The coating layer of glacial polish

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ABSTRACT

Glacial polish has previously been thought to form by removal of material by glacier abrasion. Here we identify a micrometer-scale coating layer that suggests that the uppermost interface between ice and rock forms by accreting material to the abraded surface. Bent and broken crystals in a damage zone beneath the coating layer provide evidence for abrasion at the nanoscale, which generates the fragments and amorphous matrix that ultimately compose the coating layer. Flow and shear textures within the coating suggest that this composite material is smeared over the damage zone during ice sliding, forming a smooth surface. The coating can potentially change the shear resistance and erosion rates at the bed of temperate glaciers and likely explains the relative resistance of glacial polish to postglacial weathering.

INTRODUCTION

Glacial polish, a hallmark of glaciated landscapes, is the smooth, glossy bedrock surface formed under glaciers (Fig. 1A). Glacial polish is significant both because it potentially holds information about subglacial conditions and processes, and because it forms a resistant surface that protects landscapes against postglacial weathering.

Abrasion, quarrying, and melt-water erosion operate in concert to remove rock at the base of glaciers. Long parallel grooves on glacially polished surfaces (Fig. 1A) connect the polish formation specifically to abrasive wear (Iverson, 1991). Therefore, a simple explanation for glacial polish is that it forms by abrasive removal of material at multiple scales until the surface becomes optically smooth (Benn and Evans, 2010). Although intuitively appealing, this explanation has not previously been tested by detailed investigations of the fine-scale structure of glacial polish.

In other, nonglacial, environments, abrasive wear has been shown to generate a thin coating, built of the wear products, that forms the final smooth surface. Tribolayers are common in engineering applications (Adachi and Kato, 2000), and such a coating layer was shown to exist in faults (Kirkpatrick et al., 2013; Siman-Tov et al., 2013). The extremely smooth fault surfaces include a micrometer-thick layer that coats an inner, rougher abraded surface, resulting in a polished appearance. Here we investigate microscale and nanoscale structures of recently glaciated crystalline rocks to determine whether a similar coating layer exists in glacial polish.

STUDY AREA AND METHODS

We collected glacially polished samples from the eastern part of Yosemite National Park (California, USA; Fig. 1B), a landscape long noted for its impressive polish (e.g., LeConte, 1875; Mathes, 1930). During the Last Glacial Maximum, much of the Late Cretaceous metamorphic and granitic bedrock in Yosemite was covered by glacier ice (Alpha et al., 1987). Glacier retreat during the latest Pleistocene (Alpha et al., 1987; Dühnforth et al., 2010) revealed large expanses of glacially polished bedrock (Fig. 1A). Two small modern glaciers located at the head of Lyell Canyon, the Lyell and Maclure (Fig. 1B), are not relics of the Last Glacial Maximum, but instead formed during or slightly before the Little Ice Age (Basagic and Fountain, 2011; Bowerman and Clark, 2011). An ice cave at the toe of the Maclure Glacier allows access to the ice-bedrock contact, where fresh striations, polish, and glacial flour indicate active sliding and abrasion.

We documented and sampled glacial polish at tens of sites in Lyell Canyon and Tuolumne Meadows (Fig. 1B) and conducted detailed analyses on samples from three sites: (1) metavolcanic rock exposed in the Maclure...
Glacier ice cave (Fig. DR1 in the GSA Data Repository1), (2) the Granodiorite of Kuna Crest at the head of Lyell Canyon (Fig. DR2), and (3) the Cathedral Peak Granodiorite at Daff Dome west of Tuolumne Meadows (Fig. DR3). These samples record polish formed on a variety of lithologies (Huber et al., 1989) and over time scales ranging from ca. 15 ka to the present. We imaged samples with scanning electron microscopy, and then milled cross sections perpendicular to the polished surfaces with a focused ion beam. We examined the resulting electron-transparent foils by scanning transmission electron microscopy using combined elemental analyses techniques (details in the Data Repository).

**OBSERVATIONS**

**Evidence of Abrasive Damage**

At the field scale, glacially polished surfaces on granodiorite bedrock present smooth and reflective surfaces that commonly extend contiguously across tens of meters (Fig. 1A; Fig. DR3A). Slip markers on the polished surfaces, such as arcuate cracks and striations, indicate a role for abrasion during polish formation (Figs. DR4 and DR5). Analogous to fault surfaces, the high reflectivity of the glacially polished surfaces hints at the existence of a coating layer at the micrometer to submicrometer scales.

At the fine scale, our observations reveal that the outermost 1–5 µm of the bedrock surface is intensively deformed, suggesting damage by abrasion during ice slip. An amphibole is bent along cleavage planes and fractured (between the red and the yellow lines in Fig. 2A). Orthoclase and plagioclase exhibit more fractures and dislocations toward the abraded surfaces (Fig. 3; Fig. DR6). Deflection of crystal-scale markers agree with outcrop-scale indicators of the sliding direction, suggesting that glacial slip caused the damage (Figs. 2A–2C). The fracture density in the bent crystal increases toward the sample surface (Figs. 2A–2C). The distance between adjacent fractures decreases from 500 to 1500 nm a few microns deep from the surface (below the red line in Fig. 2A) to between tens and a few nanometers ~100 nm below the polish surface. The crystal is fractured both along the cleavage planes and subperpendicular to them, allowing the in situ formation of elongated grain fragments (Figs. 2B, 2C). The fragment size, determined by the fracture density, therefore decreases toward the surface until it is impossible to resolve any crystalline structure by electron diffraction; i.e., it is amorphous material. The damage controls

the inner, glacially abraded surfaces (yellow lines in Figs. 2 and 3; Fig. DR6), which are usually rougher than the outer sample surface (green line), suggesting that a different process forms the outermost polish surface.

**Evidence of Coating during Abrasion**

A submicrometer- to a few-micrometers-thick layer composed of amorphous material and nano-size fragments caps the glacially abraded surfaces. This coating layer makes the outermost surface smoother than the abraded surface and likely accounts for the polished appearance. Wear products accumulate at the base of the coating layer in depressions along the abraded surface. In the margins of the Maclure Glacier sample (Fig. 2A), the amphibole fragments within these depressions are rotated relative to the damaged amphibole crystal (Figs. 2D, 2E), consistent with translation and rolling during slip until they were trapped within the depressions. Within the depressions, fragments that are not derived from the adjacent amphibole crystal indicate transport (i.e., slip) over a distance at least as long as the length of the underlying amphibole crystal (>10 µm). At the rock surface (just below the green lines in Fig. 2), a continuous layer, tens of nanometers thick, caps the damaged amphibole crystal and the brecciated material in the depressions. The thin coating traps these fragments and the damaged crystal to form a smooth, uniform surface.

The Daff Dome sample, the farthest down-glacier sample (Fig. 1B), is the most texturally complex, containing four distinct coating layers (separated by one blue and two dashed lines in Fig. 3A): an inner layer of mainly amorphous silica, an intervening zone of rock fragments in an amorphous matrix, an aluminum-rich amorphous layer, and an external layer of phyllosilicates. The mineral diversity of the rock fragments in the coating, representing all granodiorite minerals, suggests that these layers were derived from the underlying rock with a transport distance that is larger than the average crystal size (~1–10 nm). Some of the clasts within the rock fragments layer are clustered by mineral type, with individual clasts within clusters decreasing in size along the ice slip direction, suggesting fragmentation and smearing of fragments within a viscous matrix. Likewise, change in thickness of the coating layers along the slip direction, and the alignment of elongated crystal fragments and voids parallel to the surface, are indicative of shearing of a viscous flow (Fig. 3A; Fig. DR7).

Both the upper Lyell Canyon and Daff Dome samples have a 0.3–1.2-µm-thick outer layer of foliated phyllosilicates (Fig. 3; Figs. DR6

1GSA Data Repository item 2017334, supplemental figures, expanded methods, and detailed description of each sample, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.
Evidence of Abrasive Damage

**OBSERVATIONS**

Focused ion beam. We examined the resulting electron-transparent foils ing the in situ formation of elongated grain fragments (Figs. 2B, 2C). The evidence of a coating layer at the micrometer to submicrometer scales. At the fine scale, our observations reveal that the outermost 1–5 µm of the glacial polish surface (green line) is the platinum layer deposited during foil preparation. C: Foliated S/C fabric indicates shear deformation (green arrows, S; yellow arrows, C). Sample also shows illite and chlorite grains occur within the amorphous matrix. The latter resemble trapped vesicles or pores that were later sheared.

**MECHANISMS OF COATING FORMATION**

The coating layer of glacial polish appears to form by the accretion of sheared wear material on abraded bedrock surfaces. Abrasive wear removes material and makes the surface smoother, while simultaneously producing the wear products that become the construction material for the coating layer. The observations suggest that the deposition of the hard coating occurs during shear and at the contact of the wear layer with the hard rock surface; i.e., in the beginning deposition on the abraded surface and later on the recently formed coating layer. The observations do not constrain the exact mechanism by which the loose particulate material coalesces into the coating layer that includes the amorphous material.

Previous work in glacial environments attributed the existence of amorphous silica and calcium carbonate deposits to precipitation from thin films of regelation water. Regelation, the pressure melting of ice around bedrock bumps, produces water that may precipitate solid phases on the bedrock. These precipitates are usually correlated with the bedrock topography and are found locally on the lee (downstream) side of the bumps; this was found to be the case for both silica and calcium carbonate deposits (Hallet, 1975, 1976). However, regelation does not satisfactorily explain the spatial extent of these glacial polish coatings, which do not seem to be controlled by the topography of the ice-bedrock surface contact. Moreover, previously reported deposits of precipitated amorphous material tend to display concentric laminae parallel to the underlying surface (Hallet, 1975; Whalley et al., 1990), a feature we do not observe.

In contrast, amorphous material is known to form directly by shearing granitic material, as observed experimentally for dry and wet conditions (Yund et al., 1990; Hadizadeh et al., 2015). In these experiments, the amount of amorphous material increases and the size of fragments decreases with increasing average shear strain; hence, increases in cumulative glacier slip might increase the amount of amorphous material at the bedrock-ice contact. This may explain the spatial variations we observe in both the textural complexity and the coating layer thickness (i.e., between samples 1 and 2 and sample 3; Fig. 1B). Note that the amorphization does not need to include melting and we do not observe here the mosaic fabric utilized as evidence of rock melting in glacial striations by Bestmann et al. (2006).

An alternative interpretation for the uppermost phyllosilicate coating might be formation by post-glacial exposure of polished surfaces to atmospheric conditions (Dorn, 1991, 1998; Langworth et al., 2010). However, evidence counter to this interpretation includes the absence of common alteration clays (e.g., kaolinite, smectite) in our samples (Murakami et al., 1999), the shear fabrics of the phyllosilicate layer (Fig. 3; Figs. DR6 and DR7), and the overall continuity of polish within and between samples.

Eventually, rock fragments dragged by the glacier may destroy an already extant coating. The existence of a preserved coating implies that ultimately the aggregation process is dominant. We speculate that this long-term accumulation could arise if the wear material particle size decreases with slip, decreasing the destruction rate. However, the aggregation rate does not necessarily decrease with slip because the fine particles are always abundant. In this scenario, well-evolved and smooth surfaces should eventually accumulate thicker coating layers, although these coatings may undergo local reversal due to damage events by large fragments.

**IMPLICATIONS**

The preserved coating suggests a distinct layer at the bedrock-glacier contact during slip. Two possible candidate components of this layer are rock flour paste and silica gel, both of which are high viscosity compared to subglacier water and therefore better hydrodynamic lubricants (Brodsky and Kanamori, 2001; Goldsby and Tullis, 2002; Faber et al., 2014). The lubrication could reduce both the abrasion rate and friction. In addition, as the thin coating layer is formed during glacier slip, it may preserve information about conditions at the base of glaciers. Till and other deposits have previously been considered as the primary archives that preserve information on subglacial processes. Here we identify a new nano-scale archive that may prove datable and preserves novel information about the timing and magnitude of these processes.

The coating may explain the remarkable persistence of glacially polished surfaces, which can survive as long as 300 m.y. (Ward et al., 2014). Because the amorphous and phyllosilicate coatings are exceptionally impermeable, they shed water quickly and inhibit the colonization and growth of lichens and mosses, slowing chemical weathering. Although early work suggested that polish may perform a role in preservation (Matthes, 1930), the structural origin of the impermeability had not
previously been recognized. The coating may also explain why glacial polish erodes in a distinctive pattern of roughly circular patches (Fig. 1A; Figs. DR3A and DR3B). Where a small fracture or pit allows water to penetrate through the coating, the bedrock weathers underneath the polish, allowing slabs of polish to detach radially outward from the point of penetration. However, the coating layer is much thinner than the characteristic thickness of several millimeters along which these slabs detach from bedrock; what sets this detachment thickness remains unknown.

The comparison between glacial polish and fault mirrors may contribute to our understanding of processes operating in both fault zones and underneath glaciers. In fault systems and rock mechanics experiments, whether polished surfaces indicate high speed has been vigorously debated (Fondriest et al., 2013; Verberne et al., 2014; Siman-Tov et al., 2015). The key evidence for high speed has been rock textures attributable to high temperatures that can only be created by earthquake-like slip speeds. Here we see a polished surface that has no such thermal textures and does not require a high-temperature (high speed) origin. Both high-speed and low-speed polishes appear to exist and are potentially identifiable based on transmission electron microscopy imagery.

CONCLUSIONS

We have identified a micrometer-scale coating layer on glacially polished rocks, with microstructural evidence indicating formation by smearing and accreting comminuted rock onto the abraded surface. As the coating forms a hard, smooth layer at the base of glaciers, it may influence the sliding of temperate glaciers and likely accounts for the remarkable persistent of glacial polish. The coating has potential implications for glacial mechanics, fault mechanics, and geomorphology, and warrants further study.

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