Accelerating Landslide Hazard at Kandersteg, Swiss Alps; Combining 28 Years of Satellite InSAR and Single Campaign Terrestrial Radar Data

Rafael Caduff, Tazio Strozzi, Nils Hählen, and Jörg Häberle

Abstract

In summer 2018, in an area above lake Oeschinen in Kandersteg (Bernese Alps, Switzerland), significant terrain changes with indication of fast ground movements were observed. The NW dipping rock and debris slope named “Bim Spitze Stei” had been known to be under constant movement before. However, the rapid acceleration from a maximum volume prone to failure of about 20 mm^3 prompted the authorities to undertake a thorough analysis of the situation and analyse primary (rock avalanche) and secondary (floods and debris-flows out of the rock avalanche debris) hazard processes and the risk they pose to the nearby Village of Kandersteg. A first assessment of the most recent Sentinel-1 satellite InSAR data confirmed rapid ground movement in the order of several mm/d up to cm/d and a rapid acceleration of the west-flank of “Bim Spitze Stei” landslide from initially 7 mm/d to few cm/d within 2 weeks in July 2018. In addition, different sectors with different kinematics could be identified by interpretation of single interferograms. In a second step, an archive analysis of historical InSAR data reaching back to 1991 clearly showed that an acceleration trend from initially sub-stable conditions up to several m/a. Finally, based on the findings from the satellite InSAR analysis, a survey campaign with a terrestrial radar interferometer was performed in order to define the current state and location of the potentially outcropping glide plane in the west-flank. The successful campaign led to the observation of the presence of two active glide planes with the lowermost encompassing the maximum estimated volume of the mass in movement thus helping for the definition of potential failure scenarios thus helping in the selection of enhanced monitoring systems and increasing the preparedness for the runout-areas.

Keywords

Landslide hazard assessment • Landslide acceleration • Satellite InSAR • Terrestrial radar interferometry • Glide plane detection

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Introduction

A large part of the small mountain peak “Bim Spitze Stei” located above Lake Oeschinen at Kandersteg (Bernese Alps, Switzerland) has been known to be in constant movement for decades. Fractured bedrock in the upper part and freshly re-mobilized sediments at the middle part of the slope are the clearest signs of movement. Frequent observations at the peak area were taken by local mountaineering guides. During summer 2018 drastic changes in the area were reported, with new and unusually fast opening cracks around the peak.

The local authorities were requested to assess the current hazard and risk posed to the inhabited areas below. The volume of the unstable rock mass was estimated to be about 20 mm^3. While the slope itself does not bear any infrastructure that needs to be protected, high hazard is expected in the area of potential rock avalanche trajectory and more importantly in the area of potentially triggered secondary processes such as debris flows from sediment accumulations. In particular the village of Kandersteg, which lies downstream of the Oeschibach, needed further hazard and

V. Vilímek et al. (eds.), *Understanding and Reducing Landslide Disaster Risk*,
ICL Contribution to Landslide Disaster Risk Reduction,
https://doi.org/10.1007/978-3-030-60319-9_29

subsequently risk assessment for potential damage by floods and debris-flows that might occur after a large rock avalanche. Recent rock avalanches triggering secondary processes that occurred in the Swiss Alps (e.g. Pizzo Cengalo (Walter et al. 2020), Ritzlihorn/Spreitgraben (Frank et al. 2019), Val Selva, Ghirone (Caduff and Strozzi 2017)) suggested an exhaustive analysis of the situation.

As consequence, a monitoring system using multiple technologies was installed to assess the current displacements of the area (RT-Tachymeter, RT GNSS, Time Lapse Photography, Geophones). For an in-depth analysis of predisposition and triggering factors, geological, structural and hydrological analyses were mandated together with a historical analysis of the surface displacements in the area (Pixel Tracking on historical aerial imagery, satellite InSAR).

This paper focuses on the use of radar interferometry for the hazard assessment of a potentially large rock avalanche on different scales and platforms. After a geographical overview, we demonstrate (i) the use of near real-time satellite InSAR with Sentinel-1 data for the assessment of the current surface displacement, (ii) the use of historical InSAR data since 1991 with different sensors (ERS-1/2, ENVISAT ASAR, ALOS-1/2 PALSAR-1/2, RADARSAT-2, TerraSAR-X, Cosmo-Sky MED) to assess the evolution of the slope deformation in the past 28 years and (iii) the benefit of short campaign terrestrial radar-interferometry for assessing important structural parameters as the location of (multiple) active glide planes in the rugged parts of the target area. The results were used later for a hazard assessment mandated by the local authorities.

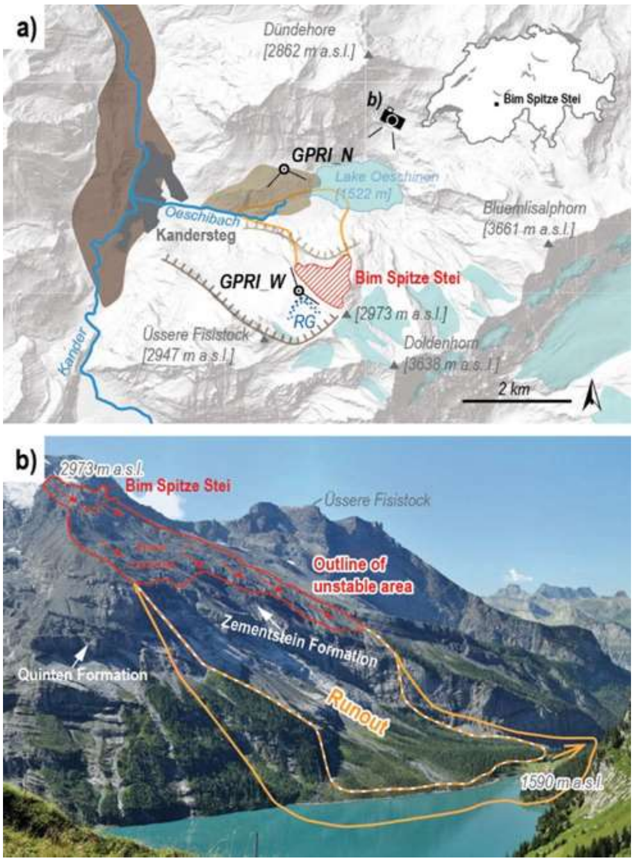

Fig. 1 Geographical overview **a** with the outline of the active landslide (red), **b** lateral view of the target area with active slide (red) and potential runout zone (orange). GPRI_E and GPRI_W are the two positions of the terrestrial radar measurements, RG is a rock glacier

Geographical and Geological Setting

Location

The “Bim Spitze Stei” area is located in the central part of the Bernese Alps, Switzerland. It is part of the ~40 km^2 large Oeschinen sub catchment that is encompassed by the mountain chain including Fisistock—Doldenhorn—Blüemlisalp—Dündehore (Fig. 1).

In the centre of the catchment lies the touristically attractive landslide-dammed lake Oeschinen. The lake drains partly in an underground-stream and then at the surface as creek “Oeschibach” towards the river Kander. On the river-fan at the outlet of the Oeschinen catchment, the village of Kandersteg is located.

Geology

From the geological point of view, the “SpitzeStei” is built from a sequence of rock formations of the infrahelvetic Doldenhorn-Nappe. Its main lithologies, from bottom to top, contain (i) light grey micritic limestone of the Quinten Formation (ii), dark limestone and marly limestones of the Zementstein Formation and (iii) dark marlstones and light grey bioclast bearing limestone, both composing the Öhrli Formation, at the “SpitzeStei” area itself. The main bedding is oriented towards NW with a dip-angle of 30°.

Several very large rock avalanches took place in the mid Holocene and characterized the main morphology of the current day Kander Valley. One very large rock-avalanche with an estimated volume of 0.8 km^3 originated from the northern face of the current day “Üsserer Fisistock” (Tinner et al. 2005). New research from Singeisen et al. (2020) suggests that this failure occurred about 3,200 years BP. The detachment zone is in direct vicinity to “Bim Spitze Stei” and consists of similar structural and geological predisposition.

Another large rock avalanche occurred ~2,300 years BP from the lower part of the target study area that led to the formation of Lake Oeschinen (Köpfli et al. 2018). Further investigations showed, that at least 6 other significant rockslide/avalanche events took place (Knapp et al. 2018).

The area that is moving spans from an elevation beginning at 2200 up to 2900 m a.s.l. This area and the slope exposition are prone to an ice-rich permafrost situation (Hauck et al. 2017). Rockglaciers close and in the target-area are a clear indication of a temperature regime supporting the formation of permafrost.

Assessment of the Current Displacements with Sentinel-1 InSAR Data

Method

As first order assessment of the spatial extent of the ground movements in the area, we considered data from the European Sentinel-1 satellite. Sentinel-1 has a 6-day observation period on the single interferometric orbits and multiple revisit orbits in the two acquisition geometries (ascending path: ENE looking; descending path WNW looking). The sensor itself has a nominal resolution in IW mode of 5 × 20 m, which was resampled for the interferometric processing to 20 × 20 m (multi-looking factor of 4 × 1) and then again resampled for geocoding to 5 × 5 m. An overview of the methodology using Sentinel-1 interferograms for the assessment of a large slope instability over the Swiss Alps is given by Manconi et al. 2018. Major limitations to the use of satellite SAR interferometry to assess landslide motion are due to the viewing geometry, the acquisition time interval, and the landcover. Around “Bim Spitze Stei”, the north facing slope and the west-shoulder of the area are both covered without significant gaps caused by layover and shadow effects. However, the view on the uppermost areas of the slope instability is largely blocked because of this effect (black areas in Fig. 2a, b).

Another limitation of satellite SAR interferometry is given by the velocity of the landslide, more precisely by the total displacements along the line-of-sight of the sensor between a revisit-cycle. The feasibility for a successful determination of surface displacement values in the interferograms is a function of the sensor wavelength (Sentinel-1: 5.6 cm [1/2 $\lambda = 2.8$ cm]), the revisit time, the spatial resolution and the extent and kinematics of the area in movement. In other words, the movement must not be too fast in order to be quantified unambiguously.

Regarding the surface cover, scenes with vegetation, snow and rockfall/avalanche within the area of interest are excluded from the analysis.

Our analysis was not restricted to archived data. An automated near-real-time interferometric processing chain was set-up to obtain the information of the current state of the movement hours after the acquisition of the newest Sentinel-1 scene.

Results

A comprehensive product from the interpretation of the Sentinel-1 interferograms of the years 2015-2018 is shown in Fig. 2. The focus of the analysis was set on the separation of areas with similar temporal behaviour. Several zones with different average deformation rates and/or the temporal signatures could be identified. Significant changes could be observed in the western part of “Bim Spitze Stei”, where an increase of the deformation started mid-summer 2018 and soon reached values that led to complete decorrelation in the 6 d interferograms (meaning >> than 2.8 cm movement).

A comparison with acquisitions from the same season in the years before showed that in this time significant movements were present as well, but the recorded surface deformations did not reach the same levels as 2018.

Additionally, the boundaries of the area affected from the movements could be mapped. However, the pixel resolution and projection errors in the steeper part of the area lead to a significant uncertainty in the estimation of the volume in movement.

Historical Analysis Using Satellite InSAR Data

Method

Similar to the above outlined assessment of the radar interferograms generated from Sentinel-1, data from various other SAR sensors were interferometrically processed. We could process X-Band data from TerraSAR-X and COSMO SkyMed, C-Band data from ERS-1/2, ENVISAT ASAR, RADARSAT-2, and L-Band Data from JERS-1 and ALOS-1/2 PALSAR-1/2, mostly along the descending geometry. After interferometric processing of the data over the subset of the test area, coherent pairs were selected and qualitatively interpreted for potential movements in the area similarly to the study performed by Strozzi et al. 2010. Wherever possible, the absolute displacement in line of sight was extracted at locations where optical targets were installed and continuously measured with an automated tachymeter starting on 13. August 2018. The displacement rates within the time intervals of the interferograms were normalized to yearly rates and plotted as time series (Fig. 3).

Results

The results of the historical analysis using satellite InSAR data are shown in Fig. 3. First measurements from the ERS-1 mission in 1991 with a 3-day repeat interval showed movement in the eastern part of the area. This patch is identified as an ice rich sediment body (i.e. a rock glacier),

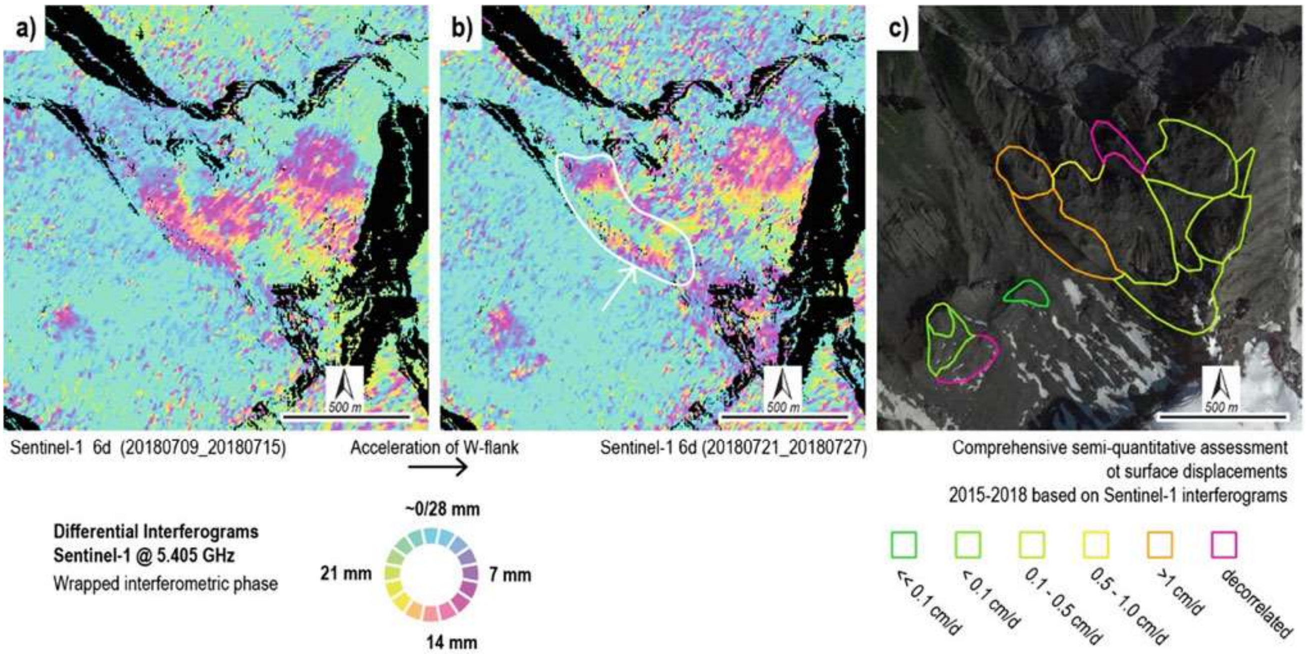

Fig. 2 Comparison of two short time (6d) Sentinel-1 interferograms **a** before and **b** after initiation of a fast acceleration of the W-flank (white outline) in mid-July 2018. A synthetic analysis of multiple Sentinel-1 interferograms from 2015 to 2018 led to the delineation of different sectors with different kinematics (**c**)

which is in continuous movement also in recent times. Even though only short revisits (1–3 d) are coherent in 1991, it is clear that the movement rates by "Bim Spitze Stei" were significantly lower than in recent observations. The western part of the area is more or less stable or slower than 5 mm/month in LOS. An increase of the deformation rate can be observed only since 2007. at Point 52 and upward. The actual onset of this movement cannot be determined from the satellite data since there is a large data gap of coherent observations between 2000 and 2005.

From 2014 onwards, the area under significant movement was increasing at the lower western boundary, including point 63.

Assessment of the Current Situation with Terrestrial Radar Interferometry

Method

In order to verify the presence and location of the main basal glide plane in the west-lateral area of the instability, a terrestrial radar interferometric campaign was executed at the beginning of August 2019. Terrestrial radar interferometry works similarly to satellite-based interferometry and is described in detail in Caduff et al. (2015). In order to plan a terrestrial radar campaign, it is important to have a rough idea of the current movement rates. Since the accessibility with the instrument to the observation point was only possible with a helicopter transport, the measurement intervals have arranged to lie within the sensitivity range of the system, i.e. more than ∼1 mm and less than about a phase cycle.

On 6. August 2019 first measurements with 2 min intervals were taken during 45 min from an inactive or transient rock glacier lobe (GPRI_W in Fig. 1). Since the Sentinel-1 analysis did not show significant movement of the rock glacier in the years and weeks before the campaign and no long term observations were planned, the risk of a moving observation platform was very small. Following the forecast of a thunderstorm, the instrument was disassembled and stored at 2470 m a.s.l. for two days.

After the rain- and thunderstorm, the instrument was set-up again on 8. August 2019 and a continued monitoring the rock slope for 26 h at acquisition intervals of first 2 min and later 5 min.

Before and after the campaign described above, additional terrestrial radar measurements were taken from Point GPRI_N located on the opposite slope of the "Bim Spitze Stei" (Fig. 1).

Results

The results of the campaign at the west-lateral area is shown in Fig. 4. A selected interferogram is projected onto a set of

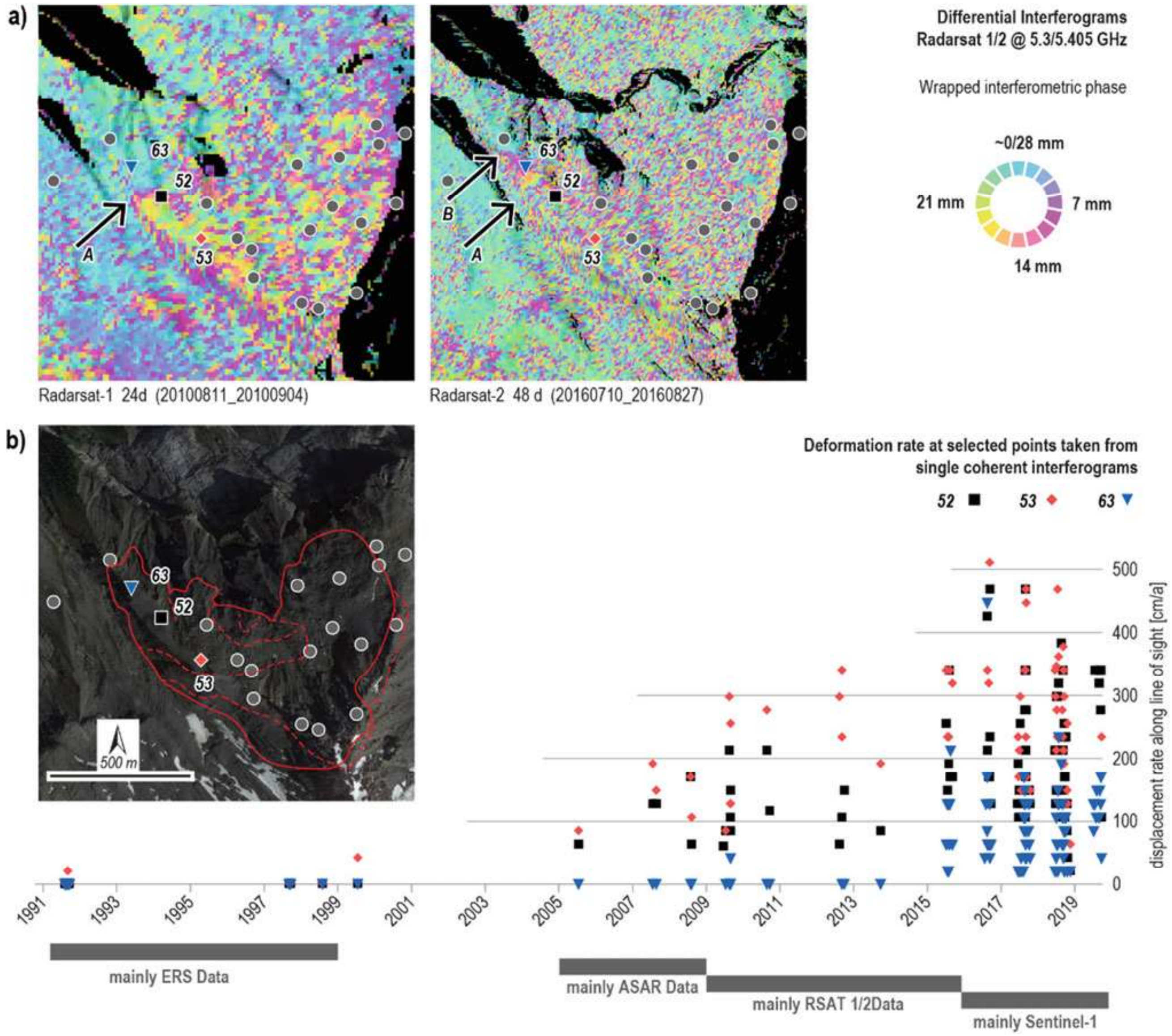

Fig. 3 Historical satellite InSAR analysis for "Bim Spitze Stei". **a** Radarsat-2 interferograms indicating a lowering of the lowest limit of deformation from location A to location B. Note the different temporal baselines of interferograms. **b** Time series of line of sight displacement rates extracted for locations 52, 53 and 63 currently measured with tachymetry

terrestrial photographs. The data clearly show the presence of several discontinuities that can be followed over the entire W-lateral area. Isolated patches showing faster movement are identified as superficial movements (settlements) of the debris or ice rich debris (white outlines in Fig. 3c). The more extended structures in the upper part of the slope (red outlines in Fig. 3c) mark the outcropping line of the basal glide planes. A lower glide plane is starting right behind the highly fractured peak area of "Bim Spitze Stei" and then steeply dips downward until its path turns and follows more or less the bedding plane of the bedrock. A second, more superficial glide plane with significantly faster displacement rates can be traced several tens of meters above the basal glide plane. This separates the peak area from the lower compartment and ultimately joining the basal glide plane in the peak area.

This observation is in very good agreement to the Sentinel-1 interferograms, but with the good spatial resolution of the terrestrial radar, the basal gliding plan can now be detected at sub-meter scale.

Conclusions and Outlook

Our study based on satellite and terrestrial radar interferometric data showed that the area of "Bim Spitze Stei" was affected from an unprecedented acceleration of the slope

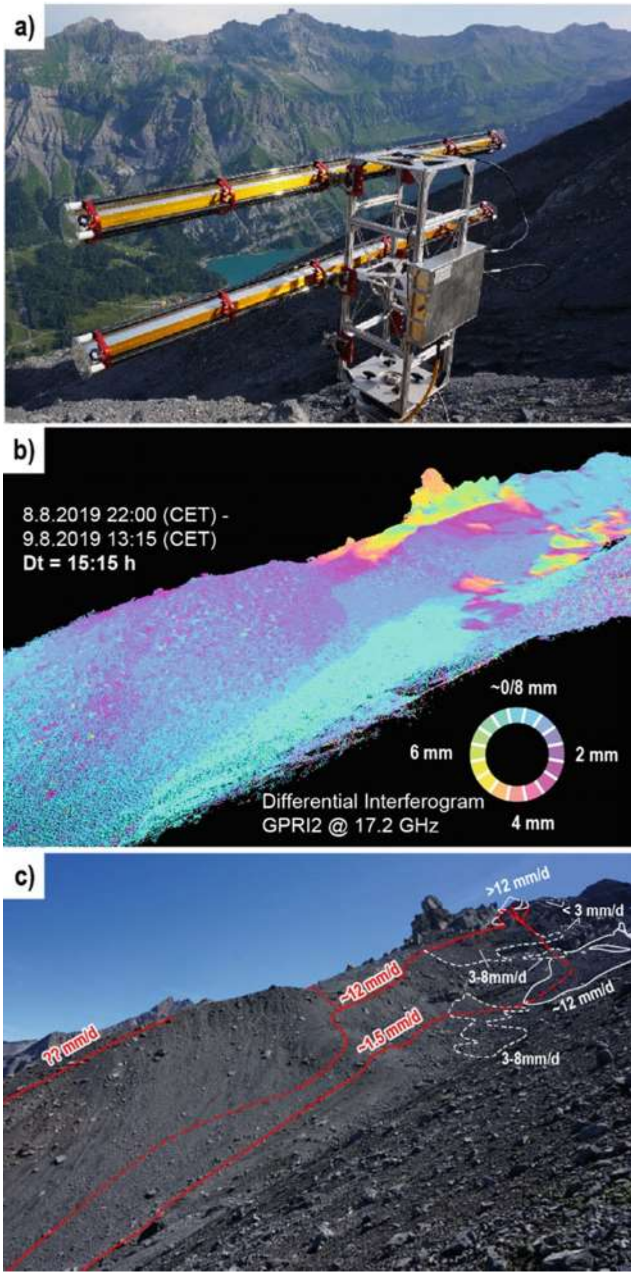

Fig. 4 **a** Setup of the terrestrial radar interferometer (GPRI) at location W. **b** 15 h Ku-Band interferogram from the west-flank in precise photo geometry. Different sectors with different kinematics could be delineated (**c**) and identified as superficial movement (white) and most importantly as set of outcropping basal glide planes (red)

movements from several cm per year to cm per day in 2018. Different zones with different times of activation and velocities could be identified using Sentinel-1. A historic analysis going back until 1991 with satellite SAR data showed that a cascading progression of the unstable areas on the western side took place between 1999 and 2005. Unfortunately, a gap in usable data hindered a more precise delineation of the events during this time.

Ground based observations delivered valuable information on the current structural situation. Two stacked glide planes could be identified and mapped along a large part of the western flank. The results from terrestrial radar interferometry, satellite SAR interferometry and other conventional observation methods are in good agreement to each other and are in accordance to the results of a drilling campaign conducted in winter 2019/20. Currently, all available observations are used for an in-depth hazard analysis and risk assessment of the down-stream areas.

Our study demonstrated the possibility of delineating and quantifying with satellite and terrestrial radar interferometry the surface motion of different sectors with different kinematics of the "Bim Spitze Stei" area. On the other hand, our analysis is also clearly stating the technological and mission specific limitations related e.g. to sensor specific parameters or the acquisition time interval. However, even though a single observation method may not be enough to get the full picture including geological modelling, influence from triggering factors, and estimation of the timing and volume of potential catastrophic slope failures, the knowledge gain can be still significant. This results in a better understanding of the mechanisms and driving forces of the slope instabilities and thus to an enhanced hazard management.

Acknowledgments Data used for this study: JERS-1 SAR, ALOS-1 PALSAR-1 and ALOS-2 PALSAR-2 data are copyright JAXA. ERS-1/2 and ENVISAT data are copyright ESA. TERRASAR-X data are copyright DLR. Cosmo-SkyMED data are copyright ASI. Radarsat-2 data are copyright MDA. Sentinel-1 images available from Copernicus. Part of the work was funded by Eureka and Innosuisse in the frame of the EUROSTARS Project E! 113220 RAMON.

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