Remote rock mass characterization

Mateusz Janiszewski, D.Sc. (Tech)
Lauri Uotinen, D.Sc. (Tech)

TERRA
Remote rock mass characterization

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School of Engineering

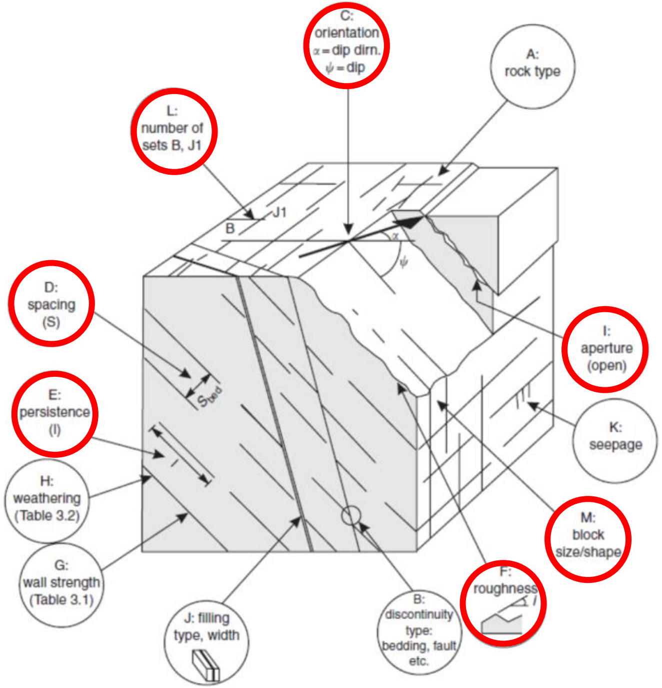
Learning goals

After this session you will be able to:

- understand the principles and techniques of remote rock mass characterization
- understand the principles and techniques of laboratory rock joint measurements

Remote rock mass characterization

- remote sensing technologies: **LiDAR** and **photogrammetry**
- high-resolution, accurate **3D models of rock mass surfaces**
- enable **detailed analysis of discontinuities** -> orientation and other geometrical properties
- map rock mass features over **large areas**
- **stastistical distribution** of parameters
- provides **unbiased data** from **inaccessible or dangerous locations**



Remote rock mass mapping

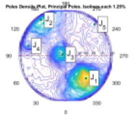
Remote rock mass characterization

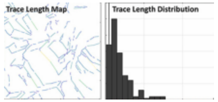
Remote sensing

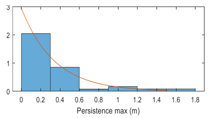
3D model of rock mass surface

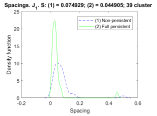
Remote rock mass characterization

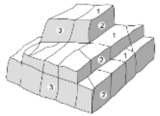
Joint set orientation	Roughness and waviness	Fracture intensity	Persistence	Spacing	Block size











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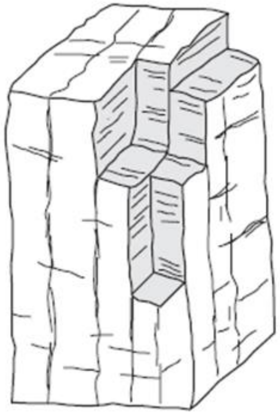
Discontinuity sets and orientation



(Wyllie & Mah, 2004)

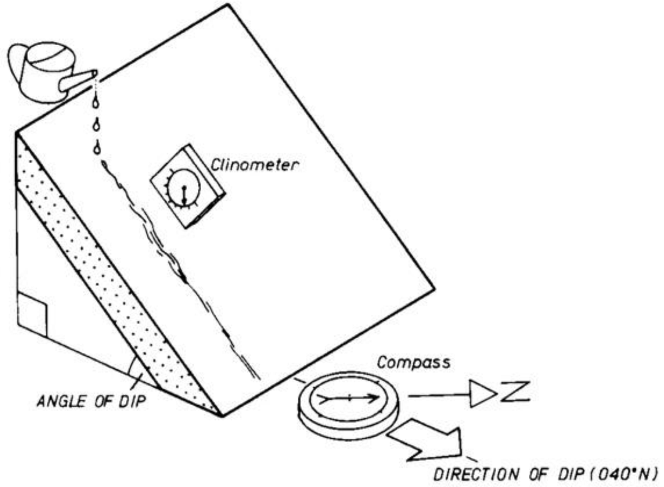
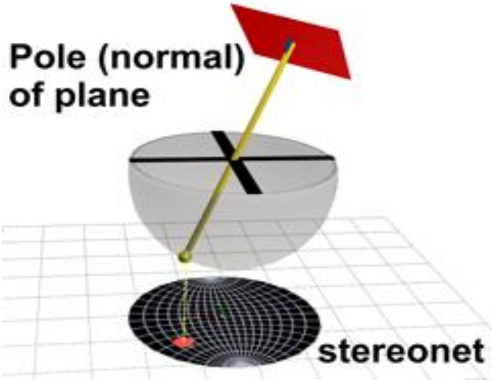
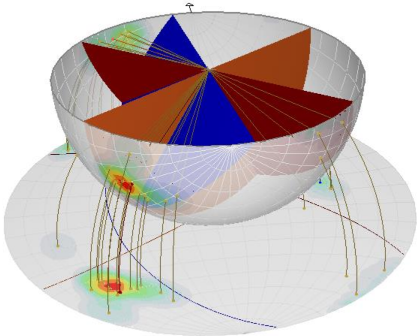


Fig. 2.3 The concepts of direction of dip and angle of dip.

Geological Maps, Lisle (2004)



Source: Maptek



Source: Rocscience

Although discontinuities are not planes but surfaces that present roughness and waviness, they are usually treated as planes when an appropriate study scale is used

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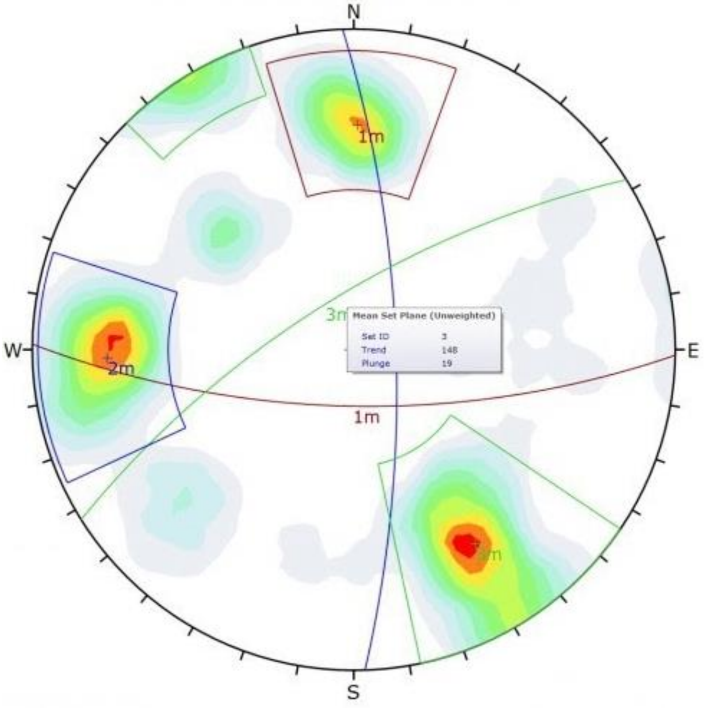
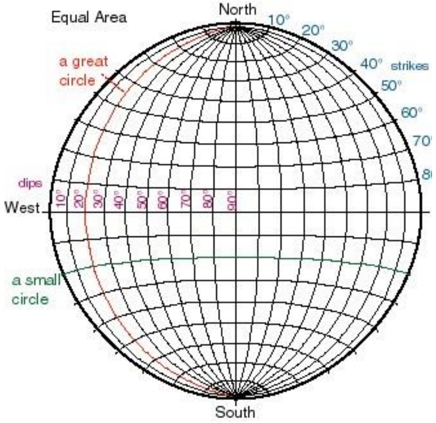
Stereonets for plotting linear and planar features

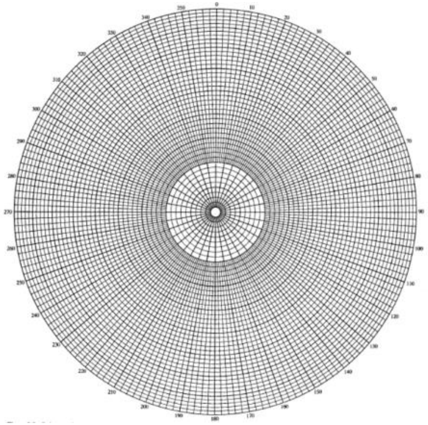


Color	Density Concentrations
	0.00 - 0.80
	0.80 - 1.60
	1.60 - 2.40
	2.40 - 3.20
	3.20 - 4.00
	4.00 - 4.80
	4.80 - 5.60
	5.60 - 6.40
	6.40 - 7.20
	7.20 - 8.00
Maximum Density	7.67%
Contour Data	Pole Vectors
Contour Distribution	Fisher
Counting Circle Size	1.0%

Plot Mode	Pole Vectors
Vector Count	303 (303 Entries)
Hemisphere	Lower
Projection	Equal Angle

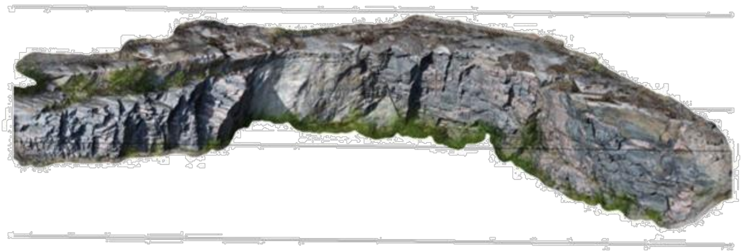


Equal area stereonet projection

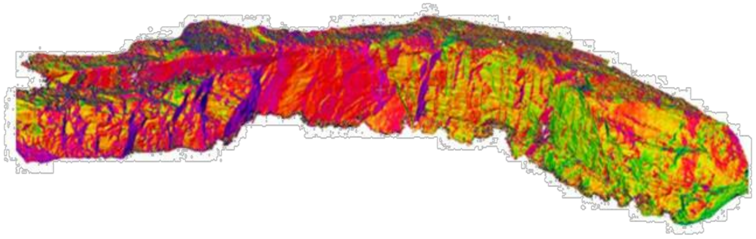


Polar equal area net

Planar discontinuity orientation



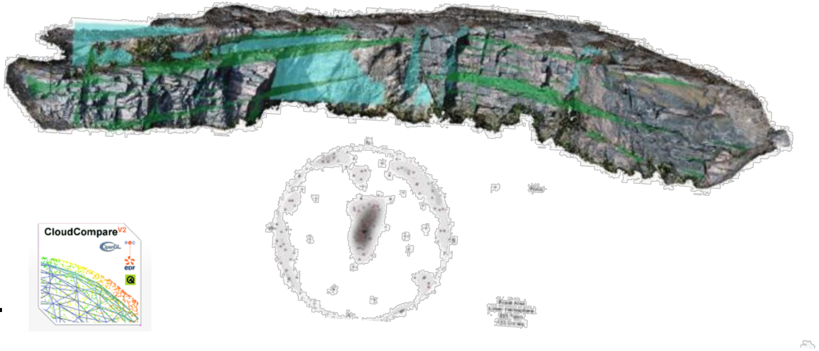
Automatic and Semi-automatic methods



e.g.

Discontinuity Set Extractor software

Manual (computer-assisted) method



e.g.

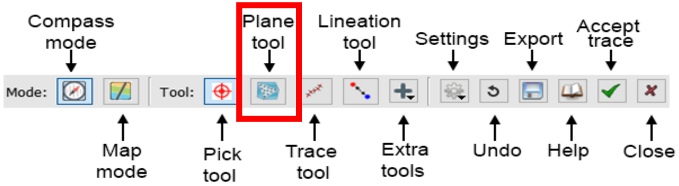
Compass plugin
CloudCompare

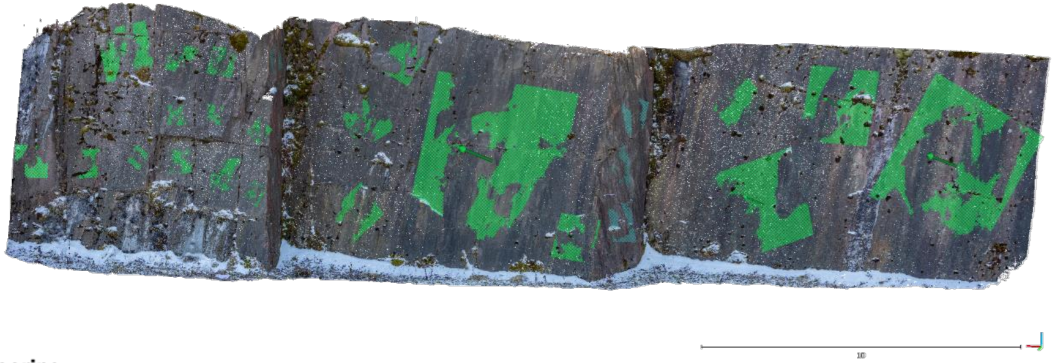
Manual (computer-assisted) method

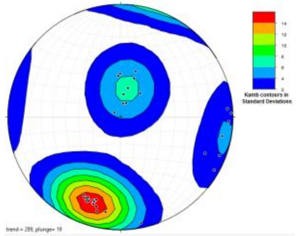
Compass plugin - CloudCompare

Compass is a structural geology toolbox for the interpretation and analysis of virtual outcrop models.

The plane tool is used to measure the orientations of fully exposed planar structures, such as joint or bedding surfaces





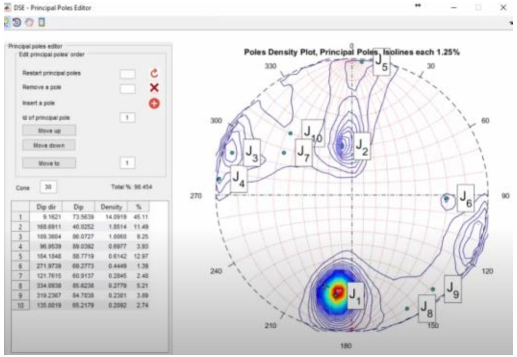


https://www.cloudcompare.org/doc/wiki/index.php/Compass_(plugin)

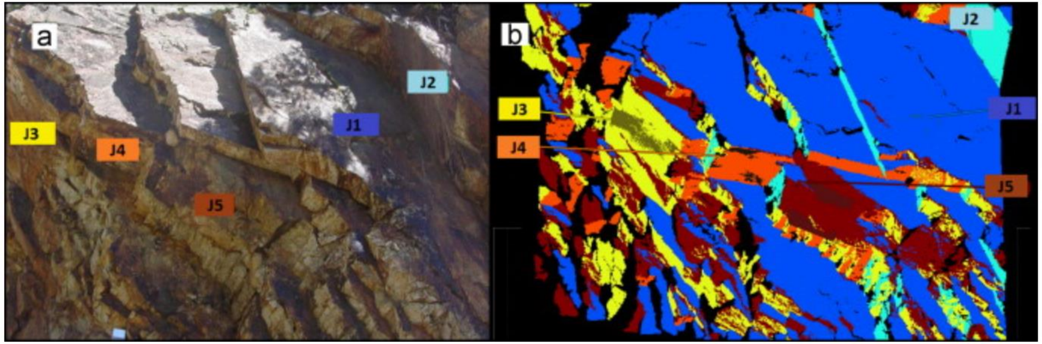
Semi-automatic method

Riquelme et al. 2014

Discontinuity Set Extractor (DSE)

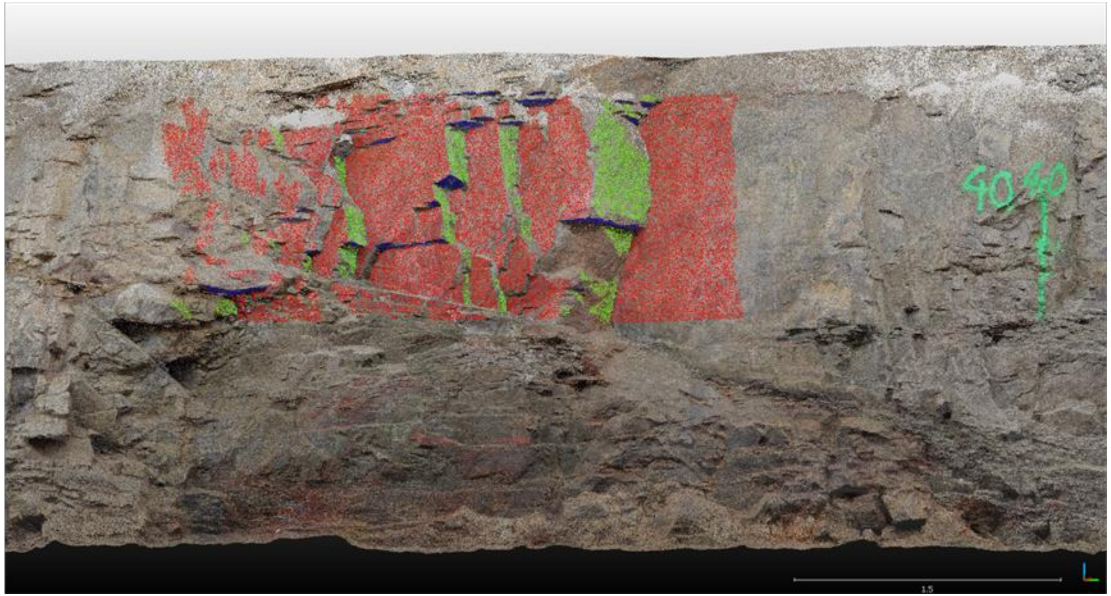


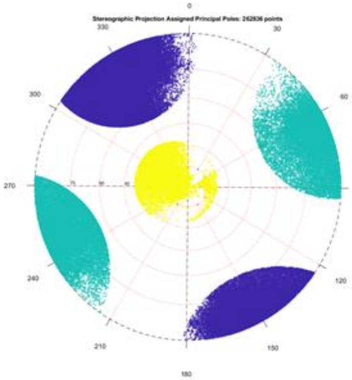
- clustering-based method
- extracts discontinuity sets from a rock mass
- input data is a 3D point cloud
- classifies the point cloud into joint sets
  - orientation
  - spacing
  - persistence

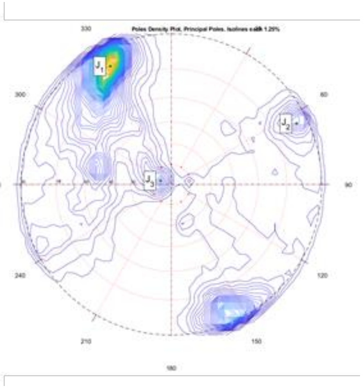


Check out an online course on DSE:
https://isrm.net/page/show/1562

Fractures were extracted from the point cloud using Discontinuity Set Extractor (DSE)





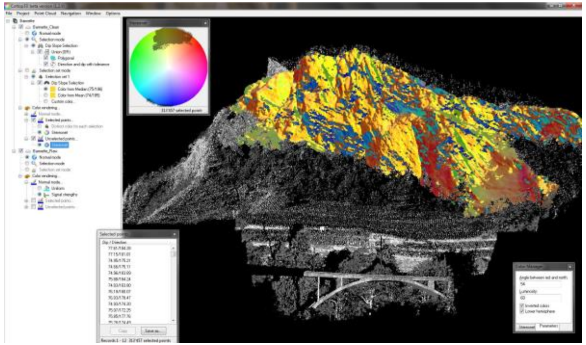


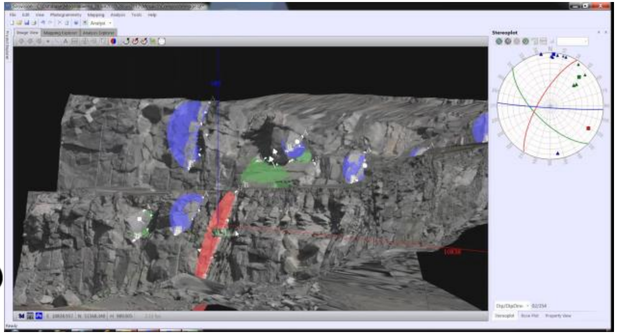
Discontinuity set	Dip direction [°]	Dip [°]
1	332.7	82.9
2	64.1	85.6
3	288.7	8.6

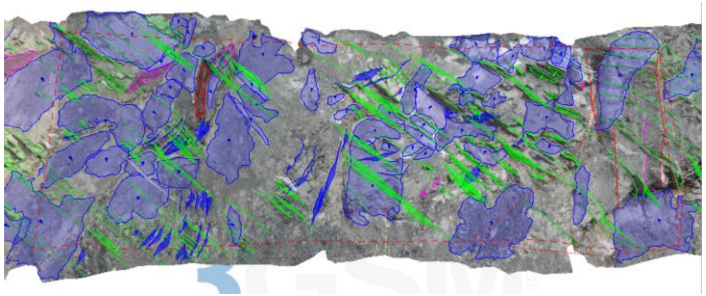
Use appropriate study scale – for example define a mapping window instead of analyzing the entire exposure

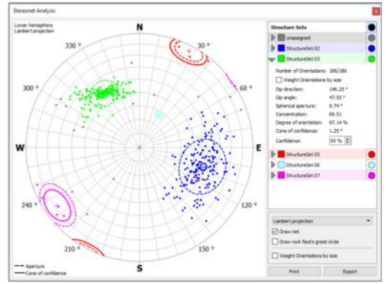
Other software

- **Sirovision (Datamine)** – stereophotogrammetry, joint plane mapping
- **ShapeMetriX (3GSM)** – photogrammetry, joint sets and orientations, spacing
- **Coltop3D – semi-automatic joint mapping**
- …



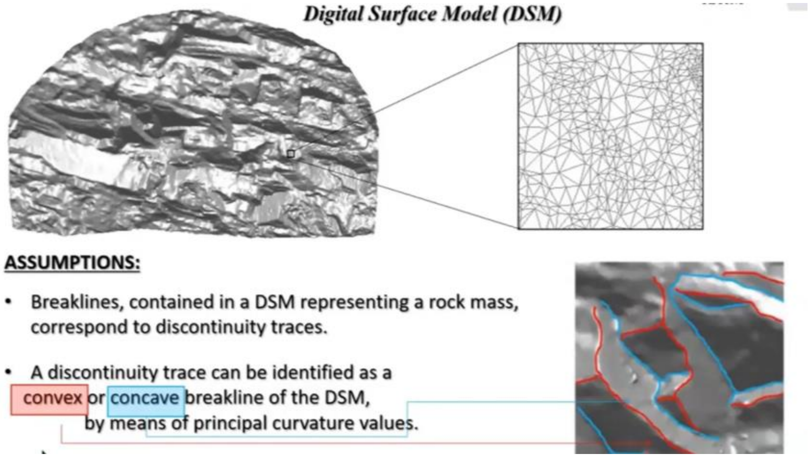






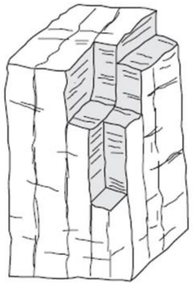
Trace mapping and sampling

- Discontinuities may appear as a trace on the exposed rock mass surface
- Developments in trace mapping:
    1. **Manual** mapping on **exposed rock mass**
    2. **Manual** mapping on **digital images**
    3. **Semi-automatic/automatic** mapping on **digital images**
    4. **Semi-automatic/automatic** mapping on **digital 3D models**



CurvaTool (Umili, 2013)

- Automatic extraction of traces
- Determination of joint sets
- Assigning each trace to a joint set
- Measurement of trace length and spacing

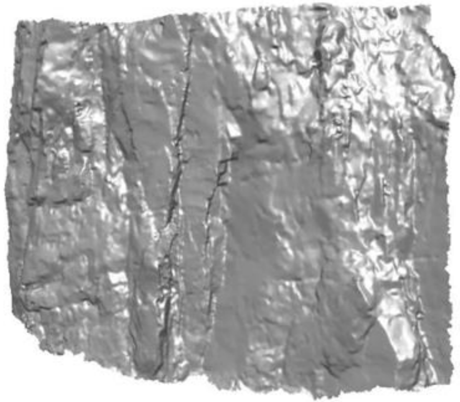


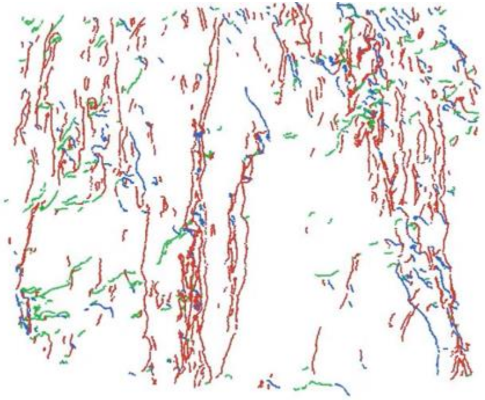
(Wyllie & Mah, 2004)

Check out an online course on remote trace mapping and sampling:
https://isrm.net/page/show/1561

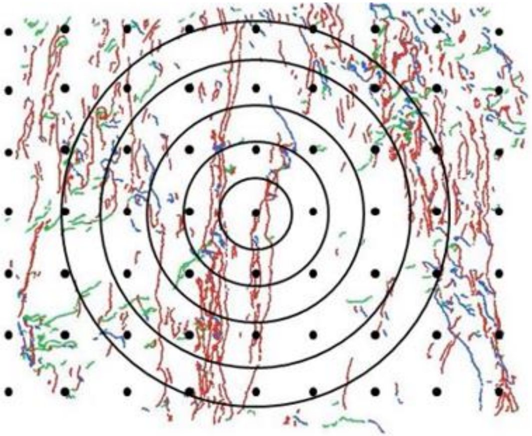
Trace mapping vs sampling

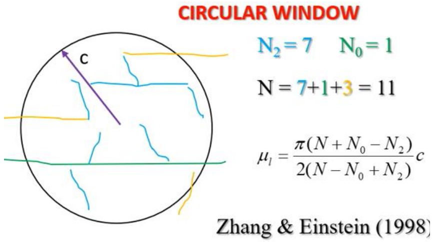
Mapping creates digital map/sketch of traces with 1:1 scale

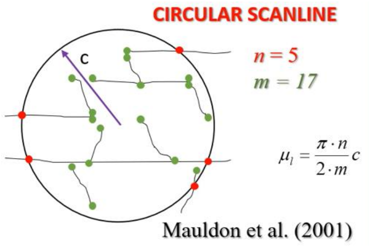




Sampling measures and counts traces







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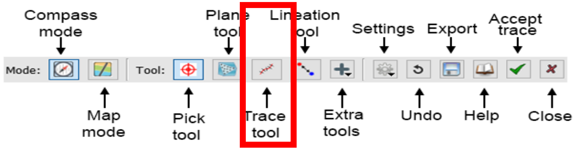
Mauldon et al. 2001

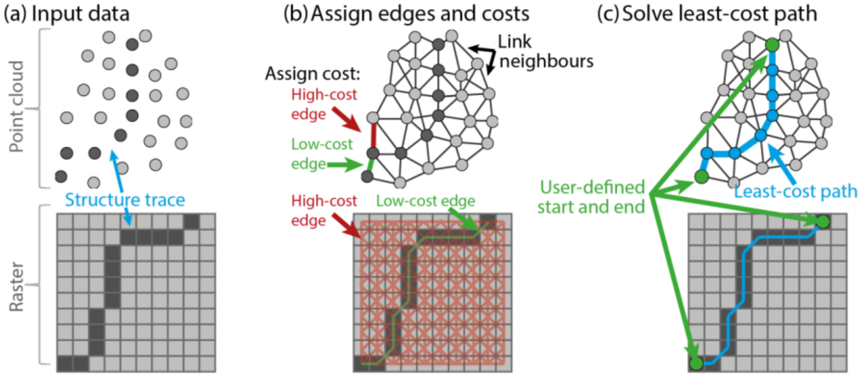
→ Statistical analysis μ_l → E(D) → E(A) → $P_{32} = \frac{N_t \cdot E(A)}{V}$

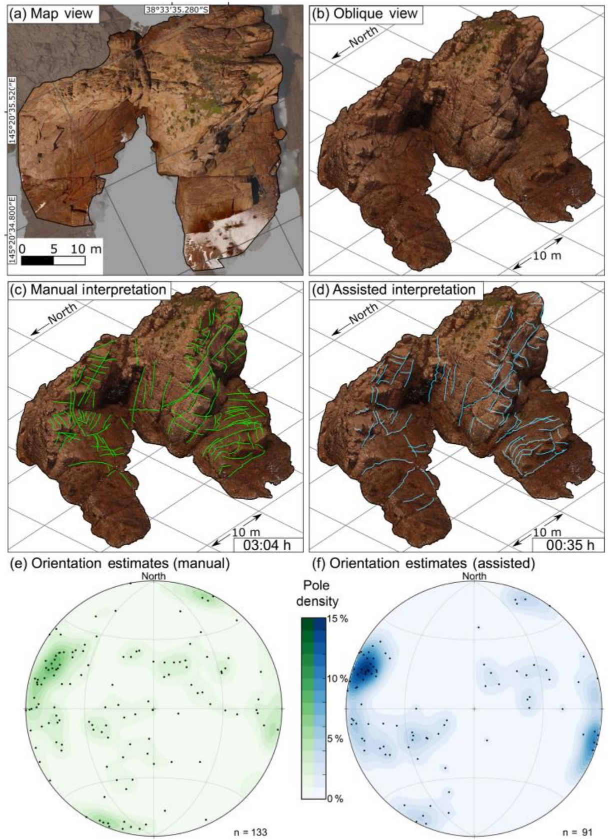
Computer-assisted trace mapping

Compass plugin - CloudCompare

The **trace tool**







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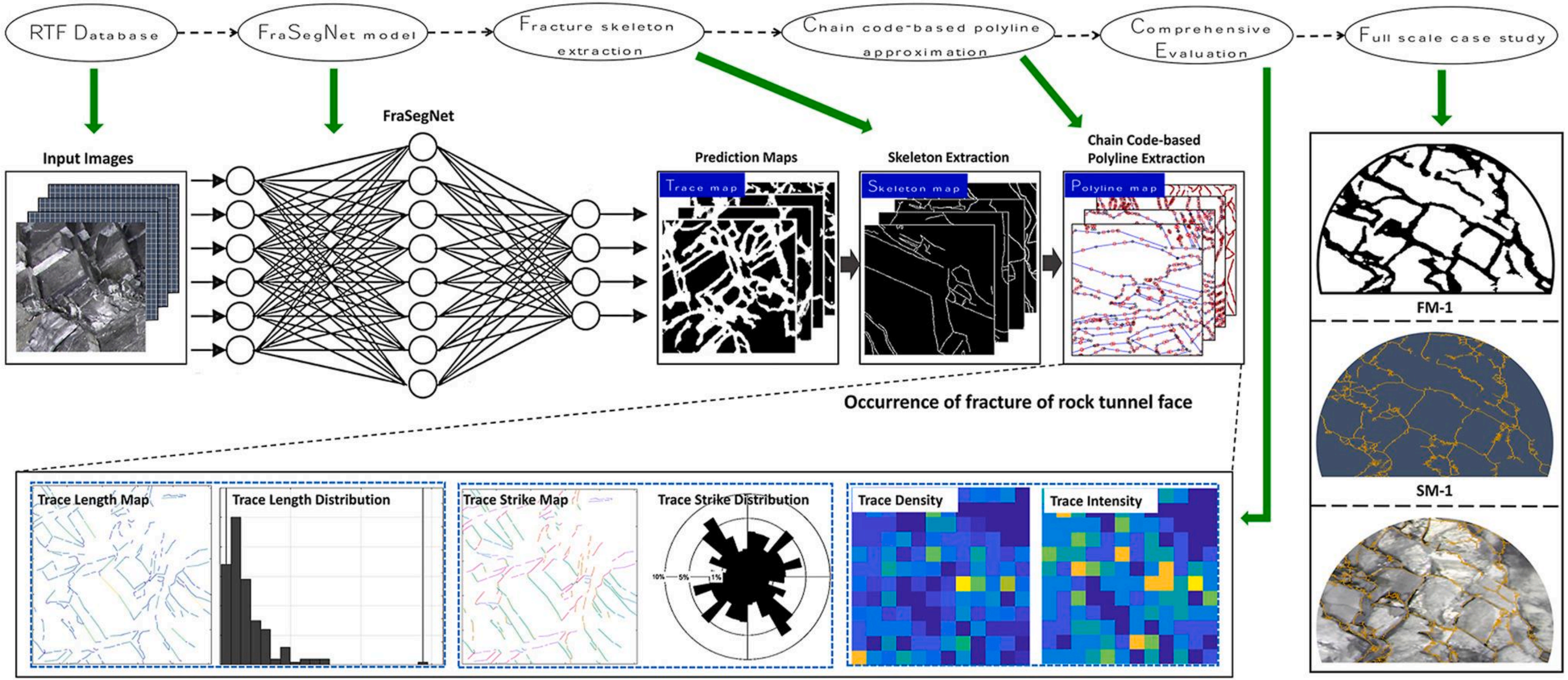
Thiele et al. 2017

Automatic trace detection – deep learning



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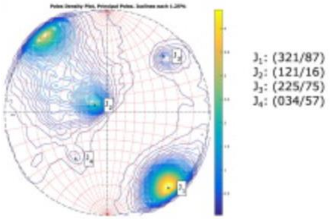
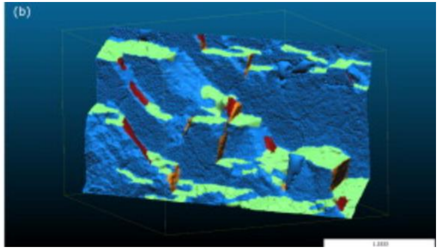
Chen et al. 2021 Automated extraction and evaluation of fracture trace maps from rock tunnel face images via deep learning. Int. J. Min. Sci. 142

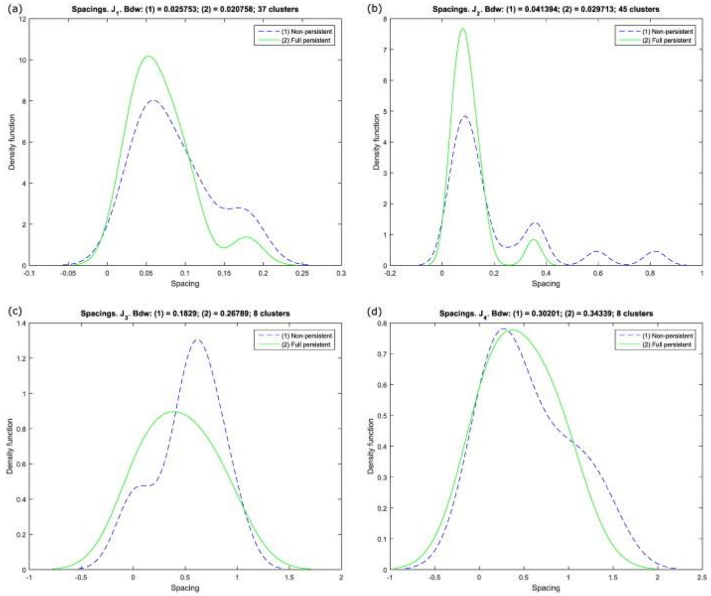
Spacing

- plays a key role in the behavior of the rock masses
- measured by counting the number of discontinuities that cut a traverse line of known length (ISRM, 1977)
- 3D measurement with remote sensing
    - calculation of the normal spacing from clustered 3D point clouds, e.g. DSE by Riquelme et al. 2015

Discontinuity spacing	Description
<20 mm	Extremely close
20–60 mm	Very close
60–200 mm	Close
20–60 cm	Moderate
60 cm–2 m	Wide
2–6 m	Very wide
>6 m	Extremely wide







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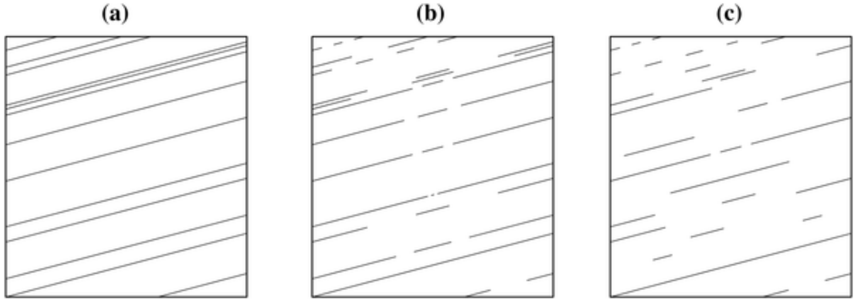
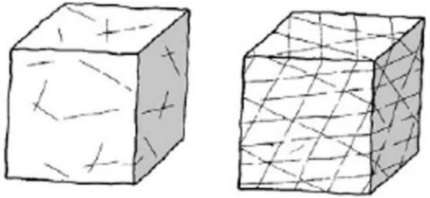
Persistence

- Aerial extent or size of a discontinuity within a plane
- One of the most important rock mass parameter but one of the most difficult to measure
- It can be crudely quantified by observing the trace lengths of discontinuities on exposed surfaces
- Persistence calculator based on clustered point clouds, e.g. DSE by Riquelme et al. 2018

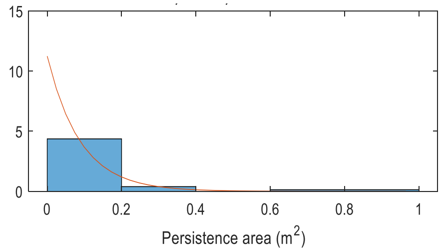


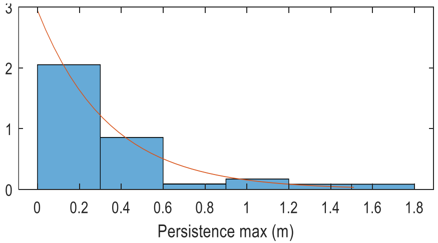
Modified from (Hudson and Priest 1983)

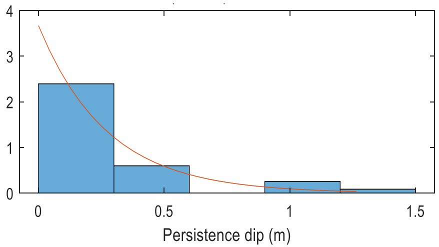
(ISRM Commission, 1978)

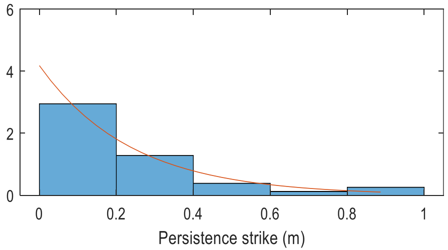


Description	Modal trace length (m)
very low persistence	<1
low persistence	1–3
medium persistence	3–10
high persistence	10–20
very high persistence	20



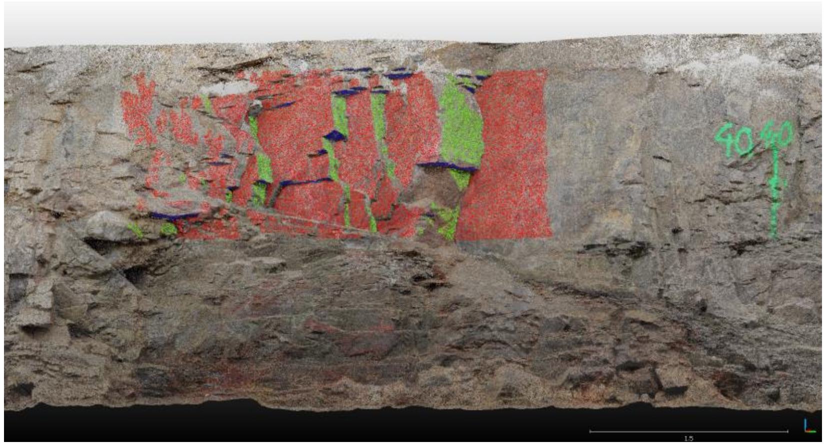


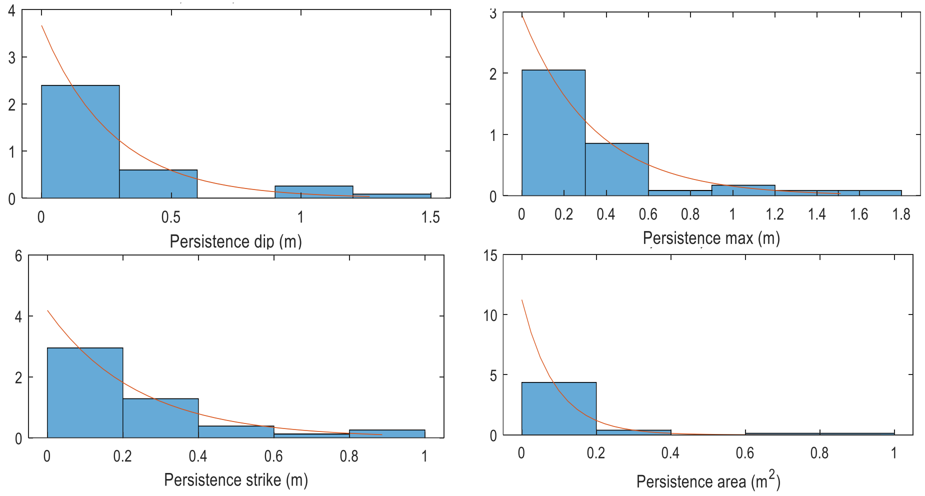




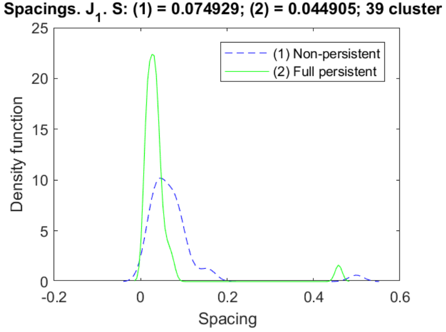
Spacing and persistence analysed in DSE

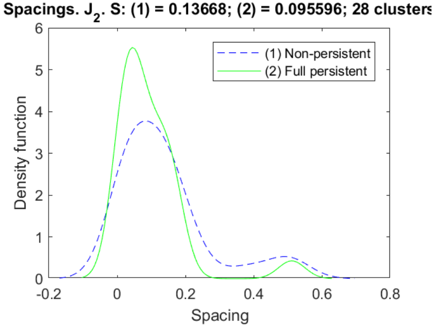
Fracture persistence

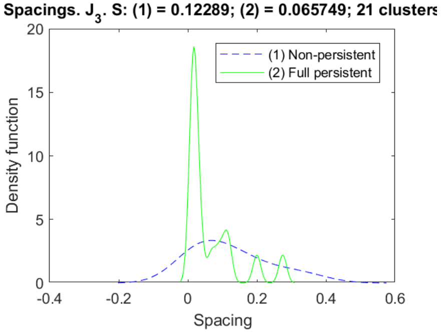




Fracture spacing







Very low persistence

Close spacing

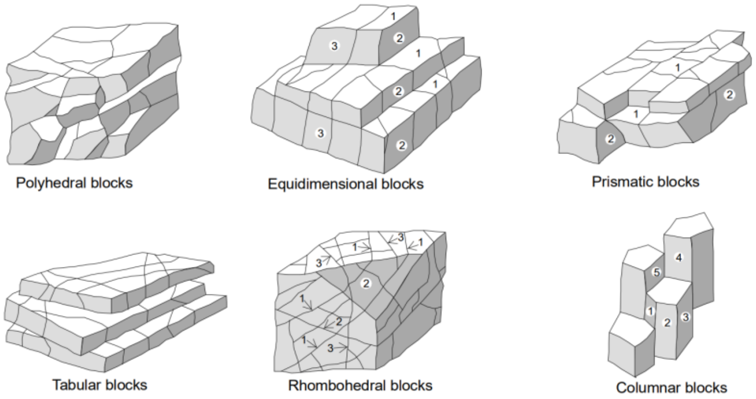
Block area and block volume

persistent fractures

$$A_0 = \frac{s_1 \cdot s_2}{\sin(\gamma_{12})}$$

s_1, s_2, s_3 are joint spacing for each joint set
γ_{12}, γ_{13}, γ_{23} are the angle between the joint sets

$$V_0 = \frac{s_1 \cdot s_2 \cdot s_3}{\sin(\gamma_{12}) \cdot \sin(\gamma_{13}) \cdot \sin(\gamma_{23})}$$



non-persistent fractures

$$A_b = \frac{s_1 \cdot s_2}{\sin(\gamma_{12}) \cdot \sqrt{p_1 \cdot p_2}}$$

p_1, p_2, and p_3 are persistence factors in the range between 0 and 1 => ratio between the accumulated fracture trace length in a sampling plane to the total characteristic length of the rock mass under consideration

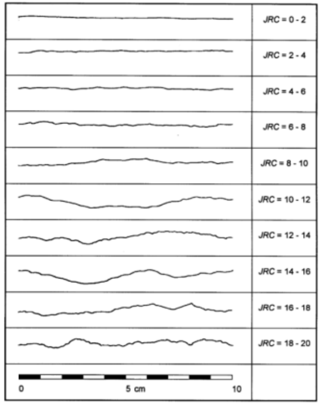
$$V_b = \frac{s_1 \cdot s_2 \cdot s_3}{\sin(\gamma_{12}) \cdot \sin(\gamma_{13}) \cdot \sin(\gamma_{23}) \cdot \sqrt[3]{p_1 \cdot p_2 \cdot p_3}}$$

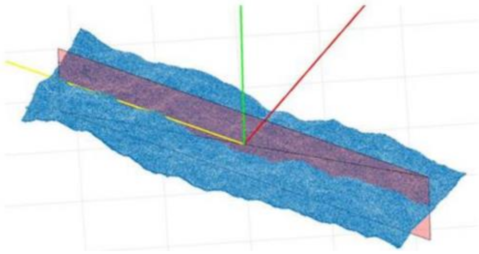
Palmstrøm, A. Characterizing rock masses by the RMi for use in practical rock engineering. *Tunn. Undergr. Space Technol.* **1996**, *11*, 175–188.

Kim, B.H.; Cai, M.; Kaiser, P.K.; Yang, H.S. Estimation of Block Sizes for Rock Masses with Non-persistent Joint. *Rock Mech. Rock Eng.* **2007**, *40*, 169–192.

Roughness

- 2D roughness profile in the shearing direction
  - Normalization of the sectioning plane
  - RMS - root mean square of the profile local slopes with intervals between measured data points





Sirkiä et al. 2016

$$JRC = 32.2 + 32.47\log(Z_2)$$

$$Z_2 = \sqrt{\frac{\sum_i^{N-1}(z_i - z_{i+1})^2}{(N-1)ds^2}}$$

where:

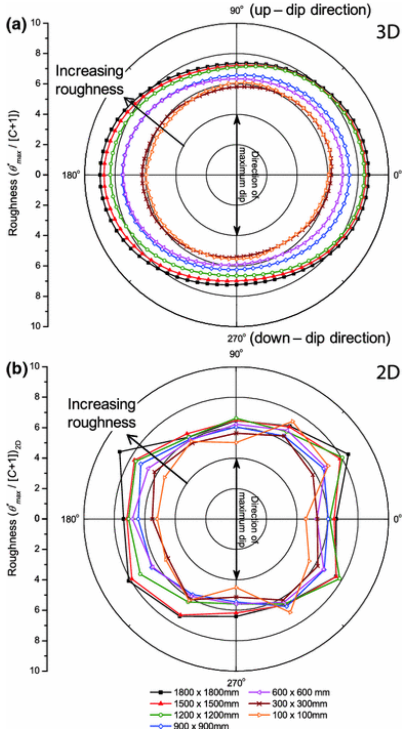
Z_2 stands for the RMS,

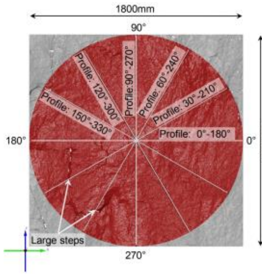
z is the height of the profile above reference line,

N the quantity of measures and

ds the distance between measures.

- Directional roughness



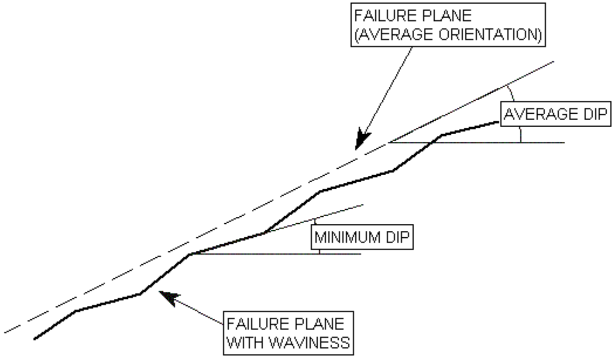


Tatone and Grasselli, 2013

Aalto-yliopisto
Aalto-universitetet
Aalto University

Waviness

Rocslope's definition:
Waviness Angle = [average dip] – [minimum dip] of joint plane



https://www.rocscience.com/help/rocslope/documentation/joints/joint-properties/waviness-angle

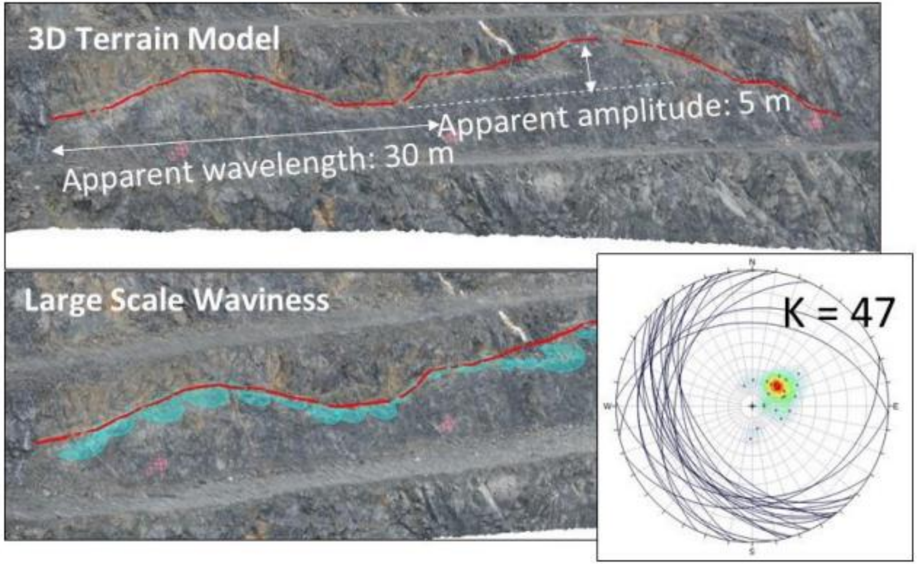
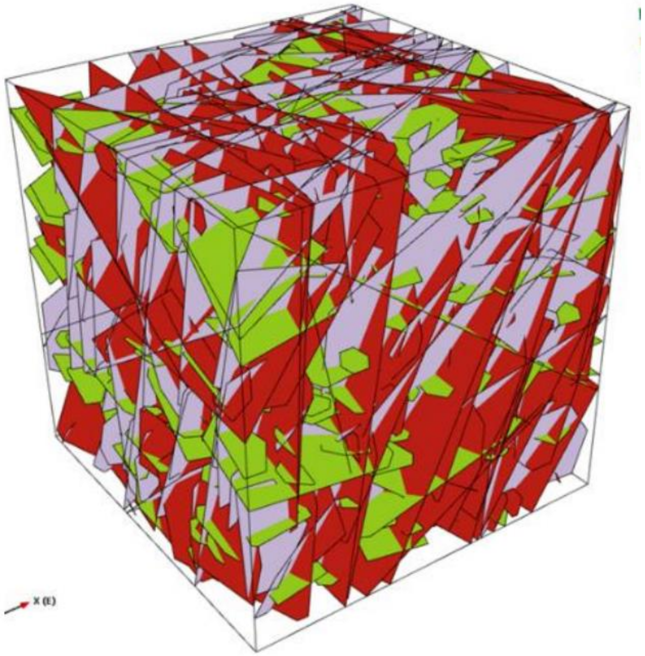


Figure 7 Waviness of a very high persistence, undulating discontinuity

Tuckey et al. 2016. Discontinuity survey and brittle fracture characterisation in open pit slopes using photogrammetry, APSSIM 2016

Discrete Fracture Network DFN model

- fractures in the rock mass are spatially variable
- their geometric, mechanical and hydraulic parameters being more accurately described by statistical distributions
- provide a more robust, probabilistic approach to capture the degree of fracturing in a rock mass



Rogers et al. 2017. Integrating photogrammetry and discrete fracture network modelling for improved conditional simulation of underground wedge stability

Unified system of fracture intensity measures

P_{ij} system

i – dimension of sample

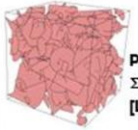
j – dimension of measurement

Table 2 The P_{ij} system of fracture intensity (after Dershowitz & Herda 1992)

		Dimension of measurement				
		0	1	2	3	
Dimension of sample	1D	P_{10} (m^{-1}) No of fractures per unit length of borehole	P_{11} Length of fractures per unit length			Linear measured (BHs, scanline)
	2D	P_{20} No of fractures per unit area	P_{21} (m^{-1}) Length of fractures per unit area	P_{22} Area of fractures per area		Areal measures (maps, drift walls, bench faces, etc.)
	3D	P_{30} No of fractures per unit volume		P_{32} (m^{-1}) Area of fractures per unit volume	P_{33} Volume of fractures per unit volume	Volumetric measures
Term		Density		Intensity	Porosity	

P10= Σ count/length $[L^{-1}]$

P21= Σ length/Area $[L^{-1}]$



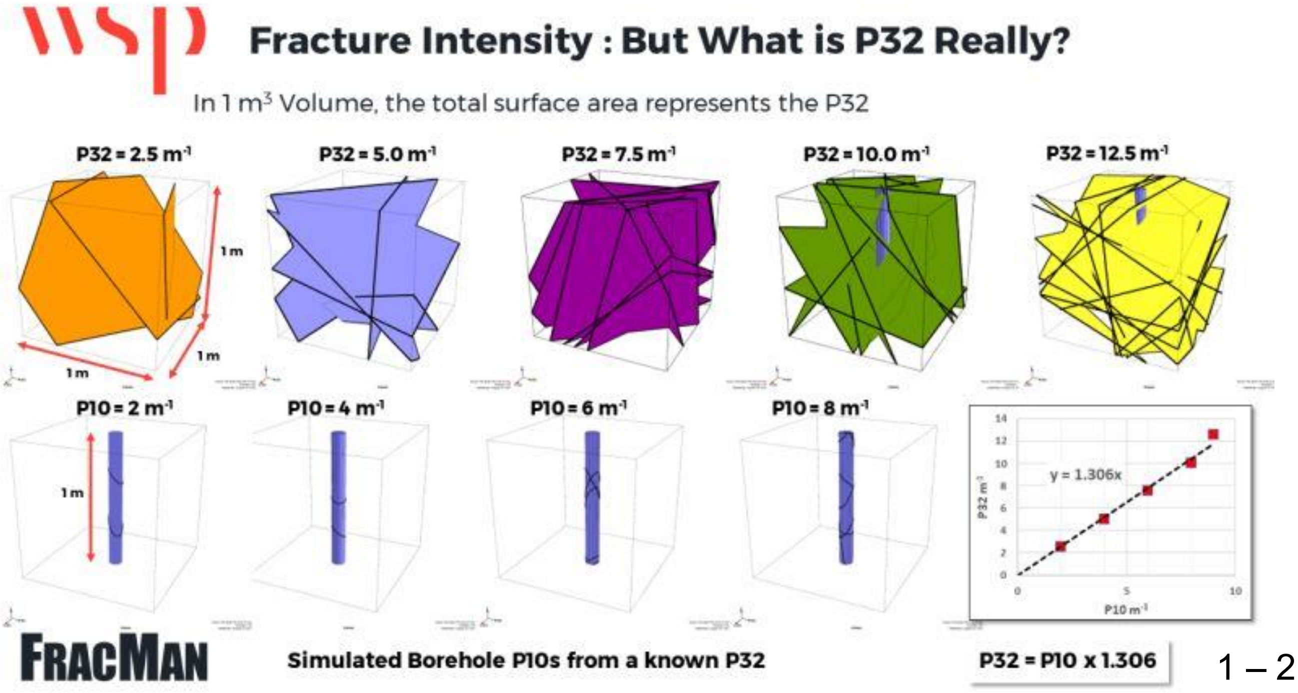
P32= Σ Area/Volume $[L^{-1}]$

Preferred for DFN but needs to be calculated from 1D and 2D data

Rogers et al. 2017

Fracture intensity P_{32}

$$\frac{\text{fracture area}}{\text{unit volume}}$$



1 – 2.5

Rogers, 2023

Discrete Fracture Network DFN model

Table 1 Primary and secondary parameters for defining a DFN model (after Rogers & Booth 2014)

	Fracture parameter	Typically sources of data
Primary	Orientation distribution	Orientated core logging, borehole image logs and mapping
	Fracture size distribution	Mapping, ideally at multiple scales
	Fracture intensity distribution	Orientated core logging, borehole image logs and mapping
	Spatial variation of fracture intensity	Analysis of borehole or mapping data
Secondary	Termination percentage	Mapping
	Aperture distribution	Logging, mapping and hydraulic testing
	Fracture shear properties	Logging, mapping and shear testing
	Fracture stiffness properties	Shear testing but most usually literature
	Fracture transmissivity distribution	Packer testing
	Storativity distribution	Packer testing, well testing

Rogers et al. 2017

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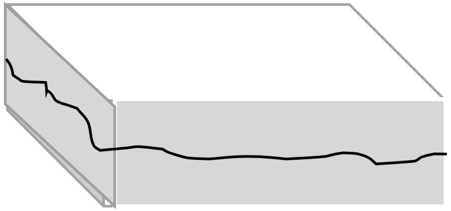
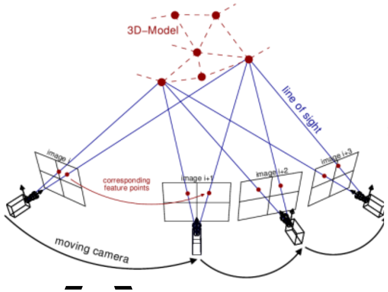
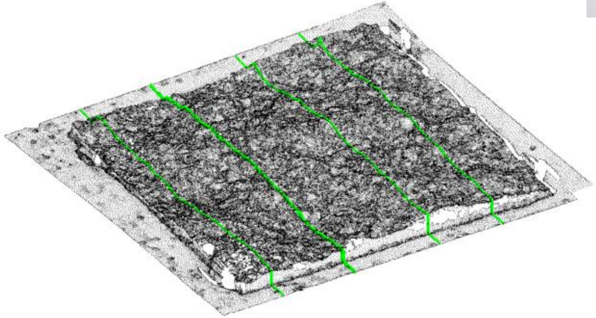
Laboratory fracture measurements

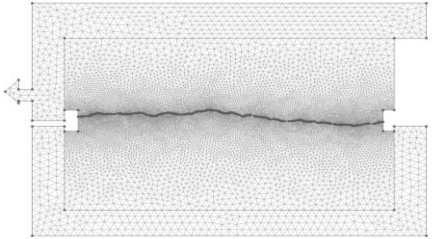
Rock joint scanning, replicating and testing

2014	• How to replicate fractures to facilitate testing under various loading conditions and scales?
2015/ 2016	• How to optimize the method of replicating fractures to better capture the critical structures?
2017/ 2018	• How closely can we analyse mechanical behaviour of rock joints using the parameters measured with photogrammetry ?

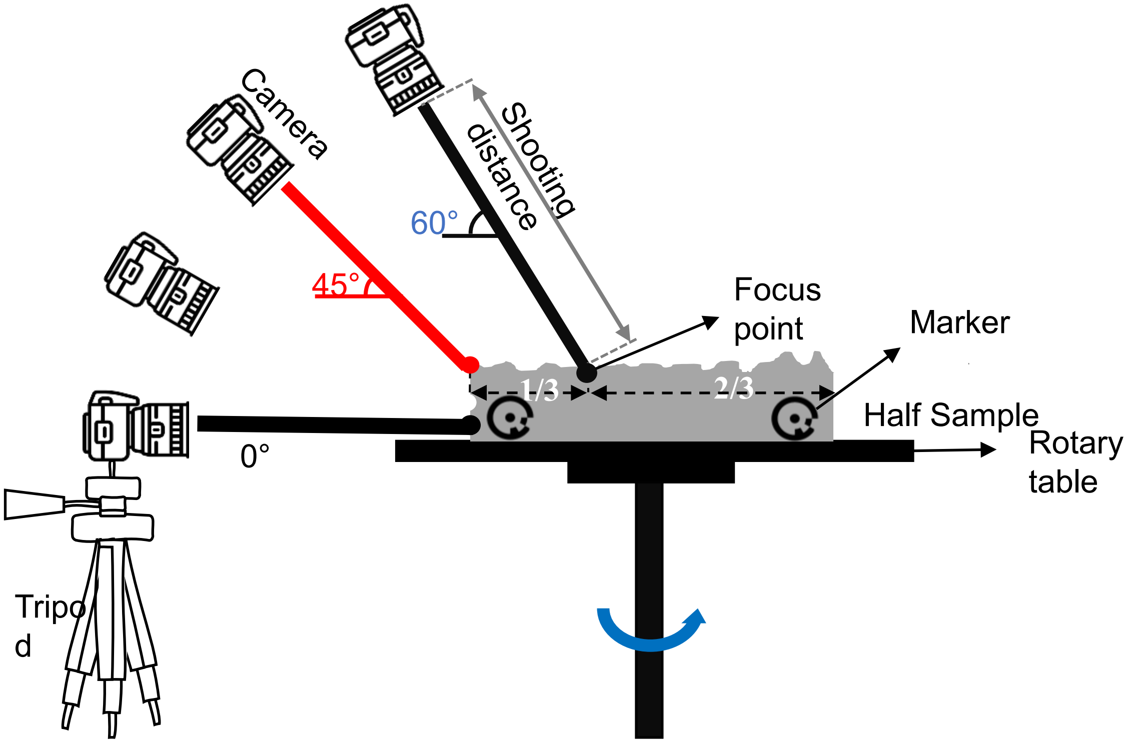




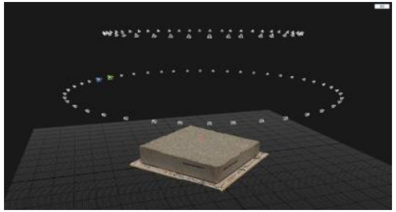


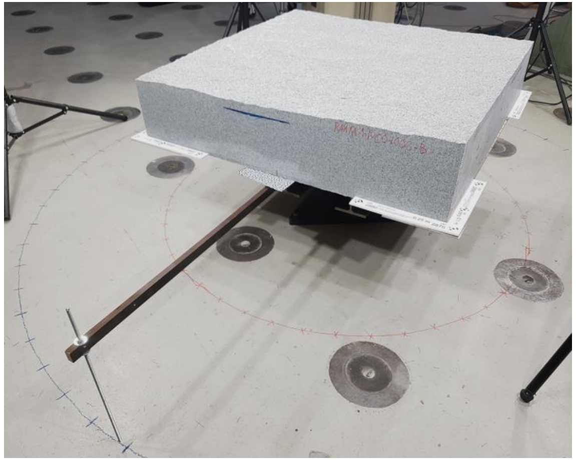


New optimal shooting angles and focus points



Reliable digitization method – stationary camera and revolving table



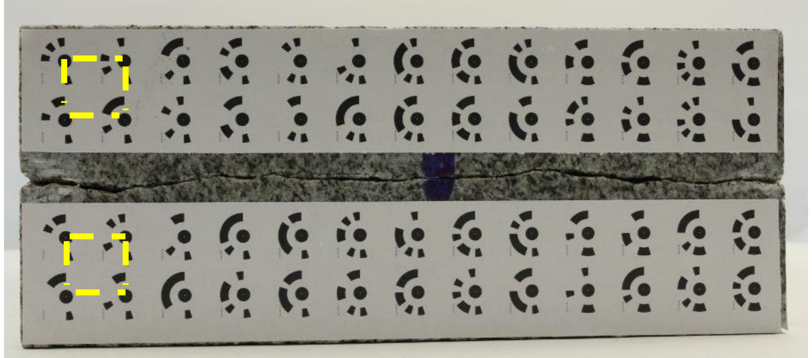


Slide credit: Masoud Torkan

Use many predetermined distances for scaling

Cut these markers

Known distances between markers- 0.0292 m
shooting angle: 0º



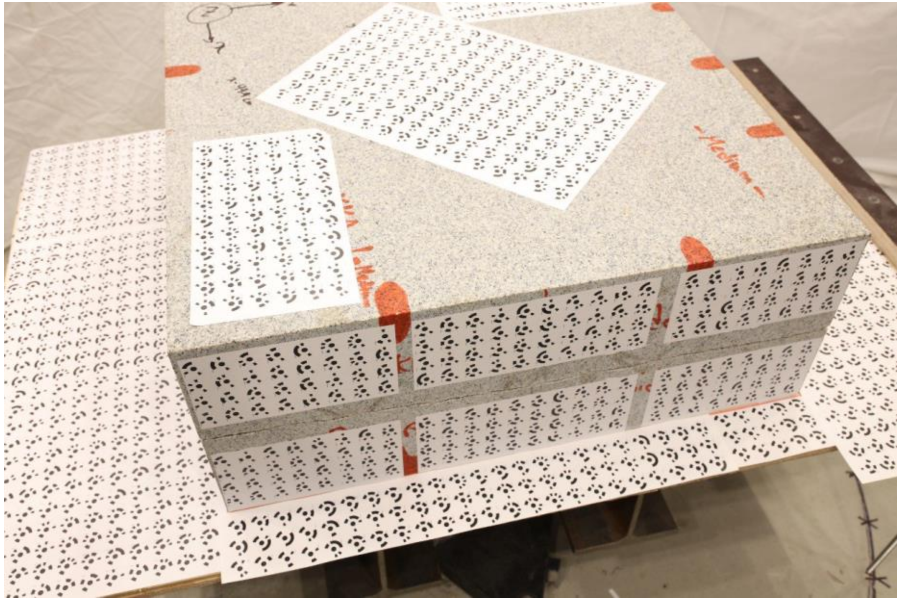
shooting angle: 0º
Known distances between markers- 0.01795 m

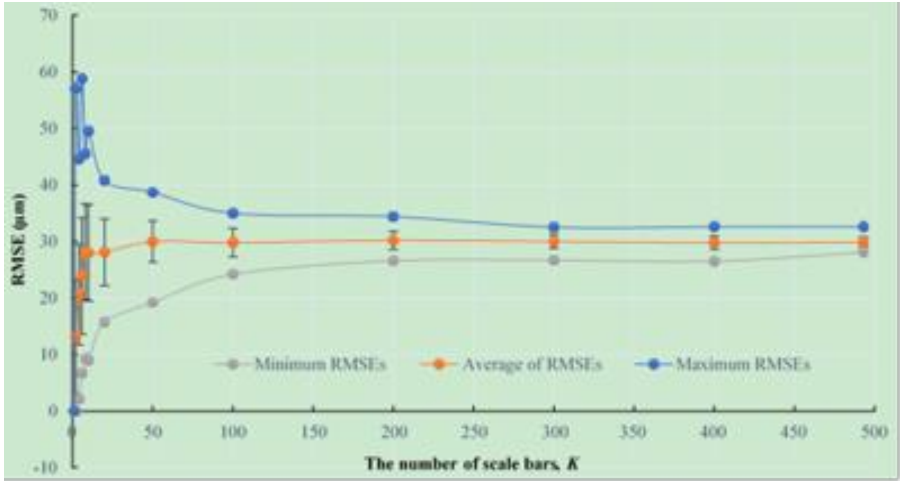
shooting angle: 30º

Accuracy (RMSE):20 micrometers

Slide credit: Masoud Torkan

Example of markers for 0.5 m x 0.5 m slab pair



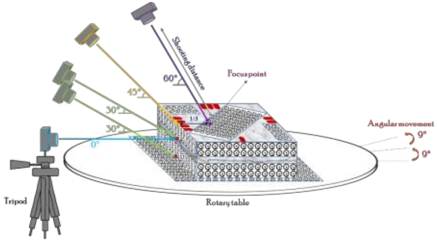


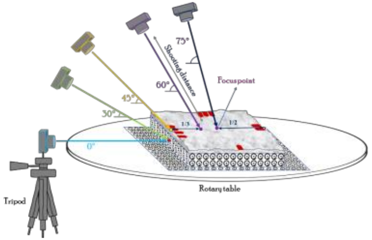
shooting angle: 30º
Known distances between markers- 0.01795 m

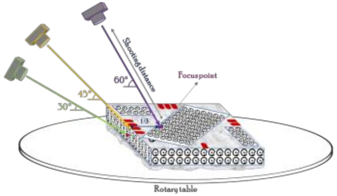
Accuracy (RMSE):23 micrometers

Slide credit: Masoud Torkan

Photographing sequence





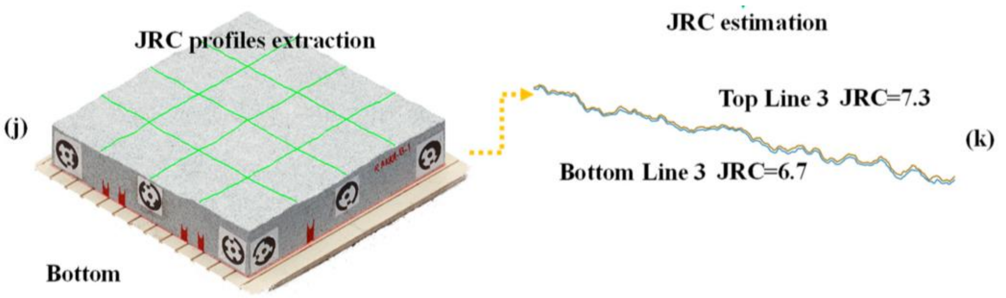


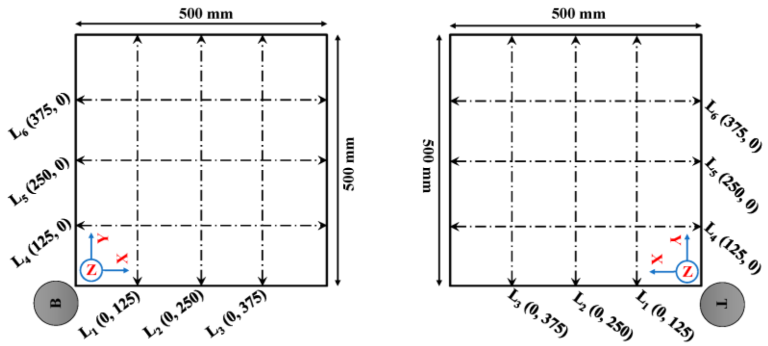
Photogrammetry to measure precise joint geometry

Real sample

Digital Twin (3D model)

Roughness measurements





In this study, the root mean square (RMS) of local slope of the profile (Z_2) (Equation (1)) was used to calculate the JRC [9].

$$Z_2 = \left[\frac{1}{N(P)^2}\sum_{i=1}^{N}(z_{i+1}-z_i)^2\right]^{\frac{1}{2}}, \tag{1}$$

where N signifies the number of intervals along each section, P is the point interval, and z_i is the height of the asperities corresponding to the height local point. Varying uniform point interval with 0.25, 0.5, and 1 mm was used based on Equations (2)–(4) proposed by Yu and Vayssade [10]:

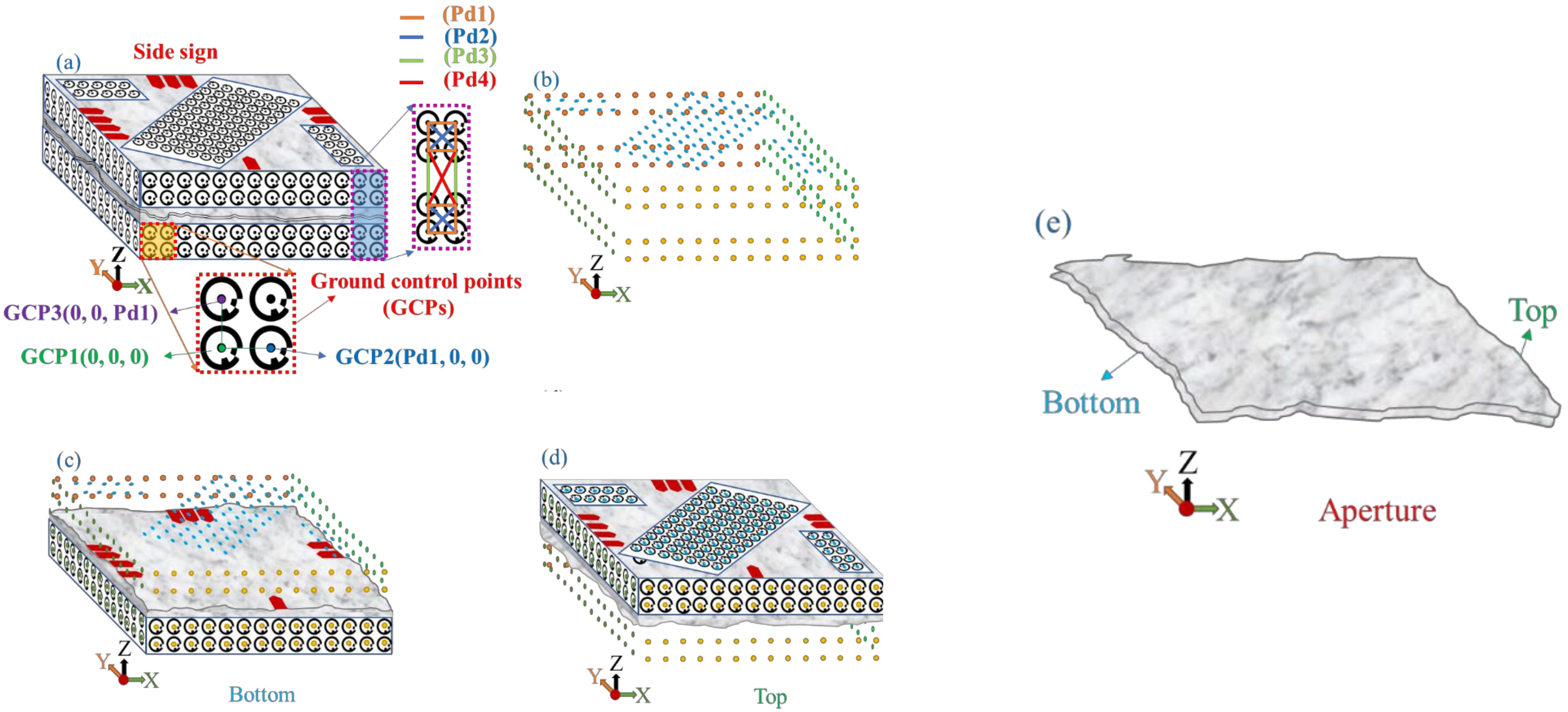
$$\text{JRC} = 60.32(Z_2) - 4.51 \text{ (Point interval: 0.25 mm)}, \tag{2}$$

$$\text{JRC} = 61.79(Z_2) - 3.47 \text{ (Point interval: 0.5 mm)}, \tag{3}$$

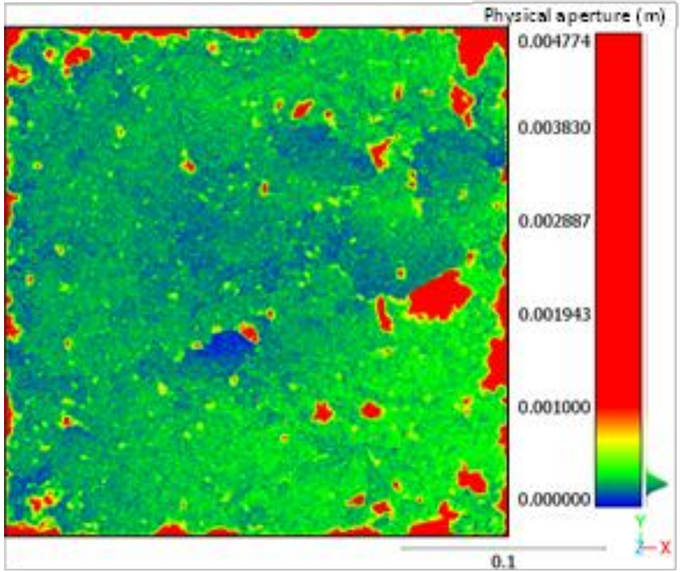
$$\text{JRC} = 64.22(Z_2) - 2.31 \text{ (Point interval: 1.0 mm)}. \tag{4}$$

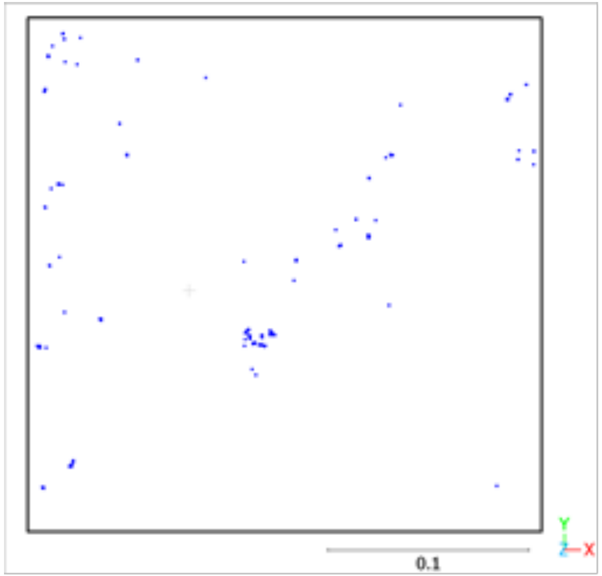
Torkan et al. 2022

Aperture measurements



Physical aperture measured along Z-direction





Numerical fluid flow prediction

- **Model Setup**

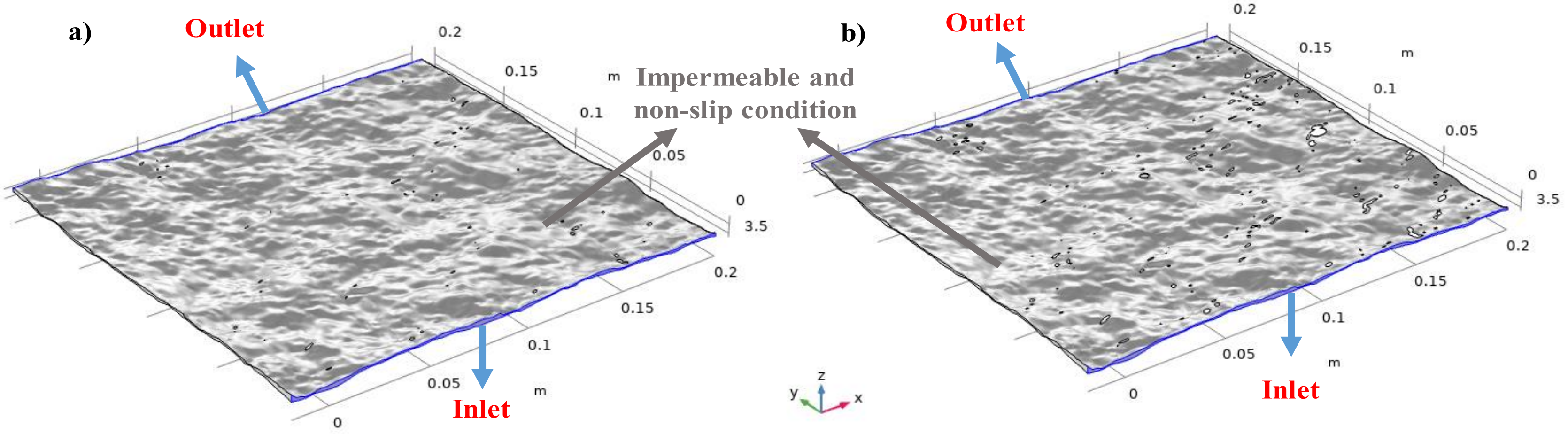


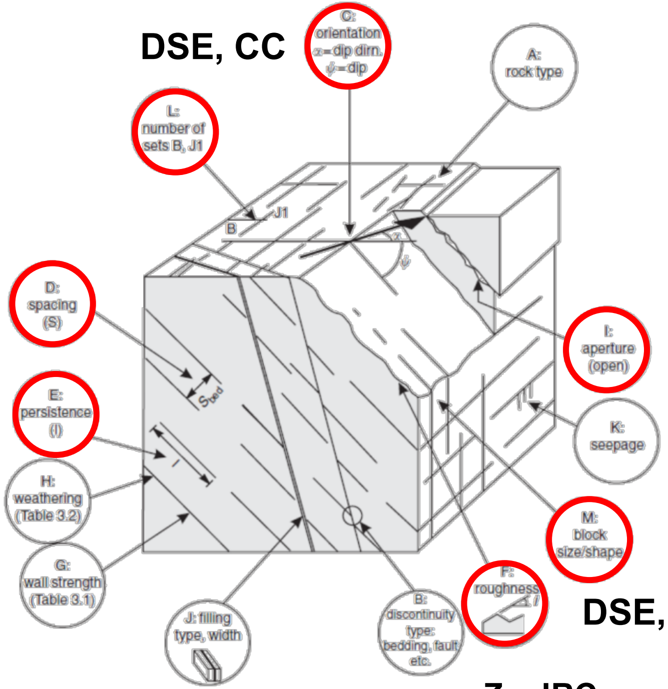
Figure 9. Boundary conditions for flow simulation for the fracture without normal stress (a) and the fracture under 0.5 MPa normal stress (b).

Remote rock mass characterization

- Control the accuracy of reconstructed 3D model
- Use appropriate study scale, for example:
    - split the studied area into structural domains if needed
    - define a mapping window
- Sample the mapped data to provide statistically relevant results
- Be aware of directional biases

DSE, CC

DSE



DSE, CC

Z_2, JRC, directional roughness