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SCIENCE

Geotechnics for rockfall assessment in the volcanic island of Gran Canaria (Canary Islands, Spain)

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ABSTRACT
The island of Gran Canaria (Canary Islands, Spain) is characterized by a large variability of volcanic rocks reflecting its volcanic evolution. The geological map provided by Geological Survey of Spain at 1:25.000 scale shows more than 109 different lithologies and it is too complex for environmental and engineering purposes. This work presents a simplified geotechnical map with a small number of classes grouping up units with similar geotechnical behaviours. The lithologies were grouped using about 350 rock samples, collected in the seven major islands of the Archipelago. The geotechnical map was used to model rockfall hazard in the entire island of Gran Canaria, where rockfalls are an important threat. The rockfall map was validated with 128 rockfall events along the GC-200 road, located in the NW sector of Gran Canaria. About 96% of the events occurred along sections of the road where the number of expected trajectories is high or moderate.

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1. Introduction

The island of Gran Canaria (Canary Islands, Spain) is a steep volcanic relief characterized by numerous deep radial ravines and a very abrupt coastline with high cliffs (Menéndez et al., 2008 and see Main Map). The geological context of the island reflects its volcanic evolution resulting in large variability of igneous rocks resulting from the built-up process of an intraplate oceanic island (Rodriguez-Gonzalez et al., 2018). Due to the geological and geomorphological characteristics, rockfalls are frequent and represent one of the most relevant natural hazards of the island (Barredo et al., 2000; Sarro et al., 2017). The road network is quite often affected by rockfalls with a high impact on the socio-economic framework of the island which is densely populated (866 thousand inhabitants in 2019) and hosts a high number of visitors per year (4.6 million visitors in 2019) (ISTAC, 2020).

Several geological maps of Gran Canaria are available at different scales. The official map (IGME, 2007) at 1:25.000 scale shows more than 109 different lithologies in an enlarged legend. Due to its complexity, the map is rather complex to use for some purposes, such as environmental studies and engineering modelling. For this reason, a simplified geotechnical map with a smaller number of classes showing lithologies with similar geotechnical behaviours represents a more appropriate tool for many applications, including those aimed at managing natural risks.

Because of the interest in the giant flank collapses occurred in the Canary Islands during their evolution as active volcanic islands, several analyses were carried out to improve the knowledge of the geological engineering properties of the volcanic deposits (Del Potro & Hürlimann, 2008; Gonzalez de Vallejo & Ferrer, 2006; González de Vallejo et al., 2008; Hernández-Gutiérrez, 2014; Rodríguez-Losada et al., 2009; Rodríguez-Peces et al., 2013). A first attempt of geotechnical map for Gran Canaria was elaborated by the regional government (territorial information system of the Canary Islands, available at https://visor.grafcan.es/visorweb/), with a special focus on ground characteristics for building construction. The map was prepared considering the geomechanical characterization of the volcanic rocks (Hernández-Gutiérrez, 2014).

In this work, we present a new, simplified geotechnical map (at 1:25.000 scale) for the island of Gran Canaria based on the geotechnical characterization of

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344 rock and soil samples collected in the seven major islands of the archipelago. The new geotechnical map was used to model and evaluate rockfall hazard at regional scale for the entire island.

2. Geographical and geological setting

The Canary Islands are located in North Atlantic Ocean, approximately 100 km away from the African coast (Morocco) (see Main Map). They represent an active ocean volcanic chain (800 km in length), consisting of eight volcanic islands aligned along a SW-NE direction. The structure and geodynamics of the archipelago are still under considerable debate, but it has been traditionally interpreted as a hotspot track (Anguita & Hernán, 2000; Carracedo et al., 1998; Fullea et al., 2015). This origin is supported by the volcanism age, decreasing from the NE (68 million years in Lanzarote) to the SW (one million years in El Hierro). The islands are dominated by mafic rocks and comprise uplifted submarine volcanic, subaerial shield volcanoes, and the remains of giant lateral collapses (Troll & Carracedo, 2016).

The island of Gran Canaria (1560 km^2) is approximately circular in shape (with a diameter of 45 km) with a maximum elevation of 1950 m at Pico de las Nieves, in the middle of the island (see Main Map). This configuration led to the formation of a set of dense radial networks of deep ravines, forming a rugged topography with a mean slope angle of 22° (Rodriguez-Gonzalez et al., 2018). Large cliffs dominate the coastline, highlighting the rugged south and western coast (Figure 1). From the geological point of view, Gran Canaria is, together with Tenerife, one of the islands with the greatest variability of volcanic rocks of the entire Canary archipelago. The main reason is due to these islands had been important magmatic differentiation process, which range from primitive basaltic to phonolite-trachyte magmas (Schmincke, 1982). Besides the distinctive lavas of the basanite basalt to trachyte phonolite series, Gran Canaria presents also other types of magma, such as tholeiitic basalts and rhyolites (Troll & Carracedo, 2016). The SW part of the island is older, formed by Miocene volcanites, whereas the younger Plio-Quaternary lavas outcrop in the NE portion where the rejuvenation volcanism, referred to the Bandama caldera (~2000 years old), took place. The Miocene Tejeda caldera (500 km^2 in surface) dominates the central-western part of the island with a relevant volume of associated ignimbrites (Hoernle & Carracedo, 2009; Rodriguez-Gonzalez et al., 2018).

The island has a subtropical climate: warm temperatures with small seasonal variations and average annual precipitation of 250 mm (AEMET, 2019). The maximum precipitation takes place during the autumn and winter months, being December the rainiest month. Heavy storms are frequent, associated with intense rainfall and strong winds, with events measuring of up to 75 mm in 24 h (Melillo et al., 2020). Regarding vegetation, the island is the most deforested of the Archipelago with a predominance of scrubs well adapted to arid conditions.

The island is frequently affected by rockfalls which have caused significant damage, mainly along the road network. An outstanding rockfall-prone area is situated along the northwestern coast of the island, where high and steep cliffs dominate the landscape (see Detailed Map 1 in Main Map). One of the most rockfall-hazardous roads in Europe is located on the island, between the localities of Agaete and La Aldea de San Nicolas, along the seashore. The GC-200 road has a length of 34 km and follows the steep outline of the coast. During the period 2010–2016, the local Road Maintenance Service reported along the road 128 rockfall events, which have caused significant damages. To reduce the rockfall hazard along the road, a 3 km long tunnel was recently inaugurated.

3. The geotechnical map

Geotechnical information is relevant for a variety of purposes, including civil engineering applications, land-use planning, or natural hazards mapping (Díaz-Díaz et al., 2017; El May et al., 2010; Valverde-Palacios et al. 2014). Reliable geotechnical maps are needed to represent the properties of soils and rocks, but standardized products and comprehensive maps are not often available. In this article, a geotechnical map for the entire island of Gran Canaria is presented. The text explains the approach we have used to prepare the map combining the official geological map and the results of laboratory and field tests of samples taken in the field throughout the Canaries.

Hernández-Gutiérrez (2014) and Hernández-Gutiérrez et al. (2017) grouped the 109 lithologies reported in the official geological map (IGME, 2007) into 11 lithotype-classes based on three criteria: lithology, texture and void ratio (Figure 2). These authors classified into two groups the basalt deposits (i.e. dykes/breccias and massive basalts) and the ignimbrite rocks (welded or not welded). Unconsolidated sediments refer to Holocene sedimentary deposits like alluvial, aeolian, beach and gravitational slope deposits.

In this work, the 11 lithotype-classes were geotechnically characterized based on laboratory tests and *in situ* analyses of 344 rock and soil samples collected in the field and coming from boreholes in the seven major islands of the Canaries. The 87 undisturbed samples derived from boreholes, with a depth ranging from 1 m to 110 m, were mainly drilled by private companies.

One hundred and four samples come from the island of Gran Canaria; of these, eight were taken

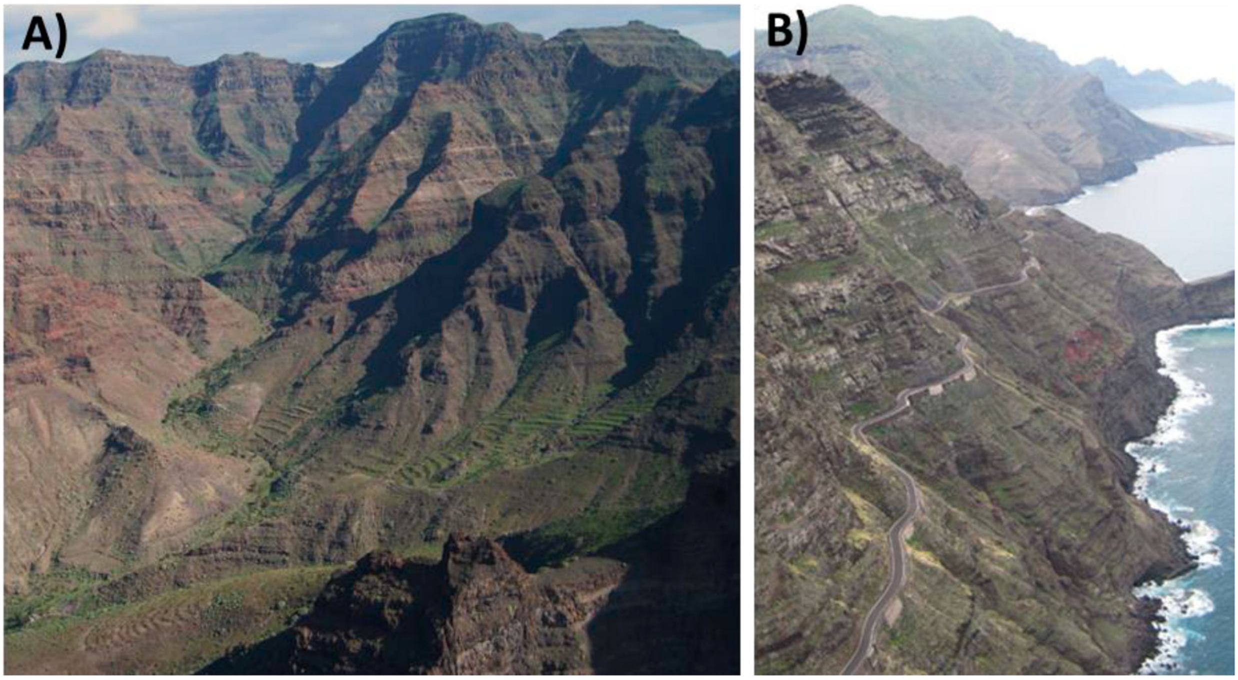


Figure 1. (a) Deep ravines in Gran Canaria (b) Panoramic view of the GC-200 road cut into steep cliffs (credits R. Sarro).

from boreholes (see locations in Figure 2). In a first step, we classified each rock and soil sample in one of the 11 lithotypes, following the criteria proposed by Hernández-Gutiérrez (2014) and Hernández-Gutiérrez et al. (2017). In the second step, numerous laboratory and field tests were carried out to identify the geotechnical characteristics of each lithotype through the statistical analysis of representative rock and soil properties (i.e. porosity, Young modulus, and uniaxial compressive strength).

For example, the uniaxial compressive strength of basalts and phonolites has higher values than ignimbrites, whereas trachytes and trachybasalts show similar values (Figure 3).

A Principal Component Analysis (PCA) was performed to visualize the association of relevant geotechnical characteristics (i.e. uniaxial compressive strength, porosity and Young modulus) with the lithotypes (Figure 4). The variables were standardized before the PCA. The plot in Figure 4 shows the distribution of the observations along the first two principal components. The first component represents 73.5% of the total variance. Positive values along the x-axis are positively correlated with uniaxial compressive strength and Young modulus, whereas negative values show a positive relationship with porosity. A generalized alignment and clustering of lithotypes along the first principal component indicates the representativeness of the classes in terms of their geotechnical properties. Ignimbrites (IGUW and IGW) have negative scores in the first component showing higher porosity and lower uniaxial compressive strength and Young modulus. Trachytes (TR) lie in the negative part of the x-axis, but close to zero, so their relationship with these geotechnical characteristics is weaker. Finally, phonolites (PHO) and massive basalts (BM) score positive on the right side, indicating the hardness of these rocks as measured by large uniaxial compressive strength and Young modulus values.

Rocks can be classified based on their mechanical properties, and the uniaxial compressive strength value is the parameter selected by many classifications (Singh & Goel, 2011). In this work, we have considered the Engineering Classification of Intact Rock based on the value of uniaxial compressive strength (USDA, 2017), since this is the only parameter available for all the 11 lithotypes. Based on this classification, the new geotechnical map groups the 11 lithotypes (see Figure 2) in seven classes (Table 1), ranging from extremely hard rock (dykes and breccias) to soils (unconsolidated pyroclastic and Holocene sediments) (See Main Map).

4. The rockfall map

The simplified geotechnical map was used to model and evaluate rockfall hazard at regional scale in the Gran Canaria island (see Rockfall Modelling Map), as the corresponding friction and energy restitution coefficients used as inputs in the rockfall modelling depends on the outcropping lithologies and the geomechanical characteristics of bedrock. We applied STONE, a three-dimensional rock-fall simulation program for modelling (Guzzetti et al., 2002). STONE requires the following input: (1) the location of the rockfalls source areas, (2) a digital elevation model, and (3) three maps showing the numerical values of dynamic rolling friction, the normal and the tangential

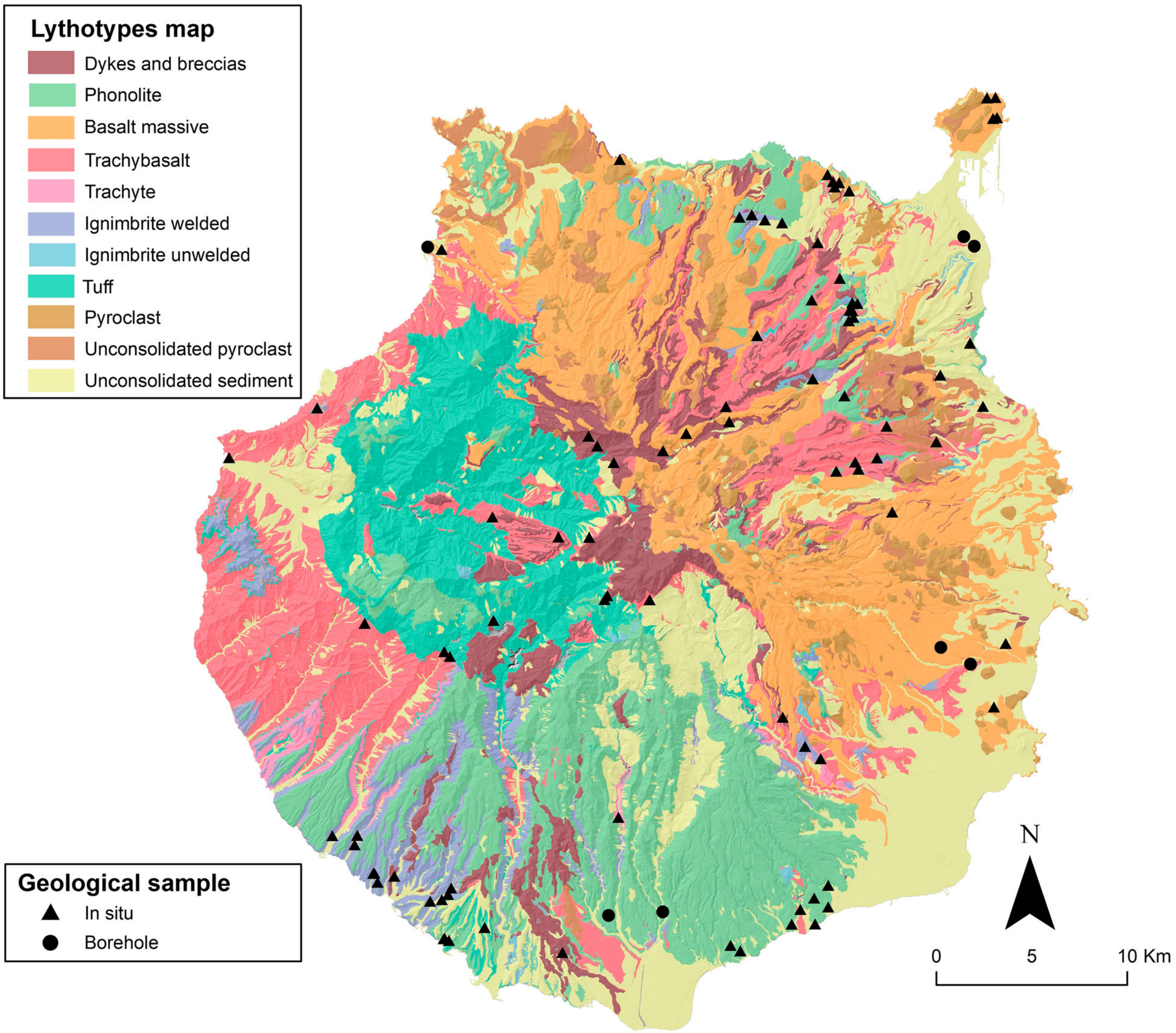


Figure 2. Lithotypes map for Gran Canaria based on Hernández-Gutiérrez (2014) and Hernández-Gutiérrez et al. (2017).

energy restitution coefficients. The software simulates a series of 3D rockfall trajectories and produces a raster map showing for each pixel the count of rockfall trajectories.

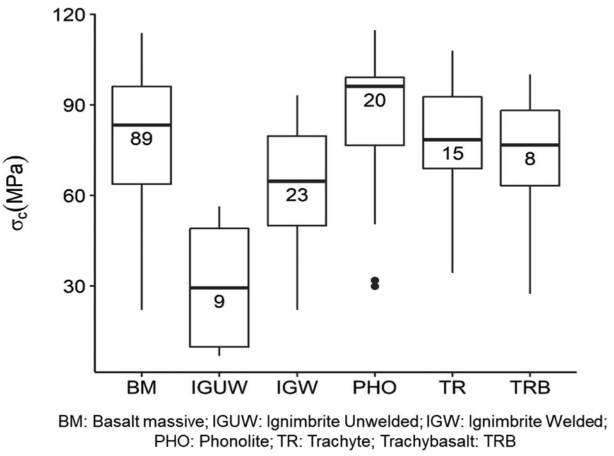


Figure 3. Boxplots of the uniaxial compressive strength values of the lithotypes shown in Figure 2. The values inside the boxes represent the number of observations for each lithotype.

The values of the dynamic rolling friction, the normal and the tangential energy restitution coefficients are usually obtained from the literature (Asteriou et al., 2012; Guzzetti et al., 2003; Guzzetti et al., 2004; Mateos et al., 2016; Santangelo et al., 2019; Sarro et al., 2014, 2018). Since the information the literature does not provide any reference value

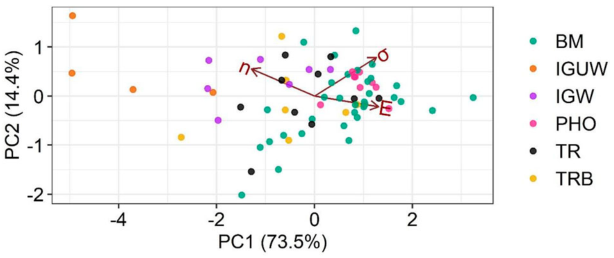


Figure 4. Biplot of the principal component analysis (PCA) of porosity, Young modulus and Uniaxial Compressive Strength. The axes show the percentage of variance explained by each component. Arrows represent variable loadings and point to the direction of the maximum correlation of the variables with the PCA scores. Abbreviations see Figure 3.

Table 1. Geotechnical classification (USDA, 2017) of the 11 lithotypes considering the value of the uniaxial compressive strength.

Lithotype	USDA classification	Uniaxial compressive strength [MPa]
Dykes and breccia	Extremely hard rock	>250
Phonolite	Very hard rock	100–250
Basalt Massive; Trachyte; Ignimbrite Welded; Trachybasalt	Hard rock	50–100
Ignimbrite Unwelded	Moderately hard rock	12.5–50
Tuff	Moderately soft rock	5–12.5
Pyroclastic	Soft rock	1–5
Unconsolidated pyroclastic; Unconsolidated sediment	Soil	<1

Table 2. Values of the coefficients used in the rockfall modelling.

	Normal restitution	Tangential restitution	Rolling friction
Extremely hard rock	64	89	0.35
Very hard rock	63	88	0.48
Hard rock	57	87	0.50
Moderately hard rock	46	78	0.55
Moderately soft rock	45	75	0.59
Soft rock	41	54	0.67
Soils	38	50	0.70

for volcanic materials, we have derived these parameters indirectly from the geotechnical map. In particularly, values were correlated with those obtained by Mateos et al. (2016) in a sedimentary environment, where the authors applied a similar geotechnical classification based on the uniaxial compressive strength (Table 2).

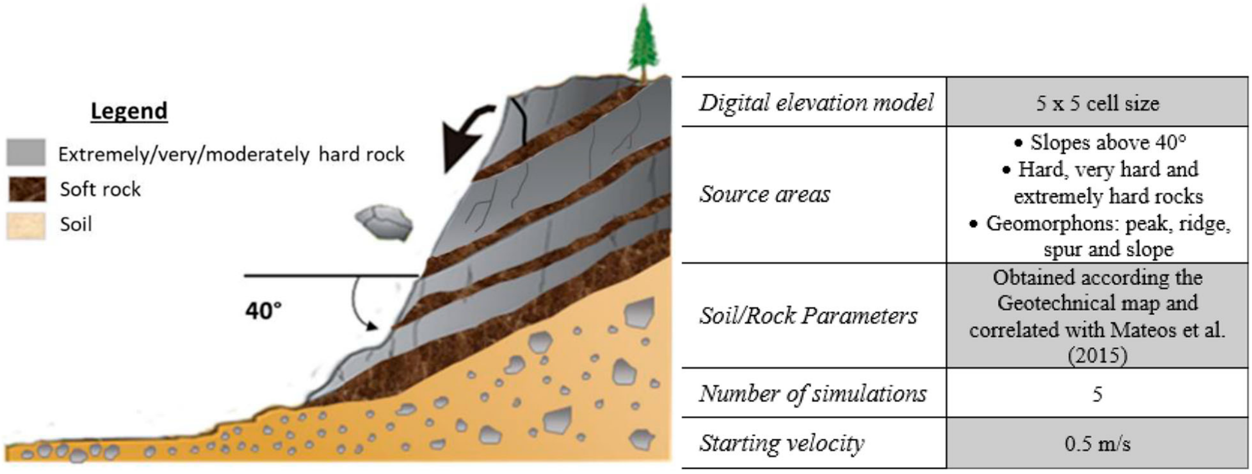
For the modelling, we used the Digital Elevation Model (DEM) provided by the National Geographic Institute at a 5 m × 5 m resolution (IGN-CNIG, 2019). Rockfall source areas were defined according to the geomorphological information and the analysis of the past rockfall events. To do geomorphological analysis, we have applied the geomorphons method (Jasiewicz & Stepinski, 2013), an approach for a semi-automated classification of landform surface into meaningful objects based on the principle of pattern recognition rather than differential geometry. The geomorphons classification contains ten types of landforms, namely: flat, peak, ridge, shoulder, spur, slope, hollow, footslope, valley and pit. For the analysis of source areas in Gran Canaria, we selected four landforms: peak, ridge, spur and slope.

In addition, the analysis of past rockfall-events allowed us to define a highly recurrent slope asset for rockfalls in Gran Canaria: the source areas are often connected to slope angle above 40° and they mainly affected hard, very hard and extremely hard rocks. Figure 5 summarizes input parameters.

4.1. Validation

The model used to derive the rockfall map of Gran Canaria was validated by exploiting 128 significant rockfalls, inventoried by the Road Maintenance Service of Gran Canaria, which affected the GC-200 road over the period 2010–2016 (Figure 6).

To validate the results of the model, we initially classified the road in three classes, based on the number of rockfall trajectories per pixel across the road obtained with STONE: Low (0–5 trajectories, green), Moderate (6–10 trajectories, yellow) and High (11–50 trajectories, red). Figure 7 shows the classified road: 11 km are crossed by a high number of trajectories, 11 km by a moderate number and 13 km by a low number. Secondly, we have counted the number of rockfall events in each class (Figure 7). About 70% of the rockfalls affected the road in sections classified as High; 26% in sections classified as Moderate, and only 4% in sections classified as Low (see Detailed Map 1 and 2).



Digital elevation model	5 x 5 cell size
Source areas	• Slopes above 40° • Hard, very hard and extremely hard rocks • Geomorphons: peak, ridge, spur and slope
Soil/Rock Parameters	Obtained according the Geotechnical map and correlated with Mateos et al. (2015)
Number of simulations	5
Starting velocity	0.5 m/s

Figure 5. Schema of a natural rockfall scenario in Gran Canaria. The table shows the input data for the rockfall modelling.

Figure 6. Examples of rockfalls affecting the GC-200 road during the event that occurred on 9th December 2016 (credits R. Sarro and J. Naranjo).

5. Discussion and conclusions

Since geological maps present – quite often – complex legends and very long explanatory texts, there is an increasing request for simple and readable maps useful for land-use decision making. In the Canary Island, a big effort was done to examine 344 rock and soil samples to extract reference geomechanical properties of the outcropping lithologies through the island. Based on the uniaxial compressive strength value of the intact rock, a simplified geotechnical map with seven classes ranging from soils to extremely hard rocks, was proposed for Gran Canaria. The most

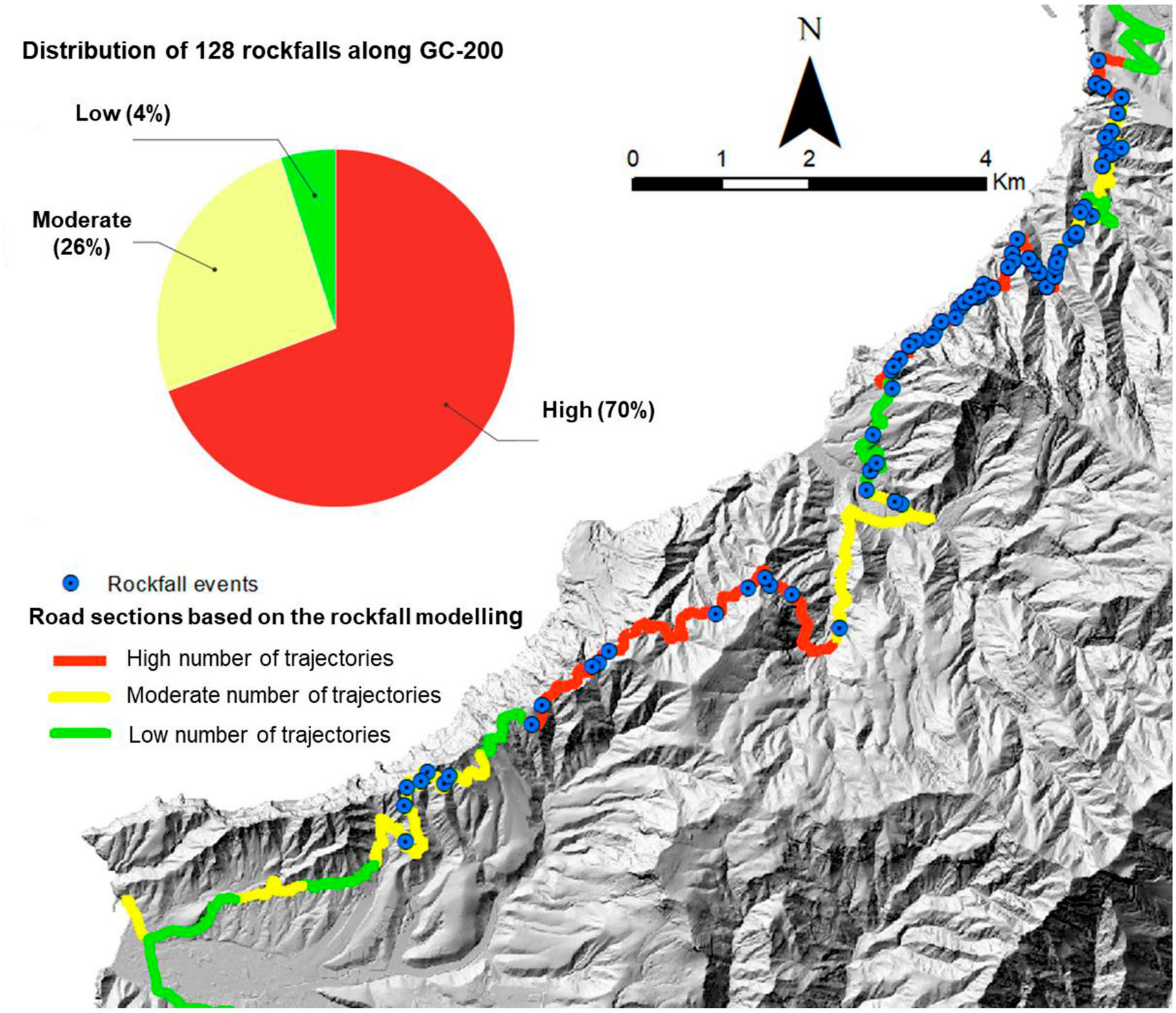


Figure 7. The GC-200 road classified in 3 classes based on the number of rockfall trajectories computed by STONE. The map also shows the locations of 128 rockfalls which affected the road in the period 2010–2016.

abundant classes are hard rocks and very hard rocks, which represent 67% of the territory. The soft materials, soils and soft rocks mainly outcrop in the eastern part of the island, where recent volcanism (Holocene) and sedimentary deposits are located (Rodriguez-Gonzalez et al., 2018). The geotechnical map provides a synoptic overview at regional scale; for local and detailed studies, detailed in-situ analysis has to be performed.

The characteristics of the bedrocks is a relevant information to determine the parameters required for rockfall modelling. These parameters are reported in the literature for many lithological types, mainly for sedimentary, metamorphic and igneous-intrusive environments. This work attempts to fill the gaps in the volcanic environment of Gran Canaria, where the parameters were validated. Data and results can be exploited to prepare rockfall modelling in other Islands of the archipelago and in other volcanic locations.

The rockfall map obtained in this work well represents the real distribution of the rockfall-prone areas of the island. The western part of the island is more prone to rockfalls. This area is the oldest one from the geological point of view and both the erosion and the volcanic uplift have been working for a long time leading to a steeper topography. The Tejeda Collapse Caldera, with a clear step morphological features, is also a relevant rockfall-prone area. The inspection of the map shows a radial distribution of rockfall prone areas located mainly on both sides of steep ravines.

To conclude, the rockfall map represents a preliminary regional hazard assessment in Gran Canaria which has been validated along the GC-200 road. Most of the inventoried rockfalls are located where the road is crossed by a high number of rockfall trajectories.

Software

STONE (Guzzetti et al., 2002) uses a ‘lumped mass’ approach to simulate rockfall processes, where the falling boulder is considered dimensionless. The input data include the following raster layers: a Digital Terrain Model; maps of the coefficients of dynamic rolling friction, and of normal and tangential energy restitution; and a rockfall source areas, with the number of simulations carried out from each pixel. In the island of Gran Canaria, we used a DTM (5 m × 5 m resolution) provided by the National Geographic Institute (www.ign.es) and we selected 5 simulations from each source pixel. STONE uses GIS technology to produce raster maps that portray for each pixel: (a) the cumulative count of rockfall trajectories, (b) the maximum computed velocity and (c) the maximum flying height. In this article, we show only the map of the number of trajectories that cross each cell of the grid.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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