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RESEARCH ARTICLE

Establishing a record of extreme debris flow events in a high Alpine catchment since the end of the Little Ice Age using lichenometric dating

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ABSTRACT
Establishing a record of large debris flow events in high Alpine areas prior to the availability of high resolution remote sensing data can be very challenging. In this study, we investigate the debris flow activity in two tributary valleys of the Horlachtal catchment in Tyrol, Austria between the end of the Little Ice Age at about 1850 and the first available area wide aerial images from 1947. To accomplish this, we calculated a local lichenometric calibration curve using the long axis diameters of the five largest *Rhizocarpon* lichen thalli at 51 different reference locations. Because of the interval-censored dating of most of the reference sites, we established a bootstrapping approach within the calibration curve calculation process. With the help of the lichenometric calibration data, we were able to date 47 old debris flow deposits in the study area. The results indicate no increasing or decreasing trends in frequencies of extreme debris flow events. In addition, the results point to a very local character of debris flow triggering precipitation events, as we can detect major differences in neighbouring valleys. Lichenometric derived datings also provide temporal informations about the end of debris flow activity at some sites in the study area and thus can contribute to a better understanding of debris flow systems.

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1. Introduction

In mountainous regions around the world, debris flows appear as natural hazards (Dowling and Santi 2014). In most cases triggered by intense rainfall events (Berti et al. 2020), they can have huge impacts on anthropogenic infrastructure as well as on the Alpine geosystems because of the large amount of transported material (Heckmann et al. 2012; Hilger 2017). Yet until today, relatively little is known about the future development of debris flow frequencies and magnitudes in a changing climate (Jomelli et al. 2007; Pelfini and Santilli 2008). Long-term and detailed records of extreme events in the past can help to improve our understanding of low frequency but high magnitude processes like debris flows and therefore are fundamental in order to predict such events in the future. Many studies, especially those that use high resolution remote sensing data like aerial images or LiDAR (light detection and ranging) data, investigate debris flow activity for the last decades or at least to the mid of the twentieth century (Bennett et al. 2012; Bernhardt et al. 2017; Dietrich and Krautblatter 2017). However, to get better insights in the process dynamics, longer records are needed. There are some studies on debris flow frequencies especially focusing on extended

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periods for example using dendrogeomorphology (Bollschweiler and Stoffel 2010) but these mostly cover channelized debris flows in lower altitudes or single debris flow systems (Kiefer et al. 2021).

In Horlachtal, area-wide slope-type debris flow frequencies and magnitudes in high altitudes since 1947 have been already analysed (Rom et al. 2023) using recent and historical aerial images. These analyses revealed no consistent trend in debris flow activity but short-term variabilities, as periods with high debris flow activity and high magnitudes (1954–1973, 1990–2009 and 2015–2018) alternate with periods of only few debris flows with less transported volumes. Dating debris flow events that occured prior to the acquisition of the first aerial images in 1947 is not an easy task. Because of the remote region far from settlements, there are hardly any historic written records of slope-type debris flows or other information like, e.g. archived photographs prior to 1947. The high altitudes ranging above the treeline prohibit the usage of dendrogeomorphology in most parts of the study area. As a consequence, lichenometric dating provides the only way to gain information about the period before the acquisition of the first remote sensing datasets.

Lichenometric dating (widely called and thereafter referred to as 'lichenometry') was developed and introduced by Beschel (1950) and is based on the assumption that lichens colonize new surfaces and grow with a predictable rate; therefore surfaces with larger lichens are older than surfaces with smaller ones (Karlén 1973; Graber and Santi 2022). With the help of a calibration curve calculated based on measured lichens on surfaces with known age, lichen sizes can also be converted to absolute dates (Bradwell 2009). However, because of the huge impact of local climate variabilities on the growth rates of lichens, calibration curves should be created with local data (Beschel 1973; Graber and Santi 2022). Due to the many uncertainties that are involved in this method, lichenometry itself (Osborn et al. 2015) or parts of it (Bull 2018) has been criticized a few times recently. Yet lichenometry provides a simple and cheap opportunity to date surfaces in high alpine areas like the Horlachtal, where other dating methods are not applicable. However, a validation of the results is necessary as this method has to deal with different types of uncertainties. Lichenometry is widely used for dating morains (Beschel 1950, 1957; Rodbell 1992; Solomina et al. 2007; Bull 2018) but debris flow deposits have been dated by this method as well (Rapp and Nyberg 1981; Innes 1983, 1985; Jonasson et al. 1991; Helsen et al. 2002; De Haas et al. 2018; Graber and Santi 2022).

In lichenometry, the use of *Rhizocarpon geographicum* (L.) DC. is very common, as it is one of the first settlers of newly formed rock surfaces (Armstrong 2011). In addition, the slow and radial growth of the lichen thalli especially in alpine environments is another characteristic that is beneficial for dating purposes (Rapp and Nyberg 1981; Rodbell 1992; Armstrong 2011). Yet there are some biotic aspects that can have effects on the quality of lichenometric derived dates. These include for example the mortality rates of lichens, the uncertainties about the shape of the growth rate-size curve, competition effects or the merging of two lichen thalli (Loso and Doak 2006; Bradwell 2009; Armstrong 2011).

In this study, we used lichenometric analyses to extend the debris flow record in the Horlachtal especially to the timeframe between 1850 (end of the Little Ice Age – LIA) and 1947. Thus, we performed lichenometric analyses in order to generate a calibration curve for the growth of lichen thalli in Horlachtal. Using this reference model, we want to date old debris flow deposits in two side valleys of the Horlachtal (namely Grastal and Zwieselbachtal) in order to improve the understanding on the occurrence of extreme debris flow events since the end of the LIA. Comparing the debris flow activity of the two side valleys, we aim to analyse spatial differences of debris flow activity on a very local scale.

2. Study area

The Horlachtal is a side valley of the Ötztal in Tyrol, Austria. Located within the Stubai Alps, it is geologically part of the Ötztal Massif with predominant east–west striking gneisses and mica schists (Becht 1995; Geitner 1999). The Horlachtal can be divided into several tributary valleys (Grastal, Larstigtal, Zwieselbachtal, Weites Kar, and Finstertal) next to the main valley. The lichenometric

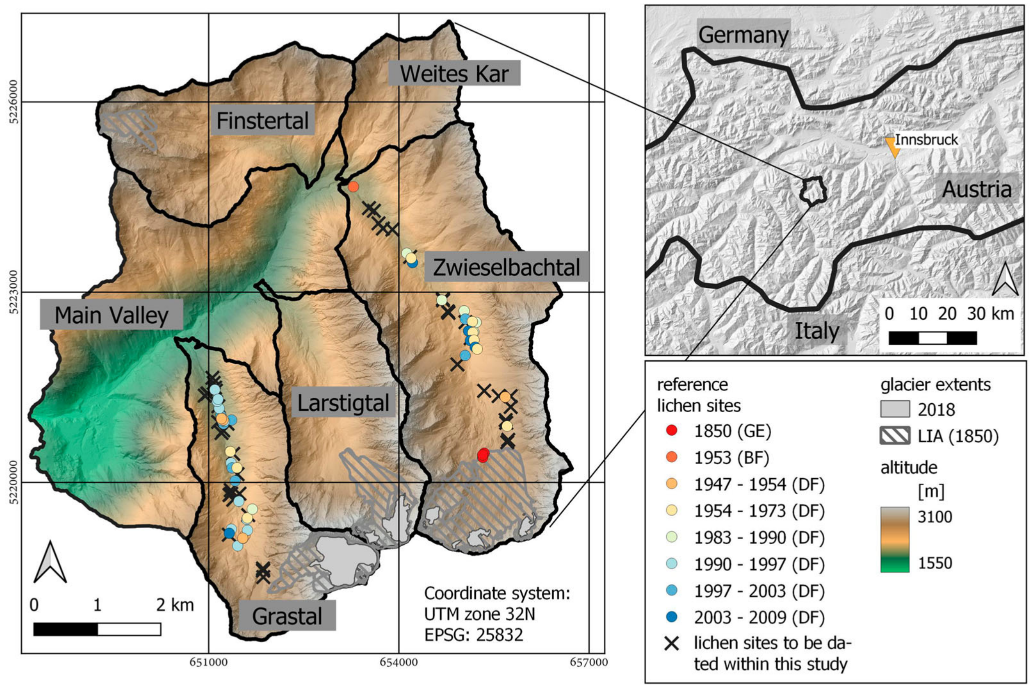

Figure 1. Location of the Horlachtal and its tributary valleys Grastal and Zwieselbachtal. LIA glacier extents are shown based on (Fischer et al. 2015). Lichenometric reference locations (location types: GE – glacier extent, BF – building foundation, DF – debris flow deposit) are depicted coloured by their respective ages. Lichen sites to be dated in this study are represented by crosses. The elevation model of the Horlachtal is based on airborne LiDAR data 2019 (own data acquisition; see Rom et al. 2023). Large-scale elevation data of Austria, Germany and Italy are based on ALOS Global Digital Surface Model ©JAXA.

analyses in this study concentrate on the Grastal and Zwieselbachtal (Figure 1) that show a huge activity in terms of slope-type debris flows (Becht 1995). These are mostly triggered by intense rainfall events that mainly occur during summer as convective thunderstorms.

The Grastal extends to an area of about 7.4 km^2, in which the Grastalferner glacier covered about 13.1% at the end of the LIA and still coveres about 6.5%. The Zwieselbachtal on the other hand is twice as large (15.1 km^2) with the Zwieselbachferner glacier covering about 12.4% of the area in 1850. Today, only approximately 1% of the area is glaciated. The treeline in the study area ranges at about 2200–2300 m. However, most of the debris flows in Grastal and Zwieselbachtal occur at elevations between 2000 and 3000 m and thus above the treeline.

3. Materials and methods

3.1. Debris flow data since 1947

By far the most common type of debris flow in the study area is the slope-type debris flow, which is further described in in Zimmermann (1990) as well as in Wichmann (2006) and Rieger (1999). This type is characterized by a hydrological catchment in the bedrock section that is located above a talus fan.

The existing debris flow record for the whole Horlachtal between 1947 and 2020 was generated via a spatial and temporal mapping of 834 single debris flows based on recent and historical aerial images (Rom et al. 2023). The results revealed no consistent trend in debris flow frequencies but rather showed alternating periods of high and low activity. Based on the findings of the geomorphological mapping, every single detected debris flow in the Horlachtal could be dated to the period in between the acquisition of two consecutive aerial images. In this way, the age of each debris flow is interval censored. In the Horlachtal, these intervals range from 19 to six years for the relevant periods. The mapping of slope-type debris flows with known ages provide the basis for the selection of reference locations for the creation of a local lichenometric calibration curve.

Not only are a large number of processes initiated during extreme precipitation events, but they are also of an exceptionally high magnitude and of a wide range. Becht (1995) reported such a large event in the Horlachtal in the 1990s. Another extreme event hit the Horlachtal in July 2022, which is currently being analysed in detail. In order to separate extreme events from medium or smaller ones, we calculated the mean debris accumulation volume per debris flow based on the data in Rom et al. (2023) in combination with the 2022 event (Figure 2). The confirmed extreme debris flow events in the 1990s and 2022 reach volumes greater than 725 m^3 per debris flow. Therefore, we used this value as a threshold for defining an extreme event in Grastal and Zwieselbachtal.

3.2. Lichenometric data acquisition

The lichenometric data acquisition at the study area was done in several field campaigns in August and September 2021. We used *Rhizocarpon geographicum* (L.) DC. lichens, which are very common on the silicate-rich rocks in the study areas (Armstrong 2002). However, we cannot completely rule out that other species of the genus *Rhizocarpon*, like *Rhizocarpon superficiale* or *Rhizocarpon frigidium*, were measured on few occasions as well, as it is very hard for non-lichenologists to differentiate between them in the field (Benedict 1988; Sass 2010).

3.2.1. Lichen size measurements

Within the field of lichenometry, many different methods to measure and analyse lichen sizes have been developed (Rodbell 1992; Bradwell 2009; Armstrong 2015). Here, both the identified reference locations (Sect. 3.2.2) as well as the locations to be dated within this study (Sect. 3.2.3) were analysed in the exact same way: We searched for the largest lichens at each predefined site and measured the diameter of about the largest 10–15 lichen thalli on their largest axis using a flexible ruler with an accuracy of about 0.1 mm (Sass 2010). Thus, we assume that the largest lichen was the first to colonize the newly formed rock surface after the stabilization of a debris flow deposition. Multiple lichens of similar size support this hypothesis (Bull 2009) and therefore we calculated the mean diameter of the Five Largest Lichen (5LL) for each site. However, it cannot be ruled out that few

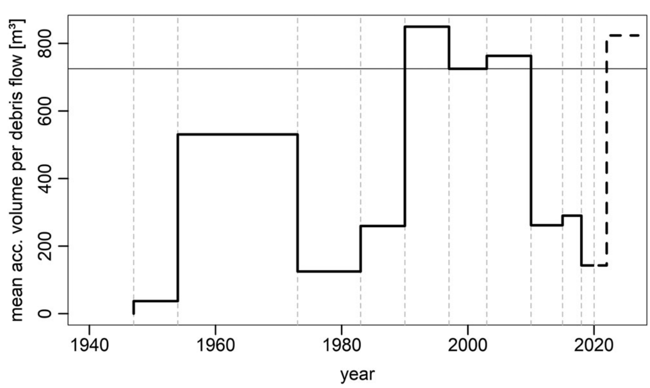

Figure 2. Mean accumulation volume per debris flow (combined for Grastal and Zwieselbachtal) based on the data in Rom et al. (2023) (solid line) and the 2022 event (dashed line). For the extreme events in the 1990s as well as the early 2000s and 2022, the volume value per debris flow always exceeded 725 m^3. The grey vertical lines represent the acquisition times of aerial images in Horlachtal.

lichens have been preserved and exposed after a debris flow event (Rapp and Nyberg 1981). To account for this, we rejected a lichen thallus with a diameter either twice as large or over 10 mm larger than the diameter of the second largest thallus (Helsen et al. 2002). On very few locations, single boulders with a large preserved lichen population were detected. If they clearly did not fit the lichen sizes of the surrounding area, these lichens were discarded. Composited lichen thalli were rejected as well but elongated thalli were measured if they did not exceed a ratio of about 1.5:1, which is in accordance to Sass (2010).

3.2.2. Selection of reference locations

The lichen sizes at reference locations are used to calculate a local calibration curve in order to determine the age of the undated sites. These locations should have accurate known ages like for example tombstones (Jochimsen 1966; Innes 1983; Rosenwinkel et al. 2015) or the foundations of buildings (Jonasson et al. 1991; Sass 2010; Armstrong 2015). In other cases landforms dated by other dating methods have been used as for example by dendrochronology (Bull 2018) or by C14 dating (Rodbell 1992; Solomina et al. 2007; Rosenwinkel et al. 2015).

There are only few studies using debris flow deposits among other dated features as reference objects (Caseldine 1991; Rosenwinkel et al. 2015). However, in this study, we mostly had to use the interval censored dated debris flow deposits for the creation of the calibration curve because there are (with one exception) no better options like, e.g. tombstones or foundations within the investigated valleys.

The sites were carefully chosen on the lower accumulation zones of the mapped debris flow deposits in Rom et al. (2023). A suitable reference debris flow deposit must be dated and identified without doubt. This means that it must not have been reworked (e.g. by erosion or by human activity) or overlain by later debris flows.

In total, we measured the lichen sizes at 47 different debris flow deposits of known age. These reference locations were supplemented by lichens found on a foundation of an alpine hutt (built in 1953) as well as three different sites of lichen covered bedrock close to the maximum glacier extent at the end of the LIA mapped by Fischer et al. (2015). According to Heuberger (1967), these glacier extents belong to the year 1850 in the Horlachtal. We tried to find additional suitable reference sites on the end morains of the 1850 extent of the Grastalferner and Zwieselbachferner but large parts of those landforms have been affected by dead ice for a long time (Heuberger 1967) and therefore growth of lichens was probably disturbed. An overview of all reference locations with their mean altitudes for each period can be found in Table 1 and their respective location in the study area in Figure 1.

3.2.3. Selection of undated locations

Along with the reference sites, locations of undated debris flow deposits of old extreme events were selected as well. Those were chosen with the help of the mapped debris flows since 1947 (Rom et al. 2023) as well as an orthophoto of 1947 and a high resolution Digital Terrain Model (DTM) of 2019. In this way, we identified debris flow deposits older than 1947 but with

Table 1. Overview of reference locations for generating a lichenometric calibration curve sorted by age.

Date	Age range [years]	Number of different locations	Mean altitude [m]	Location type	Mean 5LL [mm]
2003–2009	12–18	5	2281	debris flow deposits	4.43
1997–2003	18–24	7	2160	debris flow deposits	8.09
1990–1997	24–31	12	2152	debris flow deposits	13.63
1983–1990	31–38	6	2275	debris flow deposits	10.27
1954–1973	48–67	11	2265	debris flow deposits	19.13
1947–1954	67–74	6	2287	debris flow deposits	26.33
1953	68	1	2090	building foundation	24.80
1850	171	3	2588	glacier extent	65.13

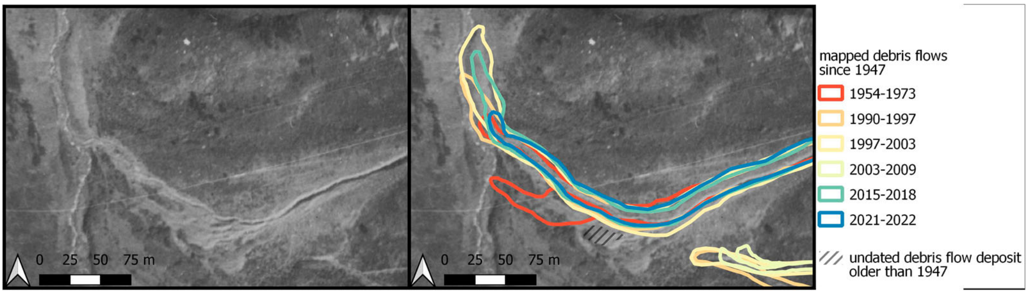

Figure 3. Example of the selection of an undated site. Left: excerpt of the orthophoto of 1947. Debris flow deposits are clearly visible. Right: mapped debris flows that happened after 1947 and reworked large parts of the deposits. Only small parts of the old debris flow is still visible today and can be used for lichenometric analyses. Source of the aerial images 1947: Province of Tyrol.

unknown age. Figure 3 shows an example of a site selection of an undated debris flow deposit. The orthophoto of 1947 reveals large-scale debris depositions of a past extreme event. Using the mapped process zones of younger debris flows, we can see that large parts of the depositions have been reworked until today (van Steijn 1999). However, a small part of the old deposit is still visible and remained untouched. As extreme debris flow events produce large depositions (Papathoma-Köhle et al. 2012) and long ranges, it is most likely that the selected undated locations originate from extreme events prior to 1947. In total, we selected and measured 47 different locations of such sites.

3.3. Generating the calibration curve

Lichenometric calibration curves have been calculated in numerous ways. Here, we used the 5LL diameter in order to calibrate the growth function. This method is well established and widely applied in lichenometry (Innes 1983; Bradwell 2009; McCarthy 2021) as it is more robust against outliers than for example the single largest lichen. Linear regression was used to determine the age based on the 5LL diameter (Beschel 1950; McCarthy 2021; Graber and Santi 2022), as this method best fits our data. As explained in Becht (1995), an extreme rainfall event usually triggers multiple debris flow processes. This in turn leads to the assumption that it is most likely for all debris flow reference locations dated within the same time interval to have occurred at the same time. Therefore, we use the mean 5LL lichen diameter of all debris flow sites of a specific time interval (1947–1954, 1954–1973, 1983–1990, 1990–1997, 1997–2003 and 2003–2009; see Table 1).

However, the problem of the interval-censored dates for the debris flow reference sites remains. There have been other lichenometric studies using interval-censored reference dates, for example those that use C14 dated landforms (Rodbell 1992; Solomina et al. 2007; Rosenwinkel et al. 2015) but the interval-censoring has not yet been adressed. In this study, we use a bootstrapping approach in order to take the censored dating into account and thus we are able to show the uncertainties of the derived calibration curves.

To clarify the generation of the calibration curve, Figure 4 illustrates the schematic process using example data. Here, six different reference sites are shown. Five of them have interval censored age, the respective age ranges are depicted with dotted vertical lines. One reference site, however, is dated to the exact year.

In a first step (Figure 4A), all interval censored locations are assigned a random but possible age within their ranges. Now, a linear model can be calculated using the Ordinary Least Square method with the 5LL diameter as independent variable. Figure 4B shows the second iteration ($n = 2$) of the procedure. Again, randomly selected ages are assumed for the interval censored sites and a linear model is defined. The light grey coloured results of the first step are still memorized. The more iterations are performed, the more possible linear regression lines can be created and saved. In Figure

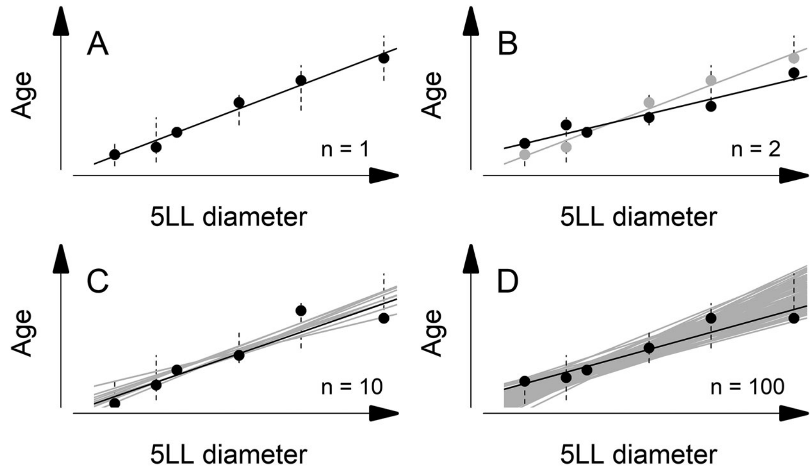

Figure 4. Schematic illustration of the generation of calibration curves using bootstrapping. More details about the calculations can be found in the text.

4C, the tenth model is created and it already shows the variability in different results. After 100 iterations (Figure 4D), the ensemble of calculated regression lines forms a kind of belt of possible reference curves.

In order to work with a sufficent enough sample size, we used 1000 iterations to calculate the lichenometric reference curves for our data.

3.4. Validation of the calibration curve

For validating the bundle of calibration curves, we used leave-one-out (LOO) cross validation. Therefore the folds equal the number of the 51 lichenometric reference locations (Webb et al. 2010). The interval-censored dates of the debris flow reference sites must be taken into account here as well. A schematic overview of one fold of the LOO cross validation process can be seen in Figure 5. One reference location acted as a test site and all other sites remained in the training data set. In a next step we calculated linear regression lines using the training dataset according to the approach explained in Section 3.3 with $n = 1000$ iterations. For each of the regressions, the 95% prediction interval was computed as well. Finally, we checked if the assigned age of the test location falls within the corresponding prediction interval of the training sites. This procedure was repeated for each of the reference locations. As a result we can calculate how often (out of the 1000 iterations) the age of each reference site fits within the 95% prediction interval.

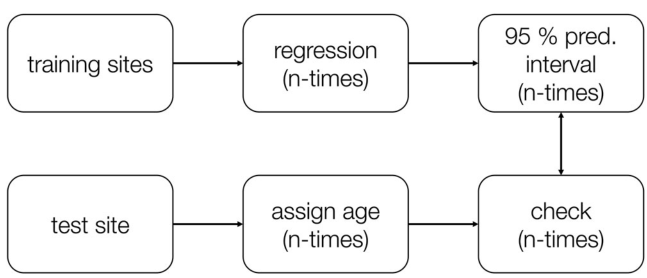

Figure 5. Schematic workflow for one fold of the LOO cross validation process, which was repeated for each of the reference locations. For more details please refer to the text.

3.5. Lichenometric dating of debris flow deposits

Using each of the 1000 regression lines from Section 3.3, the age of every undated location was predicted and the uncertainties were estimated according to the corresponding prediction intervals. In the end, the mean age of all 1000 iterations determined the estimated lichenometric age of the respective debris flow deposit. The lower and upper boundary of the uncertainty for each location was calculated by using the mean upper and lower limits of all 1000 prediction intervals.

4. Results

4.1. Lichenometric calibration curve

Using the bootstrapping approach with $n = 1000$ iterations, we established the lichenoemtric calibration curve for the Grastal and Zwieselbachtal (Figure 6). The ensemble of the 1000 calculated models shows a relatively compact band with only a small variance. Using the median values of all iterations, the calibrated lichenometric model to estimate the age based on the 5LL lichen thalli diameter would be:

$$\text{Age} = 2.598 * 5\text{LL} + 2.2663 \tag{1}$$

By repeating the bootstrapping approach but with swapped axes (age as independent and 5LL diameter as dependent variable), the median growth rate of the lichen thalli diameter in the study area could be calculated as 0.38 mm per year.

The LOO cross validation revealed that in 69% of the cases the age of a reference site falls within the 95% prediction interval. Which in turn leads to the assumption that the calibrated model is valid for about 70% of all cases. Because of the ages of the reference data sites, this lichenometric calibration curve is best valid for lichens located within the study area with an age range of 12–171 years BP. However, the reference sites are not evenly distributed over time, so that the validation may underestimate the uncertainties, especially for older periods where there are fewer reference locations.

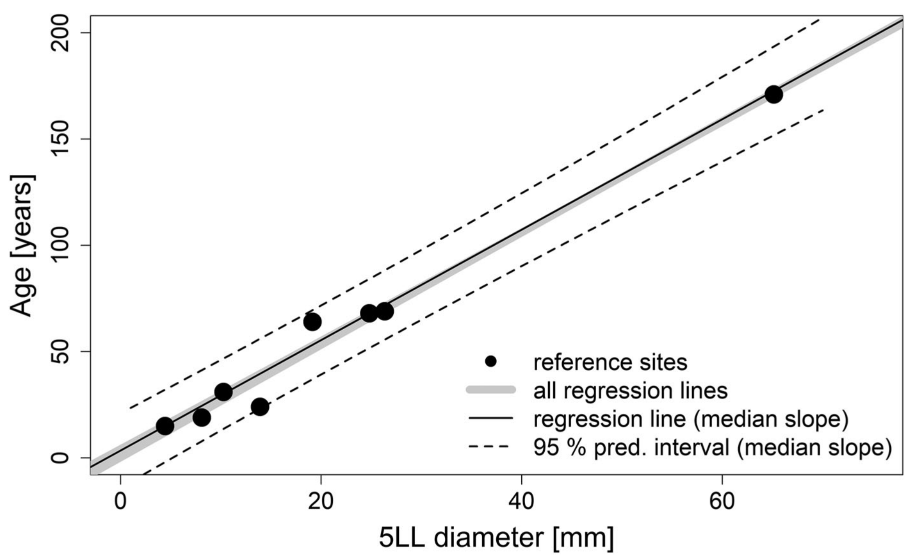

Figure 6. Lichenometric calibration curve established in Grastal and Zwieselbachtal using a bootstrapping approach.

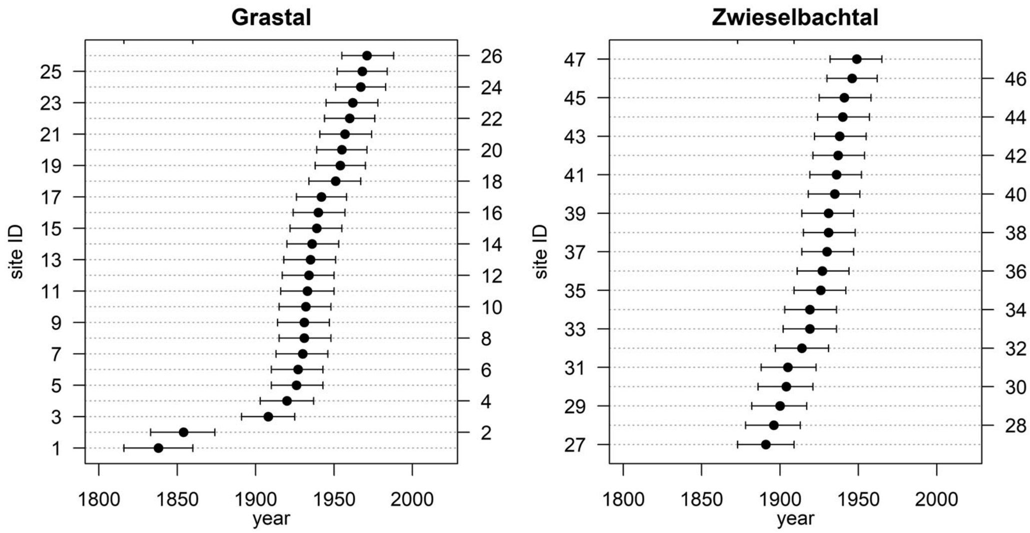

Figure 7. Lichenometric ages of formerly undated debris flow deposits in Grastal and Zwieselbachtal. The uncertainty bars are defined by the 95% prediction intervals.

4.2. Fitting the undated sites to the calibration curve

Based on the regression lines, a lichenometric age could be assigned for every formerly undated debris flow deposit with an uncertainty of about +/- 17 years according to the LOO cross validation. Figure 7 shows each of these sites and their corresponding lichenometric age separated for the Grastal and Zwieselbachtal. The Figure reveals that many of the old debris flow deposits date back to the 1930s and 1940s and that there seems to be another group clustering around 1900 in Zwieselbachtal. In the Grastal, lichenometry indicates an age group of about 170 years BP and therefore date back to the end of the LIA. Noticeable is the lack of debris flow deposits between about 1860 and 1890. Because of the selection of the sites (see Section 3.2.3), most of the debris flow deposits should have an age older than 1947. Considering the uncertainty ranges of the lichenometric dates, an age younger than 1947 was assigned to (only) three deposits in Grastal. These dates might be the result of methodological uncertainties (see Section 5.2).

The spatial and temporal distribution of the formerly undated debris flow deposits and their lichenometric ages in Grastal and Zwieselbachtal can be seen in Figure 8.

5. Discussion

5.1. The lichenometric calibration curve

Because the lichen growth rates are highly dependent on environmental conditions (Beschel 1973; Sass 2010), the lichenometric calibration curve calculated in this study is best valid only for the Horlachtal. The variability of the mean altitudes of the reference locations (see Table 1) is quite small for most periods, especially for those that are based on lichens on debris flow deposits. Here, the maximum difference in elevation is only 135 m. However, the 1850 reference sites in particular have a greater vertical distance (maximum 498 m) to the other sites. This difference in climatic conditions could result in slower growth rates and therefore affect the uncertainties of the calibration curve (Kędzia 2015).

The calculated diametral growth rate of 0.38 mm per year is in good agreement with other growth rate measurements (Rodbell 1992; Armstrong 2015, 2016) and lies within the range of other Alpine studies with rates ranging from 0.16 mm yr^{-1} to 0.5 mm yr^{-1} (Orombelli and Porter 1983; Proctor 1983; Pech et al. 2003).

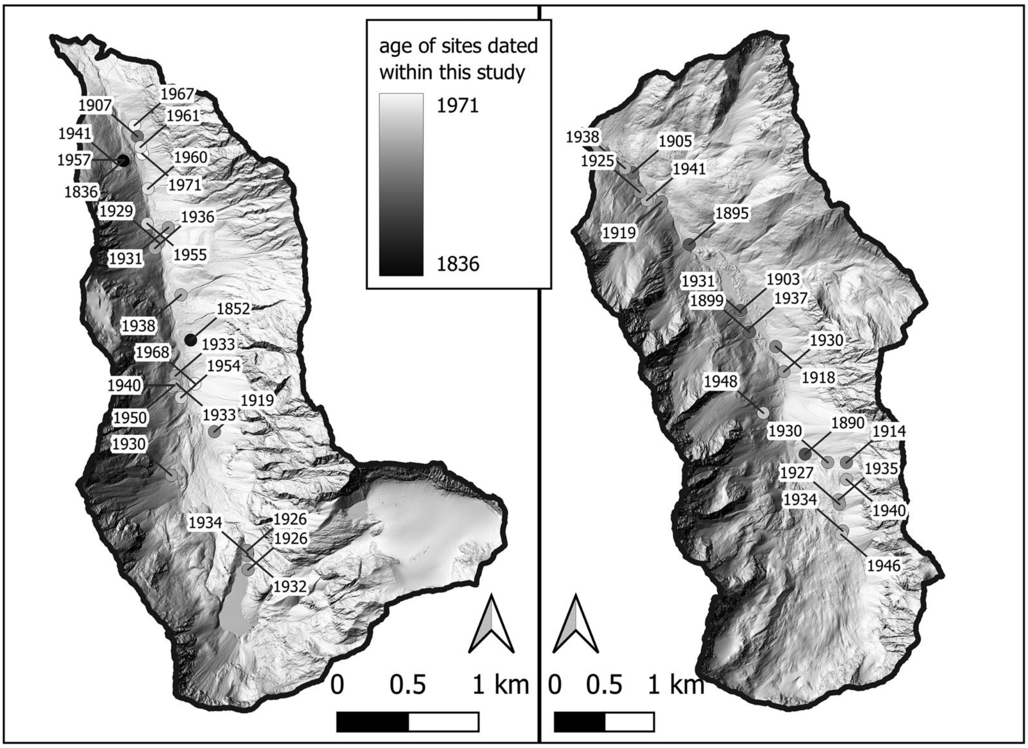

Figure 8. Location of the formerly undated debris flow deposits in Grastal (left) and Zwieselbachtal (right). The sites are shaded by their mean lichenometric age. The elevation model in the background is based on airborne LiDAR data from 2019.

Figure 9 shows the calibration curve established in this study in comparison with other lichenometric reference points in the near vicinity to the Horlachtal. The lichen locations in the Kaunertal (approximately 33 kilometres southwest of the study area) fit very well to the reference sites in this study. They also support the calibration curve between 1947 and 1850 and therefore in a period, in which there are no reference data in the Horlachtal. Sass (2010) measured 5LL lichen diamters near the Finstertal reservoir adjacent to the study area in the north. His reference data with an age up to about 70 years fit very well to our model. Only the lichens dated to the end of the LIA were slightly smaller in Finstertal.

5.2. Uncertainties

Validation of lichenometric models is not straightforward and is often negelcted in some studies, as explained in Bull (2018). Here, the LOO cross validation confirms that our model is valid for about 70% of the locations. This validation rate can be explained because the lichen growth depends highly on the specific environmental condition at each location, like for example moisture availability (Bradwell 2009). In addition, the selection and measurement of the largest lichens at each site can introduce errors as well.

Some sources of uncertainties and possible errors include the correct and exact measurement of the largest lichen diameter or incorrect assumptions regarding the largest lichens. For example, it may occurr that the first colonists already died or they could not grow unhindered due to competition (Armstrong 2015). As the boulders of debris flow deposits sometimes are quite small, the largest lichen might be a composition of several younger and smaller lichens (Beschel 1957; Clayden et al. 2004; McCarthy 2021). In some cases it has been observed that on surfaces of debris flow

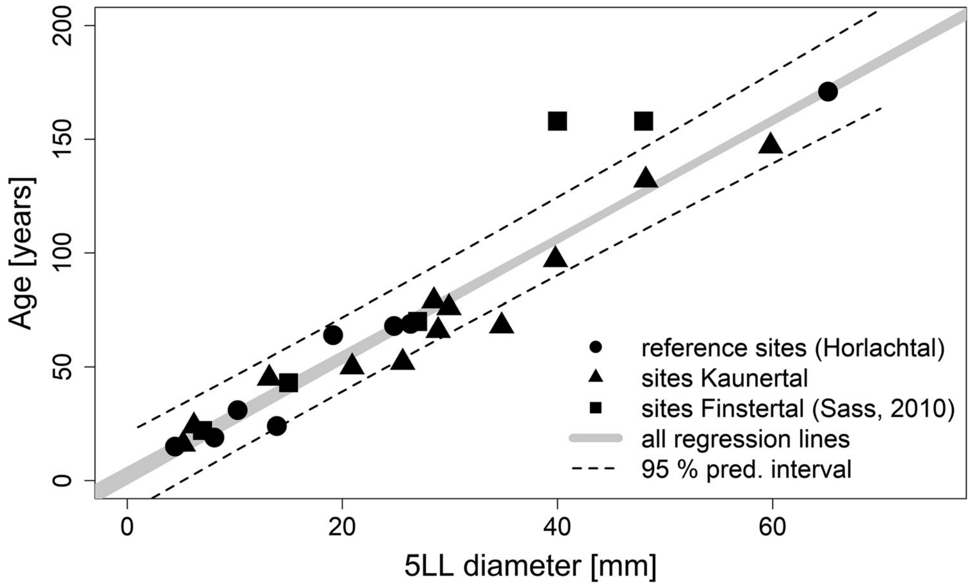

Figure 9. The bootstrapped calibration curves produced in this study compared to validation sites in Kaunertal and Finstertal.

deposits some lichen individuals did survive the mass movement (Rapp and Nyberg 1981; Rosenwinkel et al. 2015; Graber and Santi 2022). This can lead to an incorrect selection of the largest lichens and therefore to an overestimation of the age of the debris flow deposit. We tried to minimize this effect by using the 5LL method to eliminate bigger outliers.

In particular, lichens of the genus *Rhizocarpon* are vulnerable to long annual snow cover. In his study within the Colorado Front Range, Benedict (1990) showed that after five to eight years with a snow cover of 40–43 weeks, all *Rhizocarpon geographicum* thalli died. In our study, however, most of the lichen sites are located on exposed debris flow accumulation zones in the lower parts of talus slopes. Snow cover at these locations does not usually last long into the summer, so the effect of snow kill is negligible. However, one factor that may cause minor inaccuracies in our study is the variable growth of lichens in relation to stone surface aspect, as described by Dąbski (2007) in his studies of lichen growth in Iceland.

These examples of uncertainties based on biotic and abiotic factors may result in a slightly off calculation of the age based on lichenometry. Certainly, however, the uncertainties lead to the fact that the dating cannot be year-specific, but the concentration of several datings can provide time periods with an enhanced debris flow activity. We know from studies of young debris flow events in the Alps and also from investigations in the Horlachtal that debris flow events are temporally clustered, as they are triggered by rare heavy rainfall events. Using lichenometric dating, it seems to be possible to identify such extreme events for the time period before 1947 with a less good data base.

5.3. Large-scale debris flow events in Grastal and Zwieselbachtal

In combination with the debris flow record based on remote sensing data in Rom et al. (2023), the lichenometric results provide information about large-scale debris flow events in Horlachtal since the end of the LIA. For the period from 1947 onwards, the threshold value of 725 m^3 per debris flow deposition was used to define such an extreme event (see Section 3.1). If we can detect a clustering of lichenometric dates with similar ages, we can identify such extreme events prior to 1947 as well.

The periods of extreme events determined by this approach are depicted in Figure 10. In Grastal, lichenometry points to large debris flow events around 1850 as well as between 1930 and 1942.

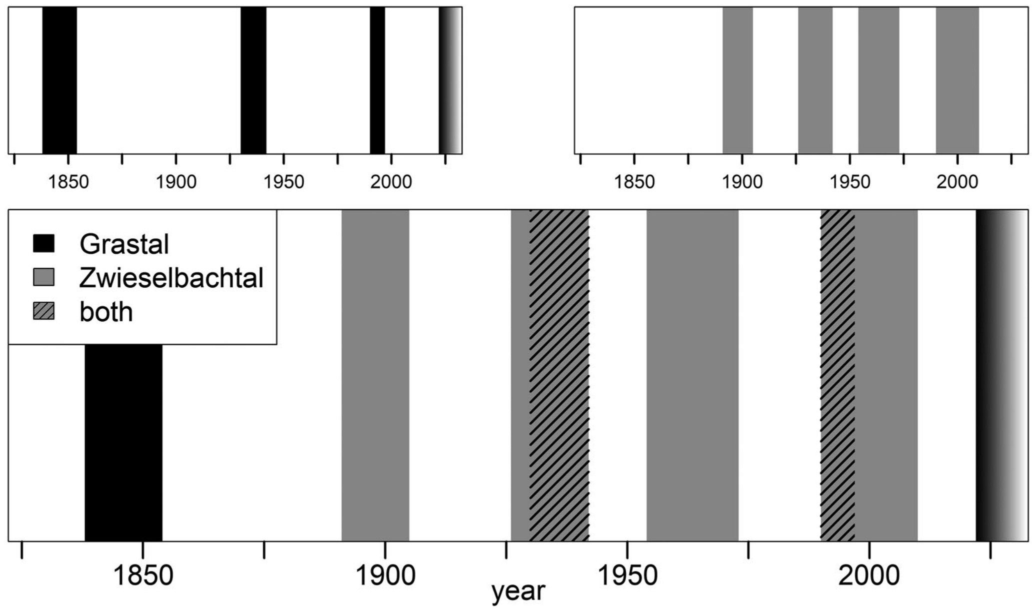

Figure 10. Record of phases with extreme debris flow events based on remote sensing data and lichenometric analyses. Topleft: Grastal data. Topright: Zwieselbachtal data. Bottom: combined record in Grastal and Zwieselbachtal.

Remote sensing data reveal such events between 1990 and 1997. Another large event could be detected in summer 2022 as well. In Zwieselbachtal on the other hand, we can identify large depositions around 1900 and again between 1930 and 1942. Since the second half of the 20th cenury, large debris flows have been triggered between 1954 and 1973 as well as between 1990 and 2009. The most recent event in 2022 is detectable in Zwieselbachtal, too, but at least some magnitudes lower compared with the Grastal.

Overall, some periods with extreme debris flow events can be detected in both study areas, whereas in some cases periods can only be detected in one of the two valleys. This in turn leads to the conclusion that heavy rainfall events that initiate large debris flows (Underwood et al. 2016; Berti et al. 2020) obviously occur on a very local scale.

The time intervals between extreme debris flow events in Grastal seem to be getting smaller, which might indicate increased activity due to climate change (Pelfini and Santilli 2008; Kapusta et al. 2010; Dietrich and Krautblatter 2017). However, it is still possible especially for the period covered with lichenometry that extreme debris flow events have been missed, e.g. due to overprinted accumulations (van Steijn 1999). This in turn might explain the long time span with no extreme event between 1860 and 1930 in Grastal.

In Zwieselbachtal, we cannot identify an increased debris flow activity for the investigated period. In fact, there is no hint for changing debris flow frequencies in the combined data set (lichenometry and remote sensing). This is comparable to other studies using mainly dendrogeomorphological methods, which also show no clear trend in debris flow frequency (Bollschweiler et al. 2008; Lopez Saez et al. 2011; Stoffel et al. 2014; Šilhán et al. 2015). Until now, we could not identify accumulations dating to the end of the LIA at around 1850 in Zwieselbachtal. Again, this might be due to overlapping depositions at the same location.

The synthesis of Grastal and Zwieselbachtal with respect to extreme debris flow events (Figure 10) does not show any visible pattern in frequency. The distribution of epochs with detected debris flow events within the time period studied could be attributed to randomness in hydrometeorological systems or other topographic and lithological parameters, which is consistent with the findings of Heiser et al. (2023) who were able to show that many alpine catchments have irregular debris flow repose time patterns. A relatively long time span with no evidence of debris flow deposition in our study area is between 1854 and 1891. This implies that either there were only few small-sized debris flows triggered in that period, or we just did not find large deposits from that time. Because of the overprinting of old debris flows by newer ones, it is more likely to miss debris flows in older periods due to the time past.

5.4. Examples of the cessation of debris flow activity

At some locations, debris flow deposits, which were dated by lichenometry, were the most recent ones we can identify there. This means that the lichenometric ages determine a temporary end of the debris flow activity at these places.

One of these sites is located in the Upper Grastal close to the historic glacier extents of the Grastalferner glacier (Figure 11A). The four dated deposits are situated on two relatively small talus cones adjacent to the Grastal lake with debris flow related landforms like levées, which are visible in the DTM of 2019. The dating information of the debris flow accumulations indicate a cessation of activity around 1930. Why the activity stopped at this point is not completely clear yet. One possibility could be that the hydrological regimes of the channel systems of the debris flow catchments changed over time as the Grastalferner retreated since the 1930s.

Another example for a similar phenomenon can be seen in the lower part of the Zwieselbachtal. Here, the five northernmost locations show lichenometric dates ranging from 1905 to 1941 (see Figure 11B). Similar to the beforementioned example, these now dated debris flow depositions are located on pretty much inactive debris flow cones. Thus, the lichenometric results show that we can date the last debris flow activity here to the first decades of the twentieth century. Possibly, the increasingly dense shrub vegetation in these relatively low altitudes prevent new debris flow events or the hydrological regimes or channel systems in the catchments changed over time like for the Grastal location.

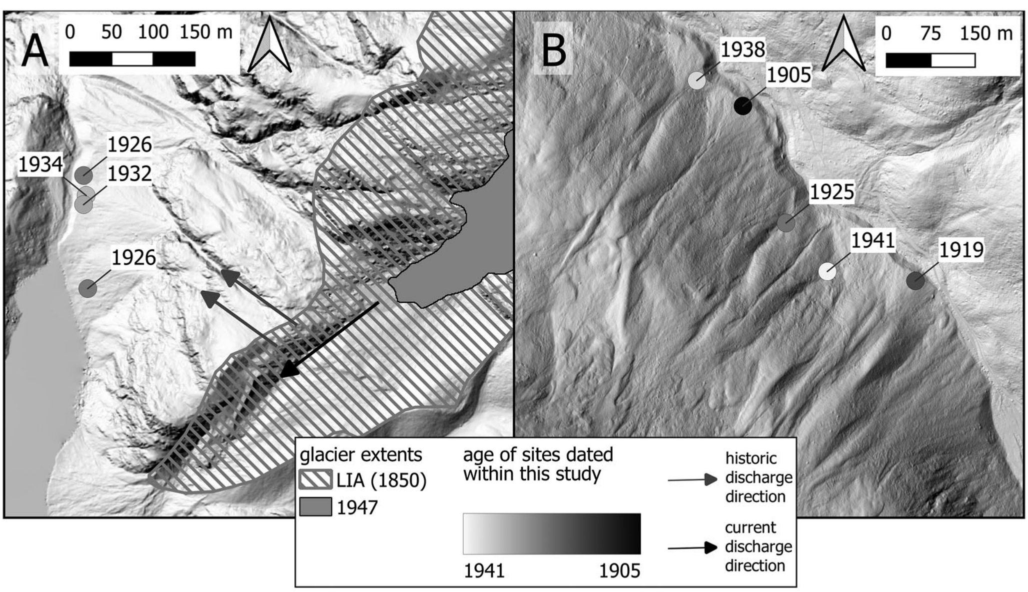

Figure 11. Lichenometric dates at locations where debris flow activity stopped. A: location in the Upper Grastal. B: location in the Lower Zwieselbachtal.

6. Conclusion

The aim of this study was to extend the existing record of extreme debris flow events in the Horlachtal back to about 1850. Because other dating methods are not applicable in the study area, we used lichenometry to date *Rhizocarpon* lichens on old debris flow accumulations. Due to the interval-censored ages of the reference locations, we chose a unique bootstrapping approach to calculate calibration curves. The used statistical method worked well for our data set. With the help of LOO cross validation in combination with 95% prediction intervals, we could show that the resulting model provides dates with an accuracy of about +/− 17 years and gives us the possibility to identify at least age clusters of debris flow deposits prior to 1947.

Using lichenometry, we are now able to get insights into the debris flow activity in Horlachtal prior to the first historical remote sensing data sets of that region. In combination with existing records of extreme events from 1947 to 2022, we can conclude the following main points:

(1) There is no evidence for a change in the frequency of extreme debris flow events in the Grastal and Zwieselbachtal since the end of the LIA.
(2) There are huge spatial differences in the detected extreme events. This implies that the heavy rainfall events that initiate debris flows can occur on a very local scale. Thus in order to investigate debris flow frequencies and triggering mechanisms in more detail, spatially and temporally high resoluted precipitation data are required.
(3) Lichenometry provides temporal information on the temporary cessation of debris flow activity at different locations in Grastal and Zwieselbachtal. However, it is still not completely clear as to why the activity stopped at these sites.

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