TECHNOLOGY USE FOR ASSISTING IN FASTER GROUND CHARACTERIZATION AND SLOPE PERFORMANCE APPRAISAL

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IAEG Commission No. 38

"Rockmass Characterization with Emphasis in Rock Slope Hazards"

6 October 2021

gecko geotechnics

EUROENGEO
3RD EUROPEAN REGIONAL CONFERENCE OF IAEG
ATHENS 2020
Leading to Innovative Engineering Geology Practices

Rock Slope Engineering

Surface Mines and Large Civil Engineering Projects

Ground Failure Risk Management

- Site Investigations
- Geotechnical Model
- Data Limitations and Uncertainty
- Design Acceptance Criteria
- Slope Stability Analysis Techniques
- Slope Excavation Economics
- Risk Management
  - Monitoring
  - Reconciliation

OPERATING SURFACE MINES AND LARGE CIVIL ENGINEERING PROJECTS IN EXECUTION PHASE

…have already completed site investigations, geotechnical model, slope stability analysis and design

MONITORING INSTRUMENTATION

surface and subsurface monitoring instrumentation

Monitoring systems

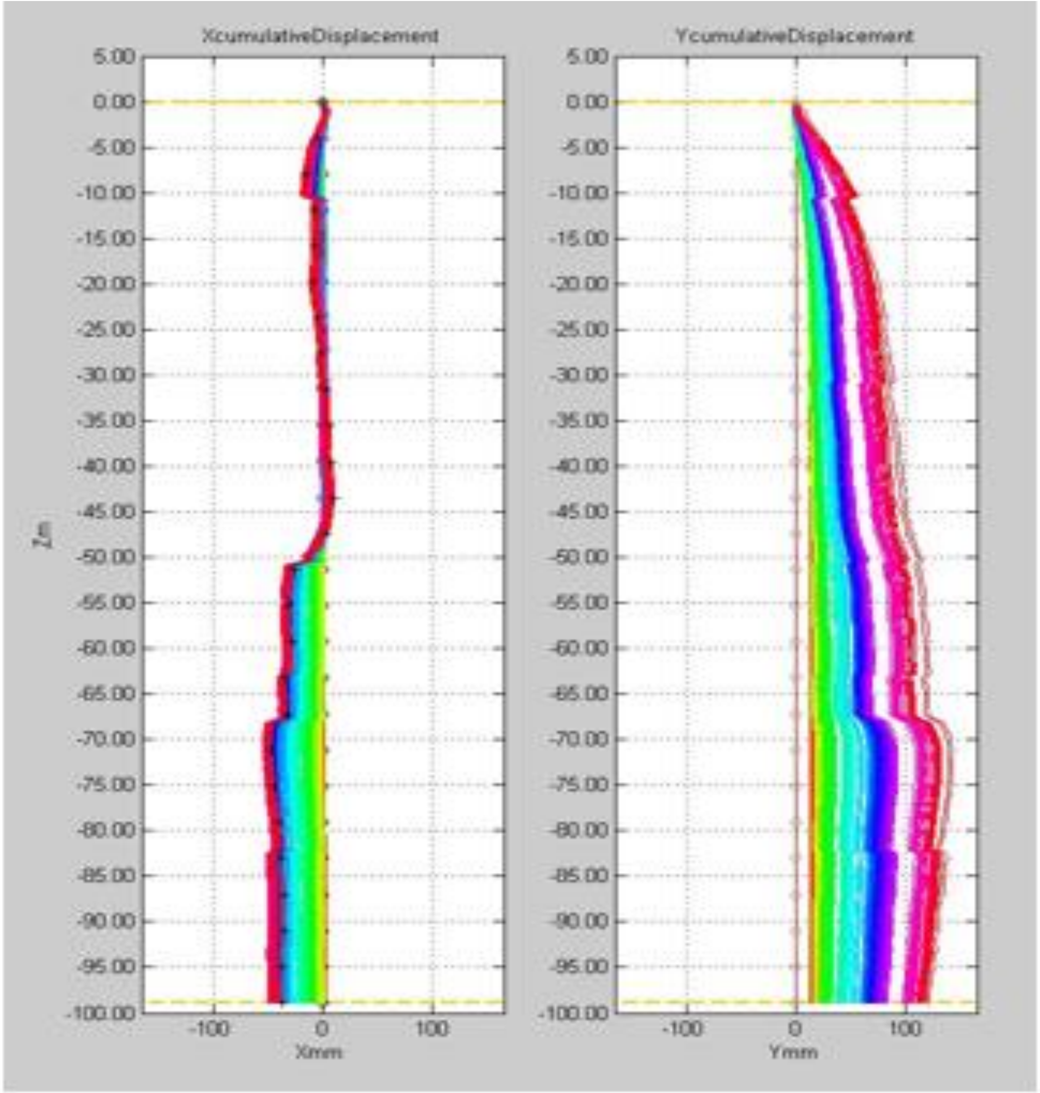
- Manual surface extensometers
- Inclinometers & shape accel arrays
- Prism monitoring system
- Ground based radars
  - RAR and SAR
  - Doppler
- Satellite monitoring system
  - InSAR
- UAV Photogrammetry
- Other
  - TDR, GPS, SMART Markers, etc…
  - Vibrating wire piezometers (VWP)

Manual surface extensometers

- Manual surface extensometers
  - Reliable
- Can be made from basic parts

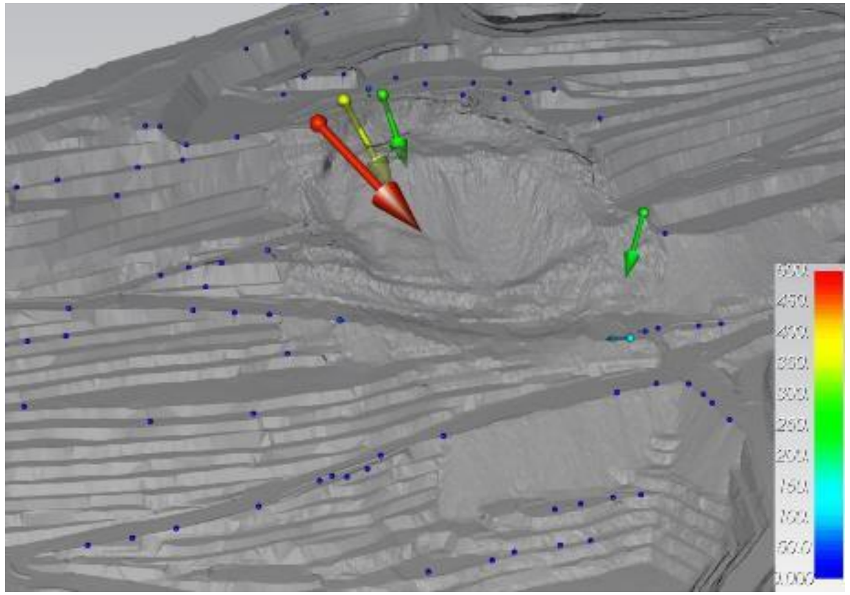
Inclinometers & shape accel arrays

- Borehole installation
- Inclinometers – biaxial deformation measured manually assuming fixed base:
  - Tilt measurements
  - Frequency typically 7 days or more
- Shape Accel Array
  - Accelerometers every 0.5m measure tilt
  - Automated measurements
  - Telemetry & alarming
  - Frequency can be hourly or less



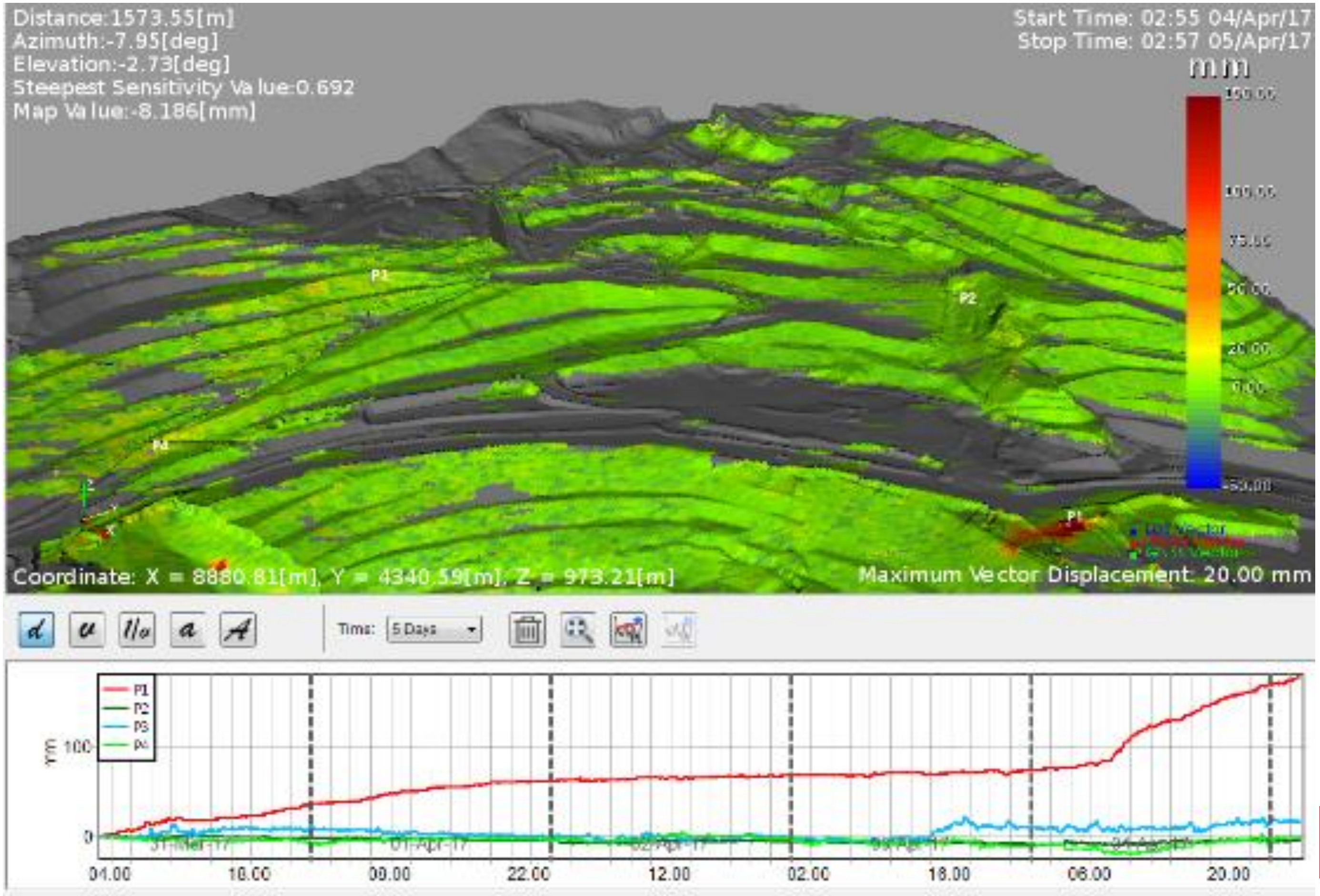
Prism monitoring system

- Automatic total stations (ATS) survey location of individual prisms at set intervals – 90 or 180 minutes
- Deformation & velocity calculated
  - Alarms can be set
- Line-of-sight required: ATS ⟶ prism
  - Desert: prism covered in dust
  - Tropics: prism covered in mildew or jungle



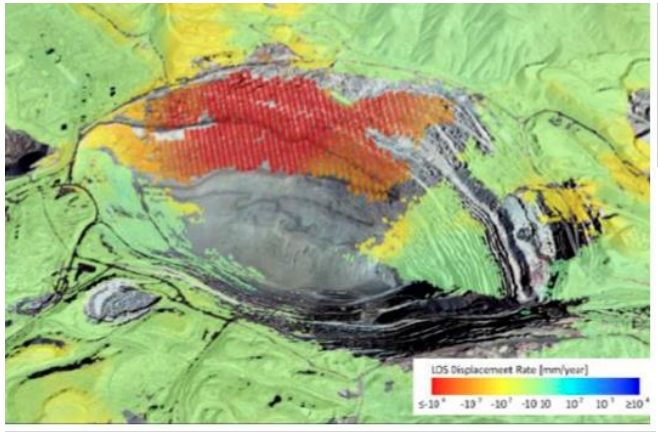
Ground-based Radar

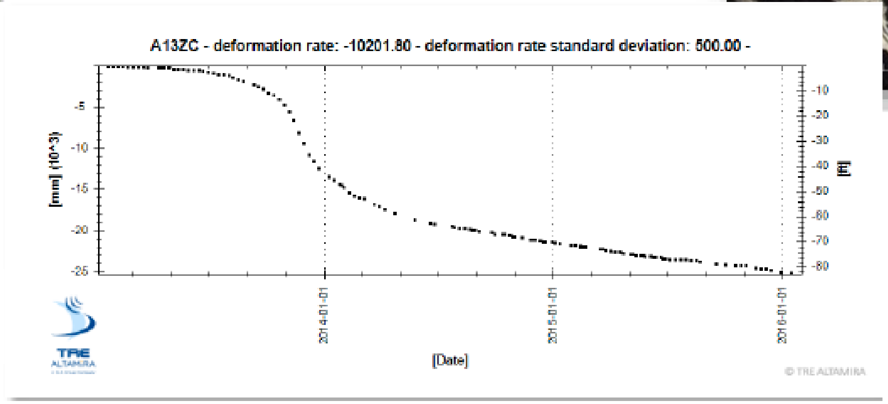
- Ability scan long distances and larger areas
- Faster data collection and processing frequency – scan time ~5 minutes
- Excellent long-term monitoring tool, highly reliable.

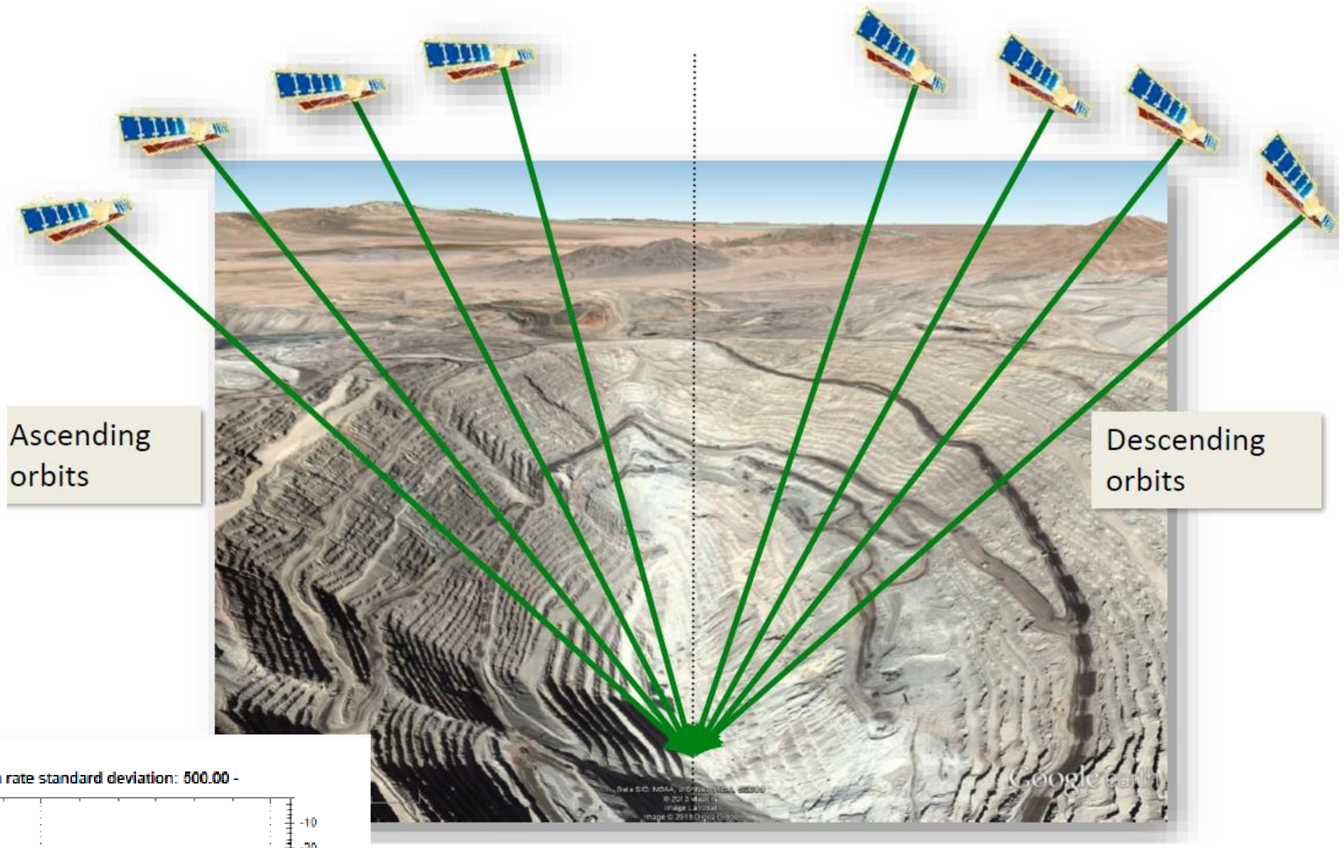


Satellite monitoring system - (InSAR)

- Satellite monitoring (e.g. InSAR)
- Ideal for monitoring large areas – mountain ranges and infrastructure corridors (particularly north-south heading)
- Manual and time consuming data processing
- 7 or more day data-intervals

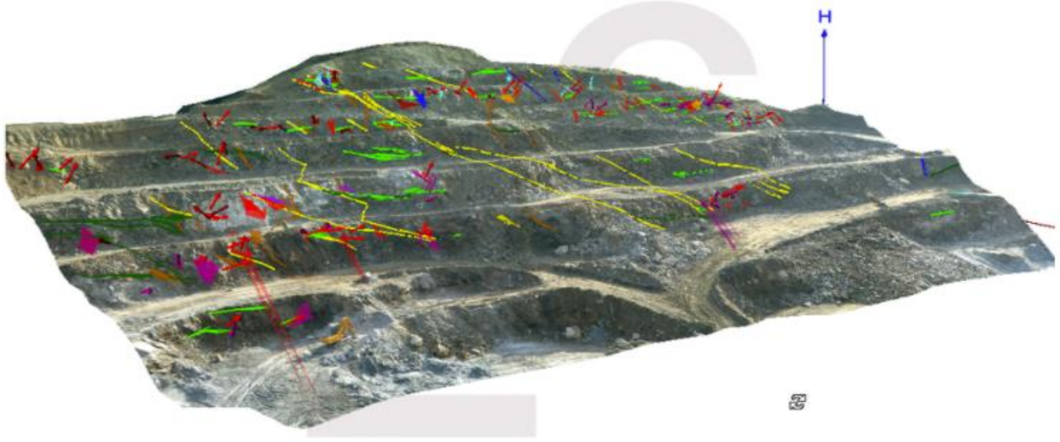


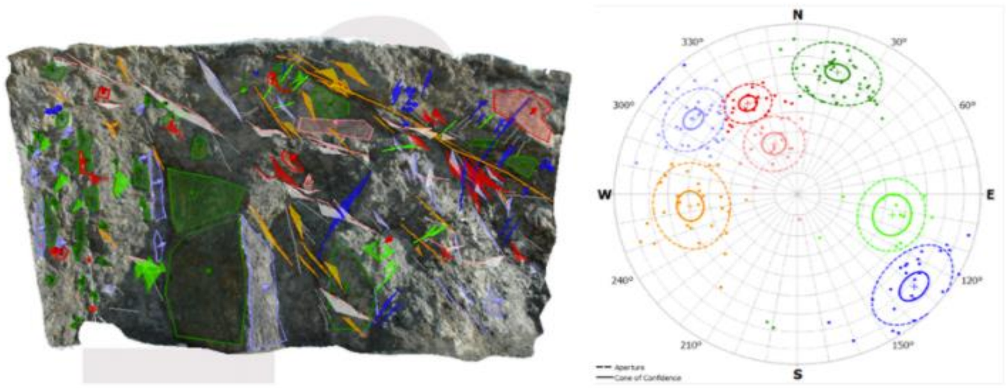


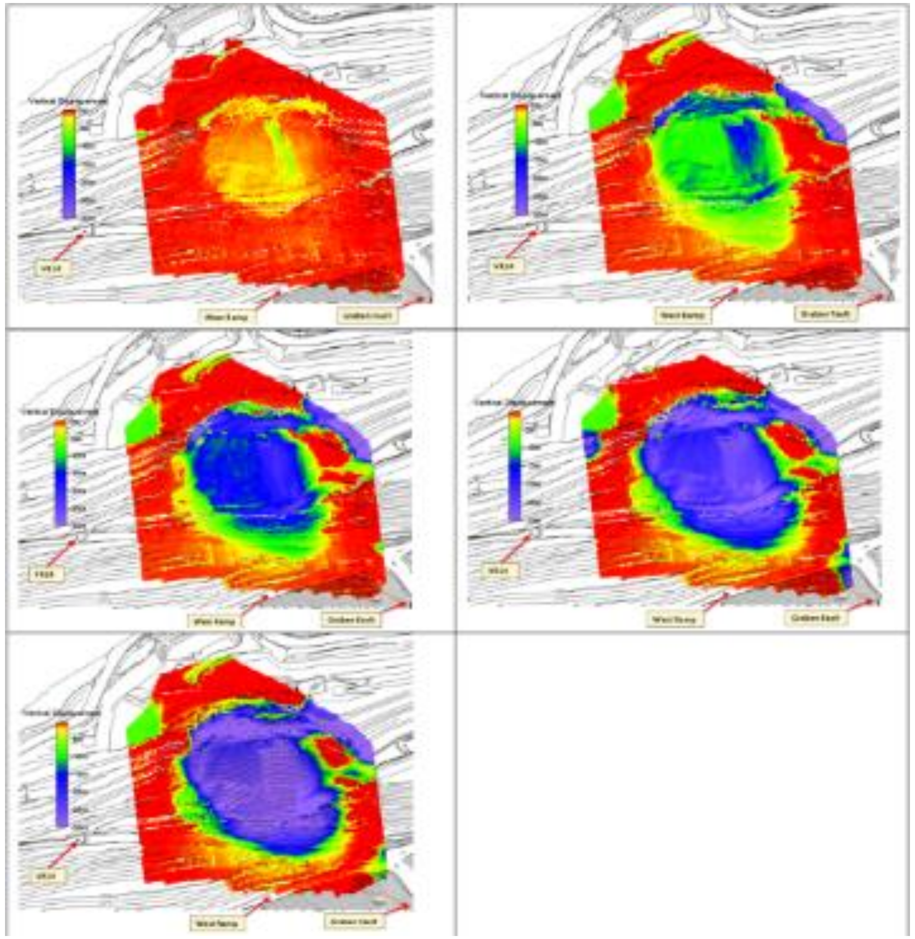


UAV photogrammetry

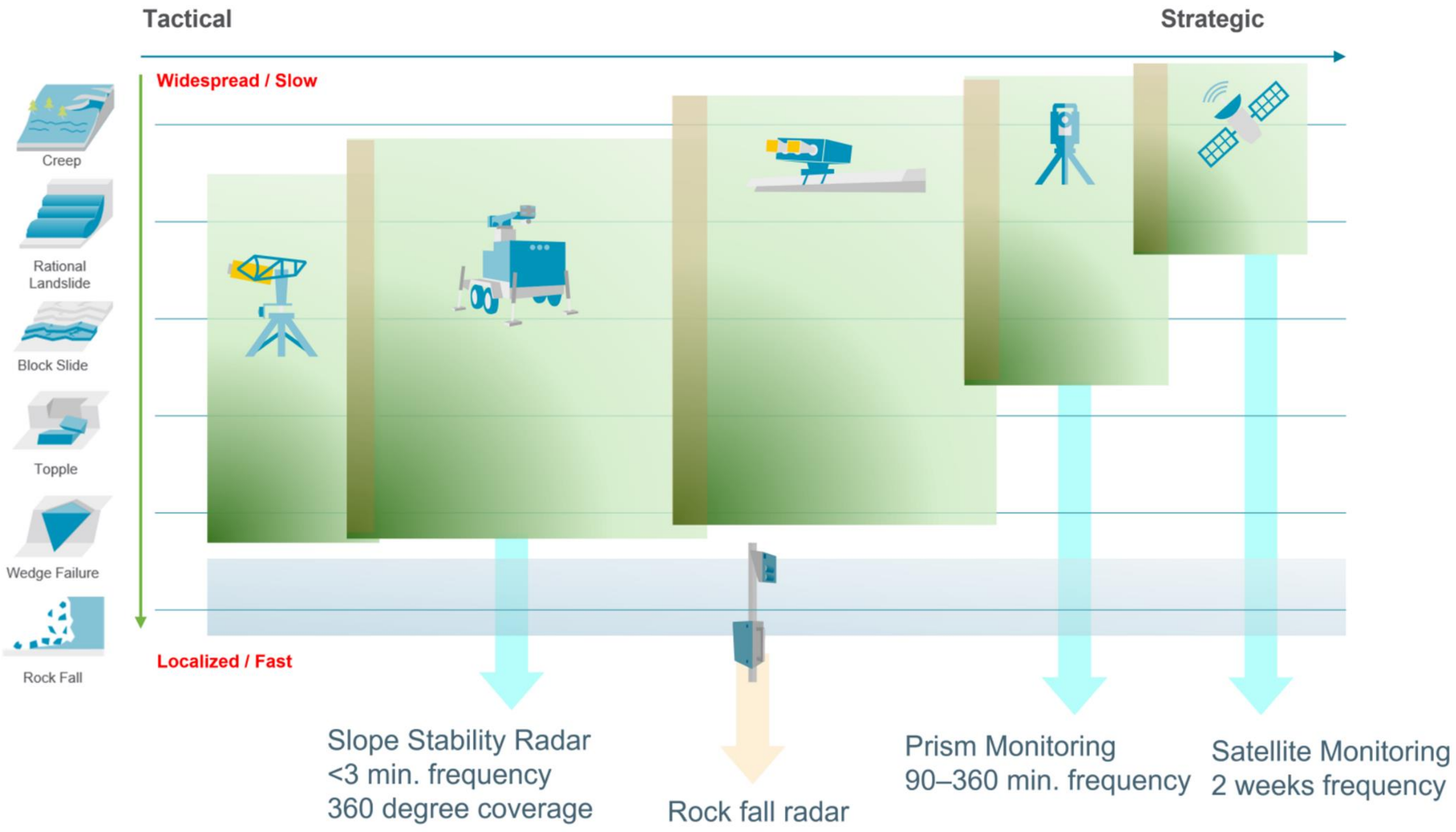
- High resolution digital terrain models (accuracy < 10cm)
- Ideal for small regions – excavations or subsidence monitoring
- Manual data processing – can be done weekly







Monitoring Frequency



ROUTINE DATA COLLECTION DURING EXECUTION

….for reconciling the geotechnical model and inputs to slope stability analyses

Mapping – manual

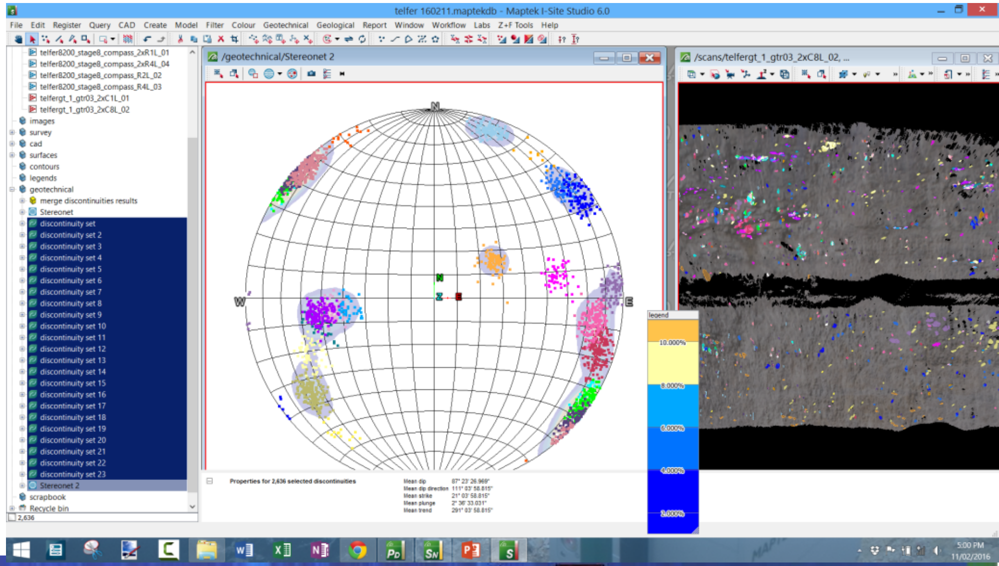
- By hand:
  - Slope face mapping
  - Remote mapping estimates (low accuracy)
- Limited ‘reach’
- Benefit: discontinuity roughness, aperture and infilling can be assessed

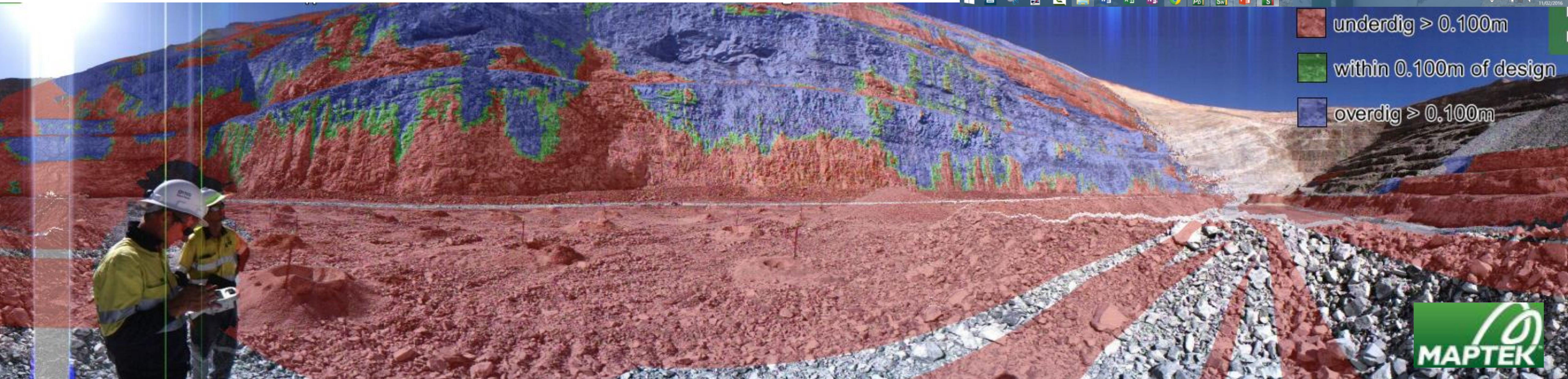
Mapping - photogrammetry

- Photogrammetry:
  - Terrestrial (tripod set-up)
  - Aerial (UAV / drones)
  - Combination of terrestrial cameras and aerial
- Fast data acquisition & processing
  - Survey controls required for terrestrial
  - Most drones have in-built GPS
- <u>Discontinuity lengths and orientations only!</u>
  - Cannot be used to evaluate the geomechanical properties of discontinuities

Laser scanning

- Laser scanning:
  - Terrestrial (tripod set-up)
  - Aerial becoming more readily available
- <u>Discontinuity lengths and orientations only!</u>
  - Cannot be used to evaluate the geomechanical properties of discontinuities





CUMBA SLOPE INSTABILITY

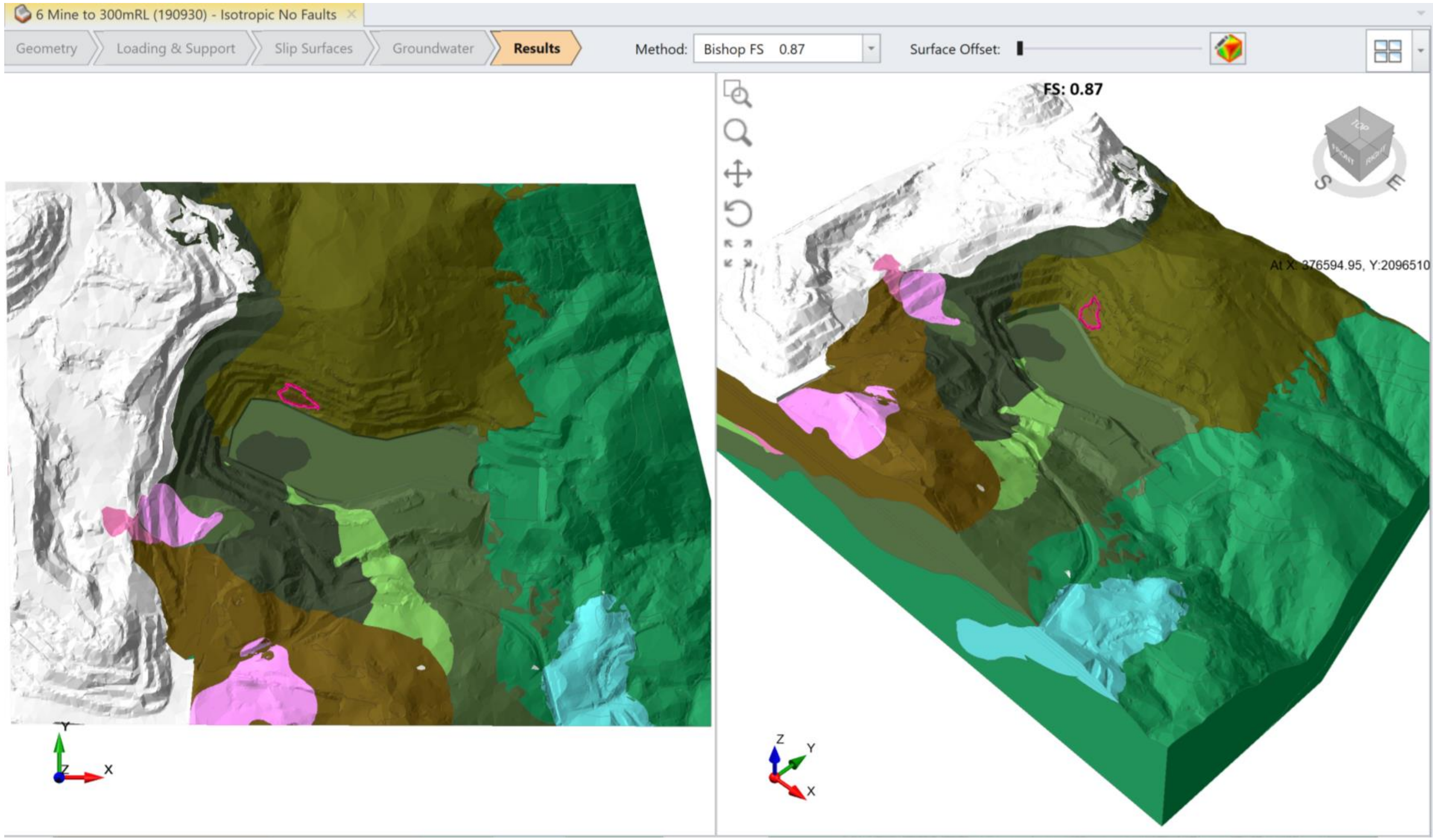
…an example of technology use to monitor, map, understand and move forward

Cumba Slope Instability - Introduction

- Tropical setting in the Caribbean
- 2,500mm annual rainfall
- Cumba was a satellite pit in a large gold mine
- High strength andesites
- Initial geotechnical model and slope stability analysis:
  - Isotropic ground conditions were assumed (Hoek-Brown failure criterion)
  - Presence of major faults was unknown prior to execution
  - 2D LE analysis only

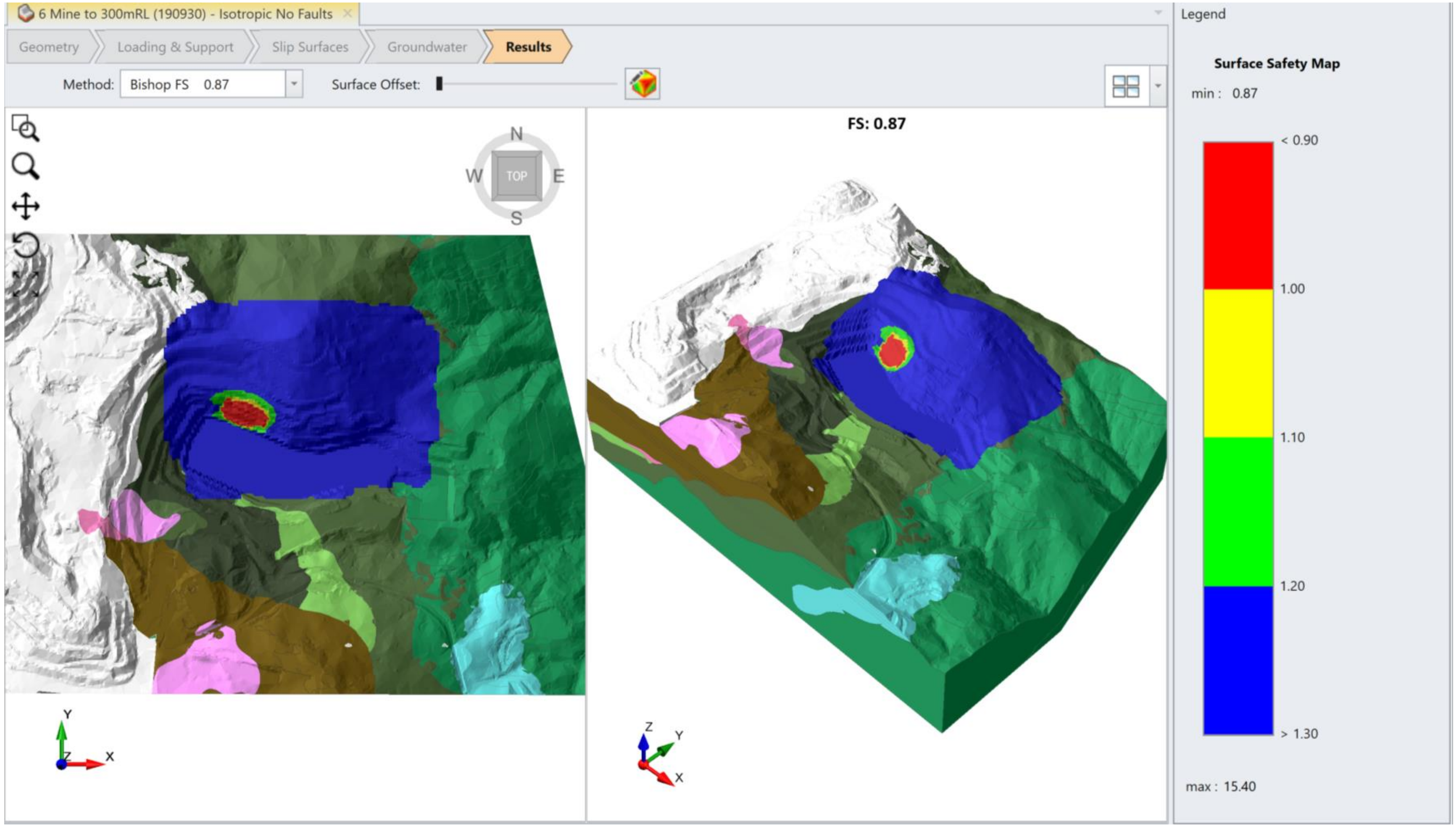
Reproduction of Slope Stability Models in 3D

- Model inputs based on original 2D analysis:
  - Isotropic H-B
  - No Faults
- Slide3: 3D limit equilibrium analysis identifies localized double bench instability



Reproduction of Slope Stability Models in 3D

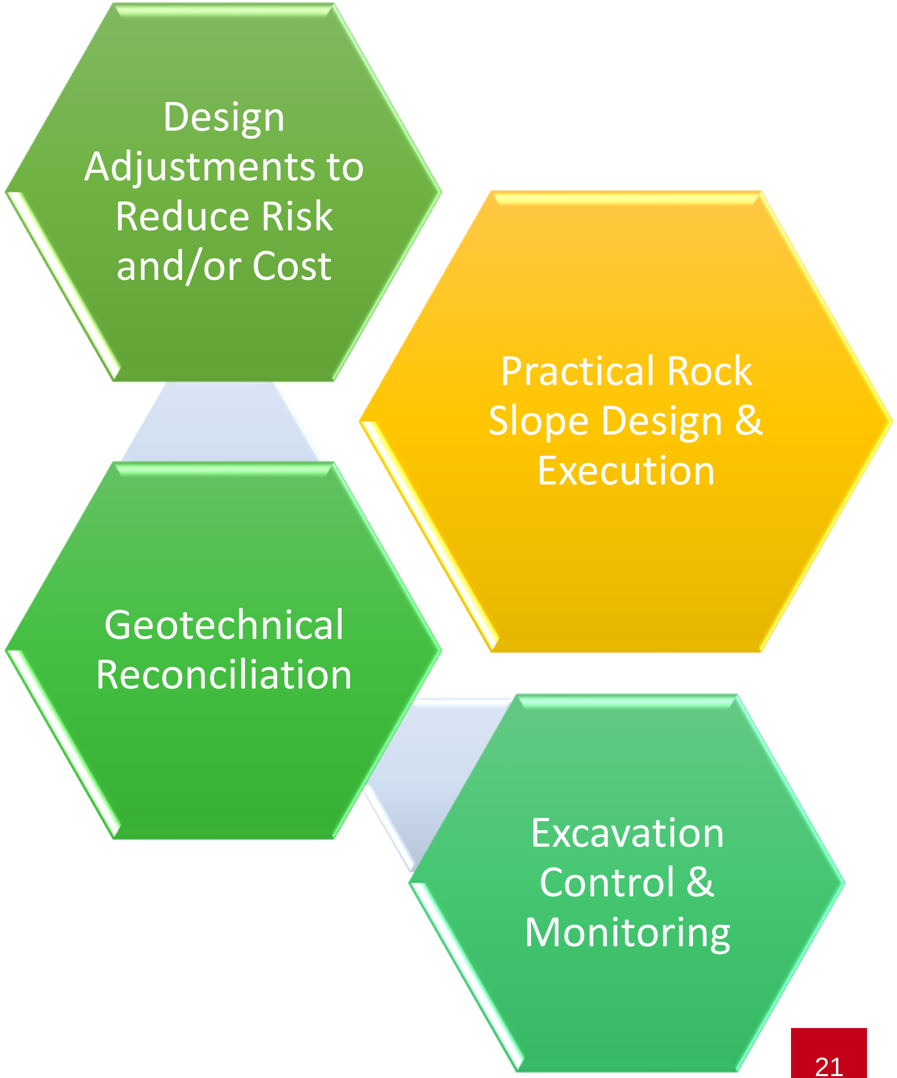
- Model inputs based on original 2D analysis:
  - Isotropic H-B
  - No Faults
  - Pore Pressure based on VWP data
- Slide3: 3D limit equilibrium analysis identifies localized double bench instability
- **Model suggests generally stable**



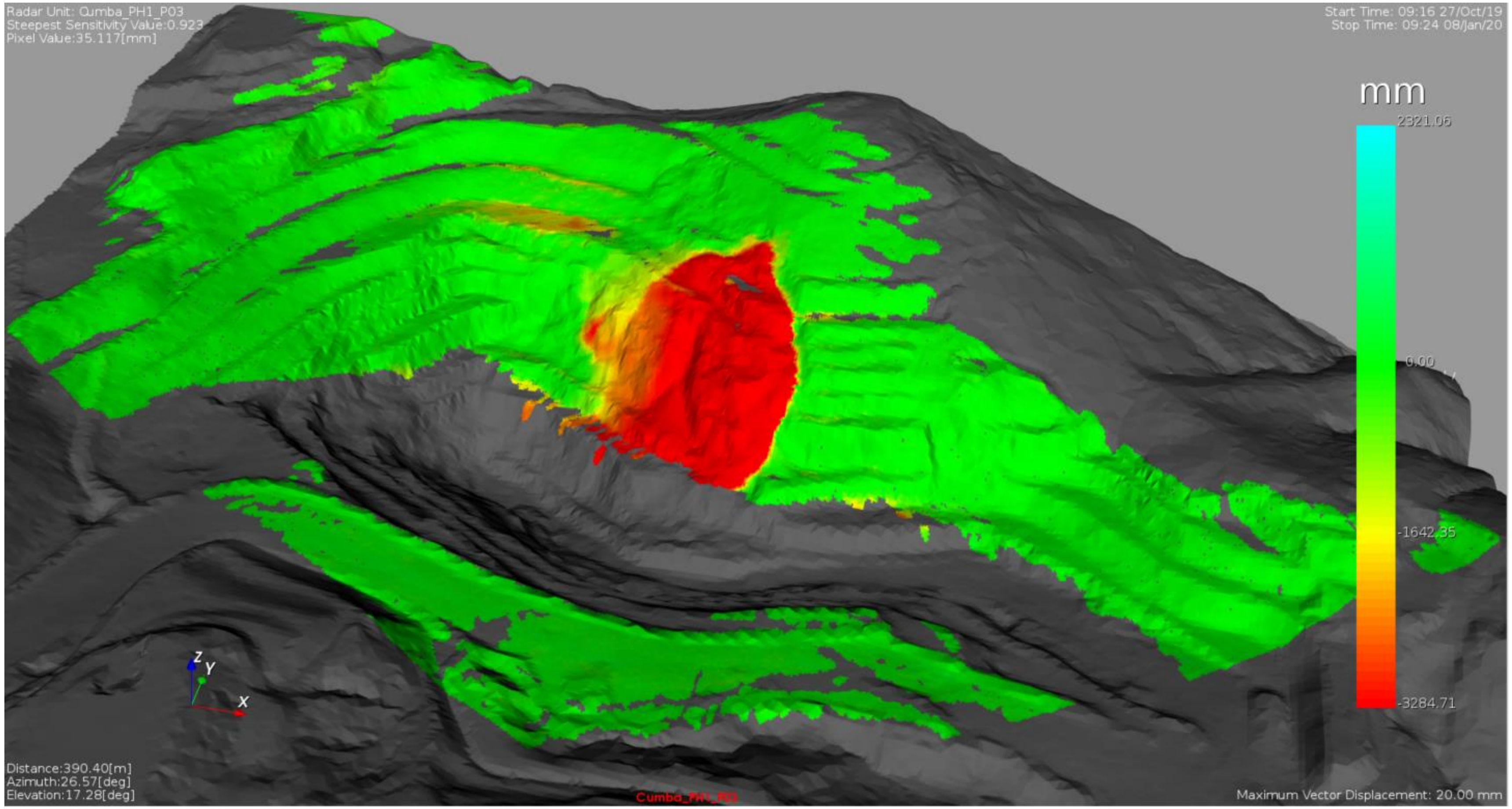
Andesite, UCS: 42 MPa, GSI 70, m_i 16

Cumba Slope Instability - Context

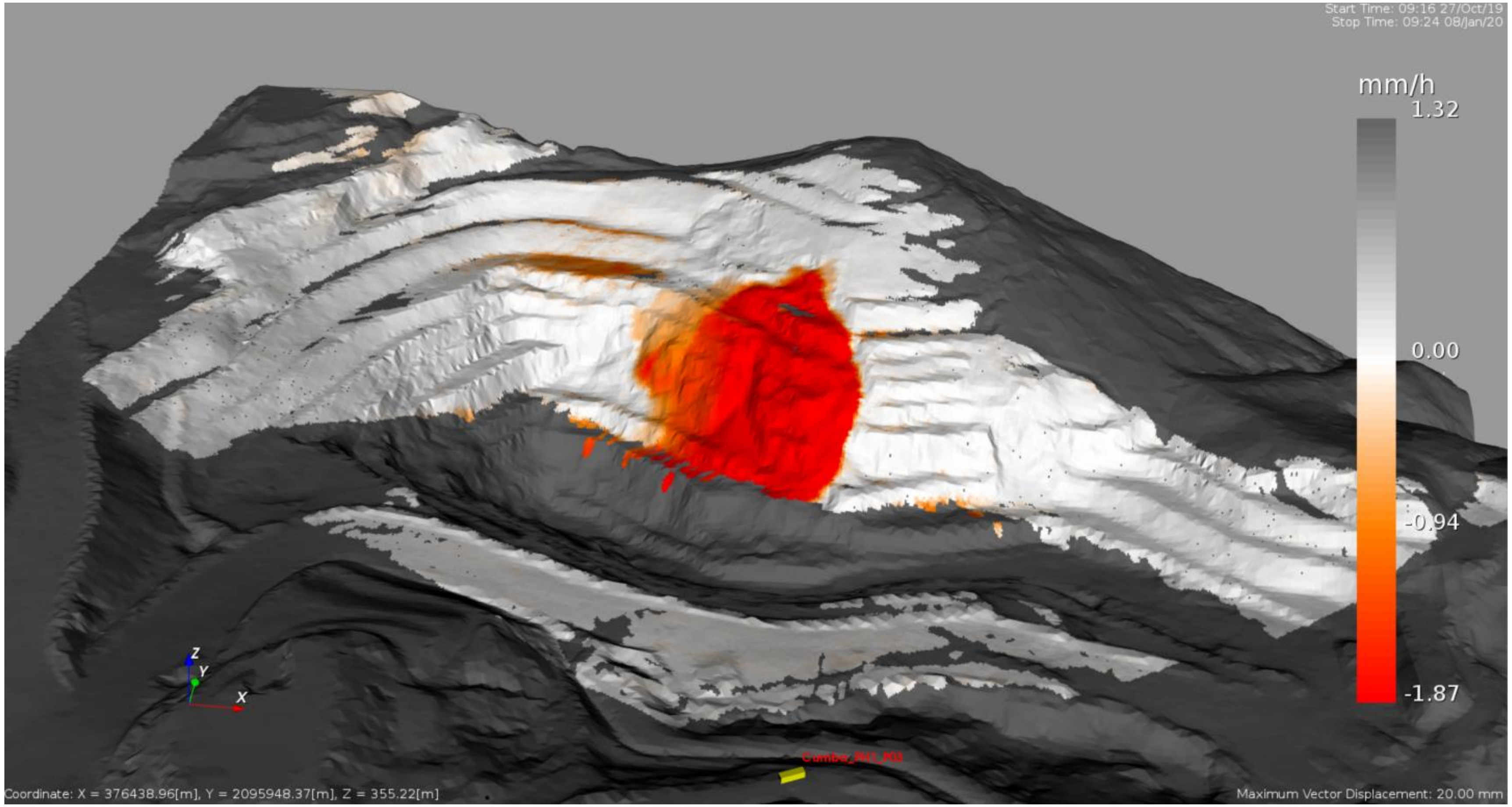
- Deformation monitoring with ground-based radar
  - IDS ArcSAR system
  - 360 degree radar, scan time <3 minutes
  - Alarming capability for evacuating personnel and equipment
- Fortnightly aerial photogrammetry
  - Low resolution for surveying application (i.e. not intended for geological mapping)
  - Major geological features still visible (multi-bench scale)
- Slope stability model development
  - 3D limit equilibrium analysis
  - With updated geotechnical model (i.e. faults)



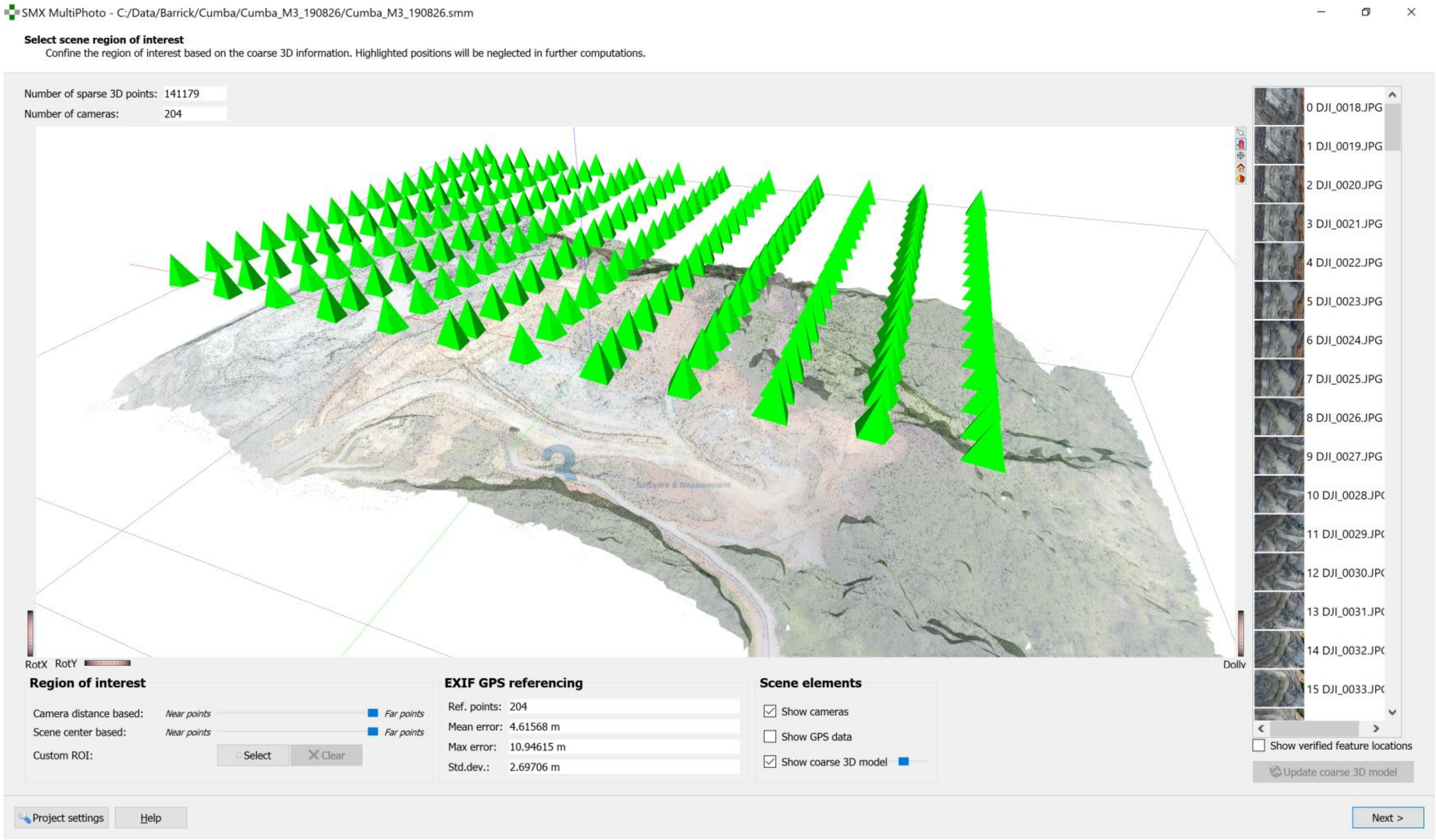
Deformation Monitoring Hotspot – 70m high



Velocity >1mm/hour

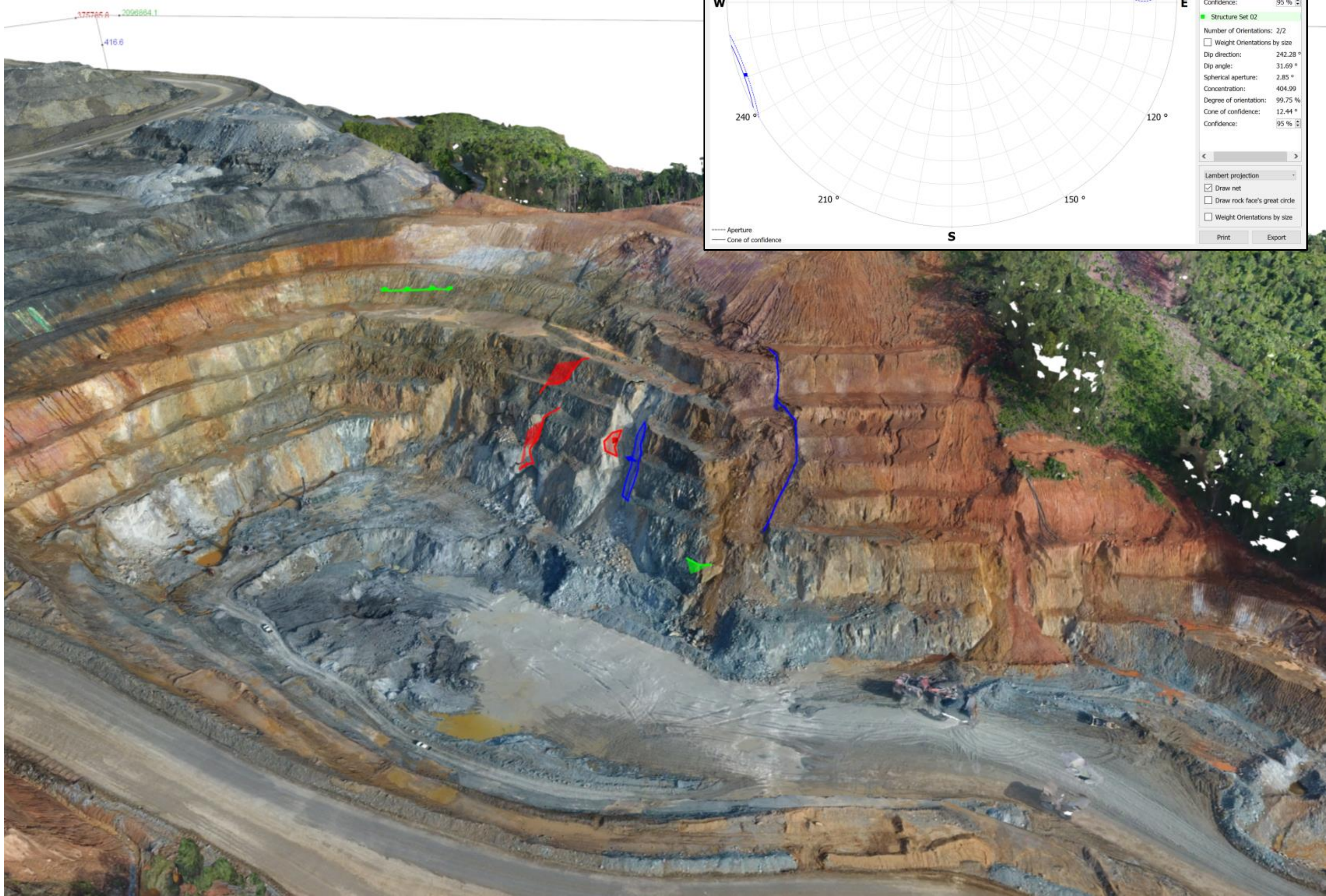


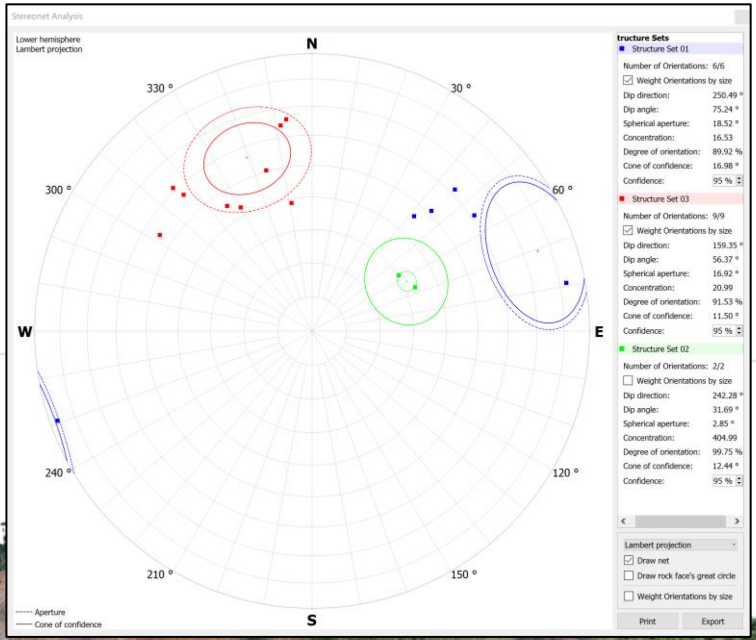
Aerial Photogrammetry – Low Resolution



Aerial Photogrammetry

- Low Resolution (surveying purpose)
- Mapping geological features
    - >10 m in length
    - Multi-bench

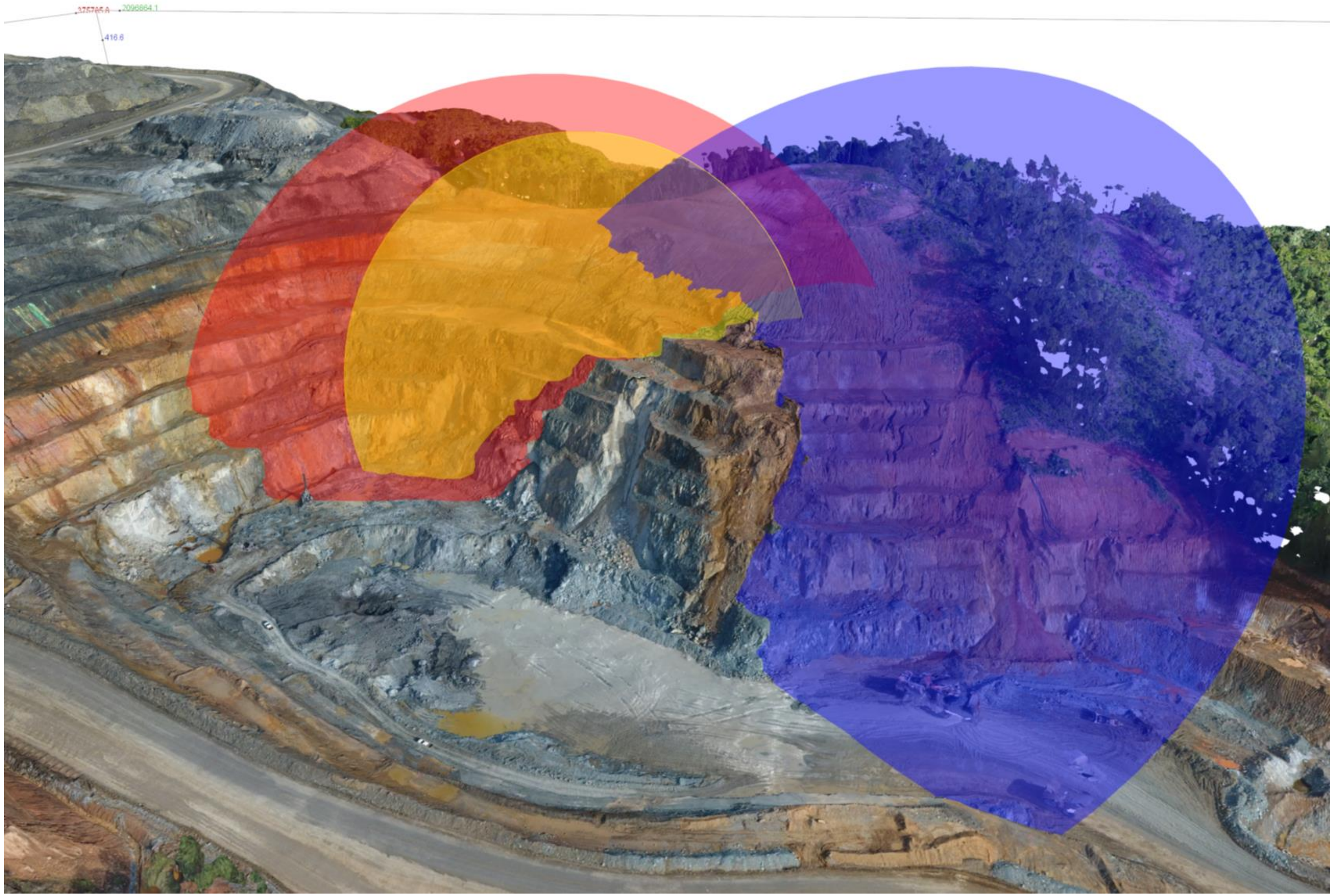




3GSM
ShapeMetriX UAV

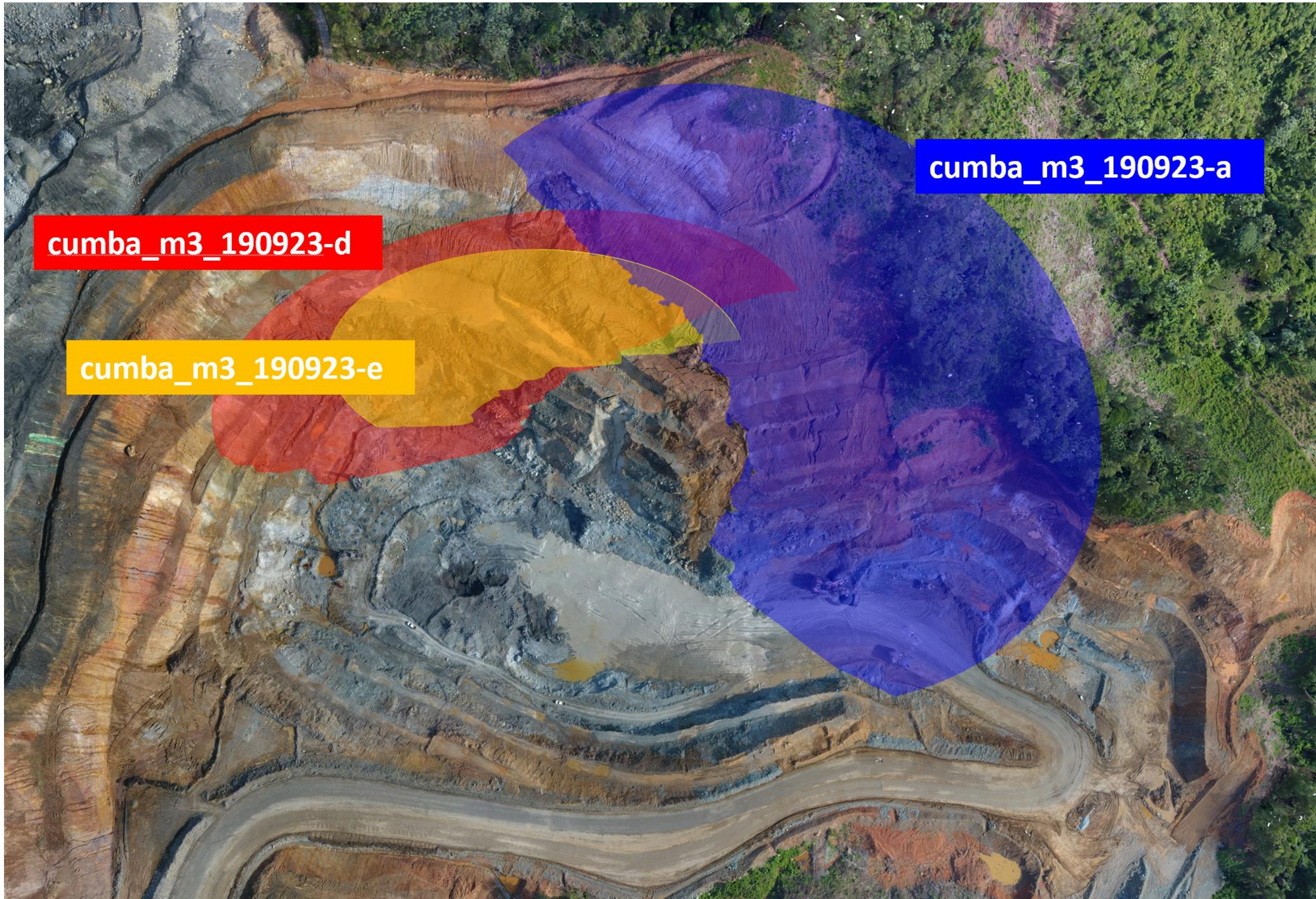
Aerial Photogrammetry

- Low Resolution (surveying purpose)
- Mapping geological features
  - >10m in length
  - Multi-bench
- Extrapolating fault planes for use in 3D stability analyses



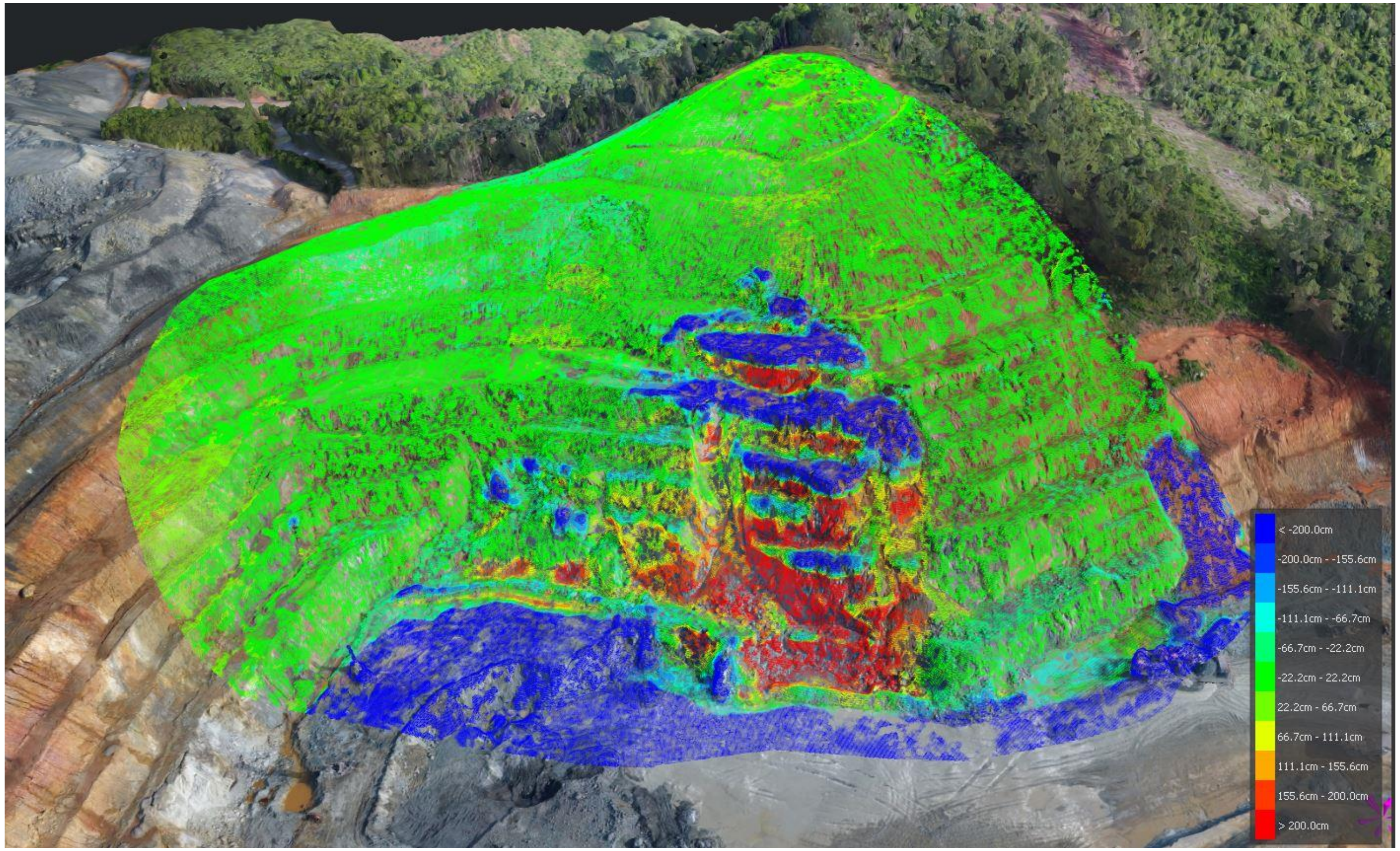
Aerial Photogrammetry

- Low Resolution (surveying purpose)
- Mapping geological features
  - >10m in length
  - Multi-bench
- Extrapolating fault planes for use in 3D stability analyses
  - Naming Faults



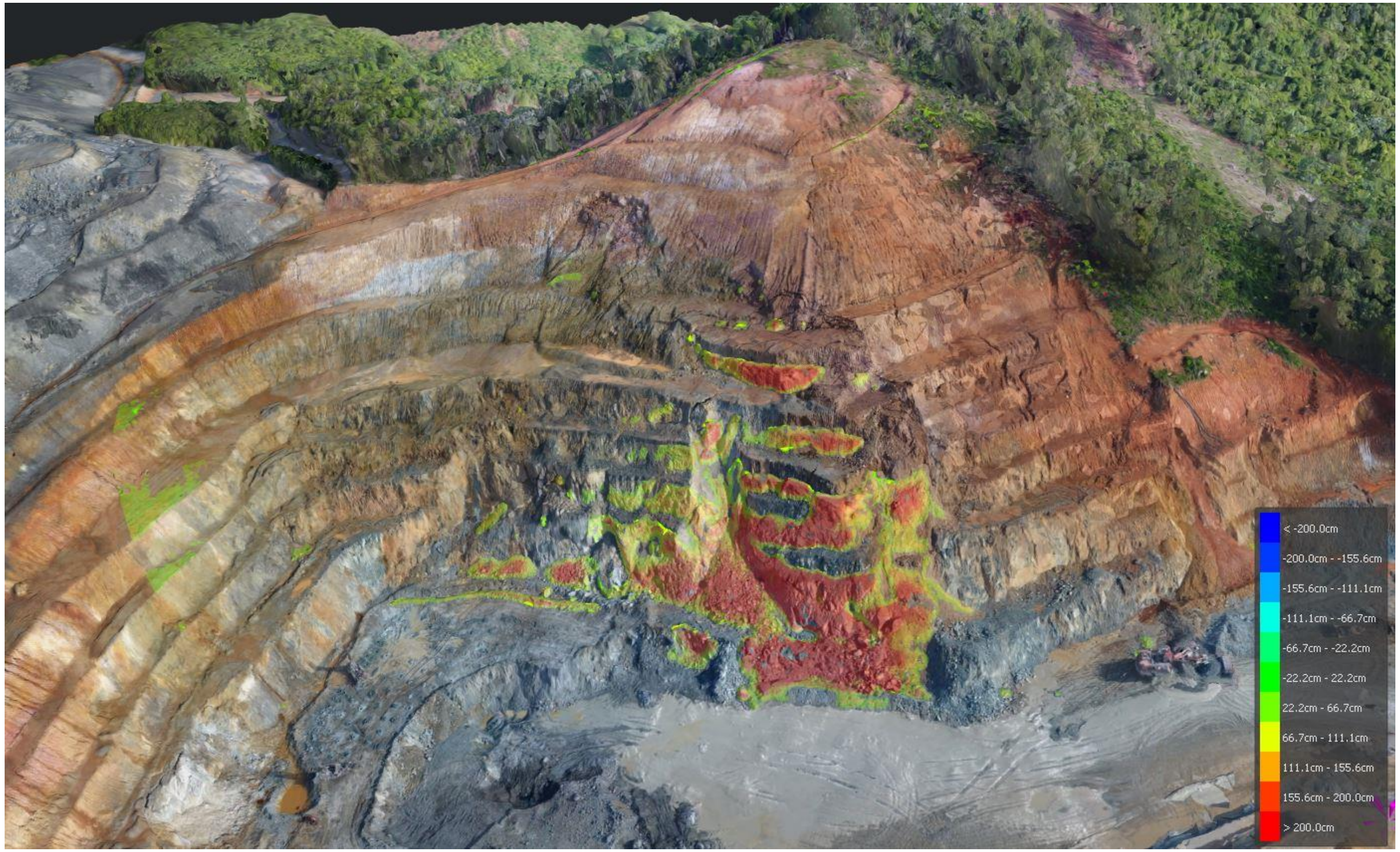
Deformation Analysis from Photogrammetry

- Photogrammetry for surveying every 2 weeks
- Vertical deformation
- 70m high instability



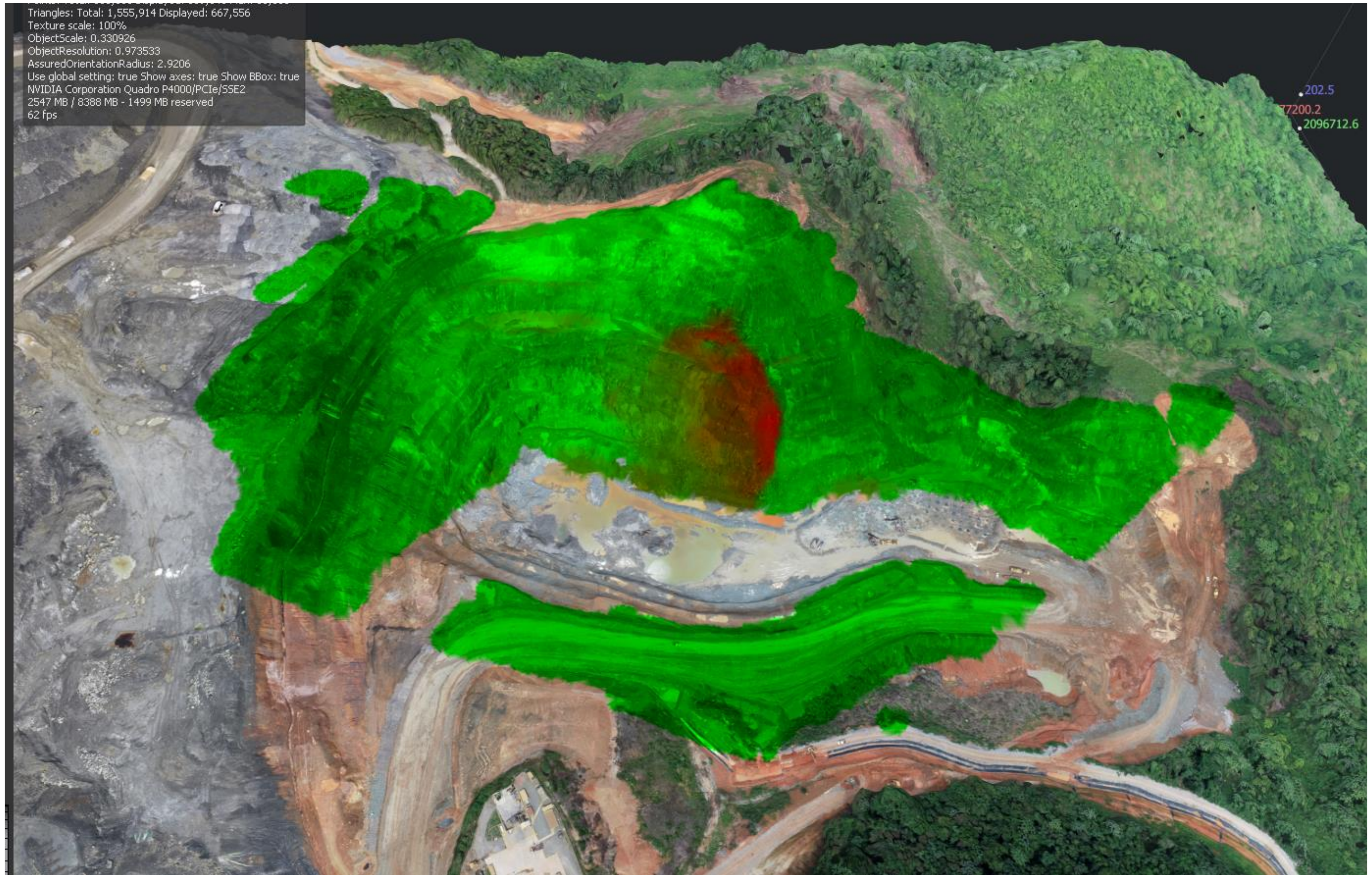
Deformation Analysis from Photogrammetry

- Photogrammetry for surveying every 2 weeks
- Vertical deformation
  - Outward only



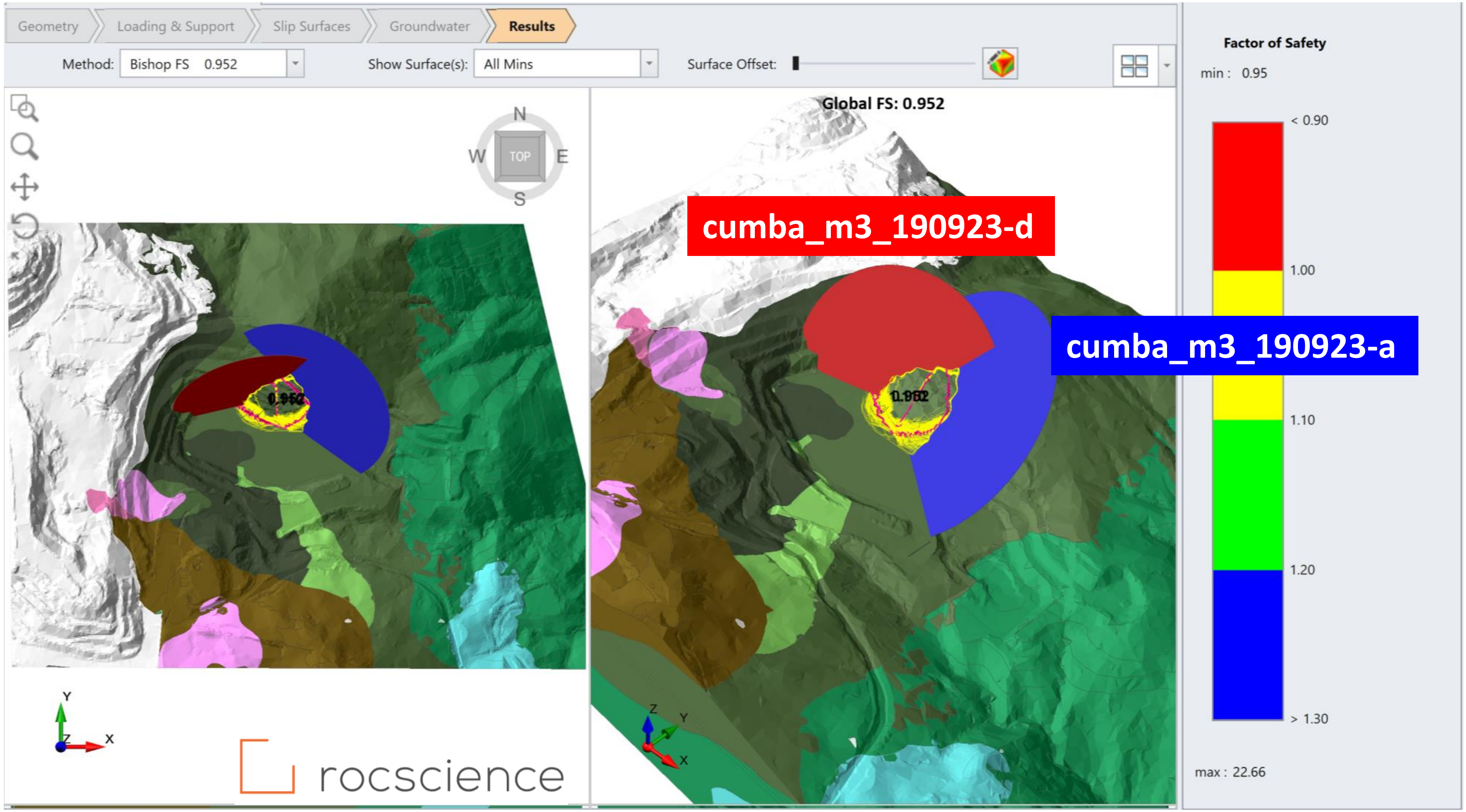
Integration of GbSAR and Photogrammetry

- Integration of GbSAR and photogrammetry
  - Visualization of radar deformation overlain on the photogrammetry model



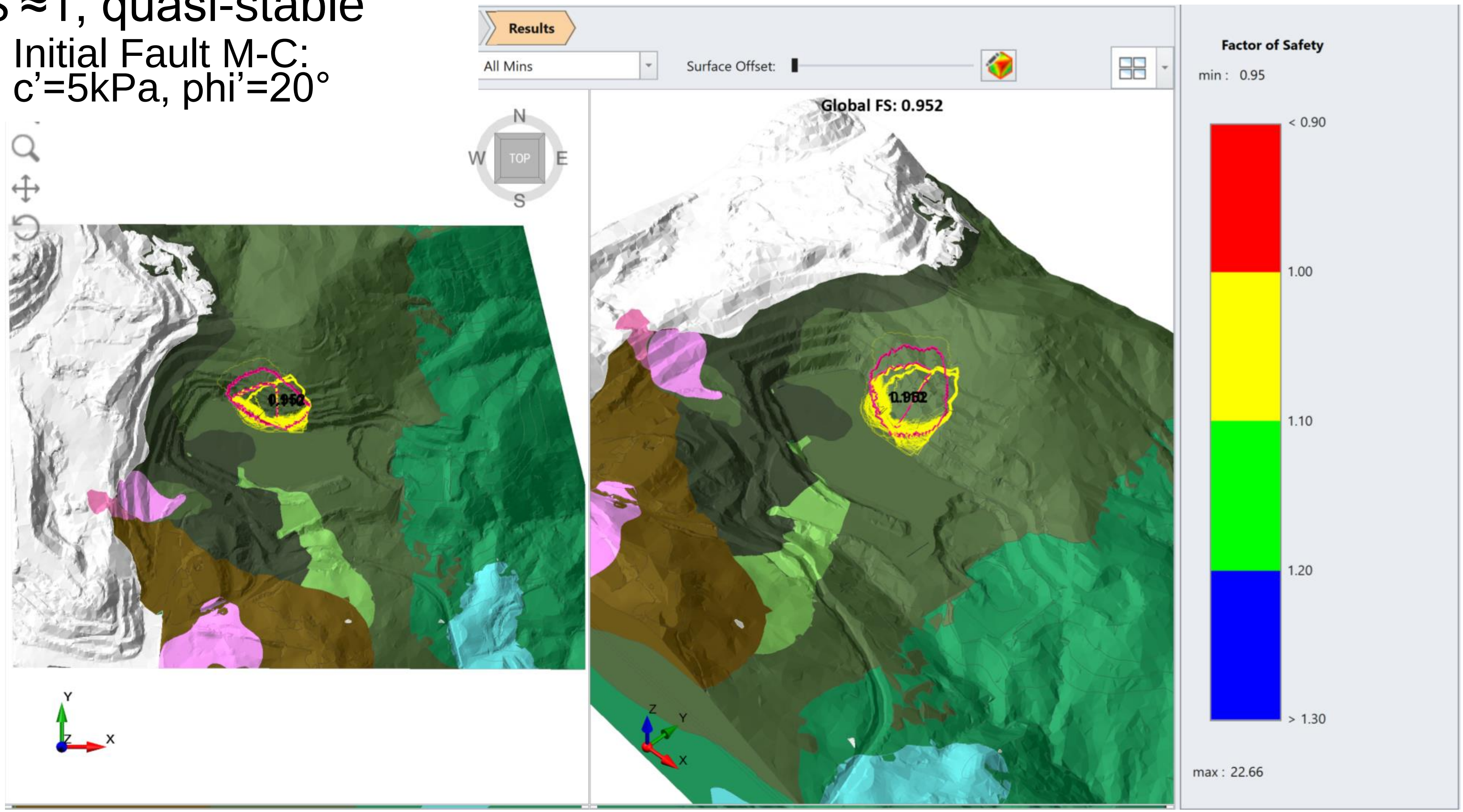
3GSM ShapeMetrix UAV – assistance from Dr Markus Pötsch

3D LE – Including Faults, Mine Floor 310mRL



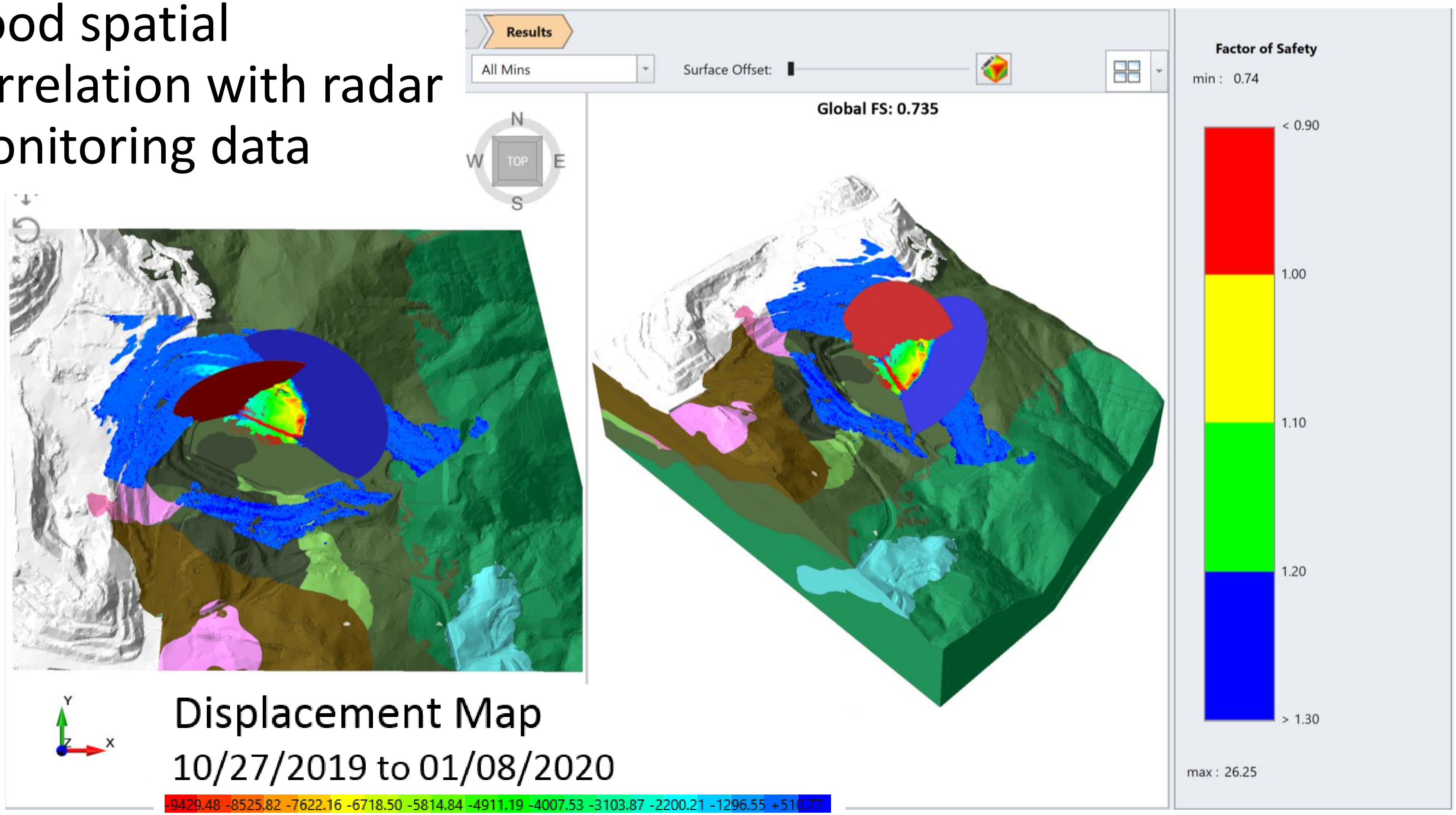
3D LE – Including Faults, Mine Floor 310mRL

- FoS ≈1, quasi-stable
  - Initial Fault M-C: c'=5kPa, phi'=20°



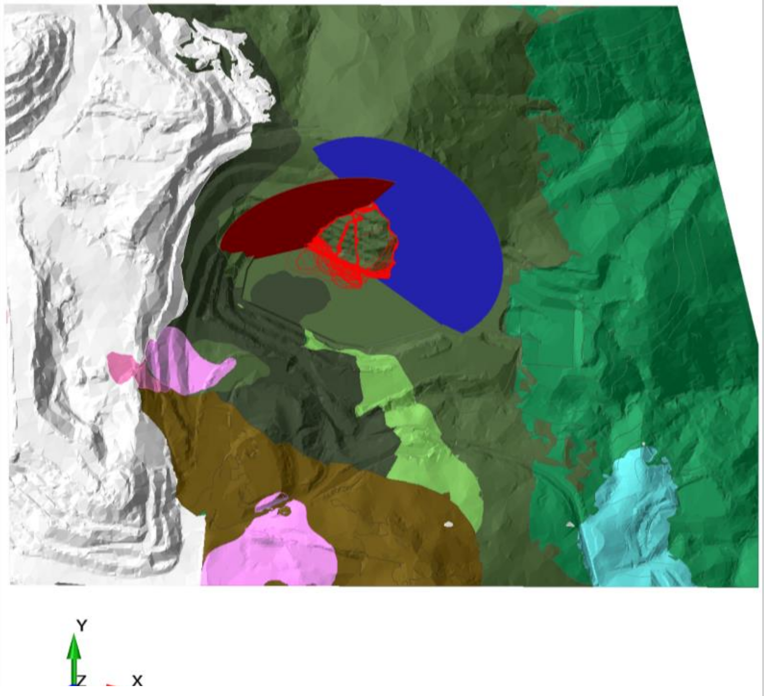
3D LE – Including Faults, Mine Floor 310mRL

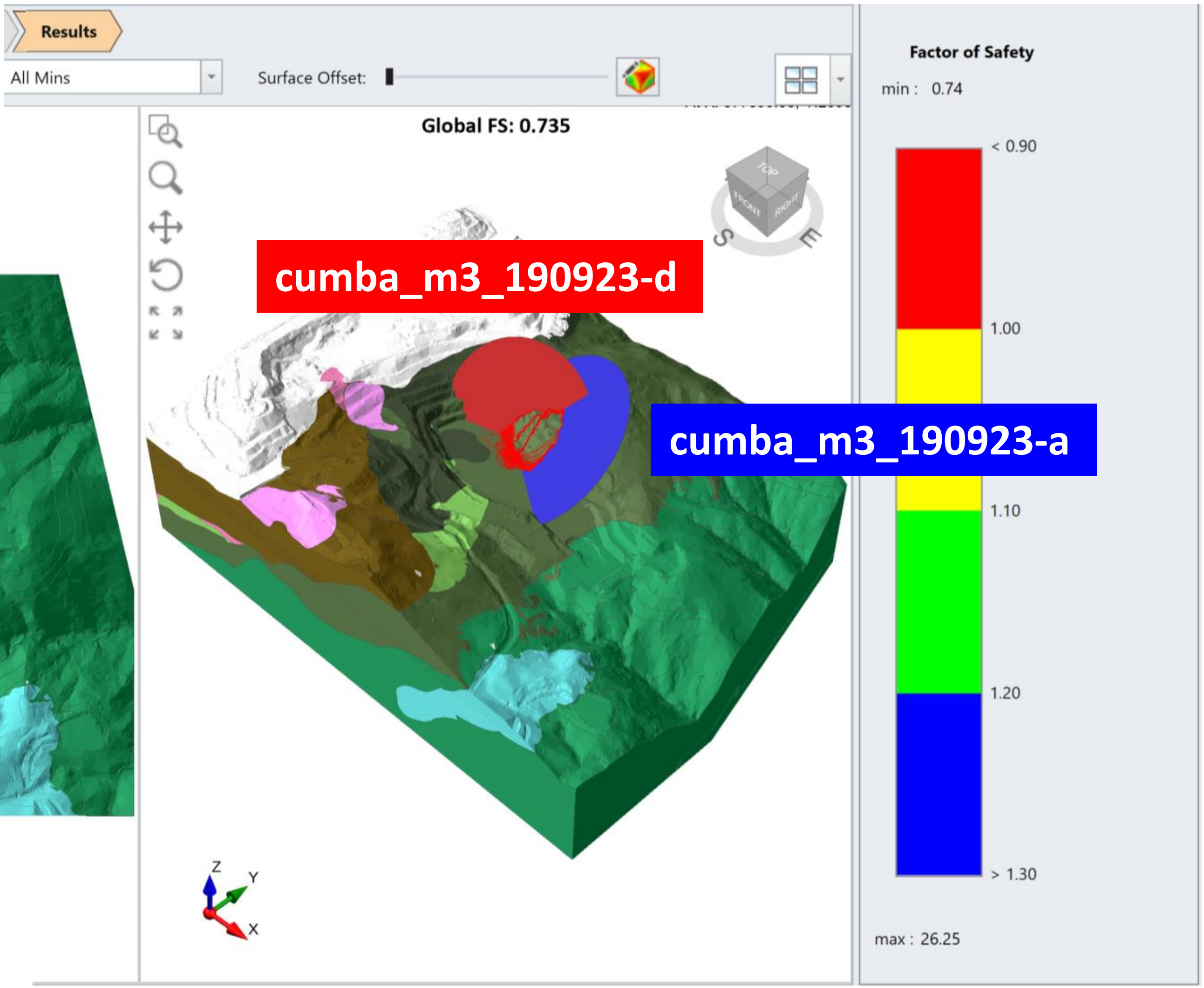
- Good spatial correlation with radar monitoring data



3D LE – Forward Prediction: Mine to 300mRL

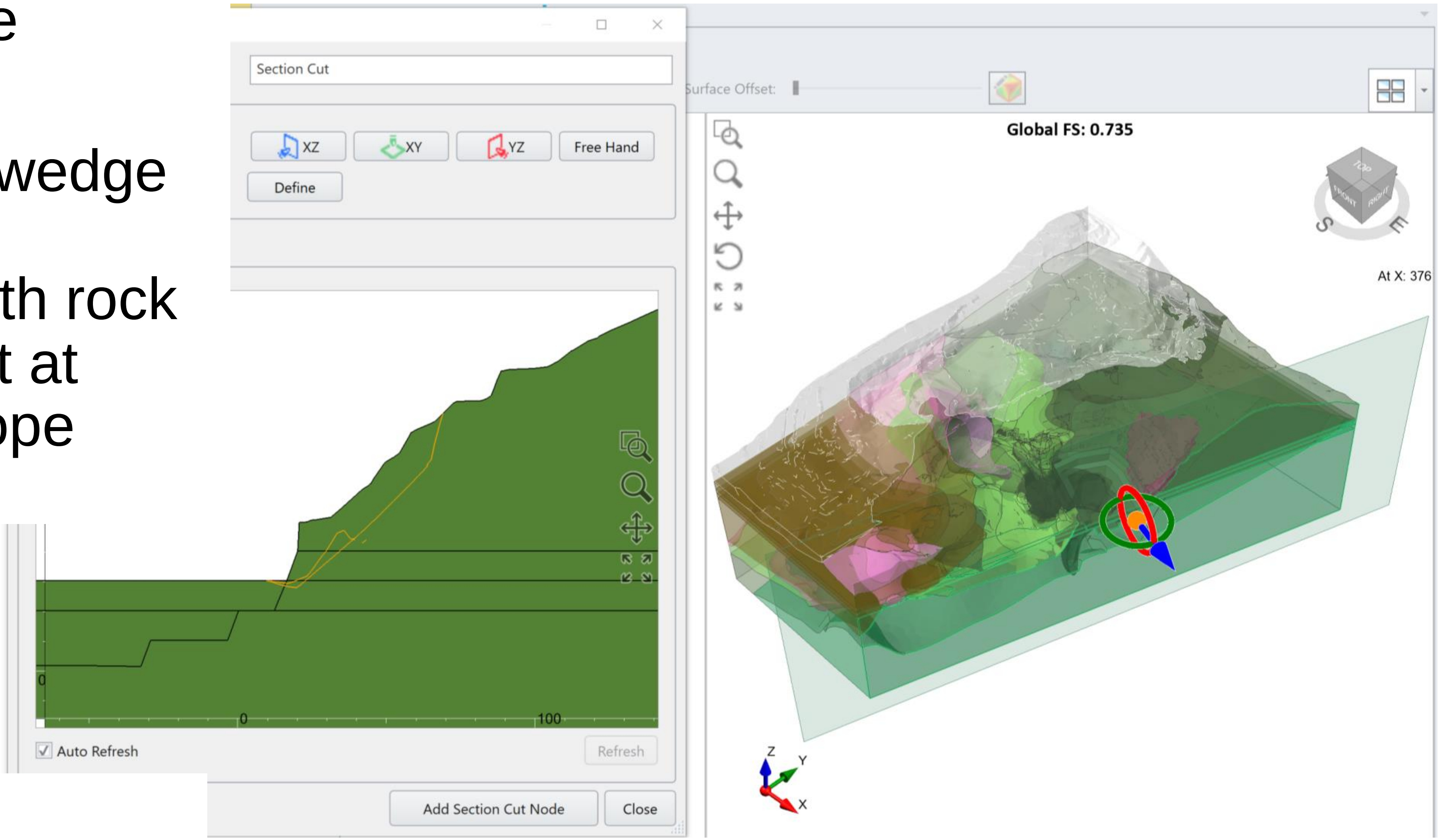
- 10m vertical advance
- FoS <<1, failure expected





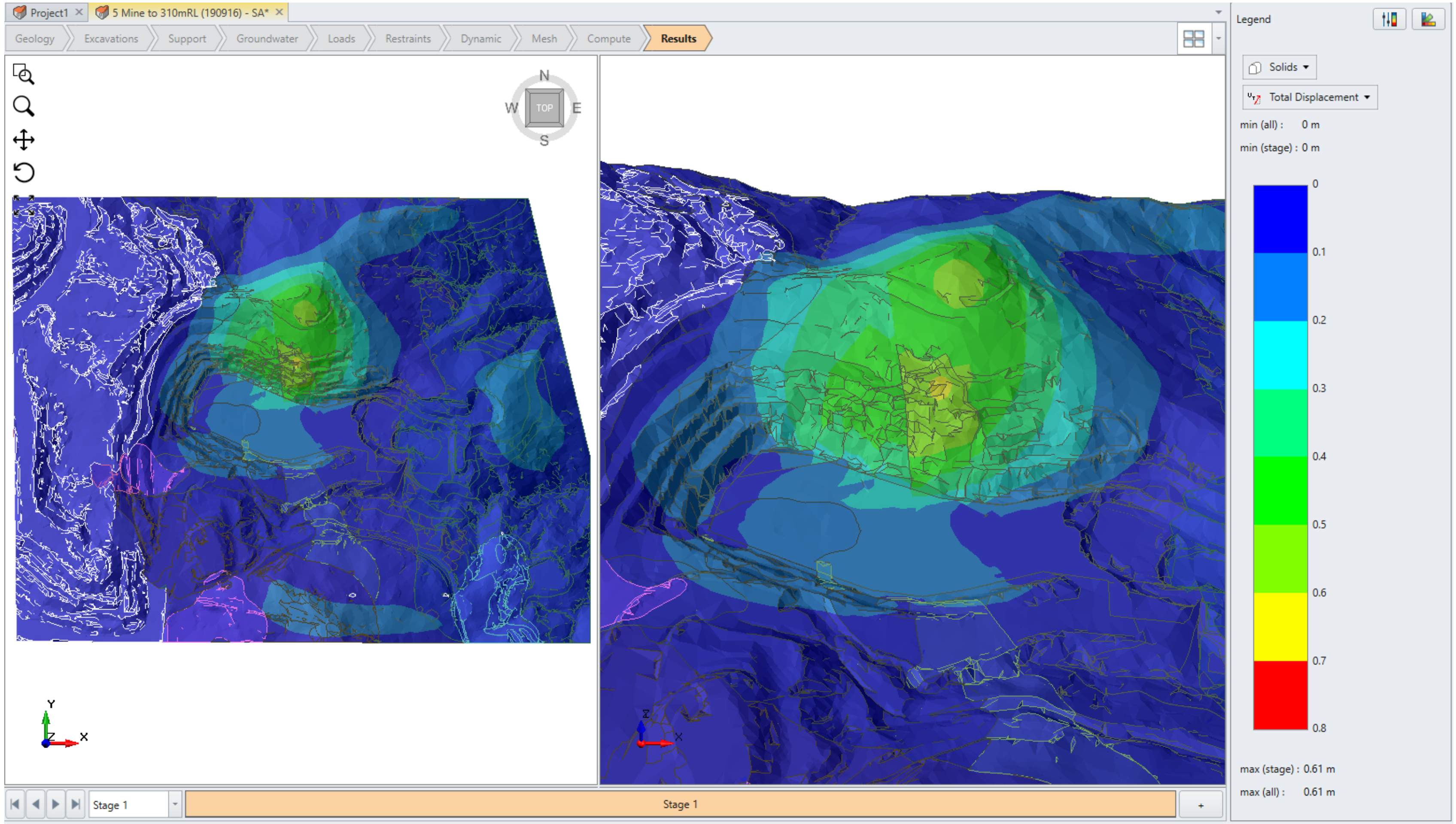
3D LE – Forward Prediction: Mine to 300mRL

- FoS <<1, failure expected
- Mechanism – wedge failure (non-daylighting) with rock mass breakout at base of the slope



3D FE – Stress Strain Analysis Mine to 310mRL

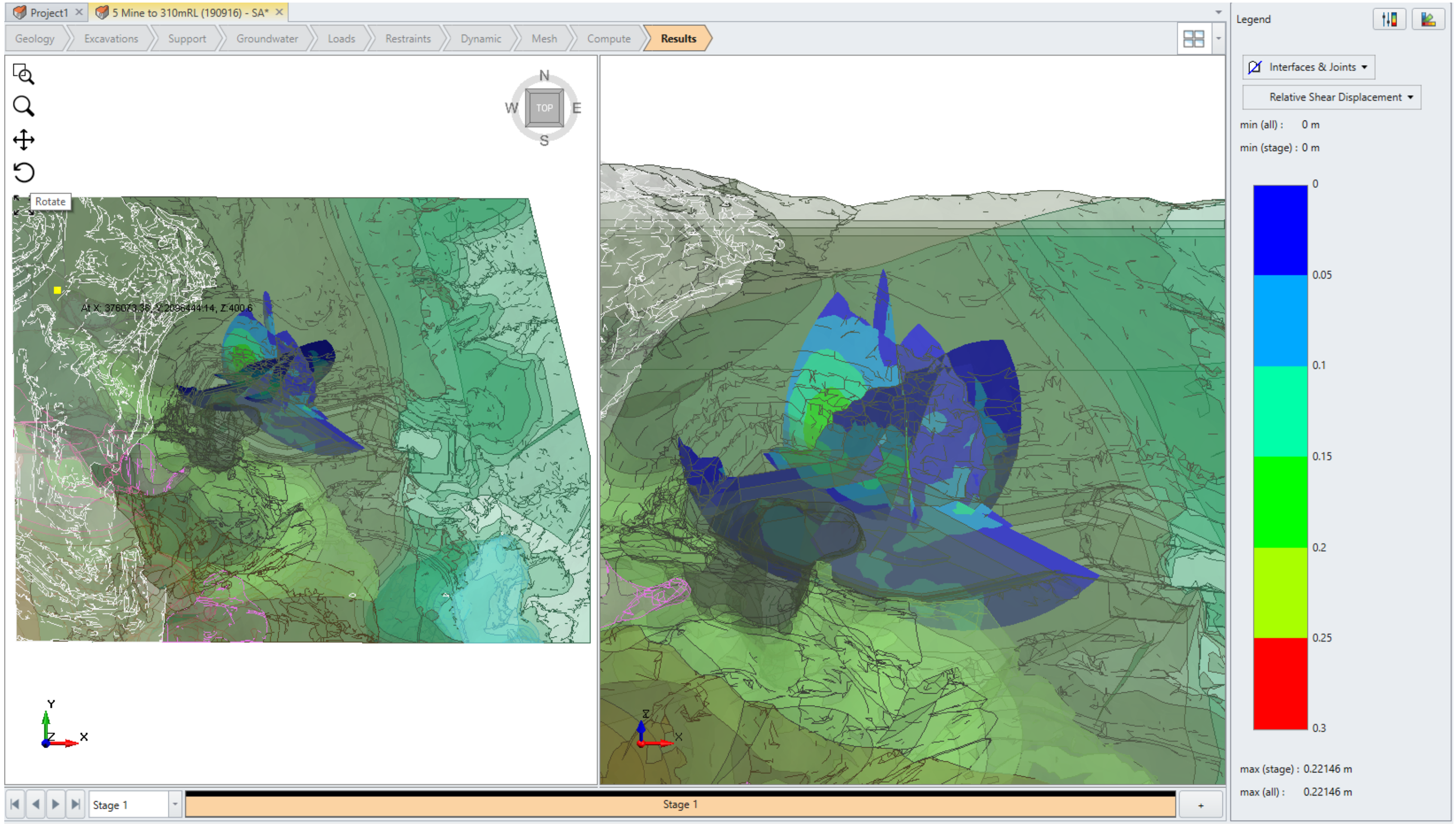
- Elastic analysis only
  - Failure mechanism validation
- Total Displacement



Rocscience RS3 – model by Dr Alison McQuillan

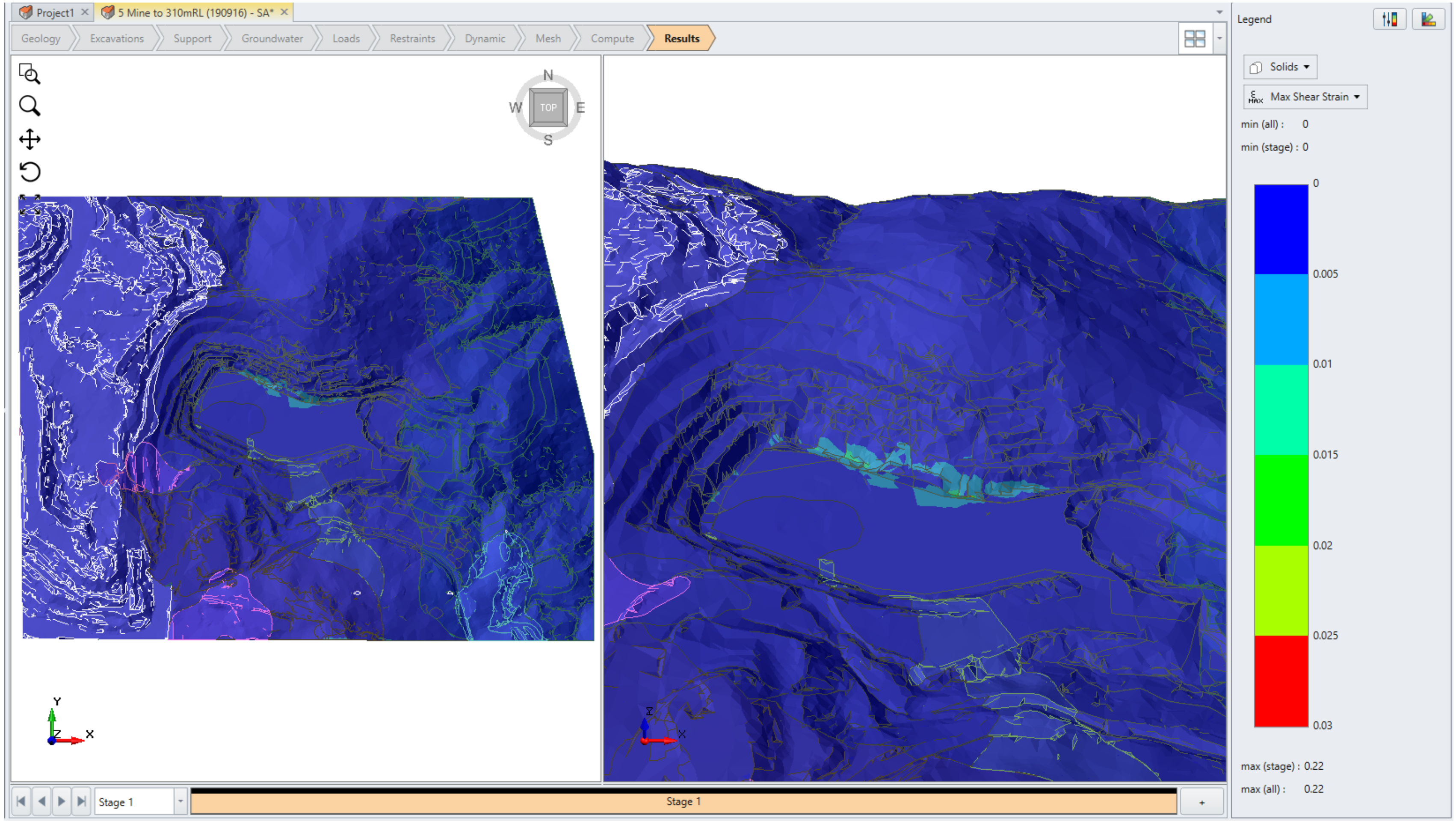
3D FE – Stress Strain Analysis Mine to 310mRL

- Elastic analysis only
  - Failure mechanism validation
- Relative shear displacement
  - Spread across faults



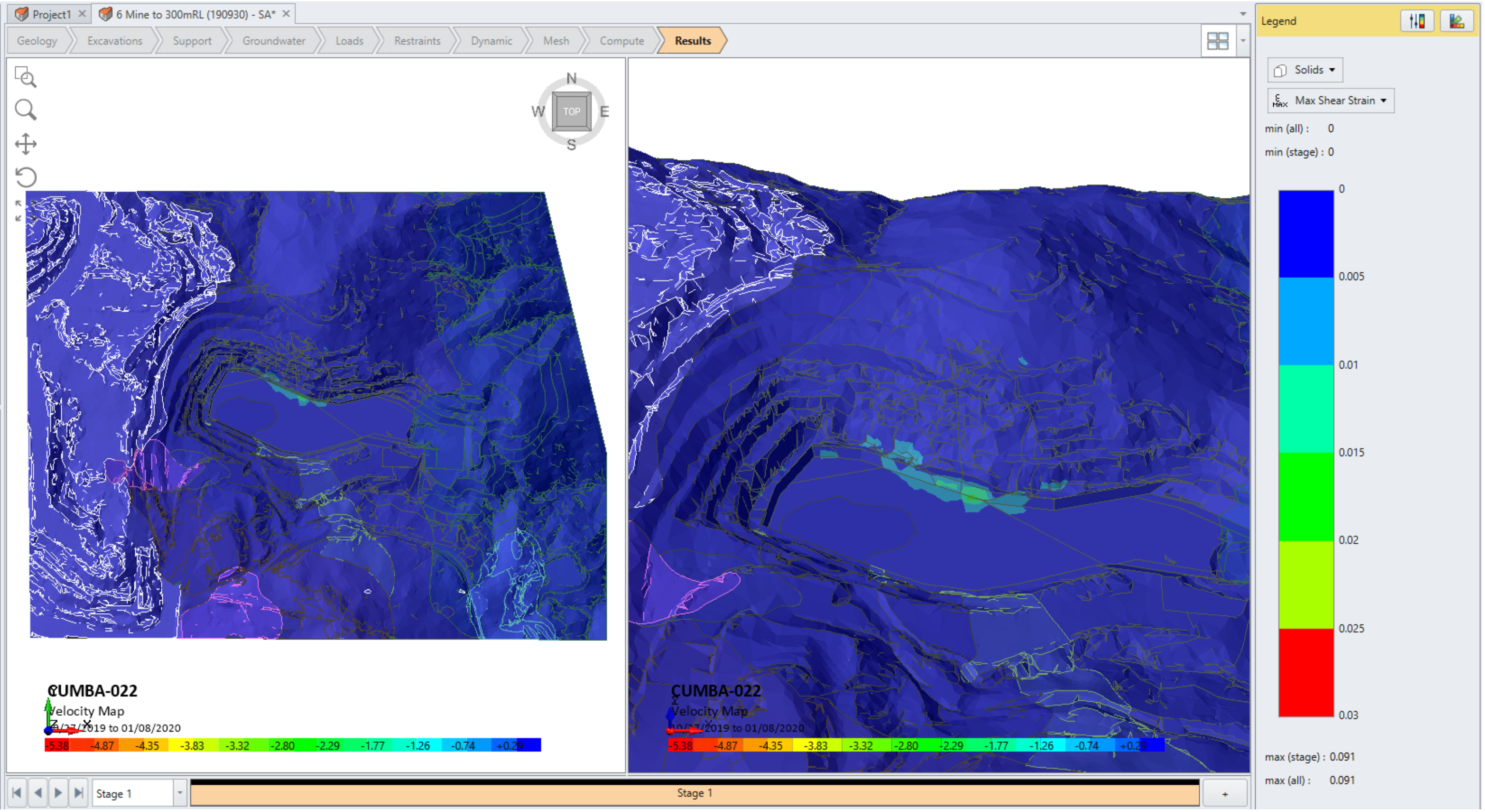
3D FE – Stress Strain Analysis Mine to 310mRL

- Elastic analysis only
  - Failure mechanism validation
- Maximum Shear Strain
  - Generally at base of slope



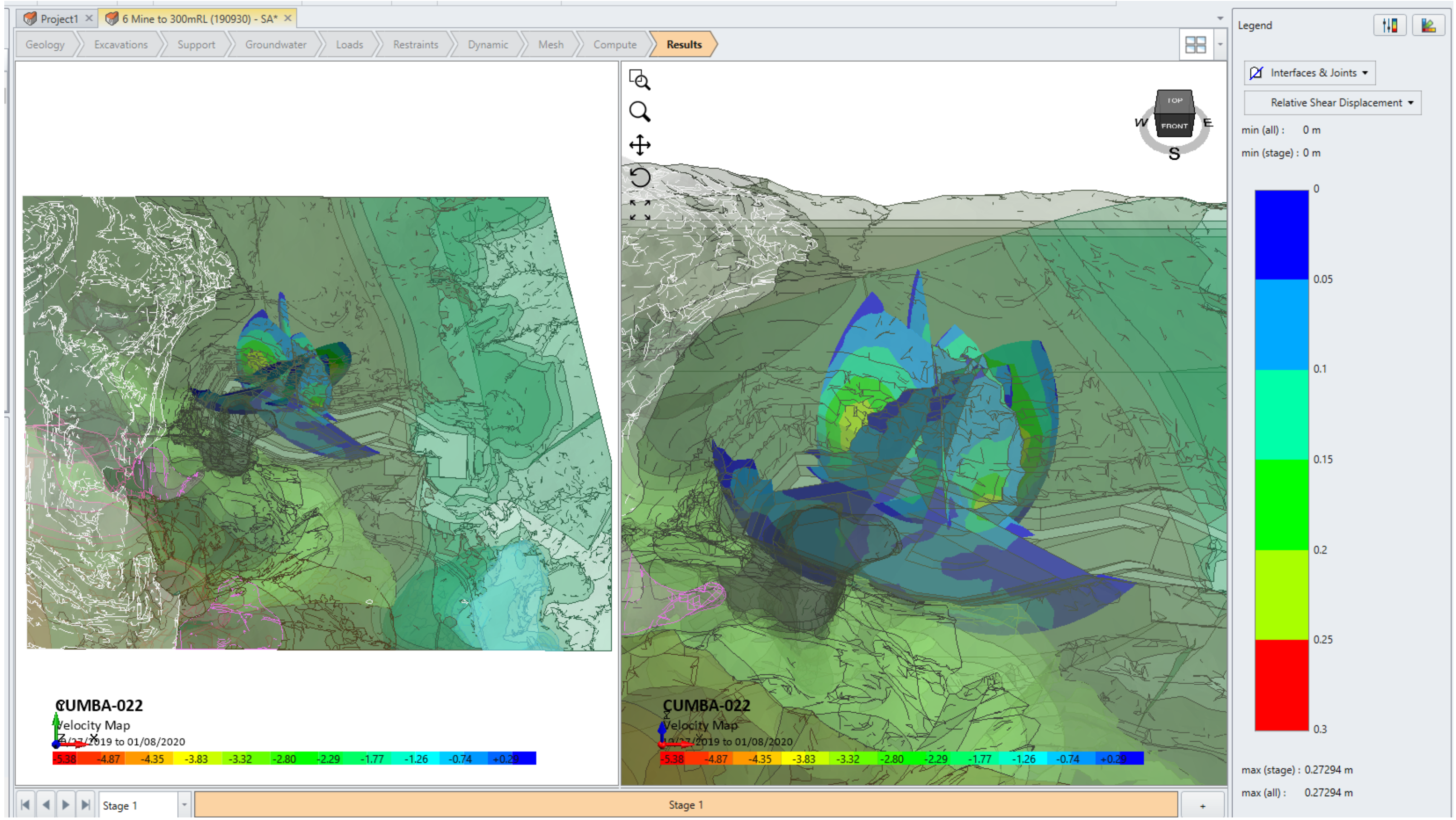
3D FE – Forward Prediction: Mine to 300mRL

- Elastic analysis only
  - Failure mechanism validation
- Maximum Shear Strain
  - More focused at base of slope



3D FE – Forward Prediction: Mine to 300mRL

- Elastic analysis only
  - Failure mechanism validation
- Relative shear displacement
  - Focusing toward the lower parts of faults



3D FE – Forward Prediction: Mine to 300mRL

- Elastic analysis only
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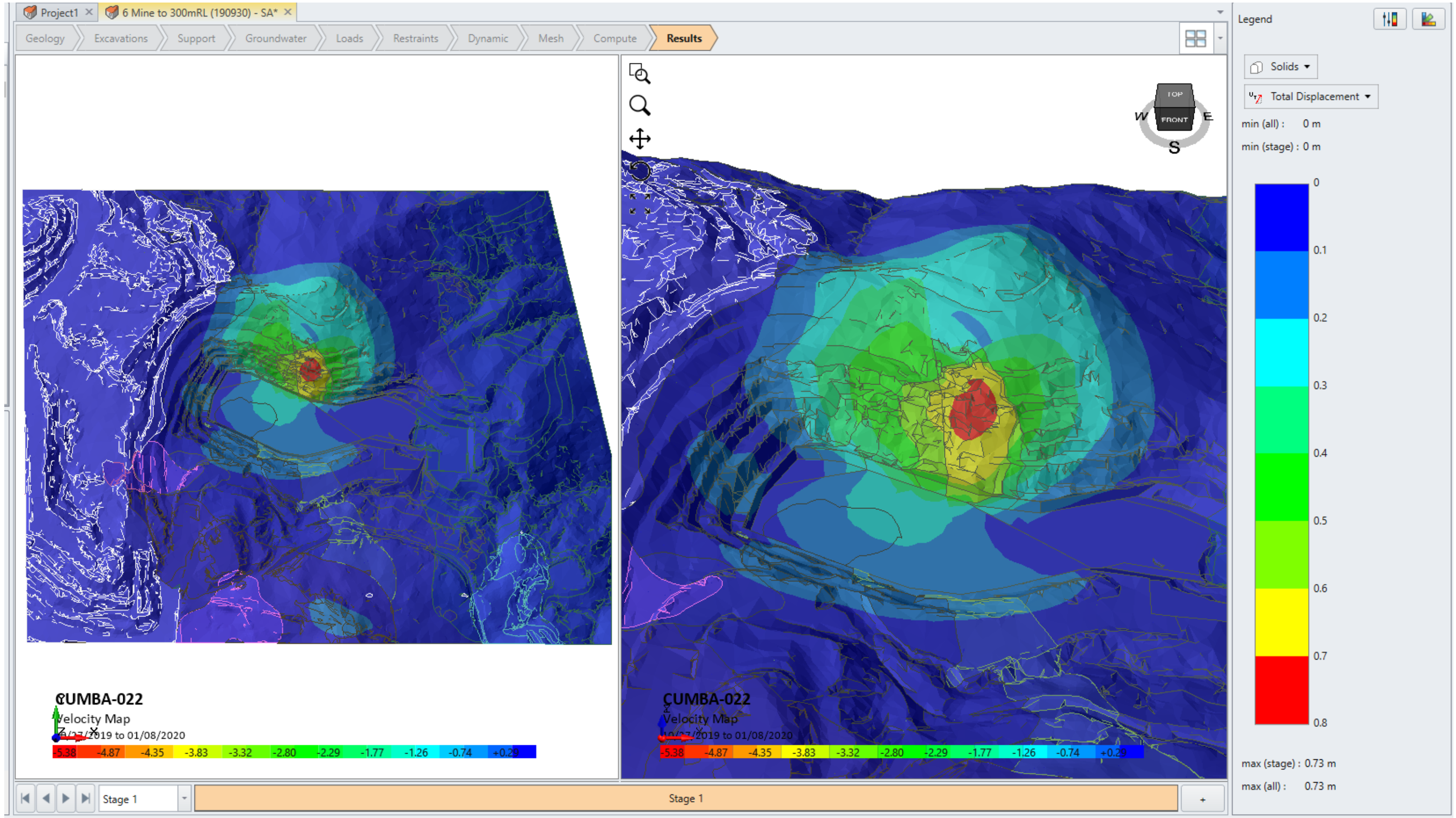
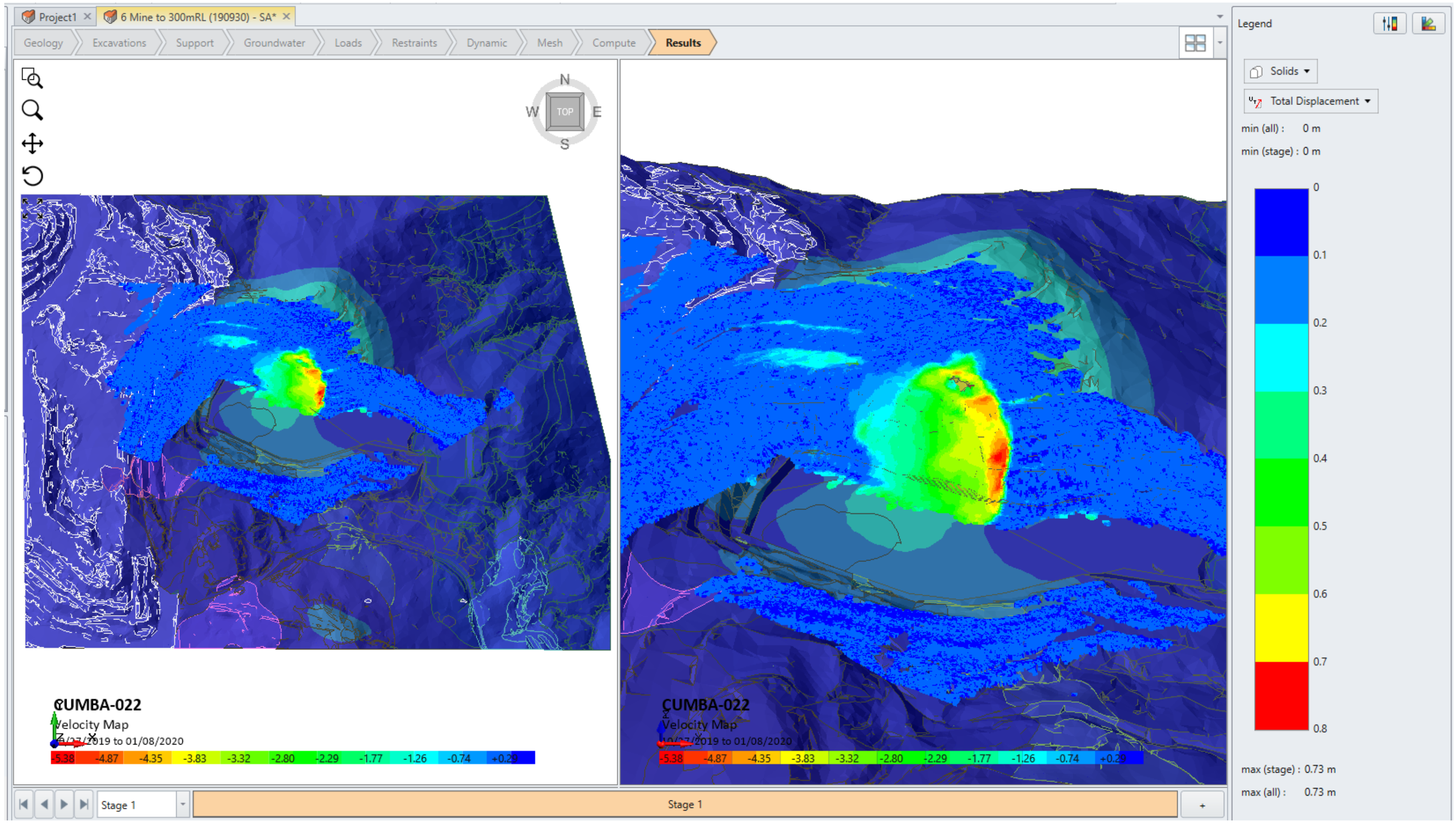
- Total Displacement



3D FE – RS3-GbSAR Deformation Integration

- Elastic analysis only
  - Failure mechanism validation
- Radar Data
  - Displacement concentrations between model and monitoring spatially match



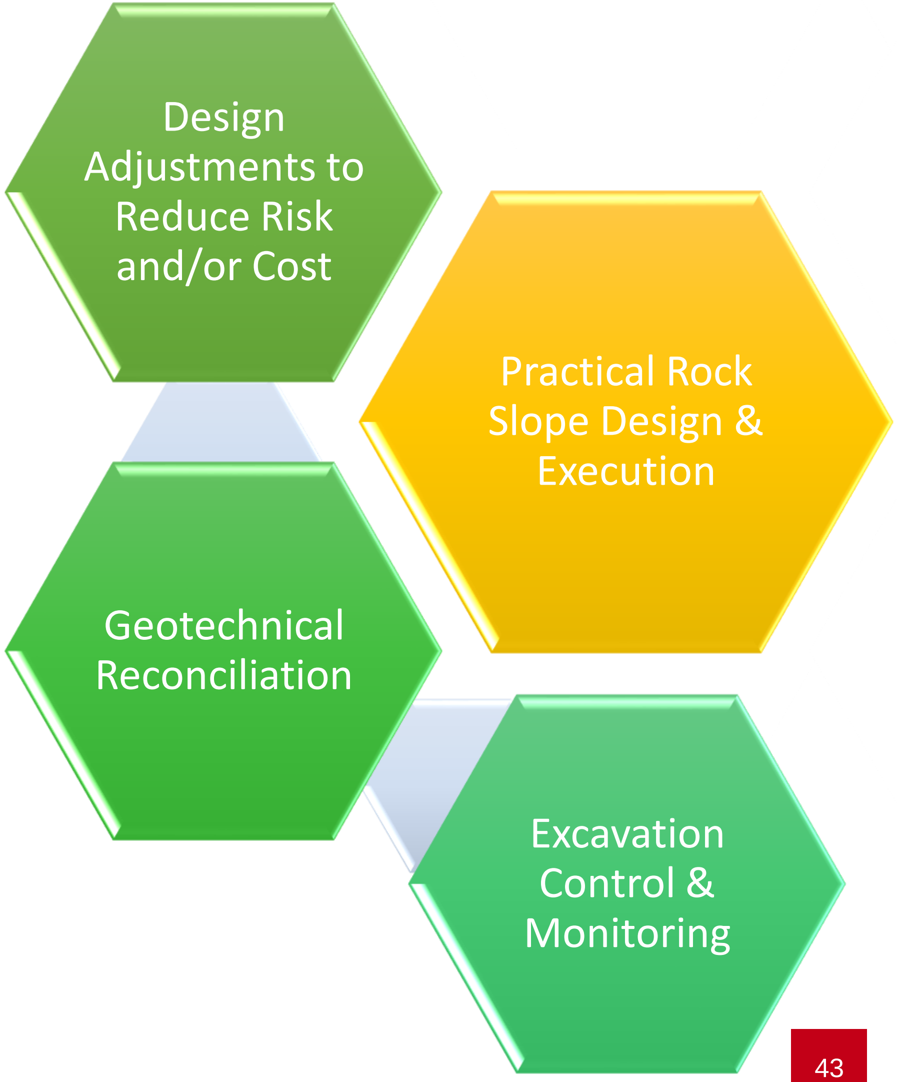
Cumba Slope Instability

Summary

- Deformation monitoring identified unexpected ground behavior
- Aerial photogrammetry used update geotechnical model
- 3D slope stability analysis indicated failure expected on next bench
- Time taken: only <3 days!

Process facilitated ground failure risk management considering both:

- Safety risks
- Economical consequences



KEY TAKEAWAYS

…use technology in an appropriate manner to understand and solve complex problems

Why monitor?

- Reduce Safety Risk
  - Higher frequency monitoring (e.g. radar, prisms, shape accel arrays)
  - Enables slope optimization where the economic consequences of failure are relatively low (key mining application for interim pit slopes).
    - Size of the prize: usually exceeds $10M-$500M USD in reduced waste stripping / additional ore recovery
- Understand ground behavior
  - Identify deviations to expected ground behavior
  - *"Know where to look first"* - prioritize ground characterization efforts in higher risk or higher uncertainty areas
- Validate simple slope stability models (qualitative)
- Calibrate numerical simulations (stress-strain, quantitative)

Why routinely reconcile geotechnical models?

- All models are wrong! …but some are useful
  - How well do you really understand geology (lithology, weathering, alteration), structure (major and minor), rock mass and groundwater from a few boreholes and surface mapping at early project stages?
- Geotechnical models contain a lot of uncertainty
  - Due to limited data collection
  - Due to limitations in data capture and analysis methods
- Reconciling geotechnical models is required as study phases and excavations progress to
  - Reduce uncertainty, better understand ground conditions and simulate behavior
  - Reduce economic risks, identify and realize opportunities
- Technology can assist us – use it to assist you to work faster where possible
  - Try not to overcomplicate it, but beware of not oversimplifying (*quite contradictory*)

Further viewing

- **Integration of Photogrammetry, 3D Slope Stability Models and Synthetic Aperture Radar**
  https://www.youtube.com/watch?v=HCu8Wqncy-o

- **Mega Models - 3D slope stability models (LEM+FEM) built for you and your team to use**
  https://www.youtube.com/watch?v=Kgu1G_nzVLw

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