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# STRATH DEVELOPMENT IN SMALL ARID WATERSHEDS: CASE STUDY OF SOUTH MOUNTAIN, SONORAN DESERT, ARIZONA

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**ABSTRACT. Analyses of ephemeral granitic drainages of $<5$ km$^2$ at South Mountain metamorphic core complex, central Arizona, reveal a previously undocumented process of bedrock strath formation in this setting. Granitic channel banks experience a higher degree of mineral decay than that of granitic channel floors. Electron microscope observations show that grussification along the granitic channel banks occurs through abiotic processes of biotite oxidation and biotic processes associated with mycorrhizal fungi and roots of plants preferentially growing along channel banks. Digital image processing of backscattered electron microscope (BSE) images measured: (a) an enhancement of porosity along channel banks 2× to 5× greater than mid-channel positions; and (b) the gradual separation of grains over a 13-year period caused by the roots of Paloverde (*Parkinsonia microphylla*) trees. Ongoing mineral decay along banks facilitates differential erosion similar to Montgomery's (2004) hypothesis. Ephemeral washes migrate laterally into the decayed granite of their banks and erode the distal end of bounding pediments, expanding beveled bedrock straths. Direct observations of strath widening in six drainages during three distinct flash floods reveal a range from 4 to 23 millimeters of lateral bank erosion and $<1$ mm of channel bed abrasion. The widening of straths is likely limited by long-term rates of *in situ* physical separation of granitic minerals.**

Key words: Strath, strath terrace, pediment, ephemeral stream, desert geomorphology

## INTRODUCTION

Since Bucher (1932) first described the term "strath," earth scientists studying river terraces and their associated landscape histories have puzzled over processes responsible for the formation of beveled bedrock floodplains, herein referred to as strath (Formento-Trigilio, ms, 2002; Montgomery, 2004; Pazzaglia, 2013). Montgomery (2004, p. 454) summarized this difficulty:

> "Models of the processes governing the formation of erosional, bedrock-cored river terraces . . . are not as well established as models of processes responsible for the formation of constructional alluvial river terraces."

Straths form during periods of accelerated lateral incision along a stream reach, widening the valley bottom, and generating an erosional unconformity of the surface underlying the channel (Gilbert, 1877; Mackin, 1937; Yokoyama, 1999; Hancock and Anderson, 2002; Montgomery, 2004; Wohl, 2008; Pazzaglia, 2013). Strath terraces subsequently occur when rates of vertical incision increase, abandoning the strath above the modern channel.

Understanding processes that create a strath and the subsequent strath terrace has become increasingly relevant. Numerous studies employ straths to analyze uplift rates, climatic driven sediment variability, erosion rates, incision rates, drainage basin evolution, among other applications (for example, Burnett and Schumm, 1983; Pazzaglia and Gardner, 1993; Merrits and others, 1994; Burbank and others, 1996; Chadwick and others, 1997; Pazzaglia and others, 1998; Reneau, 2000; Barnard and

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others, 2001; Hsieh and Knuepfer, 2001; Pazzaglia and Brandon, 2001; Wegmann and Pazzaglia, 2002; Formento-Trigilio and others, 2003; Barnard and others, 2006; Garcia and Mahan, 2009; Finnegan and others, 2014). Thus, the development of the strath form is relevant to not just the fluvial system, but a wide variety of other earth systems as well.

A long held conceptual view holds that straths form when a stream reaches a graded condition, draining to a static base level, where neither aggradation nor degradation occurs along its reach (Gilbert, 1877; Mackin, 1937; Mackin, 1948; Knox, 1975; Leopold and Bull, 1979; Bull, 1990; Bull, 1991; Hancock and Anderson, 2002). Pazzaglia (2013) explained that strath floodplains also develop where streams achieve a steady-state profile. Steady-state profiles do not change in elevation even when extrinsic properties, such as base level and tectonics, fluctuate. Thus, steady-state streams tend to incise synchronously with uplift—over graded time scales—in tectonically active regions (Pazzaglia and others, 1998; Pazzaglia and Brandon, 2001). The formation of an erosional strath surface, however, may not necessarily require that the longitudinal profile remain static for a long period. Although truncating a Holocene fluvial/deltaic complex, the Truckee River, Nevada, developed a series of six erosional terraces over a 44 year time span (Born and Ritter, 1970).

Controls on oscillations to and from grade or steady-state conditions can include a variety of intrinsic and extrinsic processes including: fluctuations in climate (Molnar and others, 1994; Pan and others, 2003; Fuller and others, 2009; Ferrier and others, 2013)—sometimes involving eustatic sea-level change (Pazzaglia and Gardner, 1993; Merritts and others, 1994; Blum and Tornqvist, 2000; Tebbens and others, 2000); tectonic uplift and base level subsidence (Born and Ritter, 1970; Rockwell and others, 1984; Merritts and others, 1994; Reneau, 2000; Lave and Avouac, 2001; Cheng and others, 2002); changing relationships between discharge and sediment supply (Hasbargen and Paola, 2000; Pazzaglia and Brandon, 2001; Hancock and Anderson, 2002; Wegmann and Pazzaglia, 2002); and intrinsic fluvial system processes such as drainage piracy (Garcia, 2006; Lee and others, 2011; Stamm and others, 2013) and basin overflow can vary the rates of vertical incision (for example, Meek, 1989a, 1989b; Reheis and others, 2007; Reheis and Redwine, 2008; Larson and others, 2010).

Conversely, a variety of conditions facilitate strath formation once a stream reaches a steady-state or grade: (1) climate-driven and/or basin intrinsic increases in sediment flux (Personius and others, 1993; Personius, 1995; Hancock and Anderson, 2002; Formento-Trigilio and others, 2003; Pan and others, 2003; Fuller and others, 2009); (2) reaching a drainage area threshold (Merritts and others, 1994; Garcia, 2006); (3) a weakened/erodible substrate exposed in the channel banks (Montgomery, 2004; Stock and others, 2005; Wohl, 2008); and (4) instability triggered by meander growth and cutoffs (Finnegan and Dietrich, 2011).

An increase in sediment supply is a dynamic control on channel behavior. Increases in sediment supply can result in an alluvial cover that, in effect, can armor the channel and protect the bedrock floor from vertical incision by raising the bed (Hancock and Anderson, 2002; Fuller and others, 2009). It may also shift the channel morphology to a braided form facilitating widening of valley floor characteristic of braided channels (Leopold and others, 1992; p. 286-295). Erosion of bedrock channels through plucking, abrasion and cavitation (Hancock and others, 1998; Whipple and others, 2000; Chatanantavet and Parker, 2009) depend largely on slope and rates of channel bed exposure to erosion (Sklar and Dietrich, 2001; Stock and others, 2005). Thus, raising the bed would limit the contact between erosional tools in transport and the bedrock surface.

A sufficiently large drainage area is also thought to be a factor in strath development (Merritts and others, 1994; Garcia, 2006; Garcia and Mahan, 2009). Merrits and others (1994) found that straths occur where drainage area provides enough stream power for lateral erosion, but far enough upstream to be independent of fluctuations in regional base level. Garcia (2006) tested this hypothesis, revealing that the intrinsic process of drainage capture, or piracy, can increase the drainage area sufficiently to facilitate the formation of straths over graded time scales. Basin overflow processes may also result in the creation and subsequent incision of straths (for example, Meek, 1989a; Meek, 1989b; Reheis and others, 2007; Reheis and Redwine, 2008; Larson and others, 2010).

The influence of channel slope on strath formation may be controlled, to a large degree, by the resistance of the underlying lithology (Gilbert, 1877), where streams flowing over resistant rocks tend to form steepened, narrow channel reaches while those flowing over weaker substrates promote valley widening and a sediment load sufficient to protect the bed from erosion. Montgomery (2004) applied this conceptual understanding to the relative erodibility of channel banks as compared to the channel floor. He discovered that perennial streams flowing over weak sedimentary lithologies develop a distinct "asymmetry in bedrock erodibility" (p. 464) resulting from mechanical weathering from wetting and drying (or freeze-thaw) of the channel banks over time. Montgomery (2004) specifically notes that strath formation does not require a bed protected by alluvium if this asymmetry exists; however, a positive feedback would occur where alluvium covers the strath.

This research expands on Montgomery's (2004) hypothesis and explores processes responsible for the development of erosional bedrock floodplains within a previously undocumented setting in the strath literature—ephemeral arid granitic drainages—in a tectonically quiescent setting. The following sections of this paper present the geological setting of the study area, followed by our hypothesis for strath formation, methods, results and then discussion.

## GEOLOGIC SETTING AND STUDY AREA

South Mountain metamorphic core complex (SMCC) is a SW-NE trending suite of small mountain ranges approximately 29 km long and hosts the South Mountain city preserve in Phoenix, Arizona (fig. 1). Metamorphic core complexes (MCC) occur throughout the North American Cordillera, forming a discontinuous belt of uplifted structures stretching from northwestern Mexico to southwestern Canada (Coney, 1980; Armstrong, 1982; Coney and Harms, 1984; Reynolds, 1985). While geomorphic research carried out in MCCs includes such topics as drainage-basin evolution (Pain, 1985, 1986; Spencer, 2000), hillslope stability (Applegarth, 2002), debris flows (Dorn, 2010, 2012), and the role of structure on drainage development (Pelletier and others, 2009), we have not found prior research on fluvial landforms and, more specifically, strath formation in MCCs.

Reynolds' (1985) research at SMCC revealed three distinct reasons to investigate the SMCC study area as a case study for strath formation: (1) fluvial terraces exist within structurally-controlled drainages suggesting dynamic change in a poorly understood small, arid fluvial system (Schick, 1974); (2) SMCC is a tectonically quiescent range thus limiting uplift as an extrinsic influence to fluvial processes; and (3) SMCC is relatively "geologically simple" being dominated by two broad types of lithology in the study area (fig. 1). The western half of SMCC consists mainly of Precambrian gneiss with alluvial fans and fan-cut terraces as the dominant alluvial landforms. In contrast, the eastern half consists of mid-Tertiary granite that host isolated and semi-continuous strath terraces and ephemeral bedrock channels. Thus, SMCC enables the assessment of strath formation in a field setting with limited tectonic and lithologic variation and with the presence of strath terraces above modern strath floodplains.

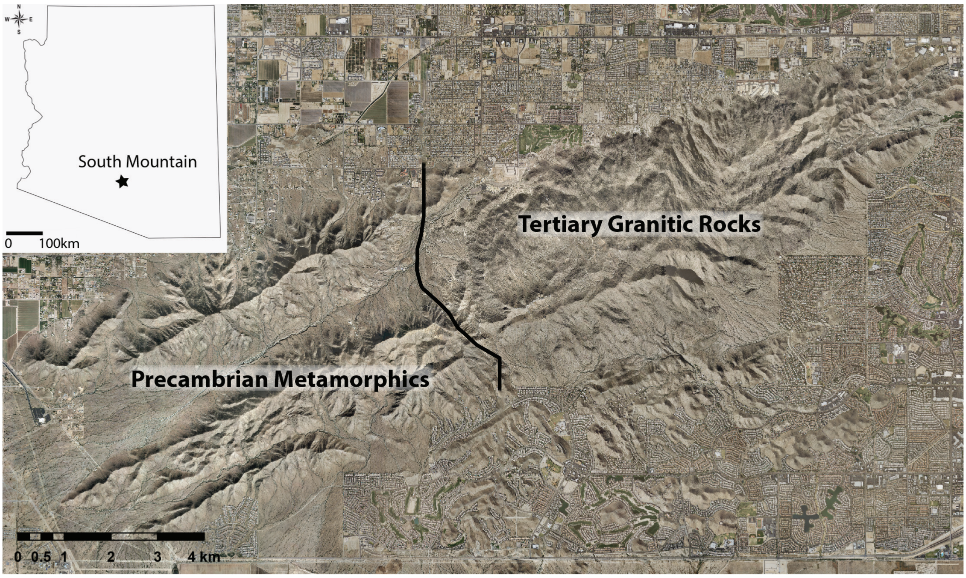

Fig. 1. Location of South Mountain, central Arizona. South Mountain is a SW-NE trending metamorphic core complex within the Sonoran Desert, Basin and Range physiographic province. Note the simplified geologic map where the NE half of the range consists of granitic rocks and the SW half contains metamorphic rocks. Alluvial fans are the dominant alluvial landform within the metamorphic lithologies while strath terraces are the dominant form in the granitic lithologies.

## HYPOTHESES OF STRATH FORMATION

The literature on stream erosion of granitic materials contains the conceptual model of stepped topography (Wahrhaftig, 1965), which suggests that small washes carrying grus erode vertically into relatively unweathered granite at very slow rates. This is due to an assumed ineffectiveness of grus to serve as an erosional "tool" on fresh granite exposures. More recent research (Sklar and Dietrich, 2001, 2004), in contrast, reveals that grain sizes that are sufficiently large to travel as bedload, but small enough to still be entrained in transport, are "efficient" abrasive tools. This suggests that quartz grains, like those seen in the grus bedload within SMCC, could be effective abrasive tools during ephemeral flash floods. Therefore, two questions inevitably arise from this conflict in the literature: (a) are rates of vertical incision through abrasion greater than rates of lateral erosion, thus inhibiting extensive strath formation in a setting underlain by granitic rock? Or, if this is not the case, (b) what are the processes responsible for facilitating lateral widening of straths in granite?

*Enhanced rock decay along stream banks fosters strath development.*—Field observations indicate the presence of bedrock straths throughout the granitic eastern half of SMCC. In these settings, ephemeral granitic washes preferentially widen straths during directly observed flash floods, the characteristic norm for flow in these arid ephemeral drainages. Montgomery (2004) hypothesized that differential weathering between the channel banks and channel bed results in differentially erodability in sedimentary lithologies, where banks are weaker than beds resulting in banks more susceptible to erosion. Concomitantly at SMCC, we hypothesize that widening of straths occurs at the expense of more thoroughly decayed granitic rock present in channel banks as compared to that of the channel bed (fig. 2). This hypothesis is also consistent with measurements in Taiwan indicating high magnitude floods have a larger impact on channel widening than vertical incision (Hartshorn and others, 2002).

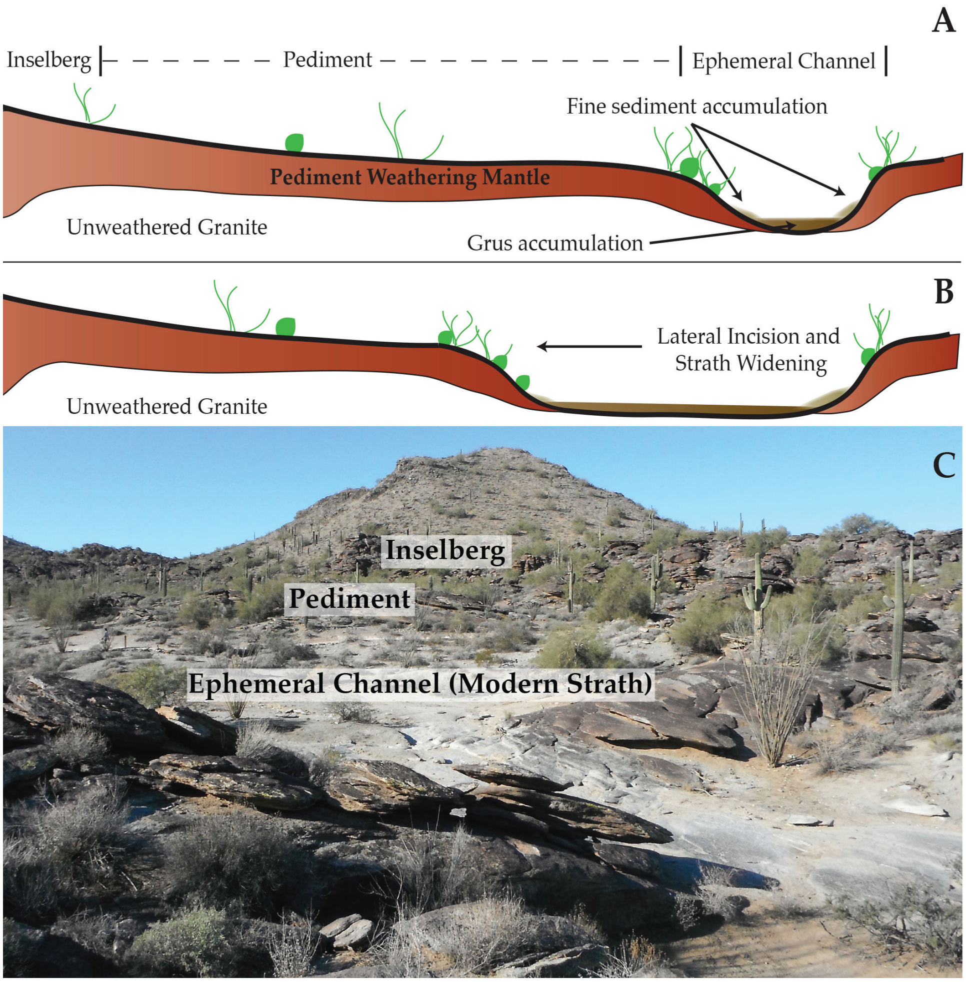

Fig. 2. A simplified diagram for the mechanism of strath widening in ephemeral granitic drainages. Scale is provided by the iconic saguaro cacti that are ~4–6 m tall. (A) The initial setting of the ephemeral streams within SMCC. Note the pediment weathering mantle exposed in the channel banks. Also note the higher vegetation density along the channel banks and accumulation of fine sediment at the foot of channel banks. (B) The presence of the pediment weathering mantle, vegetation and fine sediments create a weathering asymmetry between channel bank and channel floor, where channel banks are more highly weathered. This facilitates lateral erosion over vertical incision and strath widening during the observed ephemeral flash floods. (C) A typical landscape setting at SMCC consisting of a bedrock floored ephemeral stream channel with bounding pediments that grade up to inselberg slopes. We refer to this landscape relationship as the pediment-strath relationship.

Field observations reveal the ubiquitous presence of decayed granite in channel banks next to relatively unweathered granite on the channel floor (fig. 3). We hypothesize that decayed granite exposed along the channel bank is a function of three processes that can operate independently and in combination. First, granitic pediments grade to straths (fig. 2) and are typified by a sub-aerially weathered mantle of partially grussified rock (Mabbutt, 1966; Twidale, 1968; Cooke and Mason, 1973; Moss, 1977). Pediments within SMCC occur on the scale of meters, flanking uplands that bound the granitic drainages (Reynolds, 1985). The drainages in SMCC often flow

Fig. 3. This scene replicates throughout SMCC, where a gray-colored and relatively resistant modern strath abuts a thoroughly grussified bank. The banks of SMCC dry washes often host a dense cover of perennial plants—due to the greater availability of moisture retained along wash margins. A flash flood on August 12, 2014 resulted from 39 mm of precipitation falling in a little over one hour in the headwaters of this stream. The flash flood reached a height of 1.8 meters bank-to-bank. Spray painted dots on the fresh bedrock were slightly abraded, but strath widening was very apparent and occurred behind the person in this image. Widening was measured at 10 locations to the nearest mm (2, 2, 2, 3, 3, 4, 4, 4, 4, 6 mm) following procedures discussed in the text.

down structural weaknesses and topographic lows where adjoining pediments intersect. SMCC pediments grade to the base level of the axial wash, and channel banks expose the grussified granitic rock (fig. 3). Second, biological activity associated with roots and mycorrhizal fungi accelerate the decay of granite in the channel banks. Third, further decay could result from the greater degree of capillary water retention in fine sediments deposited at the foot of channel banks during flooding events—a concept analogous to that proposed for granite landform evolution by Oberlander (1972, 1974, 1989). Thus, we hypothesize that ephemeral washes migrate laterally into the decayed granite of their banks and erode the distal end of these small pediments, expanding beveled bedrock strath surfaces—that later become strath terraces when rates of vertical incision are sufficient to abandon the strath surface.

## METHODS

Different methods evaluated the hypothesis of strath widening facilitated by differential mineral decay. Field mapping addressed morphologic and genetic relationships among the strath, pediment and inselberg in cross-section. This effort included identifying strath terrace remnants throughout the SMCC. Additional fieldwork involved tracking storm systems from 1995 through the present and visiting field sites to conduct direct observations of flash flooding and its effect on bed and bank stability.

Laboratory methods utilized digital image processing of backscattered electron (BSE) images to measure bedrock porosity, measure rates of grussification over a period of 13 years, and to observe the biochemical action of roots and fungi.

*Field mapping.*—In the classic "pediment association" (Cooke, 1970), pediments flanking upland interfluves grade downslope to the local base level (fig. 2). To evaluate this association, we gathered cross-sectional data at locations only where we could observe and map the bedrock unconformity from the strath floodplain or strath terrace to the bedrock pediment and then up the inselberg. This was possible where erosion associated with dirt roads and trails stripped the thin colluvial cover and exposed bedrock surfaces or in locations where channel bed sedimentation was absent.

*Field observations of strath widening.*—Direct observations of strath widening in modern ephemeral washes took place during flash floods along several washes at SMCC: Kiwanis (N 33.33444 W 112.07543); Pima (N 33.36177 W 112.00549); Beverly (N 33.36832 W 111.98903); Warpaint (N 33.32630 W 112.02227); Javelina (N 33.36978 W 111.99380) and Upper Corona del Loma (N 33.33640 W 112.05286).

Direct observations were possible because of the small travel time between Arizona State University (Tempe, AZ) and field sites, when it became clear that an extensive Arizona monsoon mesoscale convective complex was likely heading toward SMCC. Automated rain gauges operated by the Flood Control District of Maricopa County (2013) are within a kilometer of each observation site and are used to monitor precipitation amounts. Each site was surveyed prior to the initiation of flow. Long nails were driven into the ends of meter sticks aligned perpendicular to the bank. Five meter sticks were placed a meter apart perpendicular to the bank. The location of the bank prior to flow was marked on each meter stick. Then, after flow ceased, the position of the bank was marked again on each meter stick. The difference estimates the amount of bank erosion during the flash flood at a location, and this approach was replicated at 5 positions along 6 washes in SMCC.

To assess vertical incision spray paint spots were placed approximately 40 cm apart on the bedrock channel bed in two cross-sections 5 meters a part—starting at the two most distant meter sticks. The idea was to mark random locations with some sort of control prior to a flash flooding event. Any amount of vertical incision would have eroded the spray paint spots, because each spray paint spot had a diameter of ~2.5 cm and a minimal thickness (<0.5 mm). In order to understand the variability in the thickness of a spray paint spot, nine test spray paint spots were placed on granitic clasts that were then broken in half. These cross sections were measured using 40× binocular microscopy with a caliper; all of the spots had thicknesses of less than 0.5 mm. While spray-paint spot survival would not exclude vertical incision at all locations along the channel cross-section, it would provide some metric of the overall significance of abrasion during the flash flooding event. Thus, following flash flood pulses, the channel floor was examined carefully at and near the spray paint spots along the cross-section. Then, all remaining evidence of spray paint was abraded off using sand paper following post-flow examination.

Despite a large number of storms experienced in the field without observed flow, three flash flood events enabled direct observation of the process of strath widening: a precipitation event of 5.4 cm in 6 hours on 8/03/05 with return interval of 32 years; an event of 3.6 cm in 3 hours on 7/24/11 with a return interval of 8 years; and 2.1 cm of precipitation in 15 minutes on 6/20/00 with a return interval of 15 years (Flood Control District of Maricopa County, 2013). While it is unlikely that the rain gauge data accurately reflects the exact precipitation received in each of the studied drainages, available gauge data provide insight into the intensity of each flow-producing event.

*Vegetation transects.*—Part of our hypothesis involves a relative abundance of vegetation on channel banks that accelerates decay of granite along the banks, as compared to neighboring landscape positions. Therefore, we established three line intersect transects (McIntyre, 1953), each with a length of 100 m along the banks of the locations of observed strath widening (Javelina, Corona del Loma, Warpaint, Pima, Kiwanis, and Beverly). The center point of these line transects was the location of measured bank retreat. These transects recorded the percent vegetation cover along the channel bank, 10 m up pediment from the bank, and 20 m up pediment from the bank.

*Rock decay as a limiting process on strath widening.*—While it is possible to measure the rock strength of banks in the field *in situ* (Wakatsuki and others, 2007), we do not believe that such measurements would inform on the circumstances that occurred during flash flooding. The wetting of the banks was irregular during the flash flood. Some banks went from a condition of very dry to saturation due to the floods, while other bank positions appeared to be close to saturation prior to the flood. Since moisture can greatly impact the physical strength of grus (Wakatsuki and others, 2007), and since the conditions were extremely irregular from place-to-place, we felt that *in situ* strength measurements would not be as telling as the microscopic understanding of long-term processes leading to the change from hard bedrock granite to a weak grussified condition.

In order to assess the role of rock decay as a process enabling strath widening, rock samples were collected from three different positions at the sites where bank erosion was directly observed during ephemeral flooding. Samples were first impregnated in the field with epoxy prior to collection in order to preserve *in situ* relationships for electron microscope study.

Each bank position sample came from the very edge of the bedrock; these are the same locations where field observations indicated erosion in response to ephemeral flooding. Each bank sample was collected 3 cm above the channel. The mid-channel position samples came from granitic bedrock, sometimes underneath a few cm of grus sand. The bedrock interior position was collected as deep as possible into the bedrock bank; depths of sample collection into the bank ranged from 80 cm to 100 cm. A pick was used to carve a very narrow trench from the channel into the bank. The trench went down to the level of the bed, allowing the collection of a sample about 3 cm above the elevation of the channel at the bank edge. Then, the trench was backfilled after sample collection.

The samples were polished for study with BSE microscopy. Using methods detailed elsewhere (Dorn, 1995), digital image processing of BSE imagery at a scale of 1000× allowed for calculation of the porosity of a sample. For each sample position, from the five different collection sites, the measured porosity is based on a cross-sectional area of 2 mm$^2$. The reported porosity includes intra-mineral pores and pores along mineral-grain boundaries. Normally, porosity measurements are presented to a hundredth of a percent based on methods detailed elsewhere (Dorn, 1995); however, given the combined nature of including different types of pores—a conservative solution is to round off to the nearest tenth.

In addition to this quantitative study of porosity, images were acquired to assess the action of roots at these bank positions. Secondary electron microscopy, combined with energy dispersive X-ray (EDX) analysis, shows the qualitative condition of quartz and plagioclase minerals that have been in contact with roots and associated mycorrhizal fungi.

*Long-term rates of grussification.*—A multi-year study to understand rates of granite grussification along channel banks started in May of 1998 within 50 meters of two of the strath-widening sites: Kiwanis and Beverly ephemeral washes. Ten rounded cobbles of fresh (relatively undecayed) granite were emplaced 10 centimeters into the bank in two settings: into the root mat of a Paloverde tree (*Parkinsonia microphylla*); and into grussified granite not in contact with plant roots. The cobbles were slowly pushed (gently hammered) into the grussified banks. Two cobbles were removed in 2003 from each position. Two more cobbles were removed in 2008. When bank erosion from the 2011 flash flood brought the cobbles closer to the bank, two more were removed in 2011.

We then measured the porosity that developed between mineral grains on the perimeter of these emplaced cobbles. The premise is that the lack of grain-to-grain attachment promotes granular disintegration or grussification (Isherwood and Street, 1976; Hoskin and Sundeen, 1985). For each cobble studied, 100 sequential perimeter mineral grains were "cut out" digitally from the backscattered electron microscope (BSE) imagery of polished cross-sections. Using the digital image processing technique described elsewhere (Dorn, 1995), analyses were "binned" into four categories: perimeter grains that showed no physical connection (attachment) in the BSE cross-section; mineral grains showing mineral-to-mineral attachment along 0.1 to 10 percent of its surface contact; mineral grains showing mineral-to-mineral attachment along 10 to 20 percent of its surface contact; and mineral grains showing mineral-to-mineral attachment along >20 percent of its surface contact.

## RESULTS

*Field mapping.*—Bedrock channels occur in all drainages (for example, fig. 2C) while isolated to semi-continuous strath terraces occur in the majority of drainages within the granitic eastern portion of SMCC (fig. 4). These drainages contain dozens of isolated strath terraces that tend to occur on the inside of meander bends. The broader pattern reveals the ubiquitous nature of terrace remnants in the granitic eastern portion of SMCC. A detailed analysis of these strath terraces is beyond the scope of this study focused on the genesis of strath floodplains. However, the presence of these strath terraces is an important addition to this research, as they demonstrate that significant vertical incision has occurred framed by periods of strath widening prior and post incision.

Old roads and trails have removed colluvial deposits exposing the bedrock strath making it possible to directly investigate the bedrock topography and the gradational relationship between hillslope (inselberg), pediment and strath. Figure 2C illustrates a typical landscape association with the pediment grading to the modern bedrock floodplain. Figure 5 exemplifies this relationship in the context of a strata terrace, revealing that the gradational pediment-strath relationship persists over longer time scales. In other words, the modern landscape contains bedrock-floored channels that are bounded by pediments graded to the channel (fig. 2C) or bounded by adjusting pediments that are graded to older strath terraces (fig. 5).

*Direct observations of strath widening during flash floods.*—The Corona del Loma, Warpaint and Pima Wash banks eroded laterally an average of 21 mm, 12 mm and 5 mm (respectively) in response to the 8/03/05 storm. The Kiwanis and Beverly wash banks eroded laterally an average of 6 mm and 4 mm (respectively) during the 7/24/11 event. The Javelina wash bank experienced an average of 9 mm of channel widening during the 6/20/00 event (table 1). In contrast, at each of the observed sites, every spray-paint dot retained paint flakes to varying degrees. Over half of the spray-paint dots were almost completely untouched. Since the spray-paint dots were <0.5 mm in thickness and neighboring granite channel bed surfaces retained a similar topographic position across the channel cross-section, relatively little bedrock incision (<0.5 mm) occurred across the entire channel width during ephemeral flow. At most, abrasion was responsible for scraping away small segments of the paint but did little to incise into the bedrock beneath the paint or in immediate proximity to the paint spots. In each case, the ephemeral flow saltated medium sand grains (grus) that were responsible for the minor abrasion of spray paint off the granitic channel bed. In

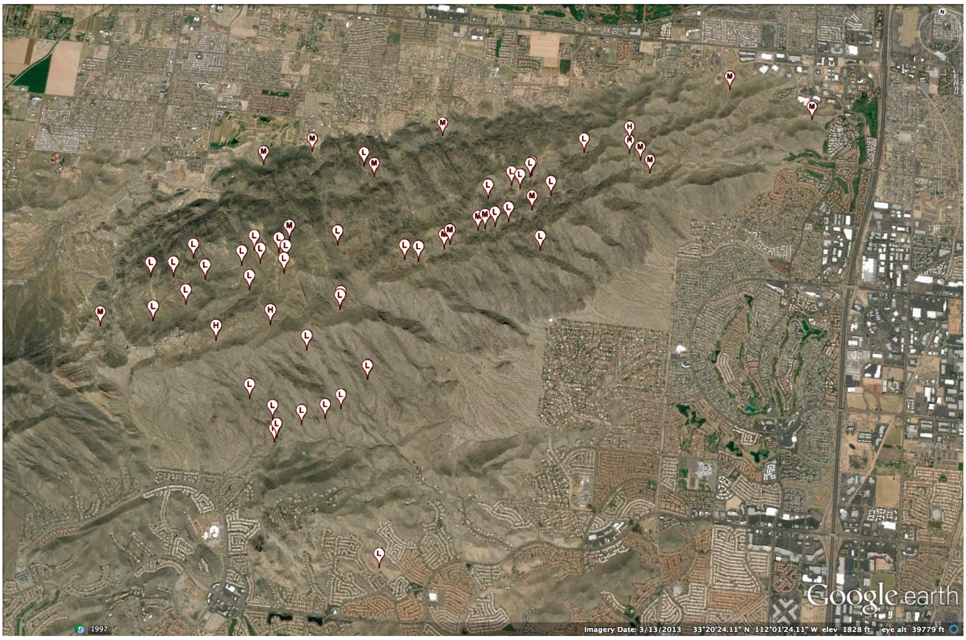

Fig. 4. Isolated strath terrace remnants are ubiquitous in the eastern granitic section of South Mountain (SMCC). The existence of strath terraces reveals a dynamic fluvial history marked by at least one significant vertical incision event temporally bounded by periods of strath carving. This map represents an effort to map all isolated strath terrace remnants within SMCC, although it is probable that we missed several locations of isolated strath terraces. H identifies the isolated remnants where we have a high confidence that the terrace form represents an extensive former strath floodplain, M symbol a medium confidence level with a much less extensive surface, and L is a lower confidence surface as some surfaces were hard to distinguish between distal pediment incision or strath surface. Locations can be viewed in a Google Earth format through a supplemental .kml file located here: http://alliance.la.asu.edu/temporary/AmJourSci/TerraceKML.kml. The base image is used following permission guidelines for Google Earth (Map Data: Google) [http://www.google.com/permissions/geoguidelines.html].

contrast, each of the bedrock channels widened measurably through bank erosion of thoroughly decayed granite. The observed process reveals a tendency of preferential widening of strath floodplains at the expense of decayed grus in channel banks during flash flooding events.

*Vegetation abundance.*—Three line intersect transects, each with a length of 100 m along the banks of the locations of strath widening, reveal that the contemporary cover of vegetation along the banks is typically double the plant cover found on adjacent pediments (table 2). Futhermore, the type of vegetation along the pediments consists mainly of *Larrea tridentata* (creosote bush) and *Encelia farinose* (brittlebush) with shallow roots systems. In contrast, the vegetation that dominates the banks have more extensive root systems of phreatophyte vegetation (for example, *Parkinsonia microphylla, Ambrosia deltoide, Encelia farinosa, Acacia greggiim, Lycium andersonii*).

*Rock decay as an enabling process for strath widening.*—The granitic bedrock banks of the six small washes that experienced erosion during ephemeral flooding show 2 to 5 times the porosity found in control samples from the interior of the bedrock (80-100 cm into the bank) and from mid-channel bed bedrock (table 3). These porosity measurements combine intra-grain and inter-grain pores that are visible in 1000× BSE images. The direct inference is that mineral decay processes that occur along the bedrock banks of ephemeral washes aid in the decomposition and disintegration of the

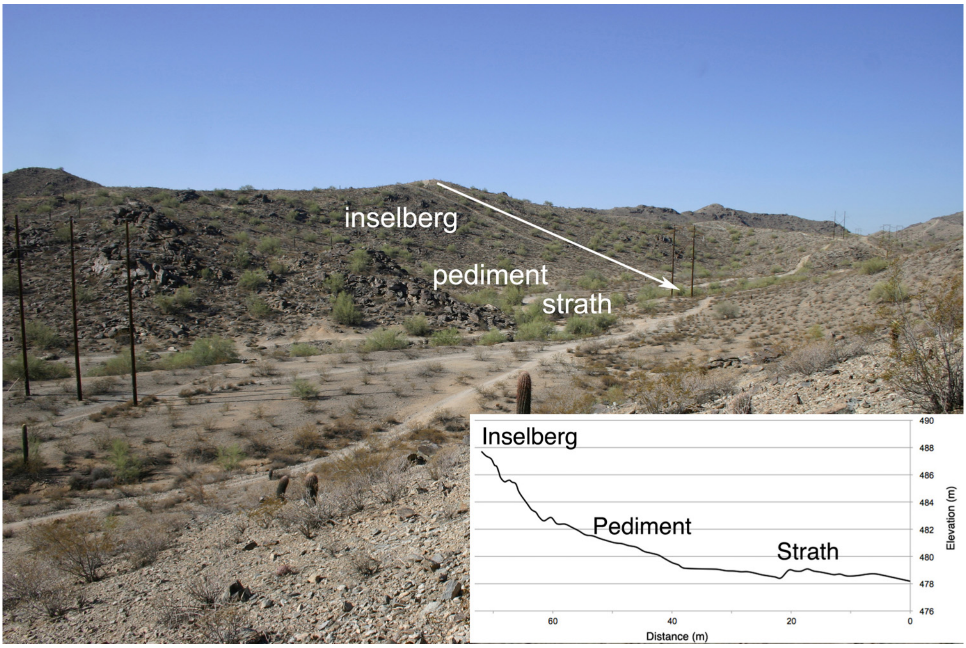

Fig. 5. An abandoned road at Beverly Canyon (to the left of the arrow) led to stripping of the colluvial cover. This facilitated measurement of a cross-sectional topographic profile along the bedrock surface from the strath terrace up to the top of the inselberg. Slope breaks between the strath, pediment and local inselberg are consistent with the hypothesis that ephemeral washes widen straths through lateral migration into banks composed of more highly decayed rock. The utility pole at the arrow provides scale. The topography observed on the strath terrace drives from the incision of small washes incising in response to local base level lowering of the trunk drainage in this watershed.

granitic bedrock—turning granitic rock into friable grus. Electron micrographs provide a visual sense of the greater degree of rock decay found along the banks of these dry washes (fig. 6). The mid-channel (fig. 6A) and bedrock interior (fig. 6D) show evidence of some porosity from ongoing discongruent dissolution, but are much less

Table 1

*Field observations of strath widening during high magnitude precipitation events*

| Wash | Precipitation Event | Bank Erosion at five positions | Strath Incision | Event Date |
|---|---|---|---|---|
| Javelina | 2.1 cm/15 min | 8, 9, 9, 9, 9 mm | not detectable | 06/20/00 |
| Corona del Loma | 5.4 cm/6 hr | 19, 21, 21, 22, 23 mm | not detectable | 08/03/05 |
| Warpaint | 5.4 cm/6 hr | 12, 12, 12, 13, 14 mm | not detectable | 08/03/05 |
| Pima | 5.4 cm/6 hr | 4, 4, 5, 5, 5 mm | not detectable | 08/03/05 |
| Kiwanis | 3.6 cm/3 hr | 4, 6, 6, 6, 7 mm | not detectable | 07/24/11 |
| Beverly | 3.6 cm/3 hr | 4, 4, 4, 4, 4 mm | not detectable | 07/24/11 |

TABLE 2

*Field observations of vegetation cover along banks and adjacent pediment in line intersect transects with a length of 100 m*

| Wash | Percent cover along the bank | Percent cover 10 m up pediment of the bank | Percent cover 20 m up pediment of the bank |
|---|---|---|---|
| Javelina | 39% | 12% | 14% |
| Corona del Loma | 41% | 23% | 19% |
| Warpaint | 27% | 13% | 13% |
| Pima | 19% | 10% | 9% |
| Kiwanis | 22% | 18% | 15% |
| Beverly | 24% | 9% | 10% |

decayed than samples collected along the wash banks (figs. 6B and 6C), where minimal physical contact occurs between decayed minerals.

The net effect of the greater porosity along channel banks can be seen in figure 3, where the gray relatively fresh granodiorite channel bed contrasts with the buff/brown thoroughly grussified bank. These grussified banks are often temporarily covered with silt and sand, deposited at the waning of a flash flooding event. This cover can store moisture, theoretically enhancing decay rates—a qualitative conjecture made in the pediment literature (Oberlander, 1974, 1989). However, our direct electron microscope observations also point to another process—root decay associated with the enhanced growth of vegetation along wash banks.

The bank vegetation cover includes *Parkinsonia microphylla*, *Ambrosia deltoide*, *Encelia farinosa*, *Acacia greggiim*, *Lycium andersonii*, *Hyptis emoryi*, and *Ziziphus obtusifolia.* Roots and associated mycorrhizal fungi penetrate into the granitic bedrock. This biotic decay results in enhanced decay of the bedrock along the channel banks (fig. 7). The notion that mycorrhizal fungi might play a key role in weakening channel banks should come as no surprise. Research over the past few years, using new microanalytical techniques, reveals the power of roots and their associated fungi to decay

TABLE 3

*Percent porosity in 2 $mm^2$ samples of granodiorite collected from three different positions at locations where strath widening was directly observed in association with ephemeral flooding: midchannel, bank, and bedrock interior*

| Sampled Wash | % Porosity at Bank | % Porosity in Bedrock Interior | % Porosity Mid-channel |
|---|---|---|---|
| Javelina | 13.0 | 4.6 | 5.1 |
| Corona del Loma | 25.2 | 13.9 | 12.2 |
| Warpaint | 22.7 | 9.4 | 6.7 |
| Pima | 15.9 | 6.8 | 5.8 |
| Kiwanis | 12.1 | 4.3 | 3.5 |
| Beverly | 16.7 | 6.8 | 3.5 |

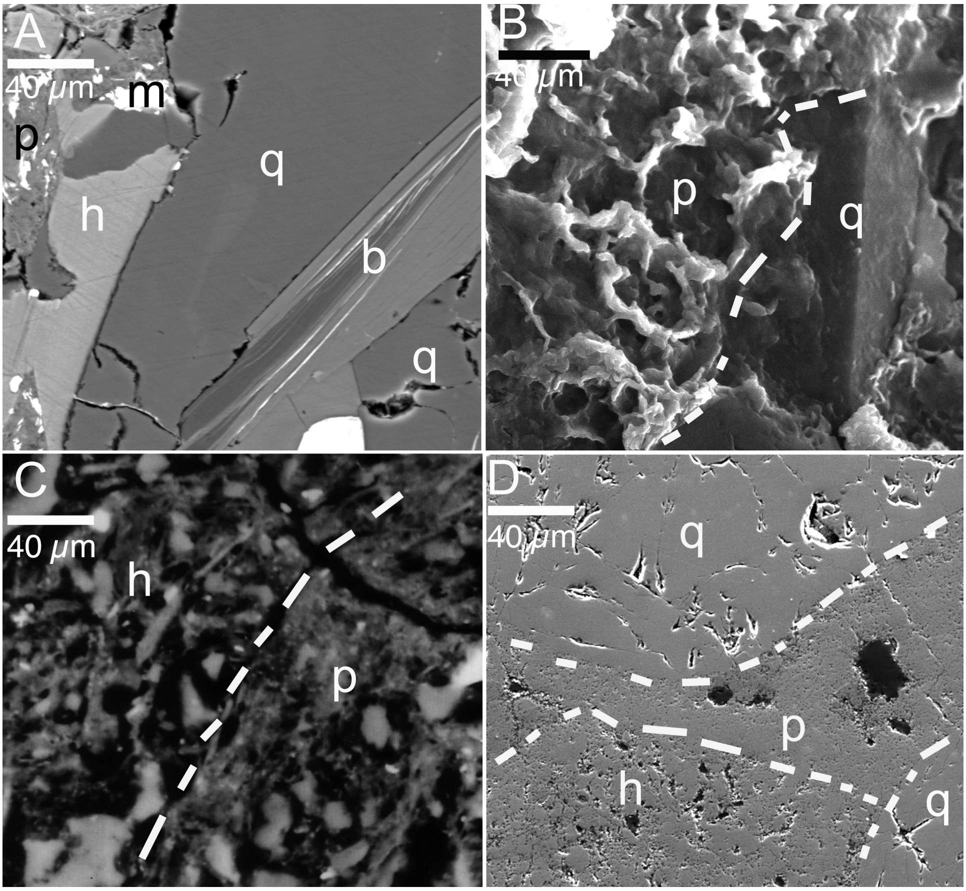

Fig. 6. Backscatter (A&C) and secondary (B&D) electron microscope imagery of granitic decay associated with the widening of a strath at Pima Wash, South Mountain. Energy dispersive X-ray spectroscopy aided mineral identification of quartz (q), biotite (b), hornblende (h), plagioclase (p), and magnetite (m). Dashed lines in B, C, and D identify mineral boundaries. Image A shows relatively undecayed granodiorite sampled in the middle of the channel, where the grain-to-grain attachment remains strong. Image B captures the very surface of the exposed bedrock on the edge of the channel, collected 3 cm up from the channel surface. Although the quartz grain is relatively undecayed, the plagioclase shows no cohesion. Image C typifies a thoroughly decayed sample of grussified granite at the margin of the channel, where there is little evidence of grain-to-grain adherence. Image D exemplifies samples collected from within bedrock adjacent to a channel—in this case collected 80 cm in from the channel margin—where the porosity shows some dissolution occurred inside the bedrock prior to exposure to the subaerial environment. Scale bars are in micrometers.

bedrock (Landeweert and others, 2001; Hoffland and others, 2004; Bonneville and others, 2009; Smits and others, 2009; McMaster, 2012; Viles, 2013).

A 13-year study comparing physical connectivity of granitic minerals on the perimeter of cobbles pushed into the banks at the Kiwanis and Beverly study sites reveals measurable changes in the samples in contact with Paloverde (*Parkinsonia microphylla*) roots. Over the study period, the percent of perimeter grains showing no evidence of inter-grain attachment and a decrease in inter-grain attachment increased steadily over 13 years (fig. 8). In contrast, the position without roots showed no observable change from the initial condition (fig. 8). The lack of observable change in the cobbles distant from Paloverde roots does not imply that grussification processes

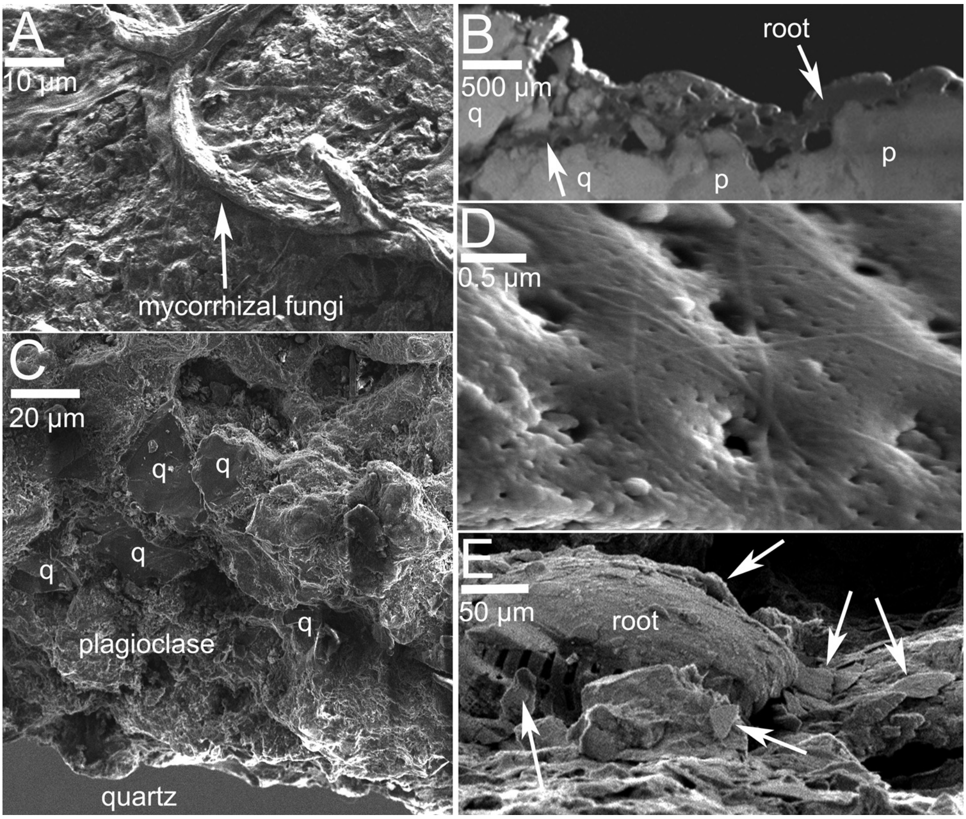

Fig. 7. Secondary electron images of rock decay along banks fronted by hard-rock straths. The images all show the effects of mycorrhizal fungi (image A) and roots (B). Mineralogy (q = quartz; p = plagioclase) is based on EDX analyses. Most of the effect appears to be the decay plagioclase grains to the point where they have very little internal cohesion. Image C highlights this where the relatively in tact quartz contrasts with the thoroughly disintegrated plagioclase. However, quartz also decays, as exhibited by dissolution pits in image D, where the pits are visible because the mycorrhizal fungi were removed. The lines on the quartz surface have the same EDX Si and O signature as the quartz, and thus they could reflect redeposition of silica. Image E shows that the process of decay can involve physical force breaking apart minerals, as evidenced by the angular particles (arrows) of quartz found in abundance in physical proximity to the root. Scale bars are in micrometers.

are lacking; it is likely that changes away from roots are not detectable with methods used over a 13 year period. These results do imply that roots and associated mycorrhizal fungi accelerate the decrease in grain connectivity—or grussification—fast enough to observe over a period of 13 years.

## DISCUSSION

Working in sedimentary rocks, Montgomery (2004) first proposed a hypothesis that differential rock decay between channel banks and bed could facilitate strath widening. The results of this research in small ephemeral granitic watersheds provide additional support for an "asymmetry in bedrock erodibility" (p. 464) facilitating strath development. Granite's tendency to break down into grus through biotite decay (Isherwood and Street, 1976; Hoskin and Sundeen, 1985), discongruent dissolution (fig. 6), and biotic processes (fig. 7) means that granitic terrains tend to produce biomodal sediment: sand-sized grus and core stones of boulder size that are not easily

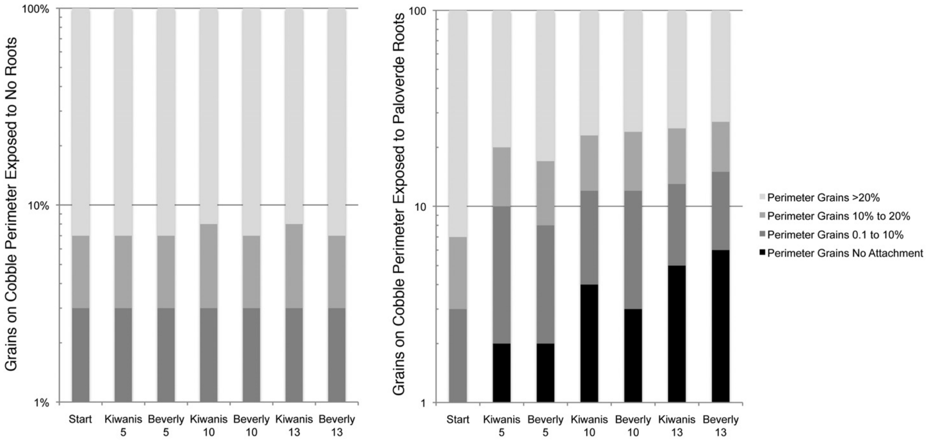

Fig. 8. A 13-year study compared physical connectivity of grains on the perimeter of granitic cobbles gently hammered into banks containing Paloverde roots and an adjacent position without roots. The percent of perimeter grains showing no evidence of inter-grain attachment increased steadily over the period at the Kiwanis and Beverly study sites with roots. In contrast, the position without roots showed no observable change from the initial condition.

transported by ephemeral desert washes. Over a 13 year period, grain-to-grain contact was reduced in cobbles placed in bank walls at locations with abundant roots (fig. 8)—providing further insight into the importance of biotic processes in enhancing grussification along the banks of desert washes (fig. 7).

Porosity in the channel banks, channel floor, and bedrock interior provide another indication of the relative rates of rock decay at SMCC. An asymmetry between bed and bank resistance to erosion—revealed through the metric of porosity—exists in all South Mountain sites; channel banks are 2 to 5 times more porous than control positions in the bedrock interior and channel bottom (table 3). This enhanced mineral decay reduces grain-to-grain contact (figs. 6 and 7) that appears to have facilitated the observed strath widening during flash flooding. We speculate that the increased porosity reduces the tensile strength of the channel bank granite allowing for impacting grains to facilitate disintegration and for increased pore water pressure to separate bank grains when saturated during flooding.

The rate of strath widening must be limited by the rate of channel bank decay, along with the frequency and magnitude of flash flooding events that reach the bank. The relative importance of bank decay and flash flooding, however, cannot be determined by a limited dataset. Consider that the Corona Del Loma and Warpaint drainages contain sites that experienced the most bank erosion and strath widening, and these sites also had the highest measured bank porosity. In the case of Javelina wash, in contrast, the most intense precipitation event (2.1 cm over 15 minutes) resulted in the third highest bank erosion in spite of having comparatively lower amounts of bank porosity. Thus, we are unable to definitively determine the relative importance of bank decay compared to the magnitude of the flood—other than to suggest that both are significant factors in strath widening in our study area.

Unfortunately, understanding long-term rates is similarly difficult. The frequency of flooding in small ephemeral washes like at SMCC during the Holocene is unknown. Similarly, long-term rates of grussification, or the detachment of individual mineral grains from bedrock, are unknown for the Sonoran Desert. The insight provided by the porosity (table 3) and grain-separation (fig. 8) studies simply reveal an ordinal ranking that supports Montgomery's (2004) notion of differential weathering influencing strath widening: (a) for 13 years cobbles emplaced in roots experienced far more loss of grain-to-grain contact than cobbles emplaced in banks away from roots; and (b) for bedrock granitic lithologies, porosity at the banks experiencing strath widening was 2 to 5 times greater than porosity inside the pediment bedrock, which experienced greater porosity than bedrock in the channel bed.

Wohl (1998, 2008) found that straths can develop in harder rocks where discontinuities, such as horizontal/subhorizonal jointing and shearing zones, facilitate bank erosion. The results of this study focusing on granitic bedrock provides yet another example of a discontinuity facilitating strath widening. In this case, the discontinuity is not structural but rather a function of a washes position at the distal end of a bedrock pediment, where a partially grussified granite is further decayed by bankside biota.

Wahrhaftig's (1965) concept of stepped topography is founded on the premise that streams carrying only grus are able to erode into beds of undecayed granite only at very slow rates. In apparent contrast, the quartz grains that are ubiquitous in grus can serve as an erosional tool to abrade bedrock channel surfaces over time (Sklar and Dietrich, 2001). In 23 years of observations of extreme precipitation events at SMCC, we observed only three flash flooding events widening straths. For each of these three events, very little channel bed abrasion took place. The spray painted spots placed along transects across the strath—with a thickness of $<0.5$ mm—were abraded in some places. However, no grooving or pitting was seen in the bedrock granite where the spray paint had been partially abraded and no significant incision appeared across the channel bed cross-sections neighboring the spray paint dots. These observations were made for each spray-painted spot during the process of removal with 60-grit sand paper. In contrast, the grooves left behind by the sand paper were more noticeable than any abrasion by the flash floods.

While no prior published data are available on vertical incision rates of ephemeral undecayed granitic washes, our direct observations are consistent with research conducted in very different climatic and tectonic settings. In Taiwan, Hartshorn and others (2002) note that high magnitude, low frequency floods increase bedrock channel width. High magnitude precipitation events at SMCC, with return intervals on the order of decades, led to far greater rates of bank erosion of the granite exposed in the channel walls as compared to that of the undecayed channel floors (table 1). While minor flows were observed in these drainages, they consisted of ribbons of clear water 2 to 30 cm across saltating occasional sand grains. These minor flows typically occur in response to 2 to 5 year recurrence interval precipitation events. Observations of even smaller flows will just move suspended sediment and some bedload around the wash and reposition it in different locations. These flows, when observed, do not expose the bed by removing the accumulation of grus observed in most locations. We have stood in the channel during flow events with a recurrence interval of 2 to 5 years and observed grus transport. These flows may abrade the surface very slightly. During flash floods, in contrast, it was certainly not safe to make direct observations in the channel. Thus, we only infer from the partial removal of the spray paint that the grains being transported at SMCC may be polishing the granitic channel beds through minor abrasion, but it appears that no measurable ($>0.5$ mm) vertical incision is occurring during flash flooding events over the last few decades.

Differential mineral decay and the resulting erosional asymmetry observed at SMCC may be relevant to other locations underlain by granitic lithologies. For example, the nearby perennial Salt River hosts terraces (Kokalis, ms, 1971; Pewe, 1978; Larson and others, 2010) that are predominantly strath cut into granitic bedrock and surrounded by actively adjusting pediment systems (Pewe, 1978). Beveled bedrock straths once formed the base level of these pediments and were carved at the expense of the pediments (Larson, ms, 2013). Thus, this location displays the same pediment-strath relationship (fig. 2) observed at SMCC. Larger pediment systems developed on granitic bedrock may, too, laterally widen and develop their iconic piedmont form through similar ephemeral erosional processes.

Three general factors that occur in the SMCC study area would tend to facilitate strath carving more generally in granitic terrains in arid regions: 1) the pediment-strath relationship (fig. 2); 2) enhanced rock decay from biological processes along the banks; and 3) enhanced rock decay by silt and fine sediments stored along the base of channel banks after ephemeral floods. We explore each of these in turn.

The existence of small pediments within the SMCC has been noted for some time (Reynolds, 1985). These small pediments are morphologically connected to strath floodplains and strath terrace remnants, as they grade relatively smoothly to each surface. We observed this pediment-strath relationship in nearly all drainages underlain by granitic rocks (for example, fig. 5). Furthermore, sites in SMCC where strath terrace remnants are not present often contain pediments that grade to the modern strath channel (fig. 2C). This is not an isolated relationship only observed in the SMCC. For example, pediments in southwest Montana have been noted to transition smoothly into strath surfaces (Sears, 2009). We have similarly observed this pediment-strath relationship throughout central Arizona where both pediment development and strath formation are associated with the stability of a local or regional base level (Larson and others, 2010).

The relevance of pediment-strath relationship rests in preparing the landscape for strath carving in two ways. First, pediments already have a gradual slope (Cooke, 1970). Therefore, it does not take a significant excavation of mass to develop a strath. Second, pediments in granitic terrain often contain partially decayed regolith sometimes called a "weathering mantle" (Mabbutt, 1966; Cooke and Mason, 1973; Moss, 1977). The channel bank, thus, exposes granitic rocks that have been decaying in the pediment position—prior to exposure along a wash bank.

The prevalence of bank-side vegetation (table 2), due to a greater abundance of water in desert washes, further enhances bank decay through biochemical and biophysical processes acting on the exposed granitic rocks. Electron microscope imagery of roots (Phillips and others, 2008; Gabet and Mudd, 2010) and mycorrhizal fungi (Landeweert and others, 2001; Hoffland and others, 2004; Bonneville and others, 2009; Smits and others, 2009; McMaster, 2012; Viles, 2013) reveal roots can physically crack rock and that plagioclase minerals in granite lose all cohesion; mycorrhizal fungi even pit quartz (fig. 7D). When combined with the abiotic processes of biotite oxidation and plagioclase discongruent dissolution (fig. 6) and the action of lithobionts (Danin and Garty, 1983; Eckhardt, 1985; Viles, 1995) seen on banks, the net effect increases porosity of the bedrock along channel banks (table 3) and further enables the strath widening observed directly during flash flooding (table 1).

Our direct observations of flooding events at SMCC reveal that silt deposits on the margin of a channel as an ephemeral flood pulse recedes. We speculate that this silt could behave similar to the mantle at the base of a classic pediment-inselberg slope. Just as the overland flow generated by an inselberg sinks into the pediment mantle and enhances granite decay at the slope break (Oberlander, 1974, 1989), water flowing down the banks and down the wash permeates into the silt and enhances moisture contact with bedrock channel walls. The ephemeral nature of these silt deposits make it difficult to test this hypothesis through a controlled electron microscope study of silt-covered and non-silt covered positions. Our observations reveal that these silt deposits can be remobilized even in small semi-annual events. Thus, the ubiquitous occurrence of straths at the distal end of granitic pediments, bankside vegetation, and ephemeral bank-side silt deposits point to a reasonable likelihood that the erosional asymmetry observed at SMCC should occur in granitic terrains at other arid and semi-arid locales.

## CONCLUSION

An asymmetry of erosion in the ephemeral channels of South Mountain results from more highly decayed granitic rocks along channel banks as compared to relatively fresh granitic rocks on channel floors. The asymmetry exists as a result of the bounding granitic pediment being sub-aerially weathered and being exposed in the channel banks. This asymmetry is further enhanced by the action of roots, mycorrhizal fungi, and perhaps moisture retention in fine sediments preserved along the banks. Since granitic rocks underlay large areas of desert in the southwestern USA and elsewhere, we anticipate that the process of strath formation via differential weathering facilitating differential erosion (Montgomery, 2004) seen at South Mountain should be widespread throughout the Sonoran and Mojave Deserts and other dryland ephemeral streams underlain by granitic lithologies.

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