The evolution of brittle and ductile structures at the surface of a partly debris-covered, rapidly thinning and slowly moving glacier in 1998–2012 (Pasterze Glacier, Austria)

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ABSTRACT: Many glaciers in alpine regions are currently rapidly receding and thinning at historically unobserved rates causing changes in the velocity field and in normal and shear stresses affecting the surface expression of structures within the ice. We studied the distribution of brittle and ductile structures at the surface of Pasterze Glacier during a 14-year period by analysing orthophotos and digital elevation models of five stages (1998, 2003, 2006, 2009 and 2012). A structural glaciological mapping key was applied. Normal faults, strike-slip faults, en échelon structures (systematic stepping of fractures), thrust faults, and band ogives were distinguished. Results indicate substantial deceleration and glacier thinning in 1998–2012. Glacier thinning was not homogenous over time related to the uneven distribution of supraglacial debris causing differential ablation or the selective ablation effects of subglacial water channels. Peculiar supraglacial features observed are circular collapse structures with concentric crevasses which form when the ice between the surface and the roof of water channels decreases. The total length of brittle structures increased from 38.4 km to 56.9 km whereas the extent of the glacier tongue decreased by 25%. The fracture density doubled from 0.009 to 0.018 m/m². Areas of the glacier tongue which were up to 100 m away from the nearest brittle structure increased by 16%. The visual appearance of thrust faults shifted upglacier due to decreasing glacier velocity causing horizontal shortening or due to exhumation of faults that did not previously extend to the surface. A large number of brittle structures are progressively independent from glacier motion. Our study suggests that glacier tongues which are in a state of rapid decay and thinning are prone to fracturing due to normal fault formation and glacier disintegration. Water further increases ablation rates substantially if rather large amounts drain through supra-, en- or subglacial water channels. © 2018 The Authors. Earth Surface Processes and Landforms published by John Wiley & Sons Ltd.

KEYWORDS: structural glaciological mapping; supraglacial debris cover; brittle structures; ductile structures; glacier change

Introduction

Glaciers in alpine regions are currently rapidly receding and thinning often at historically unobserved rates. The latest report on the behaviour of Austrian glaciers for instance revealed for the glaciological year 2016/2017 the highest mean recession rate of all monitored glaciers since the onset of the monitoring program in 1891 (Lieb and Kellerer-Pirklbauer, 2018a). Changes in glacier geometry caused by glacier recession and thinning influence the stress and strain field of an ice mass and affect the spatial pattern of crevasses (Lawson, 1996; Herbst et al., 2006). Large englacial or subglacial water channels or lakes might influence the stress and strain field of a glacier in such a way that supraglacial depressions with circular crevasses form (Morrison, 1958; Benn and Evans, 2010; p. 93). The thinning of glaciers might lead to the collapse of the roof of subglacial tunnels forming eventually subaerial channels flanked by steep ice walls (Paige, 1956). Therefore, the combined effects of glacier recession, glacier thinning, glacier hydrology and changes in the supraglacial debris cover influencing glacier surface geometry have a high potential in affecting structural conditions and changes.

Structural changes can be quantified using multi-temporal remote sensing data. Studies on the variations of glacial structures over a longer period are in general few. One example discussed the structural evolution of a surge-type glacier in Alaska (Variegated Glacier) from 1948 to 1983 (Lawson, 1996). In a second example the structural evolution of the glacier tongue of a valley glacier in Austria (Pasterze Glacier) during the period 1887 to 1997 was analysed using maps and aerial photographs from nine different stages (Herbst et al., 2006). Here, we continued the latter study by analysing the further structural
development of this glacier during the period 1998 to 2012. Our analysis is therefore a continuation of not only the study by Herbst et al. (2006) but also of other earlier studies at this glacier about supraglacial structures (Schwarzacher and Untersteiner, 1953; Untersteiner, 1955; Herbst and Neubauer, 2000).

Studying the pattern of crevasses and fractures at the glacier surface of a rapidly receding glacier using remote sensing data and combine this information with on-site data about glacier dynamics and hydrological conditions helps to reveal relationships between them. Such knowledge will be increasingly important considering the rapid pace of glacier decay as observed in alpine areas (Zemp et al., 2015). However, such combined observations of changes in the glacier geometry, in glacier dynamics but also at the same time in changes in the brittle and ductile structures over a decadal time scale and over an entire glacier tongue are rare. Quantitative observations of the evolution and the description of impacting processes on such glaciers are infrequent but needed for the interpretation of present and anticipated future glacier tongue disintegrations (cf. Zemp et al., 2015).

The present study aims: (1) to capture glacier structural conditions and changes for the time span 1998 to 2012; (2) to quantify changes in fracture density and spatial distribution of brittle structures at the glacier tongue during this period; and (3) to relate the observed structural changes to glaciation changes and hydrological conditions. We therefore tackle research questions regarding how rapid thinning of glacier ice influences the stability and disintegration of glacier tongues, how the relationship between the evolution of the supraglacial debris cover, differential ablation and surface structures is, what the effects of large amounts of englacial or subglacial (melt) water on glacier ablation and surface structures is, what the effects of large amounts of meltwater on glacier ablation and surface structures are, and what a possible mode of future glacier disintegration of alpine valley glaciers might be.

Theoretical Aspects of Structural Glaciology

Hambrey (1994) pointed out that two main categories of structures occur in glaciers, namely primary structures related to accretion or deposition of new material and secondary structures related to deformation. The second category is of relevance in this study. Secondary structures are either expressed as brittle or ductile forms and depend on the deformation fields and ice characteristics of the glacier (Nye, 1952; Hambrey and Lawson, 2000). Traces of former active crevasses can still be seen at the surfaces decades after their active formation (Lawson, 1996; Jennings et al., 2016).

Brittle structures include open fractures (crevasses), closed fractures and faults (Hambrey and Lawson, 2000). Ductile structures are for instance foliations, foliations, crevasses, faults and ogives (Hambrey and Lawson, 2000; Jennings et al., 2014). Brittle failure occurs as a result of different processes: horizontal extension of a glacier is mainly accompanied by typically 60–70° dipping shear fracturing, called normal faults. At low effective stress brittle material fails by pure opening which acts perpendicular to the direction of maximum tensile stress (Twiss and Moores, 1992; Herbst et al., 2006). Open fractures generally develop perpendicular to the bearing of the maximum tensile stress (Nye, 1952; Benn et al., 2007).

Horizontal shortening is commonly accompanied by shear fractures called thrust faults if their dip is <45° or reverse fault if the dip is >45° (Twiss and Moores, 1992; Herbst et al., 2006). Thrusting is an important process for glacial sediment transfer and consequently for glacial landscape evolution (Swift et al., 2018). Horizontal relative movement of ice or rock material without significant vertical displacement is associated with sub-vertical shear fractures called strike-slip faults (Twiss and Moores, 1992; Herbst et al., 2006). Within shear zones systematically stepping fractures or faults (i.e. en échelon pattern) often develop (Naylor et al., 1986; Twiss and Moores, 1992).

The only ductile structures we considered in our study were ogives. Several different hypotheses have been discussed regarding the formation of wave and band ogives (or Forbes bands) (Hambrey and Lawson, 2000; Goodsell et al., 2002 and references therein). One widely accepted theory is that dirty bands are related to summer passage of ice through an icefall and the cleaner ice represents the winter passage (Nye, 1958).

Study Area

The Pasterze Glacier is the largest glacier of the Austrian Alps covering 16.5 km² in 2012 (Lieb and Kellerer-Pirklbauer, 2018b). The glacier is located in the Glockner Mountains, Hohe Tauern Range, at 47°05′N and 12°43′E (Figure 1). The gently sloping tongue is connected with the upper part of the glacier by an icefall which disintegrated substantially during recent decades with first rock windows appearing in the mid-1980s (Kellerer-Pirklbauer et al., 2008) (Figure 2(a)). The rock windows in the icefall increased in extent by a factor of 2.6 solely during the period 2003 to 2009 (Kaufmann et al., 2015). Bedrock visually prevails at the icefall since about the turn of the millennium.

Since termination of the Little Ice Age around 1850 AD the glacier has undergone continuous retreat apart from short periods of stability or single years of minor advances (Wakonigg and Lieb, 1996; Lieb and Kellerer-Pirklbauer, 2018b). Pasterze Glacier did not advance substantially during the cooler and wetter periods of the 1890s, 1920s or 1965–1980 due to the slow response time (Zuo and Oerlemans, 1997). Glacier recession caused the disconnection of the glacier tongue with other glaciers such as the Wasserfallwinkel Glacier in 1895, the Hofmann Glacier in 1950 (Wakonigg and Lieb, 1996) or the Glockner Glacier in 2009 (Figure 1). 75% of the glacier tongue was covered by supraglacial debris cover in 2012. The increase of supraglacial debris over time (Kellerer-Pirklbauer, 2008) affected the glacier surface morphology due to differential ablation (Kellerer-Pirklbauer et al., 2008) influencing the glacier’s stress and strain field and hence its movement direction (Kaufmann et al., 2015). Annual glacier flow velocity measurements and glacier surface elevation changes at cross-sections at the Pasterze Glacier were initiated in the 1920s with almost continuous measurements since then (Wakonigg and Lieb, 1996; Lieb and Kellerer-Pirklbauer, 2018b). In this study we used annual data from three cross-sections covering the period 1998–2012 (data source Lieb and Kellerer-Pirklbauer, 2018b). As shown by this data, the glacier was in a stage of recession, downwasting and flow velocity decrease during the period 1998–2012 (Figure 3). Technical details of the measurement can be found in Kellerer-Pirklbauer et al. (2008).

The tongue of the Pasterze Glacier is formed by three individual flow units (1 to 3 in Figure 2(a), (b)), each of which originates in its own sub-accumulation basin or becomes separated by flow through the icefall. The three flow units are separated by centimetre- to decimetre-wide shear zones (Herbst and Neubauer, 2000). The most distinctive shear zone was recognized in 1850 AD (Schlagintweit and Schlagintweit, 1850) and was named during that time “Firmmoräne” (German meaning “firm moraine” related to its differing visual appearance compared to its vicinity). At the boundaries of the flow units medial moraines partly exist (Figure 2(a), (b)). The orientation of the foliation along cross-profiles at the glacier tongue indicates spoon-like arrangement of the foliation at each of the three flow units (Untersteiner, 1955; Herbst and Neubauer,
Arcuate band ogives can be found at the glacier surface indicating different flow sub-units (Figure 2(a), (b)). Remote sensing techniques applied at this glacier (DinSAR by Kaufmann et al., 2008 and conventional photogrammetry by Kaufmann et al., 2015) were not able so far to distinguish the three flow units related to decorrelation problems of the remote sensing data at ice and snow surfaces.

Material and Methods

High resolution orthophotos and digital elevation models (DEM) of five stages were used as the main data source for the manual mapping of brittle and ductile structures at the glacier tongue (Table I). As judged from a sensitivity analysis (reshampling of the 2012-data to coarser resolution), the slightly coarser geometric resolution of the orthophotos of the stages 1998–2009 (50 cm grid size) provided basically identical mapping results in terms of quality compared to the results of 2012 (20 cm). The mapping area at the glacier tongue decreased from 4.27 km² in 1998 to 3.20 km² in 2012 (Table I) due to glacier recession. DEM differencing was accomplished by subtracting the newer DEM minus the previous DEM, each with a raster grid size of 5 m. The 2012-DEM was resampled for this purpose to an identical resolution of 5 m. The reconstruction of the subglacial topography is based on GPR measurements (Span et al., 2005; Figure 2.160).

Structural glaciological mapping is similar to structural geological mapping involving the description of structures in ice, firm and snow such as folds, faults, foliations, and crevasses/crevasse traces and its interpretation (Hubbard and Glasser, 2005; 321). A structural glaciological study potentially consists of desktop mapping using remotely sensed data, field measurements, laboratory studies, and modelling studies (Hubbard and Glasser, 2005; 322–325). The former approach has the advantages of considering a long time span (Hodgkins and Dowdeswell, 1994; Glasser et al., 2009). In this study a simple structural glaciological mapping key was developed based on an earlier study carried out at the Pasterze Glacier (Herbst et al., 2006). In our mapping key we distinguished between the following brittle-structure types: (a) normal fault/fracture (Figure 2(c), (f)); (b) strike-slip fault/fracture; (c) sets of tensile cracks expressed as en échelon fractures (systematic stepping of fractures), and (d) thrust fault/fracture (Figure 2d,e). Crevasses and fractures form, however, as a combination of different forces (Benn and Evans, 2010) which made a clear classification not always straightforward. Despite the applied diligent classification procedure, the summarized total length of all mapped structures per glacial stage is therefore certainly more meaningful than the results for each separate type.

Normal faults were mapped as crevasses in the aerial photographs when typical glacier crevasses were identified related to an extension (partly with tensile crack formation; Benn and Evans, 2010; p. 134) or vertical shearing (classical normal fault) of glacier ice. At the margin of the Pasterze Glacier the crevasses are commonly caused by the combination of different forces (Benn and Evans, 2010) which made a clear classification not always straightforward. Despite the applied diligent classification procedure, the summarized total length of all mapped structures per glacial stage is therefore certainly more meaningful than the results for each separate type.
Strike-slip fractures are characterized by distinct shear zones and partly with systematically stepping (en échelon) fracture segments which develop where extensional flowing of ice with a reduction of flow velocity at right angles to the main flow direction act together. Thrust faults were mapped as such when large arcuate, downslope convex linear structures, cutting part (or most) of the glacier width. Sometimes, distinct supraglacial debris was visible below such thrust faults (Figure 2(e)) indicating either debris transport from a subglacial environment to the glacier surface (Hambrey and Lawson, 2000; Swift et al., 2018) or passively-transported debris-bands. Different processes potentially create foliation-parallel debris layers such as elevation of basal debris by for instance thrusting, crevasse-fill or primary sedimentary layering caused by supraglacial rockfalls above the equilibrium line (Kirkbride and Deline, 2013). Table II and Figure 4 summarize the structural mapping and classification procedure.

Band ogives were visible in and mapped for all five different stages. In general, the further away from the icefall, the more blurry are the band ogives in the orthophotos, which made the mapping sometimes difficult. Ogives have not been mapped as polygons but only as polyline features related to unclear margins. The spatial extent of the supraglacial debris cover for each stage was manually mapped using the available...
orthophotos (Table I). Observations made during numerous field trips since 2003 were also considered.

The quantification of the degree of fracturing of the glacier tongue was accomplished in two different ways. First, the fracture density was calculated by comparing the total length of the brittle structures with the entire area of the glacier tongue during each of the five stages. In a further step the length of the glacier tongue in 1998 was split into three equally long sectors (1.6 km) along the central flow line delimitating an upper, a middle and a lower sector (Figure 1). This splitting allowed quantification of the fracture density of each sector of the glacier tongue. The distance between brittle structures was calculated as a second mean for fracturing quantification. This was accomplished by computing the distance to the nearest mapped brittle structure within the mapping domain, which was for each stage the spatial extent of the glacier tongue. The distance to the nearest brittle structure was quantified for nine different distance classes (≤10 m, 10–20 m, 20–50 m, 50–100 m, 100–200 m, 200–300 m, 300–400, 400–500, and 500–600 m). Mapping and calculations were accomplished in ArcGIS.

Results: Structural Evolution of the Glacier Tongue

Figure 5 depicts the structural mapping results from all five glacial stages. The mapped normal faults, strike-slip faults and en échelon fractures have been combined in the maps depicted in Figure 5 as ‘crevasse or fracture’ for visual reasons. Figure 6(a) and 6(b) illustrates the summary statistics of all different mapped brittle structures for all five stages in total length and percentage values. The relationships between the total length of brittle structures and the area of the entire glacier tongue and the same relationship for each of the three

Table I. Base data used in this study differentiating between digital elevation models (DEMs), digital orthophotos, and glacier boundaries

<table>
<thead>
<tr>
<th>Data type</th>
<th>Date</th>
<th>Resolution and accuracy of z (cm) for DEMs</th>
<th>Comment</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEM</td>
<td>13.08.2003</td>
<td>5 m grid (+/-25-30)</td>
<td>aerial photography-based</td>
<td>Kauf. et al.4</td>
</tr>
<tr>
<td></td>
<td>22.09.2006</td>
<td>5 m grid (+/-25-30)</td>
<td>aerial photography-based</td>
<td>Kauf. et al.4</td>
</tr>
<tr>
<td></td>
<td>24.08.2009</td>
<td>5 m grid (+/-25-30)</td>
<td>aerial photography-based</td>
<td>Kauf. et al.4</td>
</tr>
<tr>
<td></td>
<td>summer 2012</td>
<td>1 m grid (unkno.)</td>
<td>ALS5; exact date unknown</td>
<td>KAGIS2</td>
</tr>
<tr>
<td>digital orthophoto</td>
<td>Aug. 1998</td>
<td>50 cm</td>
<td>exact date not known</td>
<td>NPHT1</td>
</tr>
<tr>
<td></td>
<td>13.08.2003</td>
<td>50 cm</td>
<td>same date as DEM</td>
<td>Kauf. et al.4</td>
</tr>
<tr>
<td></td>
<td>22.09.2006</td>
<td>50 cm</td>
<td>same date as DEM</td>
<td>Kauf. et al.4</td>
</tr>
<tr>
<td></td>
<td>24.08.2009</td>
<td>50 cm</td>
<td>same date as DEM</td>
<td>Kauf. et al.4</td>
</tr>
<tr>
<td></td>
<td>summer 2012</td>
<td>20 cm</td>
<td>exact date not known</td>
<td>KAGIS2</td>
</tr>
<tr>
<td>entire glacier</td>
<td>Aug. 1998</td>
<td>shapefile</td>
<td>size: 18.52 km²</td>
<td>this study</td>
</tr>
<tr>
<td></td>
<td>13.08.2003</td>
<td>shapefile</td>
<td>size: 18.14 km²</td>
<td>Kauf. et al.4</td>
</tr>
<tr>
<td></td>
<td>22.09.2006</td>
<td>shapefile</td>
<td>size: 17.65 km²</td>
<td>Kauf. et al.4</td>
</tr>
<tr>
<td></td>
<td>24.08.2009</td>
<td>shapefile</td>
<td>size: 17.28 km²</td>
<td>Kauf. et al.4</td>
</tr>
<tr>
<td></td>
<td>summer 2012</td>
<td>shapefile</td>
<td>size: 16.59 km²</td>
<td>this study</td>
</tr>
<tr>
<td>entire tongue</td>
<td>for 1998</td>
<td>shapefile</td>
<td>size: 4.27 km²</td>
<td>this study</td>
</tr>
<tr>
<td></td>
<td>for 2003</td>
<td>shapefile</td>
<td>size: 4.15 km²</td>
<td>this study</td>
</tr>
<tr>
<td></td>
<td>for 2006</td>
<td>shapefile</td>
<td>size: 3.80 km²</td>
<td>this study</td>
</tr>
<tr>
<td></td>
<td>for 2009</td>
<td>shapefile</td>
<td>size: 3.52 km²</td>
<td>this study</td>
</tr>
<tr>
<td></td>
<td>for 2012</td>
<td>shapefile</td>
<td>size: 3.20 km²</td>
<td>this study</td>
</tr>
</tbody>
</table>

1airborne laser scanning-based;
2Geographical Information Service of the federal government of the federal province of Carinthia;
3administration of the Hohe Tauern National Park;
4Kaufmann et al. (2015)
sectors are shown in Figure 6(c). The respective data are summarized in Table III. Figure 6(d) depicts the fracture density based on the length of all mapped brittle structures (in m) per unit area (in m²) for the entire glacier tongue and the three different sectors (Table IV). In Figure 7 the distance to the nearest brittle structure within the mapping area is shown for all stages. These results are also presented as cumulative percentage values (Table V).

Figure 8 depicts a longitudinal profile at the debris-poor part of the glacier tongue (cf. Figure 1 for location) during the four stages 2003, 2006, 2009, and 2012 with brittle and ductile structure based on GPR-data (Span et al., 2005) and massive lateral streams draining into the glacier tongue (cf. Figure 1). Figure 9 presents elevation differences between two subsequent stages and their relationships to the brittle structures mapped for 2006, 2009, and 2012. The following paragraphs discuss the specific results for each stage.

Stage 1998
Glacier crevasses were widespread features at the particularly left/north-eastern margin of the glacier tongue in 1998. The

Table II. Mapped structural glaciological features, with identification criteria and significance (based mainly on Benn and Evans, 2010 and Goodsell et al., 2002)

<table>
<thead>
<tr>
<th>Structure</th>
<th>Feature</th>
<th>Identification on orthophoto</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brittle</td>
<td>normal fault</td>
<td>typical glacier fractures and crevasses expressed as linear features or semi-circular to circular collapse structures</td>
<td>related to extension (partly with tensile crack formation) or vertical shearing (classical 'normal fault') of glacier ice</td>
</tr>
<tr>
<td></td>
<td>strike-slip fault</td>
<td>distinct shear zones between different flow units systematically stepping (en échelon) of fault segments by forming tensile cracks or gashes</td>
<td>caused by velocity differences of flow units develop where extensional flowing of ice with a reduction of flow velocity at right angles to the main flow direction act together causing shear stresses</td>
</tr>
<tr>
<td></td>
<td>en échelon fractures formed by tensile cracks</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>thrust fault</td>
<td>large arcuate, downslope convex linear structures, cutting part of the glacier width</td>
<td>distinct supraglacial debris was sometimes clearly visible below such thrust faults indicating englacial debris transport</td>
</tr>
<tr>
<td>Ductile</td>
<td>band ogive</td>
<td>arcuate bands (convex down-flow) with alternating dark and light ice</td>
<td>surface expression of 3D spoon-shaped structures dipping upstream within the glacier</td>
</tr>
</tbody>
</table>

Figure 4. Examples of the different types of mapped brittle structures depicted as orthophotos, orthophotos with mapped features, schematic plan view sketches, and schematic profile sketches. For orthophoto data sources refer to Table I. [Colour figure can be viewed at wileyonlinelibrary.com]
lowercase letters in Figure 5(a) indicate the following conditions at specific areas. (a) Chaotic and circular ice disintegration features consisting of normal faults as well as clearly developed thrust faults (partly with thrusted debris material) dominate close to the glacier terminus. At least some of the thrust faults are inactive because normal faults and thrust faults cannot be active at the same time. (b) Longitudinal, towards the glacier margin concave-shaped normal faults dominate in an area slightly upvalley from (a). The area in (c) is dominated by transversal normal faults caused by extensional flow and high differences in relief. In the area (d) tensile cracks partly in an en échelon pattern as well as superimposed normal faults caused by extensional flow exist, indicating decreasing flow rates towards the left glacier margin. Area (e) is characterized by normal faults expressed as chevron crevasses (Nye, 1952; Benn and Evans, 2010; p. 137) caused by lateral shear stresses at the margins. Normal faults, orientated oblique to the main flow direction are also widespread at several areas of the debris-covered part of the glacier tongue related to substantial elevation differences between the left and the right parts of the glacier tongue influencing tensile forces.

The total length of brittle structures mapped for stage 1998 was 38.4 km (Table III). 84% of the length of the crevasses and faults were classified as normal faults, 3.5% as strike-slip faults, 5.5% as en échelon fractures and 7% as thrust faults (Figure 6). The fracture density was 0.009 m/m² for the entire glacier tongue, lower at the upper sector and slightly higher at the middle and lower sectors (Table IV). The degree of crevassing and faulting expressed as distance to the nearest fracture or crevasse was by far the lowest one in 1998 compared with the later four stages. Only 14.5% of the glacier tongue was up to 10 m from the nearest brittle structure (Table V). Band ogives have been well identified at two of the three different flow units. The best developed band ogives in 1998 have been mapped at the flow unit 1 where dark and light bands were identifiable for 3.5 km below the icefall. At flow unit 2 well developed band ogives were detectable for 1.9 km below the icefall.
Stage 2003

The general pattern of brittle structures is similar to the stage 5 years earlier with ongoing ice disintegration near the left part of the glacier terminus formed by chaotic normal faults. However, some distinct changes have been observed since 1998 particularly at the lower half of the glacier tongue. The small letters in Figure 5(b) indicate the following conditions and areas: (a) first appearance of an initializing circular-shaped collapse feature with distinct concentric normal faults in the central part of the glacier tongue. The fractured area (b) in Figure 5(a) and 5(b) increased in size towards the valley center with more longitudinal, towards the glacier margin concave-shaped normal faults forming near a lateral glacier surface depression.

In contrast, the area (c) in Figure 5(a) and 5(b) with transversal normal faults caused by extensional flow and high differences in relief seemed to have little changed since 1998. Similar to area (b), the spatial extent of the area (d) with tensile cracks associated partly with en échelon fractures and superimposed normal faults caused by extensional flow has increased. Thrust faults appear progressively further upglacier suggesting more stagnant ice closer to the glacier terminus which is overridden by upvalley-located glacier ice or the exhumation of thrust faults that did not previously extend to the

Table III. Area and length of brittle structures for the entire glacier tongue and for each of the three sectors during all five stages between 1998 and 2012

<table>
<thead>
<tr>
<th>Stage</th>
<th>Area (m²)</th>
<th>Length of brittle structures (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>entire</td>
<td>upper middle lower</td>
</tr>
<tr>
<td>1998</td>
<td>4 265 119</td>
<td>1 197 052 1 873 653 1 194 414</td>
</tr>
<tr>
<td>2003</td>
<td>4 145 586</td>
<td>1 173 222 1 787 079 1 185 285</td>
</tr>
<tr>
<td>2006</td>
<td>3 798 518</td>
<td>1 141 058 1 649 079 1 008 381</td>
</tr>
<tr>
<td>2009</td>
<td>3 522 660</td>
<td>1 111 531 1 571 689 839 440</td>
</tr>
<tr>
<td>2012</td>
<td>3 203 448</td>
<td>1 064 985 1 456 419 682 044</td>
</tr>
</tbody>
</table>

Table IV. Fracture density expressed as length of brittle structures per unit area (m/m²) for the entire glacier tongue and the lower, middle and upper sectors (cf. Figures 1 and 6(d))

<table>
<thead>
<tr>
<th>Stage</th>
<th>Fracture density (m/m²) at the glacier tongue (entire and parts)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>entire</td>
</tr>
<tr>
<td>1998</td>
<td>0.0090</td>
</tr>
<tr>
<td>2003</td>
<td>0.0115</td>
</tr>
<tr>
<td>2006</td>
<td>0.0140</td>
</tr>
<tr>
<td>2009</td>
<td>0.0182</td>
</tr>
<tr>
<td>2012</td>
<td>0.0178</td>
</tr>
</tbody>
</table>

Figure 6. Summary statistics of the brittle structures at the tongue of Pasterze Glacier: (a) total length of mapped brittle structures and (b) percentage distribution, respectively, during the five different stages 1998, 2003, 2006, 2009, and 2012; (c) relationship between the length of brittle structures and the areas of the entire glacier tongue and the upper, middle, and lower sectors (cf. Figure 1), respectively; (d) fracture density expressed as length of brittle structures per unit area for the entire glacier tongue and the three sectors. Significance: *P<0.05.

Stage 2003

The general pattern of brittle structures is similar to the stage 5 years earlier with ongoing ice disintegration near the left part of the glacier terminus formed by chaotic normal faults.
Normal faults at the right, continuously debris-covered part of the glacier increased slightly in their extent and area of occurrence since 1998. For stage 2003 a total length of 47.8 km of brittle structures was mapped. Most of these features have been classified as normal faults (81.8%), 3.1% as strike-slip faults, 4.2% as en échelon fractures and 10.9% as thrust faults. The fracture density in 2003 was 0.012 m/m² for the entire glacier tongue. At all three sectors the density values had increased compared with 1998 (Table IV).

In accordance with the increase in brittle structures with decreasing area (Table III) the density of crevasses and fractures in terms of distance to the nearest fracture increased substantially since 1998. Only 25.7% of the area of the glacier tongue was more than 100 m away from fractures or crevasses (Table III). In 2003 band ogives were detected in all three flow units. The best developed band ogives were again mapped in flow unit 1. However, for this stage the lower limit of clearly detectable band ogives was about 2 km from the icefall. The shape of the band ogives in flow unit 2 was comparable with the conditions in 1998. The band ogives in flow unit 3 were short and only detectable over a horizontal distance of some 500 m.

Stage 2006

The debris-poor part of the glacier tongue in particular continued to disintegrate over large areas between 2003 and 2006. For instance area (a) in Figure 5(c) (also depicted in Figure 2 of Table V. Distance to the nearest brittle structure at the tongue of Pasterze Glacier during the five stages 1998, 2003, 2006, 2009, and 2012 presented as cumulative percentages (cf. Figure 7)

<table>
<thead>
<tr>
<th>Stage</th>
<th>≤10</th>
<th>≤20</th>
<th>≤50</th>
<th>≤100</th>
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<th>≤300</th>
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<td>40.6</td>
<td>63.0</td>
<td>84.9</td>
<td>96.3</td>
<td>99.2</td>
<td>100.0</td>
<td>100%</td>
</tr>
<tr>
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<td>28.0</td>
<td>50.0</td>
<td>74.3</td>
<td>91.4</td>
<td>96.5</td>
<td>98.5</td>
<td>99.3</td>
<td>100%</td>
</tr>
<tr>
<td>2006</td>
<td>20.9</td>
<td>32.3</td>
<td>53.6</td>
<td>74.6</td>
<td>95.4</td>
<td>98.6</td>
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<td>99.7</td>
<td>100%</td>
</tr>
<tr>
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<td>95.8</td>
<td>98.6</td>
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</tr>
</tbody>
</table>

Figure 7. Distances to nearest brittle structures at the tongue of Pasterze Glacier indicating degree of faulting and crevassing during the five different stages: (a) 1998, (b) 2003, (c) 2006, (d) 2009, (e) 2012; (f) outlines of entire glacier and glacier tongue for the different stages. [Colour figure can be viewed at wileyonlinelibrary.com]
(f) was characterized by circular collapse features with concave downvalley-shaped normal faults. Up to then the circular and semi-circular fractures did not occur at the continuously debris-covered right part of the glacier tongue. The ice collapse field in area (b) enlarged further towards the valley center. In area (c) the extent of the longitudinal, towards the glacier margin concave-shaped normal faults enlarged further upvalley (Figure 2(c)). The ice depression in area (c) had enlarged since 2003. In (d) a new semi-circular fracture was formed with concave-lateral normal faults. In area (e) the number of crevasses as well as crevasses with en échelon pattern was reduced between 2003 and 2006 indicating glacier deceleration. In general, the distribution of normal faults at the lower lateral part of the glacier tongue correlates very well with areas that experienced the highest vertical losses between 2003/06 as revealed by DEM differencing (Figure 9(a)).

For stage 2006 a total length of 53.3 km of brittle structures was mapped (Table III): 77.7% of this has been classified as normal faults and only 4.9% as either strike-slip fault or en échelon fracture. Thrust faults increased to 17.4%. The total length of thrust faults had increased substantially since 2003 from 5.2 km to 9.3 km. The apparent upper limit of their occurrence shifted again upvalley although at a lower rate compared with the earlier period 1998–2003. The semi-circular feature reported for the first time in 2003 for the central part of the glacier tongue (area (a) in Figure 5(b)) had changed only a little in appearance in 2006. The crevasse pattern at the debris-covered part of the glacier had also changed only to a minor extent since 2003. The number of oblique concave-downvalley crevasses increased related to a gain in relief between the debris-covered/right and debris-poor/left parts of the glacier tongue. The fracture density in 2006 had increased substantially since 2003 particularly at the upper and middle sector (Table IV). The degree of crevassing and faulting had changed little since 2003. Only some 25.4% of the glacier tongue was more than 100 m away from open or closed fractures (Table V).

In 2006 band ogives were not detected in flow unit 3. We identified band ogives in flow unit 1 for 3.0 km below the icefall. At flow unit 2 band ogives were visible for some 1.9 km below the icefall (same as 1998), although with areas in between where band ogives were not detectable on our orthophotos. Glacier recession and thinning of the entire glacier tongue caused a slight increase in the general slope of the glacier tongue (Figure 8).

Figure 8. Surface elevation changes and glacier thinning at the tongue of Pasterze Glacier during the stages 2003, 2006, 2009, and 2012 and its relationship to mapped brittle and ductile structures (schematic representation) and lateral streams draining into the glacier. Surface lowering in the alleged proglacial area is related to slowly melting sediment-buried ice. For data source refer to Table I. For location of the profile refer to Figure 1. Subglacier topography based on Span et al. (2005). [Colour figure can be viewed at wileyonlinelibrary.com]

Stage 2009

Between 2006 and 2009 the glacier tongue further receded. The ice fall connection between the tongue of the Pasterze Glacier and the formerly tributary Glockner Glacier (Figure 1) was lost by 2009. For 2009 our analyses indicate a massive increase

in the occurrence of normal faults. The entire lateral glacier area near the glacier terminus was in a state of disintegration and crevassing (a) in Figure 5(d)). Semi-circular collapse structures (b) developed in the transition zone between the debris-covered and debris-poor part of the glacier tongue. A strong increase in crevassing occurred in area (c) with transversal and concave-outward bended as well as semi-circular structures. The area (d) in Figure 5(d) was increasingly affected by brittle fractures compared with 3 years earlier. In (e) the areas affected by oblique normal-fault formation enlarged related to a further increase in the difference of the glacier surface elevation between the left and right part of the glacier caused by differential ablation. The formerly typical en échelon pattern in area (f) was hardly detectable anymore. Instead, area (f) was dominated by normal faults.

The area affected by thrust faults shifted again slightly further upvalley during the period 2006 to 2009. Similar to the conditions in 2006, the distribution of normal faults at the lower lateral part of the glacier tongue correlates very well with areas that experienced the highest vertical losses in the period 2006–2009 (Figure 9(b)). The total length of brittle structures was 64.0 km in 2009 (Table III). In 2009 the highest value for total length of brittle structures was mapped despite the reduction of the mapping area caused by glacier recession. 83.8% of the total length was classified as normal faults. The percentage of thrust faults decreased to 12.7% compared with 3 years earlier. The fracture density in 2009 was 0.018 m/m² and 0.023 m/m² at the middle sector (Table IV).

Also the degree of crevassing and faulting expressed as distance to the nearest fracture increased significantly between 2006 and 2009. Only 16.1% of the glacier tongue was more than 100 m away from open or closed fractures (Table IV). At flow unit 1 band ogives were identified until 2.0 km below the icefall. The band ogives were only well mappable at the right-lateral area of flow unit 1. At flow unit 2 band ogives were detected until 1.2 km below the icefall. The general slope between the glacier terminus and the icefall increased slightly between 2006 and 2009 (Figure 8).

Stage 2012

Our analysis of the 2012 stage documents an increase in the area affected by normal faults. This increase is also expressed in a higher number of circular and semi-circular features particularly at the lower third of the remaining glacier tongue. This evolution is attributed to sub- and englacial melting of ice or to massive lateral ice losses as revealed by DEM differencing of the 2009 and 2012 stages (Figures 8, 9(c)). Area (a) in Figure 5(e) is the part of the glacier tongue with the highest degree of crevassing. Area (b) changed little in its general appearance with semi-circular to longitudinal normal faults. In
areas (c) the number of crevasses decreased slightly. En échelon features are missing in this area indicating again lower glacier velocity rates compared with earlier periods.

The normal faults at the debris-covered part of the glacier tongue further increased in their extent and spatial coverage related to the ongoing effects of differential ablation between the two glacier parts. The total length of the brittle structures at the glacier tongue was 56.9 km and hence in between the values of 2006 and 2009 (Table III, Figure 6(a)). Tensile cracks expressed as en échelon structures were completely missing in 2012 (and also 2009) at the entire glacier tongue. Strike-slip faults were only 2.1% of the total length of the brittle structures. Normal faults covered 84.4% of the mapped fractures whereas thrust faults were classified for 13.4%. The fracture density in 2012 was almost identical to 2009 with 0.018 m/m² for the entire glacier tongue and highest values again for the middle sector (Table IV). The degree of crevassing in terms of distance to the nearest brittle structure in 2012 was also comparable with that of 2009 (Table V). Band ogives at flow unit 1 were mapped until 2.0 km below the icefall. We identified only traces of band ogives in flow unit 2 for some 1.3 km below the icefall. No band ogives were visible in flow unit 3.

Discussion

Spatial distribution and variations of brittle structures

Our analyses indicate that the lower two-thirds of the glacier tongue were characterized by massive ice disintegration during the period 1998 to 2012. Semi-circular collapse features evolved particularly since 2003 near the glacier terminus and since 2009 in the central part of the glacier tongue. These collapse structures, which are structurally normal faults with a concave to circular shape, are the result of large differences in glacier surface lowering over a rather short distance. These differences are related to glacier-lateral positions (Avian et al., 2007), to differences in the supraglacial debris cover influencing differential ablation (Kellerer-Pirklbauer et al., 2008) or to sub- or englacial ice ablation due to sub- or englacial (melt) water streams (Stocker-Waldhuber et al., 2017). Supraglacial meltwater channels are widespread at the surface of the Pasterze Glacier (Kaufmann et al., 2015). In addition, inflowing water is widely affecting the en- and subglacial open channels. Several streams on both sides of the valley glacier drain into the glacier system (Figures 1, 8) forming distinct ‘inverse’ glacier mouths (if at the glacier margin) or moulins (if at the glacier surface). Such a relationship of a (i) supraglacial drainage system which, (ii) drains into the glacier ice through a mouline adding water to the subglacial hydrological system, and (iii) a semi-circular to circular collapse feature further downhill is depicted for instance in Figure 2(f).

Circular to semi-circular collapse features at the surface of glaciers were reported for the first time in scientific literature in the 1930s, 1950s and 1960s (Srbik, 1937; Paige, 1956; Morrison, 1958; Odell, 1960). Srbik (1937) presented some observations from funnel-shaped collapse features at debris-covered ice of the Gurglerferner in Austria (Ferner is a local term for glacier). Paige (1956) described the formation of concentric, crescent-shaped crevasses at the surface of Black Rapids Glacier, Alaska, related to a meandering subglacial river which formed these crevasses on the outward curve of each meander by a process termed ‘subglacial stopping’ or ‘block caving’ of a thinning glacier tongue. The term subglacial stopping or block caving were proposed by John G. McCall (as noted in Paige, 1956). Figure 2(g) depicts a subglacial cavity at a collapse feature near the glacier margin at Pasterze Glacier with large ice blocks at the cave bottom (Figure 2(h)).

Morrison (1958) reported from two large circular collapse features at the snout of Alph Glacier, Canada. He described these features as systems of concentric circular or spiral crevasses with a deep hollow in the ice in the center occupied by a small lake. Furthermore, he pointed out that ice flows into the center of each such feature and that the curved fragments lean towards the center. Morrison explained the formation of the circular crevasses feature by the collapse of the roof of a subglacial tunnel. Finally, Odell (1960) described ‘curious circular features’ in aerial photographs in 1953 below the junction of the debris-covered Tasman Glacier with the Murchison Glacier valley, New Zealand, without going into detail about the formation (other than referring to Paige (1956) and Morrison (1958)).

The occurrence, distribution and dynamics of the circular collapse features at Pasterze Glacier are certainly influenced by ablation from above, within and below the glacier. If the collapse features are related to englacial water channels, the collapse should move downvalley with the glacier. If they are related to subglacial water channels, the collapse should remain in place. The question if the observed collapse features at Pasterze Glacier are related to englacial or subglacial water channels cannot be answered clearly by our orthophoto analysis because of too large time steps between two stages. However, as judged from a comparison of terrestrial photos from between 2011 and 2018 (Figure 10; each time showing August conditions), a subglacial stream relationship is clearly favored. This conclusion is also supported by the images of August 2017 and August 2018 (Figure 10(g), (h)) where the outward curve of the river is visible at the circular collapse feature. Stocker-Waldhuber et al. (2017) concluded from observations and measurements of similar depressions at four glaciers in western Austria (Gepatschferner, Mittelbergferner, Sulztalferner, Hintereisferner) that such landforms commonly seem to occur close to the glacier terminus where velocities are low and where subglacial water streams are located.

The total length of mapped brittle structures increased (apart from the last stage) over time with 38.4 km in 1998, 47.8 km in 2003, 53.3 km in 2006, 64.0 km in 2009, and 56.9 km in 2012. This evolution is remarkable if the shrinkage of the glacier tongue is considered. The spatial extent of the glacier tongue was reduced by 25% between 1998 and 2012. The fracture density increased twofold over time between the stages 1998 (0.009 m/m²) and 2009 (0.018 m/m²) for the entire glacier tongue. This trend was strong for the middle and lower sections of the glacier whereas less clear for the upper part. The fracture density values for 2009 and 2012 were rather similar suggesting that a value of 0.018 m/m² is already an extreme value.

The degree of fracturing in terms of distances to the nearest brittle structure increased substantially over time at the glacier tongue as depicted in Figure 7 and summarized in Table V. Such an attempt to quantify the degree of crevassing and fracturing and to present such an analysis visually in maps has not been reported earlier. Such maps allow, however, good visual impressions of areas far away from any sort of crevasses or faults in contrast to areas near such features. In our case we can conclude that over time the lower half of the glacier tongue of the Pasterze Glacier was increasingly affected by fracturing between 1998 and 2012 (Figure 9).

Spatial distribution and variations of ogives

Our ogive mapping supported earlier works at this glacier regarding more than one flow unit at the glacier tongue. Two sets
of ogives were recognized in the 1940s (Paschinger, 1948) on both sides of the above mentioned “Firnmoräne”, i.e. the shear zone between the two flow units 1 and 2 (Figure 2(a), (b)). No information was given by Paschinger about the horizontal extent of the ogives. The analyses of maps and orthophotos covering different stages of the Pasterze Glacier between 1887 and 1997 (Herbst et al., 2006) report band ogives only from the north-easternmost flow unit (unit 1).

Herbst et al. (2006) presented the lower limit of band ogives at flow unit 1 based on the analysis of orthophotos dating to 1953, 1958, 1969, 1978, 1983, 1991, and 1997. No ogives have been reported by them from the flow units 2 and 3. In 1953 band ogives existed at flow unit 1 only close to the icefall. In 1958 this zone of visible band ogives shifted only slightly downglacier. Between 1958 and 1969 the lower limit of band ogives shifted some 620 m downglacier. Nine years later, in 1978, band ogives were visible from the base of the icefall all the way to the cross-section SLL. Therefore, the lower limit of band ogives seemed to have migrated by 1 km in the period 1969–1978. After 1983 this lower limit was basically unchanged according to Herbst et al. (2006). In contrast, our results suggest a dramatic variability in the band ogive mapping with the largest extent in terms of horizontal expansion of band ogives in 1998. However, supraglacial debris hampered ogive mapping for the more recent stages. Furthermore, in case of unfavourable light conditions the general distinction and clear delineation of dark and light bands is not straightforward on optical remote sensing data. A detailed width analysis of bands such as presented by Goodsell et al. (2002) would be of great interest also for Pasterze Glacier. Such an analysis would be

Figure 10. Evolution of a semi-circular collapse feature at the surface of Pasterze Glacier between 2011 and 2018 (dashed circle). Note that the evolving collapse feature remains in place and is part of the glacier terminus during the last two stages. Webcam-based images are kindly provided by Großglockner Hochalpenstraßen AG (Copyright GROHAG). [Colour figure can be viewed at wileyonlinelibrary.com]
in our case highly subjective because of fuzzy margins and hence unclear delineation of the bands.

Regarding this study, the quality and the light conditions of our used orthofotos were rather similar during all five stages which consequently should yield similar results. As band ogives may not disappear and reform away from the icefall it is questionable if the quality of some of the orthophotos used in the present study, but also by Herbst et al. (2006), was sufficient to detect all band ogives.

Despite these limitations we were able to map two band ogive systems related to flow units 1 and 2 for the stages 1998, 2006, 2009, and 2012. Band ogives were commonly best developed at the border zone between flow unit 1 and 2. The most widespread band ogives were mapped in 1998 at the flow unit 1 where dark and light bands were identifiable for about 3.5 km below the icefall. The optical data dating to stage 2003 allowed us to map even at flow unit 3 band ogives. The year 2003 was therefore the only stage between 1887 and 2012 where band ogives were mappable for all three different flow units of this glacier related to optimal light conditions of the analysed orthophotos.

Movement cessation and thrust faulting

Thrust faults with downslope convexity are a distinct feature of many valley glaciers with a substantial velocity decrease towards the glacier terminus causing horizontal shortening (Benn and Evans, 2010; p. 349). Thrusting causes the transport of englacial or subglacial debris to the surface. In the latter case this would indicate a complete cross-cut of a thrust from the subglacial to the supraglacial environment. Thrust faults at the Pasterze Glacier have been reported by Herbst et al. (2006) and Herbst and Neubauer (2000) noting that the thrusts at this glacier have up-slope dips of around 25° although sometimes steeper and oversteepend thrusts have been exposed in the past. Detailed structural mapping of the thrusts in 1997 by Herbst and Neubauer (2000) revealed that thrust planes exhibit systematic strike variations and are therefore to some extent spoon-shaped.

Figure 2(e) depicts an example of thrust faults with adjacent debris material. The accumulation of debris below thrust faults at Pasterze Glacier does not necessarily indicate something about the degree of activity at such faults. The progressive exposure of englacial debris by surface ablation also leads to the accumulation of debris at the thrust planes. Thus, active thrusting is not necessary at a melting and thinning glacier to increase the supraglacial debris cover. Thrusting is presumably even more active below the icefall at Pasterze Glacier where the highest flow velocities are measured (cf. Figure 3a; BSL) and where longitudinal gradients are greatest. However, clear evidence of thrusting are lacking at the surface below the icefall. Therefore, thrust faults which formed below the icefall could be passively-transported downglacier before being exposed by surface ablation. An alternative origin of the englacial debris which is released at thrust faults might be from supraglacial rockfalls above the equilibrium line (cf. Kirkbride and Deline, 2013). Pasterze Glacier lacks substantial supraglacial slopes at the main accumulation area Rifflwinkl (Figure 1) located above the icefall therefore this process is most likely of little relevance.

Visually thrust faults at the Pasterze Glacier increased in their spatial extent over time. Thrust faults have been reported by Herbst et al. (2006) in aerial photographs dating to 1969, 1978, 1991, and 1997. No large-scale thrusts have been reported by them in aerial photographs dating to 1983. During that time the Pasterze Glacier was flowing at a rather high rate compared with the decades before as revealed by the annual glacier monitoring campaigns (Wakonigg and Lieb, 1996; Lieb and Kellerer-Pirklbauer, 2018b). The area close to the glacier terminus was actively moving during the 1970s and 1980s causing no thrust-significant horizontal shortening.

At all five glacial stages thrust faults have been clearly identified in the orthophotos. However, one has to keep in mind that a thrust fault-structure is still visible after active thrusting and subsequent ice ablation. Therefore, we were not able in our mapping approach to distinguish between active and inactive thrust faults. Related to the combined occurrence of thrust faults and normal faults in identical areas, we can assume that thrust faults close to the terminus are surely inactive. Only the highest-elevated ones at the glacier tongue were possibly formed during the time when the aerial photographs were produced.

Signs of thrust faults at the Pasterze Glacier were visible at the stage 1969 at approximately only 100 m from the glacier terminus (Herbst et al., 2006). The area of thrusting increased and shifted upvalley during the subsequent stage with data (1978). During the 1970–1980 glacier advance period no thrust was reported at this glacier; at least according to the aerial photograph analysis published by Herbst et al. (2006). Later, during the 1991 and 1997 stages the area affected by thrust-fault occurrence increased dramatically. This glacier terminus becomes an obstacle during periods of negative mass balance allowing thrust formation close to the terminus (Herbst et al., 2006). As reported in our study, the areas affected by thrust faults shifted substantially upvalley between 1998 and 2012. However, when the glacier velocity in the central and lower part of the glacier is reduced to very low levels (as it was the case at the Pasterze Glacier; cf. Figure 3a(i)), the horizontal shortening and the subsequent thrusting became less effective. This deceleration of the glacier flow velocity led to the

![Figure 11.](image)

Figure 11. Relationships between the three cross-sections at the tongue of Pasterze Glacier where the annual horizontal glacier flow velocities are measured (data as presented in Figure 3): (a) SLL versus FWL; (b) BSL versus FWL; (c) BSL versus SLL. Significance: **P<0.01, *P<0.05.
inactive of active thrust faults and the overprinting of formerly thrusted areas by normal faults and ice collapse. Glacier velocity substantially declined during the observation period at the entire glacier tongue. A large number of brittle structures can be described as being increasingly independent from glacier motion and more related to glacier stagnation and disintegration. This hypothesis is supported by correlation analysis of the mean annual horizontal flow velocities. As shown in Figure 11, the lowest of the three cross-sections with velocity data (FWL) is not well correlated with the central (SLL) and high-elevated (BSL) ones indicating decoupling of the area close to the glacier terminus from the remaining glacier part in terms of glacier flow behaviour. Furthermore, DEM differencing revealed a strong correlation between high surface differences and spatial distribution of brittle structures.

Conclusions

Manual mapping and visual interpretation of five dates of high-resolution orthophotos covering the period 1998–2012 allowed a detailed quantification of the evolution of brittle and ductile structures of the glacier tongue of Pasterze Glacier. Band ogives were always visible at the larger north-easternmost flow unit. In contrast, band ogives were mapped only in 1998 at all three flow units during all of the 13 stages mapped since 1887. The quality of the imagery and maps used varied substantially. Even with optical remote sensing data of high-quality (good illumination, little shadowing) and high spatial resolution it is not straightforward to map glaciological features such as band ogives if their degree of development is fuzzy, which is, however, the nature of these features. This highlights the indispensable need for high-resolution and high-quality base data in such analyses, an aspect which is not easy to fulfil in long-term glacier structural analysis.

The total length of mapped brittle structures at the glacier tongue increased continuously between 1998 and 2009 and dropped slightly to 2012. At the same time, the areal coverage of the glacier tongue was reduced by 25%. The fracture density at the glacier tongue doubled between the stages 1998 and 2009 from 0.009 m/m² to 0.018 m/m². The almost identical values for stages 2009 and 2011 suggest that a value of 0.018 m/m² is an extreme value for such an alpine valley glacier. The degree of crevassing and faulting increased not only in its density but also in its spatial coverage as shown by glacier tongue-wide analyses of the distance to the nearest brittle structures for each stage.

The tongue of the Pasterze Glacier is currently slowly turning into a large, partly debris-covered dead ice body. This evolution is characterized by a strong decrease in ice replenishment from further upvalley indicated by a steady narrowing of the icefall, movement cessation, accelerated thinning and ice disintegration by supra-, en- and subglacial ablation allowing normal fractures and circular collapse features to develop.

Our study shows that the rapid thinning of a glacier tongue has a severe impact on the degree of fracturing. The degree of glacier thinning and recession is not evenly distributed in areas where a discontinuous debris cover is present. Discontinuous debris covers are, however, an increasingly typical feature of fading valley glaciers. Hence the role of differential ablation on the spatial pattern of glacier surface lowering and thinning and its impact on surface structures will increase.

Meltwater originating from direct ablation or water which drains into the glacier tongue plays an important impact on thinning glacier tongues. A process called subglacial stopping or block caving might lead to subglacial cavity formation and consequently glacier surface instabilities forming funnel-shaped, circular collapse features. Such features have been described so far only at rather few cases at large, rapidly receding and meltwater-channel-influenced alpine valley glaciers.

The example presented highlights a possible mode of rather rapid glacier ice disintegration by mainly normal fault formation of a glacier system where also large volumes of inflowing water contribute to the ablation in such a degree that circular collapse structures with concentric crevasses develop when the ice between the surface and the roof of water channels decreases. Eventually, the roofs might collapse. Considering predicted future glaciation changes, such glacier tongue scenarios are of high relevance for mid-latitude valley glaciers.

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References


Kaufmann V, Kellerei-Pirklbauer A, Kenyi LW. 2008. Gleitscherbewegungsphasen mittels Satellitengestützter Radar-


