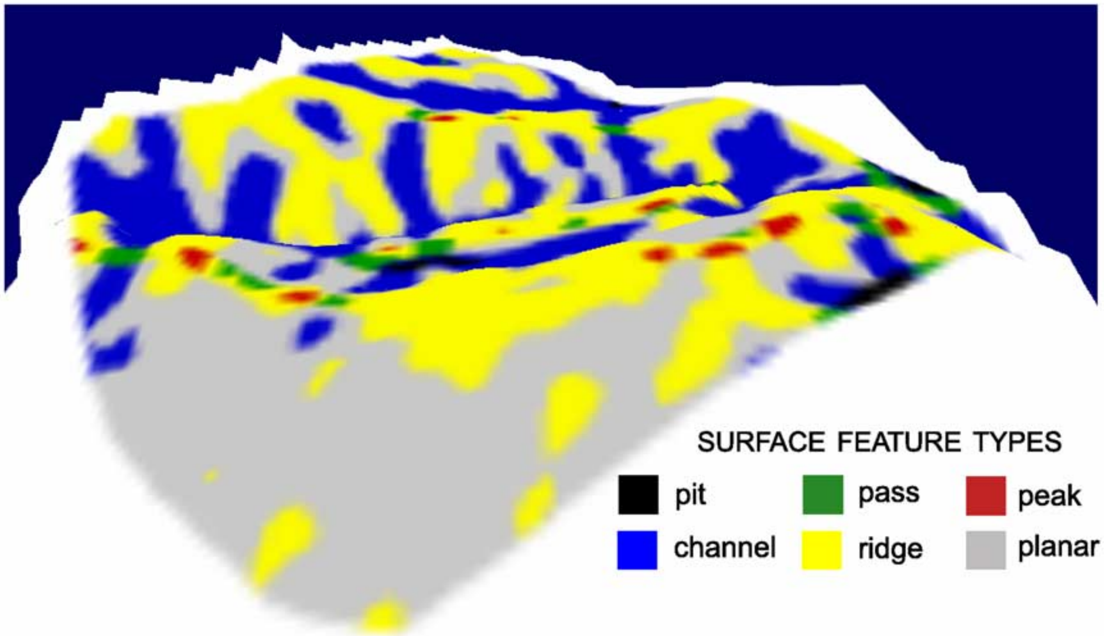

Figure 5. Morphometric classification at the 1 cm scale draped over the digital elevation model of the boulder mold from boulder Q5 at the quarry. The central trough in the image is from a large conchoidal fracture. Relief is approximately 2 cm, and the cast is approximately 13 × 15 cm.

http://www.landserf.org), percent frequency of each morphometric form was calculated for each boulder surface mold using several window scale sizes, 3 × 3 and higher. Reported morphometric class frequencies are for windows of side length ~1.5 mm (3 × 3 at the limit of resolution, ~0.5 mm as discussed below), 1, 3, and 5 cm for the 225 cm^2 molds. Threshold values of slope and curvature of 5.0 and 0.1 were used as suggested by *Fisher et al.* [2004]. Once morphometric classes were determined for each boulder, frequency percentages were computed and compared for boulders at the three sites at different scales.

4. Results

4.1. Extent of Rock Breakdown

[31] The appearance of boulders varied greatly between the three sites (Figure 6). Boulders in the quarry had pristine flood transport related features readily observable on the light gray surfaces. These included percussion fracture facets, fissures, and incipient cones (Figure 6a) [*Bourke and Viles*, 2007]. Approximately two-thirds of the quarry boulders had small, less than 1 mm wide fractures on the surface, and slightly less than half had multiple fractures including some as long as 100 cm. Lichen was completely absent from quarry boulders.

[32] Interestingly, on surface boulders, lichen tended to obscure percussion fracture facets and other fluvial features which form topographic lows by preferentially colonizing them. While fractures were difficult to identify because of lichen cover, 6 of 20 surface boulders had at least one large (>10 × 10 cm) detached rock fragment adjacent to the largest boulder fragment (Table 2, Figure 6d). These indicate in situ fracturing. On fan surface boulders, lichen coverage on a whole boulder basis varied from 30 to 100%. On a smaller scale, patchiness was evident with lichen coverage on a per facet basis varying from 10 to 100% even on a single boulder. Boulders were reddish-brown in color.

[33] At the outcrop site, boulders had few fractures on the surface; all measured less than 30 cm in length. Some cracks were wider than those at the quarry site, measuring from a few millimeters to 1.5 cm in width. Three boulders had small detached fragments. Observation of columns at the outcrop site showed numerous fractures perpendicular to hexagonal columnar jointing (Figure 6c) and locations from which some boulders fell could be identified. Fresh surfaces recently exposed by rockfall were darker in color than the surrounding brownish outcrop, indicating some oxidative weathering of the outcrop occurs prior to boulder formation. Lichen was found only rarely on outcrop boulders.

[34] In terms of physical hardness, the Schmidt hammer data reveal significant differences between the three sites at the $p < 0.05$ level (Table 2). Quarry boulders had the highest rebound values (65.2 ± 4.6), and surface boulders had the lowest (55.9 ± 8.6). Surface boulders also show the greatest variation in Schmidt hammer values. Outcrop boulders are slightly harder than surface boulders and with slightly less variation (58.4 ± 7.1). Hardness varies by lichen coverage as well as by site. Facets of surface boulders with >80% lichen cover (51 ± 10.0) were significantly softer than facets with <50% lichen cover (56 ± 11.2). No correlation was found with boulder size or number of fractures/detachments, though as noted already identification of fractures was hindered on surface boulders because of lichen cover.

[35] Petrographic microscope analyses give some greater insights into the breakdown processes. Morphologically, there are stark differences between sites in the near surface mineral grains of the boulders at millimeter to micron scale when viewed in cross section in the petrographic thin