The Use of Airborne Laser Swath Mapping on Fans and Cones: An Example from the Colorado Front Range

Dennis M. Staley and Thad A. Wasklewicz

1 Introduction

Debris fan systems are common features of mountainous environments, particularly in formerly glaciated valleys in the Arctic, Antarctic, and high mountains of the lower latitudes (Rapp 1960a, b; Albjar et al. 1979; Church et al. 1979; White 1981; Caine 1983; Perez 1993). The prevalence of these landforms in these physiographic settings is attributed to rapid weathering associated with the presence of oversteepened valley sides, stress unloading of rock walls following deglaciation, and the severity of the climate (Matsuoka and Sakai 1999; Ballantyne 2002; Curry and Morris 2004). These factors are conducive to the development of fan deposits by rockfall, debris-flow and avalanche activity, each of which represent a significant hazards to fan areas.

A majority of alpine debris fan and talus research attempts to relate fan and source area morphometry to the processes which form and sculpt the deposit (Rapp 1960a, b; Caine 1967, 1969; Kirkby and Statham 1975; Statham 1976; Carson 1977; White 1981; Perez 1989; Francou and Mante 1990; Akerman 1994; van Steijn et al. 1995, 2002; Perez 1998; Cavalli and Marchi 2008; Trevisani et al. 2009). Direct measurement of the geomorphic processes that produce and modify these features is difficult since they often operate at intermittent or relatively long temporal scales (Schumm and Lichty 1965; Schumm 1991). Instead of direct measurement, researchers often rely upon measurement of form as a method of understanding process rates and mechanics. Despite a large body of literature

D.M. Staley (✉)
Landslide Hazards Program, United States Geological Survey, Golden, CO, USA
e-mail: dstaley@usgs.gov

T.A. Wasklewicz
Department of Geography, East Carolina University, Greenville, NC, USA
e-mail: wasklewiczt@ecu.edu

M. Schneuwly-Bollschweiler et al. (eds.), *Dating Torrential Processes on Fans and Cones*, Advances in Global Change Research 47, DOI 10.1007/978-94-007-4336-6_9,
© Springer Science+Business Media Dordrecht 2013

devoted to the study of alpine debris fan morphometry, very few studies have made measurements of surface form coincident with the spatial scales at which the geomorphic processes are reflected as features on the surface (Cavalli and Marchi 2008; Trevisani et al. 2009). Most measurements of debris fan form have been made randomly or along talus profiles or transects with average point spacing between 10 and 50 m (Caine 1969; Francou and Mante 1990; Perez 1998). Field reconnaissance and morphometric analysis suggest distinct surficial forms are evident at finer spatial scales on alpine debris fans (Caine 1969; Bones 1973; White 1981; Akerman 1994; Blikra and Nemec 1998; Perez 1998). There is a need to generate measurements of surficial features and processes at fine spatial scales to more accurately quantify the resultant forms of sediment transport processes influencing alpine debris fans.

Airborne methods, such as photogrammetry, synthetic aperture radar (SAR) or interferometric SAR (InSAR) and laser range finding methods, such as airborne laser swath mapping (ALSM) have proven to be useful in the analysis of alluvial fan forms and processes (Coe et al. 1997; Catani et al. 2003, 2005; Staley et al. 2006; Frankel and Dolan 2007; Cavalli and Marchi 2008; Volker et al. 2007; Wasklewicz et al. 2008; Roering et al. 2009). These data sources are able to provide much greater detail regarding the shape and surficial form of the analyzed fans than coarse scale topographic maps (e.g. USGS 7.5-min quadrangles at 1:24,000).

Prior to (and even after) the increased availability of InSAR and airborne laser scanning data, high-resolution topographic information related to alluvial fan processes was typically constrained to photogrammetric acquisition. Stereo-matched low altitude photography allowed researchers to analyze orthoimagery and associated terrain data with resolutions typically on the order of 2 m and finer (Coe et al. 1997; Lane et al. 2000). Thorough reviews of the photogrammetric techniques and applications in geomorphic research can be found in Lane et al. (1993, 2000). Photogrammetric data have been used to produce inventories of alluvial fans (Crosta and Frattini 2004; Godt and Coe 2007), analyze alluvial fan surficial forms and processes (Crosta and Frattini 2004), and track changes associated with torrential processes using pre- and post-event imagery (Coe et al. 1997; Crosta and Frattini 2004; Roering et al. 2009).

Improvements to, and reductions in the cost of radar and laser technology allowed researchers to incorporate SAR, InSAR and laser scanning data into geomorphic research. These methods allowed researchers to study fans in greater detail than traditional photogrammetric techniques. While photogrammetric analysis permitted high resolution analysis of surfaces, the amount of effort required process these data constrained photogrammetrically derived high resolution measurements to relatively small areas. InSAR and airborne laser scanning allowed for high resolution measurements of surface form over much larger areal extents.

Interferometric synthetic aperture radar (InSAR) refers to a form of radar data processing that allows for the characterization of topography using air or spacecraft-mounted SAR systems (Massonnet and Feigl 1998). SAR systems use an antenna to produce a narrow band of electromagnetic energy directed at the surface. SAR systems both transmit and receive electromagnetic waves at wavelengths commonly ranging from 3 cm (*X band*) to 24 cm (*C band*) (Massonnet and Feigl 1998),

though shorter wavelength sensors in the *Ku band* (roughly 1.7 cm) are recently being used (Okada et al. 2007). At these wavelengths, the energy is able to travel through the atmosphere with minimal degradation. Distance from the sensor to the Earth's surface is calculated based upon the round-trip travel time of the radar wave(s). Inferometry refers to the process of improving data accuracy by processing information from two or more SAR images of the same location. The multiple images can be obtained by (1) using the same SAR antenna during sequential flightpaths or orbits (multipass InSAR), or (2) using two (or more) SAR antennae mounted perpendicular to the flight path or orbit on the same platform (single pass InSAR) (Catani et al. 2005). Depending upon aircraft height and atmospheric conditions, InSAR is able to produce digital terrain models ranging in resolution from ~30-m (Roering et al. 2009) to less than 1 m (Okada et al. 2007). Readers seeking a more thorough review of InSAR methods are referred to Gens and van Genderen (1996), Massonnet and Fiegl (1998) and Rosen et al. (2000).

Application of InSAR data to the quantification of alluvial fan and form has been relatively limited. Farr and Chadwick (1996) use InSAR to differentiate between salt-dominated weathering processes and desert varnish and pavement development of alluvial fans in China and the southwestern United States. Catani et al. (2003) use spaceborne InSAR data to derive terrain measurements useful for the identification, prediction and assessment of flood hazards on alluvial fans. Despite the limited use in alluvial fan research, InSAR is a promising tool for the quantification of alluvial fan processes and forms, particular as sensor technology permits the generation of higher resolution terrain data (Okada et al. 2007) and repeated data acquisition allow for the temporal analysis of topographic change (Rosen et al. 2000; Roering et al. 2009).

Airborne laser swath mapping (ALSM, commonly referred to as airborne LiDAR) provides a novel means of mapping and analyzing the surficial features of debris fans and cones at high spatial resolutions over large spatial extents. A detailed explanation of the history and mechanics of laser range finding data for topographic analysis is beyond the scope of this chapter. Readers seeking more details on ALSM and other forms of laser range finding should consult Shan and Toth (2009) and Vosselman and Maas (2010).

ALSM is an optical remote sensing technology that measures properties of scattered light to find range and other information of a distant target (Shrestha et al. 1999; Carter et al. 2001). For ALSM data collection, an airplane is equipped with a precise kinematic global positioning system (GPS) receiver to position the aircraft and an accurate inertial navigation system to monitor the orientation (roll, yaw, and pitch) of the aircraft. A pulsed laser ranging system, secured on the underside of the aircraft's fuselage, produces measurements of the distance to the Earth's surface by calculating the roundtrip time of the laser pulse. The aircraft flies at a speed of 150–200 km per hour at an altitude of 500–1,000 m (dependent upon topography and atmospheric conditions) above the desired site. Current generation airborne laser scanners emit laser pulses in excess of 100,000 pulses per second (Slatton et al. 2007). Combining the positioning information, aircraft orientation, and range data

from the laser sensor permits the creation of digital terrain models with horizontal accuracies of 15–20 cm and vertical accuracies of 5–10 cm (Slatton et al. 2007).

ALSM data are commonly used to produce DTMs with 1-m resolution (Shrestha et al. 1999). These high resolution data permit the evaluation of the surface form of alluvial fans at unprecedented spatial resolution over large areas. The use of this method of data acquisition for the analysis of fan system morphometry has increased dramatically in recent years, with applications related to fan systems in both arid (Staley et al. 2006; Frankel and Dolan; 2007; Volker et al. 2007; Wasklewicz et al. 2008) and alpine (Staley 2006; Cavalli and Marchi 2008; Trevisani et al. 2009) environments. ALSM data have been used to quantitatively identify the spatial patterns of debris-flow deposits (Staley et al. 2006) and distinguish debris-flow features from flood deposits (Volker et al. 2007; Wasklewicz et al. 2008) on alluvial fans. In addition, Frankel and Dolan (2007) demonstrated that the surface roughness of fans decreases over time, and measures of roughness may be used as a dating method in Death Valley, California. Cavalli and Marchi (2008) demonstrated the effectiveness of roughness indices derived from ALSM data to classify debris flow and non-debris-flow features on a single alpine alluvial fan. Trevisani et al. (2009) utilized variograms to classify the surface of alpine fans into categories similar to Cavalli and Marchi (2008). While these are novel approaches to quantifying alluvial fan and debris fan morphometry, they do not investigate the difference between the different types of processes that influence the fan surface, and the relationship of the form of the deposit to the form of the source areas.

The remainder of this chapter provides a case study that analyzes the morphometric characteristics of debris fans and source areas, and their relationship to the types of processes that contribute to the form of the fan surface. Here, we incorporate ALSM methods to analyze the surface form of debris fans and sources areas in two Alpine study areas in the Colorado Front Range (U.S.). Our analysis quantifies relationships between dominant geomorphic process and expressions of surface form (area, gradient, and roughness). We do this in two ways: (1) assessing differences in fan and source area morphometry between dominant processes, and, (2) by attempting to predict the degree of influence by debris flow based upon morphometry. Here, we pay particular attention to the morphometric characterization of debris-flow dominated fans and source areas, as they represent a greater hazard in terms of inundation area and travel distances for downslope populations than rockfall or slush flows. The quantitative relationships identified in this analysis may be used to rapidly assess the types of hazards occurring on alpine debris fans from high resolution ALSM data.

2 Study Site

This study analyzed ALSM data from 49 debris fans located in Stevens Gulch and Arapahoe Basin, which are located in the Colorado Front Range (Fig. 1). The Front Range is an exposed core of a large anticline uplifted during the Laramide

Orogeny, beginning ca. 75 million years B.P. (Kellogg et al. 2008) Both study areas are underlain by igneous and metamorphic bedrock formed as early as 1.7 billion years B.P. (Kellogg et al. 2008).

The location and form of the debris fan systems reflect the legacy of multiple Pleistocene and Holocene glacial advances, and Holocene geomorphic processes such as rockfall, debris flow, slush flow, grain flow, and talus shift (Rapp 1960a, b; Caine 1969; White 1981; van Steijn et al. 1995, 2002; Perez 1998; Cavalli and Marchi 2008; Trevisani et al. 2009). Debris fans have formed under well-developed couloirs and gullies, most of which are located along zones of structural weaknesses (Williams 1951; White 1981). Minimal couloir development occurred where bedrock was less resistant to weathering processes and valley sides are dominated by talus sheet systems.

Stevens Gulch (SG) is located immediately east of the Continental Divide near Loveland Pass (Fig. 1a). Data from 33 debris fan systems in Stevens Gulch are incorporated into this analysis. Elevations within the alpine portion of Stevens Gulch range from 3,500 m at the base of the talus slopes, to 4,350 m at the summit of Grays Peak, the highest point on the Continental Divide in the conterminous United States. Debris fans are located along the eastern and southern scarp of the valley. A gradational contact exists in Stevens Gulch between Middle Proterozoic Silver Plume granite in the northern (lower) portion of the valley and Precambrian metasedimentary biotite-gneiss in the southern (higher) portion of the valley (Kellogg et al. 2008). All 33 debris fan systems are situated above timberline.

Arapahoe Basin is located immediately west of the Continental Divide, just south of Loveland Pass (Fig. 1b). This study area is characterized by 16 debris fans. The six fans within Arapahoe Basin Ski Area glacial cirque are distributed at the base of the northwest-southeast trending ridge. A small cirque north of Arapahoe Basin contains ten well developed debris fans. All analyzed debris fan systems in Arapahoe Basin are underlain by Precambrian biotite gneiss (Kellogg et al. 2008) and are situated above treeline.

Within the study area, processes responsible for erosion, transport, and deposition of material include rockfall, debris flow, and slush flow. Rockfall is defined as the freefall, bouncing, and rolling of material shed directly from rockwalls (primary rockfall), or from debris stored on ledges or couloirs in the source area (secondary rockfall) (Whalley 1984; Matsuoka and Sakai 1999; Dorren 2003). Rockfall has been identified on fan surfaces through analysis of particle size distributions (Bones 1973; Kirkby and Statham 1975; Church et al. 1979; White 1981; Perez 1989; Blikra and Nemec 1998; Jomelli and Francou 2000) and fan profiles (Rapp 1960a, b; Caine 1967, 1983; Kirkby and Statham 1975; White 1981; Blikra and Nemec 1998; Jomelli and Francou 2000). Debris flows are defined as rapid mass movements of poorly sorted granular solids, water, and air (Varnes 1978). Debris flow produces surface features such as channels, levees, and terminal lobes that are easily identified on fan surfaces. Slush flows represent wet avalanches composed of water-saturated snow, rock debris and mud that are typically associated with spring snowmelt (Caine 1969; Jomelli and Bertran 2001; Decaulne and Saemundsson 2006). Slushflows may resemble highly viscous debris flows or low intensity, low viscosity flows resulting

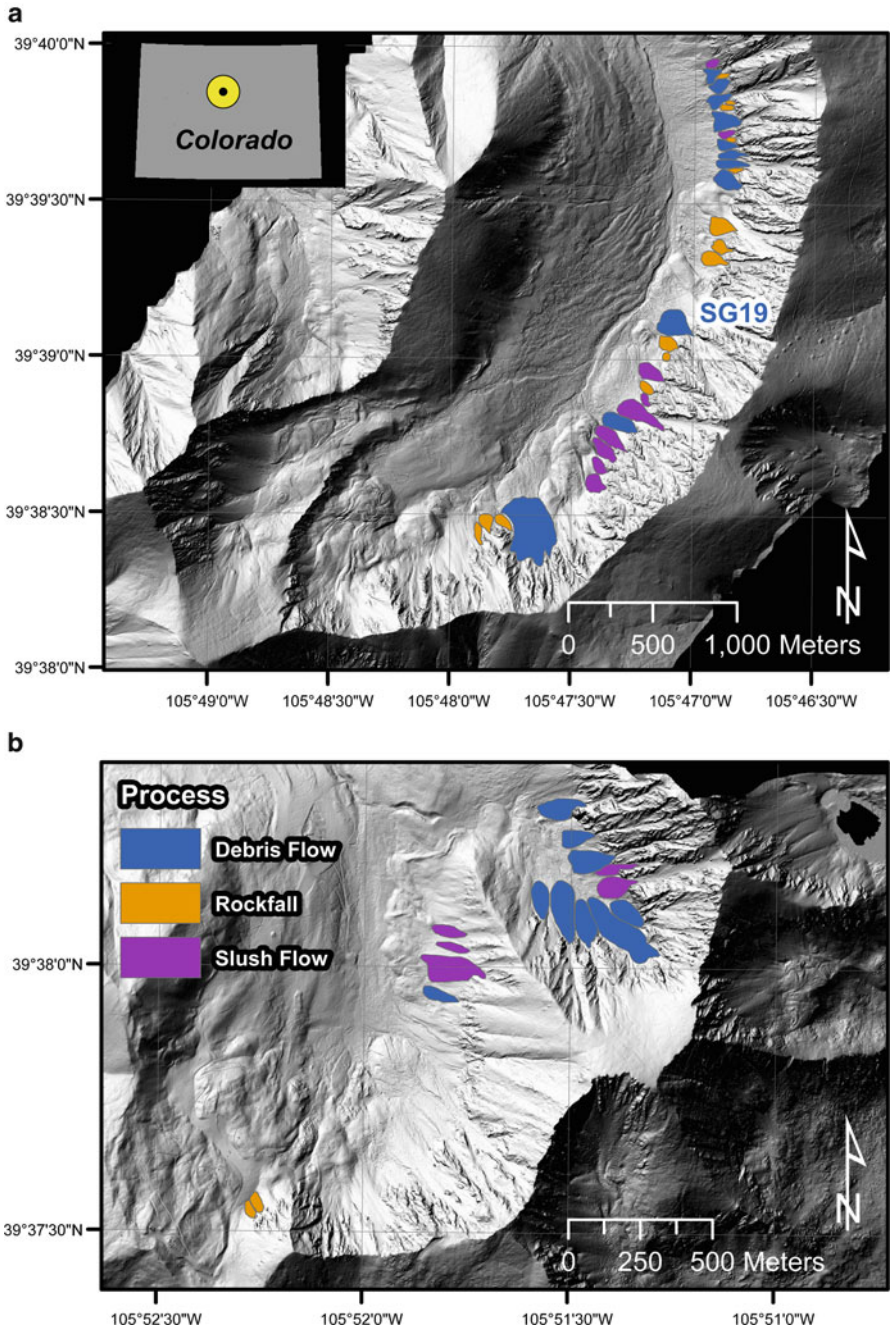

Fig. 1 (**a**) Arapaho Basin and (**b**) Stevens Gulch study locations

from ice breakups in small streams (Nyberg 1989; Bull et al. 1995; Decaulne and Saemundsson 2006). Most slushflows in the study areas resemble the former and runout only a short distance on the talus surface. Other processes, such as snow avalanches (Gardner 1970; Luckman 1977; White 1981; Jomelli and Francou 2000; Jomelli and Bertran 2001), solifluction (van Steijn et al. 1995), and frost coated clast flows (van Steijn et al. 1995, 2002) have been described in the literature, but the resultant forms associated with these processes are not evident on the fan surfaces included in this analysis.

3 Methods

3.1 ALSM Acquisition

ALSM data were generated by the NSF supported National Center for Airborne Laser Mapping (NCALM) at the University of Florida's Department of Civil & Coastal Engineering. The ALSM data collection occurred on 29 September 2005, using the following parameters: a scan angle of 20° (1/2 FOV); a scan frequency of 28 Hz; and a pulse rate of 33,333 Hz. NCALM conducted all of the post-processing of the raw ALSM data point cloud. Data were received as ASCII files that contain X, Y, and Z triplets processed from laser shots. Laser shots were obtained by using a kriging algorithm on separate flight strips that overlapped at greater than 30%. Grid nodes were combined with a weighted scheme based on strip geometry to produce a best estimate of elevation on a 1-m grid. The 1-m grid nodes contained in the ASCII file format were converted into 1-m raster grids with the aid of ArcGIS 9.1. The 1-m raster grids were imported into ArcInfo Workstation for calculation of morphometric parameters and spatial analysis. ALSM data were analyzed for the 49 alpine debris fan systems described in Sect. 2.

3.2 Derivation of Surface Morphometry

Geomorphic maps of the debris fans (Fig. 2) were derived from shaded relief and curvature maps (following the methods of Staley et al. 2006) using ALSM data. Here, planimetric and profile curvature were classified as concave, rectilinear and convex (Blaszczynski 1997; Staley et al. 2006) to create surface polygons. Each polygon was then assigned a process type based upon field observations. For each fan, the proportion of area occupied by each process type was calculated, and the process type that occupied the greatest proportion of surface area was defined as the dominant process (Fig. 3). The spatial extent of each source area was determined using the Watershed and Stream Delineation Tool developed by the Department of Civil Engineering at Texas A&M University (Olivera and Valenzuela 2006).

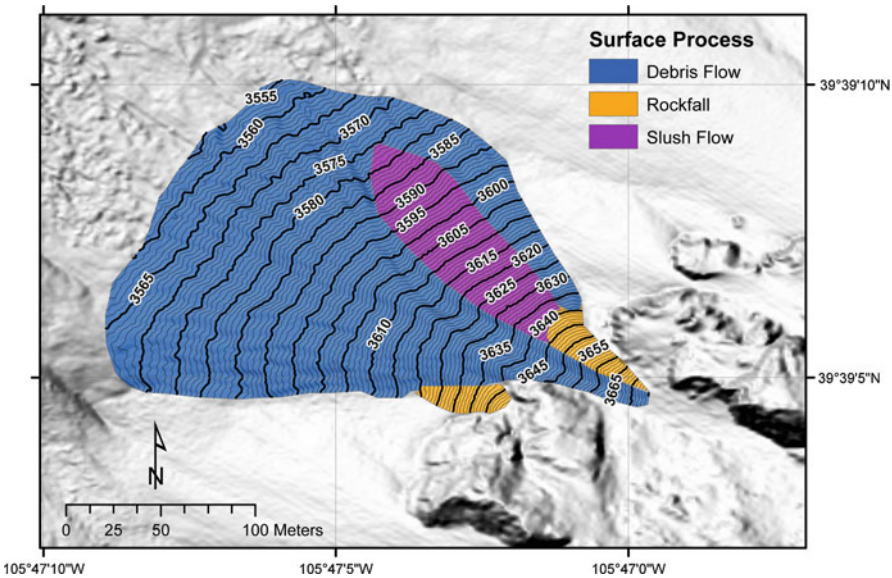

Fig. 2 Geomorphic map of the processes influencing debris fan SG19

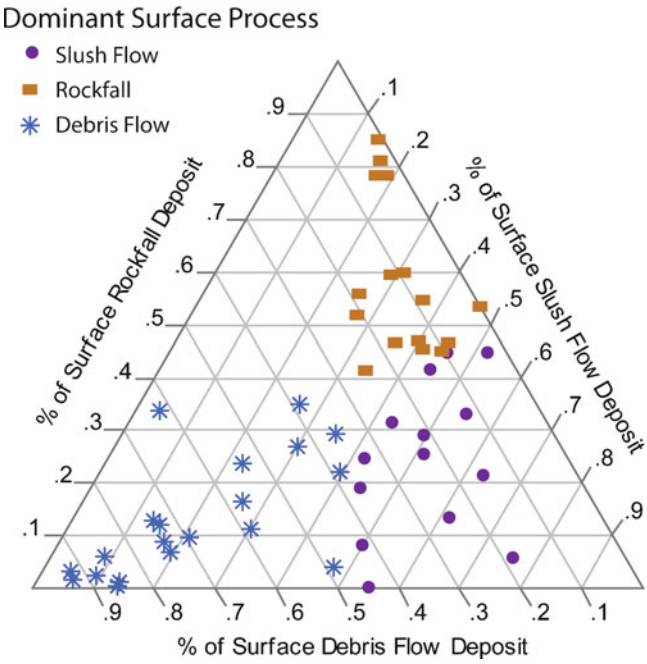

Fig. 3 Ternary diagram identifying the dominant process type and percentage of debris flow, rockfall and slush flow features on the surface of the 49 analyzed debris fans

Surface morphometry was analyzed using 2 dimensional (2D) and 2.5 dimensional (2.5D) measures. 2D measures included fan area, basin area, and the total relief of the basin. Areal calculations were determined from the geomorphic maps of the fans and source areas. Total relief was calculated from ALSM data and geomorphic maps by subtracting the elevation of the fan apex from the maximum elevation within the source area. The 2.5D measures included gradient and surface roughness. These measures were measured at length scales of 1- and 9-m using a moving window approach. These length scales were selected as they represent both the fine-scale features (1-m) and coarser-scale form (9-m) of the fan surface. The moving window calculates, on a cell-by-cell basis, the value of each parameter based upon the value of the surrounding cells. The length scale of measurement is defined by the radius of a circle centred on the cell. Gradient is defined as the change in elevation over a specified distance (represented in degrees). The roughness of the surface was quantified using the standard deviation of relative relief values at the length scales identified above. Relative relief was calculated using the methods outlined by Volker et al. (2007). Rough surfaces exhibit a higher standard deviation than smooth surfaces.

Detailed measurements of the identified terrain parameters were made for each 1-m pixel in all 49 debris fans and source areas. Areal calculations, total relief and mean values for gradient and roughness were derived for both fan surface and source areas. ANOVA, Student's t-test and linear regression analyses to statistically evaluate the morphometric differences between debris fans and source areas dominated by debris-flow processes and those dominated by rockfall and slush flow activity. Data were evaluated for normality using a Shapiro-Wilk W test and for homoscedasticity using both Leveen's and Bartlett's tests of equal variances. A simple log transformation allowed use of these tests when the original data were not able to meet the assumptions of normality and homoscedasticity, (e.g. basin and fan areas). P-values smaller than 0.05 were considered sufficient to reject the null hypotheses of the various statistical tests.

4 Results

4.1 Morphometry of Alpine Debris Fans

Geomorphic mapping of surficial features from hillshade and field validation identified 20 debris fans dominated by debris-flow processes, 16 fans dominated by rockfall processes, and 14 fans dominated by slush flow processes (Fig. 3). Assessment of the relationships between area, gradient and roughness and the dominant process exhibited on the fan surface identified some significant relationships and statistical predictability.

ANOVA results indicated significant differences in the areal extent of fans of the different process types (Table 1). The areal extent of debris-flow fans was

Table 1 Summary of mean parameter values for each fan type and ANOVA results

	Dominant fan process			ANOVA results	
Morphometric parameter	Debris flow	Rockfall	Slushflow	F-ratio	P
N	20	16	14		
Log(Fan area) (m^2)	9.2	8.2	8.8	9.62	0.0003
Fan gradient 1-m (°)	29.1	34.3	32.4	28.20	<0.0001
Fan gradient 9-m (°)	28.3	34.1	32.2	30.30	<0.0001
Fan roughness 1-m (°)	0.1	0.1	0.1	3.07	0.06
Fan roughness 9-m (°)	0.5	0.4	0.4	3.97	0.02
Log(Basin area) (m^2)	10.6	9.0	9.8	13.22	<0.0001
Basin relief (m)	342.6	190.3	278.0	13.87	<0.0001
Basin gradient 9-m (°)	40.8	44.4	43.4	3.92	0.02

significantly greater than both rockfall and slush flow dominated fans. A weak, though statistically significant positive correlation between fan area and the percent of the fan surface influenced by debris flow was identified (Fig. 4a).

Gradient differed significantly between process types at 1- and 9-m length-scales. ANOVA results yielded significant differences in gradient between debris flow, rockfall and slush flow dominated fans (Table 1). Debris-flow fans were consistently lower gradient than both rockfall and slush flow dominated fans, while rockfall dominated fans were steepest at both length-scales. At the 1-m length-scale, a strong negative relationship was identified between fan gradient and percent of surface influenced by debris-flow processes (Fig. 4b). A strong negative relationship was also identified between fan gradient and percent of surface influenced by debris-flow processes at the 9-m length-scale (Fig. 4c).

Surface roughness was also analyzed at both 1- and 9-m length-scales. ANOVA revealed significant differences between debris-flow and non-debris-flow processes only at the 9-m length scale (Table 1). At this length-scale, debris-flow dominated fans tended to exhibit greater surface roughness than either rockfall or slush flow, though rockfall and slush flow fans did not differ significantly from one another. Weak positive relationships were identified between proportion of surface area influenced by debris flow and roughness at both length-scales (Fig. 4e, f).

4.2 Morphometry of Source Areas

Analysis of source areas indicated that differences in total basin relief and basin area produced significant differences in the types of processes that were evident on fan surfaces, and therefore, fan morphometry. Debris-flow producing source areas were significantly larger than those that produced a dominance of slush flow or rockfall processes (Table 1). ANOVA revealed significant differences in basin area between all dominant process types, with debris-flow dominated sources the largest and

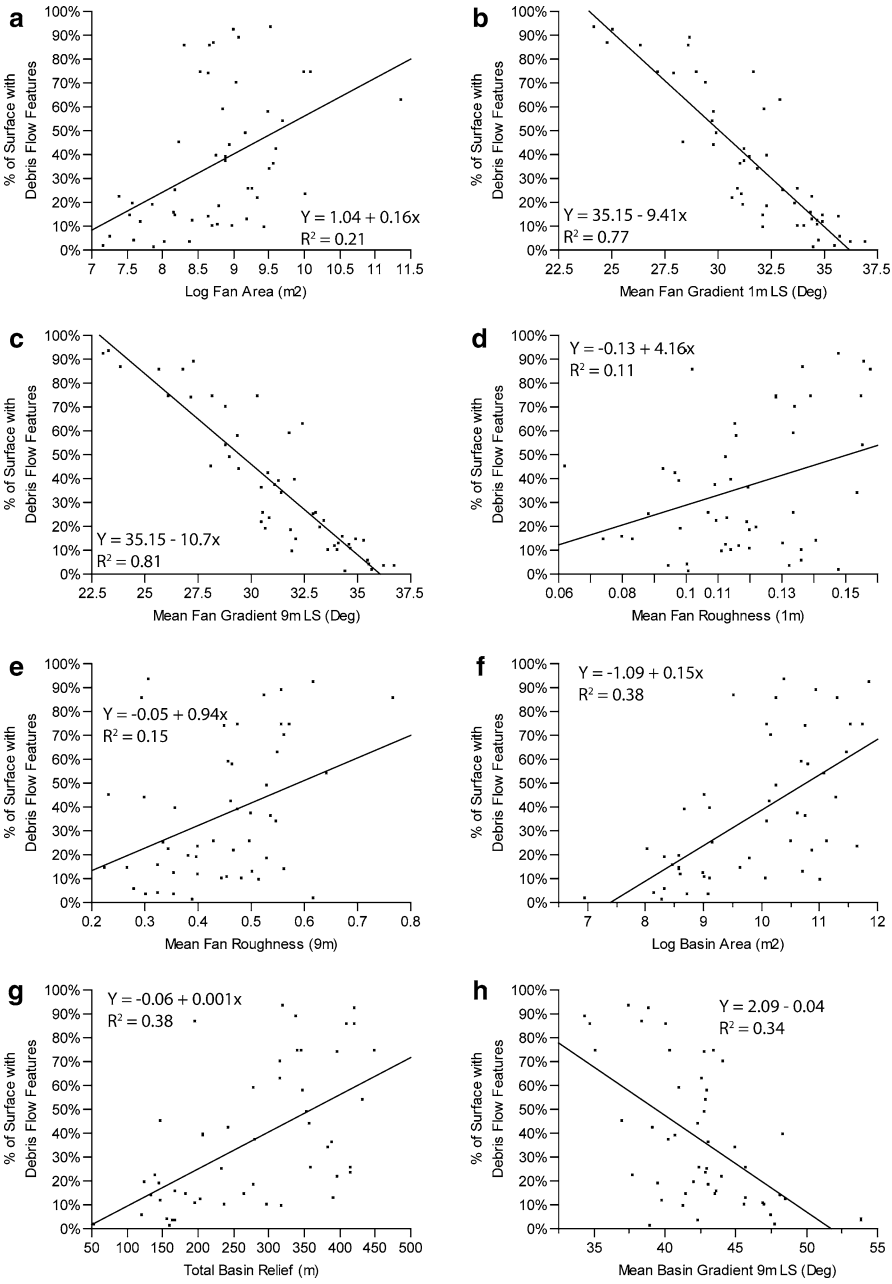

Fig. 4 Simple linear regression results assessing the relationship between morphometric parameter and fan area influenced by debris flow

rockfall dominated sources areas located in the smallest basins. A linear regression model suggested a weak positive relationship between basin area and percentage of fan surface influenced by debris flow (Fig. 4f).

Debris-flow dominated fans were characterized by source areas with significantly greater total relief than those of slush flow and rockfall dominated fans (Table 1). In addition, slush flow dominated fan source areas tended to have significantly more total relief than rockfall dominated fans. Linear regression suggested a weak positive correlation between total source area relief and the percentage of the fan surface influenced by debris flow (Fig. 4g).

No significant relationship between source area gradient and dominant process types were detected at the 1-m length-scale. At the 9-m length-scale, debris-flow dominated fans exhibited source areas with significantly lower gradients than those of rockfall dominated fans, and did not differ significantly from slush flow dominated fans (Table 1). No significant differences were identified for source area gradients at the 9-m length-scale between slush flow dominated fans and rockfall dominated fans. Linear regression suggested a very weak negative correlation between source area gradient (9-m length-scale) and the percentage of the fan surface influenced by debris flow (Fig. 4h).

4.3 Relationships Between Source Area and Fan Morphometry

Simple linear regressions were used to detect significant relations between source area morphometry (area, relief and gradient) and fan morphometry (area, gradient and roughness). Here, we report only those models that are statistically strong ($r^2 > 0.35$). As such, we only report on the relationships associated with the source area morphometric parameters of total relief, the log of basin area, and mean gradient at the 9-m length-scales. No models were able to provide a reasonable correlation between any of the source area parameters and fan roughness at either length-scale.

The log-transformed basin area was correlated with the log-transformed fan area measurement (Fig. 5a). Here, a strong positive relationship was identified between measures. A weaker, inverse relationships was identified between basin area and fan gradient (9-m length-scale).

Correlations were also identified between total basin relief and both fan area and fan gradient at the 9-m length-scale (Fig. 5). A relatively strong positive relationship existed between total source area relief and fan area, while a weaker ($r^2 = 0.37$), though still statistically significant relationship was identified between total source area relief and fan gradient. Additionally, a weak positive relationship ($r^2 = 0.39$) was identified between source area gradient and fan gradient (both measured at the 9-m length-scale).

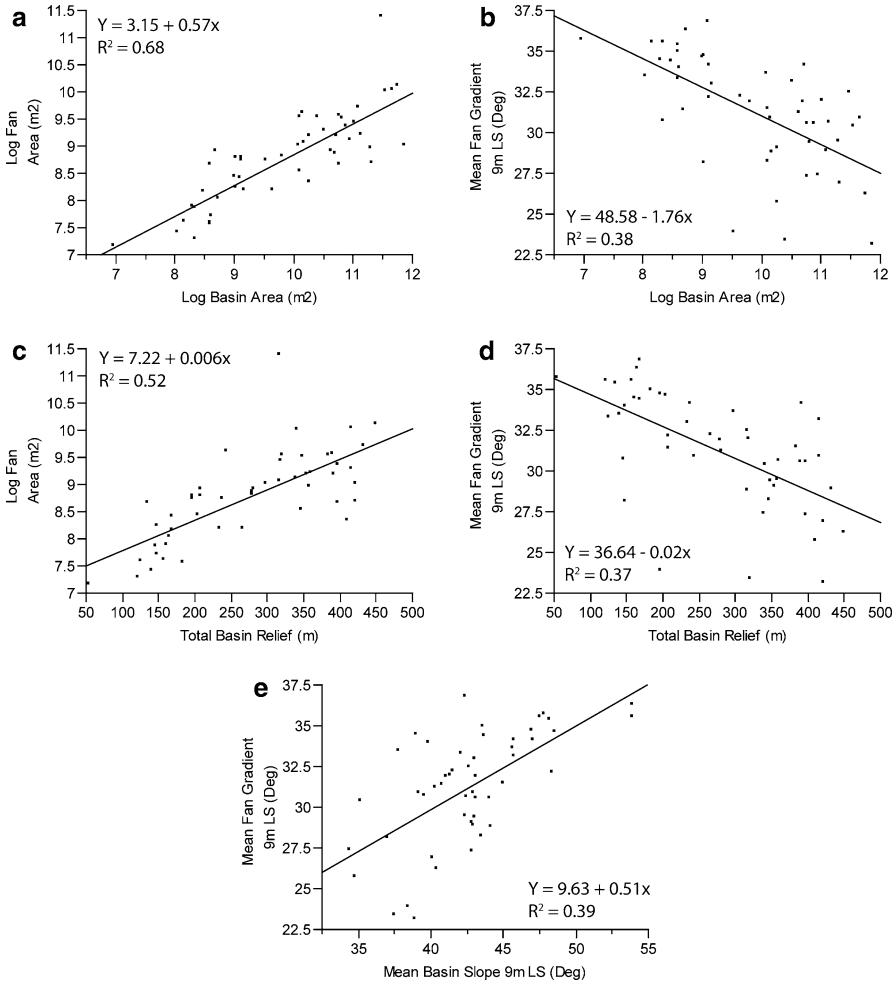

Fig. 5 Simple linear regression analyses of basin and fan morphometry

5 Discussion

This study quantified the relations between geomorphic process types and the surface form of both alpine debris fans and their source areas. Distinct differences in both fan and source area morphometry have been identified for those systems dominated by debris-flow, rockfall, or slush flow processes.

Debris-flow fans tended to be larger, have shallower gradients, and are characterized by higher surface roughness values (particularly at longer length-scales) when compared to rockfall or slush flow dominated fans. Debris-flow source areas also tended to have the greatest areas, largest total relief, and lowest gradient

of the three types of processes analyzed in this study. The larger source areas associated with debris-flow dominated fan systems were able to collect more water during precipitation events, but are also able to collect more snow blown by prevailing winds. Greater moisture availability increased the likelihood of debris-flow initiation processes in the source area or on the fan surface. Once flow was initiated, the rheology of debris flows allowed them to runout over significantly longer distances and shallower gradients than the slush flow processes operating in the study areas. As such, debris-flow systems were characterized by larger fans with lower mean gradients than other dominant process-types. Higher surface roughness values reflect the greater topographic complexity associated with debris-flow deposits relative to rockfall or slush flow deposits. Channel erosion and deposition of levees and terminal lobes produced features with higher roughness values at all analyzed length-scales.

Slush flow dominated fans tended to reside between debris-flow and rockfall dominated fans in regards to area and gradient, but be indistinguishable from rockfall fans in regards to surface roughness. Source areas for slush flow dominated systems were larger and more dissected than rockfall systems, but smaller and less dissected than debris-flow systems. Collection of snow, rain and debris were important in producing slush flow processes. Relative to debris-flow dominated systems, the slush flow systems were unable to consistently produce the runoff required to trigger debris-flow activity. Instead, snowmelt increased the pore-pressures in late-spring patches of snow. Slush flows were initiated when the pore-pressures exceeded the critical shear strength of the snowpack. These flows were not able to maintain mobility for as long a distance, or produce features with as high of a degree of topographic complexity as debris flows.

Rockfall dominated fans and their source areas tend to be the smallest and steepest of all three process types. Material shed from smaller, steeper basins has a greater likelihood of being deposited at the base of the source area, where rockfall in larger basins is often deposited on ledges or steeper channels, where the deposits are more likely to be mobilized by subsequent debris flows or slush flows. The smaller fan areas reflect the tendency for smaller, more frequent rockfall mobilized clasts to be deposited close to the fan apex. While long distance runout is possible and has been widely recognized, the relatively low frequency of this phenomenon is reflected in the relatively small size of rockfall dominated debris fans.

The general relationships identified between source area morphometry and fan surface morphometry reflect the influence of surface form on the generation of different types of geomorphic processes. Basin area, relief, and gradient represent important boundary conditions which are critical in the determining of the type, extent, and frequency of the different processes responsible for the development and evolution of alpine debris fans. These findings reflect the importance of studying both how surface form reflects the process types responsible for the development of the fans, but also how surface form influences subsequent geomorphic processes.

The rapidly increasing human population will result in significant influences on previously undeveloped mountainous regions worldwide. Settlement, as well

as transportation networks and utility corridors will all be exposed to the hazards of mountainous terrain, including debris flow, rockfall, and other mass-movement processes. In the future, airborne laser swath mapping data will become less-costly and more readily available throughout the world. These data provide an important source of topographic information for the analysis of potential debris-flow and other mass-movement related hazards. The methods documented in this case study present a means of rapidly and effectively assessing the potential hazards associated with the geomorphic processes that create and sculpt alpine debris fans. The relations defined here are specific to alpine fans in two valleys within the Colorado Front Range. While the exact relations identified in this study may not be directly transferable to other environments, the documented methods of analysis should be applicable to fans in both humid and arid environments.

6 Conclusions

The relations between geomorphic process types and surface form are significant not only to the study of alpine slope processes (with particular emphasis on talus systems), but are also applicable to the discipline of geomorphology as a whole. In this study, we have quantified the relationship between process type and form on alpine debris fan systems at high-spatial resolutions and over large spatial extents. We have found that there are statistically significant differences in the size, gradient and roughness of fan surfaces and contributing areas between systems dominated by different geomorphic processes. New insight has been gained into how geomorphic processes are reflected in, and are in turn influenced by, the surface form of various components of the alpine debris fan system.

High resolution airborne data (ALSM) have provided highly accurate terrain characterization over large spatial extents. These data were used to derive measurements of surface form, develop the statistical models and test differences between process types. The analysis has proved that it is possible to statistically differentiate the processes influence alluvial fan surfaces. These quantitative relationships provide a means to rapidly assess the extent and types of hazards associated with alpine fan systems, and plan for the reduction or mitigation of the effects of these hazards.

While we have used ALSM data in the case study in the Colorado Front Range, other airborne data sources, such as low altitude aerial photography and high-resolution InSAR data also would provide the level of detail necessary to conduct surface analyses of process types on alluvial fan systems. In addition, a multi-temporal dataset would provide insight into how these surfaces and relationships between process type and surface form evolve over time.

Acknowledgements This material is based upon work supported by the National Science Foundation under Grant No. 05–02343 (Doctoral Dissertation Research: Process – form linkages in alpine talus deposits, Front Range, Colorado, USA) and Grant No. 02–39749 (CAREER: Alluvial fan form quantification to advance geographic science and education). Any opinions,

finding, or conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors gratefully acknowledge Jeff Coe and Jason Kean for reviews that have dramatically improved this manuscript. We also would like to acknowledge Chris Smith for assistance in the field.

References

Akerman HJ (1994) Notes on talus morphology and processes in Spitsbergen. Geogr Ann Ser A Phys Geogr 66:267–285

Albjar G, Rehn J, Stromquist L (1979) Notes on talus formation in different climates. Geogr Ann Ser A Phys Geogr 61(3–4):179–185

Ballantyne CK (2002) Paraglacial geomorphology. Quat Sci Rev 21:1935–2017

Blaszczynski JS (1997) Landform characterization with geographic information systems. Photogramm Eng Remote Sens 63(2):183–191

Blikra LH, Nemec W (1998) Postglacial colluvium in western Norway: depositional processes, facies and paleoclimatic record. Sedimentology 45:909–959

Bones JG (1973) Processes and sediment size arrangement on high arctic talus, southwest Devon Island, NWT, Canada. Arct Alp Res 5(1):29–40

Bull WB, Schlyter P, Brogaard S (1995) Lichenometric analysis of the Karkerieppe slush-avalanche fan, Karkevagge, Sweden. Geogr Ann Ser A Phys Geogr 77(4):231–240

Caine N (1967) The texture of talus in Tasmania. J Sediment Petrol 37(3):796–803

Caine N (1969) A model for alpine talus slope development by slush avalanching. J Geol 77(1): 92–100

Caine N (1983) The mountains of northeastern Tasmania. AA Balkema, Rotterdam, 201 pp

Carson MA (1977) Angle of repose, angles of shearing resistance and angles of talus slopes. Earth Surf Process Landf 2(4):363–380

Carter W, Shrestha R, Tuell G, Bloomquist D, Sartori M (2001) Airborne laser mapping shines new light on Earth's topography. EOS Trans Am Geophys Union 82(46):549, 550, 555

Catani F, Farina P, Moretti S (2003) Spaceborne radar interferometry: a promising tool for hydrological analysis in mountain alluvial fan environments. In: Erosion prediction in ungaged basins: integrating methods and technique, IAHS publication No. 279. IAHS, Wallingford, pp 241–248

Catani F, Farina P, Moretti S, Nico G, Strozzi T (2005) On the application of SAR interferometry to geomorphological studies: estimation of landform attributes and mass movements. Geomorphology 66:119–131

Cavalli M, Marchi L (2008) Characterisation of the surface morphology of an alpine alluvial fan using airborne LiDAR. Nat Hazard Earth Syst Sci 8:323–333

Church M, Stock RF, Ryder M (1979) Contemporary sedimentary environments on Baffin Island, NWT Canada: debris slope accumulations. Arct Alp Res 11(4):371–402

Coe JA, Glancy PA, Whitney JW (1997) Volumetric analysis and hydrologic characterization of a modern debris flow near Yucca Mountain, Nevada. Geomorphology 20:11–28

Crosta GB, Frattini P (2004) Controls on modern alluvial fan processes in the central Alps, northern Italy. Earth Surf Process Landf 29:267–293

Curry AM, Morris CJ (2004) Lateglacial and Holocene talus slope development and rockwall retreat on Mynydd Du, UK. Geomorphology 58:85–106

Decaulne A, Saemundsson P (2006) Meteorological conditions during slushflow release and their geomorphic impact in the northwestern Icelandic Westfjords. Geomorphology 80(1–2):80–93

Dorren LKA (2003) A review of rockfall mechanics and modeling approaches. Prog Phys Geogr 27(1):69–87

Farr TG, Chadwick OA (1996) Geomorphic processes and remote sensing signatures of alluvial fans in the Kun Lun Mountains, China. J Geophys Res 101(E10):23091–23100

Francou B, Mante C (1990) Analysis of the segmentation in the profile of alpine talus slopes. Permafr Periglac Process 1(1):53–60

Frankel KL, Dolan JF (2007) Characterizing arid region alluvial fan surface roughness with airborne laser swath mapping digital topgraphic data. J Geophys Res 112:F02025

Gardner J (1970) Geomorphic significance of avalanches in the Lake Louise area, Alberta, Canada. Arct Alp Res 2(2):135–144

Gens R, van Genderen JL (1996) Review article SAR interferometry – issues, techniques, applications. Int J Remote Sens 17(10):1803–1835

Godt JW, Coe JA (2007) Alpine debris flows triggered by a 28 July 1999 thunderstorm in the central Front Range, Colorado. Geomorphology 84:80–97

Jomelli V, Bertran P (2001) Wet snow avalanche deposits in the French Alps: structure and sedimentology. Geogr Ann Ser A Phys Geogr 83(1–2):15–28

Jomelli V, Francou B (2000) Comparing the characteristics of rockfall talus and snow avalanche landforms in an alpine environment using a new methodological approach, Massif de Ecrins, French Alps. Geomorphology 35(3–4):181–192

Kellogg KS, Shroba RR, Bryant B, Premo WR (2008) Geologic map of the Denver West 30′ × 60′ Quadrangle, North-Central Colorado: U.S. Geological Survey Scientific Investigations Map 3000, scale 1:100,000, 48 pp

Kirkby MJ, Statham I (1975) Surface stone movement and scree formation. J Geol 83(3):349–362

Lane SN, Richards KS, Chandler JH (1993) Developments in photogrammetry: the geomorphic potential. Prog Phys Geogr 17(3):306–328

Lane SN, James TD, Crowell MD (2000) Application of digital photogrammetry for complex topography for geomorphological research. Photogramm Rec 16(95):793–821

Luckman BH (1977) The geomorphic activity of snow avalanches. Geogr Ann Ser A Phys Geogr 59(1–2):31–48

Massonnet D, Feigl K (1998) Radar interferometry and its application to changes in the Earth's surface. Rev Geophys 36(4):441–500

Matsuoka N, Sakai H (1999) Rockfall activity from an alpine cliff during thawing periods. Geomorphology 28:309–328

Nyberg R (1989) Observations of slush flows and their geomorphological effects in the Swedish mountain area. Geogr Ann Ser A Phys Geogr 71(3–4):185–198

Okada Y, Hirao C, Horiuchi T, Hara Y, Yedidia JS, Azarbayejani A, Oishi N (2007) Highly Accurate DSM Reconstruction Using Ku-band Airborne InSAR. IEEE Int Geosci Remote Sens Soc Symp (IGARSS):5049–5052. http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=4423996

Olivera F, Valenzuela M (2006) Watershed and stream delineation tool 2002. Available from http://ceprofs.tamu.edu/folivera/GISTools/wsdt/home.htm. Cited 15 Mar 2006

Perez F (1989) Talus fabric and particle morphology on Lassen Peak, California. Geogr Ann Ser A Phys Geogr 71(1–2):43–57

Perez F (1993) Talus movement in the high Equatorial Andes: a synthesis of ten years of data. Permafr Periglac Process 4:199–215

Perez F (1998) Talus fabric, clast morphology, and botanical indicators of slope processes on the Chaos Crags (California Cascades), USA. Geogr Phys Quat 52(1):47–68

Rapp A (1960a) Recent development of mountain slopes in Karkevagge and surroundings, northern Scandinavia. Geogr Ann Ser A Phys Geogr 42(2–3):65–200

Rapp A (1960b) Talus slopes and mountain walls at Tempelfjorden, Spitsbergen, Norsk Polarinstitutt Skrifter 119. Oslo University Press, Oslo, 96 pp

Roering JJ, Stimley LL, Mackey BH, Schmidt DA (2009) Using DInSAR, airborne LiDAR, and archival air photos to quantify landsliding and sediment transport. Geophys Res Lett 36:L19402

Rosen PA, Hensley S, Joughin IR, Li FK, Madsen SN, Rodriguez E, Goldstein RM (2000) Synthetic aperture radar interferometry. Proc IEEE 88:333–382

Schumm SA (1991) To interpret the Earth, ten ways to be wrong. Cambridge University Press, New York, 133 pp

Schumm SA, Lichty RW (1965) Time, space and causality in geomorphology. Am J Sci 263: 110–119

Shan J, Toth KC (2009) Topographic laser ranging and scanning – principles and processing. CRC Press, Boca Raton, 590 pp

Shrestha RL, Carter WE, Lee M, Finer P, Sartori M (1999) Airborne laser swath mapping: accuracy assessment for surveying and mapping applications. J Am Congr Surv Mapp 59(2):83–94

Slatton KC, Carter WE, Shrestha RL, Dietrich W (2007) Airborne laser swath mapping: achieving the resolution and accuracy required for geosurficial research. Geophys Res Lett 35:L23S10

Staley DM (2006) Process and form on Alpine Talus Cone Systems, Front Range, Colorado, USA. Unpublished PhD dissertation, University of Memphis, Memphis, 214 pp

Staley DM, Wasklewicz TA, Blaszczynski JS (2006) Surficial patterns of debris flow deposition on alluvial fans in Death Valley, CA using airborne laser swath mapping data. Geomorphology 74:152–163

Statham I (1976) A scree slope rockfall model. Earth Surf Process 1:43–62

Trevisani S, Cavalli M, Marchi L (2009) Variogram maps from LiDAR data as fingerprints of surface morphology on scree slopes. Nat Hazard Earth Syst Sci 9:129–133

van Steijn H (2002) Long-term landform evolution; evidence from talus studies. Earth Surf Process Landf 27(11):1189–1199

van Steijn H, Bertran P, Francou B, Hetu B, Texier J-P (1995) Models for the genetic and environmental interpretation of stratified slope deposits: review. Permafr Periglac Process 6:125–146

van Steijn H, Boelhouwers J, Harris S, Hetu B (2002) Recent research on the nature, origin and climatic relations of blocky and stratified slope deposits. Prog Phys Geogr 26(4):551–575

Varnes DJ (1978) Slope movement and types and processes. In: Schuster RL, Krizek RJ (eds) Landslides: analysis and control, National Research Council, Transportation Research Board, special report 247. National Academy of Sciences, Washington, DC, pp 76–90

Volker HX, Wasklewicz TA, Ellis MA (2007) A topographic fingerprint to distinguish Holocene alluvial fan formative processes. Geomorphology 88:34–45

Vosselman G, Maas HG (2010) Airborne and terrestrial laser scanning. Whittles Publishing, Dunbeath, 336 pp

Wasklewicz TA, Mihir MA, Whitworth J (2008) Surface variability of alluvial fans generated by disparate processes, eastern Death Valley, CA. Prof Geogr 60(2):207–223

Whalley WB (1984) Rockfalls. In: Brundsen D, Prior DB (eds) Slope instability. Wiley, New York, pp 217–255

White SE (1981) Alpine mass movement forms (non-catastrophic): classification, description and significance. Arct Alp Res 13(2):127–137

Williams FJ (1951) The geology of the Stevens Mine. Unpublished Masters thesis, Department of Geology, Colorado School of Mines, Golden, CO, USA