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ORIGINAL ARTICLE

# A regional rockfall database: the Eastern Alps test site

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**Abstract** Landslide databases are essential tools for risk assessment. In the Italian portion of the South-Eastern Alps these archives are managed by the Veneto Region and by the provinces of Bolzano and Trento, as part of the Italian Inventory of Landslides. About 750 rockfall events recorded in these archives were checked, put together and completed to create a new integrated database. Information on 24 new rockfalls were added from different research sources. Descriptive statistic shows that the most affected slopes with the highest frequency of rockfall are the southern ones. The distribution of rockfalls during the year presents three peaks in March, June and November. The most commonly affected lithologies are massive dolomites, effusive rocks and mica schists. Roads proved to be the most commonly involved feature. The hypsographic curves obtained from the DEMs of the provinces of Belluno, Bolzano and Trento have shown that the different areas potentially affected by periglacial processes experience rockfalls during summer and autumn, thus representing a risk to tourists and hikers. This study is the first attempt to collate and extend the available information in the various rockfall databases in the Eastern Italian Alps, with the aim at creating uniform data collection for the whole Alpine range.

**Keywords** Landslide hazard · Landslide frequency · Alpine environment · Periglacial processes · Geomorphological constrains · Dolomites · NE Italy

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## Introduction

Rockfalls are extremely hazardous phenomena that can affect mountain regions at various altitudes and in all seasons. At the lower slopes or in the valleys, they can damage roads and rail routes or property (buildings, vehicles) (Hilker et al. 2009). At higher altitudes, these events can affect tourists and mountaineers, cable cars, ski runs, trekking and climbing paths (Schoeneich et al. 2011). However, the large part of the landslides takes place in uninhabited places without causing any damage; thus, these events are generally not reported in real time. However, it is important to consider them in the perspective of understanding the evolution of high-altitude slopes in response to climate change (Davies et al. 2001; Fischer et al. 2006; Stoffel and Huggel 2012). To increase the knowledge about landslides, public administrations survey all mass movements and store information in special databases (Bateman 2003; Dussauge-Peisser et al. 2002; Hilker et al. 2009; Hungr et al. 1999). These inventories are very important tools for risk assessment. The databases collect spatial and temporal factors that play a key role in assessing rockfall threshold (Bathrellos et al. 2012; Ferlisi et al. 2012; Rozos et al. 2011, 2013). In mountain environment microclimatic factors affect slope instability conditions (Bathrellos et al. 2014), permafrost (Boeckli et al. 2011; Fischer et al. 2006), freeze–thaw cycles (Matsuoka and Sakai 1999). Rockfalls are influenced by environmental, lithological and slope factors (Hales and Roering 2005; Menéndez Duarte and Marquinez 2002; Silhan et al. 2011).

The characteristics of detachment zones are important data for analyzing potential predisposing factors for slope failure (Menéndez Duarte and Marquinez 2002); thus, this information composes the basic tools for the risk assessment

database managed through GIS software (Frattini et al. 2008; Menéndez Duarte and Marquinez 2002).

For statistical analysis of rockfall risk assessment appears very important to have complete, updated and homogeneous inventories. This paper considers the data from some archives, but no opinions about hazard-specific rockfall sites are presented.

The present study focuses on three landslide databases covering part of the South-Eastern and Central-Eastern Alps (Marazzi 2005) over an area of 17,000 km² managed by the Veneto Region (province of Belluno) and by the provinces of Bolzano and Trento. The goal of the research is to make a new complete database of rockfall events to highlight through descriptive statistic, the common possible causes of rockfall occurrence. The use of descriptive statistic turned out to be efficient in the study of landslides and other geomorphological processes (e.g., Fischer et al. 2012; Bathrellos et al. 2014).

The information gathered for this study concerns the location, data and time, altitude of triggering point, slope aspect, lithology, volume involved and type of induced damage related to every considered rockfall. This new database can be a proposal for rockfall homogenous census that can overcome and integrate the different regional archives and can be an example of homogenous information representative of the Alpine area.

The studied area is representative of a large part of the Alps because of the great variety of its rock formations, with a wide range of geo-mechanical behaviors and qualities.

A separate analysis will be made of events occurring above 2500 m asl, where there may still be periglacial processes (Baroni et al. 2004) and where there is likely to be permafrost.

## The study area

The studied area is located in the South-Eastern Alps and, from north to south, it stretches between the Italian–Austrian border and the Venetian Pre-Alps (Fig. 1). The Adamello-Presanella Massif and the Ortles Mountain Group represent the western limit, while the eastern one
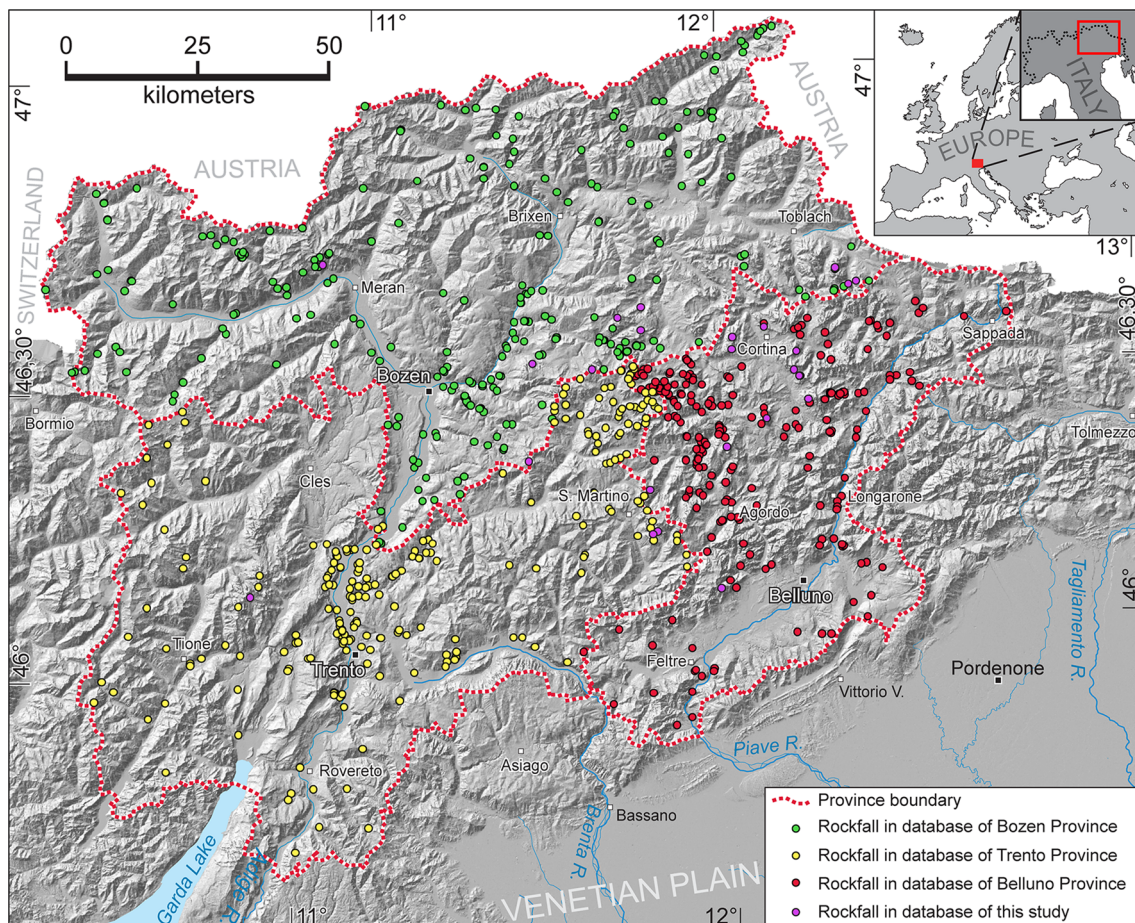


**Fig. 1** Distribution of rock falls considered in this study. *Brown dot* Belluno Province database, *green dot* Bolzano Province database, *yellow dot* Trento Province database, *purple dot*, recent events derived by newspapers and websites screening

corresponds to the border between Veneto and Friuli Venezia Giulia region.

The majority of the investigated area belongs to the tectonic unit of the Southern Alps that is separated from the Austroalpine Unit by the Periadriatic Lineament (Doglioni 1987). In the northern-most sector of the Bozen Province (i.e., Aurina Valley), a little portion of the Tauern tectonic window is present, where the lower Penninic Unit crops out (Dal Piaz et al. 2003). The bedrock consists of many different lithologies and sedimentary rocks dominate in the province of Belluno, as in that of Trento also magmatic formations (mainly ryolithes and intrusive rocks) are abundant (Fig. 2). Ryolithes are also typical in the area around Bozen, where they can reach 2000 m of thickness; whereas, the rest of its province is formed by mica schist, phyllites and gneiss, especially north and north-west of the Periadriatic Lineament. The pre-Mesozoic crystalline

basement is largely present also in the area between Trento and S. Martino di Castrozza, while the Adamello-Presanella massifs are Tertiary granodioritic batholiths.

In the Dolomites area the isolated mountain groups correspond to Triassic carbonate platforms, with vertical cliffs up to several hundreds of meters of height (Bosellini et al. 2003; Gianolla 2007). High rock walls characterize also large sectors of the Adige Valley were Mesozoic limestones and dolomites are present up to Bozen Province, where steep slopes along Adige Valley are often made by ryolithes. Carbonate rocks can be massive, but tectonic joint systems are often present and interconnected, generating a rock mass with pervasive fracturation. Cliffs of smaller dimensions are quite common also in the area of ryolithic and intrusive formations, that are often characterized by joint systems while, where metamorphic rocks are dominating, the landscape is generally gentle.
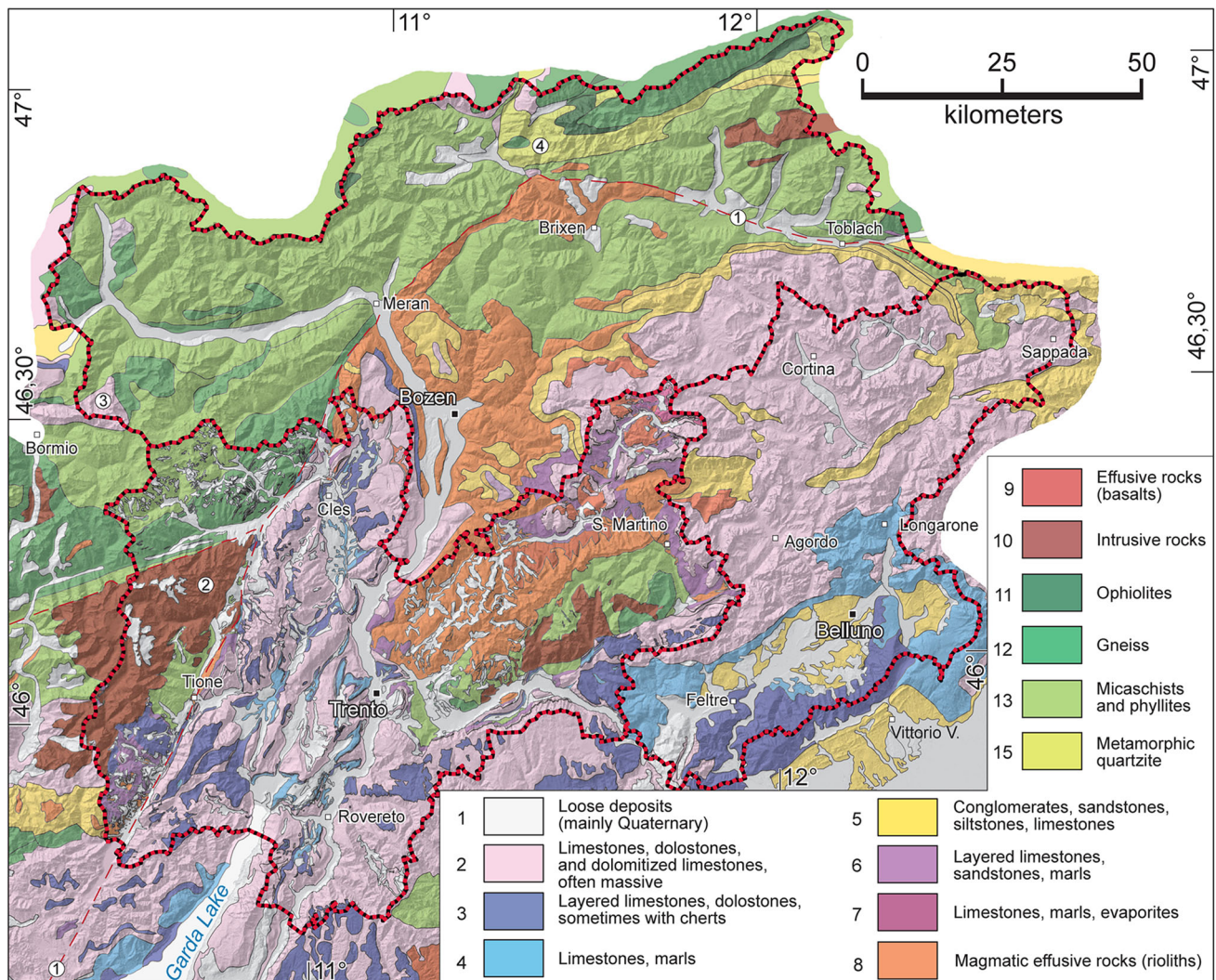


**Fig. 2** Schematic sketch of the lithologies covering the studied area (redrawn from Compagnoni and Galluzzo 2005). Legend: *1* Periadriatic Lineament, *2* Adamello-Presanella Group, *3* Ortles-Cevedale Group, *4* Tauern window

However, isolated peaks can be present, especially if gneiss crop out. In all the studied area the landscape is strongly characterized by landforms (e.g., cirques and u-shape valleys) sculpted by the glacial tongues that occupied the area in the Last Glacial Maximum (LGM) and that withdrawn to the highest valleys during the Late glacial period (Bassetti and Borsato 2005; Carton et al. 2009). From a seismotectonic point of view, the Bozen and Trento provinces are fairly inactive, whereas some earthquake sources are present in the area of Belluno. Some of the most active tectonic structures are located along the southern limit of the Venetian and Friulian Pre-Alps and earthquakes with maximum magnitude 6.5 can be generated slightly south of the considered area (Galadini et al. 2005).

The climate of the studied region is alpine with strong continental characteristics, but there are significant variations within the area. The Belluno valley, which is close to the Venetian Plain, is affected by humid breezes from the Adriatic Sea and has an average precipitation of 1276 mm/year. Mean total rainfall records in the period 1960–1990 show two maxima, one in June (151 mm) and the other in November (132 mm) (Desiato et al. 2005). However, the area of Bolzano, due to its more interior position within the Alps, has a typically continental climate, with fairly low precipitations (700 mm/year), concentrated during summer: from 1960 to 1990 the mean summer (June, July and August) total rainfall was 261 mm, which corresponds to 37.3 % of mean yearly rainfall in this period (Desiato et al. 2005). Rainfall in summer is mainly related to thunderstorms of brief duration, while in autumn it extends over longer period.

Winters are cold and summers are mild. The coldest months are December and January (mean temperatures in Bolzano (241 m asl) in the period 1961–1990 were, respectively, +1.0 and +0.2 °C), while the hottest months are July and August (mean temperatures in Bolzano in the period 1961–90 were, respectively, +22.0 and +22.4 °C).

## Data and methodology

### Source of data

Information about rockfall events derives from the regional landslide database of the IFFI Project (Italian database of landslide events) (APAT 2007). These archives are managed by the ISPRA (Institute for Environmental Protection and Research), which provides detailed, up-to-date data on landslide distribution in Italy. Regions and provinces collate information about landslides from historical reports, photogrammetric techniques and field surveys in a GIS database and in a Microsoft Access file. The location of each event is represented in a shapefile map that shows all PIFF points

(the highest detachment points of the landslides) of each event. A particular code number is assigned to each event so that every landslide can be recognized. This code number also gives access to other information (date of occurrence, damage, exposure of the slope, lithology) about a specific event in the Access database.

This study has used the IFFI database of the Veneto Region (province of Belluno) and of the Bolzano and Trento provinces. Only those events classified as topple/rockfall were examined.

### Improvements to existing landslide databases

The three databases are different for the data stored and the completeness of them, thus, a great effort has been made for make the available information homogeneous and, after comparable. In particular, there was a varying number of rockfall events in each database. There are only 461 cases in the Belluno database, whereas at least 2000 events are recorded in the others. The average number of event/km$^2$ varies from province to province (Table 1).

Some of the events recorded in the databases had to be rejected as not pertinent or useful to our study. In some cases, this was because those landslides were due to preventative interventions or slope instability signs. In others, the records were incomplete and so could not be used. For example, details regarding date, time of the day and volume (Table 2) were often missing. It was not possible to retrieve this kind of information, but other missing data could be recovered and added, such as altitude of detachment, lithology, and slope aspect.

**Table 1** Comparison between data stored in each database

| Province | Number of events | Size of the territory (km$^2$) | Average number (events/km$^2$) |
|---|---|---|---|
| Belluno | 461 | 3668 | 0.13 |
| Bolzano | 2035 | 7399 | 0.28 |
| Trento | 2965 | 6208 | 0.48 |
| Study area | 5461 | 17,276 | 0.32 |

**Table 2** Data type and number of events with complete records

| Data base field | Number of events with complete information | % Of the total |
|---|---|---|
| Date of occurrence | 517 | 67.0 |
| Time of day | 82 | 10.6 |
| Damage | 631 | 81.7 |
| Volume | 230 | 29.8 |

The percentage is calculated on the basis of all events considered in this study (774 rockfalls)

Database structure

For each province, we created a project in ArcMap (ESRI) with some useful layers, such as: a shapefile with the position of the rockfalls, a geological map, a DEM, a contour line map, provincial and municipal boundaries. Through these layers it was possible to create a new database with all selected events updated with some new information. About 774 rock fall events (Fig. 1) were stored in the new database created in Microsoft Excel.

About 750 rockfalls were taken from the IFFI archives of the three provinces and 24 new events were found in newspapers and websites. The rockfall events were arranged in rows, while columns contained the information chosen for the descriptive statistical analysis. These parameters are:

- ID code and locality: to identify each rockfall event and to go back to the original IFFI data, in particular the data stored in the access file where some information about the data and hour of happening and the damages occurred are present. The locality is useful to separate events for the province which they belong to.
- Date and time of day: important data for understanding if the rockfalls of the database are historical data or if they are recent observed falls on field. Old rockfalls happened in the first half of twentieth century are events depicted partially in old documents. Date and time of the day are useful to link the event to the climatic condition active in that circumstance that may have influenced the fall. In each period of the year a different environmental process that can be a triggering cause is active. For example, during autumn there is strong difference in the temperatures between night and day, so potential freeze–thaw cycle can occur (Matsuoka and Sakai 1999). During the spring, snowmelt can facilitate the circulation of water in the fractures modifying the hydrological condition and the state of stress. During the summer, the rising temperature can change the state of the permafrost where it is present (Fischer et al. 2006). The time of the day with the slope aspect can be a direct indication of the heat energy of sun rays: rockfalls that happen in the central part of the day in the slope exposed toward the southern and south-western quadrants are those most hit directly by solar radiation so are those with the higher temperature that can melt ice in open fractures or make dilatation in the bedrock (Gunzburger et al. 2005).
- Altitude of detachment: this information has been taken to distinguish in a general way, the landslides of periglacial environment (above 2500 m asl) to the others (see below). At higher altitude some processes as the freeze–thaw cycles are more frequent than at lower altitude, even because vegetation is absent so the bedrock is directly exposed to weathering. It is interesting to observe if the relationship between altitude and rockfalls is valid, as shown by some authors (Fischer et al. 2012; Hales and Roering 2005; Menéndez Duarte and Marquinez 2002).
- Slope aspect: the arrangement of the mountain side has an influence on the persistence of the snow, the shadow and the freeze–thaw cycles (Fischer et al. 2012, Matsuoka and Sakai 1999).
- Volume: is the measure of the magnitude of the event. It can be estimated when important occurrences take place or even when little falls make damages or interrupt human activity (for example roads).
- Lithology involved: the kind of rock mass which has been affected by the landslide episode is fundamental to establish if the presence of natural discontinuity such as layering, schistosity, cooling or tectonic joints could have played a role in promoting the detachment. These analyses highlight what lithologies are more prone to collapse, independently of slope orientation (Menéndez Duarte and Marquinez 2002). Many works noted a correlation between the lithology and the dimension of the collapsed block, hence it can be a predictive parameter of the most probable future collapse (Fischer et al. 2012). In this study, the lithologies were identified on the basis of their mechanical behavior and, thus, grouping together different geological formations according to their structural similarities rather than other geological proprieties.
- Damage incurred: is a parameter for establishing the impact that these events have on the population and to which type of events the attention are paid for. Damage is a parameter useful to focus on the material goods most hit and the impact that rockfalls have on the economy of the study area, if the rockfall risk is a real diffuse and important risk that needs more attention and prevention (Hilker et al. 2009).

Filters selected those events with common features, such as the province, the season, or the slope aspect. The selected data can be extracted and represented in graphic form.

A great effort was made to render the information homogeneous and comparable. For example, it was necessary to adopt a lithologic classification including all the categories used in the databases of the three provinces and to create a classification of the occurred damage.

To discover which geological formations are most prone to instability, the number of rockfall events was corrected according to the extent of outcropping lithology (Eq. 1) (Fig. 3):
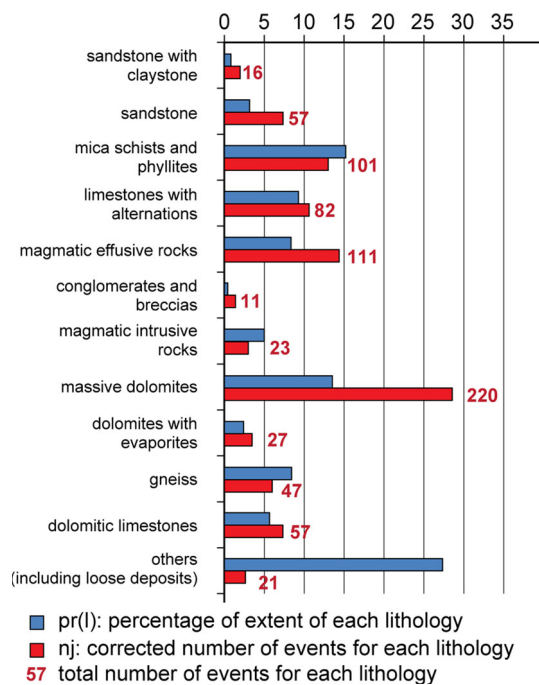
Fig. 3 Corrected number of events for each lithology ($n_j$) and percentage of extent of each rock type [$\text{pr}_{(l)}$] in the whole study area. The class "other" shows high percentage because all loose deposits are included

$$n_j = \text{pr}_{(l)} \times n, \qquad (1)$$

where $n_j$ is the number of observed rockfalls compared to the lithology of origin; $\text{pr}_{(l)}$ is the percentage of outcropping rock type in the study area. The surface covered by each lithology has been calculated in ArcGIS measuring the extent of the polygons describing the area involved in the rockfall; $n$ is the number of rock falls registered for that lithology.

A similar correction was made to compare the number of events with the altitude of detachment according to the extension of the territory above this height. The histogram realized for this purpose (Fig. 4) is based on the corrected number of events ($n_h$) according to Eq. 2:

$$n_h = n_i \times \text{ext}_i, \qquad (2)$$

where $n_h$ is the corrected number of rockfall events for a stated province; $n_i$ the number of rockfalls in the "$i$"-class of height for that province; $\text{ext}_i$ the percentage of extent of the "$i$"-class of altitude related to whole province.

A separate analysis has been made for rockfall events occurring at an altitude above 2500 m asl, where periglacial processes are active in this part of the Alpine chain (Baroni et al. 2004; Boeckli et al. 2011).

The hypsographic curves of each province was calculated and their plot diagram allowed to estimate the percentage of the territory above a determined altitude (Fig. 5a) and, thus, to estimate how much of the territory is affected by active
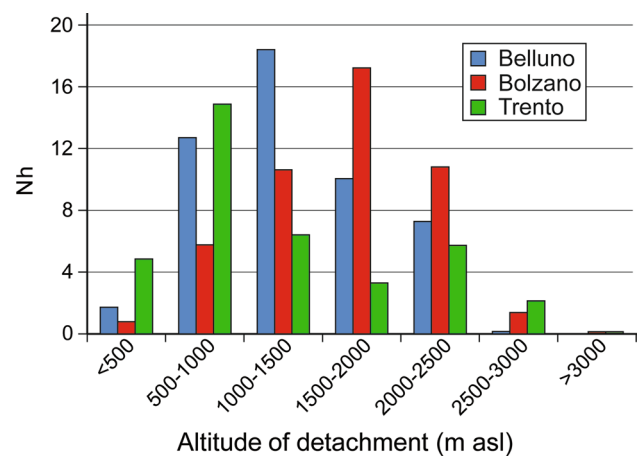


Fig. 4 Histogram of the altitudes of detachment and the number $N_h$ of rock falls corrected according to the extension of the territory for each class

periglacial processes. The hypsographic curves for the three provinces have been obtained by using the ArcGIS "Surface Volume" tool from the DEMs of each province; the DEMs of Trento and Bolzano provinces have a cell size of $10 \times 10$ m, while the one of Belluno is $25 \times 25$ m. The Surface Volume tool returns a text file with the extension of the territory above or below a given altitude. It furnishes 2D and 3D topographic surfaces of the relief energy expression. From the 2D data, the percentage of territory above each height's interval has been calculated. The hypsographic curves that have been realized show the percentage of the territory above the various altitudes.

## Results and discussion

The databases are not updated in the same way, as can be seen when the year of occurrence of a rockfall is considered. For the Belluno Province, most of the recorded events happened before 1969, while most of the events in the Bolzano province archive occurred after 1990 (Fig. 6). The more recent the records about rockfalls are, the more complete is the information.

Altitude and slope aspect are environmental variables that have an influence on the microclimatic conditions. The histogram of Fig. 7a represents the percentage, over the total, of the surface existing for every altitude interval and the percentage of rockfall events. It emerges that large part of the considered cases (25 % of the total) involved the slopes between 500 and 1000 m, even if the surface of this interval is not the most extended (15 % of the total).

In Fig. 7b the number of occurrences, distinguished for slope aspect and elevation range, highlights that the slopes more prone to collapse seems to be those facing the southern quadrants (i.e., south east, south west and south).
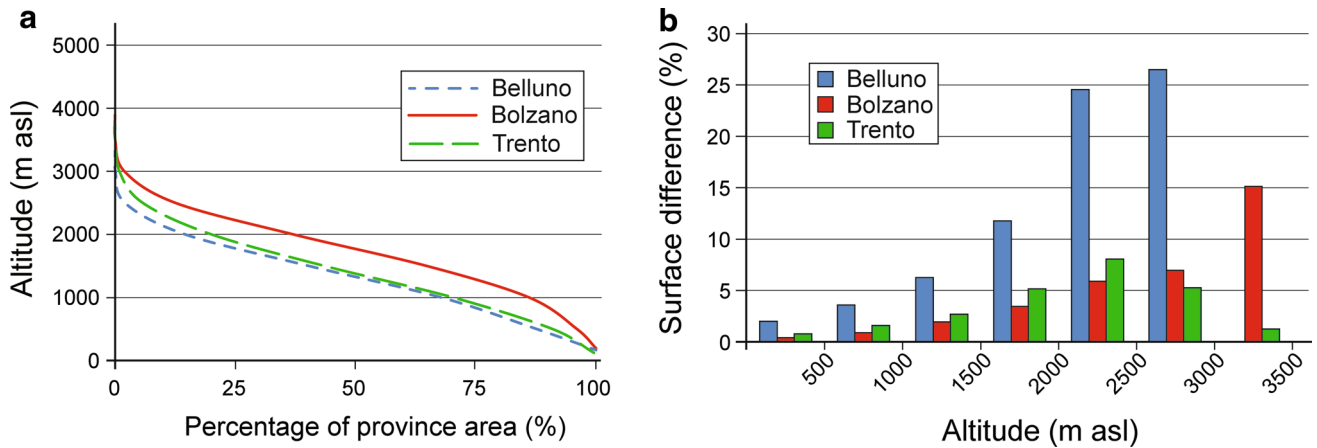
Fig. 5 **a** 2D surface hypsographic curves of the three provinces, **b** territory extent difference between 2D and 3D surface values. Larger discrepancies are present for 3D calculations of Belluno

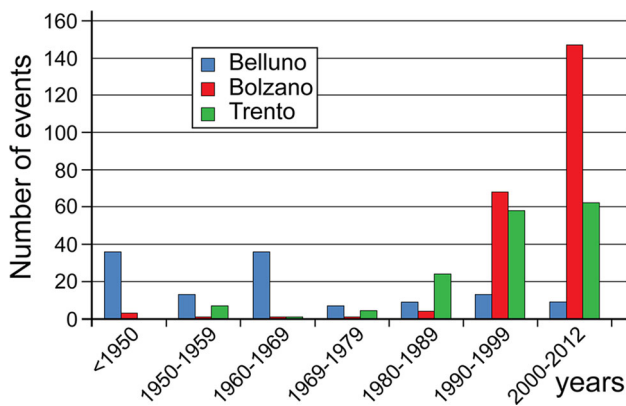Province because of the less defined DEM (cell size 25 m), if compared to Bolzano and Trento (cell size 10 m)



Fig. 6 Temporal distribution of the rockfall events recorded in the databases

Indeed, these three classes are the 50 % of the sample. The time of day when the majority of the rock falls occurred is very interesting (Fig. 8a). All time references have been adjusted to solar time, GMT +1. The analyses of the histograms highlight that the period of the day with the highest number of rockfalls is from 10:00 a.m. to 2:00 p.m.

The distribution of phenomena during the year (Fig. 8b) shows the presence of three peaks: the first in October–November, a second in June–July and a third in March. The distribution of events during the year in each province is different (Fig. 9): rockfalls in the Belluno Province show two peaks, one in March and another in November; in the Bolzano Province they are concentrated in June, with secondary peaks in April and October; in the Trento Province the distribution is mid-way between that of Belluno and Bolzano, with three peaks in February, July, and November.

Considering the landslide volume (Fig. 10a), 60.4 % of examined rockfalls have involved a rock mass of less than

100 m$^3$. About 50 % of the sample did not produce any observed damage (Fig. 10b). The most affected material assets correspond to roads and protective structures (in 25 % of all incidents). Buildings and infrastructures are the second most affected category (13 %), followed by trekking paths, agricultural lands and woods (11 %). Only 1 % of all landslides have caused injuries to people.

Massive dolomites are the most commonly involved rock type, followed by volcanic rocks and then by mica schists–phyllites (Fig. 3).

A separate analysis was made for events that occurred over 2500 m asl, in an environment where, generally, periglacial processes may be active in the Central-Eastern Alps (Baroni et al. 2004). However, not all the rockfalls occurred above 2500 m considered in this work are linked to the presence of permafrost. It has been observed that if the positions of this study's rockfalls above 2500 m are overlapped on the probabilistic map of the distribution of Alpine permafrost (APM, Boeckli et al. 2011, 2012), only in some cases there is a "possible" link with the presence of permafrost, whereas the areas where the presence of permafrost is "likely" are very rare. In the Dolomites the only recorded case of a correlation between permafrost and rock fall is on the north-eastern side of Sassopiatto Mt. where on 19th August 2010 a block of rock collapsed revealing the presence of ice on the detachment surface (Schoeneich et al. 2011). Another documented case in the South-Eastern Italian Alps is that of Hohe Wilde (L'Altissima Mt.), which occurred on 30th July 2008 (Schoeneich et al. 2011) and Thurwieser Peak with the huge rock avalanche that happens on 18th September 2004 (Pirulli 2009).

For an evaluation of the possibility that periglacial processes could interest an important portion of the territory, with a possible effect on the triggering of rockfall,
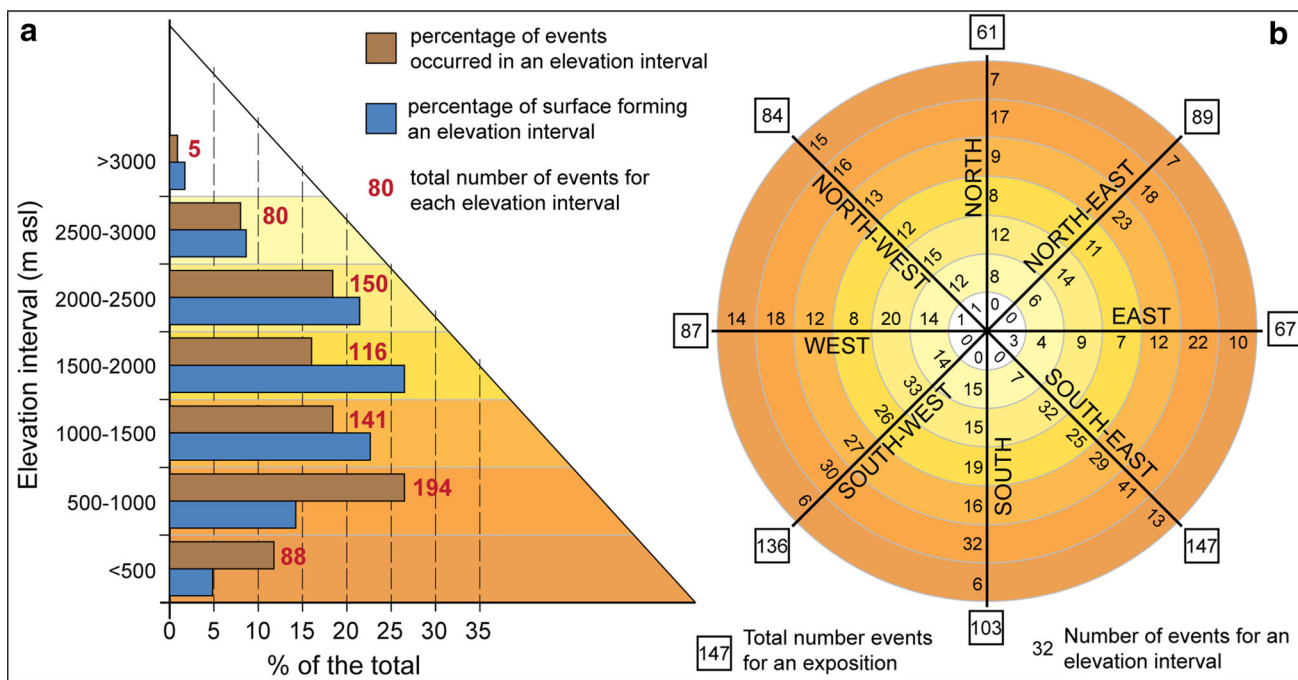
**Fig. 7** **a** Distribution of events according to the altitude and the slope aspect. Legend: *blue*) Percentage of surface covering each interval class; *brown*): percentage of events for each class respect the total number of events, **b** *rose* diagram. The *internal circle* represents growing class of altitude with the indication of the number of the rockfalls in each class
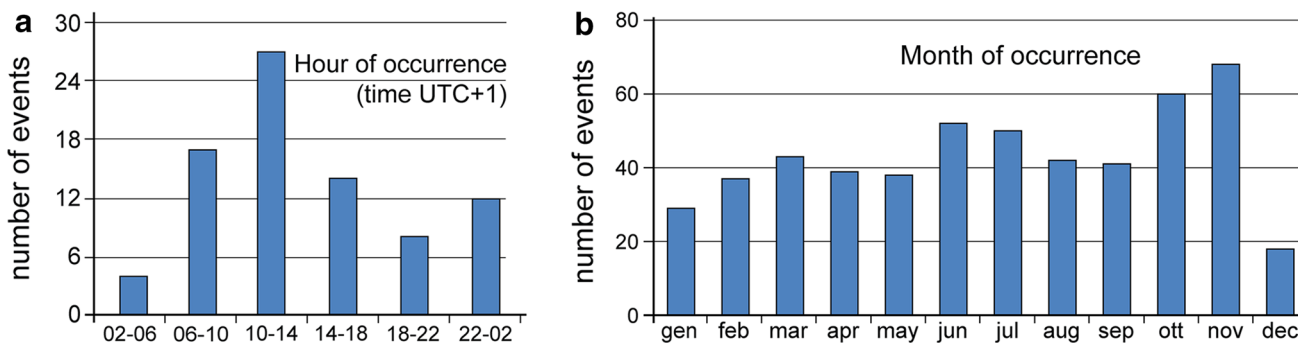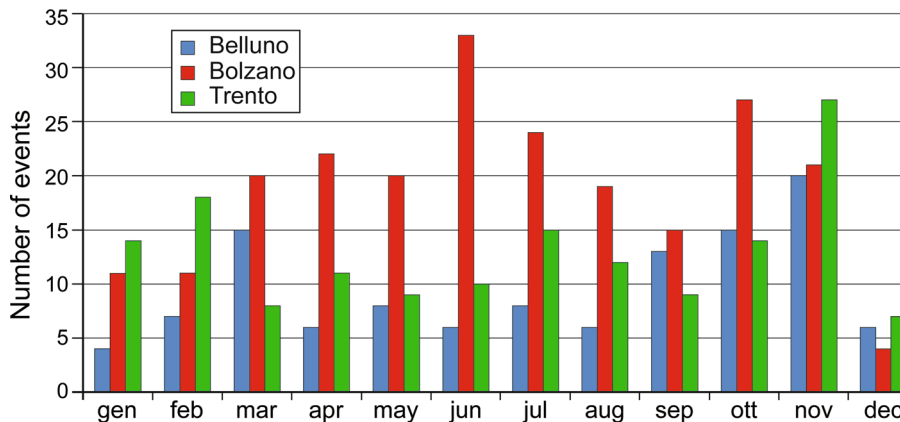


**Fig. 8** The 774 events considered by: **a** time of day, **b** month



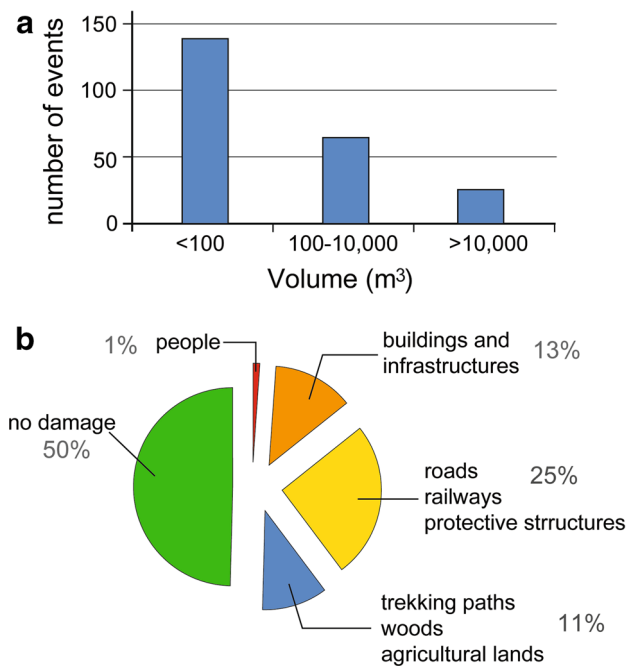**Fig. 9** Monthly distribution of events in each province

**Fig. 10 a** *Histogram* of the volumes of material involved in the considered rock falls, **b** *pie chart* with the percentage of each class of affected material assets

hypsographic curves of the study area have been realized. It has been emerged that the hypsographic curves obtained from the DEMs of the Belluno and Trento provinces are similar (Fig. 5a): they present a linear trend up to 2000 m, with 14.6 and 20.1 % of their territory above this height. From this point, the trend has a steeper gradient, especially above 2500 m. The percentage of surface on which there may be periglacial processes is only 2.1 % for Belluno and 5.8 % for Trento.

The hypsographic curve of the Bolzano Province (Fig. 5a) shows a high gradient up to 1000 m and then a linear trend up to 2500 m. Above this altitude, the curve has a steeper gradient and 12.6 % of the 2D surface of the Bolzano province may be affected by periglacial processes.

Hypsographic curves often refer to a 2D planimetric representation of the topographic surface. In a mountain environment with steep rock walls, 3D surface hypsographic curves may give a better picture of the true topography. From Fig. 5b it can be seen that discrepancies between the extent of 2D and 3D surfaces increase at higher altitudes, with a difference as great as 15 %. Differences in territorial extension at each altitude influence the incidence of rockfalls there. Other studies in other places have shown that the number of rockfall events varies with the altitude (Hales and Roering 2005; Menéndez Duarte and Marquinez 2002). Taking into account all database events, by province and altitude, it emerges that for Bolzano Province most part of the rockfalls occurred between 1500 and 2500 m (Fig. 4)

instead for Belluno and Trento ones most events interested the slopes between 500 and 2000 m.

Considering the 84 rockfall events that occurred at elevation higher than 2500 m, observations can be made regarding the altitude, the year, and the damage incurred (Table 3; Fig. 11). Most events occurred between 2500 and 2700 m, with rockfalls decreasing in frequency at higher altitudes. The last 10 years witnessed a considerable increase in the number of rock falls; in particular, the events recorded between 2007 and 2013 were three times the ones of the period 2002–2006 (Fig. 11a). As evidenced in the Swiss Alps, this trend could be explained with the increase of degradation processes at higher elevation (Fischer et al. 2012), but we can also suppose that the number of the reported events rose thanks to the growing media interest and emphasis on these phenomena in the last years. Though little information regarding the dates of periglacial events is available, it may be significant that none of the considered events occurred during winter and spring (Fig. 11b). The graph of damages (Fig. 11c), shows that 78 % of rock falls occurring above 2500 m caused no damage; 14 % affected trekking paths and rock climbing routes and damaged woods; 5 % affected roads and protective structures. It is important to highlight that very few events (only 3 out of 84) caused injury to hikers and climbers. The results of this study demonstrate that landslide inventories are important tools to set predisposing measures and to manage land use, thus, they are fundamental for the development of new settlements, the knowledge of natural hazard and its impact on the population (Bathrellos et al. 2012; Papadopoulou-Vrynioti et al. 2013).

## Conclusions

The creation and exploitation of the landslide database in mountain environment are useful for the hazard and risk assessment only if historical series of landslide events are complete, including all the useful information relative to their spatial and temporal distribution coupled with geological conditions. Hazard maps are realized from these data, in particular the predisposing factor for rock failure.

In this study, a new complete database was achieved by the implementation of existing archives with new events data and information of completion of rockfall events. Some selected parameters were used as reference to make an analysis to identify the characteristics of the detachment zones and suppose the possible relationship with the climate.

In the study area this approach allowed to observe that:

– The majority of the rockfalls have volume inferior to 100 m$^3$ (60 %) (Fig. 10a) and often caused little damage. The most affected material goods are roads

**Table 3** Analysis of rock falls selected for common features (in the column on the left)

|  | Number of events | Altitude (m ASL) | Month | Time of the day | Volume (m$^3$) | Slope aspect | Damage |
| --- | --- | --- | --- | --- | --- | --- | --- |
| All events | 772 | 500–1000 | November | 10:00–14:00 | <100 | SE | 0, 2, 3 |
| Southern slopes | 379 | 500–1000 | November | 10:00–14:00 | <100 | SE | 0, 2, 3 |
| Summer | 170 | 500–1000 | June | 14:00–18:00 | <100 | SE | 2, 3, 1 |
| Thawing period | 155 | 500–1000 | March | 10:00–14:00 | <100 | SE | 2, 0, 3 |
| Events, altitude >2500 m | 84 | 2500–2700 | July | 6:00–10:00 | 100–10000 | S, W | 0, 1, 2 |

For summer time June, July, August, September have been considered. For thawing period February, March, April, May have been regarded. The damages are indicated with: *0* no evident damage, *1* trekking paths, woods, agricultural lands, *2* roads, railway lines, protective structures, *3* buildings and infrastructure, *4* people
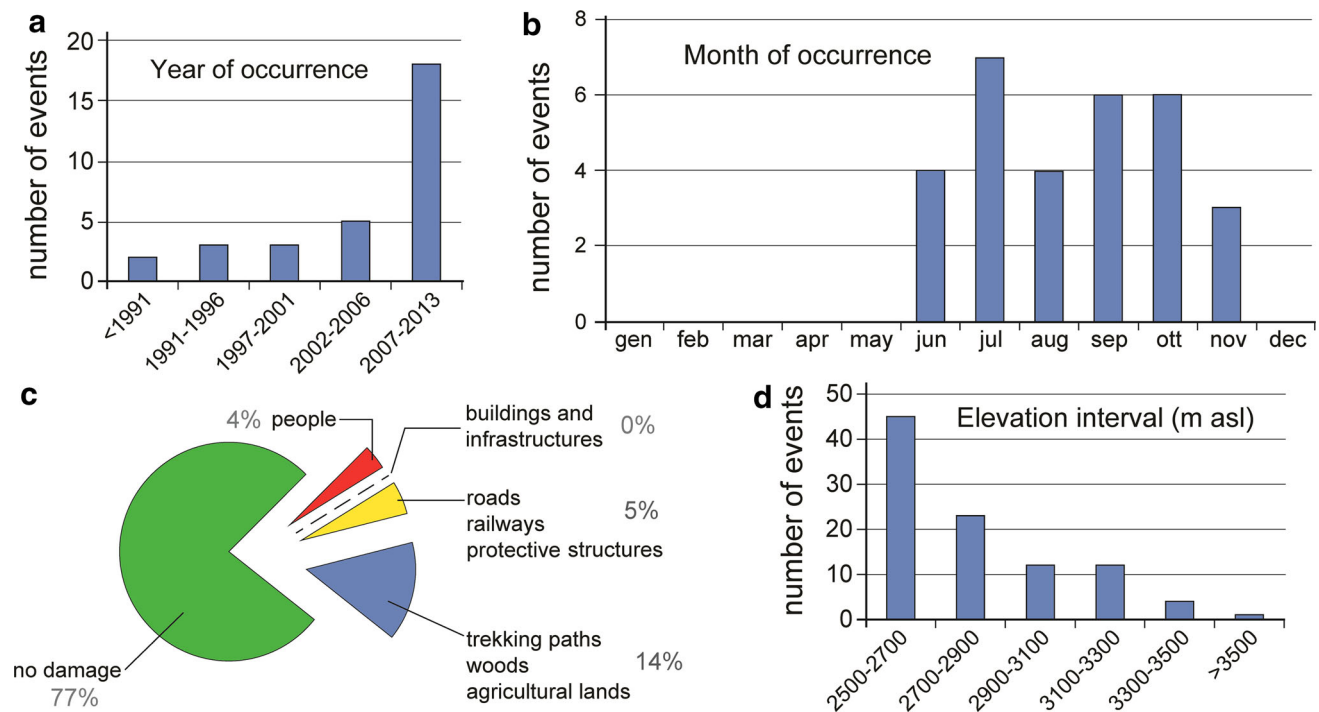


**Fig. 11** Rock falls occurring above 2500 m asl: **a** year of occurrence, **b** total number of events in each month, **c** damages incurred, **d** relationship between altitude and number of rockfall events

(25 %) followed by buildings (15 %) (Fig. 10b). A large proportion of the rock falls occurred at altitudes between 500 and 1500 m, where material goods abound and any rock falls are easily noticed (Fig. 4).

– The rock types most affected by fall events were massive dolomites followed by mica schists and then by volcanic rocks (Fig. 3). There has been a correspondence between the slope aspect and the side of the valleys most prone to rockfall (Fig. 7b): the sides with more events are those toward the southern quadrants and the hours of the day in which the events are more frequent are those between 10:00 and 14:00 hours when solar radiation is high (Fig. 8a).

– There seems to be a link between climate and rockfalls: the distribution of events during the year has three peaks in March, June and November (Fig. 8b). The magnitude of these peaks depends on the province considered and its position in the Alpine chain, which influence the climate and in particular the precipitations.

Hypsographic curves (Fig. 5a) of the three provinces have shown that only a small part of the Belluno province (2 %) is located above 2500 m and, thus, can be potentially affected by periglacial processes; whereas, the Bolzano and Trento provinces have larger areas at these altitudes (12.6 and 6 %, respectively). It was noted that on average, rock

falls in the Bolzano Province occur at a higher altitude than those of the Belluno and Trento provinces (Fig. 4).

Although at these heights most rockfalls do not cause any damage (77 %), sometimes they interrupted hiking tracks (14 %) and roads (5 %) (Fig. 11c). In 3 cases out of 84, people have been injured, a fact that stresses the importance of taking these phenomena seriously. Even if not much accurate information was available concerning the date of occurrence, it emerged that at heights above 2500 m, rockfalls happen only during summer and fall (Fig. 11b) when trekking and hiking activities are most common.

This work can be considered as a contribution to the creation of a landslide hazard map, supported by a new homogeneous archive dedicated to rockfalls.

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