Monitoring unstable parts in the ice-covered Weissmies northwest face

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ABSTRACT

The glacierized northwest face of Weissmies in the Saas valley (Switzerland) recently became unstable due to climate-induced glacier thinning of the supporting Triftgletscher below. In the case of a large break-off of ice, human infrastructure in the Saas valley is exposed to the danger of an ice/snow avalanche. A monitoring campaign was initiated with the goal of detecting precursory signals to the break-off. Interferometric and Doppler radar, optical imaging as well as GPS sensors provide measurements of surface displacements. Infrasound and seismometer arrays monitor acoustic and seismic emissions of ice avalanches and englacial fracture development. Here we discuss the monitoring methods and the results obtained so far. The unstable glacier mass did not undergo a large-scale break-off event, in fact it decelerated during the unusually warm summer months. An explanation remains elusive but likely involves subglacial processes and bedrock topography. Nevertheless, our results allow us to draw important conclusions regarding the suitability of different approaches to monitoring unstable glaciers.

KEYWORDS

glacier monitoring; ice avanlache; early warning; natural hazards

INTRODUCTION

The hazard potential of glaciers ranges from relatively small ice falls (Röthlisberger, 1978) to substantial glacier break-offs, which have killed thousands of people in the past (Lliboutry, 1975). To monitor such hazards, previous studies have focused on surface deformation and icequake activity (e.g. Failletaz et al., 2011; Dalban Canassy et al., 2012). Moreover, damage evolution (Pralong and Funk, 2006) and slider block models (Failletaz et al., 2010) have provided theoretical insights into glacier instabilities.

The thermal regime of glaciers plays a key role in processes leading to instabilities. Cold-based glaciers are frozen to their beds and fail via fracture growth. Temperate-based glaciers slide on

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the bedrock and undergo “active phases”, which may lead to large-scale ruptures (Failletaz et al., 2015). These acceleration phases usually occur late in the melting season and are caused by elevated subglacial water pressure. Ongoing climate changes affect glacier stability as previously cold glaciers may transition to temperate thermal regimes (e.g. Glacier de Taconnaz (F); Gilbert et al., 2015).
Here, we study the ice-covered northwest face of Weissmies in the Saas valley (Switzerland). Until recently, the adjacent Triftgletscher buttressed this ice cover from below (Fig. 1A). However, Triftgletscher's thinning has almost entirely removed this support (Fig. 1B).
In addition, the glacier is likely in a transition from cold to temperate as surface meltwater warms the previously cold bedrock, weakening the ice-bed interface and further promoting instability. The situation is critical, because tourist activity and – in the case of a large event – human infrastructure in the Saas valley are exposed to the danger of a glacier break-off. Therefore, a monitoring campaign was initiated to determine the frequency and volumes of icefalls, to improve our understanding of processes leading to glacier instabilities, and to detect break-off precursors. An interferometric radar and an optical camera were installed in October 2014, followed by GPS sensors, Doppler radar, an infrasound array and seismometers in June 2015 (Fig. 1C).

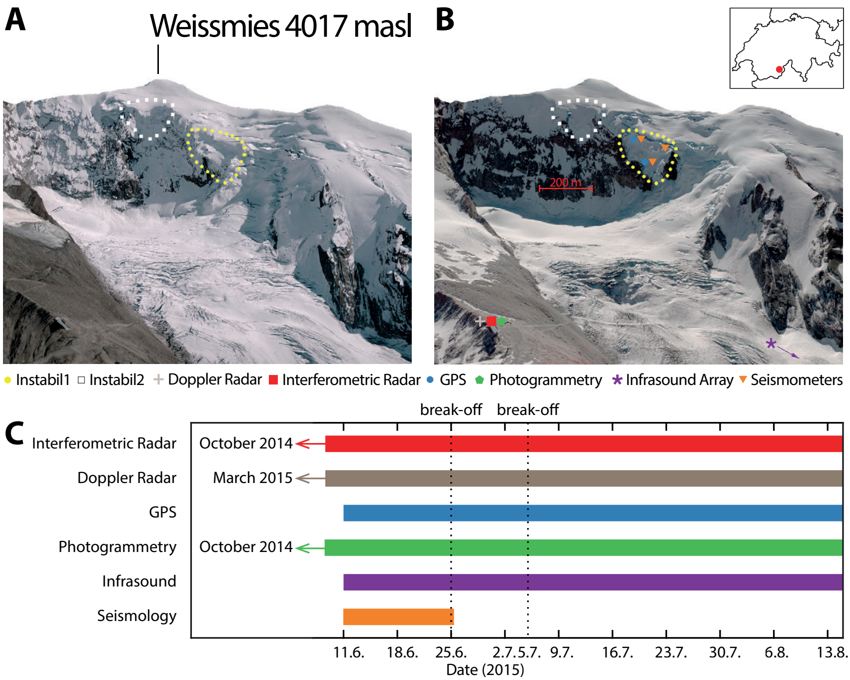

Figure 1: A) Oblique view of the unstable glaciers on the northwest face of Weissmies, between 2005 and 2009. (Source: swisstopo) B) The same view in 2014, with the position of our sensors. Note the substantial reduction of supporting ice below “Instabil1”. C) A temporal overview of the measurements during summer 2015.

Here, we discuss the observations in terms of processes affecting glacier stability. We focus on two icefalls, one of which occurred on 25 June 2015, when part of the steep ice mass "Instabil1" (Fig. 1) broke off (http://youtu.be/0aVyTfqafzg). The second ice fall originated from "Instabil2" on 5 July 2015 (http://youtu.be/m3nEzT9TIYE; a radar animation, as this event was not captured by the video camera). The estimated volumes are a few thousand m³ per event, which is only a tiny fraction of the 750 000 m³ that could potentially break off. In winter, events of more than 30 000 m³ of ice may endanger the ski resort, and a break-off of more than 200 000 m³ of ice could reach the town of Saas-Grund (information obtained from the company wasser/schnee/lawinen - A. Burkard AG, Brig).

METHODS AND RESULTS

Surface deformation

The goal of monitoring of surface deformation is to detect hyperbolically increasing surface velocities, which typically precede large break-off events (Flotron, 1977; Röthlisberger, 1978).

Interferometric Radar

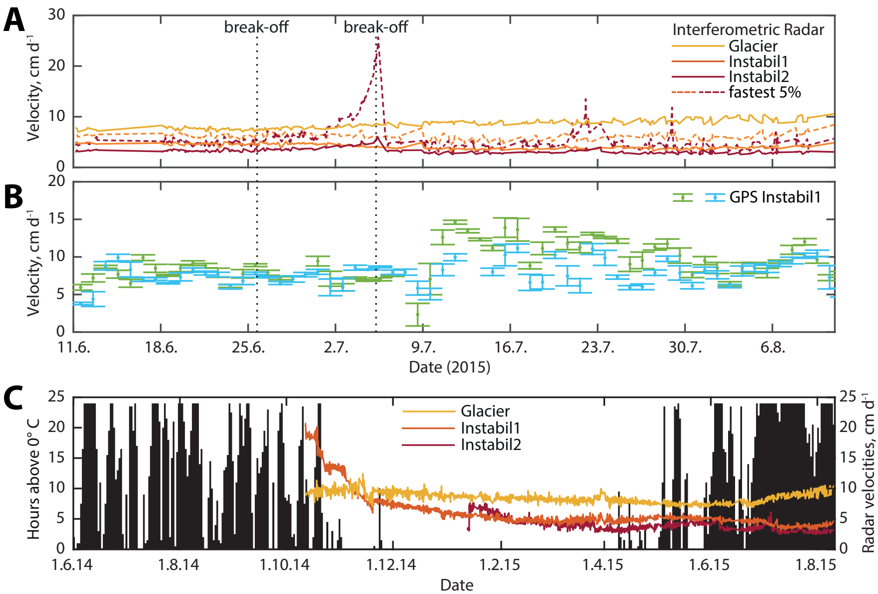

Figure 2: A) Radar line-of-sight velocities of Triftgletscher and the unstable zones. Note the increase in velocity prior to the second break-off event. B) GPS 3D velocities on Instabil1. The increase around 9 July is mostly an increase in vertical direction, likely due the GPS antenna stakes sinking into the ice. C) Long-term velocities (in color) and temperature (in hours above 0° C) clearly show that the summer of 2015 was warmer than the previous one, leading to more melt.

The interferometric radar emits microwaves (17 GHz, wavelength ≈ 1.7 cm) and evaluates the signal reflected by the glacier surface (Rödelsperger et al., 2010). Our IBIS-L system produces 2D images (azimuth and range) using the Synthetic Aperture Radar (SAR) technique. Since microwaves are affected by air humidity, temperature and pressure, atmospheric effects have to be removed. Reflection data are projected onto a topographic model to obtain a 3D image of glacier surface velocities. Uncertainties are estimated at 10% - 20% based on daily signal fluctuations, which are attributed to radar processing and not to actual glacier motion. Radar measurements are possible in low visibility weather and at night, and can be made from a safe distance (~ 2 km in this case). However, only the target motion component parallel to the line of sight is recorded.

Fig. 2A shows the average velocity of the glacier and the unstable parts during summer 2015. The movement is around 10 cm d^{-1} and fairly stable in this period. Long-term velocities (Fig. 2C) indicate that the unstable parts are significantly slower than in October 2014, when Instabil1 was moving at more than 20 cm d^{-1}.

A clear velocity increase to up to 25 cm d^{-1} precedes the icefall on 5 July (Fig. 2A). The area affected by the acceleration is readily identified in the projection onto an elevation model (Fig. 3C&D). In contrast, no elevated velocities were registered prior to the 25 June event (Fig. 2A, 3A&B).

Doppler Radar

A Range-Doppler Radar operating at X band (10 GHz), with the ability to measure azimuth angle, range and velocity was installed to detect ice avalanches. It has opening angles of 90° horizontally and 10° vertically and captures all movements up to a range of 2000 m within this area, hence also snow avalanches.

GPS

Two low-power, low-cost GPS sensors that measure the L1 frequency only were installed on Instabil1 (Fig. 1B) measuring in-situ surface velocities. A local long-haul WLAN enables wireless data transmission. Differential processing provides accuracies in the cm range (Fig. 2B). GPS sensors yield valuable ground truth data for the radar measurements. The difference between GPS and radar velocities can be attributed to projection and local site effects. However, they constitute point measurements and neither predicted nor detected the two icefalls, which occurred a few 100 m from the antennas.

Photogrammetry

In contrast to radar measurements, this method is sensitive to displacements perpendicular to the line of sight. Subsequent image templates (small sections around a feature in the image) are matched using least squares optimization (e.g. Grün, 1985). We used an optical off-the-shelf digital camera with 70 mm focal length resulting in a pixel resolution of ~15 cm, slightly varying due to the various target distances in the field of view. The accuracy of the technique is on the order of 0.05 pixel (e.g. Mass and Hampel, 2006). In our case, pronounced snow height and ice topography changes, as well as strong variations in scene illumination lead to relatively high inaccuracies of about 0.5 pixel, equivalent to 7.5 cm. The event on 5 July was captured in the image sequence, with observed peak velocities of around 30 cm d^{-1} in

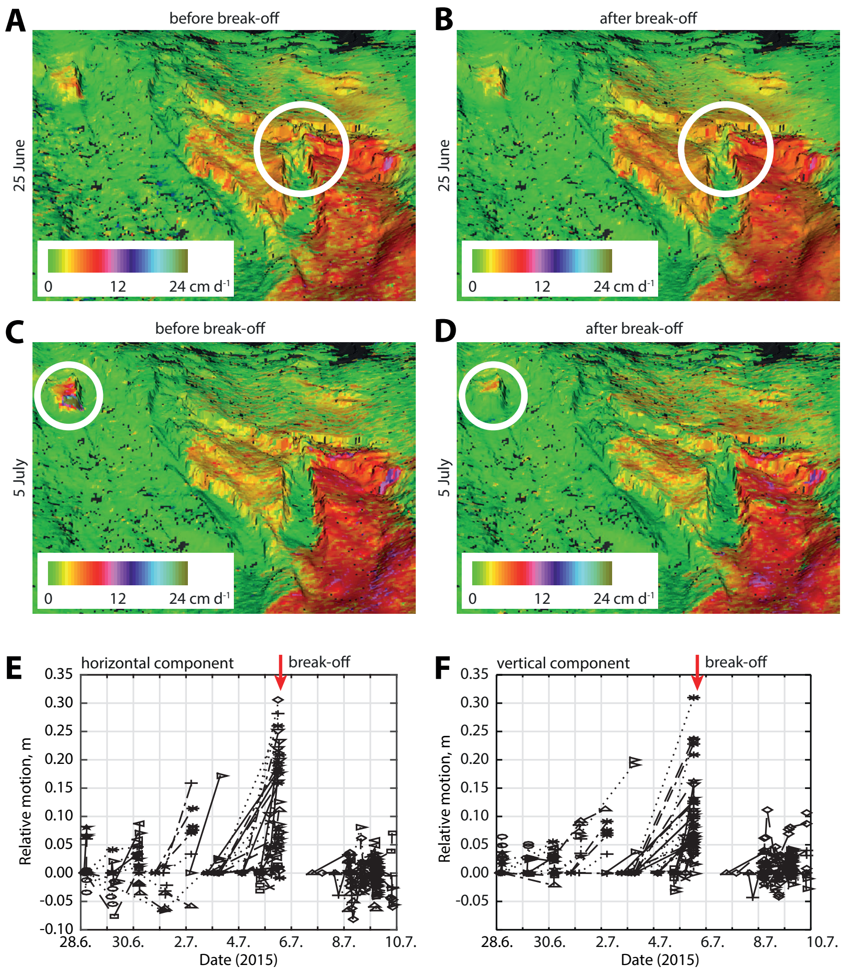

Figure 3: A) - D) Radar velocities before and after the break-off events. Note the almost identical radar images A) and B), but the clear difference between C) and D). E) & F) Displacement estimates derived from optical image sequences. The transition of image pixel to metric displacements is based on the camera-target distance. The data gap after the event is due to the loss of coherent image structures after the break-off.

horizontal and 20 cm d-1 in vertical direction (Fig. 3E&F). There was no sign in the image sequence for the earlier event (25 June).

Acoustic and Seismic Emission

Acoustic and seismic waves originate from icequakes, which are mostly tensile dislocations in the ice, or arguably arise from stick-slip motion of the glacier (Walter et al., 2008). Changes in icequake activity reflect the evolution of englacial damage prior to a glacier break-off (Failletaz et al., 2011).

Infrasound

We measured low-frequency (1-20 Hz) acoustic waves with a small aperture (150 m) 4 element infrasound array installed ~2.5 km away from the unstable glacier tongue (Fig 1B). Each array element was equipped with a differential air pressure transducer with a sensitivity of 25 mV/Pa and lower corner frequency of 0.01 Hz.

Array processing was performed on the infrasonic data applying multi-channel correlation among all elements of the array. Signal correlation is exploited to calculate arrival time differences of incoming sound waves, which are then used to determine wave parameters (event back-azimuth and apparent propagation velocity) (Ulivieri et al., 2011). Analysis was performed over 5 s windows, leading to a total of 52283 detections of coherent signals during the observation period. A variety of continuous background sources (e.g. nearby melt water streams, cultural activity) are responsible for the large number and diurnal variability of infrasound detections (Fig. 4A).

Requiring wave parameter stability reduces the detection list to 19 events (yellow crosses in Fig. 4A). Among those, the two break-offs can be unambiguously identified by their back-azimuth (Fig. 4B). During the 25 June break-off, the decreasing back-azimuth reflects the northward motion of the ice avalanche (Fig. 4D). The decrease in back-azimuth for the event of 5 July is less pronounced, as this event was moving due west, towards the array (Fig. 4F). Despite the reliable detection capability, the large 2.5 km distance between array and glacier implied a low signal-to-noise ratio. Any signals from precursory fracture activity are likely hidden in the background noise.

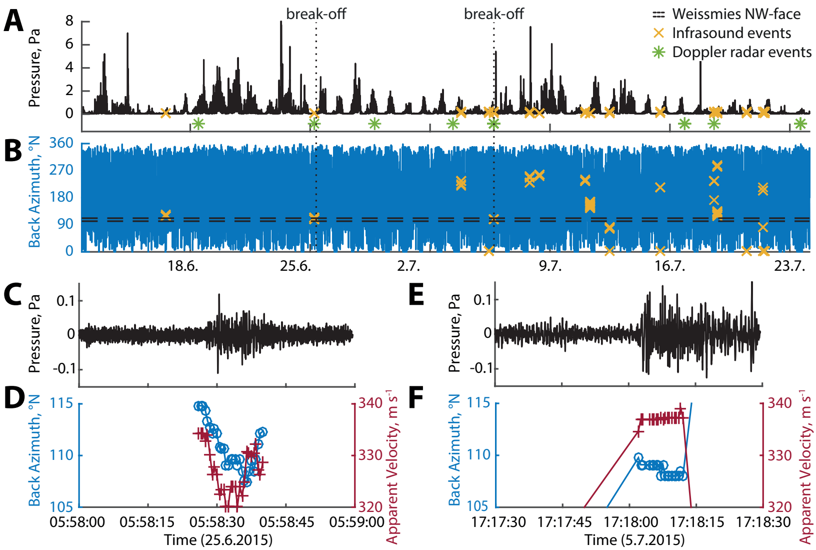

Figure 4: A) Pressure and B) back-azimuth of infrasound detections. From all events (yellow crosses), the two break-offs can be identified from their back-azimuth pointing towards Weissmies' northwest face. The Doppler radar picked up smaller events as well (green asterisks). C) - F) Pressure, back-azimuth and apparent sound velocities of the two break-off events.

Seismology

We installed three seismometers (sensitivity from 10 Hz to 500 Hz) on Instabil1, two of them collocated with the GPS sensors (Fig 1B). The seismometers were recovered after two weeks, as wireless data transmission did not work reliably. Therefore, our interpretation is limited to the break-off event of 25 June. In the hours before the break-off, no precursory activity stands out (Fig. 5A&B). Moreover, automatic icequake detections (Walter et al., 2008) indicate a steady decrease in fracture event activity (Fig. 5C).

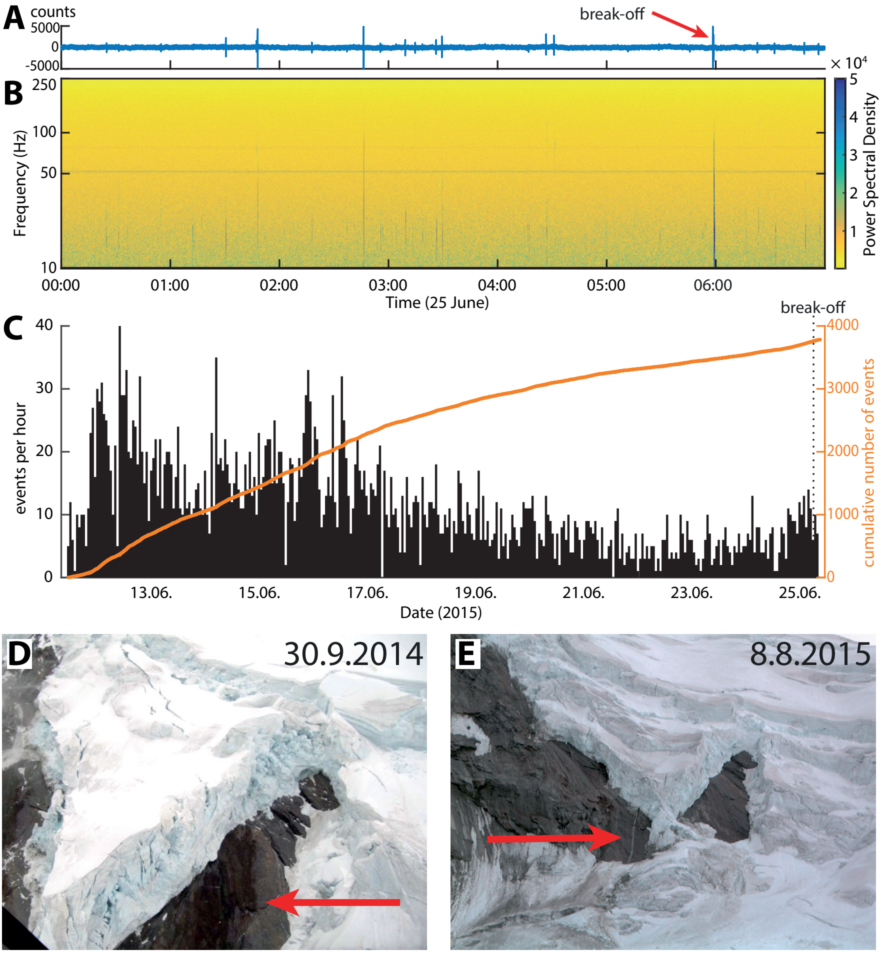

Figure 5: A) Seismogram of the 6 hours before break-off. Data gaps amounting to less than 0.01% were filled via interpolation. B) Corresponding spectrogram. Vertical spectral lines indicate icequake occurrences and highlight their broadband (10-100 Hz) character. Note the clear signal of the break-off event. The straight horizontal lines are electronic noise. C) Evolution of events in the two weeks before the break-off. D) 2014 aerial photograph of Instabil 1 showing widespread wetted bedrock and thus sheet-like subglacial melt discharge. (Source: U. Andenmatten) E) Photograph from 2015 showing a single channel of subglacial discharge.

DISCUSSION

Monitoring Methods

No large break-off events occurred during our monitoring period. Nevertheless, the interferometric radar successfully forecasted the break-off of 5 July. On the other hand, the radar detected no acceleration prior to the 25 June event. Photogrammetric analysis of this event also failed to detect changes in surface motion at least 15 minutes before break-off. Both techniques are sensitive to glacier surface motion in different (perpendicular) directions. We therefore suggest that the 25 June break-off had a different failure mechanism, which unlike the 5 July event was not preceded by an acceleration phase. Thus, instabilities of a few thousand m^3 of ice can develop and fail without speed-up.

Infrasound provided reliable detection of both break-off events and no false alarms. The Doppler radar detected the two avalanches as well as some smaller events. Similarly, the 25 June break-off generated the strongest detected seismic signal. Further analysis of the preceding icequakes is needed to clarify if these events provide some information about precursory fracture activity leading to break-off.

In conclusion, none of the presented techniques by itself is sufficient for automatic detection and forecasting of break-off events. On the other hand, break-offs of at least a few thousand m^3 of ice with precursory acceleration can be reliably forecasted using interferometric radar and photogrammetry. However, at this stage manual review of radar and photographs is needed. Infrasound, Doppler radar and seismic measurements produce clear break-off signals, which require minimal human interaction and could potentially be fully automated. A large-scale break-off of the entire unstable ice mass may produce stronger signals, including precursors, which all presented techniques are capable of detecting.

Glacier dynamics

The surface velocities on the unstable part of the glacier decreased from ~20 cm d^{-1} in October 2014 to 5 cm d^{-1} in February 2015 (Fig. 2C). During July 2015, it even decreased to an unexpected low of 3 cm d^{-1}.

In 2015, long periods above freezing substantially promoted meltwater production (Fig. 2C). Surface meltwater most likely accessed the glacier bed, where it partly refroze, warming the ice/bed contact and promoting basal sliding. Therefore, contrary to the observed slowdown, the unstable glacier part was expected to move faster during the 2015 high-melt periods. This slowdown can be explained by a change in subglacial hydraulics. Comparing images from 2014 and 2015 reveals a widespread zone of wet rock below the unstable ice in 2014 (Fig. 5D). Subglacial water was thus present under an extended part of the glacier. Conversely, a single stream exited the unstable part in 2015 (Fig. 5E). Higher amounts of available meltwater in 2015 probably lead to the channelization of subglacial meltwater flow making the drainage system more efficient during summer 2015 than in 2014. This reduced basal water pressures, strengthening the basal contact (Kamb et al., 1985), and leading to limited basal motion. Another explanation for glacier deceleration is the presence of a subglacial rock barrier, against which the ice mass has recently stabilized. There is no further evidence for this theory, but at this stage this possibility cannot be excluded. Our seismological results can explain both the sliding decrease and subglacial barrier hypothesis in terms of reduced stick-slip icequakes and less extensional crevasse icequakes, respectively.

By the time of writing, it is unclear how long the various measurements will continue in the future. This will largely depend on the future hazard assessment by the responsible authorities. Additional investigations on the englacial thermal regime with borehole measurements would help to understand the dynamical behavior of this steep ice covered face. A numerical ice flow model incorporating material damage would help to identify critical regions where crevasse formation indicates imminent failure. Finally, bedrock topography and the total ice volume, which could be obtained by ground-penetrating radar, would be an asset for future hazard assessment.

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