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A COMPREHENSIVE 3D GEOLOGICAL MODEL OF THE NORTH-EASTERN SECTOR OF THE SAN LEO PLATEAU

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EXTENDED ABSTRACT

L'abitato di San Leo, con la sua storica fortezza, sorge su una rupe rocciosa isolata nel cuore della valle del Fiume Marecchia (Rimini, Emilia-Romagna). Esistono iconografie storiche, come i dipinti del Vasari (1560), del Mingucci (1626) e l'incisione ad acquaforte di J. Balaeu (1633), che mostrano una rupe ben più estesa e con una diversa morfologia. Il crollo avvenuto nel febbraio 2014 è infatti solo l'ultimo di una lunga serie di fenomeni franosi che nei secoli hanno modellato la rupe e che con essa minacciano la sicurezza della città di San Leo e del suo patrimonio storico. San Leo è stato dichiarato "abitato da consolidare" ai sensi della L. 445/1908 con D.P.R. 217 del 18 gennaio 1951. Dal 2004, con adozione del Piano Stralcio per l'Assetto Idrogeologico (PAI) Marecchia-Conca, tutta la fascia di territorio attorno alla rupe di San Leo è perimetrata, ai sensi della L. 267/1998, come area a rischio idrogeologico molto elevato. Negli ultimi settant'anni sono stati eseguiti diversi interventi di consolidamento delle pareti rocciose, in particolare lungo la parete sud, sede dell'abitato e della via di accesso all'abitato stesso e lungo la parete est, nel settore occupato dalla fortezza. A partire dagli anni Ottanta, gli interventi per la mitigazione del rischio hanno riguardato anche le aree ai piedi della rupe, con l'intento di ridurre l'azione erosiva dei fossi Campone e Seripa e impedire lo scalzamento alla base della rupe, che è stato all'origine dei grandi crolli come reso evidente dalla frana del 2014. Nonostante gli interventi eseguiti nel passato più o meno recente il rischio da frana rimane ancora elevato. Dopo il crollo del 2014, la rupe di San Leo è stata oggetto di un approfondito studio multidisciplinare che ha visto e vede l'impiego di diverse tecniche di indagine e di monitoraggio per la prevenzione e la mitigazione del rischio. In particolare, in questo lavoro sono presentati i risultati del rilevamento geomeccanico effettuato sulla sommità della rupe, sulle carote e sulle pareti dei fori di sondaggio e l'integrazione dei dati in un modello tridimensionale che è stato generato con tecniche di telerilevamento.

La rupe di San Leo è composta da calcareniti epiliguri poggianti su argilliti liguri ed è intensamente fratturata presentando più sistemi di fratture che la suddividono in blocchi progressivamente ribassati verso i margini, quale effetto di processi tettonici e gravitativi (fossili e recenti) subiti nel corso della sua storia geologica. Il contesto geologico, strutturale e geomorfologico implica una forte predisposizione al dissesto per frana. Su tutto il perimetro della rupe sono presenti evidenze di frane di diversa tipologia e dimensioni che vanno dal semplice distacco di piccole porzioni di roccia aggettante al crollo di cospicue masse rocciose con conseguente arretramento del fronte.

Dato il contesto, la caratterizzazione dell'ammasso roccioso gioca un ruolo chiave nello studio del versante e nella progettazione di misure di mitigazione del rischio strutturali e non strutturali. Il modello geologico 3D del settore orientale della placca rocciosa di San Leo è stato sviluppato attraverso l'integrazione di dati ottenuti da laser scanner e rilievi fotogrammetrici digitali uniti a rilievi geomeccanici di carote e pareti di fori di sondaggio grazie a videoispezione. Il modello evidenzia come l'area lungo la scarpata nord-orientale, formata dall'evento del 2014, sia caratterizzata da un numero elevato di fratture, mentre l'area circostante la strada per la fortezza di San Leo lungo la rupe orientale presenti meno fratture, ma in numero maggiore aperte e localizzate prevalentemente in prossimità delle pareti laterali. Inoltre, sono stati valutati due possibili scenari di collasso, in cui è stato emulato il meccanismo di rottura dell'evento del 2014 con fratture sub-parallele alla scarpata e conseguente collasso di un volume roccioso pari a 429.000 m^3. Infine, è stata analizzata la persistenza e il comportamento delle fratture coinvolte in questi scenari, indicando che tali eventi sembrano non essere imminenti. Si può quindi affermare che la realizzazione e l'analisi del modello geologico-strutturale 3D della rupe di San Leo ha consentito un'analisi approfondita della persistenza delle fratture rilevate sulla sommità della parete e il calcolo del potenziale volume di blocchi isolati dalle fratture stesse.

Le ricerche in corso di svolgimento utilizzeranno il modello geologico tridimensionale della rupe in modo da indagare la geometria e il comportamento meccanico in profondità delle diverse unità geologiche che compongono l'ammasso roccioso, valutando la persistenza delle fratture principali anche rispetto ai dati di monitoraggio anche per localizzare i microsismi che si generano all'interno dell'ammasso roccioso in risposta alle dinamiche gravitative in atto.

ABSTRACT

The town of San Leo, situated in the northern Apennines of Italy, is subject to slope instability phenomena due to its geological/structural setting. The 3D geological model of the eastern sector of the San Leo rocky plateau has been developed through the integration of data obtained from laser scanning and digital photogrammetric surveys along with core drilling geomechanical analysis. The geological features have been integrated into one single model that enables the visualization of all structural features of the plateau, including superficial and in-depth discontinuities. The model highlights how the area rear of the northeastern scarp, formed by the 2014 landslide event, is highly fractured, whereas the eastern cliff presents lower fracture intensity. Two possible collapse scenarios have been simulated in relation to the fracture analysis that has been carried and emulating the 2014 failure mechanism, that involved a rock volume around 330.000 m^3. The analysis of persistence of the fractures involved in these scenarios indicate that such events appear not to be imminent at the present time.

Keywords: *3D geological model, geomechanical analysis, remote sensing, landslide volume*

INTRODUCTION

The town of San Leo, situated in the Northern Apennines of Italy, is a scenic spot renowned for its cultural heritage, being one of the most visited locations across the country (Fig. 1A-B). Due to the slope instability of the rocky plateau over which the city lays, the area has been declared a site with consolidation requirements since 1951.

The San Leo rock slab has been affected by numerous instability phenomena throughout its history, predominantly pertaining to lateral spreading mechanisms and secondary processes, such as rockfalls and earthslides-flows (Benedetti *et alii*, 2013; Giardino *et alii*, 2015). As a matter of fact, the San Leo plateau is subject to mass movements due to its geostructural features, being characterized by a highly fractured calcarenite plateau embedded in clay-rich terrains. Throughout the past decades, several mitigation works have been performed in order to consolidate the steep rock walls along the plateau edges (Lucente, 2019). However, after a major landslide event that occurred in 2014 affecting the northeastern cliffs (Borgatti *et alii*, 2015, Fig. 1A), it was deemed essential to investigate the rock slab in order to promote further risk assessment and mitigation actions.

The 3D geological model of the San Leo plateau developed in the current study presents the ultimate goal of providing a description of the rock mass structure and discontinuity pattern, as to obtain a better understanding of the rock mass behavior and its implications on short and long-term slope instability. Such geological model has been developed by integrating field geomechanical/structural surveys, Terrestrial Laser Scanning (TLS) and Unmanned Aerial Vehicle (UAV) data with borehole data.

The use of TLS and UAV for rock slope analyses has become common in the last few years (Lato *et alii*, 2009; Donati *et alii*, 2017; Francioni *et alii*, 2020). These techniques allow to gather important information about the morphology of the slopes and the geometry/setting of superficial discontinuities affecting the area of study (Sturzenegger & Stead, 2009). Conversely, the study of borehole data is important to describe the lithology characterizing the area and the orientation of in-depth discontinuities.

The integration of such information into a single 3D model can be of significant value in characterizing the behavior and stability of rock slopes. In this study, field- and remote sensing-based surface data were combined with borehole data in a 3D geological model, in order to infer the geometry/persistence of the open discontinuities identified in proximity of the 2014 rock failure crown. Such analysis allowed for a preliminary evaluation of slope stability and for the calculation of the volume of potential rock failures.

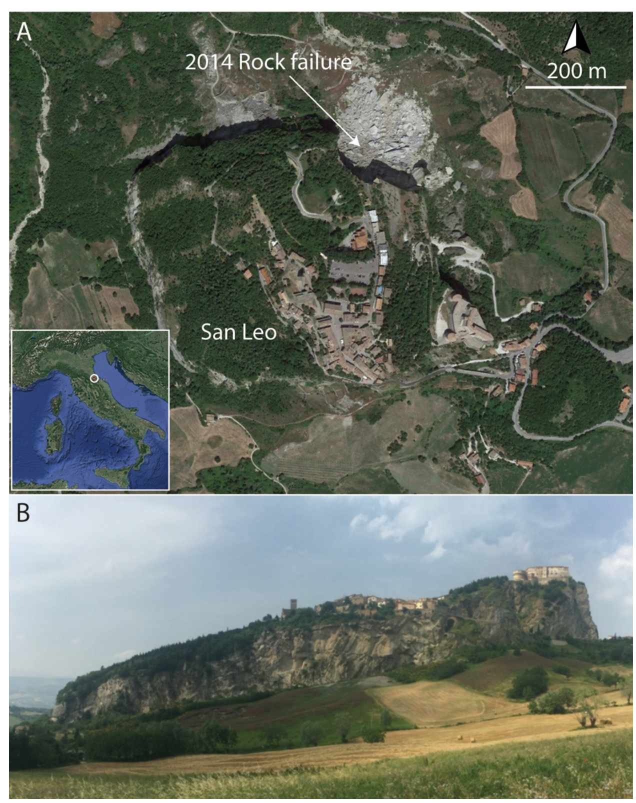

Fig. 1 - A) Location of the San Leo plateau and 2014 failure. Source: Google Earth, 2019. B) View of the town from South

MATERIALS AND METHODS

The San Leo plateau is composed by Epiligurian calcarenites resting on top of Ligurian clayshales. The interplay between geological units displaying different mechanical and rheological properties promotes lateral spreading, with tensile stresses concentrated in the stronger rock (Spreafico *et alii*, 2017). The long-term geomorphological evolution causes the progressive development of subvertical and overhanging cliffs crossed by high angle discontinuities along the edges of the rock slab. Although the rate of displacement is extremely slow, secondary rapid instability phenomena might occur (Spreafico *et alii*, 2017; Spreafico *et alii*, 2016). Given the context, the characterization of the rock mass plays a key role in the assessment of slope stability.

In this research, data obtained from different surveys methods were combined into a single 3D geological model. The surface geometry of the model was reconstructed by combining 3D point clouds derived from TLS and UAV surveys. The software CloudCompare was used to register and merge the point clouds, and to extract the orientation and persistence of surficial geostructural features. Geotechnical logging of seventeen boreholes, distributed across the San Leo slab (Figure 2), was also performed to measure the orientation and spacing of discontinuities. Eight boreholes (B01-B08) were drilled for the installation of the monitoring system along the crown of the 2014 landslide event. Eight boreholes (B09B and B09 to B15) were drilled along the road approaching the San Leo fortress in the south-eastern zone of the slab. A vertical borehole (BL01), drilled on the road along the eastern cliffs, was also logged.

Fig. 2 - Location of the boreholes in the north-eastern sector of the plateau (Source: Google Earth, 2019)

An optical televiewer (OPTV) was also used to carry out video inspections of the borehole walls. The OPTV employs an optical imaging system (i.e., a downhole CCD camera) to generate a true colour image of the borehole wall. The result is a 360° continuous and oriented image that can be used to map and compute the orientation and aperture of discontinuities. Finally, a conventional geomechanical and structural field inspection has been performed to map the open fractures located in the vicinity of the 2014 crown and the north-eastern edge of the cliff. Such fractures have been integrated with data from boreholes using the software Rhinoceros 3D.

Using the location, orientation, and length of the boreholes (Tab. 1), it has been possible to reproduce their geometry in the 3D model, together with the intersected discontinuities. Figure 3 shows the resulting 3D geological model (visualized in Rhinoceros 3D), including the 3D model of one of the boreholes (BL01) displayed as an example (Fig. 3C).

Borehole (year)	Length (m)	Dip Dir. (°)	Dip (°)
BL01 (2014)	110.57	0.00	90.00
B01 (2014)	32.50	90.00	5.00
B02 (2014)	14.80	55.00	2.00
B03 (2015)	25.10	54.00	30.00
B04 (2015)	20.70	358.00	30.00
B05 (2015)	28.20	63.00	5.00
B06 (2015)	46.60	66.00	15.00
B07 (2015)	71.00	74.00	7.00
B08 (2015)	67.20	343.00	30.00
B09 (2017)	12.50	90.00	30.00
B09B (2017)	20.00	95.00	30.00
B10 (2017)	19.00	90.00	17.50
B11B (2017)	22.40	85.00	25.00
B12 (2017)	22.60	80.00	10.00
B13 (2017)	45.00	114.00	25.00
B14 (2017)	36.60	100.00	15.00
B15 (2017)	62.30	109.00	15.00

Tab. 1 - Construction date and characteristics of installed boreholes

Once all the mapped fractures (surficial and in-depth ones) have been included in the 3D model, the geometry of major discontinuities has been extrapolated in order to infer their persistence and the potential risk of future failures. This has been carried out by extending the surficial fractures at depth (using their dip and dip direction) and verifying if such fractures come to cross one or more boreholes. In the event that fractures with similar orientation were observed in proximity of the potential intersection between the borehole and the extruded plane, it has been assumed that such surficial fracture is persistent from the plateau summit down to the position of the corresponding intersection at depth.

Once the geometry of the major discontinuities has been defined, two possible failure scenarios have been simulated in relation to the fracture analysis and the back analysis of the 2014 failure mechanism, that involved a rock volume around 330.000 m^3.

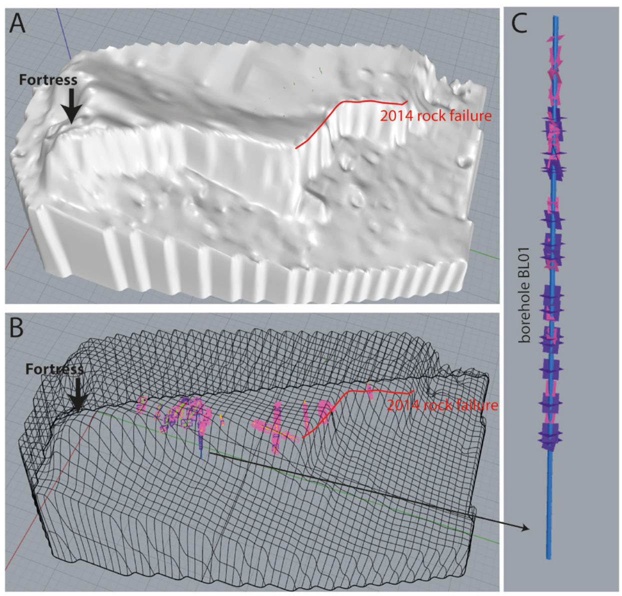

Fig. 3 - A) 3D model representation of the San Leo Plateau. B) Wireframe of the 3D model of San Leo plateau with borehole data included. C) 3D representation of Borehole BL01

RESULTS

Rock mass features at surface and at depth

A total of 554 fractures have been extracted from boreholes, 73 of which are open and 481 closed. Overall, three discontinuity sets have been identified through the stereonet of borehole data (Fig. 4A). This agrees with discontinuity sets extracted from the TLS/UAV 3D point clouds (Fig. 4B and Fig. 5A) and with previous studies (Spreafico *et alii*, 2015).

A good agreement was also noted between the highly persistent open fractures identified on the top of the rocky plateau and the sets extracted from borehole data and TLS/UAV point clouds. The joint sets K1 and K2 display a very high inclination and a NNW-SSE direction (due to their similarity, these two sets appear as a single set, K1, in the stereonet). The fracture set K3 display a high inclination and NW-SE direction. The set K4 has a direction similar to K1/K2, but with a lower dip angle (around 50°). The western lateral release surface is parallel to the set K1. This part of the rupture surface is referred to as K1.4. The northeastern cliff edge pertaining to the crown of the 2014 landslide presents the same geometry of K3 fractures. The surface of rupture is formed, in general, by planes with high dip angles, at least 70°, and dip directions towards the northeast or the southwest, ranging from 20° to 40° or 200° to 220°, respectively. Due to this, the rupture surface as a whole has been named K3.0 (Fig. 6B). Two parallel fractures associated with the joint set K3, referred to as K3.1 and K3.2 and respectively located 25 m and 45 m behind the crown, were also identified on the summit of the slab and are (Fig. 6B).

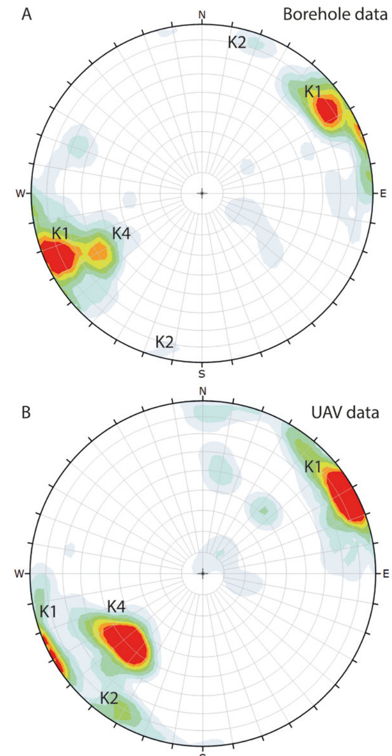

Fig. 4 - Discontinuity sets identified through boreholes (A) and UAV (B) data

Once the geometry of surficial major discontinuities has been defined, the fractures K1.4, K3.1 and K3.2 have been extended in depth using their dip and dip direction. Then, all the boreholes crossing the extruded surfaces were analyzed (Fig. 6C) to verify the presence of fractures with similar geometry in proximity of such intersection (accounting for a tolerance of ± 0.2 m with respect to the approximate location). It has been found that K3.1 intersects boreholes B04, B05 and B08 at a depth of 13 m, 9.50 m, and 8.50 m, respectively. The K3.1 fracture does not extend throughout the boreholes B06 and B07 and therefore is not continuous within the rock mass and its continuity decreases towards the center of the plateau.

It is noteworthy to mention that such fracture could reach deeper zones, but a more accurate characterization would require drilling of additional boreholes in the northeastern area of the San Leo plateau.

The discontinuity plane K3.2, only intersects two boreholes, B06 and B07. Borehole B08 is located close to K3.2, but no evidence of K3 fractures has been found in the borehole data. The

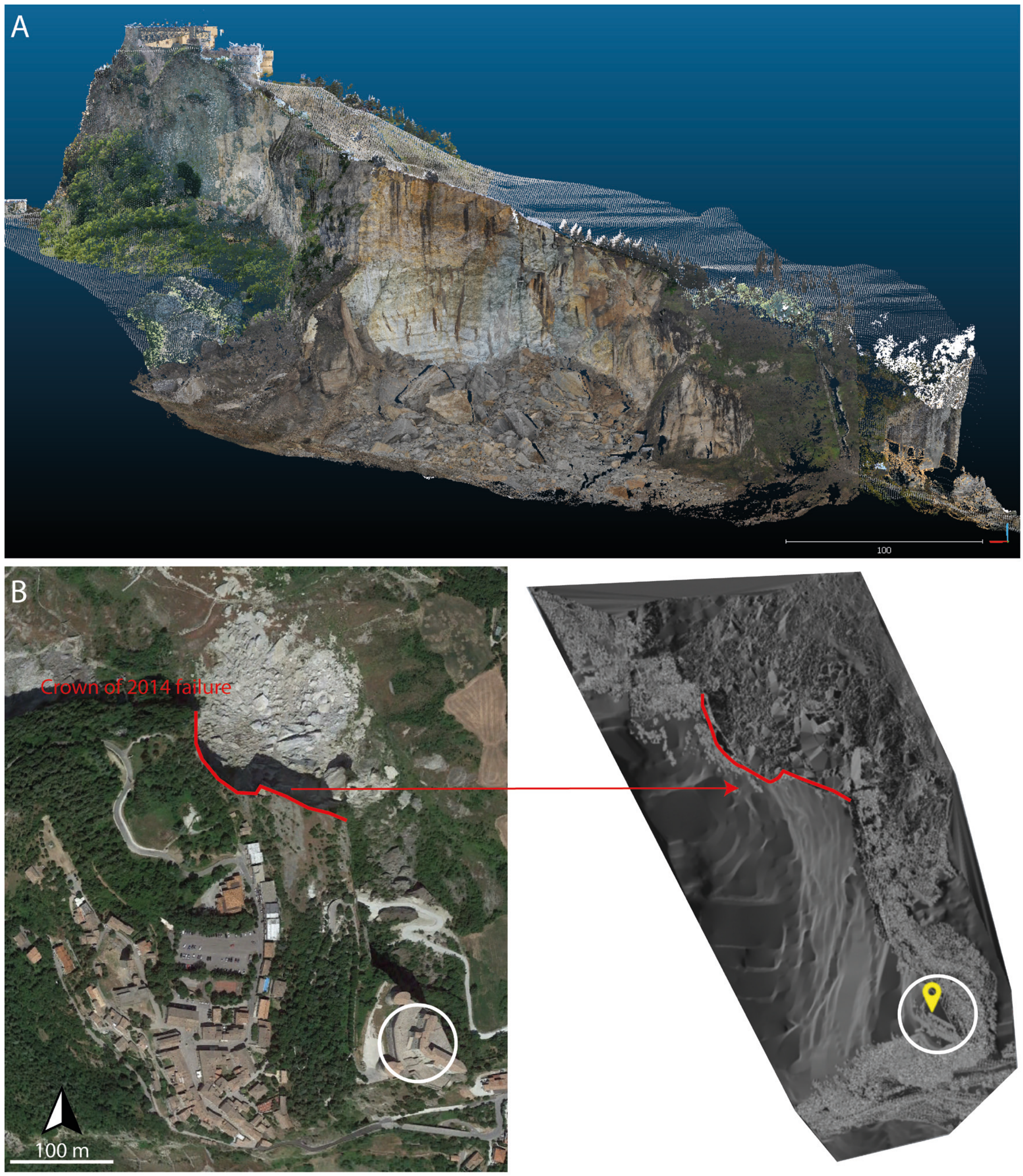

Fig. 5 - A) 3D point cloud extracted from TLS and UAV surveys. B) Area affected by the 2014 rock failure and 3D representation of the same area in the 3D Rhinoceros model. The white circle shows the location of the fortress, visible in the far left of the point cloud in A

in-depth persistence of the fracture K3.2 is therefore estimated at around 20 m.

The K1.4 discontinuity was found in B06 at a depth of 16 m. No evidence of such discontinuity has been found in borehole B07, suggesting that also in this case the continuity of the fracture decreases towards the center of the plateau.

Although fractures K3.1, K3.2 and K1.4 are clearly visible on the slab surface, they do not seem to be fully persistent in depth. These fractures extend for at least 10 m in depth, and do not appear to cut through the entire thickness of the plateau. Among these, the most persistent fracture is the K3.1, which was observed in borehole B08. However, the persistence of K3.1 is still significantly lower than that of fracture K3.0, which formed the rupture surface of the 2014 event and is about 65 m long and 40 m wide.

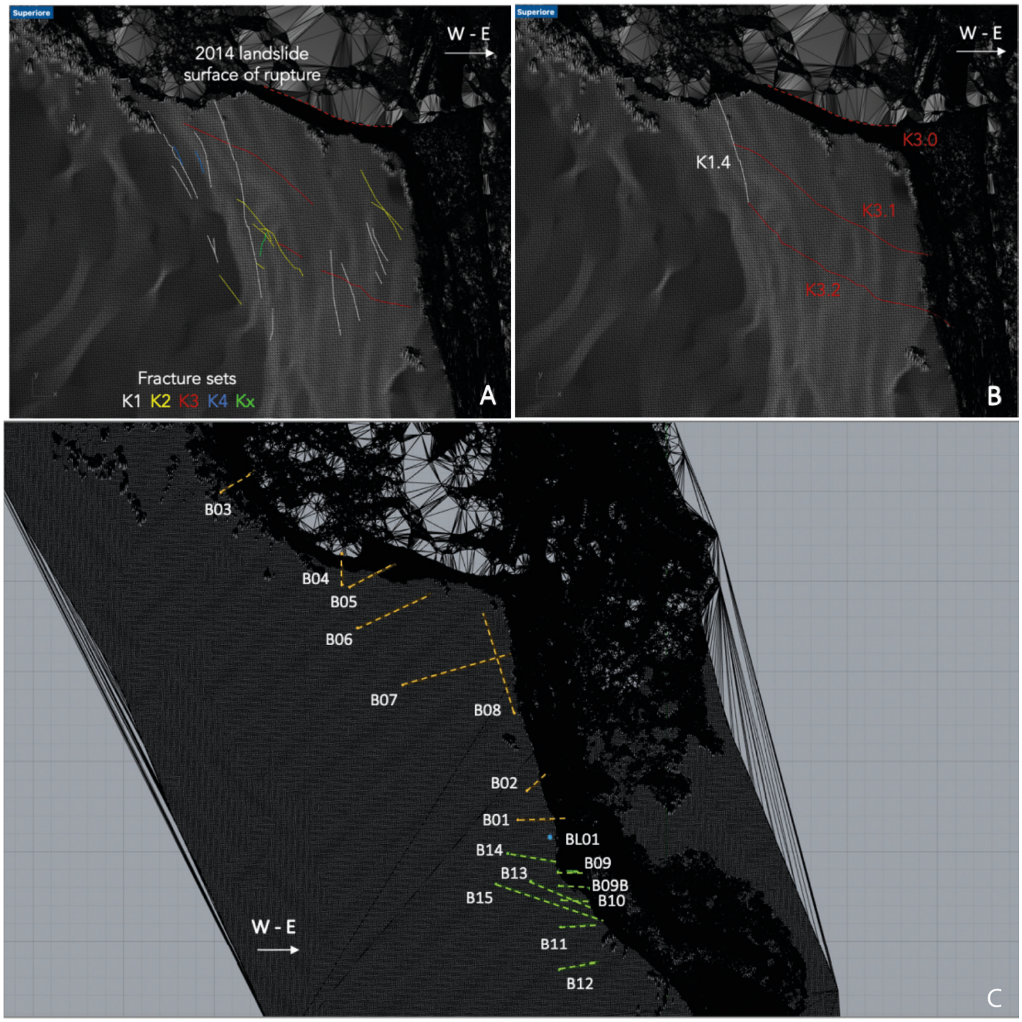

Fig. 6 - A) Fractures identified on the slab summit. B) Fractures involved in possible failure scenarios. C) Boreholes location and traces in a plan view

Failure Scenarios

Two collapse scenarios of the northeastern sector of the plateau have been evaluated. The 2014 slope failure exploited the pre-existing discontinuity plane K3.0 (Fig. 6B). The same kinematics have been emulated for the fractures K3.1 and K3.2, located approximately 25 m and 45 m south from the present-day scarp, respectively. The superficial fractures K3.1 and K3.2 have been considered the failure surfaces of the simulated scenarios. For both scenarios, the fracture K1.4 was considered a lateral release surface. Since the discontinuity planes involved in the rock slope failures have been extended and included within the 3D model of the San Leo plateau, it has been possible to define the potential volume of the rock failures along K3.1 and K3.2 (Fig. 7).

The first collapse scenario, corresponding to the failure of the rock mass bounded by fractures K3.1 and K1.4, implies a cliff retreat between 20 and 30 meters along the northeastern edge, generating a failed volume of 240,000 m^3. The second scenario would generate a further cliff retreat of additional 20 to 25 meters. The rock volume collapsing in the case of failure along the K3.2 discontinuity plane amounts for an additional 188,000 m^3. In the event of a single failure along the K3.2 discontinuity plane, the cliff edge would be subject to a 40- to 50-meters retreat with respect to the K3.0 discontinuity plane (i.e., the 2014 surface of rupture), generating a volume of 428.000 m^3. These values are comparable with the 300,000 m^3 volume displaced in the 2014 landslide, which resulted in a 40 m cliff retreat, approximately. It is noteworthy to mention that the two landslides simulated in the present study could also trigger further collapses of the north-eastern scarp, as it actually occurred during the 2014 event, implicating the displacement of an even greater rock volume.

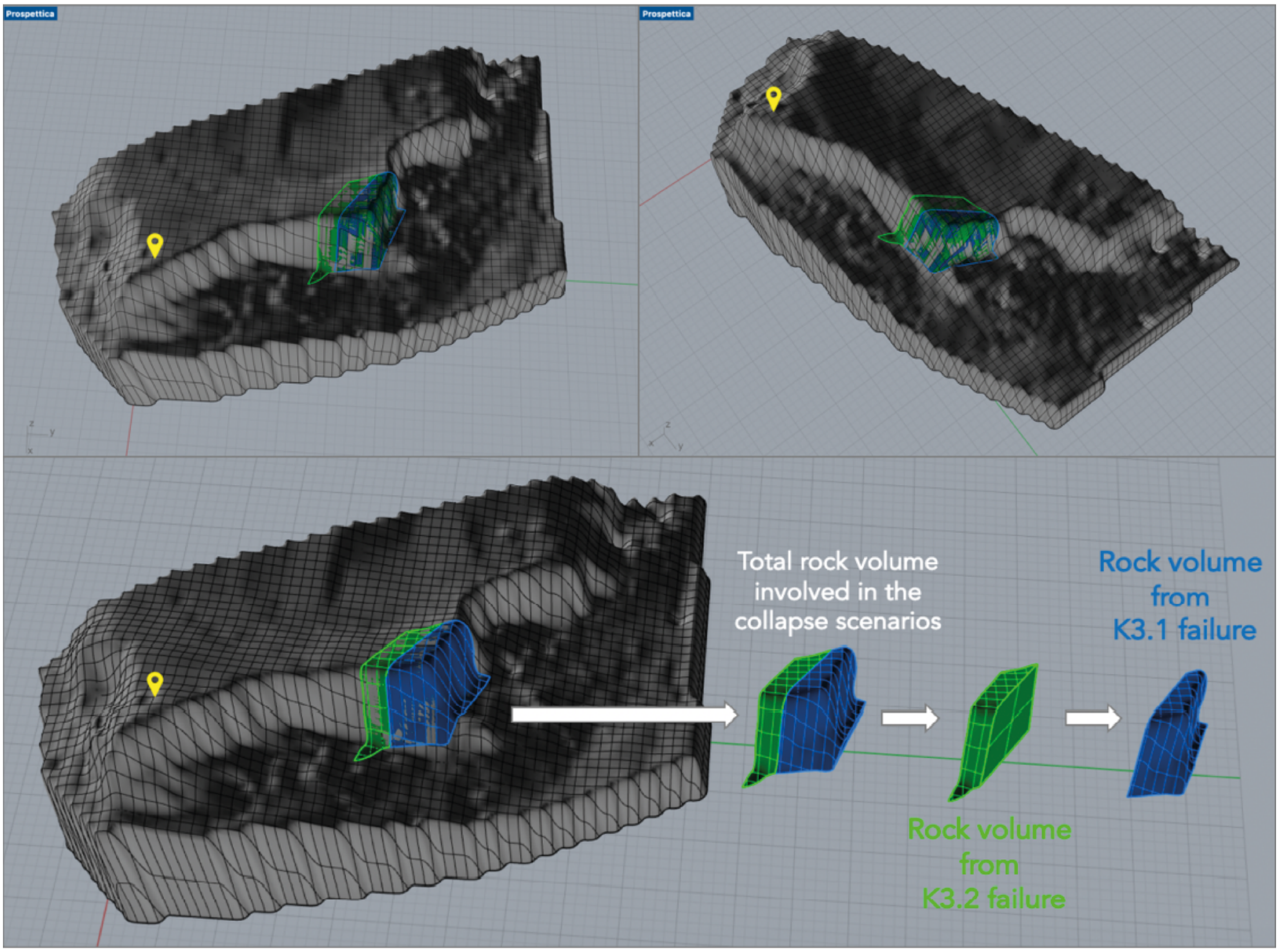

Fig. 7 - Rock volume involved in the collapse scenarios along the K3.1 and K3.2 discontinuity planes

DISCUSSION AND CONCLUSIONS

The 3D geological model of the San Leo plateau has been developed through the integration of data gathered with TLS, UAV and geomechanical surveys at surface and at depth (borehole data). In summary, a total of 24 open fractures were surveyed along the summit of the plateau. From the analysis of borehole data, 554 fractures were detected within the rock mass, including 73 open and 481 closed fractures. Additionally, 90 discontinuities were measured at the cliff surface using the TLS/UAV point cloud. The three datasets highlighted the presence of three main joint sets, K1, K3 and K4.

Along the northeastern scarp formed by the 2014 landslide event an extremely high number of closed fractures and a few open fractures (4.50%) have been found. Conversely, the area surrounding the road to the San Leo fortress along the eastern cliffs presents fewer fractures in general, but the percentage of open fractures among the features detected reaches the 30%. This might be a consequence of the 2014 event: the present-day northern cliff is carved in what was an inner and less fractured portion of the rocky slab, while the eastern sector is still in a pre-failure condition.

The analysis of superficial and in-depth (borehole) fractures has shown that some surficial fractures have high persistence and propagate at depth. This demonstrates that the surficial lineaments are the evidence of an ongoing deformation and displacements at a larger scale, as a consequence of lateral spreading mechanisms and stress release along the borders of the plateau. Nevertheless, it was noted that most of the open fractures identified on the summit of the San Leo plateau might propagate within the rock mass as closed discontinuities, if they even propagate at all.

The observation in three-dimensions of the plateau and the data from borehole and geomechanical survey has allowed for the construction of the 3D geometry of K3.1, K3.2 and K1.4

and the evaluation of their persistence. It has been observed that the K3.1 fracture reaches a maximum depth of 13 m near the eastern cliff edges, which decreases to 8.50 m towards the center of the plateau. Both fractures K3.2 and K1.4 show prominent and consistent lineaments throughout the north-eastern slab surface, but their persistence at depth within the rock mass does not seem substantial. It is noteworthy to mention, however, that a more accurate analysis of the persistence of such fractures would require the execution of further in-depth surveys in the north-eastern area of the San Leo plateau.

Based on the mechanism of the rock failure occurred in 2014, two possible collapse scenarios have been evaluated in the north-eastern cliffs. The fractures K3.1 and K3.2, located approximately 25 m and 45 m south from the cliff edge K3.0 were considered as failure surfaces. The release fracture considered for both scenarios is the discontinuity K1.4, intersecting the K3 lineaments on the summit at a distance of 90 meters from the eastern cliff. In this manner, it has been established that the rock volume in case of failure along the discontinuity plane K3.1 would be around 240,000 m^3, whereas the subsequent failure along K3.2 would amount to a collapsed rock volume of 188,000 m^3. Ultimately, in the case of a single failure involving both K3.1 and K3.2, the rock volume involved would increase to 429,000 m^3, similar to the volume involved in the 2014 landslide.

The construction of the 3D geostructural model of the San Leo plateau has allowed the in-depth analysis of fracture persistence and the calculation of potential volume of failures. It is recommended that future research should adopt the presented three-dimensional geological model of the San Leo plateau to a) make inquiries about the geometry of the different geological units that compose the rock slab, b) perform the persistence assessment of the K1, K2 and K4 fractures along the cliffs, c) evaluate the rock mass behavior through the monitoring system, and d) determine the origin of microearthquakes generated within the San Leo rock mass.

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