Monitoring of rock glacier flow velocity variations using imagery, laser scan data and ground-based interferometric synthetic aperture radar (GBInSAR) at the Finstertal reservoir (Austria)

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The Finstertal rock glacier

Figure 1: The Finstertal dam (2322 m.a.s.l) and reservoir with the monitored rock glacier.

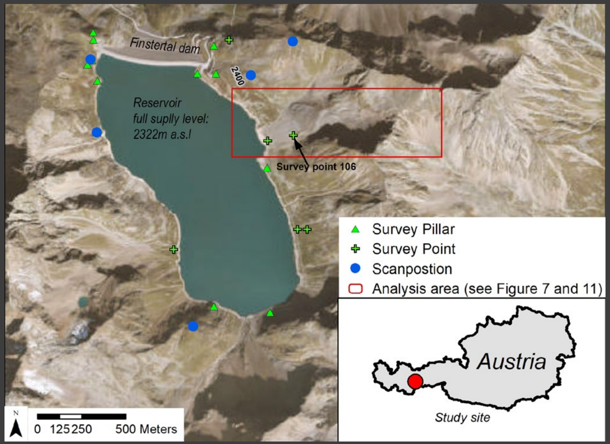

Figure 2: Orthophoto of the Finstertal reservoir

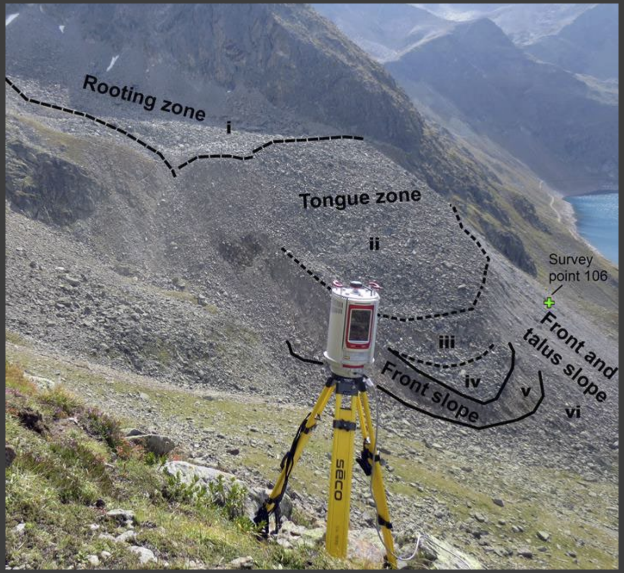

Figure 3: Different subareas of the rock glacier and the terrestrial laser scanner (Fey et al., 2018).

Finstertal is the upper stage reservoir of the TIWAG Sellrain-Silz Group located in the Tyrol, Austria. The 150 m high rockfill dam was built 1977-1980 and forms a reservoir of 60 Mio. m³ (see Figure 1 & 2). The reservoir is surrounded by stable rock slopes of orthogneiss with only little overburden of stable talus material.

About ten years ago the survey point 106 (Figure 3) showed a deformation in the range of 0.005 m/a. The deformation at the survey point 106 led to a repeated geologic survey of the rock glacier that originally was expected to be inactive. Instead of expanding the geodetic monitoring network, it was decided to intensify the remote sensing campaign with the aim to get spatial information about rock glacier deformation and to investigate the past and present deformation behaviour.

The Finstertal rock glacier is a lobate shaped rock glacier with a length of about 580 m and a width between 120 m and 250 m. Its rooting zone (Figure 3) is located at about 2.600 m a.s.l. within a small cirque surrounded by steep north facing walls, which are the source area of the rock fall material.

The delineation of different rock glacier zones is based on Fey et al. 2018 (Figure 3 and Figure 9). The rooting zone and tongue zone are covered by a coarse grained layer which contains blocks with a size of several meters. The steep rock glacier front slope (40 – 50° slope angle) is well defined (Figure 3) at an altitude of about 2.400 m a.s.l.. Big boulders at the toe of the talus slope indicate rock fall activity.

Remote sensing based monitoring

The rock glacier behaviour is reconstructed by means of already available data from national aerial imagery (1971, 1997, 2003, and 2009) and an ALS survey campaign (2006) providing a point cloud with a density of 1 – 4 points/m². Since 2014, the monitoring of the rock glacier is done annual via terrestrial laser scanning (TLS). The TLS data is recorded with a Riegl VZ-4000 long-range scanner from several positions (see Figure 4). The acquired TLS points clouds have a point density of about 25 - 400 points/m². Both, the registration and the georeferencing, is done by matching the TLS point clouds onto an already georeferenced reference point cloud by use of an ICP algorithm (Riegl 2013). For the georeferencing of the first TLS point cloud from 2014, the ALS point cloud was used as reference point cloud (Fey et al., 2018).

The accuracy of imagery and laser scan data is in the range of centimetres and well suited to analyse the annual variability of rock glaciers. Imagery and laser scan data are not suited for shorter time intervals, where the absolute displacement of a rock glacier is smaller than the measurement accuracy. For the understanding of interannual and diurnal variations in rock glacier flow velocities, a GB-InSAR system is installed on top the Finstertal dam for the purpose of monitoring the rock glacier and the surrounding talus slopes. As GB-InSAR systems allow the near real-time continuous data acquisition frequency (every 5 minutes, 24 hours per day, 365 days per year), with an acquisition range up to several kilometres, while maintaining a sub-millimetre measurement precision (Noferini et al., 2008; Casagli et al., 2010; Agliardi et al., 2013). Moreover, GB-InSAR systems can operate in steep slopes, when satellites-based InSAR is not applicable (Casagli et al., 2010).

Figure 4: Terrestrial laser scanning was performed annually since 2006 from several scan positions around the reservoir.

Figure 5: Radar-antenna of the GB-InSAR installed at the Finstertal reservoir in October 2019.

Figure 6: GB-InSAR with the radom. The Finstertal dam and the rock glacier can be seen in the background.

Historic ortho-image correlation

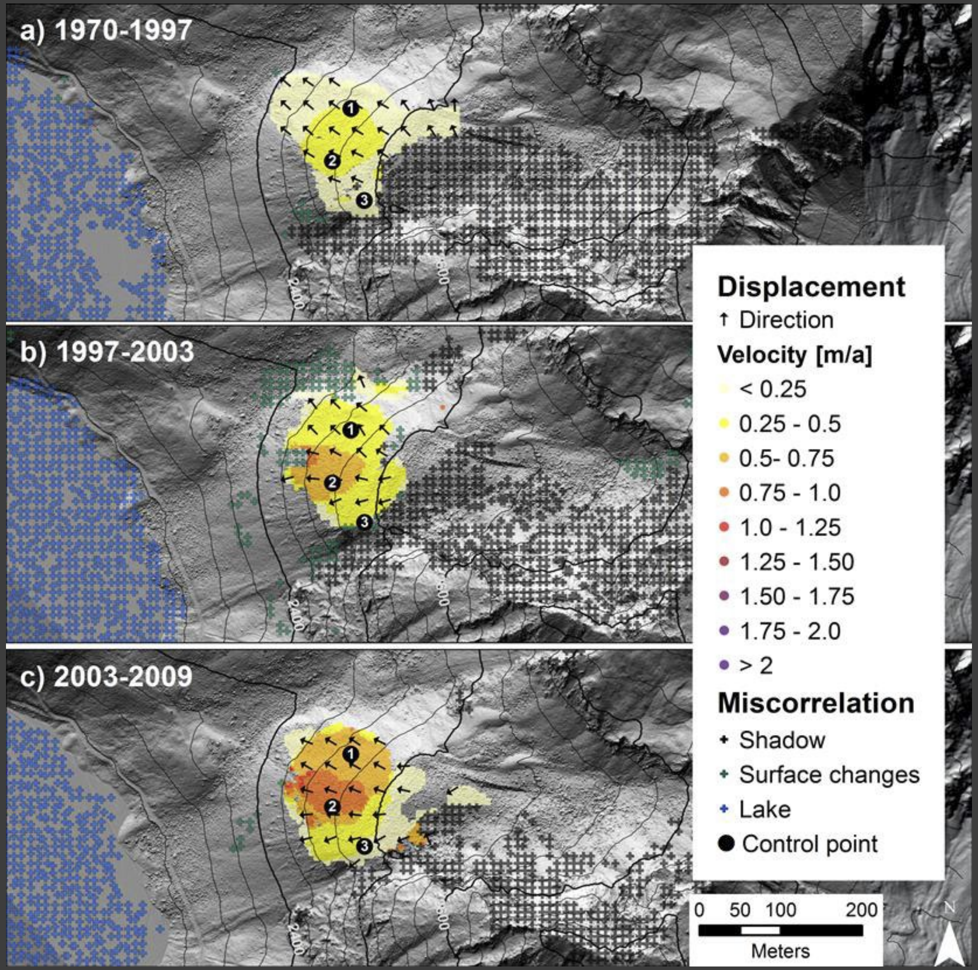

Figure 7: Displacement analyses based on historic ortho-image data between 1970 to 2009 with the locations of control point P1, P2 and P3 (Fey et al., 2018).

The slope displacement from 1971 to 2009 was analysed with image correlation techniques based on historic ortho-images (Fey et al., 2015). The principle of image correlation is based on the detection of corresponding features by searching patterns with a similar texture in two images from different epochs. A prerequisite for image correlation techniques is the preservation of the surface texture in both images. If the surface texture is destroyed (e.g. by rockfall) or has a low contrast (shadowed areas in ortho-images), no corresponding features can be found and no or only miscorrelations occur.

The results of the historic ortho-image based image correlation analyses (see Figure 7) show the activity of the rock glacier from 1970 to 2009. The annual surface flow velocities were calculated by dividing the absolute displacement length by the number of years of the period under consideration. It is assumed that the real displacement rates have varied within each period. As continuous measurements of the rock glacier displacement are not available for this period a more thorough analysis is not viable.

The analysis shows a continuous displacement of the rock glacier tongue towards North-West. At the rock glacier rooting zone no displacements are displayed. This is because i) on the historic ortho-images large parts of the rooting zone are in the shadow of the steep north facing walls and no correlations can be found and ii) the displacements are smaller than the Level of Detection (LoD) i.e. the threshold to divide between data uncertainties and real displacement (Table 1). The displacement rates and velocities at different control points (see Figure 7, P1-P3) on the rock glacier can be seen in Table 1 (Fey et al. 2018).

Airborne and Terrestrial laser scanning

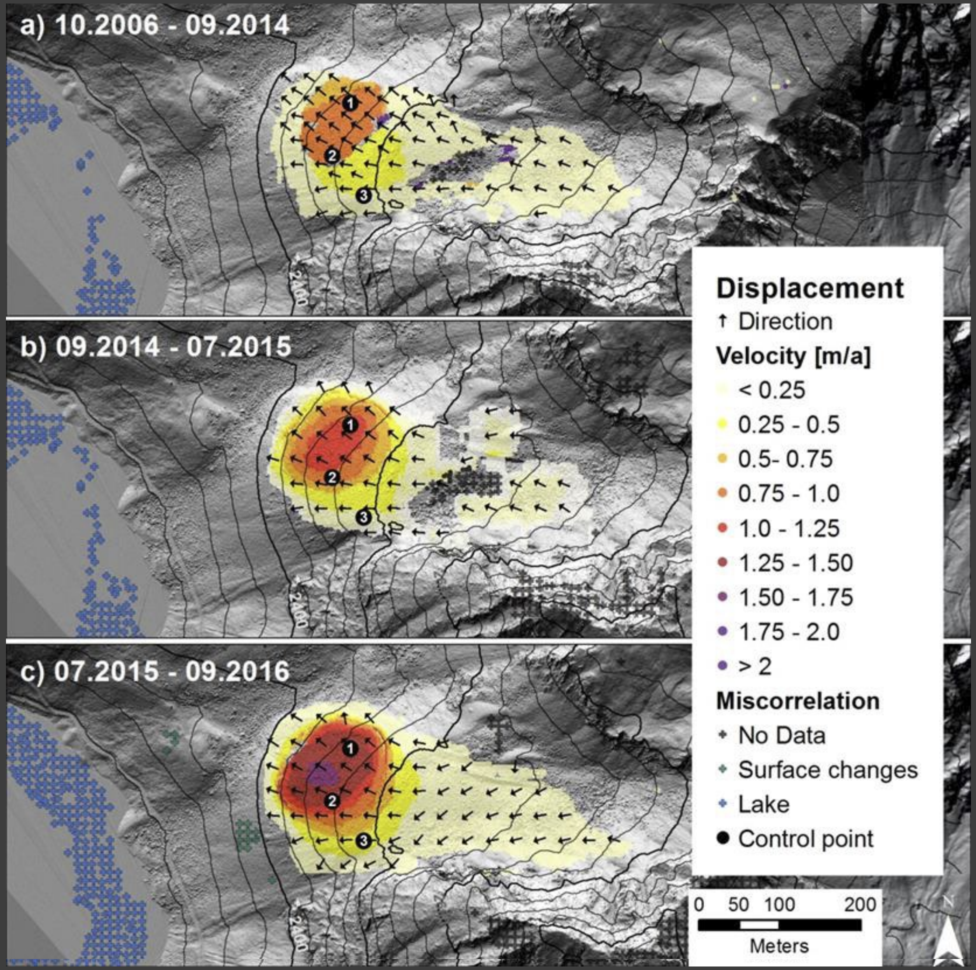

Figure 8: Displacement analyses based on laser scan data between 2006 to 2018 with the locations of control point P1, P2 and P3 (Fey et al., 2018).

In contrast to the ortho-image based displacement analyses, displacement analyses based on laser scan data (see Figure 8) have a better coverage because laser scanning as an active remote sensing technique is not affected by sun shadows.

Furthermore, smaller LoDs can be achieved (see Table 1). Since the first TLS campaign from 2014, the scan settings were improved from year to year and a smaller LoD and a better coverage were achieved. The laser scan data shows rock glacier displacements of the rooting zone towards West.

The velocity of the rock glacier is slow (< 0.5 m/a) in the rooting zone and is highest at the front parts of the rock glacier. The velocity of the rock glacier tongue steadily increased since 1971.

In the period 1970-1997 the maximum velocity of the rock glacier tongue was about 0.3 m/a. In the following epochs, the rock glacier tongue accelerated to velocities higher than 1.6 m/a, as measured till 2019 (see Table 1).

The acceleration of the rock glacier is similar to the reported increase movement speed for many rock glaciers in the European Alps since the beginning of the 21th century (Krainer et al., 2006; Kääb et al., 2007; Gärtner_Roes et al., 2010; Kellerer-Pirklbauer and Kaufmann, 2012; Scotti et al., 2017). These recent accelerations are a direct response to increasing mean annual temperatures. The warmer air temperatures are causing an increase of permafrost temperatures and a change of the ice-mechanical properties (Krautblatter et al, 2013).

Displacement & distance change analyses

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Figure 9a and 10a depict the displacement rates of the rock glacier for the periods 2017 to 2018 and 2018 to 2019. The velocity decreased in the period 2017-2018 and increase again in the period 2018-2019 (Table 1).

Figure 9b and 10b show the distance change (i.e. the distance measured along the surface normal (Fey et al. 2017)) within the respective period. At the rooting zone (subarea i), positive and negative distance changes are alternating, which can be attributed to a steady but slow displacement of the rooting zone. Snow accumulation below the north face during the acquisition time in 10.2017 are causing a negative mass change in the rooting zone in 09.2018. The fast movement of the active lobe in subarea ii causes an extension, which results together with ice melt in negative surface elevation changes. At the talus slopes at the front of the rock glacier (subarea iv) the continues relocation of sediment can be observed.

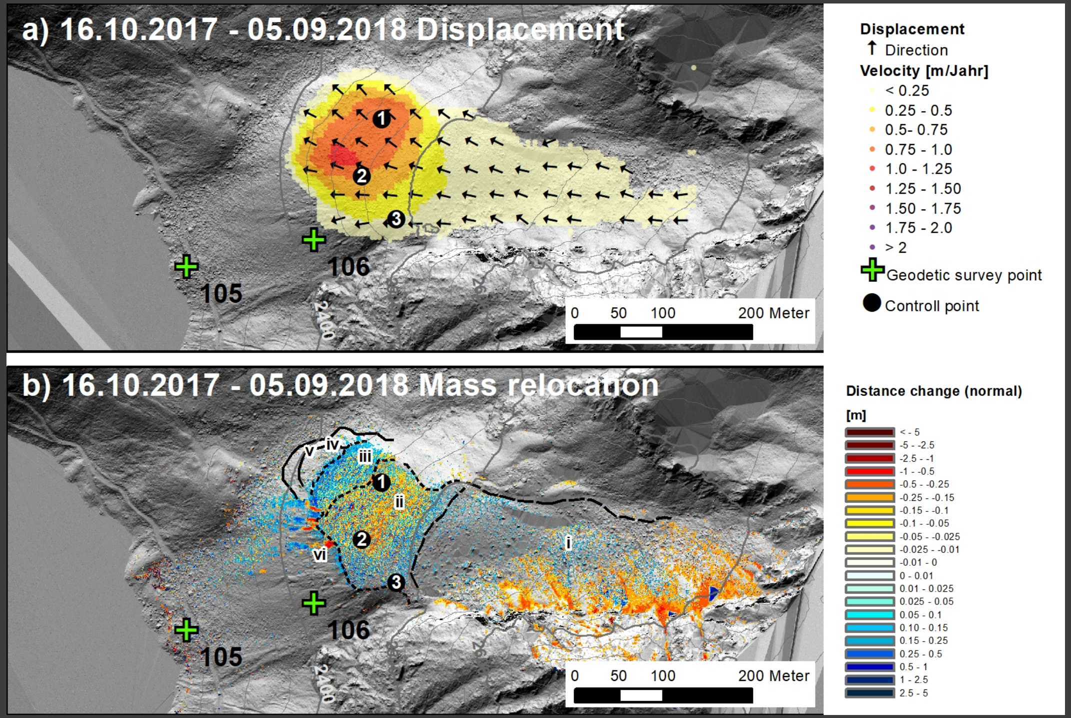

Figure 9: Displacement (a) and distance change analysis (b) based on laser scan data between 14.10.2017 to 05.09.2018.

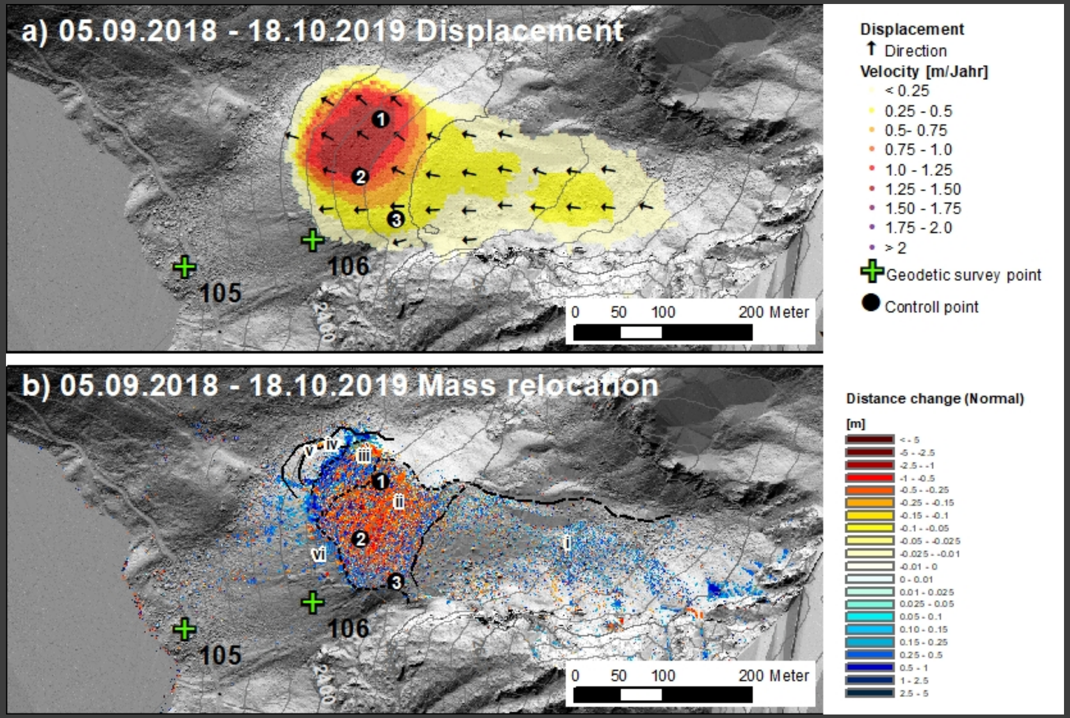

Figure 10: Displacement (a) and distance change analysis (b) based on laser scan data between 05.09.2018 to 19.10.2019.

Displacement & Velocity trends 1971-2019

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The displacement rate and surface flow velocity of the rock glacier steadily increased since the 70s till 2015. The measurements show a slight decrease for the periods 2016-2017 and 2017-2018 at the rock glacier tongue. During the period 2018-2019 an increase in velocity at subarea ii of was recorded (see Table 1, Figure 9 -12). The TLS based rock glacier monitoring will be continued.

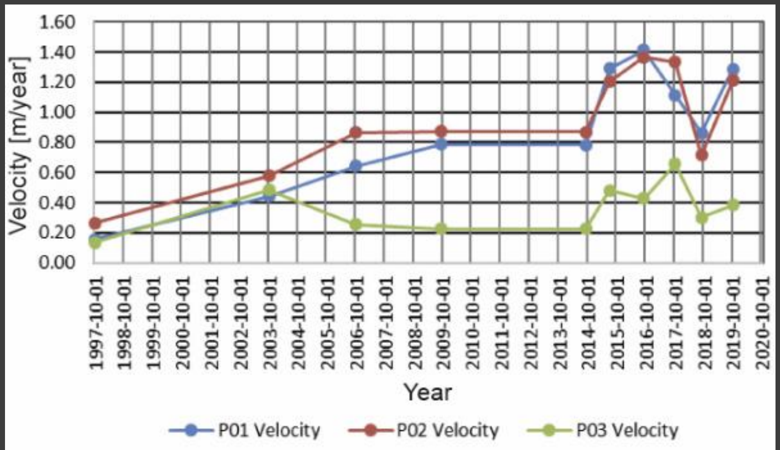

Figure 11: Velocity at the control points P1-P3 between 1971 to 2019.

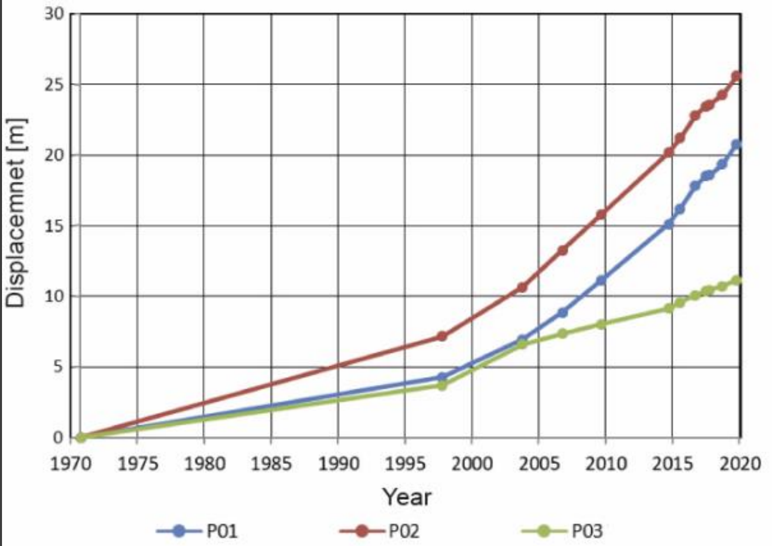

Figure 12: Accumulated displacement at the control points P1-P3 between 1971 to 2019 (mod. after Fey et al., 2018).

Epoch	Data source	Years	LoD [m]	Displacement [m] at the control points			Velocity [m/year] at the control points		
				P1	P2	P3	P1	P2	P3
1970 - 1997	Orthophoto	27	1.2	4.32	7.29	3.78	0.16	0.27	0.14
1997 - 2003	Orthophoto	6	1.3	2.64	3.48	-	0.44	0.58	-
2003 - 2009	Orthophoto	6	0.9	3.84	5.22	1.5	0.64	0.87	0.25
10.2006 - 9.2014	ALS - TLS	8	0.45	6.32	7.04	1.84	0.79	0.88	0.23
09.2014 - 7.2015	TLS	1	0.15	1.07	1	0.4	1.28	1.2	0.48
07.2015 - 9.2016	TLS	1	0.05	1.65	1.6	0.5	1.41	1.37	0.43
09.2016 - 10.2017	TLS	1	0.08	0.75	0.82	0.38	0.7	0.75	0.35
10.2017 - 9.2018	TLS	1	0.09	0.77	0.64	0.27	0.86	0.72	0.3
09.2018 – 10.2019	TLS	1	0.08	1.44	1.36	0.43	1.29	1.21	0.38

Table 1: Displacement analysis for each dataset pair, with corresponding data source, Level of Detection (LoD), total displacement and velocity [m/a] for control control points P1-P3 (mod. after Fey et al., 2018).

GB-InSAR Monitoring

During October and November 2019, a GB-InSAR system (LisaLab) (see Figure 5 & 6) was continuously monitoring the rock glacier and the surrounding slopes, with a measurement interval on roughly 10 minutes. Figures 13-15 depict the monthly displacement rates along the Line of Sight (LOS) between 09.10.2019 to 09.10.2019. Negative displacement rates indicate movement in the direction of the GB-InSAR. The analysis shows a displacement of up to 8mm/day, with the highest velocities reached at subarea ii. The highest displacement was measured at control point Pts_07 with 236 mm/month. Significant daily variations in flow velocities in the period 09.10.2019 to 09.10.2019 can not be identified. The submillimetre variations of the accumulated flow velocities shown in Fig. 15 are interpreted as data noise caused by changing atmospheric conditions. The continuous GB-InSAR based monitoring continues in Mai 2020 with the aim to analyse the intra-annual and seasonal flow velocities variations

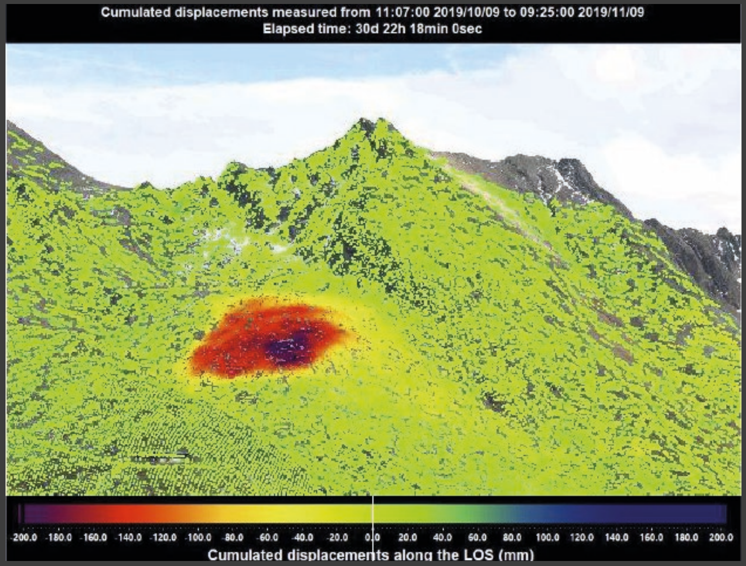

Figure 13: Cumulated displacement along the LOS [mm] from 09.10.2019 - 09.11.2019. aligned onto an optical image.

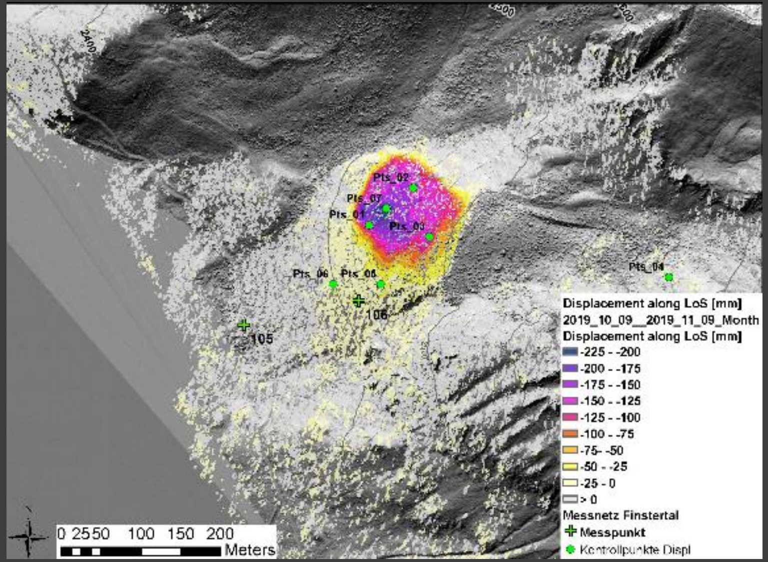

Figure 14: Projected cumulated displacement along the LOS [mm] from 09.10.2019 - 09.11.2019. with the locations of several control points.

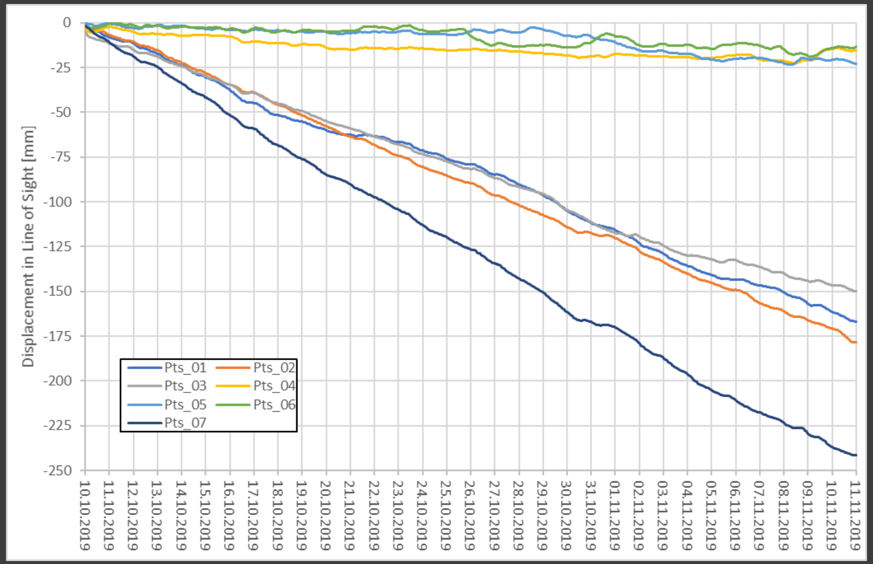

Figure 15: Cumulated displacements of control points Pts_01 to Pts_07 from 09.10.2019 - 09.11.2019. The location of the control points is indicated in Figure 14.

Outlook

The deformation rates observed at the Finstertal rock glacier is similar to deformation rates seen at other rock glaciers in the eastern alps. Kellerer-Pirklbauer et al. (2018) has shown that the surface flow velocities of 35 rock glaciers in the European alps were relatively low till the 80s. Which increases significantly in the 1990s until the early 2000s, which was followed by a drop in velocities.

The surface flow velocities reached since then again, a maximum in 2015/2016, followed again by a significant decrease. Studies show that the movement of active rock glaciers is strongly influenced by water input, ground temperature and ice content (Wirz et al., 2016; Kenner and Magnusson, 2017; Bodin et al., 2017, Cicoira et al., 2019).

The kinematic behaviour of active rock glaciers under changing climatological and meteorological conditions is poorly understood. Therefore, further analysis will focus on the influence of snow melt, temperature and precipitation on the comprehensive kinematical analysis of the rock glacier over several time scales.

Thank you for the attention!

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