Revisiting Multiparameter Relative-Age Methods to Map Late Quaternary Fan Deposits of the Soda Mountains, Mojave Desert, California, with Structure-from-Motion Photogrammetry

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ABSTRACT

Grain size and surface relief of alluvial fan surfaces derived from digital elevation models (DEMs) with clast-size resolution are used for relative-age determination and correlation of alluvial fan surfaces. Original studies relied on field measurements of individual clasts and bar and swale topography; more recent studies have focused on surface roughness derived from airborne LiDAR at scales reflecting bar and swale topography and greater. In this study, we bridge the difference in scale using low altitude aerial photography as a prototype for mapping by unmanned aircraft systems (UAS). High-resolution DEMs and orthophotos of alluvial fan surfaces ranging in age from late Pleistocene to late Holocene were produced using Structure-from-Motion (SfM) photogrammetric analysis of photos taken from pole-mounted cameras at 5-6 m in elevation.

Starting at sub-centimeter resolution, DEMs were aggregated to successively coarser resolutions ranging from 0.01-0.83 m to reflect the transition from field- to flight-scale measurements. Surfaces representing slope, in degrees, and the terrain ruggedness index were derived from the DEMs. Five proxies for surface roughness were analyzed at each aggregated size using a 3x3 moving window: standard deviation and range of elevation, standard deviation and range of slope, and mean ruggedness. Each of the roughness proxies can discriminate between late Pleistocene and younger alluvial fan surfaces and the differences are statistically significant at 0.01 level for the 0.28-m aggregated data. Range of elevation and mean terrain ruggedness can discriminate between late Pleistocene, early to mid Holocene, and mid to late Holocene surfaces. Because of the tradeoffs between flight altitude, mapping extent, and ground resolution, these preliminary results provide a target DEM resolution for future mapping using UAS. DEM resolutions between 0.15-0.30 m are fine enough to incorporate both larger clasts sizes and bar and swale topography into roughness measurements. To incorporate varnish cover into our analysis, perceived brightness of the orthophotos was also analyzed by several different metrics, but the variation of time of day of photography on the different fan surfaces created problems with lighting and shadowing.

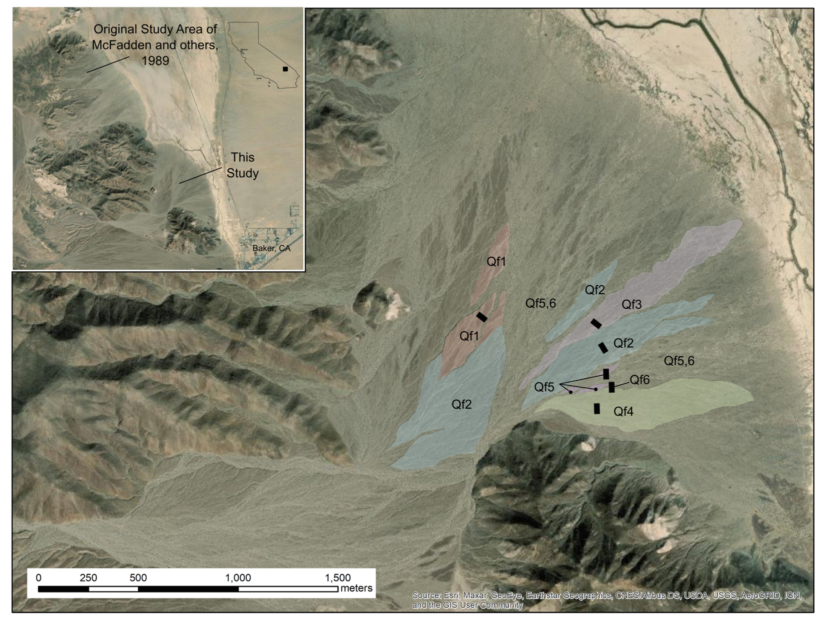


Figure 1. The original study area of McFadden and others (1989) lies just north of the current study area, on the eastern piedmont of the Soda Mountains. In order to avoid disturbances to surface characteristics that had accumulated there, the current area was selected because of the similar source area geology and alluvial fan stratigraphy. In addition, the current study area lies outside of the Mojave National Preserve and is more amenable to future UAS studies.

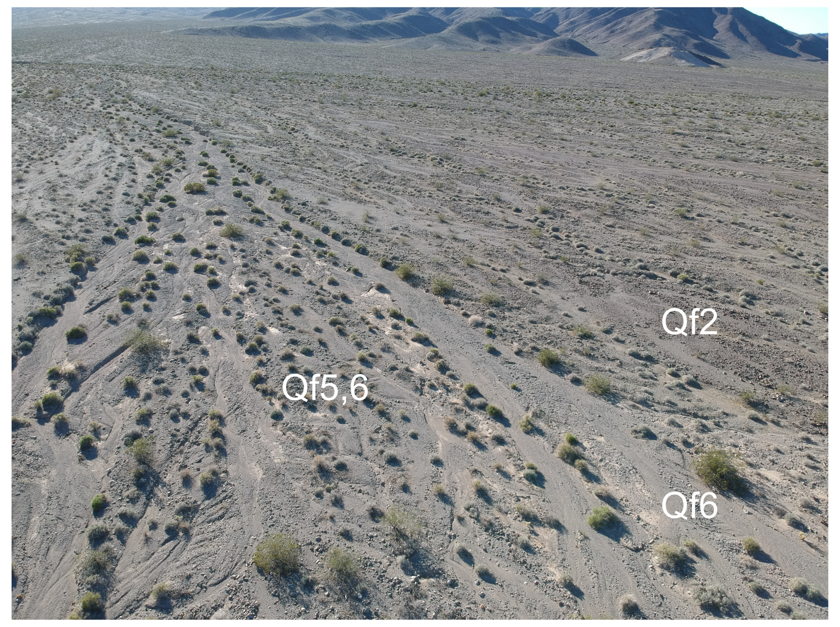


Figure 2. The RA methodology of McFadden and others (1989) included weathering characteristics of surface clasts, including varnish color and extent of the surface, rubification color on the underside, pitting and fracturing, and size and lithology compared to subsurface samples collected beneath the soil profile, soil profile development, and relief on depositional topography. Most RA parameters could not discriminate between deposits of Holocene age, but several could distinguish between Holocene and Late Pleistocene surfaces.

INTRODUCTION

Distinguishing and mapping geomorphic surfaces on desert piedmonts has benefitted from a multiparameter RA methodolgy developed by McFadden and others (1989) in the eastern Mojave Desert, California, that relied on geomorphic, sedimentologic, and pedologic observations and measurements. Subsequent studies of alluvial stratigraphy have adopted the RA methodology, but have largely focused on surface roughness attributes as opposed to clast weathering (e.g., varnish and rubification) or soil development. These studies have taken advantage of increased availability and resolution of DEMs. For example, DEMs derived from airborne LiDAR provides 1-m resolution, and recent studies have successfully delineated fan surfaces of different ages using different roughness characteristics (e.g., Frankel and Dolan, 2007; Regmi and others, 2014; Johnstone and others, 2018). Most of these studies rely on analyses that apply a filtering window that effectively negates the initially high resolution. For example, a 5x5 m filtering window (e.g., Frankel and Dolan, 2007) shifts the scale of analysis of topographic variations from individual clasts to the depositional features composed of them. This is not inherently bad, obviously, but it begs the question of whether an opportunity is lost when analyzing high-resolution digital elevation data.

In this study, we start from the clast scale (1-10 cm's), generated by SfM technology, and proceed to the scale of depositional features. There is a clear trade off between resolution and extent of coverage, but the significantly lower cost of data acquisition via pole-or helikite-mounted cameras or UAS presupposes a need for RA analysis of clast and depositional feature characteristics at the higher-resolutions possible from SfM. This study was conducted as a preliminary study before deploying a mapping-grade UAS in the near future.

Six alluvial fan surfaces were analyzed: Qf1 - late Pleistocene, Qf2 - early Holocene, Qf3 - early to middle Holocene, Qf4 - middle to late Holocene, Qf5 - latest Holocene, and Qf6 - active channel.

METHODOLOGY

Figure 3. SfM-derived DEMs provide the resolution of field-based physical measurements and the extent of coverage provided by traditional LiDAR. Low altitude aerial photography was acquired in the study using a pole-mounted Nikon DR5100 at an elevation of approximately 5-8 m. The locations of 10 ground control points were collected using a survey-grade Topcon HIPER VR positioning

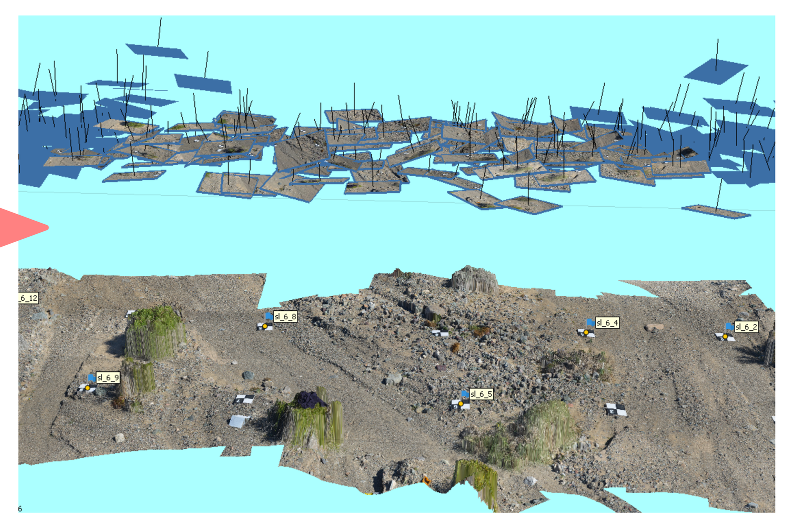


Figure 4. Agisoft Metashape was used to create orthophoto and digital terrain models using the USGS (2017) workflow. Each model comprises an area of approximately 3 x 15 m based on 113-212 photos with an overlap of >9 photos. Effective ground resolution varied from 0.76 to 1.38 mm per pixel.

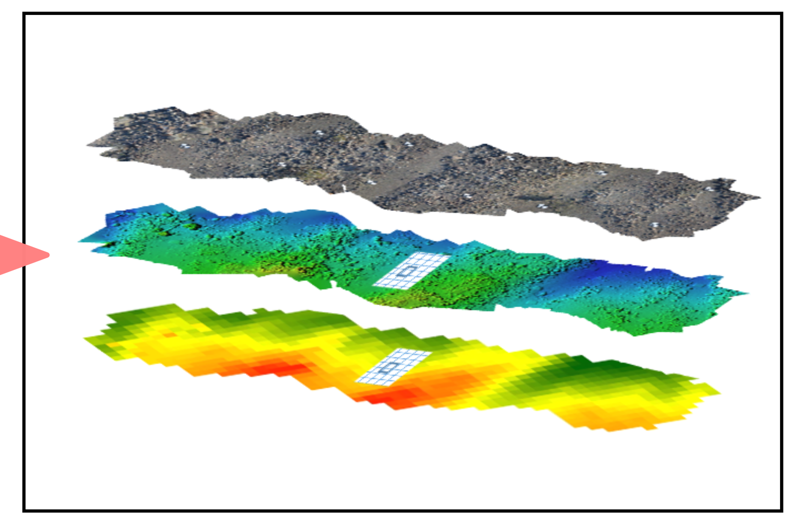


Figure 5. ArcMap 8.4 was used to create derivative surfaces from DEMs, including slope and terrain ruggedness (after Riley and others, 1999) and generate reduced-resolution rasters and rasters representing focal statistics, including mean, range, and standard deviation.

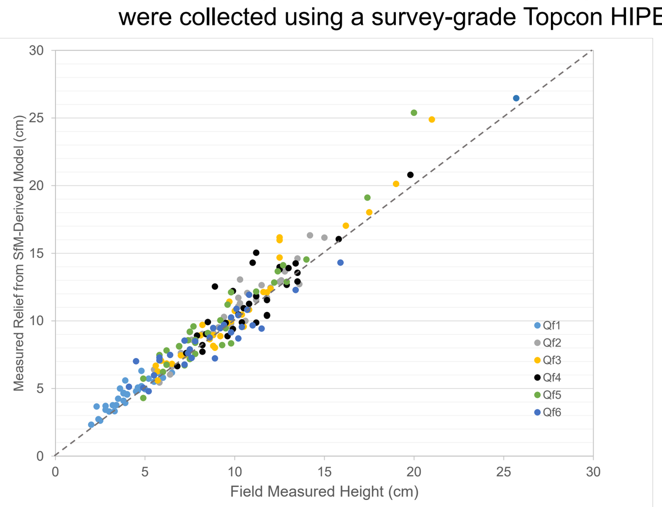
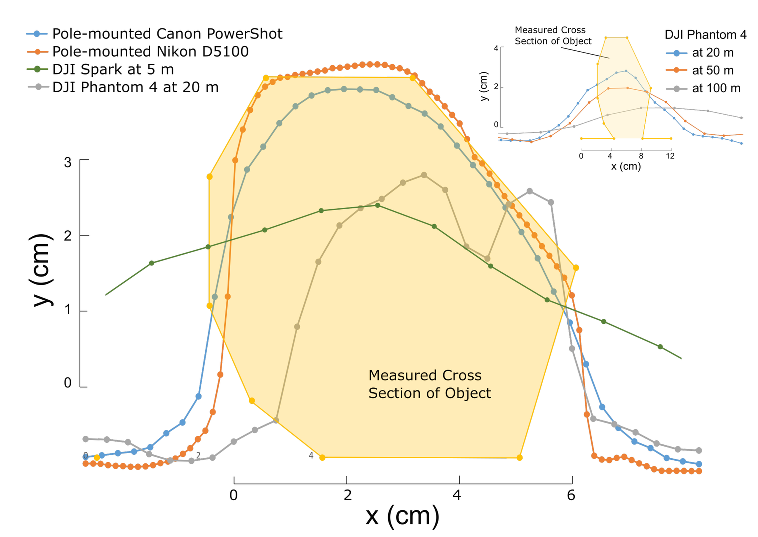


Figure 6. To evaluate the accuracy of DEMs generated by SfM and their relation to field measurements, relief of thirty of the largest clasts on each surface was measured in place and and marked by small placards for locating on orthophoto models. Relief of the same clasts was measured on the registered DEM model, and plotted against field measurements. Relief on individual clasts is overestimated when taken from the DEMs.

Figure 7. As an alternative test of the utility of using SfM-generated DEMs for measuring individual clast relief, cobble-sized objects of known dimensions were distributed across a parking lot. Photographs were taken with two different pole-mounted cameras and two UAS, one a recreational drone flown from the same height as the pole-mounted cameras, the other a mapping drone from 20, 50, and 100 m. The most accurate measurements of relief (and shape) were made from the models derived from the pole-mounted cameras.



RESULTS

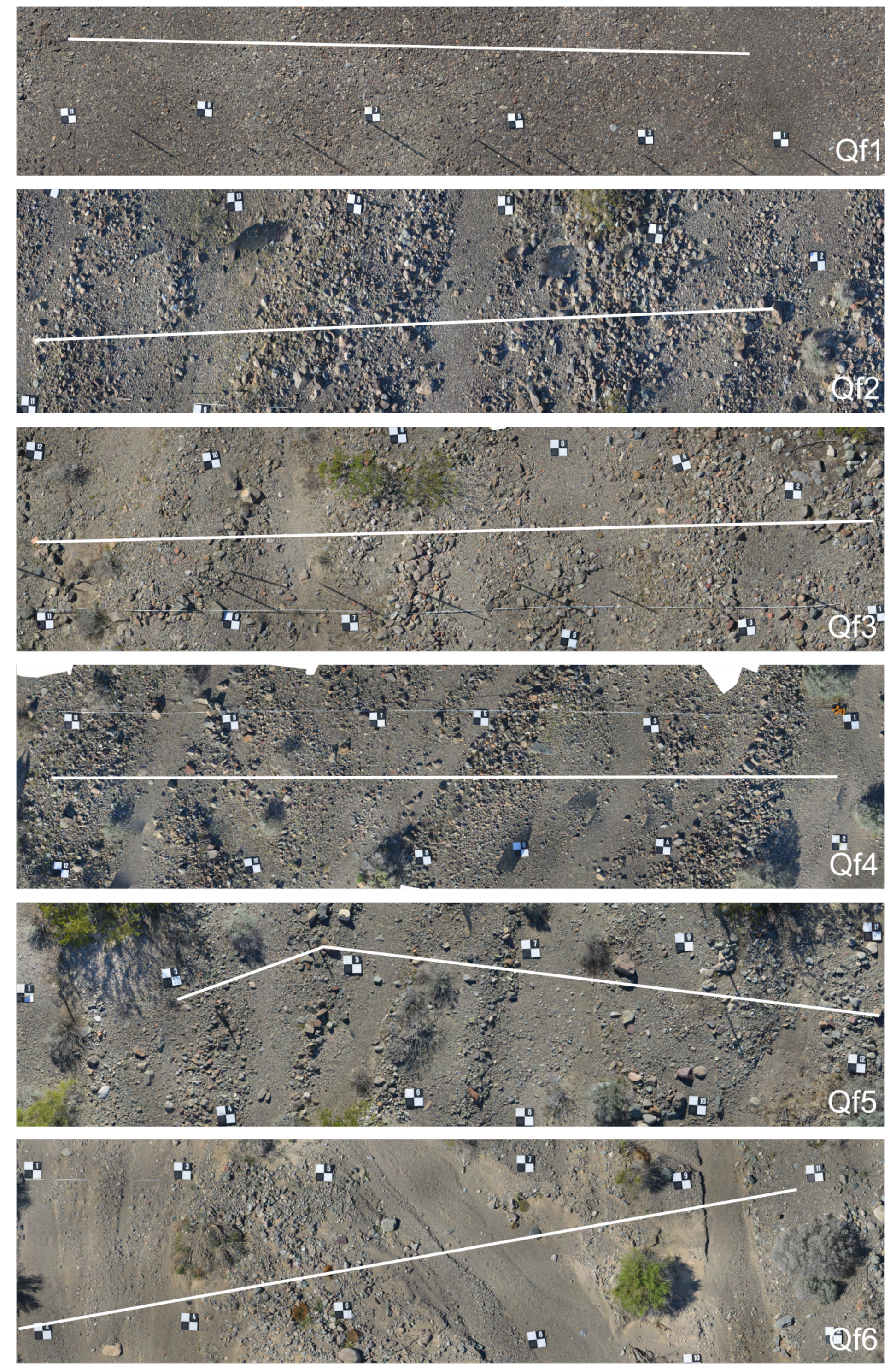


Figure 8. SfM-derived orthophotos for the alluvial fan surfaces illustrate the distribution of clasts, clast lithology, desert pavement, vegetation, and depositional features. Colors are directly comparable between surfaces as fan surfaces were photographed throughout the day under different sun angles and intensity.

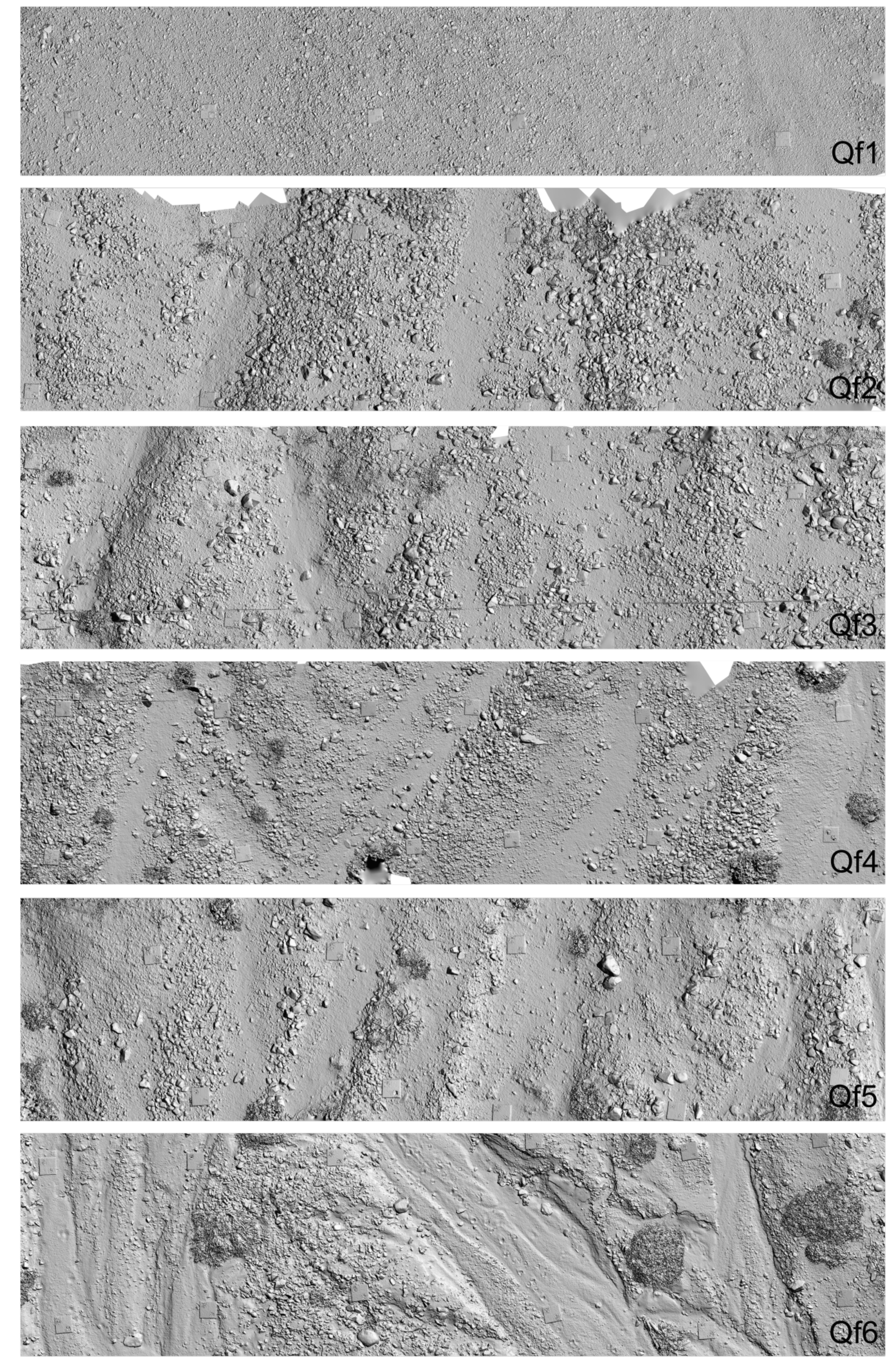


Figure 9. Shaded relief surfaces generated from the native DEMs of each surface illustrate the variation in clasts and clast sizes, vegetation, and depositional features. The flatness of survey markers mounted on foam board and their relief, approximately 0.7 cm, are apparent.

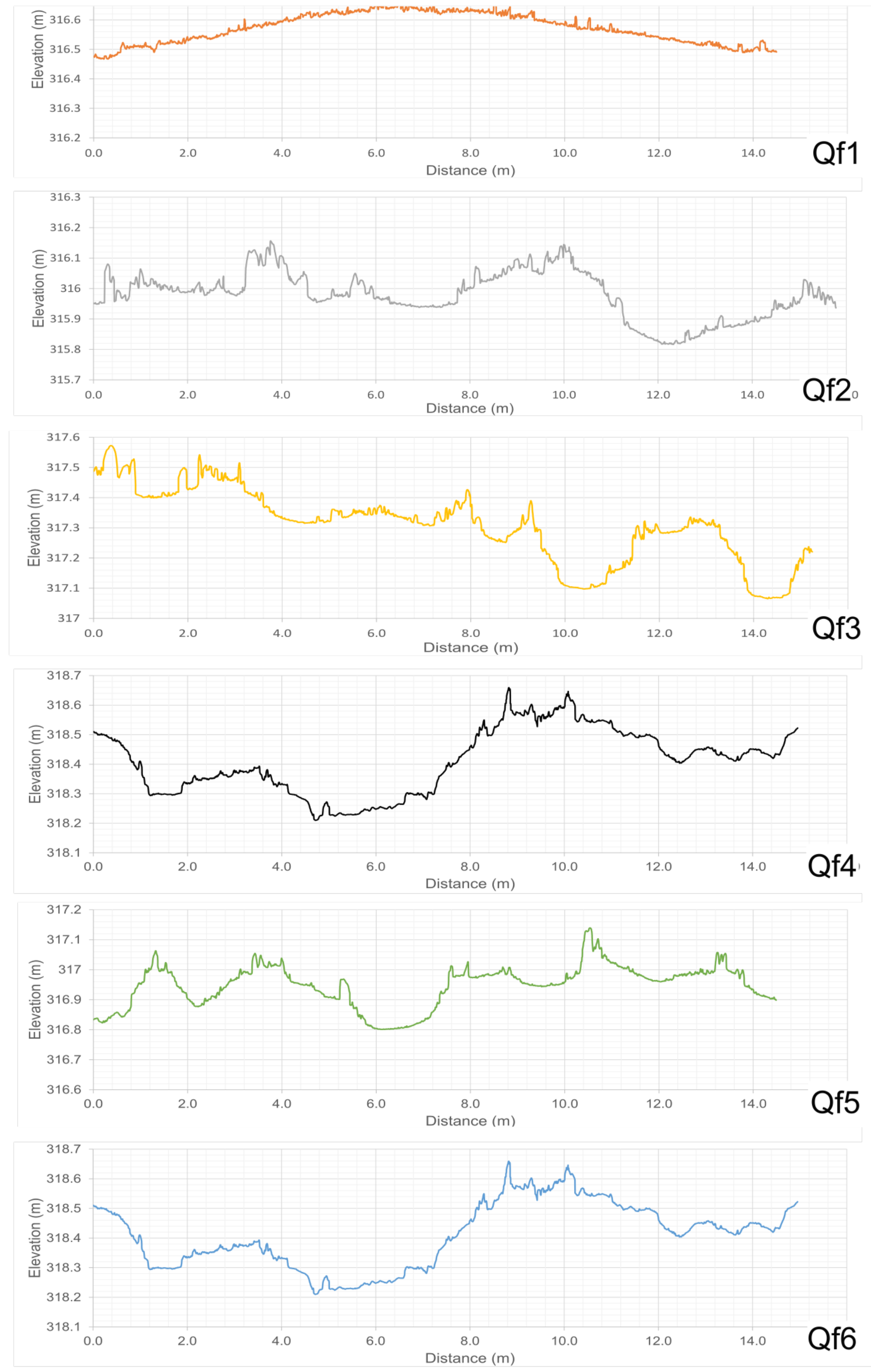
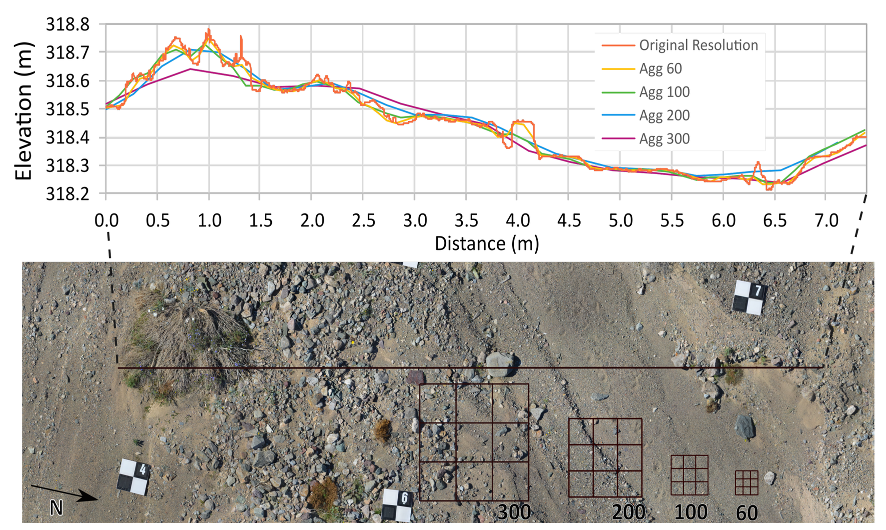


Figure 10. Topographic profiles using the native DEMs generated by SfM are shown for each surface. Their locations are shown in Figure 8. Because of vertical exaggeration, the largest clasts show up as points, but the relief of the broader depositional features is well expressed.



Representations of Scale

600	400	300	200	100	60	40	30	20	10	Aggregate
82.9	55.3	41.5	27.7	13.8	8.3	5.5	4.1	2.8	1.4	Pixel Width (cm)
248.9	165.9	124.4	83.0	41.5	24.9	16.6	12.4	8.3	4.1	3x3 Window Width (cm)

Scale of Surface Feature Recognition

Clasts
Vegetation
Depositional Topography
Fan Slope

Figure 11. Original resolution of surface DEMs was dependent on the quality of the SfM model, but all were resampled to a pixel size equal to the coarsest DEM, which was for 1.38 cm. This preserves the roughness that characterizes finer gravels, but skews other analyses like slope. At this resolution, slope values would reflect the actual top or sides of larger clasts and not depositional features or downfan slopes. To evaluate roughness and slope characteristics across multiple scales, DEMs were aggregated to pixel sizes 10, 20, 30, 40, 60, 100, 200, 300, 400, and 600 times the original size using the mean value of cells within the aggregate pixel sizes.

The topographic profiles illustrate the degree of smoothing of the DEM for various aggregates. At an aggregate of 60 (and pixel size of 8.3 cm), only the largest clasts still influence the profile and, therefore, measures of roughness. At this and larger aggregates, the relief on the profile is due to depositional features.

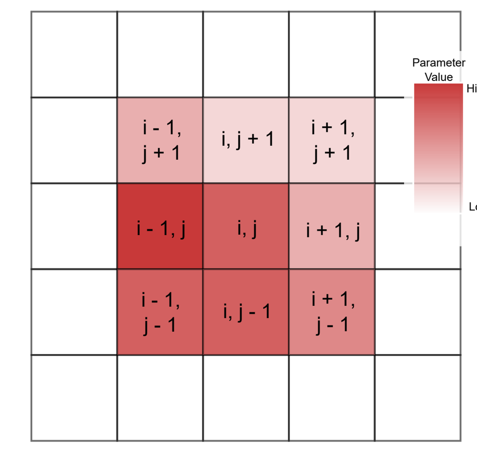


Figure 12. Schematic diagram of a 3 x 3 window in which ruggedness, standard deviation of elevation, and standard deviation of slope values are determined. Actual cell size is dependent on the aggregate (Figure 11). Using standard deviation of elevation as an example, for each aggregated surface, the standard deviation of elevation values within the moving window is assigned to the central cell (i,j). The mean value of all cells in a given surface is calculated as the mean standard deviation of elevation.

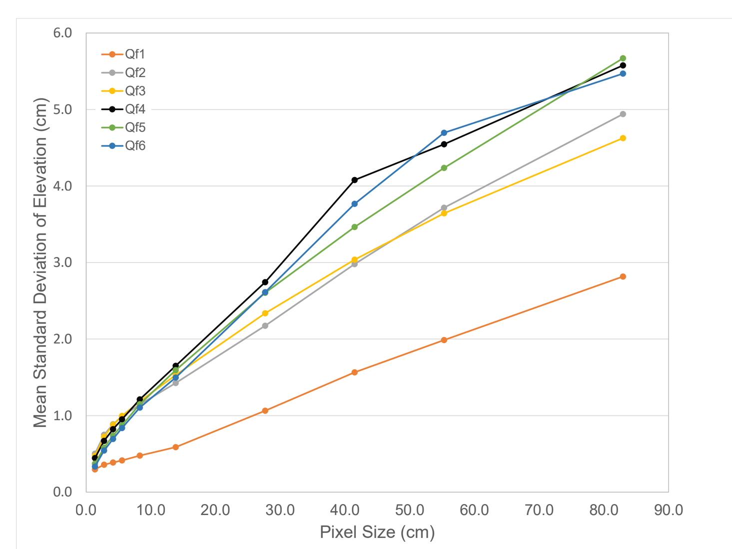


Figure 13. Mean standard deviation of elevation increases as pixel size increases (i.e., increasing aggregate and size of the moving window) and distinguishes between Qf1, Qf2,3, and Qf4,5,6 visually and statistically at pixel sizes 27.7 cm and greater. At these pixel sizes, difference in elevation across the moving window is characterizing depositional topography.

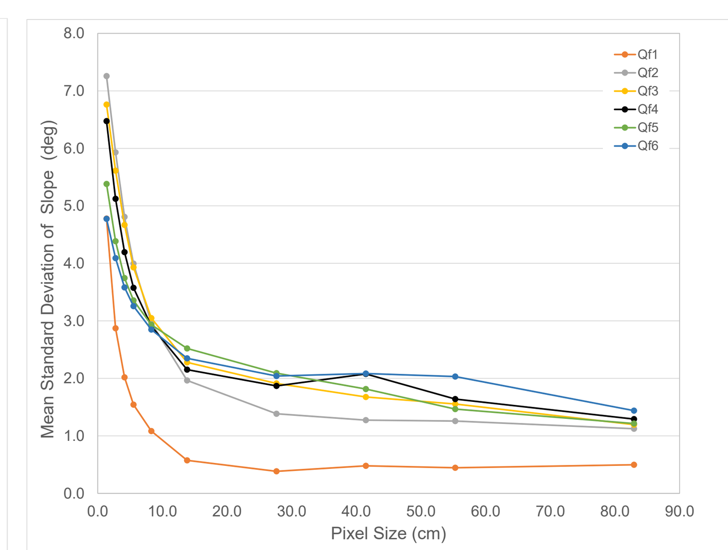


Figure 14. Mean standard deviation of slope decreases as pixel size increases and distinguishes between Qf1, Qf2,, and Qf3,4,5,6 visually and statistically at pixel sizes 13.8 cm and greater. At this pixel size, the largest clasts aere likely influencing variations in slope across a moving window, but at larger pixel sizes, depositional topography plays a greater role.

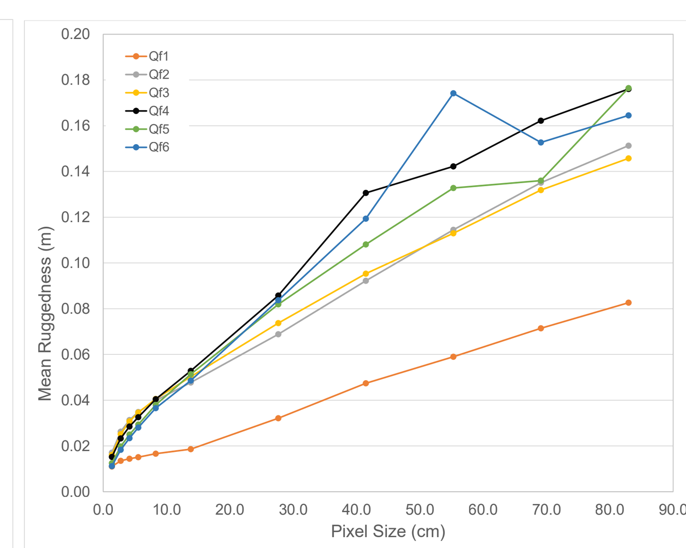


Figure 15. Ruggedness is the difference in elevation between a central cell and the mean of its eight neighbors, representing a more local measure of relief. It decreases with pixel size as the influence of individual large clasts is less. It distinguishes between Qf1, Qf2,, and Qf3,4,5,6 visually at pixel sizes 27.7 cm and greater.

DISCUSSION

In this study, we use SfM-derived DEMs and derivative surfaces to analyze surface surface roughness characteristics of alluvial fan surfaces produced by depositional processes and modified by weathering. Original relief is dependent on both depositional features like bar and swale and the coarseness of clasts that comprise them; the roughness metrics used for RA determination depend on the pixel size, and more importantly, the size of the moving window used in the analysis. Roughness metrics determined from the higher, native resolution DEMs produced through SfM- smaller pixel sizes (and a smaller moving window) - are overly influenced by individual clasts and do not discriminate between alluvial fan surfaces. Reesampling the DEMs to coarser resolution increasingly includes depositional features and even fan slope on the roughness metric while diminishing the impact of the coarsest clasts.

Roughness metrics are used to illustrate trends associated with pixel size and the differences between fan surfaces of different relative age: mean standard deviation of elevation (Figure 13), mean standard deviation of slope (Figure 14), and mean ruggedness index (Figure 15). Each example illustrates the divergence of metrics with increasing pixel size. The difference between Qf1, a late Pleistocene fan surface, and younger, Holocene surfaces is apparent at pixel sizes of greater than 2.8 cm, but at greater pixel sizes, Qf2 and Qf3, early to middle Holocene surfaces can also be distinguished from middle to late Holocene surfaces (Qf4,5,6).

The metrics presented in Figures 13-15 represent summary values to represent surfaces. The 2-sample Kolmogorov-Smirnov test tests for differences in the distribution of values between successive fan surfaces. At the increasingly coarser pixel values, the distributions are significantly different. Though this does not necessary aid in distinguishing between surfaces visually, it may be pertinent to desert pavement development (i.e., a distribution of coarser bars and finer swales may have the same mean value as a uniform pavement).

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