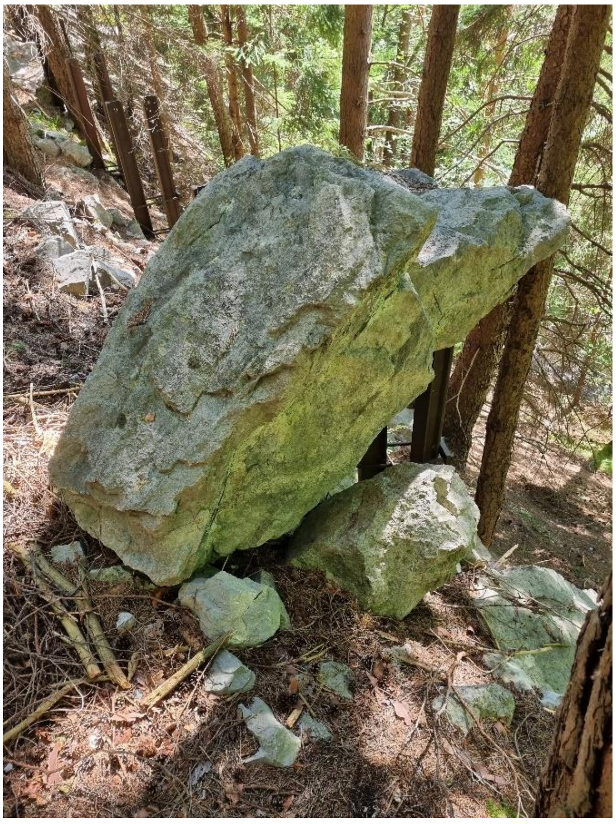
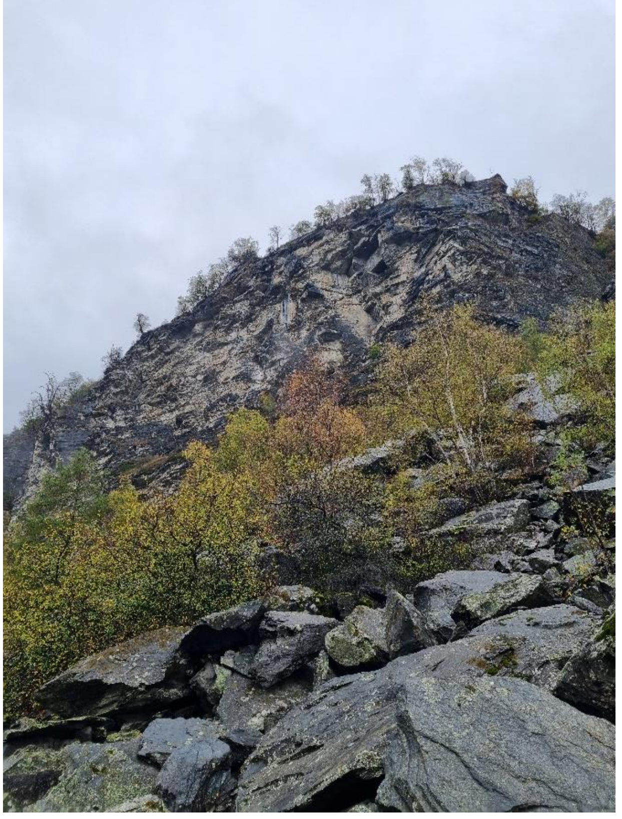
RockFreq (V.1)

Transparent description of the tool for the determination of rockfall release scenarios.





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Content

1 Introduction

RockFreq is a tool for determining release scenarios of rockfall events and individual blocks for defined return periods (e.g., 30, 100, 300 years). It is based on the derivation of magnitude-frequency relationships, which are modeled using power law distributions. The parameters of these distributions are derived based on a characterization of the rock face structure and block samples in the field. To account for the large uncertainty in the parameter estimation, uncertainty ranges are taken into account using a Monte Carlo simulation.

The model was developed based on the analysis of inventory data from numerous rock faces worldwide (Hantz et al. 2020; Hantz et al. in preparation). It is based on the idea that both the release volumes of rockfall events and the individual blocks of an event (fragments) can be characterized with a power law distribution (Moos et al. 2022). The model has been applied in ~25 areas of Switzerland and checked for plausibility using scenarios from the official hazard maps. It is to be further developed and tested on an ongoing basis by recording additional data on block size distributions and event volumes. The use of RockFreq by practitioners will allow for collecting further data to check the plausibility of the model.

RockFreq is an objective and transparent approach to determine rockfall release scenarios when inventory data is missing or insufficient. It is a promising alternative or supplement to purely expert-based approaches because i) it requires only a few parameters that can be collected with relatively little effort and ii) it is based on power law distributions and this assumption has been shown to be realistic in numerous studies. Another advantage of RockFreq is that it explicitly quantifies the release frequency and not the occurrence frequency of rockfalls, which allows for the analysis of different scenarios in the transit area (e.g. with/without protective measures). This is generally not possible with inventory-based scenarios, as historical events are usually only recorded if they cause damage.

RockFreq cannot replace the usual assessment by experts, but rather complement it. It offers the possibility of validating the scenarios, which are usually estimated on a small data basis. The estimation of the parameters remains the task of the expert. Although the tool already considers a certain range of uncertainty for the parameters, it is essential that the user checks the sensitivity and critically scrutinizes the parameter choice. By combining expert-based with this model-based approach, more objective rockfall release scenarios can be determined. The time required to record the block size distribution and the parameters is in the range of a normal field inspection. The systematic recording of a representative block sample helps to sensitize the experts to the typical block sizes and their frequency distribution.

2 Principles of the tool

The RockFreq tool is based on the fundamental assumption that the distribution of rockfall events and individual blocks (fragments) follow a "power law distribution". Many scientific studies have shown that this assumption is valid (e.g., Dussauge-Peisser et al. 2002; Melzner et al. 2020).
Accordingly, the release frequency of rockfall events can be calculated as follows:

$$F_{st}(V) = A_{st}V^{-B} \qquad \text{Eq. 1}$$

Thereby is $F_{st}(V)$ the number of rockfall events per year and hectare (spatio-temporal frequency) with a volume ≥ V («exceedance frequency»). The parameter A_{st} corresponds to the frequency of rockfall events greater than 1 m^3 and the parameter B describes the volume distribution.
The formula is valid up to a maximum possible event volume (V_{max}), which depends on the size and geological structure of the rock face. A "rockfall event" is defined as the detachment of a rock mass from the rock face between two points in time.

By multiplying the spatio-temporal frequency with the surface of the rock face, the temporal frequency of rockfall events $F_t(V)$ can be obtained:

$$F_t(V) = S\ x\ A_{st}V^{-B} \qquad \text{Eq. 2}$$

An event that releases from the rock face is usually fragmented after the impact on the slope. The volume distribution of the resulting individual blocks can also be described using a power law distribution (Ruiz-Carulla et al., 2017; Moos et al., 2018):

$$f_{st}(v) = a_{st}v^{-b} \qquad \text{Eq. 3}$$

Thereby, $f_{st}(v)$ corresponds to the release frequency of blocks with a volume ≥ v per year and hectare.

By integrating the volume of the individual blocks between a minimum volume v_{min} up to a maximum possible volume v_{max}, the volume V of a rockfall event can be calculated:

$$V = \frac{a}{(1-b)}v_{max}^{(1-b)} - \frac{ab}{(1-b)}v_{min}^{(1-b)} \qquad \text{Eq. 4}$$

For a known volume *V* and a known parameter *b*, the parameter *a* is:

$$a = \frac{V(1-b)}{v_{MAX}^{1-b} - bv_{MIN}^{1-b}} \qquad \text{Eq. 5}$$

This means that *a* and thus the block size distribution can be calculated for a specific event volume *V*. In case the maximum possible block volume v_{max} is reached in the event ($n(v_{max}) > 1$), the number of blocks with $v = v_{max}$ is:

$$n(v_{max}) = a * v_{max}^{-b} \qquad \text{Eq. 6}$$

In case the maximum block of an event (*$v_{max}(V)$*) has a volume smaller than v_{max}, it can be calculated as follows:

$$v_{max}(V) = a^{1/b} \quad \text{Eq. 7}$$

To determine the event and block volumes for scenarios of specific return periods (RP), the event volume of a specific frequency F_t (=1/RP) can be calculated:

$$V(F_t) = \left(\frac{A_{st} * S}{F_t}\right)^{1/B} \quad \text{Eq. 8}$$

$V(F_t)$ cannot become larger than the maximum possible event volume (V_{max}). In a next step, the maximum possible block volume of the event $V(F_t)$ (i.e., relevant block volume for the hazard analysis) can be calculated based on Eq. 7.
Fig. 1 illustrates the characterization of the event volume and the volume of the maximum block as well as the number of blocks with the maximum possible volume as a function of the return period.

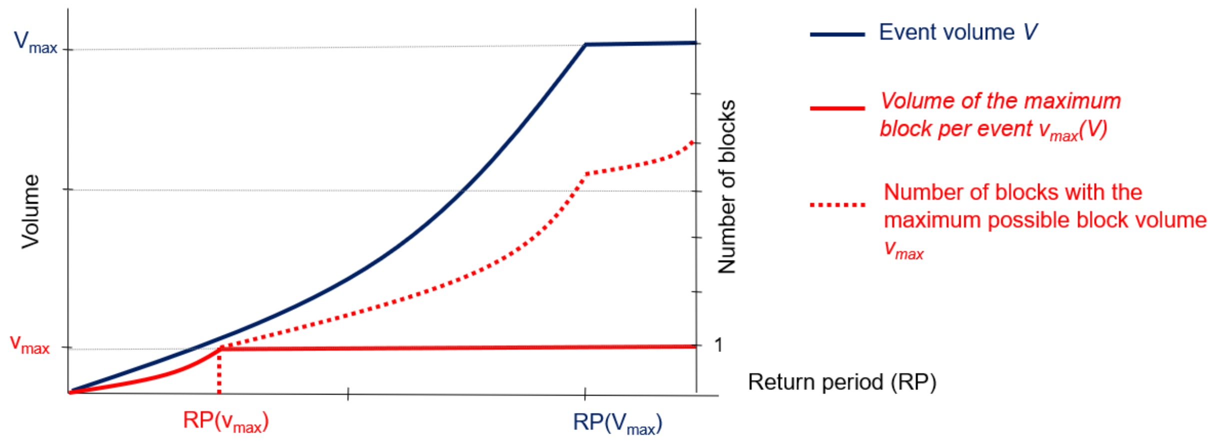

Fig. 1: Schematic illustration of the event volume (V), the volume of the largest block per event ($v_{max}(V)$) and the number of blocks with the maximum possible volume $n(v_{max})$ as a function of the return period. Based on Moos et al. (2022).

To use RockFreq, the parameters A_{st}, B, S, b and v_{max} must be known. They are based on an assessment of the rock face structure and the distances of the main discontinuities as well as random sampling of blocks (Fig. 2). The determination of the parameters is described in detail in chapters 3 and 4.

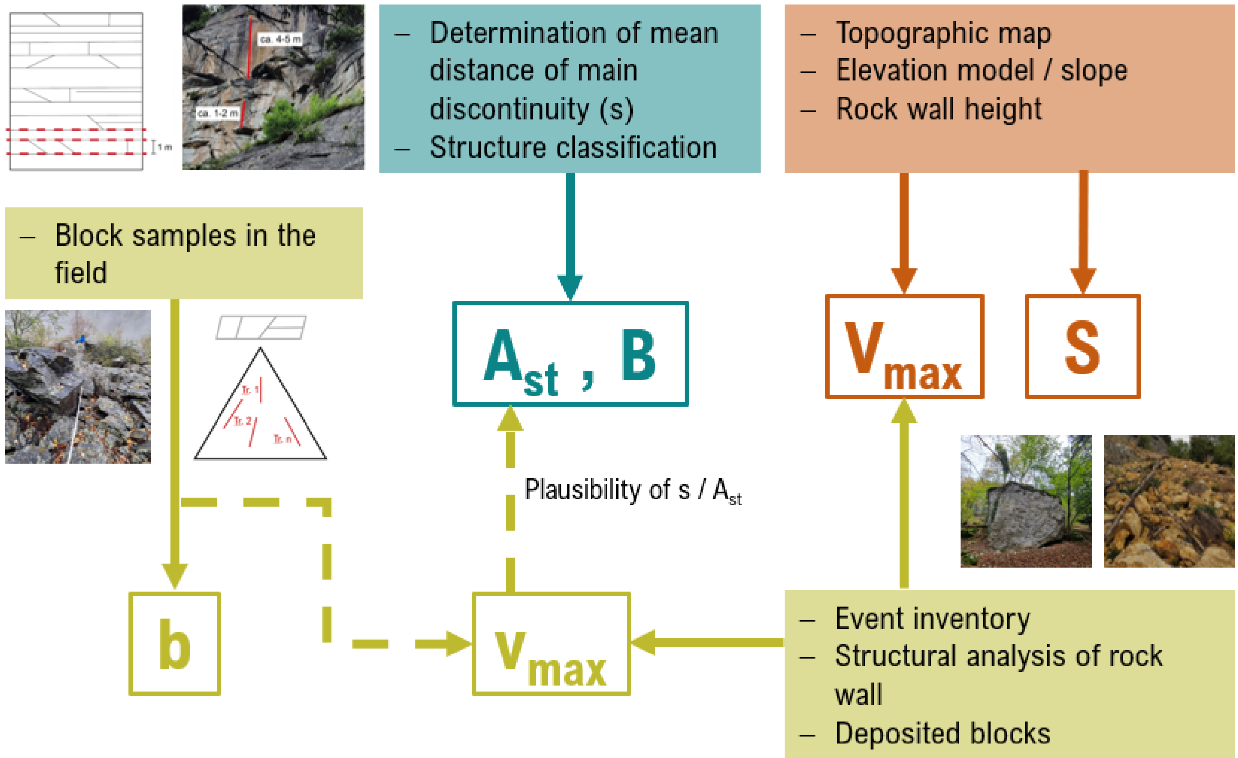

Fig. 2: Overview of the method to determine the parameters (Ast, B, b, v_{max}, V_{max}, S) for the application of RockFreq. S=Surface area of the rock face; v_{max}=maximum possible block volume; V_{max}: maximum possible event voume

3 Block size distribution

The characterization of the volume distribution of the individual blocks of a rockfall event is crucial for the hazard analysis, as the size of the individual blocks determines the runout lengths and energies. Based on a representative sample of individual blocks, the parameter b of the power law distribution can be derived, representing the complete distribution of the blocks of a rockfall event. The measurement of such a sample can be challenging, especially in the case of
i) only a few and scattered deposited blocks or
ii) very large deposits with a large number of blocks.
We propose here a field sampling method to determine a representative block size distribution for both cases.

3.1 Data collection in the field

To obtain a suitable block size distribution, a sample with a sufficiently large number of blocks is required. This should be representative of the entire fragmentation of rockfall events along the slope (i.e., from the initial fragmentation during detachment to the fragmentation after multiple impacts along the slope). As a rough rule, it can be assumed that a sample size of at least 50 blocks provides a robust power law distribution (Clauset et al. 2009). To ensure that the recorded blocks are representative, we recommend sampling transects or sampling plots along the entire slope. Depending on the size and type of depositional area, we recommend the following procedures (Fig. 3):

Talus slope: Typically, talus slopes show an increase in block sizes downslope (Ruiz-Carulla et al. 2015). Therefore, the slope must be divided into different zones with similar block sizes. In each zone, blocks are measured along at least one transect or in at least one sampling area. Transects should have a length of at least 20 m. Each block with a volume ≥ v_{min} within a transect width of 1-2 m is recorded. For this purpose, the three sides of the block are measured (a, b, c) and a correction factor for the volume of the block compared to a perfect cube is determined (f = [0,1]). Alternatively, all blocks ≥ v_{min} within a plot of 10 x 10 m can be measured. In addition, it can be useful to record large blocks distributed separately at the foot of the slope, as these are otherwise underrepresented in the sample (see Ruiz-Carulla et al. 2015).

Diffuse deposition: If blocks are only sporadically distributed across the slope, we recommend sampling a large transect of about 10-20 m width from the rock face to the lower end of the transit or deposition area or several sampling areas distributed across the slope (Fig. 3b).

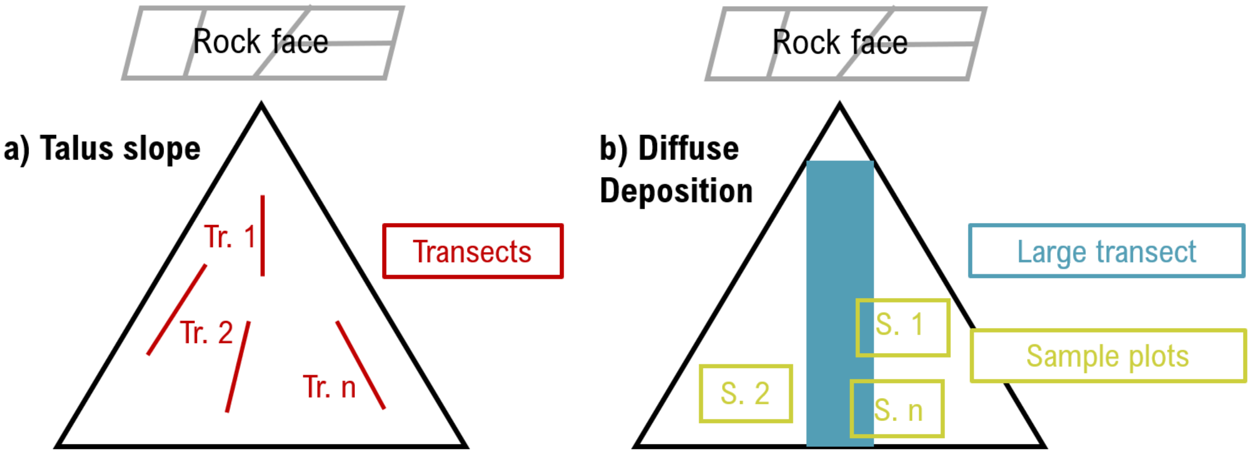

Fig. 3: Schematic overview of the suggested methods for the sampling of the block size distribution in the case of a talus slope (b) or a diffuse deposition (b).

3.2 Estimation of the parameter b

RockFreq fits a power law distribution to the volume distribution of the registered blocks using the least squares method. The uncertainty in the estimated parameter b is assessed based on a bootstrap analysis (Bengoubou-Valérius and Gibert 2013; De Biagi et al. 2017) and reported in the form of a 95% confidence interval of the b value.

3.3 Maximum block volume

The maximum block volume (v_{max}) corresponds to the maximum volume of a block that can be expected after ***the*** fragmentation ***of a detached rock mass*** along the slope. It is estimated based on previous events, “silent witnesses” (fresh and/or old boulders on the slope) ***or*** a geological assessment of the fragmentation. When calculating the scenarios, the largest block to be expected per scenario is limited by the maximum block volume (see Eq. 6 and 7).

3.4 Entry in the Tool

The recorded block volumes can be entered manually in the RockFreq tool or read in as a CSV file in the “Rock Face” section (Fig. 4). The CSV must contain a “vol” column with the volumes.

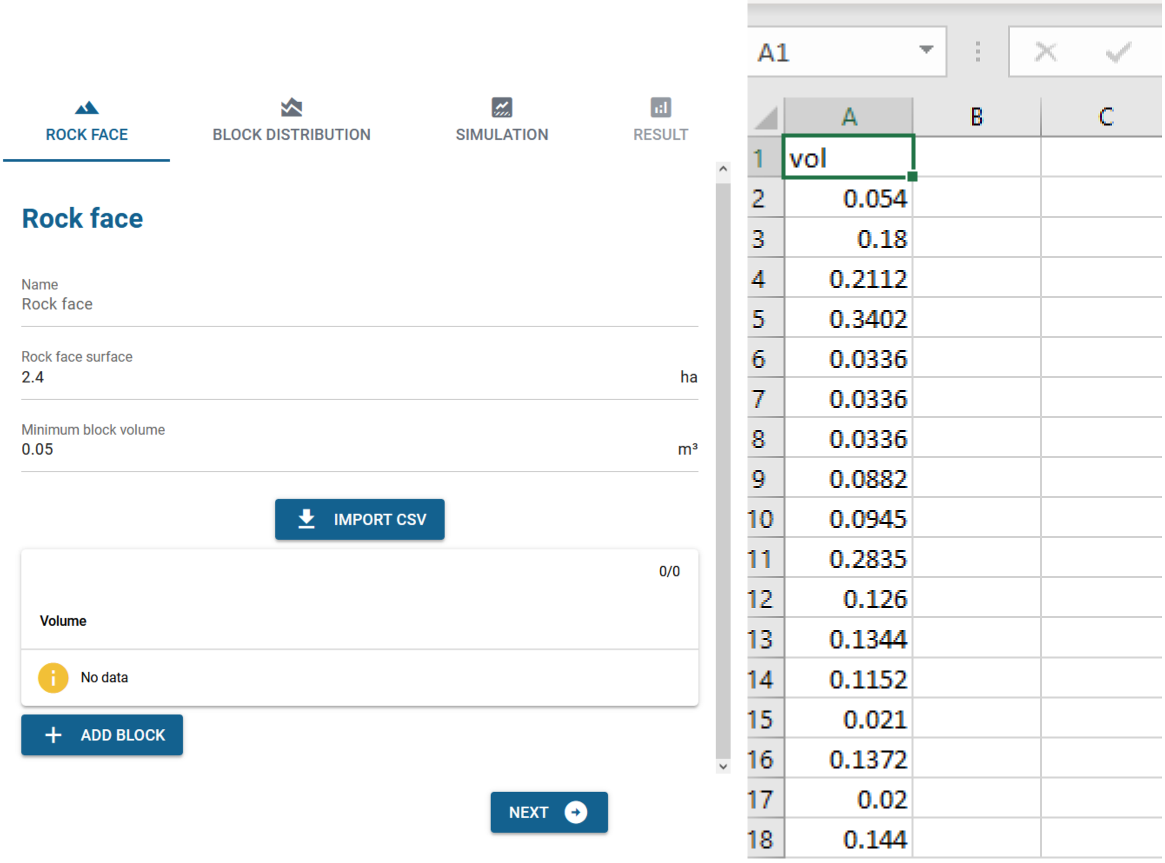

Fig. 4 : Entry of the block volumes in RockFreq (left) and format of the CSV file (right).

4 Parameter estimation rock face

4.1 Parameter A_{st}

The parameter A_{st} shows the activity of the rock face and corresponds to the annual release frequency of events with a volume ≥ 1m^3 per rock face area (unit=$yr^{-1}*ha^{-1}$).
A meta-analysis of 26 studies in which release frequencies were determined based on detailed inventories (e.g., Hantz et al. 2020; Hantz and Levy 2019) or using laser scanning data (e.g., Guerin et al. 2020; Mohadjer et al. 2020) indicated that there is a clear dependence of the parameter A_{st} on the mean distance of the main discontinuity set. Hantz et al. (in preparation) propose the following three "frequency classes" depending on the mean distance of the main discontinuities for rock faces above stable slopes (i.e., without rock faces above active large landslides) and in permafrost-free areas (Table 1):

Tab. 1 : A_{st} classes in dependence of the average distance of the main discontinuity set and the maximum possible block volume.

Average distance of the main discontinuities (m)	***Maximum possible block volume***	***A_{st} ($a^{-1}*ha^{-1}$)***
>2	*> 10 to several 100 m^3*	*0.01-0.1*
0.6-2	*> 10 m^3*	*0.05-0.5*
0.2-0.6	*a few m^3*	*0.2-2*

Accordingly, the average frequency of events with a volume ≥ 1 m^3 can be roughly estimated based on the mean distance of the main discontinuity. Based on the analyzed studies, the following exponential relationship between the minimum and maximum value of A_{st} and the mean distance of the main discontinuities (s) was determined, which is implemented in the rockfall frequency tool (Eq. 9 and Fig. 5):

$$A_{st} = [0.05, 0.27] * s^{-1.13} \quad \text{Eq. 9}$$

This relationship is slightly adjusted compared to the originally published relationship between A_{st} and s (Moos et al. 2022). The results of future studies and inventories will allow for further improving the relationship.
Since this is a general estimate for an entire rock face / rock face complex, it is important that only the main stratification is considered (see Fig. 6). This distance can be estimated by eye. However, this can be challenging, especially if the rock face is difficult to access. Alternatively, laser distance meters can also be used.

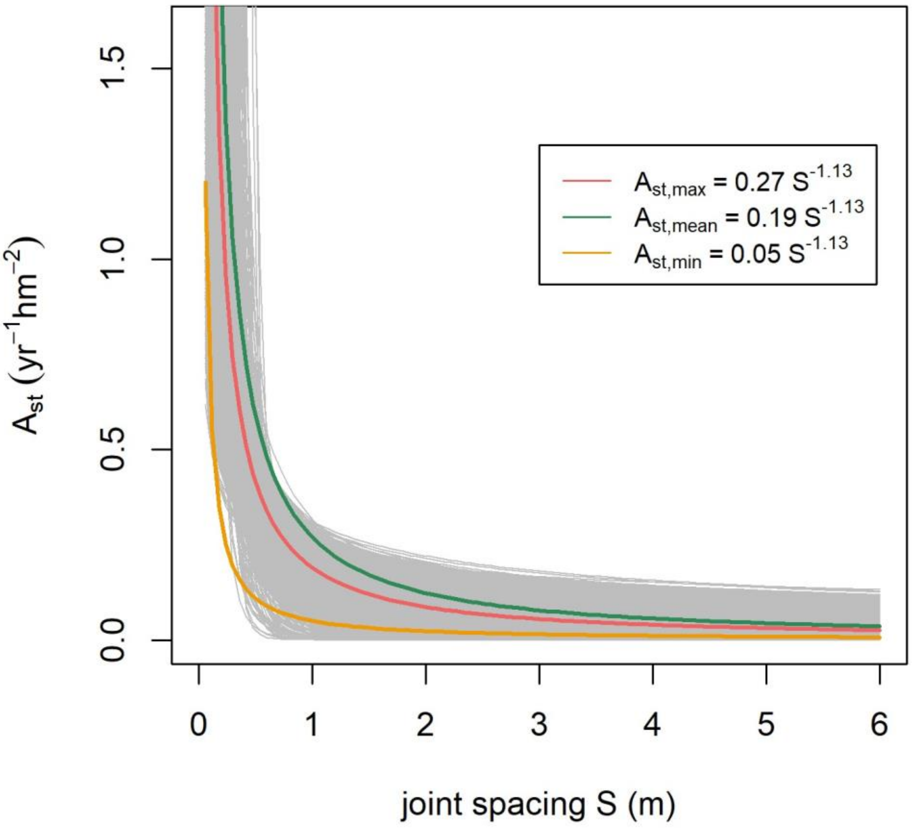

Fig. 5: Relationship between the parameter A_{st} (mean, minimum, maximum) and the average spacing of the main discontinuities (S, "joint spacing") based on a meta-analysis of 26 studies (Hantz et al. in preparation).

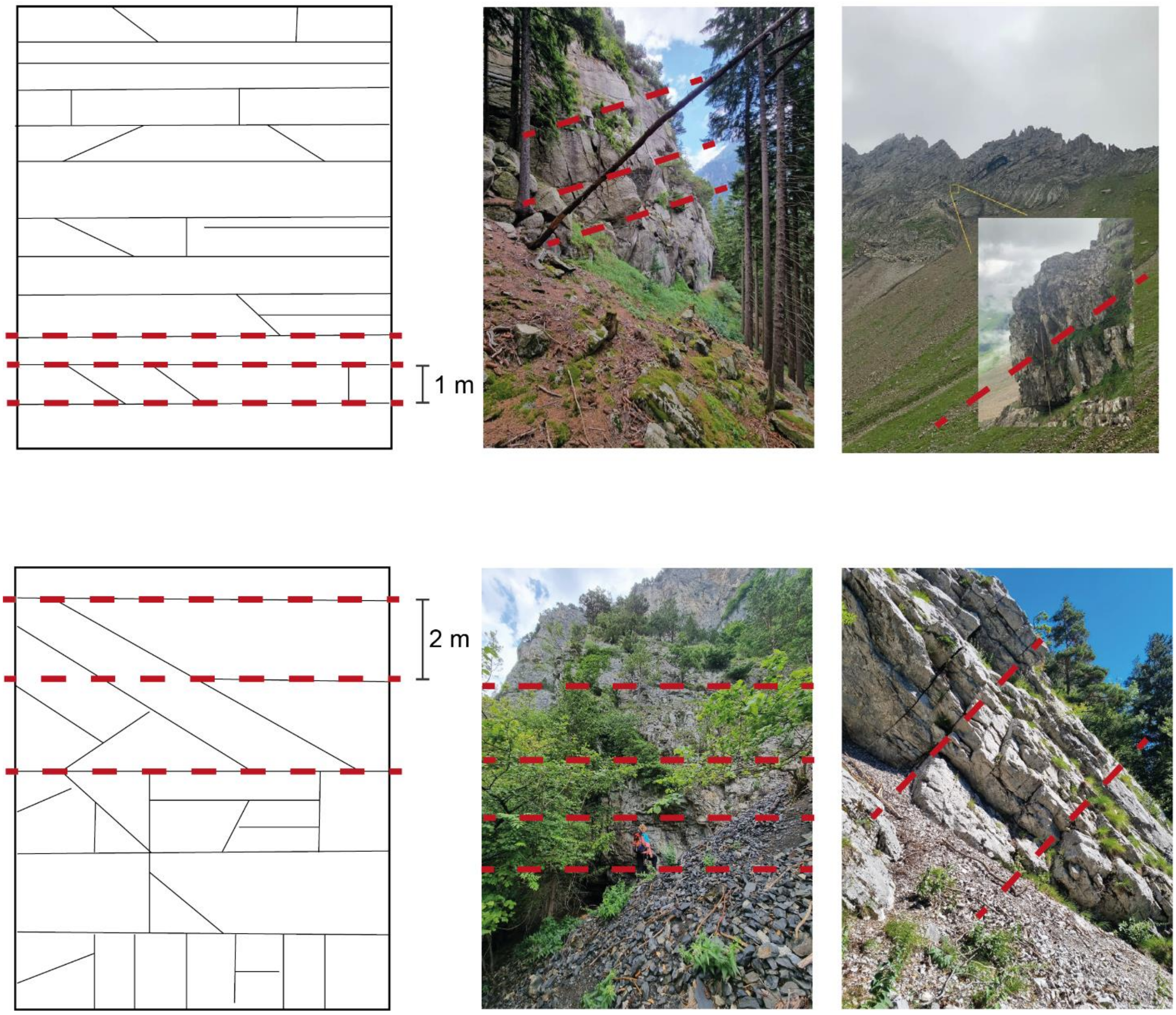

Fig. 6: Illustration of the average spacing of the main discontinuity set. The red lines are examples of observed discontinuities.

4.2 Parameter B

The parameter B describes the volume distribution of rockfall events (form of the power law) and depends on the structure of the rock face and usually varies between 0.4 and 1 (Brunetti et al. 2009; Hantz et al. in preparation). It is determined based on a classification of the rock face into six different structure types (Hoek et al. 2007, Moos et al. 2022). These structure types range from very compact, solid rock (B-value 0.3) to very fissured, disintegrated or highly laminated rock (B-value > 1.1).
An analysis of 19 studies in which B parameters of rockfall release volume distribution were determined based on laser scanning or inventory data shows that a general trend of the B parameter as a function of lithology can be observed (Fig. 7). The B-parameters of sedimentary and limestone rock faces appear to tend to be higher than those of granite or gneiss rock faces, although the variability is particularly high for gneiss.

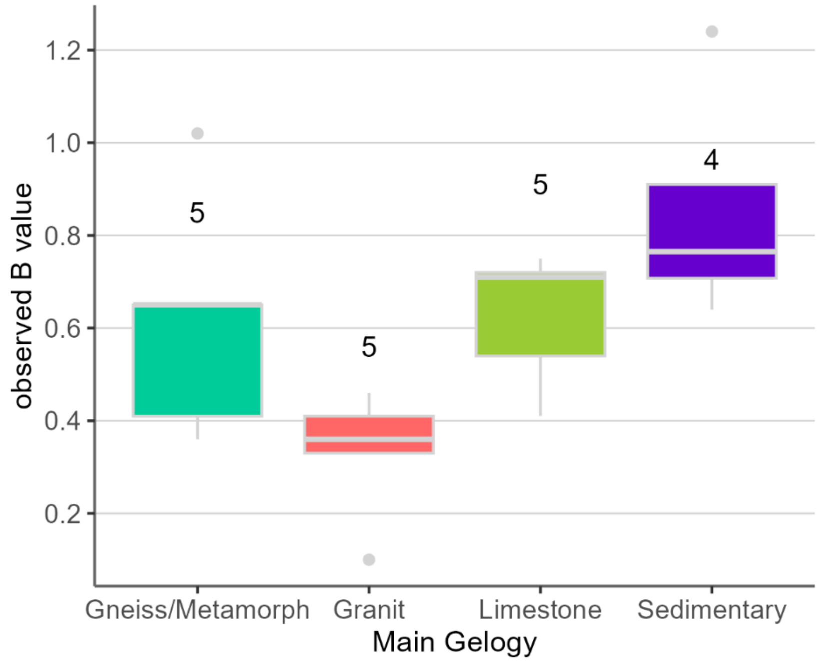

Fig. 7 : Distribution of observed B values based on 19 studies of historical inventory data of rockfall events or monitoring of rock faces with laser scanning. The considered studies are listed in Appendix A. Gneiss/Metamoprh: rock faces of gneis / metamorphe rocks; Sedimentary: other sedimentary rocks, such as clay stone, sandstone or conglomerates.

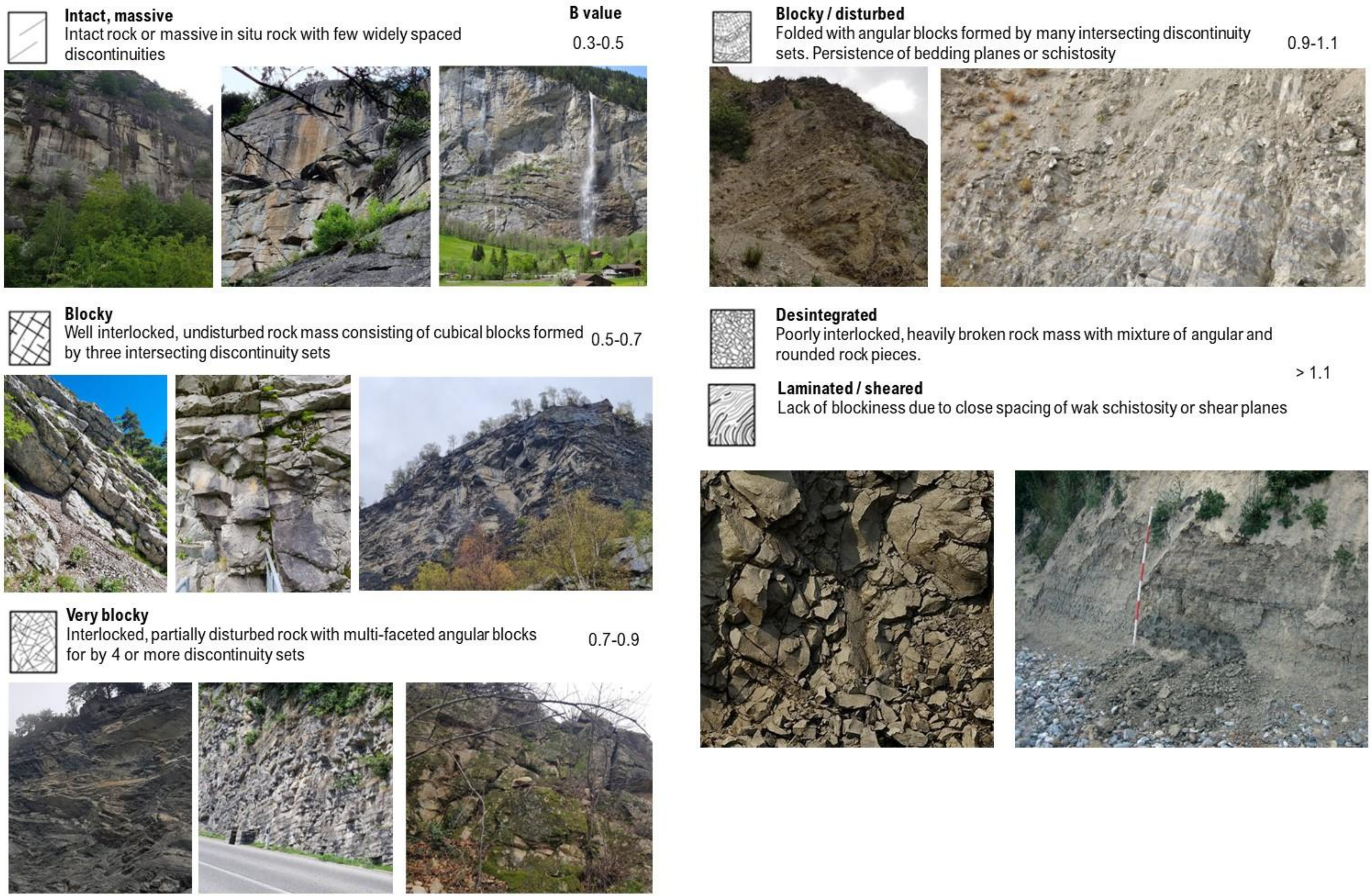

Abb. 8 : Classification of the rock structure for the determination of parameter B. The classes are based on Hoek et al. (2007).

4.3 Rock face surface

The considered surface area of the rock face can be determined on the one hand based on the topographic map (rock face height x rock face width) or based on an analysis of the elevation model (Fig. 9). For the latter, all cells with an inclination above a defined threshold value are determined and their area calculated using the following formula (according to Farvaque et al. 2021):

$$S = \sum_{1}^{nr\_cells} \frac{Res}{\cos(slope_{cell} * \frac{pi}{180})} \qquad \text{Gl. 10}$$

Where *nr_cells* corresponds to the number of cells with an inclination ≥ inclination threshold, *Res* corresponds to the area of a cell (e.g. 2x2 m) and $slope_{cell}$ corresponds to the inclination of the cell in degrees. The slope threshold value is typically selected between 50 and 60°. In the case of very homogeneous rock faces with a relatively constant slope, the two proposed methods give very similar results. In the example of heterogeneous rock faces with strongly varying height and inclination, it is recommended to calculate the rock face area based on the elevation model.

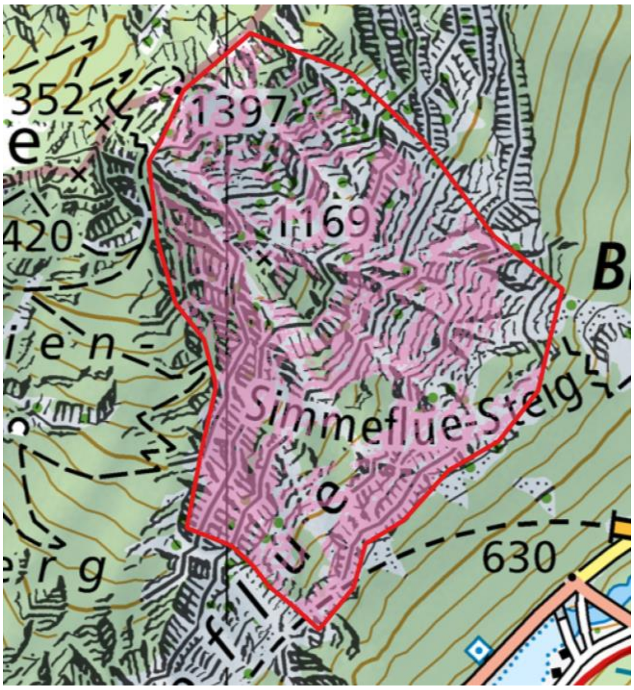

Abb. 9 : Rock face area for an example in Wimmis (CH): The surface area based on a 2m digital height model and a slope threshold of 55° is 19 ha.

4.4 Maximum event volume

The maximum event volume (V_{max}) limits the validity of the power law distribution and has to be taken into account if very rare events are considered. It depends on the size (width, height), the morphology (slope, exposure) and the structure of the rock face. The maximum event volume can be estimated in various ways. On the one hand, it can be derived based on historical events and detachment spots in the rock face. On the other hand, it can be determined based on an analysis of the rock face structure (determination of fissure bodies and slip planes) (e.g., Jaboyedoff et al. 2009; Mavrouli et al. 2015; Corominas et al. 2018).

A simple approach proposed by Moos et al. (2022) and Hoek and Bray (1981) determines the maximum event volume using a “critical slip plane”. This is a pessimistic approach that determines the “theoretically possible maximum release volume” depending on the rock face height, width, and slope. This volume is rarely reached for the considered return periods of up to 300 years.

4.5 Entry in the Tool

In the RockFreq tool, the average distance of the main discontinuities can be entered under “Simulation”. Based on this, the parameter A_{st} is calculated. The parameter B as well as the minimum and maximum possible block and event volumes are also specified under “Simulation”. The rock face surface area is defined under “Rock Face”.

5 Uncertainty analysis

In RockFreq, the uncertainty in the event and block volumes regarding the parameters A_{st}, B, b, V_{max}, v_{max} and S is quantified based on a Monte Carlo approach. Therefore, the following uncertainty ranges are assumed (vs. Moos et al. 2022):

A_{st}: $[0.05, 0.27]*s^{-1.13}$ (Eq. 9)
B: Variation of +/- 0.2
S: Variation of +/- 20%
b: Variation between the lower and upper limit of the bootstrap confidence interval (see chapter 0)
v_{max}: Variation of +/- 30%
V_{max}: Variation of -50% (determined V_{max} is considered as upper possible limit)

In each iteration of the Monte Carlo simulation, a value is randomly determined from the listed uncertainty range of the parameters and the scenarios are calculated based on this. This is repeated 10000 times. Finally, the median of the distribution of the volumes and the standard deviation are calculated.

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7 Appendix

A1. Studies used to examine the lithology dependency of the parameter B

Tabelle A1: List of the studies used to analyse the B values as a function of lithology (partially based on Strunden et al. 2015).

Lithology	*Time window*	*Volume range (m^3)*	*B*	*Reference*
Granit	*145 years*	*10^{-1} - 10^6*	*0.1*	*Guzzetti et al. 2003* *https://doi.org/10.5194/nhess-3-491-2003*
Granit	*78 years*	*50-10^6*	*0.46*	*Dussauge-Peisser et al. 2002* *https://doi.org/10.5194/nhess-2-15-2002*
Granit	*30 years*	*10^{-2} - 10^4*	*0.33*	*Hungr et al. 2002*
Granit	*30 years*	*0.1-10^4*	*0.36*	*Guerin et al. 2020* *https://doi.org/10.1016/j.geomorph.2020.107069*
Granit	*31 years*	*0.1-10^4*	*0.41*	*Guerin et al. 2020*
Jointed metamorphic	*22 years*	*10^{-1} -10^4*	*0.65*	*Hungr and Evans 1999* *https://doi.org/10.1139/t98-106*
Quartzitic and sediment	*19 years*	*10^2-10^6*	*0.65*	*Bennett et al. 2012* *https://doi.org/10.1002/esp.3263*
Gneiss	*7 months*	*10^{-4}-10^{-1}*	*1.02*	*Weidner and Walton 2021* *https://doi.org/10.3390/rs13224584*
Gneiss	*7 months*	*10^{-5}-10^{-1}*	*0.41*	*Weidner and Walton 2021*
Gneiss	*3 years*	*10^{-1}-10^3*	*0.36*	*Guerin et al. 2014* *http://www.ano-omiv.cnrs.fr/images/Publications/PDFs/StEynard/ConferenceProceedings/2014-Guerin_investigating.pdf*
Limestone, shale, mudstone, sandstone	*32 months*	*10^{-7}-10^4*	*0.73*	*Rosser et al. 2007* *https://doi.org/10.1029/2006JF000642*
sandstone	*20 months*	*10^{-6}-10^3*	*0.8*	*Lan et al. 2010* *https://doi.org/10.1016/j.geomorph.2010.01.002*
conglomerat	*12 years*	*10^{-3}-10*	*0.64*	*Janeras et al. 2021* *https://georisk.upc.edu/en/shared/rss21_tls-and-inventory-based-magnitude-2013-frequency-relationship-for-rockfall-in-montserrat-and-castellfollit-de-la-roca.pdf*
molasse	*5 months*	*10^{-3}-10*	*1.24*	*Carrea et al. 2015*

				https://link.springer.com/chapter/10.1007/978-3-319-09057-3_68
Limestone	*60 years*	*10^1-10^6*	*0.41*	*Dussauge-Peisser et al. 2003* *https://doi.org/10.3997/1873-0604.2003007*
Limestone	*two summers*	*10^{-2}-10*	*0.72*	*Gardner 1970* *Rockfall a geomorphic process in high mountain terrain. Albertan Geogapher, 6: 15–20.*
Limestone	*18 months*	*10^{-2} - 10^2*	*0.71*	*Strunden et al. 2015* *https://doi.org/10.1002/2014JF003274*
Limestone	*3 years*	*10^{-3}-10^2*	*0.75*	*Guerin et al. 2014*
Limestone	*3 years*	*10^{-3}-10^2*	*0.54*	*Guerin et al. 2014*

8 List of changes

RockFreq Version	Date	Changes in the model (*m*) or in this description (*d*)
1.0	31.05.2024	–