



Article Rock Glacier Kinematics in the Kaunertal, Ötztal Alps, Austria

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Abstract: The quantification of rock glacier kinematics on a regional basis has gained increasing importance in recent years. Here, we applied an image tracking approach on high-resolution aerial imagery to infer surface kinematics of 129 mapped rock glaciers in the Kaunertal, Austrian Alps. We find significant surface movement for 30 features with mean velocities falling between 0.11 and 0.29 m yr⁻¹ and a maximum of 1.7 m yr⁻¹. Local analysis and comparison to earlier studies reveals significant increases in rock glacier velocities in the study area. From the rock glacier inventory and high-resolution digital topography, we computed a series of morphometric parameters to analyze potential controls on rock glacier creep and to predict rock glacier activity using random forests and logistic regression models. The results point towards a stronger dependence of velocities on parameters describing general inclination, potentially acting as proxies for internal rock glacier properties, while activity states seem to be regulated mainly by rock glacier dimensions and topoclimate. Using a parameter subset, we successfully separated active from inactive rock glaciers with accuracies of up to 77.5%, indicating a promising approach to predict rock glacier activity solely relying on parameters that can be derived from regionally available data sets.

Keywords: rock glaciers; surface kinematics; feature tracking; morphometry; logistic regression; random forests; Austrian Alps

1. Introduction

Rock glaciers are globally prevalent features of creeping permafrost in the periglacial zones of high-latitude and high-altitude environments. Commonly, rock glaciers are described as lobate or tongue-shaped landforms containing composites of ice-rich sediments that move downslope in a creeping behavior under the effects of gravitational deformation [1]. As rock glaciers have been described both from a perspective of periglacial origin [2,3] and glacial origin [4], discussion on this issue has brought forth a range of genetic and morphological rock glacier definitions over the past few decades. Following an elaborate reflection on contrasting positions, Berthling (2011) [5] offers a universally applicable definition integrating both the influence of periglacial conditions on rock glacier creep behavior and the acknowledgement of different modes of origin. Berthling (2011) [5] defines active rock glaciers concisely as the "visible expression of cumulative deformation by long-term creep of ice-debris mixtures under permafrost conditions" [5]. In spite of the difficulties presented in finding a consistent definition of rock glaciers, their occurrence has been observed and documented globally in various high-latitude and high-altitude locations [2,3,6–8].

The basic principle behind the deformation inherent to permafrost bodies within rock glaciers is gravity-driven creep of the supersaturated debris-ice mixture. The majority of studies investigating rock glacier kinematics have, therefore, described their long-term steady-state creep by a viscous deformation law [2,3,9], following the observations by Glen (1955) [10] on the behavior of polycrystalline ice. These model assumptions were supported by several lab tests on the behavior of ice and debris-ice

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mixtures under varying stress and thermal conditions [11,12], and a handful of borehole deformation experiments on rock glaciers [13]. This rather simple model explains deformation rates mainly as a function of surface slope, thickness of the permafrost body, material density, and ice temperatures within the rock glacier. Further investigations, however, suspected much more complicated rheological modes, e.g., for warm permafrost temperatures [12,14], and potentially non-linear slope-dependencies in steep terrain with an increased likelihood of gelifluction and sliding processes [15]. Additionally, the effects of liquid water in shear horizons and at the permafrost base have been emphasized in multiple studies [16–18].

Commonly, a distinction is made between actively moving, inactive and relict (fossil) rock glaciers [19]. As intact rock glaciers, inactive features still contain interstitial (and excess) ice but show no signs of movement [20], which is limited either climatically or topographically [21]. The term intact comprises both active and inactive states. In relict rock glaciers, the ice is assumed to have melted out entirely, leaving behind a collapsed debris landform subject to erosional processes and vegetation succession [19]. Actively moving rock glaciers are a clear indication for permafrost conditions in high-altitude environments. Inactive rock glaciers might already have moved outside of permafrost conditions, bringing their movement to a halt.

The discrimination between different states of activity is complicated by continuous transitions during the landform evolution [22]. Therefore, solely relying on visual interpretations of surface morphology jeopardises classification accuracy and multi-temporal investigations of rock glacier evolution are necessary to draw decisive conclusions. This is why, in recent decades, the study of rock glacier kinematics has increasingly gained interest in high-alpine research [23–28]. Methodological approaches to assess rock glacier kinematics span a range of terrestrial methods (e.g., GPS surveys, geodetic analyses or terrestrial laser scanning approaches [26–29]) and remote sensing methods (e.g., photogrammetry or InSAR [30–34]). Most studies deploy a multi-methodological approach, combining a number of terrestrial and remote sensing systems [35,36].

Close monitoring of rock glacier kinematics is key to a comprehensive assessment of the landform's intrinsic processes and temporal evolution [37]. The rationale behind the investigations of rock glaciers is manifold: First, rock glaciers have been primarily studied as sensitive indicators for changes in ground temperatures due to the presence of permafrost. As rock glaciers are a common local proxy for lower limits of the distribution of discontinuous permafrost [38], information on their activity and kinematics can aid in understanding past, present, and future climate changes. Second, various studies published during the last decades attribute significant hydrological importance to their groundwater stores [39]. The insulating and damping properties of their debris cover make rock glaciers more resilient to changes in atmospheric conditions than their bare counterparts and potentially maintain these stores for a long time [39,40]. Furthermore, rock glaciers act as efficient sediment sinks and debris transport systems in high mountain sediment cascades [41–43] and provide direct evidence on permafrost degradation and related instabilities in debris-covered mountain slopes [17].

Therefore, the state of mountain permafrost has gained increasing attention in the debate focusing on climate change impacts in high-mountain regions. In this respect, rock glaciers have taken center stage, with many studies revolving around the quantification of rock glacier kinematics and their state of activity in high spatio-temporal resolution. What might control rock glacier activity and determine surface movement on a regional scale, however, has so far escaped scientific inquiry.

In this study, we investigate 129 rock glaciers in the Kaunertal in the Ötztal Alps of Western Austria. We aim to capture their surface kinematics and determine their state of activity using a motion-tracking approach on freely available aerial imagery. Using this data, we seek to identify potential controls on rock glacier activity and velocity from a series of geometric, topoclimatic and terrain parameters that were derived from digital topography. Using qualitative observations and data collected at one field site, we further shed light on permafrost degradation in the study area.

2. Study Area

Our regional survey is set in the Kaunertal, Austria; a central Alpine valley, characterized by a high density of intact rock glaciers (Figure 1) [20]. Forming part of the Ötztal Alps, the valley is drained by the river Fagge and covers a total surface area of 227.8 km², of which 9.1% (20.7 km²) are glaciated [44]. According to model calculations by Boeckli et al. (2012) [45], between ~33.9 and ~95.1 km² of the catchment area are underlain by permafrost in nearly all conditions and only in very favorable conditions, respectively. The study area is characterized by a typical dry high-alpine climate. At Weißsee meteorological station (2470 m a.s.l.), a mean annual air temperature (MAAT) of -0.17 °C and mean annual precipitation of 1000 mm to 1300 mm are recorded (2007–2018; data courtesy of Tiroler Wasserkraft AG (TIWAG)). Depending on elevation and aspect, winter snow cover can span a period from October to June. The catchment is located in the crystalline zone ('Altkristallin') of the Eastern European Alps, where the Austroalpine nappes are primarily made up of metamorphic rock. Paragneiss and orthogneiss are dominant, but amphibolite and mica-schist can be found sporadically [20,46]. The north-south oriented valley is characterized by a high topographic relief of more than 2500 m, covering an elevation range from 870 m a.s.l. at its outlet to 3535 m a.s.l. at the Hochvernagtspitze within a distance of around 30 km. More than 50% of the catchment is at elevations above the tree line (~2250 m a.s.l. [47]), where rugged bedrock topography and unconsolidated sediments in the form of talus slopes, moraines and rock glaciers dominate the landscape [48].



Figure 1. Distribution of intact and relict rock glaciers in the Kaunertal valley [49]. Rock glaciers are shown as colour-coded dots scaled to the planimetric size of individual landforms. Numbers indicate specific rock glaciers referred to in text and figures. Light blue, blue and dark blue areas show the mapped distribution of glaciers [44] and modeled coverage of permafrost occurrence in very favorable conditions and nearly all conditions [45], respectively.

A recently updated inventory comprises 129 rock glaciers [49], covering a total surface area of 8.25 km² equivalent to 3.6% of the total catchment size. The distribution of intact rock glaciers in the valley suggests permafrost occurrence reaches down to around 2270 m a.s.l. in favorable conditions on northern exposed slopes. The catchment features both ice-cemented rock glaciers [50] and rock glaciers with a core of massive ice of glacial origin [51]. Three of the valley's rock glaciers, Innere Ölgrube, Kaiserberg, and Riffeltal, have been the subject of earlier studies [50–53].

3. Materials and Methods

3.1. Rock Glacier Inventory

The creation of a standardized rock glacier inventory of Austria is still in progress, but many regional inventories are available [20,38,54,55]. We utilize a subset from an inventory of rock glacier polygons in Tyrol, as updated and compiled by Wagner et al. (in press) [49] from the results of previous studies. For this inventory, rock glaciers were delineated by identification of creep-related morphological characteristics in shaded high-resolution digital elevation models (DEMs) and aerial images. The inventory for the Kaunertal contains 129 rock glaciers, of which 104 have been classified as intact (6.96 km²), while the remaining 25 can be considered as relict (1.29 km²) (Figure 1). We acknowledge that rock glaciers classified as relict based on morphology alone may still contain substantial amounts of ice remains, as found in previous studies [21], and in-situ investigations are often necessary to provide reliable assessments. We relied on the outlines of intact rock glaciers to identify the regions of interest for our kinematic analysis. Where necessary, we corrected rock glacier outlines for alignment inaccuracies with the aerial imagery used here and for inventory creation.

3.2. Determining Horizontal Surface Movement Using Least Squares Matching

Environmental Motion Tracking (EMT) is a feature tracking software developed by Schwalbe [56] that uses a least squares matching approach (LSM) to track image features over monoscopic image sequences. LSM matches the location of image patches, i.e., rectangular windows, by minimizing the sum of squares of grey-value differences between image pairs [57]. Image patches are shifted in an iterative process around initially identified object points in a pre-defined search window (for details, see [58]). Additional radiometric and geometric matching techniques allow reducing distortions, such as illumination changes and slope deformations [59]. Algorithms like LSM have received increased attention in the study of surface deformation and mass movements due to the low financial expenses required, and the ability to monitor poorly accessible terrain by using unmanned aerial vehicles (UAV) or satellite imagery [59].

Here, EMT was utilized to track horizontal surface displacements of rock glaciers in image sequences of 4 (resp. 5) orthophotos with 0.2 m ground resolution (Table 1), acquired between 2001 and 2015 and made available by the government of Tyrol (Land Tirol). This data set was augmented by an unmanned aerial vehicle (UAV) flight campaign in 2018 at one field location to extend the observation period. Object points for tracking were regularly spaced within the rock glacier boundaries based on a 5 m grid. Image patch size was set to 100×100 pixels (400 m²), search window sizes were adapted individually. For further improvement of positional accuracies between images, mainly influenced by the quality of available DEMs for orthorectification of individual images, EMT includes additional algorithms to track fix point locations, i.e., stable points outside the moving features, alongside with the object points. Affine image transformations are then computed from potential fix point mismatches and used to correct tracked object point trajectories, ideally resulting in sub-pixel accuracies between image pairs [58]. Here, we placed fix points manually in surrounding stationary areas, mainly on exposed bedrock surfaces, where significant surface motion is unlikely (Figure S2). The accuracy of the motion correction was assessed by tracking an independent set of point locations on stable ground, correcting for mismatches between subsequent orthophotos using affine image transformation and quantifying the remaining residuals. These then served as a level of detection (LoD) measure (Table S1).

Period	Acquisition	Ground Resolution	Coverage of Inventory	
	2001-09-03		39,994 m ²	0.5%
2001–2003	2003-07-19	0.2 m *	1,795,254 m ²	23.3%
	2003-09-05		5,884,029 m ²	76.2%
2005–2009	2005-09-06		39,994 m ²	0.5%
	2007-09-24	0.2 m *	1,996,841 m ²	25.9%
	2009-09-08		1,338,780 m ²	17.3%
	2009-09-09		4,343,662 m ²	56.3%
2010	2010-07-31	0.2 *	5,135,343 m ²	66.5%
	2010-09-20	0.2 m	2,583,934 m ²	33.5%
2015	2015-08-03		2,495,913 m ²	32.3%
	2015-08-26	0.2 m *	1,622,088 m ²	21.0%
	2015-08-27		3,547,282 m ²	46.0%
	2015-08-28		53,994 m ²	0.7%
2018	2018-09-28	0.05 m ⁺	126,002 m ²	1.6%

Table 1. Available aerial imagery for the Kaunertal rock glaciers between 2001 and 2018. Coverage is given in m^2 and as a percentage share of the rock glacier inventory.

^{*} Orthoimagery provided by the government of Tyrol (Land Tirol). [†] SfM-MVS derived orthophoto of the Kaiserberg rock glacier (RG12) from acquisition using a UAV-System.

To reduce potential errors from matching image patches using EMT, we applied several neighborhood filters on the resulting object point trajectories. A combination of displacement bearing and magnitude filters around object points provided satisfying tools for error removal while keeping a maximum amount of information per feature. Circular variance $Var(\theta)$ for a number *n* of unit vectors with bearings $\theta_1, \theta_2, \ldots, \theta_n$ is given by:

$$Var(\theta) = 1 - \frac{R}{n} , \qquad (1)$$

where *R* is the length of the resultant vector, calculated by:

$$R = \sqrt{\left(\sum_{i=1}^{n} \cos\theta_i\right)^2 + \left(\sum_{i=1}^{n} \sin\theta_i\right)^2}.$$
(2)

Equations (2) and (3) were implemented using a 3×3 neighborhood filter with an arbitrary threshold set to 0.5. Additionally, deviations from the mean bearing $\overline{\theta}$ exceeding 45° in a 5×5 neighborhood were discarded. Deviations were calculated by:

$$\Delta \theta = 180 - \left\| \theta_i - \overline{\theta} \right\| - 180 \right|, \tag{3}$$

in which θ_i is the bearing at the focal point, and the mean bearing $\overline{\theta}$ is given by:

$$\overline{\theta} = atan2 \left(\frac{1}{n} \sum_{i=1}^{n} sin\theta_i , \frac{1}{n} \sum_{i=1}^{n} cos\theta_i \right).$$
(4)

Similarly, deviations from mean velocities in a 5×5 neighborhood were used to exclude erroneous trajectories. On average, around 75% of tracked object points on active rock glaciers provided consistent velocity estimates after filtering for errors.

From these, annual rates of displacements were calculated using the exact acquisition dates of aerial imagery for both, origin and endpoint of each trajectory, yielding time series of rock glacier velocities resolved at one- to five-year intervals. However, as acquisition dates of the aerial imagery show high inter-annual differences (Table 1), annual displacement rates were finally calculated over the entire observed period, i.e., from 2001 resp. 2003 to 2015. This allows for a more robust averaging of velocities and circumvents skewed estimates owed to large differences in epoch lengths.

3.3. Statistical Analysis of Kinematics-Morphometry Relations

We computed a series of candidate parameters to evaluate their potential relationships to rock glacier activity and surface kinematics. The selection of parameters was guided by an extensive review of previous studies on rock glacier kinematics that found potential influences and associations from field observations and/or lab experiments (Table 2, Figure 2). Calculation of candidate parameters is based on rock glacier polygons and a LiDAR DEM with 5 m ground resolution, acquired in 2010 and made available by the government of Tyrol (Land Tirol). From this DEM, we also extracted statistics for the rock glacier feeder basin and headwall area, which we define here as the contributing area delivering water, snow and debris to the rock glacier, and the subset of this (i.e., headwall) having inclinations exceeding 30° , respectively (Figure 2). For this calculation, all pixels above the 25^{th} elevation percentile within each rock glacier polygon were used as pour points. Following Heim (1932) [60], we define the slope of the line between the highest point of this source rock wall to the distal margin of the rock glacier body as the geometric slope (Φ_{GSL}).



Figure 2. Overview of geometric candidate parameters used for analysis. See Table 2 for abbreviations.

Assessment of morphometric controls on horizontal surface velocities was carried out using iteratively reweighted least squares (IRLS) regressions with a bisquare weight function. IRLS is a robust regression technique, iteratively adjusting weights in heteroscedastic data to reduce the influence of outliers [61]. Herein, we investigated linkages to various velocity ranges per rock glacier using percentiles of the measured values (25th, 50th, 75th, and 95th percentiles as well as absolute maximum velocities).

Group

Geometry

Morphology

Terrain

Feeder basin

Headwall

Max. elevation

Min. elevation * ⁺

N-exposedness 4

E-exposedness 4 *

Mean PISR * [†]

Height *

Area²*

Slope *

Geometric slope *

Height

Area²

Emin

E_{max}

H_{FB}

A_{FB}

 Φ_{FB}

 Φ_{GSL}

H_{HW}

A_{HW}

Parameter	Abbreviation	Unit	Source	Association	References
Length ¹ * [†]	L _{RG}	m	RGI	Age	[62]
Width 1 * †	W _{RG}	m	RGI	Thickening/thinning	[63]
Surface Area ² *	A _{RG}	km ²	DEM RGI	Yield stresses	
Height * [†]	H _{RG}	m	DEM		
Riser height ¹ * [†]	$H_{\rm F}$	m	DEM	Thickness	[64,65]
Surface slope * [†]	$\Phi_{ m RG}$	o	DEM	Shear stress PISR Snow distribution	[64]
Profile curvature * † Plan curvature * †		-		Compression/extension Subsidence Runoff characteristics	[3,22,66]
Surface roughness ³		-		Grain size distribution	[65,67]

DEM

DEM ⁵

DEM

DEM⁵

MAAT

Permafrost distribution

Potential energy Radiation

Age

Snow distribution

MAGST

Liquid water supply

Snow & avalanche input

Runoff characteristics

Liquid water supply

Debris supply

[68-70]

[71,72]

[69,70,73]

[62]

[62,74-77]

Table 2. Potential geometric, morphometric and topoclimatic parameters controlling rock glacier activity and surface velocities. All parameters are derived from a 5 m digital elevation model (DEM) and the polygon-based r

	Slope * †	$\Phi_{\rm HW}$	0	DEM	11.7		1
¹ Parameters man	ually delineated (p	animetric len	gth and wid	lth, riser height as ma	aximum elevatio	n differen	ice
between top and for	oot of riser). ² Slope-	corrected surfa	ice area aftei	² Jenness (2004) [78]. ³	Surface roughnes	s calculat	ed
as the difference be	etween the minimun	n and maximu	m elevation	in a 3 × 3 neighborhoo	od around the foc	al point [7	'9].
⁴ North-exposedr	ness as the cosine of	slope aspect,	east-expos	edness as the sine of	slope aspect. ⁵ l	DEM-filli	ng
algorithm by Wang	g and Liu (2006) [<mark>80</mark>]	. * Parameters	used in the	logistic regression and	d random forest c	lassification	on
models. ⁺ Parame	ter subset after step	vise backward	ls variable s	election using AIC.			

m a.s.l.

kWh m⁻²

yr⁻¹

m

km²

0

0

m km²

3.4. Modeling Rock Glacier Activity

Rock glacier activity can be modeled as a binary categorical variable differentiating the actively moving state from the stagnant or inactive state. The individual LoDs determined for each specimen were used as thresholds to separate active rock glaciers, (surface displacement exceeding LoD) from inactive forms (surface displacement falling below LoD). We acknowledge here that rock glaciers with surface displacement below the LoD of our analysis might still experience movement resolvable at higher precision. Multiple statistical approaches deal with the prediction of binary outcome variables based on a set of continuous and/or categorical predictors. We apply logistic regression and random forest classification to compare the effects of linear relations and threshold conditions. Both approaches have been used in a variety of geomorphological studies and proved especially promising for the modeling of rock glacier distribution [81] and rock glacier activity [82].

Logistic regression is a parametric technique like linear regression, that estimates the probability of the class membership (active/inactive) as a logistic function of explanatory variables of the form

$$\log\left(\frac{p(X)}{1-p(X)}\right) = \beta_0 + \beta_1 X_1 + \ldots + \beta_n X_n,\tag{5}$$

in which p(X) is the probability to be estimated and X_1, \ldots, X_n are independent variables. The coefficients β_1, \ldots, β_n are fit using a maximum likelihood approach, the resulting expression to the left is called the 'log-odds' of X [83]. The probability cut-off for predicting either one of the class memberships of an observation is typically held at p(X) = 0.5. The performance of the logistic models and of univariate discriminatory power of each parameter were compared by means of Akaike's Information Criterion (AIC) [84]. Using this performance measure, we built a parameter subset utilising a stepwise backwards variable selection procedure. To achieve this, reduced models were iteratively compared until the model with the lowest AIC score was found.

Random forest classification is a machine learning approach developed by Breiman (2001) [85] that is based on the idea of decision trees. In random forests, multiple trees are grown simultaneously, while the variable selection at each node is based on a random subset of predictors. Averaging the predictions of multiple trees generally leads to a more robust model. Variable importance within random forests was assessed by comparing the mean decrease in Gini index *G*, defined as

$$G = \sum_{k=1}^{k} \hat{p}_{mk} (1 - \hat{p}_{mk}), \tag{6}$$

where \hat{p}_{mk} is the proportion of observations in class *k* at a node *m* to the total number of observations in this class. If \hat{p}_{mk} approaches 1, *G* becomes indefinitely small and reaches zero for $\hat{p}_{mk} = 1$ (a pure node). The quality of splits performed by each parameter can thus be quantified by the total decrease in Gini over all splits and trees.

We start out by applying a univariate logistic regression analysis to identify those parameters with significant discriminatory power. We then proceed to use both a complete dataset and the subset from stepwise backwards variable selection to predict the probability of significant surface movement with both logistic regression and random forest classification. As the initial number of observations is low (n = 104), splitting the dataset multiple times into a reasonable ratio of training to testing data before training the model on each subset and finally averaging the predictions, can lead to a more robust model. Here, both models were trained 100 times, each time splitting the dataset into 80% for training and 20% for testing. The resulting predictions were then averaged. Comparison of the predictive models was done with the classifier performance statistic AUC (Area Under the receiver operating characteristic (ROC) Curve), which falls between 0 and 1 [86]. Models with AUCs above 0.7 usually present 'acceptable' discrimination, AUCs above 0.8 show 'excellent' discriminatory power [83].

Logistic regression models are expectedly more responsive to linear relationships between activity states and predictors, while the decision trees in random forest classification respond better to non-linearities and clear separations of active and inactive observations within these predictors and are unable to map such linear responses.

4. Results

4.1. Horizontal Surface Velocities and Spatial Variability

Using EMT, we photogrammetrically derived horizontal surface displacements of 104 intact rock glaciers in the Kaunertal for three epochs between 2001 resp. 2003 and 2015. Our results reveal significant surface movement (i.e., above LoD) for 30 of these rock glaciers throughout the observation period that were thus classified as active (Figure 3 and Figure S1). For the remaining intact rock glaciers, displacements remained below LoD, leaving 74 landforms as inactive. On average, the motion tracking approach showed LoDs of 1.17 px between image pairs, with extremes ranging between 0.27 and 5.54 px (Table S1), leaving smaller changes undetectable. In addition to errors associated with orthoimage referencing, dense snow blankets and cloud coverage during image acquisition limited the tracking capabilities in a few cases.



Figure 3. Horizontal surface velocities of 30 active rock glaciers, averaged over the entire observation period (2001 resp. 2003 to 2015). Values are shown as percentiles to illustrate the heterogeneity of rock glacier velocity fields (see Figure 1 for the location of rock glaciers).

Average horizontal velocities of active rock glaciers in the Kaunertal fall between $0.11-0.29 \text{ m yr}^{-1}$ (IQR; 2001/2003 to 2015). Maximum velocities are in the range of $0.31-0.81 \text{ m yr}^{-1}$ (IQR), with peaks reaching up to 1.77 m yr^{-1} at Innere Ölgrube and 1.52 m yr^{-1} at the Kaiserberg rock glacier, averaged over the entire observation period (Figure 3). Even the slowest rock glaciers still showed velocities exceeding 0.10 m yr^{-1} . Our data show that flow directions between due West and North-East predominate, with only a few exceptions flowing southwardly.

Creep rates show marginally lower values during the earlier interval of the observed period, i.e. between 2001/2003 and 2009 when compared to the latest measurements between 2010 and 2015. Both lower and upper quartiles show a velocity increase of roughly half a centimetre per year, from 0.040 to 0.044 m yr⁻¹ and 0.168 to 0.176 m yr⁻¹ respectively. However, we must refrain from reasoning a significant trend from the limited time series.

Most of the features show heterogeneous velocity fields, reflecting the compound structure of rock glaciers composed from overriding and adjoining lobes. In this case, a percentile-based analysis of velocities is preferred over relying on simple arithmetic means. Generally, the highest creep rates are predominantly observed in central parts of rock glaciers, located either towards the front or on secondary lobes or tongues further upslope in the case of complex features (Figure 4). In these areas, velocities are around four times higher compared to the remaining part. Deformation rates decrease significantly towards the rock glacier fringe and root zone.

In the absence of extensive ground-truthing observations, we relied on published measurements from preceding Differential GPS (DGPS) surveys on the Innere Ölgrube and Kaiserberg rock glaciers (2000/2002 to 2005; [50]) as well as the Riffeltal rock glacier(s) (2006 to 2012; [53]) to qualitatively compare our results against. Together with direct ground truthing using repeated DGPS surveys on the Kaiserberg rock glacier, though covering a different time interval (2018 to 2019), we could confirm both magnitudes and patterns of the displacements determined by the feature-tracking approach (Figure S2).



Figure 4. Horizontal surface velocity fields of selected rock glaciers: (**A**) Innere Ölgrube rock glacier (RG18), (**B**) Kaiserberg rock glacier (RG12) and (**C**) unnamed rock glacier RG14.

4.2. Rock Glacier Characteristics and Distributional Patterns

The Kaunertal rock glaciers cover planimetric areas between 0.02 km² and 0.08 km² (IQR), ranging from 0.003 km² to 0.4 km², while east- and west-exposed features show the largest dimensions. The distribution of rock glaciers and their thermal states in the superordinate mountain range are believed to be a function of geological, lithological and climatic parameters [20]. We find that the Kaunertal rock glaciers show clear patterns regarding elevation and aspect (Figure 5). With elevation, they follow a bell-shaped distribution, peaking between 2500–2600 m a.s.l. and decreasing towards the upper and lower elevation limits of 3130 and 2095 m a.s.l., respectively, covering a total vertical elevation range of ~1000 m. Rock glacier size decreases significantly with altitude, as revealed by quantile regression of the 50th and 75th percentile of the distribution. The occurrence of relict rock glaciers reaches its upper boundary at 2776 m a.s.l., while intact features are not found below 2269 m a.s.l.. Discrimination between relict and intact rock glaciers, therefore, suggests a simple altitudinal gradient. Active rock glaciers (i.e., with displacements above LoD) are situated at elevations between 2343 and 2821 m a.s.l. and peak in numbers between 2500 and 2600 m a.s.l. The differentiation from inactive features is not as distinct.

Regarding aspect, east-exposed rock glaciers predominate in numbers (n = 39) and surface area share (>30%), which is probably owed to the larger size of western tributaries over their eastern counterparts (Figures 1 and 5). Active rock glaciers prevail in eastern and western aspects and are nearly absent on south exposed slopes where solar insulation is at its highest.



Figure 5. Distribution of active, inactive and relict rock glaciers in the Kaunertal catchment, shown as (**A**) absolute numbers and (**B**) percentage share of the total surface area. Upper panel groups rock glaciers in four aspect classes (North, East, South, West), lower panel shows rock glaciers dissolved for elevation bins of 100 m.

4.3. Statistical Analysis of Potential Controls on Rock Glacier Kinematics

4.3.1. Controls on Surface Velocities

Assessment of linear relationships between creep velocities and non-transformed terrain parameters was done using IRLS regression (Table 3). Creep velocities for each feature were broken down as percentiles and analyzed separately for the 25th, 50th, 75th, and 95th percentile and the absolute maximum values.

Table 3. \mathbb{R}^2 -values for iteratively reweighted least squares (IRLS) regression on selected parameters for different percentiles of velocity distribution. Values are only given for slope coefficients significantly different from zero (*p*-value ≤ 0.05). The direction of correlation is indicated in parentheses.

	Velocity Percentiles					
Parameters	25 th	50 th	75 th	95 th	Maximum	
RG east exposedness	0.38 (-)**	0.18 (-)				
RG slope	0.19 (+)	0.16 (+)	0.21 (+)	0.43 (+)	0.26 (+)*	
RG riser height			0.14 (+)	0.21 (+)	0.25 (+)*	
RG height	0.19 (+)					
RG roughness	0.22 (+)*	0.19 (+)	0.19 (+)	0.30 (+)*	0.20 (+)	
FB area				0.16 (+)		
FB height	0.14 (+)					
FB slope	0.25 (+)*	0.16 (+)	0.14 (+)	0.24 (+)*	0.28 (+)**	
Geometric slope	0.31 (+)*	0.27 (+)*	0.32 (+)*	0.30 (+)*	0.35 (+)**	
HW area				0.15 (+)		
HW slope	0.35 (+)**	0.40 (+)**			0.28 (+)*	

* *p*-value ≤ 0.01 ; ** *p*-value ≤ 0.001 .

Overall, the statistical relationship between rock glacier surface velocities and the investigated parameters (Table 2) is weak to moderate: ten out of the 21 analyzed parameters yield significant relationships to selected velocity percentiles, yet we stress here that collinearities exist between analyzed parameters and they can only be used interchangeably. Most parameters show positive relations to rock glacier movement, while only the topoclimatic parameter east-exposedness yields

a significant negative fit for the 25th and 50th percentile of velocity data (Table 3). The analysis of catchment parameters against surface velocities yields most of the detected significant fits. In turn, elevation-based parameters and geometric descriptors of the rock glacier body hardly show significant relationships, with the exception of the rock glacier height and rock glacier riser height that show significant positive trends for the 25th percentile and 75th and 95th percentiles and the maximum, respectively. Four parameters exhibit significant positive trends for all velocity percentiles, further two parameters are significant for three out of five velocity percentiles (Table 3, Figure 6), though R²-values generally remain below 0.5. Feeder basin slope and geometric slope both are significant for all velocity ranges and have R²-values of 0.14 to 0.28 and 0.27 to 0.35, respectively. The median surface slope of the rock glacier, also significant for all velocity ranges, shows the strongest correlation of rock glacier derived parameters with coefficients between 0.16 and 0.43.



Figure 6. Scatterplots of horizontal surface velocities versus selected candidate parameters derived for individual rock glaciers and their contributing areas. Colour coded points represent velocity percentiles for each individual active rock glacier (n = 30), solid lines show significant ($p \le 0.05$) iteratively reweighted least squares (IRLS) regression lines.

4.3.2. Controls on Rock Glacier Activity

Candidate parameters were used as input variables for univariate logistic regression models to assess their individual discriminatory power to separate active from inactive rock glaciers. The resulting models were then compared using Akaike's Information Criterion (AIC). Three fits were evaluated: (1) linear fits, (2) logarithmic fits and (3) polynomial fits with two degrees of freedom. In general, geometric parameters which describe area or length specifications and cluster active rock glacier observations towards either end of the spectrum, respond best to log-transformations. Where active rock glaciers are found in narrow parameter space (e.g., elevation boundaries, potential incoming solar radiation (PISR) or surface slope) or clumped at both ends of the spectrum (e.g., east-exposedness), polynomial fits performed best. Nine out of 21 parameters show significant in-sample discriminatory power (Figure 7).



Figure 7. Conditional density distributions of rock glacier activity in relation to selected terrain parameters. Yellow and red areas correspond to conditional densities of active and inactive features, respectively; black points represent observations. Black lines and shaded areas show probability predictions and 95% confidence intervals from binary logistic regressions with either (A) logarithmic transforms or (B) polynomial transforms (two degrees of freedom) of the predictor. Only significant links ($p \le 0.05$) are shown.

Model comparison of significant correlations (p < 0.05) shows that the best discrimination of active and inactive rock glaciers is achieved by parameters describing rock glacier geometry, showing the lowest AIC scores for rock glacier height (difference between maximum and minimum elevation), which yields a strong performance gap towards other parameters. Feature length, surface area and riser height are ranked comparably high and distinguish activity states similarly well. Topoclimatic parameters show average discriminatory power, of which mean PISR performs best. Lowest in-sample performances are associated with slope aspect (east-exposedness) and minimum rock glacier elevation, while parameters on feeder basin geometry perform slightly better, with basin height and surface area yielding statistically significant fits.

Out-of-sample performance, determined by repeatedly running univariate logistic regression (LR) models with random training and testing subsets (ratio of 80% to 20% respectively), shows that the classification accuracy of individual parameters is rather low. We achieve accuracies averaging 27.6% and find a variable ranking rather dissimilar from in-sample testing. Feeder basin height performs best with an average accuracy of 34.5%, while rock glacier height and length achieve the lowest accuracies (21.7% and 24.4% respectively). The low out-of-sample discriminatory power of univariate

predictors suggests the value of using multiple independent variables in the prediction of rock glacier activity states.

4.4. Modeling Rock Glacier Activity

Using selected geometric, topographic, and climatic candidate parameters, we were able to predict rock glacier activity in the Kaunertal with an overall accuracy of up to 77.5% (AUC = 0.84), improving the highest baseline accuracy, i.e., always predicting the most frequently occurring class, by 6.3%. We prepended a collinearity analysis to remove strong pair-wise correlations between the predictors, reducing the number of parameters from 21 to 16 (Table 2). On the whole, logistic regression models (LR) outperformed random forest classification (RF) in discriminating active from inactive rock glaciers. In LR, the parameter subset increased the AUC to 0.84 compared to 0.75 for the full parameter set (Figure 8). The same subset also improved classification accuracies of the RF model, though only from an AUC of 0.80 to 0.83. We further tested RF and LR on principal components of the reduced parameter set. However, the preceding principal component analysis does not improve the performance of the RF and LR models, yielding AUCs of 0.71 and 0.75, respectively.



Figure 8. Receiver operation characteristic (ROC) curves for random forest (RF) and logistic regression (LR) models on rock glacier activity, based on either a full parameter set or a parameter subset (noted in subscript, see Table 2). Model performance metrics are given as the area under the ROC curve (AUC). TPR = true positive rate; FPR = false positive rate.

Determining an active rock glacier state generally seems more challenging throughout all investigated models, and their average classification errors are found substantially higher than those for inactive features (0.51 vs. 0.14). For active rock glaciers, LR shows better performance overall, with the reduced parameter set achieving accuracies of 60%, while the reduced RF model is accurate to only 55%. For inactive rock glaciers, however, RF shows better performance and scores average classification accuracies of 88% with the reduced parameter set. The general oddity of higher accuracies when predicting inactive features, regardless of LR or RF, can be explained by the class imbalance of the dataset (30 active vs. 74 inactive features). Baseline accuracies of each class amount to 29% and 71%, respectively.

Variable importance analysis of the RF models revealed similar parameter performance as univariate LR models (Figure 9). Again, rock glacier height leads the scoreboard with a notable gap to other parameters and other geometric descriptors of rock glacier dimensions stand out as top performers, including parameters on feeder basin and headwall geometry and morphology. Topoclimatic parameters show varying performance scores, with mean PISR in position as the second-best discriminator. Although decision trees would respond better to thresholds conditions, like elevation limits or surface slope, than to (quasi-)linear relations with e.g., geometric measures, we did not observe such qualities herein.



Figure 9. Variable importance within random forest classification models of rock glacier activity, shown as mean decrease in Gini coefficient. Results are shown for models derived from full parameter set (green lines and points) and parameter subset (blue lines and triangles), respectively. Note that the mean decrease in Gini coefficient is a relative measure and values are not comparable between the two models. Abbreviations are: RG = rock glacier, FB = Feeder basin, HW = headwall.

5. Discussions

5.1. Rock Glacier Activity, Velocity And Degradation

Applying a feature tracking algorithm to available high-resolution optical imagery, we were able to quantitatively separate 30 actively moving rock glaciers from their inactive counterparts. Alongside available studies that investigate rock glacier activity on a regional basis using differential InSAR [87,88], we build upon the few available studies that applied basin-scale quantifications of horizontal surface velocities using optical feature tracking [34,89]. Depending on, among others, ground resolution and capture interval of the available imagery, this technique has limitations resolving seasonal variability in surface movement. However, image pre-processing, computational requirements and a straightforward workflow [58] are distinct advantages over InSAR applications. Furthermore, the potential to use historic aerial imagery offers the possibility to extend the observation period to several decades.

The active rock glaciers in the Kaunertal catchment show decadal average surface velocities of several decimetres per year, which is in line with other findings from the European Alps [3,18,27]. Direct quantitative comparison to other studies proves difficult, as the applied methodologies to calculate average velocities are often elusive and the spatial and temporal resolution at which rock glaciers are monitored incorporate inter- and intra-annual velocity fluctuations. Nonetheless, previous reports on rock glacier kinematics in the Kaunertal revealed comparable displacements [50,53,90]. Furthermore, the marginal increase in surface velocities revealed by our data is also in agreement with earlier studies from the Alps (see e.g., [50,91,92] or [93]) that mostly attribute rock glacier acceleration to warming air temperatures and its effect on ice temperature, snow cover duration, and the availability of liquid water. At the Kaiserberg rock glacier, where we collected UAV-derived imagery in September 2018 to further extend the observation period, we observe a slight but significant increase in surface

velocities of the southern lobe that coincides with increasing air temperatures over the past 15 years (Figure 10). Judging from a comparison with the earliest measurements on the Innere Ölgrube rock glacier that found maximum average velocities of 0.75 m yr⁻¹ between 1938 and 1957, surface velocities more than doubled over the past 65 years [94] (Figures 3 and 4).



Figure 10. Horizontal surface velocities on the southern lobe of the Kaiserberg rock glacier (RG12) (upper panel) in relation to deviations in mean annual air temperature (MAAT) from mean over entire time-series (lower panel). Average rock glacier velocities were tracked in image-pairs from airplane survey flights for the epochs 2003 to 2010 and 2010 to 2015 (dark green) and in a combination of airplane survey data and UAV-derived imagery for 2015 to 2018 (dark red), respectively. Air temperature is shown as the deviation from MAAT over the entire observation period of the respective station; data from Weißsee meteorological station, Kaunertal courtesy of Tiroler Wasserkraft AG (TIWAG) and data from Obergurgl meteorological station, Ötztal courtesy of Zentralanstalt für Meteorologie und Geodynamik (ZAMG).

Some rock glaciers in the catchment show a stagnant front and upslope sections with considerably higher velocities, resulting in compressional zones with pronounced ridge and furrow systems that develop in front of the faster moving ice-debris mixtures, and a relatively flat extension zone trailing behind (Figure 4). Destabilization phenomena such as scarps and cracks, as effects of sharp contrasts in surface deformations [16,95], were only identified in the steeper eastern lobe of the Kaiserberg rock glacier (RG12), where considerably higher surface velocities cause an extensive creep behavior and the formation of transversal depressions. Noticeable shear zones are formed where fields of high and low deformation rates are located directly adjacent to another (Figure 4).

No exceptionally high surface velocities of several metres per year, nor dramatic acceleration or collapse of rock glacier fronts that would point to advanced permafrost degradation [16,96] were observed in the Kaunertal. However, the development of a thermokarst lake on RG08 at around 2700 m a.s.l. indicated the occurrence of subsidence effects (Figure S3). To further shed light on permafrost degradation in the study area, we carried out a case study on the Kaiserberg rock glacier (RG12), where we acquired a high-resolution DEM (0.05 m ground resolution) in September 2018 by means of Structure-from-Motion (SfM) [97] using a UAV platform. In combination with LiDAR DEMs provided by the government of Tyrol for the years 2006 and 2010, we could evaluate and quantify changes in surface elevation over time (Figure 11). We detect an overall volume loss on the order of 2×10^3 m³ yr⁻¹ during both periods (LoDs amount to ±0.36 m and ±0.30 m respectively), with most of the subsidence observed between transverse ridges and on an extensive area in the upper part of the tread, where the transition between riser and root zone becomes increasingly concave over time (Figure 11). This points towards thaw settlement by melt out of excess ice and a limited debris supply from the talus above.





Destabilization phenomena due to highly heterogeneous velocity fields are not immediately evident on the rock glaciers in the catchment. Noticeable, however, are the rock glaciers Kaiserberg (RG12) and Innere Ölgrube (RG18), where horizontal velocities of adjacent lobes are highly variable, locally exceeding 1 m yr⁻¹, resulting in the formation of longitudinal and transversal cracks on the rock glacier surface. Geophysical measurements suggest the presence of ice-rich permafrost of 20–30 m thickness with volumetric ice-contents between 40%–60% for both of these rock glaciers [90], potentially explaining elevated velocities. Nonetheless, the influence of local effects, such as preferential meltwater pathways and underlying topography might also come into play.

Rockfall activity at the margins was noticed for most of the rock glaciers with active frontal lobes, showing erosional patterns at the top of the riser and accumulation close to the foot (Figure 11). However, the runouts and associated risks are expectedly small due to the low slope inclination of the forefield. Where fronts are advancing relatively slowly (~0.05 m a⁻¹), rockfall occurrence is much more limited and a pronounced vegetation cover can be observed on the face of the riser.

5.2. What Controls Rock Glacier Kinematics in the Kaunertal?

Our study seeks to identify a set of geometric, morphometric and topoclimatic parameters controlling rock glacier kinematics, enabling us to predict rock glacier activity in a regional context. Yet, these parameters are surrogates associated with material composition, internal structure, debris and snow supply, presence of liquid water and further local influences. We therefore acknowledge that the control of these non-morphometric properties on rock glacier activity and surface kinematics might exceed the predictive power of parameters analyzed here. However, in a regional context, local parameters are not available for the entire assemblage of rock glacier landforms. Thus, we rely on

candidate predictors that encapsulate a number of local parameters and can be derived from freely available and regionally harmonized data sets.

5.2.1. Towards Morphometrically Explaining Rock Glacier Velocities

Linear analysis between rock glacier velocity percentiles and candidate predictors reveal significant correlations for five out of 14 parameters derived for the rock glacier outline and five out of six parameters calculated for the feeder basin, respectively (Tables 2 and 3). Furthermore, the geometric slope, combining geometric information from feeder basin and rock glacier, yields the most robust correlation found with R^2 -values between 0.27 and 0.35 and *p*-values of < 0.01 for all percentiles (Figure 6). We take from these results that feeder basin properties, such as average slope, area and elevation range, constitute reliable parameters to explain surface velocity variations in our study area. Potentially influenced by the presence of liquid water, these rock glaciers may exhibit accelerated creep velocities due to thermal heat fluxes and reduced friction in the shear zone [13,17,73,75].

We further find significant relationships between surface slope and surface roughness with velocity percentiles; clearly, both parameters are highly collinear. Together with the rather weak R² values of links between riser height and velocities (≤ 0.25 , p < 0.05), this implies that stress control on the Kaunertal rock glaciers might not be as important as the forcing by other parameters, such as ice content and temperatures (see e.g., [70]). Overall, the explained variance in our data is only moderate, with values generally falling between 14% and 43%.

Parameters that serve as surrogates for air-, ground- and permafrost temperatures, such as slope aspect, elevation boundaries and PISR do not show a strong correlation with velocity percentiles, despite the fact that a positive relationship between deformation rates and ground temperatures has been shown in borehole measurements by Arenson et al. (2002) [13] and experiments on ice samples by Paterson (1994) [98] and Moore (2014) [12]. Surface velocities slightly decrease with PISR and increase with rock glacier elevation boundaries, though IRLS regression is non-significant for all percentiles. We find relatively high PISR in combination with small rock glacier dimensions and a strong south-exposedness, suggesting thin permafrost thicknesses and/or low ice contents, potentially explaining reduced velocities with higher incoming radiation. Effects of varying solar radiation on rock glacier velocities have been reported before [69,70] and are not only attributed to direct energy input, but also to snow distribution and meltwater availability during the summer months [71].

Mean annual ground temperatures approaching the melting point of ice [99] could accelerate rock glacier deformation rates [13], as might be the case for the Kaiserberg rock glacier in our study area. However, inferring such thermal controls from morphometric parameters alone proves unfeasible.

5.2.2. Predicting Rock Glacier Activity in the Kaunertal

Using a LR model on a subset of 16 parameters, we are able to predict rock glacier activity in the Kaunertal with an overall accuracy of 77.5% (AUC = 0.84). Compared to earlier studies that predict the location of intact rock glaciers based on morphometric parameters [81], our model performs equally well. Applying a RF model to the same subset of data achieves similar performance (AUC = 0.83), while both, LR and RF classification accuracies fall behind when using the full parameter set. Interestingly, parameters derived from rock glacier dimensions consistently yielded the best performance scores for activity discrimination in univariate LR and the multivariate RF model, while feeder-basin measures that are strong in explaining surface velocities, show less explanatory power in this regard. Especially rock glacier height performs well in the distinction and highlights an observable threshold at around 100 m (Figures 7 and 9), below which topographic relief might be too small to overcome yield stress imposed upon the debris-ice mixture. However, mapping of the upper rock glacier boundaries is sensitive to operator bias. We therefore carefully checked rock glacier polygons and used a conservative delineation of upper boundaries.

PISR, as a proxy for energy balance at the rock glacier surface and energy fluxes into the ground [65], was observed as one of the best in-sample discriminators between activity states and scored second in

RF variable importance (Figures 7 and 9). The relationship seems to show a condition where inactive rock glaciers dominate above an arbitrary PISR threshold, although the separation between the classes is not very distinct (Figure 7). For slope aspect which also correlates with PISR, we find a significant connection to rock glacier activity, with most active rock glaciers exposed towards northeast and northwest. This is also reflected by the high performance of north- and east-exposedness in univariate LR and east-exposedness in RF variable importance. Furthermore, besides rock glacier length and surface area that prove to be good discriminators for activity states, riser height, as a rough proxy for the permafrost thickness shows a potentially strong influence of stress control on rock glacier activity, although the relationship between riser height and permafrost thickness strongly depends on the underlying topography [3]. Nonetheless, this notion is supported by statistically significant correlations between surface velocity percentiles and riser height.

Parameters derived for rock glacier feeder basins, namely height, slope, and size, as well as the slope of the rock glacier headwall are only of minor importance in discriminating between active and inactive rock glaciers in the study area. Notably, the geometric slope that showed the most robust correlation to surface velocities only contributes marginally to the classification of states of activity.

In more general terms, rock glacier activity displays an upper elevation threshold in the Kaunertal, where no active rock glaciers are found above 2900 m a.s.l. (Figure 7). We attribute this mainly to decreasing feature and feeder basin sizes with elevation, which approximate rock glacier volumes that determine the critical mass to surpass yield stresses and initiate movement.

5.3. A Tentative Assessment of the Hydrological Importance of Permafrost in an Alpine Catchment

The past decades have seen various studies that attribute paramount importance to the hydrology of rock glaciers in alpine catchments. Rock glaciers not only act as hydrological buffers that intercept melt- and rainwater and alter discharge patterns of the catchment [40,100], but growing evidence points to their role as significant alpine water stores [39,41,101]. In this regard, rock glaciers stand out as prominent indicators for all areas underlain by permafrost. A first-order quantification based on modeled permafrost distribution roughly estimates 25 km³ of subsurface ice for the Alps [102], which compares to 80–100 km³ of glacial ice [103,104]. Loss of glacial ice has recently been projected to amount to 63–94% by 2100 (reference year 2017), suggesting that the amount of subsurface ice will likely surpass glacial ice storage by that time [103,104]. In the Kaunertal, the rapidly decreasing Gepatschferner, still one of the largest glaciers of the eastern Alps, is a prime example for this development. Today, $\sim 20.7 \text{ km}^2$ of the catchment is covered by glacial ice [44], which compares to between $\sim 33.9 \text{ km}^2$ and ~95.1 km² that are underlain by permafrost in nearly all and in very favorable conditions (Figure 1), respectively [45]. However, these estimates are associated with extremely large uncertainties, calling for a more thorough quantification of subsurface ice in both regional and local contexts. The quantitative distinction between active and inactive rock glaciers might help with improving future model results on the distribution and magnitude of these subsurface water stores in high-alpine regions.

6. Conclusions

We applied an image tracking approach to infer rock glacier surface velocities on a basin scale, aiming to isolate active rock glaciers and identify potential morphometric parameters that control their state of activity. In the Kaunertal catchment, a valley of the Ötztal Alps, we find significant surface movement over a 15-year period for 30 out of 129 rock glaciers and classify these as active. The approach taken to quantitatively discriminate active and inactive rock glaciers on a regional basis has clear advantages over relying solely on field observations, terrain analysis and visual aerial imagery inspection. The LoDs of our approach, averaging just 0.02 m yr⁻¹ at an image resolution of 0.2 m, are auspicious, though we acknowledge that rock glaciers with surface displacement below LoD might still experience movement that is resolvable at higher precision, as, e.g., with differential InSAR approaches that require more extensive processing. In line with earlier studies from the European Alps that investigate rock glacier displacement of individual landforms, we detect mean surface velocities

in the range of 0.11 to 0.29 m yr⁻¹ and a significant increase over the observed period, coinciding with records of increasing air temperatures from local meteorological stations. Maximum velocities attain up to 1.7 m yr^{-1} , falling behind numerous rock glaciers that reportedly underwent dramatic acceleration in recent years. The Kaunertal rock glaciers depict clear distributional patterns of relict and intact rock glaciers regarding elevation and aspect, both in size and numbers, pointing towards topographic controls as the main drivers of ground ice distribution.

The assessment of various morphometric candidate parameters and their potential links to rock glacier velocities revealed several statistically significant and causal relationships. In particular, the analysis of feeder basin characteristics revealed a potential influence of parameters related to the presence of liquid water and sediment supply on rock glacier rheology in the Kaunertal. In contrast, we infer that the explanatory potential of gravity-induced stress on surface velocities is rather weak. The control of non-morphometric rock glacier properties, such as internal structure, ice content and the presence of liquid water, on rock glacier surface kinematics, might, therefore, exceed the predictive power of parameters analyzed herein. However, we could highlight a few morphometric parameters, such as geometric slope and feeder basin slope, as valuable proxies for internal rock glacier properties and their influence on creep.

In contrast to velocities, we find rather dissimilar relationships to rock glacier activity states. Especially geometric parameters related to stress control demonstrate high discriminatory power and point towards potential threshold conditions for the onset of movement. Discriminating rock glacier activity states from a selected number of geometric, topographic and topoclimatic parameters achieves satisfying classification accuracies of up to 75.5% for both logistic regression and random forest classification. These models indicate promising approaches to distinguish active from inactive rock glaciers solely based on morphometric characteristics. The quantitative determination of activity states using independent methods, however, are at present still indispensable for taking these models to a robust and transferable state.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-3263/9/9/373/s1, Table S1: Level of detection and horizontal surface velocity for 30 rock glaciers classified as active based on feature-tracking analysis in aerial imagery, Figure S1: Distribution of active, inactive and relict rock glaciers in the Kaunertal valley, Figure S2: Average horizontal surface velocity of the Kaiserberg rock glacier (RG12), Figure S3: The development and advance of a thermokarst lake on RG08.

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