PAPER • OPEN ACCESS

Rockfall hazard assessment of the Monte Gallo Oriented Nature Reserve area (Southern Italy)

To cite this article: F Cafiso *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **833** 012176

IOP Conf. Series: Earth and Environmental Science **833** (2021) 012176 doi:10.1088/1755-1315/833/1/012176

Rockfall hazard assessment of the Monte Gallo Oriented Nature Reserve area (Southern Italy)

F Cafiso[2], C Cappadonia[1], R Ferraro[3] and C Martinello[1]

[1] Department of Earth and Marine Sciences, University of Palermo, 22 Via Archirafi, 90123 Palermo, Italy
[2] Geotechnical engineer, Palermo, Italy;
[3] Geologist, Palermo, Italy

chiara.cappadonia@unipa.it

Abstract. The Monte Gallo area is a carbonate relief that develops a significant nature reserve and highly attracts tourism to the urbanized area of the City of Palermo (Southern Italy). The slopes are affected by several rockfall events, which have also caused death, injuries, material damage, and a strong social and economic impact. Here, a detailed geological and geotechnical study to assess the rockfall hazard relating to two sectors of the mount has been carried out. The hazard assessment at the slope scale was performed based on geological, geomorphological, geomechanical, and seismic analysis. Using both analytical and empirical methods and by means of different software, the reconstruction of the propagation areas for the eastern sector of the Mount was possible. Results were used to better understand the overall structure, characterize the rockfall source areas' kinematics, and recognize the basic failure mechanisms. The obtained runout areas were compared with each other and with those of previous studies conducted in a neighboring area, as well as with the corresponding hazard area maps of the official cartography, which is being updated. It is expected to be supplemented with maps derived from empirical models.

1. Introduction

The coastal sector of central-northern Sicily ranging from Capo Zafferano to Capo San Vito is characterized by isolated carbonate reliefs that are fundamental for the territory from an economic, social, tourist, and naturalistic perspective. The peculiar lithological and structural setting, the climate conditions, and the seismicity of the area define the conditions for the triggering of rockfall phenomena which have caused considerable material damage and, in certain cases, the loss of human life as well. These structures result from the ancient and the recent tectonic evolution that led to the present-day arrangement of the chain sector of the Sicilian collisional complex. The sizes and type of rockfall differ depending on the structural setting and the morphological processes on the slopes; the extension of propagation areas of the rockfall is conditioned by various factors such as the block size, the outcropping lithology, and slope morphology. In these areas, there are elements that are potentially at risk. Therefore it becomes essential to define the potential hazard areas to assess the risk on the territory and planning mitigation interventions. For the study area (Monte Gallo, Northern Sicily), the map containing potential block propagation areas is available (hazard zones of the national guidelines of the Italian Basin Master Plan for geo-hydrological risk mitigation - PAI). These maps overview the landslides and could be implemented through additional studies useful for planning and monitoring geomorphological risk. To provide a scenario for the danger in consideration, the analysis of the eastern sector of the Mount has been carried out; the result of such analyses is the area of propagation of the landslides and the potential trajectories of the boulders. Geological and geotechnical analyses have been conducted, and the acquired data were processed using the 'reach angle' empirical model [1,2] and the 'lumped mass' analytical model [3,4]; in this way, it was possible to obtain the runout zones and trajectories respectively; in addition, such applications have been conducted employing different software both open source and paid. The achieved results were compared with each other and to the hazard maps of the PAI [5] and those of previous studies in a sector close to the study area [6,7].

2. Methods

2.1. Geological and Geomorphological setting of the study area

Monte Gallo (561m a.s.l.) is a carbonate relief that extends for about 5km in the SW-NE direction (figure 1) from inland to the Tyrrhenian coast. It is delimited by steep slopes overlooking the plain where the City of Palermo is located and the Tyrrhenian Sea [8,9]. The whole area of the Mount forms part of a natural-oriented reserve. The study area is a sector of the emerged Sicilian Fold and Thrust Belt (FTB), which results from the deformation of the deep-water and carbonate platform tectonic units [10]. In the Monte Gallo area, the outcropping lithologies belong to the Structural Stratigraphic Units resulting from the deformation of the Panormide Domain [11] characterized by homogeneous lithologies (pelagic carbonates, mainly) intensely fractured and karstified as Monte Gallo and Cozzo di Lupo tectonic units (figure 2a) which were progressively superimposed along with N–S trending thrust [8]. The present-day setting results from the Plio-Quaternary extensional and transtensional tectonic events which have dissected the older structures.

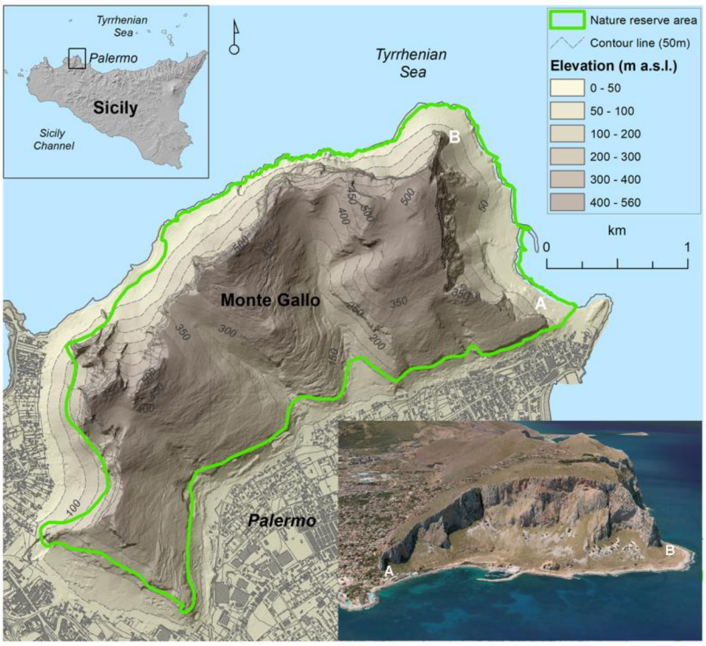


Figure 1. Location map, elevation and panoramic views (Google Earth^{TM}) of the study area (A-B).

The outcropping lithologies in the studied sector (figure 2b,c) are mainly dolostones and dolomitized limestones in massive beds intensely fractured and karstified (figure 2b,c). The lowest altitude outcrops are slope debris formed by coarse grains and blocks of carbonate nature and, to a lesser extent, quaternary deposits like calcarenites and conglomerates.

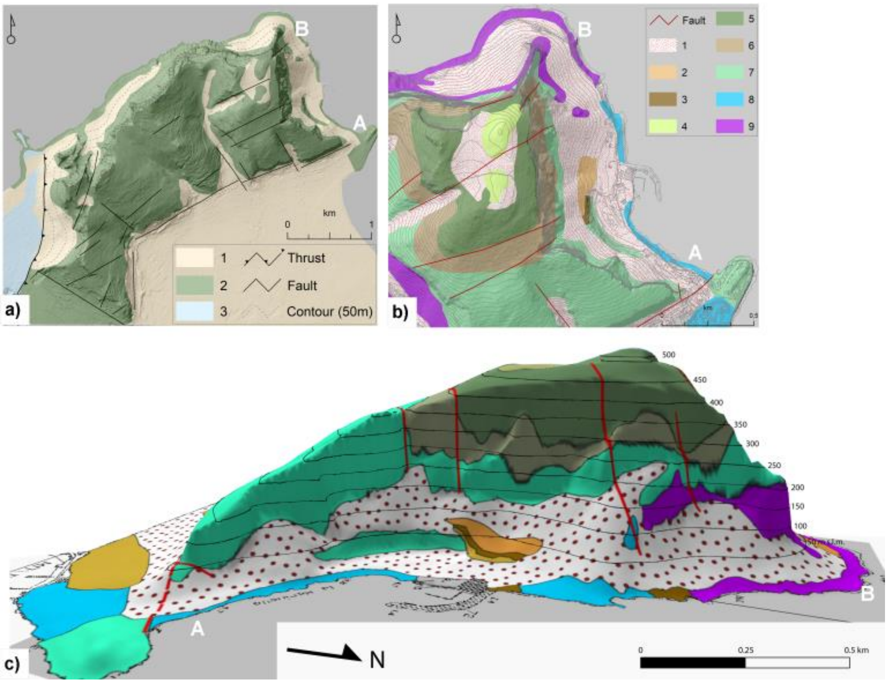


Figure 2. a) Tectonic scheme: 1 Pleistocene deposits; 2 - Monte Gallo tectonic unit; 3 - Cozzo di Lupo tectonic unit; b) Geological map (modified from [8,11]): 1- Detritus and poorly sorted materials; 2 - Stratified slope deposits with soils intercalations and cross-laminated aeolian sandstones and sands; 3 - Cross-laminated aeolian sandstones; 4- Bioclastic packstone-to-rudstone; 5 - Bioclastic packstone and floatstone; 6 - Bioclasticwackestone-packstone; 7 – Wackestone alternated with thin loferitic packstone; 8 - Dolomitized wackestone alternated with loferitic packstone and breccias; 9 - Dolostones and dolomitized limestones in massive beds; c) 3D geological view.

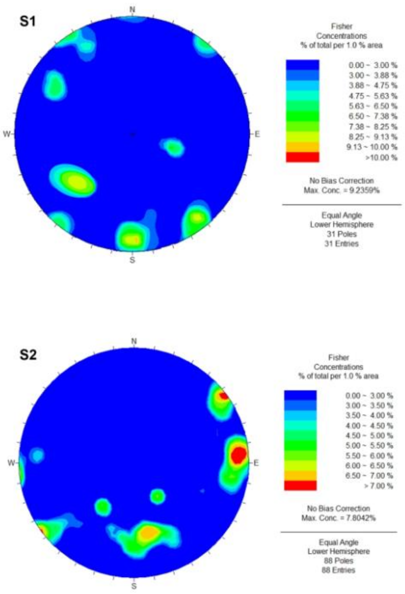
2.2. Geo-mechanical analysis

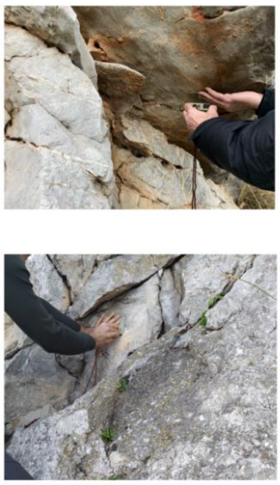
The rocky faces are affected by several rockfall phenomena. To determine geo-mechanical characteristics of the rock masses and characterize the kinematics of the rockfall source areas and recognize the basic failure mechanisms sensu [12], detailed geological and geostructural surveys have been carried out. Plane failure, wedge failure, toppling, and rock-fall have been recognized by identifying the main sets of discontinuities and their geometric relationships.

IOP Conf. Series: Earth and Environmental Science **833** (2021) 012176 doi:10.1088/1755-1315/833/1/012176

Figure 3. Discontinuities, unstable rock blocks, and boulders in the rock walls affected by rockfall phenomena.

The data of the scanline surveys were contoured using Dips 5.109 software; the results for two representative sectors (S1, S2) are presented in figure 4.





	S	F1	F2	F3	F4
	D|DR (°)	D|DR (°)	D|DR (°)	D|DR (°)	D|DR (°)
S1	39|273	86|136	81|356	65|50	-
S2	38|325	84|266	70|355	48|35	86|233

Figure 4. Contour diagram of the detected discontinuities in two representative sectors (S1, S2) and values od Dip and Dip-direction relating to the bedding plane (S) and the discontinuity sets (F1-F4).

Five discontinuity sets have been identified (of which only 4 were recognized in S1). At both stations, the bedding planes (S) are inclined at 40º to the horizontal; the sets F1, F2, and F4 include discontinuities sub-vertical, parallel, and orthogonal to the rocky slopes, while in F3 joints are inclined on average about 55 degrees to the horizontal and refer to the main tectonic lineaments. The boulders size results from the intersection of the discontinuity sets and the spacing of the individual sets. In

IOP Conf. Series: Earth and Environmental Science **833** (2021) 012176 doi:10.1088/1755-1315/833/1/012176

particular, a statistical analysis of the spacing values measured for each of the discontinuities sets was performed, which pointed how the average spacing values do not vary within the discontinuity sets but with the spatial location of the scanlines. In fact, in general, in the study area, the discontinuity spacing is between one meter and few meters, which implies the presence of collapsed and unstable blocks in the tens of cubic meters; only in correspondence to main tectonic lineaments, the decimeter discontinuity spacing determines volumes less than one cubic meter. Finally, blocks up to hundreds of cubic meters due to large values of spacing and persistence were detected only in a few places.

2.3. Seismic surveys

To identify the lithostratigraphic characteristics of the outcrop soils where the motion of the blocks takes place, essential to choosing the elastic-restitution coefficients to apply the 'lumped mass' analytical model, a detailed geophysical survey was carried out.

We carried out the seismic surveys using a 24 channel Sysmatrack seismograph on the talus slopes to improve the subsurface image and better characterize the area where the rock block movement occurs. Wave velocities were analyzed using the PSlab software.

The regolith-bedrock boundary has been modeled by combining the travel times (figure 8); the analysis of the seismic velocities revealed a three-layer composition of the underground. The first layer near the surface has velocities values of 400 ms^{-1}, and its thickness increases downslope up to 2 m. This layer corresponds to the material sorting on the surface from fines in the upper slope to larger.

In-depth, wave velocity increases up to 1000 ms^{-1} and then again to 1800 ms^{-1} at about eight meters deep. The velocity probably increases with depth between the two layers is due to increasing sediment compaction, as observed during the field survey (figure 8). The calculated P-wave velocity for the layer below is about 3500 ms^{-1}, corresponding to the bedrock. Based on the obtained results, for the application of the analytical forecasting method of trajectories (cf. next paragraph), reference was made to a motion that develops partly on the outcrop rock and partly on the detrital cover the characteristics of which (e.g., the variation with the depth of the thickness and the compaction) present, were assessed using the seismic surveys.

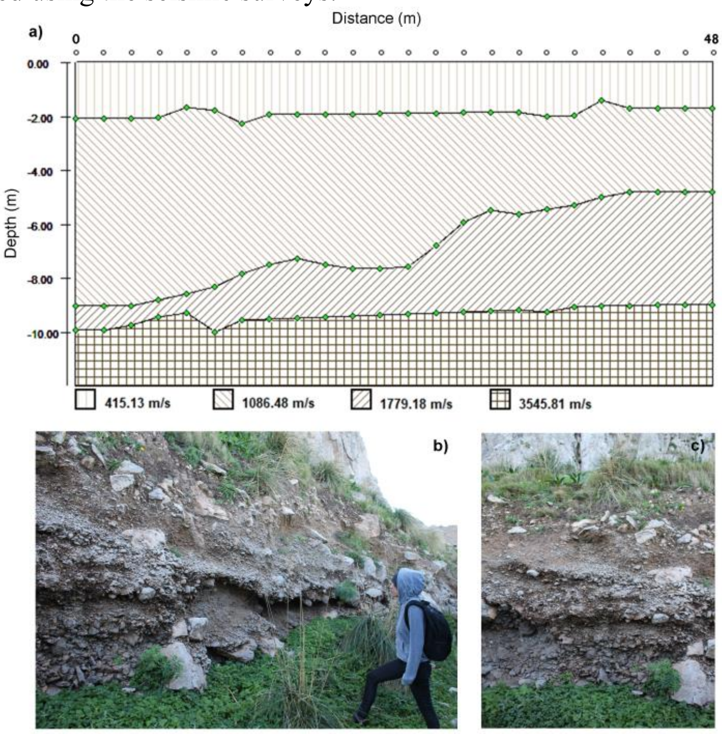


Figure 5. a) Seismic traveltimes and modelled refractor surfaces. b) and c) layers observed during the field survey.

2.4. Application of empirical and analytical models

The rockfall runout distance and the rock-block trajectories were defined through different steps and models. The input data useful for applications were collected by the steps described above, including geological, geomorphological, seismic, and geomechanical surveys of the rock masses and slope deposits. The model used is the 'reach angle' empirical model [1] and the 'lumped mass' analytical model [13]. Furthermore, different software has been used; specifically, the reach angle method was integrated into two open-source GIS modules as r.droka raster (GRASS) and Gravitational process Path Model (SAGA); the trajectories were calculated by means IS GeoMassi and Rotomap. For both methods, was used a 2m cell size digital terrain model (DTM) interpolated from LIDAR (ATA 2013); besides, as a precautionary approach, the potential detachments located in the highest scarps have been considered because the study area is characterized by the presence of several unstable elements at different altitudes.

The "reach angle" (α) is the angle between the horizontal line and the line joining the top of the slope and the farthest fallen block [1], allowing us to estimate the areas that might be reached by rockfall. The α value depends on several factors, including rockfall source altitude, slope morphology, and the presence of obstacles. This study used the average values calculated for a sector in [7] because the slopes of the study area developed along the same tectonic lineaments of one of the analyzed sectors of Mount Pellegrino; the reach angle value used is 42°. This value is also consistent with the sizes of the collapsed or unstable blocks recognized in the affected area as reported in [1]; the reach angle must be included in the range of 33-48 degrees for rockfall involving volumes smaller than 1000 m3.

To predict runout areas and at the same time acquire data about the boulders trajectories, the analytical method was applied. Rockfall dynamics is a function of the rockfall source areas, the geometry, and the mechanical properties of both blocks and slopes. It is not always easy and/or possible to define these parameters. Still, it is possible to model the energy loss at each impact point [14] by introducing energy restitution and friction coefficients. In this regard, it is necessary the study the litho-stratigraphic and mechanical characteristics of the outcrops terrains on the slopes, where the rock blocks movement occurs using the coefficients values sensu [13] and applied to the study area through comparison with the collected data during the geological and seismic surveys (table 1). These steps allowed us to define the rockfall trajectories through simulations using the 3D model Rotomap and IS GeoMassi (figure 6).

Table 1. Input parameters to define the rockfall trajectories: Kn. normal energy restitution coefficient; Kt. tangential energy restitution coefficient; Cr. friction coefficient of the rolling boulders.

	Slope Properties	COR Values		
		Kn	Kt	Cr
S1	Talus cover	0.45	0.80	0.50
	Clean hard rock	0.55	0.85	0.40
S2	Talus cover	0.45	0.80	0.50
	Clean hard rock	0.55	0.85	0.40

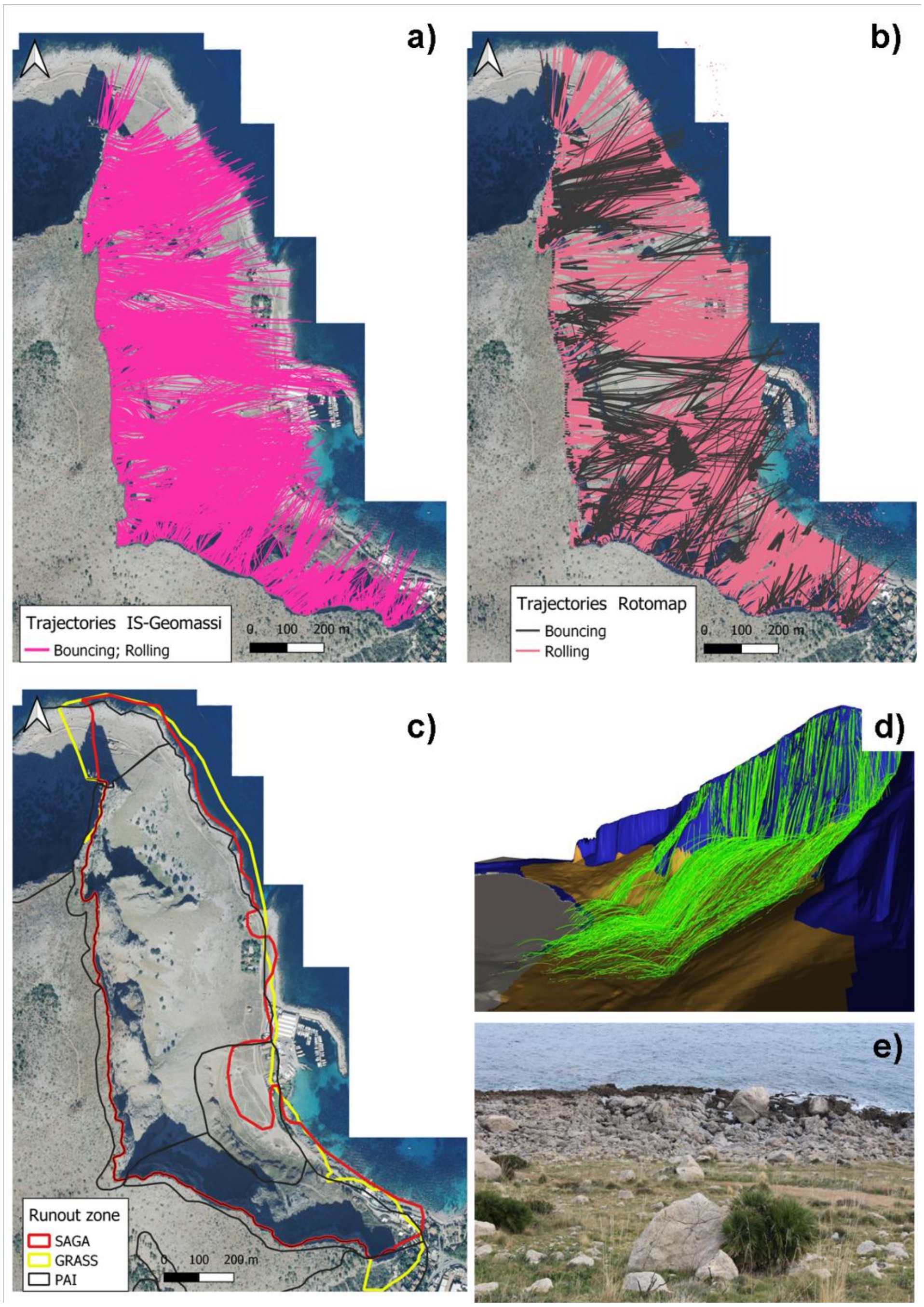


Figure 6. Blocks trajectories defined by means a) IS-Geomassi b) Rotomap; c) Rockfall runout zone defined by means Saga and Grass tools and PAI hazard zones; d) screenshot of 3D view of the IS-Geomassi analysis; e) Examples of collapsed blocks in the slope represented in frame d).

3. Results and conclusion

The study carried out in the Monte Gallo area has allowed defining the rockfall propagation areas for the slopes look out over the urbanized and reserve areas exposed to serious risk. The runout areas were defined using the 'reach angle' and 'lumped mass' methods using different software. The input data were obtained through field surveys and mechanical and geophysical investigations, and the analysis of the morphological attributes derived from a 2 m size DEM. As observable in figure 6 a, b, the comparison shows no significant differences between the trajectories directions but merely in terms of the length, especially in the analysed area's southern and northern sectors. Regarding the type of movement along the slope surface, Rotomap allows distinguishing between bouncing and rolling; these are distinguished in IS-Geomassi thanks to the 3D view (figure 6d). The runout zones obtained by the implementation of the reach angle method using an angle equal to 42°differs slightly from each other, especially in the downstream sectors (figure 6c); however, both are similar to the areas defined within the PAI that generally fall within the borders of the two different runout areas.

References

[1] Corominas J 1996 The angle of reach as a mobility index for small and large landslides *Can. Geotech. J.* **33** (2) 260–271
[2] Hunter G and Fell R 2003 Travel distance angle for “rapid” landslides in constructed and natural soil slopes *Can. Geotech. J.* **40** 1123–41
[3] Pfeiffer TJ and Bowen TD 1989 Computer simulation of rockfalls. *Environmental and Engineering Geoscience, XXVI* **1** 135–146
[4] Scioldo G 1991 Rotomap: Analisi statistica del rotolamento dei massi. *In G.Guariso (Ed.), Guida di informatica ambientale* 81–84
[5] Regione Siciliana Assessorato Territorio e Ambiente – ARTA 2006 Piano Stralcio per l’Assetto Idrogeologico (P.A.I.) - Area Territoriale tra bacino F. Oreto e Punta Raisi (040) Relazione e Carte dei Dissesti e della Pericolosità e del Rischio – 585160
[6] Cafiso F and Cappadonia C 2019 Landslide inventory and rockfall risk assessment of a strategic urban area (Palermo, Sicily) *ROL* **48** 96–105
[7] Cappadonia C, Cafiso F, Ferraro R, Martinello C and Rotigliano E 2020 Rockfall hazards of Mount Pellegrino area (Sicily, Southern Italy) *Journal of Maps* **0** 1–11
[8] Basilone L and Di Maggio C 2016 Geology of Monte Gallo (Palermo Mts, NW Sicily) *Journal of Maps* **12** 1072–83
[9] Cappadonia C, Di Maggio C, Agate M and Agnesi V 2020 Geomorphology of the urban area of Palermo (Italy) *Journal of Maps* **16** 274–84
[10] Catalano R, Merlini S and Sulli A 2002 The structure of western Sicily, central Mediterranean *Petroleum Geoscience* **8** 7–18
[11] Catalano R, Basilone L, Di Maggio C, Gasparo Morticelli M, Agate M and Avellone G. 2013 Note illustrative della Carta Geologica d'Italia alla scala 1:50.000 del foglio 594–585 “Partinico-Mondello” con carta geologica 1:50.000 allegata, pp. 1–271. Progetto Carg, ISPRA-Regione Siciliana
[12] Hoek E and Bray JW 1981 Rock slope engineering (3rd ed) In *The institution of Mining and Metallurgy* 364
[13] Scioldo G 2006 *User guide ISOMAP & ROTOMAP—3D surface modelling and rockfall Analysis* (Torino: Geo&Soft International)
[14] Crosta G B and Agliardi F 2003 A methodology for physically based rockfall hazard assessment *Nat. Hazards Earth Syst. Sci.* **3** 407–22