Geomorphology 287 (2017) 58–72

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Funnel-shaped surface depressions — Indicator or accelerant of rapid glacier disintegration? A case study in the Tyrolean Alps

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ARTICLE INFO

Article history:
Received 30 July 2015
Received in revised form 9 November 2016
Accepted 9 November 2016
Available online 11 November 2016

Keywords:
Subglacial sediments
Glacier retreat
Surface ablation
Mass balance
Climate change

ABSTRACT

Alpine glaciers have been retreating at extreme and historically unprecedented rates. While the general course of regional retreat rates reflects long-term climatic change, individual extreme events are closely related to the geomorphological settings and processes of the specific glacier. Nevertheless, these extreme events also influence the regional means and might be an important feedback mechanism accelerating the response of glaciers to climate change. In 2009, during the recent disintegration of the terminus of Gepatschferner (46°52′30″N, 10°45′25″E), a shallow circular depression appeared at the glacier tongue with a decrease of surface ice flow velocity to almost nil. In 2015 the area was ice-free. During a heavy precipitation event in August 2012, a subglacial sediment layer of > 10 m was flushed out, which accelerated the subsidence of the ice surface.

The development of this 15 to 30 m deep depression was monitored with a combination of methods in high detail, including direct ablation measurements and a time series of seven high-resolution airborne laser DEMs, plus recordings of ice flow velocity and surface elevation with DGPS. The thickness of ice and sediment layers was measured with vibroseismic soundings in 2012 and 2013. Similar developments were observed at three other glaciers with extreme retreat rates. Our investigation suggests that this mechanism has a major impact on and can be read as an indicator of a nonlinear increased response of glaciers to climate change.

1. Introduction

The retreat of mountain glaciers is one of the most prominent and visible indicators of climate change (Vaughan et al., 2013). In the 21st century, retreat rates reached a historically unprecedented level (Zemp et al., 2015). Not all glacier types and sizes are affected similarly and simultaneously by climate change. In the Eastern Alps, apart from regional differences, large valley glaciers are most strongly affected, while smaller glaciers at high elevations retreat more slowly (Abermann et al., 2011). The reason for the higher sensitivity of larger glaciers is the role of ice dynamics: decreasing ice flow velocities reduce the inflow of ice into glacier tongues (Fischer et al., 2013), accelerating thickness loss more than the ablation rates. As, globally, velocity measurements are sparse and time series are short, the question that arises is whether this mechanism is accompanied by a geomorphological feature allowing a remote-sensing-based detection of such situations. One candidate for such an indicator is circular depressions surrounded by circular crevasses. These depressions with surrounding crevasses have been widely observed, the most prominent one at the Gjalp eruption site on Vatnajökull caused by glacier melt induced by subglacial volcanic activity (Björnsson, 2002). A subglacial lake formed, and lowering of the lake level resulted in subsidence of the glacier surface (Magnusson et al., 2007). Similar geomorphological features are reported by Howat et al. (2015) caused by an outburst of a subglacial meltwater lake beneath the Greenland Ice Sheet. On a smaller scale, a similar depression with circular crevasses formed by an outburst of a subglacial melt water lake was described by Konrad (1998) for a small mountain glacier in the Sierra Nevada. Subglacial drainage systems play an important role in storage and release of water (e.g. Nye, 1976; Funk and Röthlisberger, 1989; Hooke and Pohjola, 1994).

Apart from those depressions related to subsurface energy, surface depressions can also be related to the evolution of supraglacial lakes. There, increased heat flux towards the ice leads to the formation of

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http://dx.doi.org/10.1016/j.geomorph.2016.11.006

the depression (Huss et al., 2013). In the accumulation area, surface depressions can also be formed by wind erosion (e.g. Lehning et al., 2008; Dadic et al., 2010). The formation of these depressions is not accompanied by the formation of circular crevasses.

Srbik (1937) observed surface depressions with circular crevasses during the collapse of glacier tongues in the Eastern Alps during an earlier period of extreme glacier retreat. In contrast to the above described depressions, these were situated close to the glacier terminus. Tsutaki et al. (2011) found similar geomorphological features during the retreat of the Rhone glacier and recorded surface ablation, ice thickness, surface velocity as well as volume changes during two years of investigating the impact of proglacial lake formation on ice dynamics and glacier evolution. They found an increase in ice flow velocity related to the formation of a proglacial lake, which remained after the ice retreated.

The funnel-shaped depression can thus evolve from different supra-, intra- and subglacial processes. Detailed and quantitative observations of the evolution and processes on mountain glaciers are sparse, but needed for the interpretation of these features.

On the terminus of the extremely retreating Gepatschferner (46°52′30″N, 10°45′25″E, Ötztal Alps), a surface depression evolved during a larger project focusing on comprehensive investigations of the morphodynamics and sediment budgets (e.g. Heckmann et al., 2012). The detailed surveys of surface mass balance, surface elevation, thickness and thickness changes of the glacier and subsurface sediments provided a detailed record of the evolution of this surface depression from the early beginning to the disintegration of the glacier tongue.

Surface mass balance was measured directly, by readings of ablation stakes and results from energy exchange with the atmosphere and mass gain by snow falls (Cuffey and Paterson, 2010). Local thickness changes result not only from surface mass balance but also from englacial and basal mass balance, ice dynamics and basal erosion and deposition of sediment as well as changes in water level in case of subglacial lakes (Cogley et al., 2011). Seven high-precision laser scan DEMs allowed determining the geodetic mass balance by calculating volume changes. These volume changes thus reflect surface mass balance and englacial and basal processes, as reported during the evolution of subglacial lakes. The comparison of directly measured surface mass balance to geodetic mass balance gives an indication of the role of englacial and subsurface processes, which can be validated by changes in ice thickness and subsurface sediment revealed by vibroseismics. The surface ice flow velocity was measured at the ablation stakes with DGPS. Surface elevation between the dates of the LiDAR flights was also recorded with DGPS along profiles across the depression to gain a more detailed picture of the temporal evolution of the depression, giving the first direct and qualitative process study of the formation of a circular depression on the terminus of a mountain glacier. The phenomenon of surface depression, followed by a collapse of the glacier tongue, at Gepatschferner is compared to three similar features at other extremely retreating Eastern Alpine glaciers. Although further data in other regions and for other glacier types are needed, the results can serve as a starting point for a discussion of the interpretation of depressions as indicators for extreme glacier retreats from remote sensing images, where neither repeat imagery nor elevation information is available.

2. Study sites

Gepatschferner is situated in the Ötztal Alps and mainly exposed to the north. The glacier covered an area of 15.6 km^2 in 2012. Together with the Italian part of the glacier (the Austrian – Italian border follows the ice divide at the plateau), Gepatschferner is the largest glacier of the Eastern Alps. The flow velocity of the tongue is still very high with maximum values of >50 m per year due the large firn area above 2900 m a.s.l. and the massive ice mass is moving towards a narrow outlet valley where the tongue has an average width of about 300 m down to an elevation of 2200 m a.s.l. The tongue is exposed to the northwest and reaches a thickness of >100 m (Span et al., 2005) and surface velocities of up to 50 m per year before it turns to the west in the lowest part. The surface depression is located at the lowest part of the tongue, where the surface velocity slows down to almost nil (<1 m/a). The depression occurred on the orographic right of the tongue at about 2300 m a.s.l., close to the glacier margin (Fig. 1, Annex A1). The extent of the depression on Gepatschferner and the changes therein are compared to the depressions on the nearby glaciers Mittelbergferner, Sulztalferner and Hintereisferner (Fig. 1).

The surface depression on Mittelbergferner (46°55′50″N, 10°54′8″E, Pitztal Alps) is located directly at the snout of the glacier (Annex A2). The glacier itself is a typical valley glacier and covered an area of 9.9 km^2 in 2006. The smallest of the four glaciers is Sulztalferner (47° 0′35″N, 11° 4′50″E, Stubai Alps), with an area of 3.7 km^2 in 2006, the funnel occurred at the very flat part of the glacier tongue (Annex A3). The depression on Hintereisferner (46°48′35″N, 10°46′55″E, Ötztal Alps) is also located close to the terminus (Annex A4). Hintereisferner is a typical valley glacier and covered an area of 7.5 km^2 in 2006. All of these glaciers showed extreme retreat rates in recent years (Fischer et al., 2013). Information about the extent of the glaciers is given by the Austrian glacier inventories (Patzelt, 1980; Groß, 1987; Lambrecht and Kuhn, 2007; Kuhn et al., 2012; Fischer et al., 2015).

3. Methods

3.1. Airborne laser scans

DoDs (DEM of Difference) between multiple high-resolution ALS (Airborne Laser Scan) data (Abermann et al., 2010; Wheaton et al., 2010) were calculated and revealed elevation changes (resulting from basal and surface melt, ice flow and changes of subglacial sediments). DEMs with a grid size of 1 × 1 m were generated from the mean elevation value of the point clouds and are available for the years 2006, 2009, 2010, 2011, two datasets in 2012 and 2014 within an area (circle) of 80 m radius around the centre of the depression. The basis for a calculation of DoDs is, first, the same resolution of each grid and, second, the same reference system (in this study: ETRS89 UTM 32N). An exact overlay of the individual cells of each raster is a basic requirement for calculating raster differences. The DoDs were calculated with ArcGis software by using the tool 'minus (spatial analyst)'.

Given the size of the depression, the area of interest was defined as a circle (A_c) with a radius of 80 m (below referred to as '80 m circle') around the maximum elevation change (centre of the depression) for the period 01.09.2006–18.07.2014 as a reference area for the definition of the depression. The size of the depression (A_d) is defined as the area within a boundary of 20% higher elevation changes than the mean elevation change within the whole 80 m circle ($\overline{\Delta h_c}$). Since there is no similar study in the literature, tests with different threshold values were made. The value of a mean elevation change plus 20% was chosen to separate increased elevation changes at the depression area from the range of elevation changes of the surroundings, which in turn allows a comparison of the different DoDs. So the depression is defined as the area where elevation decreased by >20% of the average decrease observed in the 80 m circle. Values higher or lower than 20% either excluded too much of the depression area or included even surrounding features. In addition, area and volume changes were calculated for the whole period (01.09.2006–18.07.2014), based on a depression with a $\overline{\Delta h_c} + 5\%$ boundary (* in Tables 1,2). The area between the depression and the defined boundary of the 80 m circle is defined as the ring (A_r) and represents the area outside the depression. Subglacial changes within the area of

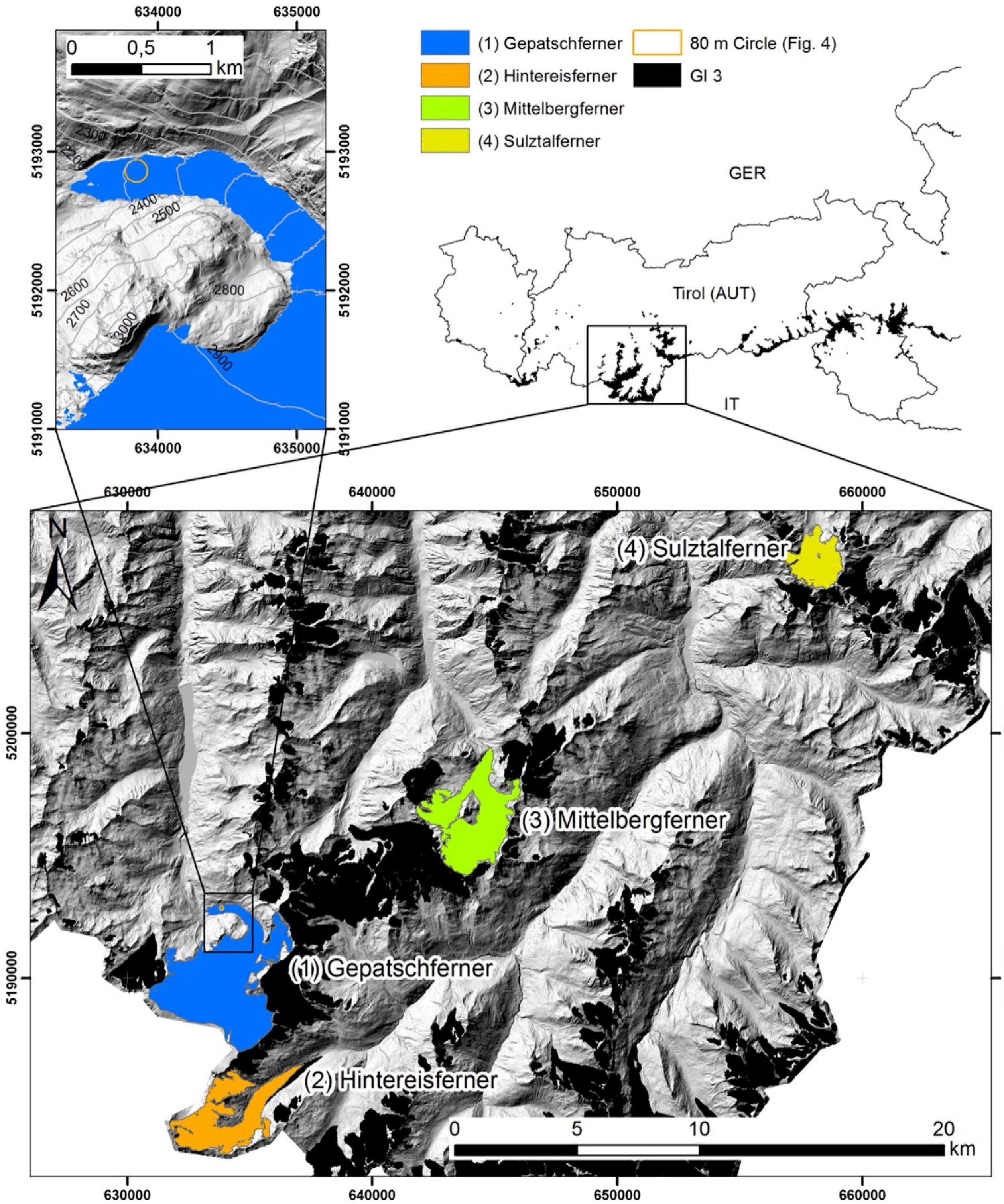


Fig. 1. Overview of the locations of Gepatschferner (1), Hintereisferner (2), Mittelbergferner (3), and Sulztalferner (4) and the location of the depression on Gepatschferner at the 80 m circle (Fig. 4) (background: Hillshade 2006). GI3: Third Austrian Glacier Inventory (Fischer et al., 2015).

the depression ($\overline{\Delta h_c} + 20\%$ and $\overline{\Delta h_c} + 5\%$) were calculated from the total volume changes within the depression (ΔV_d) less the volume changes calculated with a mean elevation change of the ring ($\overline{\Delta h_r}$) but related to the area of the depression (A_d). The information of mean volume changes per day was chosen to make the different timescales of the ALS periods comparable.

3.2. Surface mass balance

Direct (glaciological) mass balances (Cuffey and Paterson, 2010) have been recorded at the tongue of Gepatschferner since 2009 with the help of ablation stakes. One of the stakes was installed very close to the later surface depression, which first became evident as a shallow

Table 1
Mean elevation changes within the 80 m circle ($\overline{\Delta h_c}$), the ring ($\overline{\Delta h_r}$) and the depression ($\overline{\Delta h_d}$), as well as the maximum elevation change within the depression. A_d: Area of the depression ($\overline{\Delta h_c} + 20\%$). A_r: Area of the ring (the area between the 80 m circle and the beginning of the depression in Fig. 4). Area of the circle: 20,073 m². * calculated for the depression $\overline{\Delta h_c} + 5\%$.

Period			A_r (m²)	A_d (m²)	$\overline{\Delta h_c}$ (m)	$\overline{\Delta h_r}$ (m)	$\overline{\Delta h_d}$ (m)	Δh_d max. (m)
30.09.2009	–	18.07.2014	18,392	1681	−28.8	−27.7	−39.9	−47.0
28.09.2012	–	18.07.2014	17,754	2319	−11.4	−10.7	−16.6	−22.6
04.07.2012	–	28.09.2012	17,567	2506	−6.2	−5.8	−9.4	−15.4
07.10.2010	–	04.07.2012	17,859	2214	−4.7	−4.5	−6.5	−7.8
30.09.2009	–	07.10.2010	17,916	2157	−6.4	−6.2	−8.5	−9.5
01.09.2006	–	30.09.2009	$\Delta h_d < (\overline{\Delta h_c} + 20\%)$		−20.4			
01.09.2006	–	18.07.2014	18,978	1095	−48.9	−48.1	−63.5	−68.8
01.09.2006	–	18.07.2014	16,723*	3350*	−48.9	−47.2*	−57.3*	−68.8

deepening at the end of 2009. The ablation was measured and the position of the stake was reinstalled regularly until 2014. In 2013, a new stake was installed outside the depression.

3.3. Vibroseismics

Vibroseismic investigations came into operation as part of a field campaign to investigate the thickness of subglacial sediment layers on the tongue of Gepatschferner. Measurements with the ELVIS vibrator source (Eisen et al., 2010; Polom et al., 2013) at 71 geophones on a profile length of 142 m within a sweep of 10 s in a frequency range between 30 Hz and 240 Hz were performed in April 2012 and repeated in April 2013 (30 Hz–160 Hz) at the same locations marked with DGPS. The processing of the vibroseismic data was done with 'SPW' (Seismic Processing Workshop) software separated into pre-processing, signal enhancement, velocity analysis and stacking, post stack processing and the depth conversion and migration. The depth conversion from the signal travel time is based on the calculation of the 'Dix' velocities on a depth interval of 0.1 m. The seismic section was interpreted in relation to the surrounding topography and the DGPS measurements at the bottom of the depression. The verification of the interpretation of the bedrock topography was done in 2015 as the depression became ice free (Annex A5).

3.4. DGPS measurements

Surface elevation and the positions of the ablation stakes were recorded with DGPS (Gepatschferner: Topcon Hiper V; Hintereisferner: Trimble Zephyr 2). The elevation change was calculated with a DoD.

The depression on Hintereisferner was subject to investigations using DGPS and DoDs (Haberkorn, 2011). The DoD of this area was recalculated (Annex A4). On Sulztalferner the depression occurred after the latest available DEM, therefore the size and temporal development is estimated from terrestrial and aerial photos.

3.5. Errors and accuracy

The accuracy of the direct stake measurements is assumed to be ±0.01 m of each reading and ±0.02 m for the period between the readings. The extrapolation of the ablation to the surrounding area reduces the accuracy of specific mass balance to ±0.1 m w.e. (Kuhn et al., 1999).

The vertical uncertainty of the DGPS measurements varies in time and depends on the processing methods (Monteiro et al., 2005). On Gepatschferner, the accuracy with post-processing was ±0.1 m at its best. With the further development of the depression and shading effects, the uncertainty of the point measurements was ±1.5 m at its worst, giving a range of ±0.2 m to ±3 m for the elevation changes determined with DGPS. Note that the accuracy of the direct stake reading refers only to the surface ablation. The accuracy of the DGPS measurements refers to the total elevation change at the stake, which is important with respect to the DEM surface.

For the DoDs the vertical accuracy is ±0.4 m or ±0.2 m for each DEM (Bollmann et al., 2011). The ALS surveys of 2012 and 2014 were aimed at higher point densities (10 points/m²) and thus higher accuracies of the raster DEMs, which should be in the range of ±0.04 m for the DoD.

Information on the accuracy of vibroseismic soundings using a shear-wave vibrator is problematic for the profile at the surface depression and can only be estimated due to the missing information of the shear-wave velocities for subglacial sediments, the bedrock and the unknown but expected high complexity of the surrounding topography and because of the limited length of the profiles, especially in 2013. An accuracy of 10% of the ice thickness or ±5 m at the profile on Gepatschferner seems a plausible estimate and is confirmed by the verification of the interpretation in 2015 (Annex A5).

4. Results

4.1. Mass balance and ice flow velocity

The surface velocity at the stake decreased between 2009/10 and 2013/14, during the first years the velocity was about 16 m per year,

Table 2
Volume change per day within the 80 m circle (ΔV_c), the ring (ΔV_r), the depression (ΔV_d) as well as a calculated subglacial volume change per day. *calculated for the depression $\overline{\Delta h_c} + 5\%$.

Period			Days	ΔV_c [m³]	ΔV_r [m³]	ΔV_d [m³]	ΔV_d subglacial [m³]
30.09.2009	–	18.07.2014	1752	−330	−291	−38	−12
28.09.2012	–	18.07.2014	658	−348	−289	−59	−21
04.07.2012	–	28.09.2012	86	−1447	−1185	−274	−105
07.10.2010	–	04.07.2012	636	−148	−126	−23	−7
30.09.2009	–	07.10.2010	372	−345	−299	−49	−13
01.09.2006	–	30.09.2009	1125	−364	$\Delta h_d < (\overline{\Delta h_c} + 20\%)$		
01.09.2006	–	18.07.2014	2877	−341	−317	−24	−6
01.09.2006	–	18.07.2014	2877	−341	−274*	−67*	−12*

Table 3
Distance [m] and horizontal flow velocities [cm/d] of the ablation stake between each position along the cross-profile (Fig. 2).

Position	Distance [m]	Velocity [cm/d]	Position	Distance [m]	Velocity [cm/d]
1 – 2	8.1	7	8 – 9	7.9	3
2 – 3	16.0	5	9 – 10	0.1	2
3 – 4	Relocated		10 – 11	0.9	4
4 – 5	3.8	6	11 – 12	Relocated	
5 – 6	10.5	4	12 – 13	0.3	1
6 – 7	2.4	6	13 – 14	8.7	1
7 – 8	3.0	7			

decreasing to 10 m per year in 2011/12 and to almost nil with <1 m per year in 2013/14 (Table 3). The positions 3 and 4 (Fig. 2) belong to the same date (11.08.2010) as the stake was reinstalled up-glacier close to its original position.

The ablation at the stake decreased with time, as the steep ice walls of the funnel shaded the bottom of the depression. 1.09 m of ice melt was recorded during the presence of the supraglacial lake, in contrast to 3.26 m of ice melt during the same period at the stakes outside the sink, a reduction of 66% of the surface ablation under a large water column and shading effects.

4.2. Volume changes

In order to quantify the magnitude of the elevation changes as the depression developed, the DEM of 2006 was chosen as the reference before the onset of the deepening. Mean volume changes per day where calculated for the area within a radius of 80 m around the centre of the depression since 01.09.2006 (Figs. 3,4). The flight dates of the ALS campaigns are shown in Fig. 3 together with the mean values of each period. The elevation and volume change rates are given in Table 1 and Table 2. The mean volume change per day between 01.09.2006 and 18.07.2014 is -341 ± 2 m^3 within the 80 m circle, which corresponds to a mean elevation change of -48.9 ± 0.2 m between the two dates. The maximum value, which is located in the middle of the depression, amounts to -68.8 ± 0.2 m during the same period (01.09.2006–18.07.2014). The period in summer 2012 (04.07.2012–28.09.2012) shows a strongly negative value of -1447 ± 9 m^3 per day for the whole area, corresponding to a mean elevation change of -6.2 ± 0.1 m within 86 days. The maximum change of the surface height was -15.4 ± 0.1 m during the same period (04.07.2012–28.09.2012). The subglacial volume change, by separating the volume changes between the depression and a mean elevation change of the ring related to the area of the depression, amounts to -105 ± 6 m^3 per day between 04.07.2012 and 28.09.2012.

4.3. Thickness of ice and basal sediment

About half of the vibroseismic profile in 2012 lies in the depression (the location of the profile is shown in Fig. 4a). In 2013 the measurements were limited to the lower part of the profile, which is located outside of the sink, because of the steepness of the depression and the supraglacial lake. The interpretation of the vibroseismic sections of 2012 and 2013 shows the bedrock and subglacial sediment layers (Figs. 5,6). The lines 1 and 2 represent the glacier surface measured with DGPS at each Geophone in 2012 and 2013; the dots mark the bottom of the depression in August 2013 and June 2014 measured with DGPS. The bedrock of the interpretation of 2012 and 2013 is represented by the lines 3 and 4. The interpretation of the bedrock topography in 2012 and 2013 shows differences of up 7 m, which is still in the range of the accuracy of this method. The interpretation of the vibroseismic sections was done with respect to the point measurements at the bottom of the depression and the proximity of the glacier margins and gives a maximum ice thickness of 48 ± 5 m in 2012 and sediment layers with a maximum thickness of 20 ± 5 m.

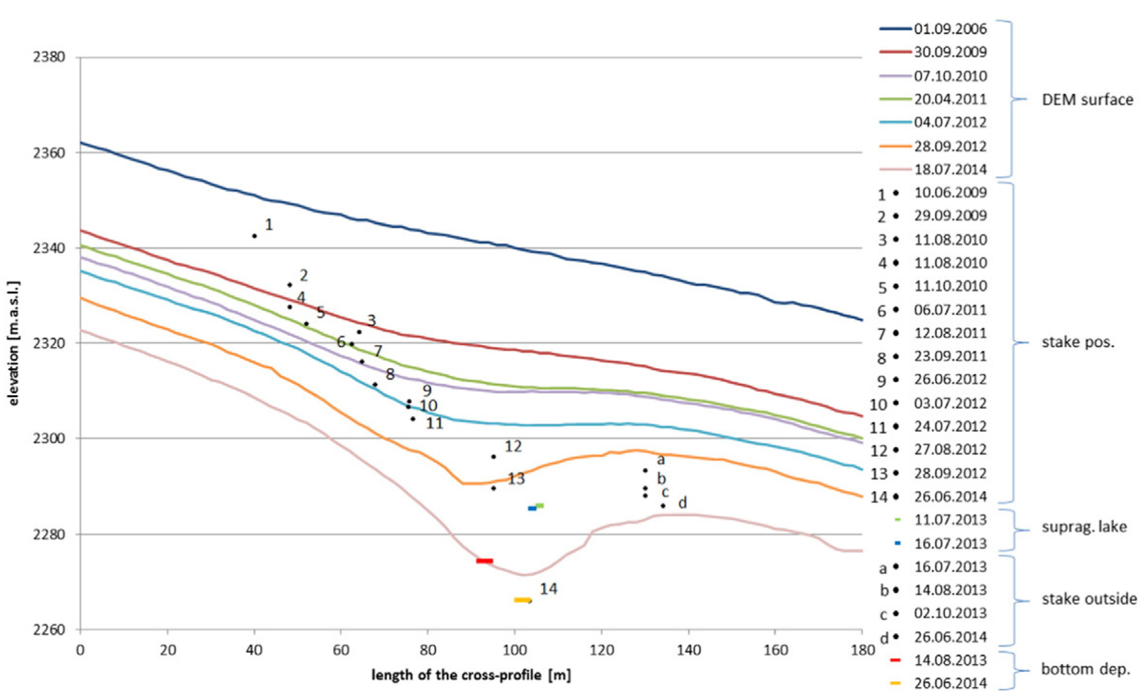


Fig. 2. Elevations of the DEMs along the cross-profile (shown in Fig. 4) and position of the stakes, the elevation of the supraglacial lake and the bottom of the depression as well as the position of a new stake outside the depression. The positions of the ablation stake and additional measurements with DGPS along the profile show the ongoing development until 2014.

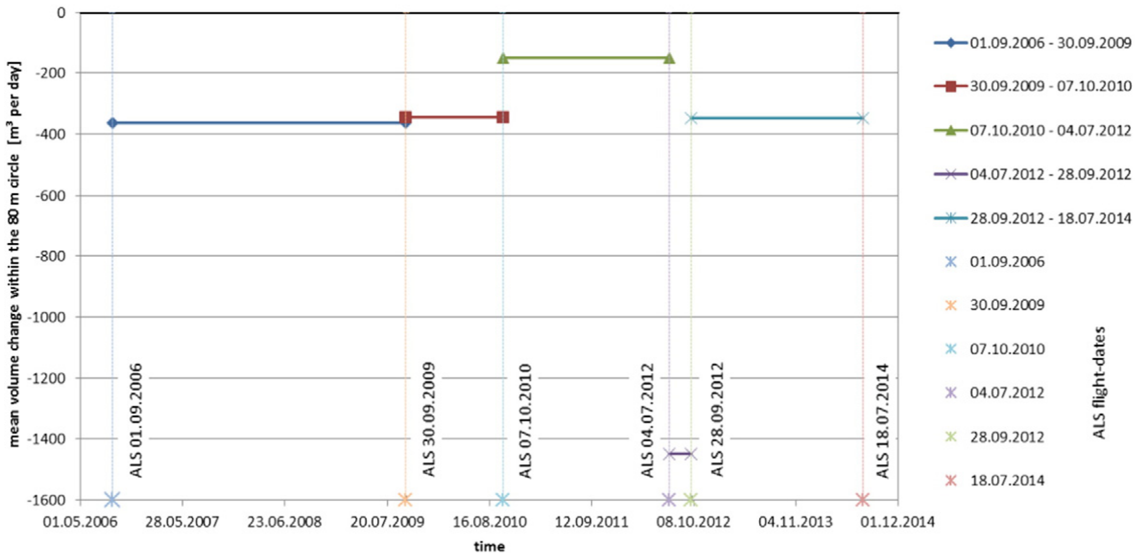


Fig. 3. Mean volume changes per day of the DoDs (DEM of Difference) between the different ALS flights within the 80 m circle (20,073 m^2).

4.4. Comparison of geodetic and direct measurements

For a comparison of changes from DoDs and direct stake readings and DGPS measurements, the different time periods must be taken into account. Mean daily change rates were calculated for the DoDs (Table 2). The height differences of the ablation stake to the surface of the DEM in 2006 along the cross-profile (Figs. 2,4) between each measurement date are shown in Fig. 7. The height difference of the DEM 2006 surface to the supraglacial lake and to the bottom of the depression is also shown in Fig. 7. The maximum subsidence, calculated for the stake measurements, was 16.6 ± 1.5 cm per day for one month (27.08.2012–28.09.2012) with a starting point just after the heavy precipitation event.

4.5. Heavy precipitation event

The acceleration of the sink process started after a heavy precipitation event on 25.08.2012, with a maximum flood at 1:00 am on 26.08.2012 and a peak discharge of 47.3 $m^3 s^{-1}$ (mean discharge 2012: 3.42 $m^3 s^{-1}$) at the gauging station Gepatschalm in the forefield of Gepatschferner (Baewert and Morche, 2014). Precipitation was measured at two weather stations, Gepatschalm and Weißsee, which are located about 3 km and 3.5 km away from Gepatschferner. Between 06:30 pm (25.08.2012) and 01:15 am (26.08.2012), the measured precipitation amounted to 37.6 mm and 38.1 mm at the two stations.

4.6. Supraglacial lake

During the winter months 2012/13 a supraglacial lake filled the depression (Annex A1), indicating the closure of the drainage system during winter months (e.g. Stenborg, 1965). The surface level of the lake was also measured with DPGS in July 2013 and returned variations of up to 0.5 m within 1 day. Between 17.07.2013 and 14.08.2013 the lake emptied and the bottom topography was surveyed with DPGS (Fig. 2) representing the depth of the funnel-shaped surface depression at its maximum depth. The difference between the lake surface on 16.07.2013 and the bottom on 14.08.2013 was −11.6 ± 1.6 m (estimated water volume: 1250 ± 200 m^3, diameter surface: ca. 15 m, diameter bottom ca. 8 m).

5. Discussion

The shallow deepening started in 2009 and slowly progressed until August 2012, with subsequent acceleration of the sink process. The process is indicated by the decrease in surface elevation, shown along a cross section in Fig. 2. The DEM in 2006 shows no surface depression and the slope was nearly constant along the profile. In July 2014 a distinct depression is visible (Fig. 2). For the calculation of the depth of the depression, the lowest elevation within the depression is compared to the elevation of a straight line extrapolating a constant inclination of the ice surface in the surrounding of the depression. In July 2014 the lowest point of the depression was 26 m lower than the flat surface extrapolated from the surrounding slope. The cross section, defined at the beginning of the measurements, did not in the end run across the deepest point of the depression. The ablation stake at position 14, which was drilled at the deepest point, was about 6 m lower than the lowest point of the profile. All other stakes were located within the profile, showing a continuous deepening of the depression at variable speed.

Surface elevation changes result from surface mass balance as well as from basal and englacial processes and from ice dynamics. To confine the contribution of basal and englacial processes to the total volume change, surface mass balance can be estimated from the stake measurements. The recorded ablation rates are lower than 10 cm/day. The daily subsidence rates are similar to the ablation at all times, apart from the summer of 2012, when subsidence was several times the ablation.

In contrast to increased flow velocities reported by Tsutaki et al. (2011), we found a decrease of the surface velocity from seven to 1 cm per day over time, apart from the period with the extreme precipitation event (Table 3). The stake at position 12 was measured shortly after the extreme precipitation event documented by the precipitation records. The subsidence as well as the horizontal ice flow velocity in this period was the highest recorded (Fig. 2). As surface mass balance did not show significant changes, a significant impact on the subsidence can be attributed to the internal and subglacial changes. The relocation of the glacier river (Annex A6) and significant changes in the proglacial morphology (Baewert and Morche, 2014) are other indications of basal processes causing sediment erosion. The results of the vibroseismic measurements exclude changes in water and air content beneath the ice.

During the presence of the supraglacial lake, the surface ablation of the water-covered ice surface was reduced. This reduction can be explained with the reduced incoming short wave radiation due to shading

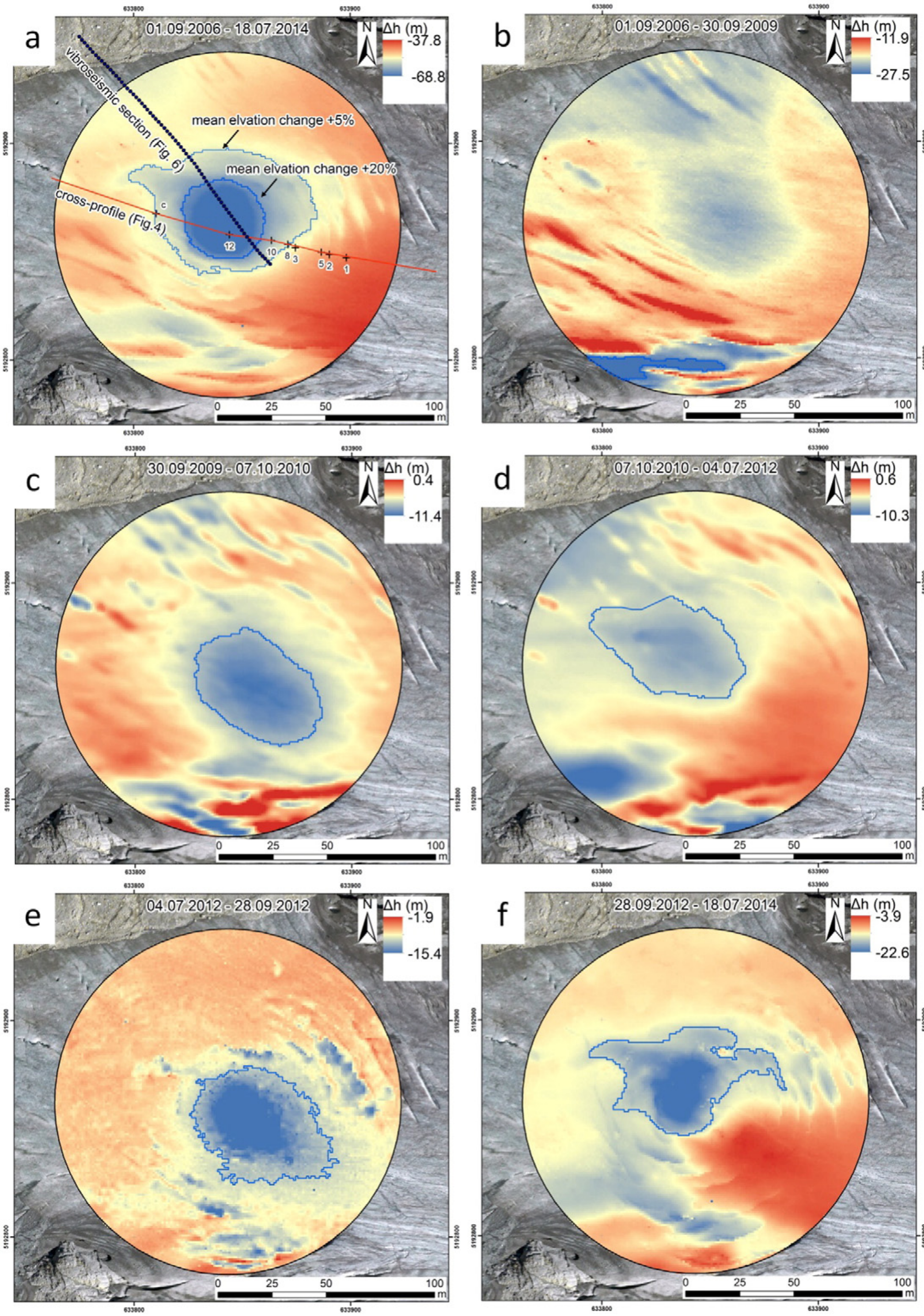


Fig. 4. DoDs (DEM of Difference) between 01.09.2006 and 18.07.2014 within the 80 m circle on the tongue of Gepatschferner (Fig. 1). The location of the ablation stakes at the cross-profile (Fig. 2) through the depression is shown as well as the location of the vibroseismic profile (Fig. 6).

at the lake by steep ice walls. The increased surface ablation measured at the supraglacial lake on Glacier de la Plaine Morte by Huss et al. (2013) might result from different radiative settings.

The vibroseismic data are interpreted on the assumption of different substrates with different signal velocities. The complex topography and interference from multiple reflections from the surrounding slopes introduce additional uncertainty. Discussing these becomes even more important at the short profile in 2013. In July 2015 the bottom of the depression became ice-free and even the subglacial meltwater channel became visible at the back of the depression as well as a solid rock in front of it (Annex A5).

A time series of images shows the development of the geometry of the funnel since 27.08.2012 (Annex A1) as well as the 3D model of the DEM since 2006 (Annex A7). This confirmed the vibroseismic

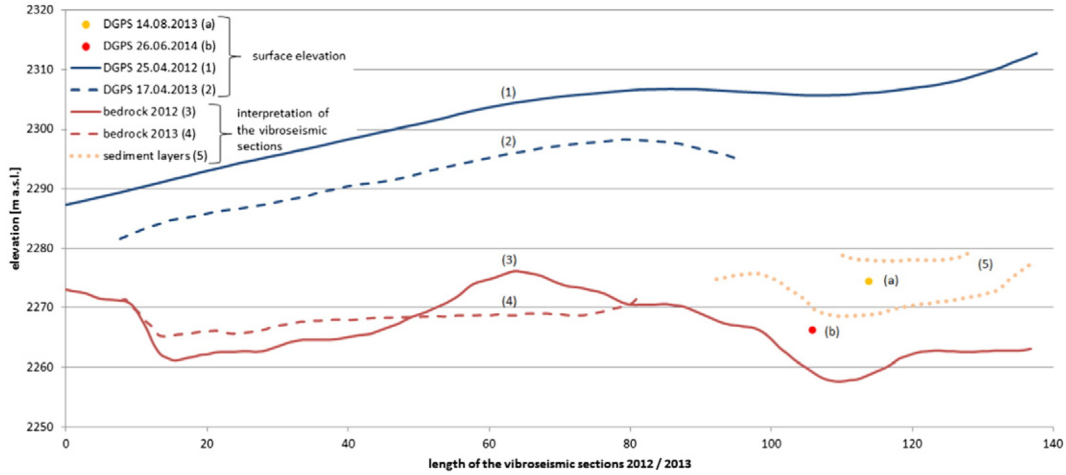


Fig. 5. Interpretation of the vibroseismic sections (3, 4) in 2012 and 2013 (location s. Fig. 4a). The lines 1 and 2 show the glacier surface measured with DGPS at each Geophone in 2012 and in 2013. The bottom of the surface depression measured with DGPS is given as dots (a, b), the location of sediment layers of 2012 as dotted lines (5).

interpretation. The remaining ice-thicknesses were plausible regarding the ongoing retreat of the tongue (Annex A6). The thickness of the subglacial sediment layers fits with the magnitude of the elevation change during the sink process. Based on the accuracy of the measurements, a remaining error of ±10% (max. ±5 m) for the bedrock and the sediment layers has to be taken into account. The displacement of a subglacial meltwater channel during a heavy precipitation event and the evacuation of subglacial sediments were earlier reported by Haeberli (1980) and Warburton (1994). The dislocation is also possible with respect to the complex topography which becomes ever more evident as the tongue retreats further (picture in Annex A6).

5.1. Comparison with depressions at other glacier tongues

Since the year 2000, the retreat of Gepatschferner has clearly been above the average of the surveyed Austrian glaciers (Fischer et al., 2013; Annex A8). Between 2013 and 2015, Gepatschferner was one of the glaciers with the largest absolute length losses, amounting to about 100 m per year. The extreme retreat rates occurred simultaneously with the depression. As a first check if the formation of depressions could be considered a geomorphological feature intrinsically linked to rapid retreats or even a mechanism behind large retreat rates, we analysed depressions at three other glaciers.

The funnel at the snout of Mittelbergferner (Annex A2) had a diameter of approximately 250 m and the elevation changed continuously in total to about −80 m within 9 years (DoD 1997–2006) in contrast to −28 m at the surrounding area of the tongue during the same period, leading to a difference of more than five meters per year. The specific topography with a bedrock sill in the front, lateral water inflow of the main meltwater discharge of a neighbouring glacier and technical measures by actors from a glacier ski resort to reduce snow and ice ablation (Olefs and Fischer, 2008) at the terminus reinforced the formation of this depression. The length change of Mittelbergferner is not surveyed annually, but the loss of glacier length can be estimated from the glacier inventories (Fischer et al., 2015) at about −20 m per year (from 1997 to 2015) and therefore also above average.

On Sulztalferner (Annex A3) a sink developed in 2007 on the very flat part of the tongue shortly after a steep slope and another sink in 2008 in the immediate proximity of the first one. Each of them developed within one year, with an elevation change of about 20–30 m and diameters of up to 125 m. The main process of the formation of these depressions was triggered by the subglacial drainage system, lateral inflow and the formation of subglacial lakes, which became visible with the ongoing retreat. In 2011 the whole area became ice free. Sulztalferner showed its largest length changes in 2005 and 2007.

On Hintereisferner (Annex A4) a shallow depression became visible in 2004 and has developed continuously since. The DoD of 26.09.2003–

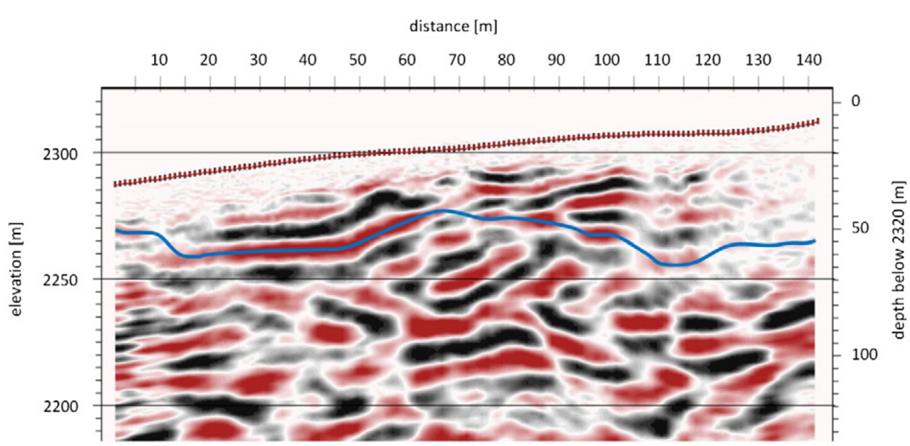


Fig. 6. Interpretation of the bedrock topography on the seismic section in 2012.

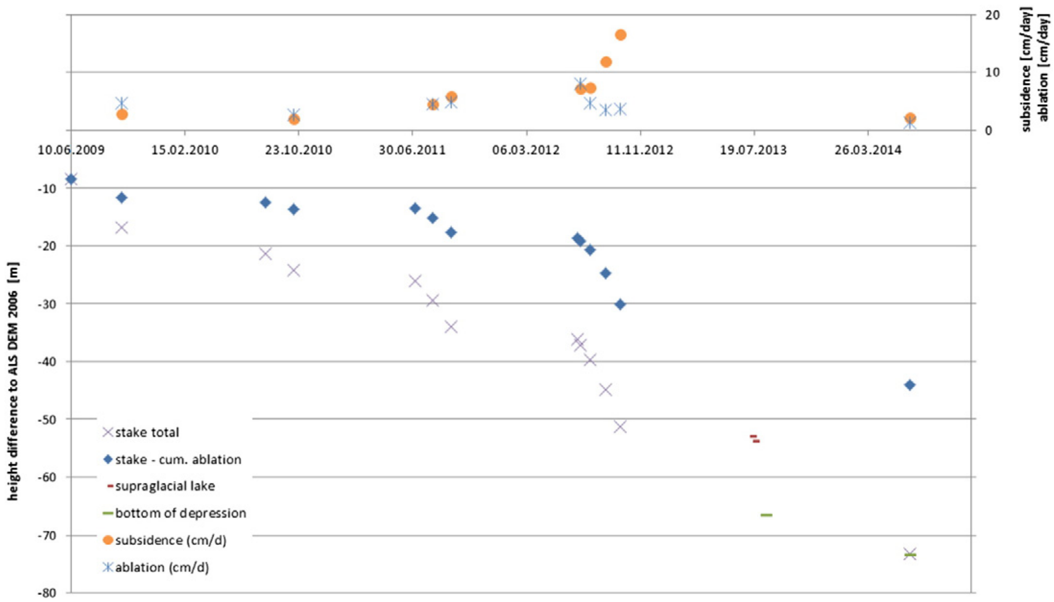


Fig. 7. Height differences of the stakes, the supraglacial lake and the bottom of the depression, compared to the ALS DEM of 2006 (left y-axis). 'Stake total': total difference between the stake elevation and the surface of the DEM 2006; 'stake – cum. ablation': 'stake total' minus the cumulative ablation. Lowering of the stake and ablation at the stake between each period per day (right y-axis).

30.09.2009 shows maximum elevation changes of −34 m within the depression in contrast to −28 m during the same period at the surrounding area calculated with the DoD, DGPS and ablation stake measurements (Haberkorn, 2011), which leads to a difference in the surface lowering of 1 m per year between the depression and the surrounding area for six years. The maximum elevation change in the whole region between 2580 m a.s.l. and 2620 m a.s.l. was −36.1 m and was found on the orographic right of the tongue as a deep meltwater channel began to form (Annex A4). The depression is still far from the terminus and Hintereisferner shows the lowest retreats of all glaciers.

What all of these depressions have in common is the location on glacier tongues close to the terminus where surface velocities are low and decreasing. The depressions are surrounded by circular crevasses indicating the subsidence. In all the depressions formation began with a slow progress in the early stage, except the depression on Sulztalferner, which developed within one year as part of the collapse of the flat part of the tongue during a phase when the tongue was separated from the upper part of the glacier.

All three funnels observed are underlain by rivers that move sediments at a higher rate. Temporary accumulation may then easily be eroded by water input following a heavy precipitation event. On Mittelbergferner and Sulztalferner the thermal heat delivered by lateral inflow of rivers could be the cause of higher basal melt rates and subglacial erosion. In an event of sudden sediment evacuation the overlying ice loses support and succumbs to fill the void, leaving a nearly circular funnel at the glacier surface.

6. Conclusion

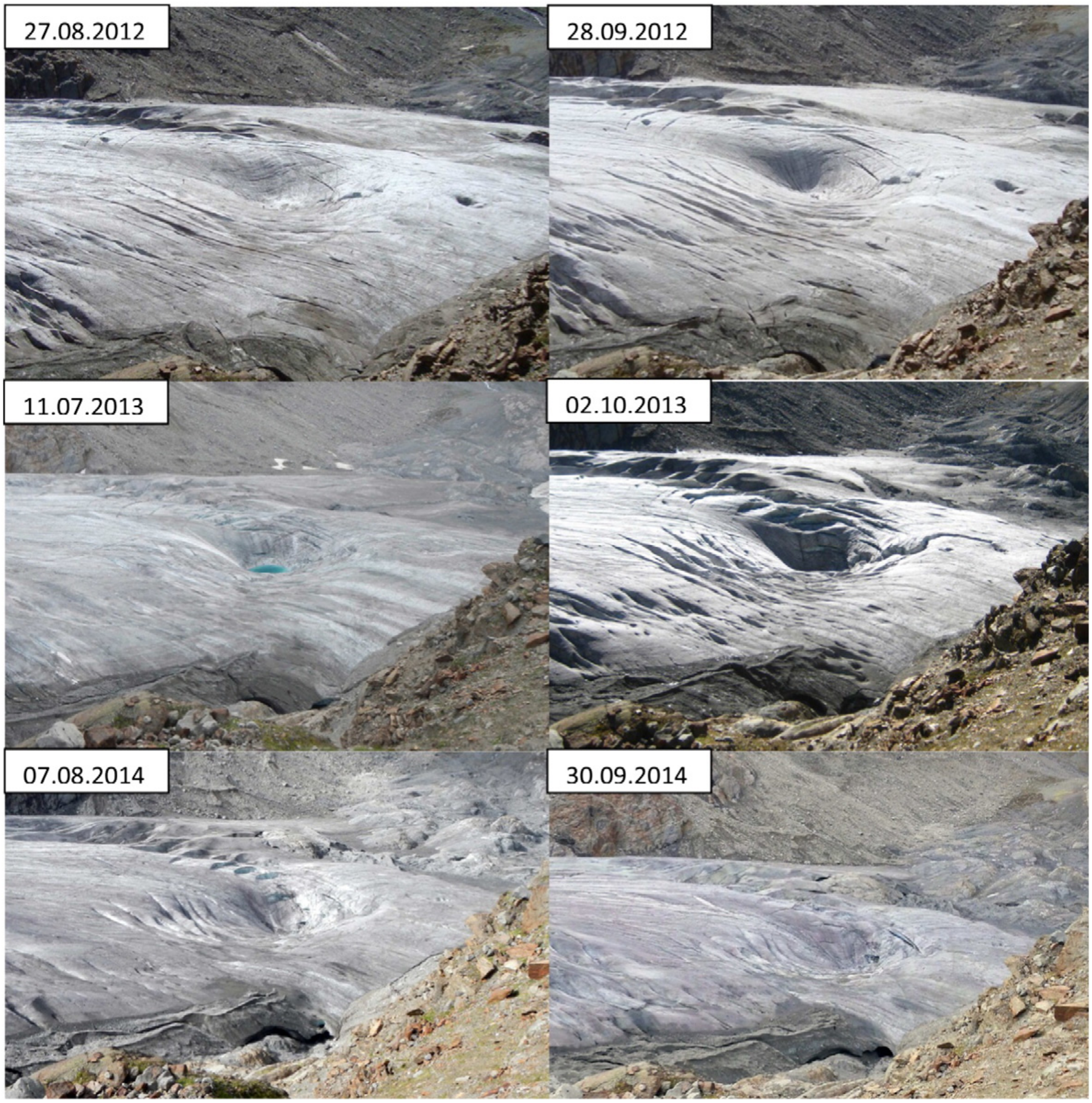
In this paper we traced the development of a deep funnel-shaped surface depression on the tongue of Gepatschferner on the basis of high resolution ALS data, DGPS measurements, vibroseismic soundings and direct glaciological investigations. A slow but steady evolution of the depression on Gepatschferner was followed by a rapid increase of the formation after a heavy precipitation event. The acceleration peaked with a subsidence of 16.6 ± 1.5 cm per day for one month (27.08.2012–28.09.2012) and resulted in a depression with a maximum depth of about 30 m. The acceleration very likely forced by the erosion of subglacial sediments during a flood event in August 2012.

The history of the retreat of Gepatschferner has been measured and documented in more detail than that of other Alpine glaciers, especially at the surface depression. Short-term measurements were performed on the tongue of Hintereisferner, while observations indicate similar behaviour of the funnels on Mittelbergferner and Sulztalferner. Their tongues still move at considerable speed and transport ice over an altitudinal range in the order of 1000 m. In that sense, while they are retreating, they are still actively adjusting to a changing climate. What we measured and observed on the tongue of Gepatschferner is thus applicable to other large, active, but retreating, glaciers and to their forefield. The situation is different with glaciers of a small altitudinal range and low flow velocities. We conclude that altitude range, subglacial water flow or later water inflow are essential criteria for the emergence of funnels on glacier tongues. Whether the occurrence of depressions can be considered an indicator of extreme retreat can only be verified after further investigations on other glaciers.

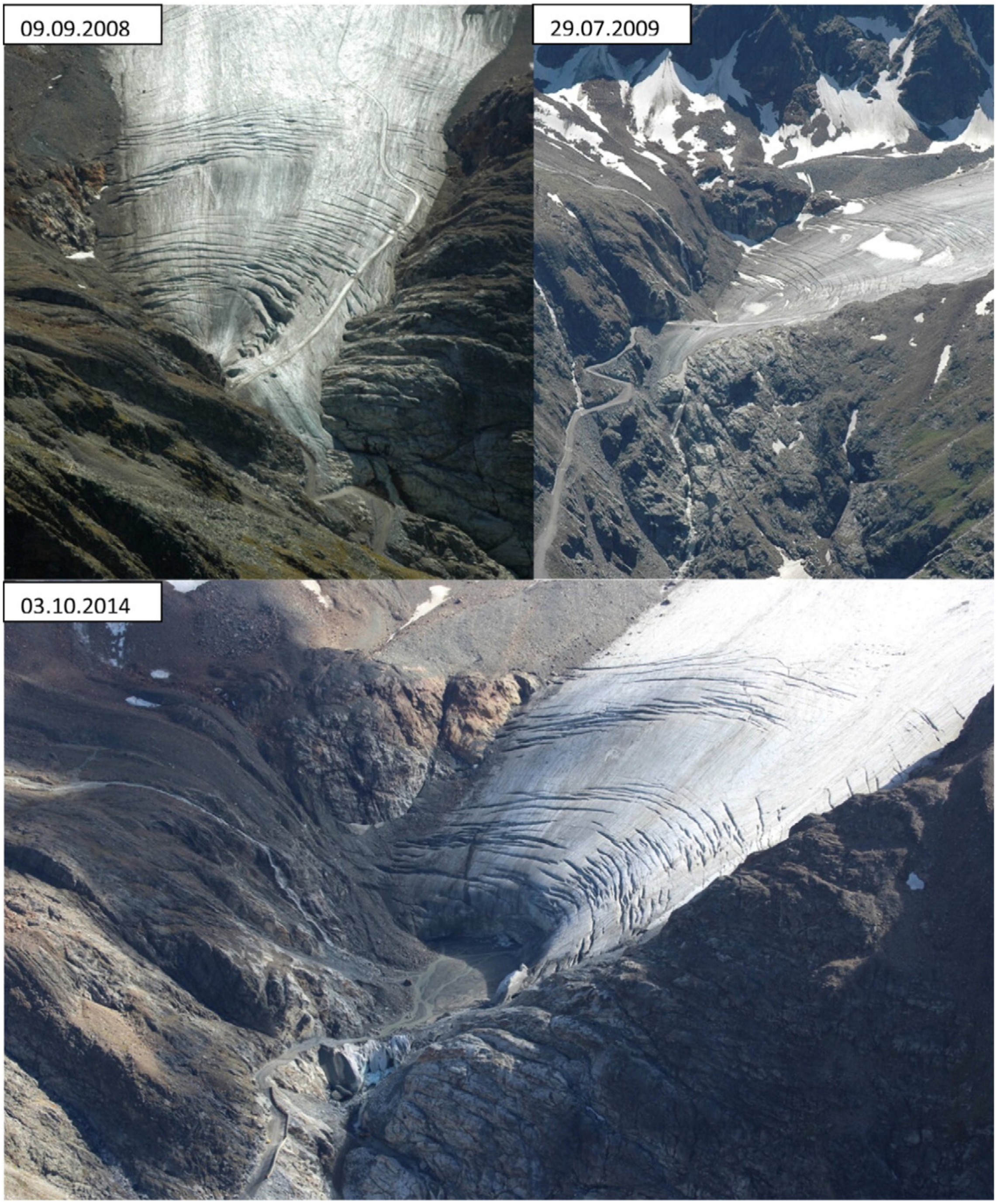
Acknowledgement

The investigations are part of sub-project 4 of the joint project PROSA funded by the German Research Foundation (DFG) (SCHM 472/17-1 and SCHM 472/17-2) and the Austrian Science Fund (FWF) (I 894-N24 and I 1646-N19). We would like to thank Günther Druivenga (Geosym GmbH) for his enthusiasm and the vibroseismic operations, Ulrich Polom (Leibnitz Institute for Applied Geophysics), Werner Chwatal (Department of Geodesy and Geoinformation, Vienna University of Technology), Olaf Eisen and Astrid Lambrecht (Alfred Wegener Institute for Polar and Marine Research) for their help with the analysis and interpretation of the vibroseismic sections. The analysis on Hintereisferner was funded by the Austrian Science Fund (FWF) (ZFT 3290, T329-N10). The contribution of many people who were involved in the fieldwork is gratefully acknowledged. We thank B. Scott for editing the English. We thank Michael Krautblatter and two anonymous reviewers who gave us useful comments which helped us to improve the paper.

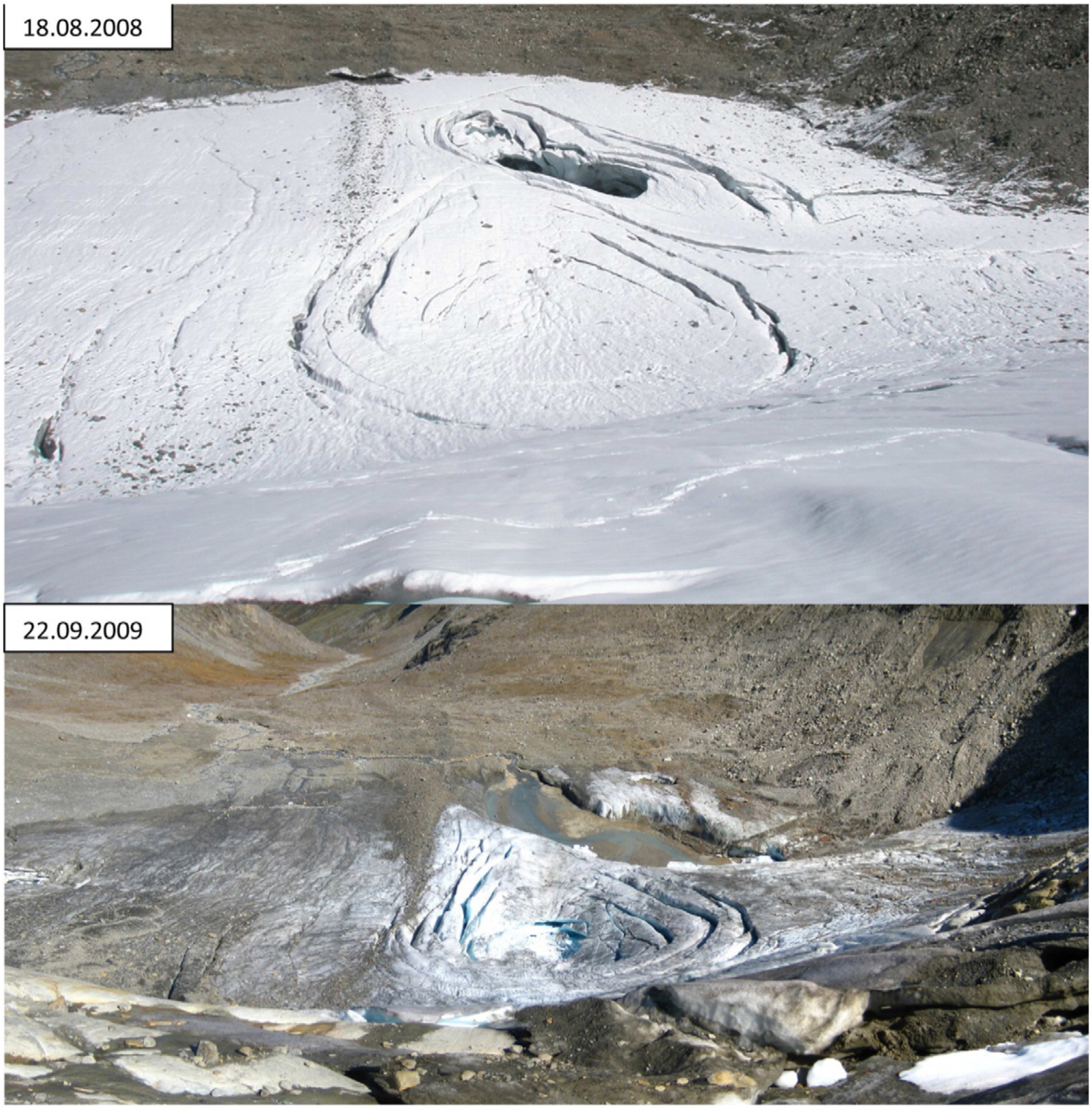
Appendix A. Annex



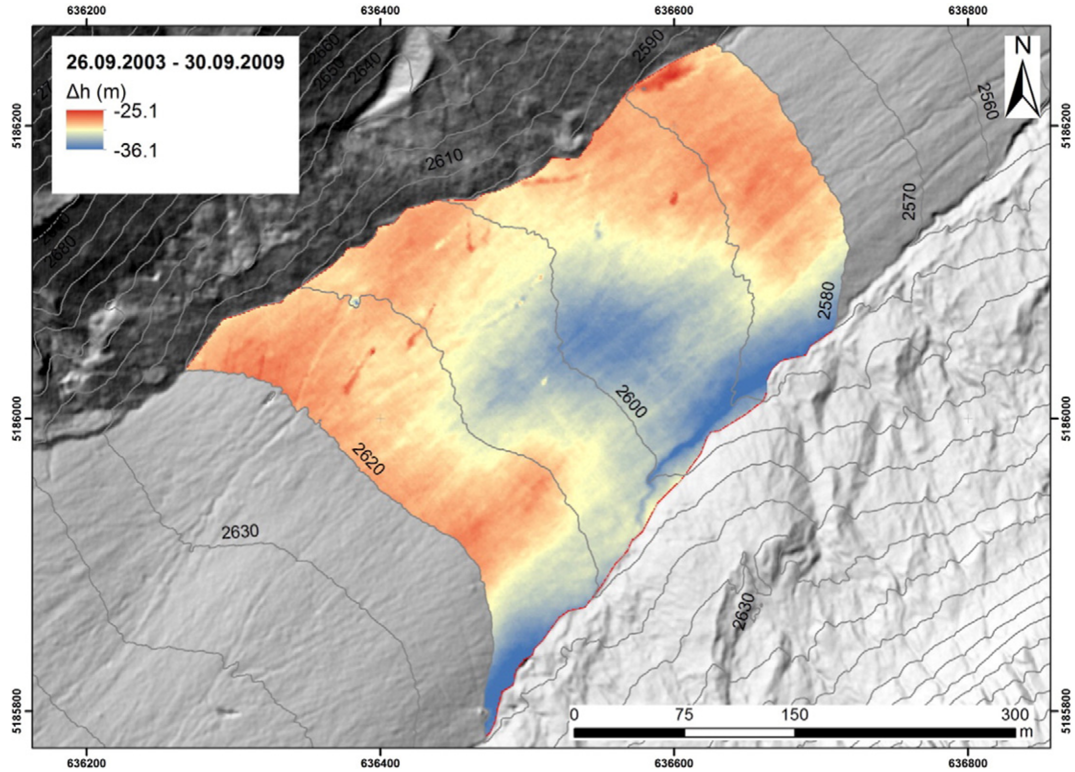
A1. Time series of the formation of the depression on Gepatschferner.



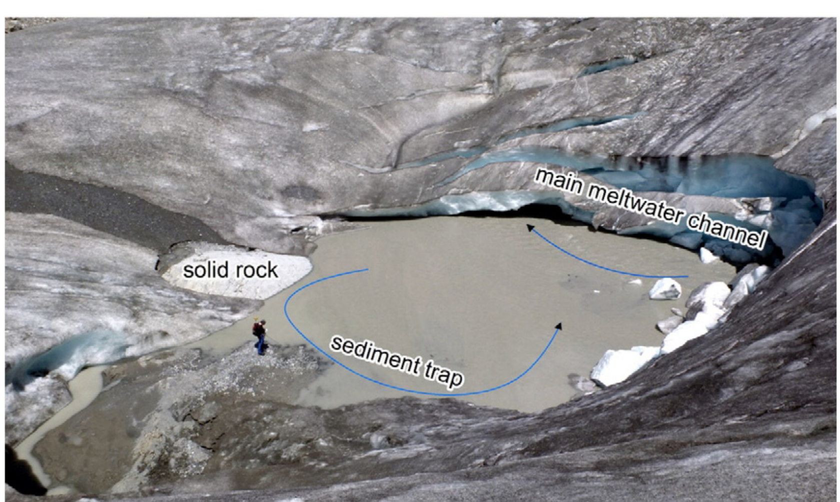
A2. Depression at the snout of Mittelbergferner (Photograph 2009: M. Olefs).



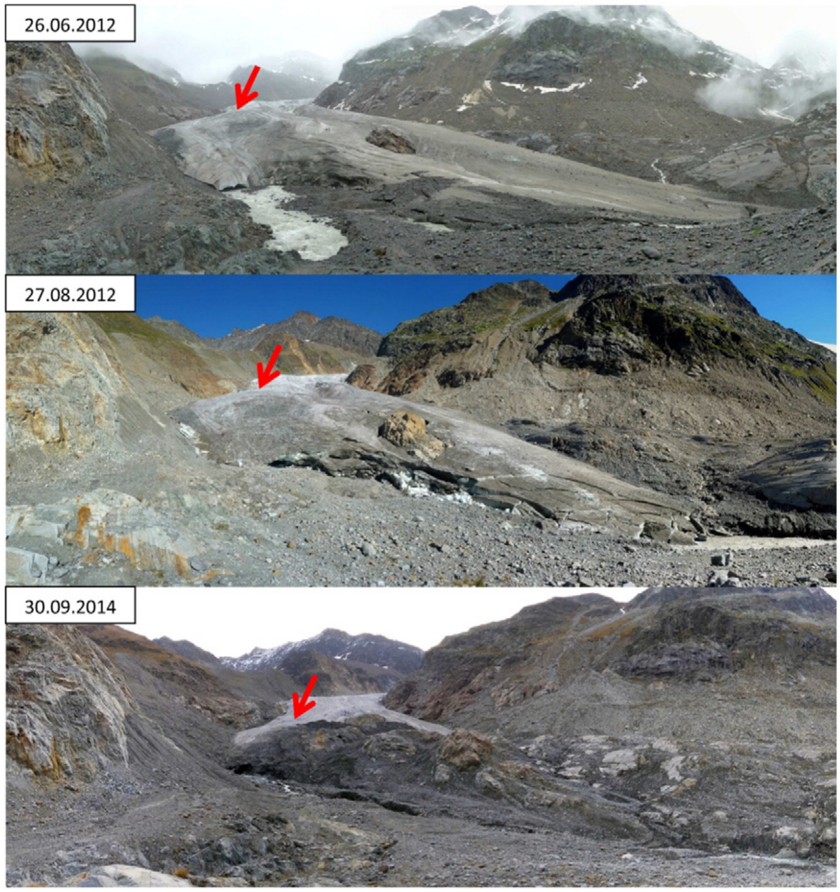
A3. Depressions on the flat tongue on Sulztalferner (Photographs: M. Olefs).



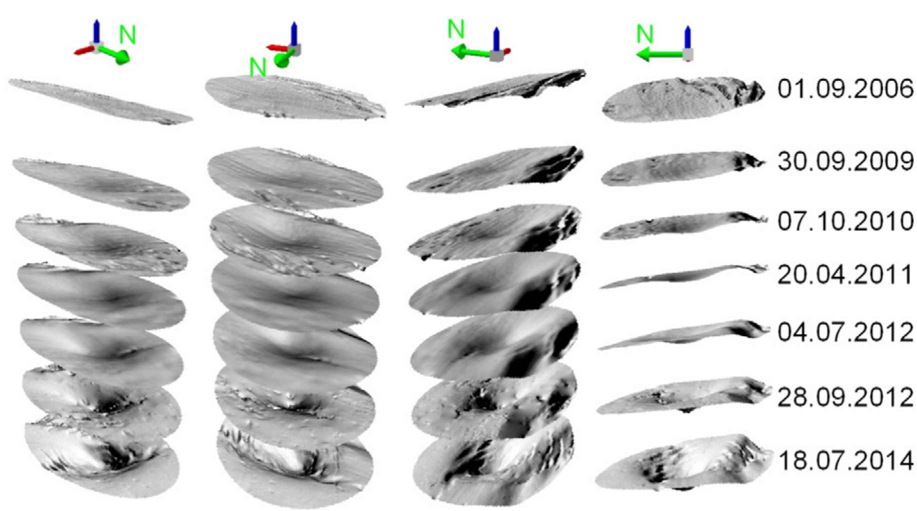
A4. DOD (DEM of Difference) 26.09.2003–30.09.2009 of the depression on Hintereisferner (Haberkorn, 2011).



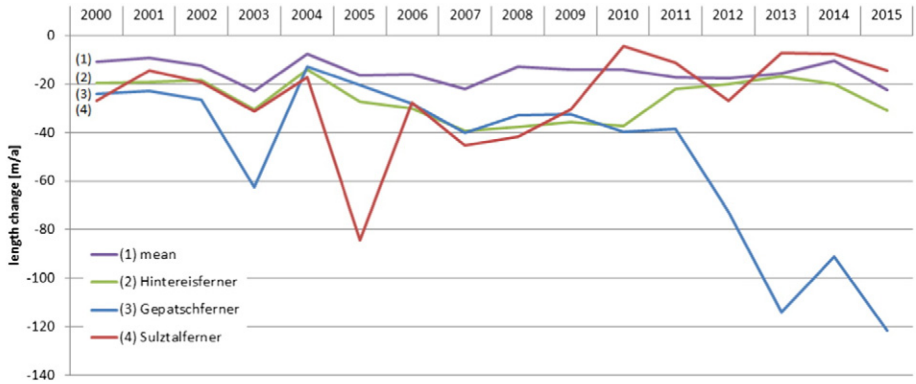
A5. Bottom of the depression (21.07.2015).



A6. Retreat of the tongue and dislocation of the main channel due to the flood event (26.08.2012). Arrow: surface depression.



A7. 3D Model of the depression on Gepatschferner within the 80 m circle for each ALS flight date, displayed with a constant offset.



A8. Length change per year of the glacier terminus of Gepatschferner, Sulztalferner and Hintereisferner. The mean refers to all Austrian glaciers which are subject to length change measurements (Fischer et al., 2013).

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