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Distribution and fractographic features of exfoliation joints in the Central Swiss Alps (Grimsel area, Aar Massif)

Martin Ziegler, Simon Loew, Jeffrey Moore, and Florian Amann
Department of Earth Sciences, ETH Zurich, Switzerland (martin.ziegler@erdw.ethz.ch)

Exfoliation joints can decisively influence the stability of slopes, groundwater flow and infiltration capacity, and they can have a major impact on the economic efficiency and safety of near-surface excavations. However, there is yet no comprehensive quantitative explanation for their formation in an alpine setting. In addition, only a few studies of fractography of exfoliation joints exist worldwide. The Grimsel area, located in the Central Swiss Alps, exhibits some of the best developed exfoliation joints in granitic rocks in Europe – many exfoliation joints show fractographic surface markings – and is suitable for analyzing the impact of glacial valley erosion and unloading on the development of exfoliation joints. Most exfoliation joints in the study area show slightly weathered surfaces and have orientations sub-parallel to the modern glacial landscape. Some valley slopes, however, show two exfoliation joint sets with different orientations: one joint set sub-parallel to the recent landscape, and one that is less inclined. This suggests that exfoliation joints may have formed at different time periods under different landscape morphologies and slope angles respectively, since exfoliation fractures form parallel to erosional surfaces. Analysis of joint data of subsurface galleries in the Grimsel area has shown that the maximum depth of exfoliation fractures below the current landscape surface can reach 75 to around 200 m. At few locations exfoliation joints curve almost continuously from one side of the valley to the other – a phenomenon often assumed but rarely visible. Exfoliation joints do not only occur in the main valley (Upper Hasli Valley) and adjacent hanging valleys at about 1200 to 2500 m a.s.l., but also at high mountain ridges up to around 3000 m a.s.l. While valley bottoms have been covered by several hundred meters to more than one kilometer of ice during the Last Glacial Maximum (LGM), the mountain ridges are believed to have formed nunataks during the LGM and have been covered by only thin cirque glaciers. Exfoliation joints at these high altitudes could be interpreted (1) to have originated prior to the LGM or (2) that exfoliation is able to develop very close to glacial trimlines and below (relatively thin) cirque glaciers respectively. As suggested by laboratory experiments and observations in deep tunnels in massive, highly stressed brittle rock, extensional fractures form in a compressive stress field at low confinement. Numerical models propose that the same processes may also apply for the development of exfoliation joints. Systematic analysis of fractographic features such as plumose structures, arrest marks and joint fringe types can contribute to our understanding of relative ages of joint sets and of the underlying fracture processes, including stress magnitudes and principal stress orientations, absolute and relative fracture velocities, and fracture propagation directions. First interpretation of fractographic features indicates that exfoliation joints mainly formed as Mode I fractures under subcritical stress conditions. Some exfoliation joints along the Upper Hasli Valley show multiple arrest marks, suggesting slow fracture velocities and low stress intensities below the critical stress intensity, and several stops in fracture propagation. Multiple fracture arrests could also be interpreted to indicate discontinuous, cyclic fracture propagation. The Grimsel area frequently shows en echelon fringes with mostly small twist angles and no tilt, indicating a change in principal stress orientation with respect to the fracture plane.