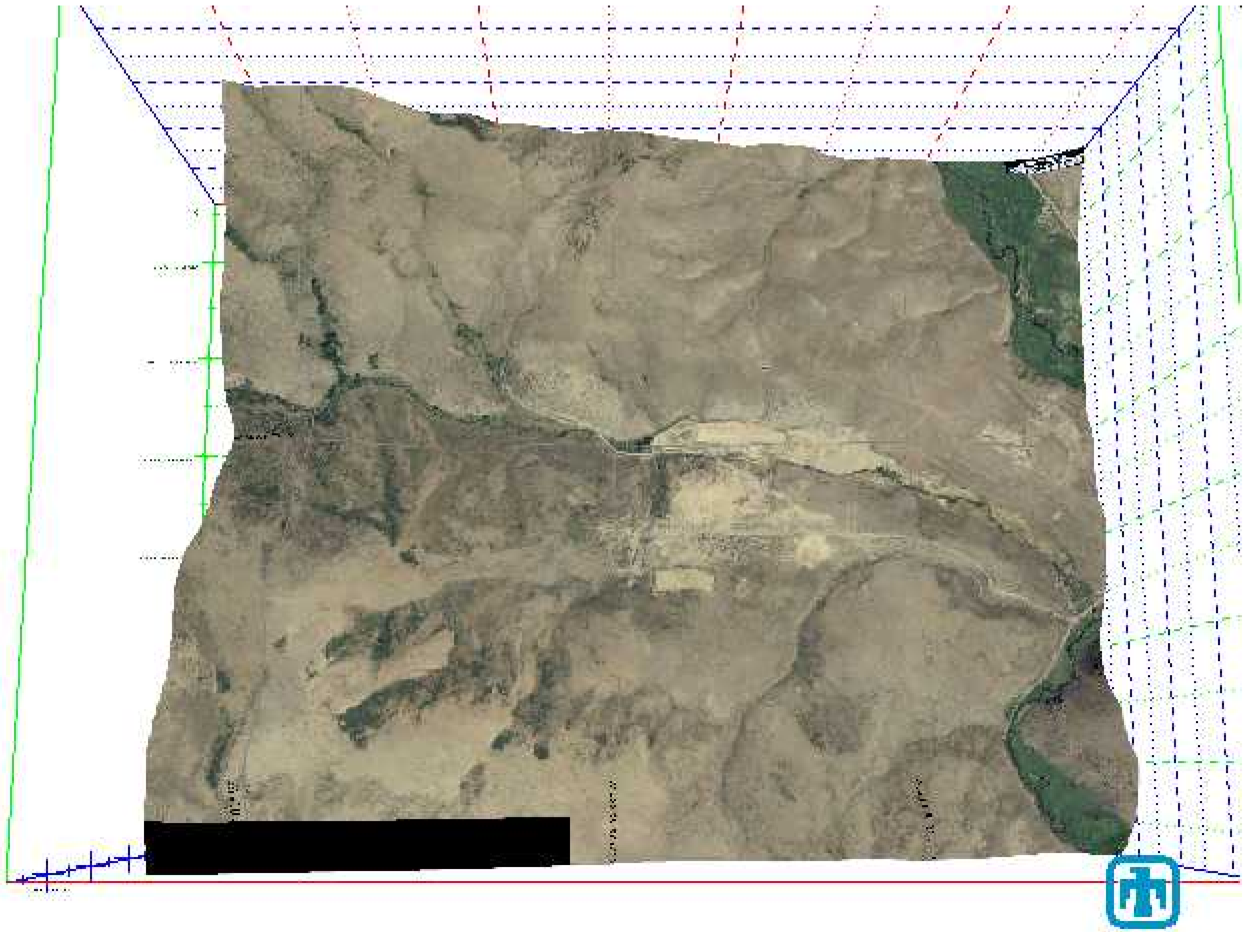
Mountain City Mine Fly-Through #2



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- **Intersections and truncations**

Paymaster Vein, Calif.

- Vein-type gold deposit
- Active 1910-1914, 1932-1944
- Relatively small mine
  - Tunnel access
  - Host rock is granitic gneiss
  - Single vein with drift along length

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- Actual widths of vein measured in numerous locations
  - Example of pinch-and-swell related to fault geometry
- Measured dips of fault allow quasi-3-D projection

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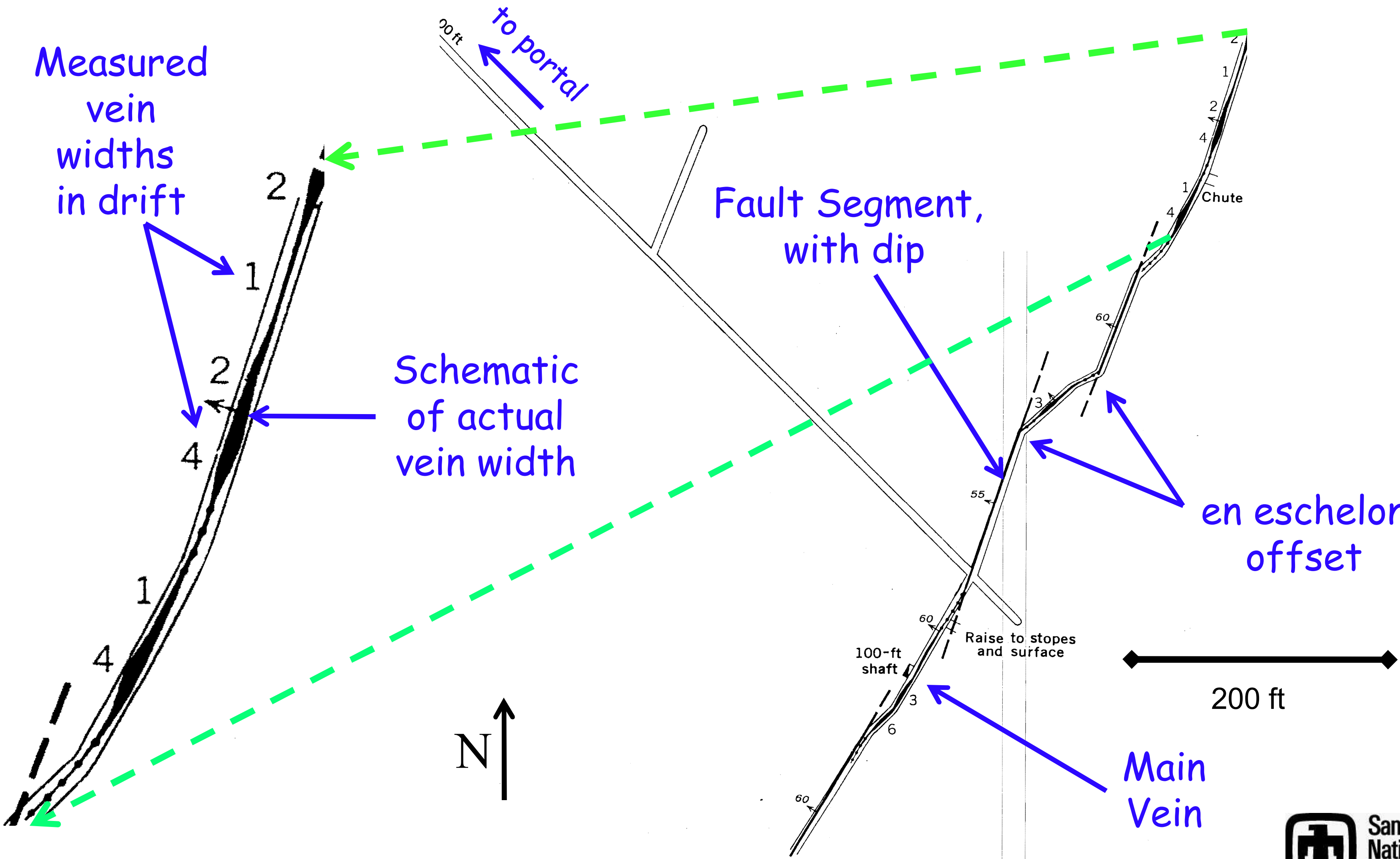
Data Available: Mine Map with Vein Widths



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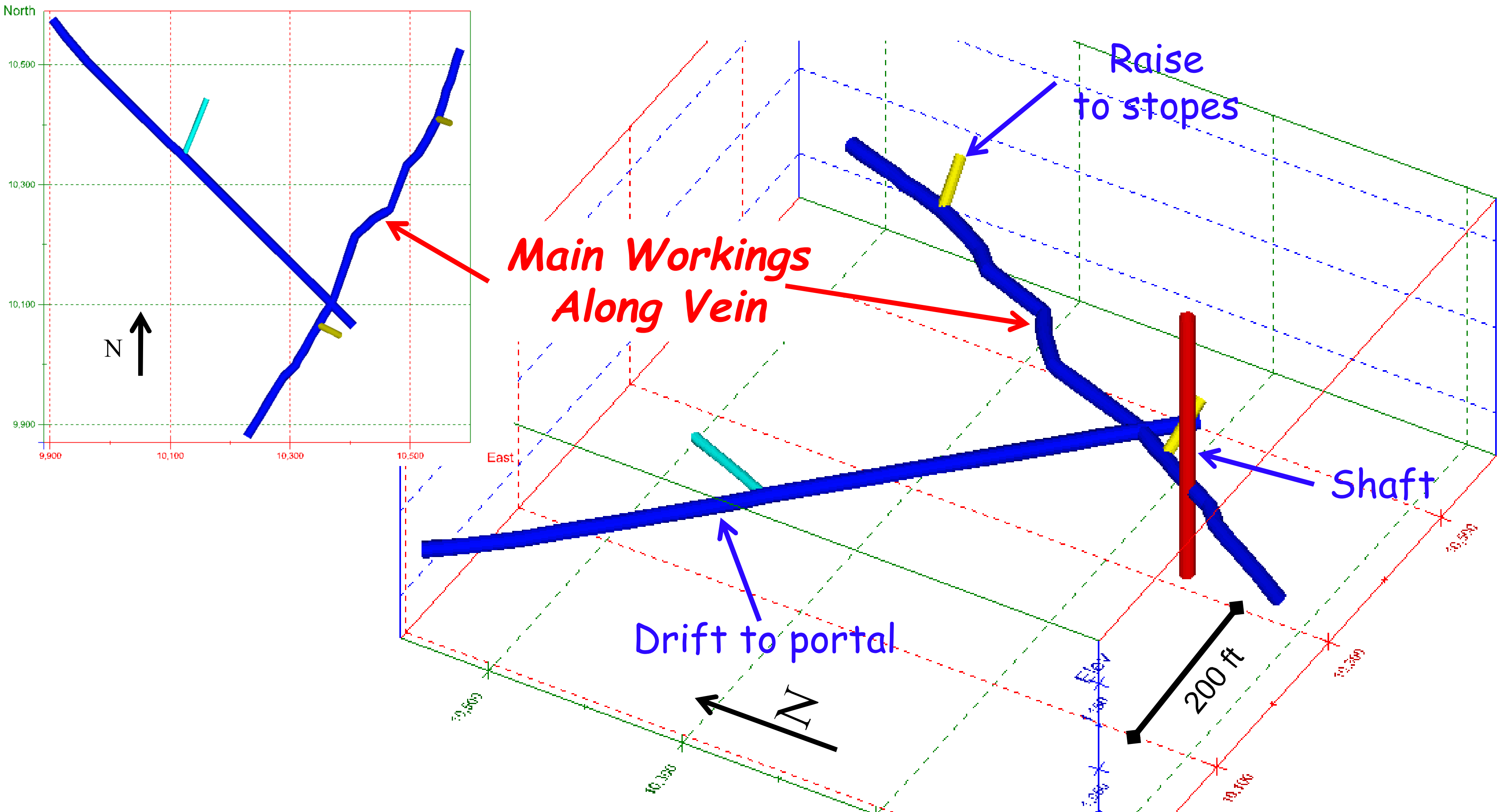
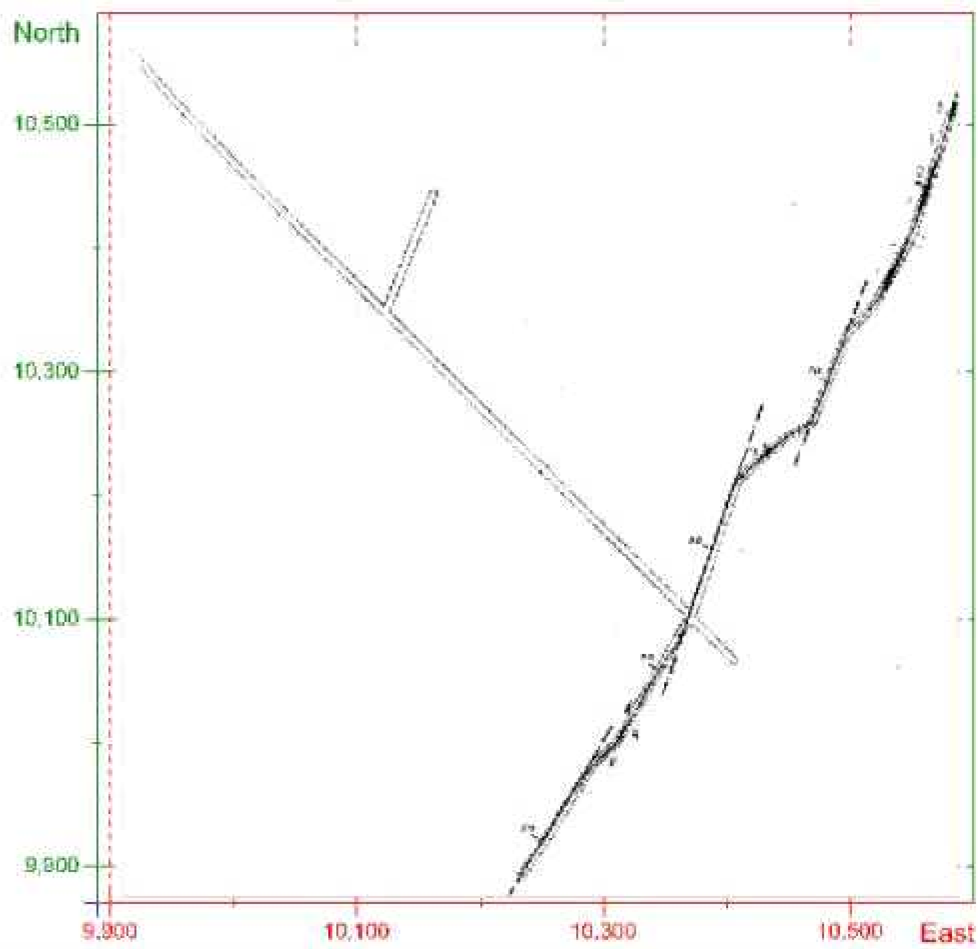
Paymaster Mine: Drifts and Workings



Paymaster Vein Fly-Through



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- *The width of the vein and associated quartz mineralization* (aka fracture aperture) *varies laterally by almost an order of magnitude*
- The vein has been offset in en eschelon style by several post-mineralization faults

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Sagamore Mine

- Vein-type gold deposit with multiple veins
  - Active 1905-1910, 1913-1917, 1942-45
  - Two tunnels ~1200 ft, plus a vertical shaft
  - Polymetallic sulphides (Zn, Cu, Pb, W, Mn)

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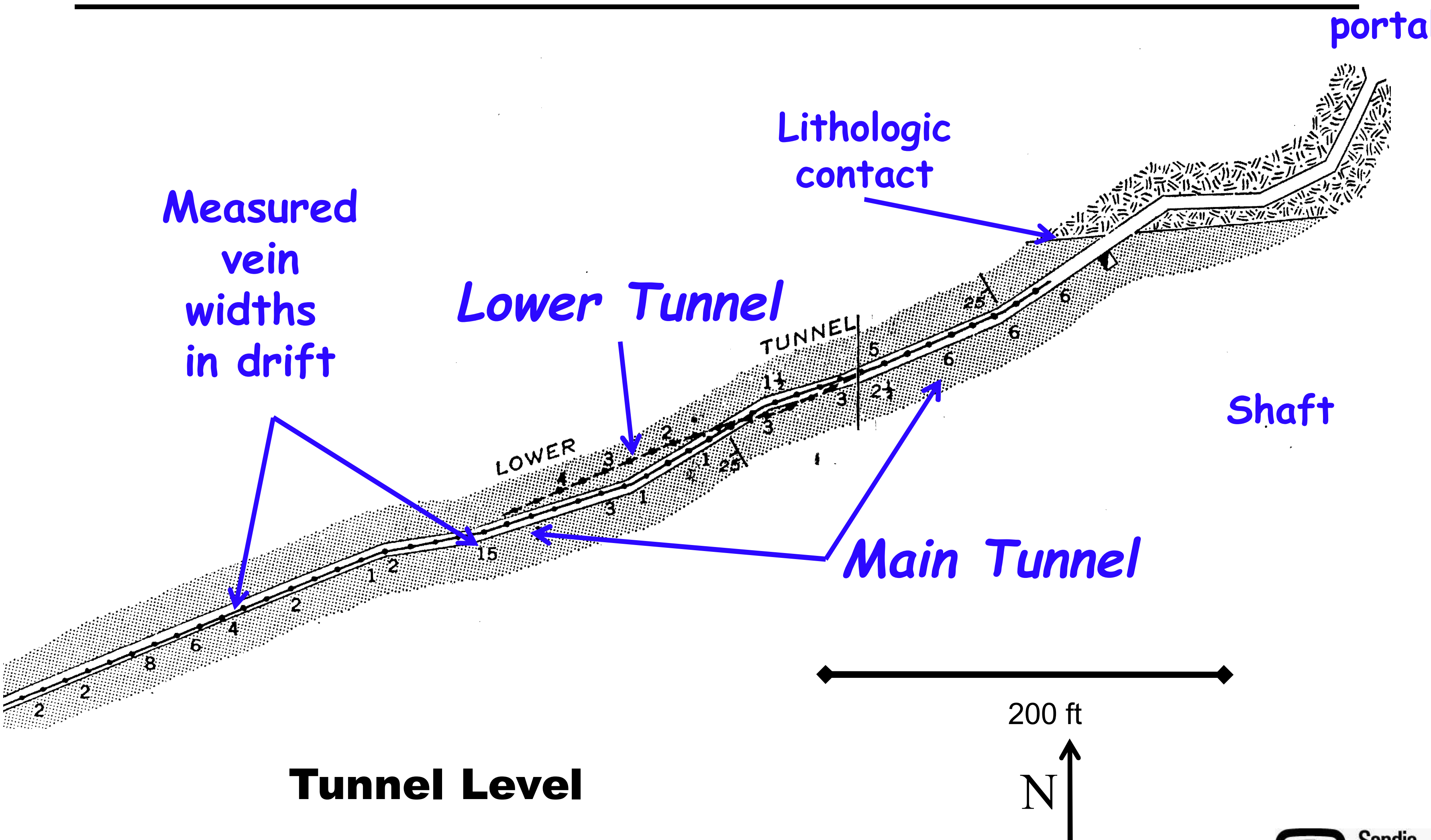
- Measured dips and two levels of workings allow quasi-3D geometrical modeling

Sagamore Mine: Data Available



Tunnel Level

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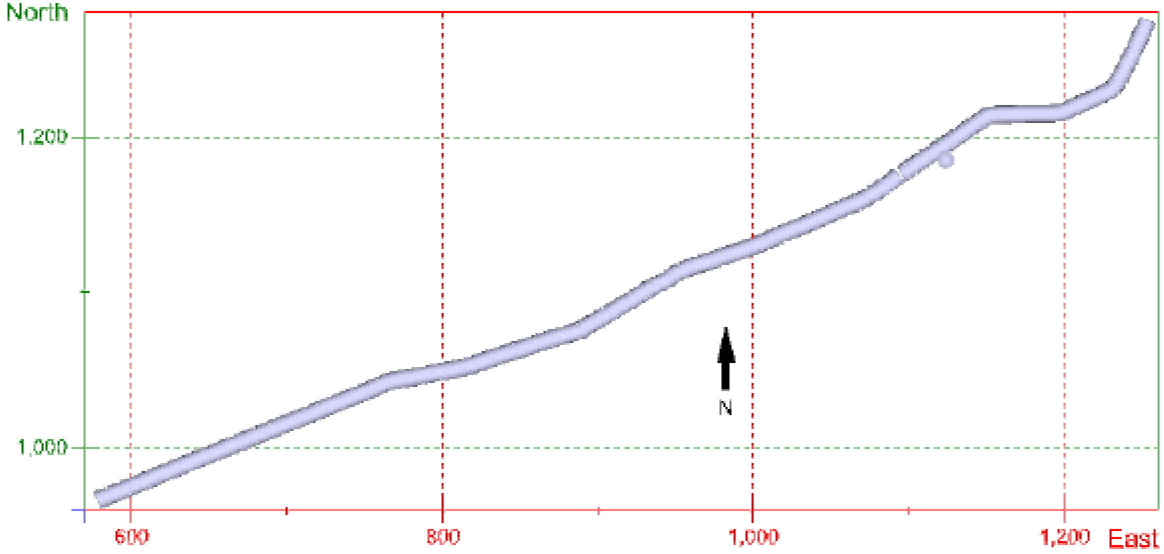
Visualization in Three Dimensions



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- Very pronounced control of vein width and mineralization by host-rock lithology
  - Vein is very prominently developed in sandstone unit, over more than 2,000 ft of strike length
  - Vein is quite inconspicuous where the fault intersects overlying shales and dolomites (note: these are *both soft and brittle* lithologies)

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Why This “Pinch-and-Swell” Variation?

- **Both the Paymaster and Sagamore vein deposits exhibit marked variation in width along strike**
- **Variation in “aperture” is inherent in any non-planar fault that exhibits movement**

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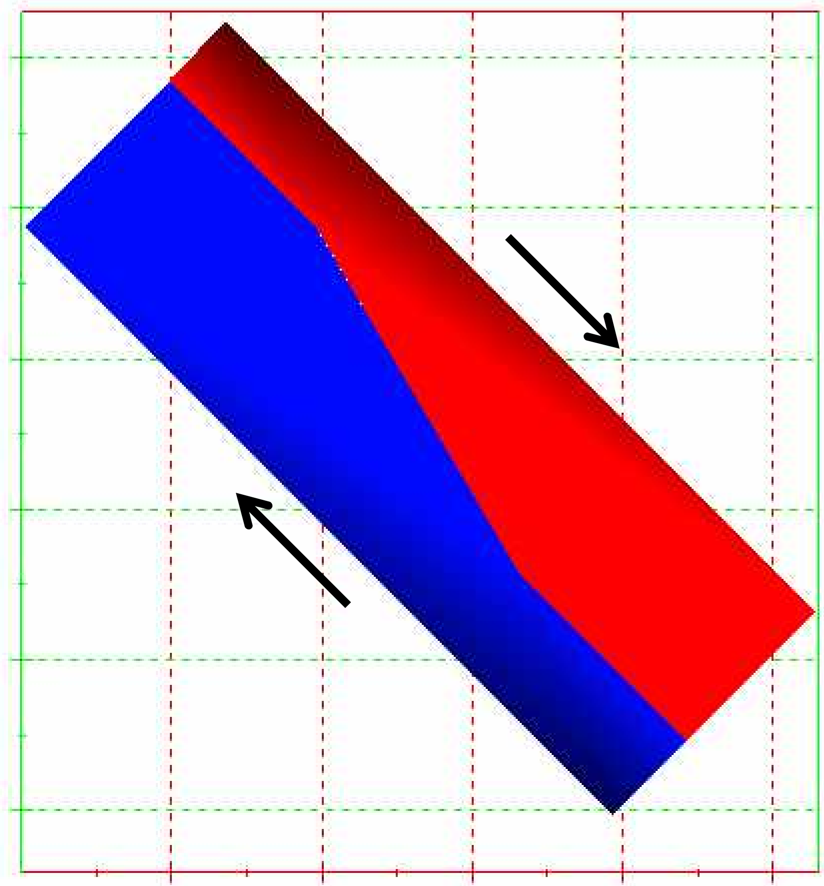
Effect of Non-planarity in Faults

Normal Faulting



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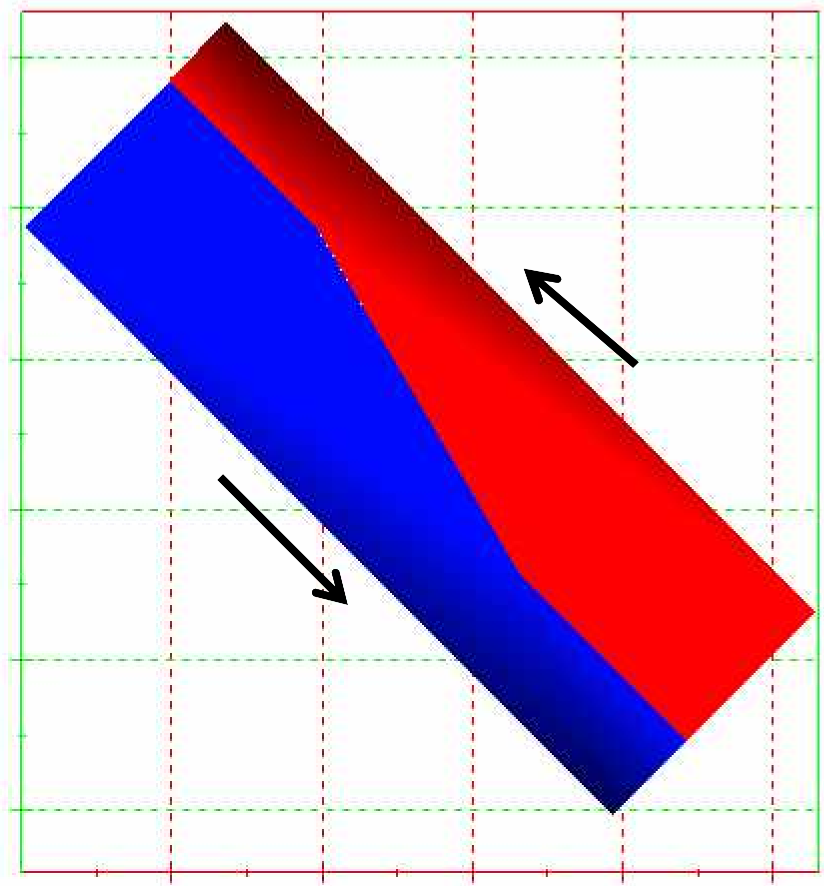
Effect of Non-planarity in Faults, part 2

Reverse Faulting



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- Variable aperture along a fault or major fracture results from non-planarity
  - Example given in 2-D, but the physics operate in full three dimensions

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- Variable aperture along a fault or major fracture results from non-planarity
  - Example given in 2-D, but the physics operate in full three dimensions
- Fault geometry may work to open fractures or it may force fractures to close and "lock"
  - Possibly associated crushing and brecciation
  - Dissipate energy

Butte, Montana

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- Discovered as a gold deposit 1864
  - 42 miles of vertical shafts
  - Thousands of miles of underground workings
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  - **Non-mineralized faults**

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Butte: Data Available

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  - Two levels separated vertically by ~1,000 ft
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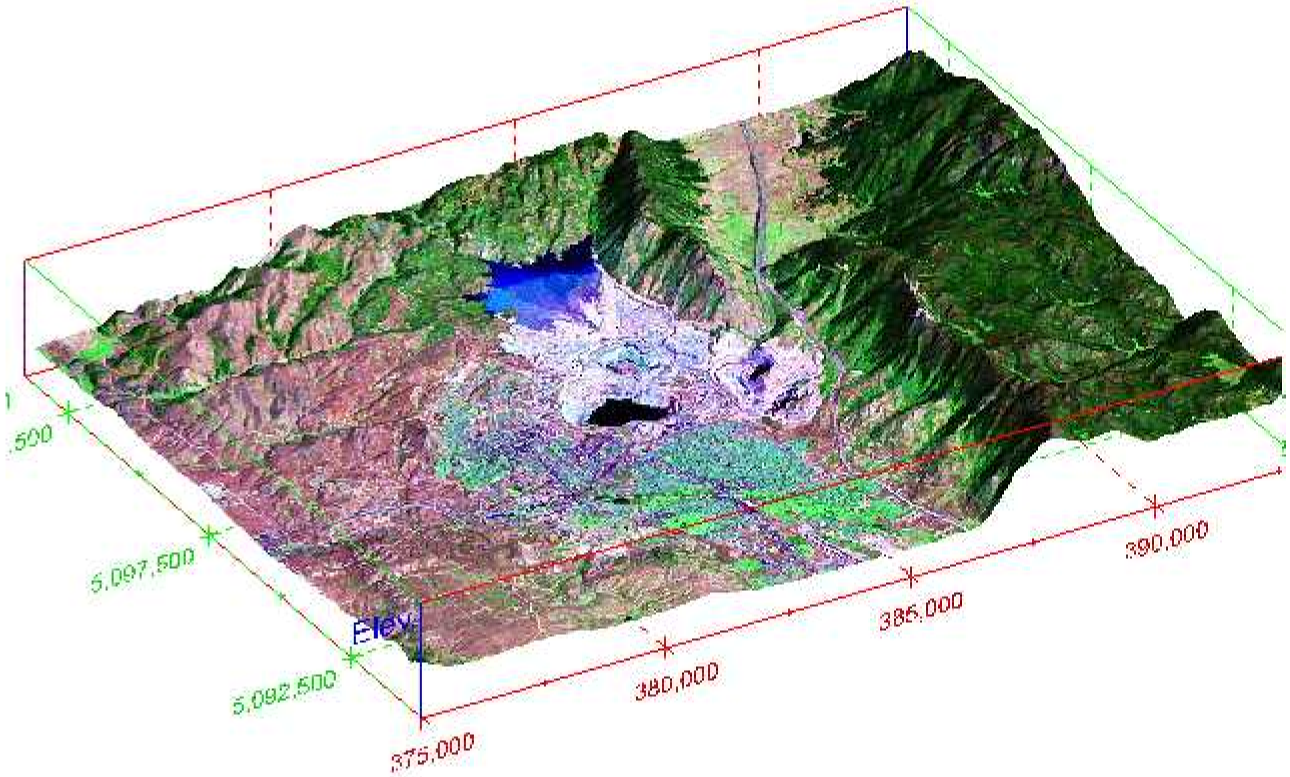
  - Two levels separated vertically by ~1,000 ft
  - Three sets of veins / faults
- Vertical cross section of district
  - Extends to 4,000 ft depth, locally
  - Same three sets of veins / faults distinguished
  - Provides third dimension in more detail
    - There is a “surprise” in the attitude of the late faults

Vein Systems of the "Richest Hill on Earth"



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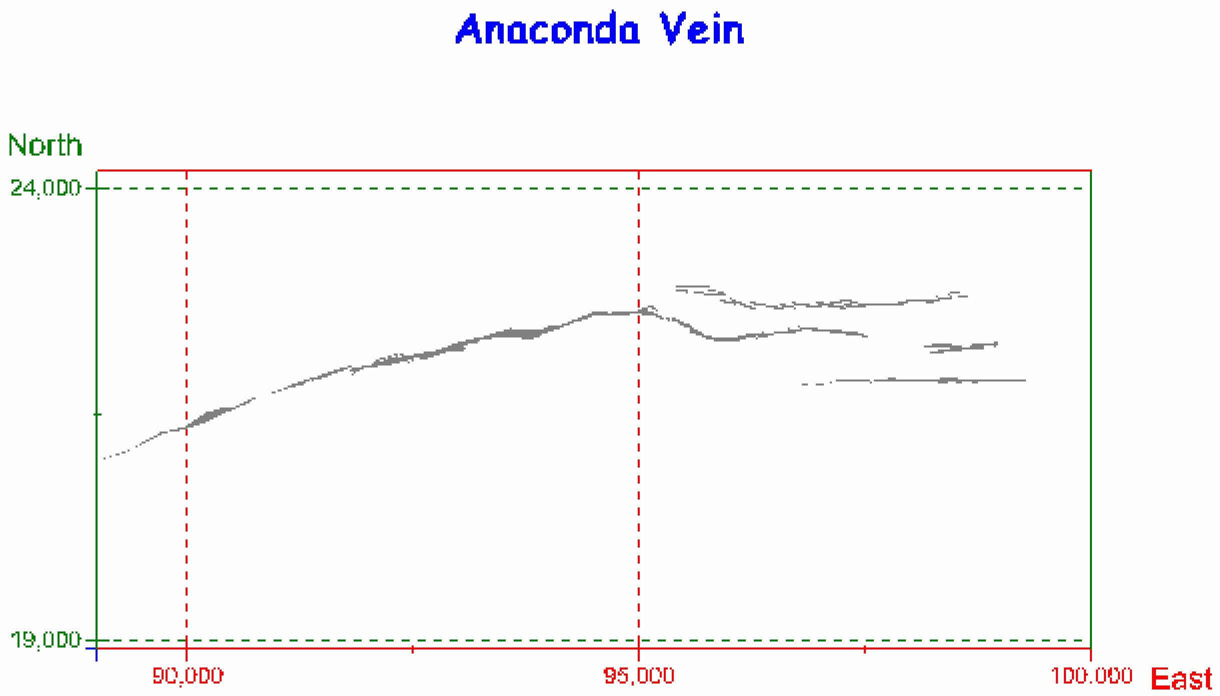
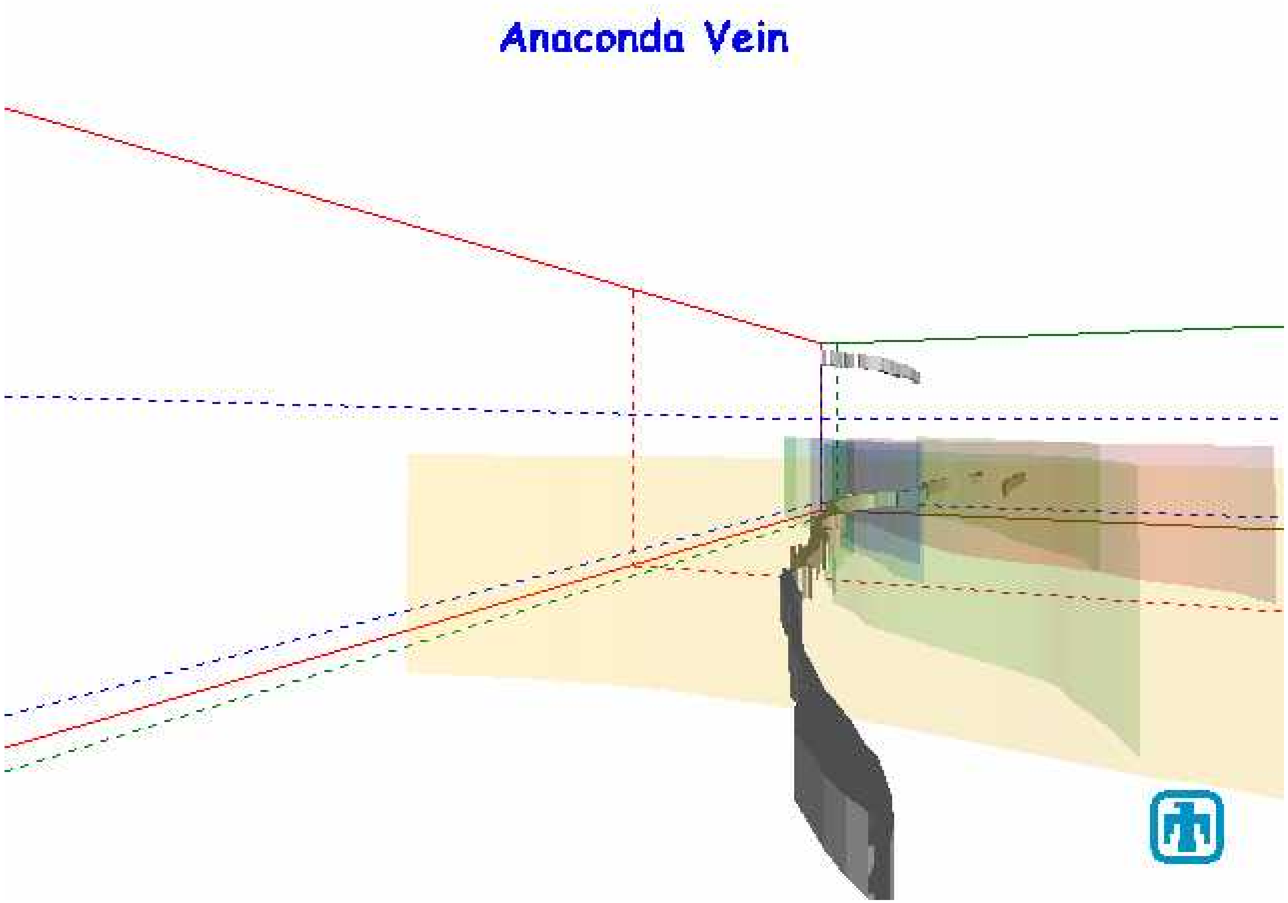
Closer Examination of the “Anaconda” Vein



Fly-Through Along the "Anaconda" Vein



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Summary of Observations: Butte District

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  - Individual faults/fractures mapped 10s/100s of m

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- Curved fracture / fault traces in plan
- Pinch-and-swell
- **Opposing dips of “similar” strike structures!**
  - **interlocking blocks resist movement**

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Faults / Fractures on the Kilometer Scale

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- Example from a fractured granitic terrane from northwestern Scotland
  - Glaciated: obscuring surficial deposits absent
  - Erosion has enhanced visualization of weakened zones

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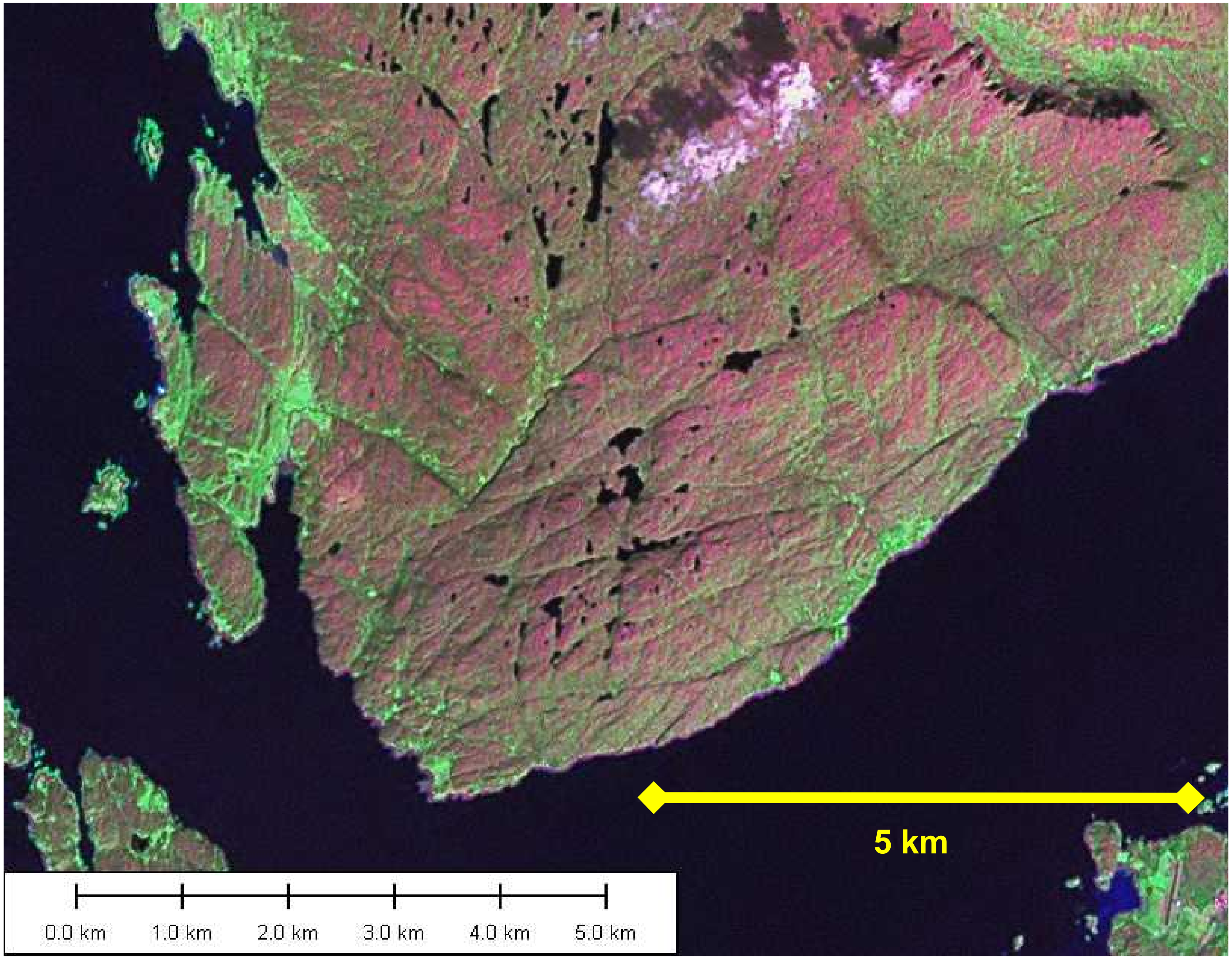

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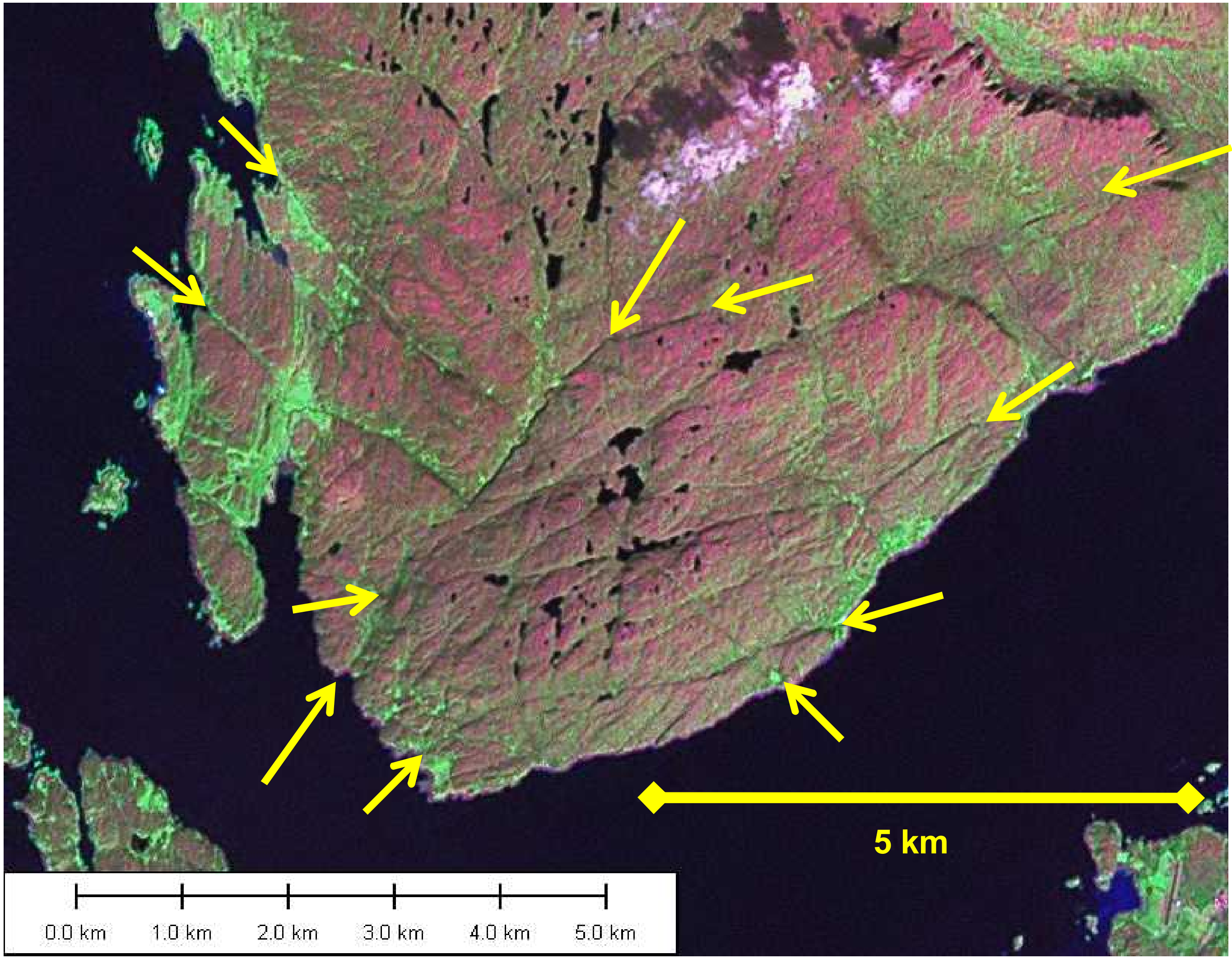

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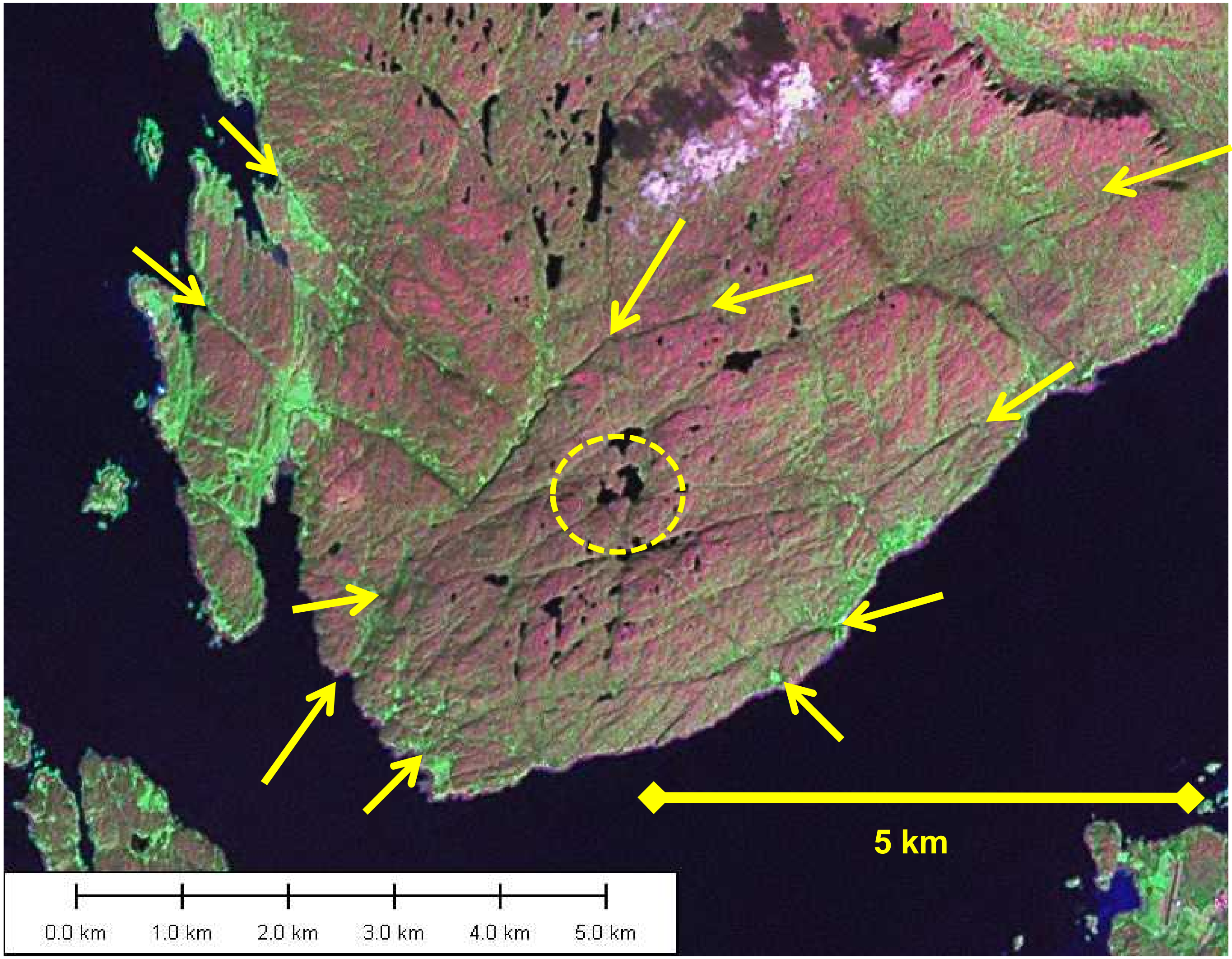

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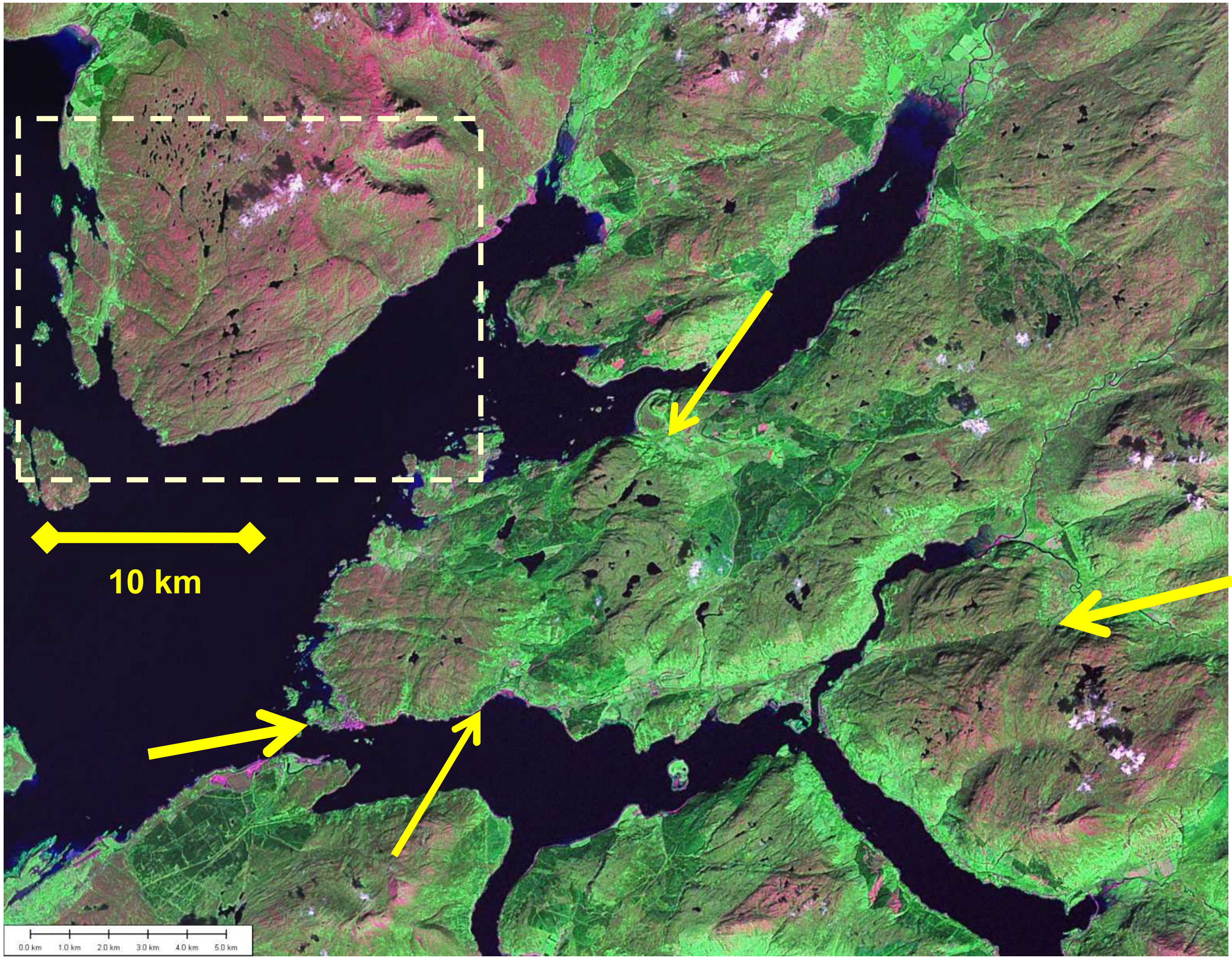
Faults / Fractures on the Ten-Kilometer Scale



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Summary of Observations

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  - Spatial heterogeneity in intensity and spacing
  - Presence of likely crushed zones at intersections

Core-scale Fracture Mapping

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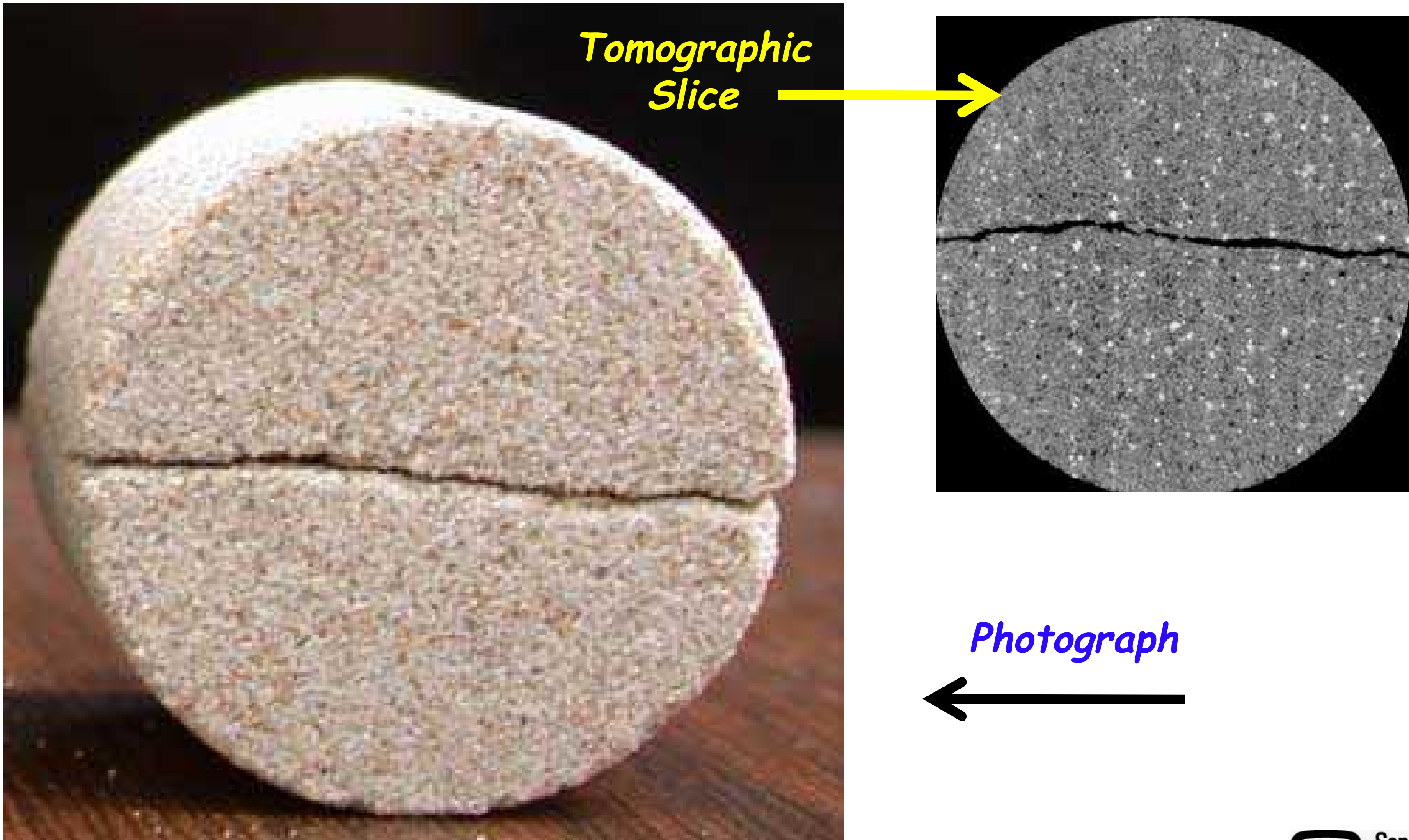
- Great interest in understanding the 3-D geometry of fracture aperture on the core scale, because secondary and tertiary hydrocarbon-recovery techniques are very sensitive to fracture size and geometry
- **Tomographic techniques have been developed to obtain quantitative 3-D images of natural and artificial fractures**
  - **Also methods for imaging air/oil/water saturation**

Grader, A. S. et al., 2005, *Multi-Phase Fracture-Matrix Interactions Under Stress Changes*, Final Report DOE Award Number: DE-FC26-01BC15355, The Pennsylvania State University, The Energy Institute ,University Park, PA 16802, December 7, 2005

Fractures on the Core Scale



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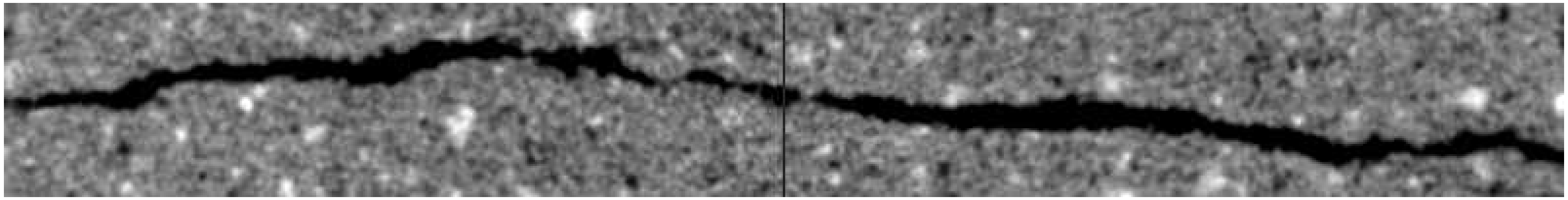
Multi-scale Geometric Similarity

Longitudinal Fracture Profile from Tomography



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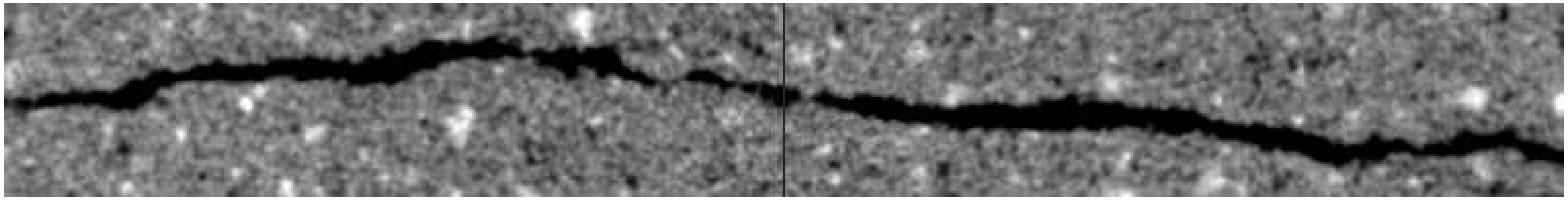

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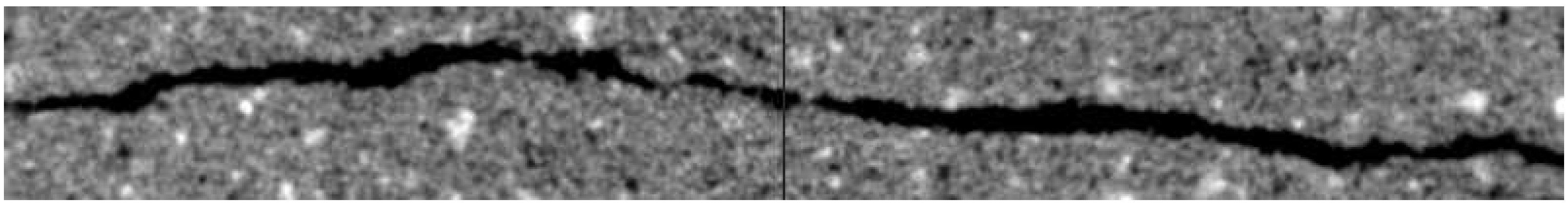

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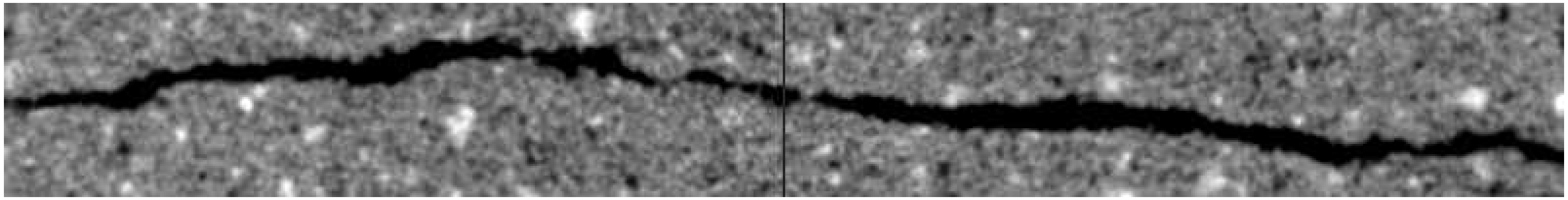

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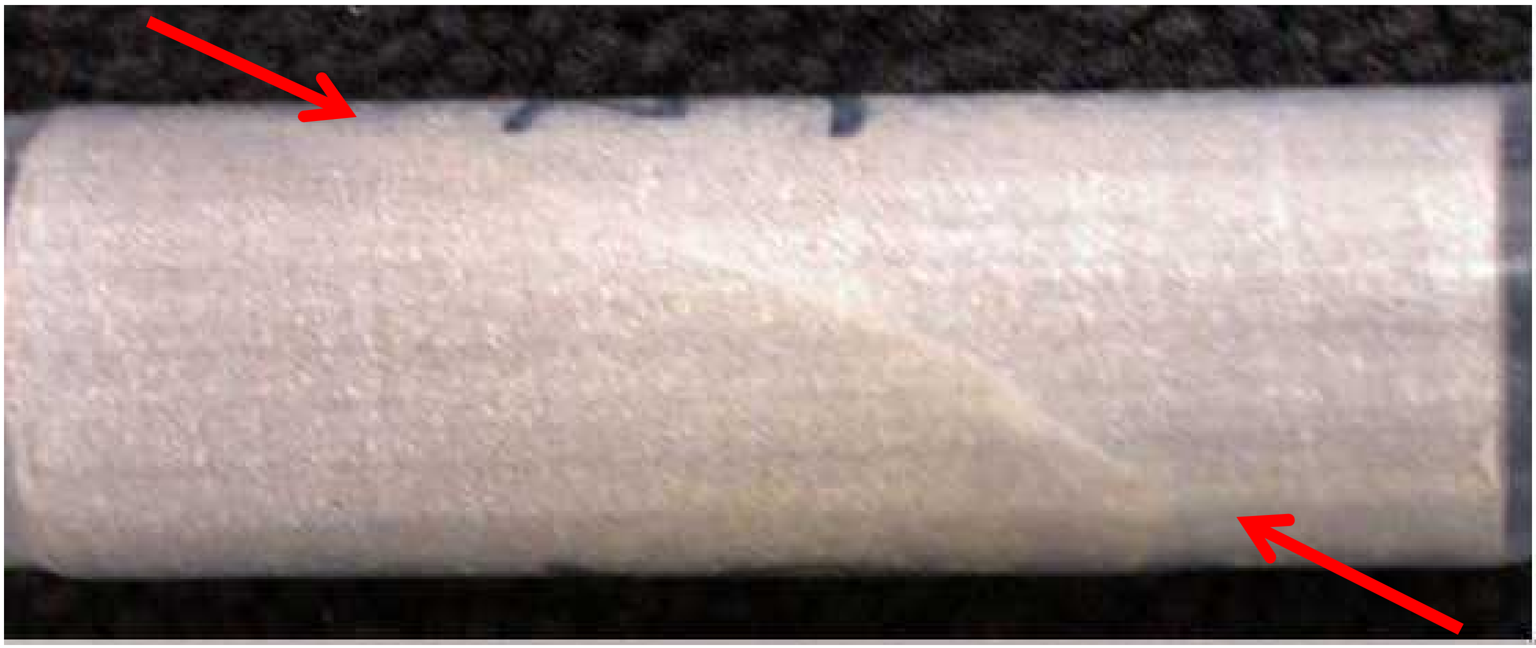
(Vein-width map from the Paymaster Mine Model)
rotated to match

Fracture in Sandstone Core Sample



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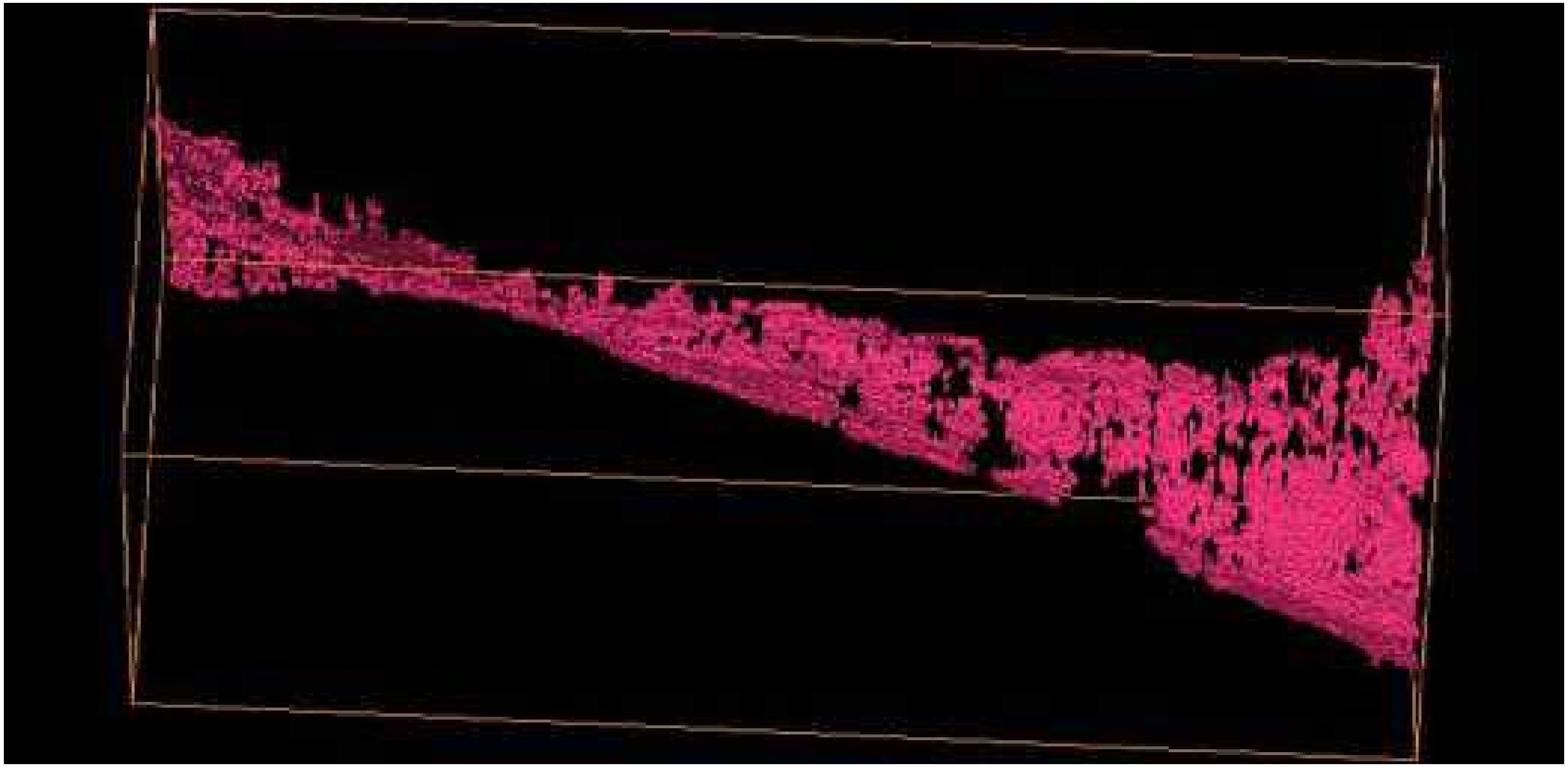
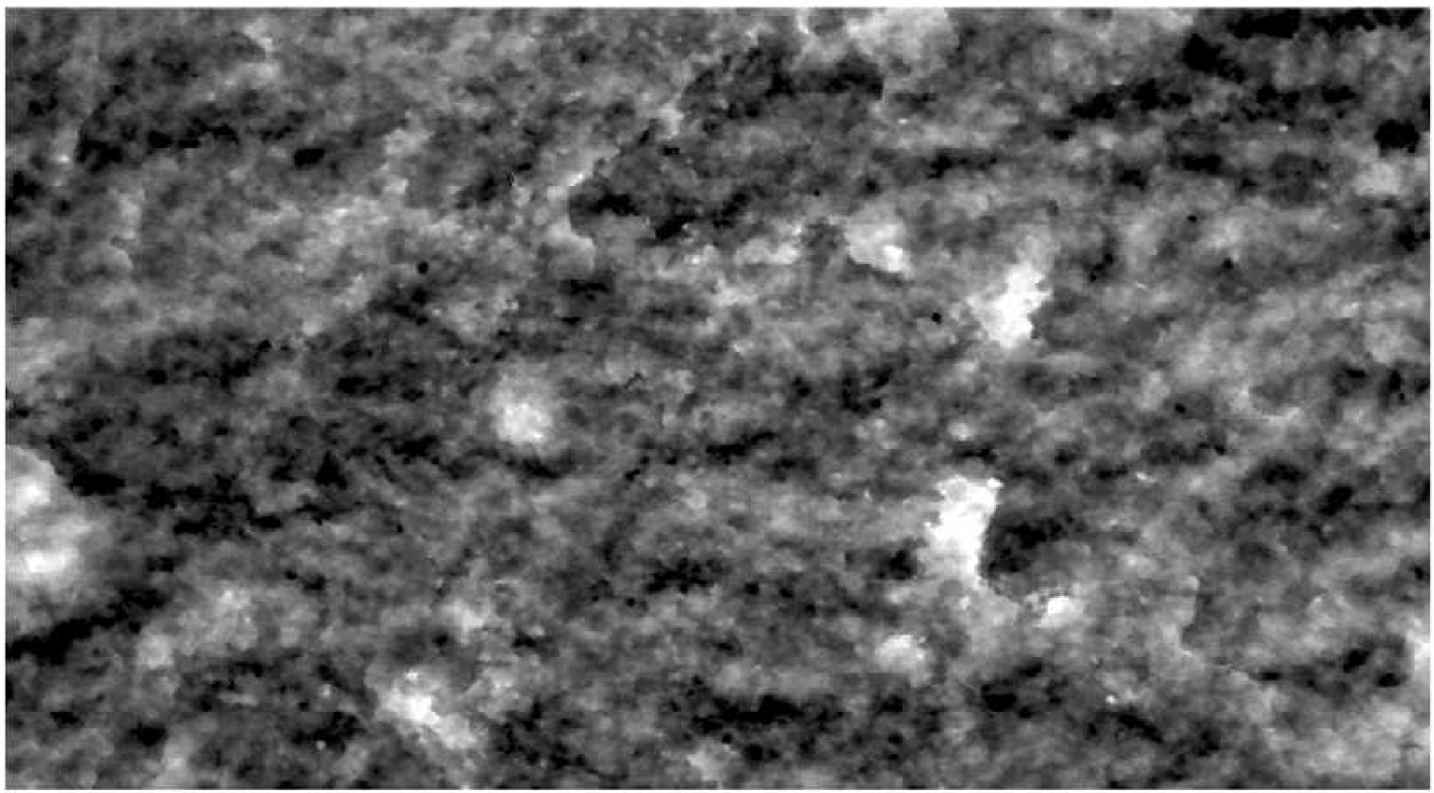
Tomographic Image

- Wildcard: longitudinal "twist" to fracture plane



Tomography: Aperture Width as Intensity

8-bit *grey-scale* image



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3-D Modeling of Aperture

- Tomographic Image of fracture
  - Intensity of each pixel represents aperture distance
  - Extract intensity values
  - Generate 3-D “solid” with one face scaled to aperture irregularities
  - Generate opposite 3-D solid with scaled aperture
  - Match opposing solids so regions with smallest aperture just touch

- Generate fly-through imagery

Visualization of Fracture on Centimeter Scale

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- *Numerical "caricatures" of complex natural fracture systems can be created that capture essential processes in shock propagation*
- There are many sources of quantitative data regarding fracture attributes

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