



A DFN Framework with Application to Rock Engineering Characterisation, Analysis & Design

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Webinar Overview: Abstract

A DFN FRAMEWORK WITH APPLICATION TO ROCK ENGINEERING CHARACTERISATION, ANALYSIS & DESIGN

This Webinar presents an integrated methodology and workflow for the characterisation and analysis of naturally fractured rocks. The Lecture's three main sections report on the Discrete Fracture Network (DFN) method and use.

The **first section** focuses on an overarching approach, covering a brief history of the approach, its basic philosophy and typical methodology, as well as outlining data and characterisation requirements of the approach.

The **second section** considers strategies for obtaining key rock mass mechanical descriptions including block size distributions, rock mass measures such as GSI values and key effective rock mass property values.

The **final section** reports how DFN description can be carried forward to perform insightful geotechnical analysis considering in situ stress prediction, kinematic block stability analysis for benches/slopes and tunnels, excavation analysis, and support strategies such as grouting and bolting etc.

These workflows are considered key to underpinning the characterisation process as well as the optimised design and construction phases of underground developments.

Section 1: Overarching Approach



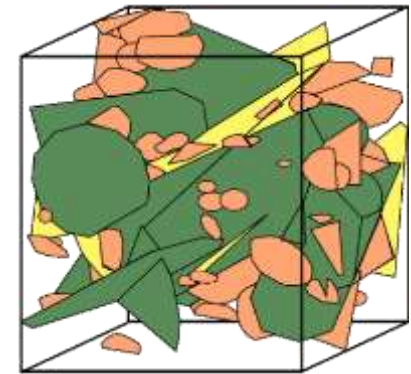
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Introduction – What is DFN??

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The **DFN** (discrete fracture network) approach has creatively grew within industry since the late 1980's – continuously innovated into a world leading commercial **software** and **consulting tool** ever since

FracMan DFN
(circa.1990)



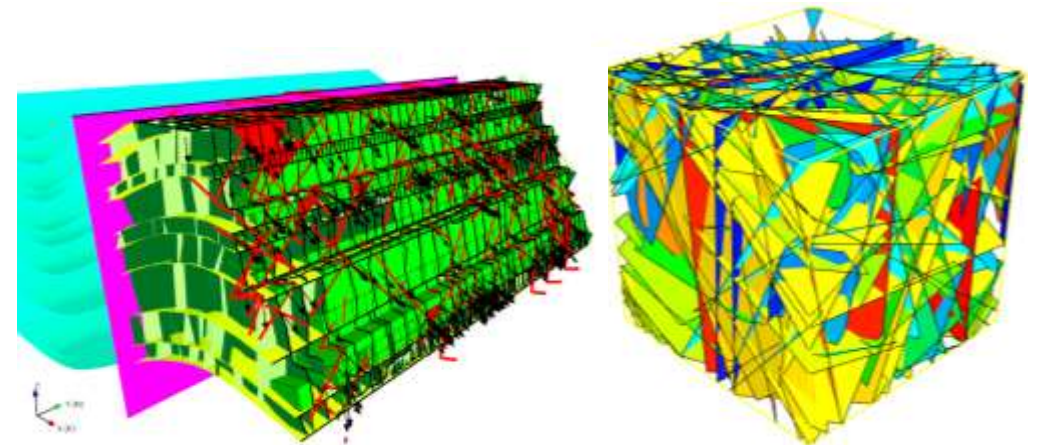
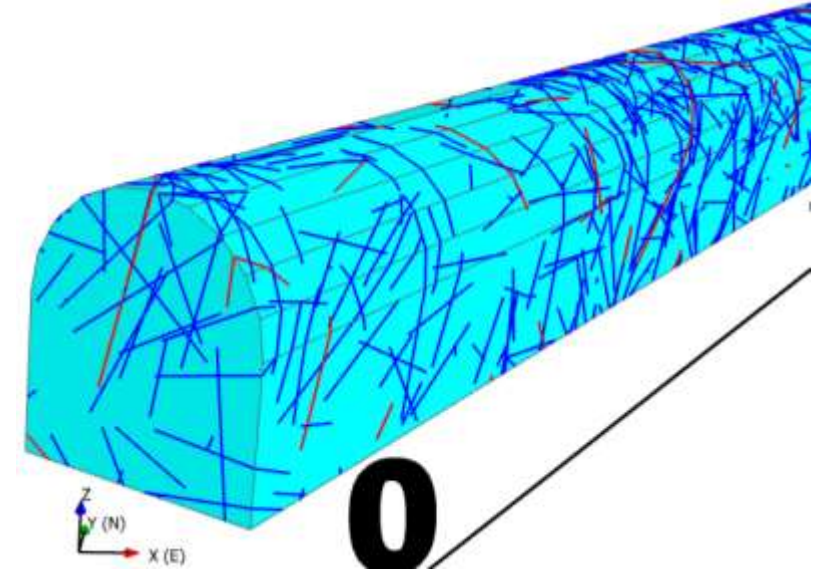
It is now **fully integrated** for the assembly and quantitative **analysis & assessment** of site descriptive data. It is **cross discipline** in taking:

- Geological, hydrogeological, rock mechanical, thermal, chemistry data

Why DFN Analysis & Modeling?

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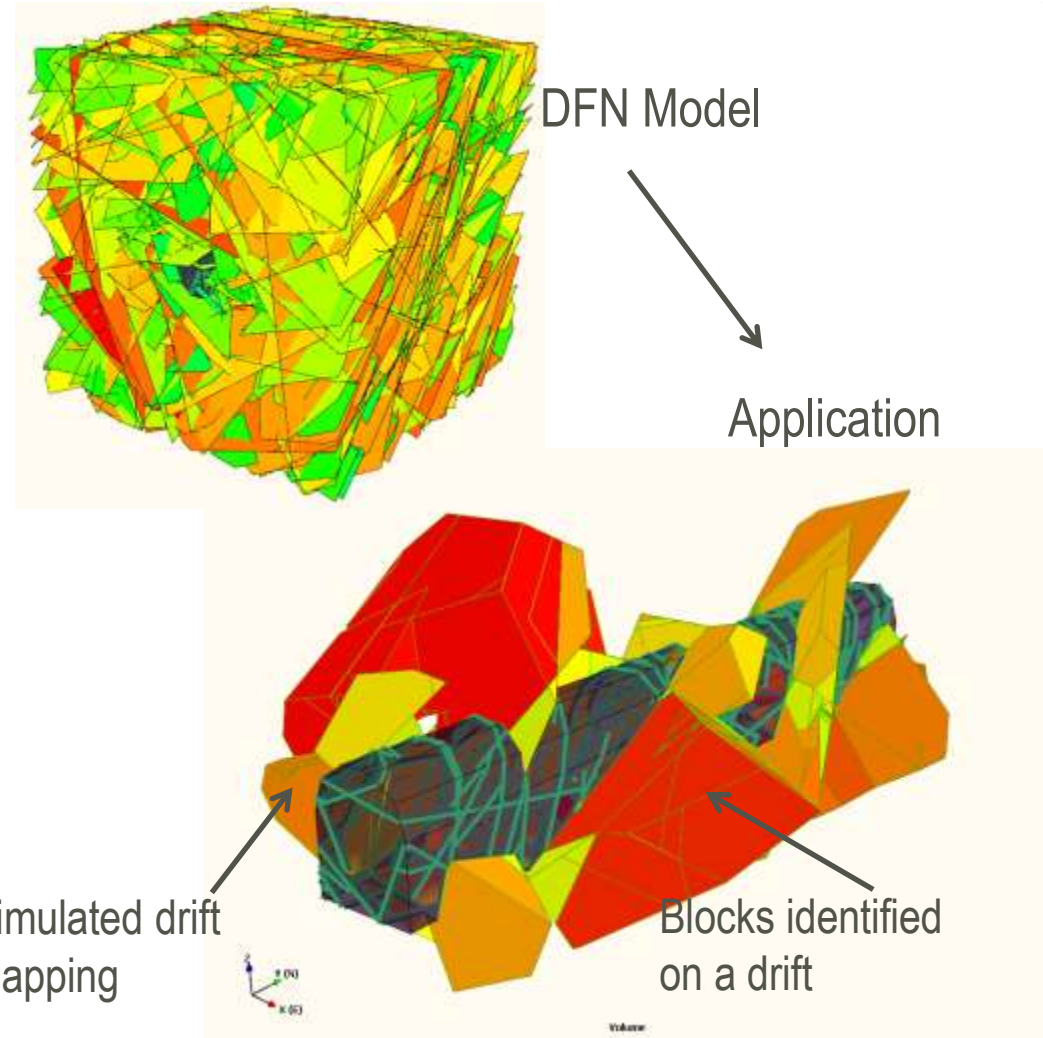
- Increasingly challenging developments require a greater level of characterisation, analysis and modelling to ensure project success
- Fractures Properties are often variable – but we often simplify things
- The assumptions we make about the fracture geometry and properties affects the behaviour of the rock mass – these are often highly conservative or highly simplified
- We can now better describe our rock mass now through advances in surface & underground mapping, borehole technology and geophysical imaging
- Discrete Fracture Network Analysis & Models provides the ideal basis for using these data
- FracMan is a leading software for tackling these issues



Idea Behind Discrete Fracture Network Modelling

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- Explicitly represent discrete fractures and the intact rock bodies in 3D Space
- Build a model of key fracture geometry, mechanical properties, storage and permeability
- Transform geological, geotechnical and well testing data into quantitative parameters to describe fracture network
- Generation of Geologically Realistic DFN models based on parameters derived from field data
- DFN modelling may be a stochastic process allowing multiple but equi-probably realizations to be created
- It's stochastic. We do multiple realisations of the same model to help constrain the predicted answer.



DFN Modelling Today

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Once we just threw fractures into a box

Now we can vary properties spatially

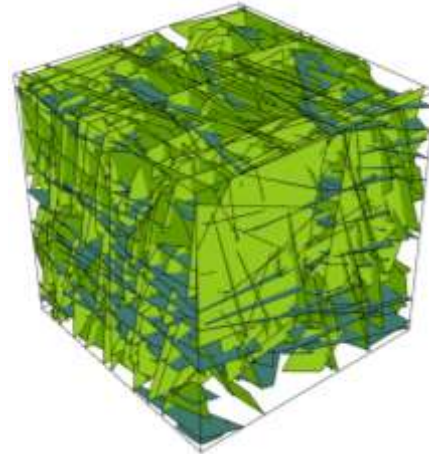
More than the “crack in the box”

Originally simple volumes with constant Poisson process fracture generation

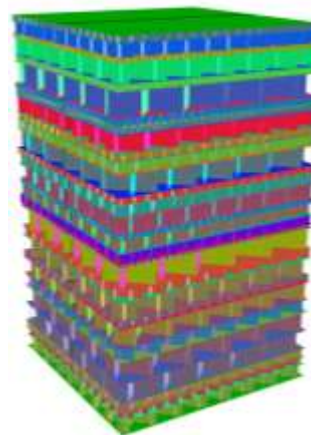
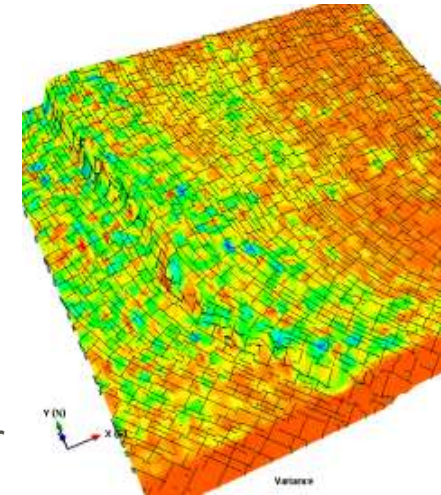
Now we can create large scale models with all properties showing spatial variation (e.g. orientation, intensity, size etc)

Before only random fracture systems could be modelled but now ordered layer bound systems

Increasingly DFN modelling is being used to aid the rock mass characterisation process



Once we just relied on disorder



Now we can recreate more ordered systems

Fully Cross Discipline & Cross Industry

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INFRASTRUCTURE

- Shafts & tunnels
- Slopes & cuttings
- Caverns and excavations
- Groundwater inflow
- Support optimization
- Construction savings (cost/time)

MINING

- Benches & slopes
- Fragmentation
- Support optimization
- In situ stress
- Pre-conditioning
- Mine water assessment

SCR / NUCLEAR WASTE

- Contaminant transport
- Safety case assessments
- Groundwater flow
- In situ stress
- Construction optimization
- Geo-events (earthquake, ice-age)

ENERGY

- Oil & gas
- Deep geothermal
- Well completion optimization
- Hydraulic fracturing / induced seismicity
- Multiphase fluid flow
- Reservoir geomechanics



DFN Toolkit Innovation & Evolution

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- Today, we must continuously **embrace technology**
- Evolving **concepts/strategies** for rapid analysis and verification of largescale fractured rock models
- Approaches & strategies must **efficiently bridge** between routine site information with computational areas
- **Geology** – fracture growth & connectivity
- **Geomechanics** – material description & engineering
- **Flow** – multiphase flow, coupled systems, & engineering
- **HPC** – data analytics, Machine Learning, with databases, and Cloud Computing

Overarching Technical Workflow

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Development of Geological Conceptual Model (GCM)

Hydraulic Properties

Geological Properties

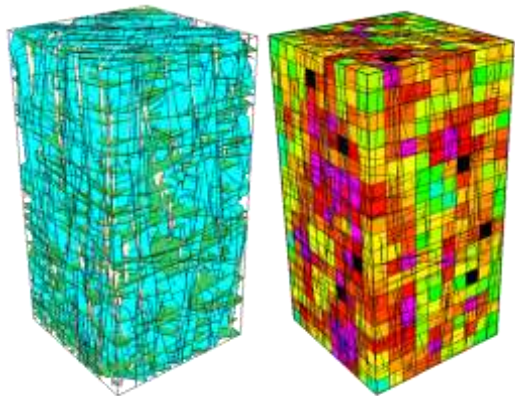
Geomechanical Properties

Develop DFN Model

What's the decision making used for?

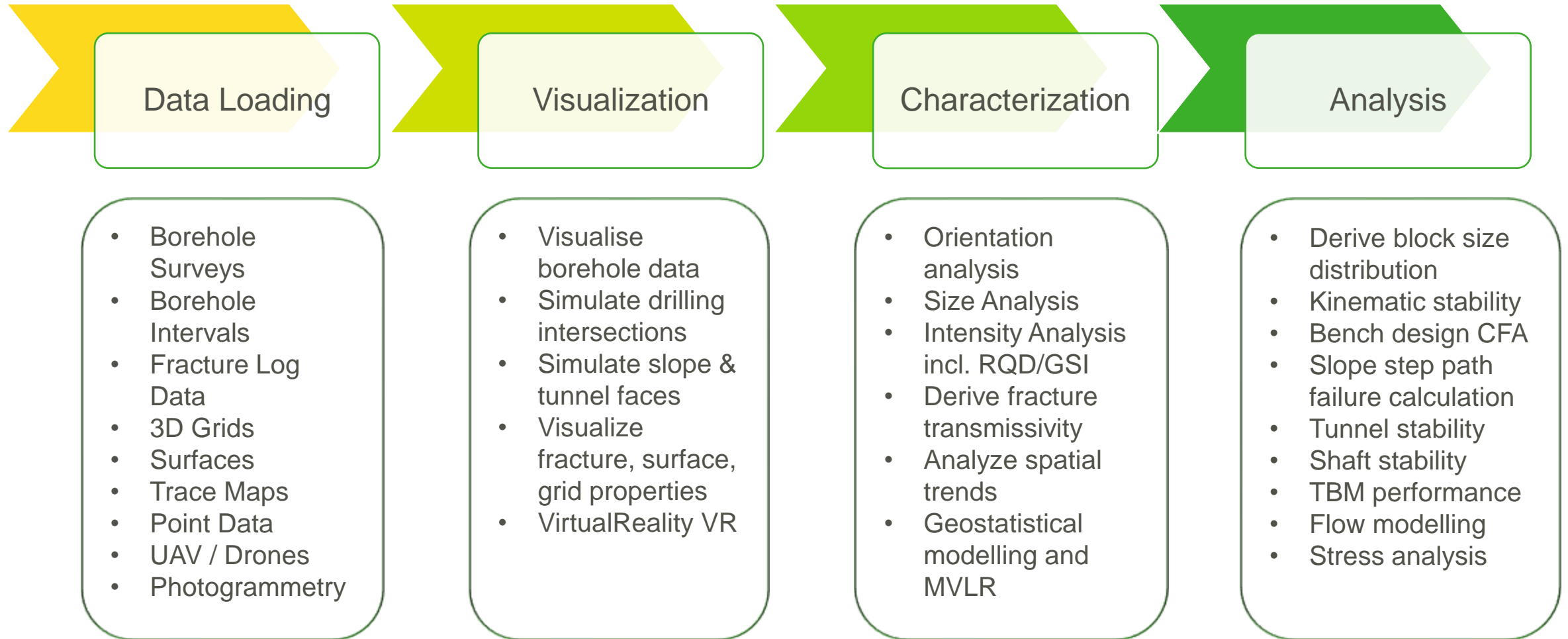
Application of DFN to Decision Making

- Implementation
- Cost/Efficiency
- Regulation
- Environment



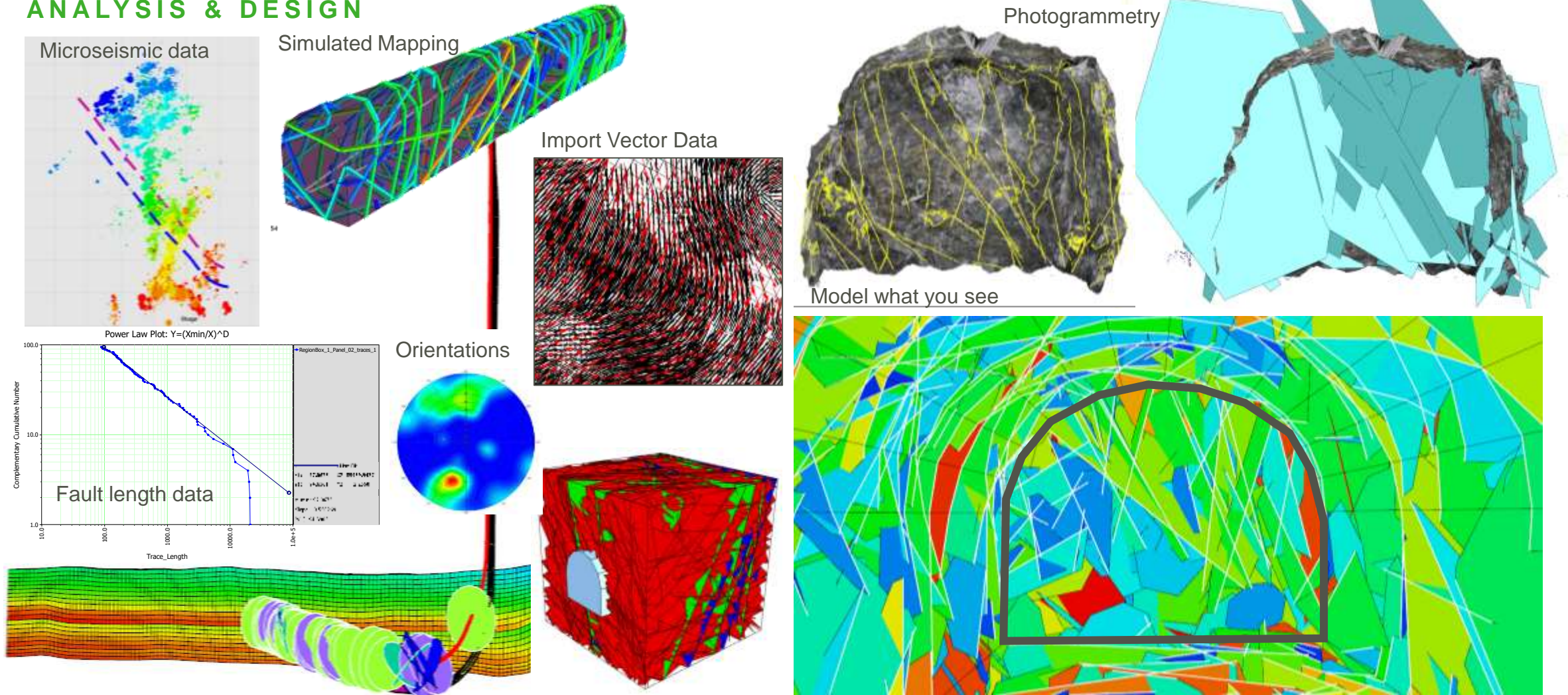
Key Elements of Geotechnical DFN Workflow & Analysis

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DFN Requires/Enables Handling Of A Wide Range Of Data

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Discrete Fracture Network (DFN) - The Detail

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- DFN modelling involves defining the geometry of structures in the rock mass and explicitly representing them in 3D Space
- We know where the big structures are so we can directly include them
- Smaller structures have known properties but are too numerous to place exactly – this leads us down the stochastic pathway
- They are modelled by defining the key geometric properties from available data, including boreholes, mapping and wireframed objects
- DFN modelling is a stochastic process, defining the network of important structures e.g. small-scale faults and joints, according to distributions of the key input parameters

Data Sources: Boreholes, Mapping, Wireframes etc

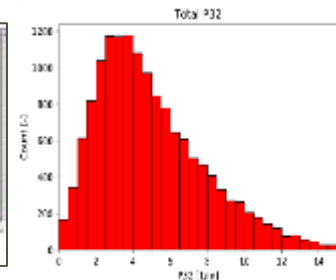
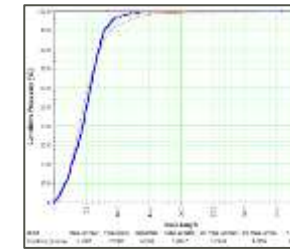
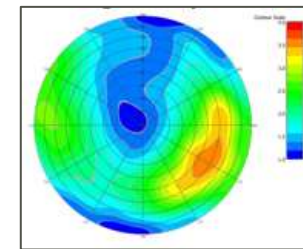
Orientation



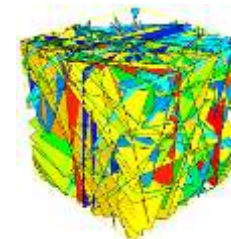
Size



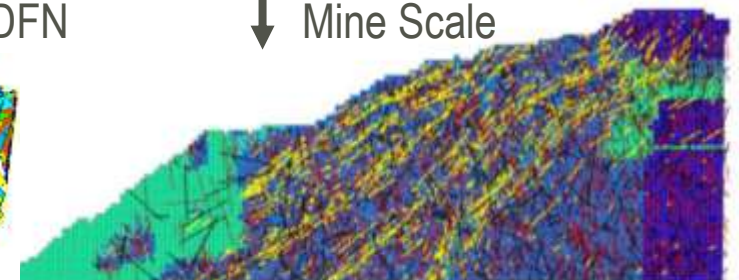
Intensity



Small scale DFN



Mine Scale



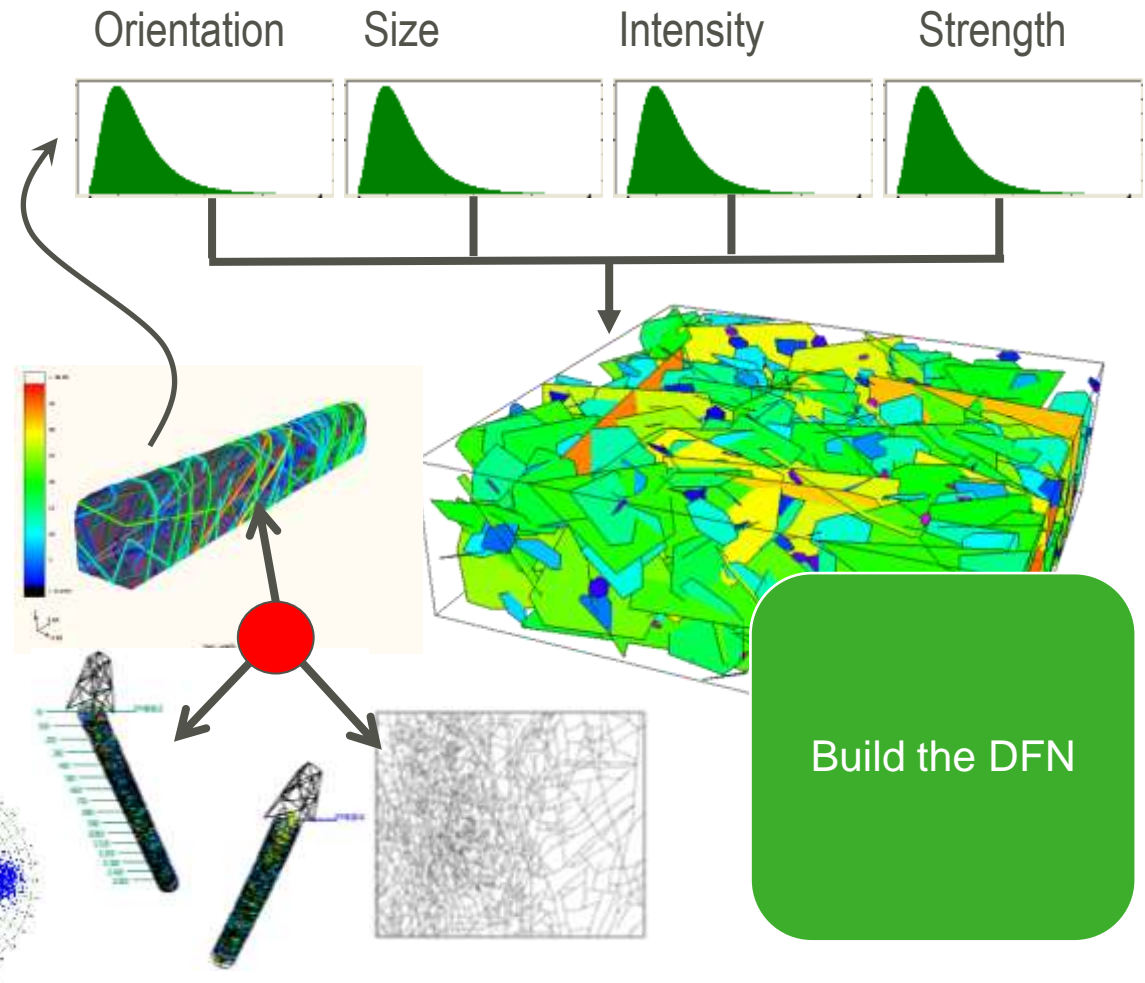
DFN Fracture Analysis: Sources and Requirements

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DFN modelling requires certain fracture properties defined

- Analysis of mapping and borehole data is carried out to define these input properties for a DFN model
- Fracture Properties needed to define
 - Fracture Orientation
 - Fracture Size
 - Fracture Intensity
 - Spatial Variation
 - Fracture Strength Properties
 - Fracture Permeability/Aperture

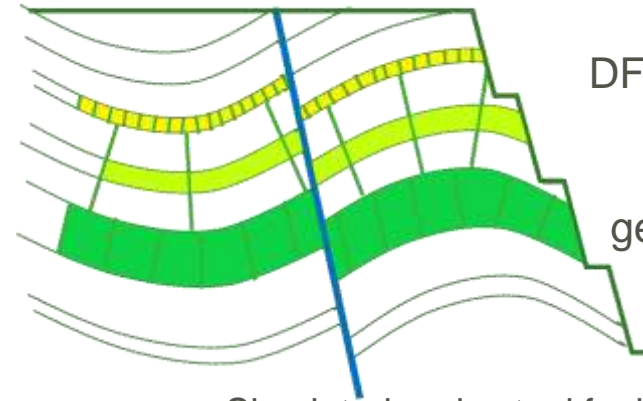
Analyse the Fracture Intersections/Traces



Generating DFN Fractures

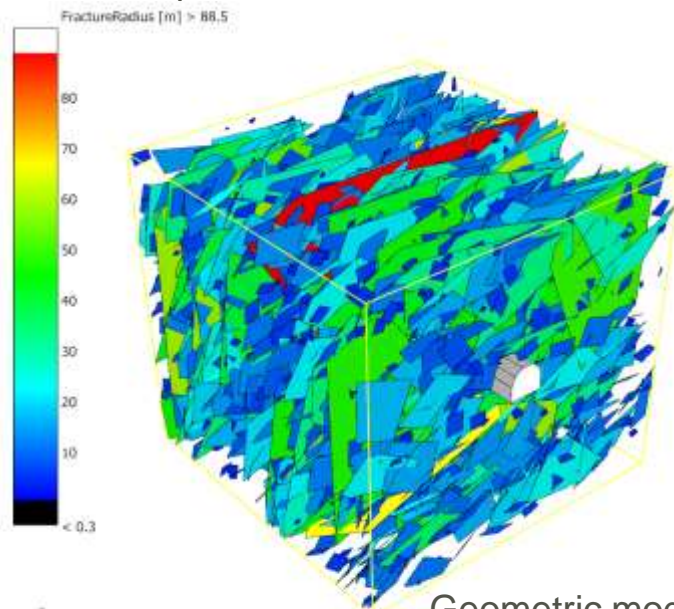
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- DFN has a rich array of methods for generating fractures
- They can be generated within a volume or within layers
- They can be built within 3D grids with spatially varying properties
- They can be extruded from trace maps

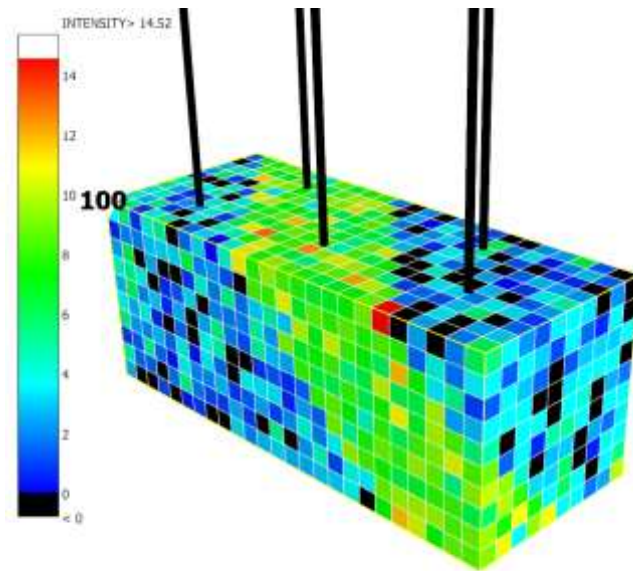


DFN allows you to capture and implement the geology, how it is

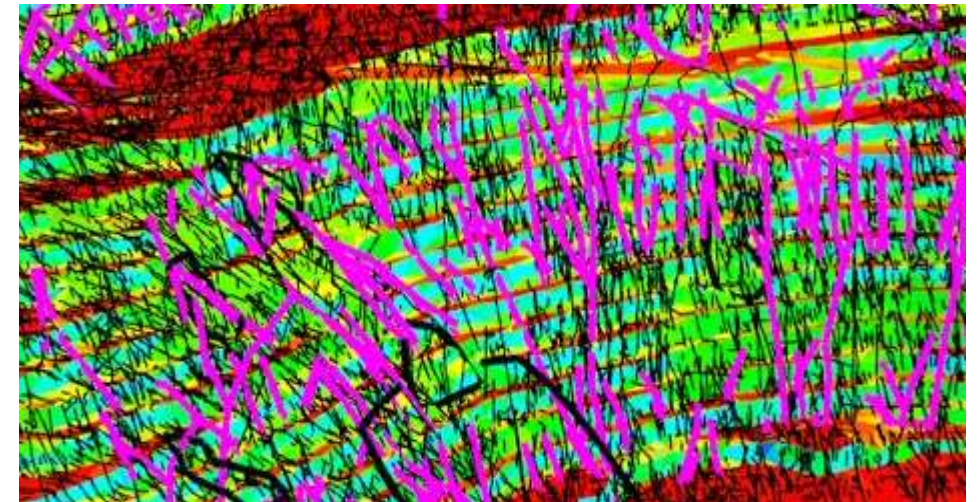
Simulated and actual fault traces on a pit



Geometric model



Geocellular model



Black Traces – Stochastic smaller faults

Purple Traces – Mapped faults

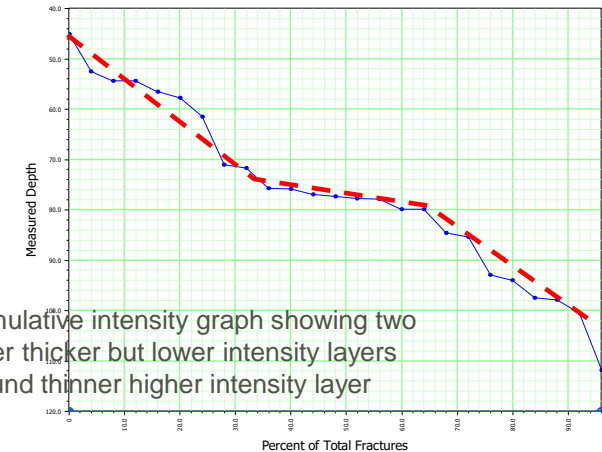
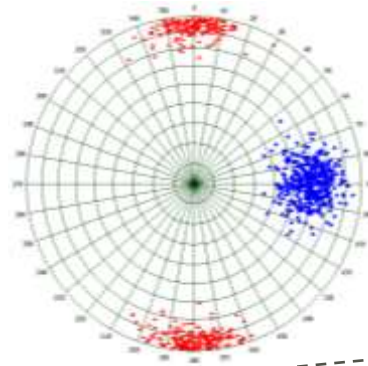
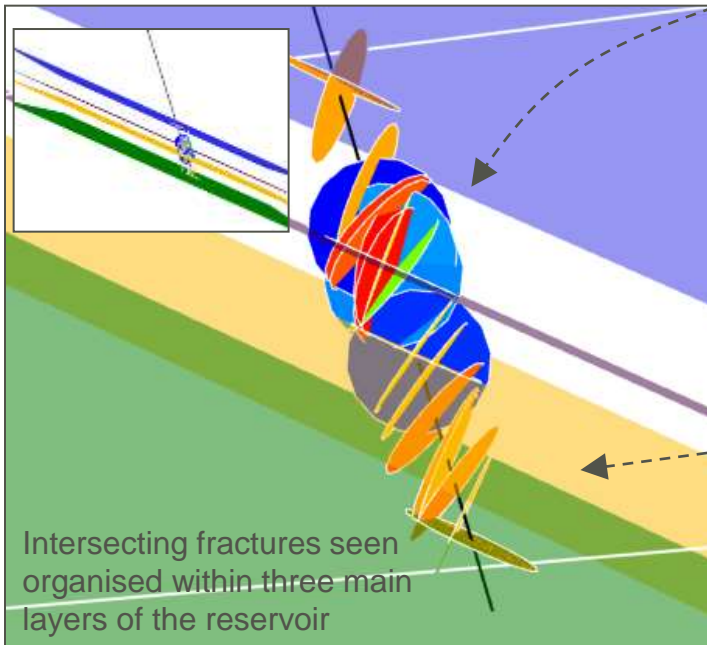
Basic DFN Model Construction & Validation

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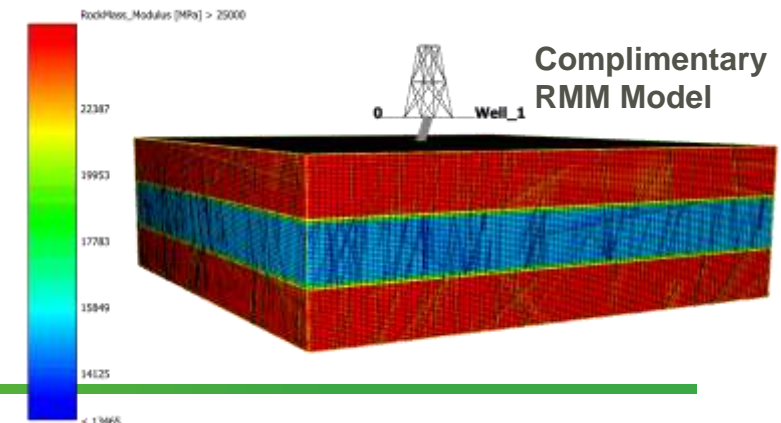
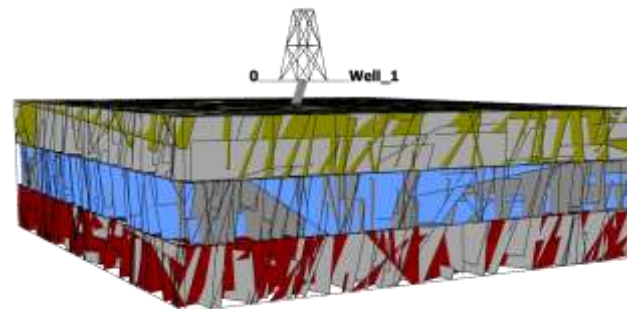
DFN model from well data requires greater conceptual push (driven from structural knowledge & concepts) and results in higher uncertainty than a model built from outcrop

Orientation: Orientation data taken from image log. Care needed to correct for bias

Fracture intensity data taken from well data



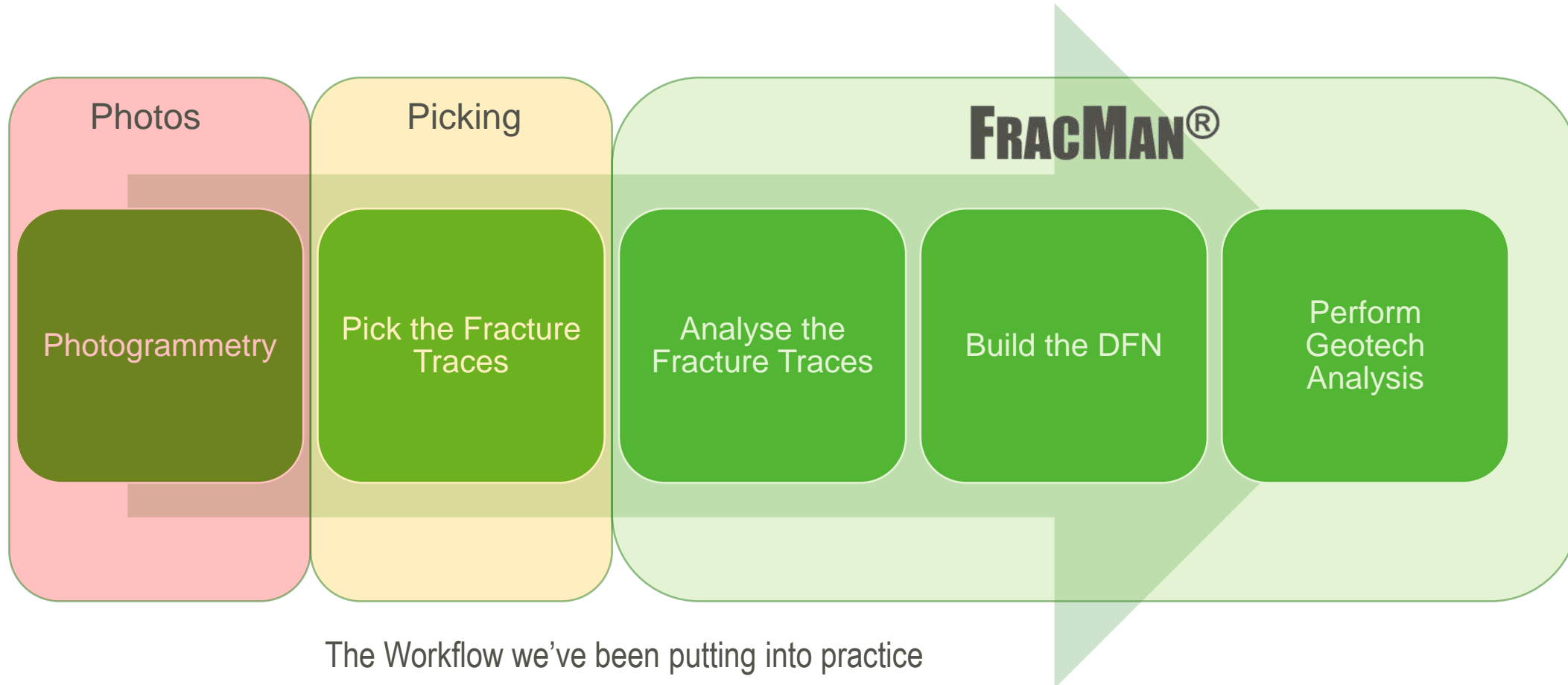
Final stacked DFN model of subsurface



Conceptual Model: Synthesising intensity data, orientation and structural knowledge helps develop a conceptual picture of how to assemble DFN model.

A Logical Photogrammetric Workflow

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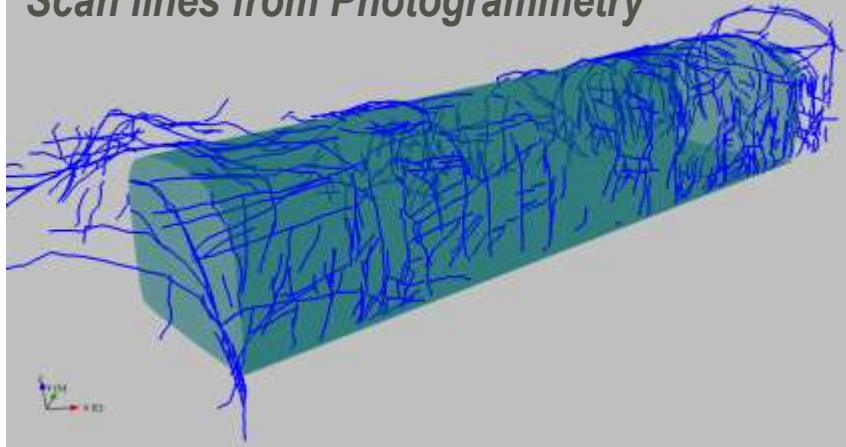


The Workflow we've been putting into practice

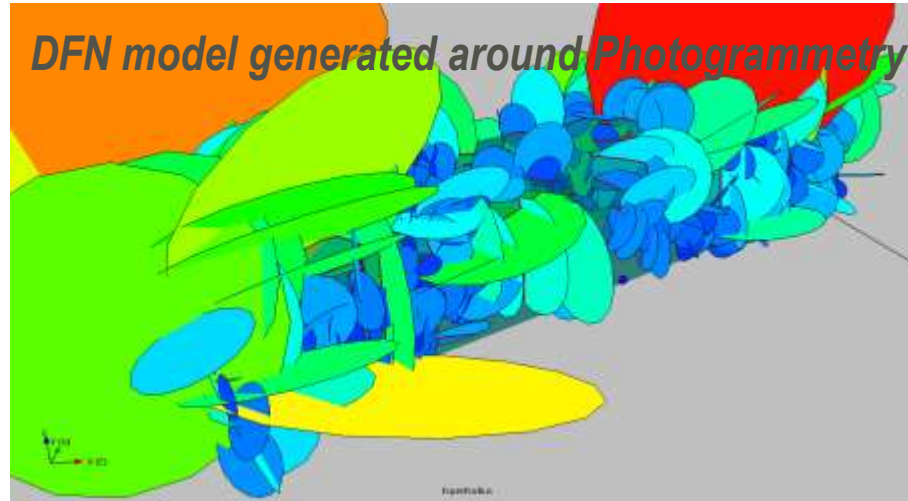
Example DFN from Photogrammetry

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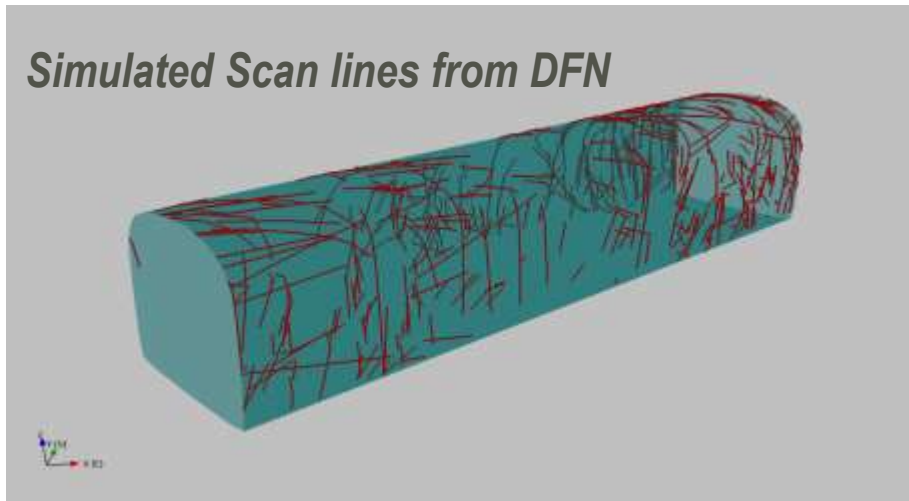
Scan lines from Photogrammetry



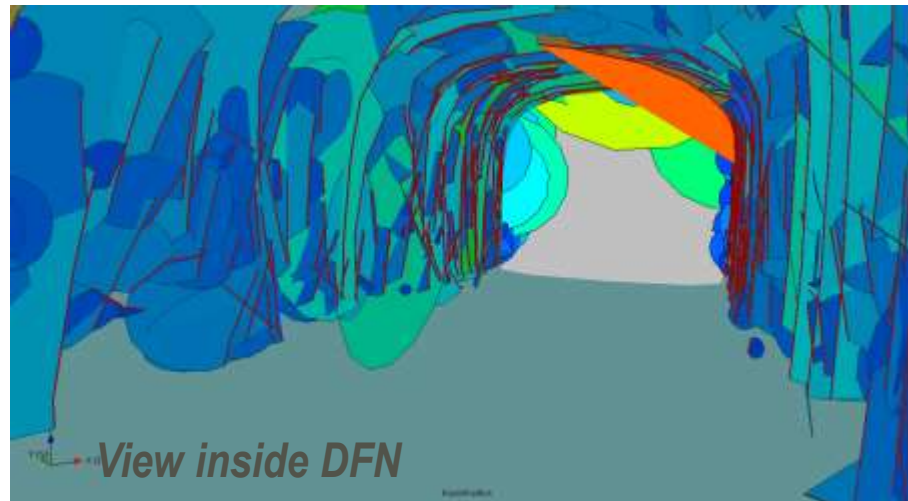
DFN model generated around Photogrammetry



Simulated Scan lines from DFN



View inside DFN



Basic DFN Model Construction & Validation

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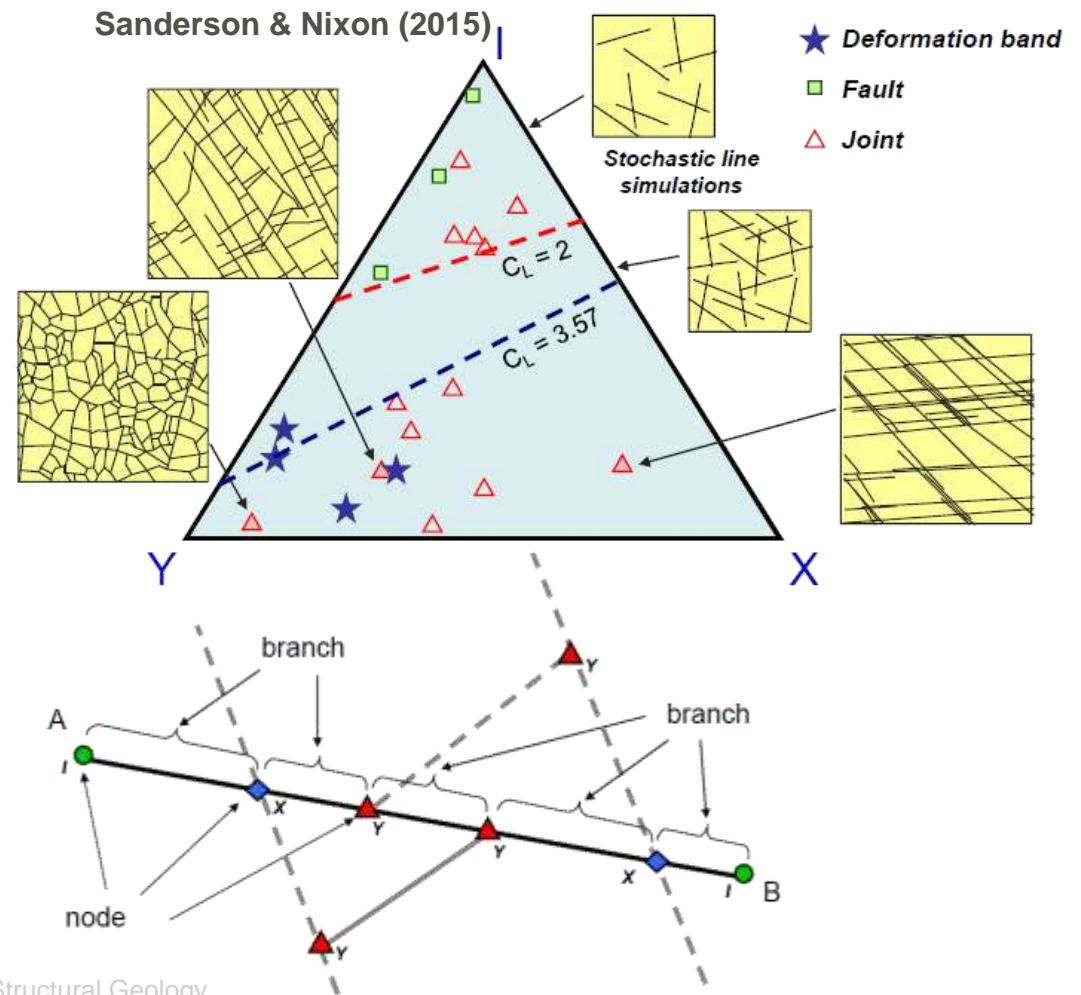
Connectivity **topology analysis** of traces

New **termination analysis statistics** – compute trace intersections, terminations and free ends

Neglect free ends of traces that have no intersections

Results **plotted on a ternary diagram** and used as a metric describing fracture connectivity and pattern

The position intensities on this diagram becomes a **target for calibration**



DJ Sanderson & CW Nixon (2015) The use of topology in fracture network characterization, Journal of Structural Geology

Fig. 1. Fracture trace (A–B), with associated intersecting fractures (dashed), showing arrangement of nodes and branches: I-nodes (circles); Y-nodes (triangles); X-nodes (diamonds).

Fracture Network Characteristics on Tunnels/Caverns

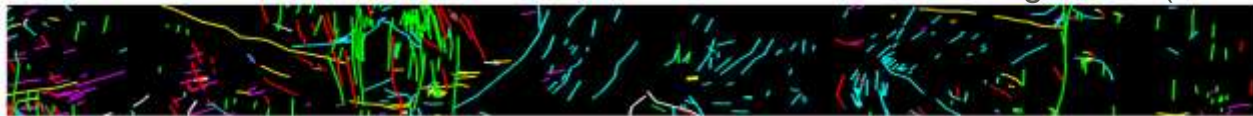
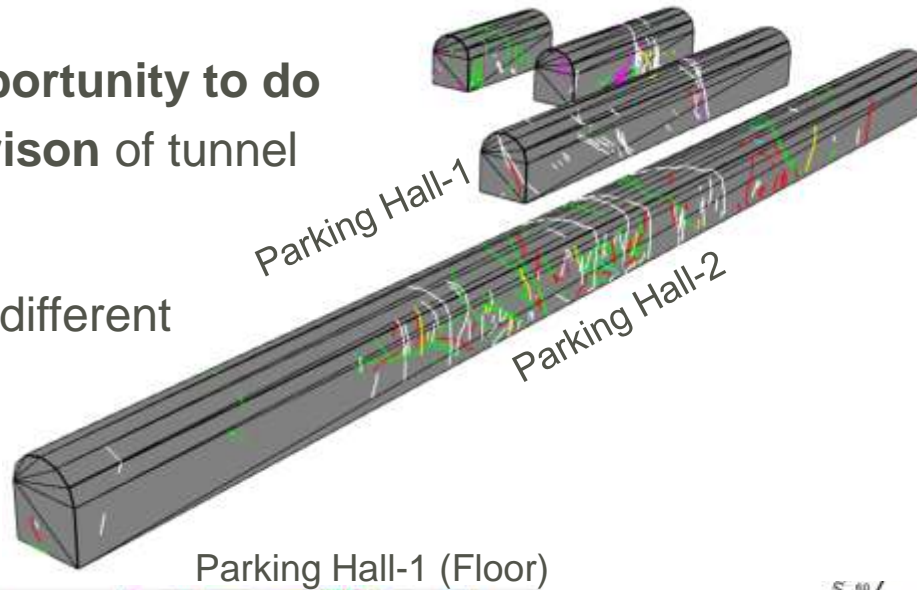
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Posiva and Golder (2018)

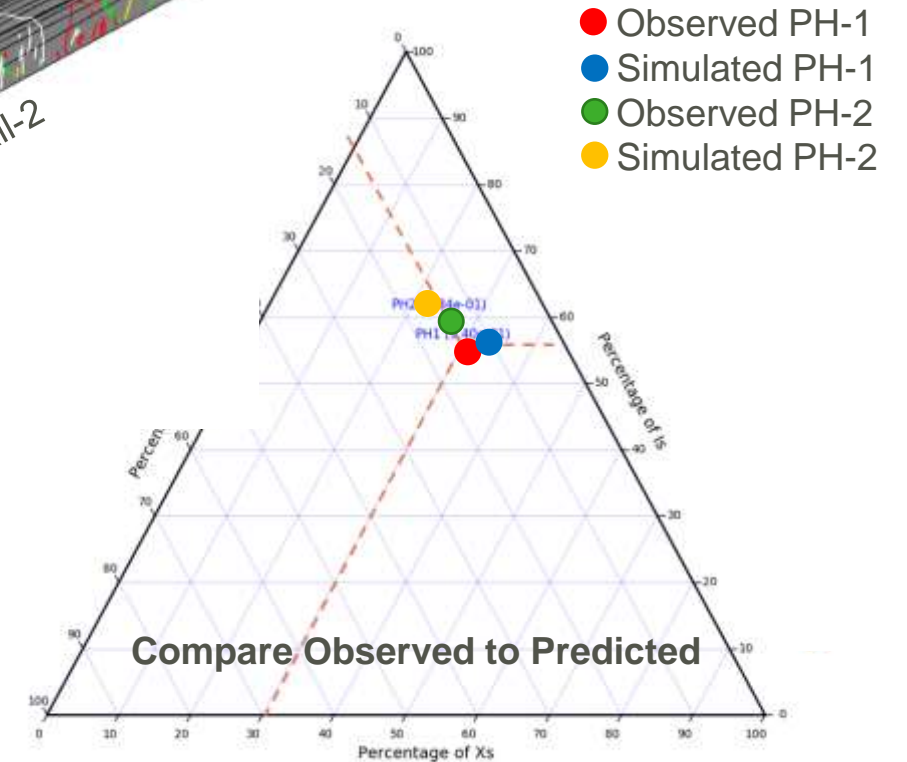
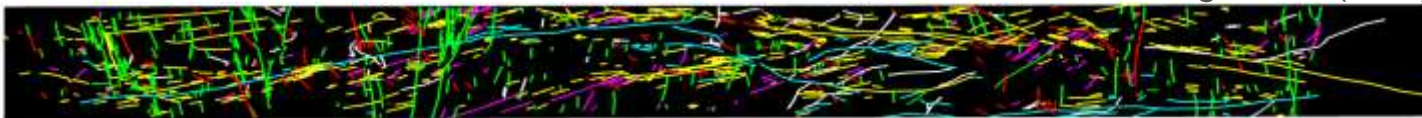
Tunnelling exposures provide **opportunity to do detailed evaluation and comparison** of tunnel trace metrics

Evaluate **X-, Y-, I-, V- metrics** for different components of multiple tunnel

Appraise DFN fit as Ternary Plot



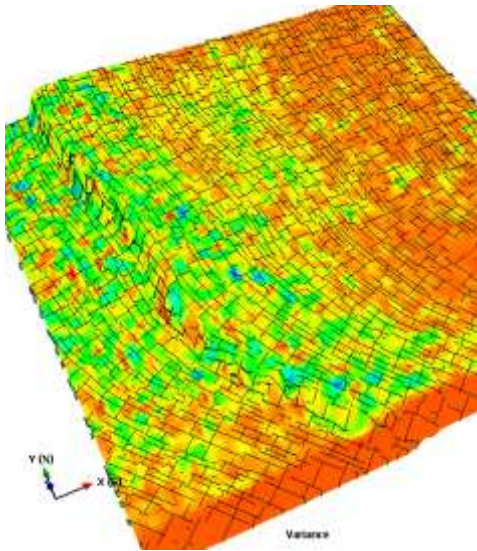
Parking Hall-2 (floor)



Summary: Integrated DFN Static Geometry Workflows

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Fully integrated workflows for determination of the fracture parameters required for your DFN to match your observed data



Fracture Orientation
Sampling Bias Correction
Automatic Fracture Set Identification

Fracture Intensity
Pij Fracture Intensity
 C_{31} Conversion (Wang/Chiles)
Flow Capacity (OxFilet)

Geometry Workflows

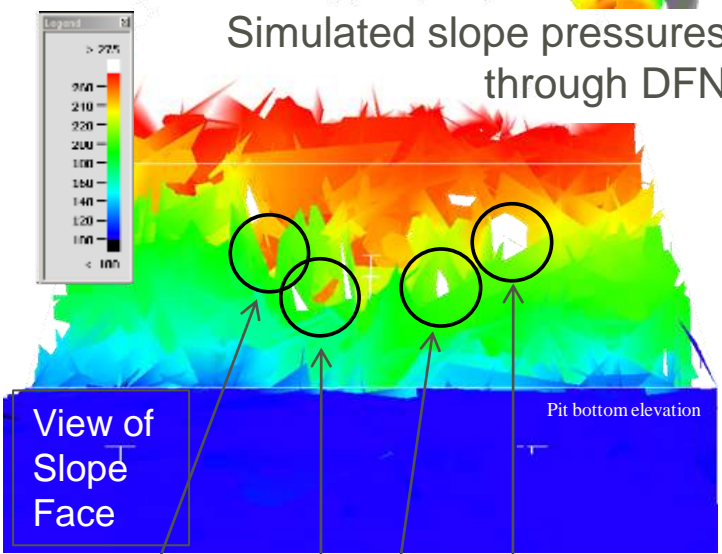
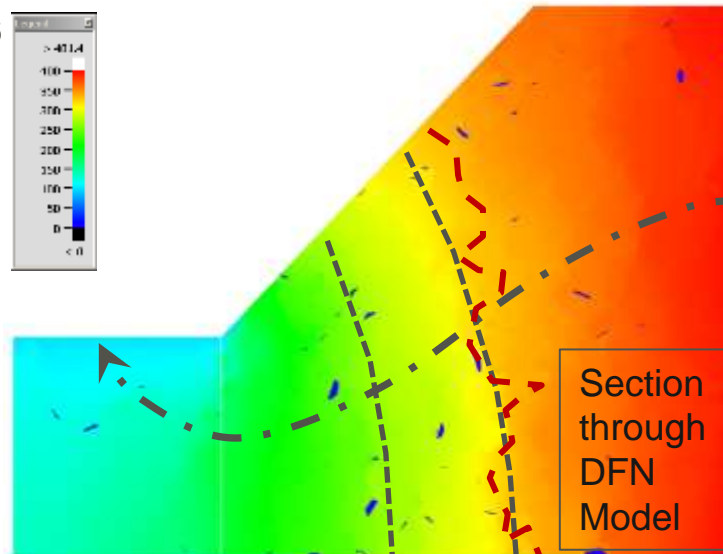
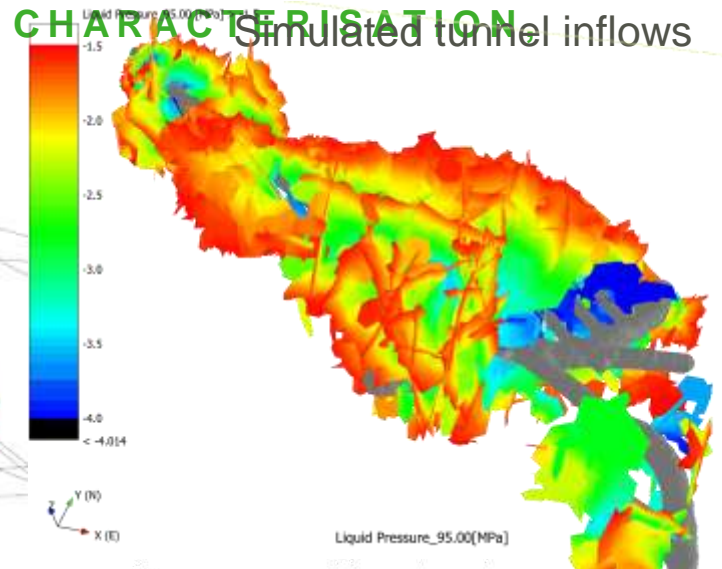
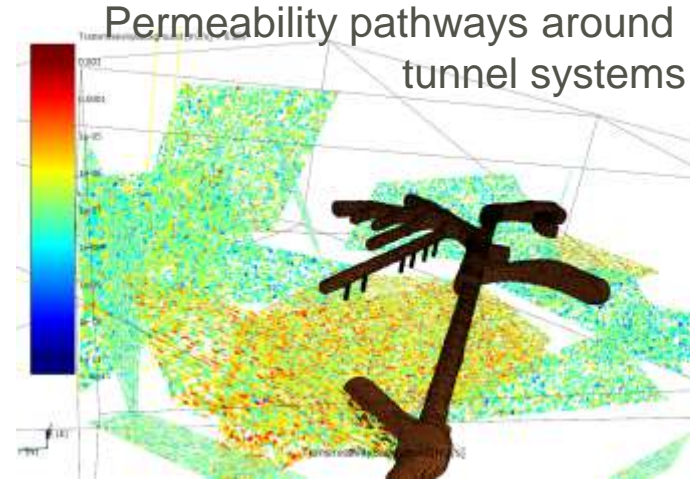
Fracture Size / Shape
Trace Length Analysis
Power Law Analysis

Fracture Properties
Flexible Equation Calculator
Data Analytics

Hydraulics – Fracture Flow

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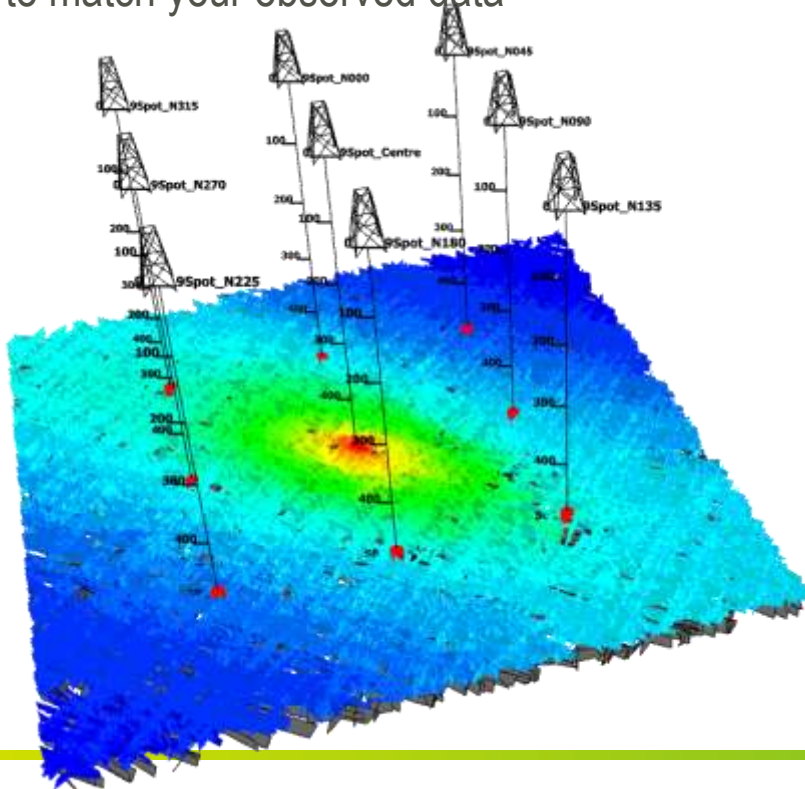
- DFN allows both steady state and transient flow analysis
- Discrete flow solutions are ideal for local water management problems with the smeared effects of continuum approaches don't allow the problem to be studied.
- We have used it to look at pressure distributions within slopes and tunnels
- Evaluate discrete tunnel inflows for pump selection and mitigation
- Probe hole optimizing for maximising coverage whilst minimising cost/time.



Summary: Integrated Dynamic Geometry Workflows

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Fully integrated workflows for determination of the fracture parameters required for your DFN to match your observed data



Fracture DFN Parameterisation
Directly uses statically calibrated DFN

Well Test Simulator
Integrated DFN flow simulation
Dual Poro – Dual Perm
Pressure, Derivative, PI
Well interference

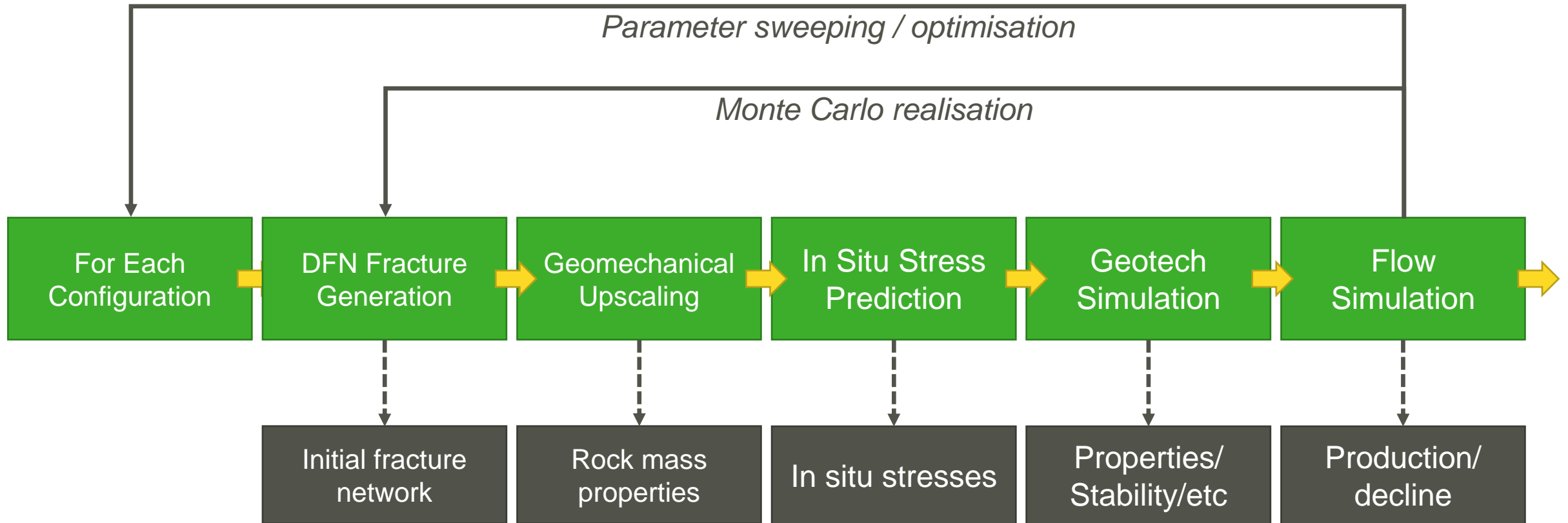
Dynamic Workflows

HydroBench
Analysis and interpretation of the observed well test data

Increased Efficiency
Get the DFN hydraulic properties right sooner
Integrated with Monte Carlo
Avoid multiplier fiddles on grid properties

Multiple Realisations & Optimisation

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DFN **workflow** from fracture creation and generation to stimulation and flow

Section 2: Rock Mass Properties



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Overview (2)

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The **second section** considers strategies for obtaining key rock mass mechanical descriptions including block size distributions, rock mass measures such as GSI values and key effective rock mass property values.

Fragmentation modelling – why all the effort?

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The **fragmentation** of the rock mass during caving has a tremendous impact on a number of cave, mining and processing design decisions including:

- Draw point or excavation spacing;
- Equipment Selection;
- Secondary breakage requirements;
- Mill set up & energy requirements

The industry has been served by BCF (block caving fragmentation) but the results have generally been considered conservative at best;

There is clearly room for improvement in how we undertake these fragmentation predictions!



Fragmentation: Unrealistic and Realistic

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Unrealistic Fractures	Realistic Fractures
Fracture occurrence often ubiquitous	Fractures are not ubiquitous but governed by an underlying spatial model
Fractures are considered infinite in length	Fractures have variable lengths
Fracture sets having non geological orientation distributions	Fracture sets have variable orientation
Fractures independent of each other	Real fractures are not independent (e.g. fractures can terminate on each other)

Why is realism important to Fragmentation ?

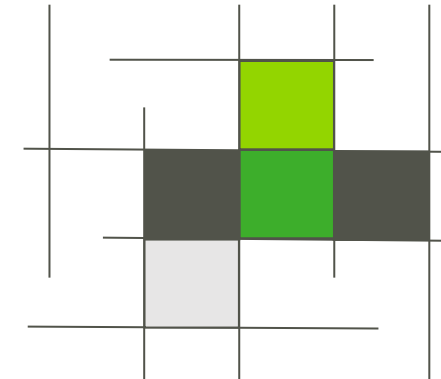
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- All blocks are formed by fractures
- But not all fractures form blocks!
- Assuming infinite ubiquitous fractures can lead to:
 - Over prediction of block formation
 - Under representation of intact rock bridges

“Infinite”
length
Fracture
Model



Finite
length
Fracture
Model



Block forming rules:

Only fully enclosed blocks = true blocks

Unclosed external blocks ≠ true blocks

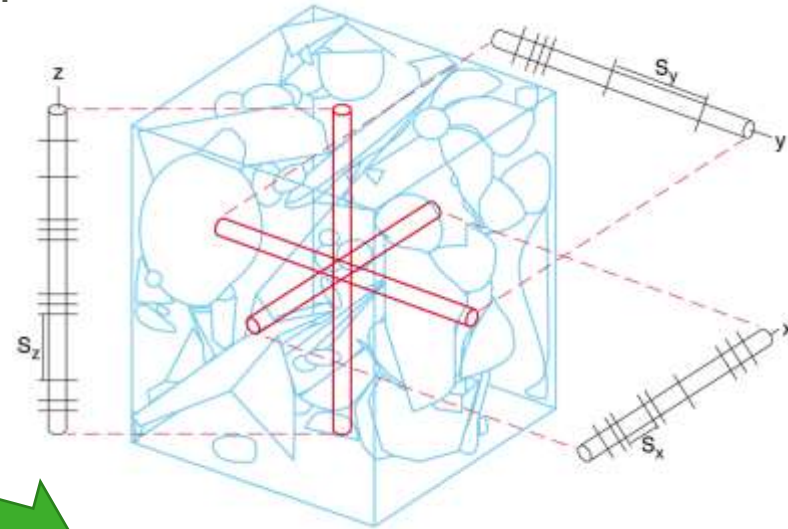
3D Fragmentation Algorithms

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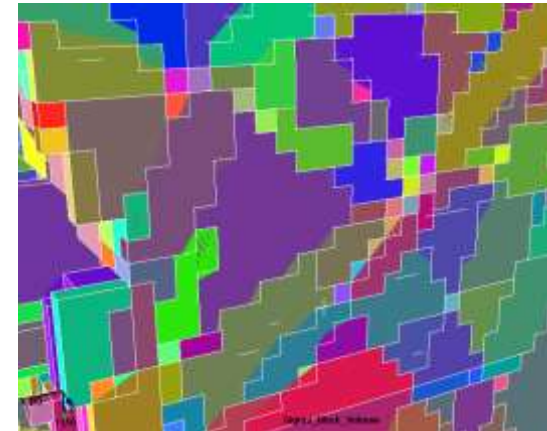
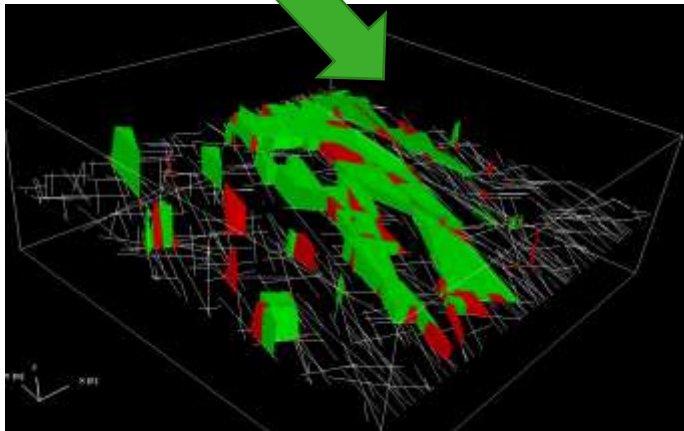
1. Multidirectional spacing distribution algorithm

2. Rapid block mapping

3. Full block search algorithm



3.



MDS “Sigma” Results

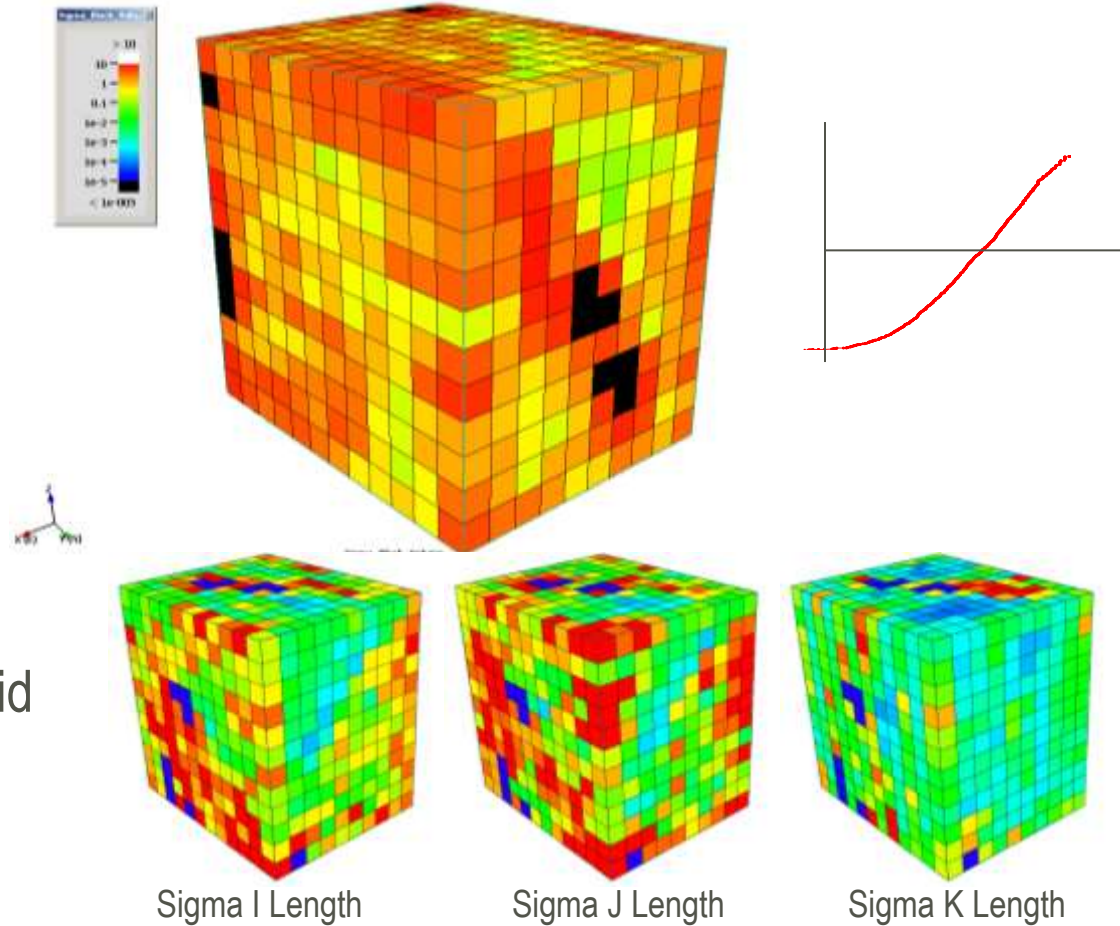
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When the Sigma calculation is run it creates following properties:

- Sigma I length
- Sigma J length
- Sigma K length
- Sigma Volume ($S_i \times S_j \times S_k$)

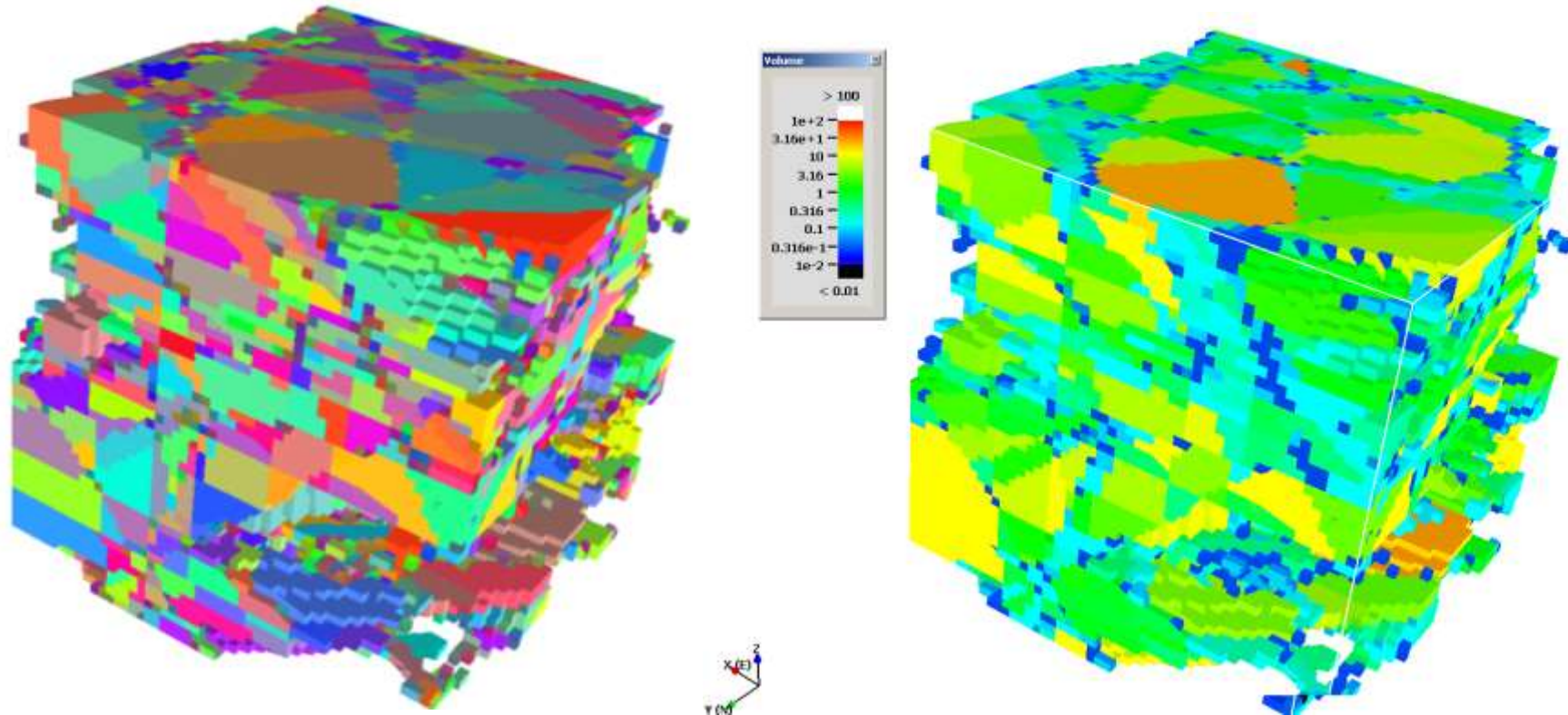
These properties can be visualised on the grid

Alternatively they can be displayed as size distribution curves



Block Mapping Results

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Individual blocks coloured

Blocks coloured by volume

Full Block Search Algorithm

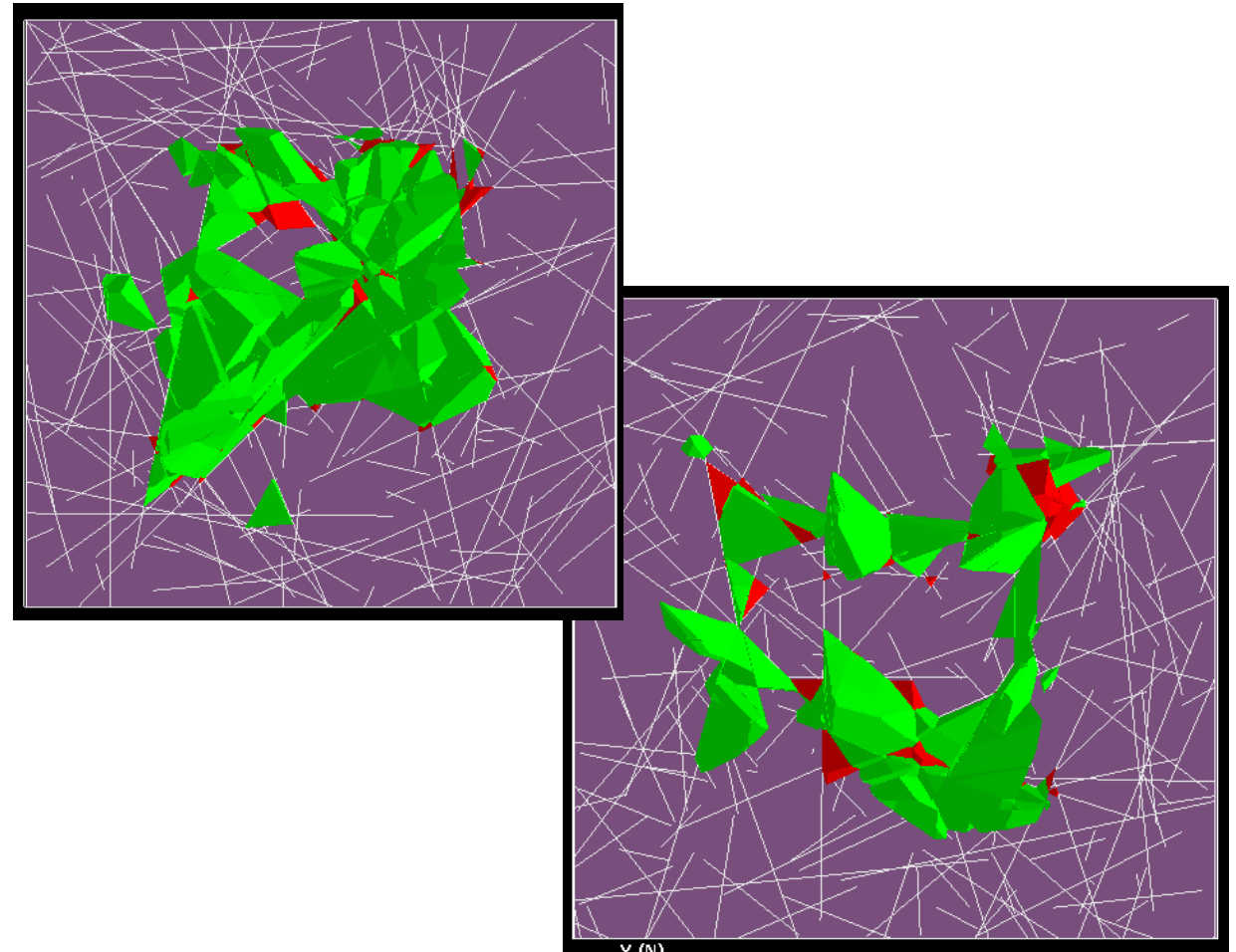
A DFN FRAMEWORK WITH APPLICATION TO ROCK ENGINEERING CHARACTERISATION, ANALYSIS & DESIGN

This is the block mapping algorithm used for kinematic stability

Searches from a free face to identify all fully formed blocks on that surface

When we search for fully formed blocks within a rock mass with “average” typical fracture intensities, we find:

- Block formation is actually not that common
- The volume of fully isolated rock mass (in situ fragment) is often defined a highly complex polyhedra shape

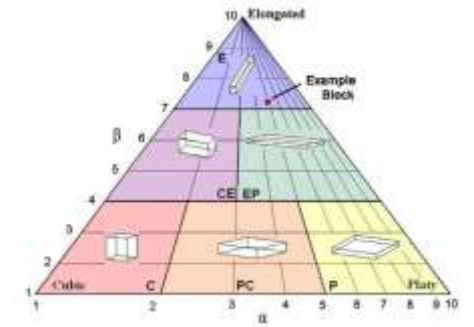


Block Forming Efficiency

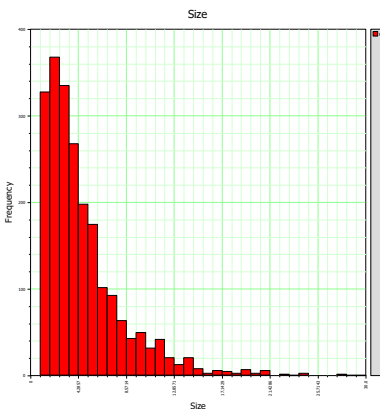
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- Block Size - Power Law model produces a reduced volume of blocks and more importantly, an increase in the number of large blocks.
- However these blocks comprise a series of partially formed blocks that would most likely fully form during

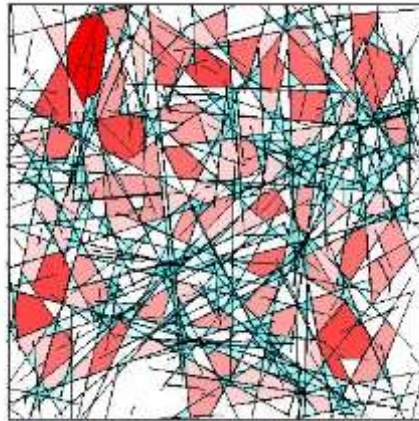
Block shape can be an important property when considering bulk flow and material handling



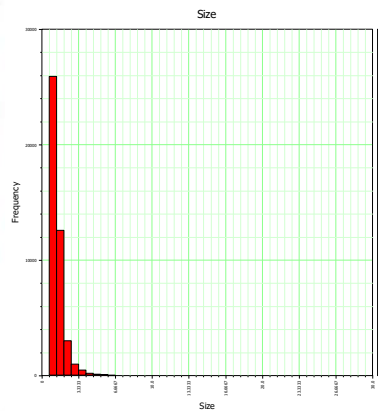
caving
Log Normal Size Dist



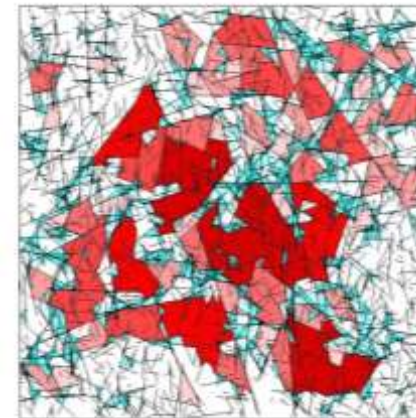
Efficient Block Formation



Power Law Size Dist

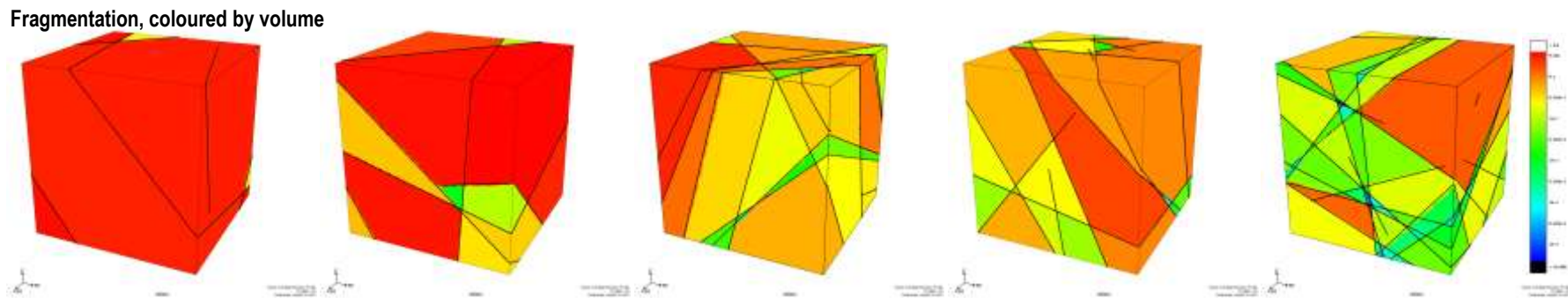
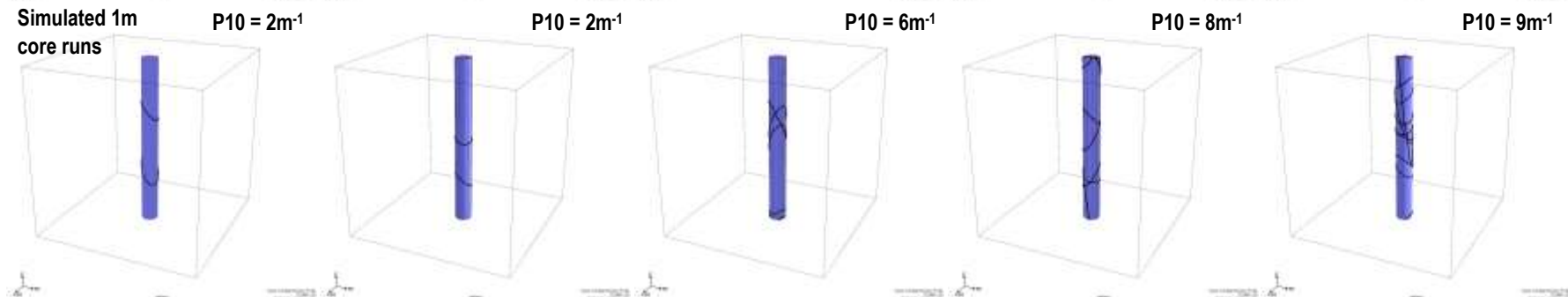
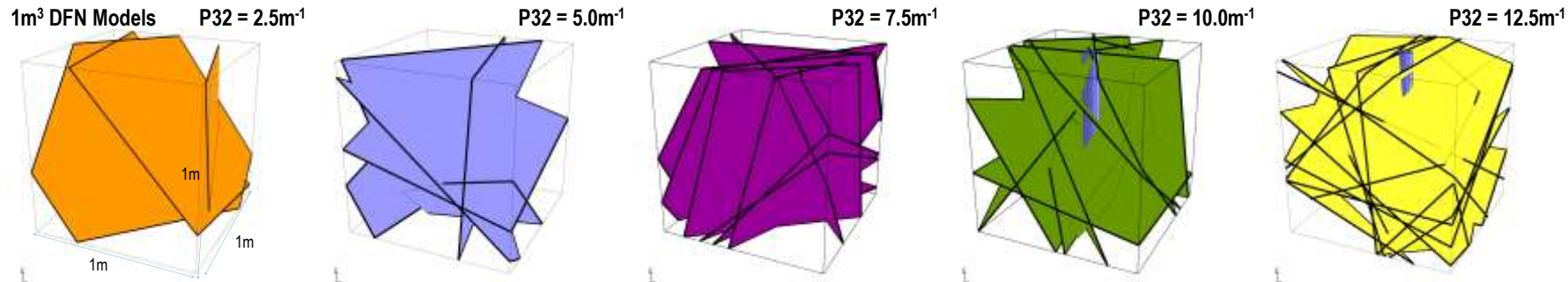


Inefficient Block Formation



What does P_{32} really mean? 1m³ models

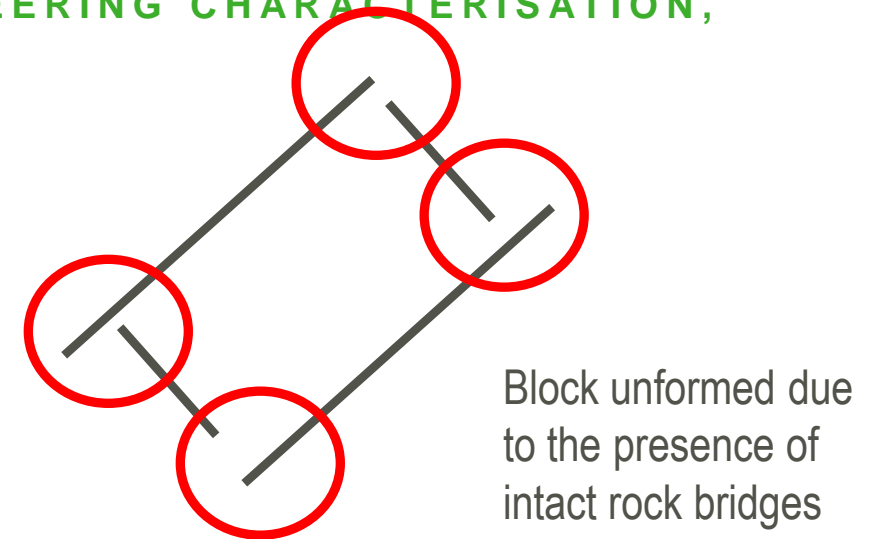
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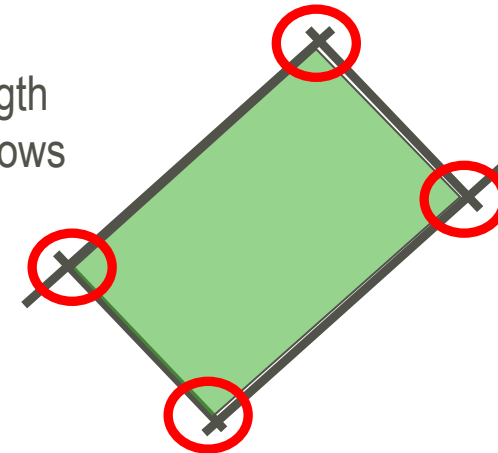
Rock Bridge Description

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- The presence of intact rock bridges in the model cause many potential blocks to not form as there is no complete block closure
- By increasing the fracture size, an increased number of blocks may form
- By incrementally increasing the fracture size, the rock bridge proportion can be determined



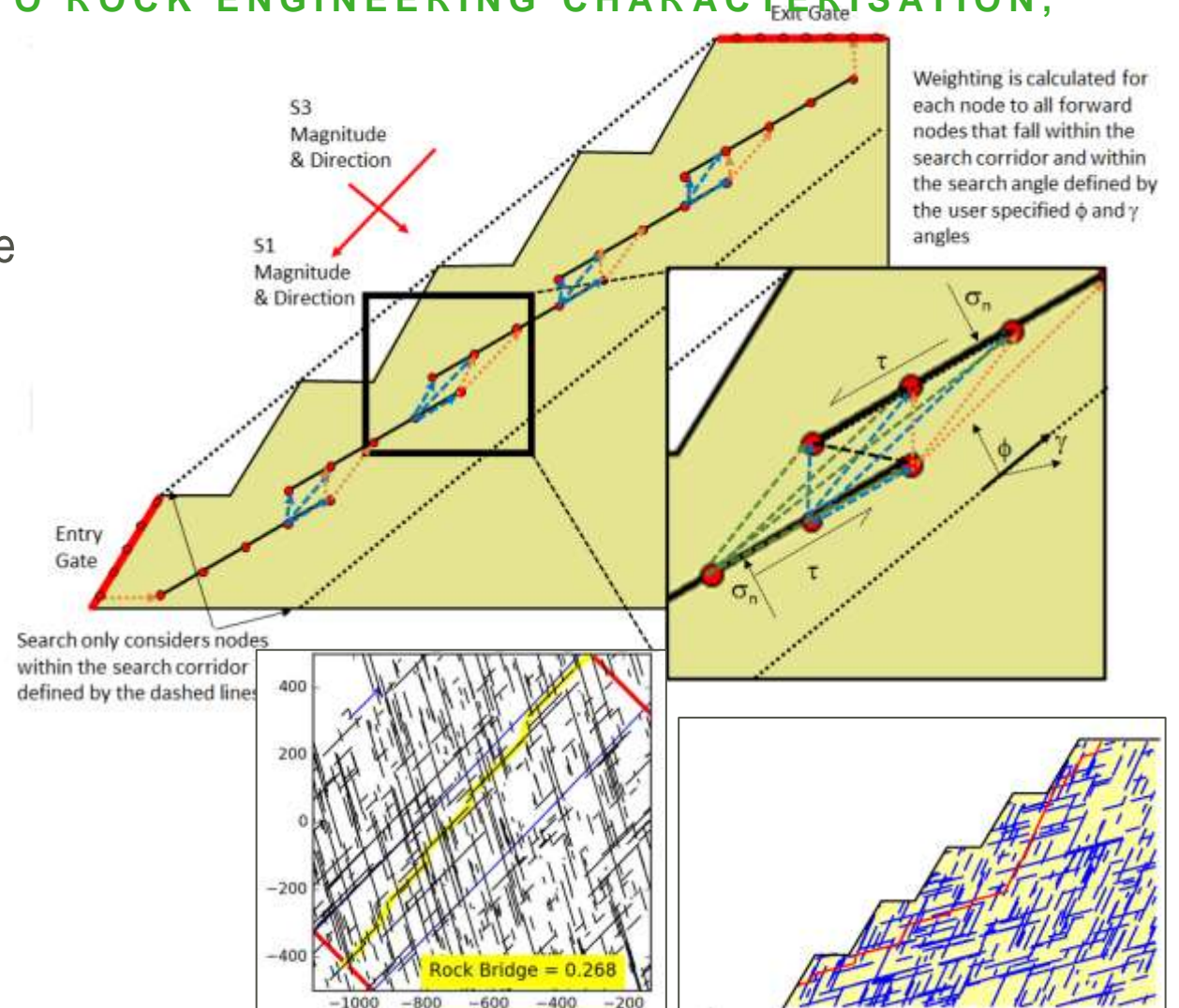
Increasing the length of the fractures allows new block to be formed



Step Path Failure Calculations & Rock Bridge %

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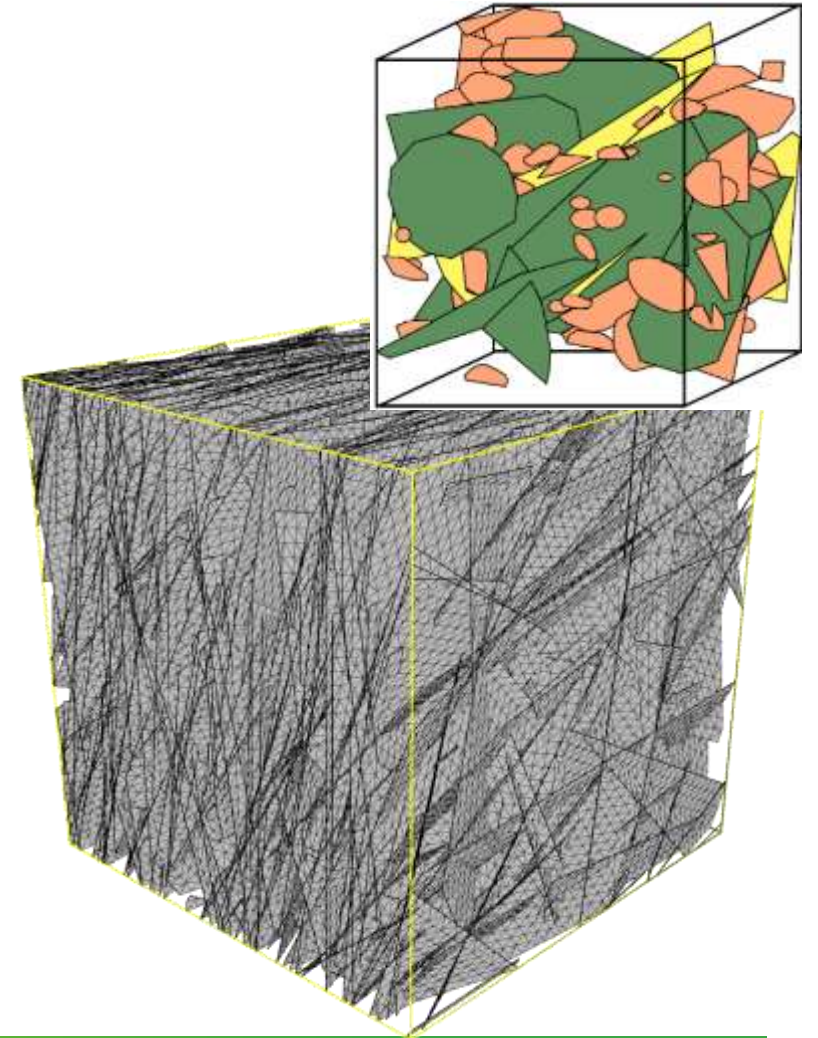
- Critical component to slope stability analysis is the accurate determination of the rock bridge percentage for incorporation into equivalent strength properties of the rock mass
- Rule based algorithm developed in DFN for automatically tracking step path failure surfaces
- Allows rapid probabilistic assessment
- User controlled weighting factors



Rational for Upscaling?

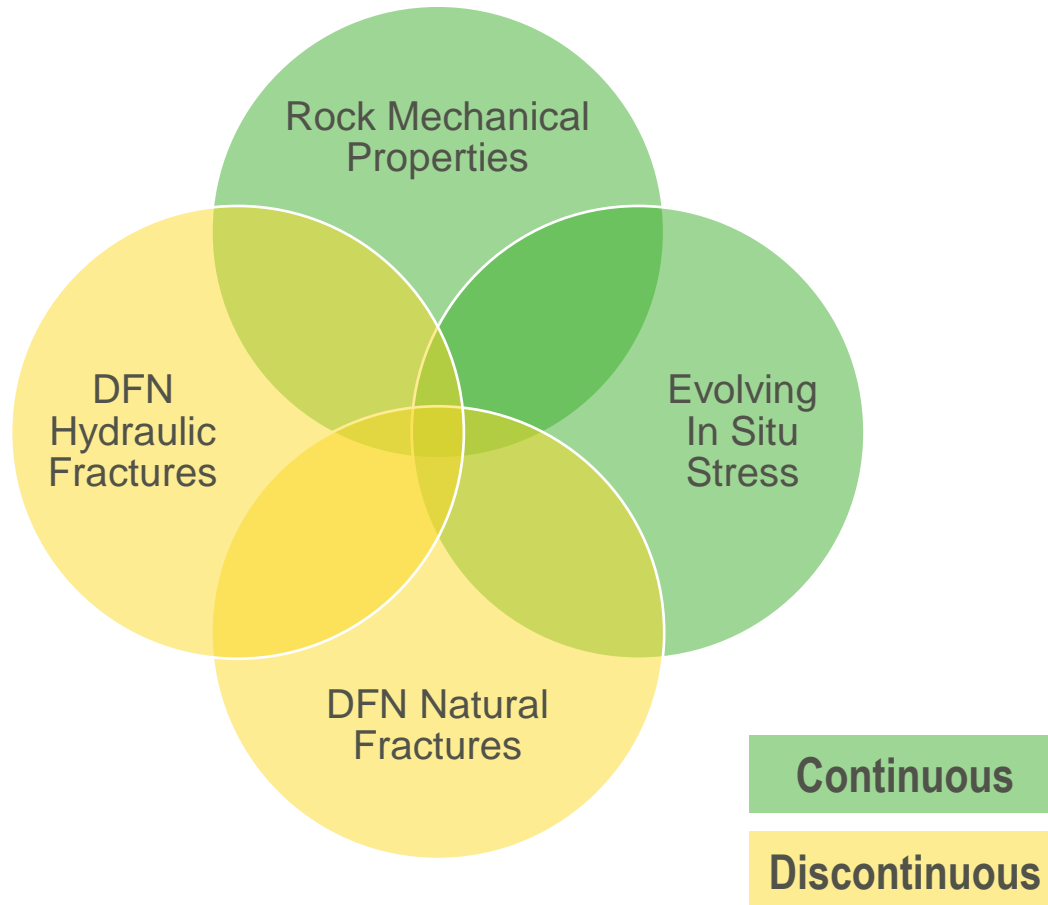
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- Describing naturally fractured rock using DFN approaches provides a level of geometrical **realism** that is impossible to include using continuum approaches
- The discrete description **provides for inclusion of important intrinsic characteristics** of the fractured domain such as fracture intersections and connectivity
- There is a **significant drawback** however with the geometrical complexity afforded by the DFN description, in that it hasn't always lent itself to traditional numerical flow-based reservoir simulators



Combining the Discrete with the Continuous

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The implemented DFN-FEM workflow makes simultaneous use of evolving key features

- Rock Mech Properties: E , ν , UCS
- Stress: Full stress tensor
- Natural fractures: Reactivation of existing fracs
- Hydraulic fractures: Induced fracs (new fracs)

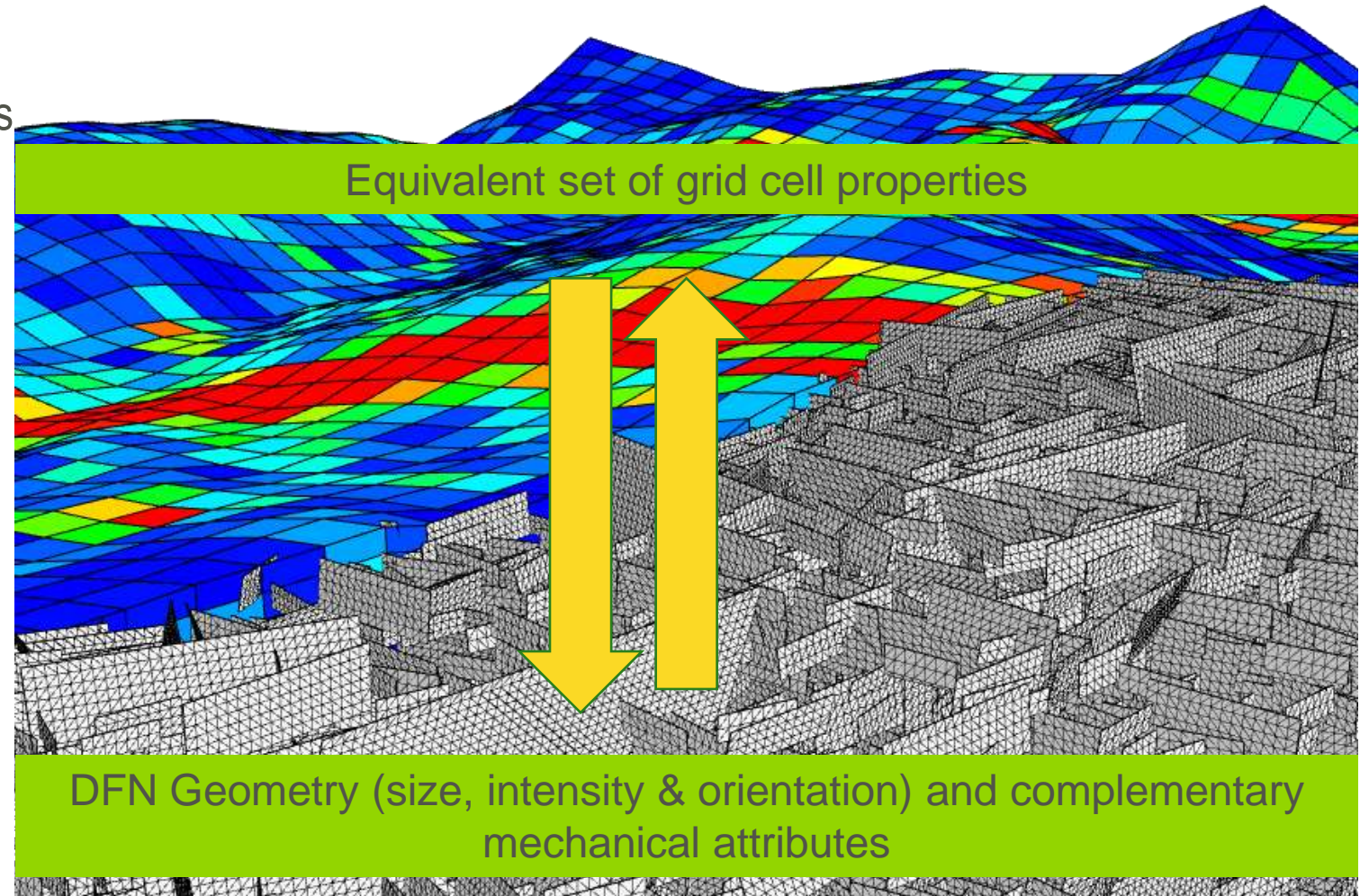
Combining the Discrete with the Continuous

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Upscaling of the discrete DFN description helps a more tractable equivalent grid-based continuum description

Routinely employed to transform the fracture attributes:

1. Flow \rightarrow permeability
2. Geomechanics \rightarrow stiffness
3. Geomechanics \rightarrow strain (from Δ aperture)



Upscaling for Rock Mass Stiffness

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Analogous to the permeability-based fracture upscaling of Oda (1982; 1983; 1984), an approach exists where the fracture mechanical properties (e.g. normal and tangential stiffness k_n and k_s) are combined with the intact rock stiffness properties Young's Modulus (E) and Poisson's Ratio (ν) to **derive the equivalent rock mass stiffness properties (e.g. E_{rm} and ν_{rm})**.

The underlying equation combining the intact with fracture based mechanical properties is:

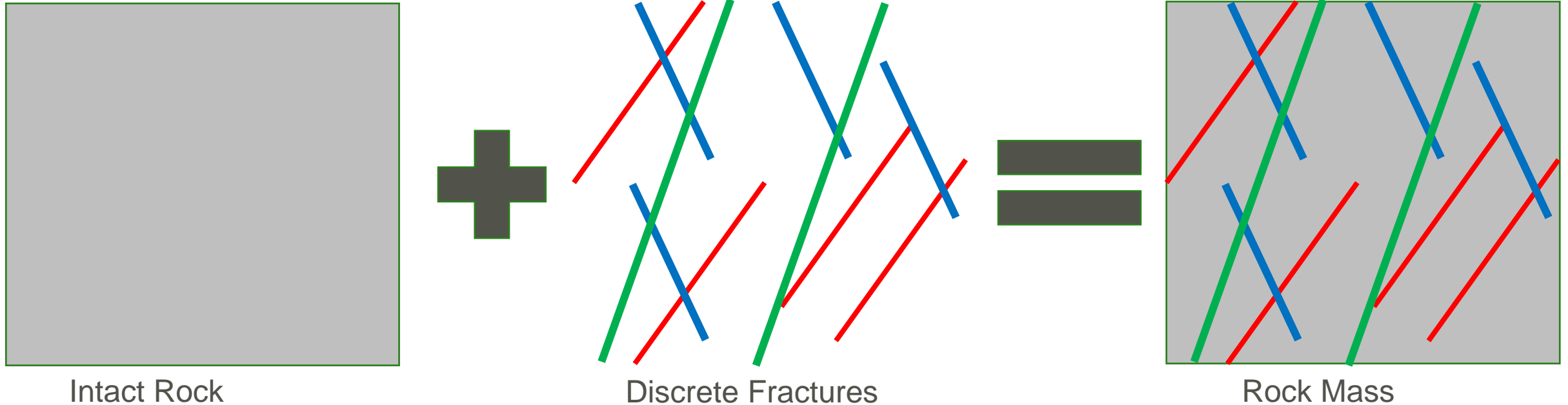
- $$\mathbf{s}_{ijkl}^{rm} = \mathbf{s}_{ijkl}^h + \Delta\mathbf{s}_{ijkl}^f$$

where the contributing components are defined by:

- \mathbf{s}_{ijkl}^{rm} [MPa⁻¹] is the elastic stiffness tensor of the rock mass (including both intact and fractures) ;
- \mathbf{s}_{ijkl}^h [MPa⁻¹] is the elastic stiffness tensor of the host (intact) rock; and
- $\Delta\mathbf{s}_{ijkl}^f$ [MPa⁻¹] is the elastic stiffness of the discrete fractures present.

Upscaling for Rock Mass Stiffness

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Using Oda (1982; 1984) the DFN fracture-based fabric tensors describe the degradation of the intact rock stiffness

$$F_{ij} = \frac{1}{V_{cell}} \sum_{k=1}^M A^{(k)} n_i^{(k)} n_j^{(k)}$$

For the case of the intact rock stiffness being assumed isotropic, the upscaled rock mass Young's Modulus values

$$E_{ij}^{rm} = \frac{E}{\frac{\pi}{2} F_{ij} + 1}$$

$$\nu_{ij}^{rm} = \frac{\nu}{\frac{\pi}{2} F_{ij} + 1}$$







Rock Mass Property Prediction

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- Predicting rock mass properties is essential to successful engineering design
- We can use Geomechanical Upscaling to predict rock mass stiffness (E_{rm} and ν_{rm}) using a combination of the intact rock stiffness and DFN fracture stiffness
- We can effectively (and simply) combine the discontinuous and continuous descriptions of rock properties to predict useful “empirical” rock properties
- For example E_{rm} and ν_{rm} and be combined with σ_{ci} (a la Hoek-Brown) to allow quantitative prediction of rock mass measures, e.g. GSI, RMR, Q

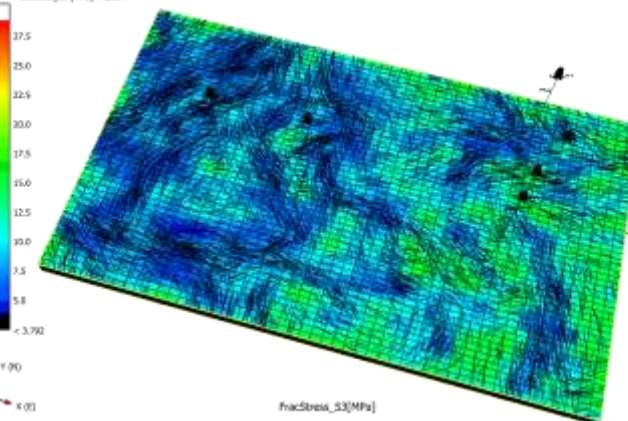
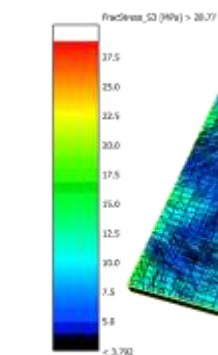
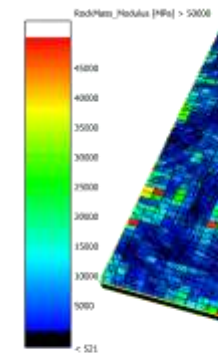
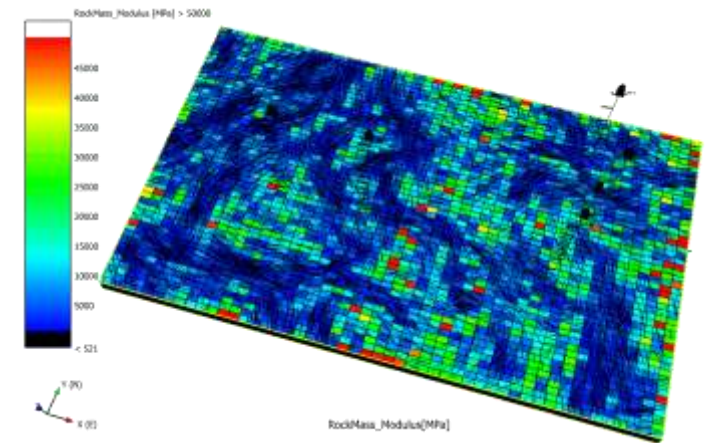
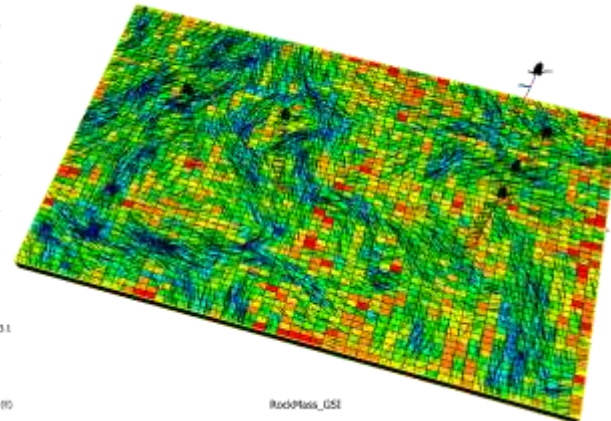
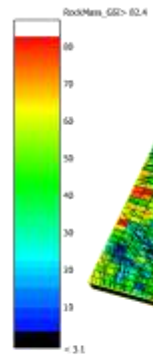
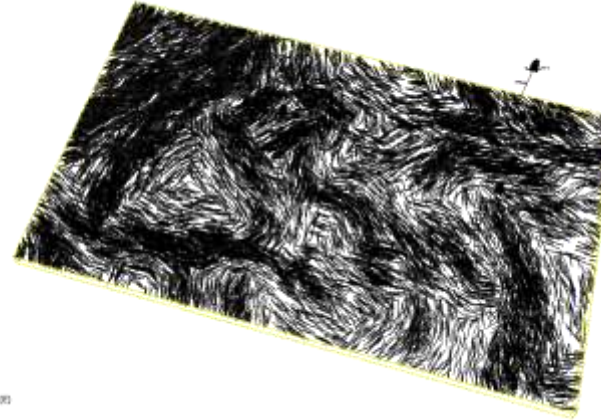
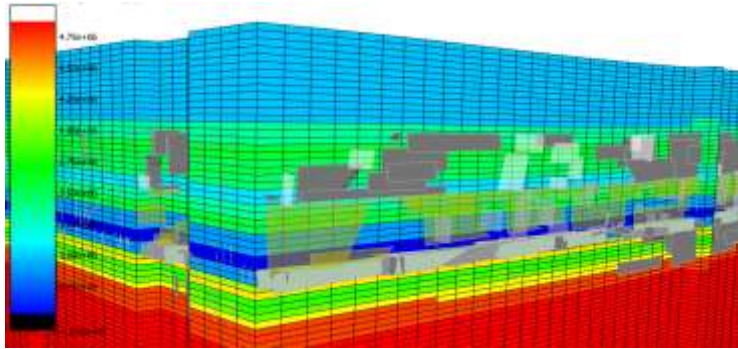
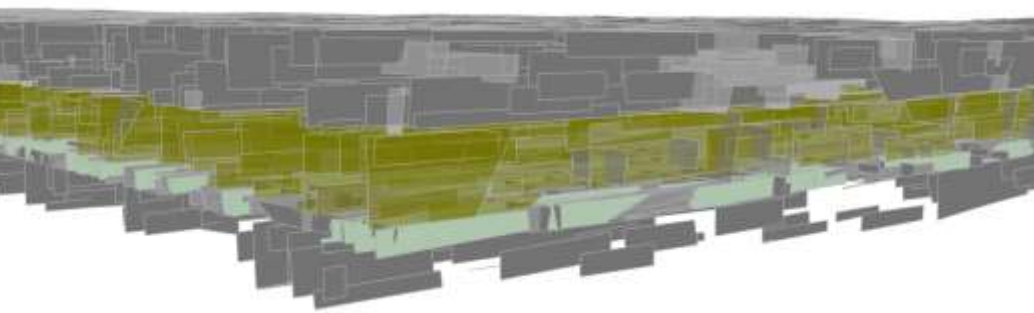
$$E_{rm} = E_i \left\{ 0.02 + \frac{1 - D/2}{1 + \exp[(60 + 15D - GSI)/11]} \right\}$$

GEOLOGICAL STRENGTH INDEX FOR BLOCKY JOINTED ROCKS				
From a description of the structure and surface conditions of the rock mass, pick an appropriate box in this chart				
	irrefaces			
		d surfaces		
			with compact	
				with soft clay

STRUCTURE	SURFACE CO				
	VERY GOOD Very rough, fre	GOOD Rough, slightly	FAIR Smooth, mode	POOR Slit-sided, l coatings or fill	VERY POOR Slit-sided, l coatings or fill
 INTACT OR MASSIVE - intact rock specimens or massive in situ rock with few widely spaced discontinuities	90		N/A	N/A	N/A
 BLOCKY - well interlocked undisturbed rock mass consisting of cubical blocks formed by three intersecting discontinuity sets	80	70			
 VERY BLOCKY - interlocked, partially disturbed mass with multi-faceted angular blocks formed by 4 or more joint sets		60	50		
 BLOCKY/DISTURBED - folded and/or faulted with angular blocks formed by many intersecting discontinuity sets			40	30	
 DISINTEGRATED - poorly interlocked, heavily broken rock mass with mixture of angular and rounded rock pieces				20	
 FOLIATED/LAMINATED - folded and tectonically sheared. Lack of blockiness due to schistosity prevailing over other discontinuities	N/A	N/A			10

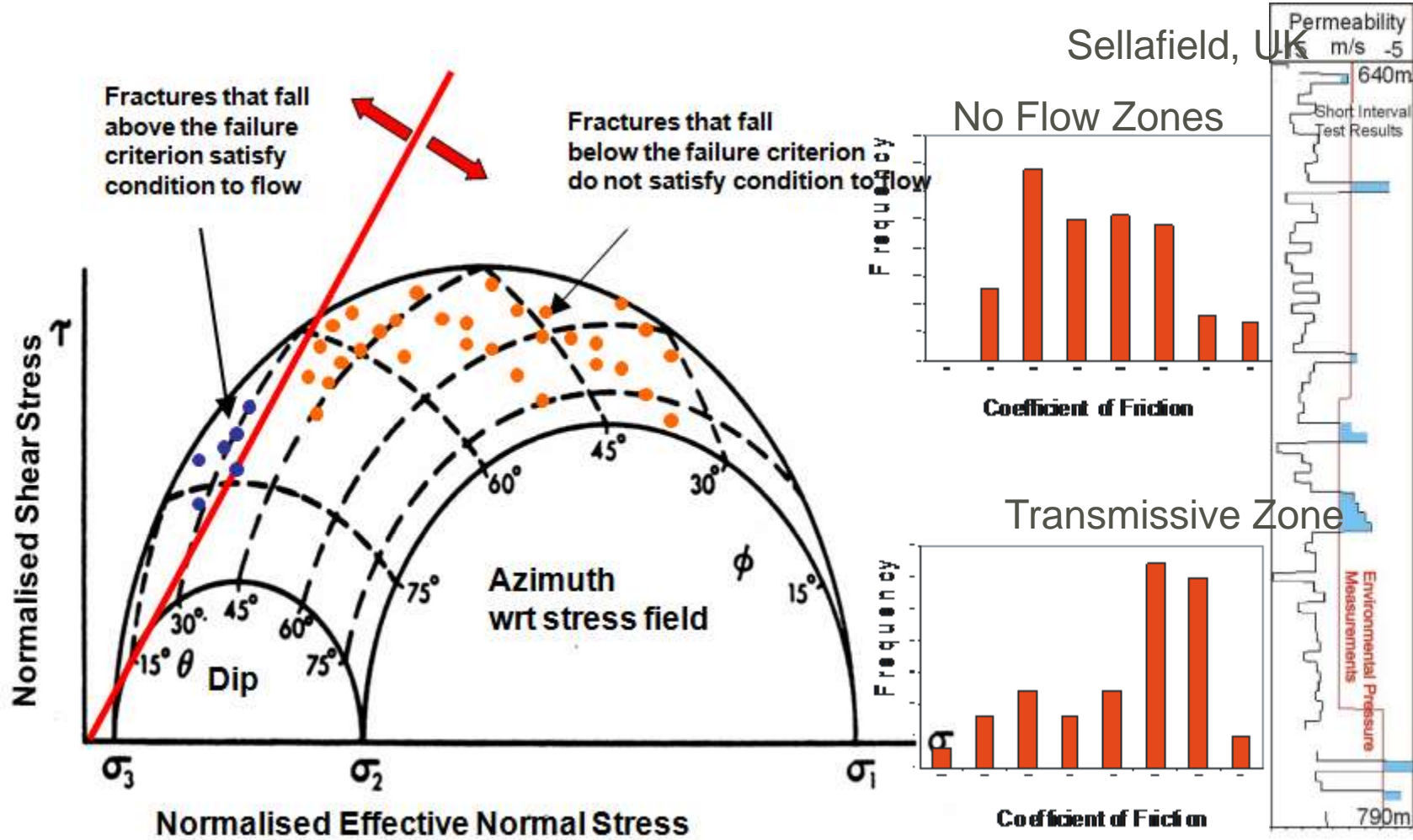
A Linked Physical Description?

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Linking Geometry, Stress & Permeability

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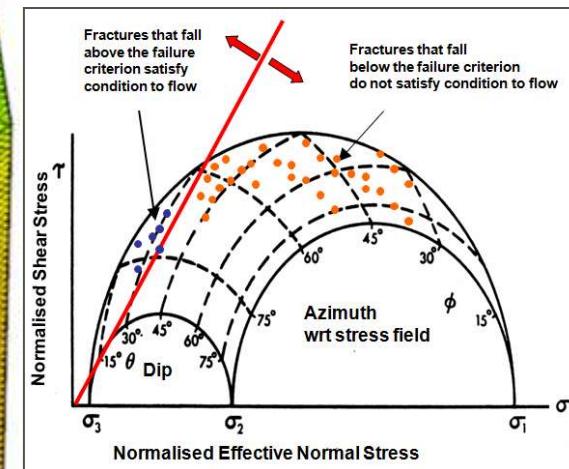
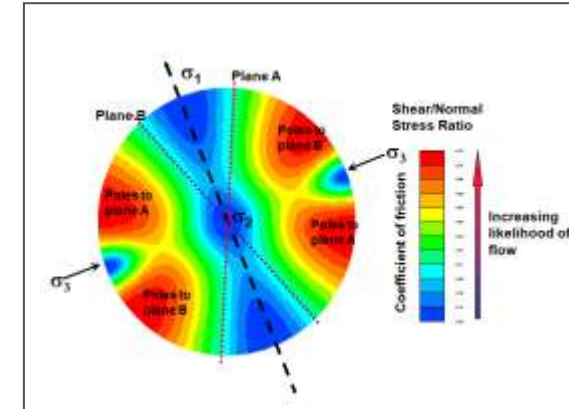
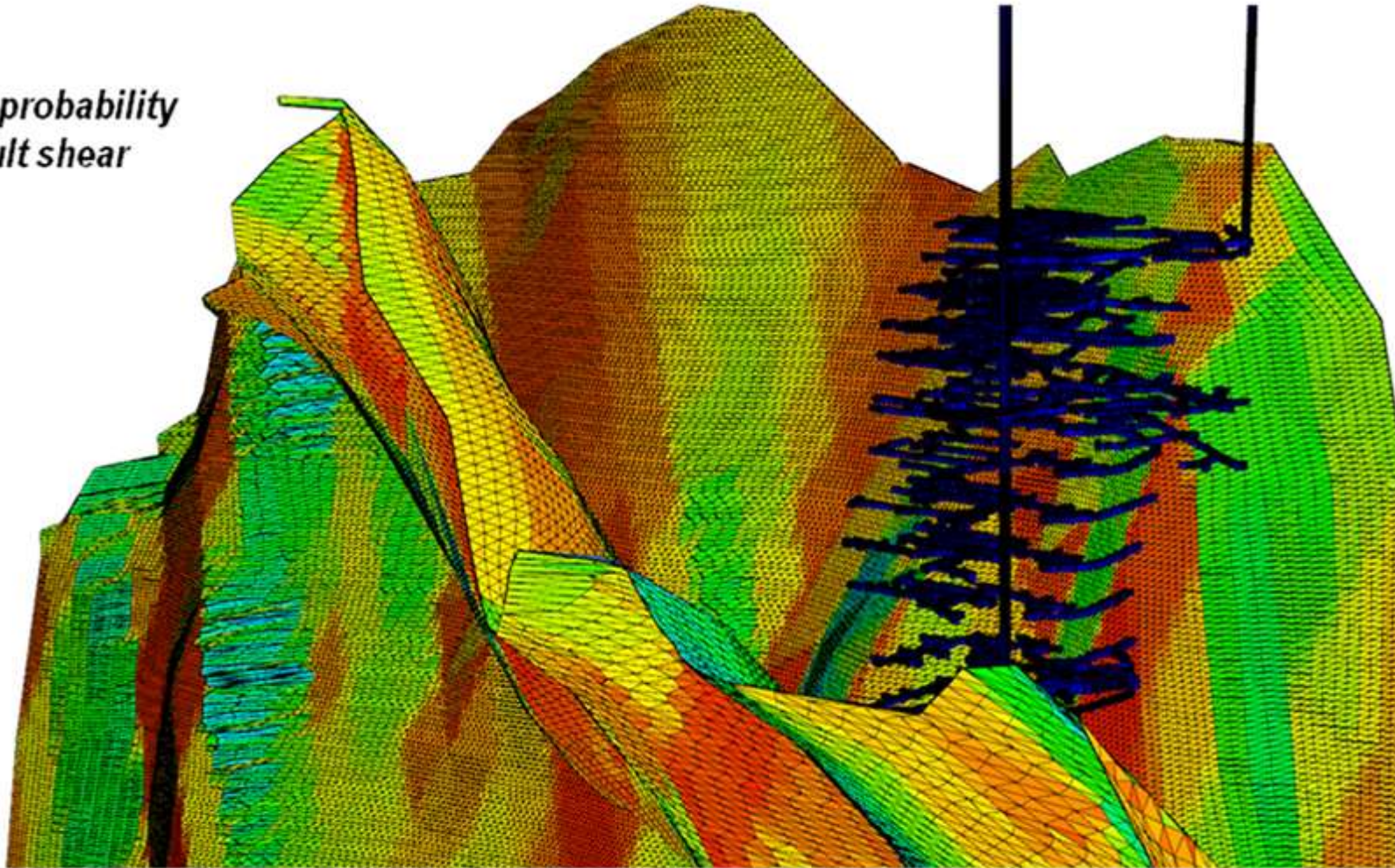
- Combining geotechnical properties with hydrogeological understanding is key in fracture analysis
- Fractures = weakness
- Fractures = permeability

Combining Stress With Discrete Faults → Shear Potential

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High probability
of fault shear



Section 3: Geotechnical Analysis



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Overview (3)

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The **final section** reports how DFN description can be carried forward to perform insightful geotechnical analysis considering in situ stress prediction, kinematic block stability analysis for benches/slopes and tunnels, excavation analysis, and support strategies such as grouting and bolting etc.

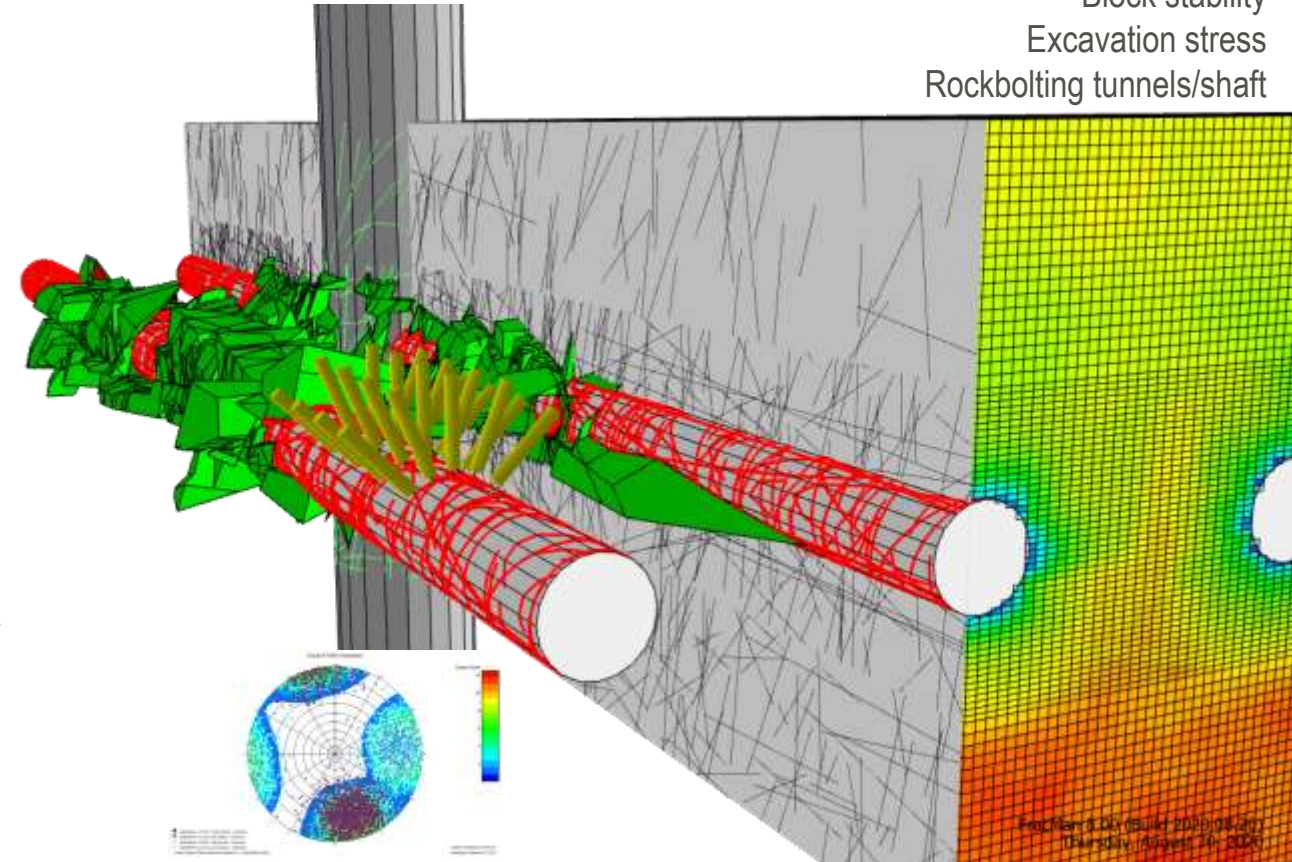
Tunnel/Shaft Kinematic Analysis

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DFN based kinematic assessment:

- Makes no assumptions or limitations of the fracture system or its block forming potential
- The fractures are described by appropriate distribution and properties ← site data
- No limitations of numbers of fracture sets, more complex excavation geometry supported, and multiple levels of support can be implemented
- Currently supports rock bolting plus shotcrete
- This is a *probabilistic* method as it identifies blocks that are geometrically possible also determining the likelihood of their formation
- Block stability including stress interaction

Fracture mapping
Block stability
Excavation stress
Rockbolting tunnels/shaft



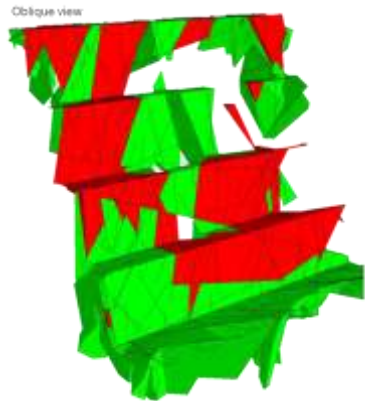
Block formation stability around tunnels and shaft

Slope & Bench Assessment Tools

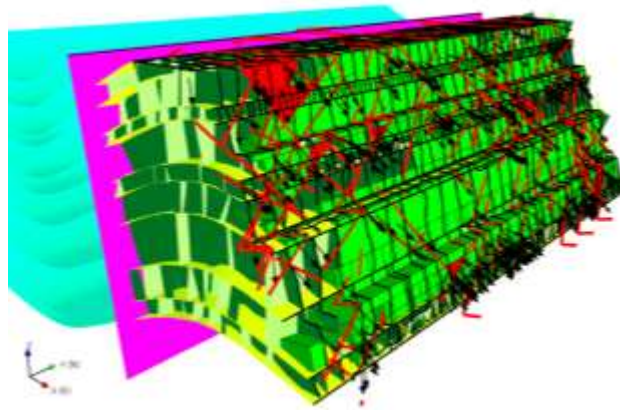
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- The same kinematic assessment for **tunnels** and **shafts**, is applicable for **slope stability** also
- Realistic modelling of rock fabric allows for steeper BFAs at the same POF than conventional analysis
- The DFN approach allows more complex geology and structure to be included within a model
- Recently an inter-ramp analysis method has been developed, linking the DFN and 3D limit equilibrium tool together

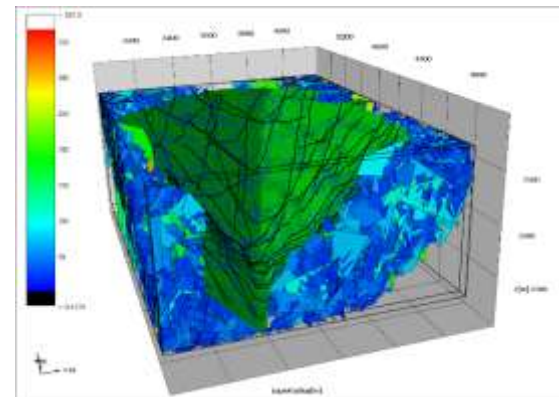
Bench scale kinematics



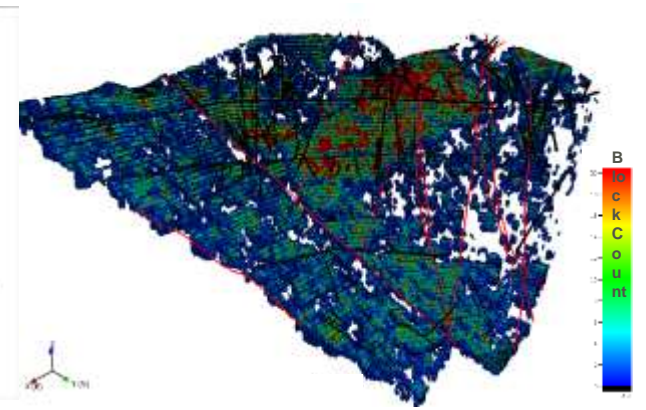
Complex layered bench stability analysis



Pit scale DFN model of major structures for fault kinematic assessment



Heat map of block forming potential & stability



DFN Grouting Analysis

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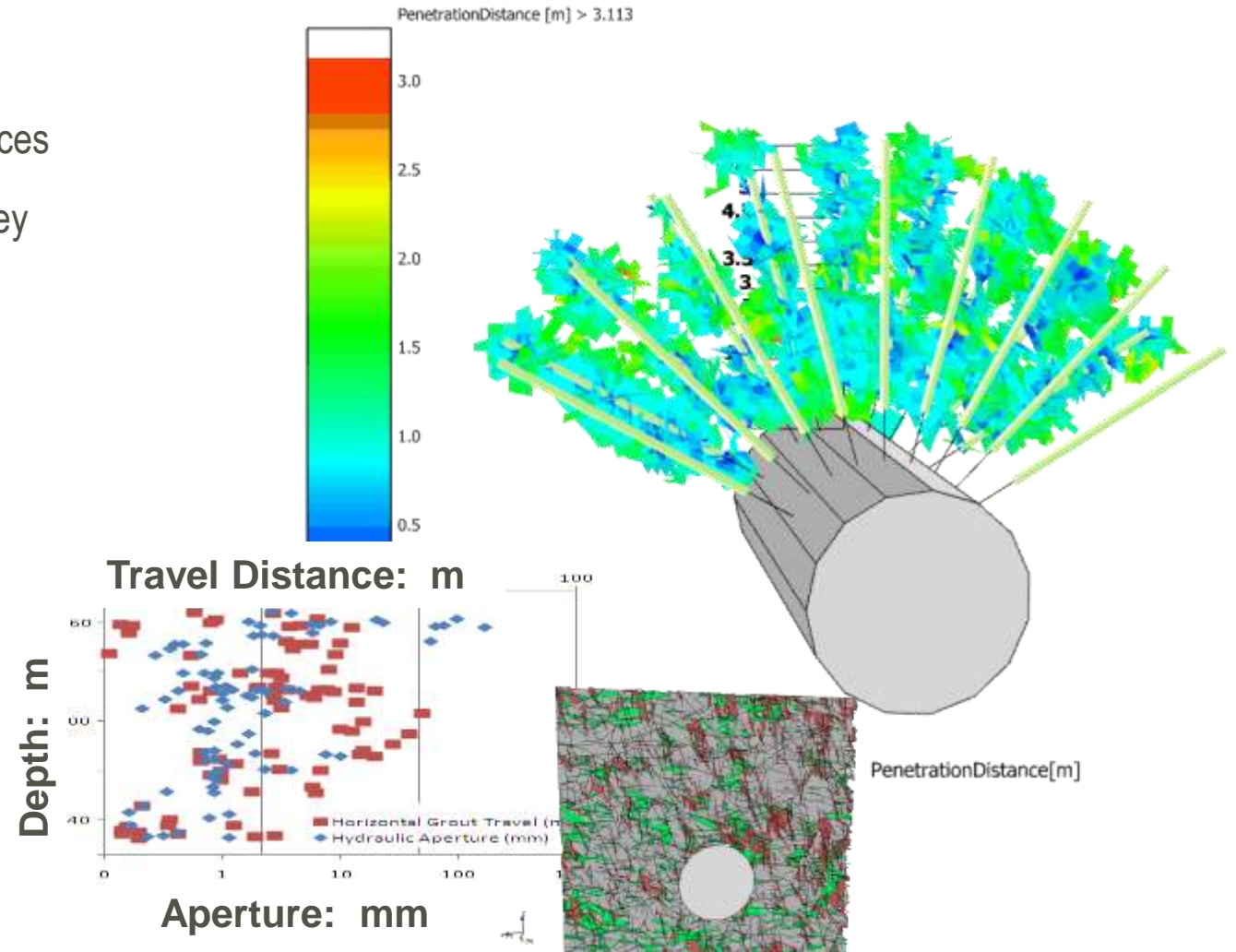
Grouting analysis helps get the paste to flow into the right places

Conceptual basis that understanding of natural fracturing is key to:

- grout rheology & take “targets”;
- establishing “grouting effectiveness”; and
- developing Grouting Protocols – hole spacing, mix thickenings, sequencing and volume cut-offs

Evolving grout front into DFN is controlled by aperture choke points, volume is controlled by fracture void

Bingham fluid central to capturing impact of density, dynamic viscosity, and yield stress (or cohesion)



Slope Demonstration Example

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Slide provides description of the basic workflow steps

1. Input Data
2. Characterisation
3. Geotechnical

Site Characterisation

Integration of available data

- * Drone photogrammetry
- * Core logging
- * Drill hole data
- * Analogue data
- * Empirical relationships

DFN Analysis & Model Build

DFN model parameters

- * Fracture orientation
- * Fracture intensity
- * Fracture size
- * Surface roughness

Basic intact rock parameters

- * Youngs Modulus / Poisson Ratio
- * UCS strength

Geotechnical Analysis

Probabilistic analysis to help constrain likelihood of a given outcome

- * Rock slope stability
- * Excavation insertion
- * Block sizing
- * Support
- * Stress analysis

Drone Acquired Fracture Trace Data

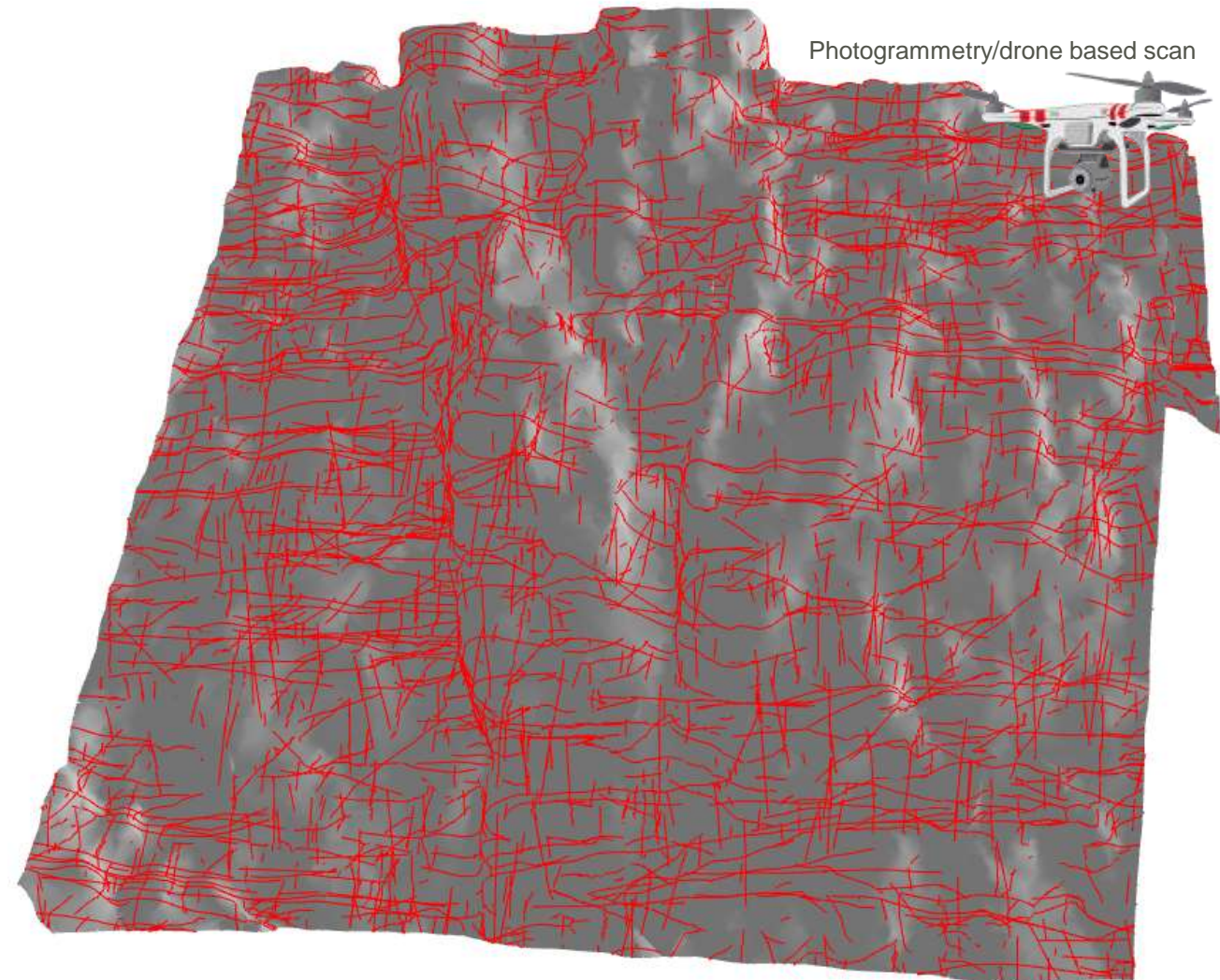
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Gathering the Data

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- Photogrammetry/drone scan of outcrop combined with some standard geotechnical logging allows **production of representative fracture data**
- Using the trace data, Golder build a **full 3D DFN model** from the observed imagery
- The DFN model **represents key discontinuities:**
 - Natural fractures
 - Bedding layers
 - Faults /dykes

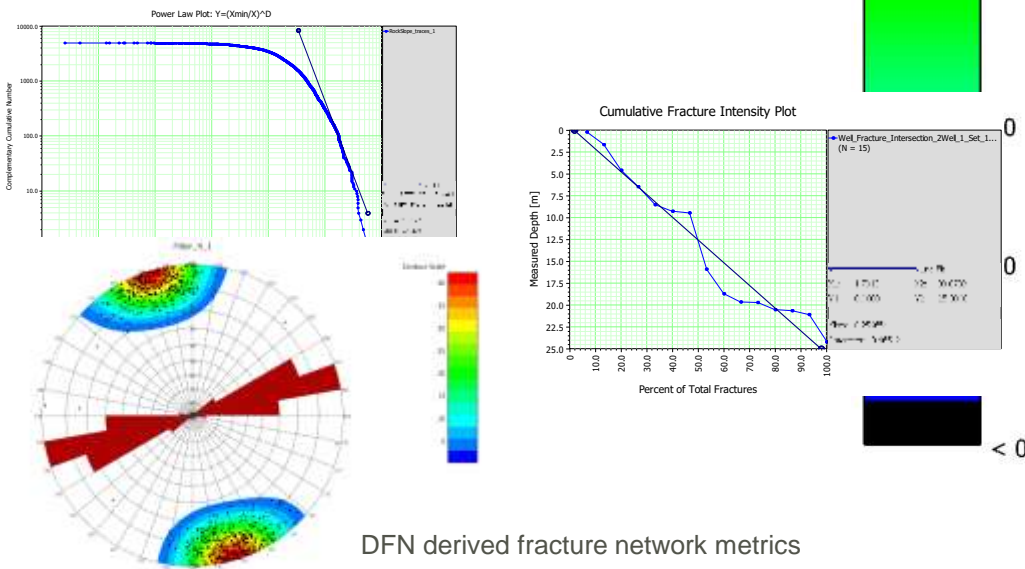


Making the DFN

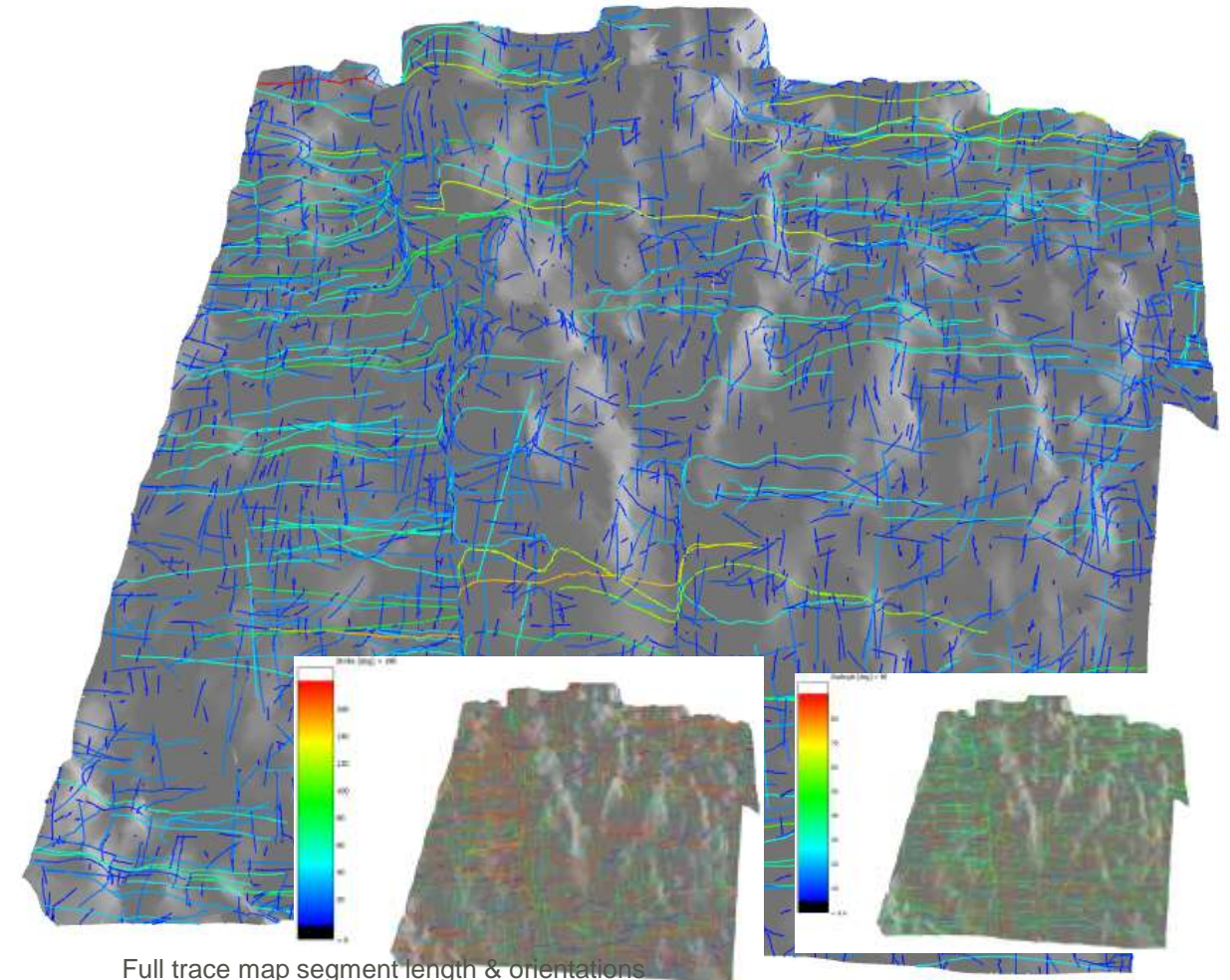
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- Analysing the trace data we characterise the DFN parameters to reflect the observation
- Reflect the **fracture geometry** as we observe it allows the model to be ground truthed

Trace_Length [m] > 57.4



DFN derived fracture network metrics

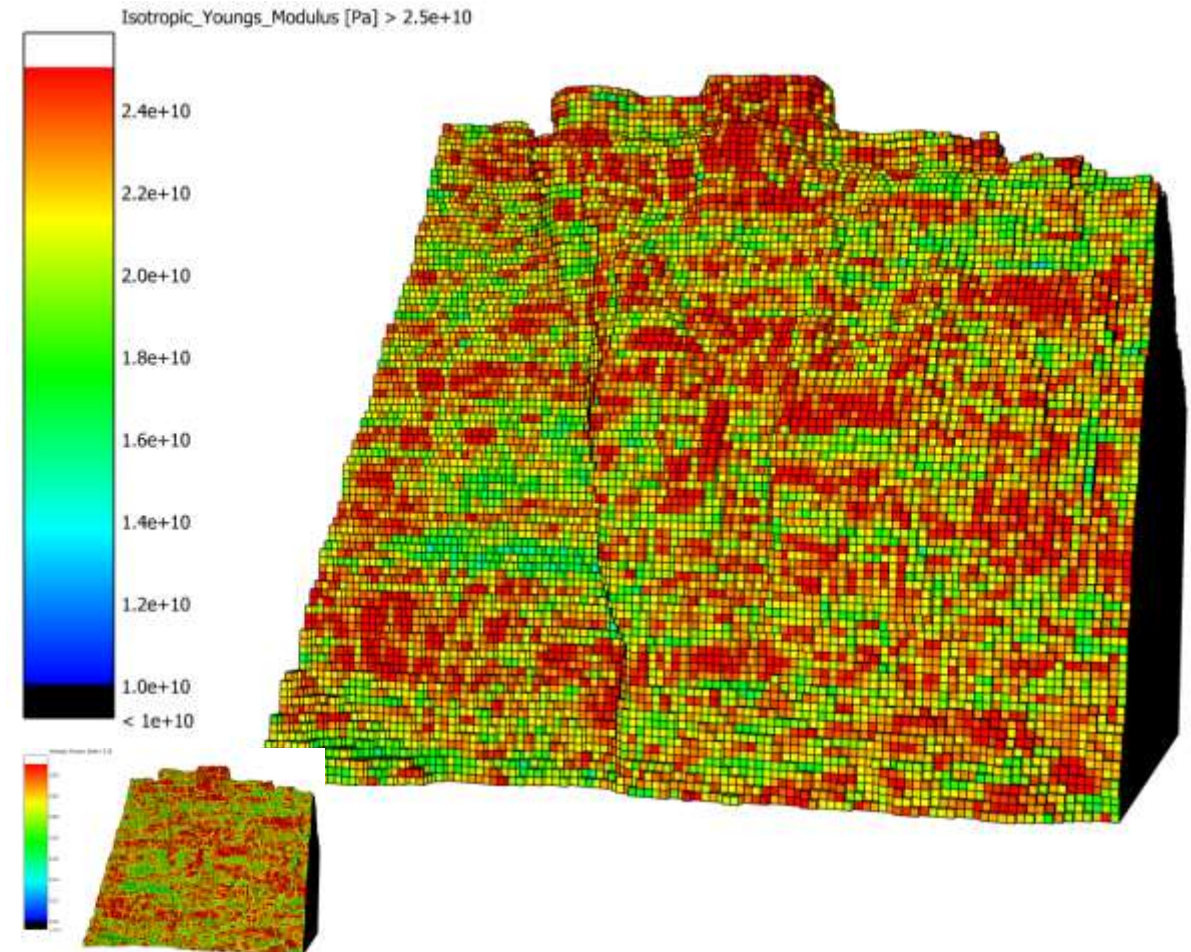
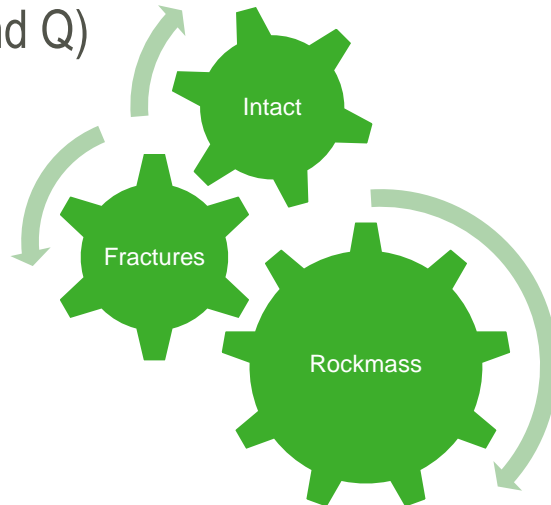


Full trace map segment length & orientations

Forecasting the Rock Mass Properties

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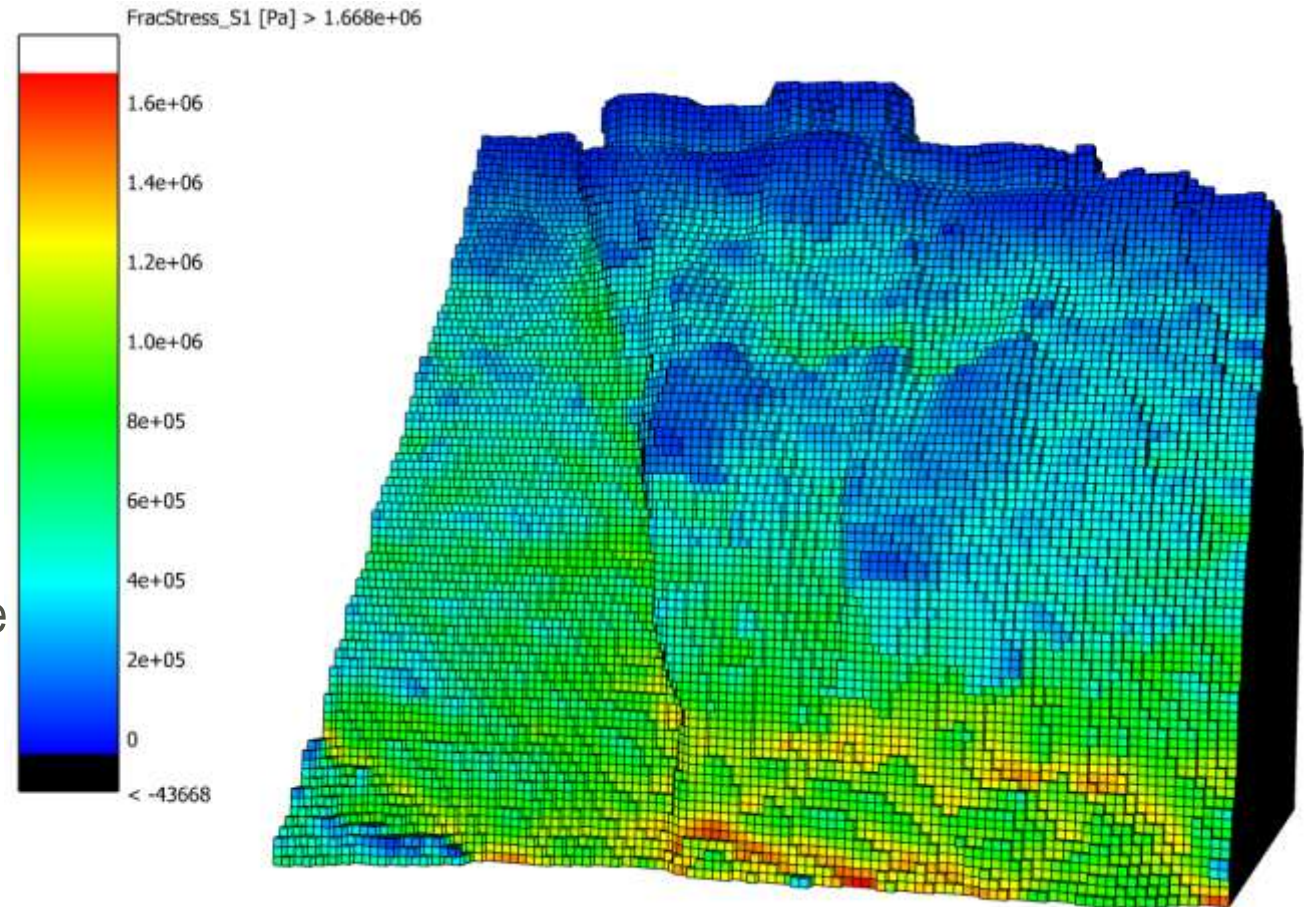
- Creation of the DFN model also allows numerical evaluation of the **rock mass properties**
- Combine the **intact** and **fracture** strength and stiffness estimates allows evaluation of the **rock mass modulus** and strength properties (e.g. GSI, RMR, and Q)



Forecasting the Rock Mass Properties

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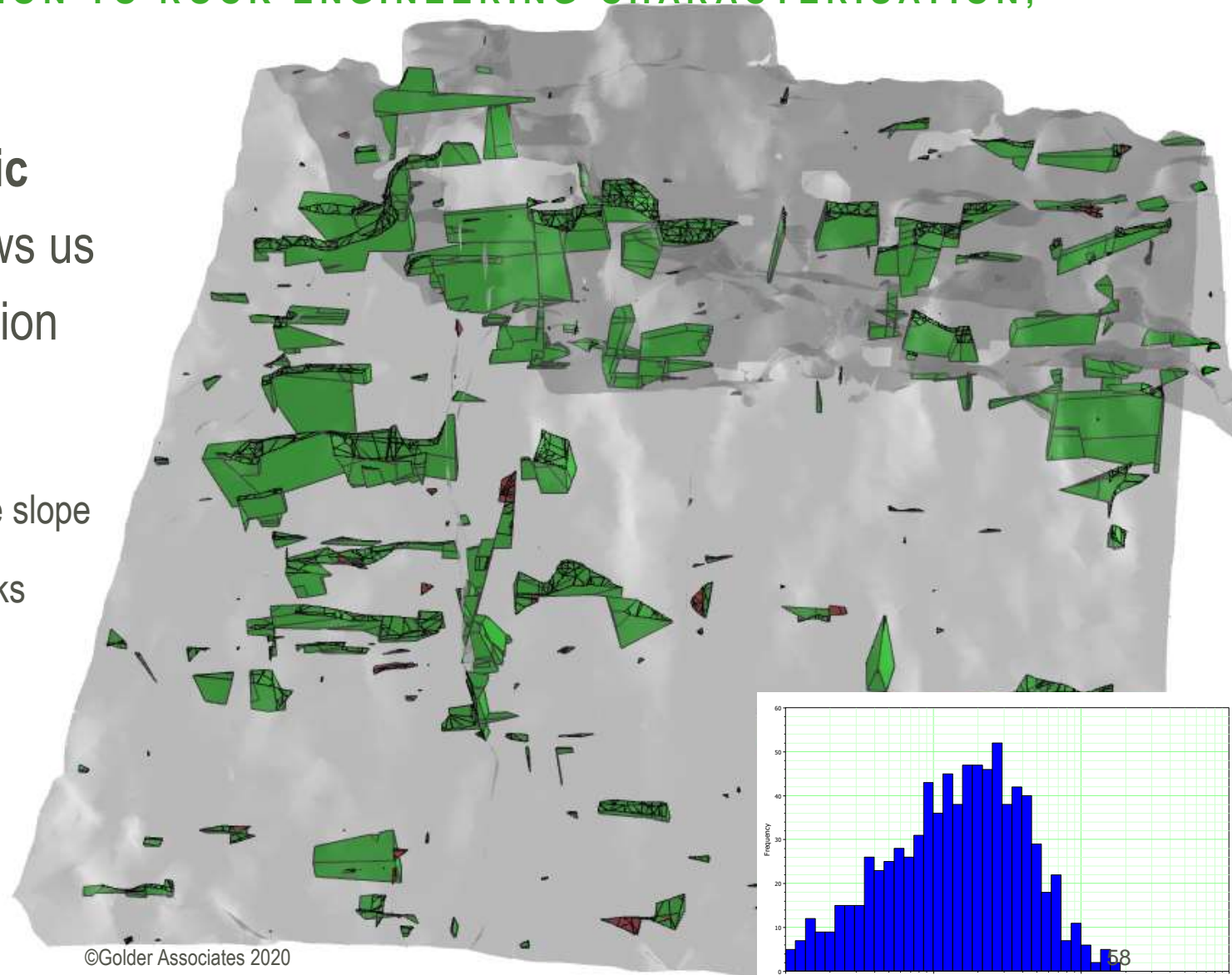
- Creation of the DFN model also allows numerical evaluation of the **rock mass properties**
- We use the FEM geomechanical stress simulator to evaluate **rock stress/displacement** response
- Combining the stress distribution with the fracture network provides for a coupled solution approach
- Stress solution then used to support other available analyses required for **Improved Design**



Slope Kinematic Stability

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- We used DFN to evaluate **Kinematic Stability** of the rock slope, this allows us to quantify uncertainty in our prediction
- We **probabilistically** evaluated:
 - Formation of rock blocks & geometry on the slope
 - Factor of Safety associated with those blocks
 - Optimization of slope angles for stability

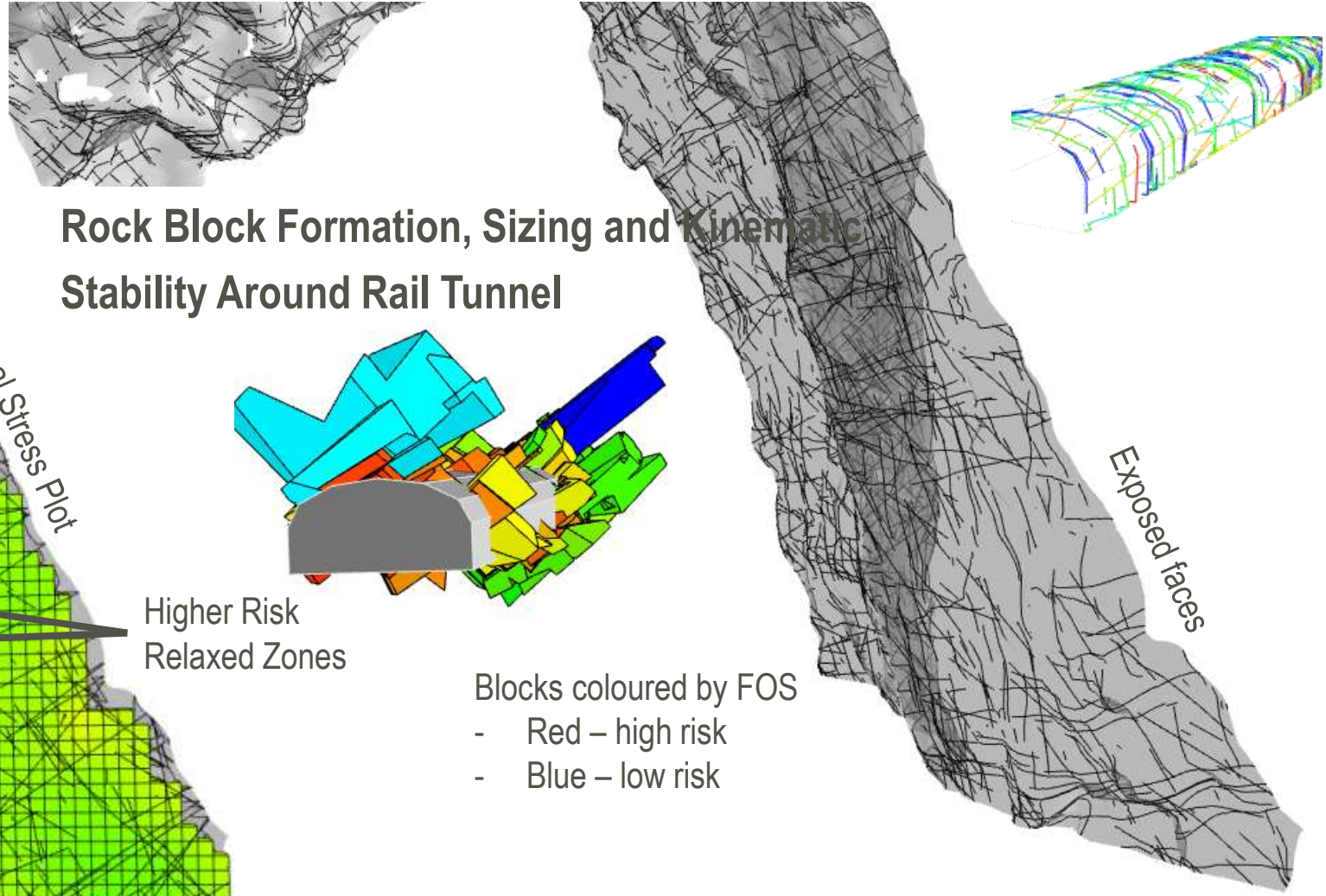
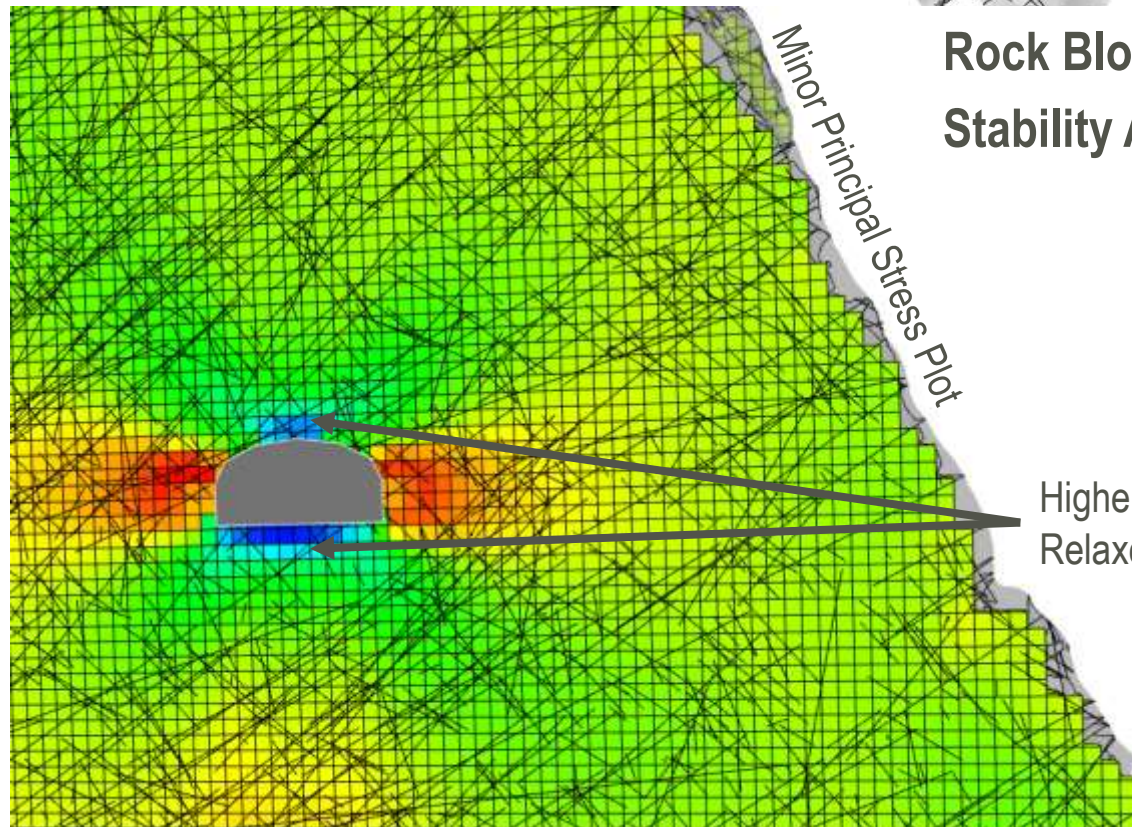


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Tunnel Kinematic Stability

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Excavation Induced Stress Relaxation

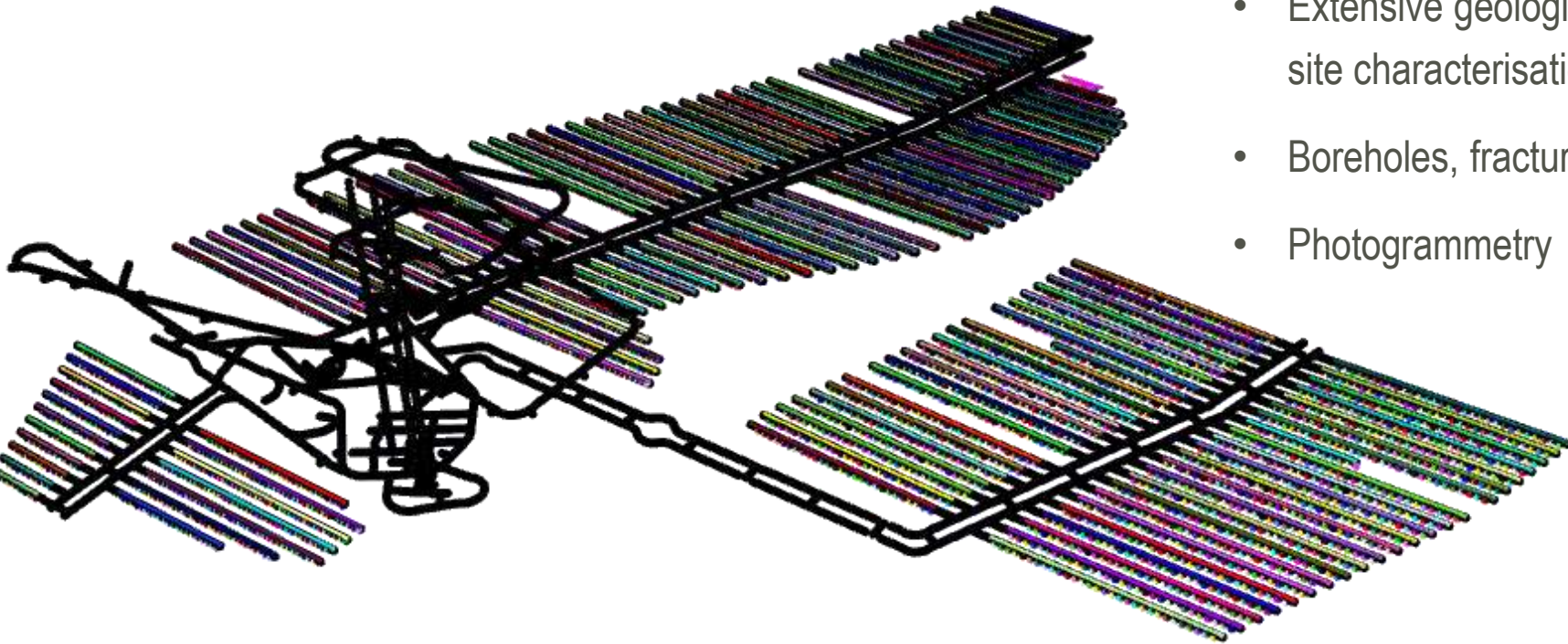


Extensive Underground Tunnel/Pit/Shaft Developments

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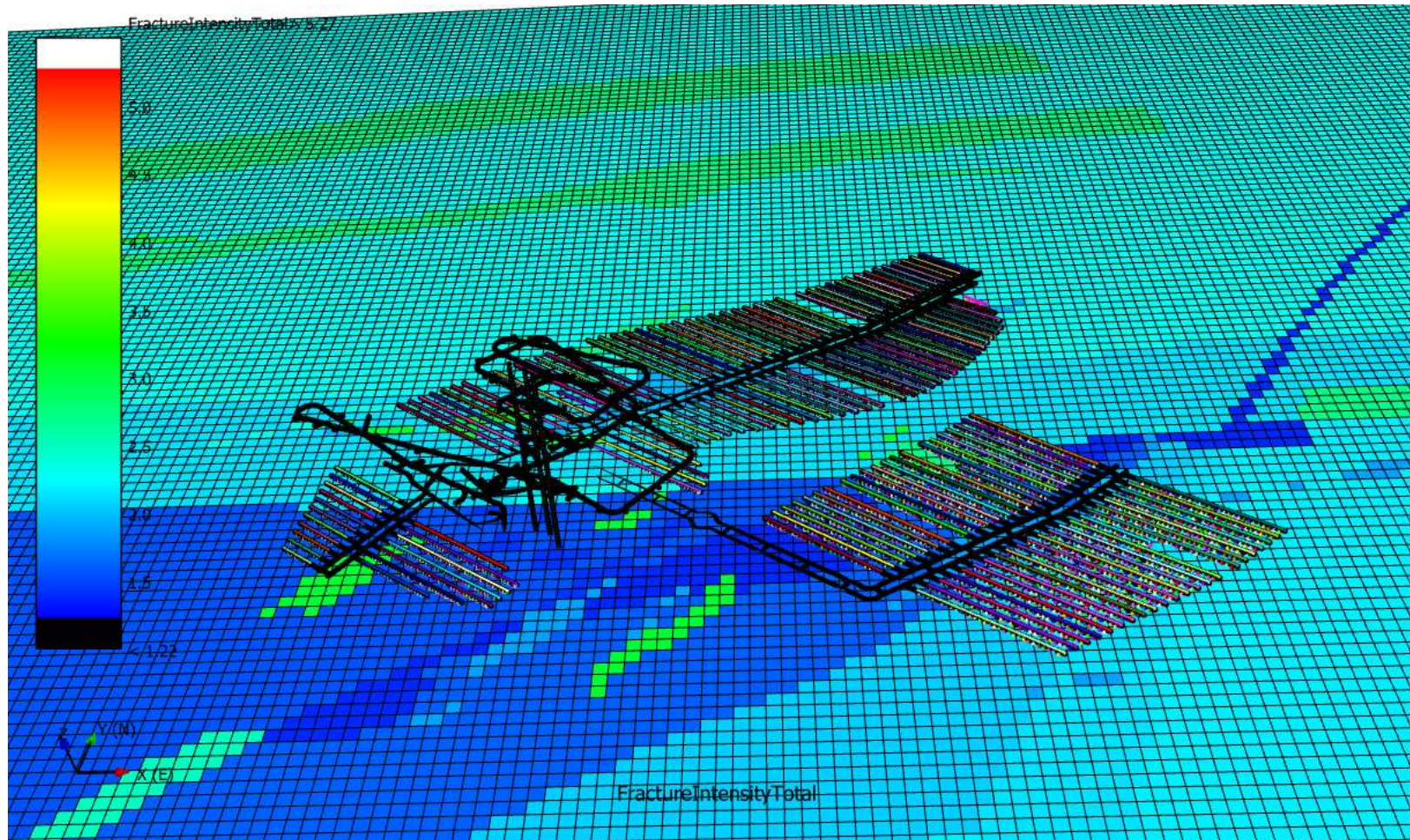
- **Hard Rock Tunnelling Development**

- ~150 tunnels, ~4200 pits, 4 shafts
- Extensive geological, hydrogeological and geomechanical site characterisation
- Boreholes, fracture geometry and hydraulic data
- Photogrammetry



Facility Scale Geological Model

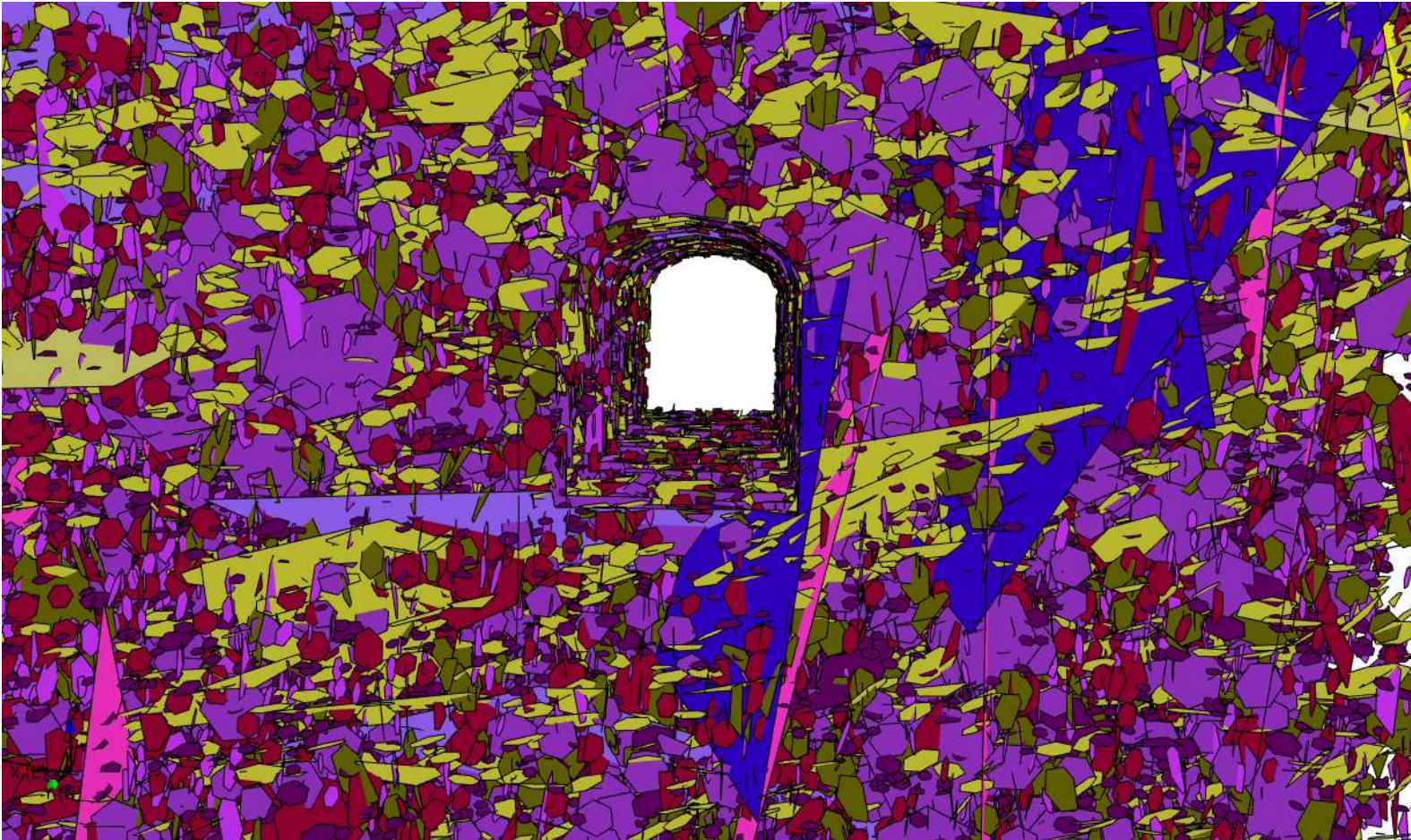
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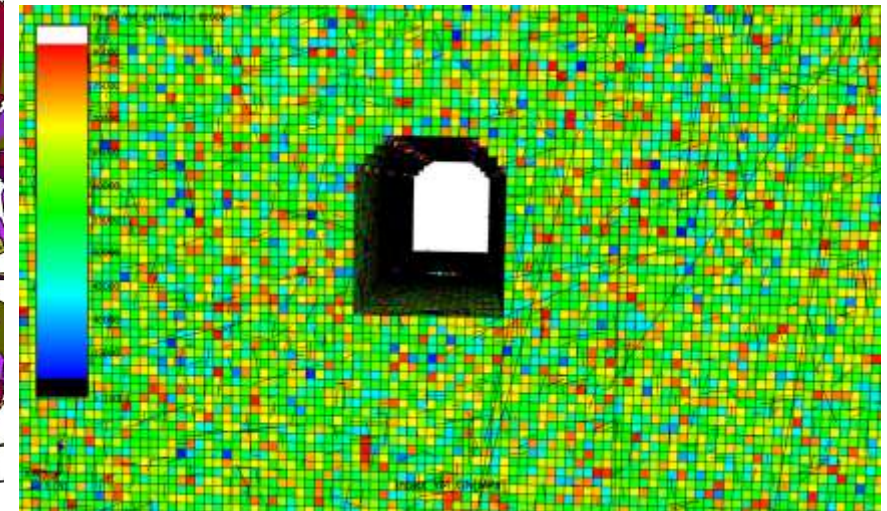
- Large scale geological model
- Various tectonic domains
- Multiple rock types

High Fidelity Tunnel Scale DFN

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- High fidelity DFN with fracture sizes ranging 0.50 – 115 metres
- Up to 400 million DFN
- Tunnel scale description overlaid with high resolution geomechanical properties



Section 4: Wrap Up



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Conclusions & Why

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Why is DFN so good? What do we do that other ways don't do?

- Fractured **rock masses** are often **variable**
- Assumptions we make about the fracture geometry and mass properties **affects the behaviour** of the rock mass
- We now **better describe** our rock mass through advances in surface & underground mapping (i.e. photogrammetry), borehole technology and geophysical imaging

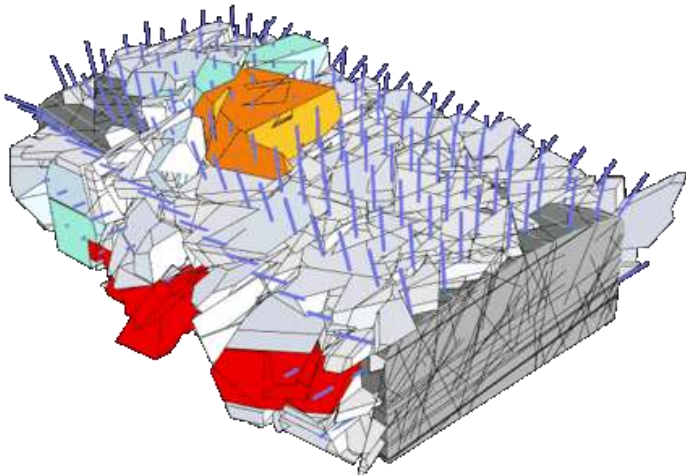
Lots of toolbox with compelling reasons to use it

- With DFN methodology provides an **innovative**, yet **quantifiable**, and **defensible** basis for using gathered data
- With better rock mass models (discrete/continuous) **we can better capture behaviour** of the rock
- DFN **works in parallel** to standard industry practices & services
- This provides our clients with a **competitive edge** to our clients over their/our competitors



GOLDER

Winning Strategies in Rock Mechanics for Tunnels & Slopes Engineering



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