Geomorphology 201 (2013) 344–362

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Distribution and inferred age of exfoliation joints in the Aar Granite of the central Swiss Alps and relationship to Quaternary landscape evolution

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ARTICLE INFO

Article history:
Received 7 February 2013
Received in revised form 3 July 2013
Accepted 6 July 2013
Available online 13 July 2013

Keywords:
Brittle fracture
Joint generations
Crystalline bedrock
Landscape evolution
Alpine valley

ABSTRACT

Exfoliation joints are well-known natural fractures limited to near the ground surface. Relatively few details, however, are known about their distribution and age in the Swiss Alps. Exfoliation joints follow the landscape surface at the time of their formation; the age of the associated landscape feature then provides a maximum age of exfoliation joints. While landscape forms can change through time, exfoliation joints preserve elements of former landscape morphologies by their undisturbed orientations. The Grimsel region of the Central Alps is well-suited for analyzing the impact of erosional episodes, and accompanying stress changes, on exfoliation joint formation in granitic rocks. Mapping above and below ground revealed that exfoliation joints are widespread and occur between valley bottoms and mountain crests within glacial (inner and hanging U-shaped trough valleys, glacial cirques, and steep mountain crests) and predominantly fluvial landforms (gently inclined linear slopes above the inner trough valleys, narrow inner-valley gorges, and steep V-shaped side gullies). Based primarily on their geometric properties at the ground surface, three exfoliation joint types were distinguished in our study area: (1) closely spaced (<1 m) joints oriented distinctly parallel to the present-day ground surface, (2) intermediately spaced (0.6–2 m) joints that are nearly parallel (<10° difference) to today's mean ground surface at a 10-m scale, and (3) widely spaced (≫2 m) joints not parallel to the ground surface. Relating the mapped distribution of exfoliation joint types to identified erosional episodes and landscape features of known and inferred ages, respectively, enables us to distinguish four exfoliation joint generations in the Grimsel area, which most likely formed during the lower Pleistocene (~1.5–1 Ma), middle Pleistocene (~0.7–0.4 Ma), upper Pleistocene (0.1–0.02 Ma), and Late Glacial/Holocene (<0.02 Ma). We demonstrate that the most prominent and deepest exfoliation joint generation is associated with erosion of the inner glacial troughs of the upper Aar valley, which likely occurred during the mid-Pleistocene Revolution. Our study shows how exfoliation joint episodes can be dated, and, conversely, that better knowledge of the distribution of exfoliation joint sets can reveal unique information about the morphological evolution of an Alpine valley.

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1. Introduction

Exfoliation joints are defined as individual joints or joint sets with orientations subparallel to the present or former ground surface and are restricted in occurrence to relatively shallow depths (e.g., Gilbert, 1904; Dale, 1923; Jahns, 1943). Synonymously, the terms *sheet joint*, *sheeting*, *pressure-release*, *stress-release* or *unloading joint*, *post-uplift joint*, *Talklüftung* (Ger.), and *Talbankung* (Ger.) are alternatively used to describe these features. We favor the geometric term *exfoliation* as the mechanical process of formation is a topic still debated today. The bulk of joints discussed in this work must be distinguished from small-scale superficial fractures, which are very closely spaced (mm to cm) and restricted to the immediate near surface, i.e., frequently within a few decimetres to metres below ground. These phenomena are thought to form as a result of stresses induced by atmospheric processes (e.g., climatic conditions, fire) related to physical and chemical weathering (e.g., Twidale, 1973).

Fractographic markings reveal that exfoliation joints form as mode I (opening mode) fractures (e.g., Bahat et al., 1999). Field and laboratory observations (e.g., Twidale, 1973; Holzhausen, 1989), as well as results from numerical studies (e.g., Leith, 2012), support the hypothesis proposed first by Dale (1923), who associated observations of compressive stresses with the formation of exfoliation joints. *In situ* stress measurements and back-calculations from buckled rock slabs in different regions suggest that high maximum principal compressive stresses (σ_1) up to a few tens of MPa can exist at shallow depths, are oriented subparallel to the ground surface, and are considerably greater than the least surface-normal principal stress (σ_3), which can be estimated from overburden thickness including topographic effects (Voight, 1966; Hast, 1967; Hoek and Brown, 1980; Adams, 1982; Carlsson and Olsson, 1982; Holzhausen, 1989).

Exfoliation joints are among the youngest fractures in bedrock outcrops and have specific common characteristics such as increasing

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0169-555X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2013.07.010

joint spacing with depth (from a few decimetres to more than 10 m) and a lack of hydrothermal mineralisation on their surfaces (e.g., Jahns, 1943; Holzhausen, 1989; Everitt, 2009). Exfoliation joints can have lateral persistence of more than 100 m (e.g., Carlsson, 1979; Bucher and Loew, 2009), and typical depths range from a few decametres to more than 100 m below the ground surface (e.g., Jahns, 1943; Lewis, 1954).

Differences in exfoliation joint orientation relative to today's topography, together with variations in the degree of joint surface weathering and joint spacing near the ground surface, suggest that exfoliation joints may have formed episodically in many areas eroded by glaciers during the Quaternary (Dale, 1923; Kieslinger, 1958; Glasser, 1997). Analyses of fractographic markings on crosscutting exfoliation joints can reveal relative joint ages and suggest that a change in topography and subsequent stress reorientation may lead to different exfoliation joint generations (Bankwitz, 1966; Bucher and Loew, 2009).

The ages of exfoliation joint sets in (formerly) glaciated regions are, however, not well understood. Jahns (1943) proposed that most exfoliation joints in granites in New England, USA, are pre-glacial in origin. He studied earlier work by Matthes (1930) from Yosemite National Park and by Vogt (1879) from southeastern Norway and concluded that only a few new exfoliation joints formed after the Wisconsin Glacial Episode (110 to 10 ka ago, with the Last Glacial Maximum around 21 ka). In addition, landscape surfaces created by the El Portal glaciation, 200 ka ago, show few exfoliation fractures. Matthes (1930) suggested a Miocene age (at least 8 Ma) for exfoliation joints on some of the domes in Yosemite's high country.

On the other hand, Bradley (1963) concluded that exfoliation joints in massive sandstones of the Colorado Plateau, USA, are most likely of Pleistocene age and are (in places) still forming today (see also Rogers and Engelder, 2004). Likewise, Kiersch (1964) hypothesised two distinct exfoliation joint sets, one of Pleistocene age and another of Late Glacial age, in limestone of the Vajont area in Italy. Owing to the absence of intersecting exfoliation joint sets, Oen (1965) suggested that exfoliation joints of the Precambrian granites of Sermersôq, Greenland (which are subparallel to landscape surfaces of unequal age and curvature) formed after the last Pleistocene glaciation. In contrast, exfoliation joints in crystalline bedrock in Sweden that contain compacted sedimentary infill and redeposited pollen with pre-Holocene signature (see review by Carlsson, 1979) are assumed to have formed prior to the last Pleistocene glaciation (cf. Mörner, 1977). Glasser (1997) divided exfoliation joints in the Cairngorm granite, Scotland, into pre-glacial (subhorizontal and parallel to the pre-Quaternary plateau surfaces, widely spaced, and more intensively weathered) and glacial (steeply dipping and parallel to glacial troughs, shallow, parallel to glacial surfaces). Both exfoliation joint generations are oriented subparallel to today's landscape surface without crosscutting each other. Similarly, exfoliation joints subparallel to slopes of Norwegian fjords, incised into pre-Cambrian gneiss, are examples of relatively young exfoliation occurring after Quaternary landscape formation.

The study area of this investigation is the Grimsel region of the Central Alps in Switzerland, located in the upper Hasli valley between Guttannen and Grimsel Pass (Fig. 1). The upper Hasli valley is situated at the headwaters of the Aar valley. Here, impressive exfoliation joint sets occur in massive granitic rocks with high Alpine relief (altitude range of about 2000 m over a distance of roughly 3300 m) in various geomorphological settings and allow investigation of spatial and temporal relationships between Pleistocene glacial landforms and exfoliation. In addition, the study area is dissected by a large number of subsurface galleries and reconnaissance boreholes (Fig. 2), which deliver crucial depth-dependant three-dimensional information about fracture patterns, as well as evidence for high near-surface *in situ* stress magnitudes easily exceeding the overburden stress (Ziegler et al., in prep.).

The goals of this study are to deduce evidence of exfoliation joint generations and to infer ages of their formation in a glaciated Alpine landscape by analysing joint geometrical properties and their relation to associated host landforms. We address fundamental questions such as: are Alpine exfoliation joint sets of Pleistocene age? And if so, what is their relation to erosional features associated with the Last Glacial period? Our analysis leads to a better understanding of the relationship between Quaternary landscape evolution and exfoliation joint formation in Alpine valleys and provides both a means to date exfoliation episodes as well approximate palaeotopography.

2. Geological and geomorphological evolution of the study area

2.1. Geological and tectonic overview

Bedrock in the Grimsel region of the Central Alps consists primarily of late Variscan intrusive rocks of the central Aar Massif, including Mittagfluh Granite (MiGr), Central Aar Granite (CAGr), Grimsel Granodiorite (GrGr), and southern stripe of the Central Aar Granite (sCAGr). These granitic rocks are surrounded by the *Altkristallin* (Ger.), i.e., primarily older, polymetamorphic gneisses and schists (Labhart, 1977; Abrecht, 1994) (Fig. 1). The CAGr is a uniform medium-grained to slightly porphyritic biotite-granite with a massive to strongly foliated structure. The sCAGr belongs genetically to the CAGr and exhibits similar mineralogical composition. A zone of gneisses and schists separates the sCAGr from the GrGr. This zone is known as *Gneis-Schiefer-Zwischenzone* (Ger.; intermediate zone of gneisses and schists ZGS). 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 MiGr is similar to the CAGr, but less foliated attributed to its low mica content (Labhart, 1977). Detailed lithological descriptions are given, e.g., by Stalder (1964).

After emplacement, these granitic rocks were first uplifted during the Permian period and then buried beneath a stack of about 2500 m of mainly Mesozoic–Cenozoic sediments of the Helvetic realm (Labhart, 1977, and references therein; Pfiffner, 2009). During the Alpine orogeny, which began to affect the southern Aar Massif about 35 million years ago, crystalline rocks of the Aar Massif underwent regional metamorphism up to medium greenschist facies (e.g., Challandes et al., 2008). ^{39}Ar—^{40}Ar biotite and white mica ages from Aar Massif orthogneisses and mylonites (GrGr, CAGr) range from 21 to 17 Ma, suggesting an early Miocene age (Burdigalian) of main ductile deformation at peak temperature conditions (Challandes et al., 2008; see also Rolland et al., 2009). Ductile deformation of the crystalline basement shows variable intensity (Labhart, 1966; Choukroune and Gapais, 1983). 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). Long-term uplift and erosion caused the crystalline basement of the Aar Massif to reach the Earth's surface during the upper Miocene to Pliocene (Michalski and Soom, 1990). Further discussion of the exhumation history of the area can be found in Willett (2010) and Weisenberger et al. (2012).

According to Rolland et al. (2009), major brittle faulting in the study area is younger than 10 Ma. Brittle–ductile faults dip steeply to very steeply (>70°) and strike at about 070° (dextral strike-slip) and 120–130° (sinistral strike-slip). Sutter (2008) described brittle faults (average orientation: 138/75, sinistral sense of movement) that comprise a reverse fault component (high angle oblique-slip faults). Brittle faults contain cataclasites, breccias, and clay fault gouge.

Our measurements of tectonic joints between Lake Räterichsboden and Grimsel Pass, and around Lake Grimsel, are in agreement with structural orientations from previous studies (Table 1). Three systematic, steeply dipping joint sets are widespread and change only slightly in their orientation (J1, J2, and J3). The tectonic joint sets J4 and J5 occur only locally. Apart from their relative constant regional orientations, the majority of tectonic joint sets, in contrast to exfoliation joints, frequently exhibit planar, smooth to slightly rough joint surfaces,

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