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Near-surface rock stress orientations in alpine topography derived from exfoliation fracture surface markings and 3D numerical modelling

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ABSTRACT

The fractographic analysis of plumose axes of exfoliation fracture surfaces from a preceding study in the Grimsel region of the Swiss Alps suggested complex directional trends of near-surface (i.e., within ~100 m below ground surface) maximum principal stress (σ_1) trajectories within the investigated inner-trough valleys (i.e., U-shaped valleys). The stress trajectories describe a pattern governed by local topographic variations. *In situ* stress measurements from the region are scarce, locally scattered, based on different methods, and, thus, difficult to interpret at regional scale. In this study, we inferred that plumose structure axes form parallel to compressive σ_1, and improve our knowledge of the near-surface three-dimensional stress field in alpine settings with complex topography. We investigated near-surface stress tensors utilising three-dimensional, elastic numerical models. Our models account for morphological details of the Grimsel area at the decametre scale. We used two models with vertical boundaries aligned N–S/W–E (0°-model) and NW–SE/SW–NE (45°-model). These models allowed investigating gravitational stresses and superimposed isotropic and anisotropic compressive stresses arising from (active) tectonic shortening and/or stresses induced by exhumation (remnant stresses). Our model results illustrate that the superposition of gravitational stresses and realistic horizontal strains reveals complex near-surface stress trajectories that widely follow the patterns of exfoliation fracture plumose axes. Our models demonstrate large variations of stress orientations within the shallow subsurface, including depth levels where exfoliation fractures formed. These variations cannot be captured by a small number of local stress measurements. Our study reveals that directional data from exfoliation fracture plumose axes of Middle to Upper Pleistocene ages can be used to constrain geologically recent and current maximum principal stress directions of the shallow subsurface of up to a few hundred metres below ground.

1. Introduction

In situ rock mass stress orientations and magnitudes are key parameters relevant for the site characterisation phase of a wide range of geotechnical projects, such as underground excavations (e.g., for underground hydro-power plants), surface mining operations, petrothermal reservoir engineering, and for analysing slope and borehole stability. During the last three to four decades the techniques to estimate rock mass stress have substantially been improved and 'stress measurements' have become a standard practice.[1,2] Virgin stresses, i.e., stresses acting in a rock mass prior to man-made disturbances, of high-magnitude can cause brittle fracturing, e.g., around underground openings in massive rock (often referred to as spalling fractures[3]) and close to the landscape surface (e.g., exfoliation fractures[4–8]), and squeezing ground conditions in weak rock and/or heavily fractured rock masses with visco-plastic behaviour.[9] Within the uppermost parts of the crust rock mass stress magnitudes are mostly anisotropic, i.e., they are not lithostatic and at least two principal stress components are of unequal magnitude.[10] The maximum, intermediate, and minimum principal stresses are denoted σ_1, σ_2, and σ_3 ($\sigma_1 > \sigma_2 > \sigma_3$; compressive stresses are positive).

Besides stress magnitudes, principal stress orientations can be relevant for a project's design, e.g., in order to align large underground caverns either normal (at shallow depth) or parallel (at large depth) to the maximum principal stress orientation.[11,12] However, rock stress data are often rare, and in many cases, come from a rather small number of boreholes and borehole-based *in situ* stress measurements. In early project phases stress measurements might be absent. Furthermore, stress measurements in boreholes characterise the stress state within a limited volume, depending on the stress measurement method used (see, e.g.,

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Table 7.2 in Ref. 2) and stress heterogeneities along the borehole. Lateral stress variations away from a borehole usually remain unknown.

Further difficulties in characterising rock mass stresses in the shallow subsurface may arise from complex, high-relief topography, such as in the Grimsel area of Switzerland. To date, most analytical and numerical studies on topographically-induced alteration of tectonic, and exhumation-induced remnant stresses are focused on two-dimensional cross valley geometries and show in-plane stress rotation (i.e., parallel to a valley cross profile), occurrence of tensile and compressive stresses, and changes of principal stress magnitudes along valley profiles. These studies contributed substantially to our understanding of stresses in (alpine) valley slopes.[7,8,13–16] However, only few published articles compared analytical or numerical model results with local *in situ* or palaeostress data, or discussed the three-dimensional orientations of principal stresses.[17–20]

Exfoliation joints, also referred to as sheet or sheeting joints, are known to follow the present or former landscape surfaces.[4] Ziegler et al.[6,21] mapped the occurrence and properties of exfoliation joints in the granitic and granodioritic rock mass of the Grimsel region of the central Swiss Alps (also known as upper Hasli valley), and investigated their fracture-mechanical formation processes by analysing fracture surface morphologies (i.e., fractographic markings), such as plumose structures (also referred to as fracture plumes). Exfoliation joints in the Grimsel area are typically composed of several co-planar fracture plumes and formed at shallow depth, as deep as about 200 m below the ground surface. These exfoliation joints provide a superb opportunity to constrain shallow Pleistocene rock mass stresses. Most plumose structures visible on exfoliation joint surfaces are non-circular and contain a plumose axis that marks the locations of fastest fracture propagation and greatest mode I stress intensity, K_I, during fracture growth[21,22] (Fig. 1). This suggests that σ_1 lies parallel to the plumose axis at the time of fracture propagation.

In situ stress measurements in the Grimsel area revealed high compressive stresses with $S_H > S_h > S_v$ (S_H: maximum horizontal stress; S_h: minimum horizontal stress; S_v: vertical stress) within the uppermost few hundred metres below the ground surface.[23–25] Such a stress state supports exfoliation joint formation under high differential principal stresses.[4,21,26,27] Based on analyses of directional trends of several hundred exfoliation fracture plumose axes, Ziegler et al.[21] concluded that near-surface principal stress orientations in the Grimsel region are governed by topographic relief, and that maximum principal stresses primarily plunge gently to moderately at differently oriented trough valley slopes (note that we use the term trough valley as a synonym for U-shaped valley).

In order to test the hypothesis that topographic stress perturbation can lead to the previously inferred orientations of near-surface σ_1 and to investigate near-surface stress trajectories in areas not covered by our fractographic dataset, we used three-dimensional, elastic finite-difference models that consider the Grimsel topography. The current and palaeo stress states are the results of superposition of different stress sources (see, e.g., Ref. 21 and references therein). We used our models here to evaluate the effect of topographic perturbation on both gravitational stresses and isotropic and anisotropic stresses arising from (active) tectonics and/or stresses induced by exhumation. This article illustrates the complexity of near-surface stress orientations, shows that they may follow certain patterns governed by topography, and demonstrates how they can be estimated from fractographic analyses supported by simplified numerical models.

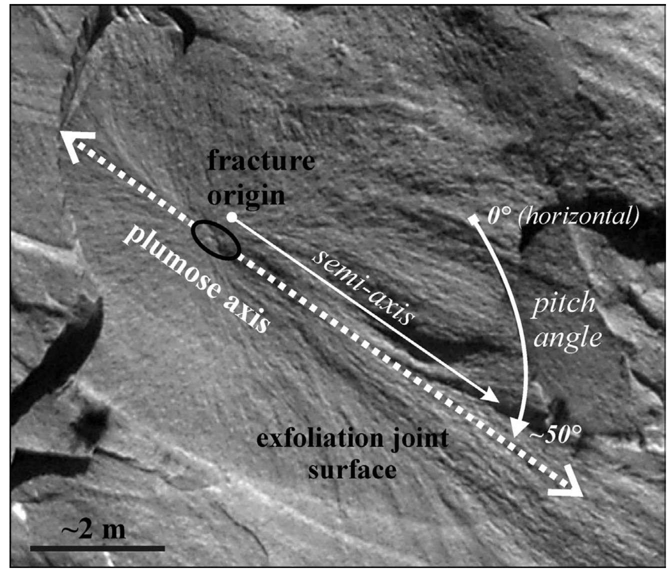

Fig. 1. Example of a radial plumose structure on a steep exfoliation joint northeast of Lake Räterichsboden[21] (for location see Fig. 3). Dotted arrows mark the plumose axis and major fracture propagation directions. The plumose axes is assumed to form parallel to the maximum compressive principal stress (σ_1) at the time of fracture propagation. The pitch (or rake) angle of the plumose axis is the angle between the plume axis and a horizontal line (strike line) as measured in the plane of the joint. It can range from 0° (horizontal plume axis) to 90° (plume axis plunges parallel to the dip direction of the common joint plane), and in this example equals about 50°.

2. Finite difference in situ stress modelling

2.1. Constitutive behaviour, intact rock and rock mass properties

The rock mass at Grimsel consists mainly of Permo-Carboniferous intrusive rocks, including (from north to south) Mittagfluh Granite, Central Aar Granite (CAGr) and Grimsel Granodiorite (GrGr) of which the CAGr is most widespread (see references cited in Ref. 6). The CAGr is a uniform medium-grained to slightly porphyritic biotite-granite with a massive to foliated structure. The GrGr can be distinguished from CAGr by its larger alkali feldspar augen (up to 2–3 cm long) and greater amount of dark mica. The granitic and granodioritic rocks are surrounded by the *Altkristallin* (Ger.), i.e., primarily older, polymetamorphic gneisses and schists. During the Alpine orogeny the rocks of the area underwent ductile to brittle deformation under greenschist facies conditions. Zones of higher ductile strain (gneiss and augen-gneiss) can be distinguished from less deformed areas (granites and granodiorites). The average Alpine foliation in the Grimsel area is oriented 149/77 (dip direction/dip angle).

In this study we strongly simplified the area's geology and assumed a linear-elastic constitutive model for the CAGr in our numerical models, with mean values of elastic properties based on data from the literature (Table 1). The CAGr is dissected by three widespread systematic joint sets with very wide joint spacings on the order of several metres to > 10 m.[6] Thus, we only slightly reduced the mean Young's modulus of intact rock (E_i) to approximate the Young's modulus of the rock mass (E_{rm}) used in our modelling. The exact value of E_{rm} is irrelevant since we varied far-field strains in the linear elastic numerical models until we received target far-field stresses. In this study we only considered total stresses. Table 1 lists intact rock strength data for the Central Aar Granite and, for comparison, the Grimsel Granodiorite. We investigated the evolving stresses in the elastic models during various loading conditions and compared the final stresses against fracture criteria to identify where extensional-type fracturing may