Hydro-Mechanical Interactions of a Rock Slope With a Retreating Temperate Valley Glacier

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Abstract  Rock slope failures often result from progressive rock mass damage which accumulates over long timescales. In deglaciating environments, rock slopes are affected by stress perturbations driven by mechanical unloading due to ice downwasting and concurrent changes in thermal and hydraulic boundary conditions. Since in-situ data are rare, the different processes and their relative contribution to slope damage remain poorly understood. Here, we analyze borehole monitoring data from a rock slope adjacent to the retreating Great Aletsch Glacier (Switzerland) and compare it to englacial water levels, climate data, and decreasing ice levels. Rock slope pore pressures show a seasonal signal controlled by infiltration events as well as effects from the connectivity to the englacial hydrological system. We find that reversible and irreversible strains are driven by: (a) hydromechanical effects caused by englacial pressure fluctuations and infiltration events, (b) stress transfer related to changing mechanical glacial loads from short-term englacial water level fluctuations and longer term ice downwasting, and (c) thermomechanical effects from annual temperature cycles penetrating the shallow subsurface, which primarily result in reversible deformation. We relate most observed irreversible strain (damage) to mechanical unloading from ice downwasting. Damage is strongest directly at the ice margin and moves through the slope at the pace of glacial retreat and advance. Locations with many retreat/advance cycles are very sensitive to landslide formation. The current climate warming impacts very sensitive valley sectors, which is confirmed by landslide distributions and activity in the study area.

Plain Language Summary  The formation of rock slope instabilities is a long-term process related to continuous rock mass weakening. For rock slopes in glaciated valleys, increased rates of rock mass damage are assumed to occur during ice retreat due to a reduction of the glacier weight and concurrent changes in rock temperatures and slope groundwater pressures. However, because direct field measurements are missing, governing processes and their relative importance are still poorly understood. Here, we analyze borehole monitoring data and compare it to englacial water levels, climate data, and decreasing ice levels. We find that the glacial hydrology influences the dynamics of the groundwater pressures in the adjacent rock slope at various timescales. We record micrometer-scale reversible (elastic) deformation and irreversible rock mass damage and identify the involved drivers. Several processes contribute to progressive rock mass weakening at different timescales and magnitudes, but most damage is related to mechanical unloading from ice downwasting and is strongest directly at the ice margin. Locations with many retreat/advance cycles are sensitive to increased damage accumulation and landslide formation. The current climate warming impacts very sensitive valley sectors, which is confirmed by landslide distributions and activity in the study area.

1. Introduction

Large rock slope instabilities develop through progressive rock mass damage during thousands of years driven by various transient environmental loads. In deglaciating environments, increased rates of damage are expected (Ballantyne et al., 2014; Grämiger et al., 2017; McColl, 2012; Riva et al., 2017), caused by stresses related to ice downwasting in combination with increased dynamics in the thermal and hydraulic boundary conditions acting on ice-free slopes (Grämiger et al., 2020). While the degree at which a slope reacts to changing environmental boundary conditions strongly depends on its predisposition and state of damage (i.e., rock mass strength, discontinuity properties and orientations, and local stress state) (e.g., Cody et al., 2020; V. Gischig et al., 2016), the relative contributions of the different drivers to progressive rock mass damage during ice retreat remain poorly known.
Until now, progressive rock mass damage in paraglacial environments has mainly been investigated through conceptual approaches and numerical models (Baroni et al., 2014; Grämiger et al., 2017, 2018, 2020; Riva et al., 2017; Spreficco et al., 2020). Most of these studies rely on assumptions regarding the mechanical, hydraulic, and thermal properties, processes and boundary conditions that so far could rarely be verified because of lack of in-situ subsurface data. This paper is part of a long-term research project, where we investigate these critical unknowns by setting up surface and subsurface monitoring systems on rock slopes adjacent to the tongue of the Great Aletsch Glacier (Hugentobler et al., 2020). While in a companion paper (Hugentobler et al., 2021) we have described and analyzed the thermal and thermo-mechanical drivers, here we focus on hydraulic and hydro-mechanical processes in a paraglacial environment at borehole and slope scale. We aim at specifically exploring the relative contributions of processes responsible for micrometer-scale borehole strain, such as rock slope and englacial pore pressure transients, longer term glacial ice downwasting, and the corresponding hydromechanical effects.

While “glacial debuttressing,” that is, loss of horizontal support due to ice retreat has often been used to describe causes for slope failure, this concept has been called into question mainly because ice demonstrates viscous behavior at low strain rates (Schulson, 1990) and therefore cannot build a strong buttress (McColl & Davies, 2013; McColl et al., 2010). Nevertheless, downwasting ice is understood to destabilize adjacent slopes due to a reduction of normal load on the toe of a landslide that reduces friction along discontinuities in the rock mass (Wyllie & Mah, 2004). However, the significance of these changes in normal load is poorly constrained, mainly because some of the ice weight is compensated by buoyancy effects during times of high englacial water pressures in temperate glaciers, and unknown coupling to the slope groundwater pressure (McColl et al., 2010).

Englacial water pressures of temperate glaciers show strong variations at diurnal to annual timescales (e.g., Fudge et al., 2005; Harper et al., 2005; Iken et al., 1996; Sugiyama & Gudmundsson, 2004). In contrast to reduced glacial loads with high englacial water pressures, quick increase of englacial water levels might also exert an additional load on the slope if these fluctuations occur at a rate that is faster than the englacial hydrological system can equilibrate with the slope groundwater.

The transient englacial hydrological system of temperate valley glaciers can be subdivided into two season-dependent end-member systems (Fudge et al., 2005). The summer system is characterized by strong daily water pressure fluctuations within a channelized drainage system driven by daily meltwater infiltration cycles and a relatively low mean water pressure in areas that are not directly connected to the main drainage network (Fudge et al., 2005; Harper et al., 2005). Water pressure measurements in glacial boreholes have shown that pressure fluctuations can have amplitudes from nearly ice overburden pressure down to atmospheric values in the main drainage conduit and directly connected channels. The amplitudes of pressure variations decay laterally in the glacier within a few tens of meters distance from the connected channel (Hubbard et al., 1995). In winter-time, the efficient drainage system of the summer ceases and a linked-cavity based system establishes causing relatively constant high water pressures within the glacier at a level close to ice overburden (Harper et al., 2005; Lappegard et al., 2006).

These variations in pressure within the glacier may diffuse into the adjacent rock slopes if both are connected through permeable structures. It is often assumed that a temperate glacier imposes a constant head boundary to the adjacent slope similar to the effect of a reservoir lake, and hence, that the slope hydraulic head is tightly linked to the glacier elevation (McColl et al., 2010). However, this might be an oversimplification, since englacial water pressures show strong temporal and spatial pressure variations and the ice-bedrock contact might be sealed with fine-grained basal till. The rate at which englacial pressure variations propagate into the slope is also a function of the hydraulic properties of the adjacent rock mass (i.e., hydraulic diffusivity), and the connectivity to the englacial hydrological system.

Hillslope bedrock hydrology also shows strong dynamics, related to temporal variations in recharge and storage-discharge functions (Fan et al., 2019; Kirchner, 2009). Phreatic groundwater levels in Alpine rock slopes normally show a seasonal signal (de Palézieux and Loew, 2019) with amplitudes dependent on the ratio between infiltration (from snowmelt and summer rainfalls) and the hydraulic diffusivity of the rock mass (Gleeson & Manning, 2008). Hydraulic properties in crystalline rocks are controlled by complex network of fractures organized within a relatively low permeability intact rock matrix (Singhal & Gupta, 2010). Hence, hydraulic properties are dependent of fracture density, connectivity, initial aperture, filling, and stress conditions (Lavoine et al., 2020);
Maillot et al., 2016). It is often observed that hydraulic conductivity and storage show a nonlinearly decreasing trend with depth due to increasing overburden stress (Achtziger-Zupančič et al., 2017; Manning & Ingebritsen, 1999). Increased fracture density and interconnectivity at the shallow subsurface can result in unconfined behavior of fractured rock aquifers, whereas at greater depth with less interconnected fractures, a higher degree of confinement is regularly observed (Keahler & Hsieh, 1994; Rahi & Halihan, 2013; Welch & Allen, 2014).

Earth and atmospheric tides also have a measurable impact on subsurface pore pressure dynamics (Acworth et al., 2016; Hsieh et al., 1987). Earth tides are caused by gravitational fluctuations related to the movement of celestial bodies relative to Earth and result in poroelastic crustal deformation, causing variations in pore pressures (McMillan et al., 2019). Atmospheric tides result from variations in barometric pressure related to thermal expansion and gravitational effects (Chapman & Westfold, 1956).

It has been shown that dynamics in hydrological behavior may have a strong impact on slope movement and instability, especially through long-term cyclic loading and fatigue. Hydromechanical effects driven by pore pressure changes can cause reversible (elastic) deformation in stable rock slopes (Guglielmi et al., 2005; Hansmann et al., 2012; Rouyet et al., 2017). In unstable slopes, pore pressure increases are often identified as main drivers for acceleration (Bonzanigo et al., 2007; Groneng et al., 2011; Guglielmi et al., 2005; Huang et al., 2018; Loew et al., 2017; Preisig et al., 2016; Wolter et al., 2020). These processes also promote progressive rock mass damage due to subcritical crack-growth and are considered as important preparatory factors for future rock slope instabilities (Guglielmi et al., 2008; McColl, 2012; Prager et al., 2008; Preisig et al., 2016; Riva et al., 2017).

Irreversible strain measured in rock slopes is often used as a proxy for rock mass damage, which in fractured rock masses comprise tensile or shear fracture propagation and breakage of intact rock bridges, degradation of asperities, and smoothing of discontinuities caused by fracture slip (Eberhardt, 2008; Grämiger et al., 2020; Preisig et al., 2016; V. S. Gischig et al., 2011b). Besides the magnitude of the hydromechanical loading (or load of any other origin), the strain reaction of a rock slope strongly depends on the rock mass properties (mainly degree of damage and the spatially varying in-situ stress states). Stress concentrations in rock slopes are controlled by the slope geometry and the presence of discontinuities (joint networks and faults) at different spatial scales (Stock et al., 2012; Styles et al., 2011; V. S. Gischig et al., 2011a, 2011b; Wolters & Müller, 2008; Young & Ashford, 2008).

Dependent on the criticality of the fracture system, a stress perturbation of a specific magnitude will either cause mainly elastic (reversible) strain if it lies below the fatigue limit, cause slow, subcritical fatigue crack growth if it lies above the fatigue limit, or even triggers quicker strain reactions if it locally reaches critical stress levels (Brain et al., 2014). Numerical simulations propose that hydromechanical stress changes related to pore pressure variations, in combination with changing mechanical loading due to ice fluctuations, are stronger drivers for progressive rock mass damage compared to purely mechanical unloading or thermomechanical stress changes in combination with ice fluctuations (Grämiger et al., 2017, 2018, 2020). These authors further show that besides long-term changes (hydromechanical and thermomechanical effects due to glacial cycles, and glacial loading and unloading cycles), seasonal thermomechanical and hydromechanical cycles are critical for generating irreversible rock slope deformation or damage.

In this study, we present data and detailed analyses of pore pressure and micrometer scale strain time series recorded in three, 50 m deep boreholes, drilled in fractured crystalline rock at the margin of the rapidly retreating Great Aletsch Glacier (Valais, Switzerland). Climatic data and englacial water levels monitored in a nearby sinkhole enable us to investigate their effects on groundwater dynamics in our rock slope and the connectivity to the englacial hydrological system. Multi-annual and highest resolution multilevel axial and radial strains monitored in our boreholes are compared to transient pore pressures, englacial water pressure variations, and decreasing glacial ice levels. We investigate these mechanical and hydromechanical responses and discuss the dominant drivers for reversible deformation, irreversible rock mass damage, and landslide formation on timescales ranging from hours to years.

1.1. Site Description

Our study site is located in fractured crystalline rock along the retreating glacier tongue of the Great Aletsch Glacier (Valais, Switzerland) (Figure 1). Bedrock outcrops along our approximately 30° dipping and NNW facing rock slope are glacially smoothed, and a distinct valley parallel ridge and furrow morphology is present. The study
Figure 1. Overview map showing the locations of the three boreholes B2, B4, and B6 aside the glacier tongue of the Great Aletsch Glacier at the Autumn 2017 ice extent (modified after Hugentobler et al. (2020)) and the approximate location of the monitored glacial sinkhole. Scaled cross sections (a–c) that intersect the borehole locations (as visualized on the map) illustrate the local ice level changes during the monitoring period between 2017 and 2021. These ice levels result from high-resolution glacial ice elevation measurements acquired during August (source: Swiss Federal Office of Topography). Earlier ice extents from years 1927 to 2014 illustrated on the map were digitized from historical aerial photos by Glueer et al. (2020). LIA (little ice age, last maxima ∼1860) and Egesen stadial (dated at ∼12 ky BP; Ivy-Ochs et al., 2008) ice extents are constraint by lateral moraines in the area of the map. The geological map from Steck (2011) was extended in areas that were ice covered during their mapping campaign.
site is located in the Aare-Massif (Steck, 2011), and the dominant lithologies consist of gneiss and granites that form the ridges, and weaker schist layers or brittle-ductile shear zones following the alpine foliation that normally form the furrows. The alpine foliation strikes valley parallel and is normally steeply dipping into the slope. Three persistent joint sets are present at the study site showing normal spacings of around 1–3 m at the ground surface and a decrease with depth (Hugentobler et al., 2020). The most persistent joint set is foliation parallel, a second joint set is steeply SSW dipping, and the third persistent joint set shows a slope subparallel orientation. The lower study area is covered by a recent, thin, and patchy till layer containing several rock outcrops.

A number of active and relict/dormant rock slope instabilities occur in the region of the current glacier tongue of the Great Aletsch Glacier (Grämiger et al., 2017). As visible on the map (Figure 1), a few 100 m SW of our study site the well monitored and documented active Moosfluh rock slope instability is located (Glueer et al., 2019, 2020; Kos et al., 2016; Strozzi et al., 2010).

The extent of the Great Aletsch Glacier is well documented since the little ice age (LIA) maximum, which occurred around 1860 (GLAMOS, 1881–2019). These data show an increased melting rate in more recent years. Since the LIA, the glacier tongue has lost approximately 300 m of ice height at our study site, and high-resolution surface models of the Great Aletsch Glacier from the years 2012–2020 show annual ice height losses of around 10 m per year (see Figure 8, source: Swiss Federal Office of Topography).

1.2. Previous Work

In summer 2017, a subsurface monitoring system containing three highly instrumented boreholes was installed beside the retreating glacier tongue of the Great Aletsch Glacier. The setup and performance of this system is described in Hugentobler et al. (2020) in detail. It consists of three ~50 m deep research boreholes that were placed with variable lateral distance to the 2017 ice margin (Figure 1) and at locations with variable rock mass quality. The boreholes are each 10 cm in diameter and were logged with geophysical and hydrogeophysical probes prior to the sensor installation. The boreholes were fully grouted after the permanent monitoring system had been installed. For a summary of the logging results refer to Hugentobler et al. (2020). All boreholes contain a temperature sensor chain with 1 m downhole spacing, a pore pressure sensor installed at the borehole end, an SAA in-place inclinometer chain with 0.5 m segment length to measure horizontal displacements, and a series connection of 10 Fiber Bragg Grating (FBG) sensors of approximately 5 m base length to measure the axial strain along the whole borehole length (Hugentobler et al., 2020).

The three boreholes were placed between 1 and 50 m from the 2017 ice margin. One of the borehole locations, B6, was drilled in a former toppling rock slope instability that currently shows low activity (Figure 1). This instability was identified by its distinct morphology with a head scarp, an outward rotated foliation, and more disturbed rock mass below (Geological Strength Index [GSI] values between 50 and 60) (Hugentobler et al., 2020). The other two boreholes were drilled at locations showing no signs of active or former slope movements and feature differences in rock mass quality (i.e., GSI values at B2 from 55 to 65 and at B4 from 75 to 85). Borehole pumping and infiltrations test results provide the following transmissivity estimates: ~10^-6 m²/s in the lower part of B2 and in borehole B4; ~10^-3 m²/s in the upper 15 m of B2, and ~10^-5 m²/s in B6. Because of instable borehole conditions in B6, no optical televiewer log could be conducted in this borehole. From observations while drilling (drilling gas pressure drop and water inflow), we assume a higher degree of fracturing and hence a higher transmissivity in the shallow meters of B6—similarly as it was measured in B2.

2. Methods

2.1. Borehole Monitoring Systems

In this study, we focus on the pore pressure, and axial (vertical) and radial (horizontal) strain measurements, collected at hourly intervals. Boreholes B4 and B6 are equipped with piezo-resistive pressure sensors (PA-27XW 10 bar by Keller AG with an accuracy below 2 mbar) installed in a 1–2 m long sand filter at 43.75 (B4) and 48.75 (B6) meters below ground surface. The pressure sensor in B2 was presumably damaged during grouting. The absolute pressure readings from the borehole sensors were corrected for atmospheric pressure variations using data from a pressure sensor installed at the study site (at TPS1 location, see Figure 1).
Horizontal deformation is monitored with in-place inclinometers (SAAF500-003 by Measurand Inc.) that consist of accelerometer-based sensor arrays installed on rigid 0.5 m long segments separated by flexible joints. Temperature sensors, installed with 1 m spacing, are used for internal correction of temperature related variations in segment length. Vertical strain along the borehole is recorded by temperature-corrected, pre-strained FBG strain sensor chains (SC-01 by Sylex Fiber Optics s.r.o.) of approximately 5 m base-length. To improve the measurement precision, static hourly strain measurements are gained by measuring for around 30 s every hour and averaging the recorded strain. In Hugentobler et al. (2020), we show that the installed strain monitoring system can reliably detect vertical elongations/compressions strains with a precision of below 1 µε (∼4 µm) for the FBG sensors of 4–5 m base-length, and horizontal displacements with a precision of around 0.1 mm for the in-place inclinometer sensors with 0.5 m segment length.

Pore pressure and horizontal deformation (SAA in-place inclinometer) time series have been nearly continuously recorded since early October 2017 with only a few gaps of some days to a few weeks of duration related to battery issues. Vertical strain time series measured by the FBG system are reliably recorded since July 2018. A data gap from April to July 2018 that exists in all sensors of borehole B2 is related to a temporary glacier readvance that overrun the borehole location and disrupted the sensors from the data loggers. All borehole monitoring systems (data loggers, power supply, and transmission) were dismantled in summer 2021.

2.2. Glacial Sinkhole Pressure Measurements

In August 2019, we installed a piezo-resistive pressure sensor connected to a datalogger (PAA-36XiW with GSM-2 logger by Keller AG) in a glacial sink hole at around 40 m depth. This sensor functioned until January 2021 but only recorded clear water pressure variations until April 2020. The glacial water pressure sensor is corrected for atmospheric pressure fluctuations, has a measurement accuracy of 3 mbar, a measurement interval of 10 min, and had a daily data transmission.

As mentioned in the introduction, the glacial drainage system is expected to be highly channelized and confined. It is therefore possible that the pressure levels in the glacial sinkhole are disconnected from the main glacial drainage system and only reflect local variations. We assessed this possibility based on the existing knowledge about the temporal dynamics of englacial hydrological systems inferred from ice boreholes drilled in the Aletsch Glacier (Grämiger et al., 2020), as well as from investigations at other temperate valley glaciers (Fudge et al., 2005; Harper et al., 2005; Hubbard et al., 1995; Lappegard et al., 2006). In particular, if the sinkhole is connected to the main drainage system, we expect steady diurnal pressure variations during the summertime which peak when surface temperatures are high, pressure peaks corresponding to rainfall events, as well as high, relatively constant pressures during the winter time. These factors are further investigated in Section 3 when the glacial pressure measurements are presented.

2.3. Time Series Analysis of Head Fluctuations

As will be shown in Section 3, the pore pressure monitoring time series contains high frequency signals of >1 cycle per day (cpd). We hypothesize three potential causes of these signals: (a) atmospheric pressure fluctuations, (b) earth tides, and (c) slope hydraulic response to englacial pressure head fluctuations. To test these hypotheses, we applied filter techniques and spectral analysis. First, we used a high pass filter to extract frequencies greater than 1 cpd. We then applied a fast Fourier transformation (FFT) to detect the frequency bands at which cyclic signals occur.

The resulting amplitude spectra from the pore pressure sensors in the boreholes were compared to those expected for the three potential causes detailed above. To test whether atmospheric pressure or earth tides are the cause, we compared the FFT results of the pore pressure sensors to the calculated amplitude spectra for the atmospheric pressure sensor at the study site and computed earth tides in the study area using the software TSoft (Van Camp & Vauterin, 2005). Additionally, we fit tidal components from earth and atmospheric origin to our continuous pore pressure data using the MATLAB’s Tidal Fitting Toolbox (Grinsted, 2022). A comparison of the relative amplitude of earth and atmospheric tides contained in the pore pressure signal allows for the interpretation of the degree of confinement of an aquifer (Rahi & Halihan, 2013). Finally, we explored potential glacial control on these signals by computing the time lag between pressure fluctuations in the glacial sinkhole and the rock
slope. For this, we use a moving window cross-correlation MATLAB function (Marwan, 2020) with overlapping windows of 24 hr length.

### 2.4. Pore Pressure Diffusion

Pressure diffusion in continuum type aquifers is regulated by the hydraulic diffusivity of the media, \( D = T/S = Kb/S \) (m²/s), where \( S \) is the dimensionless storage coefficient that in a confined aquifer is defined as \( S = bS_s \), where \( b \) is the aquifer thickness and \( S_s \) is the specific storage. \( T \) is the transmissivity of the aquifer (m²/s) and \( K \) the hydraulic conductivity (m/s).

To investigate the relationship between diurnal pressure cycles measured in the glacial sinkhole and diurnal pressure head fluctuations in the boreholes, we use an analytical solution for one-dimensional pressure diffusion of a sinusoidal head boundary in a semi-infinite confined aquifer (Equation 1, e.g., Zhou (2008) and references therein). This equation shows that the sinusoidal head signal imposed at the boundary occurs at a distance \( x \) from the boundary with a reduced amplitude (damping) and a phase shift (time lag) effect. Equation 2 shows that the lag time \( t_L \), that is, the time needed for the signal to diffuse from the source (here the subglacial drainage channel) to a given point in the slope, is proportional to the distance \( x \) from the point to the source and proportional to \( \sqrt{S/T} \) (i.e., \( \sqrt{1/D} \)).

\[
H(x, t) = H_0 e^{-x\sqrt{S/T}} \sin \left( \frac{2 \pi t}{t_0} - x\sqrt{\frac{S}{T}} \right)
\]  
\[
t_L = \frac{x \sqrt{S}}{4 \pi T}
\]

\( H \) is the hydraulic head of the aquifer relative to a defined reference level (in m), \( x \) is the distance (m) to the boundary, and \( t \) is time. \( H_0 \) equals the amplitude of the sinusoidal head signal (in m) and \( t_0 \) the period of the oscillation.

Although, it is evident that pressure diffusion in crystalline rock is controlled by a complex network of fractures, our approach aims at estimating a bulk hydraulic diffusivity between the valley bottom, where head fluctuations occur (i.e., in the main subglacial drainage channel), and the borehole location close to the ice margin. The highly fractured near surface bedrock layer below the glacial ice (outside the subglacial drainage channel) is treated as a confined aquifer, the possibly unconfined section in the bedrock outside the glacier lateral margin is hereby neglected. The direct length between source and the monitoring borehole B4 is estimated to be 320 m.

### 2.5. Strain Data Analysis

We use both the in-place inclinometer system (horizontal deformation) and the FBG system (vertical deformation) to investigate the deformation characteristics in our instrumented rock slope observed during glacial ice retreat. Because of the lower displacement resolution of the inclinometer system (cf. Section 2.1), it is mainly used to investigate the long-term irreversible displacement magnitudes, depth intervals, and directions at the three borehole sites and is provided in Appendix B. The main analyses of the transient deformation processes from various drivers at different timescales are based on the higher-resolution FBG strain data. For these analyses, we differentiate rapid strain events that occur within the measurement interval of 1 hr, short-term strain events that occur within few hours to several days, and longer term strain trends that are observed at timescales from month to years.

In Section 3 and 4, we compare monitored pore pressures and FBG strain data from our boreholes. Changing mechanical (glacier) loads affecting the rock slope are transmitted through stress transfer into the rock mass, and therefore occur nearly immediately at the time of the load change. We hypothesize that rapid strain events might be driven by changing mechanical loads related to quickly changing water levels in the glacier and therefore compare our strain data to glacial sinkhole pressure data. Additionally, we investigate the timing of all rapid strain events occurring in the remaining period of the nearly 3-year long time series, where we do not have englacial pressure monitoring data. To investigate potential long-term effects of mechanical unloading due to ice downwasting, we compare annually retrieved glacial levels (source: Swiss Federal Office of Topography), visualized in 2D cross section through the three borehole locations, to the strain history of all FBG sensors.
While reversible strain probably is related to elastic deformation, we relate irreversible strain components with plastic deformation and progressive rock mass damage (Hugentobler et al., 2020, 2021). The differentiation between reversible and irreversible strain is not always trivial, because strain occurs in positive and negative direction and at different timescales. For the differentiation of strain signals at timescales of hours to a year, we compare the strain signals to the dynamics of the potential drivers for deformation (e.g., pore pressure and temperature). Strain that recovers after perturbation is defined as reversible and the portion of strain that remains after perturbation it is defined as irreversible. For longer term strain trends, we discuss the displacement characteristics and potential drivers to define if it is interpreted as reversible or irreversible deformation.

3. Results and Interpretation

In this section we present the results obtained using the methods described in Section 2. The last paragraph in the subchapters of this section additionally contain interpretations of the results on which following subchapters build on. We first describe and explain the englacial pressure measurements, and provide justification that these are likely representative of the overall drainage system at this location. Next, we use these pressure measurements, as well as our other meteorological and subsurface data, to describe the long- and short-term pore pressure dynamics in the slope. Finally, we combine this understanding of the glacier and slope hydrology with measured deformation data to characterize the hydromechanical processes acting in our monitored slope at daily, yearly, and decadal timescales.

3.1. Englacial Water Pressure Dynamics

We hypothesize that glacier head fluctuations are an important driver of high frequency head fluctuations in the adjacent rock slope in summertime. To investigate this, we first assessed whether the pressures measured in the glacial sinkhole likely reflect the overall glacial drainage network at this location, based on the criteria given in Section 2.2. The pressures recorded by our sinkhole sensor at an initial depth of 40 m show englacial water level variations between 8 August 2019 (start of the measurements) and 28 April 2020 (Figures 2c, 3c and 3h). During summer 2019, the pressure sensor measured atmospheric pressure values during nighttime and most of the day indicating that water level in the sinkhole must be below the sensor elevation. Only in the early afternoon pressure readings indicate a rise of the water level to elevations of ~5–20 m above the sensor (i.e., up to 20–35 m below ice surface). These diurnal signals peak at the time of maximum surface temperatures and are only measured for a few hours a day (Figures 2c and 3c). At some days, pressure peaks also occur at other daytimes and coincide with rainfall events. During wintertime, pressure measurements indicate generally high englacial water pressures, often very close to the elevation of the ice surface, and some abrupt, low magnitude changes in water levels occur. As will be described in more detail below, these pressure measurements correspond to those expected of the englacial hydrological system, giving us confidence that the glacial sinkhole measurements are representative of the broader system. After 28 April 2020, the monitored pressure stayed constant at values close to atmospheric pressure for the rest of the sensors’ lifetime (in January 2021) with only few, weak excursions.

We relate the diurnal pressure peaks in 2019 that occur in the afternoon to daily meltwater cycles that quickly fill the highly transmissive channelized englacial hydrological system, with which the monitored sinkhole presumably was connected during that period. We propose this because of the very constant diurnal signals measured over the whole summer season and no observed significant direct inflow into the sinkhole from supraglacial channels. The atmospheric pressure values and the absence of diurnal fluctuations in summer 2020 can be explained by a decoupling of the sinkhole from the englacial hydrological system probably due to ice movement. The hypothesized ice movement and trapping of the sensor is supported by the fact that it was not possible to retrieve the sensor anymore after this event. Such observed changes in hydrological response, also at a decimeter-scale, are consistent with water pressure measurements made in boreholes of other temperate valley glaciers that only show strong pressure fluctuations (similar to our observed magnitudes), if they are directly connected to the englacial hydrological system (Fudge et al., 2005; Harper et al., 2005). Further, we relate sinkhole pressure peaks that coincide with rainfall events during summer 2019 to a quick filling of the englacial hydrological system by rainwater infiltration into the glacier (cf. Barrett & Collins, 1997) and possibly also increased glacial ice melting due to rainfall. High englacial water levels measured during winter 2019/2020 agree well to the characterized winter end-member of the englacial hydrological system in literature (cf. Section 1; Fudge et al., 2005; Harper et al., 2005). The transition from the summer mode with diurnal pressure fluctuations to the winter mode...
observed in the sinkhole is characterized by an asymptotic approach to the steady high pressure wintertime value. This is consistent with transition characteristics measured by Fudge et al. (2005) in their boreholes classified as “Type 2.” Abrupt changes in the steady wintertime water levels could be related to ice movement and related opening/closing of new flow paths (cf. Harper et al., 2005).

### 3.2. Long-Term Rock Slope Pore Pressure Dynamics

We have combined our measurements of glacial water pressures with meteorological data and borehole pore pressure measurements in order to understand the drivers of long-term pressure variations in the slope. Figure 2 shows pressure head variations in the two boreholes (panels a and b), pressure head measured in the glacial sinkhole (panel c), surface temperature measured at the study site and precipitation (provided by Swisstopo) (panel d). Pressure head variations in B4 show annual amplitudes from 15 to 20 m and have a clear seasonal cycle. The highest values are measured during springtime (indicated with a star symbol in Figure 2a) caused by annual snowmelt, followed by a long-term head recession over the rest of the year superimposed by smaller events arising from intense summer rainfalls. In late winter, pressure heads tend to approach annual minimum values around 10 ± 5 m, and might show a lowering trend over the years (e.g., no. 1–3 in Figure 2a). In B6, a more damped signal is observed compared to B4 with a weaker seasonal amplitude of only 1–2 m. The difference in the hydrological signals measured in the two boreholes may be related to the differences in local fracture
density, transmissivity, and connectivity (cf. Section 1.2). We assume that the increased transmissivity in the disturbed rock mass of the inactive slope instability around B6 causes an efficient draining of the surface layer at this borehole location and hence keeps the pressure head after regrouting the deformation sensors in summer 2018 relatively constant. Additionally, infiltration from a creek fed by springs located some decameters above the borehole is assumed to stabilize the pressure head in B6.

We interpret the unusual recession shape approaching minimum head values in B4 in late winter (no. 1–3 in Figure 2a) to be related to a constant head boundary effect of the temperate Aletsch Glacier during the winter season. In winter 2020, this cannot be observed because of some rainfall events during wintertime that caused rock slope infiltration. To support this hypothesis, we show the ice elevation of the lateral ice-rock contact, from a cross section through B4, relative to the sensor depth in this borehole (Figure 2a, dashed black line). In winter 2018 and 2019 the ice elevation line is a few meters above the minimum head value and in winter 2021, the line is about 10 m below the minimum value. The observation of water ponds at the glacier-slope contact exactly at the time of minimum head values in winter 2019 (no. 2, Figure 2) was made during a maintenance visit. This shows that the hydraulic head in the glacier during this late wintertime can even be few meters above the glacier-slope contact line and provides support to our hypothesis.

3.3. Short-Term Rock Slope Pore Pressure Dynamics

3.3.1. Controls on High Frequency Pressure Signals

During the summer season, diurnal head fluctuations are superimposed on the seasonal pressure head variations discussed in the previous section. The occurrence of these diurnal fluctuations in the time series is illustrated by the magnitude of the high pass filtered head in Figures 2a and 2b), which visualizes frequencies larger than 1 cpd.
These fluctuations are observed in both boreholes (see Figures 3a and 3b), but the pressure head amplitude of the signal varies (~0.25 m in B4 and ~0.05 m in B6 in summer 2018 and decreasing amplitude values down to approximately 1/3 in 2020). In both boreholes, the maximum values occur in the afternoon. Figure 3 also shows that during wintertime (December), although glacial dynamics reached a steady state (Figure 3c), both boreholes still show cyclic signals at frequencies of 1 cpd and greater but with a clearly lower amplitude (factor 2–10) with respect to the summer signals. The higher amplitude summertime fluctuations in the slope cease simultaneously with the diurnal sinkhole fluctuations (observed in November 2019; see Figure 3).

As mentioned in the methods section, these high frequency pressure signals may be caused by a combination of earth tides, atmospheric pressure variations, and glacier head fluctuations. In Appendix A, we present the detailed investigation of this signal. We specifically aim at modeling the effect of Earth and atmospheric tides in order to separate their effects from the one emerging from glacial head fluctuation. In addition, the analysis also provides insights into the properties of the aquifer at the two borehole locations. Appendix A shows that the wintertime high frequency signals (Figures 3f and 3g) are likely caused by a combination of Earth tides and atmospheric pressure variations. However, Appendix A also shows that Earth tides and atmospheric pressure variations cannot explain the higher amplitude summertime diurnal signals. This indicates a direct relationship of englacial and slope pressure head signals.

3.3.2. Pore Pressure Diffusion Between Glacier and Rock Slope

As summarized in the previous section, there appears to be a strong correlation between glacier and slope pressure head fluctuations during summer and fall. In the present section, we quantitatively analyze the correlation between these two signals, assuming that this correlation is controlled by pore pressure diffusion in the fractured bedrock. Signal analysis from borehole B4 suggests that the aquifer to the monitoring interval behaves as confined. This is supported by both the analysis of Earth and atmospheric tides (Appendix A) and the interpretation of borehole pumping test results (data not presented here) that show accurate predictions with transient pore pressure diffusion solutions assuming confined conditions, as classically observed for deeper fractured rock aquifers (Barker, 1988; Theis, 1935).

We compare the two signals for the borehole B4 location (Figure 4), with a showing the pressure peaks measured in the glacial sinkhole and the high pass filtered data of the pore pressure in B4. Panel b of Figure 4 shows the pressure head measured in the borehole with the diurnal fluctuations superimposed to the long-term recessions. The temporal evolution in lag time between englacial and pore-pressure head signals considering data from B4, calculated based on the cross-correlation analysis described in Section 2.3, is provided in Figure 4c. During recharge events, the computed lag-time shows negative excursions. The excursions are artifacts because no clear diurnal signals can be compared in the cross-correlation analysis, which is used to calculate the lag-time. This is because the high pass filtered borehole pressures are disturbed by the head rise due to infiltration and often no signals at all are detected during these times in the glacial sinkhole.

Negative values in Figure 4c indicate a clear delay of a few hours of the borehole pore pressure peaks compared to the glacial signal. During rain-free pressure head recession periods (Rec1–Rec4, Figure 4), we found that the lag time decreases with advancing time in the recession period (Figure 4c). Figure 4d shows the daily mean pressure head as a function of the corresponding lag time computed for the four indicated recessions. This plot shows a clear linear relationship between both variables with a decreasing trend in lag time as pressure head decreases.

We further process these data to quantify the hydraulic diffusivity involved at different pressure heads and recessions (analytical solution provided in Section 2.4). The range (mean, min., and max.) of hydraulic diffusivities is marked in Figure 4d as vertical lines. Additionally, we provide the relationship between the mean daily pressure head and computed hydraulic diffusivity (Figure 4e).

There are different ways to interpret Figure 4d, which have implications for the hydromechanical related data and interpretation presented in Section 3.4. Either it reveals a transient state in diffusivity (D) or flow path length/geometry (α) (see Equation 2). While a change in the heterogeneous pressure diffusion pathways in our fractured aquifer path might be possible, the modification in lag time is probably mostly controlled by changing diffusivity. This change could be caused by unsteady T or S in response to transitory hydraulic and/or mechanical conditions involved, as it has been shown in other studies (Elkhoury et al., 2006; Manga et al., 2012). For example, in confined aquifers a change in pressure head can cause hydromechanical deformation, for example, fracture.
opening due to increased pore pressures. This can have an effect on both terms that control the hydraulic diffusivity (i.e., $T$ and $S$) because of changes in the rock mass porosity.

We therefore assume that the observed linear relationship between the lag time and the pressure head in the borehole is related to hydromechanical effects that cause changes in fracture aperture (i.e., change in rock mass porosity) and thus also change the hydraulic diffusivity. Hydromechanical effects related to pore pressure changes in the rock slope are addressed in Section 3.4.3.

### 3.4. Hydromechanical Couplings at Diurnal, Seasonal, and Decadal Timescales

The high-resolution vertical FBG strain data monitored in the three research boreholes, as well as the understanding of slope pore pressure dynamics provided in the previous section, allows for a detailed investigation of the drivers of the different superimposed deformation processes that occur at various timescales and magnitudes. Raw data of the 10 strain sensors installed in borehole B4 and B2 are shown in Figure 5 and Figure 7, respectively. Data of B6 are provided in Appendix C (Figure C1). Besides the strain time series that are plotted in the center of their anchoring depth interval, with FBG-1 being the shallowest sensor and FBG-10 the deepest, we additionally show the magnitude of the pressure head monitored in the corresponding borehole (for B4, B6; gray area) and precipitation data (lower panel). Figure 7 of B2 strains additionally contains time series of the pressure measured in the glacial sinkhole for comparison.

We observe reversible (elastic) strain signals, strain signals that show both a reversible and irreversible component, as well as clearly irreversible strain signals. Reversible strain occurs for example, on a diurnal cyclicity with magnitudes of about 5 µε and can be detected in most deeper sensors during summertime (see indicated signals in Figure 6a and Section 3.4.1). Reversible strain also occurs on an annual cyclicity, which can be clearly observed.
in the near-surface sensors FBG-2 and 3 of Figure 5. According to the findings in Hugentobler et al. (2021) these annual strain cycles are related to thermoelastic strain in connection with annual surface temperature cycles penetrating the shallow subsurface.

Comparison of rapid (e.g., label a in Figure 5) and short-term strain events (e.g., label b in Figure 5) with potential drivers for deformation (e.g., precipitation events, pore pressure changes, temperature changes, and close earthquakes) revealed that the majority of these events coincide with precipitation or pore pressure changes (Hugentobler et al., 2021). Short-term strain events, further discussed in Section 3.4.3, often show similarities in timing and duration with pressure head signals measured in the borehole and therefore are interpreted as hydro-mechanical effects driven by pore pressure fluctuations in fractures for example, caused by rainfall or snowmelt infiltration (cf., Hugentobler et al., 2021). Rapid strain events manifest as steps in the time series, occur as both extension and shortening, typically show magnitudes of a few to 20 µε, and often occur at several sensors simultaneously. We address the origin of these signals in Section 3.4.2. Strain events that coincide with the timing of the seasonal switch of the englacial hydrological system are considered in Section 3.4.4. Longer term (at our multi-annual timescale) irreversible trends observed in the strain time series (e.g., FBG-7 and FBG-10 in Figure 5) and potential causes are addressed in Section 3.4.5.

In Figure 6, the strain time series of the lower six sensors of borehole B4 are compared to pressure readings from the glacial sinkhole sensor, the pressure head in the borehole, precipitation information, as well as surface
3.4.1. Diurnal Strain Cycles

The subsurface strain measurements feature diurnal cycles, which we relate to pressure fluctuations measured in the adjacent Aletsch Glacier (Sections 3.1 and 3.3). The comparison of the summer and winter time series shows that the diurnal strain fluctuations are only present during summertime (Figure 6). This matches with the measurements made in the glacier and borehole pressure sensors, as described above. Clear strain cycles only occur at sensor depths below the pressure head of the borehole (see Figure 5 and Figure C1, Appendix C). These diurnal strain signals show a positive or negative correlation with diurnal pressure head cycles and start and stop at the same time in the year. According to the findings presented in Section 3.3, we relate the diurnal fluctuations in the pressure head to glacial water pressure fluctuations driven by daily meltwater cycles that diffuse below the glacier into the rock slope aquifer. The strain cycles that occur simultaneously with diurnal pressure head fluctuations in the slope are understood as poroelastic effects driven by pressure fluctuations in transmissive fractures.
Strain sensors where the diurnal strain signal shows a positive correlation with the pressure head are interpreted to monitor at least one transmissive fracture in the interval (e.g., FBG-5, FBG-6, and FBG-7 between Step 1 and Step 2 in Figure 6a). A negative correlation with pressure head (e.g., FBG-9 between Step 1 and Step 2 in Figure 6a) can be explained by monitoring intervals that intersect unconnected open fractures that do not show strong pressure fluctuations. In this case, water pressure increase in fractures outside the interval can cause closing of the structure within the specific interval. Further, there are strain sensors that do not show diurnal...

Figure 7. Temperature-corrected Fiber Bragg Grating strain time series of individual 4.81 m base-length sensors installed in borehole B2 modified of after Hugentobler et al. (2021). The strain data (colored lines) is plotted at the center of the specific depth interval with anchoring depth labeled on the right side. Positive strain equals axial extension and negative strain contraction. The strain scale is provided in the upper left corner in microstrain ($\mu$m/m). The black line in the lower center of the upper panel contains pressure time series monitored in the glacial sinkhole for comparison. The gray bars in the upper plot label specific times referred to in the text. Label (a) indicates a strain step in sensor FBG-4 that was identified as an artifact and therefore is not used for interpretation. Label (b) indicates a high-intensity rainfall event referred to in the text. The lower bar plot shows the cumulative total precipitation data per 24 hr from the Bruchji weather station (Valais) located approximately 6 km away from the study site (data provided by MeteoSchweiz). Cyan bars indicate precipitation that probably occurred as snow (i.e., at surface temperatures below 1°C (Jennings et al., 2018)).
fluctuations but are located below the pressure head in the borehole (e.g., FBG-8 and FBG-10 between Step 1 and Step 2 in Figure 6a). This behavior can be explained by monitoring intervals that contain closed, unconnected fractures (or potentially intact rock). Borehole televiewer images from borehole B4 (cf., Figure 4 in Hugentobler et al. (2020)) show that the above discussed sensor intervals contain at least one mapped discontinuity, which supports our interpretation. Similar observations have been made in experiments of the Grimsel Underground Test Site (Krietsch et al., 2020).

3.4.2. Rapid Strain Events

As described in Section 2.2, rapid strain events are present in our FBG data, which are often irreversible and likely related to progressive rock mass damage. The rapid strain events indicated with red dashed lines in Figure 6a show a temporal correlation with pressure peaks measured in the glacial sinkhole without any time delay. This is also the case for all the other rapid strain events that occurred in any of the three boreholes during the time when glacial pressure variations could be measured (i.e., between August 2019 to April 2020). Two specific
rapid events of Figure 6, one coinciding with a glacial pressure peak related to heavy rainfalls (Step 1) and one coinciding with an afternoon meltwater peak (Step 2), are illustrated in a zoom with increased temporal resolution in Figure C2 (Appendix C).

As mentioned above, we relate summertime pressure peaks measured in the glacial sinkhole to a quick filling of the channelized glacial hydraulic system due to diurnal glacial meltwater cycles or heavy rainfalls. The highest glacial melting rates naturally occur at daily maximum temperatures in the afternoon. Because these rapid strain events occur without any measurable time delay with glacial pressure peaks—and not with a few hours delay from the glacial pressure diffusion to the B4 borehole location (Section 3.3.2)—these strain steps cannot be explained by hydromechanical effects related to pore pressure diffusion.

We interpret these signals to be triggered by critical stress states in the slope, resulting from mechanical loading of the glacier at high or low englacial water levels. The analyses of the timing of rapid strain events show that they either coincide with (a) daily maximum surface temperatures (i.e., filled englacial hydrological system by meltwater), (b) heavy rainfall events (i.e., filled englacial hydrological system by rain and rainfall induced meltwater), or sometimes with (3) daily minimum temperatures (i.e., empty englacial hydrological system). The minority of rapid strain events that coincide with minimum daily temperatures often show a reversed strain orientation compared to the previous rapid strain event. Because these rapid events normally occur at several sensors simultaneously, we assume that they reflect a cascade of slip events triggered in the fracture network. The rapid events do not occur at every extreme loading stage (Figure 6). We propose that this is related to a cyclic fatigue process in the fractured rock slope, where many loading cycles induce subcritical fracture propagation until reaching the criticality of the fracture network. Then macroscopic slip is triggered at an apparently random stress perturbation.

The hypothesis that rapid strain events often reflect progressive rock mass damage events (e.g., fracture slip) is supported by the observation of abrupt changes in hydromechanical behavior during such events (e.g., step 2 in Figure 6 and Figure C2, Appendix C). This specific event illustrates how the hydromechanically driven diurnal strain cycles can start (FBG-8 and FBG-9) or switch orientation (FBG-7) after a rapid strain event. This change in hydromechanical behavior could be explained by fracture propagation (or slip) inducing changes in hydraulic connectivity of the fracture network.

3.4.3. Short-Term Strain Signals

As introduced above, short-term strain signals at timescales from hours to several days (up to few weeks) often correlate with the pressure head signal in the borehole, which reacts to rainfall and snowmelt infiltration. This is illustrated in Figure 6, where the strain of FBG-7 clearly follows the pressure head variability induced by a rainfall infiltration event (Rec2, panel a, b) or shows good agreement with the winter pressure head in general (panels d and e).

Similar to the diurnal strain cycles, we propose that these short-term strain signals originate from hydromechanical effects related to pore pressure changes. In contrast to the diurnal cycles that show reversible (elastic) strain, short-term strain signals are often composed of both reversible and irreversible strain components. A significant rapid strain event that coincided with a high-intensity rainfall event in early October 2020 (see label b in Figure 7) was recorded in borehole B2. Although we do not have pore pressure data from borehole B2, we assume a similar pressure increase as measured in B4 during this exceptional event that probably triggered the clearly irreversible strain of some tens to few hundreds of microstrain measured in several shallow FBG sensors of B2. In the other two boreholes, only a minor strain reaction was detected during this specific rainstorm event. We explain this with either higher rock mass quality (B4, cf., Section 1.2) or only minor pore pressure reactions to infiltration caused by increased transmissivity (B6, see Figure C1).

3.4.4. Seasonal Transition of the Englacial Hydrological System

We observe distinct signals in the FBG strain data of borehole B2 which are likely related to the seasonal transition of the englacial hydrological system, described in Sections 3.1 and 3.2 (see Figure 7). A comparison of the strain data with water pressures measured in the glacial sinkhole (black line in figure) shows that the timing of the switch of the englacial hydrological system coincides with specific strain signals measured in most of the sensors.
These signals last for some weeks, often show cyclic behavior, strain magnitudes around 20 µε, and mark the start or stop of the diurnal strain cycles that occur only during summer season. The time at which these signals occur differs between years. These distinctive signals are also clearly detectible in spring 2019 and fall 2020. While these signals are clearest in B2, the borehole located most proximal to the glacier margin, they also occur in the other boreholes, but are slightly lower in magnitude in B6 (around 15 µε) clearly lower in magnitude in B4 (∼10 µε, see Figure 6d, step 7) located further away from the glacier margin.

We propose that these strain signals are caused by varying glacial loads related to changing water content in the glacier during the seasonal transition phase of the englacial hydrological system. These strain signals cannot be related to direct hydromechanical effects because no such signals occur in the pore pressure data of B4 and B6. Based on interpretations of englacial water pressures from many boreholes along the total length of a temperate glacier, Fudge et al. (2005) and Harper et al. (2005) described in detail the transition phase from summer mode (diurnal pressure fluctuations) to winter mode (steady, high englacial water pressures), and vice versa. Fudge et al. (2005) observed episodic, acyclic water pressure events throughout autumn before values became high and stable. During the spring transition phase, Harper et al. (2005) noted an approximately 2 weeks long period where both pressure records and glacial sliding velocity demonstrated a high level of activity related to increased meltwater supply and the evolution of the subglacial drainage system.

3.4.5. Long-Term Rock Slope Response to Glacier Retreat

The strain data measured in the three boreholes features a long-term trend, which we relate to mechanical effects from ongoing ice downwasting at our study site. The comparison of ice levels at the three borehole locations with the vertical strain history between fall 2018 and spring 2021 (Figure 8) indicates systematic axial shortening (negative strain) following the decreasing glacial ice level. In borehole B2 and B6 the negative strain is detected at shallow sensors, whereas in B4 negative strain is observed also at greater depth. We have to note, that there are also some strain sensors that do not show a negative strain following ice retreat.

Axial shortening measured with the FBG system together with a downslope oriented movement measured in horizontal direction (see inclinometer data in Appendix B, clearly detected in B2 and B6) can originate either from slip along toppling fractures steeply dipping into the slope or sliding fractures dipping in downslope direction. Both frequently occur at our study site (see Figure 4 in Hugentobler et al. (2020)). We propose that the observed deformation, that follows the glacial ice level, originates from fracture slip or creep related to the destabilizing effect from unloading by glacial downwasting (i.e., reduced normal load on fractures). Processes potentially driving longer term elastic deformations in deglaciating environments such as rebound from ice unloading or thermoelastic expansion due to ground warming after ice retreat cannot explain the observed negative (contractional) strain. Hydromechanical and thermomechanical fatigue processes may contribute to the observed negative strain trend above ice elevations but are unlikely to cause the systematic strain signals following ice elevation, especially the one observed in B4. This is because significant pore pressure magnitudes predominantly occur at deeper borehole locations and thermomechanical effects are restricted to the shallow thermally active layer (Hugentobler et al., 2021).

3.5. Magnitudes and Drivers for Irreversible Strain

To improve our understanding of irreversible strain magnitudes and mechanisms in our time series we provide a comparison of rapid, continuous, and total irreversible strain at each sensor (Figures 9a–9c) and a time- and depth-integration per borehole location (Figures 9d–9f). Total irreversible strain per sensor is calculated as the difference between the strain recorded at the start and end of our monitoring period. We use only two full years instead of the nearly 3 years of strain data to cancel out annual cyclic thermoelastic driven strain detected in the shallow sensors (Figures 5 and 7, Figure C1 and Hugentobler et al. (2021)). Rapid strain events (i.e., fracture slip) were automatically retrieved from the time series and divided in events with magnitudes smaller and greater 20 µε. Continuous strain (i.e., fracture creep) is then calculated by a subtraction of the strain resulting from the summed up rapid events and the total irreversible strain. The provided magnitude of rapid events in Figures 9a–9c reflects the difference between the sum of the positive rapid strain events and the sum of the negative rapid events (illustrated with the error bars in the plot).
Figures 9a–9c emphasizes big difference in activity between the three borehole sites and the depth dependence of the strain signal. In agreement with the inclinometer data (Appendix B), B2 shows the highest activity and B4 and B6 show clearly lower activity. In most sensor intervals of B4 and B6, continuous strain accounts for most of the total irreversible strain and rapid strain events play a minor role (Figures 9b–9f). In B2, continuous strain also plays an important role for total irreversible strain, but rapid strain events account for more than 50% of the total irreversible strain (Figures 9a and 9d). The dominance of rapid events for the total irreversible strain is related to a single high-intensity rainfall event in October 2020 (label b in Figure 7) that resulted in all rapid events >20 με (black bar) in this borehole. Rapid events <20 με related to changes in mechanical glacial loads do not show an increased effect in this borehole compared to the other two.

We attribute most of the continuous irreversible strain in all the boreholes to ice unloading effects (cf., Section 3.4.5), and a minor portion of the continuous irreversible strain to accumulate from not fully reversi-
ble short-term hydromechanical driven strain events correlating with pressure head fluctuations (Section 3.4.3). Although rapid strain events related to changes in mechanical glacial loads (events <20 με) are numerous, and account for significant strain in extension and contraction direction (error bars in Figure 9), these events do not dominate the total irreversible strain of the 2-year sampling period. In B6, the sum of these rapid events shows strain in extension direction, which is the opposite direction of the total irreversible strain. The rapid strain events >20 με that are related to the single high-intensity rainfall event strongly affected the total irreversible strain of the two years in the shallow 20 m of B2. According to borehole televiewer images, the shallow 25 m of this borehole shows an increased fracturing compared to greater depth or the B4 site and contains many open or filled joints (Hugentobler et al., 2020).

4. Discussion

4.1. Transient Boundary Conditions at a Retreating Glacier Margin

In this section, we summarize our understanding of thermal, hydraulic, and mechanical boundary conditions that affect a rock slope subject to glacial ice retreat at timescales of our monitoring campaign (i.e., from hours to 3 years, Figure 10). Such data supported knowledge is unique and crucial for understanding of the main drivers for deformation and progressive damage in paraglacial rock slopes.

Thermal boundary conditions in our monitored rock slope were investigated in detail in Hugentobler et al. (2021), considering changes on timescales ranging from days to decades. Bedrock below temperate glacier ice stays at a relatively constant temperature of around 0°C. Above ice elevations, diurnal temperature cycles affect the uppermost decimeters of the rock surface and occur only during the snow free summer season (Figure 10a). Seasonal temperature cycles penetrate down to a depth of 15–20 m (Figure 10b) with temperature amplitudes that exponentially decay with depth (Hugentobler et al., 2021). On decadal timescales, glacial retreat leads to bedrock exposure and changes the thermal boundary to a new mean annual ground temperature that penetrates the subsurface down to greater depth at a pace controlled by the thermal diffusivity of the rock mass (i.e., around 150 m in a century; Hugentobler et al., 2021; Figure 10c).

Changes in hydraulic boundary conditions in a glacial adjacent rock slope that occur at timescales from hours to decades are illustrated in Figures 10d–10f. At the timescale of days, diurnal meltwater cycles and rainfall infiltration into the glacier during summertime cause strong pressure fluctuation in the subglacial drainage channel (with magnitudes from nearly ice overburden down to atmospheric values) that diffuse into the adjacent rock aquifer (Figure 10d). We show that the pressure diffusion from the subglacial meltwater channel, through the fractured bedrock below the glacier ice, to the ice-free bedrock slope occurs under predominantly confined conditions (Section 3.3.2). In the adjacent ice-free bedrock, rainfall infiltration causes variations in the phreatic groundwater table of the slope (Figure 6). On the seasonal timescale (Figure 10e), glacial hydraulic boundary conditions vary with high, relatively constant englacial water levels during wintertime and lower mean englacial water levels during summertime (Figure 3). Above ice elevations, snowmelt infiltration during springtime causes yearly maximum phreatic groundwater tables and a general recession over the rest of the year that is interrupted by summer-time rainfall infiltrations (Figure 2). The transient hydraulic head levels of both the glacier and the rock slope control the interaction of the two systems, which is subject to seasonal changes and can vary along the glacier. At regional scale, the slope head should be higher than the current glacier elevation in our study area, and water from the slope should exfiltrate above and below the glacier, as indicated by the spring line close to borehole B6. At local scale we observe an (higher permeability) active layer including the depth of all our monitoring boreholes. In this layer, the groundwater table is relatively flat and strongly connected to the englacial system, which can locally be higher than the slope head, especially during wintertime. On timescales of decades (Figure 10f), mean winter (and summer) hydraulic head levels in the glacier are assumed to decrease in concert with the ice surface.

Our results show that the variations in mechanical boundary conditions (or loads) caused by a temperate valley glacier on the adjacent rock slope are more complex than had been previously described. Our observed rapid bedrock strain signals coinciding with some of the extreme englacial water level states, summarized in Section 3.4.2, are likely caused by rapid changes in the mechanical load of the glacier with an empty or water filled englacial drainage system (Figure 10g). Similarly, but at seasonal timescales, the spring and fall transition time of the englacial hydrological system from low, dynamic summertime water pressures to steady, high winter-
time pressures coincides with characteristic strain reactions in our bedrock slope (see gray bars in Figure 7). On the timescales of decades, changing glacial loads from ice downwasting cause irreversible vertical shortening deformations in our monitored rock slope (Figure 8).

4.2. Rock Slope Reactions to Changing Boundary Conditions

All the above changes in boundary conditions cause changes in loading conditions of the glacial adjacent rock slope and lead to reversible and irreversible slope deformations at different magnitudes and timescales. Table 1 compiles our recorded strain signals from Section 3 and Hugentobler et al. (2021). This table comprises ranges of

Figure 10. Visualization of thermal (panel a, b, and c), hydraulic (panel d, e, and f), and mechanical (panel g, h, and i) loads that affect glacial adjacent rock slopes and potentially drive deformation and progressive rock mass damage at timescales from hours to decades. Thermal boundary conditions (BC) are in detail investigated in Hugentobler et al. (2021).
Our detailed analysis of subsurface hydromechanical (present study) and thermomechanical (Hugentobler et al., 2021) responses supports the identification of potential drivers for irreversible deformation down to a depth of around 50 m and at timescales from hours to a few years. In boreholes B4 and B6, the highest irreversible strains, which we relate to progressive rock mass damage, are assumed to be driven by mechanical unloading due to long-term glacial ice downwasting. In borehole B2, a high-intensity rainfall event triggered rapid irreversible deformation (presumably by pore pressure increase from infiltration) that slightly exceeded the magnitude of the 2-year continuous deformation mainly attributed to ice unloading (Figure 8). Additionally, hydromechanical effects related to snowmelt and summertime rainfall infiltration and changes in mechanical loading due to some extreme stages of englacial water levels were identified to contribute to the irreversible deformation.

Our monitoring data support the hypothesis that retreating temperate valley glaciers cause significant thermo-hydro-mechanical perturbations of the boundary conditions affecting adjacent rock slopes and contributing to progressive rock mass weakening (Ballantyne et al., 2014; Grämiger et al., 2020; McColl, 2012; McColl & Draebing, 2019; Prager et al., 2008; Riva et al., 2017). The few previous numerical studies that investigated paraglacial rock slope evolutions over the timescales of glacial cycles have chosen simplified, but adequate, assumptions for thermal and hydraulic boundary condition including annual pore pressure and temperature cycles (Grämiger et al., 2018, 2020). However, diurnal cyclic glacial loads during the summer season related to fluctuating water levels in the glacier have never been considered in such studies. Our in-situ data show that these effects also promote progressive rock mass damage, probably similar to hydromechanical effects (Section 3.5). Additionally, we show how a single high-intensity rainfall event triggers hydromechanical damage exceeding the levels of 2 years exposition to all the other drivers in this environment. This emphasizes the importance to consider extreme weather events as drivers for rock mass damage over longer periods of time.

In contrast to the numerical study of Grämiger et al. (2020), who found that hydro-mechanical effects accompanying glacial ice fluctuations are more efficient in generating rock mass damage than only changes in mechanical ice loads, we postulate that the largest observed irreversible strain magnitudes are related to unloading from ice retreat. However, the relative importance of the different drivers is probably not constant at the slope scale. Processes directly related to transient glacial boundary conditions (e.g., pore pressure diffusion effects from transient englacial water pressures, stress transfer from changing glacial loads, and surface temperature changes related to newly uncovered rock surface) cause the strongest stress perturbations in the rock slope below ice levels or close to the glacier margin, that is, where our boreholes are located. Longer term delayed subsurface temperature changes due to deglaciation impact the rock slope far away from the ice margin (Hugentobler et al., 2021). Conversely, hydromechanical effects related to pore pressure fluctuations above ice levels with amplitudes mainly controlled by the ratio of infiltration and hydraulic diffusivity as well as thermomechanical effects related to annual temperature cycles impact the whole rock slope above ice elevations. Although, no relationship between strain events in the boreholes and nearby earthquakes could be observed during our monitoring period (cf. Hugentobler et al., 2021), earthquake activity potentially increased by glacio-isostatic adjustment.

### Table 1

| BC       | Timescale | Panel Figure 10 | Total strain magnitudes | Strain characteristics |
|----------|-----------|-----------------|------------------------|------------------------|
| Thermal  | Years     | b               | 60 με (~4 m) – 5 με (~20 m)† | Mainly reversible, continuous |
| Hydraulic| Days (summer) | d        | 5 με                  | Reversible, continuous |
| Hydraulic| Years     | e               | 20 με                  | Partly reversible, continuous |
| Mechanical| Days (summer) | g       | 5–10 με (max. ~20 με) | Often irreversible, rapid |
| Mechanical| Years     | h               | 20 με                  | Mainly reversible, continuous |
| Mechanical| Decades  | i               | Between 0 and ~100 με/a | Irreversible, continuous |

†Hugentobler et al. (2021). †Without considering the high-intensity rainfall of October 2020.
(Ballantyne et al., 2014; Cossart et al., 2014) could also contribute to progressive rock mass damage on the long-term.

For slopes in valley sections that experienced multiple ice retreats/readvances in the past, increased damage can be expected and therefore a higher likelihood of failure following deglaciation. For slopes upstream of the Holocene Minimum (Figure 1), we expect much less ice fluctuations, more gradual ice thinning, and a higher likelihood of delayed failure. The impacts of the current dramatic climate change can be related to this conceptual model: Ice retreat from the LIA Maximum to the level of the Holocene Minimum might be accompanied by stronger slope reactions due to higher degree of cumulated damage, than later ice retreat upstream of the Holocene Minimum. The transition from damage to sliding (manifested in the field, e.g., as a slowly creeping rockslide) is expected to be a gradual and a long-lasting process (e.g., Grämiger et al., 2018). Finally, some rock slopes can transition into rapid motion, depending on material properties, degree of slope damage, displacement kinematics, and ice elevation with respect to the landslide base. A variety of such scenarios were observed and reported for the recent evolution of landslides in the area of the Great Aletsch Glacier tongue (Glueer et al., 2019, 2020; Kos et al., 2016; Storni et al., 2020).

In summary, our in-situ data show that reversible and irreversible deformation is a result of stress changes from superimposed thermo-hydro-mechanical processes that may act at similar orders of magnitude. The relative importance of the different drivers for progressive rock mass damage depends on the slope location relative to the glacier margin, mechanical, and hydraulic rock mass properties (controlling local stress magnitudes and stress transfer), and depth (controlling thermo-mechanical stress magnitudes, cf. Hugentobler et al., 2021)). The current position of most Alpine glaciers relative to their late-glacial and Holocene history makes the adjacent rock slopes very sensitive to rapid glacial retreats caused by current climate warming.

5. Conclusion

This study is based on a detailed analysis of subsurface borehole monitoring data in a rock slope affected by rapid glacial ice retreat and englacial water level measurements from a nearby glacial sinkhole. This data set allows us to constrain the previously hypothesized transient thermal, hydraulic, and mechanical boundary conditions that act at different timescales and induce small rock slope deformations in such a deglaciating environment. This knowledge is key for the understanding of the main processes contributing to progressive rock mass weakening that potentially leads to the formation of paraglacial rock slope instabilities over long timescales. The main findings of this study can be summarized as follows:

1. Pore pressures in our rock slope are affected by both direct snowmelt and rainfall infiltration and hydraulic boundary conditions caused by the adjacent temperate glacier. Similar to non-glaciated Alpine rock slopes phreatic groundwater levels in the slope show an annual cyclicity with maximum level after snowmelt infiltration in spring followed by a recession over the rest of the year that is interrupted by infiltration from significant rainfall or snowmelt events in summer and fall. Englacial water levels of temperate valley glaciers affect pore pressures in adjacent rock slopes on (a) diurnal timescales during summertime with pressure signals diffusing into the slope, (b) on annual timescales as a constant head boundary due to high constant water levels that define a minimum elevation of the phreatic slope water table, and (c) on decadal timescales with minimum wintertime phreatic slope water tables following the ice elevations.

2. Rapid- and short-term total (i.e., reversible and irreversible) deformation at timescales from hours to weeks in our monitored rock slope can be attributed to (a) poroelastic responses of diurnal fluctuations in pore pressures caused by englacial water pressure fluctuations diffusing into the slope, (b) stress transfer from changing mechanical glacier load related the diurnal englacial water level changes, and (c) hydromechanical effects related to pore pressure fluctuations from snowmelt and rainfall infiltration events.

3. Longer term total (i.e., reversible and irreversible) deformation at timescales from month to years are related to (a) thermomechanical effects from annual temperature cycles penetrating the shallow subsurface, (b) hydromechanical effects from seasonal pore pressure fluctuations driven by the main snowmelt in springtime and an overall recession over the rest of the year, and (c) mechanical unloading related to glacial ice downwasting.

4. Irreversible deformation, which we relate to progressive rock mass damage, showed to be mainly driven by longer term stress changes related to mechanical unloading from glacial ice downwasting, and shorter term
stress changes from diurnal mechanical loading cycles related to englacial water level fluctuations and hydro-mechanical effects related to pore pressure variations from snowmelt and rainfall infiltration.

5. Highest localized slope damage is observed directly at the lateral ice margin and migrates through the slope during glacial retreat and advance. Areas with many such fluctuations are expected to have greater accumulated Holocene damage than slope sectors above the Holocene Minimum, and greater sensitivity to rock slope instability. This hypothesis is supported by observed landslide density and activity in the Great Aletsch Glacier tongue area. The current rapid glacier retreat caused by climate change occurs in very sensitive sectors of many Alpine valleys.

Appendix A: Pore Pressure Signal Deconvolution and Effects of Earth Tides

As visible in Figure 3 during wintertime, both boreholes additionally show signals at frequencies at around 1 cycle per day (cpd) and greater. These signals occur at pressure head amplitudes of ∼0.02 m, which is slightly lower than the diurnal summertime fluctuations in B6 but an order of magnitude lower than the daily summertime cycles in B4. A signal deconvolution into the frequency domain (using fast Fourier transformation) allows a detailed analysis of the signals contained in the data. Because the signals strongly differ between the summer and winter season, we provide the signal analysis in the frequency domain for both seasons (Figure A1). Hence, amplitude spectra in the frequency band between around 1–2 cycles per day are calculated for atmospheric pressure, earth tides in the study area computed with Tsoft (Van Camp & Vauterin, 2005), and pore pressures in boreholes B4 and B6. The results in Figure A1 show that during winter season peaks in the amplitude spectra of the B4 pore pressure signal show similar frequencies as the computed earth tides. B6 pore pressure signal during wintertime shows the same frequencies as the atmospheric pressure. During summer season, the amplitude spectra of the pore pressures in the two boreholes show a clearly dominating peak at the frequency of 1 cpd. These peaks show an amplitude increase of one order of magnitude in B4 and about five times in B6 compared to wintertime. Although a 1 cpd frequency peak also occurs in the computed earth tides and the atmospheric pressure, these signals cannot explain the observed amplitude increase in the pore pressures during summer season because they stay more or less constant over the whole year. Hence, the 1 cpd peak observed in the pore pressure readings of the two boreholes must be explained by a different process.

As introduced above, the existence of main tidal components (e.g., O1, K1, M2, and S2) and its relative amplitudes compared to atmospheric tides (e.g., S1 and S2) contained in pore pressure measurements allow to investigate the degree of confinements of aquifers. A description of the origin of the most important Earth and atmospheric tidal components can be found in Table 1 of McMillan et al. (2019). Fitted tidal components on the
undisturbed sections of the high pass filtered wintertime pore pressure data in borehole B4 and B6 are provided in Figures A2c–A2f in the time and frequency domain. For comparison the computed Earth tide signal for the study area is provided in Figures A2a and A2b. The fitted tidal components for B4 data can account for around 50% of the signals’ variance during wintertime and for the B6 data for about 30%.

According to Rahi and Halihan (2013) an aquifer behaves semiconfined when the S2 component dominates but M2 is still present. If M2 is dominating, the aquifer behaves confined and where M2 is not present the aquifer is unconfined (Bredehoeft, 1967; McMillan et al., 2019; Rahi & Halihan, 2013). According to this classification, the aquifer around B4 behaves confined and at B6 semiconfined.

**Appendix B: Horizontal Deformation**

The cumulative horizontal deformation in the B2 and B6 shows a clear overall downslope movement indicated with the black arrows in the map view illustration (Figures B1a–B1d). At B4 location the overall movement direction is slope parallel. The highest magnitude of about 17 mm in approximately 2 years is observed in borehole B2 and clearly lower values are measured in B4 and B6. In B2, the majority of the deformation occurs in the uppermost 20 m but minor deformation is also observed in greater depth (Figure B1e). In B4, deformation...
is distributed over the whole length of the borehole but shows early activity in greater depth (Figure B1f). Deformation in B6 predominantly occurs at few discrete locations (Figure B1g). Superimposed to these irreversible trends, annual reversible cyclic deformation is also observed (e.g., in B4 in downslope direction, Figure B1b).

**Figure B1.** (a–c) Map view illustrations of cumulative horizontal deformation over time of boreholes B2, B4, and B6 measured with the SAA in-place inclinometer system adapted from Hugentobler et al. (2021). The black arrows indicate the mean movement direction. (d) Map view of the three borehole locations. (e, f, g) Cumulative displacements of each segment form the borehole end up to the surface in direction of the main movement.
Appendix C: FBG Strain Time Series

Figure C1. Temperature-corrected Fiber Bragg Grating strain time series of individual 4.83 m base-length sensors installed in borehole B6 visualized after Hugentobler et al. (2021) with added data form winter/spring 2021. The strain data (colored lines) are plotted at the center of the specific depth interval with anchoring depth labeled on the right side. Positive strain equals axial extension and negative strain contraction. The strain scale is provided in the upper left corner in microstrain (μm/m). The elevation of the pressure head is provided as a gray area in the background. The lower bar plot shows the cumulative total precipitation data per 24 hr from the Bruchji weather station (Valais) located approximately 6 km away from the study site (data provided by MeteoSchweiz). Cyan bars indicate precipitation that probably occurred as snow (i.e., at surface temperatures below 1°C (Jennings et al., 2018)).
Figure C2. First row plots: Zoom on rapid strain events (Step 1 and 2) illustrated in Figure 6. FBG strain data of the lower six sensors of B4 (FBG-5 to FBG-10) is plotted with 10 με offset for better visualization. Second row plots: Pressure head measured in borehole B4 at 43.75 m depth and cumulative total precipitation data (per 24 hr) provided by MeteoSchweiz from the weather station “Bruchji” (Valais). Third row plots: Pressure measured in the glacial sinkhole at approximately 40 m depth and surface temperature measured at the study site.

Data Availability Statement
Data are stored in the ETH Research Data Collection and are accessible under https://doi.org/10.3929/ethz-b-000505871.

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