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Latest Pleistocene–Holocene debris flow activity, Santa Catalina Mountains, Arizona; Implications for modern debris-flow hazards under a changing climate

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ABSTRACT

Hazard mitigation for extreme events such as debris flows requires geologic mapping and chronologic information, particularly for alluvial fans near mountain fronts in the southwestern United States. In July 2006, five consecutive days of monsoonal storms caused hundreds of debris flows in southeastern Arizona, particularly in the southern Santa Catalina Mountains north of Tucson. Before 2006, no historical debris flows from the Santa Catalina Mountains reached the populated mountain front, although abundant evidence of prehistoric debris flows is present on downslope alluvial fans. We used a combination of surficial geologic mapping and ^{10}Be exposure dating to produce a debris-flow history for Pima and Finger Rock Canyons. The largest debris flows, of latest Pleistocene to early Holocene age, covered much of the apices of alluvial fans formed at the mouths of these canyons and extended up to 3 km downslope. These debris-flow deposits were inset against higher and older alluvial surfaces with few debris-flow deposits of late Pleistocene age. The ^{10}Be ages in this study have considerable scatter for surfaces believed to be of uniform age, indicating the dual possibilities of inheritance from previous cosmic-ray exposure, as well as the potential for composite deposits derived from numerous debris flows. We then used an empirical inundation model, LAHARZ, to assess probable magnitudes of the older debris flows to evaluate possible initiation mechanisms. In-channel and terrace storage within the canyons is not sufficient to generate volumes likely needed to produce the larger late Pleistocene to early Holocene debris-flow deposits. The abundance of latest Pleistocene and early Holocene deposits suggests that large debris flows were generated during the instability associated with climate and vegetation changes at the Pleistocene–Holocene transition. Under present watershed conditions with limited sediment supplies, modern debris-flow hazards are generally limited to within mountains and near mountain fronts.

1. Introduction

Urban development on alluvial fans near mountain fronts exposes housing and infrastructure to numerous geologic and hydrologic hazards. In the arid and semiarid southwestern United States, historical debris flows have commonly occurred following extreme precipitation or following high frequency, low magnitude rainfall in recently burned watersheds (Wohl and Pearthree, 1991; Pearthree and Youberg, 2004; Cannon et al., 2008; Kean et al., 2011). In this environment, debris flows are extreme hydrologic events that deliver considerable amounts of large-caliber sediment to active alluvial fans (Wells and Harvey, 1987), dominating fan deposition patterns and profoundly influencing flow paths during smaller floods. Floodplain management strategies typically focus on 100-year floods or smaller, and flood control measures in this region generally utilize channel–bank stabilization measures or require building above the calculated 100-year water surface, ignoring the potential for channel aggradation and subsequent overbank deposition during debris flows (Webb et al., 2008). An understanding of past debris-flow magnitude and frequency, as well as of prehistoric areas of deposition, is essential for placing the hazard of debris flows into a temporal framework in order to assess risk (Youberg et al., 2008). Moreover, because evidence left by debris flows tends to persist in the landscape for a long time, the significance of abundant undated debris-flow deposits is difficult to evaluate when assessing modern hazards.

During the last week of July 2006, southern Arizona experienced five consecutive days of early morning storms generated from monsoonal moisture interacting with a persistent low-pressure system centered over northwestern New Mexico (Magirl et al., 2007). This series of

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storms culminated on July 31, when the last pulse of rain fell on already saturated watersheds in the Santa Catalina Mountains north of Tucson (Griffiths et al., 2009). Floods of record occurred in several washes throughout southeastern Arizona, and hundreds of hillslope failures and debris flows were generated in at least four mountain ranges (Pearthree and Youberg, 2006; Webb et al., 2008). Debris flows occurred in nine canyons along the eastern half of the Santa Catalina Mountains (Fig. 1). Debris flows exited or nearly exited the mouths of five of these canyons (Fig. 1), damaging roads, bridges, and one private home close to the mountain front (Webb et al., 2008).

No reports of previous historical debris flows that exited the Santa Catalina Mountains have been made. Evidence of prehistoric debris flows, however, is abundant on the now-developed fans at the mouths of all canyons along the mountain front (Youberg et al., 2008). While debris flows were previously recognized as a hazard in Arizona's mountains and canyons (Webb et al., 1988; Wohl and Pearthree, 1991; Webb et al., 1999; Pearthree, 2004), the number and extent of debris flows from the 2006 event were unexpected; and it dramatically illustrated the potential for sizable debris flows to exit canyons and adversely impact properties near canyon mouths.

Following the 2006 debris flows, studies were conducted to assess the magnitude and frequency of the 2006 event (Webb et al., 2008) and of prehistoric debris-flow deposits found on the alluvial fans along the mountain front (Youberg et al., 2008). In the Santa Catalina Mountains, Webb et al. (2008) documented floods of record on Sabino and Rillito Creeks; and numerous debris flows generated from 435 shallow, translational hillslope failures with an average failure depth of 0.75 ± 0.4 m that, as a whole, produced a total of ~670,400 m^3 of transported sediment. Youberg et al. (2008) documented debris-flow deposits on all fans along the mountain front ranging in age from late Pleistocene to modern, with older deposits containing larger caliber clasts and extending farther from the mountain front than modern deposits (Youberg et al., 2008). The ^{10}Be cosmogenic samples were collected from boulders in four canyons in an attempt to provide numerical age estimates for the deposits. These results generally corroborated the relative age dating of the geologic mapping but showed significant inheritance and reworking issues (Youberg et al., 2008).

Two companion studies expanded on the work of Webb et al. (2008), providing a detailed assessment of the 2006 storm event (Griffiths et al., 2009) and an assessment of the efficacy of a statistically calibrated, empirical, inundation model (LAHARZ) for mapping hazard zones in arid and semiarid environments (Magirl et al., 2010). Recurrence intervals for the individual daily storms were <2 years, while return intervals were >50 years for 2-day storms and ~1000 years for the entire multiday storm (Griffiths et al., 2009), re-enforcing the rarity of the 2006 storm event.

LAHARZ is a GIS-based empirical model developed to map hazard zones from volcanic lahars (debris flows) (Iverson et al., 1998;

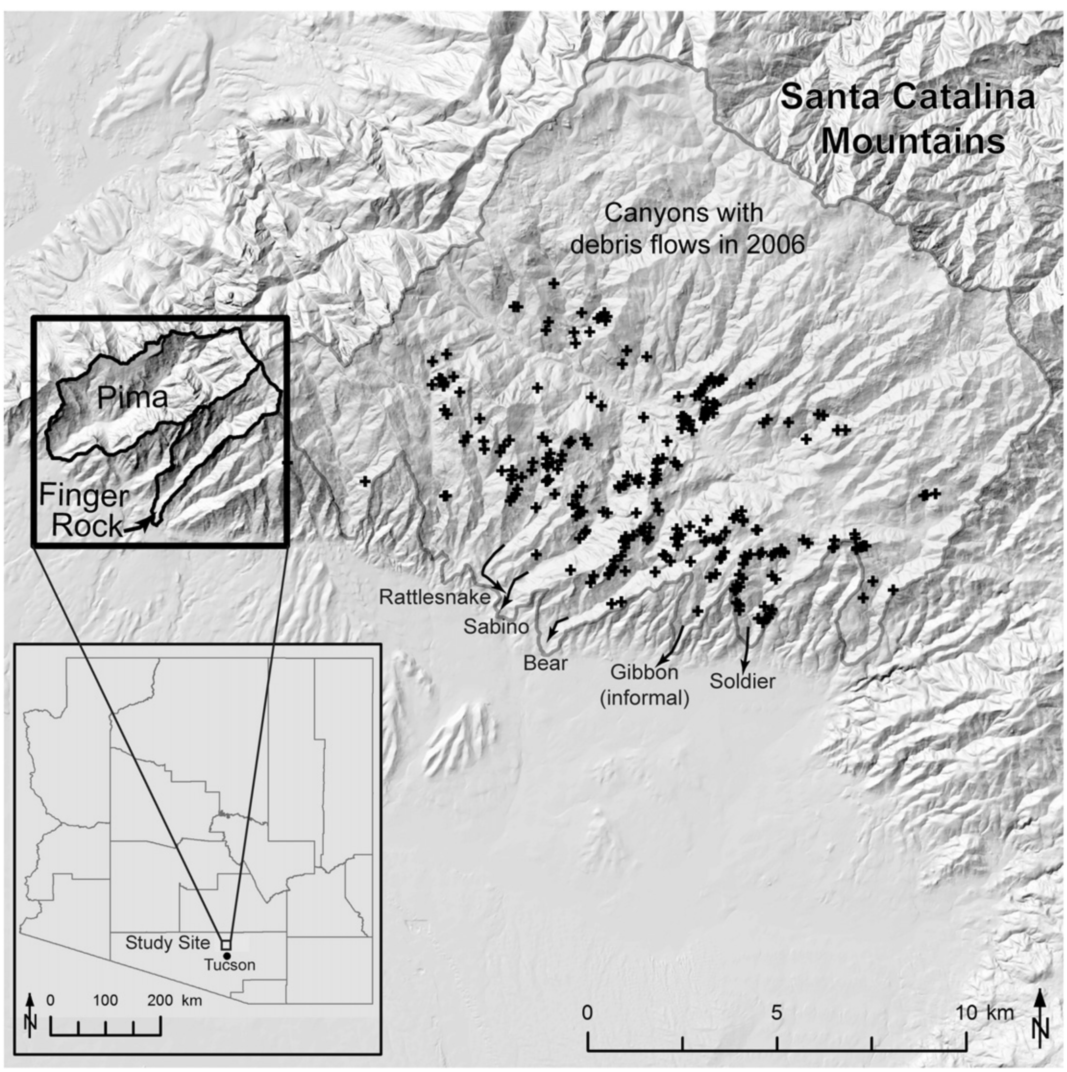

Fig. 1. Location of the study site on the western end of the Santa Catalina Mountains north of Tucson, AZ. The study canyons, Pima and Finger Rock, are outlined in black. Crosses show locations of hillslope failures in the eastern canyons that had debris flows in 2006. Arrows indicate canyons where debris flows exited, or nearly exited, canyon mouths in 2006.