USING CLIMBER'S GUIDEBOOKS TO ASSESS ROCK FALL PATTERNS OVER LARGE SPATIAL AND DECADAL TEMPORAL SCALES: AN EXAMPLE FROM THE SWISS ALPS

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Temme, A.J.A.M., 2015. Using climber's guidebooks to assess rock fall patterns over large spatial and decadal temporal scales: an example from the Swiss Alps. *Geografiska Annaler: Series A, Physical Geography*. 97, 793–807. DOI:10.1111/geoa.12116

ABSTRACT. High-mountain geomorphic processes enjoy increasing scientific and societal interest. This is because these processes are perceived to be changing more than elsewhere and because their effects on infrastructure and tourism are significant. Rock fall is among the processes that receive most attention due to its presumed intimate relation with permafrost, which is widely degrading. However, over decadal temporal scales and for entire mountain ranges, there is very limited information on the changes in frequency and location of rock fall. This hampers our understanding. Here, I assess the value of information contained in a 146-year record of climber's guidebooks of the Bernese Alps in Switzerland to derive changes in rock fall danger. The results show that guidebooks' authors, themselves experienced climbers, perceived increases in rates and changes in positions of rock fall. The increases were mainly reported since the year 2000. It appears that datasets derived from guidebooks can provide valuable context for more detailed, higher resolution data sources.

Key words: rock fall, permafrost, climbing guidebooks, danger, Bernese Alps

Introduction

There is strong interest in high-mountain landscape dynamics, both from a societal perspective and a scientific perspective. High mountains are both expected and observed to change significantly as a result of globally increasing temperatures (Haeberli 2005). Two direct effects of this temperature rise are glacial retreat and permafrost degradation. Glacial retreat, which is mainly caused by increasing summer temperatures (rather than decreasing winter precipitation; Oerlemans 1986), is globally expected to result in more variable spring discharge and reduced summer discharge in rivers draining mountain ranges (Huss *et al.* 2008). Over the next few decades, this can have a significant negative effect on flooding risk and the provision of water to large continental rivers. Over shorter timescales, glacial retreat can cause glacial damming and subsequent outburst floods that threaten mountain infrastructure (Clague and Evans 2000; Richardson and Reynolds 2000; Huggel *et al.* 2002).

Permafrost degradation, although less visible than glacial retreat (Haeberli *et al.* 2011), is also expected to have wide-ranging consequences, particularly through its effect on rock stability (Ravanel and Deline 2011; Ravanel and Deline 2013b). After permafrost, the perennially frozen condition of rocks, retreats, periods of freeze and thaw alternate. Periodic freezing damages unbroken rock (Amitrano *et al.* 2012). Periodic thawing of ice-filled rock joints raises water pressures and reduces friction, causing rock to fall (Davies *et al.* 2001). Even warming of ice before thawing can reduce stability of broken rock and increase rock fall (Davies *et al.* 2001). The effect of temperature rise on permafrost retreat and hence on rock stability is particularly rapid where rock walls are not protected by a (possibly water holding) debris cover that dampens temperature fluctuations (Hoelzle *et al.* 2002). These unprotected conditions are common in the steep rock walls of high-mountain environments. Rock fall in this context is the falling of rock along an overhanging, vertical or sub-vertical wall, followed by bouncing, flying or rolling onto lower slopes (adapted from Varnes 1978).

Increased high-mountain rock fall activity in the European Alps in recent years has mainly

DOI:10.1111/geoa.12116

been linked to higher temperatures and permafrost degradation. This is supported by ample empirical evidence, for instance in the warm summers of 2003 and 2008 (Gruber *et al.* 2004; Ravanel *et al.* 2013; Ravanel and Deline 2013b), and for the last 150 years (Ravanel and Deline 2011). At the same time, Swiss government statistics suggest that (medium altitude) rock fall affecting infrastructure increased in the colder period between 1950 and 1980 (Gruner 2004). These apparently contradictory results may be explained by the fact that a lower altitude site is predominantly unfrozen and rock weathering and subsequent rock fall can be enhanced by increased freezing, whereas a higher altitude site is predominantly frozen or even under permafrost and rock weathering and rock fall may increase with increased warming.

It has proved difficult to move beyond such correlations, among others because it is difficult to accurately determine rock fall rates (Gruber *et al.* 2004; Michoud *et al.* 2012). Some high-magnitude low-frequency rock avalanche events of geomorphic significance are well studied (Huggel *et al.* 2012), such as in Switzerland the 1988 Tschierva rock avalanche (Fischer *et al.* 2010) and the 1991 collapse of a slope near Randa (Sartori *et al.* 2003) and in Austria the 2007 Burgstall rock falls (Kellerer-Pirklbauer *et al.* 2012), but low-magnitude high-frequency rock fall events (alternatively described as debris falls; cf. Whalley 1974) are more difficult to quantify. Physical, auditive, seismic, dendrogeomorphic and remote sensing methods are currently available for this purpose.

Physical crack meters have been used at submetre spatial scale to observe the growth of individual rock clefts as a measure of growing risk of rock fall, for instance by Matsuoka (2008) and Hasler *et al.* (2012). Sensitive microphones have been used to record the sound of rock breaking under the influence of diurnal temperature variations (Amitrano *et al.* 2012). At the spatial scale of small catchments, geophone approaches record numbers of falling rocks in streams (Rickenmann *et al.* 2012). Seismic methods measure the effect of the impact of individual falling rocks (Got *et al.* 2010; Levy *et al.* 2011).

Dendrogeomorphology has probably contributed most to understanding rock fall dynamics at larger temporal scales, up to several centuries (Stoffel *et al.* 2005). With this method, ages of trees and of damages to trees by rock impact are measured using tree rings (Stoffel and Perret 2006). This limits its application to lower altitude sites where forests underlie rock fall source zones. The efficacy of forests in protecting population centres and infrastructure from rock fall has been studied in most applications of this method (Perret *et al.* 2004; Stoffel *et al.* 2006; Rammer *et al.* 2010; Corona *et al.* 2013), although the seasonality and origin of rock fall has also been studied (Schneuwly and Stoffel 2008).

Finally, remote sensing methods are used, mainly to remotely determine volumes of fallen rock. Among remote sensing methods, terrestrial Lidar has become the most popular one (Rabatel *et al.* 2008; Ravanel *et al.* 2009; Haas *et al.* 2012). In glaciated regions, observation of supra-glacial debris from aerial photographs has been used to estimate rock fall rates from headwalls (Heimsath and McGlynn 2008). Most importantly, a large set of historical photographs of famous rock walls near Chamonix in France was used by Ravanel and Deline (2011) to extract spatially and temporally explicit information on rock falls greater than 500 m^3.

Most of these methods of observation are characterised by the fact that they are of small spatial extent – up to a maximum of a mountain face or a small catchment and typically much smaller. The main exception is offered by the work of Ravanel and Deline (2011), which presents the best method available so far for larger temporal and spatial scales, but which may be limited to often-photographed sides of mountain ranges. In addition, only climber's photographs and dendrogeomorphic methods have the potential to provide data over decadal timescales, where the dendrogeomorphic methods are limited to the forest zone and overlying slopes, and photographs offer less temporal and spatial detail in less-photographed regions. Information about high-mountain rock fall patterns and changes over larger spatial scales and over decadal timescales remains difficult to obtain. As a result, it is difficult to empirically assess the correspondence between changing temperature regimes and high-mountain rock fall over these time scales, or to link environmental factors to spatial differences in rock fall.

New sources of information are required to achieve this goal. In this study, I assess the value of an unconventional source: a 146-year series of climber's guidebooks. Climbing route descriptions in such guidebooks describe the conditions that prospective climbing parties can encounter, including the danger of rock fall. It is conceivable that these descriptions contain a spatially and temporally explicit record of change in conditions encountered by climbers that may be linked to changing rates of rock fall. Such a record would cover a larger spatial and temporal scale and hence allow comparison with timeseries or maps of driving factors at such scales, yet clearly be more qualitative than current records.

The objective of this study is to find out whether climber's guidebooks indeed describe spatially and temporally changing dangers of rock fall, and if so, whether these patterns can be linked to environmental conditions.

Regional setting

The Grindelwald region of the Bernese Alps in Switzerland, and more specifically the five mountains Jungfrau, Mönch, Eiger, Finsteraarhorn and Schreckhorn, were selected as a study site (Table 1, Fig. 1). There are three reasons for this choice. First, there is a long history of alpinism in the European Alps in general, and in this region in particular, starting with the first ascent of Jungfrau in 1811. This long history is beneficial because it means that multiple repeat climbs of popular routes had been made before climber's guidebooks started to be published from the second half of the nineteenth century (Ball 1864). Most other routes that are currently in use had been climbed at least once before the 1950s. This increases the support (*sensu* Finke *et al.* 2002) for the information in guidebooks, because the information is more often based on the opinions of many persons. The summits of the five mountains can be climbed over more than a hundred climbing routes. Out of these, 63 climbing routes were selected for this study. Routes that end at a subsidiary summit or ridge, that are very recent, or that largely follow an older route were not selected.

Second, the region continues to be a very popular climbing destination to this day, partly due to well developed high-mountain infrastructure such as the Jungfraubahn railway that runs from the town of Grindelwald to an altitude of about 3500 m a.s.l. The large numbers of climbers and the frequent repeats of many of the climbing routes mean that there have been regular updates to climber's guidebooks.

Third, lithological variation in the region is large. The two main lithological groups that compose the European Alps are both present; Palaeozoic crystalline basement rocks and Mesozoic sedimentary rocks from the Tethys sea, mainly limestones. During the Tertiary, when the Alpine orogeny started, the original position of both lithologies was disturbed through crustal shortening, among others, in the form of thrust faults. Subsequently, erosion of the newly formed mountain range resulted in a spatially complex pattern of Palaeozoic gneisses, granites and amphibolites and Mesozoic limestones in the study area (Swiss Federal Office of Topography 2010).

Rock fall dangers have long been recognised in the Swiss Alps and more specifically in the Bernese Alps, although they have only received scientific attention where they potentially impact lower-elevation infrastructure such as roads (Baillifard *et al.* 2003; Michoud *et al.* 2012) and quarries (Lugon and Stoffel 2010; Pedrazzini *et al.* 2010). The only work focused in the Grindelwald valley was a mapping of geomorphic danger, mainly for population centres and mountain infrastructure by Kienholz (1977).

Some work has been done on the relation between rock fall and seasonal or climatic effects. Analysing governmental statistics of recorded (low altitude) rock fall events for all of Switzerland between 2001 and 2010, Gruner (2012) concluded that rock falls occur mainly in spring, when meltwater enters cracks that may have been enlarged or created by frost activity in the preceding winter. This is in agreement with earlier dendrogeomorphic work in Saas Balen in the South of Switzerland (Schneuwly and Stoffel 2008), where about three-quarters of observed rock fall scars on trees originated between October and May, and with pioneering work in the Canadian Rockies (Luckman 1976).

In the last 100 years, a nationwide increase in large low-altitude rock fall events was reported in Switzerland between 1950 and 1980, presumably due to colder winter temperatures leading to rock mass contraction and an increase in frost cracking (Gruner 2004). Before 1950, and after 1980, such cold spells were reported less often. The temporal evolution and spatial pattern of common, smaller (often <10 m^3) high mountain rock fall events remains unknown.

Over Holocene timescales, there is no clear indication of a relation between rock fall and climate. Focusing on rock fall cones in Lake Lucerne (Switzerland), Schnellmann *et al.* (2006) concluded that climate was not an important determinant than earthquakes for the very substantial events that dominated the record – although long periods of rain appear to have been an important trigger in the last 2000 years (Gruner 2006).

Methods

This study has been performed by literature research. Route descriptions were read from climbing

Table 1. Summary information on the five selected mountains.

Mountain	Altitude (m a.s.l.)	First ascent	Routes selected	Geology
Jungfrau	4158	1811	14	Granite, gneiss and limestone
Mönch	4107	1857	16	Granite, gneiss and limestone
Eiger	3970	1858	10	Limestone
Finsteraarhorn	4274	1829	12	Gneiss and amphibolite
Schreckhorn	4078	1861	11	Granite

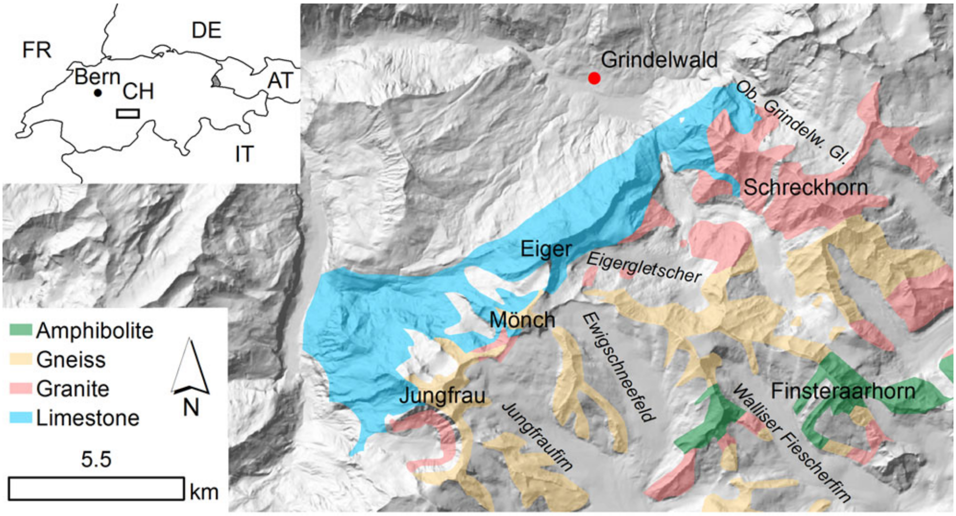


Fig. 1. An overview of the study area in the Bernese Alps, with the five selected mountains, several major glaciers and the town of Grindelwald indicated. Topography is shown with hillshading and surface colours are a simplified indication of geology. No colours are shown where ice and glaciers cover the surface, or outside of the area of interest. Figure based on information from Swiss Federal Office of Topography (2010).

guidebooks and formalised in a database from which analyses were made. An introduction to climbing guidebooks is required to place this formalisation in context, before I discuss data collection and analyses.

Brief history of climbing guidebooks

For the first 100 years of their existence, most climbing guidebooks attempted to describe the complete range of routes climbable on a mountain, by offering directions to prospective climbing parties. This distinguished them from the few early books of climbing history (Studer 1896) that typically had a more limited reach. Recently, guidebooks that present only a fraction of possible routes (typically a selection of less difficult, less dangerous, and hence more often climbed routes) have become more popular (e.g. Mosimann 2006). To avoid a bias towards safer routes, guides selected for this study are all of the type that describes all climbable routes, with the exception of Mosimann (2006), which was included because it adds temporal detail to the record for the last decade.

The earliest climbing guidebooks were written in the second half of the nineteenth century by British climbers, who were at that time climbing many mountains and routes in the European Alps for the first time, accompanied by their local guides. Later, in the Central European Alps, translations of these guidebooks appeared in German, published among others by the then-young Swiss Alpine Club (Schweizer Alpen Club, SAC, since 1863). In the early 1900s, local climbers started taking the lead in opening up new routes and consequently guidebooks started to be originally written in German. The number of routes to be described increased strongly, leading to the subdivision of the Alps into regions and zones that have guidebooks dedicated to them. Route descriptions started focusing on conditions typically encountered by prospective climbing parties rather than on conditions encountered by (the few) previous climbing parties, although routes of limited interest or extreme difficulty rarely experienced a repeat climb and descriptions of these largely remained based on those made by the first party.

Guidebook writers are very experienced mountaineers, often mountain guides, who have intimate knowledge of conditions on climbing routes in the region or zone that they write about. This knowledge is gained both by making frequent climbs and by corresponding with other experienced climbers and mountain hut guardians who in this way contribute to the validity and support of descriptions. Authors typically write a number of subsequent editions of the guidebook for their region or zone before handing over to a successor. They have often been contributors to guidebooks for their region or zone before they became authors.

There are dozens of climber's guidebooks describing some or all of the routes in the study area, most of which were written in the last few decades. Only 17 guidebooks were selected for this study. The four oldest guidebooks, from the nineteenth century, were written by Ball in English (Ball 1864, 1866, 1876, 1882). For all of the Alps, these were the first guidebooks summarising conditions for prospective climbers. Only Swiss Alpine Club guidebooks were selected from the twentieth and twenty-first centuries to minimise the possible effect of differences in danger perception between climbing cultures from different countries. These guidebooks are written in German and divide the Bernese Alps into different zones that usually separate descriptions of routes on Schreckhorn from those on the other four mountains. Schreckhorn was described in this manner in six consecutive guidebooks (Blodig 1923; Wyss 1955, 1964; Mosimann 1982, 1996, 2006), and Jungfrau, Mönch, Eiger and Finsteraarhorn were described in eight guidebooks (Hug *et al.* 1931; Bodmer 1956, 1970; Hausmann 1981, 1989, 1997, 2010; Mosimann 2006). The number of routes described per guidebook increased over time, reflecting the opening of new, often very difficult routes that could not previously be climbed, although descriptions were also stopped for some routes that were deemed to have become too dangerous. In total, the 63 selected routes were described in 386 route descriptions.

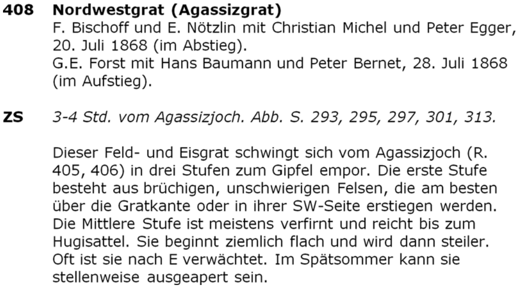
The assessments that writers and their informants make are subjective. What some perceive as a safe, negligible frequency of falling rocks may be dangerous to others, which introduces uncertainty into conclusions drawn from climbing guidebooks. There are several potential sources of non-random subjective differences in danger assessments. First, climbing cultures are perceived to vary between countries. In this study, however, the switch from British guides to early Swiss guides in the first half of the twentieth century did not result in changes in perceived danger level. Only Swiss guides were used after this point to minimise this potential problem.

Second, danger perception may change over time. It is possible, for instance, that when alpinism was a fringe sport in the nineteenth and early twentieth centuries, substantial risk was deemed acceptable by the few enthusiasts and professionals. In modern alpinism, thousands of hobbyists enjoy climbing but are perhaps less happy to accept and less able to assess danger. This change in readership may have affected the assessments by guidebook authors who may more than before prefer to err on the side of caution. It is not possible to assess whether and to which degree this is the case.

Third, the assessments of danger in recent guidebooks may have been influenced by the scientific and societal attention for climate change and resulting changes in landscape processes. This attention has increased dramatically in the last two decades, and perceptions may have subsequently changed, leading to different assessments for the same situation. It is not possible to assess to which degree this is the case, although authors and their informants in guidebook forewords and commentaries clearly indicate the fact that climbers are themselves observing large changes, rather than taking information from other sources (e.g. Hausmann 2010). Also in the individual route descriptions, there are indications of clearly self-observed changes in danger level, such as in the 2010 guidebook by Hausmann, where a route on the Mönch West Face is described as having 'im Sommer heute viel Steinschlag' (nowadays, much rock fall in summer).

Data collection

A typical description of a climbing route gives information on the starting and end points, usually mountain huts or cols; the date the route was first climbed and the persons involved; the difficulty level; the route to be followed; the time that



408 **Nordwestgrat (Agassizgrat)**
F. Bischoff und E. Nötzlin mit Christian Michel und Peter Egger, 20. Juli 1868 (im Abstieg).
G.E. Forst mit Hans Baumann und Peter Bernet, 28. Juli 1868 (im Aufstieg).

ZS *3-4 Std. vom Agassizjoch. Abb. S. 293, 295, 297, 301, 313.*

Dieser Feld- und Eisgrat schwingt sich vom Agassizjoch (R. 405, 406) in drei Stufen zum Gipfel empor. Die erste Stufe besteht aus brüchigen, unschwierigen Felsen, die am besten über die Gratkante oder in ihrer SW-Seite erstiegen werden. Die Mittlere Stufe ist meistens verfirnt und reicht bis zum Hugisattel. Sie beginnt ziemlich flach und wird dann steiler. Oft ist sie nach E verwächtet. Im Spätsommer kann sie stellenweise ausgeapert sein.

Fig. 2. An example climbing route description for the NW ridge of Finsteraarhorn, the highest mountain of the Bernese Alps. The NW ridge is called Agassiz ridge because it faces the nearby mountain Agassizhorn. Both are named after Swiss-American geologist Louis Agassiz, who was the first to propose the existence of ice ages (Agassiz 1840). The main part of the description translates into: ‘This rock and ice ridge sweeps up from the Agassiz col to the summit in three steps. The first step consists of broken, non-difficult rocks, that are best climbed over the crest of the ridge or along its southwest side. The middle step is mostly firn and reaches up to the Hugisattel (a small col). It starts relatively flat and then becomes more steep. There is often overhanging snow on the east side. In late summer, this part may be icy’. A description of the third step is made in another route description.

different sections of a route take; and the conditions and dangers typically encountered – possibly as a function of the season (Fig. 2).

Traditionally, climbers distinguish between subjective and objective dangers when planning trips. In this terminology, subjective dangers include fatigue, bad preparation or bad equipment, difficult orientation and psychological dangers such as group thinking and overestimating one’s stamina (Pereira 2005). These dangers are personal and differ between climbers and between climbing parties. Objective dangers are those that the high mountain environment presents to anyone equally, including rock and ice fall. For the purposes of this study, I focused only on objective dangers described in guidebooks, and additionally only on those objective dangers that have a link to rock fall. Note that this does not suggest that writers’ assessments of these objective dangers are not subjective.

The information pertaining to rock-fall-related objective danger is available in three forms. First, direct mention of the degree of danger of rock fall, ranging from unmentioned to ‘much endangered by rock fall’. Second, a general advice about the route, ranging from unmentioned to ‘discouraged’ or even ‘no longer described in this guidebook’ when a route has become too dangerous. Third, mention of the quality of the rock encountered on a climb. Rock quality is typically referred to in categories ranging from ‘solid rock’ to ‘very broken’, where the latter is an indication of danger. The northwest ridge of Finsteraarhorn described in Fig. 2 has this type of information (‘broken rock’). The direct mention of rock fall danger appears to present the strongest link to geomorphic activity, followed by the general advice and lastly the indication of rock quality, which may be less indicative of danger when routes are less steep.

The information in each of the three types was collected from every route description (Table 2), and translated into binary indicators to reduce the subjectivity inherent in author’s assessments. The translation process was simple: any mention of rock fall danger, any negative advice, or any negative comment about the rock quality resulted in a ‘true’ value in the respective indicator. In addition, an overall binary indicator was recorded that combined the information in the other three indicators. A ‘true’ value for this indicator was recorded if the value of any of the three binary indicators was ‘true’. Where routes were no longer described because it was mentioned that they had become too dangerous, a ‘true’ value was inferred. All routes from the 2006 guidebook that described only often-climbed and safer routes (Mosimann 2006) were ignored when using these indicators, because they would introduce a bias towards safety.

However, both the more detailed information in the descriptions, and the guidebook of Mosimann (2006) were used to extract changes over time in route descriptions. This was done under the assumption that descriptions of the same route were changed consciously if at all, but that no stringent standardisation between routes was made. So, in temporal analysis, a change from ‘dangerous’ to ‘very dangerous’ for a certain route was recorded as an indication of perceived increased danger, whereas in spatial analysis, a route that is ‘discouraged’ would get the same value for the binary indicator as another route that is ‘strongly discouraged’.

When recording information from the guidebooks, it became apparent that ice fall danger was also mentioned for several routes. Although much less often available, this information was also collected to serve as contextual information for changes in rock fall.

Finally, the environmental factors geology, aspect and position on the mountain were recorded for every route (Table 2). Position on the mountain was categorised as slope, ridge, pillar, face, couloir, in order of increasing exposure to surrounding rock (Fig. 3). Conventional knowledge predicts

Table 2. Information collected from literature.

Information type	Data type	Data format
Per route		
Name	Nominal	Text
Position	Ordinal	Slope/ridge/pillar/face/couloir
Geology	Nominal	Amphibolite/gneiss/granite/limestone/mixed
Aspect	Nominal	N/NE/E/SE/S/SW/W/NW
Per route description		
Year of description	Interval	Integer
Author of description	Nominal	Text
Rock fall danger	Nominal	Text
Ice fall danger	Nominal	Text
Rock quality	Nominal	Text
Route advice	Nominal	Text
Overall danger	Binary	Yes/ no

Fig. 3. From left to right, a typical slope (part of the normal route on Jungfrau), ridge (the SE ridge of Finsteraarhorn), pillar (SE side of Schreckhorn), face (the N face of Eiger) and couloir (SE couloir on Finsteraarhorn).

that routes with more exposure to rock are more endangered. Lithology was expected to relate to rock strength, and aspect was expected to relate to the annual temperature regime. Another expected determinant of the temperature regime is the altitude. However, the altitude range of a route, or of dangerous sections of a route could not be recorded because this information is not generally provided in a description.

Analyses

During exploratory analysis, it was found that assessments of danger in descriptions changed more often when guidebook authors changed, than when consecutive guidebooks were written by the same author. This possibly indicates that the first guide written by an author receives more attention than the second and third guides where descriptions might be copied without a strict reassessment. This would mean that the route descriptions in second and third guides by one author are not independent observations of rock fall danger. The analyses described below were therefore repeated for a second dataset of 157 descriptions that were only taken from the first guidebook written for a mountain by every author (Ball 1864; Blodig 1923; Hug *et al.* 1931; Wyss 1955; Bodmer 1956; Hausmann 1981; Mosimann 1982, 2006). The latter guidebook was used only in temporal analysis and only for its descriptions of Jungfrau, Eiger, Mönch and Finsteraarhorn, since the author had already described routes on Schreckhorn in 1982. Because the second and later books by the same author were left out, the subset has less temporal resolution and extent than the full dataset.

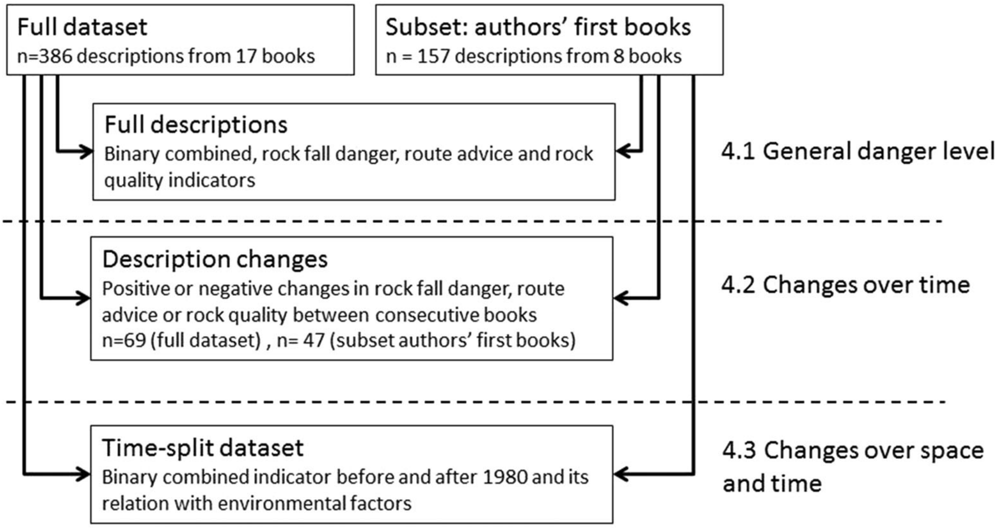


Fig. 4. Analysis overview showing the use of the full dataset and the subset of descriptions from the authors' first books in the general, temporal and spatio-temporal analyses.

Three sets of analyses were performed. The first, space- and time-averaged analysis considered the probability of danger per mountain from the three types of information (rock fall danger, route advice and rock quality) and the overall danger. Second, changes over time were considered by listing danger-related changes in route descriptions between consecutive guidebooks, using the full detail of the information available in the descriptions. For instance, a change in a description from 'dangerous' to ' very dangerous', or a change in advice from 'discouraged' to ' strongly discouraged' would result in an entry. In the full dataset, 69 such changes were described, and in the subset of authors' first guidebooks, 47 changes were described.

To evaluate the temporal evolution of changes in descriptions, the net number of negative changes (more dangerous) in every climbing guide was divided by the period to the preceding guide, and by the number of routes selected for this study that were described in the guide. This resulted in an annual probability of negative change in a route description.

Third, the binary combined indicator was used in spatio-temporal analysis. For this purpose, both the full dataset and the subset of authors' first books were time-split into a part before 1980 and a part after 1980. This year was chosen because it allowed an approximately half–half division of the observations. Time-splitting of the full dataset resulted in one part of 158 descriptions from before 1980 and another of 228 descriptions from after 1980. Time-splitting of the subset of authors' first books resulted in one part of 87 descriptions from before 1980 and another of 70 descriptions from after 1980.

For each of the resulting four datasets, the average binary danger indicator was calculated for each class of geology, aspect and position. Two-way analysis of variance was then used to assess whether the effects of these factors on the binary danger indicator was significant. A classification tree was fitted to assess the extent to which variation in perceived danger can be predicted by the three factors. The significance level used for splitting nodes and merging categories was 0.25, the minimum number of records in a parent node was 16, and the minimum number of records in a child node was 8.

Results

General danger level

Averaged over time and space, authors report rock fall danger on about half the routes on the five mountains (Table 3), with routes on Finsteraarhorn most often dangerous, and those on Mönch least often dangerous.

Changes in perceived danger over time

Over the last 148 years, in 69 cases (19% of all route descriptions) there were one or more changes in the

Table 3. Time- and space-averaged danger of rock fall on the five studied mountains for the full dataset/dataset with only authors' first guides.

	Probability of			
	dangerous rock	negative advice	bad quality rock	any rock fall-related danger
Jungfrau	0.17/0.15	0.34/0.28	0.13/0.07	0.56/0.48
Eiger	0.43/0.42	0.02/0.00	0.08/0.08	0.43/0.42
Monch	0.13/0.13	0.13/0.16	0.14/0.16	0.34/0.37
Schreckhorn	0.38/0.32	0.09/0.05	0.44/0.53	0.62/0.63
Finsteraarhorn	0.27/0.22	0.20/0.19	0.54/0.49	0.70/0.65

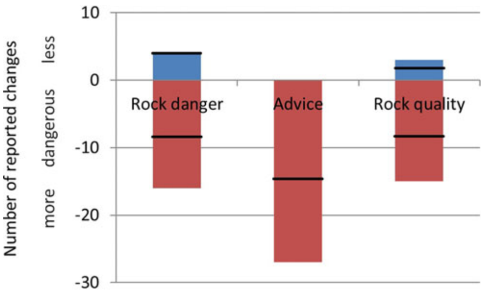


Fig. 5. Changes in reported rock fall danger, rock quality, and climbing advice between guidebooks. Negative changes (more dangerous) and positive changes (less dangerous) are separated. Coloured columns indicate values from the full dataset, black lines indicate values from the subset of the authors' first guidebooks.

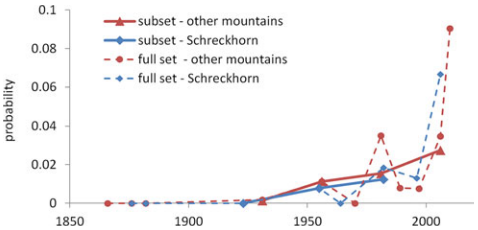


Fig. 6. Annual probability of negative change concerning rock fall in a climbing route description for the last 150 years. Descriptions of routes on Schreckhorn and the other four selected mountains were in different climbing guides and therefore separated.

perceived danger of a route between consecutive guidebooks. These changes in description were predominantly negative (Fig. 5). Changes in the description of rock fall danger were negative in 16 cases and positive in four cases. Rock quality was reported to be worse in 15 cases, and better in three cases. Climbing advice became more discouraging in 27 cases, with no descriptions becoming more encouraging. Of the total 63 selected climbing routes, seven are no longer described in recent guidebooks because of a perceived increase in the geomorphic dangers that climbers can expect. Comparable results emerge from the subset of authors' first guidebooks, where the perceived danger differed between guidebooks in 37 cases (23% of all descriptions).

The increased danger is in some cases illustrated by minor changes to climbing routes, such as those made in response to a rock fall event that was observed in 1937, reportedly as a result of a lightning storm on the Northeast Ridge of Jungfrau (Bodmer 1956), and in response to the building of extra facilities at the Jungfraubahn railway station at Jungfraujoch in between Mönch and Jungfrau (Hausmann 1989). However, the large majority of climbing routes remained unchanged and hence followed the same line over a mountain between their first ascent and the most recent guidebook.

The number of changes in perceived danger strongly increased over the last decades (Fig. 6). For the full dataset, probability of a negative change was highest in the most recent climbing guide (Hausmann 2010), where about 40% of routes were described as more dangerous than in the preceding guide (Mosimann 2006), equivalent to 10% per year. For the sub-dataset of authors' first guidebooks, the probability of a negative change increased monotonically over time, up to about 3% per route per year over the 25 years between 1981 and 2006 for Jungfrau, Mönch, Eiger and Finsteraarhorn.

Figure 6 confirms that occasionally a change of guidebook authorship coincides with a high probability of reported change in descriptions (in the full dataset). For Schreckhorn, this change occurred in 1955 and 1982, and for the other four mountains, it occurred in 1956 and 1981. This suggests that particularly in the period roughly between 1950 and 1985, differences in danger perception between authors may have affected the record. The subset of authors' first guidebooks does not suffer from this effect, yet still shows a

Table 4. Probabilities that average danger is homogenous between the categories of position on a mountain, aspect, and geology for the subset of descriptions from authors' first guidebooks, time-split into sets from before 1980 and after 1980.

p (average danger = homogenous)	Before 1980	After 1980
Position	0.098	0.012
Aspect	0.401	0.549
Geology	0.132	0.131

gradually steepening increase in perceived danger. Note that the highest annual probability of a negative change in perceived danger is calculated for Jungfrau, Mönch, Eiger and Finsteraarhorn for the most recent guidebook by Hausmann (2010) which followed the guidebook by Mosimann (2006). Since Hausmann had already written an earlier guidebook on the four mountains (1997), this guidebook was not considered an author's first guidebook – nevertheless many routes were considered to be more dangerous in 2010 than in both earlier guidebooks, clearly indicating a reconsideration of the descriptions.

Changes in perceived danger over time and space

Average probabilities of perceived danger differ between categories of geology, aspect and position on the mountains, as well as between both periods (Fig. 7). Probabilities of homogeneity between classes are lower for the full dataset ($p < 0.02$) than for the subset of descriptions from authors' first guidebooks, which is consistent with copying of descriptions between consecutive guidebooks of the same author. Therefore, probabilities of homogeneity for the subset are considered more appropriate and reported here (Table 4).

For the subset, position on a mountain ($p < 0.1$) and geology ($p = 0.13$) are the most significant determinants of geomorphic danger, whereas aspect is a less significant determinant of geomorphic danger, especially after 1980 ($p = 0.55$). Average binary danger is largest for routes facing (south)-east or -west, with the lowest values in the northeast and southwest, particularly after 1980. Average danger increased from before 1980 to after 1980 on all aspects except for north- and southeast-facing routes, with the most substantial increase on routes facing west. In terms of geology, average binary danger was highest for routes on granite and amphibolite, and considerably lower for routes on limestone and gneiss. Average danger on all lithologies increased from before 1980 to after 1980 (except for limestone in the subset), with the increase on amphibolite most substantial. Climbing routes using a couloir to get to the summit were most endangered, followed by face and pillar routes. The lowest average binary danger was experienced on routes following ridges or slopes (usually glaciers). The most common routes – those on mountain faces – experienced the largest rise in average binary danger, with the most-often climbed routes on flatter slopes experiencing a decrease.

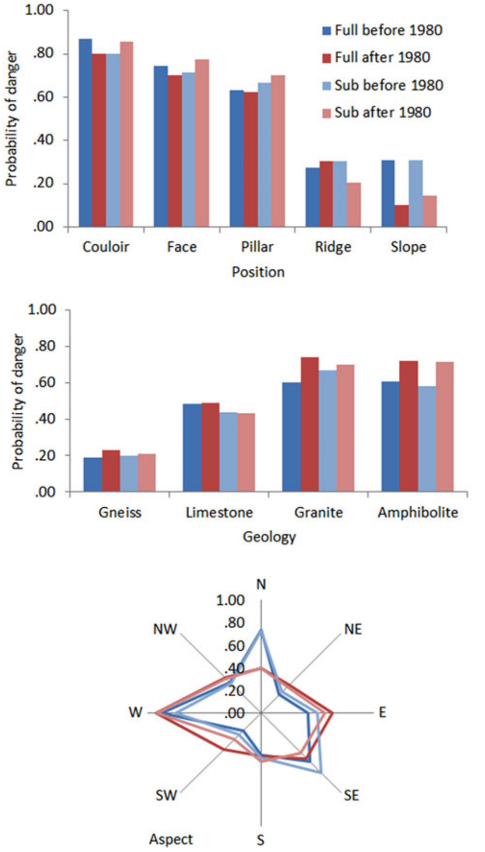


Fig. 7. Average value of the binary danger indicator for classes of position on a mountain, geology and aspect from route descriptions from before 1980, and after 1980.

Classification trees for the four datasets using position on a mountain, aspect and geology as independent variables explain between 72% (for the full dataset before 1980) and 81% (for the subset of authors' first guidebooks before 1980) of variation in binary danger. In all cases, position on a mountain was the first variable to be used for classification. For the subset, geology was the second-level (and final) variable to be used, both for the descriptions from before 1980 and after 1980. For the full dataset before 1980, geology was the second-level variable and aspect was the third-level variable. For the full dataset after 1980, geology was used as the second-level (and final) variable.

Discussion

The results show that there is a signal of spatially and temporally variable danger of rock fall perceived by the writers of climbing guidebooks. This perceived danger has remained largely stable over the period from 1864 to about 2000, but has increased substantially in the last decade. This increase is also apparent when only focusing on authors' first guidebooks. Since guidebooks are written and published about once every two decades, or once per decade more recently, there must be a lag from several years up to two decades between actual increases in rock fall danger and changing descriptions of danger in guidebooks. Keeping this in mind, it is nonetheless attractive to compare the guidebook record with existing datasets of rock fall variation over time. In particular, Ravanel and Deline's (2011) dataset of rock falls of over 500 m^3 in the Mont Blanc Massif since the Little Ice Age is of interest given its temporal overlap with our dataset. Ravanel and Deline find that 70% of rock falls in their inventory occurred during the two decades preceding 2011, a finding that is similar to guidebook results considering the time lag inherent in the latter. This is despite Ravanel and Deline's focus on larger falls and study areas that are 100 km apart. At the same time, the dataset from guidebooks is clearly unable to resolve effects on danger of individual warm summers, such as 1945, 1947, 2003 and 2008, or of earthquakes, that are clearly visible and documented in other datasets (Deline *et al.* 2008, 2011; Ravanel *et al.* 2010; Ravanel and Deline 2011). The general increase in temperatures over the Alps, which is faster than the global average increase (Beniston 2006), and which causes permafrost degradation, may drive the decadal-scale dynamics.

Perceived danger is larger in couloir, face and pillar positions than on slopes and ridges, and generally largest on routes in granite and amphibolite. The effect of position on perceived rock fall danger is intuitive. Routes that have more rock surface potentially contributing to rock fall, and especially the funnel-shaped couloirs, clearly experience more rock fall, which does not mean that there is more rock fall when expressed per rock wall surface, or per aerial surface. The results also seem to confirm the important role of aspect in determining where the surface is perennially frozen (Boeckli *et al.* 2012). Aspect had previously been discussed as a determinant of ground surface temperature by (Salzmann *et al.* 2007), and by extension of frost cracking intensity (e.g. Anderson *et al.* 2013), and is now seen to extend into rock fall danger. For the Bernese Alps, the fact that east and west aspects experience the largest rock fall danger, suggests that there, freeze–thaw cycles are strongest or occur more often. This fits with the observation that daily temperatures fluctuate strongest in these aspects (e.g. Hall *et al.* 2005).

Another known important determinant of temperature is elevation, due to its control on mean annual temperatures and hence on frost cracking intensity (Hales and Roering 2007). Information about elevation is difficult to extract from guidebooks, which are usually not very explicit about where on a route rock fall danger is situated, and the role of elevation as a determinant can therefore not be assessed with this dataset.

The effect of rock type on rock fall danger is more difficult to relate to existing work. Rock strength clearly plays a role in determining rates and conditions of cracking (Augustinus 1995), and will vary between the rock types that were studied. However, the fact that softer rock types (e.g. limestone) crack faster than hard rock types (e.g. granite) does not mean that rock fall rates from that rock type are greater. Other factors that determine the relation between rock type and rock fall include albedo (Hall *et al.* 2005), joint spacing and orientation and frost cracking history. Moreover, over geological timescales, mountains consisting of softer rocks may more quickly weather and erode under frost-cracking regimes and therefore lower their slope or leave the zone of alternating freezing and thawing faster than mountains composed of harder rocks. It is therefore not possible to clearly interpret the observed relation between lithology and rock fall danger in terms of rock mechanics. The observation that rock fall danger is largest on granite and amphibolite routes therefore may be specific to this case study. More research in this field is necessary.

Finally, it is intuitive to expect a relation between rock fall danger and slope steepness. Slope steepness is another factor that is not reported in climber's guidebooks but that could conceivably be measured for the dangerous sections of routes by detailed topographic analysis. However, as mentioned before, guidebooks rarely mention which sections of routes are dangerous – it is almost exclusively an assessment at the route level.

The statistically significant relations of rock fall danger with geology and position on a mountain seem to offer a way forward into rock fall danger mapping. As it stands, between 72% and 81% of the spatial variation in perceived rock fall danger can be explained with these variables. If relations with elevation and slope were found to be significant, such maps could become interesting resources for geomorphologists and spatial planners next to mountaineers.

Returning to the five mountains in the study site (Table 3), Schreckhorn and Finsteraarhorn were described to experience the largest rock fall danger, averaged over all selected routes. Based on the subsequent analysis, this appears to be because these mountains have no routes in the 'slope' positions, and they are on granite (Schreckhorn) or amphibolite (Finsteraarhorn) lithologies.

Geomorphic significance

Rock fall danger is not the same as rock fall or rock fall rate. It is therefore not straightforward to translate the findings presented here into geomorphic terms. The fact that a climbing route is dangerous, does not contain information about where or how high the rocks are originating, or about where they end up. In landscape positions such as couloirs that can receive rocks from different sides, it is impossible to say from which side falling rocks arrive. This implies that the minimum spatial resolution that can be reached with this data source is about equal to the distance between climbing routes on the mountain. For this study, which used mountains with relatively many routes, that distance is up to about 200 m.

The most directly applicable type of information, the danger of rock fall, is available in only few categories ('no danger', 'some danger/dangerous', 'a lot of danger/very dangerous'). The binary indicator obviously has only two possible values. This means that the results reported here have low thematical resolution. However, as illustrated above, generalised information about where in a landscape there is danger for rock fall can be extracted. This allows for meaningful comparisons with more detailed rock fall inventories from other sources, or at a smaller spatial scale, and can offer a basis for extrapolation of these results.

Rock fall danger implies that rocks fall frequently enough to be of concern to climbers. Therefore, it relates best to the high-frequency, low- or medium-magnitude fall events (typically <1 m^3, often < 10 m^3) that can often be observed by climbers (usually without causing accidents). Although low-frequency high-magnitude rock fall events are also observed and mentioned in climber's guidebooks, these are only translated into higher dangers when the slope after the high-magnitude event is more prone to low-magnitude events (as is the case at the Aiguille du Dru in the French Alps, which remains dangerous after several high-magnitude events). By implication, conclusions drawn from changing reported levels of rock and ice fall danger pertain to rates of low-magnitude events and only to those of larger-magnitude events when and where these coincide with low-magnitude events.

Extracting information from climber's guidebooks can be seen as an early, filtered form of crowd sourcing. It is intriguing to contemplate a more direct form of crowd sourcing, where modern technology such as a simple application on climbers' cell phones is used to capture nearly live information on rock fall events (such as the Alps Risk app: www.Alp-Risk.com or the network of observers described in Ravanel and Deline 2013a). If enough observations of this type are done, a more detailed spatial and temporal analysis will be possible.

Retreat of permanent snow and ice

Next to rock fall danger, guidebooks contain information about ice fall danger – although there are less routes where this is potentially the case. Therefore, it was not possible to perform a detailed spatial or temporal analysis. However, some interesting conclusions can still be drawn. Over the entire series of guidebooks, the perceived danger of ice fall was reported decreased in five cases and increased in only one case, as opposed to the concurrent increase in rock fall danger. In all cases, decreased danger resulted from glacial retreat and the melting of permanent snow and ice from high positions threatening the lower parts of climbing routes. An example is the west face route on Eiger, which was originally threatened by ice fall from a small overlying glacier, and which is now reported safer due to that glacier's retreat.

The decrease of snow and ice cover over time is further illustrated by minor changes to climbing routes that were advised in eight cases. The clearest example is for the most-climbed (therefore called 'normal') route to the summit of Jungfrau, for which small changes to the advised route were reported in response to retreating ice and snow on four different occasions (Hug *et al.* 1931; Bodmer 1956; Hausmann 1981, 2010).

Because ice and snow retreat can lead to the exposure of rock slopes with a minor debris cover, they may lead to an increase in rock fall danger. This has not been observed in the datasets used in this paper, but it may be an important dynamic in areas with a larger decrease in snow and ice cover, for instance those that have lower average slopes than the study area.

Conclusions

Climber's guidebooks constitute the only source of information about patterns of small (<1 m^3) rock fall in high mountain environments over spatial scales of mountain ranges and temporal scales of decades. Where available, they appear to allow a more detailed spatial than temporal assessment of rock fall patterns. Reported danger in the study site in the Bernese Alps in Switzerland has hardly changed in the twentieth century, but has seen a substantial overall increase in the first decade of the twenty-first century. Dangers are highest in couloir positions, on east or west aspects and for granite and amphibolite lithologies. The clear relation of rock fall danger to these route properties conceivably allows for the mapping of rock fall danger over entire mountain ranges. Geomorphologically, rock fall danger seems to be linked most strongly with low-magnitude high-frequency rock fall rates, so that maps of rock fall danger can conceivably be read as maps that link to rates of frequent rock fall, and hence allow for meaningful comparisons with maps of postdicted permafrost changes.

Acknowledgements

This study has partly been performed at the Zentralbibliothek Zürich in Switzerland, where the Swiss Alpine Club Archive is situated. Guidebooks were made accessible, and work was greatly facilitated by the support and insights of T. Germann at the Zentralbibliothek. The advice of M. Hunziker, writer of alpine guidebooks, and H. Ott, executive director of the Swiss Alpine Club was also greatly appreciated. Several anonymous reviewers, Dr Ludovic Ravanel and Dr Arjun Heimsath are thanked for their helpful comments and constructive advice.

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Manuscript received 28 Oct., 2014; revised and accepted 27 Aug., 2015