



# Route Stability Index (RSI): an Index for the Assessment of Rockfall-Related Hazards in Rock Slopes Equipped for Sport Climbing

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Received: 18 January 2022 / Accepted: 13 June 2022 / Published online: 25 June 2022  
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## Abstract

A multidisciplinary geomechanical method to evaluate and quantify rockfall hazards in rock slopes equipped for sport climbing is presented. This method exploits close-range survey data obtained from terrestrial laser scanner (TLS) and unmanned aerial vehicle-based digital photogrammetry (UAV-DP) and integrates them with traditional scanline survey data collected in the field. Based on the acquired information, a kinematic analysis is performed to predict the location of structurally controlled rock failure mechanisms. An index denoted as route stability index (RSI) is then proposed to quantify the associated hazard along sport climbing routes in the study area. In addition, hazard is also assessed at the overall slope scale. The method was successfully applied at an abandoned climbing site historically affected by rockfalls, 5 km north of Florence (Italy). RSI can be adopted as part of the planning and monitoring strategies for the management of risk related to outdoor climbing activities, which are becoming an important part of Italian and European geo-tourism.

**Keywords** Hazard assessment · Rockfalls · Outdoor sport climbing · Kinematic analysis · RSI · Close-range methods

## Introduction

In recent years, there has been a significant increase in the number of outdoor sport climbing practitioners all over the world. In 2020, the Italian Federation of Sport Climbing (FASI) registered more than 35,000 competitive and non-competitive climbers (FASI 2021). This number is expected to increase following the Olympic debut of sport climbing at the Tokyo 2021 Olympic Games (IFSC 2020).

The Italian Alpine Club, or Club Alpino Italiano (CAI), defines sport climbing as *the athletic gesture that links climbing passages, with or without interruption, aimed at completing the itinerary without falling or hanging onto the rope. [...] For vertical and horizontal progression only the rock can be used. [...] It's practiced on specially equipped natural sites or in artificial structures. In both*

*cases there are rest and protection anchors already installed* (CAI 2013). In the last 40 years, many rock slopes have been equipped with bolts and protections for sport climbing practice. These climbing facilities have been primarily designed and implemented—often based on private funding and labor—on rock slopes, geo-sites, and geologically and historically landscape-relevant areas (Gunn et al. 2020; Marrosu and Balvis 2020). In 2016, the national board of CAI published the first Italian guidelines for the equipment of natural sites for rock climbing (CoNaGAI 2016a, b). Outdoor sport climbing is therefore increasingly contributing to the Italian geo-tourism — a term indicating a form of tourism that takes advantages of the geographical features of the visited site, from the environment to local traditions (Leonard and Mao 2003). The remarkable geological heterogeneity, geomorphological setting, and climatic conditions of many bedrock cliffs in Italy and Europe have played an important role in triggering the growth of sport climbing, which can be regarded as a specialized form of geo-tourism (Leonard and Mao 2003; Bollati et al. 2014; Borgatti and Tosatti 2010; Marrosu and Balvis 2020).

Unfortunately, this growth has not been accompanied by a coordinated effort to ensure appropriate management and safety of the climbing sites. As dynamic components of the

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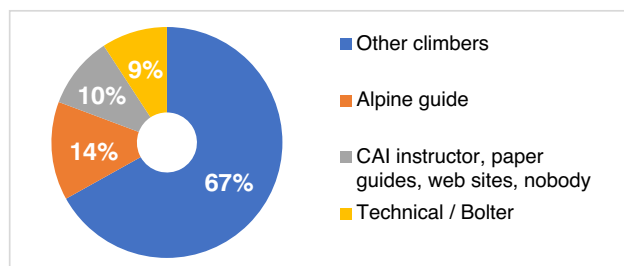
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environment, more attention should be given to the hazards potentially endangering people frequenting these locations (Panizza and Mennella 2007). In particular, climbers are usually unaware of the full range of risks involved in activities such as outdoor sport climbing, due to the often superficial knowledge of ongoing slope instability processes.

The results of a research questionnaire carried out for this study, on a sample of 146 Italian climbers, highlighted that the main vehicles of knowledge about hazard and risk in climbing sites are 67% other climbers, 14% alpine guides, 9% bolters, and 10% other subjects (Fig. 1). In the last 20 years, several methodologies have been developed to assess hazards on natural rock walls equipped for sport climbing practice, mainly by focusing on geomorphological hazard, rock quality, and tourist capability and vulnerability (Panizza 2005a; Motta et al. 2005a, b; Motta and Motta 2005, 2007; Panizza and Mennella 2007; Panizza 2009; Motta et al 2009; Borgatti and Tosatti 2010). To this aim, different forms of survey for the assessment of hazards in climbing sites were proposed in the 1990s by Amanti et al. (1994) and Amanti and Pecci (1995) based on traditional rock mass classifications (Barton 1973; Barton et al. 1974; Bieniawski 1973, 1974, 1976). Furthermore, a geomorphological-based survey methodology was proposed by Motta et al. (2009).

There have been significant recent advances in the field of close-range methods applied to geosciences. “Close-range” refers to all survey methods implying a camera/scanner-to-object distance of up to about 300 m (Wolf and Dewitt 2000). Many authors have recognized the potential and advantages of these techniques for rock slope characterization and monitoring in natural and urban environment (Abellán et al. 2009; Dotta et al. 2017; Fanti et al. 2013; Frodella et al. 2021; Gigli and Casagli 2011; Gigli et al. 2012, 2014a, b; Jaboyedoff et al. 2008; Sturzenegger and Stead 2009). Also, Borgatti and Tosatti (2010) confirmed the importance of how close-range methods combined with traditional geomechanical characterization could lead to useful methods to assess hazard in rock slope equipped for sport climbing practice. The method proposed in this study



**Fig. 1** Diagram representing the main vehicles of knowledge about hazard and risk in climbing sites. Data collected for this study are based on a sample of 146 Italian climbers

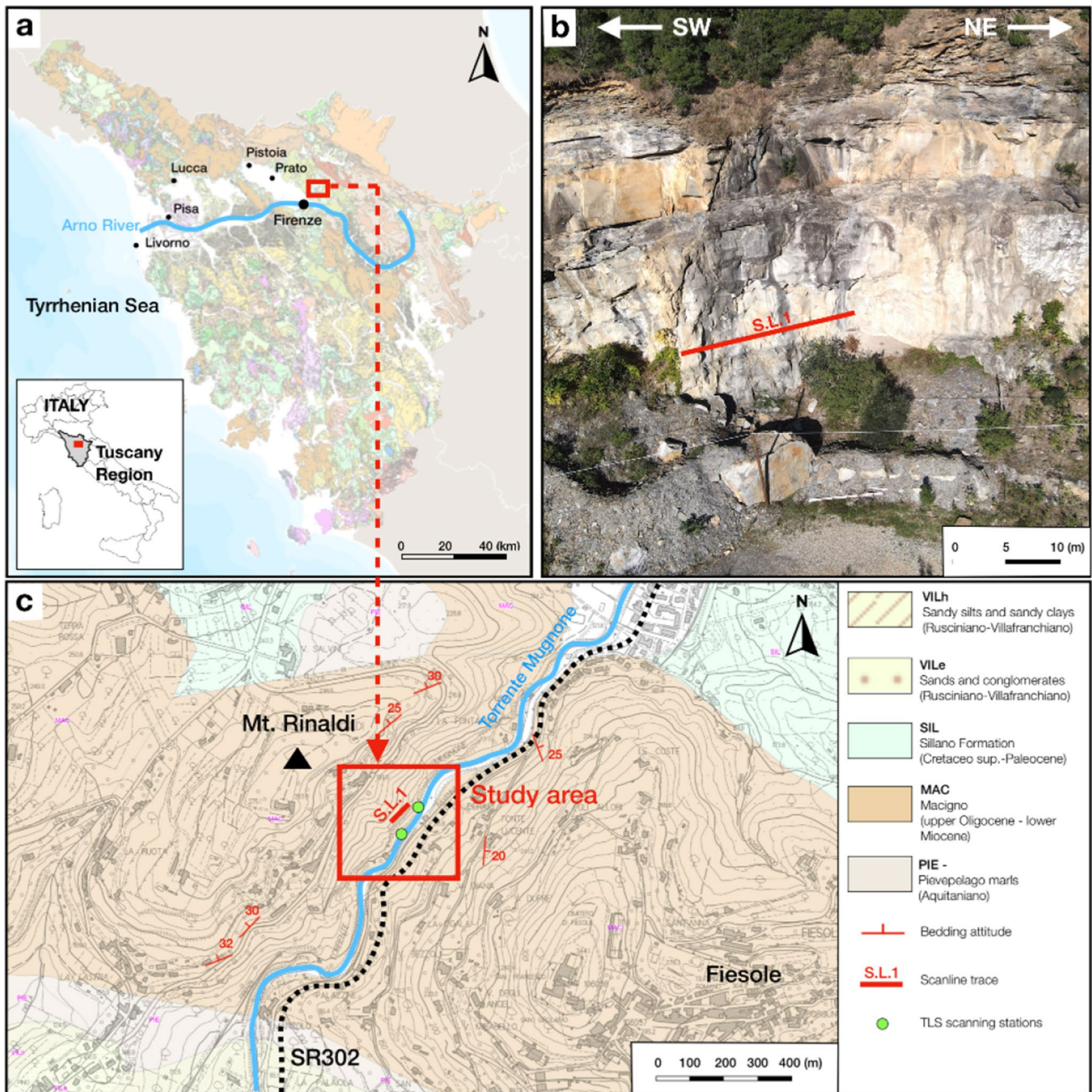
is based on two close-range survey methods: terrestrial laser scanner (TLS) and unmanned aerial vehicle-based digital photogrammetry (UAV-DP). Furthermore, this is complemented by a traditional geomechanical survey based on the suggested methods by the International Society for Rock Mechanics (ISRM 1978, 1985). For the purposes of rock mass classification, the Geological Strength Index (GSI) introduced by Hoek and Brown (1980, 2018) is used.

## Study Site

Many Italian climbing sites were born in decommissioned rock quarries (Amanti et al. 1996, 1998). The study site of this paper is an abandoned quarry where the so-called pietra serena was excavated (Rodolico 1953). This historical climbing site is located 5 km north of Florence, Italy (Fig. 2). From a lithological point of view, the cliff face exposes a sequence of Oligo-Miocene sedimentary beds of turbidite origin belonging to the Monte Modino Sandstone Formation, which can be classified as a feldspathic graywacke. This formation is characterized by alternating coarse and massive arenaceous layers, and less coherent, thinner, and darker pelitic-silty layers. It belongs to the upper part of the Tuscan Succession, which is one of the stratigraphic units that constitutes the backbone structure of the Northern Apennines. The latter is an orogenic chain with thrust and folds formed as a result of several tectonic phases occurred starting from the Upper Cretaceous. Specifically, the study area is part of an anticlinal structure that joins Mount Ceceri with Mount Rinaldi (Azzaroli 1958; Ferrini and Pandeli 1982; Bastogi and Fratini 2004). The layers generally dip towards N-NE. However, slumping and syn-sedimentary deformations, in addition to tectonic deformations, often complicate the geometry of the outcropping strata (Ferrini and Pandeli 1982). The choice of this site was suggested by the considerable knowledge of the area from a geological-scientific point of view and the high frequentation by climbers of the Faentina climbing site in 1980–2000. Moreover, in 2014, there has been a rockfall of about 120 m<sup>3</sup> that involved some of the equipped climbing routes (Fig. 3). All these features make testing and calibrating the proposed method and the route stability index (RSI) appropriate for this lithology.

## Data Collection

The proposed method is centered around in situ surveys and data collection. To obtain an accurate 3D model of the rock slope, geospatial data were obtained by close-range techniques: terrestrial laser scanner (TLS) and unmanned aerial vehicle-based digital photogrammetry (UAV-DP). Geomechanical parameters were collected by mean of a traditional scanline survey. According to Priest (1993), whenever possible, data measured by a traditional survey at the foot of



**Fig. 2** Area of study. **a** Details of Tuscany geological map 1:250,000. **b** Aerial image of the Faentina climbing site. **c** Focus on the study area, with location of the scanline (red line) and TLS surveys (green point)

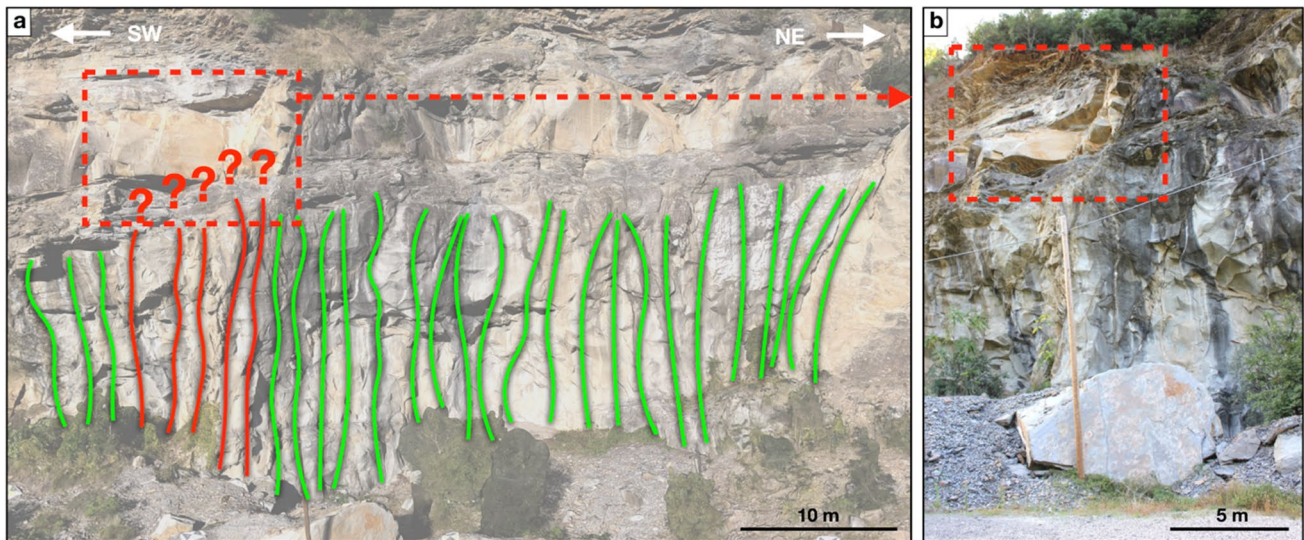
the slope should be integrated with close-range survey for validation purposes.

**UAV-DP Survey**

UAV-DP was used to create a high-resolution 3D model of the investigated rock slope. Digital photogrammetry (DP) is a rapid, efficient, accurate, and safe technique to collect 3D geometric data from stereoscopic overlaps of photo

sequences (Frodella et al. 2021). In recent years, UAV-based photogrammetric surveys have become increasingly popular in geological studies applied to landscape and environment management (Sturzenegger and Stead 2009). This has shown to provide promising improvements for monitoring and studying natural environments such as equipped sites for sport climbing. For this study, a close-range aerial photogrammetric survey was carried out using the DJI Mavic Air 2 quadcopter (Table 1). This UAV is equipped with a





**Fig. 3** **a** Maps of equipped climbing routes (green lines) overlapped on a 3D textured model of the slope. Red lines indicate routes affected by the 2014 rockfall. Question marks indicate the positions

of route tops before the landslide. **b** Detachment area (red dashed box) and related rockfall deposit

3-axis gimbal-stabilized digital camera. Three hundred fifty-five images with an overlap higher than 80% have been captured during a manual piloted flight. Structure-from-motion (SfM) image processing has been applied with the Agisoft Metashape software (Agisoft 2019). A dense point cloud of about 210,000 points was generated. After removing vegetation and unwanted objects, the number of points reduced to 146,000. This point cloud was used to generate a high-quality textured mesh composed of 34,919,399 faces and 17,465,520 vertices. To obtain a high-quality georeferenced 3D model, 10 ground control points (GCPs) were used (Fig. 4). A sub-decimeter resolution was achieved. Error results in vertical projection are due to the absence of GCPs at the top of the quarry. Thanks to the 12-megapixel resolution of the photos, a high-resolution true-colored 3D model was created. This model allowed visualization of the results obtained from the kinematic analysis and the related values of RSI for the chosen climbing routes.

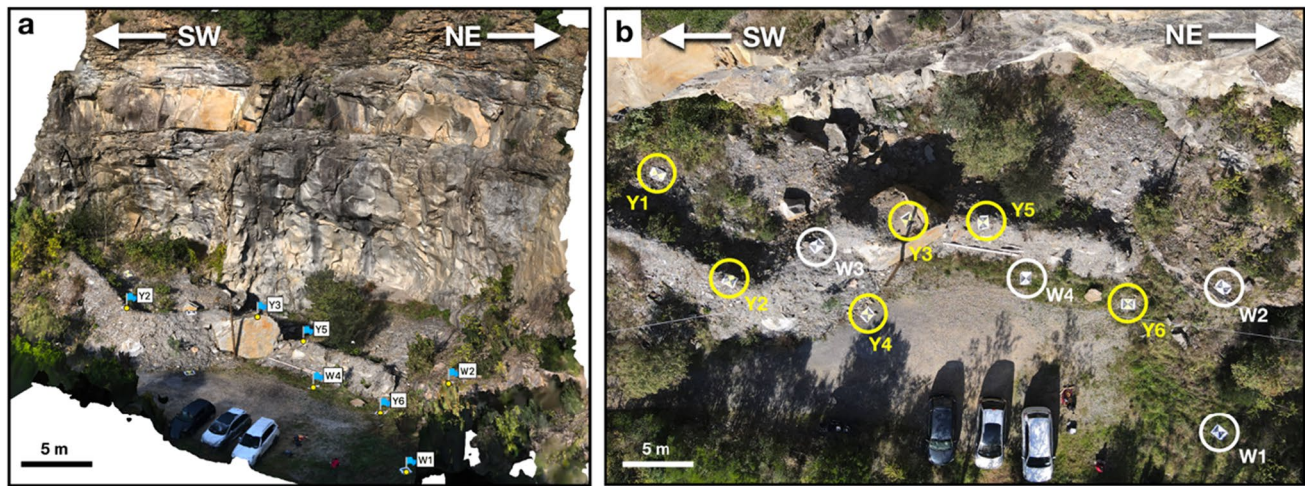
## TLS Survey

The TLS system used in this study is a RIEGL VZ-1000 with a near-infrared laser wavelength and acquisition

speed up to 122,000 points per second (Table 1). At a distance of 100 m, the instrument accuracy in a standard deviation is 8 mm and precision in a standard deviation is 5 mm (Riegl 2019). The XYZ of each point is known by its distance and relative direction from the TLS. Scanner-object distance is obtained by calculating the round-trip time of a laser pulse to reach the object surface from the emission point and return. Resolution depends on the object distance and the chosen angular spacing between two points. The manufacturer indicates that the scanning range is from 2.5 to 1400 m for a target with 90% reflectivity, and 700 m for a target with 20% reflectivity. A complete 3D point cloud of the Faentina climbing site was obtained using 2 TLS scans (001 and 002) from 2 different point of views (Fig. 5). The two point clouds were merged together in a single data set to reduce possible occlusions. Vegetation and unwanted objects were manually removed using the CloudCompare software (CloudCompare 2020). The final product is composed of approximately 105,000,000 points. Six cylindrical targets were used to georeference this point cloud, each with a GPS-scanned position with reference to the ED50/UTM zone 32 N (EPSG:23032) coordinate system. This point cloud

**Table 1** Technical information of DJI Mavic Air 2 and RIEGL VZ-1000

Devices	Weight (kg)	Sensor accuracy (")	Pixels (M)	Field of view (°)	Lens (mm)
DJI Mavic Air 2	0.57	1/2	12–48	84	24
Devices	Weight (kg)	Accuracy (mm)	Divergence (mrad)	Resolution (arcsec)	Angular step (°)
RIEGL VZ-1000	9.8	5	0.3	1.8	0.0024–0.288



**Fig. 4** a High-resolution 3D model of the climbing site with georeferenced GCPs. b Zenithal view of the study site. Markers are evidenced by yellow and white circles

was later re-sampled and the relative distance between points was set to 0.02 m. The scanner-to-slope distance was on average 25 m in both scans.

The orientation of discontinuity planes was manually extracted from the obtained three-dimensional data by means of the clustering and best fitting plane tools built into CloudCompare. In the last decade, several authors have proposed reliable discontinuity extraction approaches from 3D point cloud data (Battulwar et al. 2021) using the free and open-source CloudCompare (CC) software package, often in combination with traditional field surveys (Papathanassiou et al. 2020; Riquelme et al. 2015). In particular, the best fitting plane tool in CC, which is based on a least-squares best-fit approach, was used to calculate dip and dip direction of the generated planes. All poles to the discontinuities were plotted in a stereographic projection to identify the discontinuity sets and modal planes, which served as input for the kinematic analysis and geomechanical characterization of rock slope stability.

The TLS stereographic projection consists of 94 poles which allowed to identify 4 discontinuity sets, with BG indicating bedding and JN1, JN2, and JN3 indicating other joint sets (Fig. 5). The average orientation is 300/35 (dip direction/dip) for BG; 195/80 for JN1 (given by fairly scattered poles); 91/66 for JN2; and 286/79 for JN3.

### Field Survey

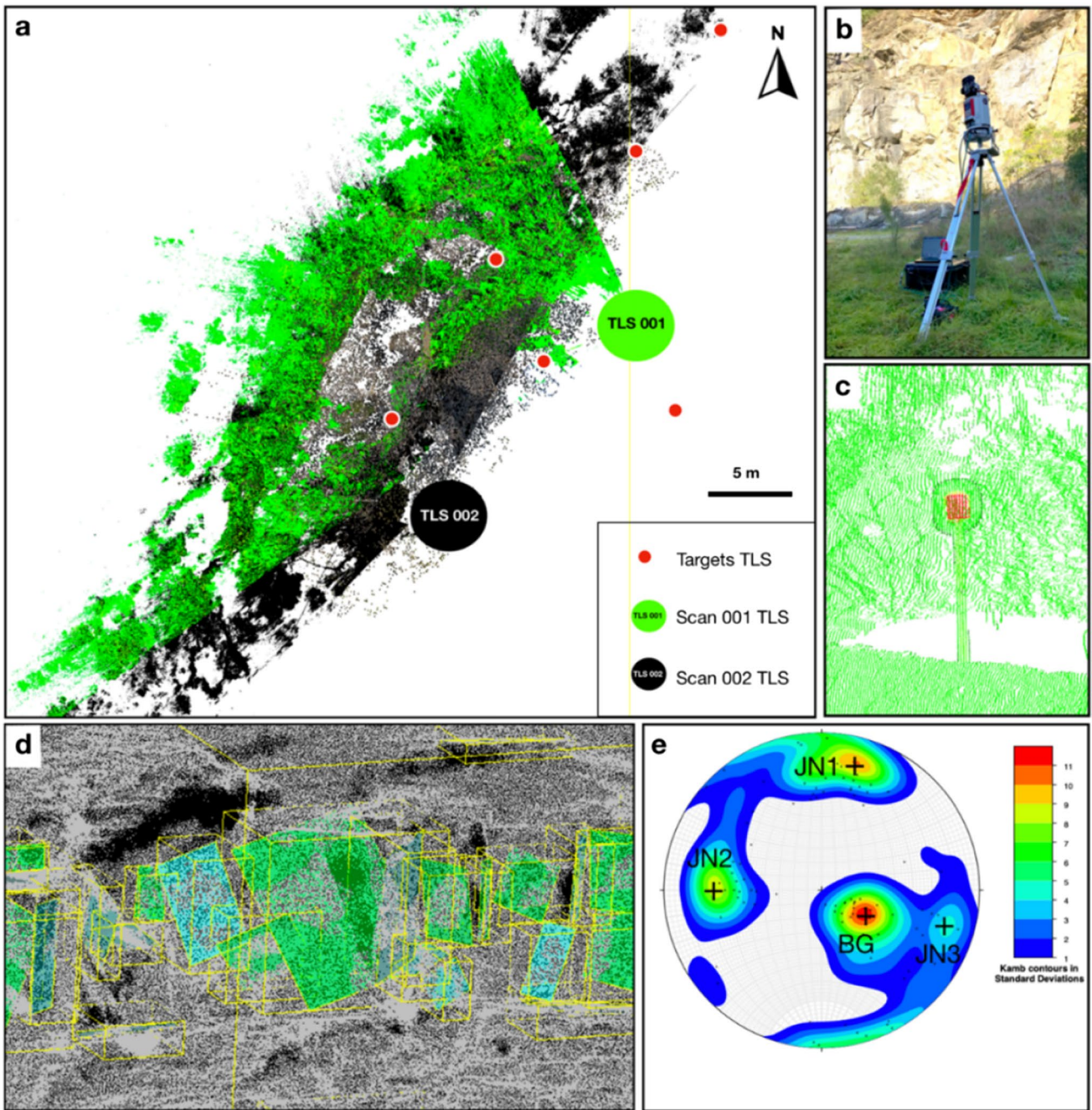
Close-range method surveys were integrated by a traditional field survey to obtain a quantitative description of the rock mass discontinuities (Borgatti and Tosatti 2010; Priest 1993). For instance, similar rock mass characterization approaches have been used in the context of discrete fracture network (DFN) modelling (Giuffrida et al. 2019,

2020; Pontes et al. 2021). For this study, only one scan-line survey (10 m long) was possible at the foot of the slope (Fig. 2) because of the hazardous state of the rock wall. Geo-mechanical data were collected by means of a Schmidt Hammer L-type and a Barton Profiler to obtain average values of joint compressive strength (JCS) and joint roughness coefficient (JRC), respectively. Measurements were carried out according to the methods suggested by ISRM (1978, 1985), allowing the estimation of the main geo-mechanical features (orientation, aperture, trace, persistence, roughness, joint wall strength) of the discontinuities (Table 2).

### Kinematic Analysis

In order to identify the potential rock failure mechanisms, a spatial semi-automatic kinematic analysis (Gigli and Casagli 2011) was carried out by comparing the rock face orientation with the geometric arrangement of the discontinuity sets. The kinematic analysis allows to map the spatial probability of occurrence for the following instability mechanisms: plane failure (PF) (Hoek and Bray 1981), wedge failure (WF) (Hoek and Bray 1981), block toppling (BT) (Goodman and Bray 1976), and flexural toppling (FT) (Goodman and Bray 1976). For each instability mechanism, a kinematic hazard index ( $C$ ) was calculated based on the ratio between the number of poles ( $N$ ) or intersections ( $I$ ) belonging to the respective critical area within the stereographic projection and the total number of poles (Casagli and Pini 1993):





**Fig. 5** TLS survey. **a** Zenithal view of the two TLS point clouds (green point cloud is the 001 scan, black point cloud is the 002 scan), scanning workstations (black and green circles) and targets (red circles). **b** RIEGL VZ-1000 scanner. **c** Observed reflectivity of the target

in the TLS point cloud. **d** Manually extracted best fitting planes on CloudCompare. **e** Stereographic projection of the 94 poles to the discontinuities manually extracted from the point cloud

$$C_{PF} = \left( \frac{N_{PF}}{N} \right) \cdot 100$$

$$C_{BT} = \left( \frac{N_{BT}}{N} \right) \cdot \left( \frac{I_{BT}}{I} \right) \cdot 100$$

$$C_{WF} = \left( \frac{I_{WF}}{I} \right) \cdot 100$$

$$C_{FT} = \left( \frac{N_{FT}}{N} \right) \cdot 100$$

**Table 2** Characteristics of the measured joints along the traditional scanline survey. \* for trace X, beyond outcrop; R, against rock; D, against discontinuity; \*\* for Schmidt Hammer average rebound (R) values are reported

N° JN	X (m)	Alpha (°)	Beta (°)	Termination (*)	Trace (m)	Aperture (mm)	JRC (1–20)	Sclerometer (**)
1	0.07	285	70	DD	6	3	4–6	18 (inclined 90°)
2	0.4	265	90	DR	5	2		
3	1.3	180	70	XX	10	2	6–8	23 (inclined 90°)
4	2.1	185	80	RD	1.3	2	8–10	18 (inclined 90°)
5	3.55	334	75	DD	1.2	0	2–4	26 (inclined 90°)
6	3.7	210	78	DR	1.5	1		
7	5.15	173	68	RR	5	2		
8	6.65	218	70	DR	7	1	6–8	21 (inclined 90°)
9	7.3	183	75	RR	3	1		
10	7.4	173	85	DD	7	3		
11	8	185	63	DD	1.5	2		
12	8,15	187	87	DD	3	1		
13	10.2	215	73	DR	6	2		
14	10.4	173	78	XX	10	3	10–12	23 (horizontal)

This analysis was performed using a MATLAB tool called DiAna-K. The input parameters were slope orientation, discontinuity orientations (dip and dip direction as manually extracted from the TLS point cloud), and an averaged basic joint friction angle of 30°. A resultant peak friction angle of 44° was derived by using an average JRC of 7 with the approximation proposed by Maksimović (1996). Intersections and equivalent friction angles were automatically calculated. The output results of this kinematic analysis can be exported in .xlt, .txt, or .stl file extension. The 3D kinematic analysis results show the spatial distribution of the relative kinematic hazard index values on the surface of the investigated climbing site (Fig. 6). A color scale quantifies the probability occurrence values for each instability mechanism, with color varying from low probability values (blue) to high probability values (red).

The study case showed relatively high values of kinematic hazard index. Higher values were related to PF (max 27%) and FT (20%). WF probability (17%) is also significant. Only BT shows a very low index (less than 1%). Moreover, a global kinematic index (GKI) was calculated to quantify the overall rock instability hazard of the slope, regardless of the source instability mechanisms. For this study, GKI reaches very high values of up to 43%, testifying the tendency of the investigated climbing site to generate structurally controlled failures.

### Route Stability Index

The concept underlying the RSI is that every climbing itinerary, one-pitch or multi-pitch, often intersects areas affected by possible instability mechanisms along its progression. The proposed index (RSI) aims to correlate and unify the

geomechanical properties of rock mass and the critical areas that a climbing route crosses in his path by returning a relative value of route hazard. The area involved in the calculation of RSI is called “climber’s action area” and extends approximately 1.5 m to the right and 1.5 m to the left of the climbing route.

The RSI is defined as follows:

$$RSI = (0.4 \cdot \ln JCS - 0.84) \cdot GSI \cdot \left[ 1 - \left( \frac{GKI_{mean}}{100} \right) \right]$$

where:

JCS: joint compressive strength;

GSI: Geological Strength Index;

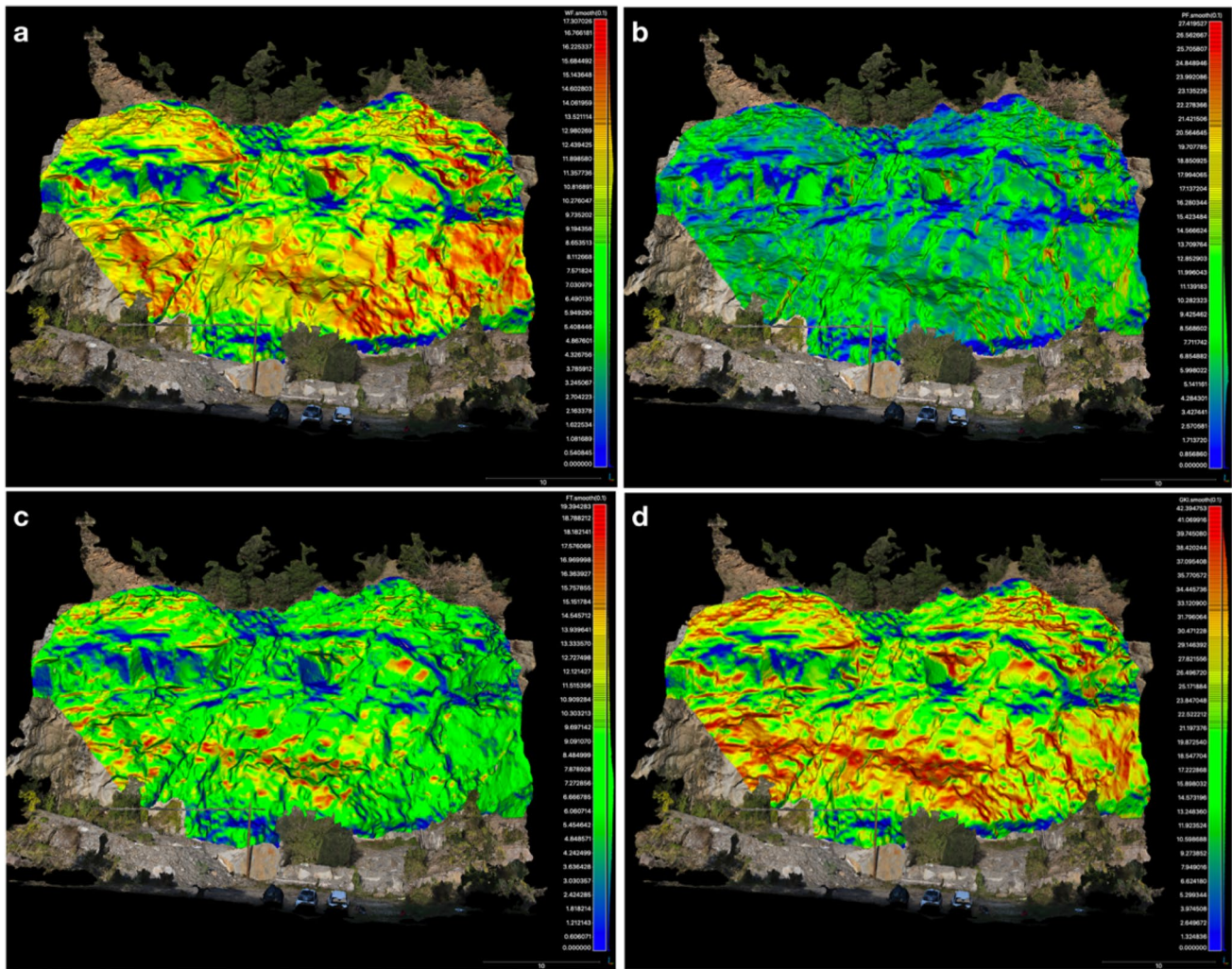
GKI<sub>mean</sub>: average of the global kinematic index distribution.

The use of JCS, GSI, and GKI to define the route stability index (RSI) is due to the fact that each parameter carries information about rock mass strength, specifically its state of fracturing, the state of discontinuity weathering, and the kinematic predisposition to instability mechanisms.

The equation is composed of three factors:

- (1)  $(0.4 \cdot \ln JCS - 0.84)$  is an adimensional factor varying between 0 and 1 (Fig. 7a). Input values of JCS must be higher than 9 MPa in order to have positive value of natural logarithm. For  $JCS \geq 100$  MPa, the input value remains 100.
- (2) GSI (Hoek and Brown 1980) is the Geological Strength Index. For this case study, a GSI chart specifically designed for flysch formations was used (Hoek and Brown 2018).
- (3)  $\left[ 1 - \left( \frac{GKI_{mean}}{100} \right) \right]$  is an adimensional factor varying between 0 and 1 (Fig. 7b) that takes into account the





**Fig. 6** Results for the 3D kinematic analysis overlapped on the 3D mesh of the study site. **a** Wedge failure (WF) max value 17% (deep red color). **b** Planar failure (PF) 27%. **c** Flexural toppling (FT) 19%. **d** Global kinematic index (GKI) up to 43%

global kinematic index (Fig. 6d). Input values of  $GKI_{mean}$  range from 1 to 99 and represent the statistical average of GKI values distribution, with 0 and 100 having no meaning.

The calculation of RSI relatively to a single climbing route returns an adimensional numerical value that can be subjectively translated into a color class: red if the value ranges between 0 and 25 (low stability value); orange if between 25 and 50 (medium stability value); and yellow if between 50 and 100 (moderate stability value).

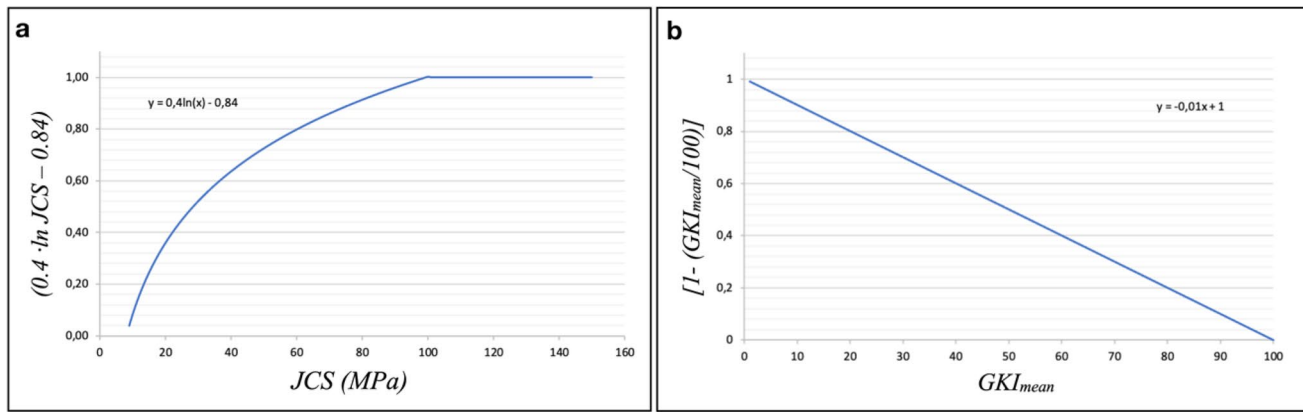
By making reference to these colors, every climber, alpine guide, environmental guide, or CAI instructor can quickly understand the relative hazard of each climbing route for their goals.

The investigated climbing site allows to validate the proposed method and the RSI (Fig. 8) for the case of flysch lithology. For this study, six equipped climbing routes were chosen

to calculate the RSI. A Geological Strength Index equal to 60 was evaluated in the field (GSI in the range 55–65), while JCS and average JRC have been respectively estimated to be 34 MPa and 7 from the traditional scanline survey. Then, a  $GKI_{mean}$  was obtained by the kinematic analysis carried out in the climber's action areas of the six routes (Fig. 8a). Using the presented formula, RSI values have been subsequently obtained. The colors resulting from the RSI were overlapped on the high-quality 3D model of the site (Fig. 8b). Two routes have an orange color (medium stability value) and all the other routes are red (low stability value).

Several rockfalls occurred in the past years allowed to tentatively propose the limits between the different RSI classes. The presence of red and orange colors (yellow is absent) testifies the potentially critical stability of the rock face. The attribution of a red color is due to the fact that each climber's action area of the red routes is predisposed to several instability mechanisms, as visually verified in the field.





**Fig. 7** **a** Graphic visualization of the factor  $(0.4 \cdot \ln JCS - 0.84)$ . **b** Graphic visualization of the factor  $\left[1 - \left(\frac{GKI_{mean}}{100}\right)\right]$

So, subjective judgement is still necessary at this moment for the interpretation of the RSI. The RSI thresholds between red–orange and orange–yellow may become more statistically driven in the future as other rock walls equipped for sport climbing practice are investigated.

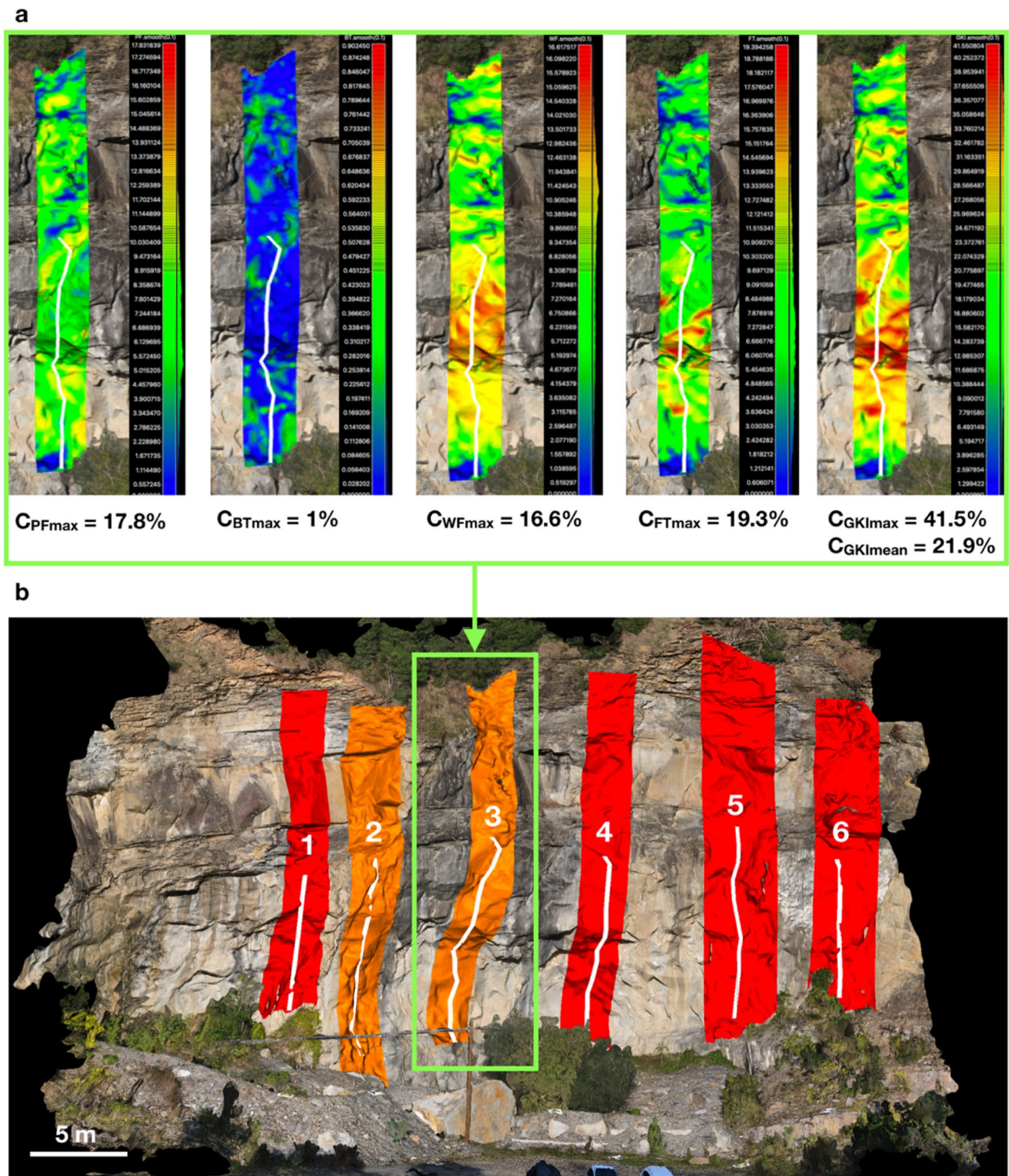
### Discussion

Most of the Italian regions have optimal geological and geomorphological characteristics for the practice of outdoor sports such as sport climbing, trekking, and canyoning (Leonard and Mao 2003; Marrosu and Balvis 2020). All these activities take place outdoors, in natural environment. In the last 40 years, several sport climbing sites have been equipped around the world within national parks, geoparks, and geosites. In Italy, there is a consolidated geo-tourism for outdoor sports in regions such as Sardinia, Valle d’Aosta, Trentino-Alto Adige, Liguria, and Tuscany (Motta et al. 2005a, b; Motta and Motta 2005, 2007; Panizza and Mennella 2007; Panizza 2005b, 2009). Unfortunately, the growth of this sport branch has not been accompanied by a coordinated management project ensuring an appropriate use of climbing sites. Marrosu and Balvis (2020) highlighted that practicing outdoor sport such as sport climbing could lead to an unsustainable development of tourism in delicate natural environments. Moreover, the awareness of people who usually practice this kind of activities is superficial and exposes them to natural hazards. The validity of this latter point has been further testified by the survey conducted during the course of this study: in Fig. 1, it is shown that the main vehicles of knowledge about hazards and risks in climbing sites are 67% other climbers, 14% alpine guides, 9% bolters, and 10% other subjects. Due to this, Borgatti and Tosatti (2010)

pointed out the importance of giving correct information about rockfall-related hazard in climbing sites by means of strategically placed warning panels.

This research pointed out the possibility to improve the awareness of outdoor sport practitioners using geomechanical hazard assessment to evaluate the probability of active instability mechanisms on equipped rock slopes. To this goal, TLS and UAV-DP techniques allowed us to obtain a detailed georeferenced three-dimensional model of the investigated slope. Differently from methods previously proposed in the last two decades, which are based primarily on in situ evaluation and geomorphological characterizations (Motta et al. 2005a, b; Motta et al. 2009), this study demonstrates how close-range methods coupled with semi-automatic kinematic analysis and in situ survey could provide improved insights into the assessment of rock wall hazards for sport climbing activities. Indeed, the aim of any hazard assessment method should be to identify the location and distribution of possible sources of rock falls. Thanks to TLS and UAV-DP, it is now possible to obtain increasingly accurate and reliable results. On the obtained high-resolution point cloud, a rock fall susceptibility analysis was carried out to identify possible critical areas. The obtained susceptibility indexes vary on a scale from 0 to 100%. The results of this rockfall probability assessment were governed by the rock mass structural setting, not taking into account the influence of rockfall triggers such as rainfall, seismic activity, and wind. This close-range procedure was integrated with field observations carried out on traditional geomechanical survey (measurement of JCS, JRC, orientation, trace, aperture, and termination of discontinuities).

At the study site, kinematic analysis of four modes of failure was conducted (Fig. 6 and Fig. 7a): plane failure (PF), block toppling (BT), flexural toppling (FT), wedge failure (WF). The



**Fig. 8** Example of RSI application to the study case. **a** Kinematic analysis results related to the “Climber’s action area” of route 3. Results are visualized on the UAV-DP-based mesh. **b** RSI colors

chart for six sport climbing routes in the investigated climbing site (low-medium stability values)

highest index values were produced by PF (27%) and FF (23%), then by FT (19%) and WF (17%). The assessment of the overall

rockfall susceptibility is quantified by a global kinematic index (GKI). The latter reach values up to 43% of probability that at

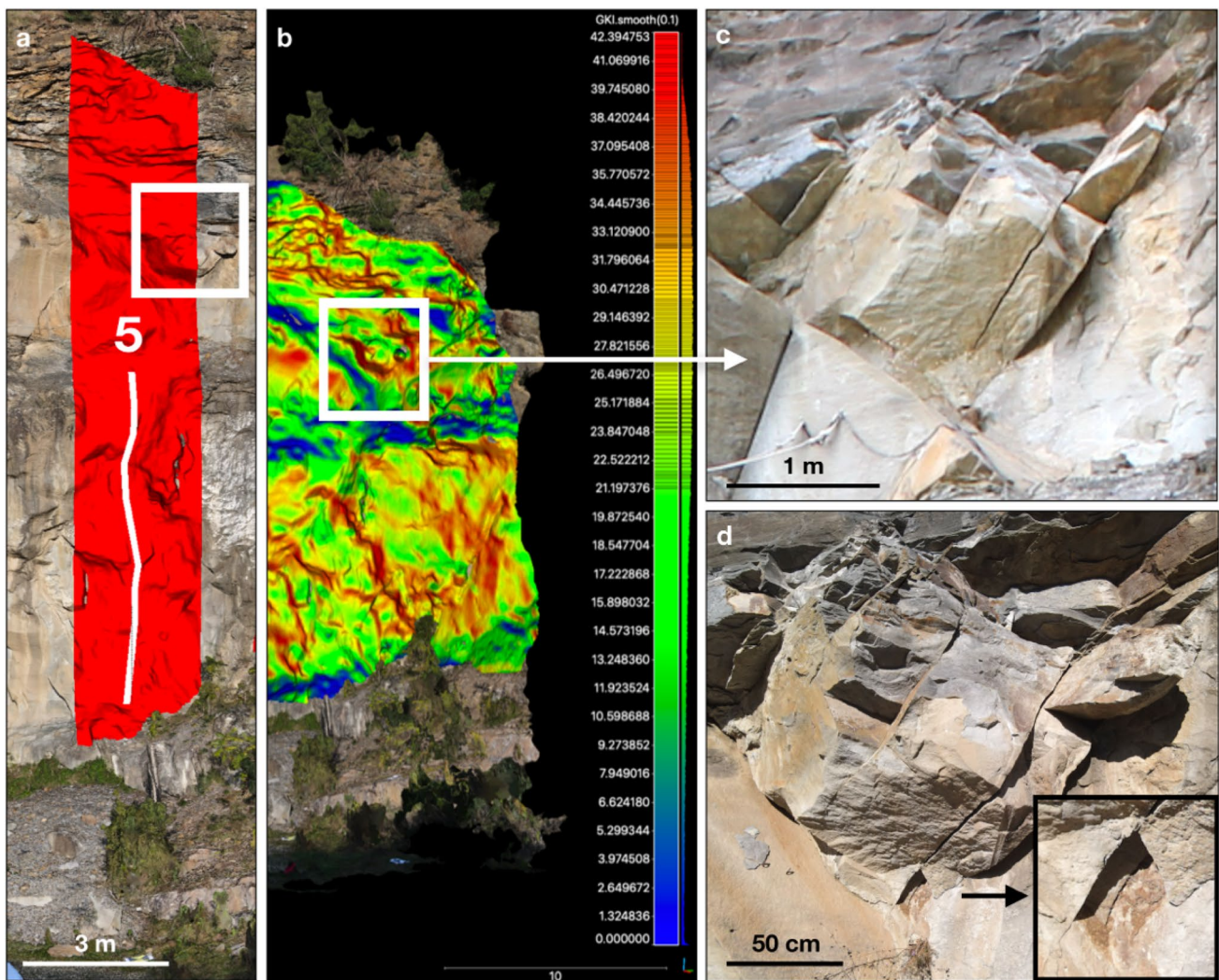


least one of the failure mechanisms is kinematically feasible on the slope (Fig. 6d). A visual inspection was carried out in situ to validate the critical areas highlighted by the procedure results. Thanks to the proposed route stability index (RSI), the obtained data about rockfall susceptibility are merged with rock quality data to return a value (and a color) that give us an idea of how hazardous each climbing route is. To assign the thresholds between different colors, a subjective evaluation made by an operator on the field is at this time necessary. To confirm whether these values are appropriate, continuous monitoring could be implemented to quantify real rockfall events occurred on the identified route climber's action areas. To this aim, a 1-year visual monitoring was carried out in the study site to check out any possible precursory sign of rockfall. The most interesting structurally controlled rock failure mechanism identified on the

rock slope was the failure of a key-block at the bottom of an unstable wedge. The latter was highlighted during the kinematic analysis (WF=17% and GKI=42%) and is located at the top of the climber's action area of the climbing route number 5 (Fig. 9).

The study confirms the possibility to obtain quick and useful data to be processed in a relatively short time. The importance of the proposed method lies in the fact that hazard assessment, and calculation of RSI, can be done both on climbing site already equipped with bolt and anchors and on climbing sites still to be equipped.

When a climbing site requires a geological/geotechnical report for preliminary studies for safety aims, RSI can already give an idea of which rock slope sectors could be more safely equipped for sport climbing practice.



**Fig. 9** Example of visual survey's result aimed to confirm the reliability of the proposed RSI. After 1 year from the first survey, a key block at the bottom of an unstable wedge has fallen. This wedge has reached the highest values of WF (17%) and GKI (42%) as a result of the preliminary kinematic analysis carried out for the rock slope. **a**

RSI applied to the climbing route number 5, red color. The wedge is identified by the white square. **b** Max value of GKI is reached at the base of the wedge. **c** RGB image of the wedge in July 2019. **d** Same wedge in July 2020, a key block has fallen at the bottom of the wedge

## Conclusions

The proposed method aims to quantify the probability of structurally controlled instabilities on rock walls equipped for sport climbing. Thanks to the three-dimensional properties of the outputted data, visualization of the route stability index (RSI) is user-friendly. RSI expresses the relative tendency to instability of the studied rock slope. Three color classes are assigned to the calculated RSI values: yellow, orange, and red. When the climber's action area (i.e., 1.5 m on the right and 1.5 m on the left of the climbing route) is red, values falling in the low stability class are produced by the analysis ( $0 < \text{RSI} < 25$ ); orange indicates medium stability ( $25 < \text{RSI} < 50$ ); and yellow indicates moderate stability value ( $50 < \text{RSI} < 100$ ). Of course, hazards and risks are always present in outdoor sports and cannot be eliminated. They are inherent part of outdoor sports and activities and people should have appropriate awareness of that. According to the CoNaGAI guidelines (2016a, b) regarding the implementation of the equipment of climbing sites, bolters and climbers should acquire a more detailed knowledge about geological risks and environmental restraints. To this goal, this study highlighted the fact that the proposed method to quantify the relative kinematic hazard of each sport climbing routes can become a useful tool for risk management in areas equipped for sport climbing practice. Trained and aware climbers can reduce the probability to get injured, or even die, during the practice of sport climbing. So, the basic principle of this study is to provide a tool to preemptively raise the awareness of climbers about existing rockfall hazards.

The method can be applied to geological contexts similar to the presented study site. To apply this procedure on other rock slopes equipped for sport climbing practice, further validation and calibration of the RSI are warranted if markedly different lithologies (igneous and metamorphic) or sedimentary facies are involved.

**Funding** Open access funding provided by Università degli Studi di Firenze within the CRUI-CARE Agreement.

## Declarations

**Competing Interests** The authors declare no competing interests.

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