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# Relating the compensational stacking of debris-flow fans to characteristics of their underlying stratigraphy: Implications for geologic hazard assessment and mitigation

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ABSTRACT

Compensational stacking is the tendency for sediment transport systems to fill topographic lows through avulsion. This article quantitatively relates, for the first time, compensational stacking patterns within debris fans to characteristics of their internal stratigraphy and discusses implications to geologic hazard assessment and mitigation. Three exceptionally well-exposed debris fans were selected in Colorado for quantitative stratigraphic analyses. In each fan, the cross-sectional stratigraphy was subdivided into discrete depositional units (debris-flow and stream-flow deposits). The bounding surfaces between the depositional units were used to analyze the compensation index ($\kappa_{cv}$) of the fans, which is a measure of their compensational or avulsion tendencies. In the measured datasets, $\kappa_{cv}$ ranged from 0.63 to 1.03. Values close to 0.5 represent intermediate levels of compensation, whereas values approaching 1.0 reflect high levels of compensation. The compensational values ($\kappa_{cv}$) were statistically compared to some physical, observable characteristics of the fans including: (1) debris-flow size, (2) amount of stream-flow deposits, (3) debris-flow composition, and (4) longitudinal position on the fan. These parameters correlated, either positively or negatively, to $\kappa_{cv}$, supporting their use as proxies for assessing the degree of compensational stacking in settings where large-scale cross-sections of a fan are unavailable. Such empirical results can be used by geologists and engineers for avoidance and mitigation measures of land use on debris fans.



## 1. Introduction

Debris flows are a type of sediment-gravity flow that commonly occurs in arid to semiarid regions in which the introduction of excess water (pore pressure) mobilizes loose material on steep slopes into a potentially devastating flow of rock, soil, and water (Allen, 1985). The continued expansion of human population into mountainous regions, where debris fans are common, has greatly increased the hazardous effects of debris flows in terms of damage to infrastructure and human life. In light of this, there lies a need to increase our understanding of the processes that govern debris fans and their development through time to help predict and mitigate debris-flow hazards.

A significant volume of research addresses initiation conditions, recurrence intervals and incorporated materials of debris flows; however, their likely paths and avulsion habits are not as well understood (Whipple, 1992). Addressing these knowledge gaps could increase the efficacy of mitigation measures, such as infrastructures that deflect incoming debris flows, and avoiding construction and habitation in likely paths of future debris flows.

Recent sedimentology techniques have been developed to characterize the compensational tendencies of sediment transport systems (Straub et al., 2009; Wang et al., 2011; Straub and Pyles, 2012). Compensational stacking, an autogenic/morphodynamic process, is the tendency of sediment transport systems to fill topographic lows in order to reduce the potential energy of the system (Straub et al., 2009). The primary mechanism responsible for compensation is avulsion, the process by which a channel aggrades to a threshold elevation and then shifts to a topographic low (Straub et al., 2009). In an attempt to quantify compensational stacking, the compensation index ($\kappa_{cv}$), which is a surface-based statistic, was developed and implemented on fluvial, deltaic, and deepwater depositional systems (Straub et al., 2009; Wang et al., 2011; Straub and Pyles, 2012). The compensation index ($\kappa_{cv}$) ranges from 0 to 1, which represents the continuum from pure vertical stacking of stratigraphy to perfect compensation, respectively.

This article applies the compensation index to three well-exposed debris fans in southern Colorado to test how compensational stacking of debris fans relates to readily measurable parameters of the debris-fan stratigraphy including: (i) debris-flow size, (ii) amount of stream-

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flow deposits, (iii) debris-flow composition, and (iv) longitudinal position on the fan. Such empirical results provide users with a simplified way to assess compensation, and therefore the avulsion tendencies of a debris-flow-dominated fan, in order to guide and optimize the design of mitigation measures. The timing and distribution of the sedimentation events measured at these sites is not considered in this research, so magnitude, frequency, and controls such as climatic conditions are not evaluated.

## 2. Field areas

Three outcrops of debris fans in Colorado were chosen for this study on the basis of their dominant depositional mechanism(s), quality of exposure, size of exposure relative to the fan as a whole, safety of surroundings, and ease of access (Fig. 1). To be valid for analysis, each outcrop had to exhibit clear stratigraphy of largely debris-flow origin consisting of at least five overlapping, discrete debris-flow events whose boundaries could be traced across the exposure. Additionally, each fan shows no evidence of post-depositional deformation by faulting or settlement, therefore the stratigraphy of these fans is assumed to be controlled solely by depositional events. The three exposures chosen for analyses are located near Woodland Park, Poncha Pass, and Grand Mesa. The geologic setting of each is discussed below.

The Woodland Park debris fan is exposed in a road cut along U.S. Route 24, just south of Woodland Park in Teller County, Colorado (Fig. 1). The debris fan overlies a bedrock exposure of the Fountain Formation, which is a Permian/Pennsylvanian-aged arkosic sandstone with interbedded conglomerate and shale (Wobus and Scott, 1977). Farther up the mountainside, Ordovician and Cambrian sedimentary strata are present in the form of the Manitou limestone and Sawatch sandstone as well as outcrops of the pink, coarse-grained, and highly erodible Pikes Peak granite (Wobus and Scott, 1977). The analyzed portion of the fan is exposed in a road cut that was excavated through the proximal part of the fan (Figs. 1, 2).

The Poncha Pass debris fan is located along U.S. Route 285, on the western side of Poncha Pass in south-central Colorado (Fig. 1). Poncha Pass follows a valley carved by Poncha Creek, which itself follows a normal fault system that divides the bedrock geology of the pass between Miocene-age sedimentary Dry Union Formation and Oligocene andesite lavas and breccias to the west and Precambrian felsic and hornblendic gneisses to the east (Tweto et al., 1976). Debris-flow material is sourced from the surficial geology of the western side of the valley including sand, conglomerate, and ash fragments characteristic of the Dry Union Formation as well as andesites and breccias (Tweto et al., 1976). Although this fan experienced significant erosion since its deposition, the clarity of strata, extent and size of the outcrop, and ease of access validated its use in this study. The analyzed portion of the fan is exposed in a road cut that was excavated through the medial part of the fan (Figs. 1, 3).

The Cedar Mesa debris fan is located southeast of Cedaredge, Colorado, and is associated with massive alluvial and debris-flow deposits along the southern margin of Grand Mesa in western Colorado (Fig. 1). The geology of the Grand Mesa region of Colorado consists of Cretaceous and Tertiary marine and nonmarine sedimentary deposits that dip gently to the north and are capped by a series of Miocene basalt flows (Yeend, 1969). Quaternary erosion resulted in descending tiers of river gravels deposited by the North Fork Gunnison River as it migrated to the south (Noe and Zawaski, 2013). Quaternary deposits formed in

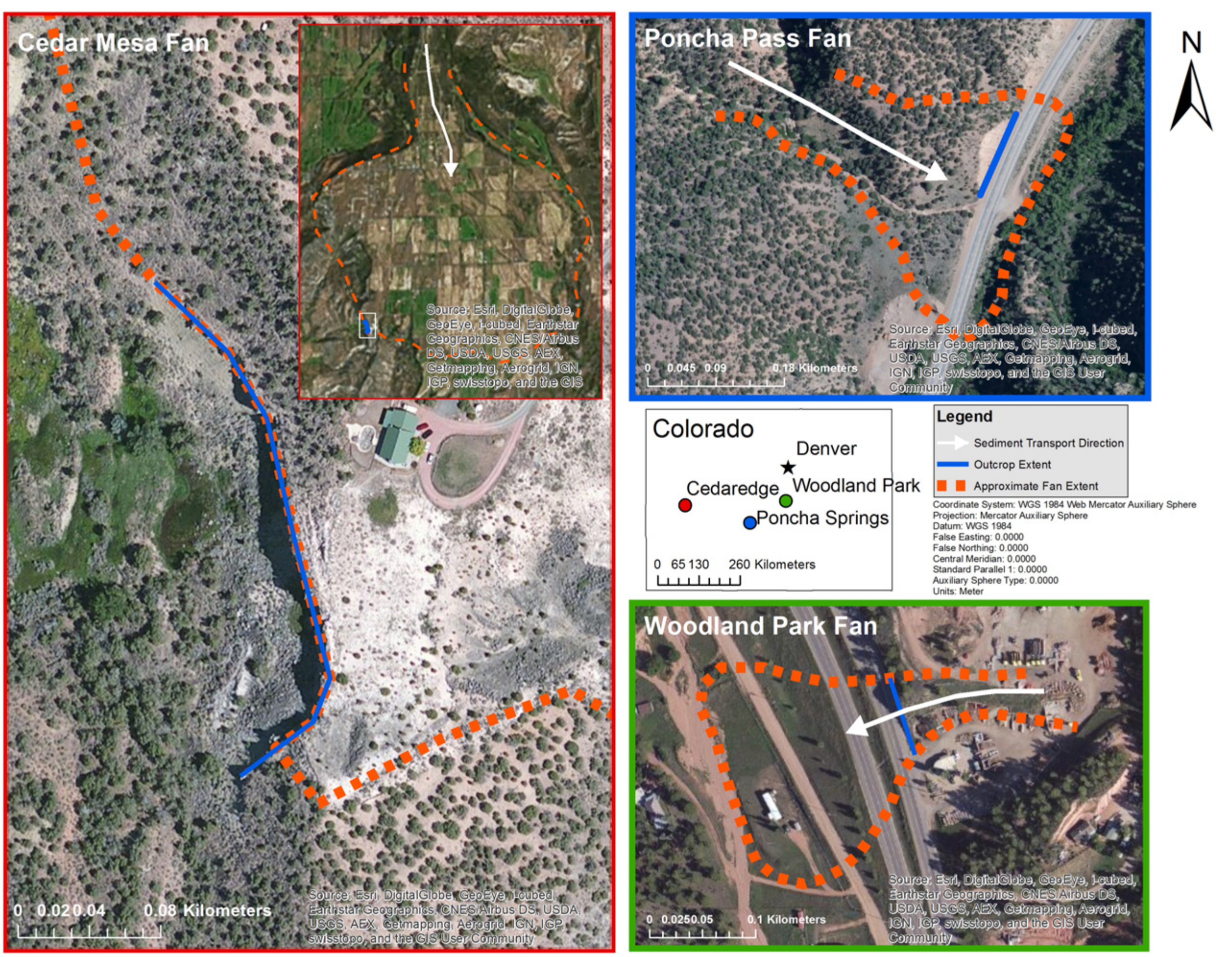


**Fig. 1.** Map showing the locations of the study areas in Colorado: Woodland Park, Poncha Pass, and Cedar Mesa fans.