ORIGINAL ARTICLE

Assessment of rockfall potential in the Kula (Manisa, Turkey) Geopark Region

Adil Binal · M. Ercanoğlu

Abstract The term Geopark is an interrelated phenomenon of geology, landscape, civilisation and society. One of the first Geopark areas in Turkey will be founded in the Kula district of Manisa. This region is an impressive area with its archaeological, historical and tourism-related features and its geological characteristics, such as cinders and maars, tectonic structures and earth pillars. Moreover, the earth pillars in the region present high-rockfall potential due to their geometric and lithologic peculiarities, formed by erosional processes. The present study aims in investigating the rockfall potential in this area by means of experimental investigation and numerical analyses. Extensive field studies including determination of earth pillar locations with rockfall potential, geological description of the earth pillars, scan-line surveys on discontinuities, identification of slope profiles, measurement of actual fallen block dimensions and sampling procedures were carried out. The eight earth pillar profiles were analysed to determine the run-out distances of basalt blocks and seven blocks were found to be capable of reaching the transportation line. For future protection purposes, barrier designs were suggested by computer analyses. Additional analyses were performed to determine rockfall-prone areas, taking into consideration the mapped rockfall source areas. Based on these analyses, the transportation line is threatened by potential rockfall. These results are in accordance with conclusions of the runout distance analyses. As a consequence, environmental aspects and rockfall phenomenon of the Kula Geopark Region must be taken into consideration during the planning process. It should also be pointed out

that we have to own the values of geological heritages and to protect them based on the scientific and rational approaches.

Keywords Earth pillar · Geopark · Kula · Rockfall · Rockfall proneness

Introduction

A rockfall event involves the displacement of single block or several rock boulders detaching from their original locations by falling and subsequent bouncing, rolling, sliding and deposition (Varnes 1978; Hutchinson 1988; Evans and Hungr 1993). It is one of the most hazardous natural processes, and has a great potential of threatening lives, roads, settlements and other facilities due to its rapid movement and high-energy bearing features. In general, rockfall hazard results from two processes: (1) detachment of a rock volume from the upper part of the slope (local failure of slope) and (2) propagation of this volume along the slope (Hantz et al. 2003). Different geological, geomorphological, climatologic and human effects may contribute to the occurrence of these processes, such as earthquakes, weathering, discontinuities, freeze and thaw cycles, rainfall, road cuts and so on.

To evaluate the potential hazard related to an unstable rock slope, it is essential to understand the processes and mechanism driving the instability (Eberhardt et al. 2002). However, in general, assessment of rockfall mechanism is a challenging work due to its complex nature. As in many landslide cases, analysis of a cause and effect relationship is not always simple, as a landslide is seldom linked to a single cause (Aleotti and Chowdhury 1999). For rockfalls, main difficulties arise from the determination of exact

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locations of source areas and characterisation of the physical and geotechnical parameters. Furthermore, geometrical and mechanical characteristics of the surface material vary dramatically along a slope (Agliardi and Crosta 2003). Therefore, characterisation of contributing factors to rockfall initiation becomes important and should be elaborately investigated.

Given the scientific literature of rockfall assessments, there are different analysis techniques, such as numerical models, geographical information system-based evaluations and two- or three-dimensional approaches (Duarte and Marquínez 2002; Eberhardt et al. 2002; Agliardi and Crosta 2003; Ayala-Carcedo et al. 2003; Baillifard et al. 2003; Dorren and Seijmonsbergen 2003; Dorren et al. 2004; Jaboyedoff et al. 2005; Copons and Vilaplana 2008; Yılmaz et al. 2008). Many of these studies are focused on analyses of rockfall mechanism and run-out distance of moving a mass. To minimise damages, it is important to evaluate the mechanism and causes of rockfall event. Thus, it may be possible to obtain information for mitigation efforts and protective measures.

Similar to many countries, particularly those located in mountainous regions, Turkey faces rockfall hazards and their consequences. In Turkey, rockfalls constitute 10% of the damage caused by natural hazards. In addition, given the statistics provided by Gökçe et al. (2008), 1,703 settlements and 19,422 people have been affected by a total of 2,956 rockfall events so far. Therefore, particularly in recent years, rockfall assessments and analyses have become an important topic for many geoscientists in Turkey, such as Aksoy and Ercanoğlu (2006), Ulusay et al. (2006), Topal et al. (2007), Yılmaz et al. (2008), Tunusluoğlu and Zorlu (2009).

This study was carried out in a possible Geopark area in Turkey. This region was selected for its geological, historical and tourism-related significance and, of course, proneness to rockfall hazard. A Geopark is a geographical area, where geological heritage sites are part of a holistic concept of protection, education and sustainable development. However, until recently, no international recognition of geological heritage sites of national or regional importance and no international convention specifically on geological heritage have existed (GGN 2008). The Geopark concept has been developed in recent years, with the intention of promoting economic development through sustainable geotourism based on the geological resources of the park (Gray 2008). In other words, the Geopark term is related to a region or an area where geological, archaeological, cultural and/or historical characteristics are considerably important and needs to be protected. Main goals for establishing a Geopark should be education of people about geosciences and the environment, providing sustainable development, and protection of geological heritage

for next generations by reaching broader communities. In accordance with the national legislation or regulations, a Geopark shall contribute to the conservation of significant geological features, including representative rocks, mineral resources, minerals, fossils, landforms and landscapes (GGN 2008). As can be seen from the definitions and concepts related to Geopark, it is indispensable to make use of geological features and geosciences in every step of establishing a Geopark.

In light of the above-mentioned concepts, the present study aims in analysing the rockfall issue in one of the first possible Geopark areas in Turkey, the Kula Geopark Region. Unfortunately, because the Kula Geopark is in a rockfall-prone area, rockfall hazard assessment seems to be a vital issue in this Geopark area. To evaluate the rockfall potential of the study area, fieldworks by means of scanline surveys, earth pillars' dimensions, and slope profiles, as well as laboratory studies on geomechanical properties of geological units were carried out to assess the rockfall event characteristics in the region. 2D (two-dimensional) rockfall analyses, including block trajectory, run-out distance, velocity, bounce height and kinetic energy of the blocks were carried out based on the field and laboratory data, and rockfall potential of the selected area was evaluated for individual cases. Finally, to evaluate the areal distribution of rockfall event in the selected region, additional analyses were performed to evaluate rockfall-prone areas.

Study area

The Aegean region is known as one of the most popular historical and touristic regions in Turkey because of its history of civilisation and culture, which dates back to ancient times. The Kula district is located in the western part of the Aegean region (Fig. 1). The district has been an important settlement area since ancient times. Strabon, the famous historian, named this region 'KATAKEKAUMENE', which means 'burnt land', as a result of volcanic activity approximately 2,000 years ago Ozaner 2006). In addition, 26,000-year-old primitive human footprints have been found in the region. European Union took these features into consideration and donated €103,800 to build a Geopark in the Kula region. This area will be one of the first Geopark areas in Turkey when the project is completed.

In addition to its historical and archaeological importance, the Kula region also attracts the interest of many geoscientists because of its complicated regional geological features (Fig. 2). Thus, there are a multitude of scientific studies related to different geological features of the region (e.g. Ercan et al. 1983; Şen 2002; Bayhan et al.
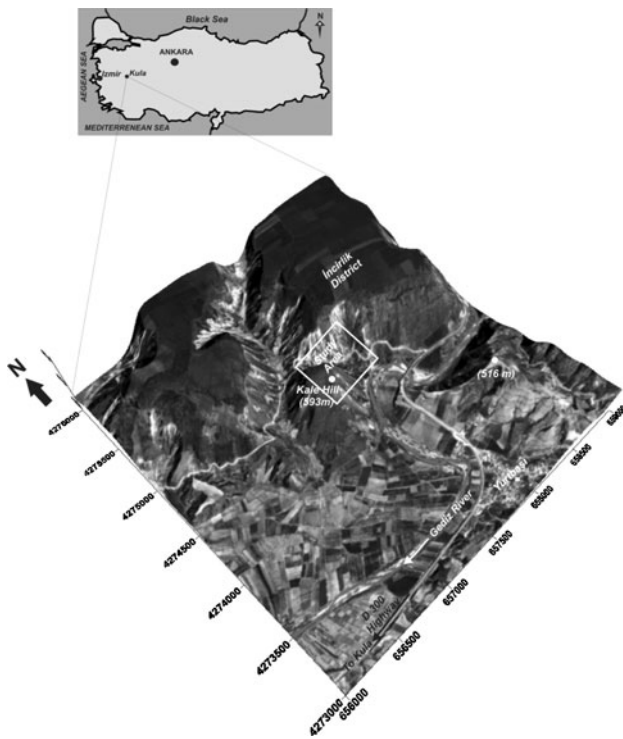
Fig. 1 Location map of the study area overlaid by the SPOT 5 panchromatic satellite image

2006; Holness and Bunbury 2006; Westaway et al. 2006; Ersoy et al. 2008; Çiftçi and Bozkurt 2009). The region includes many volcanic fields, and is located on a horst structure in the north of the Gediz Graben area (Ercan et al. 1983). Şen (2002) stated that the Kula volcanic field consists of 79 cinder, 8 spatter cones and 5 maars. Volcanological evolution of this field is divided into three main stages. The first generation is characterised by the effusive activities (lava flows) and exhibits a basaltic character. This unit is located in close to Burgaz (see Fig. 2). The age of this unit was given 1.1 My by Borsi et al. (1972). The second and third generations involve the maars, the cinder cones and the associated lava flows.

The study area falls into the first generation basaltic part (see Fig. 2). This mainly covers the underlying Middle-Upper Miocene claystone and mudstone, in addition to sandstone, marl and tuffite layers. Owing to its high susceptibility to wind and water erosion, earth pillars are common in the region, and wide gaps were formed amongst the earth pillars as a result of their weak and poorly consolidated structures (Fig. 3). The top of the earth pillars is generally composed of weathered basalt blocks belonging to the first generation of volcanic products, whilst the root parts consist of yellow to green coloured mudstone. The geometrical, geological and structural features make the region prone to rockfall instability. Based on the field observations, the main rockfall source area

comprised the basalt blocks situated at the top of the earth pillars. Rockfall initiation commonly takes place as a result of hanging basalt blocks from the top of the earth pillar to the toe of the slope (Fig. 4a). However, only one fallen mudstone block has been observed in the area (Fig. 4b). However, we were not able to determine the exact source area of that block. Therefore, rockfall source areas in the study area are considered as the earth pillar locations. These locations were mapped directly during the field studies and shown in Fig. 5a.
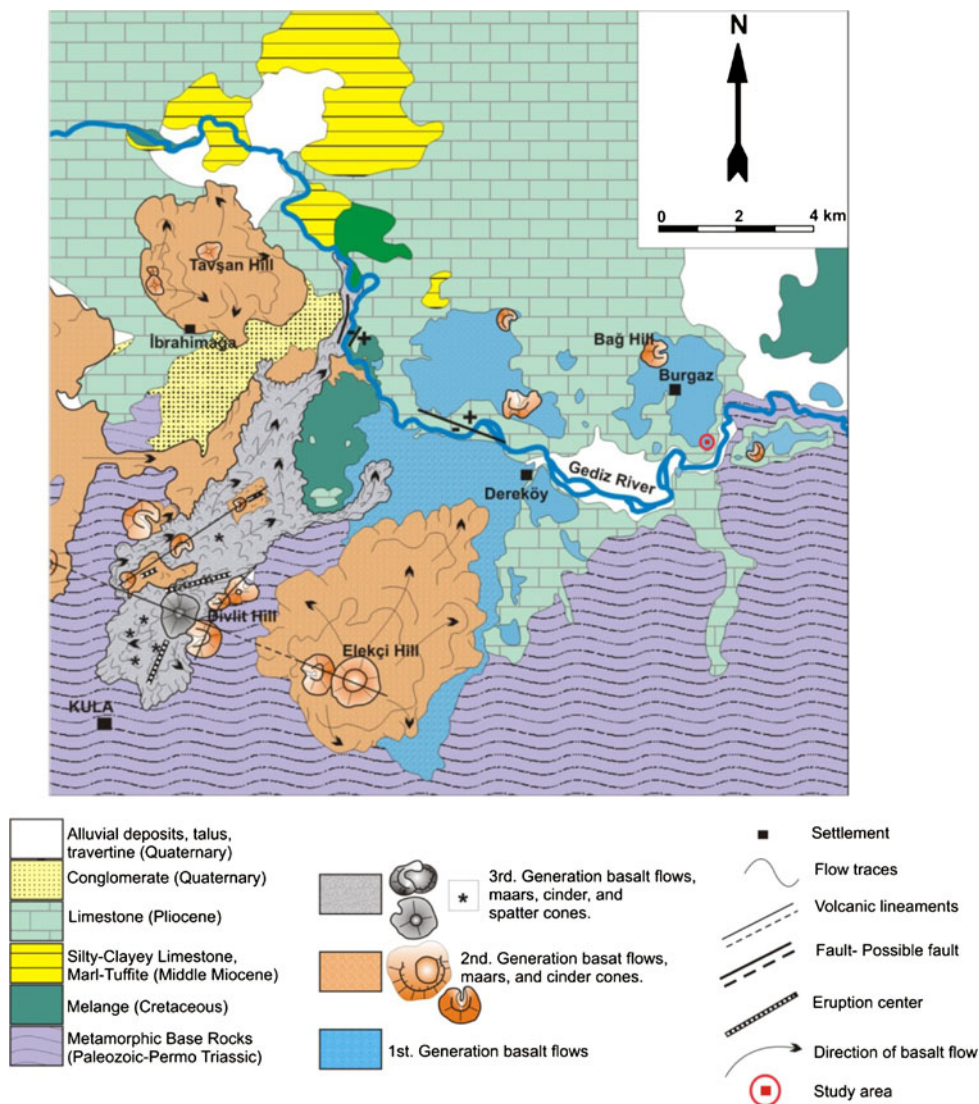
The study area covers approximately 1.5 km^2 and is located at the eastern part of the Kula Geopark Region; the closest settlement to the study area is Yurtbaşı (see Fig. 1). Regarding the geomorphological features, topographical elevations range between 400 and 615 m, and the most important elevation is the Kale Hill (593 m). Topographical features have tendency to decrease roughly from the northeast to the southwest. The earth pillars show steep topographical features in the study area, with slope angles reaching up to 77° (Fig. 5b). All these features were extracted from the digital elevation model (DEM) of the study area with a ground resolution of 10 m, created by implementation of contour lines of the 1/25,000 scale topographical map.

In situ characterisation and material properties

During the field studies, 80-m length systematic scan-line surveys along three lines were carried out based on the ISRM (2007) standards to describe the properties of discontinuities belonging to the earth pillars (Figs. 6, 7). The aperture of discontinuities of mudstone ranges from tight (0.1 mm) to wide (>10 cm) and the average spacing is 2.26 m. In addition, the joints show high persistency (>20 m). The apertures of joints were generally filled by sand and silt-size material, based on the field observations. The joint surfaces are categorised as planar and rough, according to the ISRM (2007) standards. Regarding water conditions, no water or seepage was observed on the joint surfaces. Finally, to evaluate the discontinuity orientations, a discontinuity contour diagram was plotted by entering the measured dip and dip directions during the scan-line surveys into a computer code, namely DIPS (Version 5.1) (RocScience Inc. 2002). Based on these analyses, it was revealed that three major joint sets were found in the study area with dip and dip directions of 82°/247°, 87°/180° and 87°/094°, respectively (Fig. 8).

Two fallen basalt blocks were observed on the road in the study area (see Fig. 4a) during the field studies. Their distances from earth pillars, falling heights and inclinations of profiles were determined with laser distance meter (Bosch DLE-150) and cocla compass to calculate the normal and

Fig. 2 Regional geological features of the study area and its vicinity (after Şen 2002)

tangential coefficients of restitution of earth pillars for the back analyses stage, as explained in the next section. In addition, three block samples were collected from the field to determine the geomechanical properties and the basic friction angles of both the mudstone and basalt samples.

Laboratory tests were carried out to evaluate the material properties. Tests to determine water absorption by weight, apparent porosity, unit weight and the uniaxial compressive strength were performed based on the ISRM (2007) suggested methods. The average values of the W_{abs} and number of the basalt samples were determined to be 2.3 and 5.3%, respectively. The average unit weight of mudstone samples (20.6 kN/m^3) was lower than that of the basalt samples (25.2 kN/m^3). The average uniaxial compressive strengths of mudstone and basalt samples were 8.6 and 101.5 MPa, respectively. All these properties are shown in Table 1. Water absorption by weight and apparent porosity parameters of the mudstone could not be

determined due to the weak structure of the material and its easy dispersion feature in water.

To determine the basic friction angle between basalt and mudstone, a shear box test apparatus (Fig. 9) was used. That apparatus was first used by Binal (1996) to determine basic friction angle between different ignimbrite rock samples. With this apparatus, cylindrical core samples were cut in 1-cm height, and were surrounded by hard stiff plastic material in order that they could be subjected to direct shear box tests under dry or saturated conditions. The thickness of the basalt blocks on the top of the earth pillars range between 0.2 and 1 m. Therefore, the tests were performed under 31, 42 and 53 kPa normal stress levels, taking into consideration, the dimensions of basalt blocks. Owing to the dispersion feature of mudstone, the direct shear box tests were carried out under dry conditions and basic friction angle was identified as 30.5° between basalt and mudstone (Fig. 10).

Rockfall analyses

In the present study, to evaluate rockfall potential of the Kula earth pillars, eight different slope profiles with high-rockfall potential, which are close to transportation roads were analysed in 2D with Rocfall (Version 4.0) computer program (Rocscience Inc. 2002). Selected input parameters for the analyses are given in Table 2. Profiles were created regarding the locations of the earth pillars and hanging blocks, as well as slope angles and distances from the road. The weights of eight hanging blocks located at the top of

Fig. 3 A view from the earth pillars in the study area

earth pillars were calculated using the average density of basalt blocks multiplied by their volumes: the weights vary between 130 and 2,290 kg (Table 3). Some of these blocks are shown in Fig. 11. Initial data for vertical and horizontal velocities of blocks have been assigned as '0 m/s' due to the positions of hanging blocks on the earth pillars.

The restitution parameters used for rockfall analyses describe the way in which rockfall behaviour is modified by its impact on the slope as well as restitution, which is most commonly defined by separate parameters for velocity loss in each of the normal and tangential directions to the slope (Richards et al. 2001). Many studies are available in the literature related to the determination of site-specific coefficients of restitution (Chau et al. 2002; Okura et al. 2000; Richards et al. 2001; Agliardi and Crosta 2003; Dorren et al. 2004, Ulusay et al. 2006; Giacomini et al. 2009) due to the importance of these parameters in rockfall analyses. However, these values may be significantly different, depending on the conditions at each site (Topal et al. 2007). Therefore, in this study, back analyses to determine the coefficient restitutions were taken into consideration for the two basalt blocks. The material wizard section of the RocFall program was used to calculate coefficients of normal (R_n) and tangential (R_t) restitutions of the earth pillars. Different R_t values and corresponding R_n values related to the fallen blocks were sketched on the graph and were shown in Fig. 12. The values at the intersection of these curves were assigned as R_n (0.223 ± 0.052) and R_t (0.586 ± 0.102). In rockfall simulation analyses, the rocks to throw parameter was selected as 1,000 similar to previous studies (e.g. Ulusay et al. 2006; Topal et al. 2007), slope roughness was selected as 2 due to discontinuity conditions, and the friction angle was 30.5°, based on the direct shear test evaluations (see Table 2). Next, 2D rockfall analyses were carried out for the so-called eight earth pillar profiles. Based on these
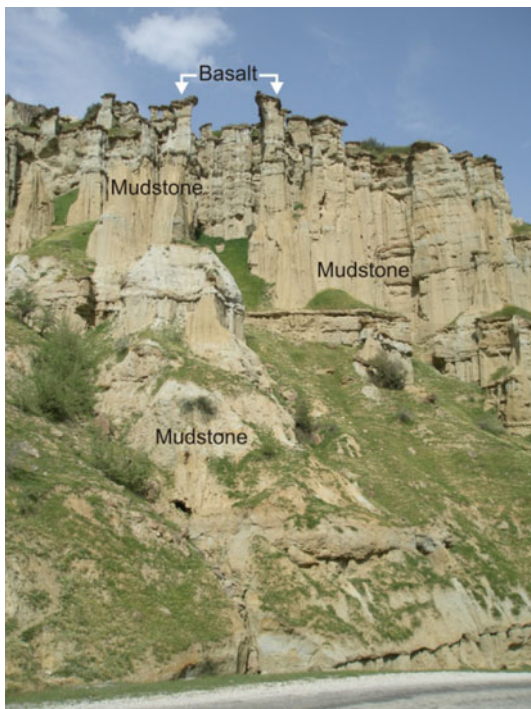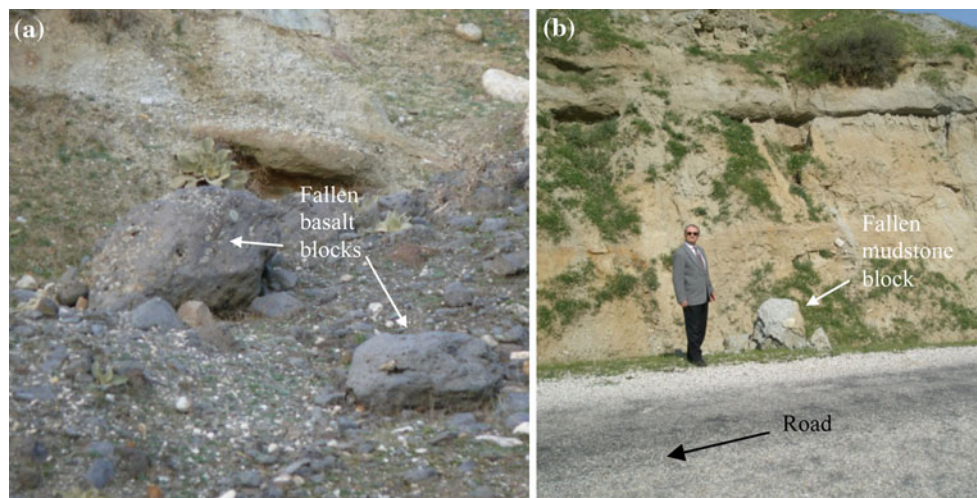

Fig. 4 Fallen rock blocks identified in the study area: **a** basalt and **b** mudstone

Fig. 5 DEM-based maps of the study area: **a** elevation and **b** slope angle

Fig. 6 Views from the field study locations: **a** scan-line survey and **b** block sampling

analyses, trajectories of hanging blocks were obtained (Fig. 13). The highest speeds of basalt blocks related to their volumes change between 8.71 and 21.28 m/s, kinetic energies vary from 6.53 to 496.92 kJ and run-out distances are between 7.44 and 39.29 m, respectively (Table 3). Analyses revealed that all blocks, except for the block of Profile 3, had the capability of reaching the road passing through the study area. In other words, this means that seven blocks have a potential of threatening transport on the road and endangering human life in the Geopark area. Eventually, to prevent the consequences of the rockfall hazard, protection barriers were also taken into consideration for the future designs in the Geopark area. Rockfall analyses were repeated for the protection barrier height calculations based on the non-elastic barriers that represent the worst conditions and located at the edge of the road. The maximum barrier heights were determined to be between 0.5 and 3 m (Table 4). The rockfall trajectories with these preventive barriers were also shown in Fig. 14.
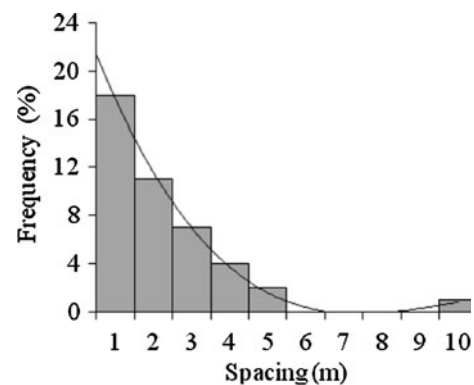

Fig. 7 The histogram showing the distribution of discontinuity spacings of mudstones

According to these calculations, the maximum 3-m barrier, which is inexpensive, will be sufficient to protect transportation and human lives when considered with respect to the cost/benefit issues.

All those analyses were performed for the individual blocks with rockfall potential based on the field observations and measurements. However, in addition to those analyses, to present the spatial and areal distribution of

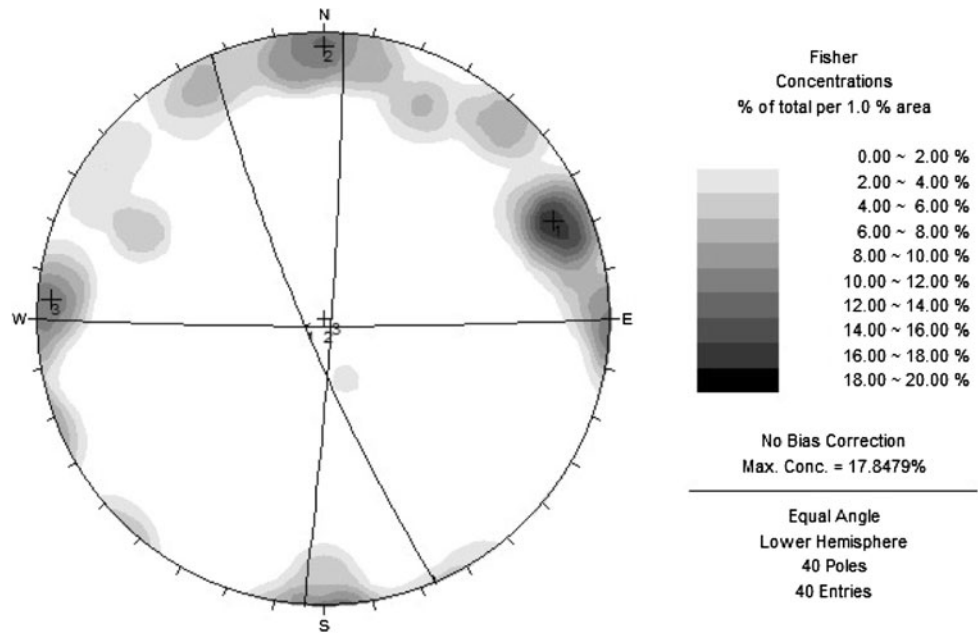**Fig. 8** Discontinuity contour diagram of the major sets of the mudstone

Table 1 Some physical and mechanical properties of samples

Rock type	Parameters	Max	Min	Average	Standard deviation (σ)	Number of samples (n)
Basalt	W_{abs} (%)	2.4	2.2	2.3	0.09	5
	N (%)	5.7	5.3	5.5	0.14	5
	γ (kN/m^3)	25.7	25.0	25.2	0.27	5
	UCS (MPa)	103.7	99.7	101.5	1.99	5
Mudstone	γ (kN/m^3)	21.1	20.1	20.6	0.42	5
	UCS (MPa)	9.0	7.9	8.6	0.43	5

Fig. 9 Shear box test samples to determine the basic friction angles between basalt and mudstone

Fig. 10 Shear envelope for basalt-mudstone samples under dry conditions

potential rockfall areas, additional computer code, namely Conefall (2003) was employed. The program is designed to roughly estimate the potential rockfall-prone areas. The principle of the program is that a rock block can propagate from its source to the point of the intersection of the topography, with the line starting from the source point making an angle φ_p with horizontal. The space where a block c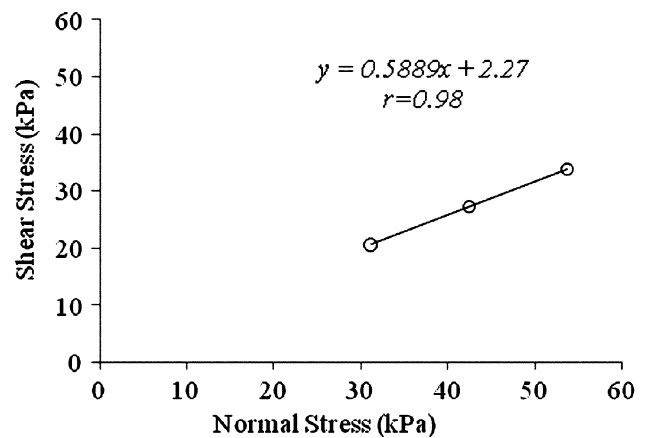an propagate from a grid point is located within a cone of slope φ_p, with a summit placed at the source point (Conefall 2003).

To evaluate the spatial potential of rockfall-prone areas, ASCII format '*.grd' files of the DEM and the mapped

rockfall source areas were utilised (see Fig. 5a). The value of −1 was assigned to represent the no-source areas, whilst the rockfall source areas had a value of 1 in the ASCII grid file. The other crucial input of the program was the cone angle, and it must have been set usually within the range between 27° and 38° (Conefall 2003). Four different cone angles (27°, 30°, 33° and 38°) were selected to produce

potential rockfall areas (Fig. 15). The main reason behind the utilisation of four different angles was to observe the change in areal distribution of rockfall-prone areas. When

Table 2 Input parameters utilised in rock fall simulations

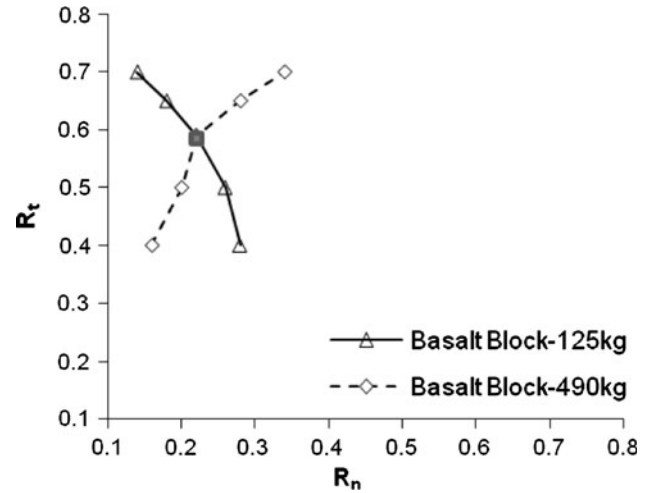| Parameter	Value
Number of block throws	1,000
Minimum velocity cut off (m/s)	0.1
Sampling interval	50
Number of generation	Random
Coefficient of normal restitution (R_n)	0.223 ± 0.052
Coefficient of tangential restitution (R_t)	0.586 ± 0.102
Initial velocity (m/s)	0
Friction angle for the basalt blocks (φ)	30.5°
Slope roughness	2

Fig. 12 The coefficients of normal (R_n) and tangential (R_t) restitutions calculated from the back analyses

Table 3 Results of the rockfall simulations

Location number	Earth pillar height (m)	Weight (kg)	Translational velocity (m/s)			Total kinetic energy (kJ)			Bounce height (mm)			Blocks end points (m)		
			Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
1	18.8	1,100	8.47	17.41	11.09	50.31	178.59	84.25	0.8	5.08	2.12	4.50	23.06	15.63
2	17.1	413	2.68	16.91	7.68	2.08	59.14	17.28	0.1	1.59	0.49	5.65	34.24	20.96
3	9.21	475	0.91	16.10	9.52	1.92	64.5	29.42	0.09	5.92	1.58	18.57	24.10	20.33
4	13.1	1,680	5.32	21.28	15.22	35.29	426.46	249.11	0.06	4.49	1.31	24.89	26.50	26.48
5	22.6	926	5.57	19.64	11.17	23.35	178.71	72.91	0.01	2.11	0.57	37.71	39.29	39.24
6	25.2	2,290	4.10	20.83	11.10	30.14	496.92	183.64	0.03	2.68	0.81	31.59	34.36	33.38
7	6.1	130	5.95	9.35	7.20	3.21	6.53	4.38	0.04	0.76	0.29	4.13	7.44	5.76
8	4.1	273	0.95	8.71	3.51	0.40	10.34	2.28	0.01	0.17	0.04	5.66	14.10	6.52

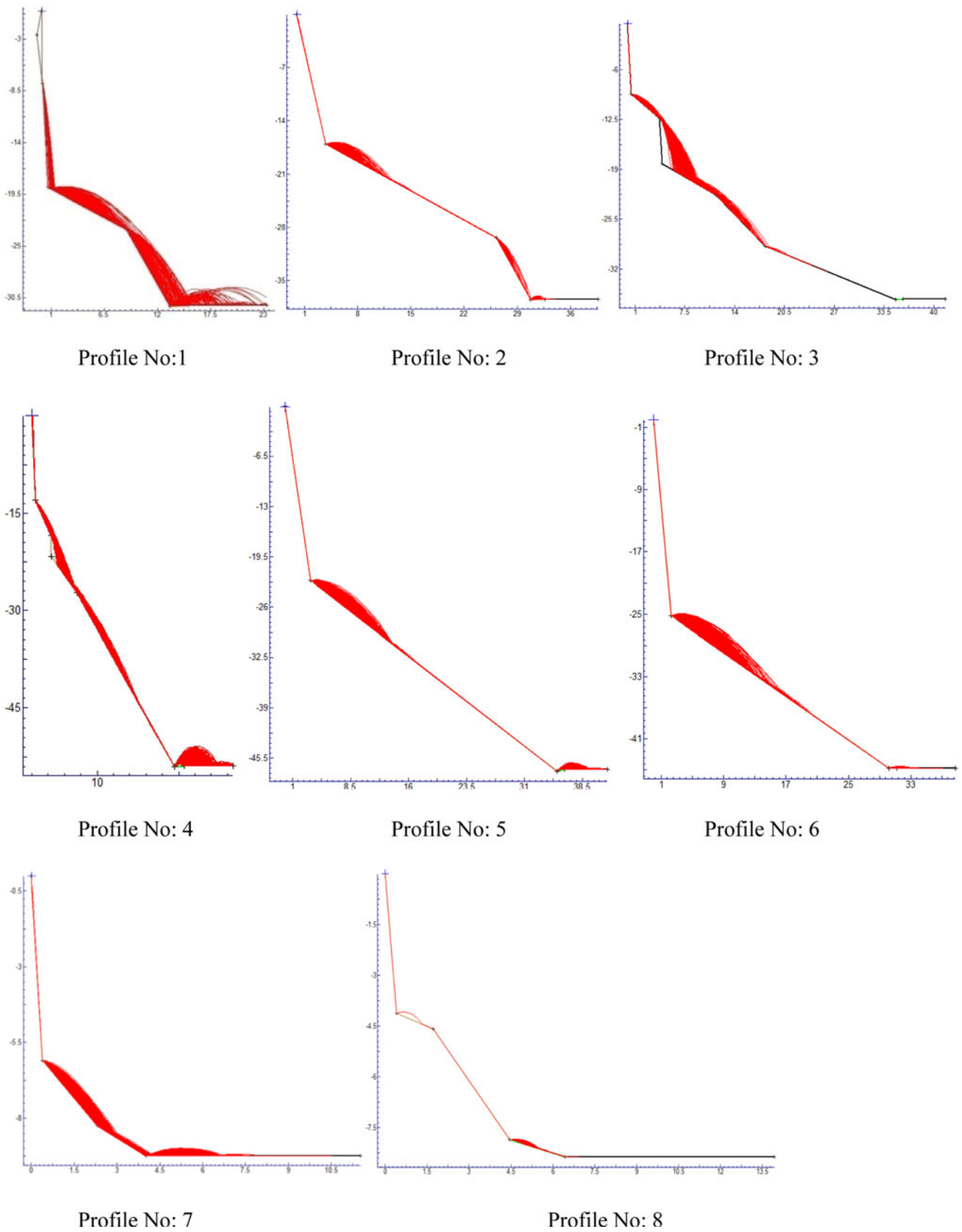**Fig. 11** Pictures of some of the hanging blocks at the top of the earth pillars

Fig. 13 Trajectories of the analysed earth pillars with rockfall potential

Table 4 Maximum barrier height suggestions for the profiles

Profile number	Maximum barrier height (m)
1	3.0
2	0.5
4	3.0
5	1.0
6	0.5
7	0.5
8	0.2

combined with the field observations and individual rock-fall analyses, a cone angle greater than 30° should not be selected for the study area because no rock block can reach the road at these angles (Fig. 15c, d).

Results and conclusions

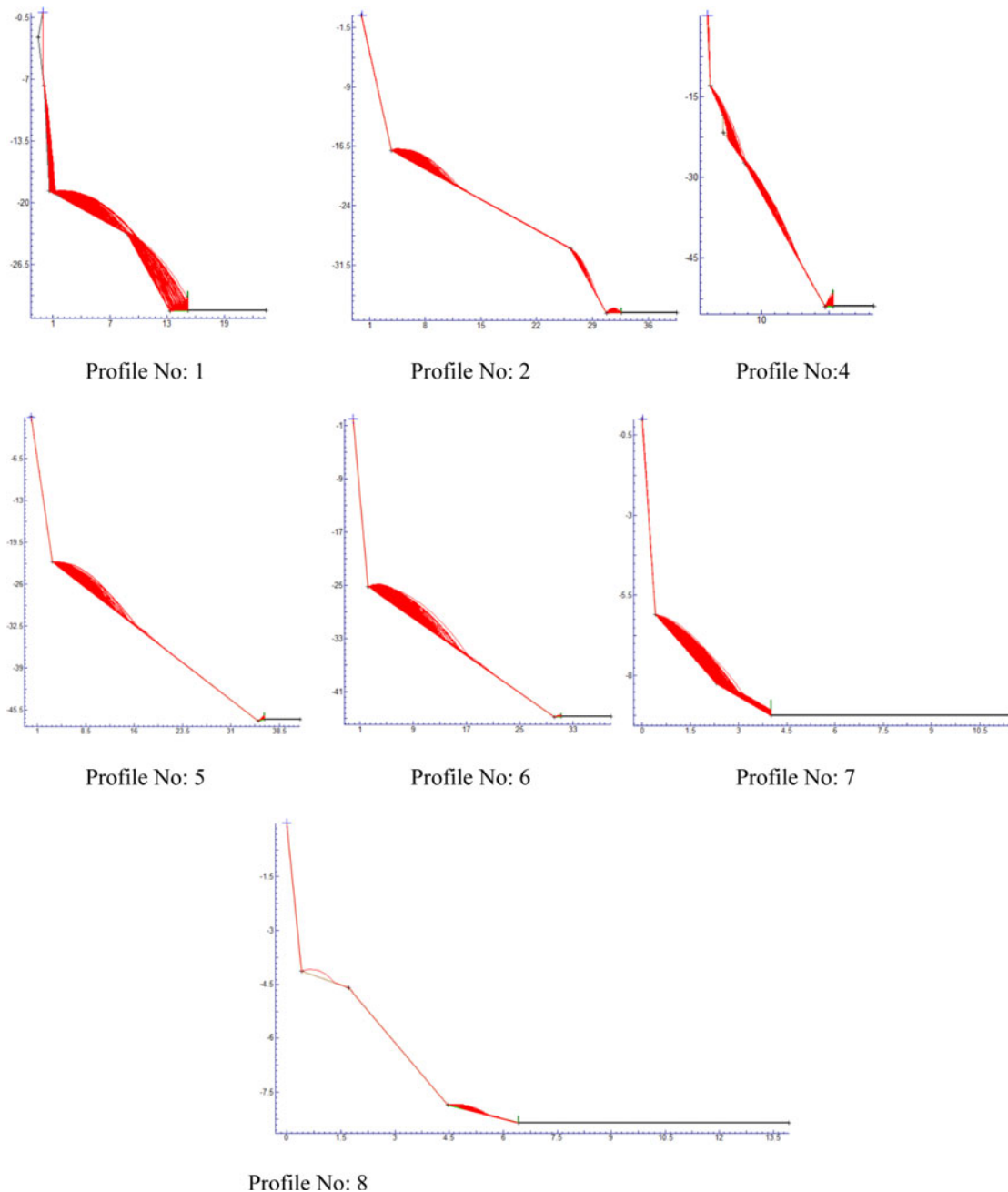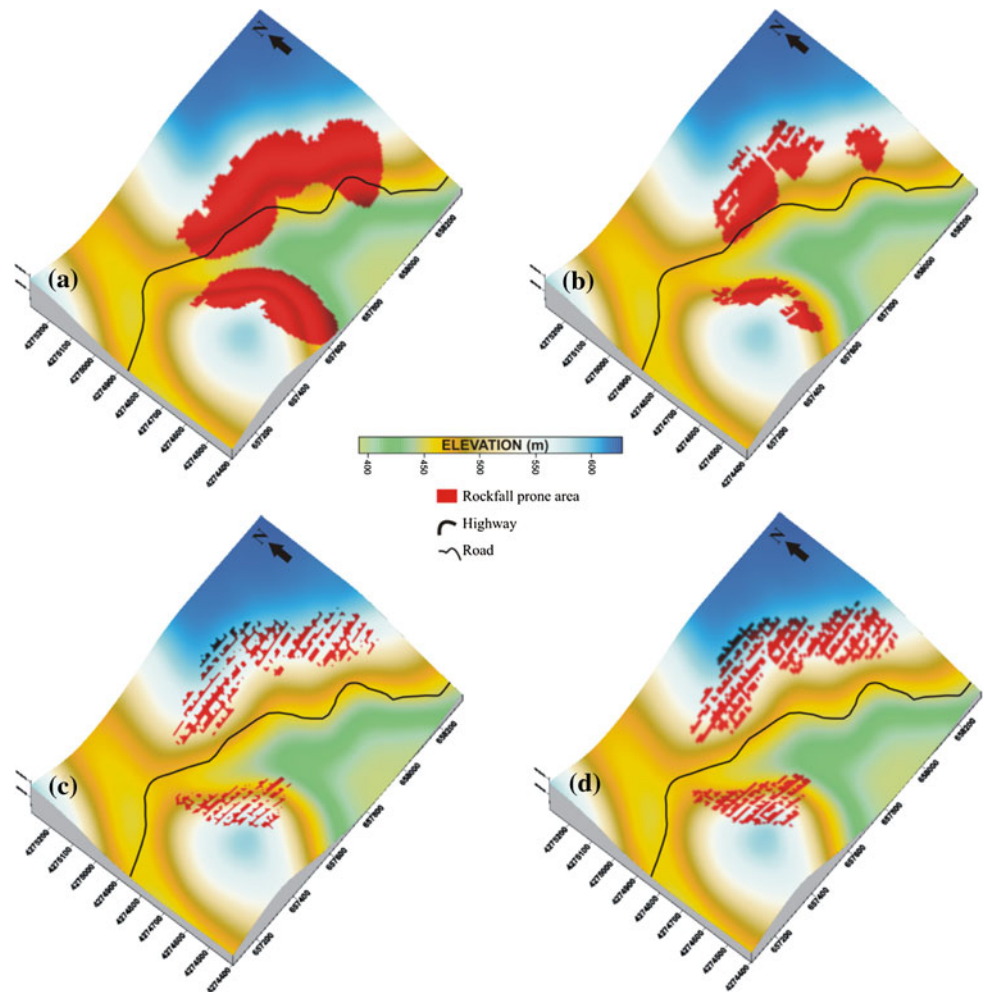Based on the work reported in this paper, the following results and conclusions can be drawn:

Profile No: 1   Profile No: 2   Profile No:4

Profile No: 5   Profile No: 6   Profile No: 7

Profile No: 8

Fig. 14 Rockfall trajectories of the profiles with the barrier protection

Fig. 15 Rockfall-prone areas produced by different cone slope angles: **a** 27°, **b** 30°, **c** 33° and **d** 38°

1. To evaluate the rockfall potential in the Kula Geopark Region, extensive fieldworks, such as scan-line surveys, sampling, measurements and observations, were performed. Based on the fieldworks, it was determined that the earth pillars, formed by basalt blocks at the top and mudstone bodies from top to the bottom, were responsible for rockfall occurrences. Thus, the areas covered by the earth pillars were considered rockfall source areas. Regarding the discontinuity characteristics, three major joint sets were determined. Generally, the discontinuities have high persistency, tight to wide apertures, planar and rough surfaces and wide spacing in average.

2. Collected data from the field studies and laboratory tests were combined to perform rock analyses. These analyses were carried out in two different stages for individual blocks and for areal distribution related to the source areas. For individual blocks, eight profiles were taken into consideration, and it was revealed that, except for one profile (Profile No. 3), the blocks of seven profiles had the capability of reaching the transportation line passing through the study area. For determination of rockfall-prone areas, analyses were carried out for two different source areas. Both analyses showed that transportation lines could be affected by the rockfall process. Therefore, to avoid the consequences of rockfall events, barriers were utilised in the rockfall analyses as protective measures. The maximum required barrier height was calculated as 3 m, and this measure also seems to be sufficient with respect to economic considerations. Producing these sorts of maps and assessments may provide valuable information for decision makers, particularly for this type of special area.

3. In addition to the region's proneness to rockfall events, triggering factors, such as earthquakes and rainfall may play an important role in rockfall initiation when the location of the region is considered. In addition, erosional processes are effective on earth pillars' stability, continuously weakening mudstones. Eventually, these earth surface processes can be considered for detailed analyses and future works.

4. Owing to the fact that geology is the staple point of the Geopark concept, various disciplines of geosciences, such as engineering geology, palaeontology, volcanology, geomorphology and sedimentology should interactively considered when establishing a Geopark. In addition to legislative issues related to governmental and local administrations, success can only be achieved by taking into consideration different interdisciplinary works related to protection.

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