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Growth of exfoliation joints and near-surface stress orientations inferred from fractographic markings observed in the upper Aar valley (Swiss Alps)

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ABSTRACT

Granitic rock mass of the upper Aar valley (Grimsel area, Switzerland) contains distinct generations of exfoliation joints, which formed during different stages of the Pleistocene, subparallel to distinct glacial valley palaeotopography. The bulk of exfoliation joints shows prominent, common fractographic features: (1) radial plumose structures with distinct plume axes; (2) arrest marks superimposed by plumose striations; and (3) gradually-developing en échelon fringe cracks. Multiple arrest marks reveal that exfoliation joints formed incrementally and, together with the absence of hackle fringes, suggest stable, i.e., subcritical fracturing conditions. Smooth transitions from plumose structures on the parent plane to en échelon fringe cracks, combined with non-systematic stepping senses of fringe cracks, suggest local (vs. temporal) stress field variations. Assuming that plume axes formed parallel to the maximum principal compressive stress (σ_1) enables us to infer near-surface palaeostress orientations and compare them with classical borehole-based *in-situ* stress data. The majority of plume axes suggest (1) persistently subhorizontal to slightly inclined σ_1 orientations at trough valley slopes and (2) near-surface variability of σ_1 orientations originating from topographic perturbation caused by glacial valley erosion superimposed on the regional stress field. Our investigations of fracture surface morphologies yield unique insights into exfoliation fracture formation, such as directional trends of fracture propagation and associated palaeostress orientations within Alpine valley slopes.

1. Introduction

Exfoliation joints, also known as sheet or sheeting joints, form about parallel to landscape surfaces and are restricted in occurrence to the uppermost tens to about two hundred metres below ground surface (e.g., Dale, 1923; Gilbert, 1904; Jahns, 1943; for terminology see Ziegler et al., 2013, and references therein). Exfoliation joints are thought to form under high compressive principal stresses (σ_1, σ_2; compressive stress is positive) that are oriented subparallel to the ground surface and considerably greater than the surface-normal oriented, least principal stress (σ_3) (e.g., Dale, 1923; Martel, 2011). Evidence for high differential compressive stresses near the ground surface comes from field observations, such as rock bursts or heave of rock sheets (e.g., Ericson and Olvmo, 2004; Holzhausen, 1989; Twidale and Bourne, 2000, and references therein), *in-situ* rock stress measurements (e.g., Hast, 1967; Holzhausen, 1989), and is supported by results from numerical studies (e.g., Leith, 2012). High near-surface stresses can originate from: 1. the elastic response of laterally confined rock mass to erosional unloading (Nadan and Engelder, 2009; Nichols, 1980; Voight, 1966), 2. ice unloading during deglaciation (Carlsson and Olsson, 1982), 3. active regional tectonics (Greiner and Illies, 1977; Park, 1988; Pascal et al., 2010; Stephansson et al., 1991), 4. topographic perturbation in areas of high relief (e.g., Miller and Dunne, 1996; Savage et al., 1985), or 5. a combination of these mechanisms (e.g., Savage and Swolfs, 1986).

Whereas the processes of exfoliation joint formation in terms of regional stress origin and magnitudes have been discussed widely (e.g., Cadman, 1970; Twidale, 1973, and references therein), only few studies investigated local (on the scale of joints) stress conditions derived from exfoliation joint surface markings (Bahat et al., 1999; Bucher and Loew, 2009; Holzhausen, 1989). The surface morphology of joints can contain unique information about the underlying mechanics of the fracture processes and the developmental stages of a nucleating and propagating joint and joint set. Furthermore, certain fractographic markings are thought to record the orientations of principal stresses at the time of exfoliation joint formation. Similarly, orientations of maximum and minimum horizontal stresses (S_H, S_h) have been inferred from fractographic features on coring-induced disc fractures (Kulander and Dean, 1985). Since many exfoliation joints are relatively young rock mass features, occur in various rock types, and are widespread in many areas and landscapes of the world (e.g., Bradley,

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1963; Holzhausen, 1989; Jahns, 1943; Nichols, 1980), these joints may represent a rich data source of relatively recent and palaeostress orientations operating close to the landscape surface.

The first goal of this study is to describe and characterise the 'inventory' of observed surface morphologies of exfoliation joints in granitic rocks of the Grimsel region located in the Central Alps, Switzerland. We aim to demonstrate that the fractographic record increases our understanding of the kinematics and fracture mechanisms of exfoliation joints in Alpine valleys. The second goal is to deduce the pattern of maximum (palaeo) principal stress orientations (σ_1) near the ground surface from novel analysis of the fractography of exfoliation joints. We compare these stress orientations with the existing and new data from near-surface borehole-based *in-situ* stress measurements and show that this approach substantially enhances our knowledge of near-surface stresses in Alpine valley slopes.

2. Principles of joint fractography

2.1. Overview

The surface morphology of joints, i.e., natural brittle fractures in rocks that form primarily under mode I loading conditions (e.g., Kulander and Dean, 1985; Pollard and Aydin, 1988), has fascinated geologists for more than one hundred years and has been studied in different rocks and on different joint types (e.g., Bahat et al., 2012; Bankwitz, 1966; Hodgson, 1961; Kulander et al., 1979; Pollard and Aydin, 1988; Woodworth, 1896). With rock fractography, information as to fracture modes, fracture type and processes, palaeo and *in-situ* stress directions and magnitudes, relative ages of differently oriented joints and joint sets, location of joint origins, and (changes in) joint propagation velocities and directions can be obtained. Furthermore, the fractographic record allows a distinction to be drawn between subcritical (i.e., $K_I < K_{Ic}$) and (relatively rare) postcritical (i.e., $K_I > K_{Ic}$) propagation, and between stable and unstable jointing, respectively (see discussion by Engelder (2007) and Bahat et al. (2012)). Subcritical fracture propagation may be facilitated by different processes, e.g., stress corrosion (e.g., Anderson and Grew, 1977; Atkinson, 1984; Darot and Gueguen, 1986).

Joint surfaces can consist of different types of fractographic features (Bankwitz, 1965; Hodgson, 1961; Woodworth, 1896). The fractographic markings are expressions of the underlying fracture processes and distinct fracture modes, i.e., normal-opening (mode-I), sliding (mode-II, shear perpendicular to fracture front), tearing (mode-III, shear parallel to fracture front), and mixed mode propagation (i.e., superposition of fracture modes I, II, and III; Cooke and Pollard, 1996; Irwin, 1958; Pollard and Aydin, 1988). Sections 2.2 to 2.5 will introduce the most common fractographic features, which provide the basis for later discussion of exfoliation joint formation.

2.2. Fracture origin

Brittle fractures initiate at existing flaws, which act as stress concentrators (e.g., Griffith, 1921, 1924). From these flaws three-dimensional cracks develop and tend to align perpendicular with the direction of σ_3, maximising the ratio of mode I/mode II (III) stress intensity (e.g., Kranz, 1983, and references therein). Grain boundary, intra-, inter-, and transgranular (multigranular) cracks are assumed to represent the most important flaws in crystalline rocks (e.g., Kranz, 1983; Nadan and Engelder, 2009; Vollbrecht et al., 1991). Fracture initiation takes place at larger, preferably shaped and oriented cracks (e.g., Wang and Shrive, 1999). The crack size depends on rock homogeneity. Fracture origins are usually too small to be directly identified macroscopically in rocks (e.g., Pollard and Aydin, 1988). However, the arrangement of striations and ripple marks on fracture surfaces (see Sections 2.3 and 2.4; Fig. 1) can be used to trace back the origin(s) of a joint.

2.3. Striations and plumose structures

Striations are those parts of a fracture, which morphologically resemble alternating linear or systematically curved ridges and valleys (e.g., Roberts, 1961). Striations form parallel to the directions of fracture propagation (e.g., Bahat, 1991). Joints frequently show striations right away from the fracture origin on the so-called parent (fracture) plane or parent joint (Savalli and Engelder, 2005; see also the description of the *quasi-static mirror plane* by Bahat et al. (2005: 126–127); Fig. 1).

The configuration consisting of an origin, an axis, and striations is known as feather structure, plumose structure, or plume (Pollard and Aydin, 1988, and references therein). The plume axis (or plumose structure axis) marks the direction(s) of highest fracture propagation velocity (Kulander et al., 1979; Kulander and Dean, 1985; Savalli and Engelder, 2005; Section 6.2.1). The axis commonly shows greater relief than the surrounding striations. Plume axes can be straight (S-type, also called herringbone or chevron mark) or curved (C-type). Furthermore, the plume morphology can exhibit rhythmic changes in roughness attributed to variations in propagation velocity (Bahat, 1991; Bahat and Engelder, 1984; Pollard and Aydin, 1988, and references therein). Plumose structures of S- and C-type typically occur in layered sedimentary rocks with the plume axis about parallel to the bedding (e.g., Bahat and Engelder, 1984). Where no such geometric relationship can be made, plumes are simply called 'radial'. Radial plumes are commonly observed in rather isotropic rocks, such as granites.

Striations consist of a complex microstructure of tensile and shear zones (Bahat et al., 2007) and originate by similar mechanisms like en échelon fringes (mixed mode I/III; Pollard and Aydin, 1988; cf., Chemenda et al., 2011). Morphologically, however, striations originate on the parent plane, while en échelon fractures are restricted to the fringe (Section 2.5). The development of striations is likely dependent on rock lithology and grain-size (e.g., Engelder, 1987; Gash, 1971; Holzhausen, 1989).

2.4. Ripple marks

Curvilinear ridges and furrows, which are oriented perpendicular to striations, are known as ripple marks (Fig. 1). Ripple marks surround the fracture origin in circular, elliptical, or parabolic ribs (e.g., Pollard and Aydin, 1988, and references therein). The concave sides of ripple marks point towards the fracture origin making ripple marks clear indicators of propagation directions. Ripple marks form under mixed mode I/II loading (e.g., Pollard and Aydin, 1988; Younes and Engelder, 1999). Concentric and not concentric (asymmetric) arrangements are known (e.g., Bahat, 1991; Gash, 1971). Synonymously, ripple marks are called rib marks, annular or conchoidal structures, and are used as an umbrella term for arrest marks and undulations (Bahat et al., 2005). Arrest marks are thought to be associated with an arrest in fracture propagation indicating fracture growth in distinct increments (e.g., Guin and Wiederhorn, 2003: experiments with soda lime silicate glass show that arrest marks form at renewed fracture opening, i.e., post arrest; Kulander and Dean, 1995) or slow (subcritical) crack velocity (for glass $<10^{-2}$ m/s, according to Murgatroyd (1942)). Arrest marks are elsewhere referred to as hesitation lines or kinks (Younes and Engelder, 1999). In contrast, undulations form by 'rapid' fracture propagation (e.g., Weinberger and Bahat, 2008, and references therein). Crosscuts through arrest marks in the direction of fracture propagation commonly show asymmetrical shapes in forms of cuspate waves or "line[s] separating tilted panels" (e.g., Kulander and Dean, 1995, and references therein), whereas undulations rather show symmetrical, rounded (sinusoidal) crosscuts with smooth crests (Bahat et al., 2005, and references therein).

2.5. Joint fringe zones

Joint margins can consist of a fringe zone (or zones) of different types such as en échelon fringe or hackle fringe (Bahat, 1991; Bahat