Cosmic-ray muon radiography data disclose active erosion underneath an Alpine glacier where it originates

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1. Project description

This project has assembled a team of geologists and physicists to map the base of the Aletsch and Eiger glaciers using cosmic-ray muon radiography to explore the mechanisms of glacial erosion in the area where glaciers originate. This project has been supported by the Swiss National Science Foundation for a total of 4 years between 2015 and 2019 (project number 159299, funds awarded to Proffs. Schlunegger and Ereditato). We are close to complete this project and to publish our final results. The project had three major components: (i) updating the muon-radiography technology, (ii) exploring the potential controls of the bedrock on the attenuation patterns of muons, (iii) reconstruction of the 3D geological architecture of the study area since variations in the bedrock architecture might influence the attenuation of the incoming muons, and (iv) application of the technology to the Aletsch and Eiger glaciers where they originate.

As a first step, we designed and developed a detector that bases on the emulsion-film technique to collect patterns and directions of incoming cosmic-ray muons when these particles pass the bedrock and the overlying glaciers. We have presented the basic concept, the design of the detector and the emulsion gels in the open access journal 'Instruments' (Ariga et al., 2018). Here, we report the major features of the upgraded technology. The advantage of the selected technology is quite obvious: emulsion films do not need any electric power supply or maintenance, and they allow for the measurement of the muon flux and direction behind a large target volume. The base unit of our new detector is a plastic base film, on both sides of which the emulsion gel is poured. This allows us to measure the track angle of the incoming muons by connecting the closest emulsion grains to the base. This track angle is essentially not affected by distortions due to possible mechanical alterations of the detector. These "micro-tracks", if straightly aligned on different layers, allow us to identify so-called "base-tracks". Micro-tracks and base-tracks are then automatically measured through an automated readout scanning system that has been developed for the purpose of this project.

We mounted the films on a modular detector placed at a depth of 100 m below the Earth surface. Each module consisted of a stack of eight films interleaved with metal plates (lead or stainless steel, 1 mm thick), acting as absorbers and diffusion centers for low-energy particle background, like electromagnetic showers and upward-going charged particles. Two such modules were placed in a frame (12.5×10cm^2) yielding a 250 cm^2 effective detection area (Fig. 1).

Figure 1. Detector installed and mounted on the bedrock within the Jungfrau railway tunnel. The detector has a view towards the south and is designed to identify the muons that penetrate the interface between the Aletsch glacier and the underlying bedrock (Ariga et al., 2017).

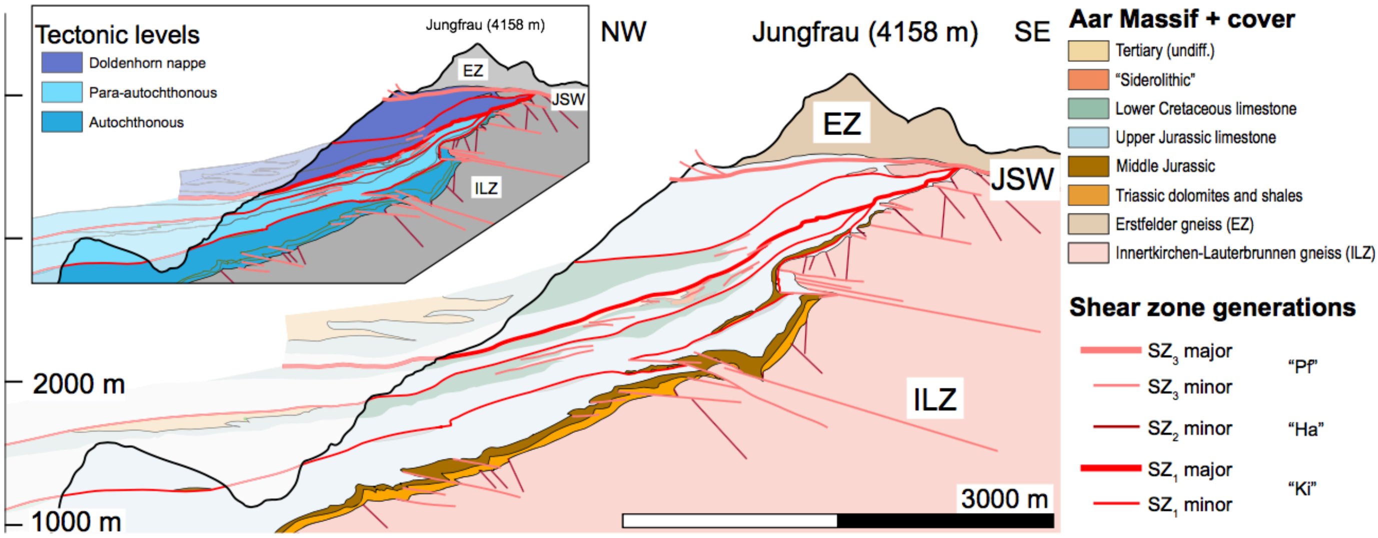

Figure 2. Tectonic cross-section through the Jungfrau region. This section has been accomplished based on the compilation of previously published geological maps, which was updated by own structural investigations and geological mapping. We found that because of the melting of the glaciers, new exposures offered further constraints to reconstruct the geological architecture of the region. In addition, it was possible to employ high-resolution aerial photos to produce an updated geological map. This allowed us, for the first time, to trace thrusts and faults across the Eiger mountain and to yield a high-precision reconstruction of the geological architecture of the Jungfrau region including the famous mountains Eiger, Mönch and Jungfrau. (Mair et al., 2018)

As a second step, we explored how and to what extent the lithological composition of the bedrock has an influence on the attenuation of the muon flux. This study has been motivated by the variations in the bedrock lithology one is confronted to when working in the Jungfrau area. In the past years, the community has conventionally employed an artificial bedrock referred to as the 'standard rock' upon calculating the attenuation of muons. In particular, through a literature research, Lechmann et al. (2018) found that the muon absorption rate has been considered to depend solely on the density of traversed material (under the assumption of a standard rock) but the variation in chemical composition has not been taken seriously into account. Accordingly, we decided to address this problem through the derivation of an energy loss equation for different minerals and mineral assemblages that can be used for any rock type on which mineralogical data are available. We found that the muon fluxes for every rock below 300 m do not depart more than 2.5 % from their respective density-modified standard rock flux. The chemical composition effect can thus be considered as negligible when compared to the systematic uncertainty originating from the muon flux model. However, if the rock column exceeds a thickness of 300 m, then the muon flux calculation will be significantly biased when one employs the standard rock assumption and thus neglects the effect of the chemical composition. This systematic error would then later turn into an over- or an under-estimation in the assessment of density structures. Because the thicknesses of the bedrock in all our experiments is less than 150 m, we are quite safe upon applying the standard model approach in our experiment, but we acknowledge that the lithological variations of the bedrock have to be considered in future surveys where broader areas will be imaged. We have published these results in the open access journal 'Solid Earth', where we particularly explored how the mineralogical compositions imprint on the attenuation of muon fluxes (Lechmann et al., 2018). Because bedrock exerts a central control not only on the attenuation of muon fluxes (if the thickness exceeds 300 m), but also on the erosional mechanisms and rates of glacier, we decided to reconstruct the geological architecture of the Jungfrau area with high resolution. We proceeded through the updating of pre-existing maps and collecting structural data and reconstructed a structural map and a tectonic section. These data were interpreted together with microstructural data and peak metamorphic temperature estimates to establish a geologic-geodynamic framework suitable for both basement and cover. Based on this information, we found that the exhumation and deformation of the bedrock occurred during two stages of shearing in Aar Massif's basement, which induced in the sedimentary rocks first a phase of folding. This latter phase of deformation was accompanied by the formation of a new foliation. We presented the updated geological map and the new section in the open access journal 'Solid Earth' (Mair et al., 2018). The results of this work are presented below in the framework of a tectonic section across the Jungfrau region on the eastern side of the Jungfraujoch (Figure 2). It shows that the bedrock describes a complicated architecture where the crystalline basement of the European continental plate was stacked through thrusting. Mesozoic limestones and dolomitic rocks form the core of this nappe stack and are intensely sheared and partially thinned. Our survey with the emulsion detectors is situated on the eastern side of sections displaced in the figure below, and muons were partially crossing the crystalline basement rocks of the Innertkirchen-Lauterbrunnen gneiss on those detectors that were mounted with a view towards the Aletsch glacier. The other detectors, which we employed for surveying the Eiger glacier on, measured muons that crossed limestones only. Nevertheless, since the penetrated bedrock was thus less than 300 m thick, we could safely employ the standard bedrock composition to account for the density dependent attenuation of muons.

As a third major task, we applied the new technology to the lateral margin of the Aletsch glacier next to the Jungfraujoch. For this purpose, we installed three new cosmic muon detectors (sites D1 to D3, Figure 3a) made of emulsion films at three sites along the Jungfrau railway tunnel close to the Jungfraujoch, and we measured the shape of the bedrock under the uppermost part of Aletsch glacier (Figures 3b, 3c). We could map the continuation of the bedrock-ice interface up to a depth of 50 m below the glacier's surface, where the bedrock surface dips at 45°± 5°. This was the first successful application of this technology to a glaciated environment. We published the results in the Journal 'Geophysical Research Letters' (Nishiyama et al., 2017).

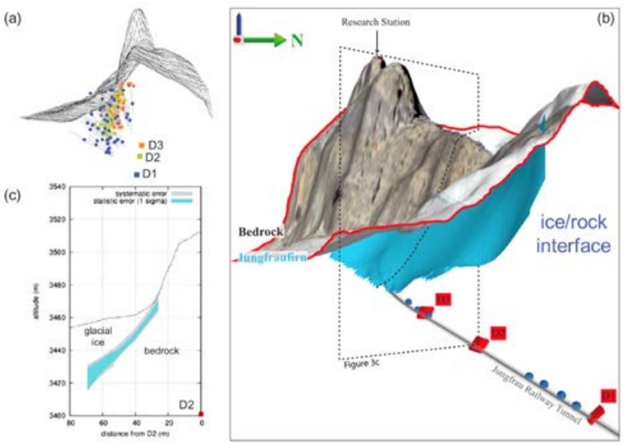

Figure 3. a) Sites of detectors D1, D2 and D3 and inferred interface between the bedrock and the Aletsch glacier close to the Jungfraujoch. b) 3D reconstruction of the research site along with the course of the tunnel of the Jungfraubahnen. Detectors are mounted on the bedrock within the railway tunnel (see also the detector frame illustrated in Figure 1). The incoming muons were used to reconstruct a section through the bedrock/glacier interface in the survey area, which is illustrated in Figure 3c.

We finally measured the shape of the Eiger glacier where it originates. We are currently finalizing this experiment and have submitted a corresponding article to the open access journal 'Scientific Reports' (Nishiyama et al., 2019). We found evidence of active glacial carving underneath the Eiger glacier where it originates. In fact, the bedrock is vertical to nearly overhanging underneath this glacier. This was somewhat surprising as this is the first time that evidence for active glacial carving is presented in an area above the ELA (Equilibrium Line Altitude) of a glacier.

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