[57] Boulder breakpoint behavior is also intriguing if in fact breakpoints indicate changes in the dominance of multiple surface-shaping processes [*Shepard et al.*, 2001]. Most surface boulders had no breakpoints, while at least a third of quarry boulders had breakpoints. This may reflect the fact that the surface texture of quarry boulders results from breakdown action at two distinct scales during fluvial transport: submillimeter smoothing of the surface by abrading sand grains and greater than centimeter-size roughness enhancement via collisions with larger entrained particles to create sharp percussion features. In contrast, boulders exposed at the surface may already have had signatures from these competing processes erased or degraded by dominance of surficial weathering processes which do not generate scale-dependent signatures over millimeter to centimeter. These conclusions about the meaning of fractal parameters are necessarily speculative since, to our knowledge, the millimeter-scale roughness of rock surfaces has only infrequently been measured with respect to weathering [e.g., *McCarroll and Nesje*, 1996] and not previously using this technique.

[58] Morphometric class abundance textural analysis bears out the interpretation from fractal roughness parameters. At small scales, quarry boulders are relatively featureless, dominated by planar features. This agrees with observations of quarry boulder samples in cross section and is consistent with fractal analysis data and the smoothing of the boulders during flood transport and subsequent lack of weathering to further alter the surface. The increased number of ridges on surface and quarry boulders (but not outcrop boulders) at the few centimeters scale may be due to the fact that sharply outlined centimeter-size percussion features resulting from fluvial transport (percussion fracture facets, ridges and terminations, for example) are being detected. Greater roughness of the surface boulders is expressed in channels and ridges, perhaps because of "dissection" of the surface by water where grains are more easily weathered, making these preferred flow paths during rainfall and creating micro channels. Outcrop boulders also have rougher texture than quarry boulders, expressed in greater numbers of pits, peaks, and passes. This might result from inherent roughness of the fracture planes of the rock.

[59] The reduced number of significant differences between sites in terms of morphometric class abundance at larger (few centimeters) scales most likely results from the fact that sample size decreases as scale increases for the $\sim$15 cm $\times$ $\sim$15 cm molds. Sampling larger surface areas and sampling more boulders would improve the data set. The sharp increase in the number of pass features on outcrop boulders with increasing scale may be because small scale (centimeter or less) pit features are classified as pass features at higher (few centimeters) scales when larger window sizes are used for class assignation.

[60] A final consideration is whether these parameters would have been useful in identifying distinct populations of boulders if it were not known, a priori, that there were boulders with three distinct weathering histories. This situation might be typical of an alluvial fan or outwash plain, containing boulders of different ages and lithologies and has arisen in considering the origin of boulders at the Mars Pathfinder landing site [e.g., *Basilevsky et al.*, 1999]. To address this question, principal component analysis (PCA) was performed using six boulder morphologic parameters: long axis, radius of curvature ratio (R_c/R_a), average edge angle, RMS height at 1 mm, RMS height at 1 cm, and $H1$ from RMS height. These were the parameters which produced significant differences among the Ephrata boulders in t tests for site to site differences (plus $H1$ to provide a parameter for roughness scaling behavior). In the PCA, the correlation matrix was used in all calculations to standardize the mean and variance of data. The six computed principal components explain 32%, 30%, 16%, 13%, 5%, and 3% of the variance, respectively. Boulders from the three sites do tend to cluster spatially (Figure 13). Moreover, from plots of the reprojected parameters and data for the first, second, and third components, it is apparent that the shape parameters (long axis, R_c/R_a, and edge angle) contain different information about the boulders than the surface textural parameters based on RMS height. Shape parameters distinguish flood-transported from nonflood-transported boulders while the textural parameters differentiate surface weathered boulders from those which have not been surface weathered. This suggests that to fully explain the natural variation in boulder morphology, it is critical that any quantitative parameter set employ metrics to describe both shape and texture. These different types of morphological data may record evidence from different types of processes.

[61] At present, the shape and textural parameters readily distinguish between flood-transported and talus populations. It is apparent, however, that some overprinting of flood transport signatures is occurring under the surface weathering regime. Percussion marks are being degraded by lichen on surface boulders and continuing fracturing changes the nature of facet angles and curvature. The timescales required for complete overprinting at this site must, however, be far greater than the 10^4 years which have passed since the boulders were transported.

6. Conclusions

[62] A comprehensive parameter set that quantifies complete boulder morphology (size, shape and surface texture) has been successfully developed and tested in this study. Size was measured by lengths of the boulder axes. Shape was calculated using standard sedimentological scales for form [*Sneed and Folk*, 1958] coupled with measures of the angles and radii of curvature of facet edges. Digital models of surface texture were parameterized by measuring fractal scaling of roughness and by morphometric classification.

[63] Using combinations of the parameters, three populations of boulders at the Ephrata Fan site were distinguished: (1) compact boulders with highly curved edges meeting at angles of 115° whose surfaces were smooth at all scales, with some few centimeter-scale ridge and pit features; (2) compact boulders with mostly highly curved edges meeting at angles with median value 115° (and a tail of lower values) and with a rough surface texture exhibiting continuous scaling behavior; and (3) smaller compact boulders with very low curvature edges, whose edge angles had bimodal peaks near 90° and 115°, and whose surfaces were rough but exhibited discontinuous scaling behavior with large numbers of ridges and peaks identified at centimeter scale or less.