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Impact of consecutive extreme rainstorm events on particle transport: Case study in a Sonoran Desert range, western USA

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ABSTRACT

Quantifying erosion rates in different landscape settings provides insight into how landforms change under different climatic, tectonic and anthropogenic influences. Sediment traps designed to capture grus detached from granitic hill crests of an arid Sonoran Desert mountain range were placed prior to every precipitation event over a three-year period, just above rills that drain areas between 18 and 68 m^2. The slopes are underlain by moderately to strongly weathered granitic rocks to a depth of about a meter. Within this 3-year window, a 1000-year precipitation event followed 27 days later by a 500-year event detached granitic grus in amounts far greater than previous storms, capturing between 22× and 63× the average amount transported in the previous 59 rain events — indicating the non-linear nature of the response of grus detachment to precipitation intensity. Considering every precipitation event over a 3-year period, no detachment occurred from events with less than 2 mm of total rainfall, and only minimal erosion occurred from rainfall events with totals between 2 and 10 mm with durations typically less than 30 min. Detachment increased greatly with rain intensities of 36 mm/h or more. Grus detachment from these arid crests increases with drainage area, a higher percentage of exposed soil, and steeper slopes. $^{87}Sr/^{86}Sr$ ratios reveal that suspended sediment transported from hill crest to trap derives from recycled dust and not the local granite bedrock.

1. Introduction

Developing a better understanding of processes and rates of soil particle erosion remains an important part of geomorphology research, with considerable progress made recently (Garcia-Ruiz et al., 2015). Still, relatively few studies exist for arid slopes (Crouvi et al., 2015) and even fewer along the crests of arid ranges. Thus, this project commenced in 2011 to gather data on detachment of particles from arid granitic crests during every precipitation event. Fortuitously, the end of the three-year study included two extreme storms 27 days apart at South Mountain, a Sonoran Desert range surrounded by metropolitan Phoenix, Arizona. During the 2014 Arizona summer monsoon season, a 1000-year precipitation thunderstorm event took place on August 12, followed by a longer-duration 500-year soaking by hurricane moisture on September 8, 2014.

Extreme rainstorms shed light on earth surface processes that shape arid and semi-arid landforms (Lekach and Schick, 1983; Schick, 1988; Pickup, 1991; Shaw et al., 1992; Dick et al., 1997; Coppus and Imeson, 2002; David-Novak et al., 2004; Mather and Hartley, 2005; Harvey, 2006; Moharana and Kar, 2010), for example in highlighting the importance of soil and vegetation conditions (Osterkamp and Friedman, 2000) or in emphasizing the importance of runoff coefficients (Puigdefabregas et al., 1998). Given the relative paucity of geomorphic data associated with extreme desert rains, value exists in a realistic research practice (Richards et al., 1995) linking the properties of a field area to insights obtained through unique observations.

The focus of this paper rests in reporting and analyzing basic field observations on grus detachment events in response to regular precipitation events and also to extreme rainstorms on desert slopes. The field area section of this paper sets the stage. The methods section then outlines: (a) gathering 3 years of data on grus detachment near interfluves; (b) analyzing granitic decay near sediment trap sites through electron microscopy; and (c) determining stable strontium-isotope ratios to differentiate *in situ* detachment of rock material from eolian dust. The results and discussion sections explore how the geomorphic impact of consecutive extreme storms compare with less extreme precipitation events on arid granitic ridge crests.

2. Field area

South Mountain stretches approximately 29 km and forms a municipal preserve in Phoenix, Arizona, USA. The study area is in the eastern portion and consists of mid-Tertiary granitic rock types (Fig. 1). Metamorphic core complexes such as South Mountain in Arizona formed concurrently with upper crustal extension from the release of compressional stress after the Mesozoic Sevier and Laramide Orogenies (Nations and Stump, 1981; Coney and Harms, 1984; Holt

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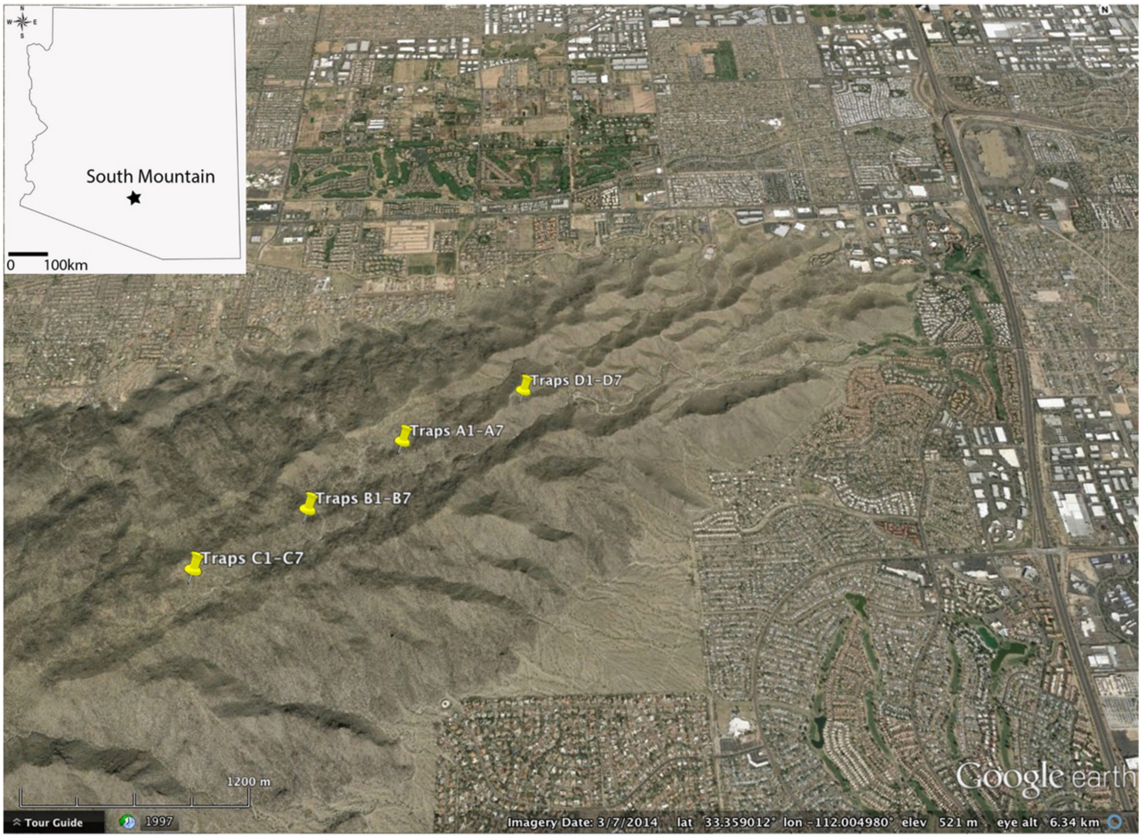

Fig. 1. The 28 sediment traps are distributed across four study ridge crests within South Mountain. These are in the eastern half of South Mountain in Tertiary granitic rock types. The base image from 2014 is used following permission guidelines for Google Earth [http://www.google.com/permissions/geoguidelines.html].

et al., 1986). South Mountain's uplift ended ~8–14 Ma ago (Spencer, 1984; Reynolds, 1985).

The climate and vegetation of South Mountain represent the rest of the Sonoran Desert in central Arizona. Annual precipitation averaging 208 mm splits evenly between summer and winter maxima (Climate Office of Arizona, https://azclimate.asu.edu/climate/climate-of-phoenix-summary/). Winter rainfall derives from Pacific cold fronts and low-pressure systems. Moist air masses from the Gulfs of Mexico and California, combined with surface heating and upper level tropospheric disturbances, generate summer thunderstorms during the July–September Monsoon season that sometimes extends into October from Pacific hurricane moisture.

Sonoran Desert trees grow along ephemeral washes and on hillslopes where overland flow concentrates, including palo verde (*Parkinsonia microphylla*), ironwood (*Olneya tesota*), and elephant trees (*Bursera microphylla*). Desert scrub vegetation found on slopes includes creosote bush (*Larrea tridentata*), brittlebush (*Encelia farinosa*), triangle-leaf bursage (*Ambrosia deltoidea*), catclaw acacia (*Acacia greggii*), desert globe mallow (*Sphaeralcia ambigua*), and ocotillo (*Fouquieria splendens*). Hillslopes also host succulents such as saguaro (*Carnegiea gigantea*), barrel (*Ferocactus cylindraceus*) and hedgehog (*Echniocereus engelmannii*) cactus.

Detachment of granitic grus from bedrock exposures limit erosion rates in the eastern half of South Mountain that is composed of granitic lithologies (Fig. 2A, B). Granitic slopes mix decayed bedrock, relatively fresh bedrock with kopje (Twidale, 1982) forms, tors and detached granitic grus to create a landscape of irregularly-shaped steep bedrock slopes and smoother grus-covered forms that are less steep (Fig. 2A, B). A slope map (Fig. 3) sheds additional light on granitic landforms; in the granitic eastern half of South Mountain, slopes steeper than 23% provide a proxy for the location of granitic bedrock that is detachment limited. In contrast, grus transport dominates on slopes lower than ~23%. A working hypothesis is that these grus-dominated slopes are underlain by granitic rock that has undergone sufficient dissolution and alteration in the subsurface to not be in a detachment-limited condition. Since the sediment traps were placed in zones of already detached granite, a component of this research assesses the working hypothesis of subsurface weathering.

3. Extreme rain events

An August 12, 2014 1000-year precipitation event occurred when Mexican monsoon moisture "juiced" the atmosphere over Arizona, with the triggering mechanism being an upper-level inverted trough moving into the area from Baja California. For the August 12 event, the Arizona State Climatologist's rain gage at South Mountain measured 26 mm in 10 min, 68 mm in 50 min and 86 mm in 100 min translating into intensities of 154, 81, and 51 mm/h or a 200-year, 500 ± year, and 1000 ± year event (Dr. Nancy Selover, Arizona State Climatologist, personal communication, 2014). Radar reveals South Mountain to have been the focus of the most intense precipitation that took place over time span of less than 2 h.

The September 8, 2014 event contrasted greatly in that remnant moisture from eastern Pacific Hurricane Norbert moved over the entire south-central portion of Arizona, leading to precipitation lasting over 4 h and generating even more rain for South Mountain than the August 12th thunderstorm complex. The event started with 36 mm in 25 min (87 mm/h). Another 68 mm then soaked the range over the next 285 min (14 mm/h) where precipitation intensities occasionally exceeded 30 mm/h, but only for 5 min at a time. Other rain gages across South Mountain reflect these amounts and intensities. Taken as an entire event, the September 8 storm produced the wettest day on record in Phoenix, AZ, and it is considered a 500-year precipitation event by the U.S. National Weather Service.