DEBRIS FLOW FAN EVOLUTION, CHALK CREEK NATURAL DEBRIS FLOW LABORATORY, COLORADO

By

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Abstract

Terrestrial laser scanning (TLS) is a surveying technique used to gather dense point cloud data that can be converted to high-resolution digital elevation models (DEM). TLS techniques are employed in the current study to monitor changes to a debris flow fan following five separate debris flows over twenty-five months (May 2009 to July 2011). This thesis represents a combination of two peer-reviewed journal articles. The first focuses on a new critical review of the six predominant themes dominating the last 40 years of alluvial fan dynamism studies. The themes include the development of conceptual models, field experiments, physical models, numerical models, high-resolution morphometric analyses, and climate change scenarios. Each theme is presented independently, but as highlighted in the concluding statements, there should be greater efforts placed on integrating scientists from these disparate approaches to provide greater understanding of alluvial fan evolution. A case study is also presented in support of the review and contains pilot results from the first debris flow recorded for this study at the Colorado Natural Debris Flow Laboratory near Buena Vista, CO, USA.

The second chapter examines the spatial and temporal changes of 5 different debris flows and two surfaces that represent conditions prior to each debris flow season. What makes this study unique is the monitoring of debris flow fan evolution on an event-to-event basis. Repeat high-resolution DEM data are exploited to assess the 2D and 3D changes on the alluvial fan surface. The findings show significant deposition from all of the debris flows, with the adjacent trunk stream (Chalk Creek) at the fan toe being dammed by each flow. Debris flow erosion was constricted to the main channel, often near the alluvial fan apex. The alluvial fan toe experienced significant erosion during flooding and channel migration of Chalk Creek. Surface roughness was variable over the short period of this investigation. Surface roughness decreased until the last two debris flows, where surface roughness increased substantially. Evidence for a "high-low effect" was also identified over the monitoring period. Repeat TLS surveying provides important insights into the morphometric and sediment transport related to debris flow fan evolution.

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CHAPTER 1: ALLUVIAL FAN DYNAMICS – REVISITING THE FIELD

Field studies continue to be deeply ingrained in geographic research and education (Driver, 2000; Powell, 2002). Geomorphology, a subfield of geography and geology, is rooted in field experiences that pervade every area of study in geomorphology. Graf (1984) traces the origins of geomorphological field research in the United States (Gilbert, 1877; Davis, 1909; Dutton, 1882) back to the field excursions of the early federal surveying expeditions. These early expeditions attempted to detail the varied western landscapes in the United States with an eye toward assessing resource availability. The maps, diagrams, photography, and measurements acquired from these early surveys paved the way for observations and measurements made by pioneering geomorphologists like G.K. Gilbert and W.M. Davis. Davis' work was predominant for the first half of the 20th century until his landscape evolution models were later refuted, which led to the "championing" of Gilbert's more systematic fieldwork and multiple hypothesis testing approach (Sack, 1991, 1992). While neither Davis nor Gilbert developed a long-lasting theory about landscape evolution, much of our current understanding landscape development has some link to the refuting of their work or the expansion of their understanding of landscape dynamics.

Subsequent to the work of Davis and Gilbert, field observations and measurements of processes and landforms have gone through a long, arduous progression as new methods and technologies have become available to geomorphologists. Recent technological advances provide opportunities to conduct shorter-term studies of landform evolution via monitoring a site or multiple sites in the field (Berger et al., 2010; Zinger et al., 2011; Wasklewicz et al., 2012). The integration of multiple technologies has also produced new insights into (McCoy et al., 2011) and models of (Schürch et al., 2011) landform and landscape evolution. This is not to suggest that advances in technology are the only means to advance knowledge, rather by independently using or integrating new technologies there are opportunities to enhance our current understanding of the environment and provide further means to corroborate past findings, validate newly developed and past models, and provide further information to support dating techniques.

Fieldwork has also been supported with other approaches that include: physical (laboratory) modeling; numerical modeling; remotely-sensed morphometric studies; and relative-age and numerical dating techniques. Conceptual models have also developed from fieldwork and advances in technology (Blair and McPherson 2009; Schürch et al., 2011). The benefits of the aforementioned approaches are obvious to most geomorphologists as they provide further information to advance our understanding of landform and landscape evolution. They have also provided valuable information where field processes are not currently active, occur too infrequently to measure, or occur in potentially life threatening locations that make them difficult to capture. However, there remain many scenarios where these approaches need to be corroborated by or developed in conjunction with field data. An absence of field data limits the validity of the results from studies not working with data from real-world processes and forms.

Here we use a review of alluvial fan dynamics (shorter and longer-term alluvial fan evolution) and a case study to explore how new field technologies can advance our understanding of landform evolution. Alluvial fan studies have closely followed the broader research trends in geomorphology (Lecce, 1990; Blair and McPherson, 2009). As such, this article not only highlights the relevance of this approach to scientists and the public concerned with alluvial fans, but also to other areas of geomorphological research. We examine the current understanding of alluvial fan dynamics along six predominant research themes pervading the alluvial fan literature, which has not been done in prior reviews of the alluvial fan literature. The current themes include: conceptual models of alluvial fan development; field experiments; physical models; numerical models; high-resolution morphometric analyses; and climate change scenarios. These themes are examined independently at the onset of the article, but are integrated in our discussion of the case study.

Alluvial Fans

Alluvial fans are common features located at the edge of valleys (commonly river valleys or fault-controlled valleys) adjacent to steep drainage basins. Alluvial fan morphometry is the direct result of sediment transport from the adjacent drainage basin to the valley. Debris flows, fluvial flows, or a combination of both are the dominant formative processes often associated with alluvial fan dynamics. Fluvial flows consist of sheetfloods or channelized flows. Sheetfloods are sediment-laden flash floods exiting a confined feeder stream onto the unconfined fan surface. The sheetflood expands outward as it moves down-fan because the flow is no longer confined in the constricted feeder channel. The most common deposits associated with sheetflooding are vertically alternating planar-bedded couplets, which range from 10 to 30 cm in thickness (Blair and McPherson, 2009). The deposits can contain boulders, but predominately consist of pebble and cobble gravel regularly interstratified with laminated, pebbly granule gravel and granular coarse sand. Sheetflow deposits are not well preserved because sheetfloods are rare events and secondary processes rework these deposits rapidly. Channelized flows are constrained to the pre-existing channels near the fan apex and often incise rectilinear channels within the upper part of the alluvial fan (Wasklewicz et al., 2008). Channelized flows may give way to sheetflooding or a more distributary flow pattern in the middle and lower portions of the alluvial fan. The bed of the channelized flow may contain a coarse lag and the principal facies include a thick bed of cobble deposits that can grade to coarse sands (Blair and McPherson, 2009).

Debris flows are a common source of material associated with long-term alluvial fan development. Debris flows consist mainly of sand, gravel, and boulders with silt and clay contributing less than ten percent of flow accumulation (Iverson, 1997). Debris flow initiation can result from a variety of processes that include conversion of a shallow landslide (Takahashi, 1981, Costa, 1984, Iverson et al., 1997), impulsive loading from hillslopes (Bovis and Dagg, 1992), entrainment via fire-hosing at the interface between bedrock and colluvium in the source areas (Johnson and Rodine, 1984, Coe et al, 2008), entrainment of dry ravel as overland flow enters gullies or continues through channels (Gabet and Bookter, 2008), and progressive bulking of stored materials within the drainage network (Cannon et al., 2003). One or more of these initiation mechanisms can be associated with debris flows that deliver materials to alluvial fan surfaces.

Field observations and video recordings indicate debris flows surge or exhibit a wavelike pattern (e.g., Beaty 1963; Okuda et al. 1980; Suwa and Okuda, 1981; Ohmori and Shimazu 1994; Hungr, 2000; Hürlimann et al., 2003; Imaizumi et al., 2005; McCoy et al., 2010). Occasionally, watery flows (slurries) precede or follow the main surge on the fan surface. Independently or in combination with the debris flow, the watery flows can produce significant erosion along the feeder channel and fan surface channels (Harvey, 2002; Berger et al., 2010). Debris flows tend to produce a catenary channel form that is often terminated at the lateral extent by debris flow levees; whereas, fluvial erosion on the alluvial fan surface tends to lead to the development of rectilinear channels (Wasklewicz et al., 2008). Debris flow erosion within the channel has been recently linked to the passage of the granular debris flow front (Berger et al, 2011) and is likely associated with coarse sediment impacting the bed. Scour depth is also positively correlated with bed water content (Iverson et al., 2011; McCoy et al., 2010, 2011).

Early research hypothesized debris flows deposited when dewatering thinned the flow and/or a reduction in alluvial fan slope caused plastic yield strength to equal shear strength (Johnson, 1970). Debris deposition has also been associated with varying channel dimensions, whereby debris flows overtopping channels or debouching from channels onto the alluvial fan surface (e.g. where the feeder stream meets the fan surface or at the intersection point) decrease their depth and are likely to decrease velocity thereby enhancing deposition (Johnson, 1970; Johnson and Rodine, 1984; Hooke, 1967, 1987; Whipple and Dunne, 1992). A third mechanism associated with debris flow deposition is grain-contact friction and bed friction that occur at locations where high pore-fluid pressure decreases or is absent (Major and Iverson 1999). Frictional resistance is most pronounced at the margins of the flow, which promotes levee deposition adjacent to the flow as well as debris dams and snouts at the surge margin (Major and Iverson 1999). All of these depositional processes and features often contain the coarsest particles, which produce distinct topographic features evident on many alluvial fan surfaces (Whipple and Dunne 1992).

Regardless of the formative processes operating on an alluvial fan surface, significant modification to alluvial fan surface topography can result during and after an event. Topographic changes in turn impact the magnitude, trajectory, inundation, and run-out length of subsequent events entering onto the alluvial fan surface (Pelletier et al., 2005). These interactions are further complicated when built environments are constructed on alluvial fan surfaces. Many metropolitan areas throughout the world have experienced uninhibited expansion of humans and infrastructure onto alluvial fans (e.g. Meek, 2009). Alluvial fans represent an ideal site for property owners as they often provide cooler conditions, cheaper or undesirable land in some regions (marginal land because the terrain is dynamic), and/or a better view of the landscape. Occupation of an alluvial fan surface places humans at greater risk to flood and debris flow hazards (Pelletier et al., 2005). A need exists to expand our scientific understanding of alluvial fan dynamics and integrate these findings in a manner that reduces risks to human inhabitants and provides better knowledge for future management of these locales.

Despite significant advances in the previously mentioned six core themes of alluvial fan research, there remains a need to investigate fan changes on an event-by-event basis within a field setting. With a few notable exceptions, such as the work of Okuda and Suwa (1981), Okuda et al. (1980), Suwa and Okuda (1981, 1983), Lopez Saez et al. (2011), and Schürch et al. (2011b), this task has proved to be relatively rare. The elusiveness of analyzing debris flows and floods on fan stems in part from the long time intervals between debris flows in many locations throughout the world (Liu and Broecker, 2008). This makes it exceedingly difficult in the lifetime of a scientist to capture a single or multiple events. This is not to suggest that these areas have not been recently active. To the contrary, work from the Phoenix (Arizona, USA) metropolitan area has shown recent Holocene debris flow activity on alluvial fans that had previously gone undetected (Dorn, 2010). There are also issues of being at the "right-place-at-the-right-time". Even when debris flows or floods do occur, the event is not always noticed or it is difficult to mobilize a research team to capture the environmental changes. Furthermore, not all debris flows or floods actually make it out of the source area to debouch onto the alluvial fan surface. Rather, the floods infiltrate into or the debris flows are stored along the feeder channel within the drainage basin. All of these factors, combined with the limitations of most dating techniques to provide an accurate sequence of sediment deposition have led to a limited understanding of how debris flows, floods or the combination of the two interact with and vary spatially and temporally along an alluvial fan surface. Furthermore, few studies have been able to examine the impact of multiple debris flows or floods on an alluvial fan surface in the field.

Conceptual Models of Alluvial Fan Dynamics

Blair and McPherson’s (1994) field observations, research, and extensive literature review of the processes operating on fans supply evidence to advance one of the more sophisticated conceptual models of alluvial fan development. A pre-alluvial fan phase is the initial component of this model and results from the development of a talus cone constructed by gravity flow processes that include rock falls and rock avalanches. Gravity-dominated events are important to the initial development of a v-shaped drainage basin that allows subsequent mass wasting events to move onto the cone during stage one of alluvial fan development. An incipient alluvial fan develops during stage-one and contributes to the foundation of the alluvial fan. This surface influences and in-turn is influenced by debris flows as well as continued input from the gravity flow events. Bedrock weathering within and rock fall from the drainage basin provide material for debris flow production and produces a ramp-like foundation that permits flows to travel greater distances away from the mountain front. Stage-two development produces the common composite alluvial fan morphology whereby the alluvial fans can be broken into two types of developmental pathways. Type I consists of multiple interacting primary processes where not all the debris flows contribute to the formation of the alluvial fan. Some debris flows do not make it down the channel and onto the fan surface rather sheetfloods become the dominant contributing factor in Blair and McPherson's (1994) type one alluvial fan. Type II alluvial fans are dominated by debris flows that deposit at or very near the alluvial fan apex. Stage three of alluvial fan formation results when both Type I and II processes lengthen the incised channel. A main factor for stage three to occur is the formation of an incised channel that directs all subsequent fluid and gravitational flows farther away from the mountain front. The alluvial fan progrades in correspondence to an increased drainage area during stage three.

A more recent conceptual model considers debris flow processes and forms as they relate to alluvial fan evolution (Schürch et al., 2011a). Schürch et al. (2011) present limited results to support this model and therefore, we consider it a conceptual model. The authors present a more rigorous view based upon field monitoring at Ilgraben, Switzerland and a thorough review of the literature to propose new advances that would improve the modeling of debris flow processes as they relate to alluvial fan dynamics. These include: (1) self-channelization flows as propagate across the fan surface; (2) when certain criteria are exceeded the debris flow erodes into the fan surface; (3) periodic avulsions occur when certain criteria are met; (4) the scaling of emergent channels are comparable to those found on natural fans; and (5) flows can stop at multiple locations along the fan surface. The model has been presented as a means to examine both short- and long-term alluvial fan dynamics.

Physical Models of Alluvial Fan Dynamics

Physical models have a long-tradition within the alluvial fan evolution literature (Hooke and Rohrer, 1979; Schumm et al., 1987; Zarn & Davies, 1994; Bryant et al., 1995; Whipple et al., 1998; Cazanacli et al., 2002; Davies & Korup, 2007) and date back to seminal research conducted by Hooke (1967). While physical models have been criticized for exhibiting scaling issues, having limited exogenic controls, and in some instances having difficulties finding field analogues for the models, they provide key information regarding the interactions between alluvial fan processes and morphometry as well as insights into long-term alluvial fan development. Experimental physical modeling can be categorized into two basic types of studies based upon the goals of the study: (1) morphometric relationships and (2) specific flow behaviors along the fan surface.

Early physical modeling efforts focused on catchment and alluvial fan relationships as well as alluvial fan-scale morphometric characteristics. Several experiments were able to produce specific morphometric characteristics often associated with debris flow events such as levees, lobes, sieve lobes, and debris dams (Hooke, 1967; Zimmermann, 1991). Experimental alluvial fans also provided further support for the concept that larger source areas correlate with lower slope values and that alluvial fan slope varied azimuthally (Hooke and Rohrer, 1979). Alluvial fan slope variations were associated with a low-high effect, whereby sediment deposition builds to an undetermined height and is diverted to repeat the process on another section of the modeled alluvial fans (Hooke and Rohrer, 1979; Zimmermann, 1991). In general, the modeled fan surfaces exhibited realistic profiles and alluvial fan slope measurements, with alluvial fan slopes varying between 4° to 18° in the experimental settings (Hooke, 1967; Hooke and Rohrer, 1979; Zimmermann, 1991).

Physical modeling experiments have also examined flow characteristics of debris flows as they interact with the alluvial fan surface. A major thrust of this research has been to examine the runout distances along the fan surface as well as channel avulsion. Zimmermann's (1991) experimental work did not yield relationships between debris flow runout distances and debris flow velocity, but the flows did provide evidence of backfilling behind the surge fronts. Backfilling behind the surge front is a process analogous to debris dams, which are often identified in the field (Hooke, 1967). More recent work identified runout distances that far surpassed any recorded at field sites used for comparative purposes (D'Agostino et al., 2010).

This overestimation was attributed to scaling and roughness issues that reduced the amount of energy dissipation along the length of the flume and through the runout zone on the fan surface.

Lateral channel shifts were another commonly identified component of the physical modeling experiments. After multiple debris flows deposited sediment to an undetermined height, subsequent debris flow channels avulsed and deposited on topographic lower portions of the alluvial fan or flume/stream table (Hooke and Rohrer, 1979; Zimmermann, 1991). This process would then be repeated to produce the conic fan shape of an isolated alluvial fan and large variations in alluvial fan slope across the alluvial fan surface. Similar patterns of alluvial fan adjustment have also been identified in experimental alluvial fans built from fluvial events (Clarke et al., 2008; Nicholas et al., 2009). Experimental alluvial fans experienced multiple channel formations and changing channel geometry during alluvial fan development. Eventually, a single main channel incised at the alluvial fan apex and the alluvial fan prograded. Progradation was followed by a decline in alluvial fan aggradation rates, driven mainly by increasing alluvial fan area and an upper limit on sediment accommodation space (Clarke et al., 2008).

Numerical Models of Alluvial Fan Dynamics

Numerical modeling represents another manner of controlled experimentation used to test alluvial fan dynamics. Numerical modeling approaches often vary boundary conditions, process mechanics, and/or interactions with surface roughness (Tucker and Hancock, 2010). A vast majority of the research employing numerical models validate results with 2D measurements from topographic maps or coarse-resolution DEM (e.g. De Chant et al., 1999; Clevis et al., 2003; De Chant 2004). Validation with these sources provides very reasonable results, but does not factor in the 2.5D to 5D (5D considers space, time, and scale [van Oosterom and Stoter, 2010]) changes that often are critical to determining topographic responses and long-term changes to alluvial fans. This further limits our ability to use these results to assess/predict alluvial fan evolution. A need exists to produce models that are reconciled with field data focused on process-form interactions. There are currently only a few locations where flow records exist and virtually no locations where long-term topography has been monitored in a spatially and temporally meaningful way. Very few studies have examined the role of debris flows in numerical alluvial fan modeling with a majority of the studies focusing on fluvial flows (e.g. Magirl et al., 2010). The aforementioned limitations lead to a rudimentary review of both fluvial and debris flow alluvial fan numerical modeling experiments related to fan topographic changes.

De Chant and others (1999) developed a diffusive sediment transport model with radial flow to examine scale-independent sediment surface profiles from a series of alluvial fans. Surface topography from the model runs resulted in (1) a relatively ‘homogeneous” fan surface where the entire surface was depositionally active during sheet flooding, and (2) a topographically complex fan surface developed from fluvial flows within a channel(s). Modeled fan surfaces with well-defined channels and channel processes were found to closely approximate real world fan profiles. Environmental variables (e.g. climate, lithology) were less significant to overall fan morphology. Basic sedimentary and flow processes were evident from the uniformity of the sedimentary geometry of alluvial fans and suggested diffusion principles likely persisted across the alluvial fan surface and were responsible for fan morphology.

Other numerical models have considered morphometric changes associated with external forcing factors. In general, results highlighted 2D changes in fan topography, size, and shape (e.g. Coulthard et al., 2002; Clevis et al., 2003; Nicholas and Quine, 2007). Alluvial fans in these modeled scenarios had a tendency to prograde during periods with minimal tectonic activity or in periods with increased precipitation (Clevis et al., 2003; Densmore et al., 2007). There was general agreement that fan progradation corresponded with a decline in alluvial fan slope (Clevis et al., 2003; Densmore et al., 2007). Clevis et al. (2003) indicated juvenile alluvial fans developed topographical complex surfaces as there was a propensity for these newly formed alluvial fans to contain coarser particles. Coarse lobes or patches were often later associated with the phases of progradation or retrogradation.

Modeled alluvial fan surface topography also varied in response to channel entrenchment and channel avulsion (Coulthard et al., 2002; Clevis et al., 2003; Nicholas and Quine, 2007). Grids developed from Coulthard et al. (2002) simulated varying surface topography associated with the presence of either single-thread channels, multiple channels, and/or cutoff channels after avulsions. Alluvial fan-head entrenchment led to alluvial fan segmentation and progradation thereby creating varied surface complexity associated with a predominance of secondary erosional processes on the segmented portion of the alluvial fan (Nicholas and Quine, 2007; Pepin et al., 2010).

Field Observations of Alluvial Fan Dynamics

Field observations have been a major source of information within the debris flow alluvial fan research. Our review concentrates on early debris flow studies as our case study is concerned with debris flows interaction on an alluvial fan. There are two main sites where influential work was conducted, in the Kamikamihori Valley, Japan and in the White Mountains of California, USA. Suwa and Okuda (1983) recorded topographical changes as well as processes affecting the alluvial fan surface through a variety of observation methods that included several cameras (8mm video and 35mm) capturing information at various time-intervals. Iron rods were driven at mesh points every 25 meters to make a grid for return visits for measurements as well as fixed rings on the rods to measure the amount of scouring (Suwa and Okuda 1981). In general, the authors found erosional processes dominating the alluvial fan apex (fan head incision), while depositional and sorting processes dominated in the middle and lower fan sections. Alluvial fan head spreading did not occur as fast as predicted because of natural levees emplaced from past debris flows (Suwa and Okuda 1981). However, erosion and deposition were present near the alluvial fan apex. Degradation resulted from debris flow channel incision (Okuda and Suwa, 1984). Levees formed adjacent to some channel sections. The alluvial fan mid-section displayed a higher concentration of boulders and gravel, while the alluvial fan toe was a smoother, flatter surface composed mainly of sand to pebble-size material (Suwa and Okuda, 1983; Okuda and Suwa, 1984). Much of the deposition occurred within the channel or original water course (Okuda and Suwa, 1984). Over the entire record of observation it would appear that the dominant locus of deposition was moving upstream along the main water course (Okuda and Suwa, 1984).

Suwa and Okuda (1983) also highlighted the role of debris flow lobes in developing topographic complexity. Field mapping and sediment analyses found debris flow lobes were deposited at a number of locations across the entire alluvial fan surface. Debris flow lobes in the lower portion of the fan tended to be thinner deposits and produced a flatter topographic pattern. The upper and middle portions of the fan tended to be thicker and more rounded debris flow lobes. Calculations of the “micro-relief” (standard deviation of each transversal section) across the alluvial fan indicated a much higher relief along the upper and middle section of the alluvial fan when compared with the lower alluvial fan.

Beaty (1963) conducted research on debris flow fans in the White Mountains of California, USA. Debris flow activity was prominent in areas with steep slopes, sparse vegetation, and summer thunderstorms. Fan surface roughness was high in this locale, often associated with well-defined channels, levees, debris flow lobes, and occasional boulders present on many fan segments. Recent deposit depths decreased downslope from the fan apex. Particle size on the fan surface decreased downslope. Large boulders were also transported to the alluvial fan surface and occurred on many different alluvial fan segments, but were not found beyond approximately two-thirds of the alluvial fan length (the distance most debris flows travelled). Large boulders were found to block channels at a variety of locations along the length of the alluvial fan. Blockage by large boulders often led to channel avulsions, which impacted the location and amount of debris flow deposition. Highly fluid debris flows were also identified in the White Mountain alluvial fans. These often deposited as lobes farther down the alluvial fan surface. Although the flows were highly fluidized, there was little evidence for dewatering. Instead the lobes set-up much in the way that concrete settles. These lobes tended to be less blocky than debris flow deposits located farther up the alluvial fan surface.

High-Resolution Morphometric Analysis of Alluvial Fans

Direct measurement of the geomorphic processes that produce and modify alluvial fans is difficult since they often operate at intermittent or relatively long temporal scales (Schumm and Lichty, 1965; Schumm, 1991). Instead of direct process measurement, researchers often rely upon measurement of form as a method of understanding process rates and mechanics. Prior to the mid-2000’s, relatively coarse resolution data were used to analyze the morphometry of alluvial fans. Data sources included both traditional and GPS surveying (McCarthy et al., 1997), 1:24000 (or smaller) scale topographic maps (Kostaschuk et al., 1986), and digital elevation models with pixel resolution ≥ 10-meters (Crosta and Frattini, 2004). Recently, high-resolution terrain data, such as those derived from airborne laser swath mapping (ALSM, commonly referred to as airborne LiDAR) and interferometric synthetic aperature radar (InSAR), and low altitude aerial photography have become increasingly utilized in alluvial fan morphometric and process studies (Catani et al., 2003; Catani et al., 2005; Staley et al., 2006; Frankel and Dolan, 2007; Volker et al., 2007; Cavalli and Marchi, 2008; Wasklewicz et al., 2008; Trevisani et al., 2009; Berger et al., 2011). These data sources are able to provide much greater detail regarding the surficial form of the analyzed alluvial fans than those associated with more coarse scale topographic measurements derived from topographic maps and DEMs with resolutions ≥ 10-meters.

Incorporation of ALSM data in alluvial fan research has increased dramatically in recent years, with applications related to alluvial fan systems in both arid (Staley et al., 2006; Frankel and Dolan, 2007; Volker et al., 2007; Wasklewicz et al., 2008) and alpine (Cavalli and Marchi, 2008; Trevisani et al., 2009; D'Agostino et al., 2010; Staley and Wasklewicz, In Press) environments. Most commonly, ALSM data from a single point in time have been used to calculate morphometric parameters to which information regarding fan evolution and related geomorphic processes have been attributed. For example, Staley et al. (2006) utilized measurements of gradient and profile curvature to identify depositional zones on the surface of several debris flow dominated alluvial fans in Death Valley, California, USA. Working in the same locale as Staley et al. (2006), Volker et al. (2007) used local relief to differentiate between alluvial fans dominated by fluvial processes (referred to in the paper as mixed-flow alluvial fans) and those dominated by debris flow processes (classified by the sedimentological properties evident on the alluvial fan surfaces). Wasklewicz et al. (2008) expanded upon the work of Volker et al. (2007), and used planimetric curvature to identify channels and interfluves. Morphometric analysis of channel and interfluve width and relief yielded significant differences between fluvial and debris flow dominated fans, suggesting higher dissection and susceptibility to erosion by secondary processes on fans dominated by fluvial processes. Cavalli and Marchi (2008) utilized the morphometric parameters of planimetric curvature and surface roughness to classify the surficial features of an alpine alluvial fan in the Italian Alps. They demonstrated the effectiveness of these metrics in distinguishing recent debris flow activity from other surface types, such as fluvially-reworked debris flow deposits and anthropogenic structures. Trevisani et al. (2009) conducted a spatial continuity analysis on an alpine alluvial fan influenced by debris flow, rockfall, and snow avalanche activity. Analysis of the variogram suggested that spatial continuity analysis may be used for the identification of a topographic signature of these processes, and used in subsequent automated classifications of alluvial fan processes.

InSAR has also been used to quantify the morphometry of alluvial fans. InSAR allows for the development of terrain data from air or spacecraft-mounted SAR systems (Massonnet and Feigl, 1998). While SAR imagery collected from a single point in time may be used to produce terrain data of sufficient accuracy for the characterization of alluvial fan morphometry (Lane et al., 1993; Lane et al., 2000; Catani et al., 2005), much more accurate results are obtained when InSAR data are used to assess topographic changes that occur between two points in time (Smith, 2002). Application of InSAR data to the quantification of alluvial fan form has been relatively limited. InSAR has been used to differentiate between salt-dominated weathering processes and desert varnish pavement development of alluvial fans in China and the southwestern United States (Farr and Chadwick, 1996). Spaceborne InSAR data have also been used to derive terrain measurements useful for the identification, prediction and assessment of flood hazards on alluvial fans (Catani et al., 2003).

Photogrammetrically derived low altitude aerial stereophotos are capable of producing terrain models with a horizontal resolution of 2 m or finer (Lane et al., 1993; 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) and Lane et al. (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 assess topographic changes from debris flow processes using pre- and post-event imagery (Coe et al., 1997; Crosta and Frattini, 2004; Berger et al., 2011).

Climatic Change and Fan Morphometric Changes

Dorn (1994) proposed four models to relate climatic changes to alluvial fan development: (1) transition-to-drier-climate; (2) paraglacial; (3) humid-period aggradation, and (4) periglacial. From these models Dorn concluded the time scales of alluvial fan formation are definitely long enough to experience climatic influences. The transition-to-drier-climate model has the most relevant relation to debris flow activity. Areas lacking vegetation react more strongly to climatic events because of the increased potential for the erosion of hillslope sediments via mass wasting events (Dorn 1994). The Cronese-1 fan (near Baker, California, USA) was used as an example. Climatic change was associated with mass wasting as remnant debris flow levees corresponding to the age of the climatic response were evident on this fan.

Ritter et. al. (2000) looked at four different fan deposits from oldest to youngest Qf1, Qf2, Qf3, and Qf4 in the Buena Vista Valley. The relationship found on Qf3 shows that climate change is the primary factor in alluvial fan evolution. The alluvial fan surface was affected by hillslope vegetation, soils, and hydrology that were controlled and manipulated by the climate and climate change. Observations showed that alluvial fans in the study area had a concave profile downslope because of telescoping or secondary flows that creates alluvial fans downslope of the original fan. Younger sediments were found to be deposited on older surface through incision. These sediments continued downslope to develop a new alluvial fan segment. The authors also observed this phenomenon in Klondike Canyon, Nevada, USA. This style of alluvial fan progradation has been referred to as a telescoping effect. Colombo (2005) found the old alluvial fan surface contained a higher slope than the section of the alluvial fan that was telescoping through the old surface. Surface complexity of the older alluvial fan segment can also be increased as entrenchment takes place and multiple treads and risers from terrace development associated with alluvial fanhead entrenchment (Bowman, 1978)

Frankel and Dolan (2007) investigated surface roughness of alluvial fans in Death Valley, California, USA with lithostratigraphic ages ranging from Q4b (active surface) to Q2a (oldest and higher topographic surface). Surface roughness measurements were taken at the center of each alluvial fan unit to remove conflation of values from steep channel walls. Each scale of surface roughness was different from one another at the 99% confidence level. Their results showed that with increasing age, the surface roughness of the alluvial fan tends to smooth out up to 70 kya. After 70 kya, surface erosion increased via secondary processes acting on the alluvial fan surface. The relationship between surface age and roughness may be useful as both a relative and absolute Quaternary dating method for alluvial fans in arid environments.

Case Study of Debris Flow Related Changes to Fan Morphometry from the Chalk Creek Natural Debris Flow Laboratory

In the following section, we present a case study of the morphometric changes that occurred on an alluvial fan in response to a debris flow produced during a rainstorm that occurred on 15 September 2009 in Chalk Cliffs, Colorado. We assess the 2- and 3-dimensional changes that occurred on the fan surface, and relate these findings back to the literature reviewed in previous sections.

Study Site

The case study was conducted at Chalk Cliffs, a portion of the Mount Princeton batholith consisting of highly fractured and hydrothermally altered quartz monzonite (Miller, 1999) (Fig. 1). The analyzed alluvial fan has a drainage area of 0.3 km^2. The basin is characterized by steep bedrock cliffs (>60°) with colluvial toe slopes typically at or near the angle of repose. The drainage basin has a relief of 514 m above the location where the channel enters the bajada. Local residents have engineered the channel on the bajada to protect adjacent houses from debris flows and maintain a consistent location of the active channel. This channelization has resulted in the recent development of a small, unvegetated alluvial fan at the confluence with Chalk Creek that is subject to multiple debris flows each summer. Table 1 summarizes the basic fan characteristics in 2009.

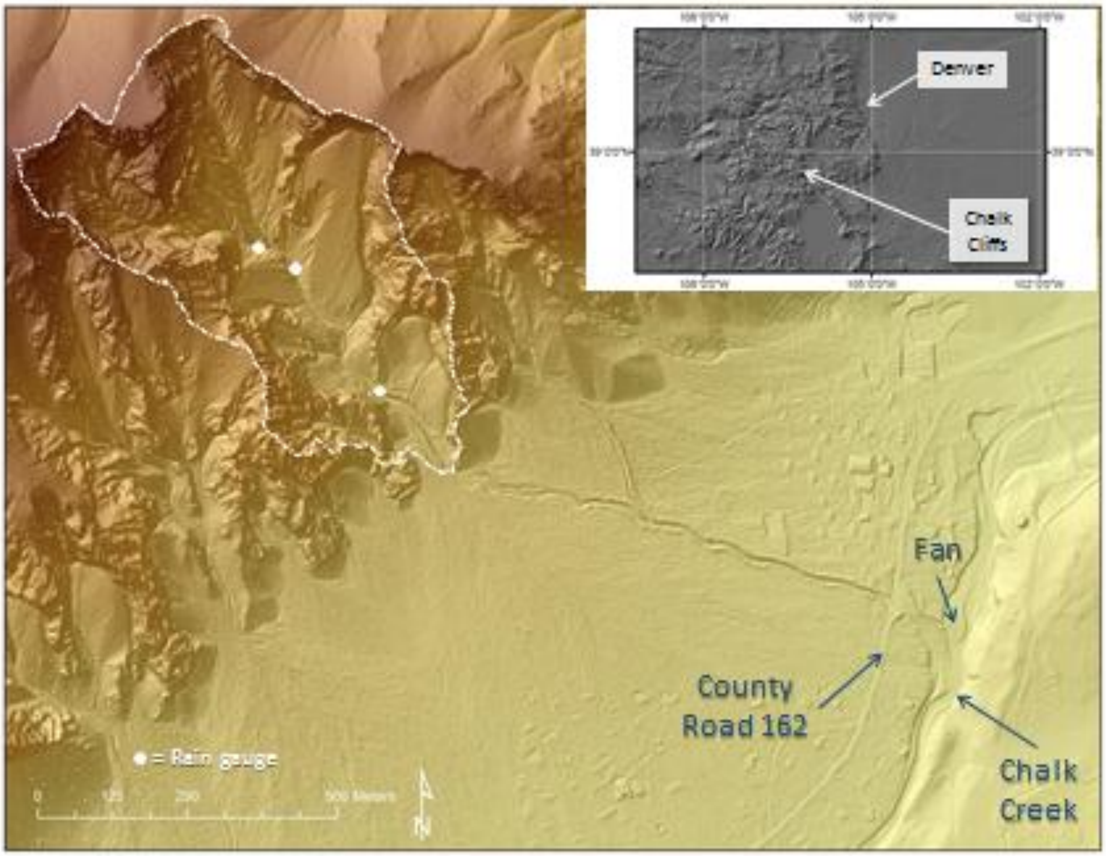
Table 1- Basic morphometric and volumetric changes

Fan (date)	Area (m^2)	Perimeter (m)	Length (m)	Width (m)
5/29	3192	238	104	40
9/27	3501	250	105	43
Total deposition (m^3)		Total erosion (m^3)		Fan area affected (%)
390.2		6.2		33%

Debris flows are the predominant mechanism associated with the development of this alluvial fan. Debris flows are hypothesized to form via a “fire-hosing” effect in the upper portion of the basin (Coe, et al, 2008). Further materials are added to the flow via progressive bulking of materials (McCoy et al., 2010, Staley et al., 2011). Not all debris flows from the basin arrive at the alluvial fan surface; in 2009 only one of the four debris flows debouched onto the alluvial fan surface. The other three events were stored in the upper and middle sections of the channel above the alluvial fan. The engineered channel crosses Chafee County Road 162 (CR162) approximately 50 m upstream of the alluvial fan. Debris flow material passes through a concrete road crossing prior to arrival at the alluvial fan apex.

The storm that initiated the debris flow under investigation occurred on 15 September 2009. Rain gages situated in the drainage basin (Fig. 1) recorded 25 mm of rainfall over a period of 1.9 hours. Peak 10-minute intensities of 38.1 mm/hr were recorded at the same rain gage.

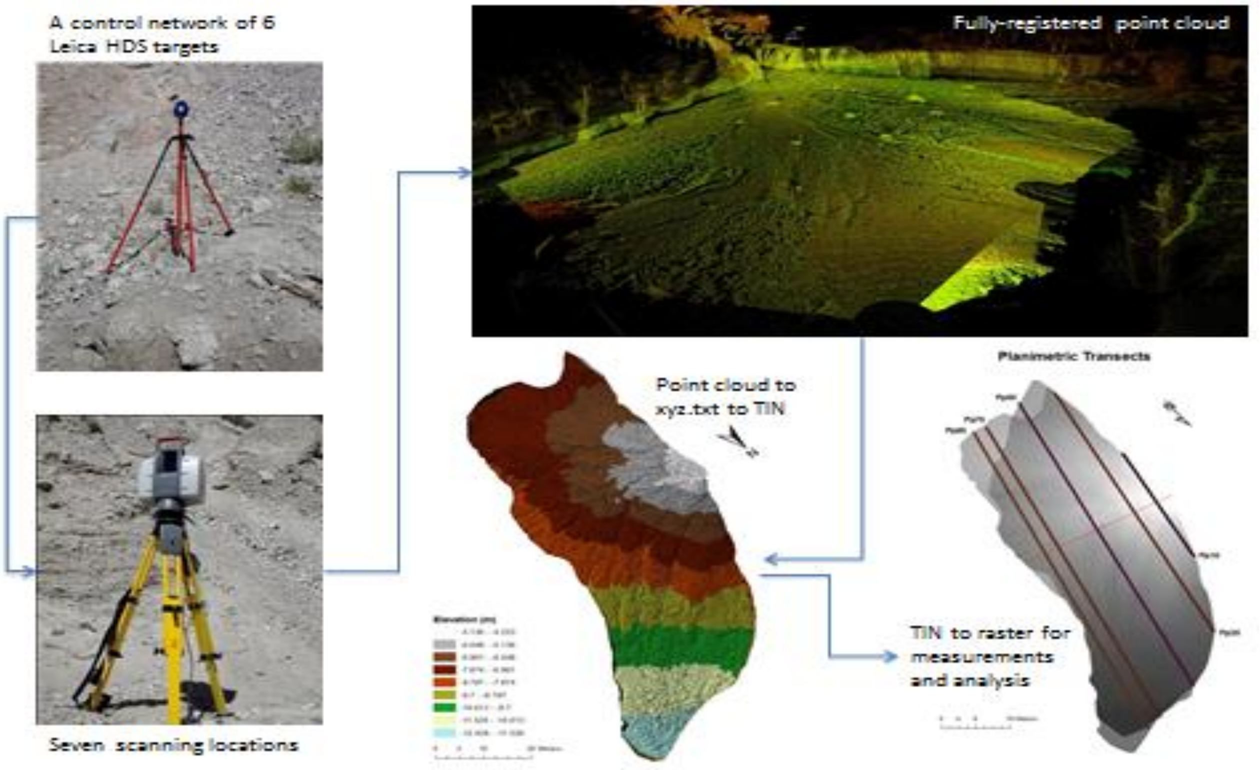
Figure 1- The case study location and site



Methods

A Leica ScanStation 2 was used to collect high-resolution terrain data prior to the event (29 May 2009) and two weeks following the debris flow (29 September 2009). The scanner was set up on a tri-pod and powered with a generator for both surveys. Scanning parameters and field-of-view (FOV) were developed in Leica HDS Cyclone 6.x software on a Dell XFR D630 connected to the scanhead via a TCP/IP connection. A rotating mirror directed pulsed laser light to the fan surface and the laser light was reflected back to the scanhead. Each return was recorded as a point with a series of x, y, z, and i values to the laptop.

Figure 2- The work-flow for the case study



Common reference points in the FOV were used to register the multiple point clouds gathered from six different scanning positions occupied in the pre and post debris flow surveys. These common reference points were a combination of three temporary and three permanent Leica HDS flat 15.25 cm circular targets. Permanent targets were set on rebar that had been cemented into place to permit a target pole to be consistently placed during future surveys. Temporary targets were set-up on tri-pods on the alluvial fan surface. Scanner placement and surveys at several locations reduced surface shadowing effects.

Two registered point clouds were used in this study. The first was taken not long after snowmelt in the basin, and a second was taken later in the season immediately after the largest debris flow of the season debouched onto the alluvial fan surface. All of the scans performed during this study had a maximum scanning distance of 50-75 m. Registration was performed in Leica HDS Cyclone 6.X software with registration errors not exceeding 3 mm.

Each registered point cloud was exported as a text file and converted to a digital terrain model (DTM) in ArcGIS 9.x . A DTM of difference (DoD) was calculated by subtracting the pre-event surface from the post event surface (Wheaton et al., 2010). Negative values indicate areas of erosion, while positive values indicate areas of deposition. The extent of the debris flow impact was mapped using heads-up digitizing from the DoD surface. From this, descriptive statistics were calculated from the positive (deposition) and negative (erosion) topographic changes. Estimates of volumetric changes were determined from multiplying elevation changes by the pixel resolution.

Longitudinal and planimetric profiles were generated using the EZ Profiler extension. Five hundred points were collected along each profile. The longitudinal profile indicates how elevation changes over the distance down the extent of the fan. Planimetric profiles (across the fan surface) were taken at 10%, 25%, 50%, 75%, and 85% of the total distance along the longitudinal profile.

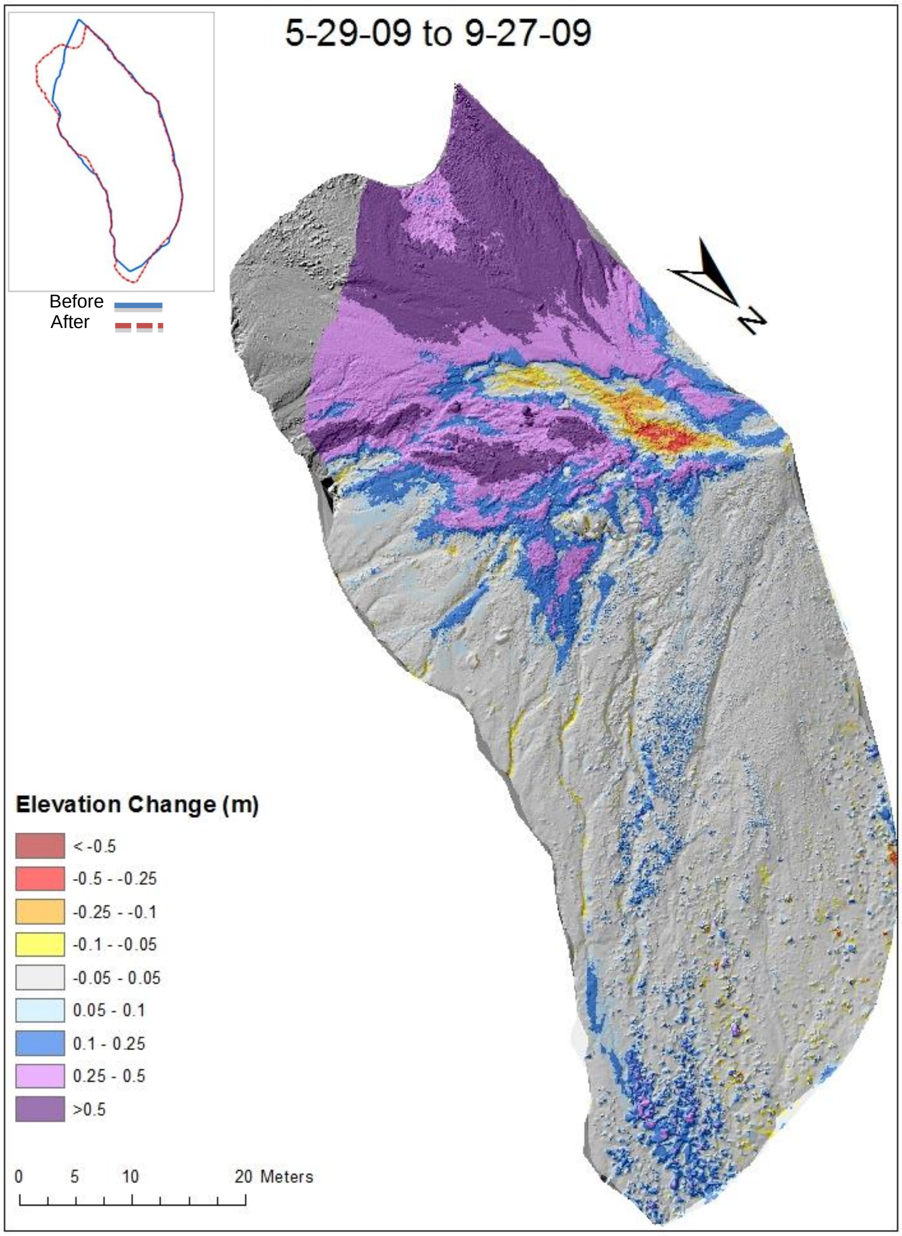
Surface roughness is derived from the two surveys by calculating the standard deviation of slope (Frankel and Dolan, 2007). Surface roughness is considered at several spatial scales (0.2m, 0.3m, 0.4m, 0.5m, 1m, 5m, and 10m) for the two surveyed surfaces. Surface roughness measures are extracted from ~500,000 grid cells and plotted to examine the magnitudes and patterns of surface roughness changes.

Results

The debris flow of 15 September 2009 substantially modified the alluvial fan morphometry (Fig. 3). In all, 33% of the original alluvial fan surface was altered during the event. The surface area of the alluvial fan increased from 3192 m^3 to 3501 m^3, while the perimeter of the original alluvial fan increased from 238 m to 250 m. Total deposition on the alluvial fan was calculated to be 390.2 m^3 and total erosion was 6.2 m^3. These volumes do not represent the total volume of material involved in the debris flow event. Material was deposited on CR162 above the alluvial fan apex, and at the alluvial fan toe. Based on our field observations, it is likely that Chalk Creek eroded the material deposited at the toe immediately after the event.

The maximum depth of deposition was 1.06 m and maximum erosion depth was 0.46 m (Fig. 3). Deposition in the form of a large lobe and to a lesser extent debris flow levees dominated the area impacted by the debris flow. The relatively small volume of material eroded during the event was largely constrained to the channel, and likely represents fluvial reworking during the recessional flow based on observed rectilinear channel banks (Fig. 3).

Figure 3- DTM-of-Difference for first event



Longitudinal profiles showed similar topographic variations as were derived from the DoD (Fig. 4). Aggradation was prominent along the Pro1 and Channel profiles, while Pro2 (the main channel) contained a mixture of degradation near the apex and aggradation nearer the toe (Fig. 3). Profiles that increased in length in response to aggradation via the debris flow (Pro1 and Pro3) tended to decrease in slope (Table 2). Two other profiles (Pro2 and Pro4) remained about the same length and the slope along this transect remained the same or experience a minor increase (Table 2). Profiles where aggradation occurred tended to become less topographically complex (smoothed) in areas associated with the debris flow deposition (Fig. 4 and 5). Longitudinal and planimetric profiles both indicate the fan is steeper on the downstream side of the alluvial fan (Fig. 4 and 5)

Planimetric profiles predominantly highlighted the deposition on the left third of the fan looking up the fan (Fig. 5). Channel degradation can be identified in the planimetric profile at 25% distance down the fan and channel aggradation was evident at 50% distance down the fan (Fig. 5). Minor fluctuations on the right side of the fan were associated with vegetation growth. The DTMs were not filtered because the vegetation was sparse and occurred only on the portion of the fan not impacted by the debris flow.

Table 2- Slope measurement before and after the debris flow extracted

Profile	Slope 5/29 (m/m)	Slope 9/27 (m/m)
Pro1	0.086	0.068
Channel	0.097	0.099
Pro2	0.095	0.082
Pro3	0.121	0.120
Pro4	0.104	0.103
Avg.	0.101	0.094

Figure 4- Longitudinal profiles for first event

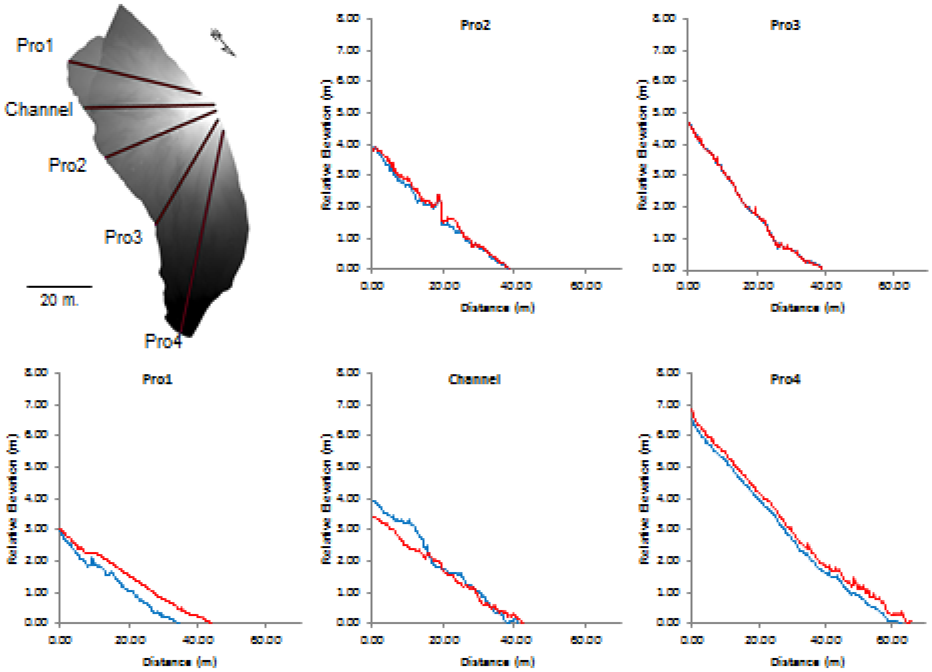
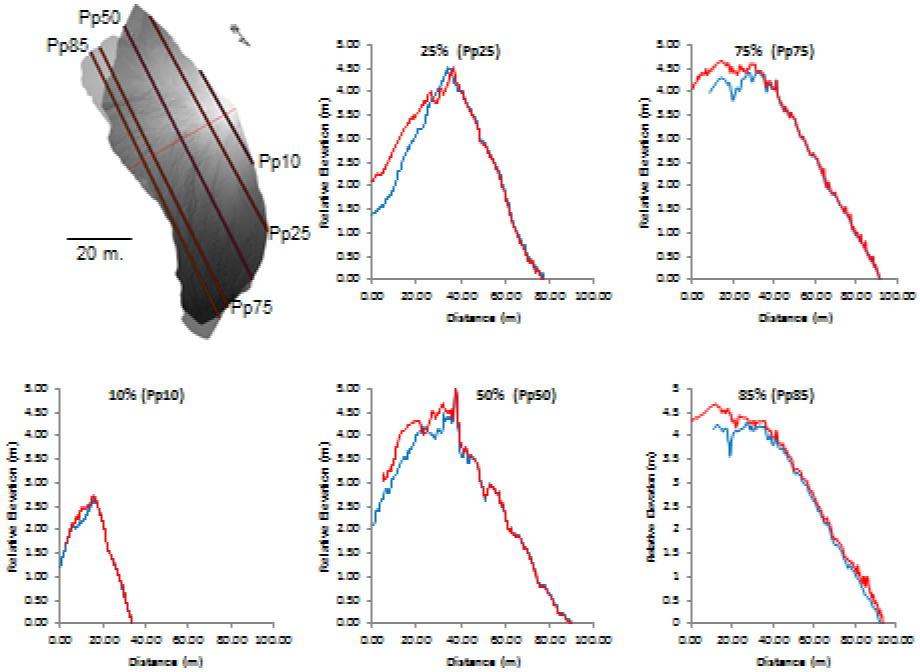
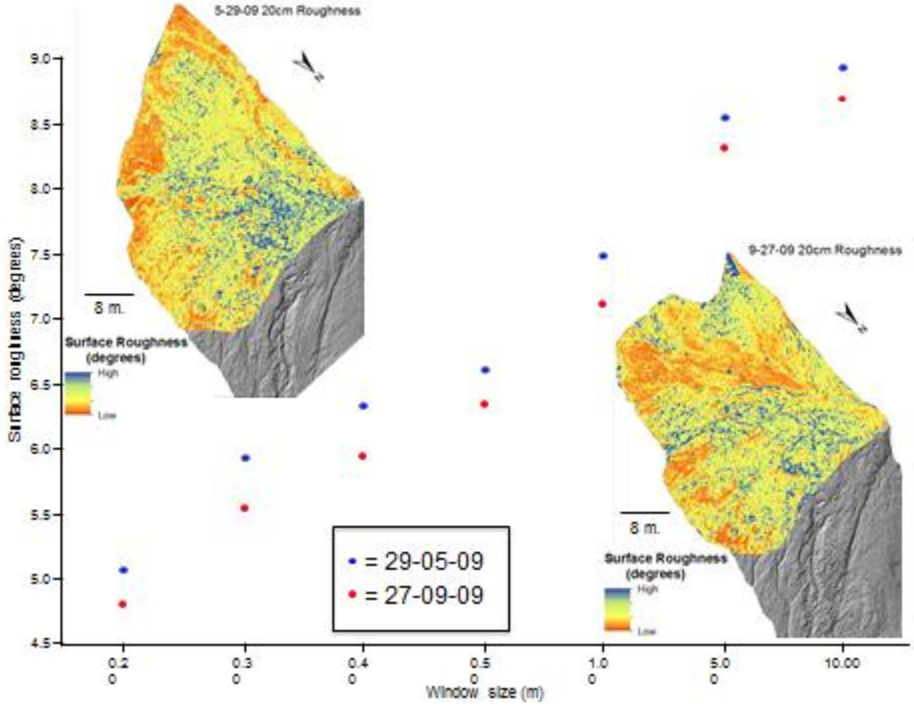


Figure 5- Planemetric profiles for first event



Surface roughness for all scales showed a significant smoothing trend after the debris flow event (Fig. 6). A topographically smoother surface occurred outside the main channel. A lobe of material containing fines at the surface was deposited from the debris flow and led to a smoother surface in these locations. Surface roughness tended to be higher in the channel at all spatial scales after the debris flow (Fig. 6).

Figure 6- Surface Roughness for first event



Case Study Discussion in the Context of the Review of Alluvial Fan Dynamics

The debris flow in the case study was predominantly depositional. Aggradation was confined to one-third of the fan surface. The concentration of deposition is indicative of a low-high effect. We hypothesize the low-high effect will continue to cause deposition on the same one-third of the analyzed fan for some period of time prior to a shift in the loci of deposition. Deposition following the avulsion should occur in the direction of a low point on the fan as shown in the physical modeling experiments of Hooke and Rohrer (1979) and Zimmermann (1991).

Debris flow runout occurred along the entire fan length and was impeded by the riverbank adjacent to the alluvial fan toe. The debris flow entered the alluvial fan scouring the channel near the alluvial fan apex to the mid-fan. Fan head scouring was identified in many of the numerical modeling experiments and field studies (Okuda and Suwa, 1981; Suwa and Okuda, 1983; Okuda and Suwa, 1984; Coulthard et al., 2002; Nicholas and Quine, 2007; Densmore et al., 2007; Pepin et al., 2010). Wasklewicz et al. (2008) was able to differentiate channels carved from fluvial processes from those associated with debris flow based upon channel bank shape. Fluvially-sculpted channels tended to have more rectilinear banks than those channels produced by debris flow. Our field and DEM analyses indicate the channel erosion was likely produced during the water-rich recessional flow, with only minor contributions from forces associated with the debris flows.

Fan slope in numerical modeling scenarios often decreases after a debris flow event (Clevis et al., 2003; Densmore et al., 2007). Slope from the case study showed a highly variable response where increases, decreases, and no changes to slope were identified from longitudinal profiles. The inconsistency in the fan slope response to the numerical modeling results speaks to the environmental setting of the fan and the water to sediment size ratio of the debris flow. The analyzed fan, located adjacent to Chalk Creek, had little accommodation space as a steep valley wall constricted approximately one-half of the fan width. The remaining portion of the fan had more accommodation space as the trunk stream valley width expands. However, despite the extra accommodation space, the extent of the space is smaller than more typically studied settings like the Basin and Range of the Southwestern United States and other similar settings worldwide.

Lack of accommodation space has been noted in a number of other settings (Mills, 2000; Hashimoto et al., 2008). Locations with limited accommodation space often lack progradation and frequently fans in these settings retrograde (Mills, 2000). The lack of progradation is a likely reason why the alluvial fan slope had not significantly changed in some locations after the debris flow debouched from Chalk Cliffs. Chalk Creek also erodes the alluvial fan toe significantly after the debris flow event, which would shorten the alluvial fan and increase gradient. This was not a major source of change in the current study, but is an important aspect to alluvial fans forming in river valleys. In areas where slope decreased, the alluvial fan expanded and this fits with the numerical modeling experiments.

Finally, surface smoothing was identified in areas where deposition occurred. This phenomenon is linked to the higher water to sediment ratio in the debris depositing on the alluvial fan surface. Staley et al. (2006), Volker et al. (2007), and Wasklewicz et al. (2008) all identified significant local breaks-in-slope (associated with debris lobes and snouts) on alluvial fans where debris flows were more clast-rich. Profiles from the case study alluvial fan lack topographic variations identified in the previously mentioned studies. Frankel and Dolan (2007) observed the most recent alluvial fan segments generated from debris flows had a higher surface roughness, while older fan segments became progressively smoother until ~70 kya and then roughness increased in older deposits as a result of secondary processes operating on the fan segments. Our results provide evidence that the recent debris flow deposits had lower surface roughness values than the previous alluvial fan surface at the same location. The reduction in surface roughness we find in the current study might result from a number of scenarios. Modifications to the debris flow deposits prior to or after our first survey of the alluvial fan surface may have increased roughness via any one or a combination of the following: (1)

meltwater flows to the fan surface; (2) secondary erosional processes; or (3) flood flows from the adjacent trunk stream eroding the surface to make the older surface topographically more complex. While the current study cannot rule out any of the above, field observations and site mapping do not lend support to any of these suppositions. The decreased surface roughness likely results from differences in the depositional characteristics of the recent material that could result from following scenarios: (1) the debris flow snout consisted of coarse sediments and the more liquid tail with smaller particle sizes pushed over the coarser grains as the coarse particles settled and deposited the finer materials in the interstices of the coarse snout to produce a smoother surface (Iverson et. al., 2010); (2) the coarser material in the debris flow snout deposited at the fan toe and the finer, wetter material in the tail deposited on the fan surface and compacted to the less rough surface; or (3) the debris flow became consistently finer as it travelled to the fan surface (Suwa and Okuda, 1983). The third hypothesis is the most likely scenario based upon our field interpretations. McCoy et al. (2011) found tracer rocks (small cobbles) within 0.5m of the surface of the new, smooth deposit or slightly exposed at the surface. A wetter, matrix of finer material likely deposited and settled much in the manner that concrete sets up (this phenomenon was previously identified by Beaty, 1963) to form this smoother surface.

Recent and Future Directions

We have highlighted the variety of approaches being used to examine alluvial fan dynamics. The varied techniques and analyses used to date reflect the historical development of research on alluvial fan dynamics and the broader field of geomorphology in general. Our literature review and case study provide evidence that a great deal more work is required to understand the recent and long-term evolution of alluvial fans. The case study represents a newly developing approach to understanding landform and environmental changes. Admittedly, the current case study is limited to a single debris flow altering a fan. More events are needed to make broader inferences on alluvial fan dynamics. However, this example has provided corroborative field evidence to previous work on alluvial fans, while concurrently showing the potential for innovative findings regarding topographic and morphometric changes to alluvial fans. The analysis of high spatial and temporal resolution field data holds significant merit to unraveling the complex interactions associated with landscape change. Terrestrial laser scanning can be used as one component of this type of research. This is not meant to downplay the role of other approaches to collecting high-resolution topographic data. Indeed, terrestrial photogrammetry techniques from the ground and the air could be used to expand the spatial extent and temporal rate of data collection. Further technological advances are likely right around the corner in regards to high-resolution topographic data acquisition. Scientists, planners, and managers must be willing to adapt these new technologies and integrate them to inform the public and other members of the scientific community.

Another critical observation is that a major advance in research on alluvial fan dynamics is going to require more than just topographic data at greater spatial and temporal extents. We have isolated several different approaches to studying alluvial fan dynamics, but the reality is that these isolated techniques need to be improved and combined to make greater strides toward understanding of fan dynamics. Based on our experience, this will require two major developments to take place.

First, we believe there is a need to make equally innovative developments in the means of collecting process-oriented data in the field to link with techniques such as terrestrial laser scanning. Specifically, the spatial extent of process-oriented data collection needs to be expanded from cross-sections and points on the fan surface to cover more of the spatial extent of the fan surface and match the extent of the topographic change data. Our work shows that changes are not confined to the channel, but rather the event covers ~33% of the fan surface. Expanding the process-oriented data collection to cover the entire fan surface would produce robust process-form relationships that can be used to explain alluvial fan dynamics. Some would argue the process-oriented data can be developed more efficiently and in a more cost-effective manner from numerical or physical modeling experiments. We do not dispute this fact, but we would strongly advocate a need to corroborate the modeled results with field data. Regardless, new developments in the field of alluvial fan dynamics will require the integration of field data and modeled results.

Second, the integration of process-oriented field data and topographic data will require new collaborative efforts. Experts from both areas must come together to design projects that begin to examine longer-term landform and landscape dynamics. As an example of this, another ongoing project at the Colorado Natural Debris Flow Laboratory has combined scientists from different academic institutions and research scientists from the Federal Government to conduct repeat terrestrial laser scanning surveys in combination with a variety of instruments that collect process-oriented data within the drainage basin (McCoy et al., 2010, 2011; Staley et al., 2011). Our collaborative efforts in the drainage basin have produced new findings, some of which are important to understanding alluvial fan dynamics, but more monitoring of the alluvial fan and greater coverage of the alluvial fan surface with process-oriented information are required to produce a more detailed understanding of alluvial fan dynamics.

The research group has been funded through a variety of avenues that have included federal, non-profit, and state funds (state funds through internal grants from East Carolina

University). This is one of several possible recipes for this style of collaborative research. Further opportunities to bring together geomorphologists from different regions of the world to develop a network of long-term research sites would be a logical next step. Ideally, different scientists using varied approaches to studying fan dynamics would bring their expertise to the table and develop focused questions on alluvial fan dynamics. One could envision a diversified team of scientists focused on a single objective at multiple sites around the world. This group would contain expertise in modeling, application of multiple field data collection techniques, mathematics, computer visualization, and educational expertise to assist in conveying the results to a broader community. The group would also require a series of supporting technicians as this effort would be quite labor intensive in terms of maintaining equipment, storage of large data sets, managing the public dissemination of the findings and data, as well as employing and verifying a strong educational component. Certainly an effort like this would require more funding opportunities. These would need to be developed independently and collaboratively at national and state levels. The goal of these funding efforts is to support this style of research and the design of new instrumentation to examine processes acting on alluvial fans and linking it with the high-resolution topographic data.

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CHAPTER 2: DEBRIS FLOW FAN EVOLUTION

The term landscape evolution in geomorphology describes how a landform or a series of landforms change through time. Mass wasting events (debris flows and landslides) are common occurrences in many landscapes throughout the world. Much of the mass found in alluvial fans (cone-shaped landforms) and bajadas (coalescing alluvial fans) can be attributed to debris flows. Reasearch examining debris flow fan evolution have focused mainly on qualitative observations on debris flow and alluvial fan surface interactions (Beaty 1963), modeled the potential changes to alluvial fans (Hooke 1967, Hooke and Rohrer 1979), or coarsely investigated changes from a single event (Suwa and Okuda 1983). There is a need to increase the scientific understanding of how alluvial fans change on an event-by-event basis within a field setting. We use high-resolution terrestrial laser scanning techniques to monitor the impacts of five debris flows on alluvial fan development during a period that extends from 5-29-09 to 7-14-11. A small alluvial fan at the Colorado Natural Debris Flow Laboratory near Buena Vista, CO, USA served as the monitoring site.

Literature Review

This literature review contains a critical review of themes pervading the last forty years of research related to alluvial fan dynamism. The themes include the development of conceptual models, field experiments, physical models, and high-resolution morphometric analyses. Each theme is presented independently, but the results and conclusions of this study integrate past results from these reviews. This study not only validates past results, but also contributes new results and approaches to the field of geomorphology.

Field Observations

Field observations represent a major source of information used to investigate the evolution of debris flow fans. Suwa and Okuda (1983) studied debris flow activity on a fan in the Kamikamihori Valley of Japan because of the high frequency of debris flow events on the fan surface. These authors noted topographical changes as well as processes affecting the fan’s surface through a variety of observation methods that included several cameras (8mm video and 35mm) capturing information at various time-intervals. Iron rods were driven at mesh points every 25 m to make a grid for return visits for measurements as well as fixed rings on the rods to measure the amount of scouring (Suwa and Okuda 1981). Erosional processes dominated the alluvial fan apex (alluvial fan head incision), while depositional and sorting processes dominated in the middle and lower fan sections. Alluvial fan head spreading did not occur as fast as predicted because of the natural levees emplaced from past debris flows (Suwa and Okuda 1981). Channel incision resulted from debris flow erosion (Okuda and Suwa, 1984). Levees formed adjacent to some channel sections. The deposition within the alluvial fan mid-section displayed a higher concentration of boulders and gravel, while the alluvial fan toe was a smoother, flatter surface comprised mainly of sand to pebble-size material (Suwa and Okuda, 1983; Okuda and Suwa, 1984). Over the entire record of observation, deposition extended upstream along the main water-course of the alluvial fan (Okuda and Suwa, 1984).

Suwa and Okuda (1983) also highlighted the role of debris flow lobes in developing topographic complexity. Field mapping and sediment analyses showed that the debris flow lobes were deposited at a number of locations across the entire fan surface. Debris flow lobes in the lower portion of the fan tended to be thinner deposits and produced a flatter topographic pattern.

The upper and middle portions of the alluvial fan tended to be thicker and more rounded debris flow lobes.

Calculations of the “micro-relief” (standard deviation of each transversal section, equivalent to the planimetric profiles in the current study) across the fan indicated a much higher relief along the upper and middle sections of the alluvial fan when compared with the lower section of the alluvial fan (Suwa and Okuda, 1983). This lower deposit depth or lower relief has been noted by Beaty (1963). Below the alluvial fan apex, the deposit depths decrease, as does the sediment size. A similar spatial distribution of material on alluvial fan surfaces has also been identified by Whipple and Dune (1992) and they posit this pattern is controlled by the channels and the physical properties of the debris flows. The size of the incised channel determines the amount of material deposited downslope and flooding (Whipple and Dune 1992, Beaty 1963). Beaty (1963) also noted the coarseness or amount of deposition on a fan surface can also be affected by a blockage. For example, a large boulder can be deposited at any point along the alluvial fan, but most often in the alluvial fan apex or mid-section to create a dam that often causes a change in the directions of subsequent flows on the alluvial fan surface.

Surface water (often referred to as tailwater) is also commonly associated with debris flows, especially those with higher fluid concentrations (Beaty, 1963). The tailwater can cause erosion of the channels. Debris flows with higher fluid concentrations can also lead to debris flow lobe deposition whereby the lobes settle much in the manner of concrete.

Physical Models

Physical models have a long tradition within the alluvial fan evolution literature (Hooke and Rohrer, 1979; Schumm et al., 1987; Zarn & Davies, 1994; Bryant et al., 1995; Whipple et al., 1998; Cazanacli et al., 2002; Davies & Korup, 2007) and date back to seminal research conducted by Hooke (1967). Criticisms of physical modeling approaches used to examine alluvial fan evolution include: scaling issues; the limited use of exogenic controls; and in some instances the limited ability to identify field analogues. Despite these limitations, physical models have provided key information regarding the interactions between debris flow processes and alluvial fan morphometry, and insights into long-term alluvial fan development.

Early physical modeling efforts focused on catchment and alluvial fan relationships as well as alluvial fan-scale morphometric characteristics. Several experiments produced specific morphometric characteristics often associated with debris flows such as levees, lobes, sieve lobes, and debris dams (Hooke, 1967; Zimmermann, 1991). Experimental alluvial fans also provided further support for the concept that larger source areas are associated with lower slopes and that alluvial fan slope varied azimuthally (Hooke and Rohrer, 1979). Variations in alluvial fan slope also produced a high-low effect, whereby sediment deposition builds to an undetermined height and is later diverted to a lower portion of the alluvial fan and subsequent debris flows repeat the process on the lower portion of the modeled fans (Hooke and Rohrer, 1979; Zimmermann, 1991). In general, the modeled alluvial fan surfaces exhibited realistic profiles and alluvial fan slope measurements, with the alluvial fan slopes varying between 4° to 18° in the experimental settings (Hooke, 1967; Hooke and Rohrer, 1979; Zimmermann, 1991).

Later alluvial fan physical modeling experiments have attempted to model flow characteristics of debris flow events as the flow interacts with the fan surface. A major thrust has been to examine the runout distances along the fan surface as well as channel avulsion. Zimmermann’s (1991) experimental work did not yield relationships between debris flow runout distances and debris flow velocity, but the flow events did provide evidence of backfilling behind the surge fronts. This process would be analogous to debris dams often identified in the field. D'Agostino et al. (2010) identified runout distances that far surpassed any recorded at their field sites and attributed this overestimation to scaling and roughness issues that reduced the amount of energy dissipation along the length of the flume and through the runout zone on the fan surface.

Lateral channel shifts were also identified in physical models. After multiple debris flows deposited sediment to an undetermined height, subsequent debris flow events avulsed channels or went from a higher portion of the alluvial fan (often associated with debris flow lobes) and deposited on topographically lower portions of the alluvial fan or flume/stream table (Hooke and Rohrer, 1979; Zimmermann, 1991). This process would then repeat itself and produce the conic alluvial fan shape of an isolated alluvial fan. Lateral channel migration has also been identified in laboratory experiments where the migration occurs much more rapidly in the absence of debris flow levees on the experimental alluvial fans (Suwa and Okuda, 1981). Continuous deposition from multiple debris flows in a laboratory setting has also been shown to build the alluvial fan from one side to another increasing not only the area of the alluvial fan, but also the volume (Hooke, 1967). Coulthard et al. (2002) do not directly mention a “high-low effect”, but signs of this are present in the erosion/deposition results of the Cam Gill Beck alluvial fan. This process of sediment migration from side to side is deemed as the “high-low effect”.

Morphometric analyses from remotely-sensed airborne platforms

Recently, Airborne Laser Scanning (ALS) data have been used to quantify static morphometric features and surfaces on alluvial fans (Staley et al, 2006; Volker et al, 2007; Cavalli and Marchi, 2008; Wasklewicz et al., 2008). Staley et al. (2006) found the depositional patterns on the debris flow fan are dependent on the individual fan system and can deposit at numerous locations. Alluvial fan gradient was also determined to play a significant role in runout distances. Steeper surfaces were more frequently associated with deposition. Lower gradient alluvial fan surfaces tended to have a more frequent fluid flow instead of the viscous flow associated with steeper gradients. Volker et al. (2007) found fan morphometry was quite distinct between debris flow and mixed-flow fans. Mixed flow alluvial fans tend to be longer and wider compared to debris flow dominated alluvial fans. Distinct differences in the topographic complexity of the fan surfaces were also identified at a variety of spatial scales, where the debris flow dominated alluvial fans displayed consistently higher topographic roughness when compared to the mixed flow alluvial fans. Cavalli and Marchi (2008) examined relief maps, plan curvature, and topographic roughness to explore a surface roughness index from ALS data. The profile created from the DTM surface showed much more intricate detail compared to the field profile collected. There tended to be higher surface roughness at the fan apex along with higher values around the channels and levees across the fan's surface.

Morphometric studies from Terrestrial Laser Scanning (TLS)

There have been very few studies to date that employed TLS to investigate debris flow fan dynamics. Schürch et al. (2011) used a combination of terrestrial laser scanning methods with flow hydrograph data to establish a record of erosion and deposition after a series of debris flow events. Schürch et al. (2011) considered results from 14 debris flows, which permit the investigation of 11 DEM of difference surfaces. Debris flow depth was correlated with the magnitude of erosion. As debris flow depth increased, there were correspondingly higher erosion values along the feeder channel and alluvial fan. Debris flow depth caused significant force at the debris flow front that perpetuated higher: basal shear stress; impact stresses from coarse particles recirculating at the debris flow front; and hydraulic pressure at the debris flow front from rapid undrained loading and liquefaction of the channel bed. These characteristics are important factors in debris flow fan evolution. The higher the magnitude of a debris flow the more incision or erosion will occur at the fan front (apex), along with the feeder channels enlarging because of an increase in fluvial movement. This increase in magnitude can initiate the migration of channels, thereby changing the alluvial fan dimensions.

Variations in Alluvial Fan Roughness

Surface roughness is a common measure calculated and analyzed in geomophometric studies. ALS surveying methods have given reliable and accurate spatial resolution to examine varying spatial and temporal scales of surface roughness. Surface roughness is an essential land-surface parameter (Grohmann et al., 2010) and an important habitat characteristic (Zawada and Brock, 2009). Grohmann et al. (2010) describes six methods for deriving surface roughness that are dependent upon scale and spatial resolution. The six measures of surface roughness include: area ratio, vector dispersion, standard deviation of residual topography, standard deviation of elevation, standard deviation of slope, and standard deviation of profile curvature. The standard deviation of slope was found to more accurately represent topographic complexity (identifying both smooth surfaces and breaks-in-slope) and was hypothesized to provide the best results for geomorphological analyses. Frankel and Dolan (2007) provided an example of the application of surface roughness using the standard deviation of slope. These authors examine variations in surface roughness within different alluvial fan segments. Alluvial fans in Death Valley, California, USA had lithostratigraphic ages ranging from Q4b (active surface) to Q2a (oldest and higher topographic surface). Surface roughness measurements were taken at the center of each alluvial fan unit to remove conflation of values from steep channel walls. Each scale of surface roughness was different from one another at the 99% confidence level. Their results showed that with increasing age, the surface roughness of the alluvial fan tends to smooth out up to 70 kya.

After 70 kya, surface erosion increased via secondary processes acting on the alluvial fan surface.

Fan Toe Variability

Hashimoto et al. (2008) provide an extensive analysis of morphometric differences from alluvial fan toes in Japan and the Southwestern USA. Alluvial fan toes tended to be well preserved in an arid climate, while under more humid conditions they are in constant flux. Most of the redistribution of sediment on the alluvial fan toes in humid climates is accredited to rivers in close proximity to the fan toe. The rate at which sediment is relocated on the humid alluvial fan toes depends on the magnitude of the water source, proximity to a fluvial source, and amount of rainfall. The morphometric characteristics of the alluvial fan toes varied more frequently in Japan because of the increased slope in which debris flows occur. Japan has a much more dynamic environment for debris flows, which creates a higher debris flow frequency. Alluvial fans in an arid environment with the absence of high frequency of fluvial processes; tended to have a steeper slope. The steeper slope of alluvial fans may come from a larger grain size from the source area because of the lack of fluvial processes to enhancing weathering processes. If there is a lack of fluvial processes interacting with the fan’s surface, then the larger grain sediments will accumulate, creating a steeper slope.

Research Questions

The research goals for this study are designed to validate previous approaches, and contribute new techniques and knowledge to the field of geomorphology. The alluvial fan located at Chalk Cliffs, CO provides an ideal setting for showing the short-term effects of debris flow and alluvial fan interactions, how these results compare to different locations, and how fan toe dynamics affect the evolution of the alluvial fan. . These conditions found at the sight provide the opportunity to address several questions that will aid in our understanding of alluvial fan dynamics. These include:

Q1 – What are the short-term changes to an alluvial fan experiencing frequent debris flows?

Initial field observations after each debris flow and pilot results from the first debris flow event lead to the to hypothesis that the alluvial fan surface under investigation will continue to be dominated by deposition. The debris flow deposits will be constrained to only a small proportion of the entire alluvial fan surface and develop a high-low effect as hypothesized in the physical models by Hooke (1967) and Hooke and Rohrer (1979). As such, it is hypothesized that there will only be limited erosion within the channel, but not to the extent evidenced by Suwa and Okuda (1984).

Q2 – How (dis)similar are the short-term alluvial fan changes at the Colorado Natural Debris Flow Laboratory to findings at other locations?

This is relatively larger overarching question that has pervaded the alluvial fan literature for some time. As such, I can examine all aspects of the question. Instead the focus is on two more specific research questions:

Q2A Does the degree of surface roughness remain constant over a short period of time after multiple debris flows?

Field observations and pilot results lead me to hypothesize that the alluvial fan surface will smooth over the surveying period. The hypothesis runs counter to previous work that has suggested recent debris flows create rougher surfaces (Frankel and Dolan, 2007; Scheidl and Rickenmann 2010).

Q2B How much variation in the fan toe occurs and does this influence subsequent flows?

The study site in Colorado provides an ideal location to study active variations in alluvial fan toe erosion as the alluvial fan abuts Chalk Creek. Hashimoto et al. (2008) concluded secondary erosional processes resulting from adjacent master streams play an important role in the determination of alluvial fan topography along with a strong sediment redistribution rate. Shifts in the Chalk Creek channel will likely play a role in the development of the alluvial fan.

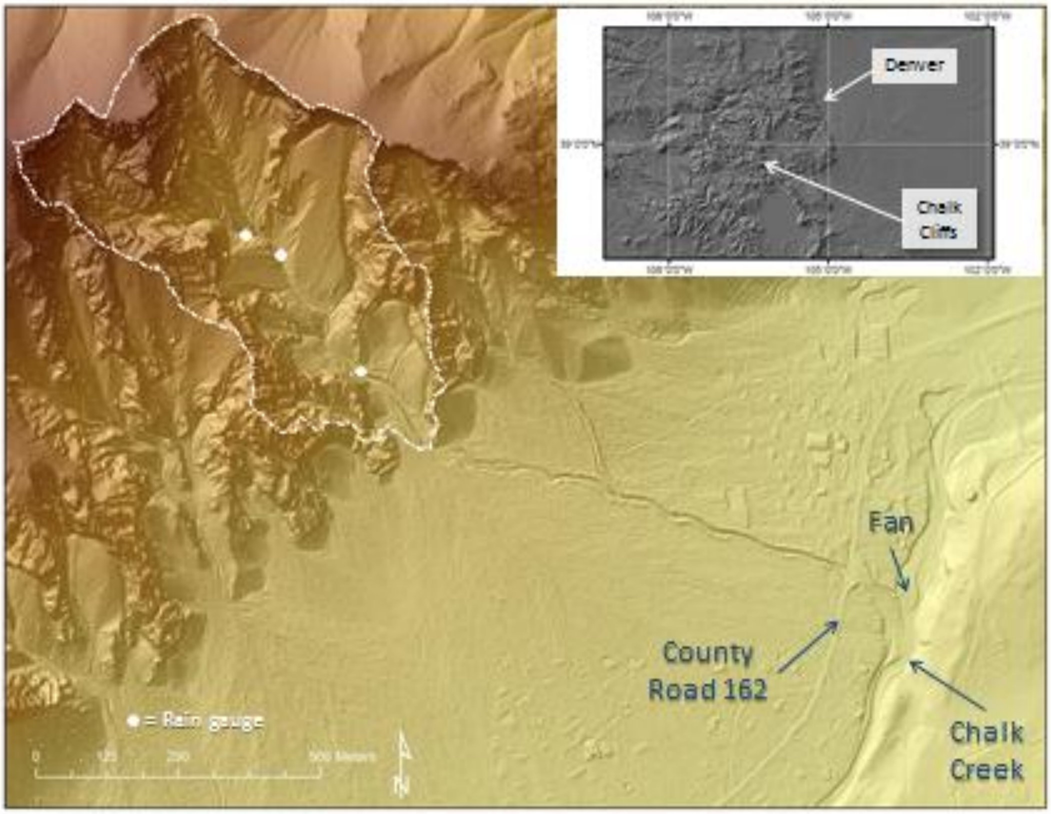
Regional Setting

Study area

The research is conducted in the vicinity of Chalk Cliffs, which is located in the Sawatch Mountain Range of Colorado (Fig. 7). Chalk Cliffs is part of the Mount Princeton batholith and consists of highly fractured and hydrothermally altered quartz monzonite (Coe et al, 2008). Chalk Cliff sits on the northern extent of the Rio Grande Rift and normal faulting is a dominant component in the generation of relief. Hot springs are located along the fault line adjacent to the range. The hot springs are a remnant of a hot water system that contributed to the hydrothermal alteration of the monzonite that composes Chalk Cliffs area.

The source area for the alluvial fan under investigation is a small semi-arid drainage basin (drainage area of ~0.3 km^2). Many slopes in the upper and middle portions of the drainage basin are at the angle of repose. There is exposed bedrock throughout a large portion of the drainage basin. The elevation of the east/west basin confluence is 2767 m and the elevation for the fan is 2519 m. The alluvial fan has developed from channelized debris flows, where the older bajada was channelized to protect adjacent houses from debris flows.

Figure 7- The Study Location and Site



Debris flows are the dominant alluvial fan formative process in the Chalk Cliffs vicinity. The debris flows form via a “fire-hosing” effect in the upper portion of the basin (Coe et al. 2008). Further materials are added to the flow via progressive bulking of materials along the channel in the drainage basin (McCoy et al. 2010) as well as the channelized flow through the bajada (evident from field observations). Short term rainfall initiates the majority of the debris flows captured in the study area of Chalk Cliffs, CO (McCoy et al. 2011). Not all debris flows from the basin arrive on the fan surface; in 2009 only one of the four debris flows debouched onto the fan surface. The other three events were stored in the upper and middle sections of the channel above the alluvial fan. Some data for these events are not available because the gauging stations in the upper basin were either wiped out by the event or were not working. The data was collected from instrumentation located coincident with the upper rain gauge site on the site map (Fig. 7, Table 3). The original alluvial fan surface was collected on May 29, 2009 (at the time of the first TLS survey) with an area of 3192 m^3. Table 3 shows the debris flow date and the actual date of TLS collection (McCoy et al. 2010, McCoy et al. 2011 and Coe et al, 2010).

Table 3- Debris flows and associated information monitored during this study (Modified from McCoy et al. 2010, McCoy et al.2011 and Coe et al, 2010)

Debris flow Date	Collection Date	Rainfall (mm)	Volume of flow in upper basin(m^3)
Initial surface	5/29/2009		
9/15/2009	9/27/2009	25	1100
Second season surface	5/31/2010		
6/2/2010	6/3/2010	No data	No data
6/28/2010	7/9/2010	19	2800
7/29/2010	8/19/2010	No data	No data
6/30/2011	7/14/2011	11	900

Materials and Methods

Field sampling

An initial scan of the alluvial fan surface occurred on May 29, 2009. A Leica Scanstation 2 was used for the first two scans and a Leica C10 scanner has been used to collect high-resolution data subsequent to the initial scans. The scanners were set up on a tri-pod and powered with a generator or batteries. The scanning parameters were developed in Leica HDS Cyclone v 6.x and 7.x software on Dell XFR D630 and XFR D640 laptops that were connected to the scan head via a TCP/IP or wireless connection. Point cloud data were stored on the laptops. The Scanstation 2 and C10 scanners have a full-dome field-of-view and ranges of ~300m. A rotating mirror directed pulsed laser light to the fan surface and the laser light reflected back to the station. Each return was recorded as a series of x, y, z, and i values.

Common reference points (a combination of temporary and permanent 6” planar circular Leica targets) in the field of view (FOV) were used to register multiple point clouds gathered from various scanning positions. The scanner must be placed in various locations to reduce the amount of shadowing from objects in the FOV and to be able to scan a large area. In the current study, six target positions were used with three permanent and three non-permanent target locations. Rebar was placed in the ground and a small hole drilled in the top of the rebar for the center tripod pole to continually be placed in the same spot for future scans. The temporary targets are set up on tri-pods at various locations on the alluvial fan surface depending on the alluvial fan topography and FOV. The placement of the scanner at various locations enabled the creation of a 2.5-D view of the alluvial fan. All of the scans performed during this study had a maximum scanning distance of between 50-75 meters. All registrations were performed in Cyclone software with registration errors not exceeding 3mm.

The original fan was scanned on May 29, 2009 (beginning of the 2009 season surveying campaign). Scanning campaigns performed after the original scan were as follows: September 27, 2009 (after a debris flow [adf]), May 31, 2010 (beginning of 2010 season surveying campaign), June 3, 2010 (adf), July 9, 2010 (adf), August 19, 2010 (adf), and July 14, 2011 (adf). During each campaign, at least six positions were occupied with the TLS to produce a comprehensive point cloud of the alluvial fan. Each registered point cloud was exported as a text file, imported to ArcGIS 10.x a multipoint feature, converted to a TIN, and converted to a digital terrain model (DTM) via a linear interpolation methods (Wheaton et al., 2010). Each DTM possessed a 5cm planimetric resolution and had vertical resolution of 0.01cm.

Longitudinal and planimetric profiles

Longitudinal and planimetric profiles are generated using the EZ Profiler extension. Five hundred points have been collected for each profile across the fans. The longitudinal profile indicates how elevation changes over the distance down the extent of the fan. Longitudinal profile locations are at 35 degrees (long5), 60 degrees (long4), 95 degrees (long3), 130 degrees (long2), and 170 degrees (long1). Planimetric profiles are taken at 10%, 25%, 50%, 75%, and 85% along the longitudinal profile. Profiles are calculated for all the seven events at the exact locations for comparative purposes.

DTM of difference and volumetric measurements

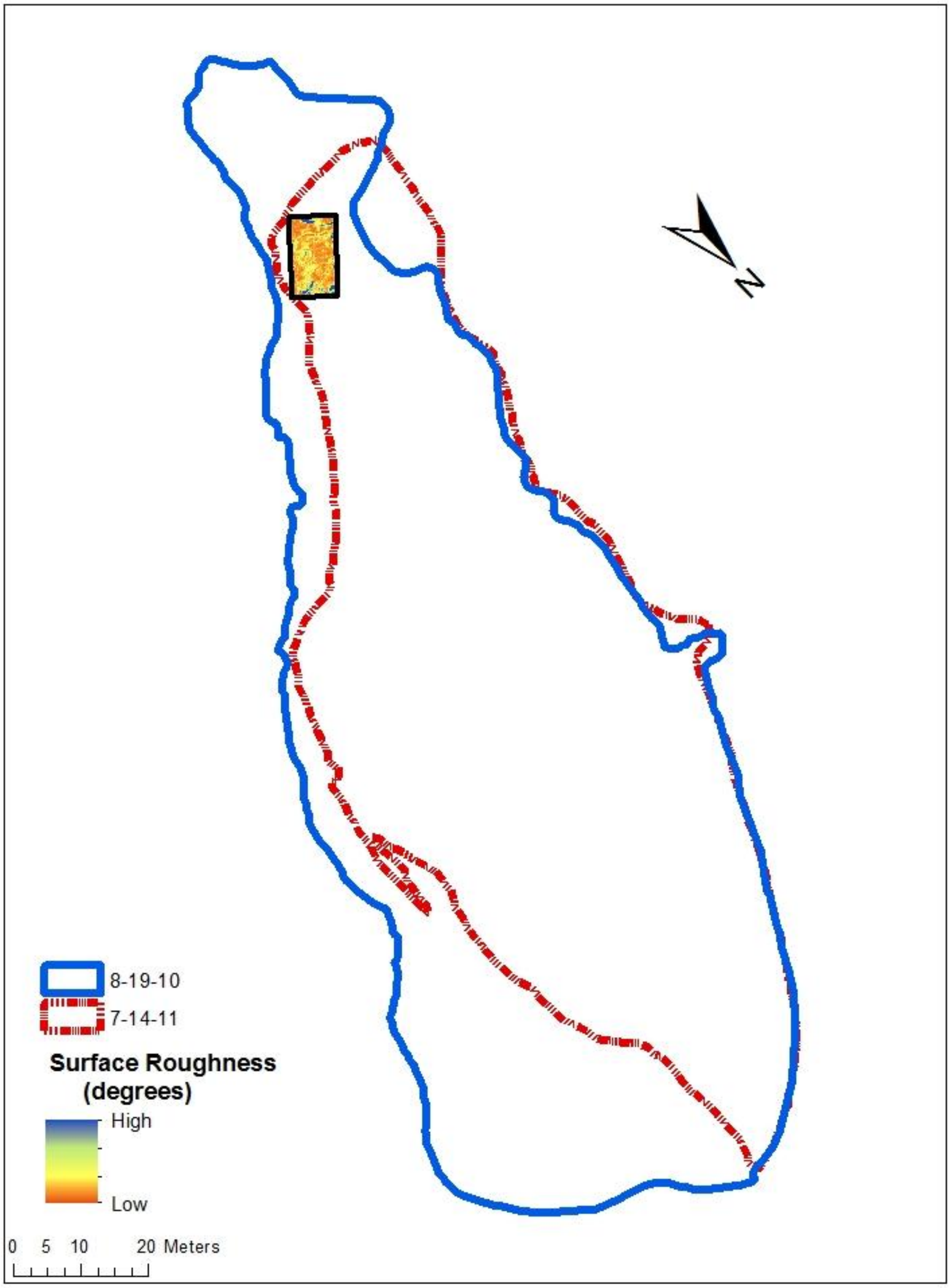
A DTM of difference is developed from the fan prior to and after each individual debris flow. The DTM of difference techniques follow methods in Wheaton et al., (2010). The general principle of this approach is two DTM's of the same planimetric resolution are subtracted to produce an elevation difference between each event.

Volume measurements are attained through multiplying the elevation difference by the cell resolution (0.05m x 0.05m) and then summing each cell where material was eroded or deposited on the alluvial fan surface. The debris flow extent is mapped for each event using heads-up digitizing. The boundary of the debris flow extent is used to mask the volume surface and acquire the volume measurement for each event

Surface Roughness Measurements

Surface roughness is derived from all the surveys by calculating the standard deviation of slope (Frankel and Dolan, 2007). Surface roughness is investigated at several window sizes (0.2m, 0.3m, 0.4m, 0.5m, 1m, 5m, and 10m) for each event. Measures of surface roughness are gathered from ~500,000 grid cells for each event. These measures are plotted as an average roughness value to consider 5D (space + time + scale) differences in surface topography. Surface roughness is selected from the same area (the original fan depositional area) for each event to remain consistent with the first event and to produce uniform results. An additional surface roughness analysis is conducted on the southeast section of the fans to compare results of the last two events (new sediment) with previous events to determine if there are any different surface roughness patterns on newly developed fan segments. The surface roughness of the new fan segment (Fig. 8) is created by using a 5m by 8m rectangle to extract the data into the rectangle in ArcGIS ArcMap10.

Figure 8- Surface Roughness Location of New Segment



Fan toe dynamics

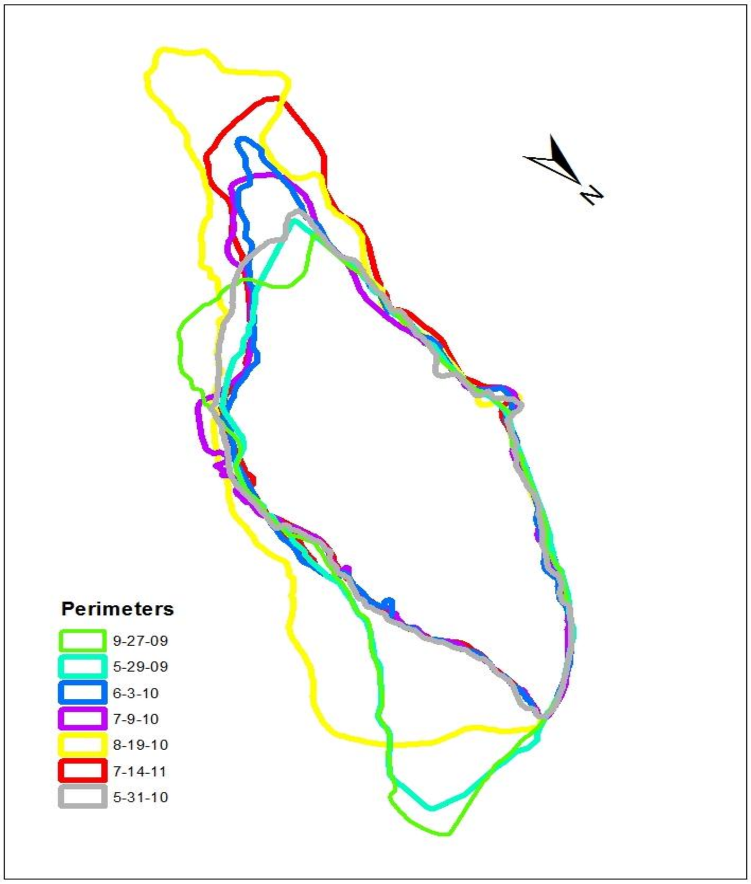
Fan toe erosion and deposition are measured volumetrically on an event-to-event basis, and because of vegetation and discharge, finding a common reference point between each event is difficult. The reference points for determining the fan toe dynamics were based on physical and biological structures adjacent to either end of the fan toe. Volume measurements differ from those previously described in the DTM of difference section. Volumes of the fan toe are calculated directly from each point cloud. Leica's Cyclone Software v 7.x is used to configure a reference plane between all the events using the reference plane function. The reference plane function was used from the top of the fan toe to the adjacent bank with evidence of debris flow deposits. The point cloud is converted into a mesh surface (a triangulated solid surface). Volume measurements are taken by setting the reference plane for each event and are based on the amount of erosion to the fan's toe below the common reference plane.

Results

Alluvial fan dimensions and profiles

Alluvial fan perimeters throughout the monitoring process fluctuated from being elongated to being eroded back closely to the original size between each event (Fig. 9). The perimeters of each fan provide valuable insight into the debris flow fan development. 5-29-09 to 9-27-09 has a new lobe of deposition on the southeast side of the fan and remnants of concave shape associated with erosion from the meandering of Chalk Creek. Significant erosion on the northeast section of the fan along with minor geomorphic changes to the southerly end occurs between 9-27-09 to 5-31-10. Minor changes to the northeast fan toe and concave shape erosion on the southeast end are evident after the debris flow on 6-3-10. Deposition from this event occurs on the southern end as evidenced by the protruding feature in this locale. The alluvial fan perimeter is slightly modified from 6-3-10 to 7-9-10 with erosional rounding on the southern end and fan toe extension on the east side. Significant changes in perimeter occur between 7-9-10 to 8-19-10. A convex lobe of deposition is evident on the northeast side of the alluvial fan. The new deposit is also associated or concomitant with a northerly migration of the channel. The south end of the fan has also significantly extended and enlarged the fan area. The last survey 8-19-10 to 7-14-11 showed that the previous alluvial fan perimeter was reduced as Chalk Creek eroded the fan toe.

Figure 9- Perimeters of each event



Longitudinal and planimetric profiles further highlight the spatial variability of the debris flow deposition and erosion for each event. The channel profiles (Fig. 10) show a decrease in elevation until 6-3-10 with significant deposition and then a gradual increase in elevation until a large event on 8-19-10. The extension of the channel over time is also shown by the channel profiles. The longitudinal profiles show that the greatest surface variability (indicated by elevation difference) occurred at the channel (Fig. 11). The greatest surface elevation change was seen in profile 1 at 22m distance after 7-14-10 event with almost two meters of deposition. Profile 4 and 5 showed very little change on the majority of the profile except for the new material going past the drop off from previous fan surfaces. This is because a majority of the profiles were taken beyond the active area impacted by the debris flow. Planemetric profiles are relatively uniform on the overall shape of the profile even though there is an elevation difference, except for the last two events which are elevated and elongated from the others (Fig. 12). Profile 25% shows the least amount of variability between events. The uniform shape of the profiles starts to decrease Profile 50% because surface variability increases on the northeast portion of the alluvial fan. Profile 75% shows the greatest elevation difference because of the deposition that took place on the 8-19-10 event. The morphometry (topographic variability) of the planimetric profiles at 25% and 50% keep a relatively uniform shape downslope between the surveys. Elevations at these locations were raised slightly as the alluvial fan aggraded from the debris flow. Planimetric profiles 75% and 85% showed the greatest morphometric variability after the debris flow. Profile 75% shows the greatest elevation difference between surveys with almost 2 meters of elevation at the 60m distance. 8-19-10 is definitely an outlier with regard to the 1m elevation gain as seen in the 75% profile between the 40m to 80m distance compared to the 9-27-09 event. 8-19-10 at the 85% profile has the highest coverage displayed by the distance and the highest elevation at the 70m distance. The 75% and 85% profiles for 8-19-10 show the greatest topographic variability compared to all other recorded events (Fig. 12).

Figure 10- Channel Profiles

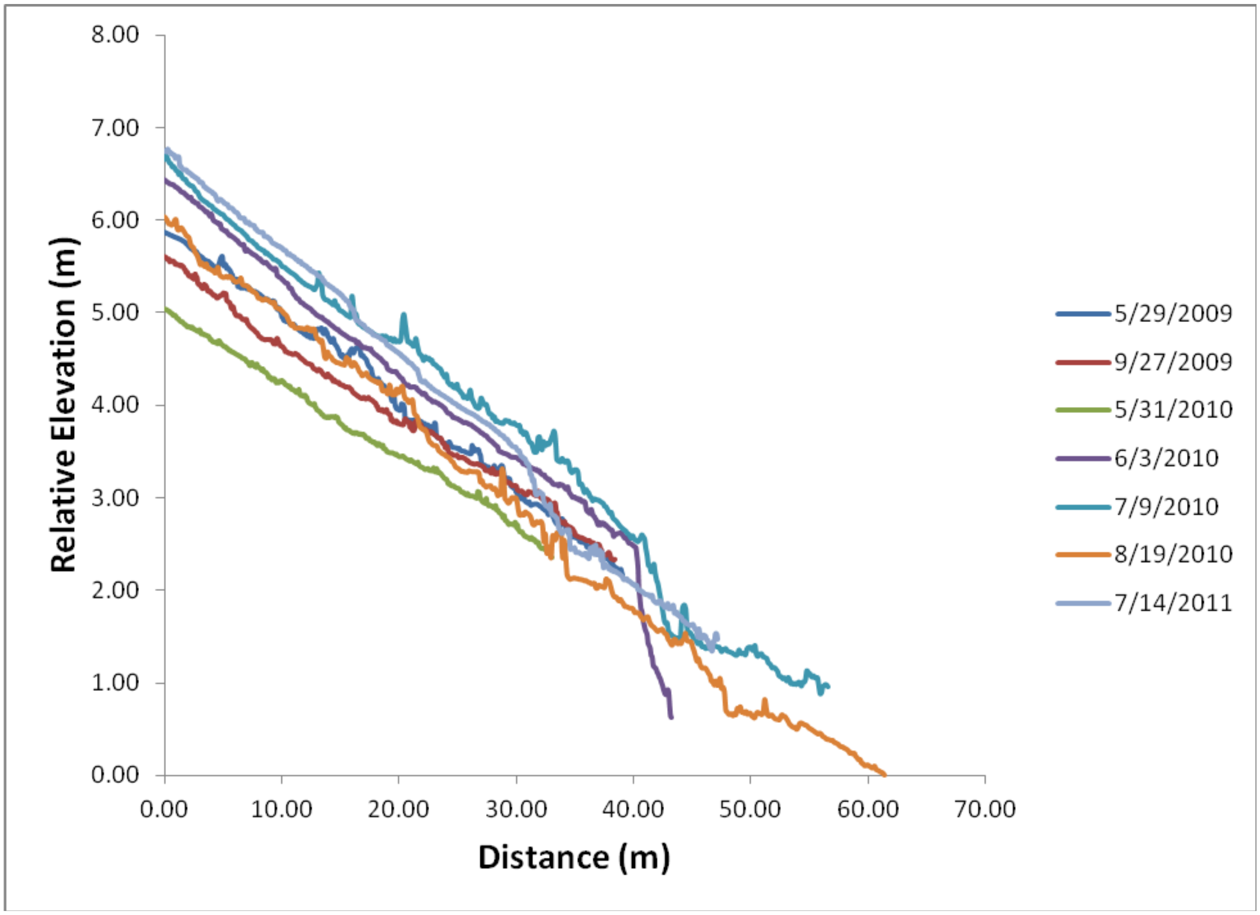


Figure 11- Longitudinal Profiles

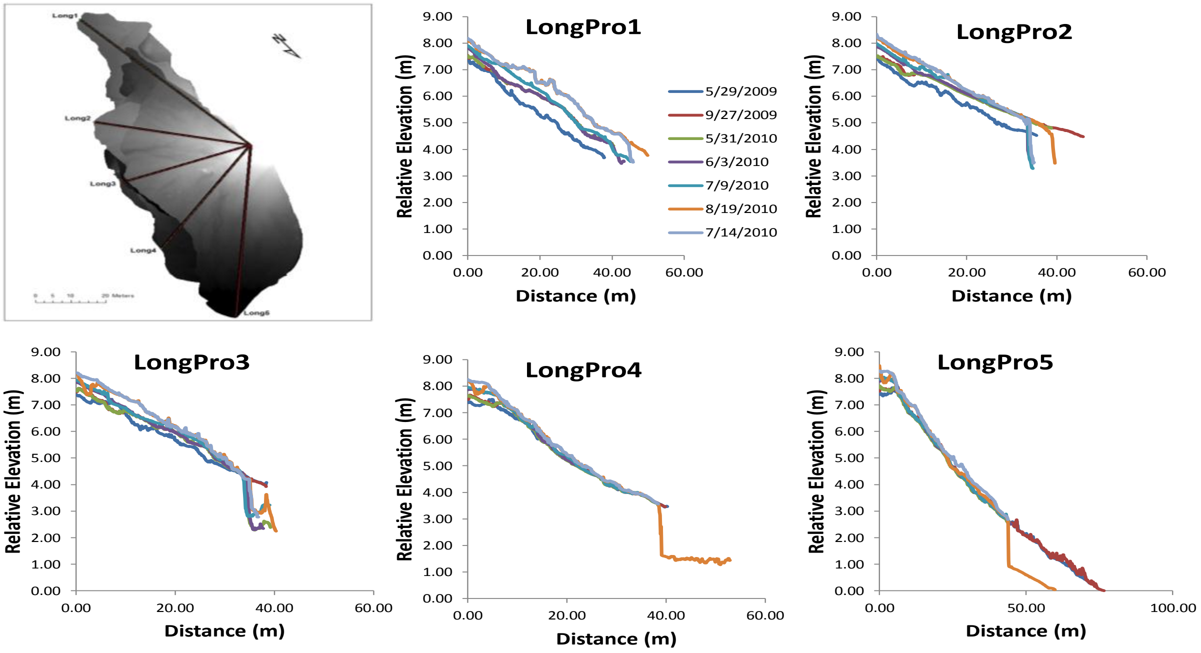
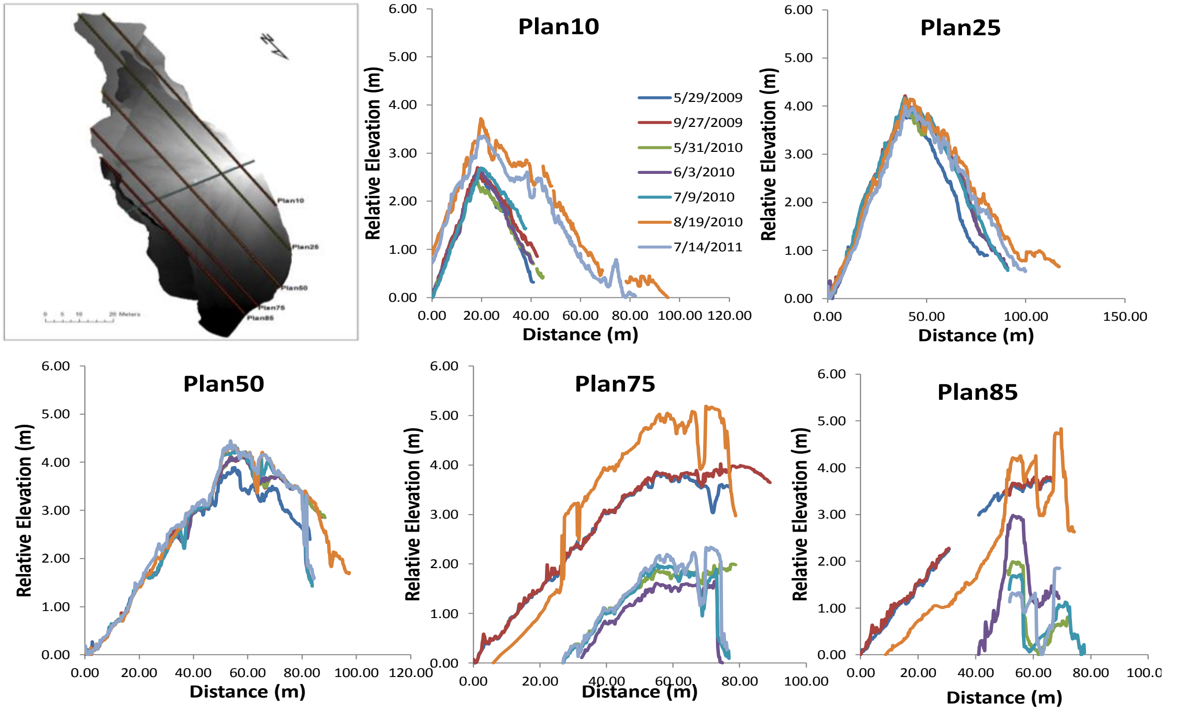


Figure 12- Planemetric Profiles



DTM-of-difference and volumetric changes

From event 5-29-09 to 9-27-09 the volumetric changes resulted in an increase of fan area by 309 m^2. Total deposition across the fan surface was 390 m^3 and total erosion was 6 m^3. A majority of the erosion was associated with the main channel. The maximum depth of deposition was 1.06 m and maximum erosion depth was 0.46 m (difference model [Fig. 13]) Erosion is most prominent along the channel. Deposition was greatest adjacent to the channel and drops off the farther away from the channel.

The alluvial fan from the event on 9-27-09 to the beginning of the new season on 5-31-10 lost 7122 m^3 with limited deposition. The alluvial fan area decreased by 1046 m^2 (Fig. 14). These significant changes to the fan dimensions are tied to melt water flooding along Chalk Creek and do not reflect debris flow and alluvial fan interactions.

The next debris flow produced 68.15m^3 of deposition and 55.39$m^3$of erosion (5-31-10 to 6-3-10), with a majority of the erosion occurring along the alluvial fan toe (Fig. 15). There was a total gain of 1394 m^3 after the debris flow with only a 15m^2 in total area gained. The deposition was highest at the alluvial fan apex and tapered off midway down the alluvial fan surface (Fig. 15).

The alluvial fan surface starts to show substantial deposition after the next debris flow (6-3-10 to 7-9-10). A total of 172.25m^3 of material was deposited, while 32.86m^3 was eroded during this event. Morphometric changes are confined on the alluvial fan surface with little area difference because of an area gain of only 33m^2 with 1043.67m^3 of newly deposited sediment as seen by the perimeters (Fig. 16). Deposition was prominent along the main channel, as well as along either side of the main channel.

The greatest amount of difference occurs between 7-9-10 and 8-19-10 when compared with previous surfaces. There was 575.69 m^3 of deposition and 22.07 m^3 of erosion (Fig. 17). There are significant changes to the alluvial fan morphometry with this event, a volumetric gain of 12,971m^3, and an area gain of 1311m^2. Erosion was confined to the channel, with deposition prominent on the upstream (Chalk Creek) end of the alluvial fan.

The next TLS survey (8-19-10 to 7-14-11) represented a longer period between scans. The time interval represents a meltwater season followed by a large debris flow. The total change to the alluvial fan surface during this time was 115.9m^3 deposition with 73.59m^2 of erosion (Fig. 18). Of greater importance is the large loss in alluvial fan volume (1,698.48 m^3) and decrease in area (1049m^2). These significant changes in area and volume result from the erosion of the alluvial fan toe from flooding along Chalk Creek.

Figure 13- DTM-of-Difference for 5-29-09 to 9-27-09

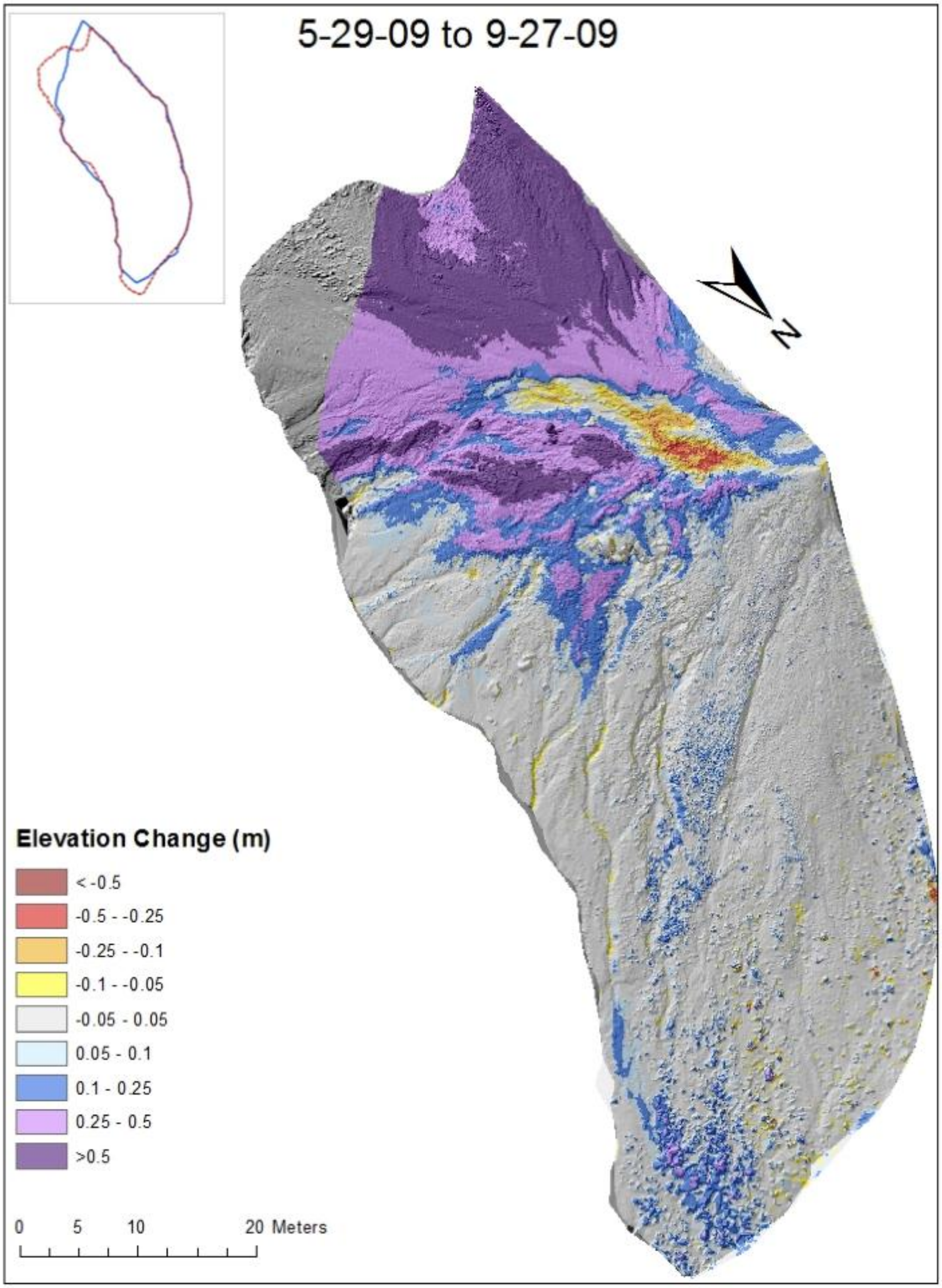


Figure 14- DTM-of-Difference for 9-27-09 to 5-31-10

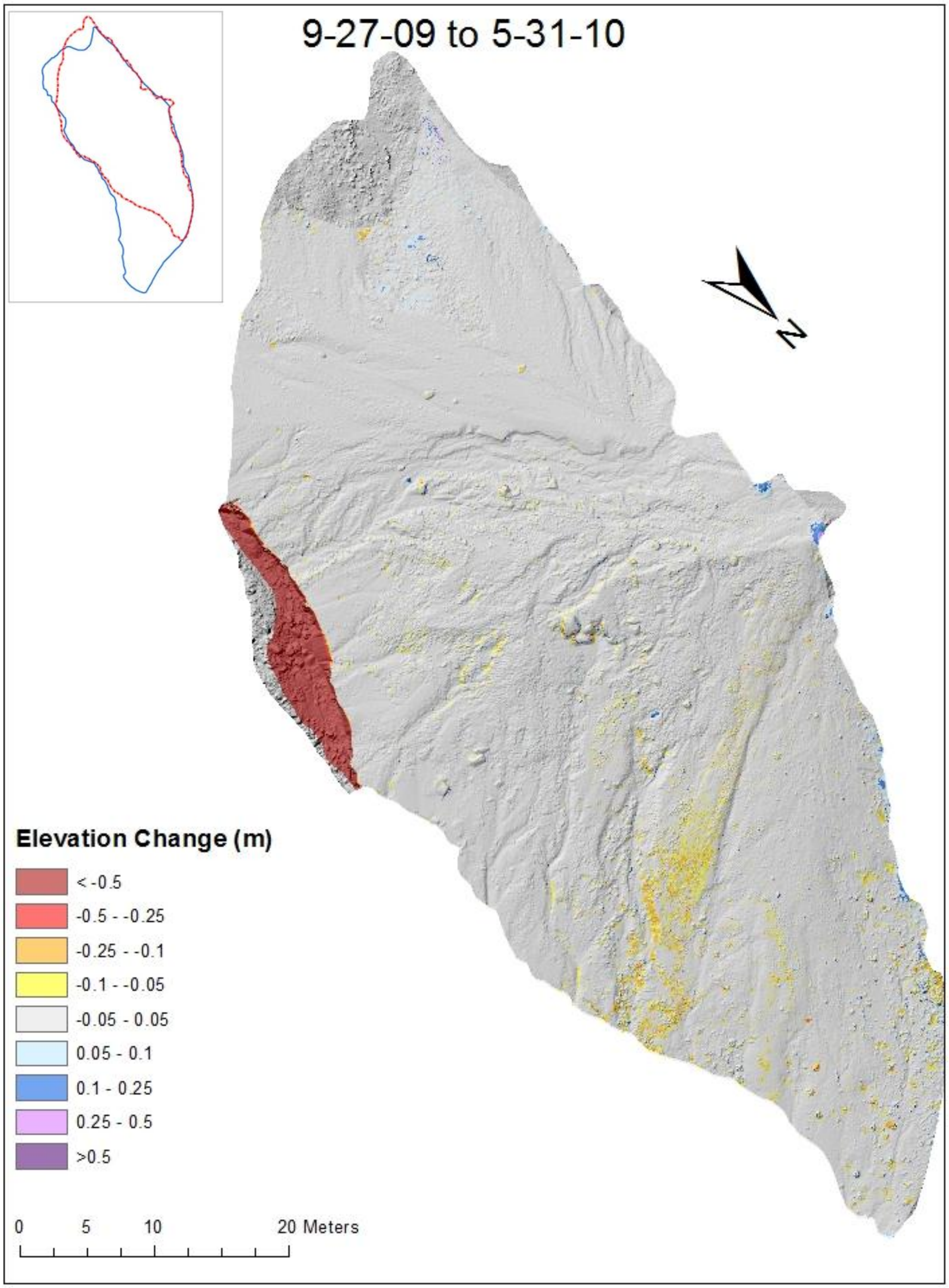


Figure 15- DTM-of-Difference for 5-31-10 to 6-3-10

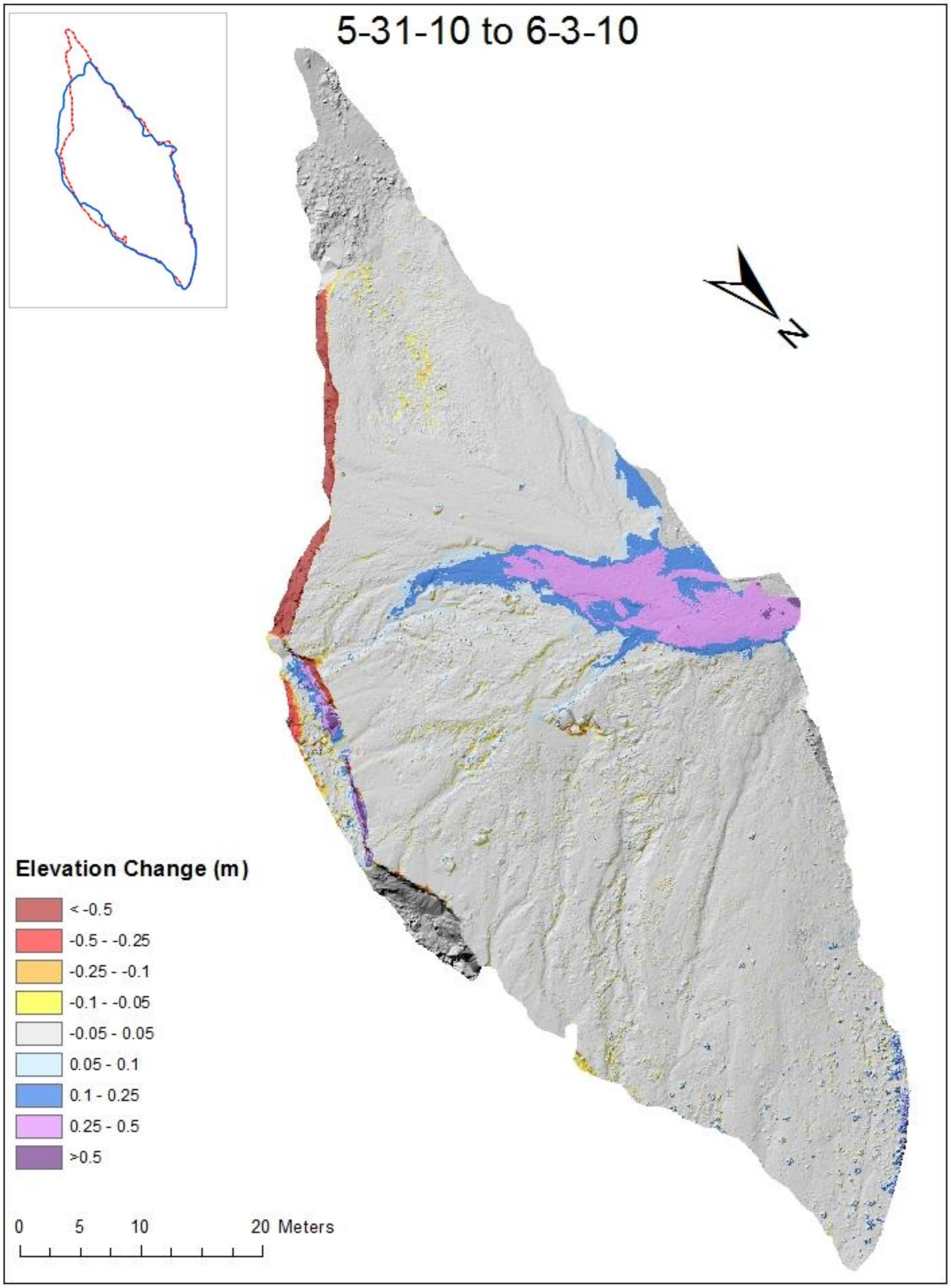


Figure 16- DTM-of-Difference for 6-3-10 to 7-9-10

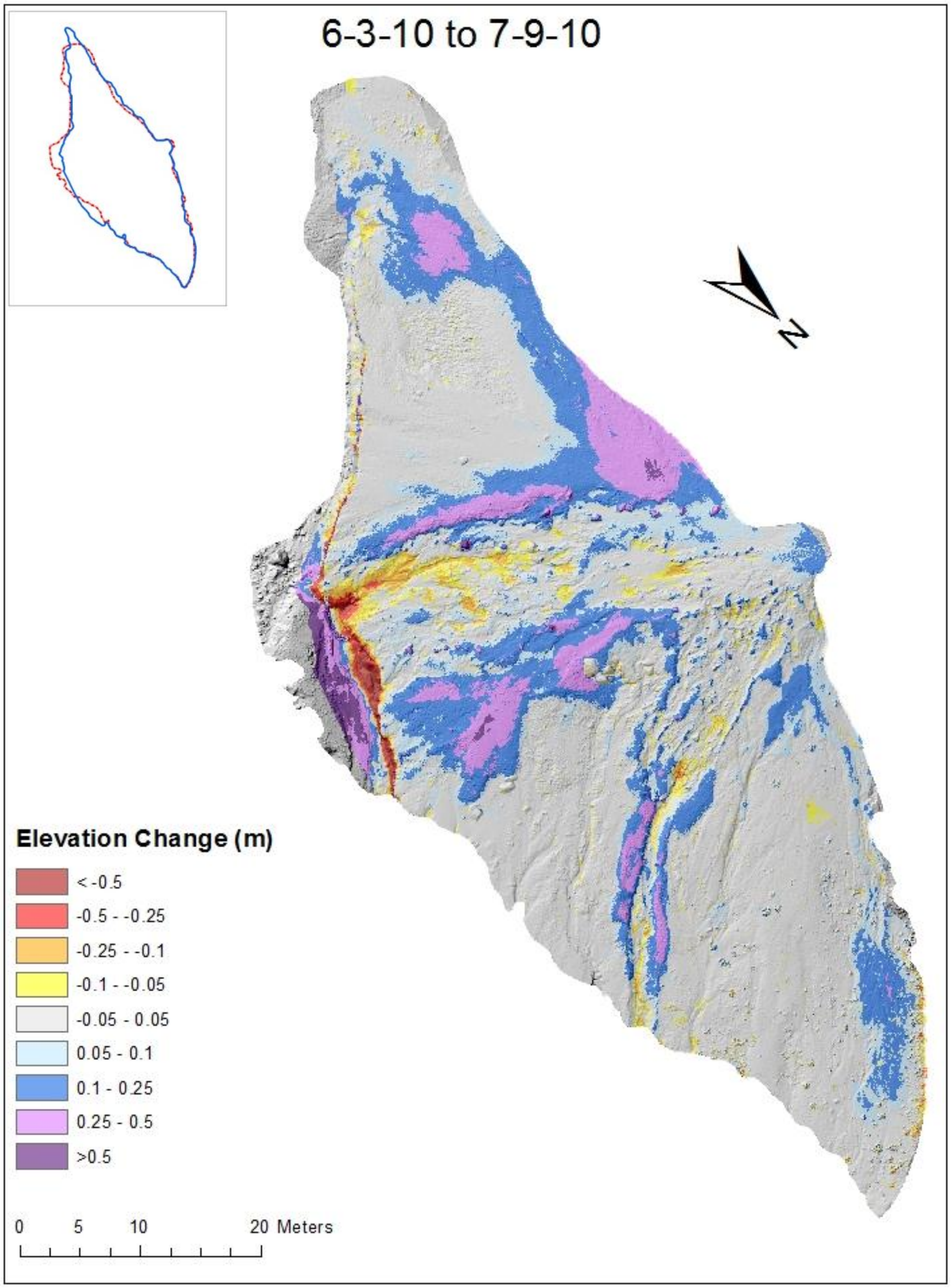


Figure 17- DTM-of-Difference for 7-9-10 to 8-19-10

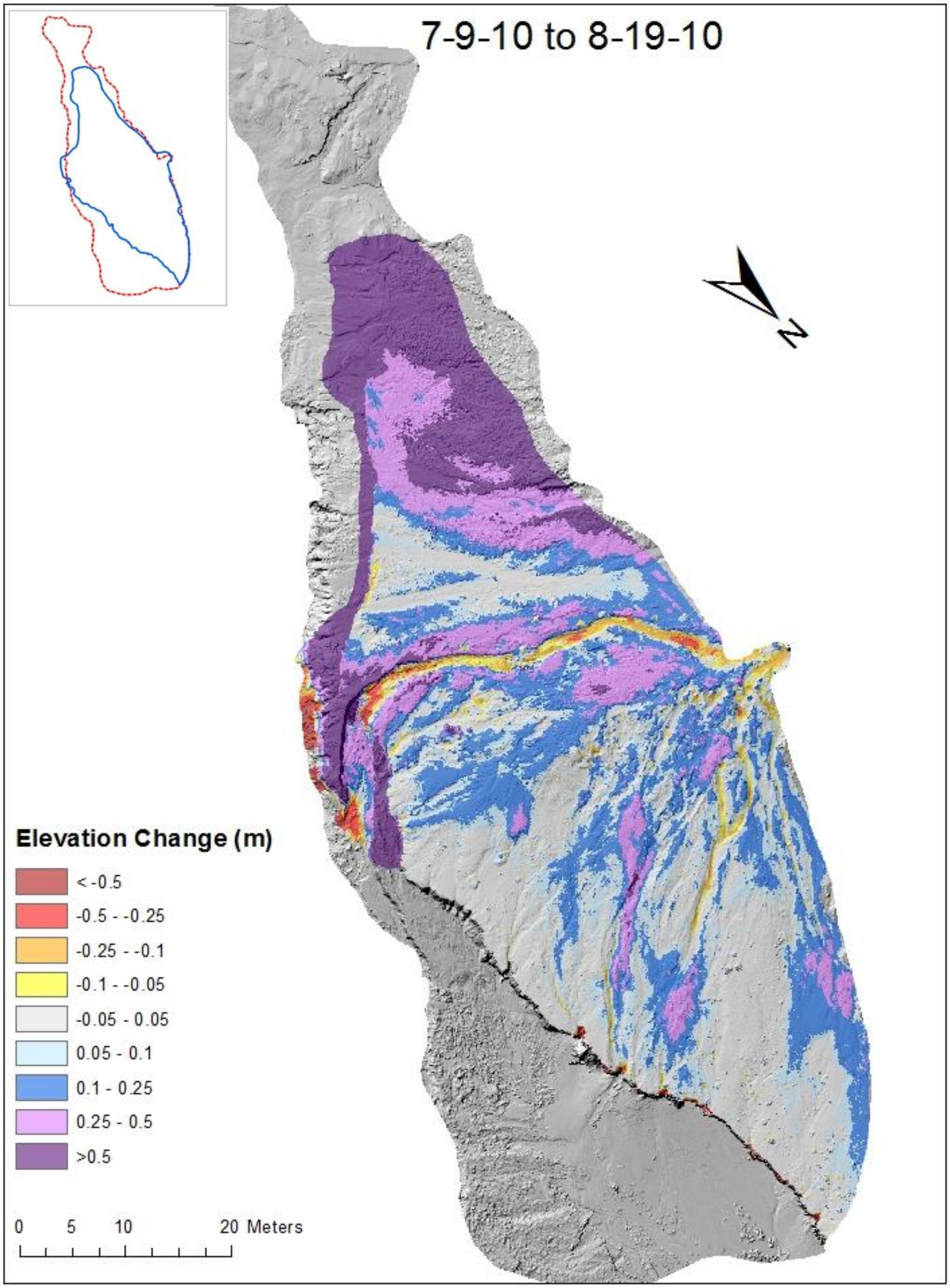
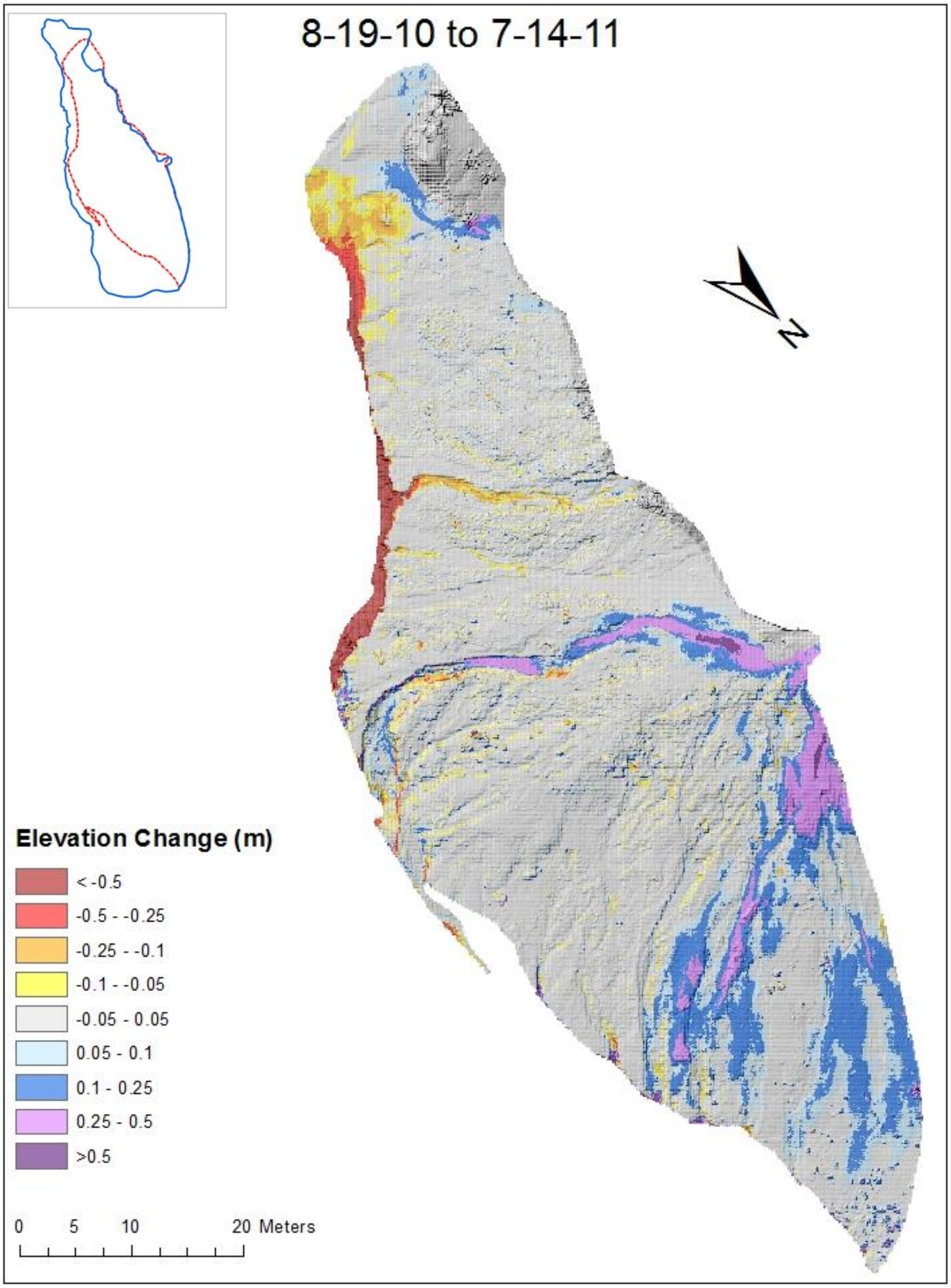


Figure 18- DTM-of-Difference for 8-19-10 to 7-14-11



Surface Roughness

Surface roughness for all scales from event 5-29-09 to 9-27-09 showed a significant smoothing trend after the debris flow (Fig. 19). Smoother surfaces are confined to outside the main channel where the lobe of material deposited and surface sediment of the debris flow deposit contained much finer particles than were evident in the channel. Surface roughness tended to be higher in the channel at all spatial scales after the debris flow (09-27-09). The next three alluvial fan surfaces remain smoother when compared to the initial scan surface (05-29-09), except for the debris flow on 07-09-10 (Fig. 25) where the roughness increases at the larger scales of measurement. The larger scale sizes, where roughness had increased, reflect the addition of several large boulders deposited on the surface as well as modifications to channel dimensions of the alluvial fan surface. The higher surface roughness was generally confined around the channel and on the fan toe, but necessarily in the channel. The alluvial fan surface after the next debris flow (scanned on 8-19-10) showed a large increase in surface roughness (Fig. 26). The surface roughness values dramatically increased from this event, the largest recorded during our monitoring (Fig. 19). The higher surface roughness values were almost completely confined in the initial main channel and erosion was located along other secondary channels as the flow and/or tailwater overtopped the main channel (Fig. 27).

Surface roughness from newly developing fan segment was also examined (Fig 20 & 28). The surface roughness was only derived from the last two events because those events were the only ones present in that new area. The new portion of the alluvial fan surface from 8-19-10 showed some of the lowest (smoothest) surface roughness values (2.28 at the 20cm scale) compared to the lowest values of the previous series of 4.33 at the 20cm scale (Fig. 20). The second highest surface roughness values at the 20cm scale occurred on 7-14-11 when compared to all the fan surfaces. At the 1m scale, 7-14-11 fits directly between the end of the first 5 events and the beginning of the last two events with a value of 9.03 (Fig. 19). The surface roughness values (Fig. 20) of the new sediment correlate with the larger sample size in that the surface roughness increases significantly from 8-19-10 to 7-14-11.

Figure 19- Surface Roughness Statistics

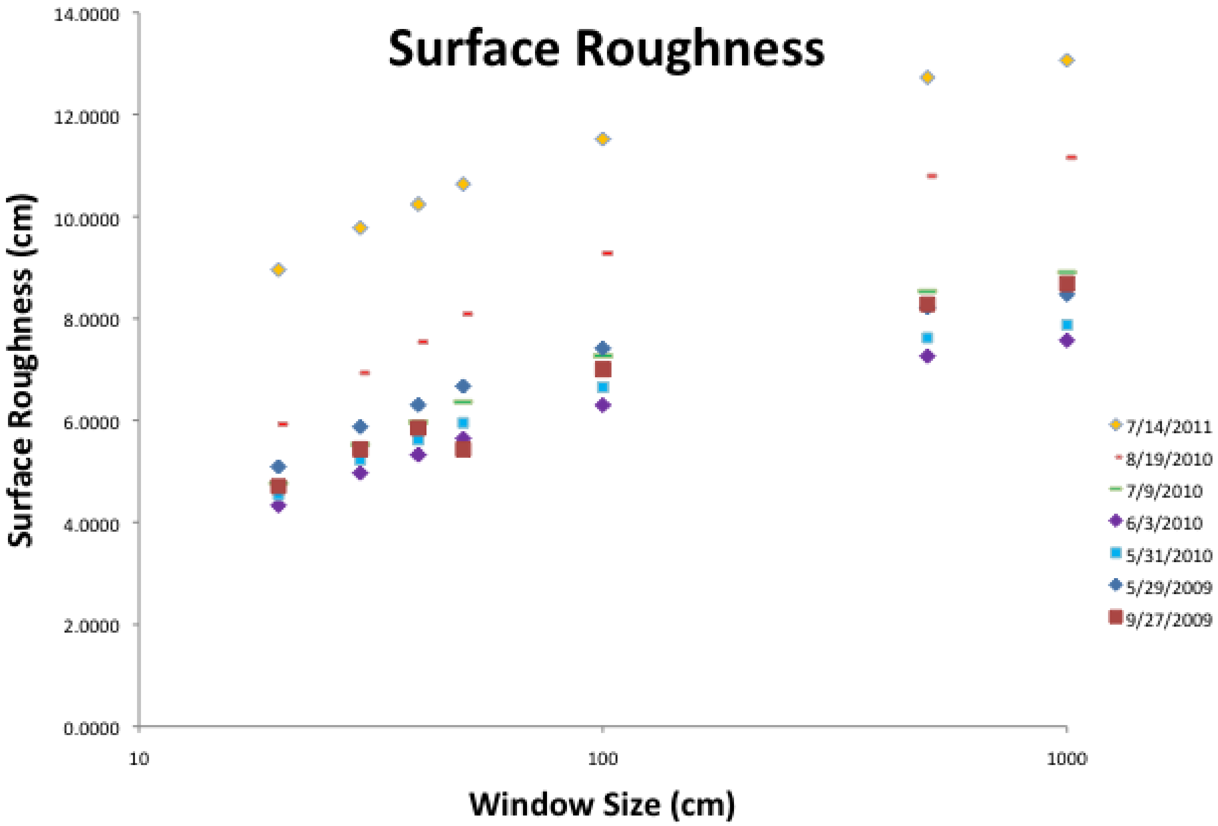


Figure 20- Surface Roughness Statistics for New Segment

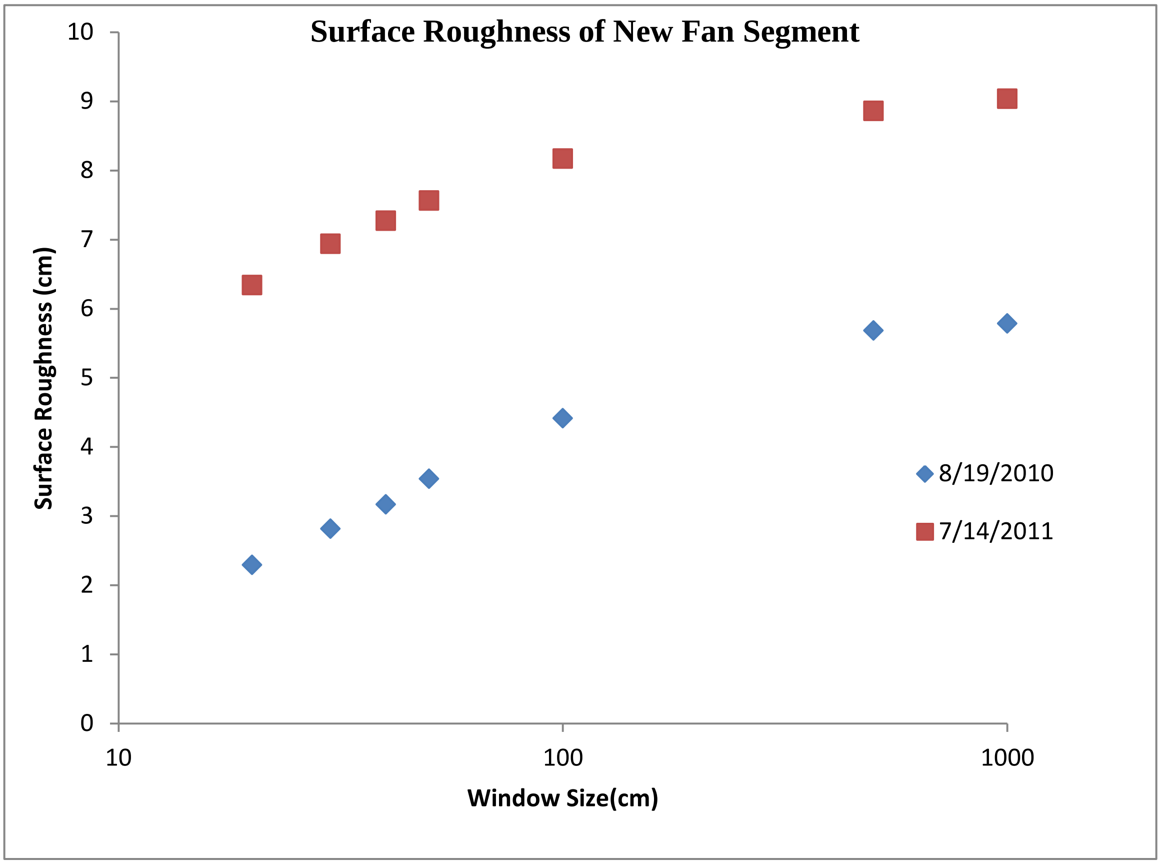


Figure 21- Surface Roughness Statistics for 5-29-09

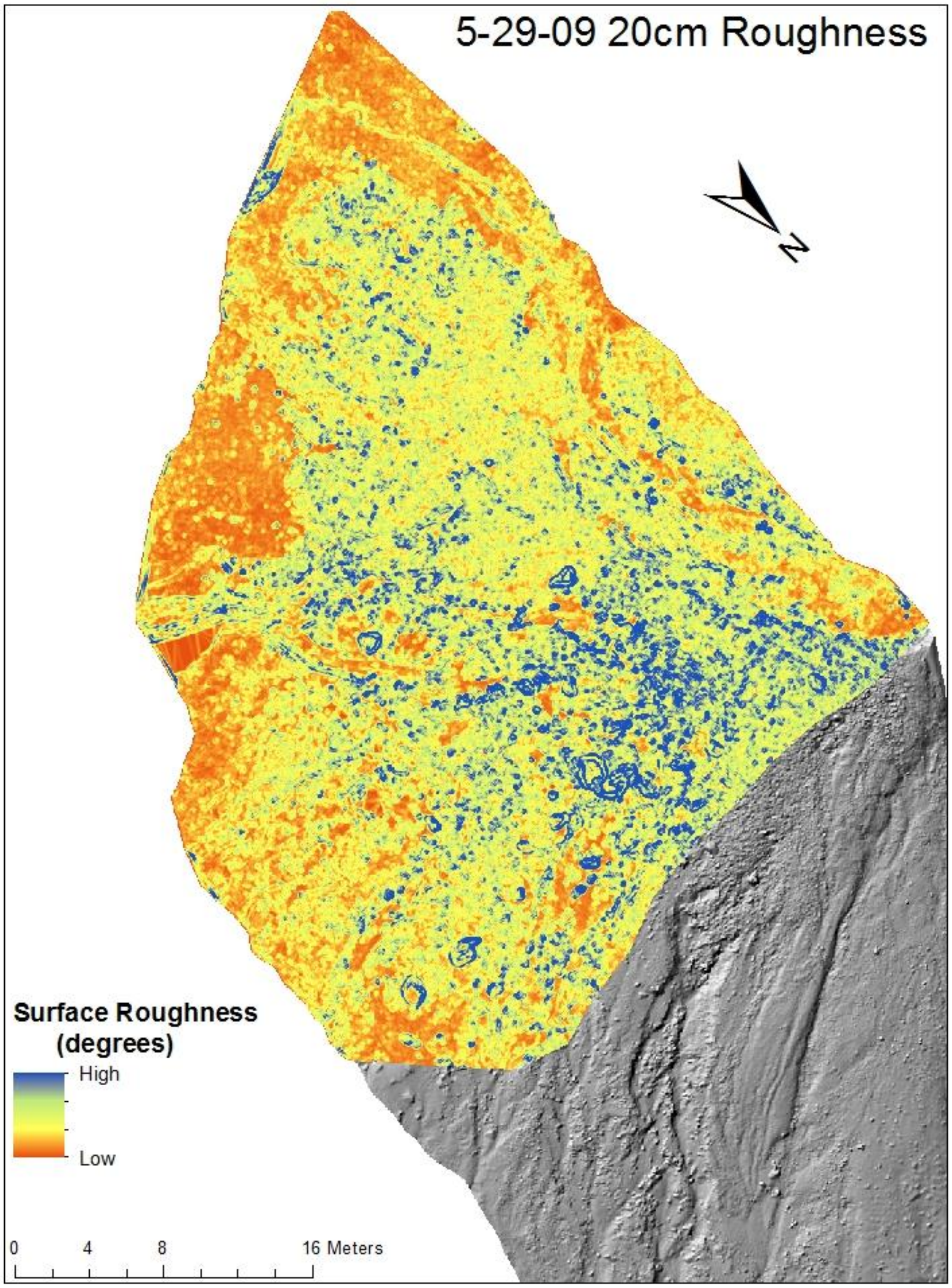


Figure 22- Surface Roughness Statistics for 9-27-09

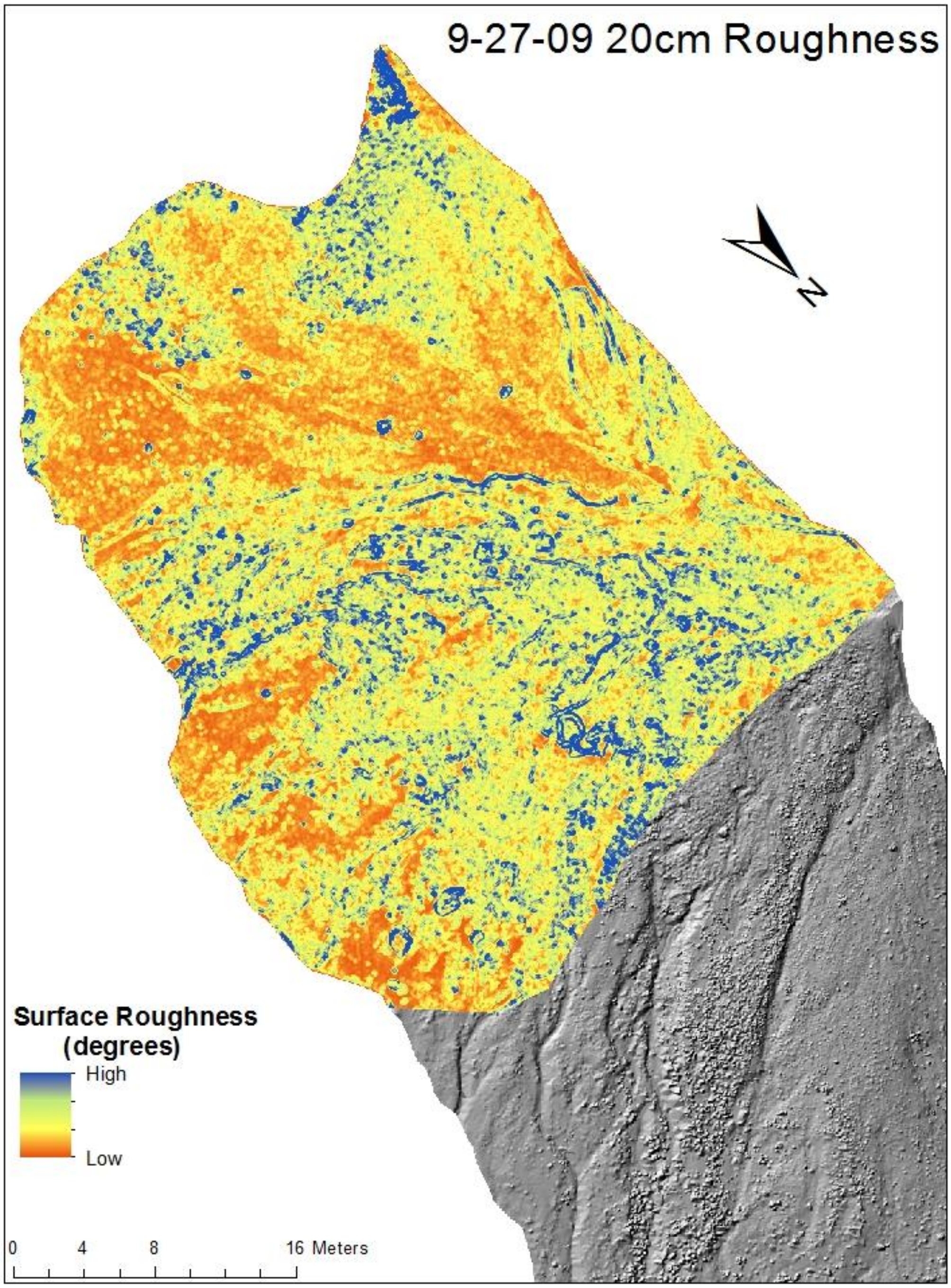


Figure 23- Surface Roughness Statistics for 5-31-10

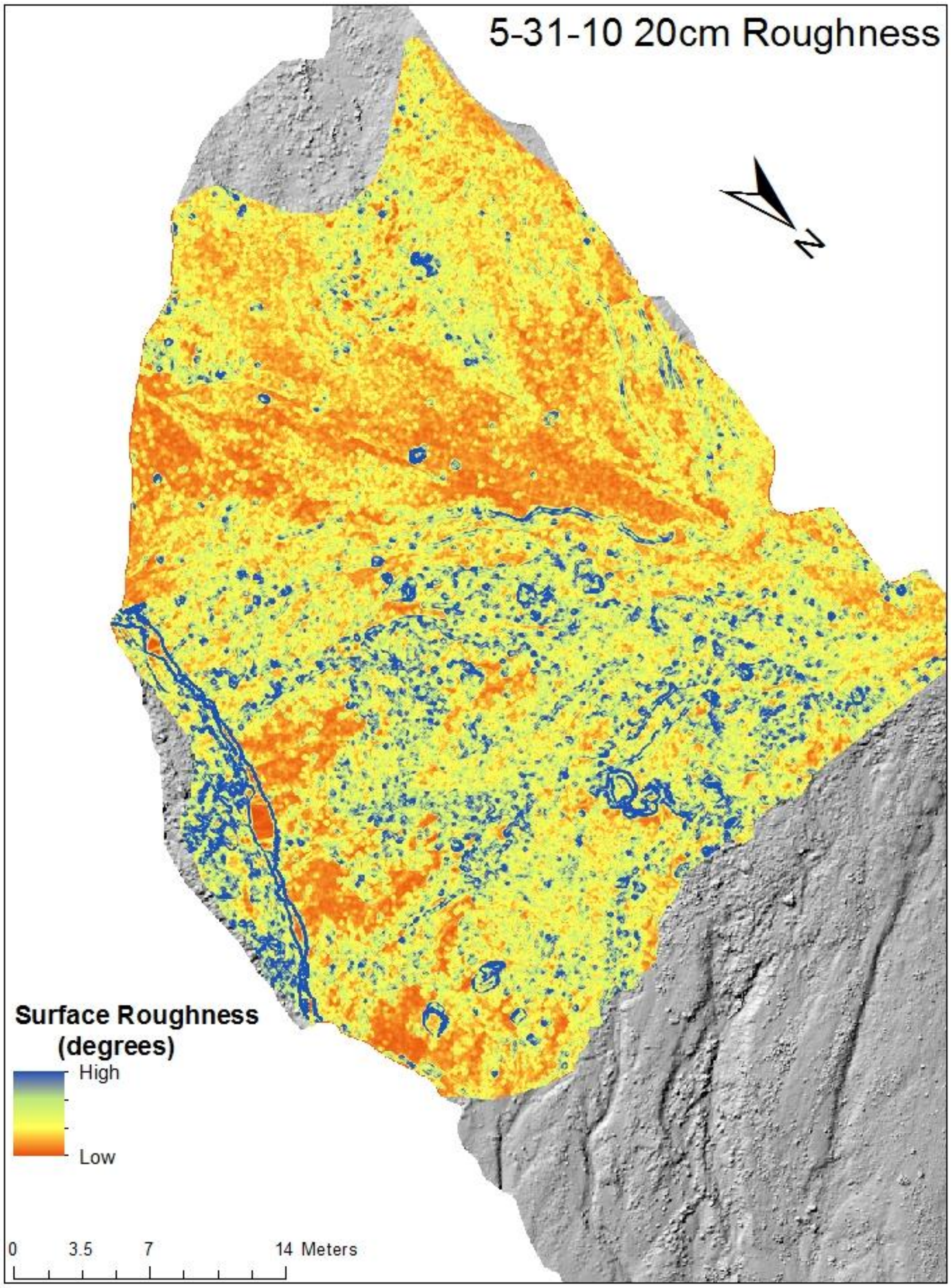


Figure 24- Surface Roughness Statistics for 6-3-10

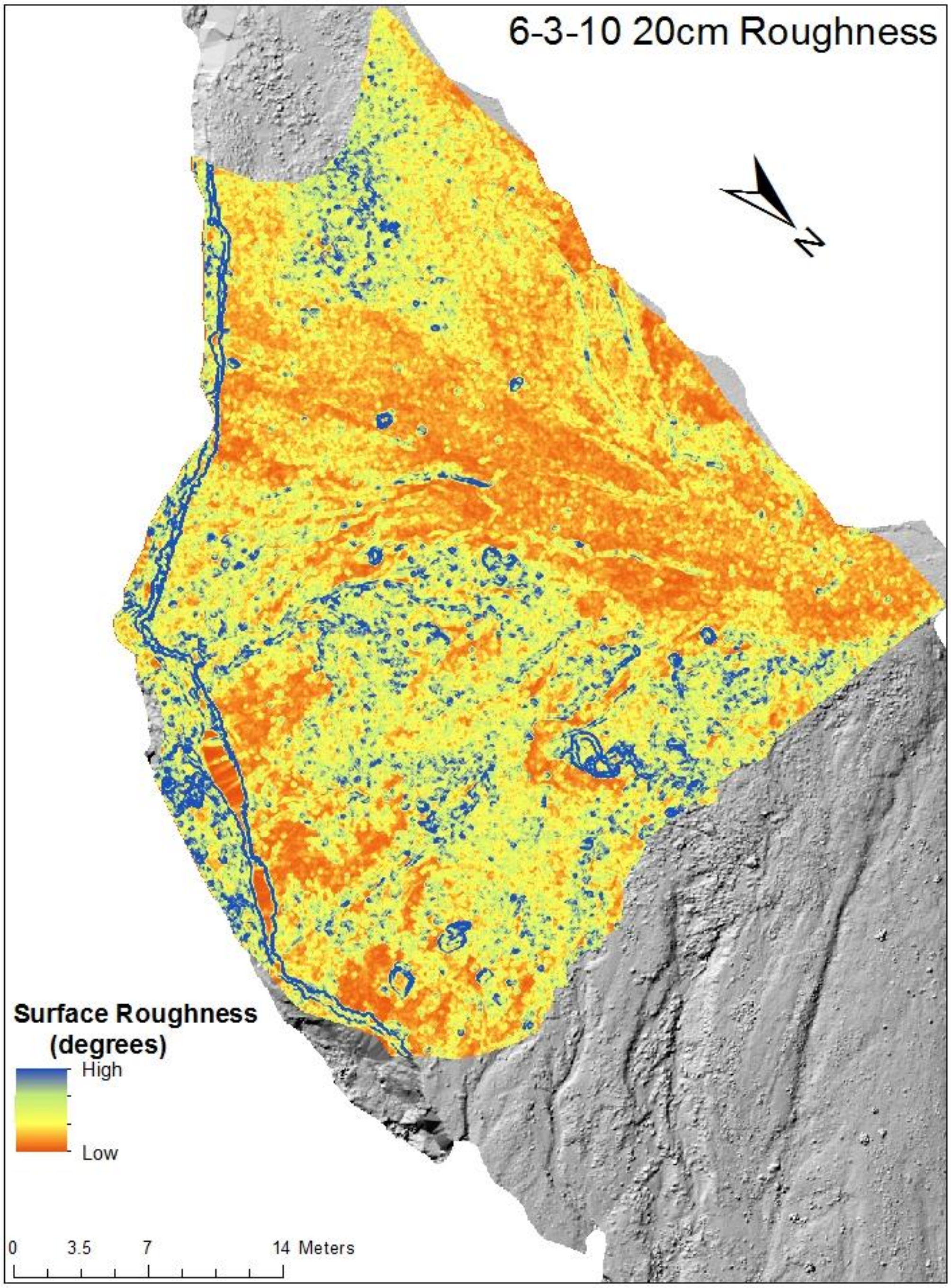


Figure 25- Surface Roughness Statistics for 7-9-10

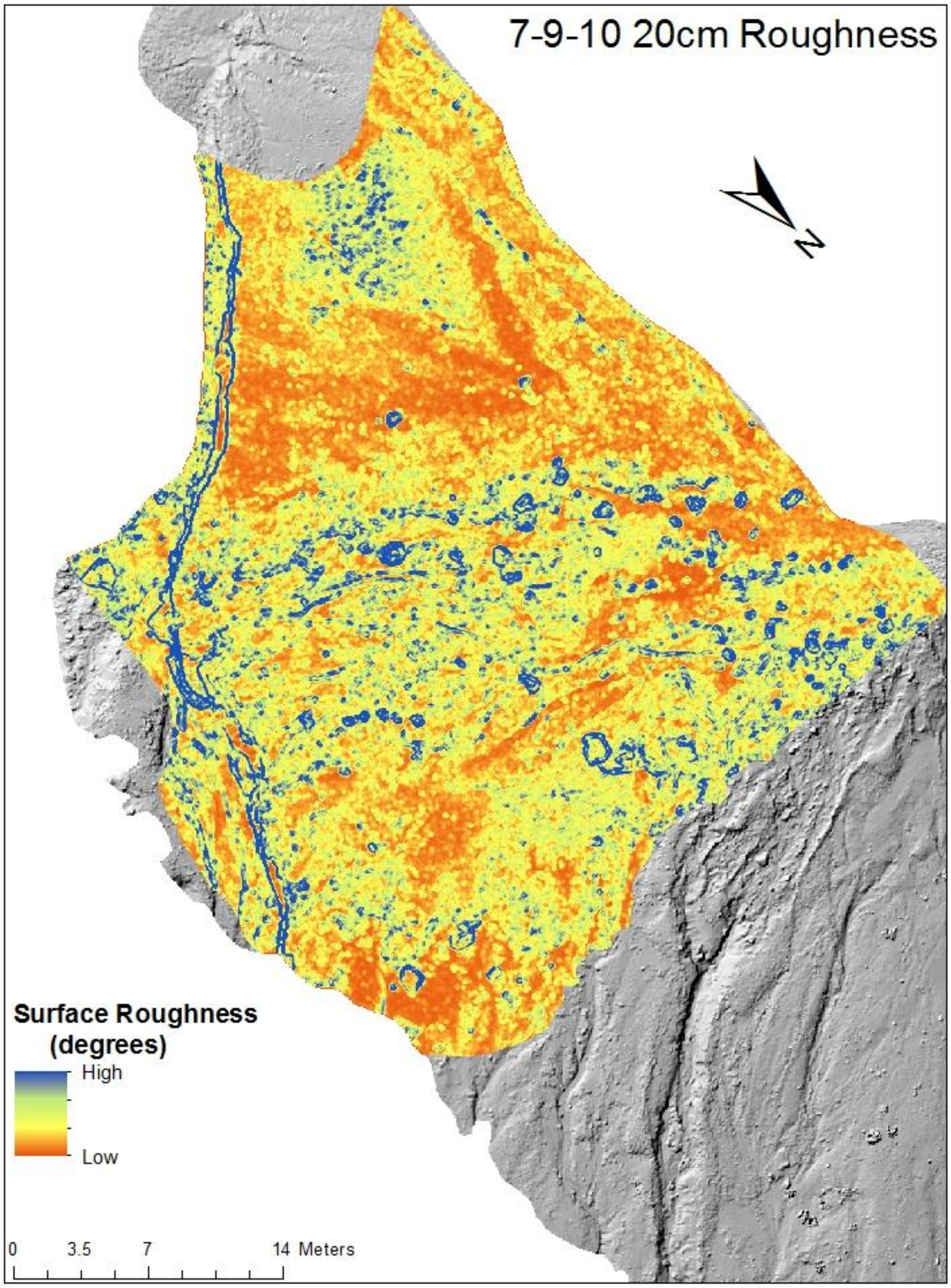


Figure 26- Surface Roughness Statistics for 8-19-10

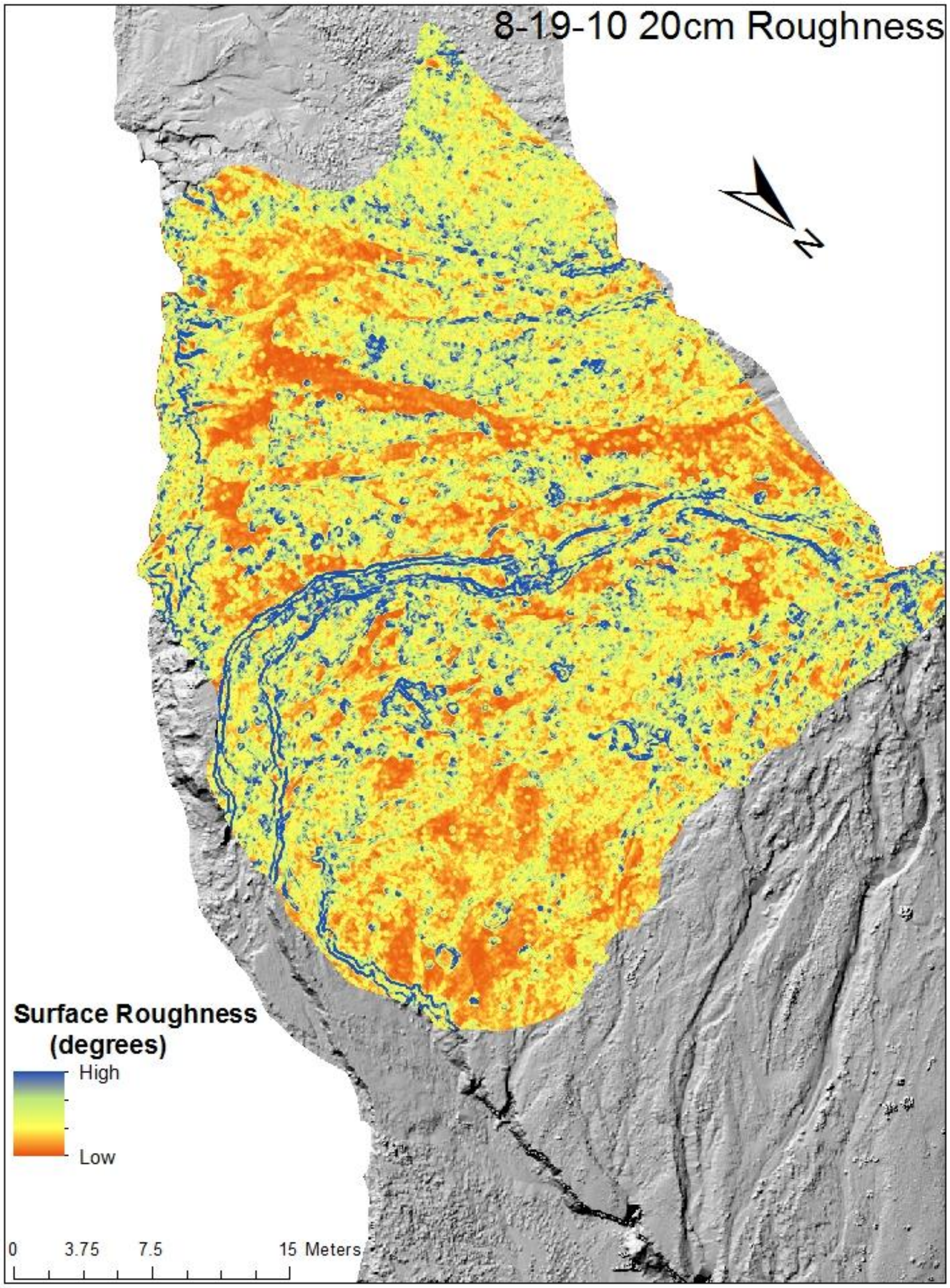


Figure 27- Surface Roughness Statistics for 7-14-11

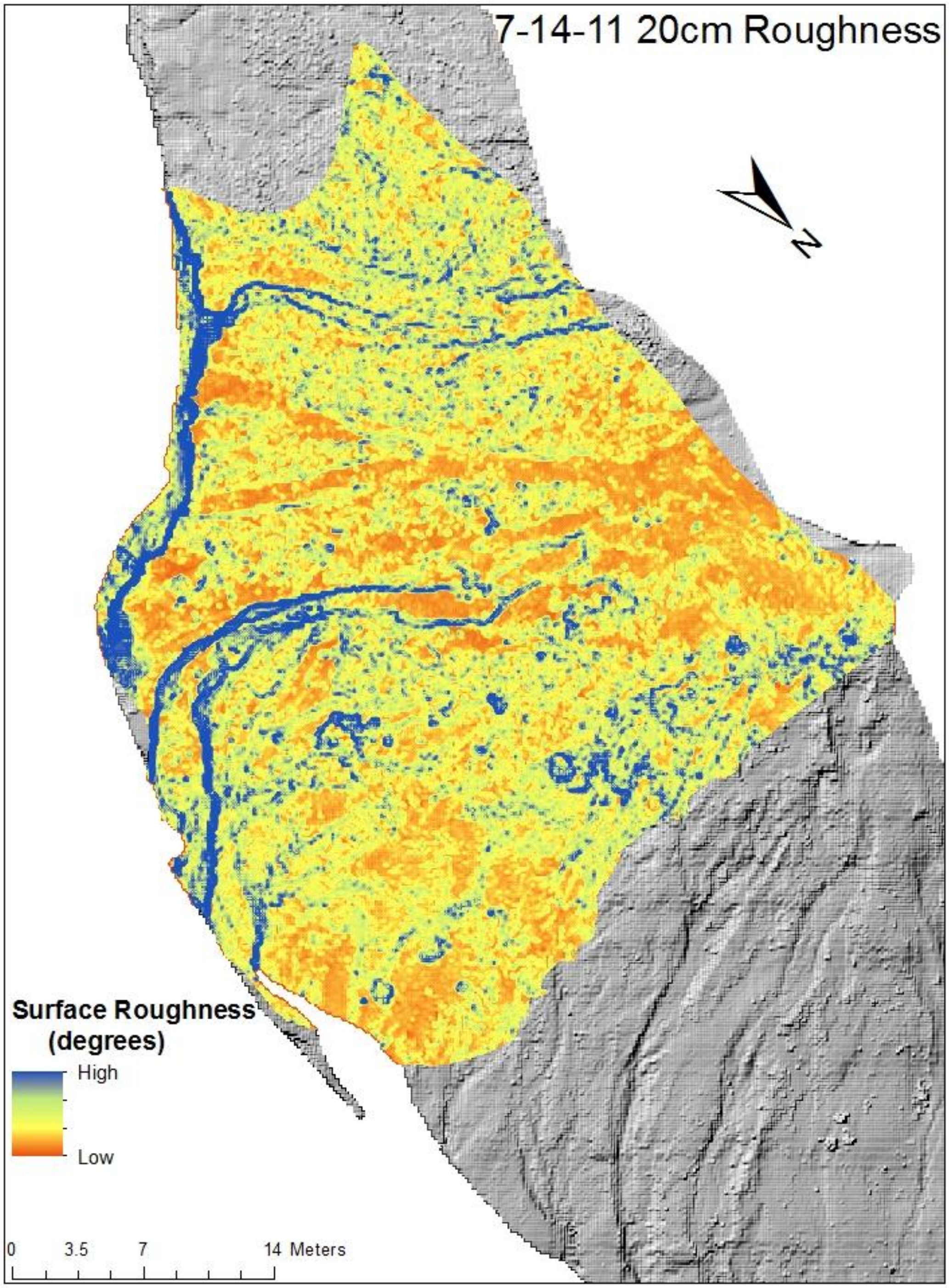
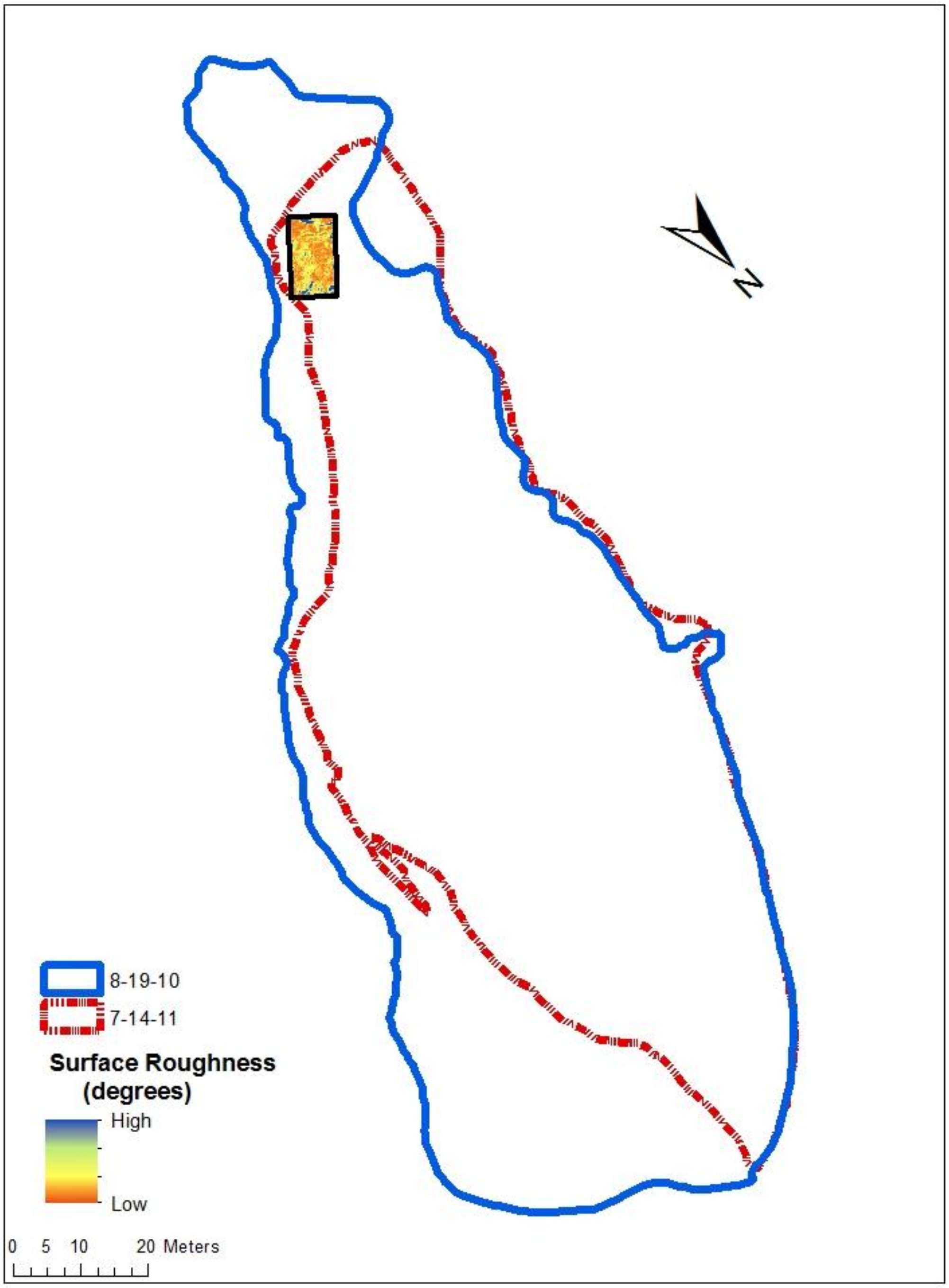


Figure 28- Surface Roughness Statistics for New Segment



Fan toe Dynamics

The fan toe had gains and losses through the time series collected and the two largest gains and losses were the last two events captured, as seen in Table 4. The previously described changes to the fan toe planimetric dimensions corresponded with volumetric changes. The first event (9-27-09) produced a volumetric change of 125 m^3. The relief from this fan toe to the bed of Chalk Creek is very low due to the small volume change of the fan toe (Table 4). Next, 5-17-10 showed a substantial leap in volume with 604 m^3. The channel is smoother on the floor and has a greater elevation difference than the previous event. 6-3-10 has a similar result as 5-17-10 with a volume of 578 m^3 with minor changes to Chalk Creek floor. 7-9-10 was another leap in volume with a 914 m^3. This increase is caused by the width and depth of the Chalk Creek increasing, creating more friction on the alluvial fan toe. The first decrease in volume was seen in 8-19-10 with 577.8756m^3. This makes sense because 8-19-10 was the largest event by far and the increase in deposition would constrict Chalk Creek and decrease the fan toe erosion. The final event produced another volume increase with 735.0828m^3 (Table 4), which is opposite of the previous fan in that the fan area decreased but fan toe accretion increased.

Table 4- Fan Toe Dynamics Statistics

Fan Toe Dynamics		
5/29/2009	**Volume of Channel (m3)**	**Sediment Transport (m3)**
9/27/2009	125.60	1952
5/31/2010	604.55	-7122
6/3/2010	578.75	1394
7/9/2010	914.97	1043
8/19/2010	577.87	12971
7/14/2011	735.08	-11698

Discussion

A majority of the debris flow deposition occurring on the alluvial fan surface occurs in the form of lobes of material adjacent to the active channel. Suwa and Okuda (1984) identified a similar pattern of deposition, but also found erosional processes dominated the fan apex. Only two events had erosional processes dominating the fan apex and the majority of the erosion was constricted to the channel at the unnamed fan at Chalk Creek Natural Debris Flow Laboratory. These two events (5-29-09 to 9-27-09 and 7-9-10 to 8-19-10) had significant erosion at the fan apex, but this is likely a result of debris flow snout incision and/or tailwater following the debris flow surge(s).

The migration of sediment from side to side is a common function associated with the formation of cone-shaped deposits of an alluvial fan. However, Hooke (1967) identified a "high-low effect" in physical laboratory experiments, whereby sediment builds in one section of the fan for an extended period of time and then a shift in the loci of deposition occurs that leads to the development of a new alluvial segment. A "high-low effect" is evident on the alluvial fan examined in the current study (Figs. 29 & 30). The majority of the deposition was confined to the southern and central portions of the alluvial fan with an average of ~2 m of deposition in these areas during the 25 month period. A shift in the locus of deposition over the last two events is evident from the DTM-of-difference maps. The shift in deposition occurs in both the feeder channel as well as on the fan surface. The feeder channel crosses the county road above the fan surface. Earthen levees have been constructed by the Colorado Department of Transportation (CDOT) to maintain a consistent channel to the fan. CDOT stopped maintaining the flow constriction toward the end of the current study. The lack of the CDOT control structures enabled the channel to shift to the south above the fan surface and deposit the beginning of a new fan segment on the southern portion of the fan. The lack of the control structures permits the feeder channel to migrate in a fashion that would be analogous to two potential scenarios associated with natural channel conditions. The first scenario involves an incised feeder channel cutting through an older fan segment. A debris flow could laterally erode the older fan segment to allow deposition to occur in a new direction. A second scenario could occur along bedrock constricted feeder channels, whereby a large bedrock failure or long-term weathering at the mouth of the feeder stream might permit an abrupt shift in the stream course. This would promote the deposition of material to a different alluvial fan segment.

Deposition also shifted slightly from the south/central portions of the alluvial fan to the lowest elevations on the northern portion over the last two debris flows. This is evidenced through levees lining some of the channels and some smaller lobate deposits (Fig. 30). Despite the expansion of the fan in southerly direction, there is enough material continuing down the feeder channel to overtop the channel in the apex and begin to form the high point located here to the lower elevations on the northern portion of the fan. This provides evidence to support the "high-low effect" as found in the physical models of Hooke (1967).

Multiple high-resolution DEM permits surface roughness to be derived at several spatial scales and through a period of time. The majority of the series of events shows a smoothing trend except for the last two events. The fan surface continues to smooth after each event until the main fan channel became larger, other secondary channels became reoccupied by debris flows, and larger particles are exhumed or deposited on the fan surface. Coarser particles exposed or deposited at the alluvial fan surface and along the channels, levees lining some of the channels, and rectilinear channels associated with tailwater erosion are noted (in the field and through the various mapping exercises) common features that increase surface roughness. Past studies

(Frankel and Dolan, 2007) found higher surface roughness values located on the channel walls and, when the scale of feature roughness increases, so does the surface roughness values. The results from the current study also convey some new and distinct insights into the short-term variability of alluvial fan roughness. Frankel and Dolan (2007) found a long term cycle of smoothing and around approximately 70 kya there is an increase in roughness when a stable threshold of sediment erosion is crossed on the older alluvial fan segments. The current study indicates short-term variability in surface roughness as debris flows of varying water content and materials deposit and erode the surface. This pattern is present at all spatial scales of analysis on the alluvial fan surface and expands our understanding of short-term variability of surface roughness thereby expanding the work of Frankel and Dolen (2007). The most recent lithostratigraphic units exposed on the alluvial fan surfaces globally reflect a composite of multiple depositional/erosional events.

Chalk Creek, adjacent to the alluvial fan toe, has an effect on the sediment relocation process and alluvial fan toe dynamics as seen from volume measurements of the creek channel size (Table 4). The amount of deposition and run out distance associated with each event has a direct relationship with the volume of the creek channel or the fan toe dynamics. The overall trend is such that when there is a net gain of deposition and the run-out distance surpasses the previous event the channel becomes smaller or confined. When there is net erosion and the run-out distance does not overtop the channel or surpass the previous fan's perimeter then the channel volume increases. The one exception shown in this study happened on 7-9-10, when there was a volumetric gain of 1043m^3 and the channel volume increased as well. This happened because, even though there was a gain of sediment, the runout distance was too short and did not surpass the previous fan's surface far enough. The significant redistribution of sediment between each event definitely concurs with Hashimoto et al. (2008) and their studies that state that close proximity to a fluvial source will enhance the fan toe dynamics.

Figure 29- DTM-of-Difference for 5-29-09 to 5-31-10

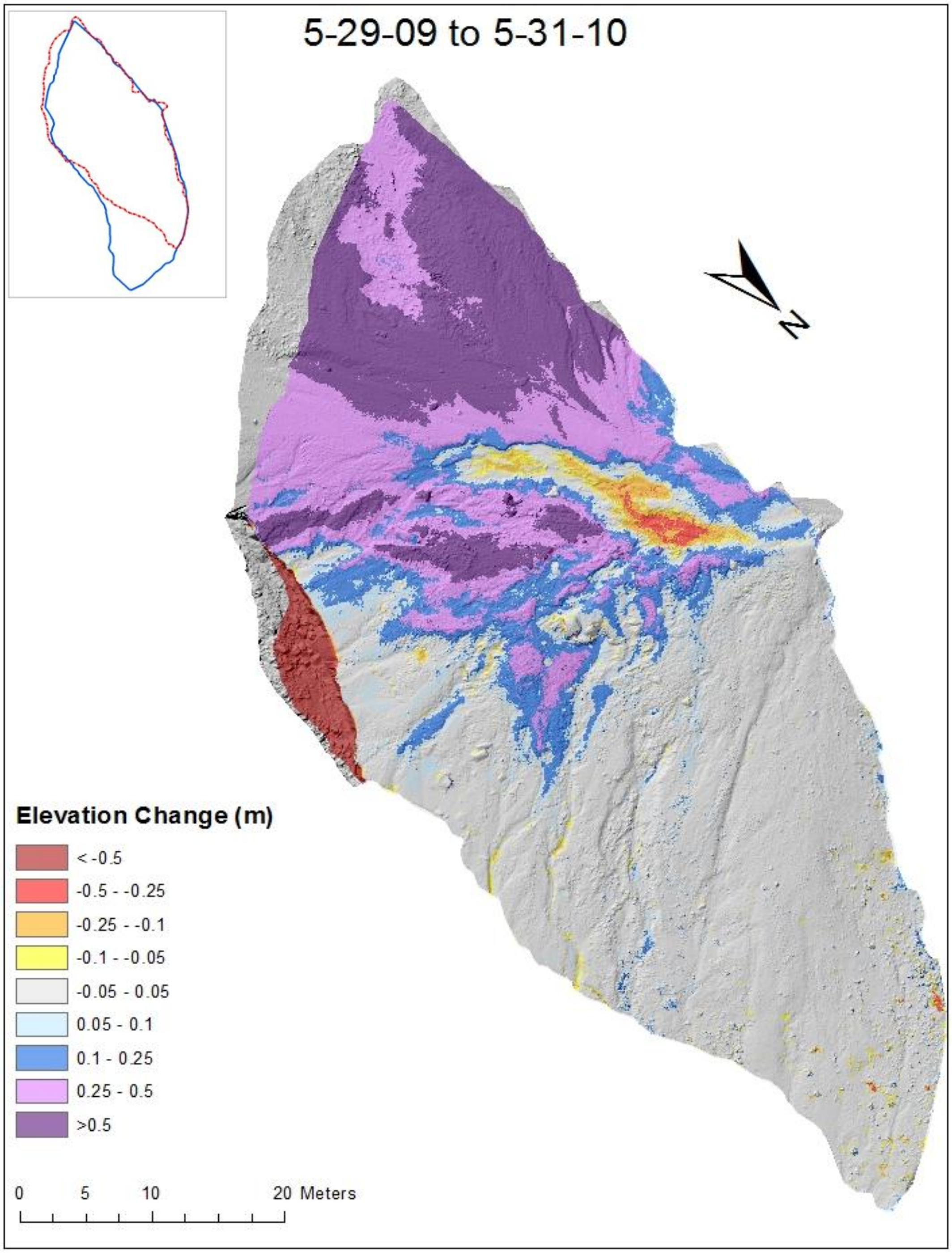
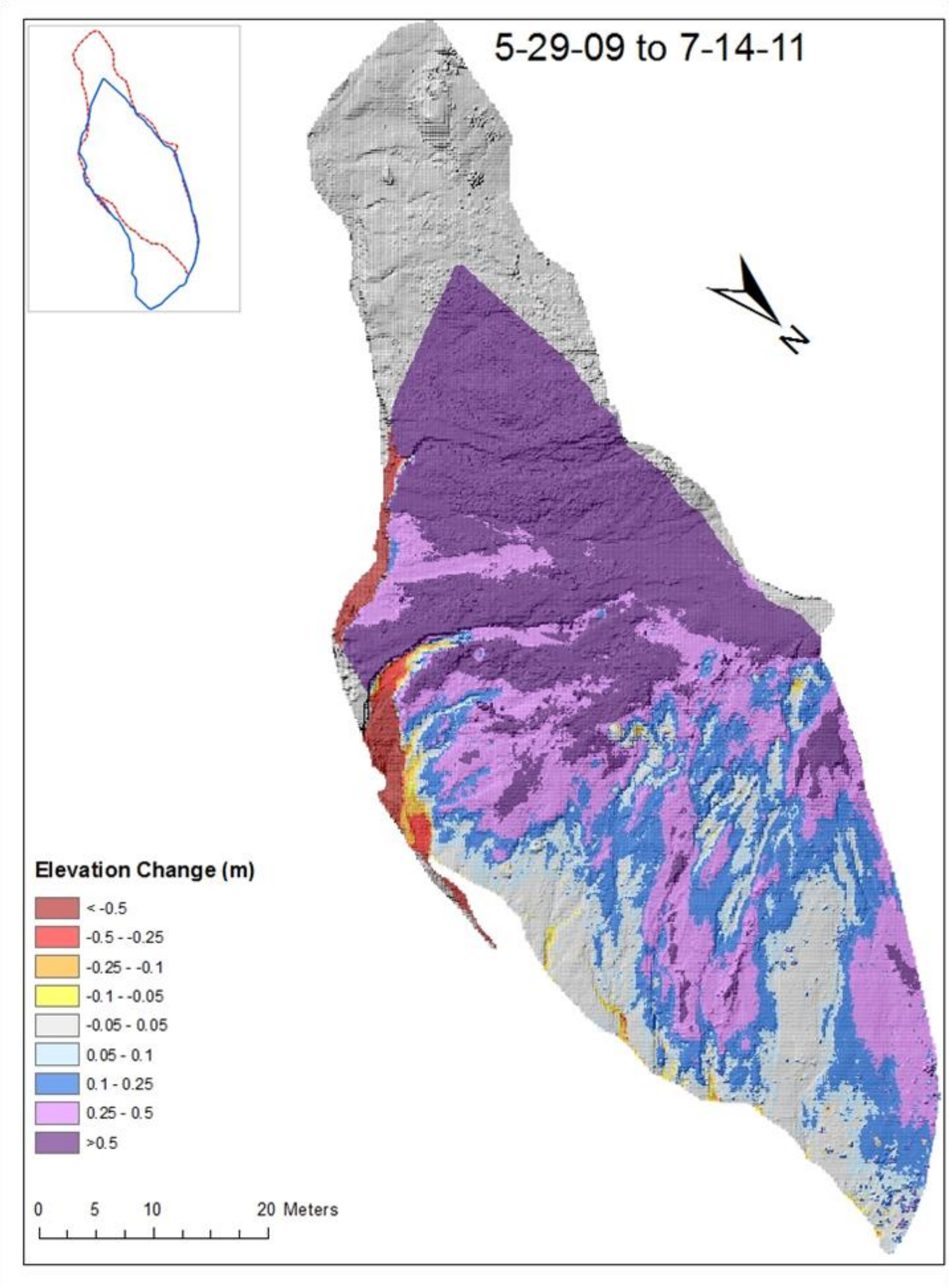


Figure 30- DTM-of-Difference for 5-29-09 to 7-14-11



Conclusion

The surface topography of a debris flow dominated alluvial fan at the Colorado Natural Debris Flow Laboratory near Buena Vista, CO, USA was surveyed seven times to capture changes associated with five debris flows and two initial season scans. The difference from the first to last survey shows a high-low effect is present. Deposition is predominantly confined to a single portion of the fan surface. Sediment deposition migrates during the final two debris flows during the monitoring period. A new alluvial fan segment begins to develop as the feeder channel shifts above the fan apex. In conjunction, portions of the debris flows continue down the existing feeder channel and overtop the channel at the fan apex. The overtopping of the existing debris flow channel on the alluvial fan surface produces an initial shift in deposition from higher to lower portions.

Surface roughness shows a smoothing trend through the entire monitoring process until the final two events. Short-term variability in surface roughness, as debris flows of varying water content and materials deposit and erode the surface, persist at all spatial scales of analysis. These findings expand our knowledge of short-term variability of surface roughness and thereby, build on the work of Frankel and Dolen (2007). The most recent lithostratigraphic units exposed on the alluvial fan surfaces globally reflect a composite of multiple depositional/erosional events. This is especially the case as our findings indicate the surface roughness is highly variable from event-to-event.

The alluvial fan toe dynamics in the current study show exceptional variability because of the alluvial fans close proximity to an adjacent trunk stream. All of the debris flow events dammed the channel and the debris dams were subsequently overtopped and breached. Alluvial fan toe erosion was not spatially or temporally consistent, but localized erosional hotspots were identified with and coincident to flow constrictions, flood stages, and areas where the channel meanders through the alluvial fan surface.

The current study contributes valuable information that fills in a gap in the research literature whereby alluvial fan evolution on an event to event basis has not been adequately addressed in terms of the spatial or temporal variability in processes and forms. Not only are debris flows uncommon to witness, but to have a series of debris flows captured on an alluvial fan surface in high resolution provides the ability to quantify the magnitude of geomorphic change. This research is of the upmost importance because of the expansion of human populations onto alluvial fans. The results presented are only an initial step for future research and show the capabilities of terrestrial laser scanning as a geomorphological research instrument.

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