



OPERE GEOTECNICHE E MATERIALI GEOSINTETICI NEL CONTRASTO ALL'EROSIONE COSTIERA, FLUVIALE E DI VERSANTE

Il rilievo geomeccanico: introduzione sui metodi e sui parametri utili all'analisi della fratturazione degli ammassi rocciosi e analisi cinematica di stabilità di versanti in roccia

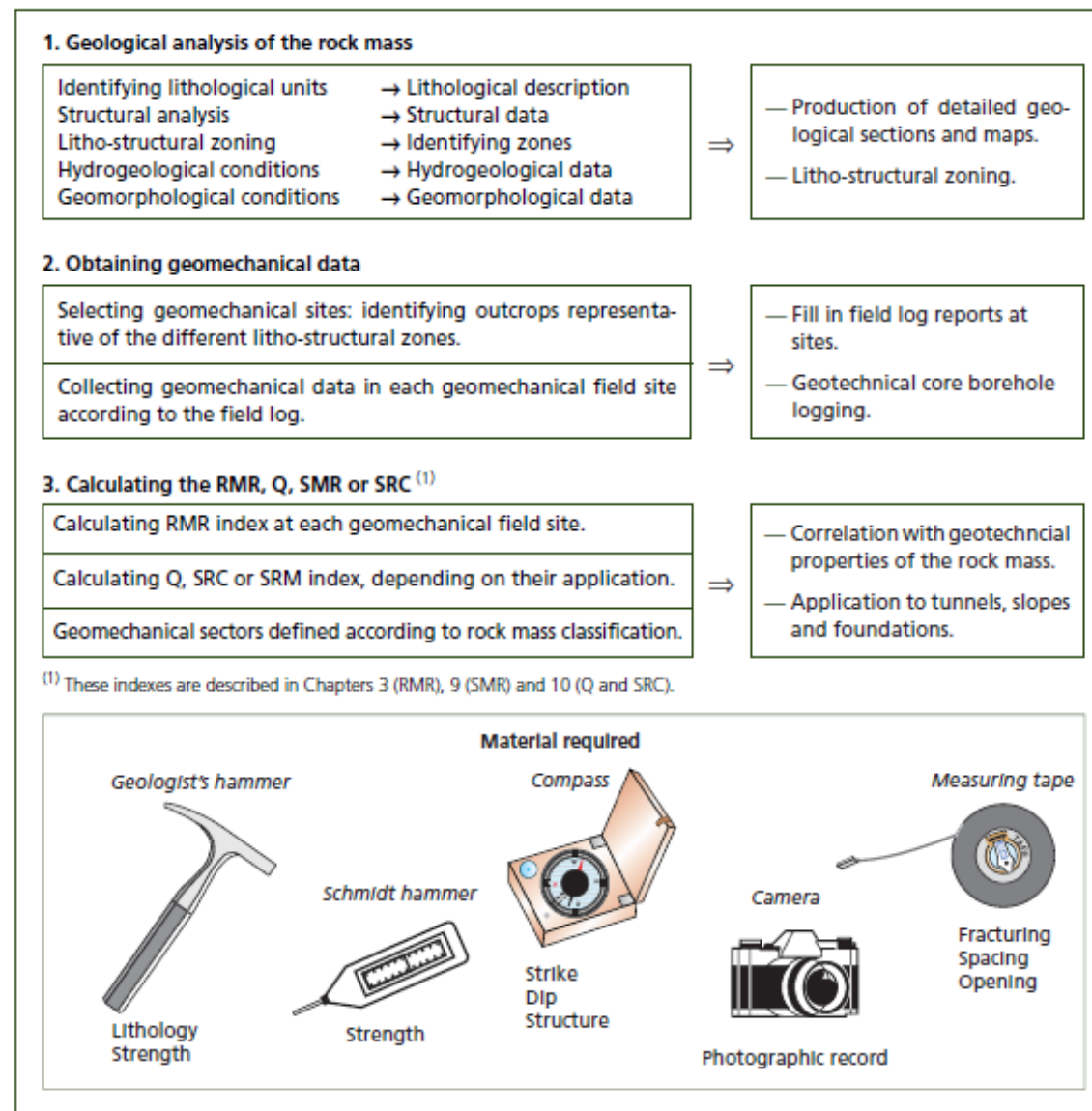
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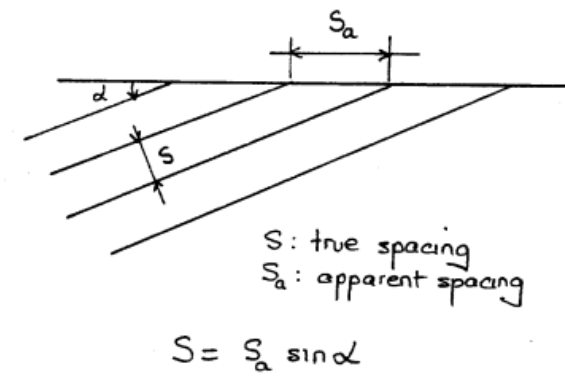
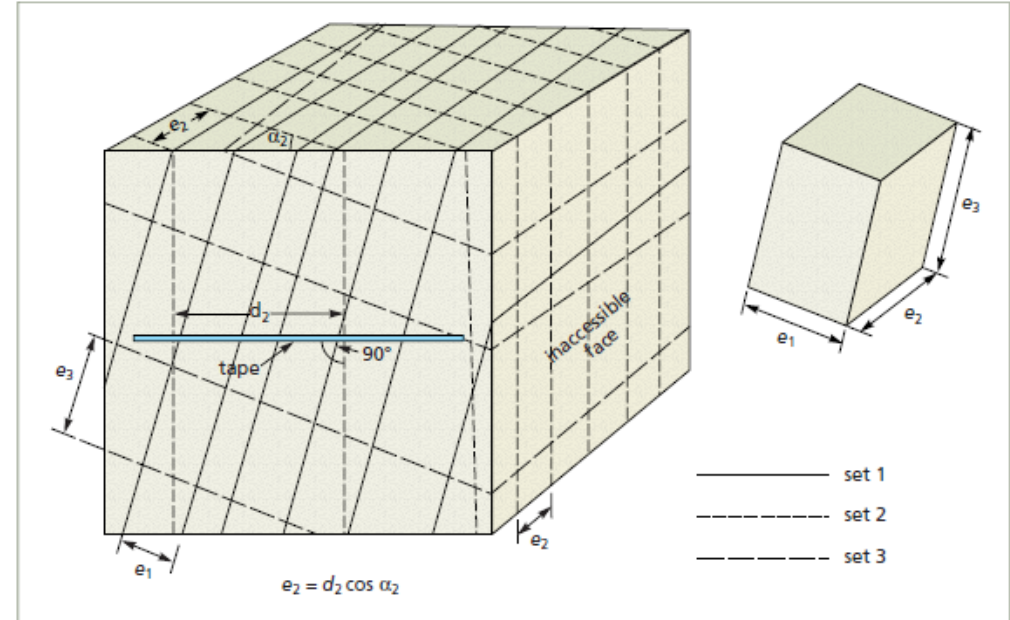
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L'analisi geomeccanica di terreno

- Strumento essenziale **proprio del geologo** utile per fornire un quadro preciso riguardo lo stato di fratturazione e resistenza dell'ammasso roccioso e calcolo dei parametri utili alla progettazione ingegneristica



Il metodo scanline 1D (geomeccanico convenzionale)



Correzione di Terzaghi

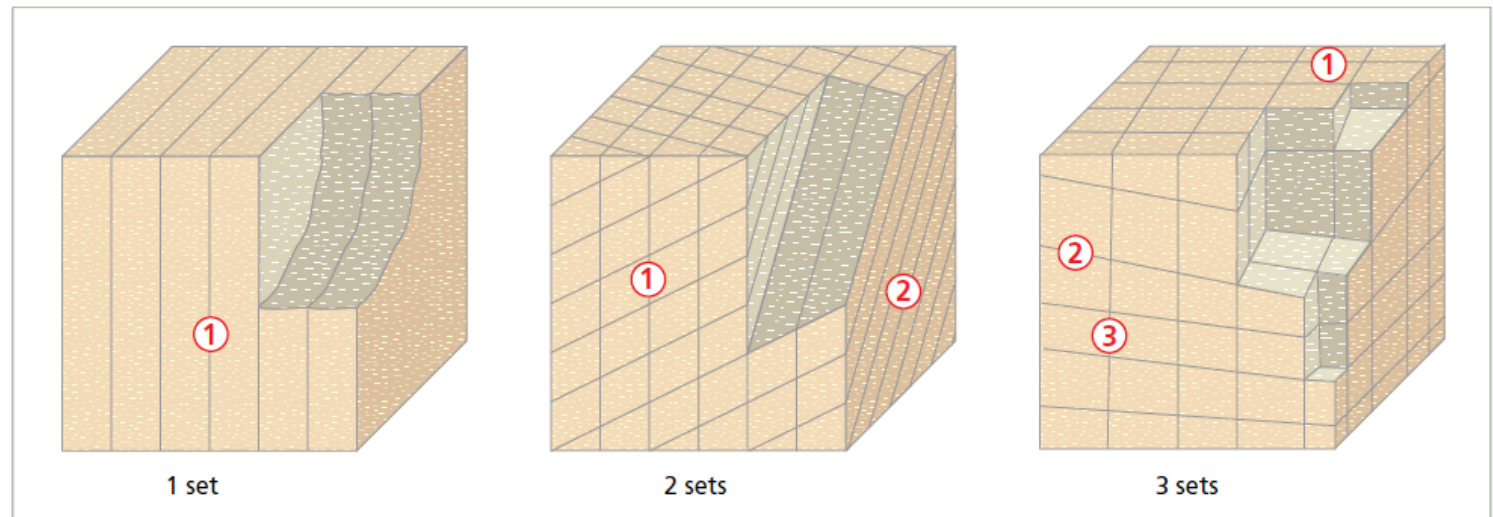
Numero ed orientazione delle superfici di discontinuità

Table 6.10 CLASSIFICATION OF ROCK MASSES BY THE NUMBER OF SETS OF DISCONTINUITIES

Type of rock mass	Number of sets
I	Massive, occasional random joints
II	One joint set
III	One joint set plus random
IV	Two joint sets
V	Two joint sets plus random
VI	Three joint sets
VII	Three joint sets plus random
VIII	Four or more joint sets
IX	Crushed rock, earth-like

(ISRM, 1981).

Diagrammi a blocchi



Dimensione del blocco

Può essere spiegato da due parametri:

- l'indice di dimensione dei blocchi ***lb***, che rappresenta le dimensioni medie dei blocchi che caratterizzano l'affioramento. Ad esempio, per una roccia sedimentaria con la stratificazione e due set di discontinuità perpendicolari tra loro, l'indice ***lb*** sarebbe definito come:

$$lb = (e1 + e2 + e3) / 3$$

dove *e1*, *e2* ed *e3* sono i valori medi della spaziatura nei tre gruppi di discontinuità.

Il ruolo della dimensione dei blocchi è decisivo in quanto condiziona il comportamento dell'ammasso roccioso e le sue proprietà di resistenza e deformazione.

Dimensione del blocco

- il parametro **J_v** (conteggio volumetrico dei giunti): il numero totale di discontinuità che intercettano un volume unitario (m^3) di massa rocciosa. Poiché l'osservazione tridimensionale di un affioramento è difficile, il valore di J_v viene solitamente determinato per ogni set contando le discontinuità che intercettano una certa lunghezza e misurando perpendicolarmente allo strike di ogni insieme (o, se ciò non è possibile, correggendo la misura dello strike apparente). Ad esempio, per un ammasso roccioso con tre serie di discontinuità (J_1 , J_2 e J_3):

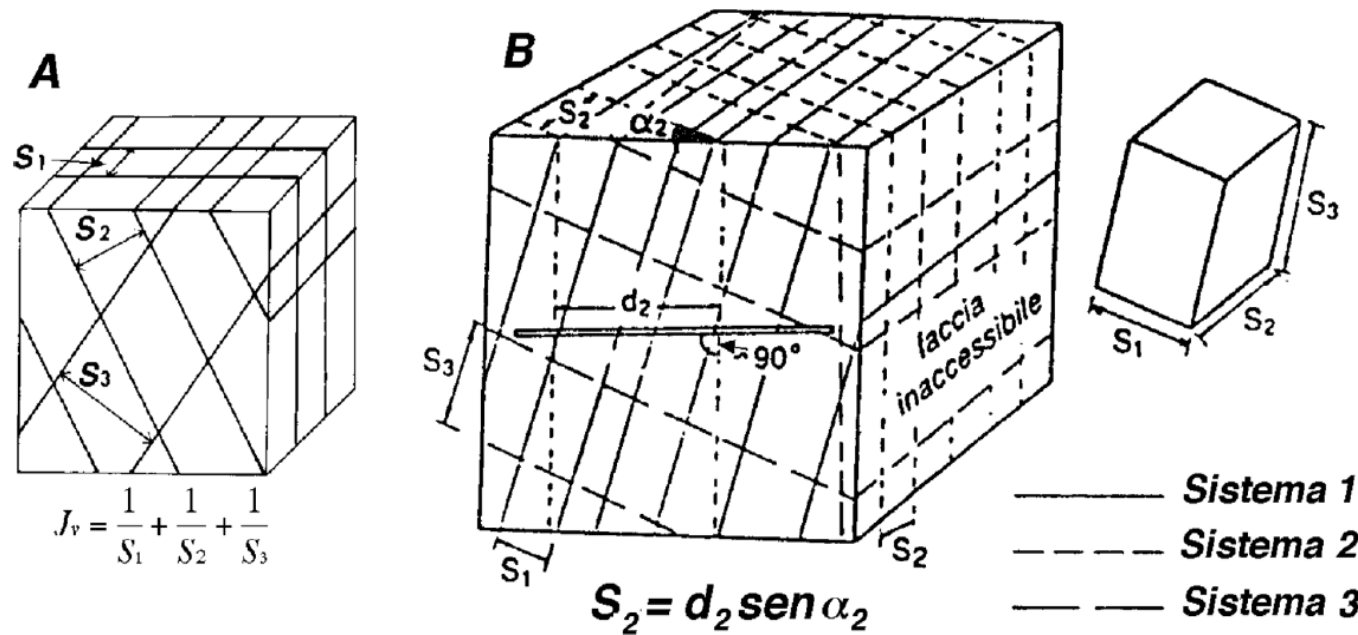
$$J_v = (n^{\circ} J_1/L_1) + (n^{\circ} J_2/L_2) + (n^{\circ} J_3/L_3)$$

Table 6.11 DESCRIPTION OF BLOCK SIZE BASED ON NUMBER OF DISCONTINUITIES

Description	J_v (joints/ m^3)
Very large blocks	<1.0
Large blocks	1–3
Medium-sized blocks	3–10
Small blocks	10–30
Very small blocks	>30

(ISRM, 1981).

Il J_v come stima del grado di fratturazione



Classification of the J_v is as follows:

	DEGREE OF JOINTING					
	very low	low	moderate	high	very high	crushed
$J_v =$	< 1	1 - 3	3 - 10	10 - 30	30 - 60	> 60

Palmstrom (2001)

Classificazioni basate su dimensione del blocco e forma

Table 6.12 CLASSIFICATION OF ROCK MASSES BASED ON BLOCK SIZE AND SHAPE

Class	Type	Description
I	Massive	Few joints or very wide spacing
II	Blocky	Blocks approximately equidimensional
III	Tabular	Blocks with one dimension considerably smaller than the other two
IV	Columnar	Blocks with one dimension considerably larger than the other two
V	Irregular	Wide variation of block shape and size
VI	Crushed	Heavily jointed rock mass

(ISRM, 1981).

Table 6.13 ROCK BLOCK DIMENSIONS AND DESCRIPTION

First term	Maximum dimension
Very large	>2.0 m
Large	0.6–2 m
Medium	0.2–0.6 m
Small	60–200 mm
Very small	<60 mm
Second term	Shape of block
Blocky or cubic	Equi-dimensional
Tabular	Thickness much less than length or width
Columnar	Height much greater than cross section

(BSI, 2003).

Sistemi di classificazione degli ammassi rocciosi

Rock Quality Designation, RQD (Deere & Miller, 1966)

Rock Mass Rating, RMR (Bieniawski, 1989)

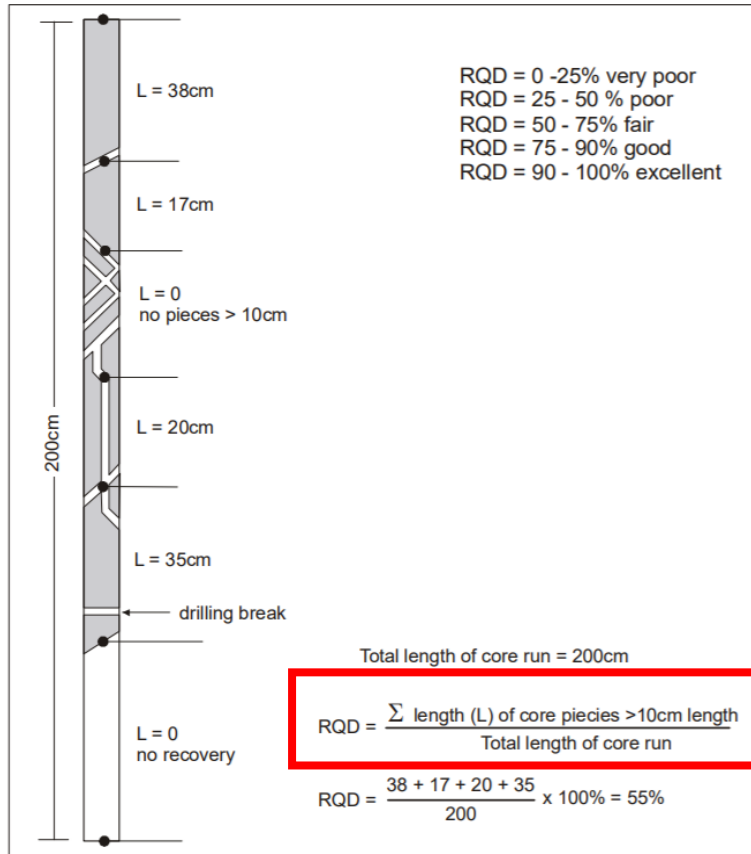
Tunnelling quality system, Q-system (Barton, 2002)

Geological Strength Index, GSI (Hoek et al., 1992)

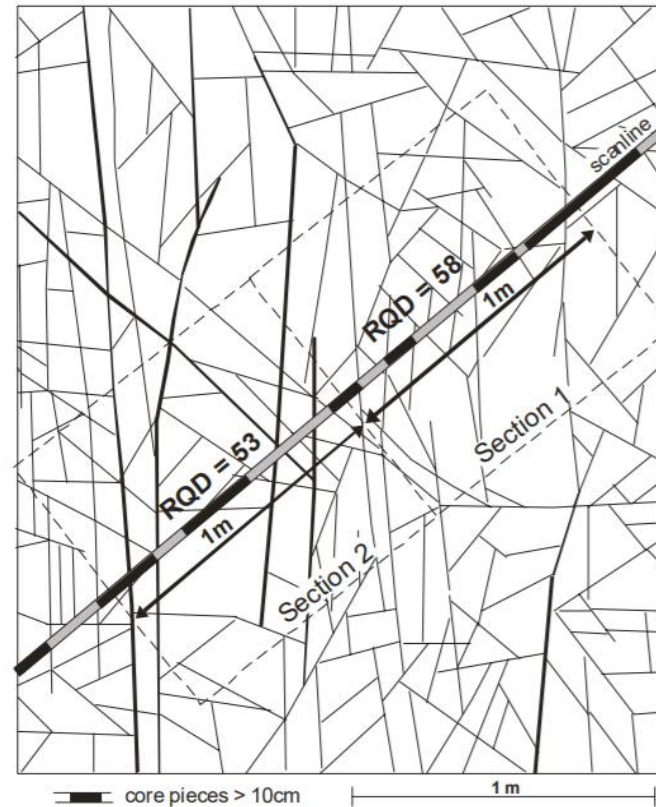
The Rock Quality Designation, RQD

$$RQD = 115 - 3.3 J_v$$

(RQD = 0 for $J_v > 35$, and RQD = 100 for $J_v < 4.5$)



(slightly modified after Deere, 1989).



Parte integrante del RMR e Q-system. In condizioni di ammasso roccioso debole, il valore di RQD viene assunto pari a zero

→ Svantaggio: questa condizione porta a stimare un valore inappropriato del sistema RMR e Q-system per la classificazione dell'ammasso roccioso.

Table 3.11 ROCK MASS CLASSIFICATION BY RQD	
RQD %	Quality
<25	Very poor
25-50	Poor
50-75	Fair
75-90	Good
90-100	Excellent

Rock Mass Rating (RMR)

Sviluppato da Bieniawski nel 1973 e aggiornato nel 1979 e nel 1989, è un sistema di classificazione dell'ammasso roccioso che mette in relazione gli indici di qualità con i parametri geotecnici dell'ammasso roccioso e con i parametri di scavo e sostegno nelle gallerie.

Resistenza a compressione uniassiale

RQD

Spaziatura delle discontinuità

Condizioni delle discontinuità

Circolazione idrica sotterranea

Correzione per l'orientazione delle discontinuità

Il valore RMR si calcola sommando i punteggi assegnati ai vari parametri

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

PARAMETER		Range of values // ratings							
1	Strength of intact rock material	Point-load strength index	> 10 MPa	4 - 10 MPa	2 - 4 MPa	1 - 2 MPa	For this low range uniaxial compr. strength is preferred		
		Uniaxial compressive strength	> 250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa	1 - 5 MPa	< 1 MPa
	RATING		15	12	7	4	2	1	0
2	Drill core quality RQD		90 - 100%	75 - 90%	50 - 75%	25 - 50%	< 25%		
	RATING		20	17	13	8	5		
3	Spacing of discontinuities		> 2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm		
	RATING		20	15	10	8	5		
4	Condition of discontinuities	Length, persistence	< 1 m	1 - 3 m	3 - 10 m	10 - 20 m	> 20 m		
		Rating	6	4	2	1	0		
		Separation	none	< 0.1 mm	0.1 - 1 mm	1 - 5 mm	> 5 mm		
		Rating	6	5	4	1	0		
		Roughness	very rough	rough	slightly rough	smooth	slickensided		
		Rating	6	5	3	1	0		
5	Ground water	Inflow per 10 m tunnel length	none	< 10 litres/min	10 - 25 litres/min	25 - 125 litres/min	> 125 litres /min		
		p_w / σ_1	0	0 - 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5		
		General conditions	completely dry	damp	wet	dripping	flowing		
	RATING		15	10	7	4	0		

p_w = joint water pressure; σ_1 = major principal stress

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS

	Very favourable	Favourable	Fair	Unfavourable	Very unfavourable
RATINGS					
Tunnels	0	-2	-5	-10	-12
Foundations	0	-2	-7	-15	-25
Slopes	0	-5	-25	-50	-60

C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 - 81	80 - 61	60 - 41	40 - 21	< 20
Class No.	I	II	III	IV	V
Description	VERY GOOD	GOOD	FAIR	POOR	VERY POOR

D. MEANING OF ROCK MASS CLASSES

Class No.	I	II	III	IV	V
Average stand-up time	10 years for 15 m span	6 months for 8 m span	1 week for 5 m span	10 hours for 2.5 m span	30 minutes for 1 m span
Cohesion of the rock mass	> 400 kPa	300 - 400 kPa	200 - 300 kPa	100 - 200 kPa	< 100 kPa
Friction angle of the rock mass	< 45°	35 - 45°	25 - 35°	15 - 25°	< 15°

Qualità dell'ammasso roccioso da RMR

Table 3.27 ROCK MASS QUALITY ACCORDING TO THE RMR INDEX

Class	Quality	RMR rating	Cohesion (MPa)	Friction angle
I	Very good	100–81	>0.4	>45°
II	Good	80–61	0.3–0.4	35°–45°
III	Fair	60–41	0.2–0.3	25°–35°
IV	Poor	40–21	0.1–0.2	15°–25°
V	Very poor	<20	<0.1	<15°


Table 10.7 GUIDELINES FOR EXCAVATION AND SUPPORT OF 10 M SPAN ROCK TUNNELS IN ACCORDANCE WITH THE RMR SYSTEM

Rock mass class	Excavation	Rock bolts (20 mm diameter, fully grouted)	Shotcrete	Steel sets
I Very good rock RMR: 81–100	Full face, 3 m advance.	Generally, no support required except spot bolting.	–	–
II Good rock RMR: 61–80	Full face, 1–1.5 m advance. Complete support 20 m from face.	Locally, bolts in crown 3 m long, spaced 2.5 m with occasional wire mesh.	50 mm in crown where required.	None.
III Fair rock RMR: 41–60	Top heading and bench, 1.5–3 m advance in top heading. Commence support after each blast. Complete support 10 m from face.	Systematic bolts 4 m long, spaced 1.5–2 m in crown and walls with wire mesh in crown.	50–100 mm in crown and 30 mm in sides.	None.
IV Poor rock RMR: 21–40	Top heading and bench, 1.0–1.5 m advance in top heading. Install support concurrently with excavation, 10 m from face.	Systematic bolts 4–5 m long, spaced 1–1.5 m in crown and walls with wire mesh.	100–150 mm in crown and 100 mm in sides.	Light to medium ribs spaced 1.5 m where required.
V Very poor rock RMR: ≤20	Multiple drifts 0.5–1.5 m advance in top heading. Install support concurrently with excavation. Shotcrete as soon as possible after blasting.	Systematic bolts 5–6 m long, spaced 1–1.5 m in crown and walls with wire mesh. Bolt invert.	150–200 mm in crown, 150 mm in sides, and 50 mm on face.	Medium to heavy ribs spaced 0.75 m with steel lagging and forepoling if required. Close invert.


Horseshoe-shaped tunnels, maximum width 10 m, maximum vertical stress 250 kp/cm².

(Bienawski, 1989).

Class I (RMR = 81-100) and Class II (RMR= 61-80) rock masses




Cretaceous dolomite. Very good quality. Two main sets of discontinuities.




Granite. Good quality. Several sets of weathered discontinuities.

Class III rock masses (RMR= 41-60)




Ordovician slate. Fair quality. High fracturing degree. Weathering degree: III.




Ordovician quartzite. Fair quality. High fracturing degree. Very hard intact rock.

Class IV (RMR= 21-40) and Class V (RMR ≤ 20) rock masses



Ordovician quartzite. Poor quality. Weathered and heavily jointed rock mass.



Palaeozoic slate. Very poor quality. Heavily jointed. Degree of weathering: V.

Q-system

Il Sistema Q è stato sviluppato da Barton, Lien e Lunde nel 1974 e si basa sullo studio di un gran numero di gallerie. Questo sistema di classificazione può essere utilizzato per stimare i parametri geomeccanici di un ammasso roccioso e per la progettazione preliminare del supporto di gallerie e cavità sotterranee. L'indice Q si basa su un calcolo numerico di sei parametri espressi come:

$$Q = \frac{RQD}{J_n} \cdot \frac{J_r}{J_a} \cdot \frac{J_w}{SRF}$$

Dimensione dei blocchi ←

Stato di stress →

Resistenza al taglio tra i blocchi ↓

dove:

- RQD è il Rock Quality Designation.
- J_n è il numero di joint set.
- J_r è un indice basato sulla rugosità.
- J_a è un indice basato sull'alterazione
- SRF è lo stress reduction factor

Q-system

$$Q = \frac{RQD}{J_n} \cdot \frac{J_r}{J_a} \cdot \frac{J_w}{SRF}$$

Table 10.3 VALUES OF CHARACTERISTIC PARAMETERS OF THE Q INDEX		
1. Rock Quality Designation		RQD (%)
A	Very poor	0–25
B	Poor	25–50
C	Fair	50–75
D	Good	75–90
E	Excellent	90–100
Notes: - Where RQD values are obtained of ≤ 10 (including 0), a nominal value of 10 is used to evaluate Q. - RQD intervals of 5, i.e. 100, 95, 90, etc. are sufficiently accurate.		
2. Joint set number		J_n
A	Massive, no or few joints	0.5–1
B	One joint set	2
C	One joint set plus random joints	3
D	Two joint sets	4
E	Two joint sets plus random joints	6
F	Three joint set	9
G	Three joint set plus random joints	12
H	Four or more joint sets, random, heavily jointed, "sugar-cube", etc.	15
J	Crushed rock, soil-like	20
Notes: - For tunnel intersections, use (3.0 x J _n) - For portals use (2.0 x J _n)		
3. Joint roughness number		J_r
a) Rock-wall contact. b) Rock-wall contact before 10 cm shear		
A	Discontinuous plane	4
B	Rough or irregular, undulating	3
C	Smooth, undulating	2
D	Slickensided, undulating	1.5
E	Rough or irregular, planar	1.5

Barton, 2000

Table 10.3 VALUES OF CHARACTERISTIC PARAMETERS OF THE Q INDEX (CONT.)			
F	Smooth, planar		1.0
G	Slickensided, planar		0.5
Note: - Descriptions refer to small-scale features and intermediate scale features, in that order.			
c) No rock-wall contact when sheared			
H	Zone containing clay minerals thick enough to prevent rock-wall contact		1.0
J	Sandy, gravelly or crushed zone thick enough to prevent rock-wall contact		1.0
Notes: - Add 1.0 if the mean spacing of the relevant joint set is greater than 3 m. - J _r = 0.5 can be used for planar, slickensided joints with lineations, provided the lineations are oriented for minimum strength. - J _r and J _a classification is applied to the joint set or discontinuity that is least favourable for stability both from the point of view of orientation and shear resistance, τ (where τ = σ _n tan (J _r /J _a)).			
4. Joint alteration number		φ_r	J_a
a) Rock-wall contact (no mineral fillings, only coatings)			
A	Tightly healed, hard, non-softening, impermeable filling, i.e. quartz or epidote.	–	0.75
B	Unaltered joint walls, surface staining only.	25–35°	1.0
C	Slightly altered joint walls. Non-softening mineral coatings, sandy particles, clay-free disintegrated rock, etc.	25–30°	2.0
D	Silty- or sandy- clay coatings, small clay fraction (non-softening)	20–25°	3.0
E	Softening or low friction clay mineral coatings, i.e. kaolinite or mica. Also chlorite, talc, gypsum, graphite, etc. and small quantities of swelling clays.	8–16°	4.0
b) Rock-wall contact before 10 cm shear (thin mineral fillings)			
F	Sandy particles, clay-free disintegrated rock, etc.	25–30°	4.0
G	Strongly over-consolidated non-softening clay mineral fillings (continuous, but <5 mm thickness)	16–24°	6.0
H	Medium or low over-consolidation, softening, clay mineral fillings (continuous, but <5 mm thickness)	12–16°	8.0
J	Swelling-clay fillings, i.e. montmorillonite (continuous, but <5 mm thickness). Value of J _a depends on percentage of swelling clay-size particles, and access to water, etc.	6–12°	8–12
c) No rock-wall contact when sheared (thick mineral fillings)			
K L M	Zones or bands of disintegrated or crushed rock and clay (see G, H and J for description of clay condition)	6–24°	6, 8 or 8–12
N	Zones or bands of silty -or sandy- clay, small clay fraction (non-softening)	–	5.0
O P R	Thick continuous zones or bands of clay (see G, H and J for description of clay condition).	6–24°	10, 13 or 13–20
5. Joint water reduction factor		Water pressure (kp/cm²)	J_w
A	Dry excavations or minor inflow, i.e. <5 l/min. locally.	<1	1.0
B	Medium inflow or pressure, occasional outwash of joint fillings.	1–2.5	0.66
C	Large inflow or high pressure in competent rock with unfilled joints.	2.5–10	0.5
D	Large inflow or high pressure, considerable outwash of joint fillings.	2.5–10	0.33

Barton, 2000

Q-system

Caso 1



Caso 2



Caso 3



Caso 4



Table 10.3 VALUES OF CHARACTERISTIC PARAMETERS OF THE Q INDEX (CONT.)

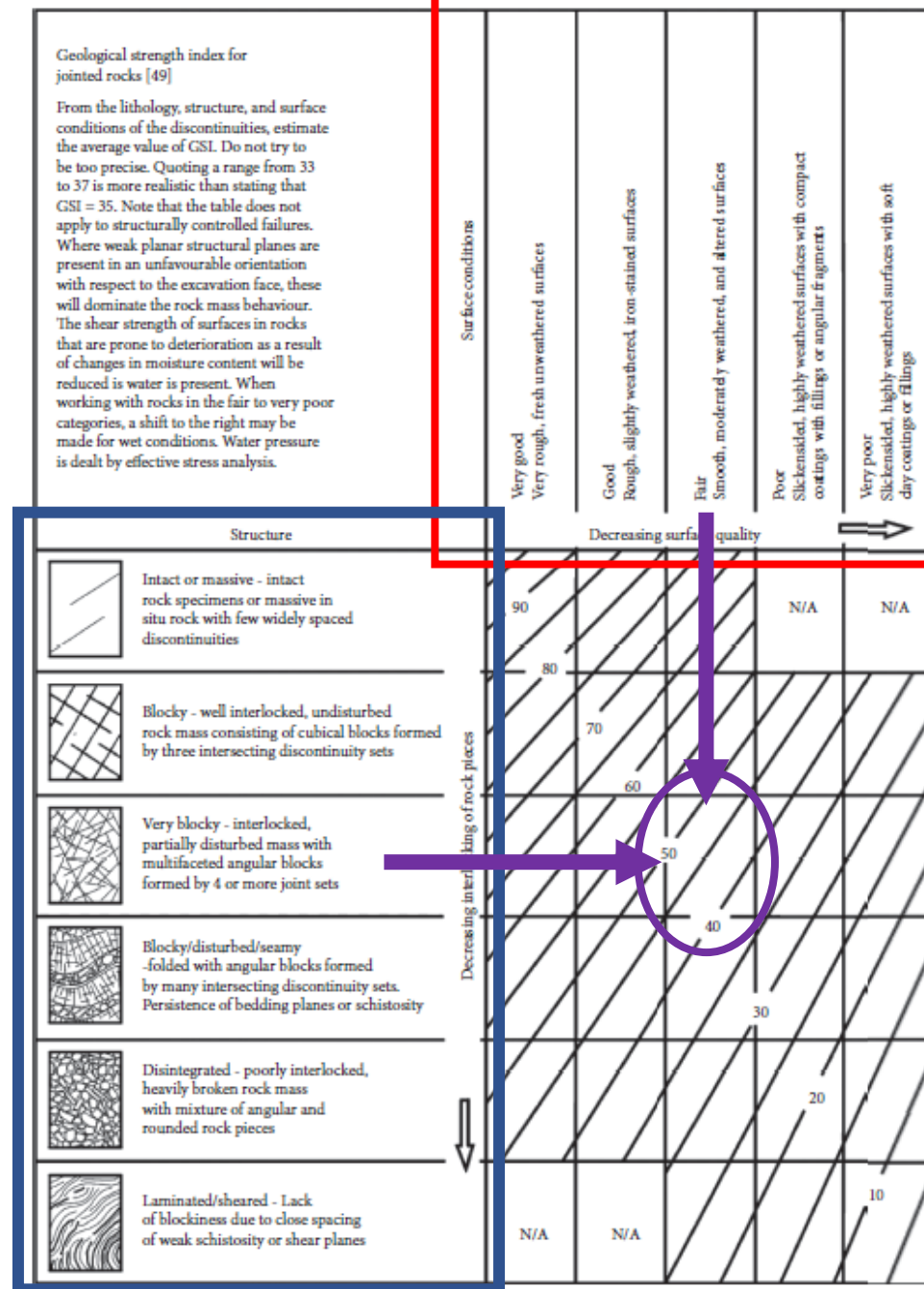
E	Exceptionally high inflow or water pressure at blasting, decaying with time.	>10	0.2–0.1
F	Exceptionally high inflow or water pressure continuing without noticeable decay.	>10	0.1–0.05
<i>Notes:</i>			
- Factors C, D, E and F are raw estimates. Increase J_w if drainage measures are installed.			
- Special problems caused by ice formation are not considered.			
6. Stress reduction factor			
a) Weakness zones intersecting excavation, which may cause loosening of rock mass when tunnel is excavated			SRF
A	Multiple occurrences of weakness zones containing clay or chemically disintegrated rock, very loose surrounding rock (any depth)		10
B	Single weakness zones containing clay or chemically disintegrated rock (depth of excavation ≤50 m)		5
C	Single weakness zones containing clay or chemically disintegrated rock (depth of excavation >50 m)		2.5
D	Multiple shear zones in competent rock (clay-free), loose surrounding rock (any depth)		7.5
E	Single shear zones in competent rock (clay-free), depth of excavation ≤50 m)		5.0
F	Single shear zones in competent rock (clay-free), depth of excavation >50 m)		2.5
G	Loose open joints, heavily jointed or "sugar-cube", etc. (any depth)		5.0
<i>Notes:</i>			
- Reduce these values of SRF by 25–50% if the relevant shear zones only influence but do not intersect the excavation.			
b) Competent rock, rock stress problems		σ_c/σ_1	σ_θ/σ_c
H	Low stress, near surface, open joints.	>200	< 0.01
J	Medium stress, favourable stress condition.	200–10	0.01–0.03
K	High stress, very tight structure. Usually favourable to stability, may be unfavourable for wall stability.	10–5	0.3–0.4
L	Moderate slabbing after >1 hour in massive rock.	5–3	0.5–0.65
M	Slabbing and rock burst after a few minutes in massive rock.	3–2	0.65–1
N	Heavy rock burst (strain-burst) and immediate dynamic deformations in massive rock.	<2	>1
<i>Notes:</i>			
- For strongly anisotropic virgin stress field (if measured): When $5 \leq \sigma_1/\sigma_3 \leq 10$, reduce σ_c to $0.75 \sigma_c$. When $\sigma_1/\sigma_3 > 10$, reduce σ_c to $0.5 \sigma_c$, where σ_c = unconfined compression strength, σ_1 and σ_3 are the major and minor principal stresses, and σ_θ = the maximum tangential stress (estimated from elastic theory).			
- Few case records available where depth of crown below surface is less than span width. Suggest SRF increase from 2.5 to 5 for such cases (see H).			
c) Squeezing rock: plastic flow of incompetent rock under the influence of high rock pressure		σ_θ/σ_c	SRF
O	Mild squeezing rock pressure	1–5	5–10
P	Heavy squeezing rock pressure	>5	10–20
<i>Notes:</i>			
- Cases of squeezing rock may occur for depth $H > 350 Q^{1/3}$ (Singh et al., 1992). Rock mass compression strength may be estimated from $q = 0.7\gamma Q^{1/3}$ (MPa) where γ = rock density in kN/m^3 (Singh, 1993).			
d) Swelling rock: chemical swelling activity depending on presence of water			SRF
R	Mild swelling rock pressure		5–10
S	Heavy swelling rock pressure		10–15

(Barton, 2000).

Geological Strength Index (GSI)

Vantaggi:

- utilizzato per stimare le proprietà di resistenza e deformazione dell'ammasso roccioso in base al criterio di rottura di Hoek e Brown per la modellazione numerica e l'analisi di progetti di ingegneria delle rocce.
- Utilizzabile anche in presenza di rocce molto scadenti, al contrario di RMR e Q, che utilizzano RQD come parametri di input (dove RQD = 0)



6 categorie per la struttura

5 categorie per la qualità della superficie

Esempio:
 Un struttura «Very-blocky» e qualità della superficie «fair»
 → **GSI = 40 - 50**

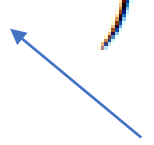
GSI

Parametri criterio di rottura di Hoek & Brown

Criterio di rottura generalizzato per stimare la resistenza degli ammassi rocciosi fratturati

$$\sigma_1 = \sigma_3 + \sigma_c \left(m_b \frac{\sigma_3}{\sigma_c} + s \right)^a,$$

UCS



m_i determinato mediante prove triassiali su campioni di carota (roccia intatta), ove possibile, o stimati in base a una descrizione qualitativa del materiale roccioso, come descritto da Hoek e Brown (1997).

dove:

$$m_b = m_i \exp \left(\frac{GSI - 100}{28 - 14D} \right)^a,$$

Per $GSI > 25 \rightarrow$

$$s = \exp \left(\frac{GSI - 100}{9} \right),$$

$$a = 0.5.$$

Per $GSI < 25 \quad s = 0. \quad a = 0.65 - \frac{GSI}{200}.$

GSI

Parametri criterio di rottura di Hoek & Brown

Generalised Hoek-Brown Criteria		Surface condition					
$\sigma_1' = \sigma_3' + \sigma_c (m_b (\sigma_3'/\sigma_c) + S)^2$		Very good	Good	Fair	Poor	Very poor	
σ_1' = major principal effective stress at failure σ_3' = minor principal effective stress at failure σ_c = uniaxial compressive strength of intact pieces of rock m_b , s , and α are constants which depend on the composition, structure, and surface conditions of the rock mass		Very rough, unweathered surfaces	Rough, slightly weathered, iron-stained surfaces	Smooth, moderately weathered, or altered surfaces	Slickensided, highly weathered surfaces with compact coatings or fillings containing angular rock fragments	Slickensided, highly weathered surfaces with soft clay coatings or fillings	
Structure							
	Blocky - very well interlocked, undisturbed rock mass consisting of cubical blocks formed by three orthogonal discontinuity sets	m_b/m_i s α E_m ν GSI	0.60 0.190 0.5 75,000 0.2 85	0.40 0.062 0.5 40,000 0.2 75	0.26 0.015 0.5 20,000 0.25 62	0.16 0.003 0.5 9,000 0.25 48	0.08 0.0004 0.5 3,000 0.25 34
	Very blocky - interlocked, partially disturbed rock mass with multifaceted angular blocks formed by four or more discontinuity sets	m_b/m_i s α E_m ν GSI	0.40 0.062 0.5 40,000 0.2 75	0.29 0.021 0.5 24,000 0.25 65	0.16 0.003 0.5 9,000 0.25 48	0.11 0.001 0.5 5,000 0.25 38	0.07 0 0.53 2,500 0.3 25
	Blocky/seamy - folded and faulted with many intersecting discontinuities forming angular blocks	m_b/m_i s α E_m ν GSI	0.24 0.012 0.5 18,000 0.25 60	0.17 0.004 0.5 10,000 0.25 50	0.12 0.001 0.5 6,000 0.25 40	0.08 0 0.5 3,000 0.3 30	0.06 0 0.55 2,000 0.3 20
	Crushed - poorly interlocked, heavily broken rock mass with a mixture of angular and rounded blocks	m_b/m_i s α E_m ν GSI	0.17 0.004 0.5 10,000 0.25 50	0.12 0.001 0.5 6,000 0.25 40	0.08 0 0.5 3,000 0.3 30	0.06 0 0.55 2,000 0.3 20	0.04 0 0.60 1,000 0.3 10

FIGURE 3: Hoek and Brown failure criterion linkage with the GSI [63].

GSI

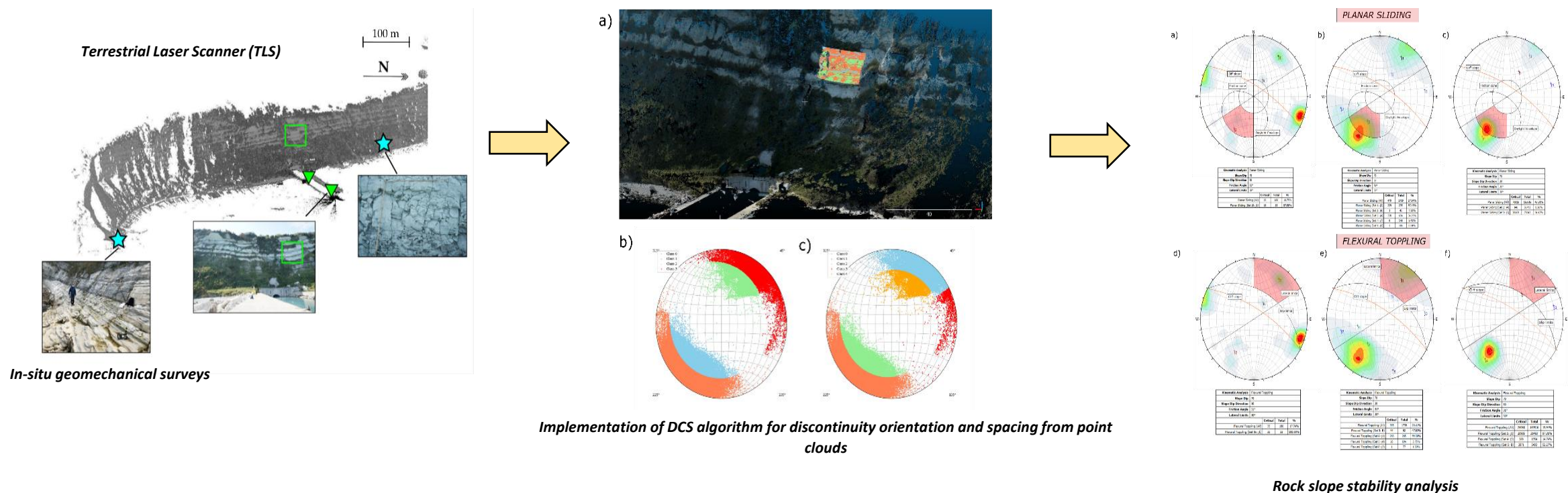
Stima del Rock Mass Deformation Modulus

TABLE 2: Empirical models for rock mass deformation modulus.

S. no	Empirical model	Unit	Name of the researcher	Parameters	Year	References	Equation no.
1	$Erm = Ei(s^a)^{0.4} Ei = 50 \text{ GPa}, s = e^{((GSI-100)/9)},$ $a = 0.5 + (1/6)(e^{(-GSI/15)} - e^{(-20/3)})$	GPa	Sonmez et al.	$Ei, GSI, s,$ and a	2004	[86]	(24)
2	$Erm = (1 - (D/2))\sqrt{(\sigma_c/100)}10^{((GSI-10)/40)}$ for $\sigma_c < 100 \text{ MPa}$	GPa	Hoek et al.	$GSI, D,$ and σ_c	2002	[78]	(25)
3	$Erm = (1 - (D/2))10^{((GSI-10)/40)}$ for $\sigma_c > 100 \text{ MPa}$	GPa	Hoek et al.	$GSI, D,$ and σ_c	2002	[78]	(26)
5	$Erm = Ei\{0.02 + ((1 - (D/2))/(1 + \exp((60 + 15D - GSI)/11)))\}$	MPa	Hoek and Diederichs	$GSI, D,$ and Ei	2006	[77]	(27)
6	$Erm = 10^5\{((1 - (D/2))/(1 + \exp((75 + 25D - GSI)/11)))\}$	MPa	Hoek and Diederichs	GSI and D	2006	[77]	(28)
7	$Erm = Ei(e^{(GSI-100)/A})$	GPa	Ván and Vasarhelyi	$GSI, Ei,$ and A	2010	[87]	(29)
8	$Erm = \tan(\sqrt{1.56 + (\ln(GSI))^2})\sqrt[3]{\sigma_c}$	GPa	Beiki et al.	GSI and σ_c	2010	[88]	(30)
9	$Erm = \sqrt{(\sigma_c/100)} * 10^{(GSI-10)/40}$ for $\sigma_c < 100 \text{ MPa}$	GPa	Palmström and Singh	σ_c and GSI	1998	[89]	(31)
10	$Erm = Ei(s)^{3/4}$, where $s = e^{((GSI-100)/9)}$	GPa	Sonmez et al.	$Ei, GSI,$ and s	2004	[59]	(32)
11	$Erm = 0.35 * \exp^{0.06GSI}$	GPa	Majdi et al.	GSI	2012	[90]	(33)
12	$Erm = \sqrt{(Ei/100)}10^{((GSI-20)/35)}$	GPa	Majdi et al.	GSI	2012	[90]	(34)

Caso studio 1:

Implementazione di una procedura machine learning semi-automatica per il calcolo di orientazione e spaziatura delle discontinuità



Mammoliti, E., Di Stefano, F., Fronzi, D., Mancini, A., Malinverni, E. S., & Tazioli, A. (2022). A machine learning approach to extract rock mass discontinuity orientation and spacing, from laser scanner point clouds. *Remote Sensing*, 14(10), 2365.

Introduzione al problema

Svantaggi del rilievo geomeccanico convenzionale:

- Time-consuming
- Acquisizione di un numero limitato di dati
- Non è possibile effettuarlo ovunque



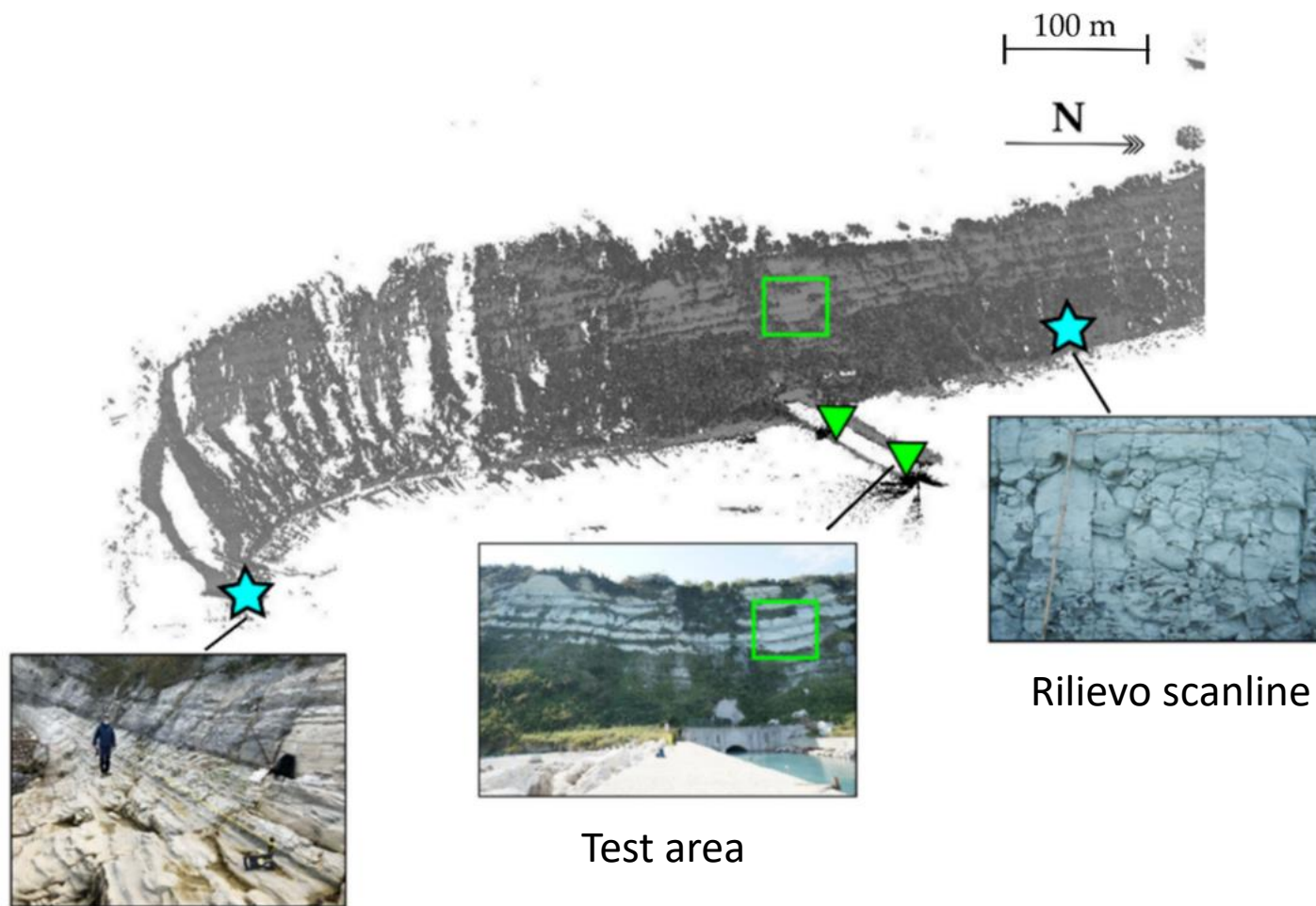
Vantaggi Laser Scanner 3d, drone:

- Acquisire un numero elevato di dati
- Raggiungere zone poco o per nulla accessibili
- Elaborazioni veloci

Rilievo Laser Scanner 3D



TLS RIEGL VZ-400i

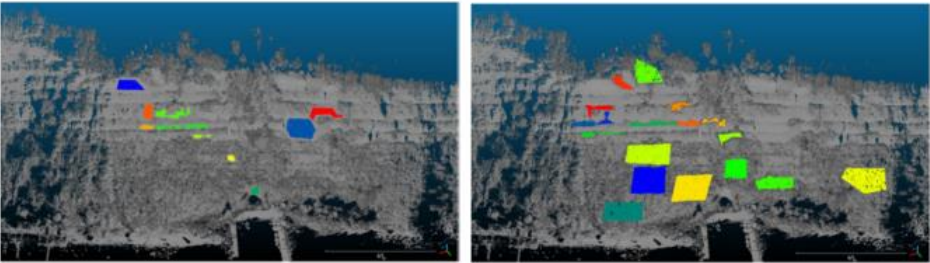


Rilievo scanline

Test area

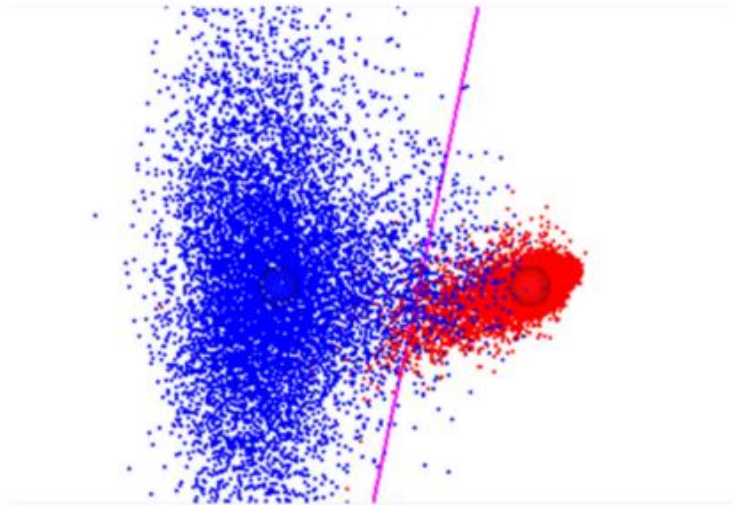
Rilievo scanline

Elaborazione dei dati: Rimozione della vegetazione



(a)

(b)



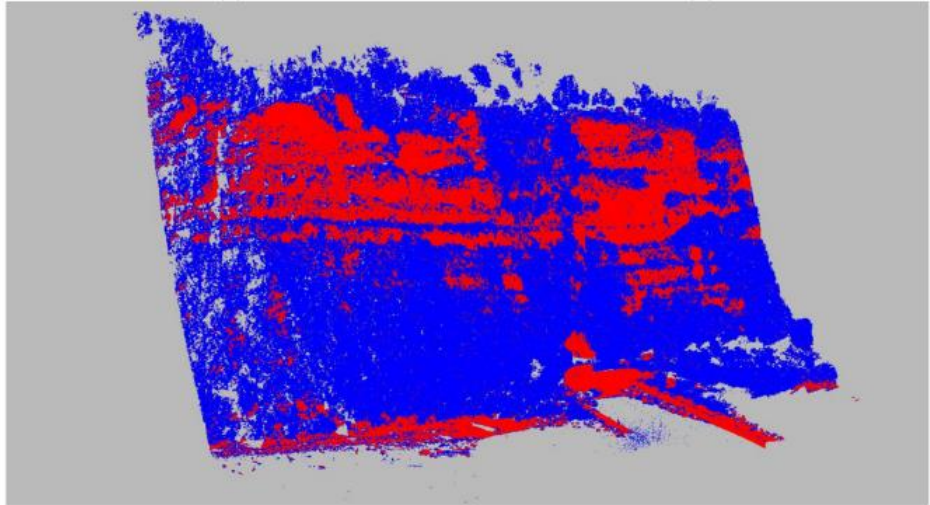
■ Class 1: vegetation
■ Class 2: rock

Statistics:

Class 1: vegetation	
Total	10,000
Truly classified	9,645
Falsely classified	355
Dist. to boundary	- 8.33359 +/- 3.96772

Total	10,000
Truly classified	9,771
Falsely classified	229
Dist. to boundary	6.5478 +/- 2.26026

Balanced accuracy (ba): 0.9708 (97%)
 Ficher Discriminant Ratio (fdr): 10.6206



(c)

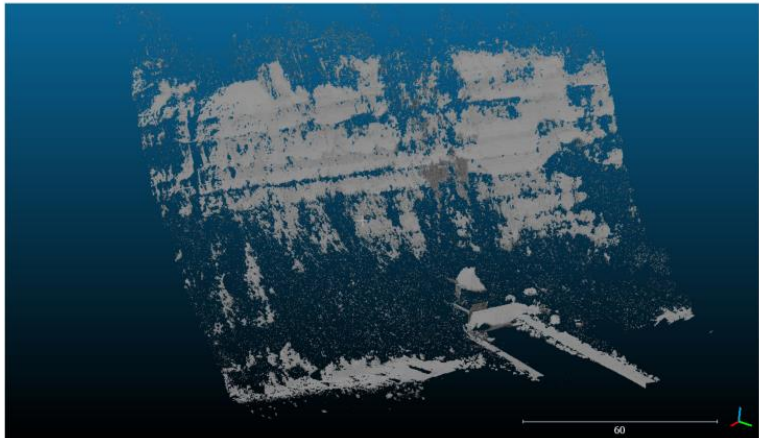


Figure 7. Filtered rock surface after removal of the vegetation coverage.

Plugin CANUPO di CloudCompare

Implementazione dell'algoritmo DCS

Step 1:

Calcolo dei valori di dip angle e dip direction partendo dalle normali dei punti

$$d(\theta_1, \theta_2) = \min(2\pi - |\theta_1 - \theta_2|, |\theta_1 - \theta_2|)$$

$$distf(\alpha_1, \alpha_2, \beta_1, \beta_2) = \sqrt{dist(\alpha_1, \alpha_2)^2 + dist(\beta_1, \beta_2)^2}$$

Step 2:

Stima del numero di classi (set di discontinuità) attraverso il metodo Error Sum of Squares (SSE)



(a)

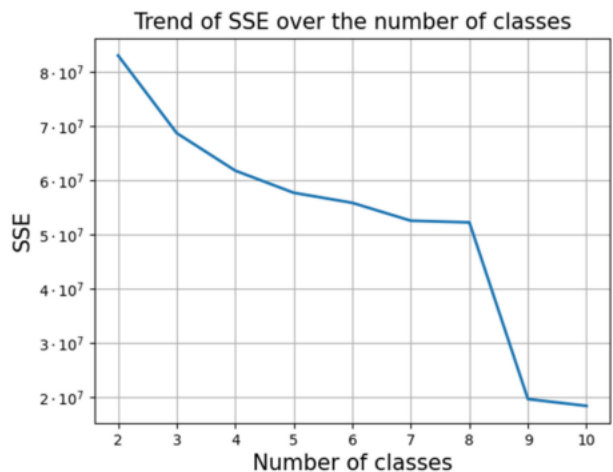
Step 3:

Possibilità di intervenire nella procedura inserendo centroidi manualmente e guidando l'algoritmo nel ri-calcolo

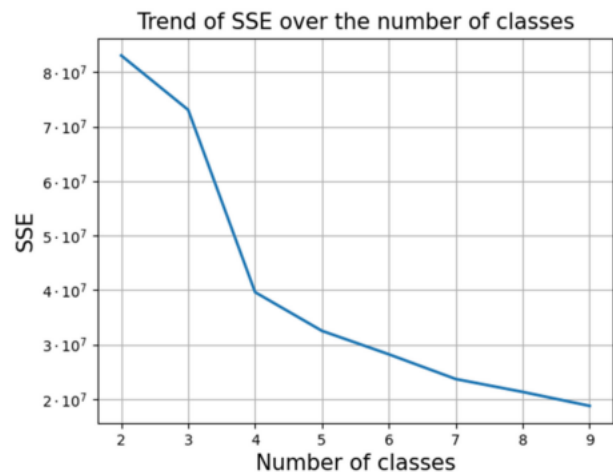
Step 4: calcolo della spaziatura per ogni set

$$d(N, P_2, P_1) = \frac{\vec{N} \cdot (\vec{P}_2 - \vec{P}_1)}{|\vec{N}|}$$

where N is the normal, P_2 is a given (3d) point and P_1 is a reference point.



(a)



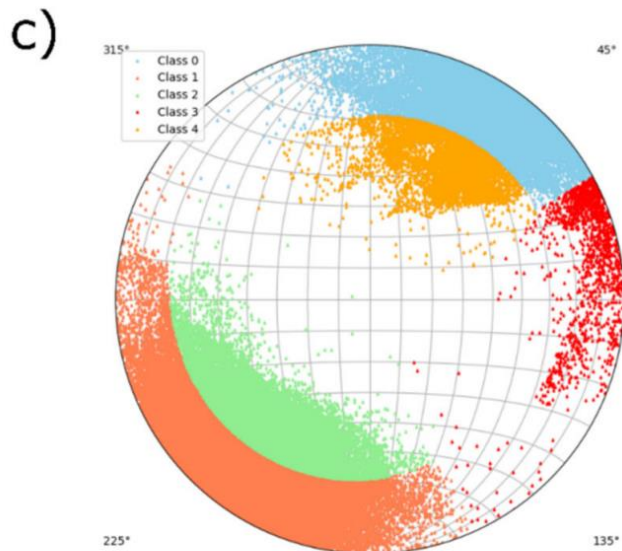
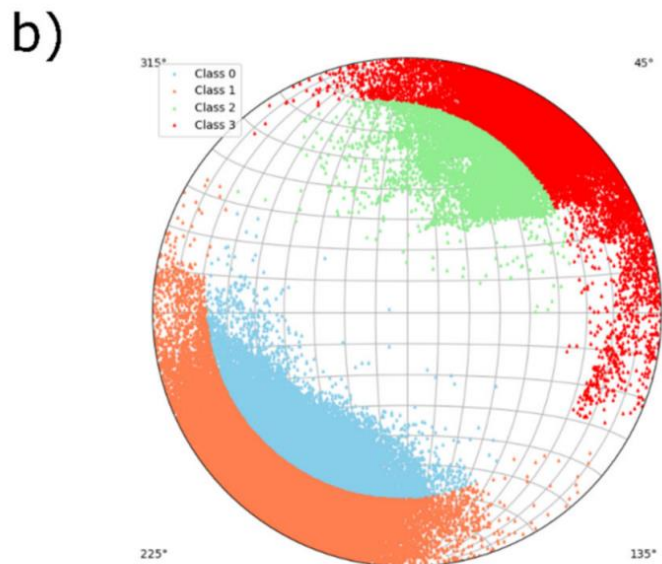
(b)

Risultati

Table 2. Dip direction and dip angles of the poles of each identified discontinuity set. The relating number of points over the total number of points is reported in percentage.

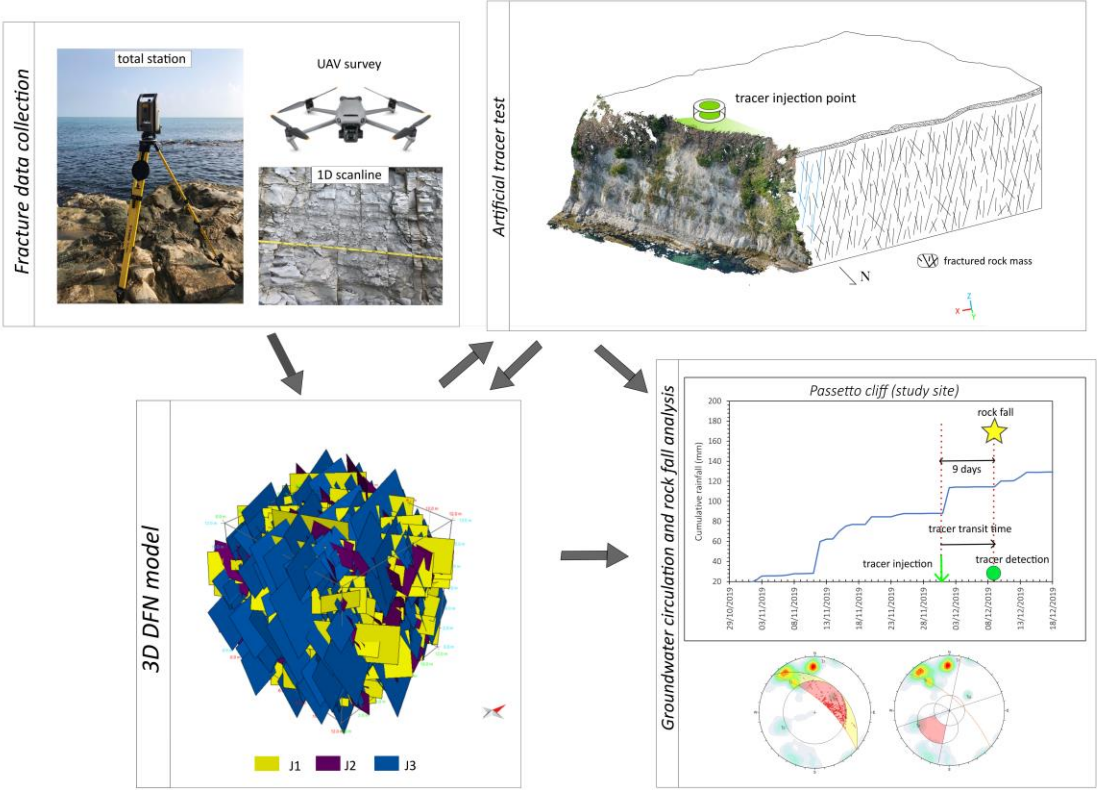
Cluster ID	Field Survey Orientation (F)	DCS Algorithm		FACETS Orientation		
	DA/DD [°]	DA/DD [°]	Δmc	(DA/DD) [°]	Δmc	$\Delta DSC-F$
j1	76/203	78/211	2/-8	75/211	1/-8	-3/0
j2	66/36	73/38	-7/2	73/32	-7/4	0/6
j3	80/290	79/261	1/29	79/262	1/28	0/-1
j4	n.d./n.d.	56/40	n.d./n.d.	49/31	n.d./n.d.	7/9
Bedding (B)	36/212	52/208	n.d./n.d.	48/209	-12/3	4/-1
j5	n.d./n.d.	n.d./n.d.	n.d./n.d.	73/344	n.d./n.d.	n.d./n.d.
j6	n.d./n.d.	n.d./n.d.	n.d./n.d.	47/76	n.d./n.d.	n.d./n.d.
j7	n.d./n.d.	n.d./n.d.	n.d./n.d.	74/76	n.d./n.d.	n.d./n.d.
RMSE	n.a	9.01/15.2		7.0/14.8		19.8/14.7

Where n.a. = not available; n.d. = not detected; DA = dip angle; DD = dip direction; Δmc = difference between measured and calculated dip and dip direction. $\Delta DCS-F$ = difference between dip/dip direction calculated by DCS and FACETS.



Caso studio 2:

Discrete Fracture Networks e test con traccianti artificiali per la determinazione della conducibilità idraulica delle fratture in una falesia instabile



Mammoliti, E., Pepi, A., Fronzi, D., Morelli, S., Volatili, T., Tazioli, A., & Francioni, M. (2023). 3D Discrete Fracture Network Modelling from UAV Imagery Coupled with Tracer Tests to Assess Fracture Conductivity in an Unstable Rock Slope: Implications for Rockfall Phenomena. *Remote Sensing*, 15(5), 1222.

Le frane in roccia nella costa Anconetana (Marche)



Home > Ancona > Cronaca > Con l'estate tornano le f...

Con l'estate tornano le frane sul costone di Mezzavalle

La frana di ieri su un Portonovo

CM cronachemaceratesi.it la tua provincia in rete

Martedì 17 Maggio 2022 - 23:23

HOME TUTTE LE NOTIZIE SPORT POLITICA EVENTI ECONOMIA TERREMOTI

Cade un masso dalla rupe del Passetto, pericolo in spiaggia

ANCONA - Nessun ferito, area transennata all'altezza della Seggiola del

Home > Ancona > Cronaca > Frana al Conero, al Trav...

Frana al Conero, al Trave due feriti

E' successo dopo il lido di Mezzavalle nel tratto interdetto al g stati portati all'ospedale

Corriere Adriatico.it

Piovono massi sulla Grotta azzurra Frana ancora la falesia del Passetto

ANCONA Domenica 24 Dicembre 2017

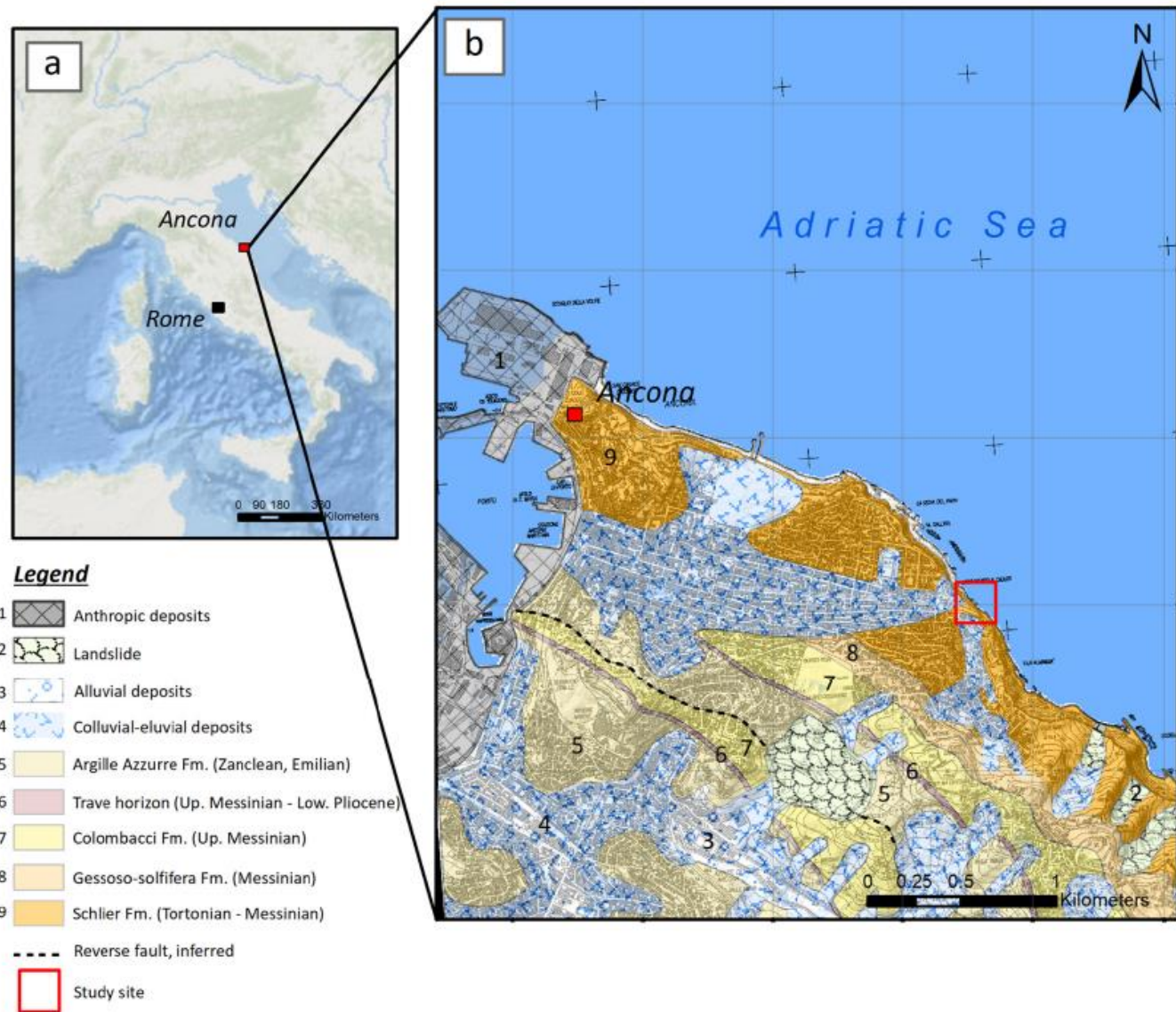
Una frana al Trave

Più di 30 eventi di instabilità documentati tra il 1991 to 2022 da articoli di giornale

INSTABILITY EVENT SITE	DAY OF OBSERVATION
Ancona - Passetto cliff	03/09/1991
Portonovo - Site between fisherman cooperative and Mezzavalle	22/06/1995
Ancona - Scalaccia beach	25/11/1998
Conero	08/02/2013
Portonovo	04/02/2014
Passetto - Seggiola del Papa	22/06/2014
Mezzavalle	08/08/2014
Cardeto	11/07/2017
Cardeto	24/12/2017
Passetto	22/03/2018
Frate beach (Conero)	30/06/2018
Trave di Portonovo	05/07/2018
Trave di Portonovo	12/08/2018
Frate beach (Conero)	11/06/2019
Mezzavalle	16/06/2019
Cardeto	15/07/2019
Trave di Portonovo	02/08/2019
Passetto	09/12/2019
Mezzavalle ridge	19/06/2020
Mezzavalle	05/07/2020
Trave	08/07/2020
Trave	17/08/2020
Trave	27/08/2020
Trave	05/06/2021
Trave	07/08/2021
Site between Mezzavalle and Trave di Ancona	20/08/2021
Trave	25/09/2021
Mezzavalle	01/07/2022
Trave	21/08/2022

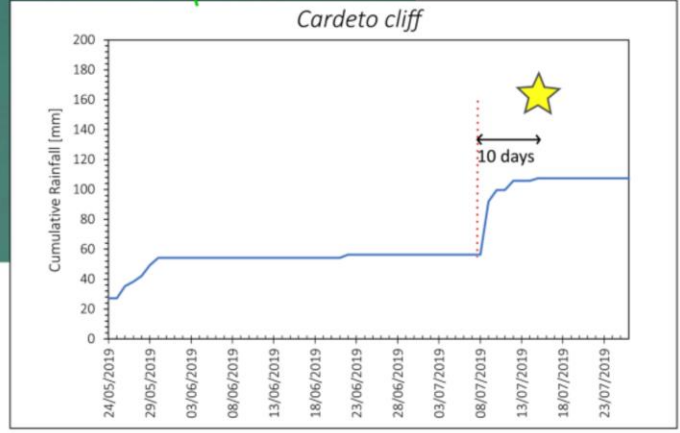
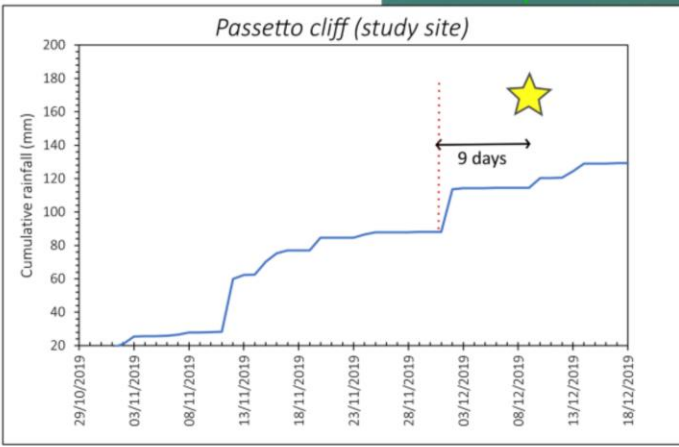
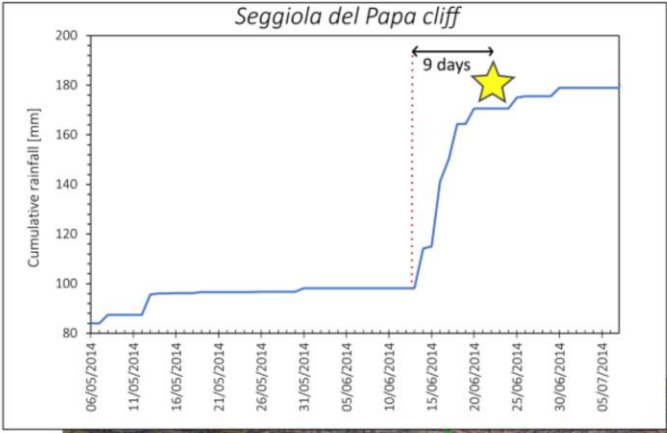
Geologia dell'area indagata

- Formazione Geologica dello Schlier formata da calcari marnosi e marne calcaree (Tortoniano, Messiniano)
→ acquitardo
- Alto grado di fratturazione



Evidenze

≈ intervallo di 10 giorni tra le piogge e i crolli in roccia (★)

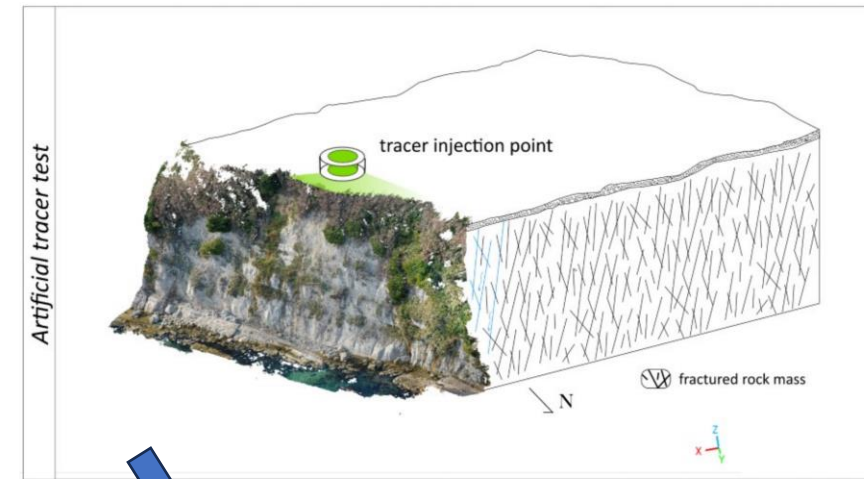
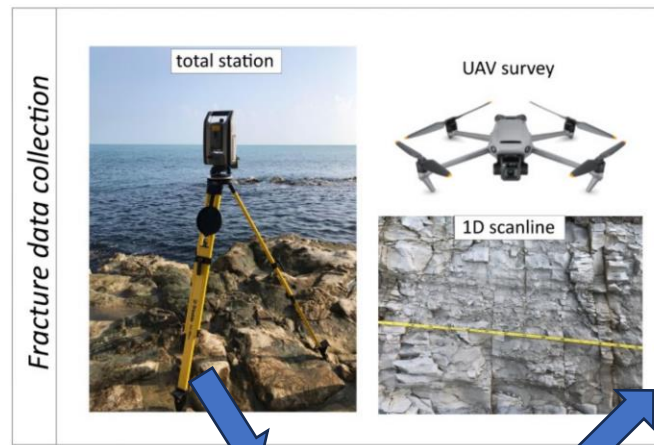


Mammoliti et al., 2023

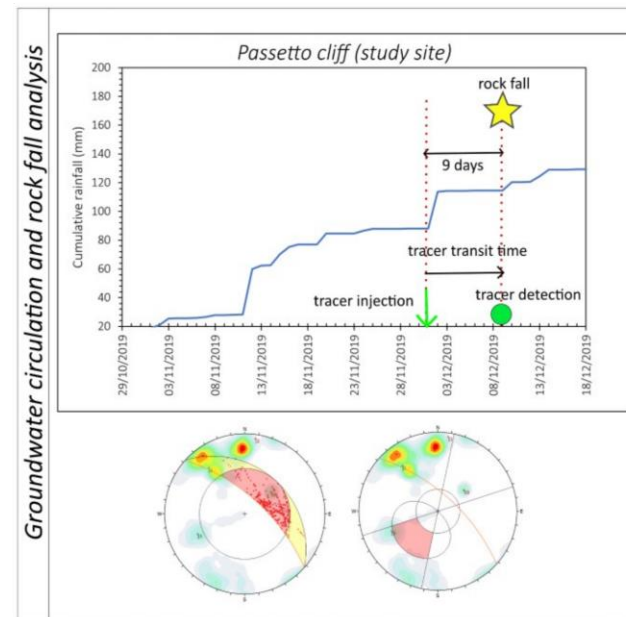
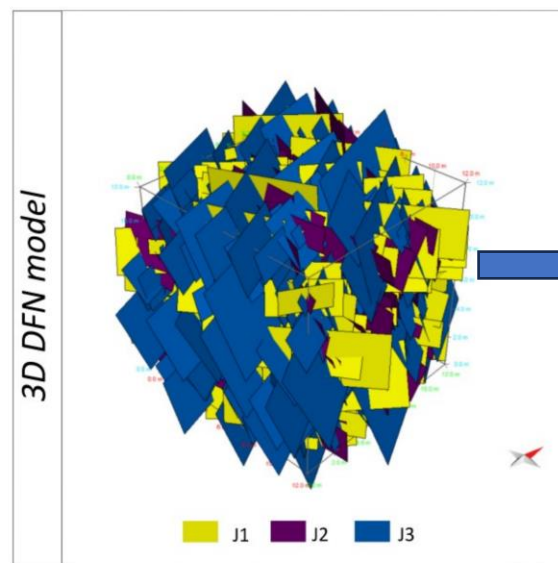
- Elisa Mammoliti. Scuola di Scienze e Tecnologie, Sezione di Geologia, Università di Camerino

Strategia di ricerca

- Unmanned Aerial Vehicles survey (UAV) e scanline 1D
- Modellazione DFN
- Test con traccianti artificiali (per validare la conducibilità idraulica derivata da DFN)



Mammoliti et al., 2023



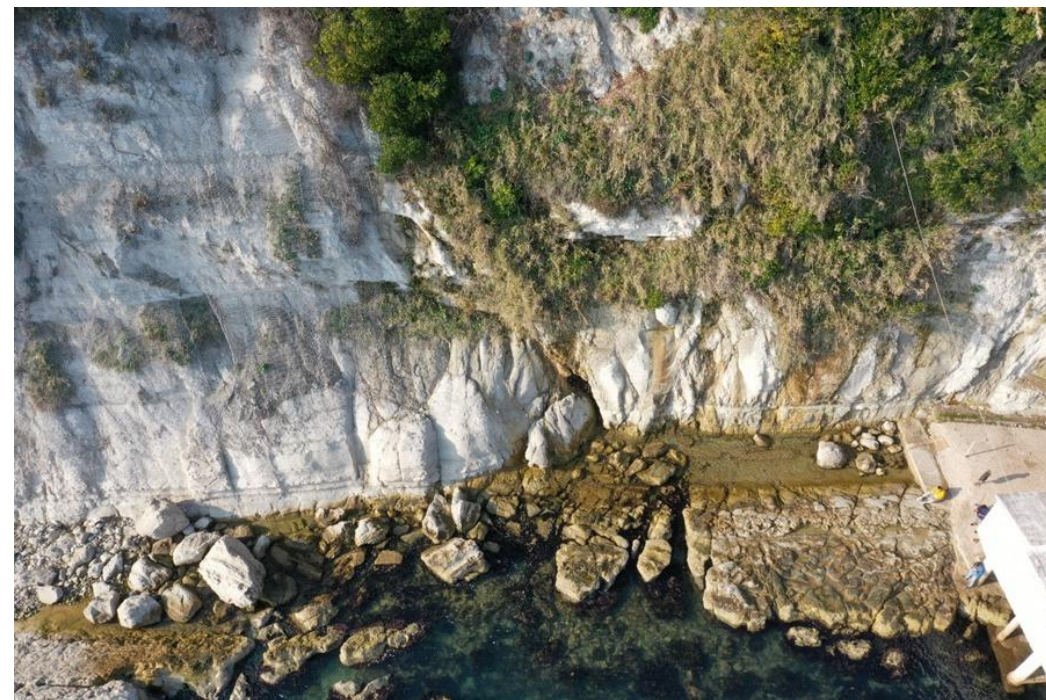
Rilievo drone

Perspective 30°



points: 47,476,384

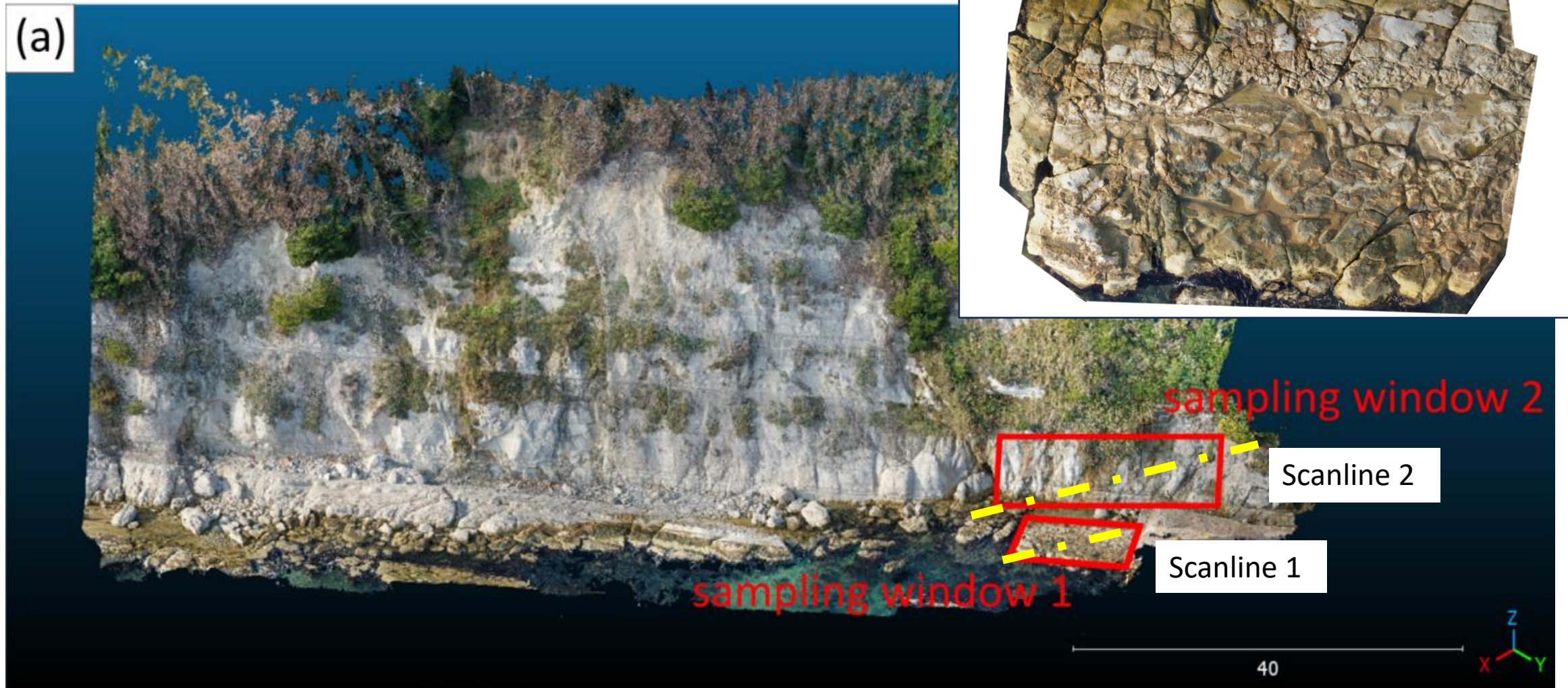
18 ground control points used for georeferencing the point cloud



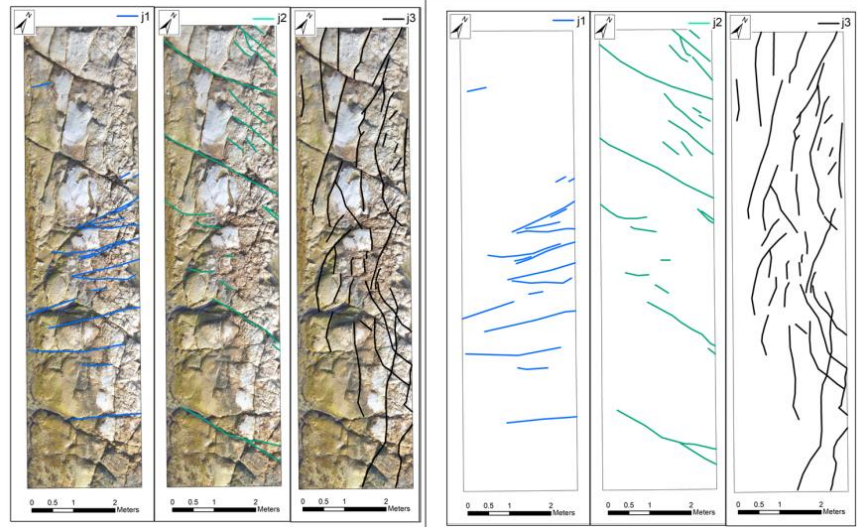
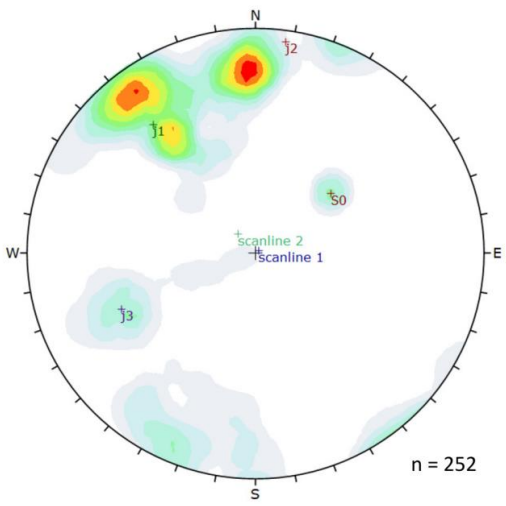
Trimble S7 Total Station

- *Elisa Mammoliti*. Scuola di Scienze e Tecnologie, Sezione di Geologia, Università di Camerino

Selezione di finestre di campionamento nella nuvola di punti

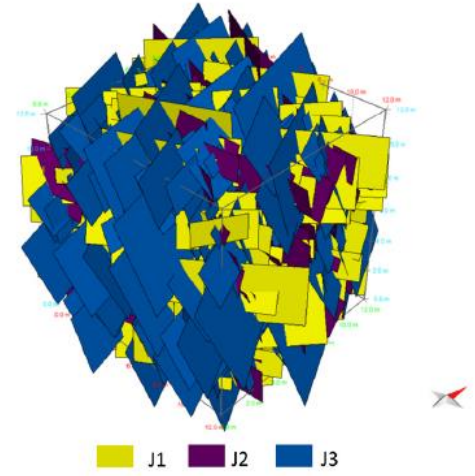
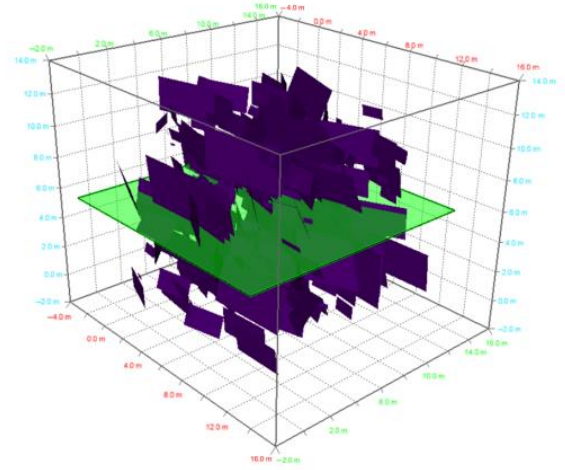


DFN



	J1	J2	J3
Mean P ₂₁ (sampling window 1, m/m ²)	0.96	0.74	1.89

- Identificazione dell'orientazione media e dell'apertura degli insiemi di fratture dal metodo scanline
- Calcolo di P₂₁ dall'analisi delle fratture utilizzando lo strumento NetworkGT (ArgGIS)
- Determinazione di P₃₂ attraverso un approccio iterativo (software Move)
- Costruzione del modello DFN e calcolo della conducibilità idraulica

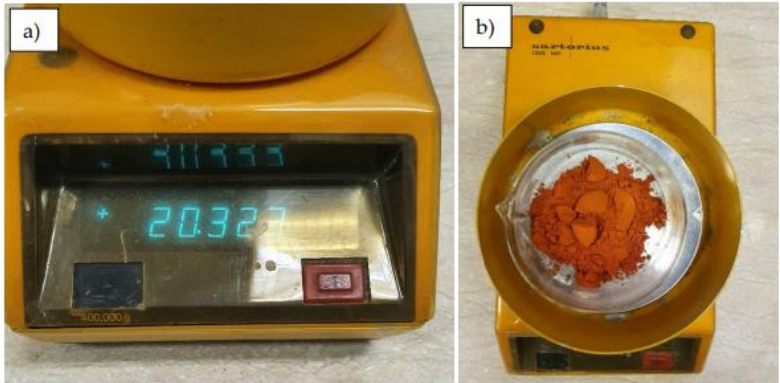
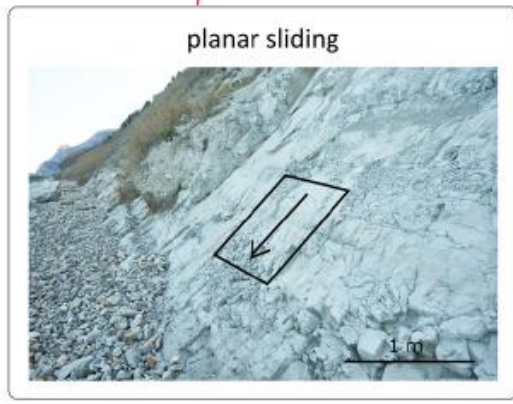
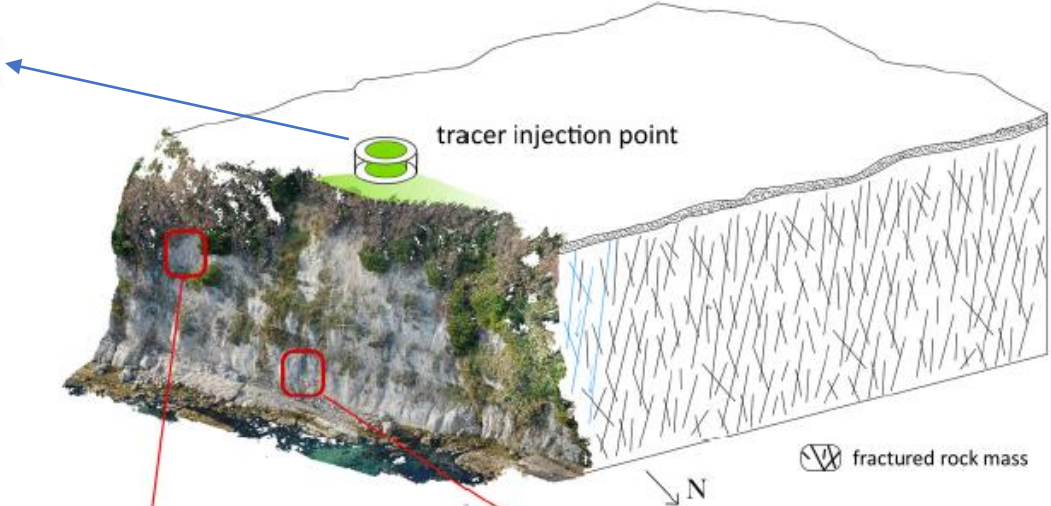


Test con traccianti artificiali

20 g di fluoresceina immessa al top della falesia attraverso l'infiltrometro a doppio anello.

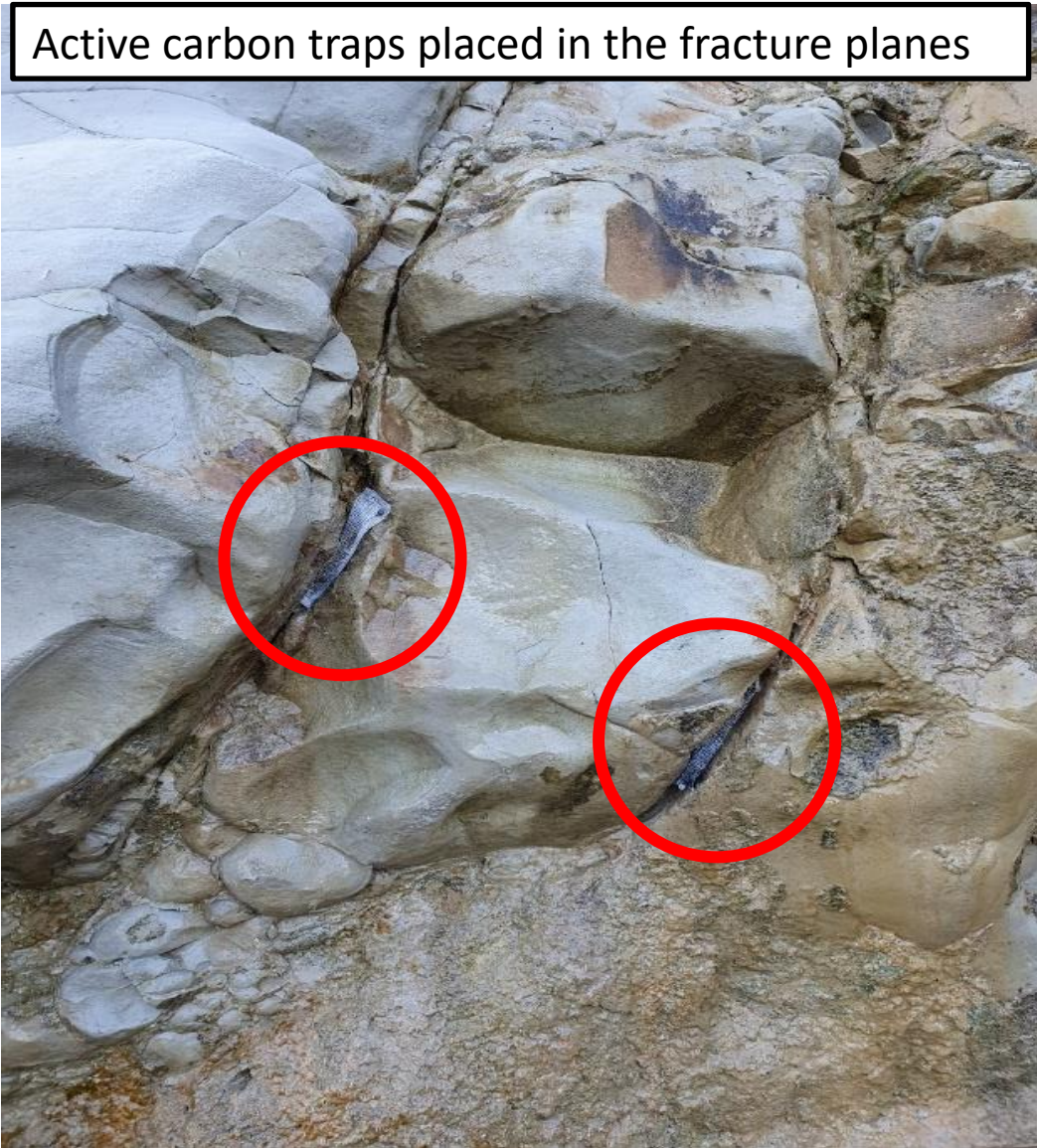
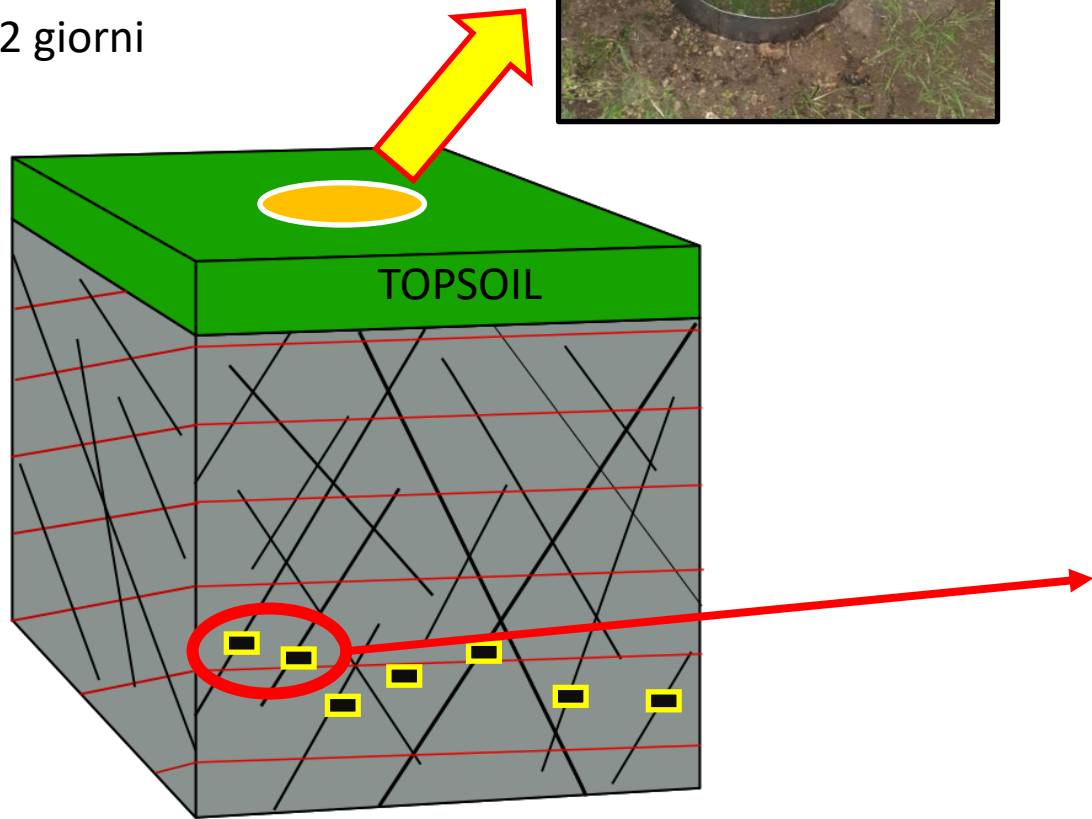
Scopi:

- Misurare la permeabilità del suolo al top della falesia;
- Iniettare il tracciante attraverso le fratture e misurarlo alla sua base



Punti di monitoraggio del tracciante

Carboni attivi sostituiti ogni 2 giorni



Conducibilità idraulica delle fratture

- La conducibilità idraulica delle fratture calcolata attraverso test con traccianti è simile a quella modellata con DFN.
- Il valore di conducibilità satura (Ksat) del topsoil è di un ordine di grandezza superiore alla conducibilità delle fratture.
- Pertanto, il tempo che l'acqua piovana impiega per attraversare il topsoil è trascurabile rispetto al tempo che impiega per attraversare l'intera altezza della scogliera (nel sito di indagine è di circa 5-6 m).

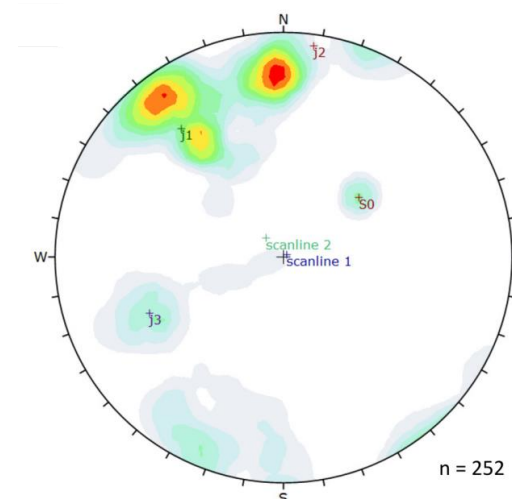
		J1	J2	J3	S0
Dip angle/Dip direction (°)		71/141	88/188	65/67	46/231
Fisher value		25.9	14	81	867
Fracture trace length (m)	Min	0.2	0.2	0.18	n.d.
	Mean	1.82	1.60	2.22	n.d.
	Max	12.46	11.32	13.87	n.d.
	Std Dev	2.06	2.14	2.86	n.d.
Hydraulic aperture (mm)	Min	0.18	0.12	0.18	n.d.
	Mean	0.24	0.19	0.25	n.d.
	Max	0.95	0.5	0.5	n.d.
Mechanical aperture (mm)	Min	0.90	0.70	0.90	n.d.
	Mean	0.95	0.85	1.00	n.d.
	Max	2.60	1.80	1.80	n.d.

- 3 discontinuity sets + bedding

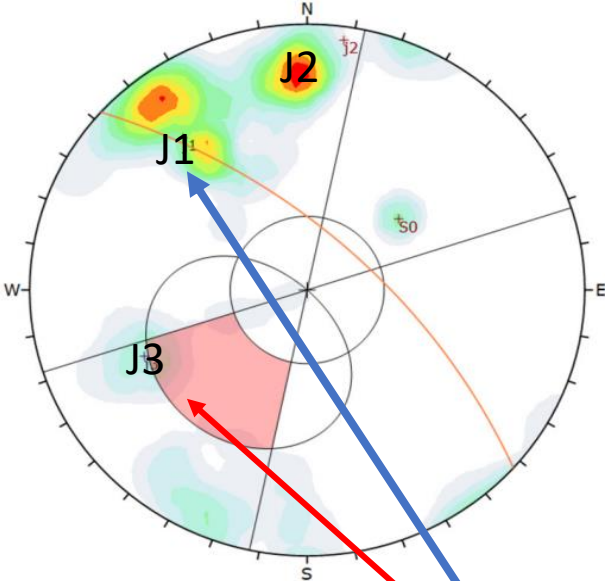
		Average K (cm/s)
DFN	fractures	2.91×10^{-3}
Tracer test	fractures	2.89×10^{-3}
	topsoil	$1.8 \times 10^{-2} *$

Where * is the Ksat.

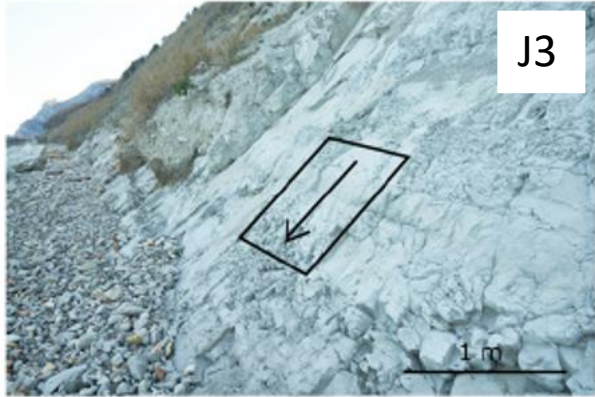
Mammoliti et al., 2023



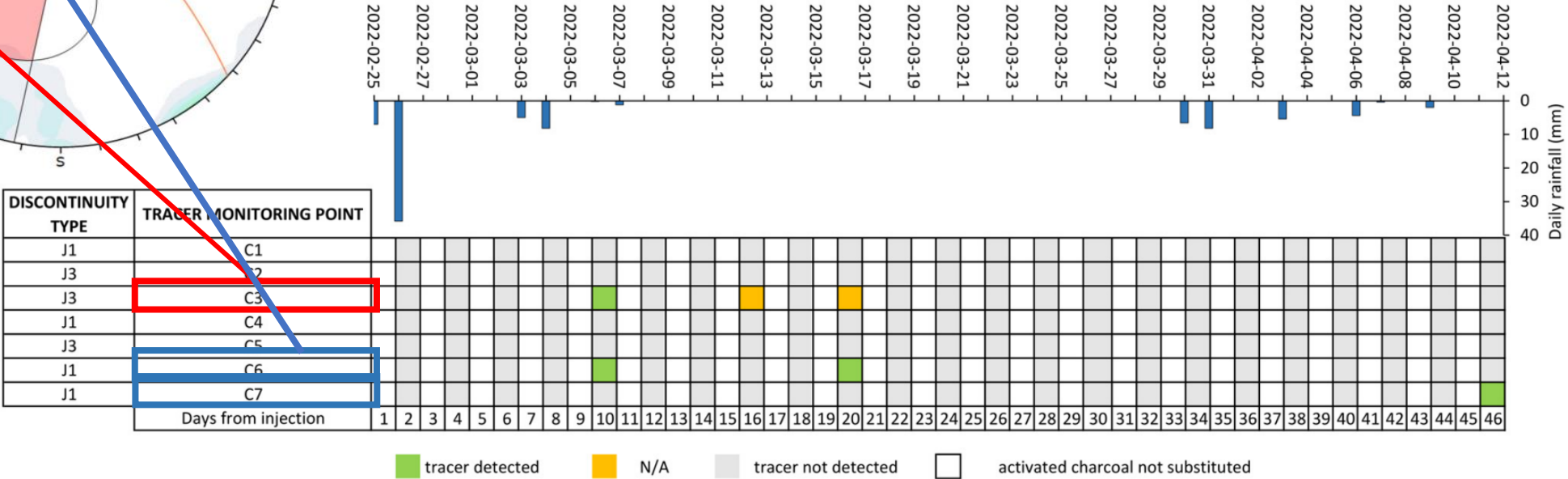
Scivolamento planare

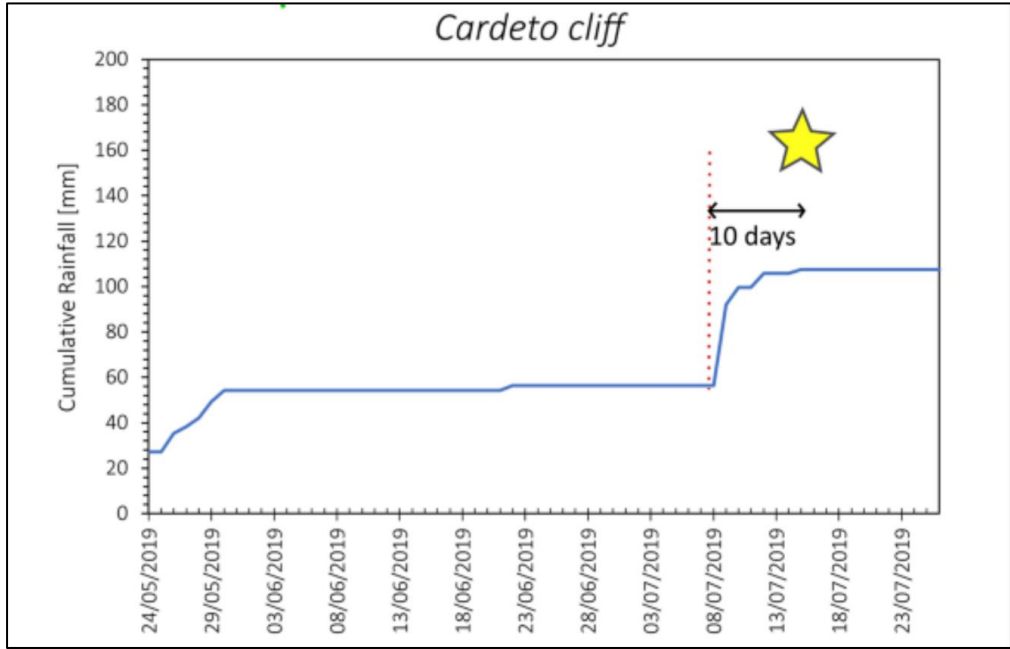
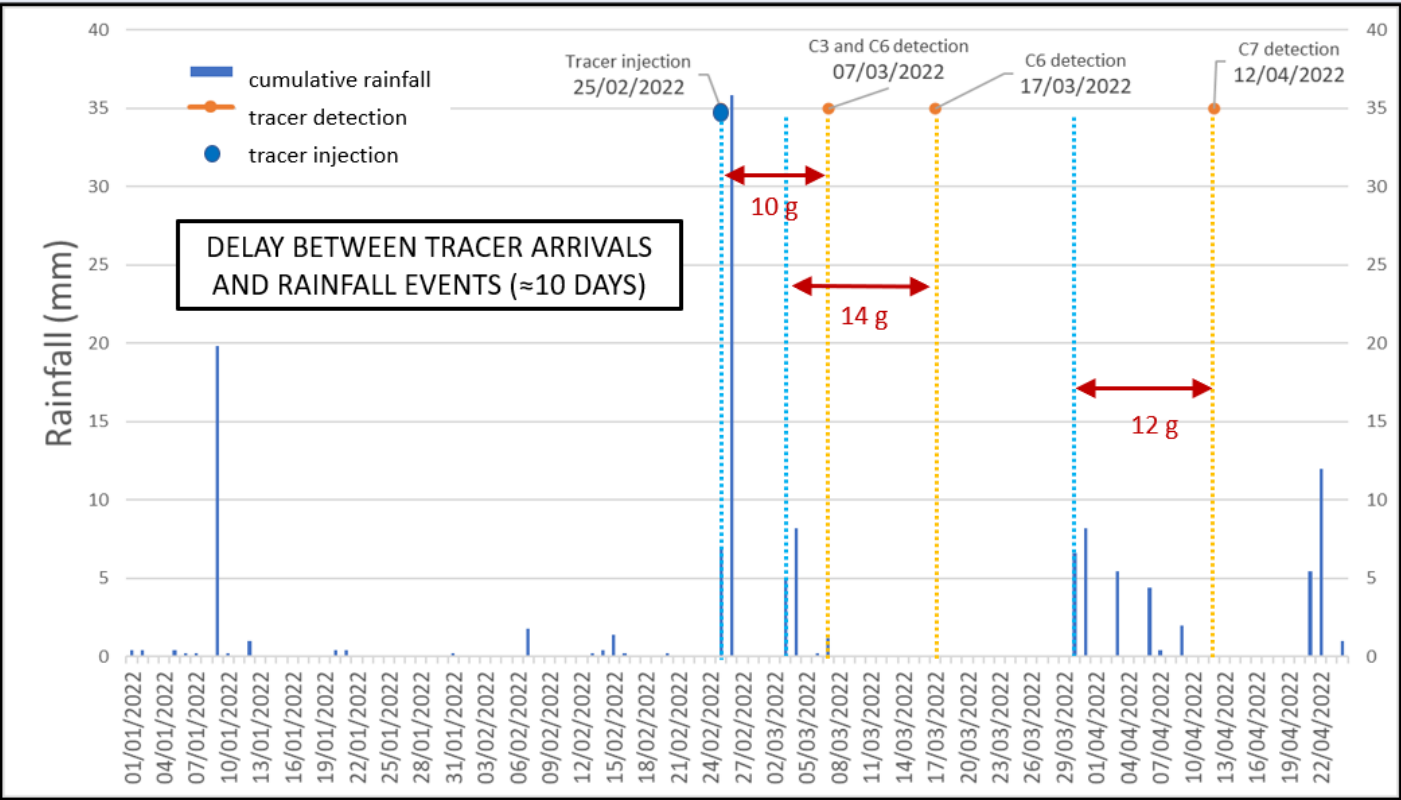


planar sliding



Il primo arrivo del tracciante è avvenuto dopo circa 10 giorni dall'iniezione e una quantità significativa di tracciante è stata rilevata solo nei punti di monitoraggio C3 e C6, situati nel set di fratture J3 e J1.





Il tracciante è arrivato circa 10-12 giorni dopo l'iniezione, lo stesso intervallo di tempo che intercorre tra le precipitazioni e le cadute di massi nella zona.

Grazie per l'attenzione!

