Formation of spectacularly flat granite outcrops through hydrofracturing

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Abstract

A series of near-planar subhorizontal bedrock surfaces is developed in Precambrian gneissic granite basement in SW Sweden. These surfaces are located within 0.1 – 10 km of the 150 m-high Halleberg and Hunneberg table mountains, which are comprised of marine sedimentary units capped by a dolerite sill. The near-planar bedrock surfaces have traditionally been interpreted as exhumed remnants of a regional Subcambrian unconformity. We evaluate an alternative hypothesis that these spectacular surfaces are attributable to formation and erosional exploitation of subhorizontal sheeting joints by the late Quaternary Fennoscandian Ice Sheet. We use a combination of landscape analyses in a GIS, field measurements of bedrock jointing, laboratory analyses of basement chemical weathering, ground penetrating radar imaging of subsurface jointing, erosion rates from cosmogenic nuclides, and numerical ice sheet modelling. This diverse dataset supports the following interpretations: (1) marine erosion of weathered rock during the Cambrian transgression was likely important to the formation of the regional SCU; (2) the spectacular flatness of the surfaces studied is attributable to Quaternary glacial erosion, with sheeting joints providing a first-order structural control; (3) subhorizontal hydrofracturing of bedrock in the near-surface (perhaps up to hundreds of meters depth) occurred in either a marine proglacial or a subglacial/ice marginal setting. This hydrofracturing was promoted by episodic drainage of supra-glacial meltwater ponds along crevasses and fractures in the ice that are directly connected to the ice sheet bed, and by ice sheet deformation around the steep sides of the table mountains. Basal meltwater could temporarily decouple the ice sheet margin from its bed and generate subglacial (and/or proglacial) water pressures in the bedrock that are sufficient to generate subhorizontal fractures hundreds of meters long. Glacial ice subsequently exploited these subhorizontal planes of weaknesses to erode blocks (with volumes potentially exceeding 125 m^3, based on observations elsewhere in southern Sweden), leaving remnant near-planar bedrock surfaces.

Introduction

Subhorizontal surfaces developed in Precambrian gneissic granite in the city of Trollhättan and the nearby village of Nordkroken, along Lake Vänern, SW Sweden, are renowned for being remarkably planar (Fig. 1; Rudberg et al. 1976; Johansson et al. 2001). Owing to their exceptional flatness (relief is tens of cm over 1000s of square meters), their location in a low relief landscape that characterizes much of lowland Sweden (and well beyond), and their proximity to the Halleberg and Hunneberg table mountains comprised of Cambro–Ordovician sedimentary rocks capped by dolerite sills, these surfaces have been interpreted as exhumed remnants of a regional Subcambrian unconformity, the Subcambrian peneplain (SCU; Johansson et al. 2001). They might also be considered as analogue surfaces for the former relief of the SCU across regional-to-continental scales and offer potentially key support to landscape evolution models that treat present-day relief as having evolved from surfaces that were initially almost entirely flat. Indeed, these exceptionally flat surfaces are central to the education of students and the general public regarding the SCU and are a central feature of a proposed UNESCO-listed regional geopark (Geopark 2019). However, the processes by which these remarkable surfaces formed have not been explored in detail. Hence, the aim of this study is to explore formation mechanisms for near-planar bedrock elements within the overall low-relief landscape and to help frame their importance for models of low-relief landscape evolution. This is of importance for Forsmark, the proposed underground repository for spent nuclear fuel in Sweden.

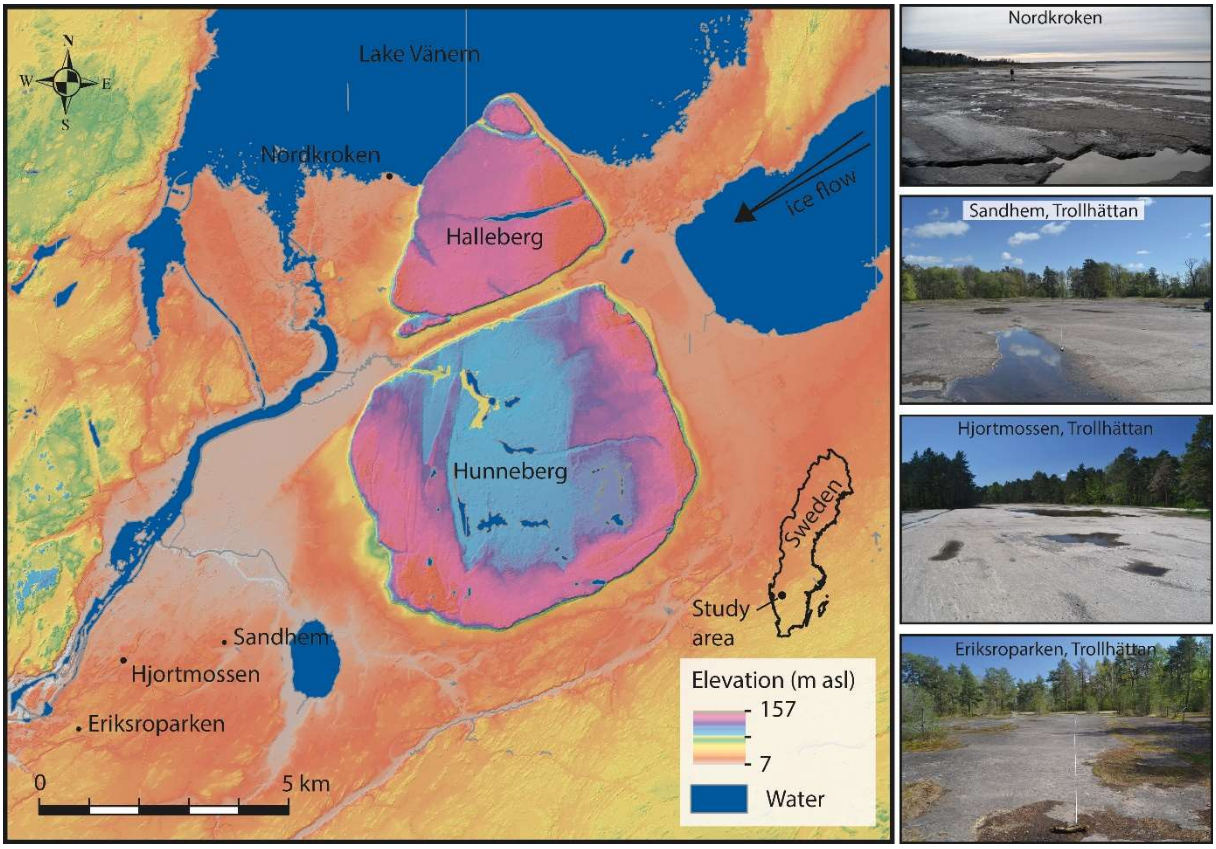

Figure 1. Study locations at Nordkroken and in Trollhättan, SW Sweden. Near-planar surfaces at Nordkroken, Sandhem, and Hjortmossen are located on kernels of porphyritic, coarse-grained gneissic granite. The Eriksroparken surface is located on coarse-grained gneissic granite. Granite emplacement ages are 1.5 – 1.6 Ga (Geological Survey of Sweden).

Results

Model simulations of ^{10}Be and ^{26}Al isotopes produced *in situ* (13 samples) at the Nordkroken and Trollhättan near-planar bedrock surfaces indicate that glacial erosion of bedrock over the last glacial cycle ranged from decimeters to meters, and potentially more than 10 m (Goodfellow et al. 2019). The most erosion, likely a result of glacial stripping of sedimentary cover rocks, is inferred at locations within hundreds of meters of the table mountains, but we cannot rule out that the erosion cut into granitic basement. Inferred glacial erosion rates are collectively higher for these locations than for 36 sites located in the Forsmark region (Hall et al. 2019), consistent with the higher ice sheet basal sliding rates deduced for Trollhättan-Nordkroken (Näslund et al. 2003). The isotopic data also indicate that the near-planar surfaces were glacially eroded rather than being uneroded SCU remnants.

If glaciers exploited sheeting joints to develop the flat surfaces, then we expect some subhorizontal sheeting joints would still exist in the subsurface. Ground penetrating radar (GPR) indicates that this is indeed the case. Figure 2 shows that at Nordkroken, strong GPR reflectors occur subparallel to, and with a few meters of, the topographic surface. We interpret these to be sheeting joints, with the weak lower reflectors being artefacts (“multiples”). Subhorizontal joints were also imaged extensively at Hjortmossen and beneath the flanks of the Sandhem outcrop but were largely absent from beneath the Eriksroparken outcrop. We are developing a three-dimensional model of the subsurface joints at Nordkroken from reflectors along multiple GPR transects to illuminate how the joints formed.

We interpret the available data as indicating that the nearly-planar current bedrock surface reflects the removal of bedrock between nearly-planar sheeting joints.

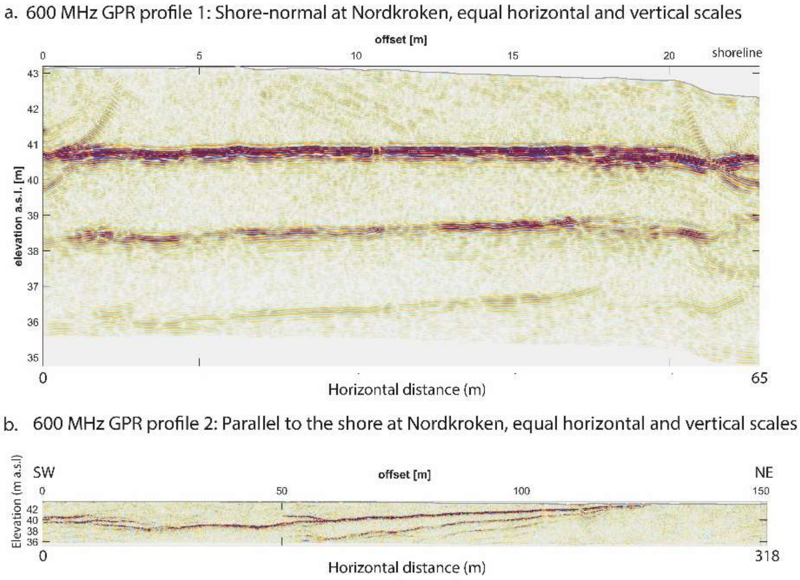

Figure 2. Examples of 600 MHz GPR images of subsurface jointing at Nordkroken. These transects are located orthogonal to each other. Strong reflections are shown in purple, and weak reflections are shown in yellow.

Figure 3 shows conceptually how pressurized subglacial water could open sheeting joints and lift the overlying rock beneath low-relief topography. Consider an ice sheet that is wasting away, of thickness *h*, with a supraglacial lake (typical of the current Greenland margin). Water can flow through vertical fractures in the ice (crevasses) and the rock, and that horizontal regional stresses are high (~35 MPa). These conditions would cause nearly horizontal hydraulic fractures to open in front of the ice sheet at depths as great as ~*h*/3 below the ground surface. Hydraulic fractures could extend to a far greater depth in front of the ice than they could beneath the ice. The actual depth and lateral extent of the hydraulic fractures depends on the ice thickness, water volume, and subsurface distribution of fractures.

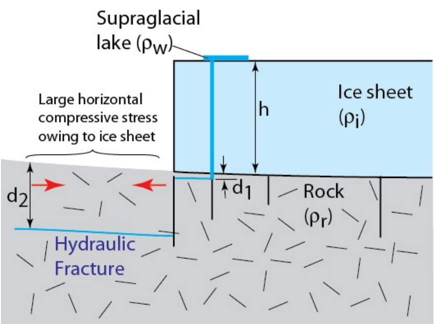

Figure 3. Cartoon showing how sheeting joints (in blue) might form in bedrock through hydrofracturing associated with high water pressures generated by a melting ice sheet. Pre-existing vertical fractures are shown in heavy black lines.

Our model simulations of basal ice sheet conditions over the study area, using basal sliding rates of 200 m/yr (Näslund et al. 2003) and ice sheet thicknesses of 1000 m and 500 m, predict water fluxes and water pressures that vary both spatially and temporally (Figure 4). Cavities form on the lee sides of topographic obstacles and permit the highest water fluxes (as great as 60 $m^3/(m \cdot s)$). In these locations and during periods where water flux is high, the water pressure is high enough to decouple the ice sheet. Conversely, during periods of low water flux, the water pressure at the base of the ice is lower. Bedrock fracturing may be favored during periods of high water pressure, particularly during periods when water fluxes return to high, but are accompanied by a lagging decrease in effective pressure. Erosion of bedrock may be favored during periods of high effective pressure, when the ice sheet is coupled to its bed.

Interpretations

Work is ongoing but our existing data support the following interpretations: 1). marine erosion of weathered rock during the Cambrian transgression was likely important to the formation of the regional SCU; 2) the extreme flatness of the surfaces at Trollhättan and Nordkroken is attributable to Quaternary glacial erosion that exploits sheeting joints; 3) the SCU explanation for the flat surfaces does not account for the presence of sheeting joints; 4) hydraulic fracturing appears to have played a key role in opening subhorizontal fractures in the bedrock; this could have occurred in either a marine proglacial setting or an ice-marginal setting. This hydrofracturing was promoted by episodic drainage of supra-glacial meltwater ponds through crevasses to the base of the ice sheet bed, with ice sheet deformation around the table mountains enhancing this fracturing process. This mechanism could temporarily lift the ice sheet from its substrate and generate subglacial (and/or proglacial) water pressures in the bedrock sufficient to open and drive subhorizontal fractures in the bedrock. Glacial ice subsequently exploited these subhorizontal fractures to erode blocks with volumes as great as 125 m^3, based on observations elsewhere in southern Sweden, leaving remnant near-planar bedrock surfaces.

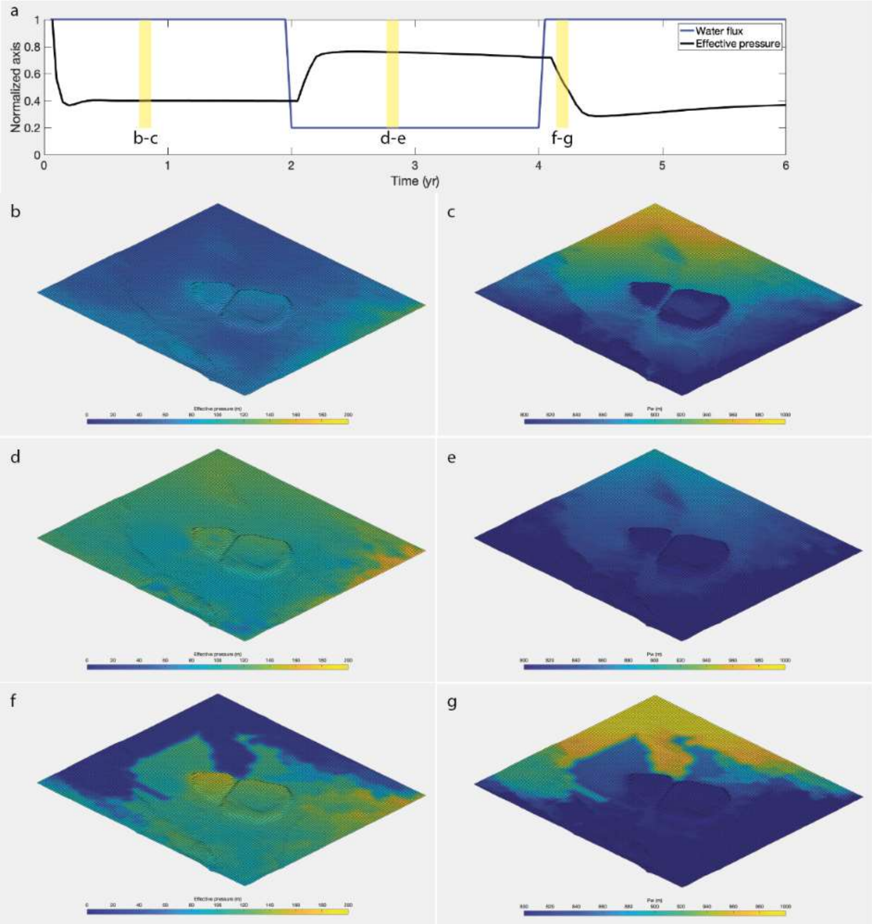

Figure 4. Ice sheet model simulations. Ice flow is from the NE (top corner) of the panels, ice thickness is 1000 m, flow rate is 200 m/yr (Näslund et al. 2003), and the model grid is 40x40 km. (a). Imposed temporal evolution of subglacial water flux and associated changes in effective pressure. The blue line shows water flux with a maximum normalized value of 1 for the first ~two years of the model simulation, after which it decreases to normalized value of 0.2, before returning to its maximum value at ~4 years. The black line shows effective pressure, which displays an inverse relationship to water flux. Panels 'b-g' show results for the simulation periods indicated by the labelled yellow bars in panel 'a'. Left- and right-side panels show effective pressure and water pressure, respectively.

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