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1 Estimating rockfall frequency in a mountain limestone cliff 2 using terrestrial laser scanner

3
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9 This report was written in 2013

10 11 **Abstract**

12 Terrestrial laser scanner has been used to detect rockfalls which occurred in a high rock wall of
13 the Subalpine Chains, from a survey station located up to 900 m from the cliff. Using a threshold
14 of 0.1 m in term of distance variation, 344 rockfalls larger than 0.05 m³ have been detected for
15 a period of 1180 days, in a rock wall of width 750 m and height 200 m. The complementary
16 cumulative distribution of the rockfall volume is well fitted by a power law, with an exponent
17 b of 0.75 ± 0.04 . In order to compare the rockfall frequencies in different geological contexts,
18 a rockfall activity parameter has been considered, which is the number of rockfalls larger than
19 a given volume, which occur per century and per hm². For the thinly bedded limestone making
20 the cliff surveyed, the number of rockfalls larger than 1 m³ is 0.85 rockfalls per year and per
21 hm². It is two orders of magnitude higher than the number obtained for massive limestone cliffs
22 of the Subalpine Chains in the Grenoble area.

23 24 **1 Introduction**

25 Estimating rockfall frequency is needed to characterize a diffuse rockfall hazard (Hungr, 1999;
26 Picarelli et al., 2005; Fell et al., 2005; Hantz, 2011). Up to now this frequency is determined
27 from historical inventories. The minimal volume detected in these inventories can be relatively
28 small when the rock blocks fall on a road or railway from a cut slope, but it is larger when they

1 fall from a high rock cliff (Dussauge et al., 2002). In the last years, terrestrial laser scanner
2 (TLS) has been used to detect rockfalls by comparing digital cliff models obtained from
3 successive datasets.

4 On the east coast of the Great Britain, Rosser et al. (2005) detected 810 rockfalls greater than
5 10^{-3} m^3 , occurred during 16 months in a coastal cliff of 300 m in width and 65 m in height. In
6 the same area, Lim et al. (2010) detected 114,500 rockfalls occurred in a period of 20 months
7 in 5 cliffs covering $16,000 \text{ m}^2$, the height of which ranging from 35 m to 70 m. The small
8 distance from the survey station to the cliff face (maximum 70 m) allowed them to detect
9 rockfalls as small as $1.25 \times 10^{-4} \text{ m}^3$. These cliffs are formed from mudstone, shale, siltstone and
10 sandstone. On the coast of Normandy (France), Dewez et al. (2013) detected 8500 rockfalls
11 greater than 10^{-3} m^3 , occurred in a period of 27 months in a chalk coastal cliff of 50 m in height
12 and 750 m in width.

13 In Catalonia (Spain), Abellan et al. (2010 ; 2011) have monitored two continental cliffs from a
14 distance of about 100 m. They considered a detection threshold of 10^{-3} m^3 , according to Rosser
15 et al. (2005). A number of 42 rockfalls were detected in a period of 10 months in a cliff of 25
16 m in height and 150 m in width, formed from sedimentary rocks (marl, sandstone, silt, clay),
17 and 7 rockfalls were detected in a period of 22 months in a basaltic cliff of 35 m in height and
18 200 m in width.

19 In the French Alps, Rabatel et al. (2008) and Ravanel et al. (2012) have monitored two granitic
20 rock walls in high mountain from survey stations located about 100 m from the rock face.
21 According to the uncertainties, they used a thickness threshold of 0.1 m. Two rockfalls were
22 detected in a period of 12 months in a wall of 200 m in height and 300 m in width, and 6
23 rockfalls in a period of 24 months in a wall of 50 m in height and 400 m in width.

24 It appears at first sight from this review that the spatial-temporal rockfall frequency (number of
25 rockfalls per unit of surface and time) for a given minimal volume strongly depends on the
26 geological and geomorphological contexts (lithology and structure of the cliff, erosion factors).
27 The development of TLS allows to precise the frequencies corresponding to different contexts
28 and further to determine the influence of the geological and geomorphological factors on the
29 spatial-temporal frequency. In this paper, we study the rockfall frequency in a typical limestone
30 cliff of the Subalpine Chains.

1 The cliff surveyed sit on top of a densely forested talus slope. It ensues that the survey station
2 had to be located relatively far from the cliff, which makes the detection of rockfalls more
3 difficult than in the previous studies.

4 **2 Description of the cliff and measurements**

5 The Mont Saint-Eynard (1308 m) is located 4 km to the North of the Grenoble centre and towers
6 above a residential area of the town (Fig. 1 and 2). Its geological context has been described by
7 Gidon (2013). The South-East face consists of, from top to bottom: a 120 m high limestone cliff
8 (Tithonian and upper Kimmeridgian stages); a 100 m high forested slope of marl and marly
9 limestone (Kimmeridgian stage); a 240 m high limestone cliff (Sequanian stage); a 300 m high
10 forested talus slope, covering marl and marly limestone of the Oxfordian stage. This paper
11 describes the results obtained for the Sequanian cliff.

12 The survey station was located at the foot of the talus slope, on a protection embankment at an
13 elevation of 580 m. The inclined distance to the cliffs ranges between 625 m and 900 m. Note
14 that no place was found closer to the cliffs. Photographs and laser measurements were carried
15 out on August 27, 2009 and November 19, 2012.

16 The laser scanner technology also called LiDAR (Light Detection And Ranging), is based on
17 the acquisition of a point cloud using a time-of-flight distance measurement of an infrared laser
18 pulse which reflects on the topography. The raw data consist of the x, y, z coordinates of each
19 reflection point and the intensity of the reflected pulse. The y axis corresponds to the outward
20 axis of the laser camera and x and z axes are parallel to the sides of the scene (x is roughly
21 horizontal).

22 We have used two Optech systems: ILRIS-3D in 2009 and ILRIS-LR in 2012. The main
23 characteristics of these systems are given in Table 1. It can be seen that ILRIS-LR has a higher
24 repetition rate, allowing a greater number of points to be measured for a given period of time.
25 In the distance range concerned, it can also measure surfaces having a lower reflectivity than
26 ILRIS-3D. According to the distances given above and the accuracy given in Table 1, the
27 expected accuracy of our distance measurements ranges from about 5 cm for the closest points
28 to 7,5 cm for the farthest ones. Two scans were taken to cover a cliff width of about 750 m.

29

30 **3 Data analysis**

31 The software 3DReshaper Application have been used to process the point clouds.

1 **3.1 Cleaning the raw point cloud**

2 Vegetation has a lower reflectivity than the rock making up the cliff. Thus, a reflectance
3 threshold has been chosen to remove most of the points corresponding to vegetation. After
4 cleaning, the point clouds consisted of 2.7 Mpt in 2009 and 12.8 Mpt in 2012. They are shown
5 in Fig. 3. The average distance between the points ranged from 21 to 29 cm (according to the
6 distance from the camera to the cliff) in 2009 and from 10 to 13 cm in 2012.

7 **3.2 Georeferencing**

8 Georeferencing the LiDAR point clouds was made by registering these with a Digital Elevation
9 Model (1 m x 1 m) using Lambert 2 extended (x,y) coordinates and NGF IGN 69 leveling (z).
10 The DEM is shown in Fig. 4. Then the coordinate system has been rotated in order to easily
11 determine the width and the thickness of the fallen compartments. The width is defined
12 horizontally, parallel to the cliff (new x direction), the thickness is defined horizontally,
13 perpendicular to the cliff direction (new y direction) and the height is parallel to the z axis
14 (unchanged). The positive direction is inside the cliff for the y axis and towards the East side
15 for the x axis.

16 **3.3 Meshing the 2012 point clouds**

17 The more recent point cloud (2012) has been transformed in a mesh (polyhedrons), made up of
18 2.7 million of triangles and 1.3 million of vertex (Fig. 5a and 5b). The average distance between
19 the vertex of the polyhedrons ranges from 26 to 36 cm (according to the distance from the
20 camera to the cliff). Note that the number of vertex is about ten times less than the initial number
21 of points of the cloud. This reduction is associated to the noise reduction process we used in
22 3DReshaper and is also necessary for numerical reasons. The registration of the 2012 point
23 cloud with the corresponding mesh gives information about the roughness of the rock surface
24 at the scale of the triangles making up the mesh. It appears that about 50 % of the points are
25 closer than 1 cm from the mesh, 90 % are closer than 3 cm and 99 % are closer than 7 cm. Note
26 that, in the later case, most of the deviations larger than 7 cm are located on vegetation areas,
27 which have not been suppressed in the cleaning process.

1 **3.4 Registration of the point clouds**

2 As georeferencing with the DEM was not precise enough, the 2012 mesh and the point cloud
3 acquired in 2009 have been registered (fitted) together in order to put them exactly in the same
4 coordinate system. Ideally, the deviations between these objects should be due only to rockfalls
5 occurred between 2009 and 2012. But in reality, there are other causes of deviations: (a)
6 measurement inaccuracy; (b) the 2009 measurement points do not correspond to the 2012 ones
7 and consequently, are not exactly on the triangles defined by the 2012 vertex (due to the
8 curvature and the roughness of the rock surface); (c) the later cause is accentuated in areas
9 where the triangles are large (this situation occurs particularly near the limits of the mesh); (d)
10 vegetation element which has not been removed; (e) earth slide due to the impact of an
11 overlying rockfall. Consequently, a deviation threshold has to be set for the detection of true
12 rockfalls.

13 **3.5 Detection of the rockfalls with visual checking**

14 In a first stage, a deviation threshold was set to 0.2 m in order to make possible checking the
15 rockfalls by comparing photographs taken in 2009 and 2012 (for a lower threshold, most of the
16 rockfalls are not visible on photographs). A rockfall has been considered certain when a positive
17 deviation is observed and the comparison of the 2009 and 2012 photos shows that a rockfall
18 has occurred between these dates. Such a comparison is shown in Fig. 6. When a positive
19 deviation is observed and the comparison of the 2009 and 2012 photos shows that no rockfall
20 has occurred, the deviation has been considered to be a false rockfall. The false rockfalls which
21 have been obtained are due to the conditions (c) or (d) expressed in the later paragraph. When
22 a positive deviation is observed and the photo comparison cannot conclude if a rockfall has
23 occurred or not, the deviation has been considered to be an uncertain rockfall if the conditions
24 (c) or (d) occur or a probable rockfall if these conditions don't occur. This situation occurs more
25 and more when the extent of the deviation zone decreases (Fig. 7). The reason is that small
26 rockfalls are difficult to observe on photographs. Fig. 7 shows the proportions of certain,
27 probable, uncertain and false rockfalls as a function of the rockfall volume.

28 For the 162 certain and probable rockfalls detected, the volume has been calculated by creating
29 a watertight mesh, starting from the 2009 and 2012 surfaces of the fallen rock compartment,
30 which were not initially attached. This procedure is manual and time consuming. At this stage
31 of analysis, 169 events have been detected, out of which 2 false rockfalls and 5 uncertain ones.

1 The minimal and maximal volumes detected are respectively of 0.018 m³ and 81 m³. The
2 complementary cumulative distribution function of the rockfall volume is shown in Fig. 8. A
3 power law has been fitted to the data. It can be seen that the fitting is better when considering
4 only the volumes greater than 0.1 m³.

5 **3.6 Detection of the rockfalls without visual checking**

6 In a second stage, the deviation threshold has been lowered in order to detect smaller rockfalls,
7 which cannot be checked with photographs. According to the accuracy expected (Sect. 2), the
8 deviation threshold has been set to 0.1 m. In this stage, 295 additional events have been
9 detected, out of which 229 probable rockfalls. Although smaller volumes are detected with a
10 deviation threshold of 0.1 m, it occurs that the minimal volume detected is the same (0.018 m³)
11 as with the 0.2 m threshold. The complementary cumulative distribution function of the rockfall
12 volume is shown in Fig. 9. The fitting to a power law is better when considering only the
13 volumes greater than 0.05 m³.

14

15 **4 Discussion**

16 The distribution function of the rockfall volume has been studied by several authors (see
17 reviews in Dussauge-Peisser et al., 2002, and Brunetti et al., 2009). Most of them found that
18 the complementary cumulative distribution function is well fitted by a power law:

$$19 \quad N = aV^{-b} \quad (1)$$

20 where V is the rockfall volume, N is the number of rockfalls larger than V, a and b are constants.
21 The validity of a power law to describe the rockfall volume distribution has been tested by
22 Dussauge-Peisser et al. (2003) using a χ^2 test. The constant a represents the number of rockfalls
23 whose volume is greater than 1 m³ (assuming the law is valid for this volume range). It depends
24 on the size of the cliff, the length of the observation period and the geological and
25 geomorphological context. On the contrary, the exponent b only depends on the geological and
26 geomorphological context. Its value has been determined for some different contexts
27 (Dussauge-Peisser et al., 2002). For the particular contexts studied up to now, it ranges from
28 0.4 to 0.72. Its standard deviation has been estimated in some cases (Dussauge-Peisser et al.,
29 2003) using a maximum likelihood method:

$$30 \quad \sigma = b / \sqrt{N_0} \quad (2)$$

1 where N_0 is the number of events considered and b is the exponent value in Eq. (1).

2 Fig. 8 shows the volume distribution function for the rockfalls detected in this study using a
3 threshold of 0.2 m, most of which having been checked visually (Fig. 7). It can be seen that the
4 distribution function is well fitted by a power law for volumes greater than 0.2 m^3 , with an
5 exponent of 0.69 ± 0.07 and a correlation coefficient of 0,983. But the volumes lower than 0.2
6 m^3 are underrepresented, probably by under-sampling. This is confirmed by Fig. 9, which
7 shows the volume distribution function for a threshold of 0.1 m. This function is well fitted by
8 a power law for volumes greater than 0.05 m^3 , with an exponent of 0.75 ± 0.04 and a correlation
9 coefficient of 0,994. Now the volumes lower than 0.05 m^3 are underrepresented. This
10 underrepresentation can be due to the limited resolution of the investigation method or reflects
11 the real distribution of the rockfall volume. The fact that the exponent value is not significantly
12 changed by passing from the visually checked rockfalls (Fig. 7) to the numerically detected
13 ones (Fig. 8), suggests that the obtained inventory is exhaustive for volumes greater than 0.05
14 m^3 .

15 For comparing the rockfall activities of cliffs in different geological and geomorphological
16 contexts, it is necessary to consider the number of rockfalls per unit of time and space (spatial-
17 temporal frequency). For this purpose, we introduce the rockfall activity parameter A_{st} , which
18 is a (from Eq. 1) divided by the cliff surface and the length of the observation period. In order
19 to calculate this parameter for the Mont Saint-Eynard lower cliff (Sequanian), a mean height of
20 200 m and a width of 750 m have been considered, which give a value of 0.85 rockfalls per
21 year and per hm^2 , using the a -value of 41 given in Fig. 8.

22 Hantz et al. (2003) analyzed the cumulative distribution of rockfall volumes between 10^2 and
23 10^7 m^3 , occurred in the 120 km long limestone cliffs of the Grenoble area, which include the
24 Mont Saint-Eynard cliff. They found that a power law well describes the distribution, with an
25 exponent of 0.55 ± 0.11 and a rockfall activity of 0.0047 rockfalls per year and per hm^2 . It
26 appears that both parameters b and A_{st} are significantly different for the two considered rock
27 fall populations: $b = 0.75 \pm 0.04$ and $A_{st} = 0.85$ for the Mont Saint-Eynard; $b = 0.55 \pm 0.11$ and
28 $A_{st} = 0.0047$ for the Grenoble area. As the power law parameters for the two inventories were
29 determined from volumes ranging respectively from 0.05 m^3 to 100 m^3 and from 100 m^3 to 10^7
30 m^3 , it is more pertinent to compare the rockfall activities by using the numbers of rockfalls
31 larger than 100 m^3 , which occur per century and per hm^2 . These numbers are respectively of

1 2.7 and 0.037, giving a ratio of 72. Several reasons can be proposed to explain this strong
2 discrepancy:

3 (a) The rockfalls for the Grenoble area were known from a historical inventory which is
4 probably not exhaustive.

5 (b) Most of the rockfall volumes for the Grenoble area were estimated from historical sources,
6 with more uncertainty than for the Mont Saint-Eynard.

7 (c) The cliffs of the Grenoble area consist of different calcareous rocks of Jurassic and
8 Cretaceous age, including mostly massive limestones (metric to decametric thickness), whereas
9 the cliff studied consists only of thinly bedded limestone of Sequanian stage (thickness of 20-
10 50 cm).

11

12 **5 Conclusions**

13 Terrestrial laser scanner can be used to detect rockfalls which occur in high rock walls from a
14 survey station located up to 900 m from the cliff. Using a threshold of 0.1 m in term of distance
15 variation, 344 rockfalls larger than 0.05 m^3 have been detected for a period of 1180 days, in a
16 rock wall of width 750 m and height 200 m.

17 The complementary cumulative distribution of the rockfall volume is well fitted by a power
18 law, with an exponent b of 0.75 ± 0.04 and a rockfall activity parameter A_{st} of 0.85 rockfalls
19 per year and per hm^2 . These parameters characterize the rockfall frequency in a thinly bedded
20 limestone cliff of the Subalpine Chains.

21 They are significantly different from those which have been obtained from a historical rockfall
22 inventory covering 120 km of cliff consisting mostly of massive limestone: For this inventory,
23 the b -value is 0.55 ± 0.11 and the theoretical number of rockfalls larger than 100 m^3 , which
24 occur per century and per hm^2 , is 0.037 instead of 2.7 for the thinly bedded limestone.
25 Terrestrial laser scanning of large cliff surfaces of massive limestone in the Subalpine Chains
26 is needed to better investigate the rockfall frequency in these cliffs.

27

28 **Acknowledgements**

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2 funding. They also thank Alex Loye, Benoît Fragnol, Battista Matasci and Jérémie
3 Voumard who performed laser scannings.

4

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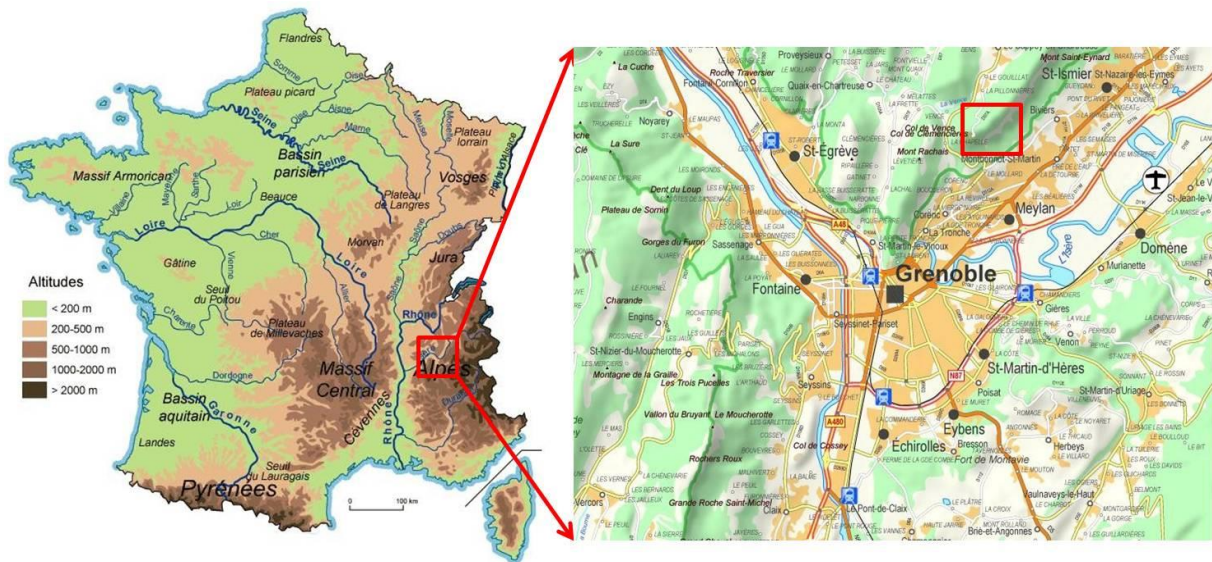
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20

1 Table 1. Main characteristics of the laser scanners used.

Parameter	ILRIS-3D	ILRIS-LR
Range 80% reflectivity	1200 m	3000 m
Range 10% reflectivity	400 m	1330 m
Minimum range	3 m	3 m
Laser repetition rate	2500 to 3500 Hz	10 000 Hz
Raw range accuracy	7 mm @ 100 m	7 mm @ 100 m
Raw angular accuracy	8 mm @ 100 m	8 mm @ 100 m
Field of view	40° x 40°	40° x 40°
Minimum step size	0,001146° (20 µrad)	0,001146° (20 µrad)
Maximum density	2 cm @ 1000 m	2 cm @ 1000 m
Rotational speed	0,001 to 20°/sec	0,001 to 20°/sec
Beam diameter	22 mm @ 100 m	27 mm @ 100 m
Beam divergence	0,009740° (170 µrad)	0,014324° (250 µrad)
Laser wavelength	1535 nm	1064 nm
Integrated camera	3,1 MP	3,1 MP

2



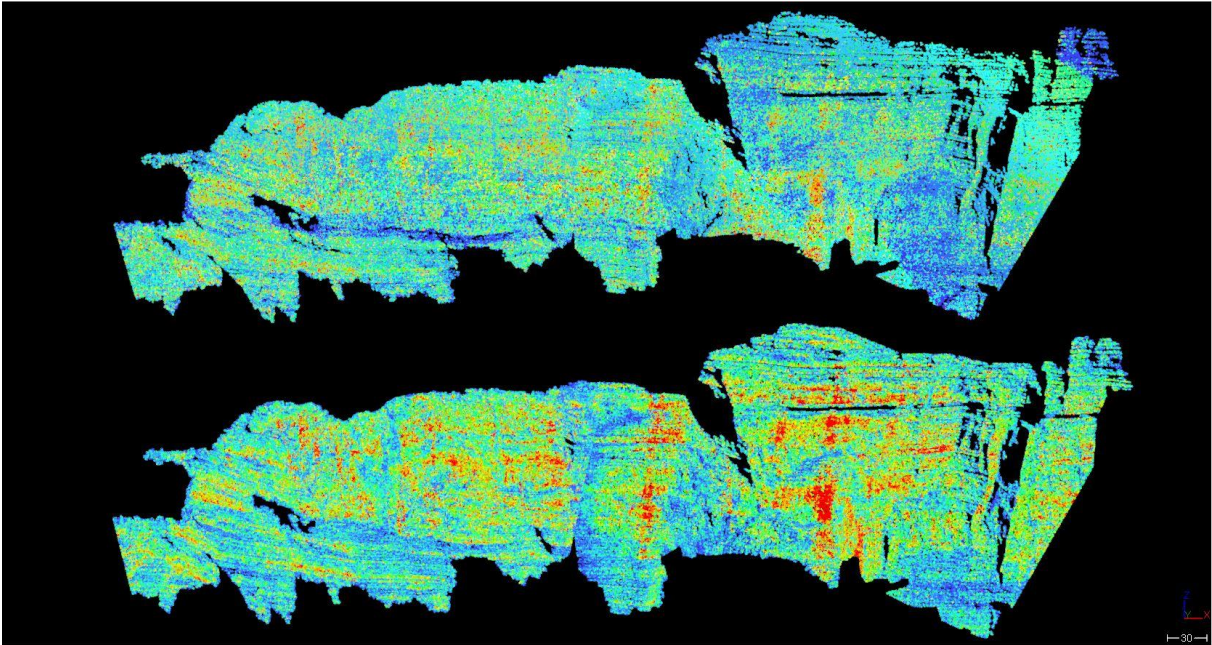
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Figure 1. Location of the Mont Saint-Eynard. Inhabited areas appear in beige in the right map.



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Figure 2. Photograph of the Mont Saint-Eynard cliff.



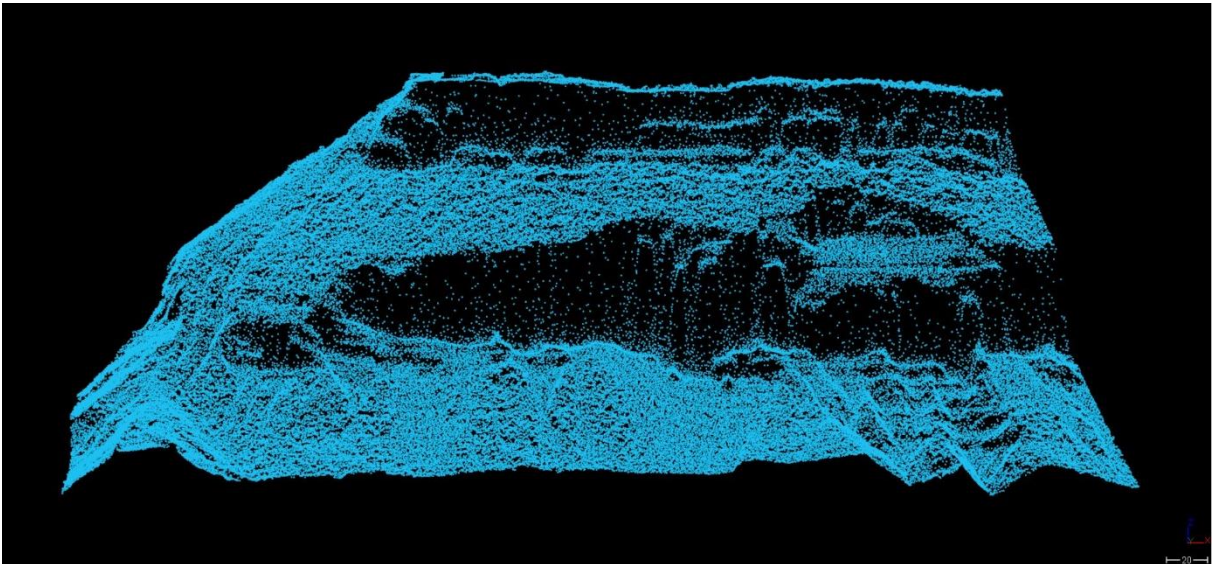
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3 Figure 3. Point clouds measured in 2009 (high) and 2012 (low). Red: high reflectance. Blue:
4 low reflectance.

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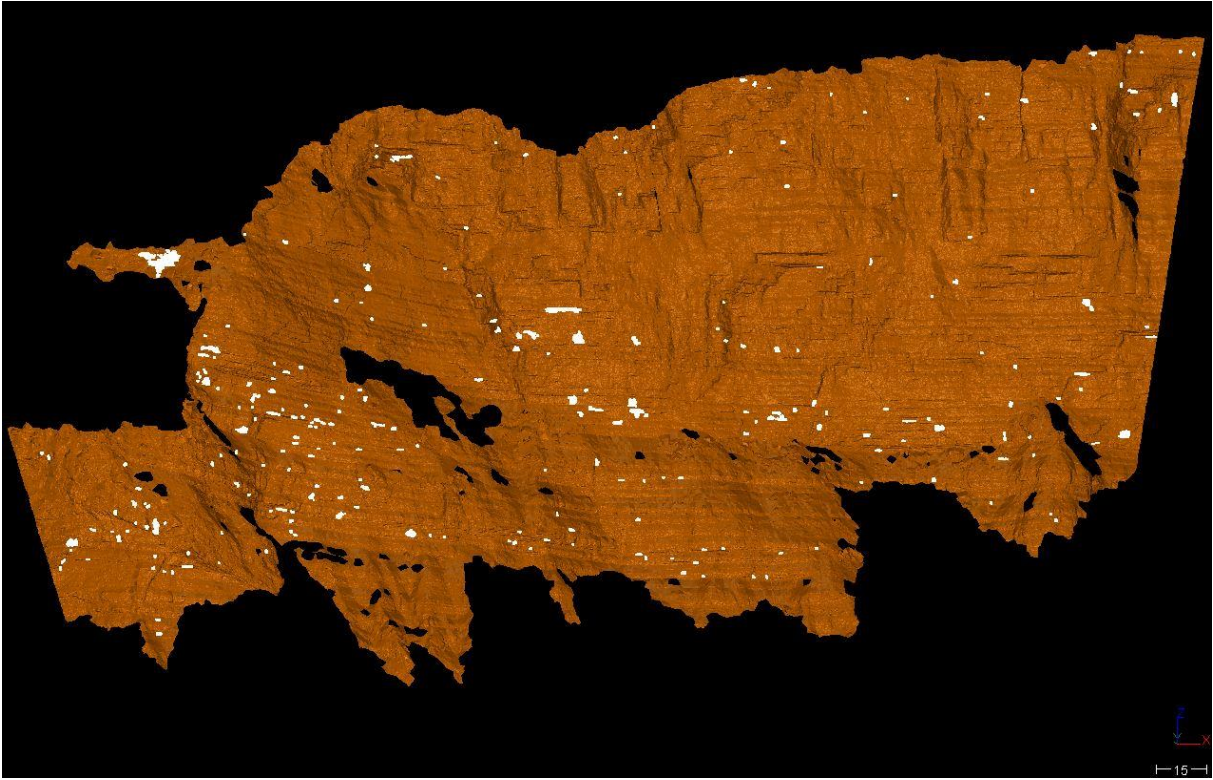


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9 Figure 4. Digital Elevation Model used for georeferencing (1 m x 1 m grid).

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3 Figure 5. Upper: Mesh for the left scene 2012 and rockfall detected (white spots). Lower: Mesh
4 for the right scene 2012 and rockfall detected (white spots).

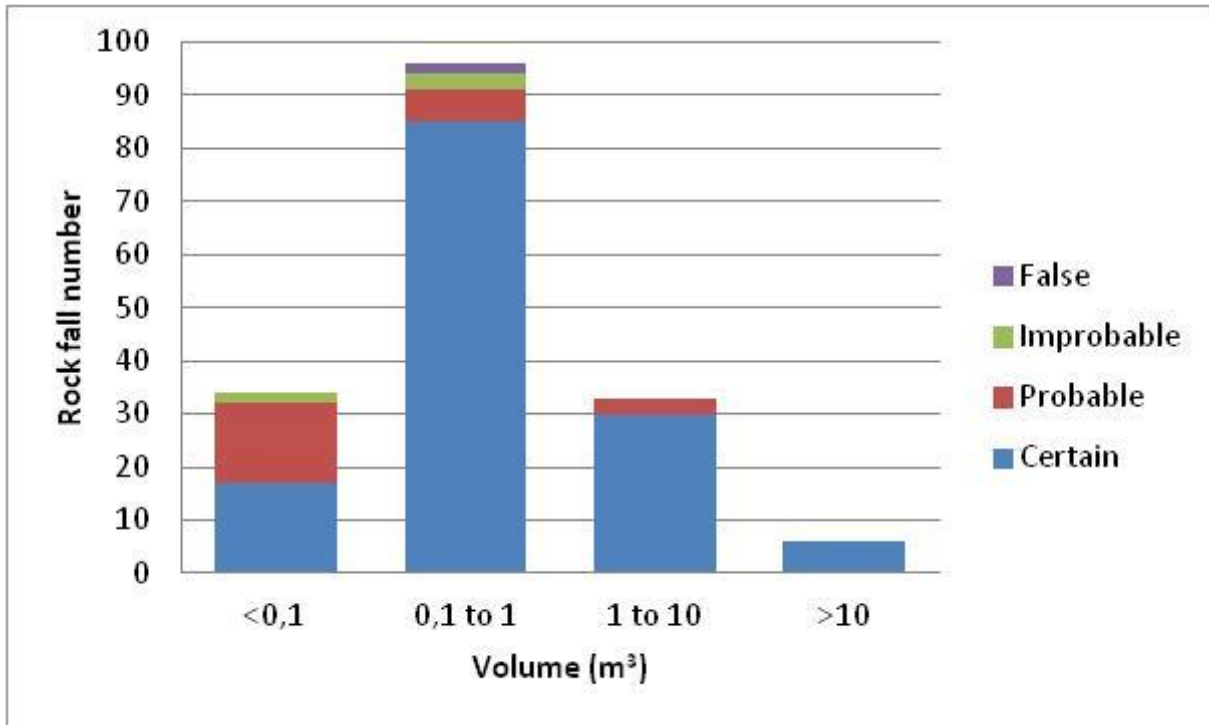
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3 Figure 6. Rockfall proven by comparison of 2009 and 2012 photographs (81 m³).



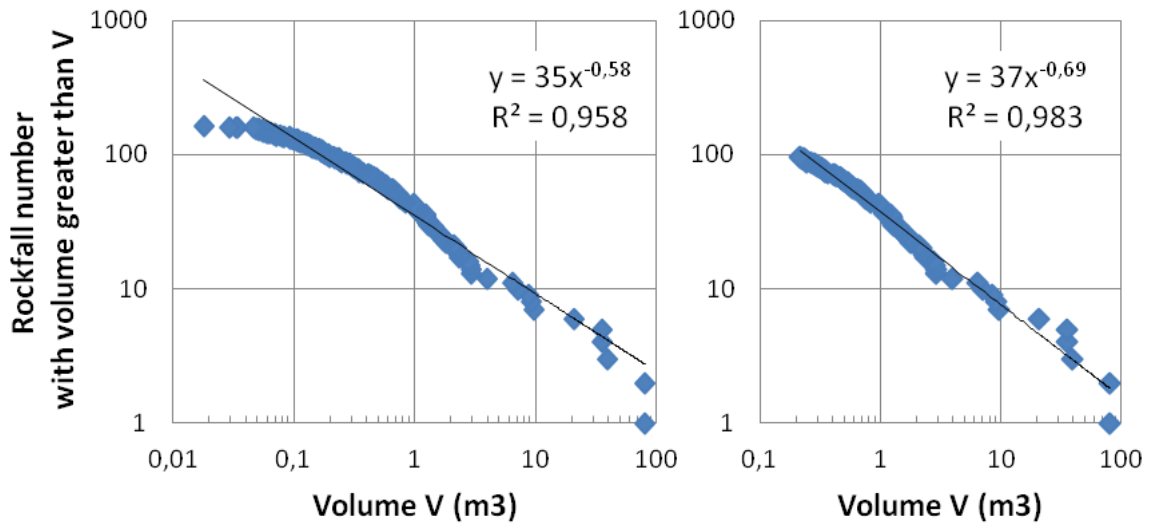
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6 Figure 7. Proportions of certain, probable, uncertain and false rockfalls as a function of the
7 rockfall volume, for a deviation threshold of 0.2 m.

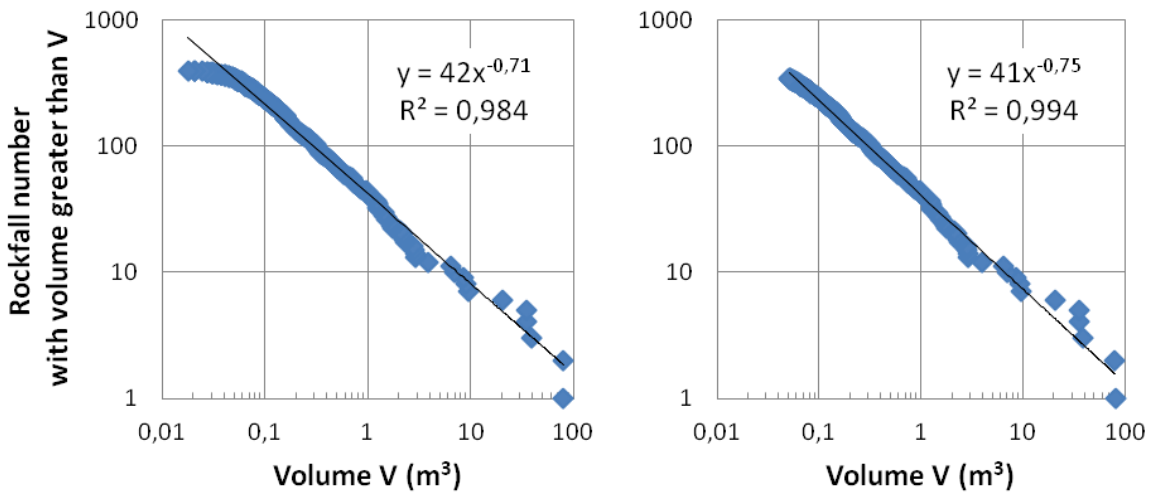
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Figure 8. Distribution function of the rockfall volume for a deviation threshold of 0.2 m.
Left: Volume > 0.01 m³ (162 events). Right: Volume > 0.2 m³ (96 events).



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Figure 9. Distribution function of the rockfall volume for a deviation threshold of 0.1 m.
Left: Volume > 0.01 m³ (391 events). Right: Volume > 0.05 m³ (344 events).