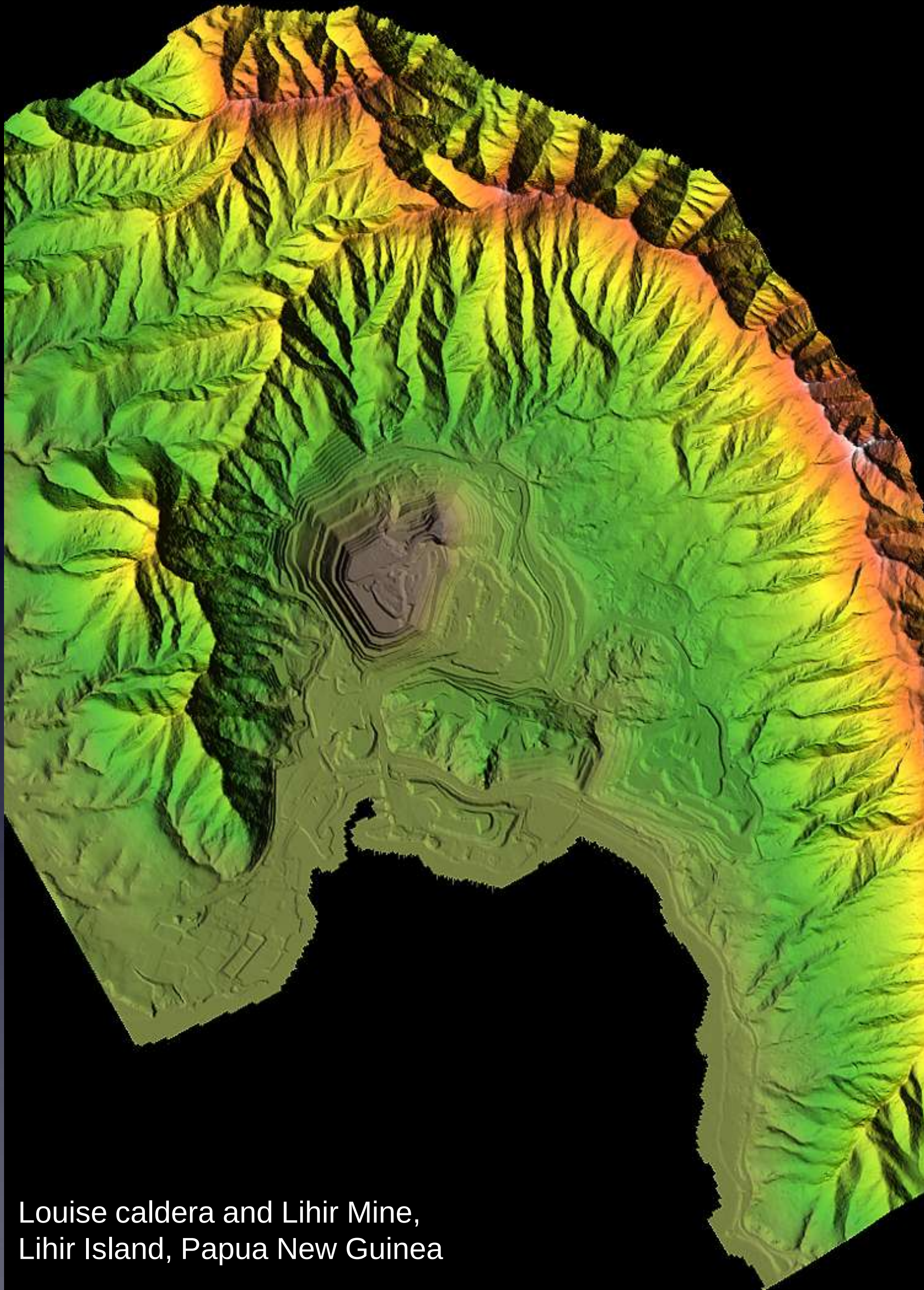
# Using Airborne LiDAR and GIS Technologies for Field Verified Virtual Landslide Hazard Mapping

*A New Approach to an Old Problem with Examples from Papua New Guinea and San Francisco*

William C. Haneberg
*Haneberg Geoscience, Seattle*

Haneberg Geo•science

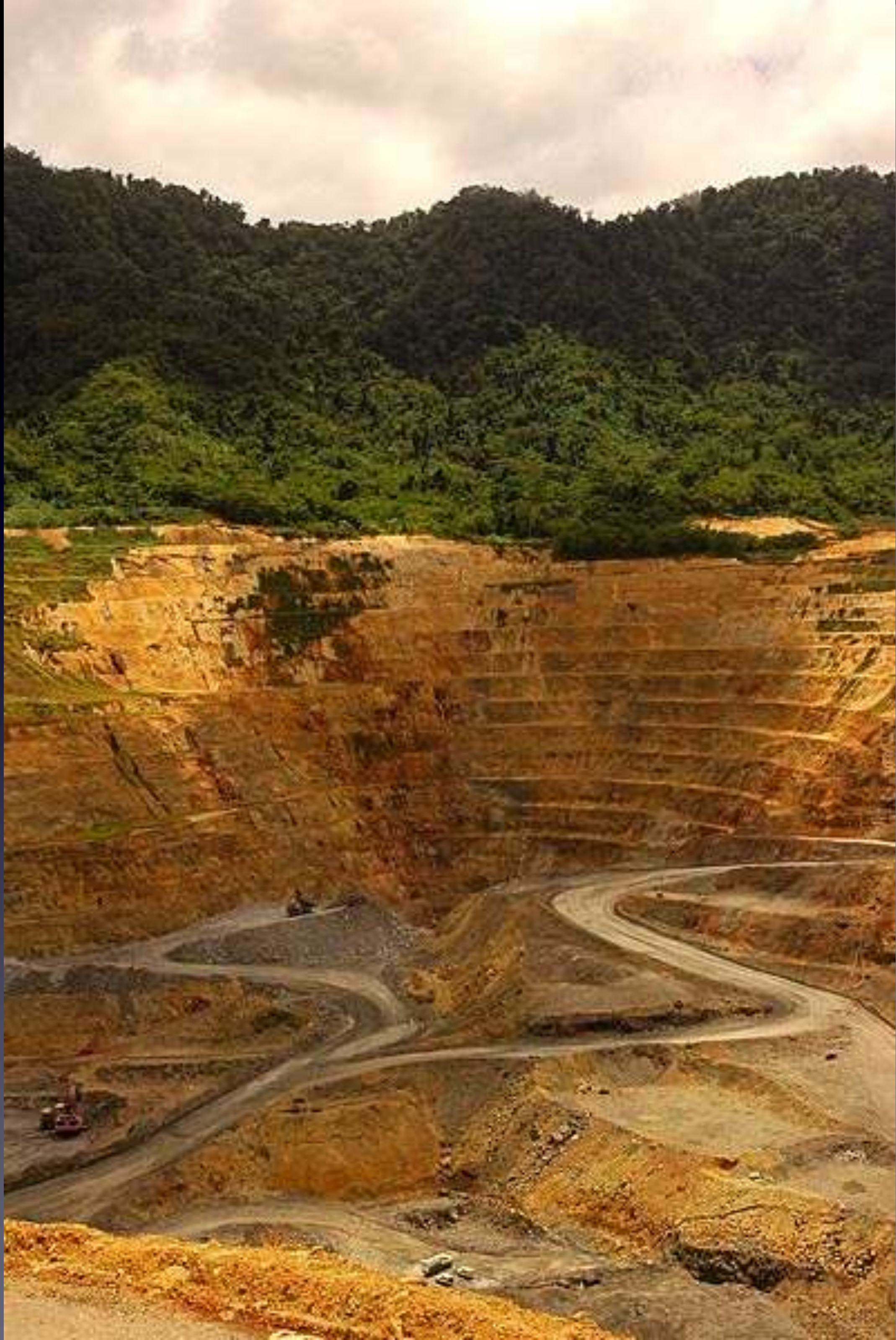
Airborne LiDAR and GIS are fundamentally changing the way we approach fieldwork by offering the ability to map virtually in the office and leverage the value of fieldwork in steep and heavily forested terrain



Louise caldera and Lihir Mine,
Lihir Island, Papua New Guinea

**BUT...**

we geologists rarely come close to utilizing the full potential of either technology!

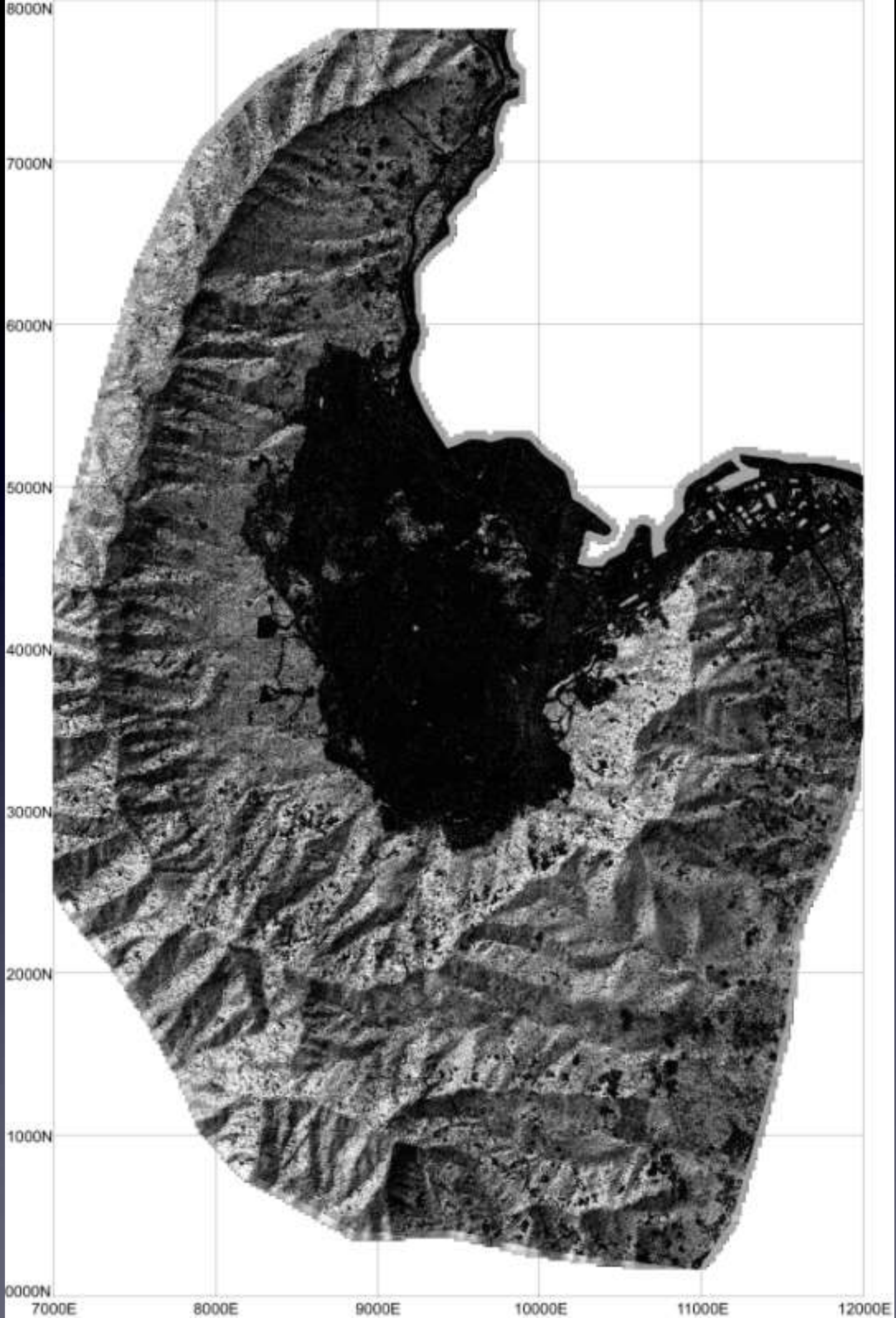


GPS
Z
Y
X
IRS

- Work your LiDAR vendor if you can!
  - Think about geo-applications during project planning
  - Ask for the xyz(i) point cloud
- Create an optimally interpolated DEM
  - Use ground strike density in geologically critical areas
- Create a suite of derivative maps
- Use multi-layered virtual mapping
- Verify and revise virtual maps with fieldwork
- Integrate process-based or empirical models
- Be active, not passive LiDAR users!

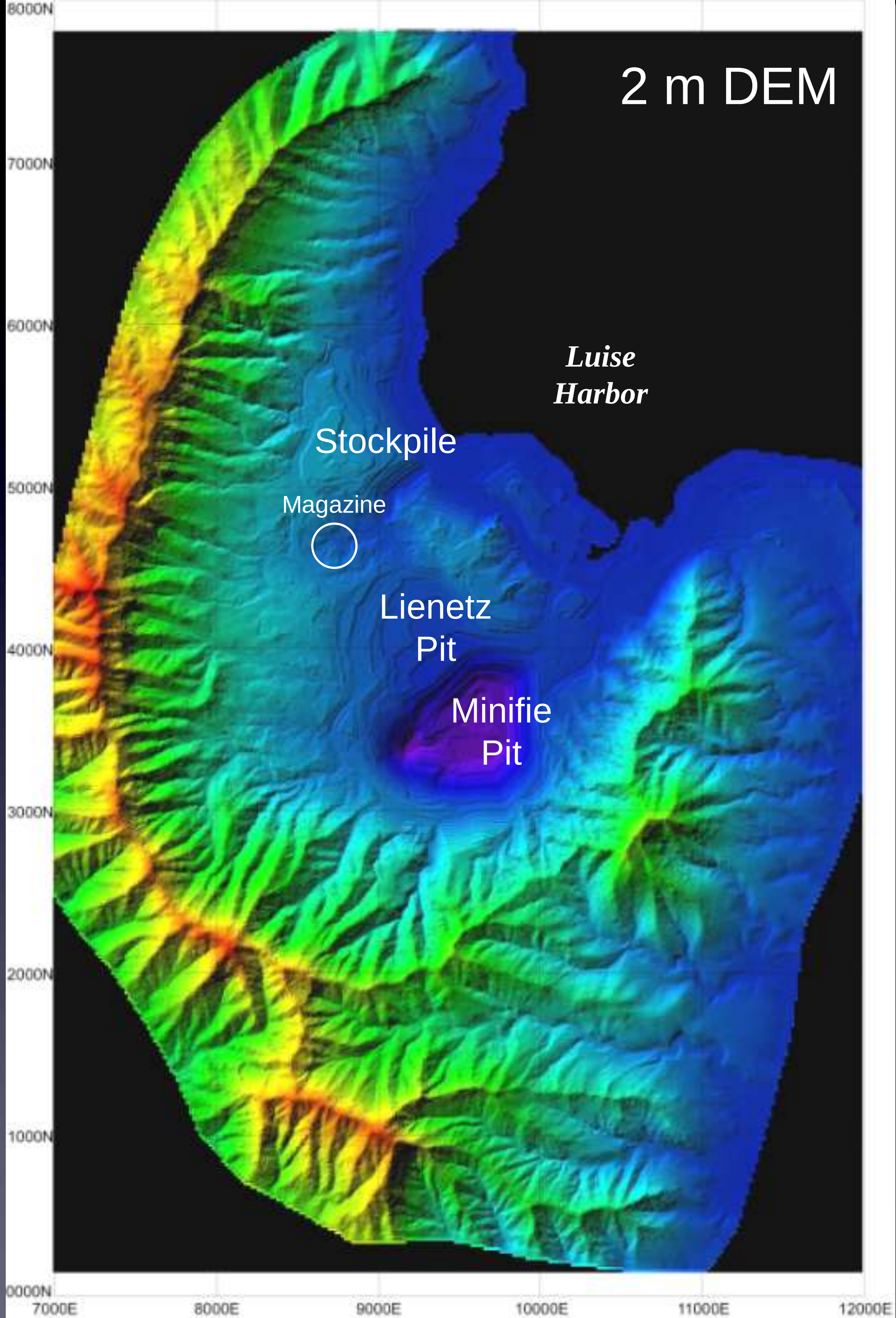
# Point Clouds

- Examine ground strike density and clustering in geologically critical areas
  - Guide DEM creation
  - Assess DEM reliability
- Lihir LiDAR results
  - Onsite processing
  - 3x to 6x coverage
  - 86.2 million non-ground
  - 9.6 million ground
  - 5% canopy penetration



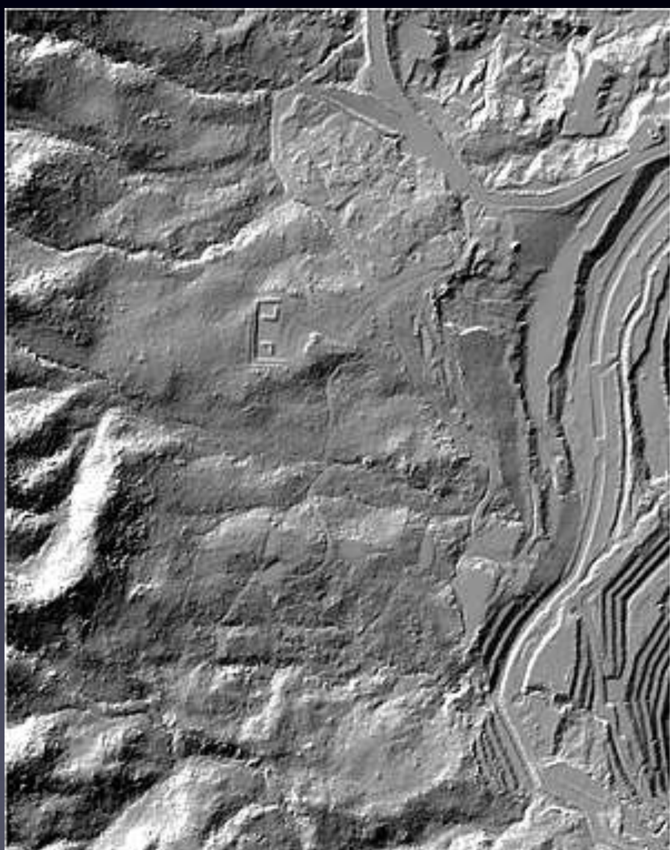
# DEM Creation

- Experienced geologists should supervise DEM creation for geo-mapping
- Use continuously differentiable surfaces
    - Splines with tension ± smoothing
    - Nonlinear natural neighbors
    - Inverse distance
- Never use TINs for geology
    - Ever
    - I mean it!

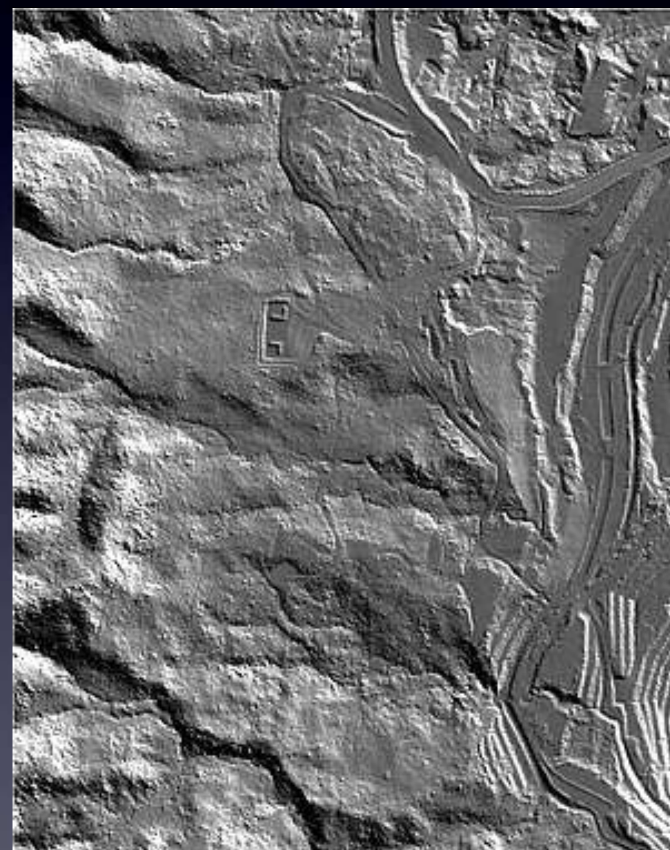


# Multiple shaded relief images

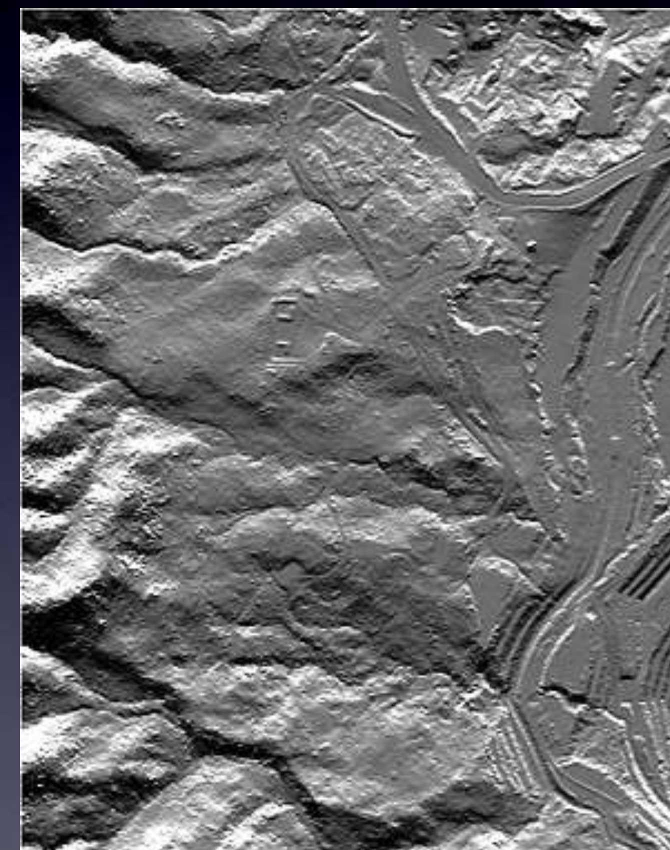
NW Lighting



NE Lighting

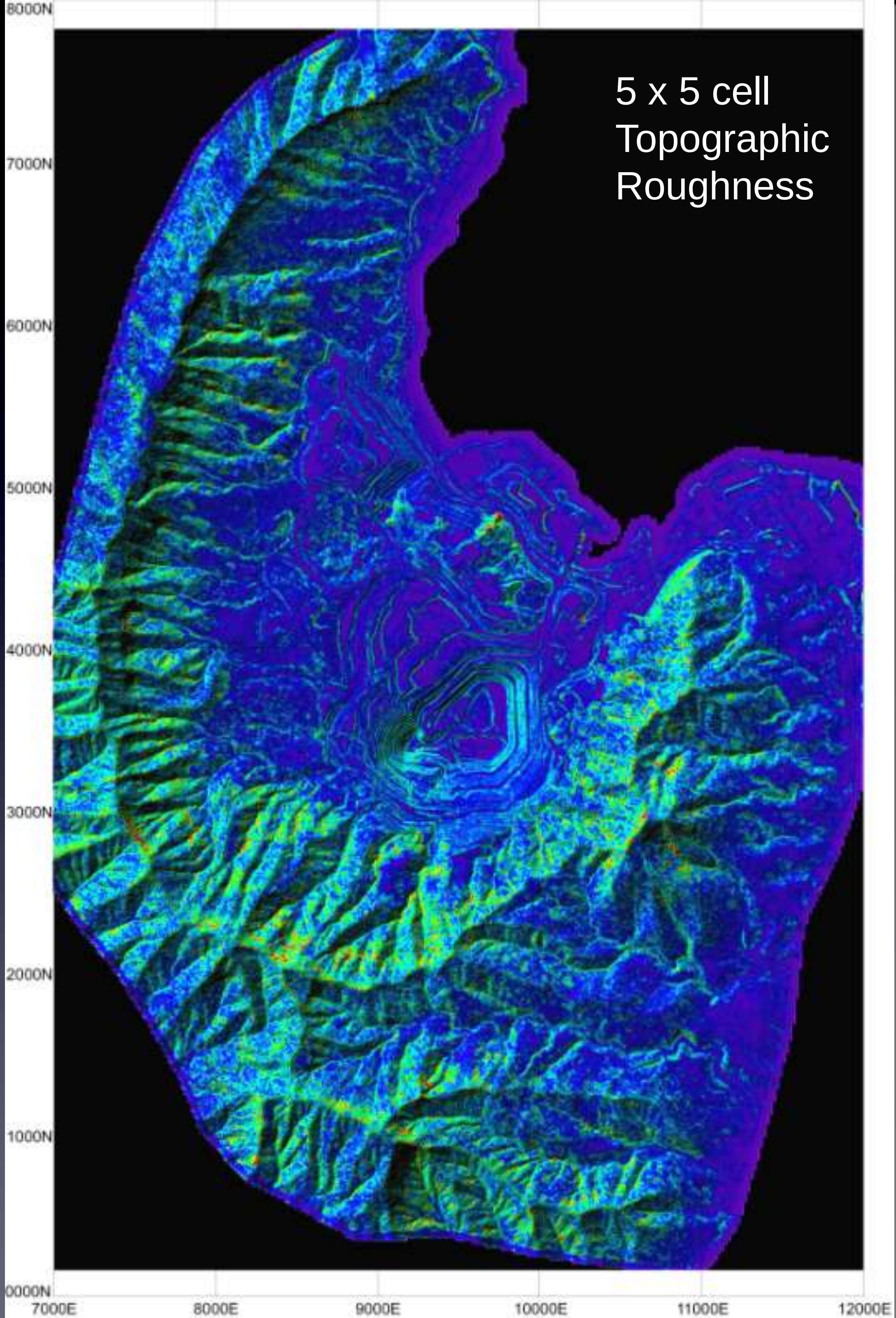


Composite



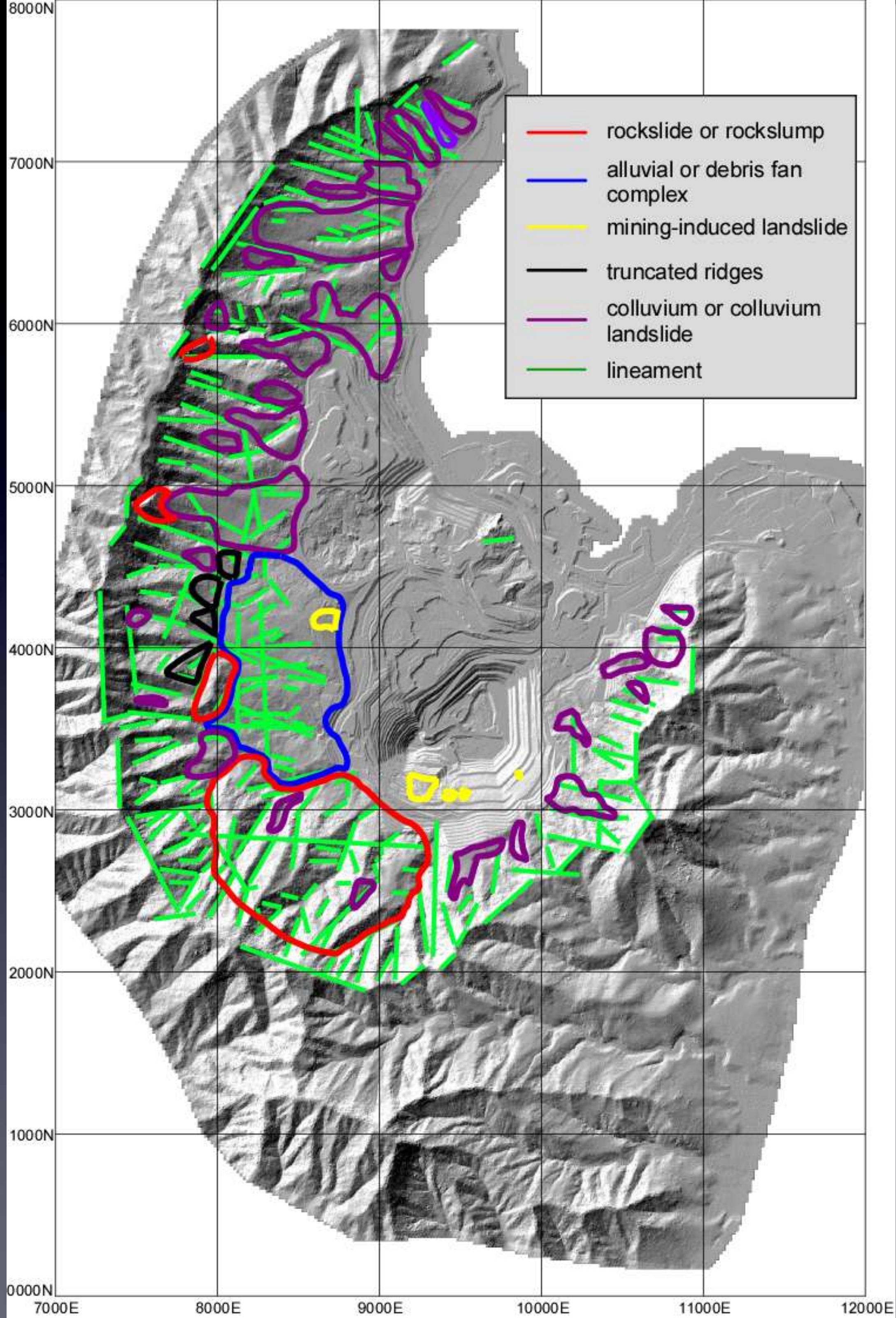
# Derivative Maps

- Slope angle and aspect
- Residual topography
  - Original - Smoothed
- Topographic roughness
  - Residual variability
  - Eigenvalue ratios
  - Laplacian curvature
  - Area ratios
  - Elevation diversity
- Plan and profile curvature
- Smoothing + edge detection



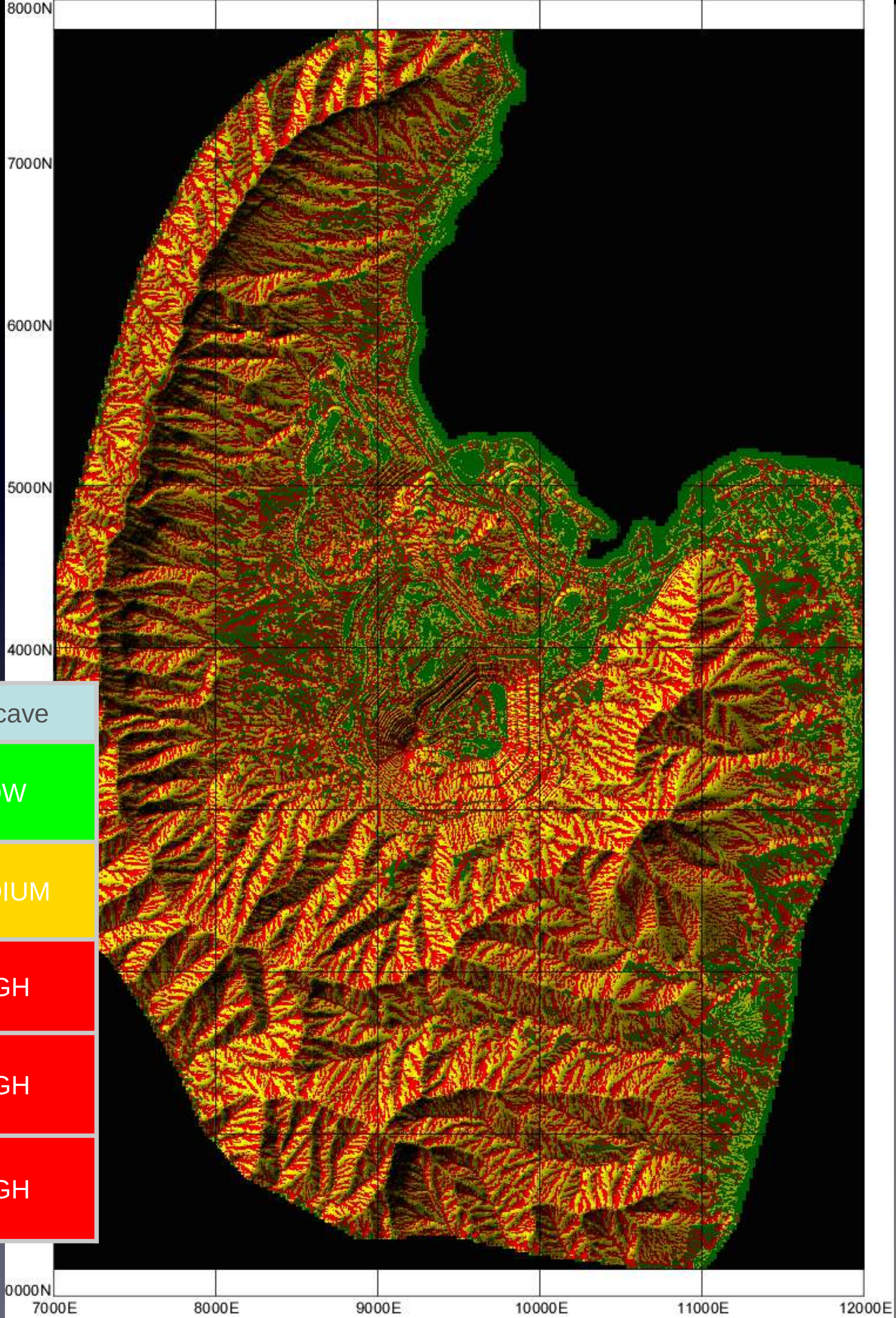
# Virtual Mapping

- Assemble all the layers in a vector drawing program
  - GIS capable if possible
  - Non-LiDAR data, too!
- Put a blank layer on top and map landforms
- Alternate underlying layers to accentuate features of interest
- Refine and revise
- Go to the field
- Refine and revise again



# Empirical Hazard Models

Qualitative shallow landslide and debris flow hazards WA DNR SMORPH model




| | Convex | Planar | Concave |
|---|---|---|---|
| 0° ≤ θ ≤ 6° | LOW | LOW | LOW |
| 6° ≤ θ ≤ 12° | LOW | LOW | MEDIUM |
| 12° ≤ θ ≤ 18° | LOW | LOW | HIGH |
| 18° ≤ θ ≤ 25° | LOW | MEDIUM | HIGH |
| θ > 25° | MEDIUM | HIGH | HIGH |

# LiDAR Based Landslide Hazard Mapping and Modeling Using a Multi-layered GIS Approach, UCSF Parnassus Campus, San Francisco, California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William F. Cole

*GeoInsite, Los Gatos*

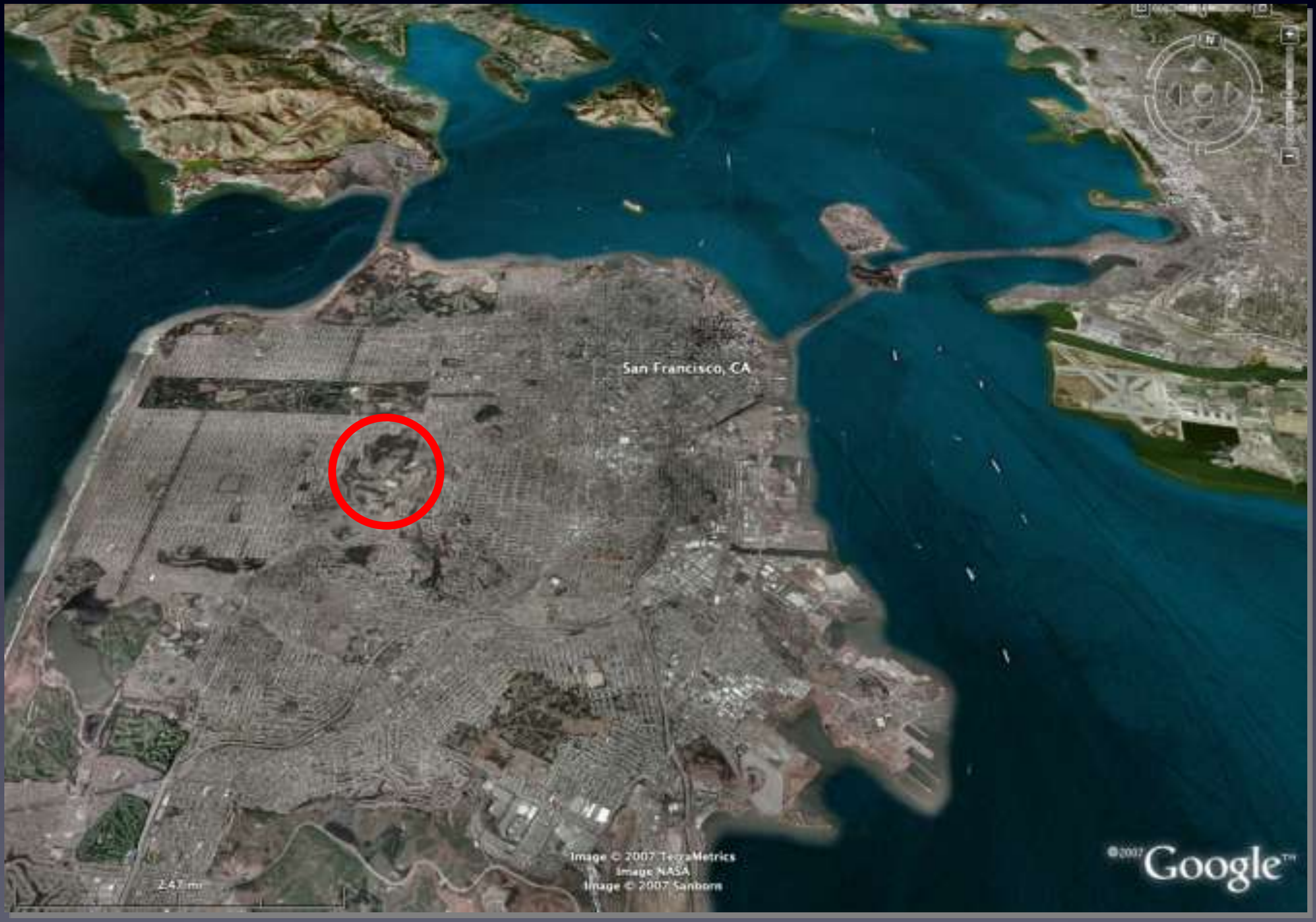
Gyimah Kasali

*Rutherford & Chekene, San Francisco*


Haneberg Geo•science

# Objective

- Perform a slope hazard assessment of the UCSF Parnassus Campus on steep and heavily forested Mount Sutro in San Francisco




**USGS Orthophoto**
**30 cm (1 foot) Resolution Obtained 2/27/04**

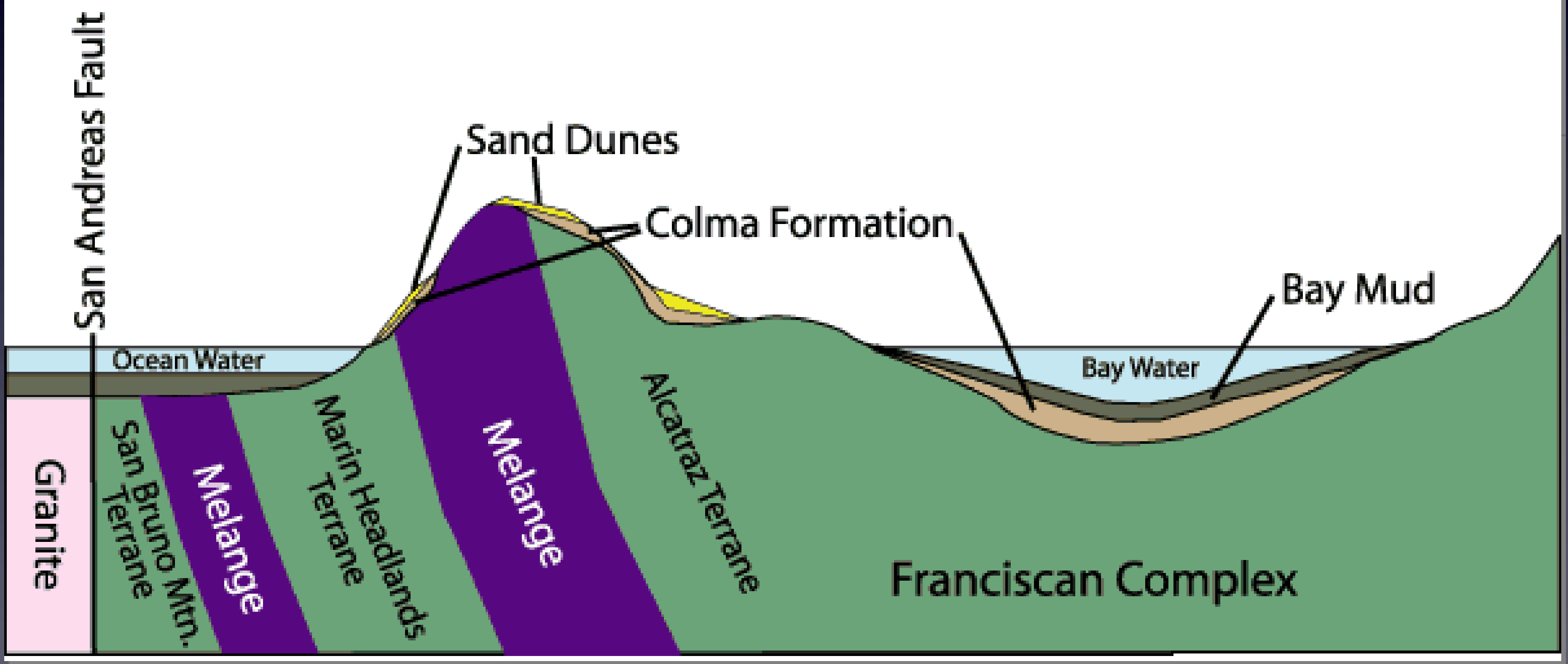
**UCSF Slope Stability Risk Assessment**
Rutherford & Chekene June 2006

# Approach

- Create a high resolution topographic base using airborne LiDAR
- Perform field-based engineering geologic mapping of accessible areas
- Incorporate existing borehole data and geotech reports
- Refine the maps using multi-layered virtual mapping techniques in the office
- Use physics-based probabilistic slope stability modeling to evaluate static and seismic extremes
- DEM based watershed delineation*

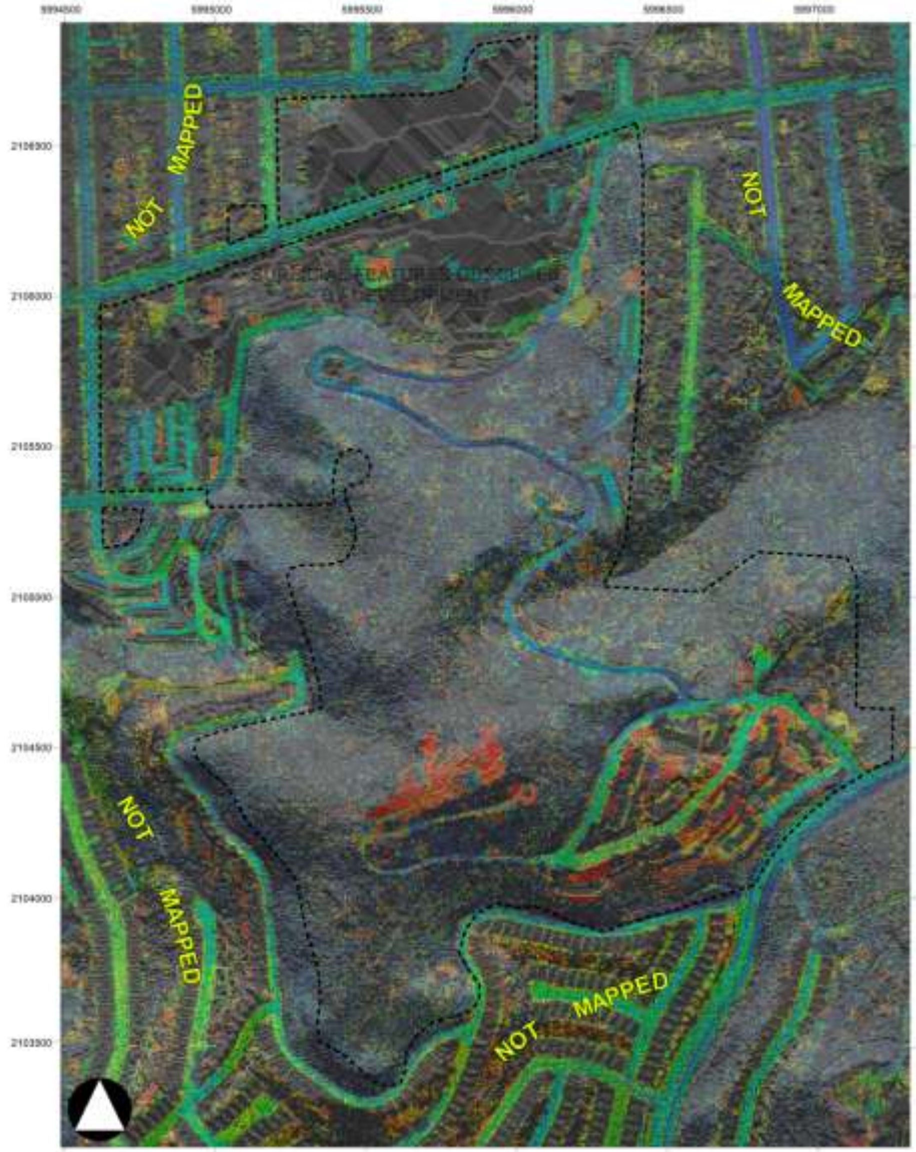
# West - East X-Section

## Northern San Francisco Peninsula to Oakland




source: National Park Service

| LiDAR Quality | Flying Altitude | FEMA Contour Interval | Typical LiDAR Spot Spacing | Vertical RMSE |
|---|---|---|---|---|
| High | 3000’ | 1.0’ | 3.3’ | 0.3’ |
| Standard | 4500’ | 2.0’ | 4.5’ | 0.6’ |
| Low | 6500’ | 3.3’ | 6.5’ | 1.0’ |




Campus boundaries are approximate and based on data supplied by UCSF

500 0 500 1000 feet

scale 1:3750

Grid Ticks: California State Plane Zone 3, US Survey Feet NAD83 HARN

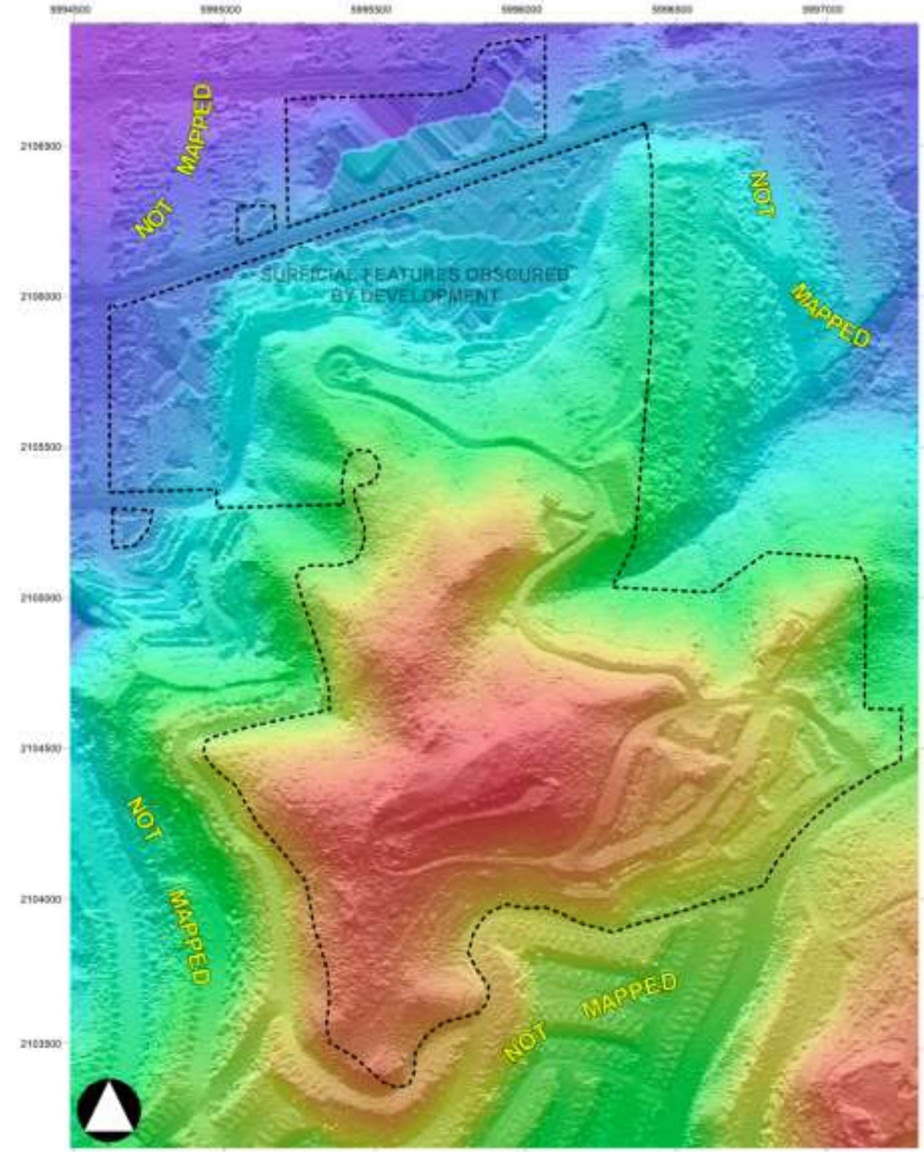
high intensity

low intensity

**Map 1: Log$_{10}$ LiDAR Return Intensity**

**UCSF Slope Stability Risk Assessment**

Rutherford & Chekene June 2006




Campus boundaries are approximate and based on data supplied by UCSF

500 0 500 1000 feet

scale 1:3750

Grid Ticks: California State Plane Zone 3, US Survey Feet NAD83 HARN

elevation in feet (NAVD 88)

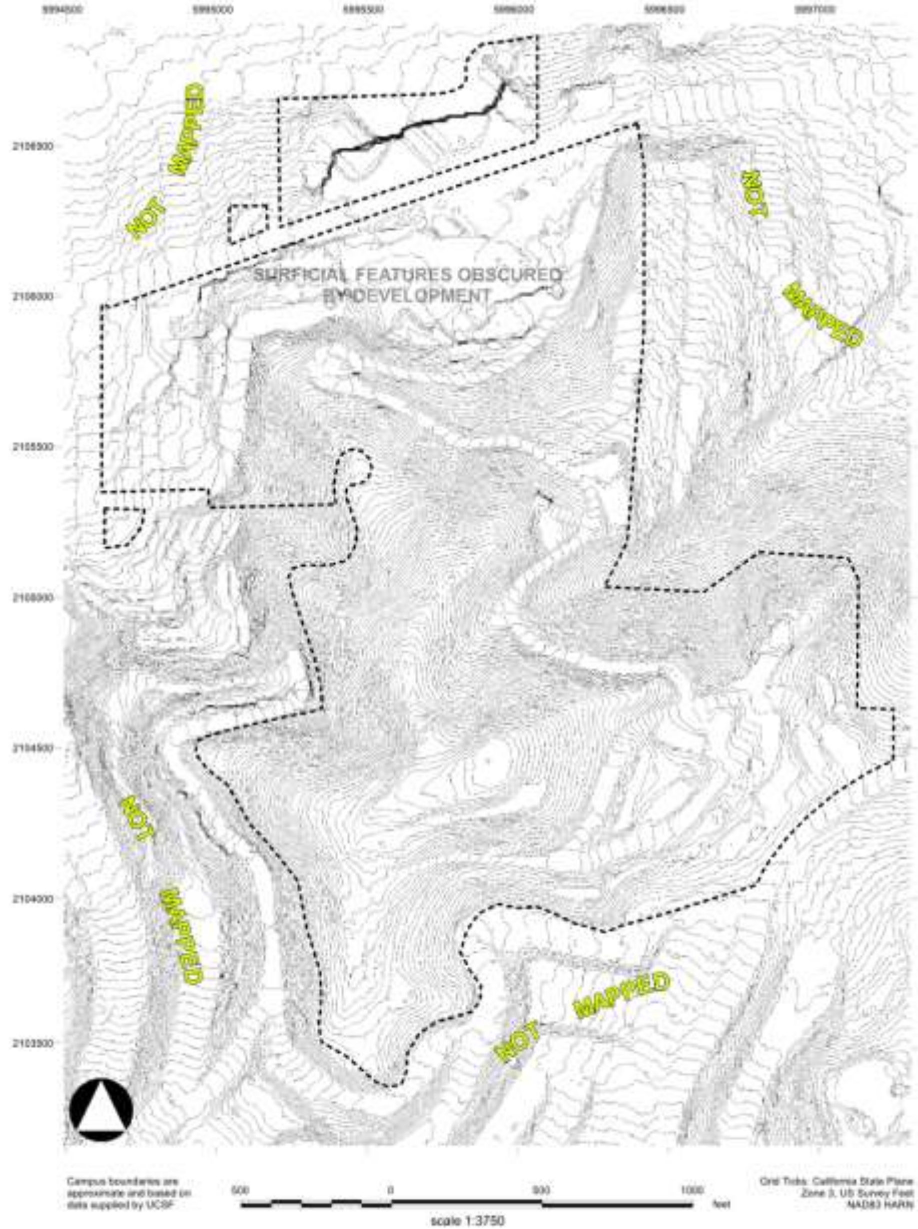
278 916

**Map 2: Digital Elevation Model**

2 Foot Grid Spacing

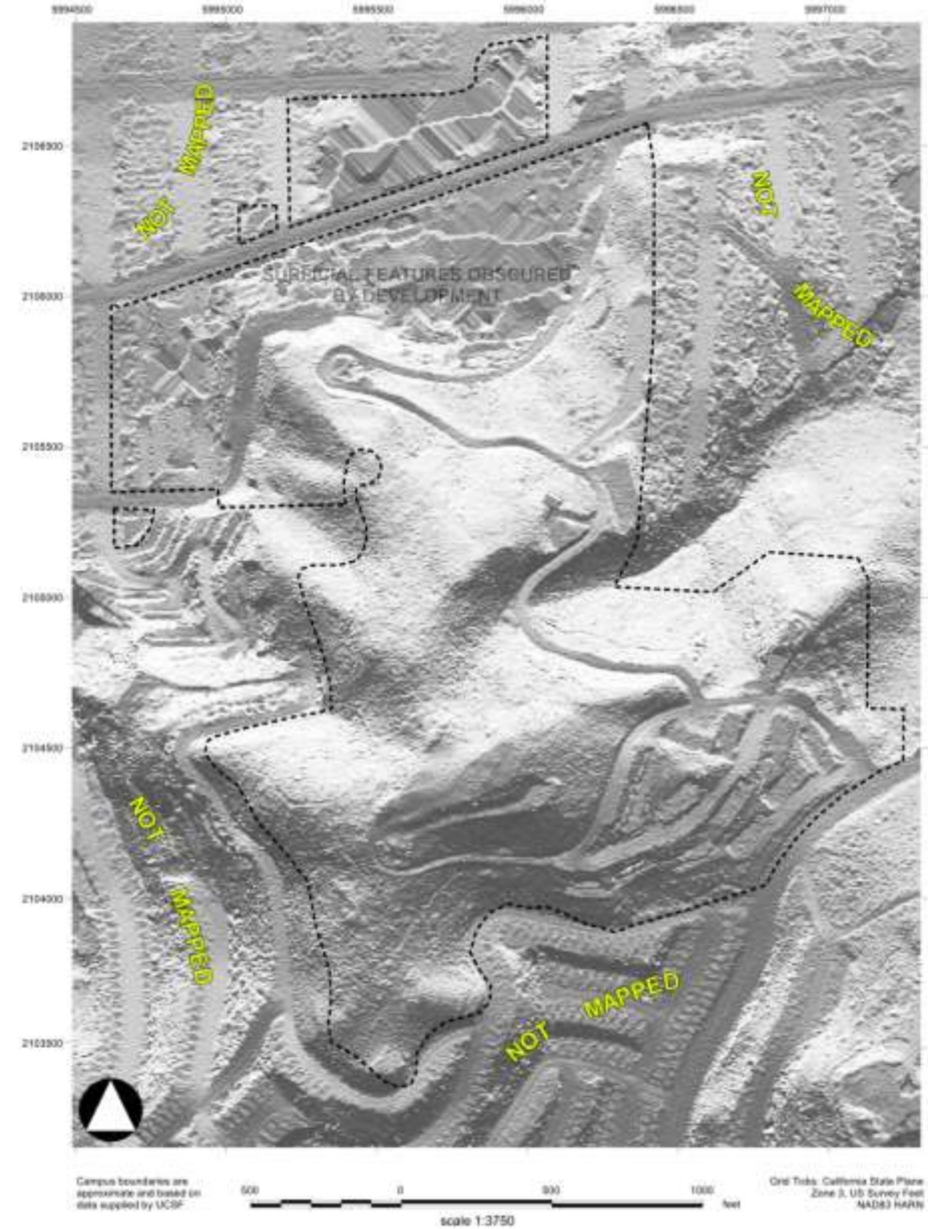
**UCSF Slope Stability Risk Assessment**

Rutherford & Chekene June 2006




**Map 4: Topographic Contours**
5 Foot Contour Interval

**UCSF Slope Stability Risk Assessment**
Rutherford & Chekene June 2006




**Map 5: Shaded Relief Image**
Simulated omnidirectional illumination

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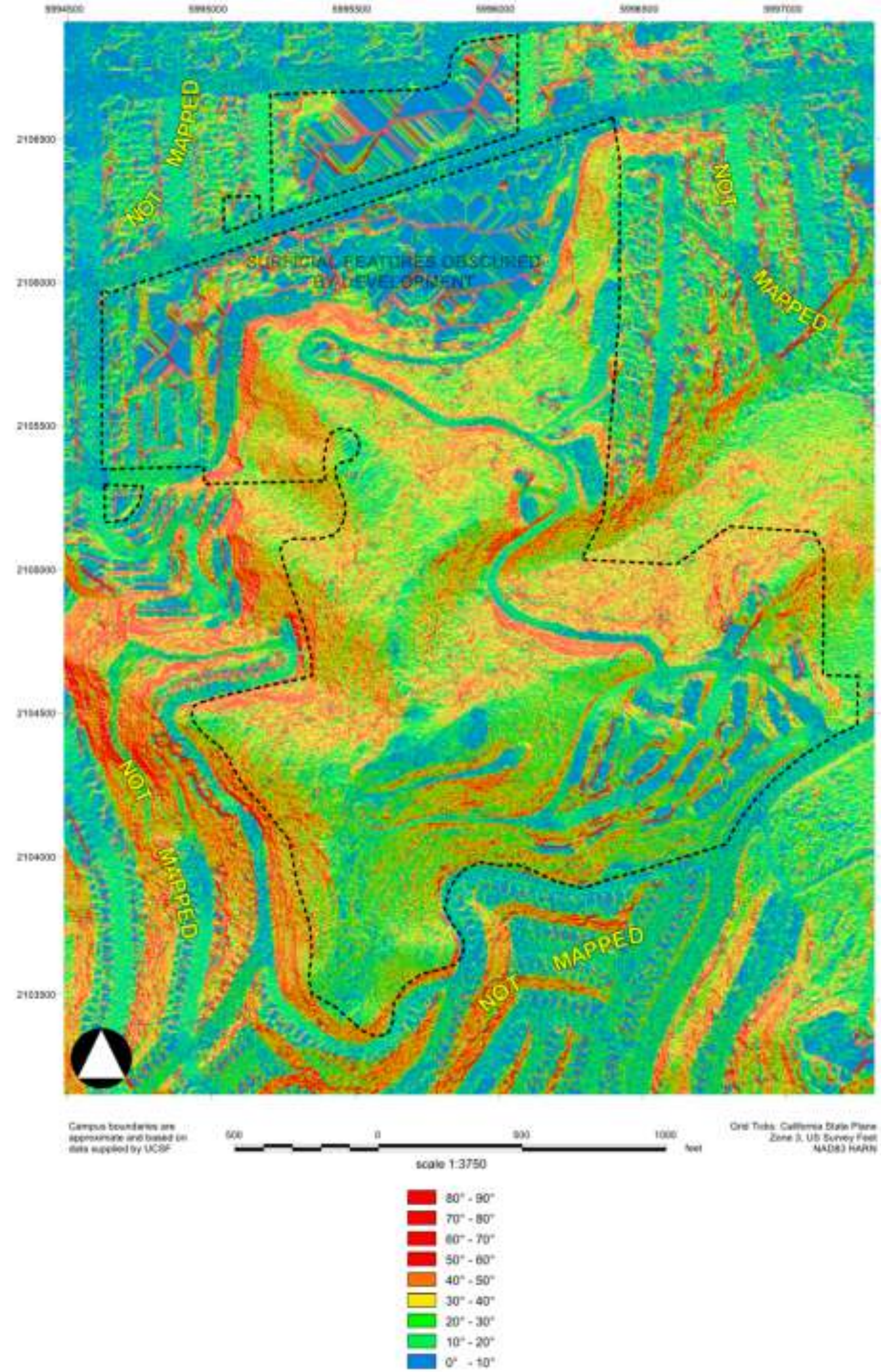
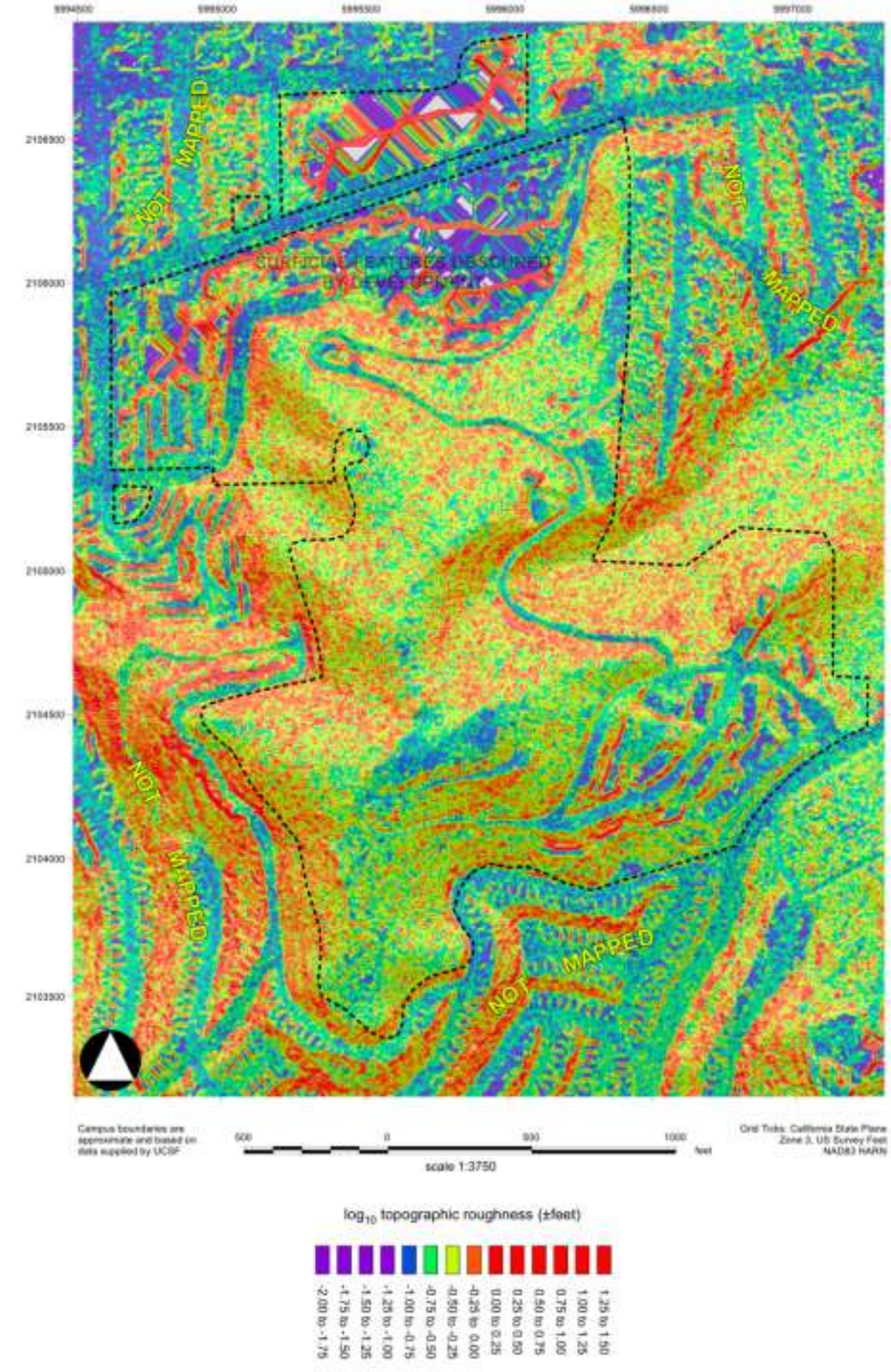
Rutherford & Chekene June 2006



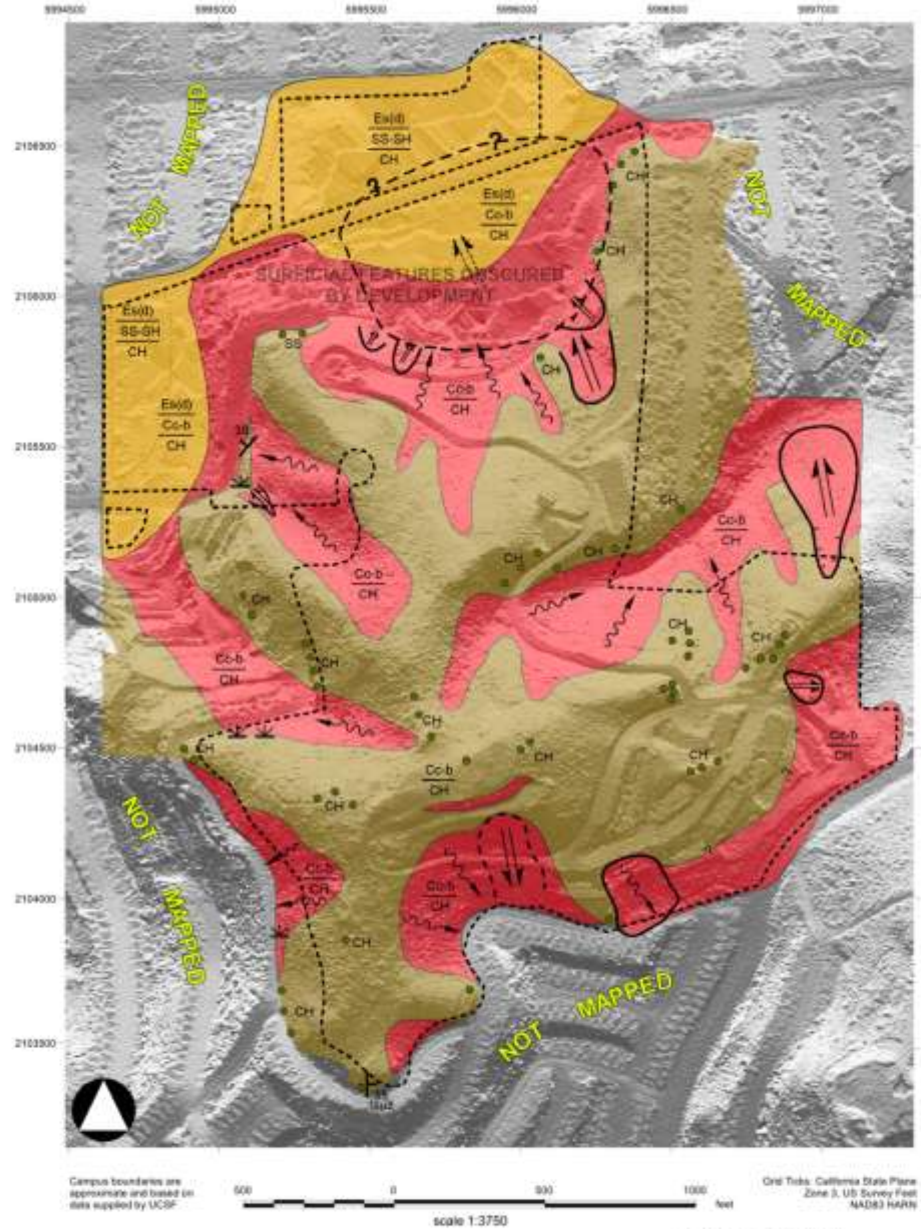

**Map 6: Maximum Slope Angle**

**UCSF Slope Stability Risk Assessment**
Rutherford & Chekene June 2006




**Map 7: Topographic Roughness**
**5 Cell Moving Window**

**UCSF Slope Stability Risk Assessment**
Rutherford & Chekene June 2006



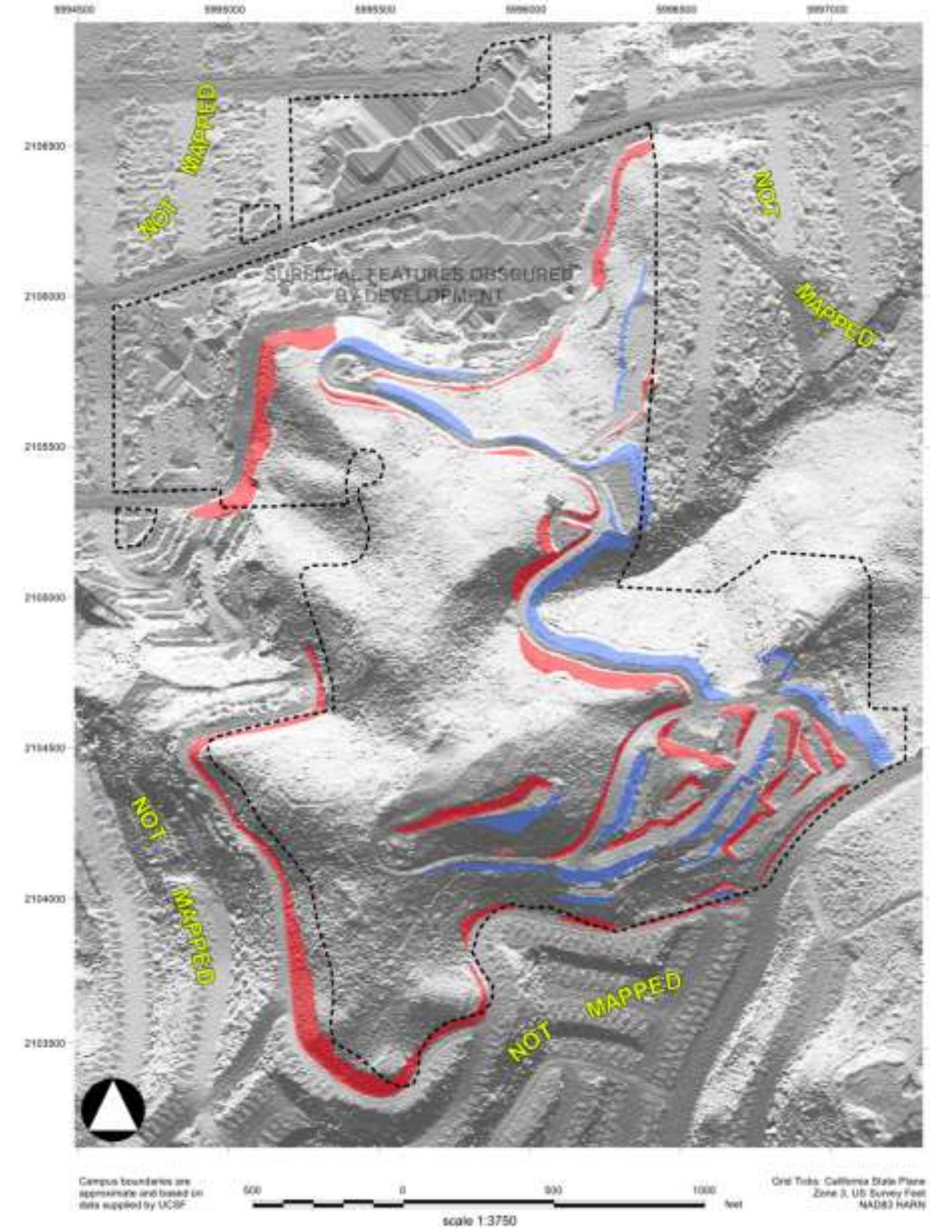

| | |
|---|---|
| Es(d) | Eolian sand (dune) |
| Cc-b | Colluvium, clayey-bouldery |
| CH | Chert (Franciscan) |
| not exposed SS | Sandstone (primarily Colma Formation, some Franciscan) |
| SS | Shale (Colma Formation) |

Stacked units indicate stratigraphic sequences. Map symbols based on the Unified Engineering Geologic Mapping System (Keaton & DeGraff, 1994). Geologic contacts dashed and/or queried where uncertain.

- soil creep, showing direction of movement
- landslide, showing direction of movement
- seep or spring
- strike and dip of planar feature (bedding unless noted)
- bedrock outcrop

**Map 9: Engineering Geologic Map**

**UCSF Slope Stability Risk Assessment**
Rutherford & Chekene June 2006



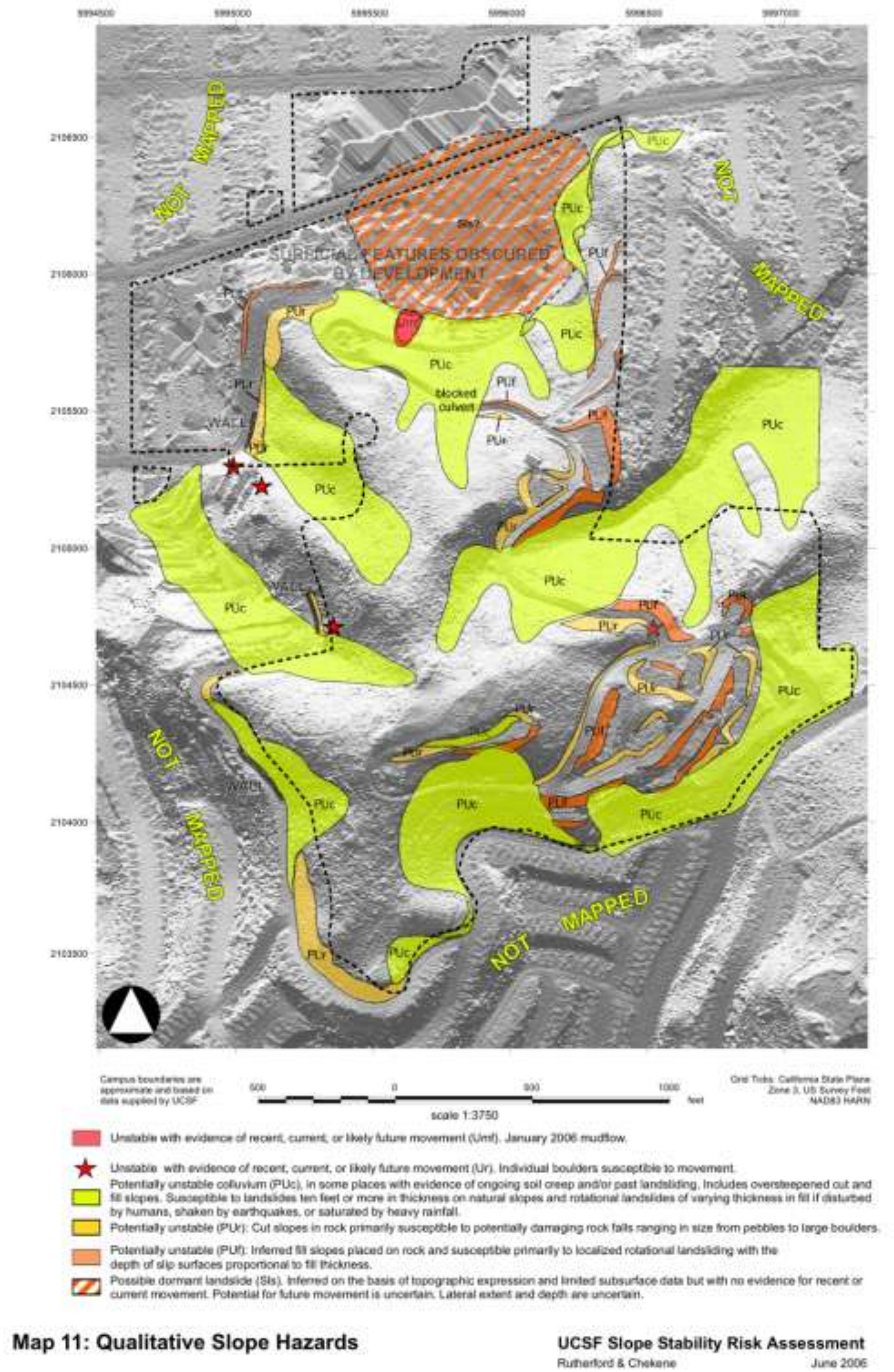

- Cut slopes
- Fill slopes

Cut and fill slopes inferred on the basis of field observations, topographic breaks shown on LiDAR imagery, and a general knowledge of construction practices. Boundaries are approximate and some cuts or fills may not be shown.

**Map 10: Cut and Fill Slopes**

**UCSF Slope Stability Risk Assessment**
Rutherford & Chekene June 2006

active landslides or rockfalls
potentially unstable colluvium
potentially unstable cut slopes
potentially unstable fill slopes



# PISA-m Modeling

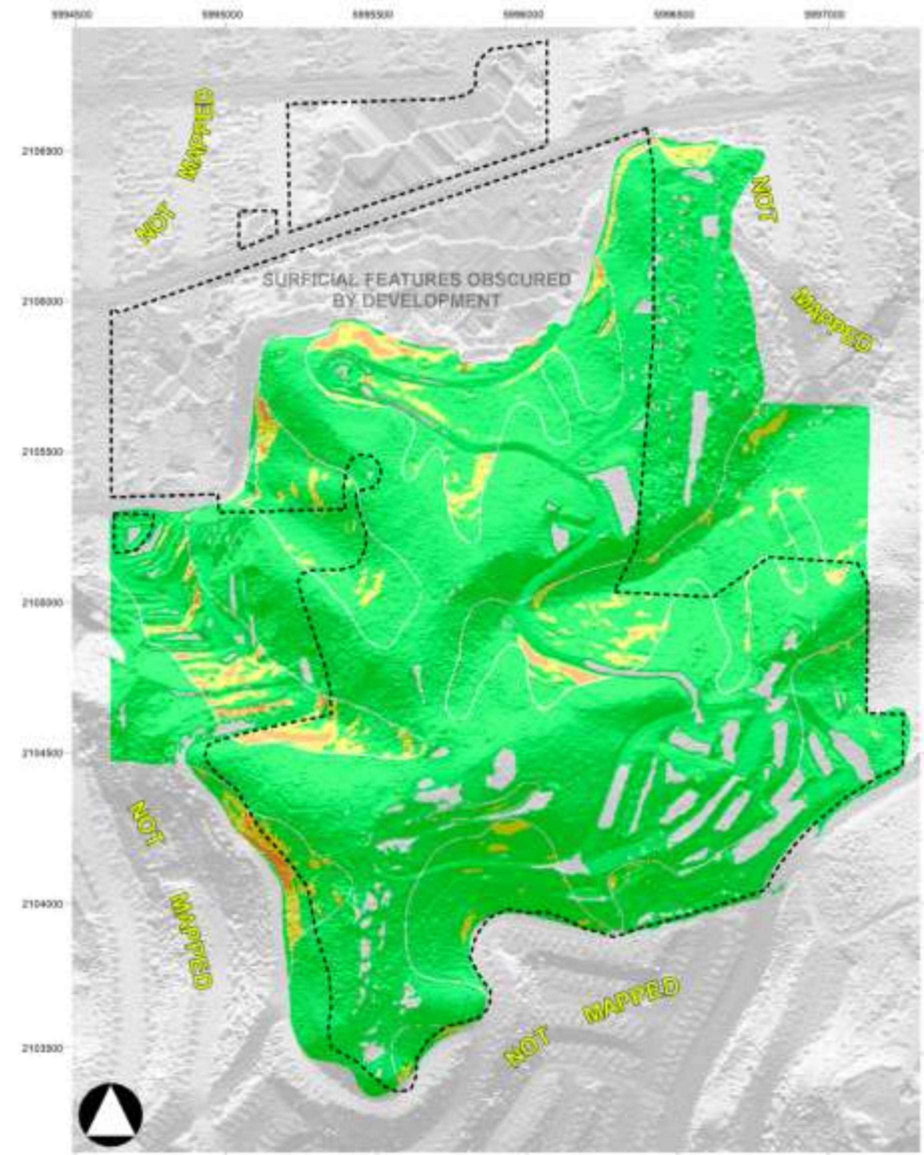
- Map-based probabilistic infinite slope stability using FOSM approximations
    - Haneberg, 2004, *Environmental & Engineering Geoscience*
- Incorporates input uncertainties using probability distributions
    - Similar to USFS LISA
- Calculates FS mean, standard deviation, Prob FS ≤ 1 plus seismic results
- Geotechnical input defined by engineering geologic map units
    - Thin colluvium over bedrock
    - Thick colluvium in hollows
- Three scenarios for this project
    - Wet static, wet seismic, dry seismic

# Wet Thin Colluvium

| Variable | Distribution | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|
| phi | normal | 30° | ±1.67° | | |
| c | normal | 400 psf | ±130 psf | | |
| thickness | normal | 2.5 feet | ±0.84 feet | | |
| h | normal | 0.5 | ±0.084 | | |
| moist weight | uniform | | | 100 pcf | 120 pcf |
| sat weight | uniform | | | 120 pcf | 130 pcf |
| root cohesion | normal | 100 psf | ±32 psf | | |
| tree surcharge | none | 0 | | | |

# Wet Thick Colluvium

| Variable | Distribution | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|
| phi | normal | 30° | ±1.67° | | |
| c | normal | 400 psf | ±130 psf | | |
| thickness | normal | 10 feet | ±3 feet | | |
| h | normal | 0.75 | ±0.084 | | |
| moist weight | uniform | | | 100 pcf | 120 pcf |
| sat weight | uniform | | | 120 pcf | 130 pcf |
| root cohesion | none | 0 | | | |
| tree surcharge | none | 0 | | | |




Campus boundaries are approximate and based on data supplied by UCSF

500 0 500 1000 feet

scale 1:3750

Grid Ticks: California State Plane Zone 3, US Survey Feet NAD83 HARN

**Prob [ FS ≤ 1]**

- $0.75 < p \leq 1.00$
- $0.50 < p \leq 0.75$
- $0.25 < p \leq 0.50$
- $0.00 < p \leq 0.25$
- not calculated*

Probability that the calculated static factor of safety (FS) is less than 1 for the geotechnical soil properties described in the accompanying report. Values near 1 indicate a high probability that movement will occur under the specified conditions. Values near 0 indicate a low probability that movement will occur under the specified conditions. Calculations were based on the first-order, second-moment method described in Haneberg (2004, A rational probabilistic method for spatially distributed landslide hazard assessment: *Environmental & Engineering Geoscience*, v. 10, p. 23-47).

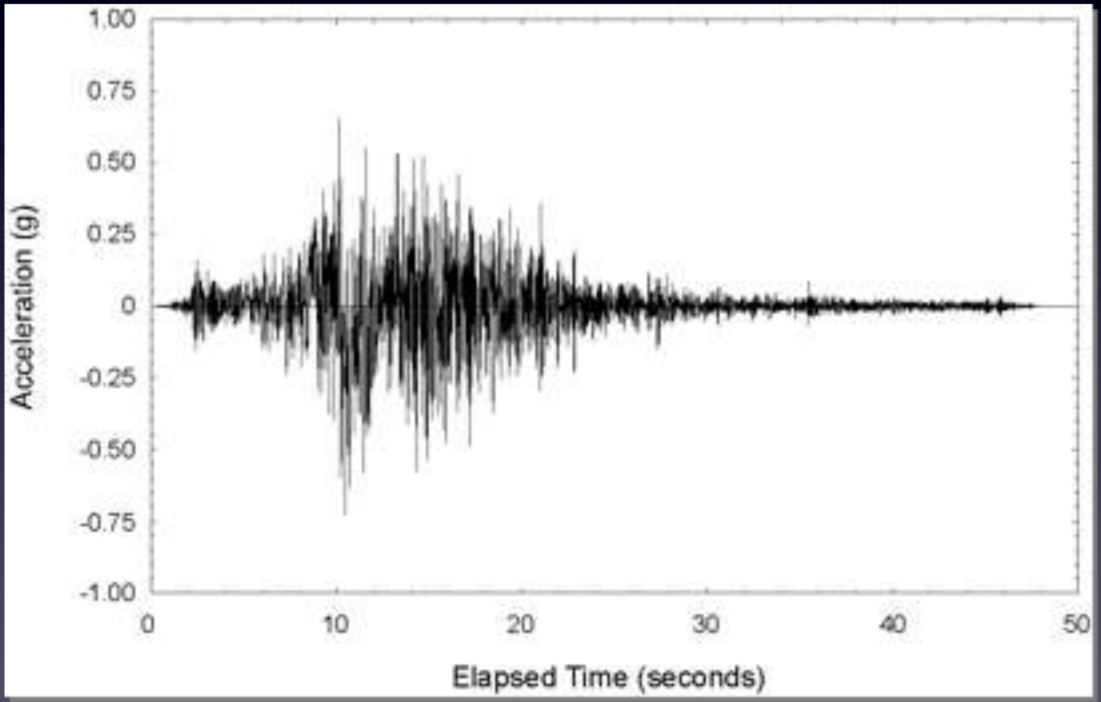
*slope < 5° or outside model boundary

**Map 12: Probabilistic Slope Stability**
**Wet Static Conditions (Revised model of March 2007)**

**UCSF Slope Stability Risk Assessment**
Rutherford & Chekene June 2006

# Model Earthquake

- 1992 Landers M 7.3
- Southern California Edison Lucerne station
    - Wilson *et al*, 2000, CDMG Seismic Hazard Zone Report 043
    - $I_A$ = 7 m/s from 260° record
- Jibson's simplified Newmark method
    - Prob $D_N$ > 30 cm



Campus boundaries are approximate and based on data supplied by UCSF

500 0 500 1000 feet

scale 1:3750

Grid Ticks: California State Plane Zone 3, US Survey Feet NAD83 HARN

**Prob [ $D_N$ > 30 cm]**

| | |
|---|---|
| red | $0.75 < p \leq 1.00$ |
| orange | $0.50 < p \leq 0.75$ |
| yellow | $0.25 < p \leq 0.50$ |
| green | $0.00 < p \leq 0.25$ |
| white | not calculated* |

*slope < 5° or outside model boundary

Probability that the calculated Newmark displacement ($D_N$) is greater than 30 cm for the geotechnical soil properties described in the accompanying report and an earthquake of Arias intensity $I_A$ = 7 m/s. Values near 1 indicate a high probability that movement will occur under the specified conditions. Values near 0 indicate a low probability that movement will occur under the specified conditions. Calculations were based on the first-order, second-moment method described in Haneberg (2004, A rational probabilistic method for spatially distributed landslide hazard assessment: *Environmental & Engineering Geoscience*, v. 10, p. 23-47) and the regression model developed by Jibson et al (2000, A method for producing digital probabilistic seismic landslide hazard maps: *Engineering Geology*, v. 58, p. 271-289).

**Map 13: Probabilistic Slope Stability**

**Wet Seismic Conditions ($I_A$ = 7 m/s) (Revised model of March 2007)**

**UCSF Slope Stability Risk Assessment**

Rutherford & Chekene June 2006

Campus boundaries are approximate and based on data supplied by UCSF

500 0 500 1000 feet

scale 1:3750

Grid Ticks: California State Plane Zone 3, US Survey Feet NAD83 HARN

**Prob [ $D_N$ > 30 cm]**

| | |
|---|---|
| red | $0.75 < p \leq 1.00$ |
| orange | $0.50 < p \leq 0.75$ |
| yellow | $0.25 < p \leq 0.50$ |
| green | $0.00 < p \leq 0.25$ |
| white | not calculated* |

*slope < 5° or outside model boundary

Probability that the calculated Newmark displacement ($D_N$) is greater than 30 cm for the geotechnical soil properties described in the accompanying report and an earthquake of Arias intensity $I_A$ = 7 m/s. Values near 1 indicate a high probability that movement will occur under the specified conditions. Values near 0 indicate a low probability that movement will occur under the specified conditions. Calculations were based on the first-order, second-moment method described in Haneberg (2004, A rational probabilistic method for spatially distributed landslide hazard assessment: *Environmental & Engineering Geoscience*, v. 10, p. 23-47) and the regression model developed by Jibson et al (2000, A method for producing digital probabilistic seismic landslide hazard maps: *Engineering Geology*, v. 58, p. 271-289).

**Map 14: Probabilistic Slope Stability**

**Dry Seismic Conditions ($I_A$ = 7 m/s) (Revised model of March 2007)**

**UCSF Slope Stability Risk Assessment**

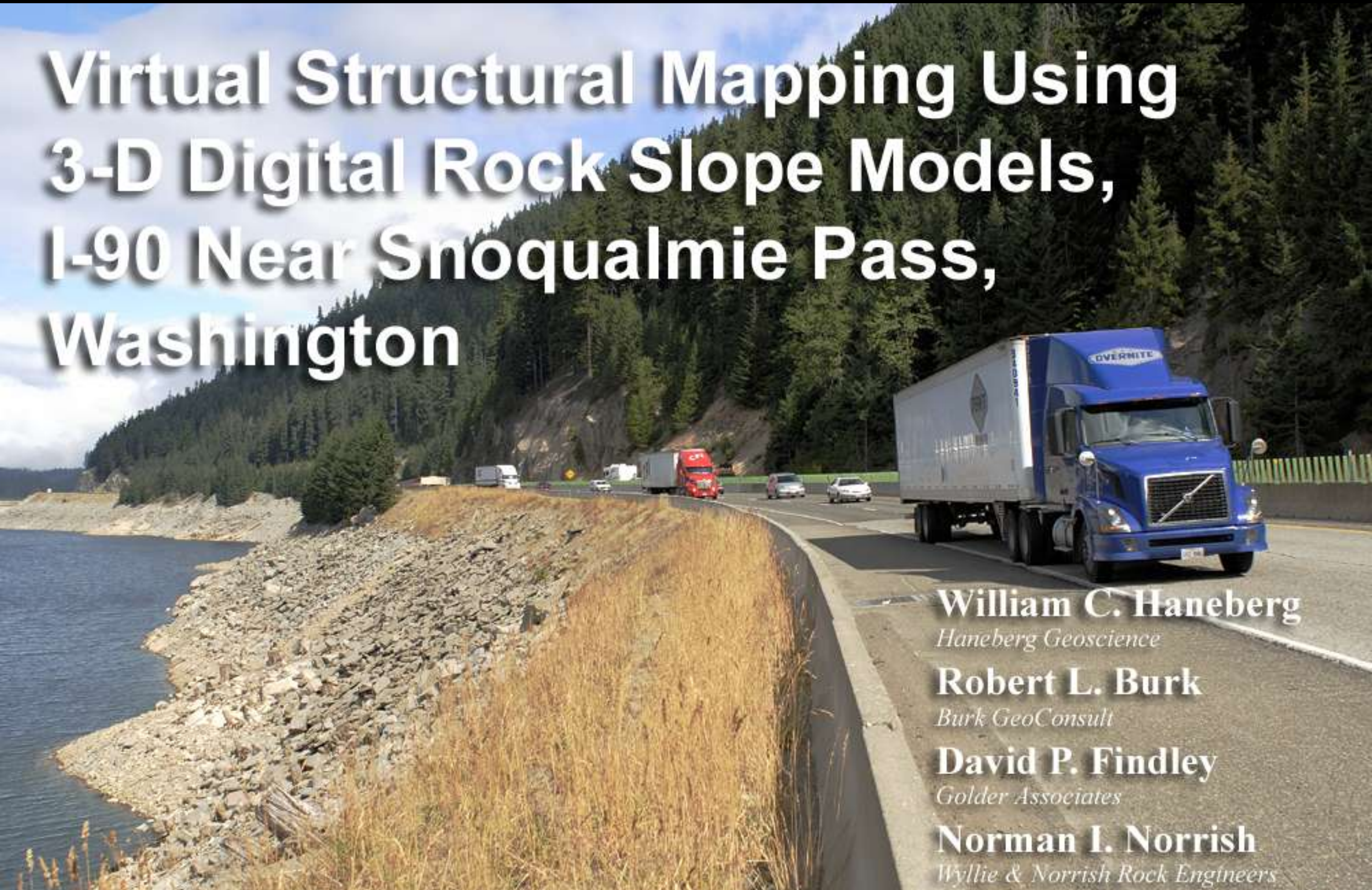
Rutherford & Chekene June 2006

# Summary

- High-res airborne LiDAR provided an invaluable topographic base for engineering geologic mapping in steep urban forest land
- Combination of field mapping and office-based virtual mapping using georeferenced LiDAR derivative maps leveraged the value of fieldwork
- Physics-based probabilistic modeling allowed analysis of rare conditions that would have been impossible to evaluate using field observations alone
- Qualitative hazard maps and quantitative probabilistic model results complement each other by providing insight into a variety of possible landslide scenarios

Haneberg Geo•science

# Virtual Structural Mapping Using 3-D Digital Rock Slope Models, I-90 Near Snoqualmie Pass, Washington




**William C. Haneberg**
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*Burk GeoConsult*
**David P. Findley**
*Golder Associates*
**Norman I. Norrish**
*Wyllie & Norrish Rock Engineers*


Snoqualmie Pass East
Hyak-Keechelus Dam
Summer 2006
90
Midway Curve
Milepost 66
Winter 2006
Nf-4823
Image © 2007 TerraMetrics
© 2007 Navteq
© 2007 Europa Technologies
© 2007 Sanborn
©2007 Google
4559 ft
Pointer 47°18'15.64" N 121°17'05.10" W elev 2675 ft
Streaming 100%
Eye alt 17341 ft

# Project challenges

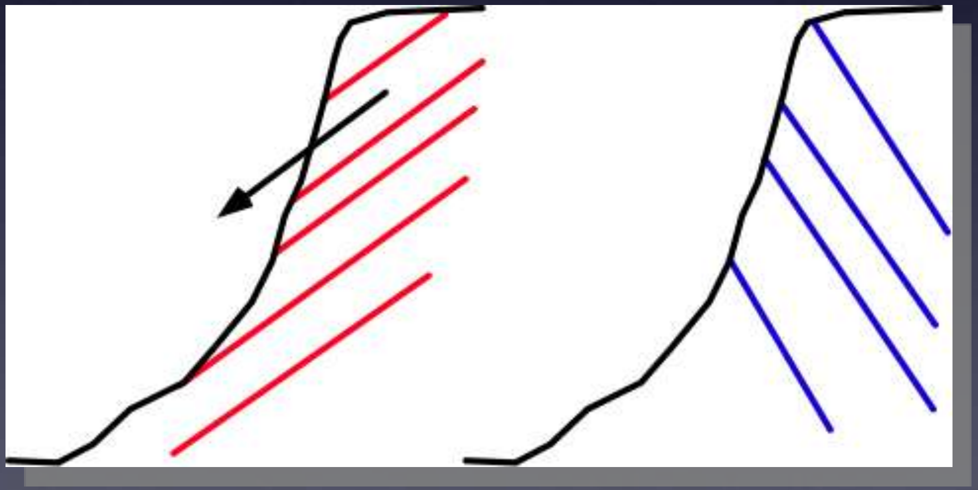
- Safely and efficiently map discontinuities along > 2 miles of marginally stable rock slopes along a busy highway
  - Midway Curve MP66 (Golder Associates, 2006)
  - Hyak-Keechelus Dam (URS Corporation, 2006-2008)
- Predominantly fractured Cenozoic volcanic rocks
- Only lower portions of slopes accessible on foot
- Icy winter conditions and fast-track schedule for Midway Curve Milepost 66 project
- Heavy summer traffic precluded lane closures for Hyak-Keechelus Dam project

# Our approach

- 3-D rock slope modeling
  - Digital photogrammetry for model creation
- Collaborative virtual discontinuity mapping
  - Geology + engineering team approach
- Traditional fieldwork for important details
  - Discontinuity orientation verification
  - Weathering
  - Joint aperture and filling
  - Intact rock quality

# Why map discontinuities?

- They control the behavior of discontinuous rock
  - Joints
  - Faults
  - Sedimentary bedding
  - Volcanic flow contacts
  - Metamorphic foliation



# Why photogrammetry?

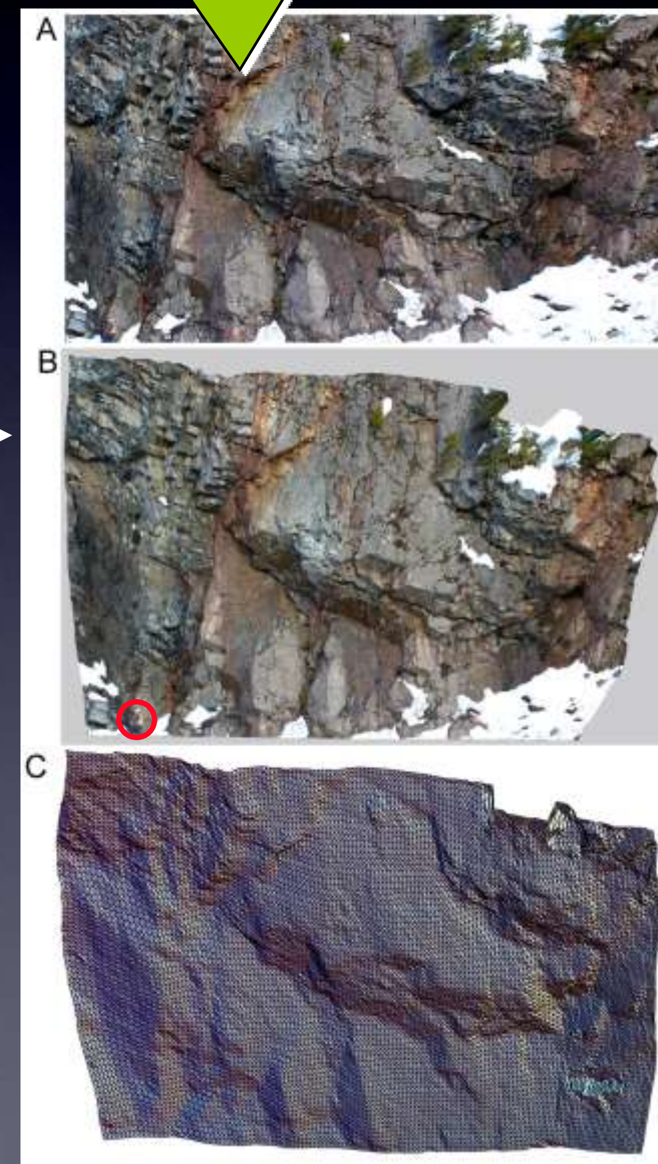
- 1/2000 positional and 1° angular accuracy or better
  - More than adequate for most discontinuity mapping
- Economical
  - Start-up cost is about 1/10 of a laser scanner
  - Off-the-shelf hardware easy to replace if damaged
- Limits exposure to dangerous conditions
- Photo fully integrated with 3-D mesh
  - Laser scanners have varying capabilities
- Software with geologic mapping capabilities
  - Knowledge-based virtual fieldwork approach

# Procedure

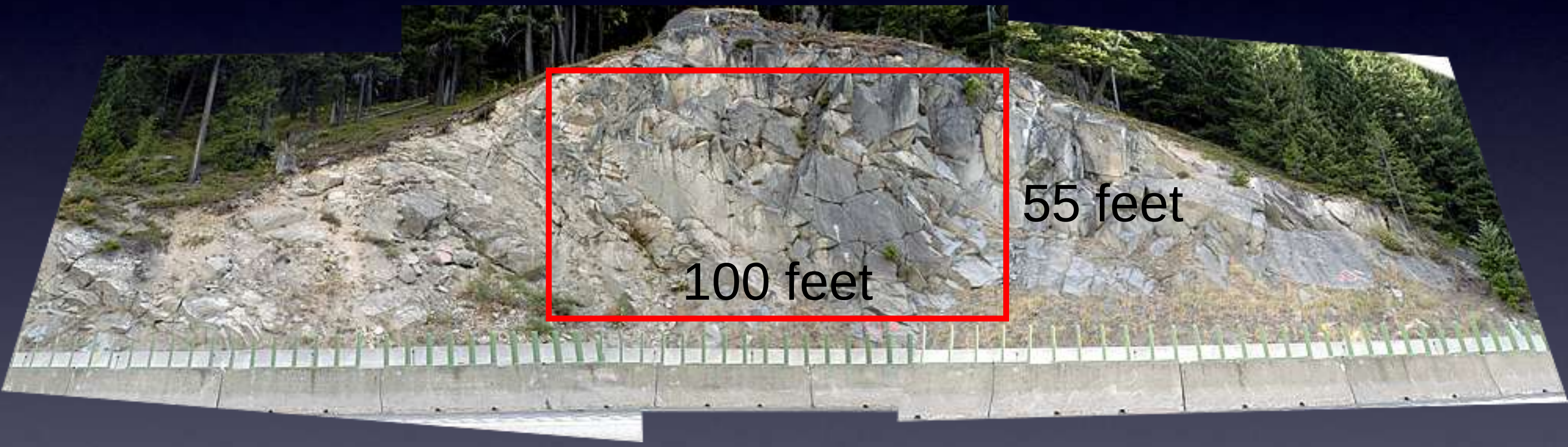
- 6 megapixel photos
- 125 feet long by 65 feet high
- 7700 square feet
- 425,523 xyz points
- 1.6 inch average spacing
- ±0.23 inch estimated RMSE


Digital Photogrammetry Software

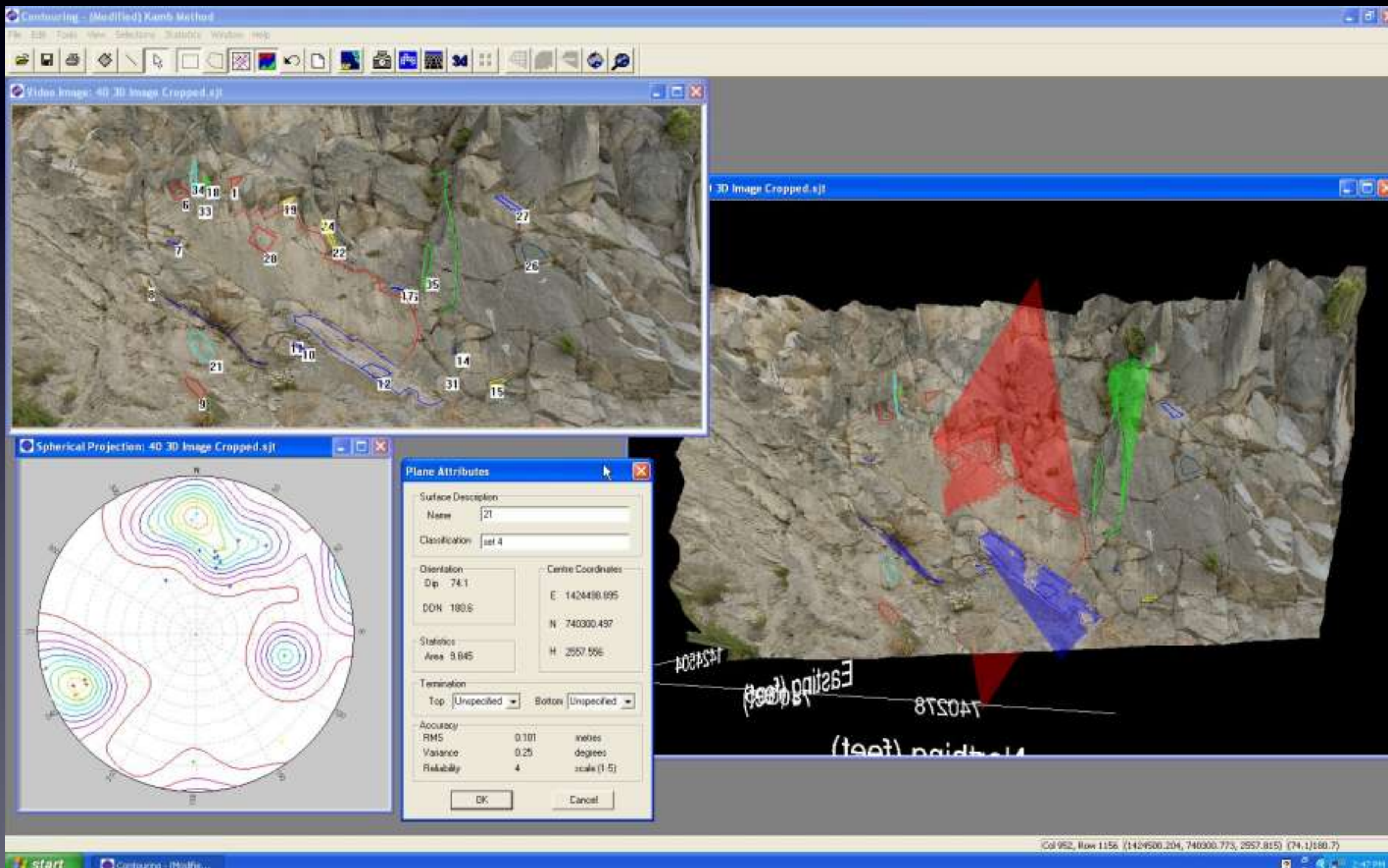
Geometry



# A typical project slope



# Virtual structural mapping

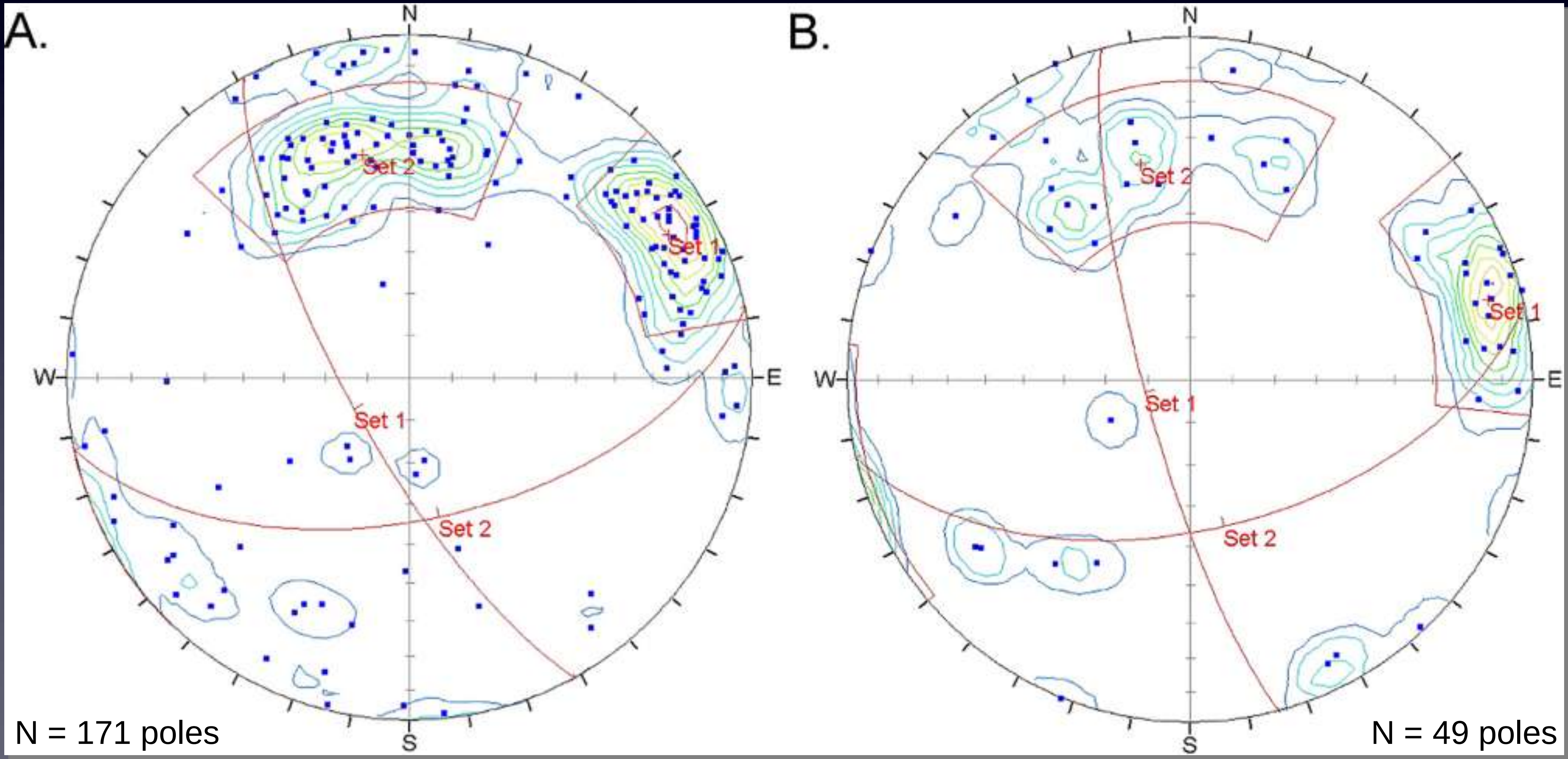


# 3-D discontinuity visualization

QuickTime™ and a
Microsoft Video 1 decompressor
are needed to see this picture.

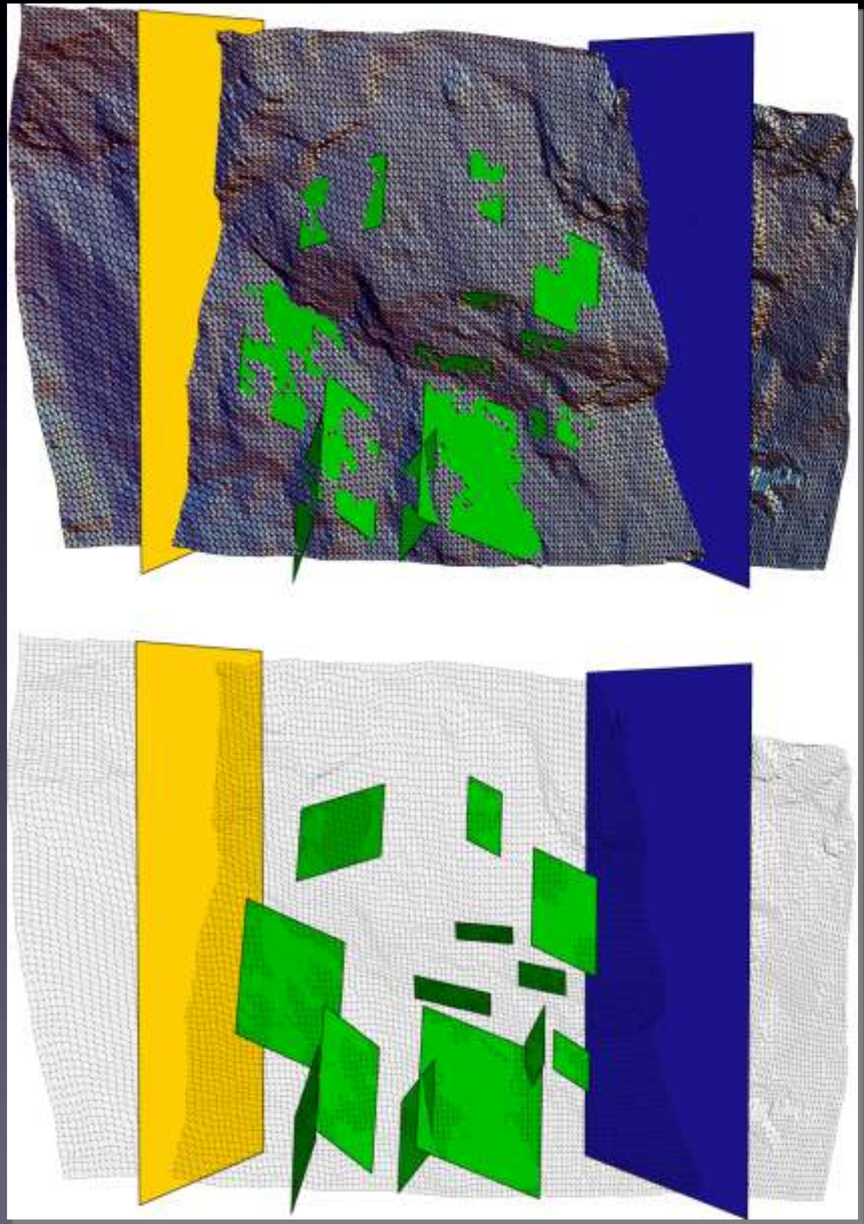
# Field verification

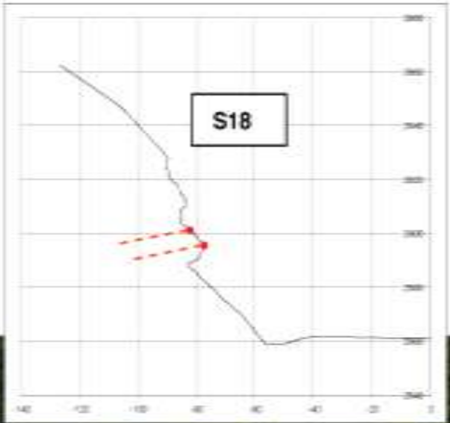
Computer Compass



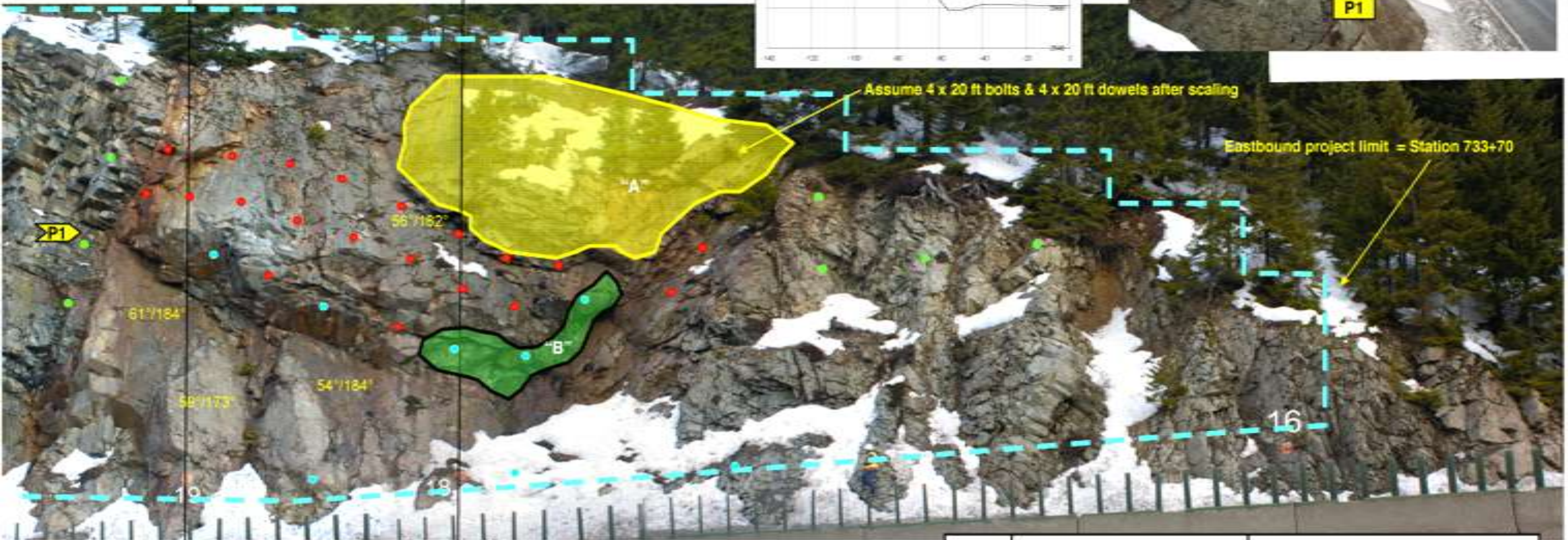
# Profiles and planes

- Profile extraction along vertical planes with arbitrary strike
  - Text, AutoCAD, or Excel output
  - Import into Mathematica for additional modeling
- Individual planes and traces can be plotted in 3-D to better understand discontinuity networks
- Solid surface or transparent wire mesh










54°/184° = dip / dip direction

**Stabilization Sequence:**

? Remove rock slab at location "A" using mechanical scaling.
? Intensive hand scaling with selective mechanical scaling of entire slope including tree removal from face and 15 ft beyond crest to clearing limit.
? Install rock bolts or dowels from **top down** at specified locations and as directed by the Engineer.
? Apply 4-inch minimum thickness fiber reinforced shotcrete at location "B".
? Install horizontal drains at locations shown (upper row = 5 @ 30 ft, lower row = 3 @ 40 ft)
? Install 12" x 12" cable net with double-twist wire mesh to limits shown (12 ft +/- 2 ft above ditch).

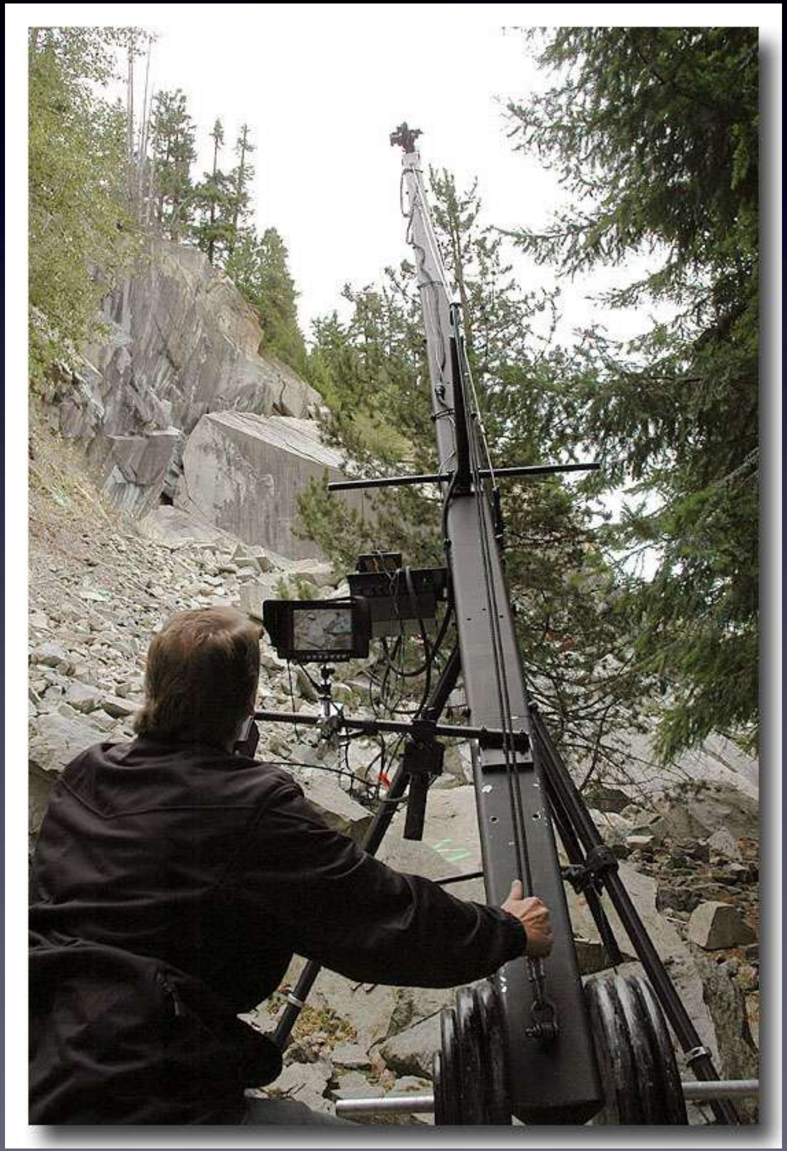
| KEY | STABILIZATION ITEM | EST QTY (Sheet 6) |
|---|---|---|
| Red dot | 60 kip tensioned rock bolt | 24 x 20 ft = 480 ft |
| Green dot | 60 kip untensioned rock dowel | 12 x 20 ft = 240 ft |
| Cyan dot | Horizontal drain | 3 x 40 ft + 5 x 30 ft = 270 ft |
| Yellow fill | Scaling / Debris removal | 40 crew hr & 2 machine day / 2000 cy |
| Green fill | Shotcrete | 40 ft x 10 ft x 4 in = 5 cy |
| Cyan dashed line | Cable Net Slope Protection | 140 ft x 70 ft avg = 9800 sf |

wyllie & norrish ROCK ENGINEERS

# I 90 MP 66.27 – 66.31 (Left) WB

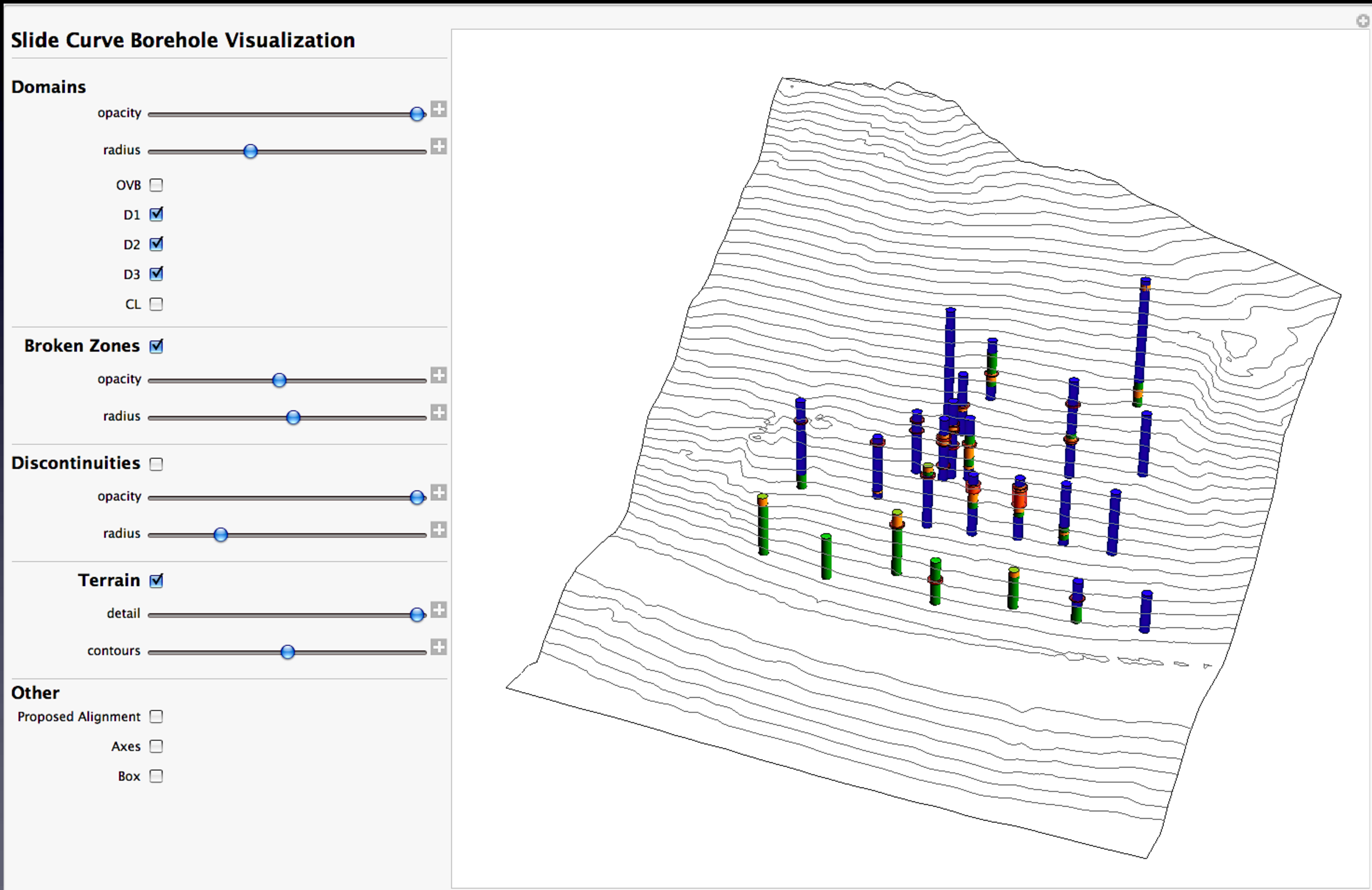
Golder Associates

# It’s not perfect, though

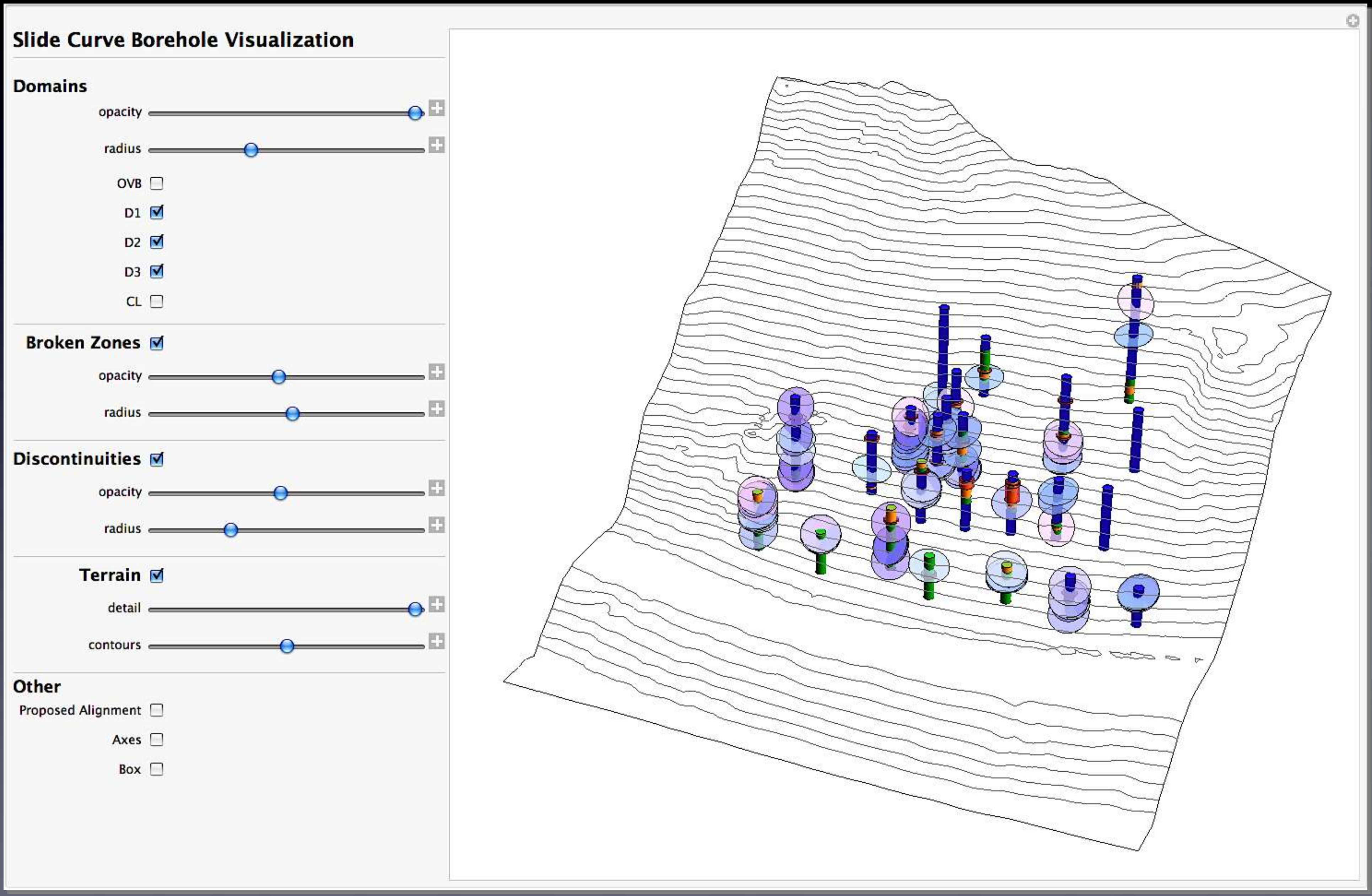


- Highly oblique lines of sight can yield poor to unusable results
- Camera boom experiment didn’t work
- Technology isn’t foolproof!

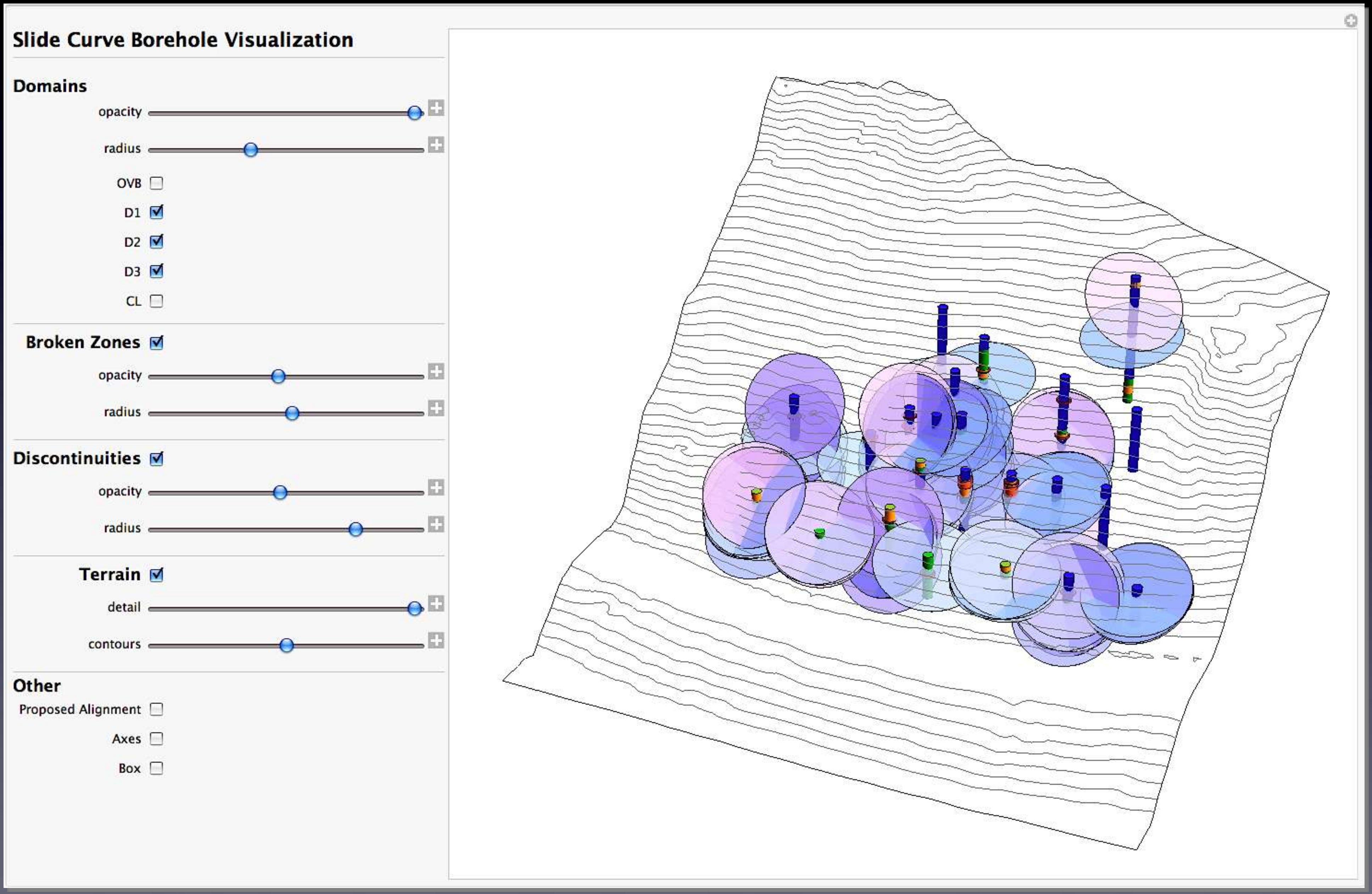
# Subsurface models, too



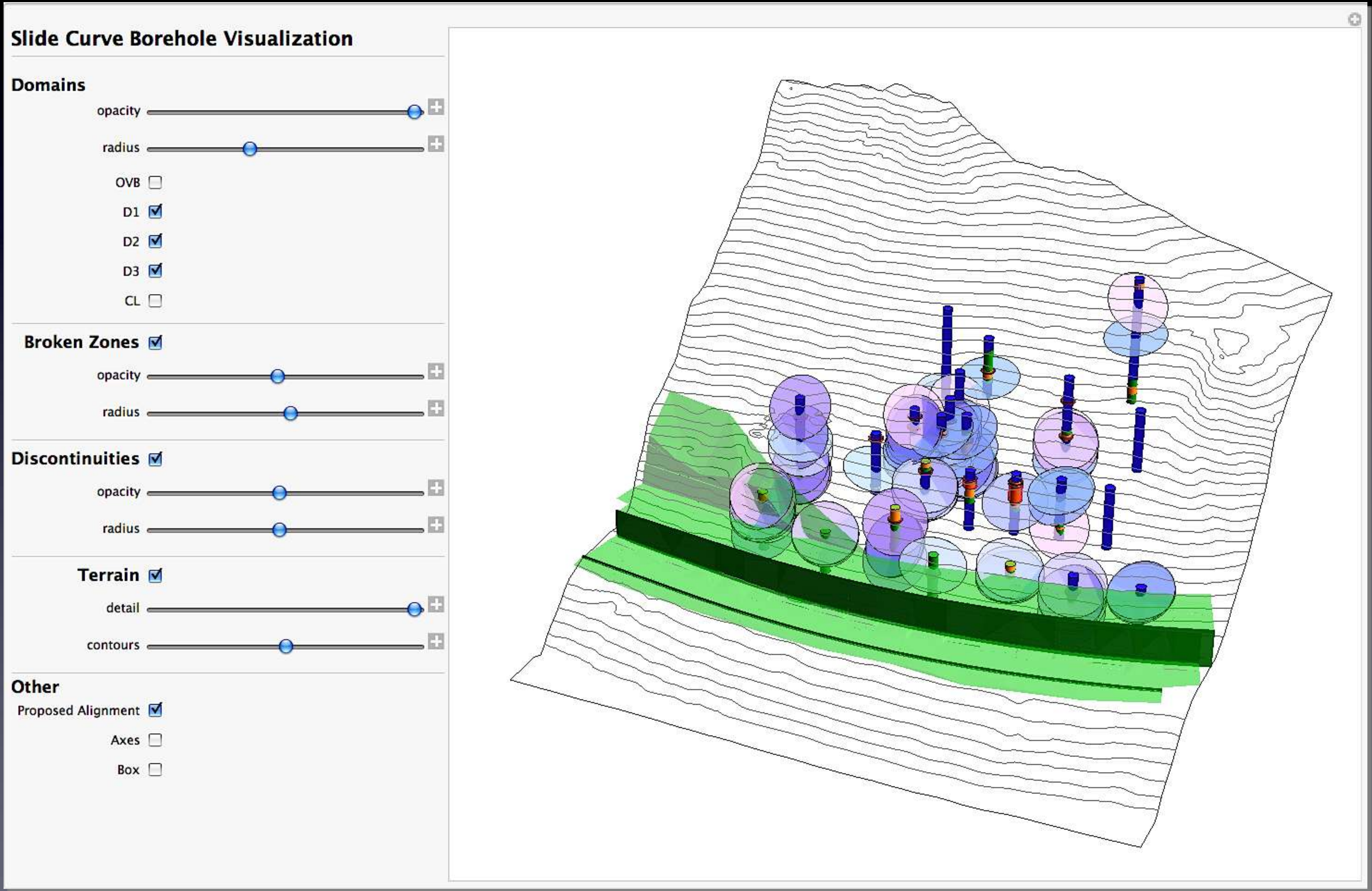
# Subsurface models, too



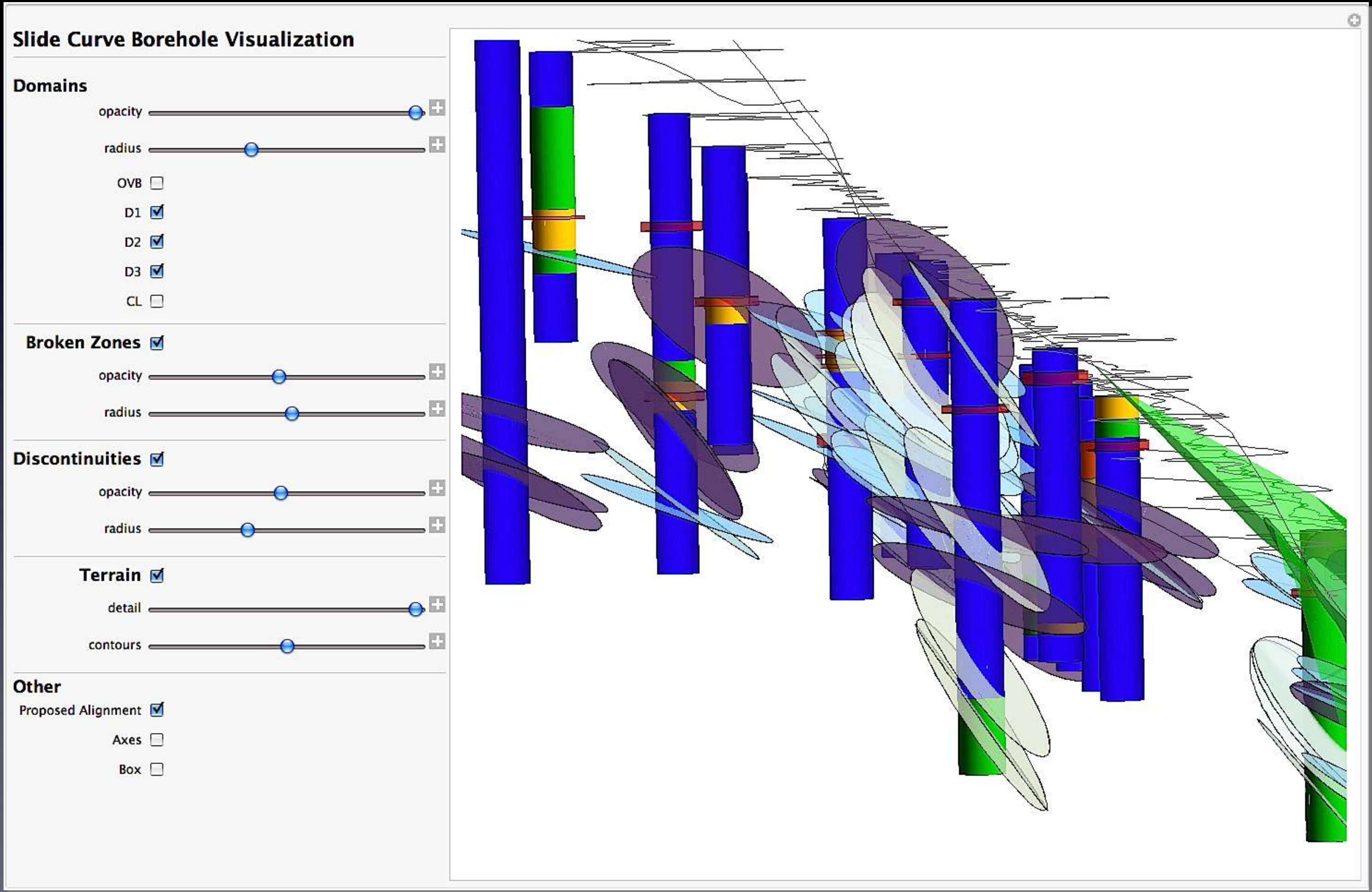
# Subsurface models, too



# Subsurface models, too



# Subsurface models, too



# Summary

- Practical 3-D data collection under challenging conditions
- Virtual fieldwork is geologically attractive
  - Collaboration between geologists and design engineers
- Custom development of additional capabilities
  - Profiles, joint system visualization, joint roughness coefficients
- ACEC-WA Engineering Excellence Awards for MP 66
  - Silver: *Originality or Innovative Application of New or Existing Techniques*
  - Gold: *Social, Economic, and Sustainable Design Considerations*
- Will never eliminate the need to touch the rock
  - Joint filling, weathering, rock mass quality not conveyed in photos