Desert fluvial terraces and their relationship with basin development in the Sonoran

Desert, Basin and Range: Case studies from south-central Arizona.

by

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ABSTRACT

A fundamental gap in geomorphic scholarship regards fluvial terraces in small desert drainages and those terraces associated with integrating drainages. This dissertation analyzes four field-based case studies within the Sonoran Desert, south-central Arizona, with the overriding purpose of developing a theory to explain the formative processes and spatial distribution of fluvial terraces in the region. Strath terraces are a common form (Chapters 2, 3, 4) and are created at the expense of bounding pediments that occur on the margins of constraining mountainous drainage boundaries (Chapters 1, 2, 3). Base-level fluctuations of the major drainages cause the formation of new straths at lower elevations. Dramatic pediment adjustment and subsequent regrading follows (Chapter 3), where pediments regrade to strath floodplains. This linkage between pediments and their distal straths is termed the *pediment-strath relationship*. Stability of the base level of the major drainage leads to lateral migration and straths are carved at the expense of bounding pediments through an erosional asymmetry facilitated by differential rock decay between the channel bank and bed. Fill terraces occur within the Salt River drainage basin as a result of the integration processes that connect formerly endorheic basins (Chapter 4). The topographic, spatial, and sedimentologic relationship of the Stewart Mountain terrace (Chapter 4) points to a different genetic origin than the lower terraces in this basin. The high Stewart Mountain fill terrace records the initial integration of this river. The strath terraces inset below the Stewart Mountain terrace are a result of the pediment-strath relationship. These case studies also reveal that the under-addressed drainage processes of piracy and overflow have significant impacts in the evolution of drainages the lead to both strath and fill terrace formation in this region.

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DEDICATION

I dedicate this dissertation to my mother and father, Dale and Lisa Larson. If not for the

family vacations each summer growing up, to the incredible landscapes of the American

West, I never would have found my passion in life. There is absolutely no conceivable

way I would be here today without their love and support. I also dedicate this

dissertation to my advisor Dr. Ron Dorn, who has guided me on this incredible journey

both as an advisor and friend. I can't begin to thank you enough.

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Chapter 1

INTRODUCTION

The focus of this dissertation is to explicate the formation and spatial distribution of arid fluvial terraces within the Sonoran Desert, south-central Arizona. An accumulation of over two centuries of literature exists regarding fluvial terraces. Within that literature a fundamental understanding of the significance, scientific utility and nature of the terrace form has developed. The significance of the fluvial terrace is far reaching beyond just the earth sciences and includes fields interested in mineral resource potential, building/construction materials, agriculture, irrigation, archeology, etc. (Pazzaglia 2013). However, the fundamental 40 year old observation of a desert fluvial geomorphologist, Asher P. Schick, point to an immense gap in our understanding of this landform:

> "the study of fluvial terraces of small watersheds in the arid zone seems
> to have been neglected" (Schick 1974).

Upon reviewing the vast literature on fluvial terraces I have found that it is not only the terraces in small arid watersheds that have been neglected, but arid terraces as a whole that are poorly understood. This is not meant to infer that our understanding of arid rivers is lacking, as an abundance of research focuses on fluvial systems in drylands (e.g. Bull and Schick 1979; Yair and Kossovsky 2002; Flerchinger and Cooley 2000; Lange 2005; Graf 1982, 1988, 2000; Chowdhury and Sharma 2009; Ma, Wang, and Edmunds 2005; Taylor and Hudson-Edwards 2008; Genxu and Guodong 1999). However, the majority of terrace studies focus, as Schick (1974) posits, on large regional scale drainages. Even more apparent is that the vast majority of these papers investigate fluvial

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systems in any combination of the following settings – temperate or high precipitation regime climates (e.g. Pazzaglia and Gardner 1993; Pazzaglia and Gardner 1994; Montgomery 2004; Bookhagen et al. 2006), tectonically active regions (e.g. Wegmann and Pazzaglia 2002, 2009; Scharer et al. 2006; Robustelli 2009; Lave and Avouac 2000; Hsieh and Knuepfer 2001; Gao et al. 2005; Formento-Trigilio et al. 2003; Dortch et al. 2011; Colombo et al. 2000), and drainages adjusting from direct impacts from post-Pleistocence glacial epochs (e.g. Knox 1995; Trowbridge 1954; Flock 1983; Johnson, Davie, and Pedersen 1998; Knox and Attig 1988; Davis 1902; Quinn 1957; Rittenhour, Blum, and Goble 2007; Erkens et al. 2009). There are many more categories that the immense terrace literature could be subdivided into, but the fact remains that the overwhelming majority of terrace research has ignored the formation of fluvial terraces in the desert/arid setting, and particularly within Arizona's Sonoran Desert (e.g. Pope 1974; Kokalis 1971; Pewe 1978; Larson et al. 2010; Huckleberry et al. 2012; House et al. 2005).

The purpose of this dissertation is to build on the fundamental work of past terrace researchers, by contributing case studies from the perspective of a fluvial geomorphologist within the Sonoran Desert. The purpose of this chapter is to introduce the fluvial terrace and summarize our current understanding of the form. In so doing, this chapter will provide the conceptual background understanding for the case studies in the remaining chapters of this work. A complete and comprehensive review of the voluminous literature on fluvial terraces is beyond the scope of this dissertation. Therefore, this introductory chapter will attempt to explain the terrace form highlighting seminal works and reviews that have synthesized and constructed my current

understanding of fluvial terraces.

The first section of this chapter will discuss the history of fluvial terrace research and how our modern idea of the form has developed. It will also describe the different classifications of fluvial terraces and how they are distinguished from one another. The next section will discuss the processes responsible for the incision and the subsequent formation of fluvial terraces. The last section will highlight the four studies within this dissertation, the objectives of each research project, and how each of these studies furthers our understanding of arid/desert fluvial terrace formation.

THE FLUVIAL TERRACE

The history of fluvial terrace literature spans approximately two centuries where Miller (1883) suggests that Playfair (1802) was likely first to recognize the significance of the terrace form within a landscape:

> "When the usual form of a river is considered, with the trunk divided into many branches which rise at a great distance from one another, and these again subdivided into an infinity of smaller ramifications, it becomes strongly impressed on the mind that all these channels have been cut by the water themselves. The changes which have taken place in the courses of rivers are to be traced in many instances by successive platforms of flat alluvial land, rising one above another, and marking the different levels on which the river has run at different periods of time."

The prevalence of fluvial terrace research dramatically began its ascent during the mid to late 19th century where a variety of researchers began to describe and take note of the form (e.g. Lesley 1878; Dana 1881; Nelson 1893; Miller 1883; Hitchcock 1833, 1857; Darwin 1846; Prestwich 1864; Home 1875; Upham 1877; Whitaker 1875). This resulted in wide variety of explanations for the origin of the form. Miller's (1883) summary of

some of this early literature exemplifies the inadequate understanding early researchers had in regards to the significance of the fluvial terrace:

> – *Summary of possible origins of terraces* –
> 1. Ancient sea margins
> 2. Ancient river flats deserted on the account of elevation (tectonic uplift)
> 3. Ancient river flats, episodically incised in response to climate change
> 4. Relics of former monstrous floods
> 5. Shorelines of former spasmodically tapped lakes
> 6. Uplifted fluvio-marine banks
> 7. Morainic debris banked against melting glaciers
> 8. Submarine deposits
> 9. Features produced by river action during down cutting, when impulses of erosion took effect

Early terrace research clearly created the backbone for our contemporary understanding of the landform, but struggled to define exactly what a terrace represents and its origin. It was not until the fundamental works of G.K. Gilbert and W.M. Davis (Davis 1902; Gilbert 1877) that our contemporary understanding of the term emerged (Pazzaglia 2013, p. 2). Presently, we understand fluvial terraces as a landform that represents the former floodplain of the current river that has been abandoned at a level higher than the modern channel (Leopold, et al. 1964, Schumm 1977, Petts and Foster 1985, Bull 1990, Ritter, et al. 2002, Hugget 2003, Harden 2004, Charlton 2008).

The surface of the former floodplain is known as the terrace tread, while the slope that rises to the tread is generally referred to as the terrace scarp, berm, or riser (Campbell 1929, Ritter, et al. 2002). Fluvial terraces are mapped/correlated as either paired or un-paired terraces. Paired terraces match elevation and theoretically have the same geochronologic significance on both sides of the river valley (Leopold, et al. 1964, Schumm 1977, Ritter, et al. 2002). Paired terraces occur when vertical stream incision is

greater than lateral migration of the stream channel (Schumm 1977). These terraces can record a single incision event or multiple events that lead to uniform incision and terrace formation. Un-paired terraces do not match in elevation on either side of the river valley. They often have a staggered topography from valley side to valley side and likely form when lateral migration coincides with some degree of vertical incision (Leopold, et al. 1964, Schumm 1977, Charlton 2008). These terraces can represent a combination of episodic incision and lateral planation, being created as the river both incises slowly and migrates laterally through its valley. It is also possible to have unpaired terraces as the result of the erosive lateral migration of the river obliterating remnants as well.

Terraces can be classified as either depositional or erosional. The most common depositional terraces are fill terraces (Bull 1990) and require an aggradational event within the stream valley, a period of floodplain formation and subsequent incision of the stream channel abandoning that floodplain (Ritter, Kochel, and Miller 2002). Another form of a depositional terrace is a nested-fill terrace that forms when a valley fills–incises–and fills again, but with a different fill source being nested inside the older fill. Erosional terraces include strath (Bucher 1932) and fill-cut terraces. Particular emphasis is placed on explaining strath terraces as they are the most prevalent terrace form observed during the case studies in this dissertation. Bull (1990) suggests that beveling of bedrock straths and the strath terrace are the "fundamental tectonic stream-terrace landform" and they are often found where streams have tectonically induced downcutting. However, within the Sonoran Desert tectonics has been dormant for eight million years. This necessitates a more thorough look at strath terrace formation. The difficulty in understanding strath terraces is exemplified by Montgomery (2004):

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> "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."

Recent research suggests that the conditions for major strath carving (Bull 1990) occur when rates of lateral erosion exceed rates of vertical incision, during a period of vertical stability (Yokoyama 1999; Montgomery 2004; Wohl 2008; Pazzaglia 2013; Hancock and Anderson 2002; Gilbert 1877; Mackin 1937). Formation of the erosional strath is followed by channel incision, leaving behind the strath terrace (Mackin 1937). An adequately thick veneer of resistant alluvium may be necessary to preserve the strath as a terrace (Montgomery 2004; Garcia 2006; Garcia and Mahan 2009).   Processes leading to strath formation have long been thought to occur when a stream reaches a graded condition, where it drains to a static base level, and neither aggradation nor degradation occurs along its reach (Bull 1990; Hancock and Anderson 2002; Leopold and Bull 1979; Gilbert 1877; Mackin 1937, 1948; Knox 1975; Bull 1991). Pazzaglia (2013) indicates that straths develop when the stream has achieved either a profile of steady state or grade, drawing a careful distinction between the two. Steady state profiles do not change in elevation even when extrinsic properties, like base level, fluctuate. Steady state streams strive to incise synchronously with uplift in tectonically active regions (Pazzaglia, Gardner, and Merritts 1998; Pazzaglia and Brandon 2001). This does not necessarily require a lengthy period of a static longitudinal profile. In the case of the Truckee River, Nevada, a suite of six erosional terraces formed within a 44 year time span as the result of minor fluctuations in base level (Born and Ritter 1970). Controls on the oscillations to and from grade/steady-state include: fluctuations in climate (Pan et al.

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2003; Fuller et al. 2009; Molnar et al. 1994; Ferrier, Hupper, and Perron 2013)—sometimes involving eustatic sea-level change (Blum and Tornqvist 2000; Tebbens et al. 2000; Pazzaglia and Gardner 1993; Merritts, Vincent, and Wohl 1994); tectonic uplift and base level subsidence (Lave and Avouac 2001; Cheng et al. 2002; Rockwell et al. 1984; Born and Ritter 1970; Reneau 2000; Merritts, Vincent, and Wohl 1994); changing relationships between discharge and sediment supply (Wegmann and Pazzaglia 2002; Pazzaglia and Brandon 2001; Hancock and Anderson 2002; Hasbargen and Paola 2000); and intrinsic fluvial system processes such as drainage piracy (Garcia 2006; Stamm et al. in Press; Lee et al. 2011)

Once a stream reaches a steady-state or grade, recent research suggests different conditions can facilitate strath formation: (1) climate-driven and/or basin intrinsic increases in sediment flux (Personius 1995; Personius, Kelsey, and Grabau 1993; Pan et al. 2003; Fuller et al. 2009; Hancock and Anderson 2002; Formento-Trigilio et al. 2003); (2) reaching a drainage area threshold (Merritts, Vincent, and Wohl 1994; Garcia 2006); (3) a weakened/erodible substrate exposed in the channel banks (Montgomery 2004; Wohl 2008); and (4) inherent instability triggered by meander growth and cutoffs (Finnegan and Dietrich 2011).

An increase in sediment supply may be a dynamic control on channel behavior, resulting in an alluvial cover that, in effect, armors the channel and protects the bed from vertical incision (Fuller et al. 2009; Hancock and Anderson 2002). This is further supported by research that indicates erosion of bedrock through plucking, abrasion and cavitation (Whipple, Hancock, and Anderson 2000; Chatanantavet and Parker 2009; Hancock, Anderson, and Whipple 1998) and channel slope largely depend on rates of

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channel bed exposure to erosion (Sklar and Dietrich, 2001; Stock et al, 2005). A change

in the nature of sediment flux may also allow for channel morphology to shift to a

braided form, thus facilitating widening of its valley and these two process may work in

harmony.

A sufficiently large drainage area is also thought to be a factor in strath

development (Merritts, Vincent, and Wohl 1994; Garcia and Mahan 2009; Garcia 2006).

Merrits et al. (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 piracy can increase the drainage area sufficiently to facilitate the

formation of straths over graded time scales. Drainage evolutionary processes associated

with basin overflow (e.g. Reheis, Miller, and Redwine 2007; Reheis and Redwine 2008;

Meek 1989a, 1989b; Larson et al. 2010) may also result in the creation and subsequent

incision of straths.

The influence of channel slope on strath formation may be controlled, to a large

degree, by the resistance of the underlying lithology (Gilbert 1877). Because streams

flowing over resistant rocks form steepened, narrow channel reaches and those flowing

over a weak substrate form wide, low sloped channel reaches, weak substrate allows for

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 found that perennial streams flowing

over weak sedimentary lithologies developed a distinct "asymmetry in bedrock

erodibility" (p.464) resulting from mechanical weathering via wetting and drying (or

freeze-thaw) of the channel banks over time. Montgomery (2004) specifically noted that strath formation did not require a bed protected by alluvium if this asymmetry exists – but a positive feedback would occur where alluvium covers the strath. Others have suggests that bedrock discontinuities (i.e. horizontal/subhorizontal jointing and shear zones) could also facilitate bank erosion and strath development in more resistant lithologies (Wohl 1998; Wohl 2008)

Fill-cut terraces are similar although they do not bevel the bedrock "strath." The stream valley has filled with alluvium and the alluvium is first eroded to form an erosional surface, followed by incision into this floodplain. It is important to note that the highest terrace in a valley filled with alluvium is likely a fill terrace and is depositional in origin. Fill-cut terraces are inset within the fill terrace and represent progressive incision events within a stream valley.

THE CAUSE OF FLUVIAL TERRACE FORMATION

Incision mechanisms resulting in the fluvial terrace form can result from changes in intrinsic or extrinsic variables in the fluvial system, ultimately influencing the balance between sediment discharge (Qs) and stream fluid discharge (Q). Working under the paradigm that streams tend towards grade (Mackin 1948; Gilbert 1877; Davis 1902; Bull 1990; Schumm 1977), a steam's Q transports all Qs in a state of equilibrium (Baker and Ritter 1975; Mackin 1948; Bull 1979; Schumm 1977). A concave-upwards graded longitudinal profile is a function of the Q/Qs relationship, or competence of the stream (Gilbert, 1877), as the fluvial system tends to steadily increase in discharge and bed load grain size decreases downstream. For grade to establish, base level must remain

stationary (Bull 1991; Knox 1975; Gilbert 1877; Leopold and Bull 1979), unless in a steady-state form that allows the river profile to remain stationary (Pazzaglia 2013). However, graded streams rarely occur in natural settings, because of the truly dynamic and variable nature of streams (Marcus and Fonstad 2010; Fonstad and Marcus 2010). For the purpose of understanding terrace formation, however, a major alteration of grade can generate a response of aggradation or incision of the channel and this concept can be used to better understand the system in terms of incision and aggradation.

Tectonism, uplift and/or subsidence can significantly alter grade and result in terrace formation. Stream terraces, therefore, have the potential to generate insight into the tectonic history of a drainage basin (Berryman et al. 2000; Bull 1990; Holbrook and Schumm 1999; Carcaillet et al. 2009; Leopold and Bull 1979; Merritts, Vincent, and Wohl 1994; Peters and Balen van 2007; Zuchiewicz 2011; Pewe 1978; Westaway et al. 2004; Maddy 1998; Westaway 2003; Hsieh and Knuepfer 2001). When tectonism alters the streams gradient (or slope), it influences the ability the stream to transport sediment downstream. For example, tectonic uplift in the headwaters increases stream gradient, giving that stream a greater ability to transport sediment. If the sediment load does not change, the stream incises into its channel, abandoning its former floodplain as a terrace. Base level subsidence generates a similar effect, increasing the stream gradient and causing incision which results in terrace formation. A drop in base level can result from tectonic subsidence or eustatic sea level lowering.

Climatic oscillations have long been recognized as an important factor in stream incision (Kock et al. 2009; Brigland and Westaway 2008; Knox 1995; Molnar et al. 1994; Bull 1991, 1990; Leopold, Wolman, and Miller 1964; Houben 2003; Hsieh and Knuepfer

2001; Tebbens et al. 2000; Bestland 1997; Fuller et al. 1998; Knox 1983). Changes in precipitation influence the streams ability to transport sediment. Vegetation change alters the sediment input into a stream as well (Quinn 1957; Bull 1991; Huntington 1907; McDonald, McFadden, and Wells 2003; Throckmorton and Reheis 1993; Wells, McFadden, and Dohrenwend 1987). Climate also influence eustatic sea level change, that raises and lowers base level of an entire drainage basin (Blum and Tornqvist 2000; Tebbens et al. 2000).

Lithologic differences also impact incision (Ritter, Kochel, and Miller 2002; Colombo et al. 2000; Garcia 2006). As a drainage basin evolves it often erodes headward and laterally across a landscape. This may alter the materials mined by a stream and its tributaries. For example, changes that produce larger or smaller clasts can result in aggradation or incision. Changes in particle size can also impact the autogenic processes within a drainage network, where streams originating in mountains have a steeper gradient and higher elevation than neighboring tributaries that may originate over softer lithologies in the piedmont. This can lead to drainage captures by the lower elevation/gradient piedmont stream, that would cause aggradation; subsequently incision into the channel results from readjustment of the longitudinal profile (Ritter 1972).

CASE STUDIES FROM THE SONORAN DESERT, SOUTH-CENTRAL ARIZONA

In order to address the fundamental gap in our understanding of the nature of fluvial terraces in arid/desert environments, and particularly within the Sonoran Desert, several important concepts were addressed in the following research. First, drainages of varying scales were analyzed to determine if the nature of fluvial terraces change

between a variety of watershed scales. As Schlick (1974) suggests, "The study of fluvial terraces of small watersheds in the arid zone seems to have been neglected," therefore it is important to address the issue of scale to determine if a model can be developed throughout all of the regions drainage basins. The smaller drainages of South Mountain, an isolated range in south-central Arizona, were investigated along with significantly larger drainages of the Salt and Verde River system. Second, drainages that contained both fill and strath terraces were investigated to determine the driving mechanisms in the formation of both fundamental types of fluvial terrace. Both fill and strath terraces exist within the Salt and Verde River systems however, they are predominantly strath for the smaller South Mountain drainages. Third, a study of pediment evolution in response to the Salt River drainage adjustment was conducted. Pediments serve as functional components of the drainage basin and reflect the nature of adjustment within the fluvial system. It was observed that strath terraces reside upon these surfaces and this observation suggests a relationship between the terrace and pediment forms that is not clear at present. A series of four pediment surfaces were analyzed along the Salt River to evaluate these complex response mechanisms to dynamic river adjustment. Lastly, often overlooked intrinsic drainage processes were evaluated as possible terrace forming mechanisms. Within each drainage investigated recently established deterministic criteria (Douglass et al. 2009a, 2009b; Douglass 2005) were applied, as well as other field interpretations, to determine the impact of intrinsic drainage processes. The dissertation addressed each of these issues through a series of case studies, highlighted below:

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The alluvial fan-cut terrace: A review and criteria to differentiate from fluvial terraces.– As prominent landforms in many geomorphic settings, alluvial fans and fluvial terraces often coexist within a single drainage basin. This juxtaposition, in some instances, has proved problematic for researchers who have not clearly or successfully distinguished fluvial terraces from truncated tributary fans. This confusion could relate the lack of a clear definition of the landform, since fan-cut terrace, truncated alluvial fan, toe-cut alluvial fan, alluvial terrace, and incision of the lower end of a fan piedmont all refer to the same genetic landform. This paper presents criteria to aid in the identification of an alluvial fan-cut terrace as an abandoned alluvial surface formed by the truncation of tributary alluvial fans by streams flowing perpendicular to the fan surface. Truncation occurs through lateral erosion ('toe cutting') or through vertical incision by the axial drainage lowering base level. A case study from the Basin and Range province in central Arizona illustrates the criteria, where a sequence of abandoned alluvial surfaces strongly resembles fluvial terraces, but use of the proposed criteria reveals them to be fan-cut terraces.

Strath development in small arid watersheds: Case study of South Mountain, Sonoran Desert, Arizona.– Analyses of modern straths and strath terraces in small arid drainages of <5 km^2 reveal two previously undocumented processes that appear to be responsible for carving bedrock erosional floodplains in granitic lithologies of the South Mountain metamorphic core complex, central Arizona. The first process involves an asymmetry of erosion due to enhanced rock decay along channel banks, compared to channel bottoms. Ephemeral washes flowing in topographic lows between bedrock pediments cut straths through lateral migration into the pediment's weathering mantle, a

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process observed during several flash floods. This process is further facilitated by bedrock decay through abiotic processes like biotite oxidation that is subsequenty enhanced by mycorrhizal fungi associated with the roots of plants growing along stream banks. A second process of strath formation relates to aggradational piracy along the margins of the range. Piracy leads to an increase in drainage area and regrading of the stream's longitudinal profile. The increased drainage area accessed during long profile adjustment forms a bedrock strath immediately downstream of the capture point, while post-piracy adjustments form straths upstream of the capture. Erosional floodplains produced by these processes experienced subsequent incision, forming strath fluvial terraces. The mechanisms for incision, however, remain unclear. Those drainages flowing into the Salt River incised at the onset of the last glacial maximum, according to ^{14}C and VML ages, and this could relate to a shift in the position of the Salt River towards South Mountain or incision of the Salt River itself. In contrast, the pirated drainage flows south towards the Gila River incised into its highest strath between Heinrich Events 1 and 2 — suggesting a possible link to climatic change. The causes of Holocene strath incision events ~4100 cal BP and ~300-650 cal BP possibly correlate with regional fluvial adjustments seen in larger southwestern USA rivers.

The control of base level on pediment processes, a case study from the lower Salt River Valley, central Arizona.– The scholarly research on granitic rock pediments includes very little discussion on the role base level fluctuations. This study investigates the controls of base level on granitic rock pediments flanking inselberg mountain ranges in south-central, Arizona. When base level is lowered, terrace incision occurs and pediments respond by regrading to strath floodplains of the Salt and Verde rivers.

Pediments regrade through different mechanisms working in concert: headward erosion; stream piracy; and lateral migration. Headward erosion of pediment drainages begin at the base of the pediment in response to base level lowering. The largest drainages erode headward more efficiently and create a local base level on the pediment surface. The largest pediments respond with the greatest erosion rate (averaging ~90mm/ka) while the smallest pediments have erosion rates an order of magnitude lower (~ 7-8mm/ka). Tributaries retreating from these master drainages incise into the remnant pediment surfaces and can capture pediment streams on the former surface. Stream piracy processes resulting from headward eroding drainages work to increase drainage area of the capturing stream and lowering the relict pediment surface over time. Finally, lateral erosion occurs predominantly in the distal reach of the master pediment drainages. It also occurs when large pediment drainages converge, suggesting a drainage area relationship facilitating lateral erosion. Each of these processes resulting in planation down to a new pediment surface adjusted to a lowered base level.

Stewart Mountain Terrace: A new Salt River terrace with implications   for landscape evolution of the lower Salt River valley, Arizona.– Stream terraces of the Salt River form the interpretive backbone of Plio-Pleistocene landscape evolution of central Arizona, because they represent the base level of all tributary streams. This paper presents a new addition to T.L. Péwé's Salt River Terrace sequence (in decreasing topographic position and age: Sawik, Mesa, Blue Point, and Lehi) that has been unrefined for the last thirty years. The existence of an older, higher terrace was predicted by research suggesting that the lower Salt River originated by lake overflow from an ancestral Pliocene lake in the Tonto Basin. Field reconnaissance, aerial photo

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interpretation, and sedimentological analysis revealed this terrace on the north side of the

Salt River, named here the Stewart Mountain Terrace (SMT). Where exposed, the fluvial

sediments of SMT overlay Tertiary basin fill unconformably. SMT sediments are

characterized by ~50 m thick fluvial gravels found more than 70 meters above remnants

of the Sawik Terrace. Although the gravels are distinctly Salt River in origin, Stewart

Mountain gravels differ from the lower and younger Salt River Terraces. The clast sizes

are much larger on average and host a significantly different lithology. Because of these

differences the SMT has profound implications for the understanding of regional

drainage reorganization after basin and range extension. The existence of this terrace and

its distinct gravels are consistent with, but do not prove, a lake overflow mechanism for

the initiation of through flowing drainage in the Salt River valley.

Chapter 2

THE ALLUVIAL FAN-CUT TERRACE: A REVIEW AND CRITERIA TO

DIFFERENTIATE FROM FLUVIAL TERRACES

**ABSTRACT.   As prominent landforms in many geomorphic settings, alluvial fans
and fluvial terraces often coexist within a single drainage basin. This juxtaposition,
in some instances, has proved problematic for researchers who have not clearly or
successfully distinguished fluvial terraces from truncated tributary fans. This
confusion could relate the lack of a clear definition of the landform, since fan-cut
terrace, truncated alluvial fan, toe-cut alluvial fan, alluvial terrace, and incision of
the lower end of a fan piedmont all refer to the same genetic landform. This paper
presents criteria to aid in the identification of an alluvial fan-cut terrace as an
abandoned alluvial surface formed by the truncation of tributary alluvial fans by
streams flowing perpendicular to the fan surface. Truncation occurs through
lateral erosion ('toe cutting') or through vertical incision by the axial drainage
lowering base level. A case study from the Basin and Range province in central
Arizona illustrates the criteria, where a sequence of abandoned alluvial surfaces
strongly resembles fluvial terraces, but use of the proposed criteria reveals them to
be fan-cut terraces.**

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INTRODUCTION

Alluvial fan-cut terraces (**fig. 1**) form as a result of the interaction between a drainage basin's axial stream and alluvial fans debouching from tributary drainages (Leeder and Mack 2001). They often form through lateral erosion of a non-incising axial stream, a process referred to as 'toe-cutting' (Leeder and Mack 2001). They also develop when incision of the axial incises lowers the base level of the tributary fan (Colombo, et al. 2000, Colombo 2005). Fan-cut terraces are important features, in part, because of their broader implication for stratigraphic basin analysis and groundwater studies (Leeder and Mack 2001).

Fan-cut terraces occur frequently in many geomorphic settings, leading to their study in the Andes Mountains (Colombo, et al. 2000, Colombo 2005), Death Valley (Blair and McPherson 2009), Big Lost River Basin of Idaho (Leeder and Mack 2001), along numerous rivers in northern India (Bedi 1980, Chatterjee and Sarkar 1982, Chopra 1990, Jana and Dutta 1996, Kumar and Aravindan 2007, Uniyal, et al. 2010, Kesari 2011), the UAE and Oman (Al-Farraj and Harvey 2005), and New Zealand (Carryer 1966) to name a few. Within the Basin and Range of western North American they exist as a dominant landscape feature (Gile, et al. 1981, Pederson 1981). For example, Pederson's (1981) classification of landforms for soil scientists includes alluvial fans whose lower surfaces have been truncated by the main trunk stream of a basin axial drainage. These fan-cut terraces remain distinct from fluvial terraces that often co-occur above modern axial washes. Directly above the fluvial terraces, however, erosion of the lower end of a fan piedmont mimics the appearance of a fluvial terrace (**fig. 2**).

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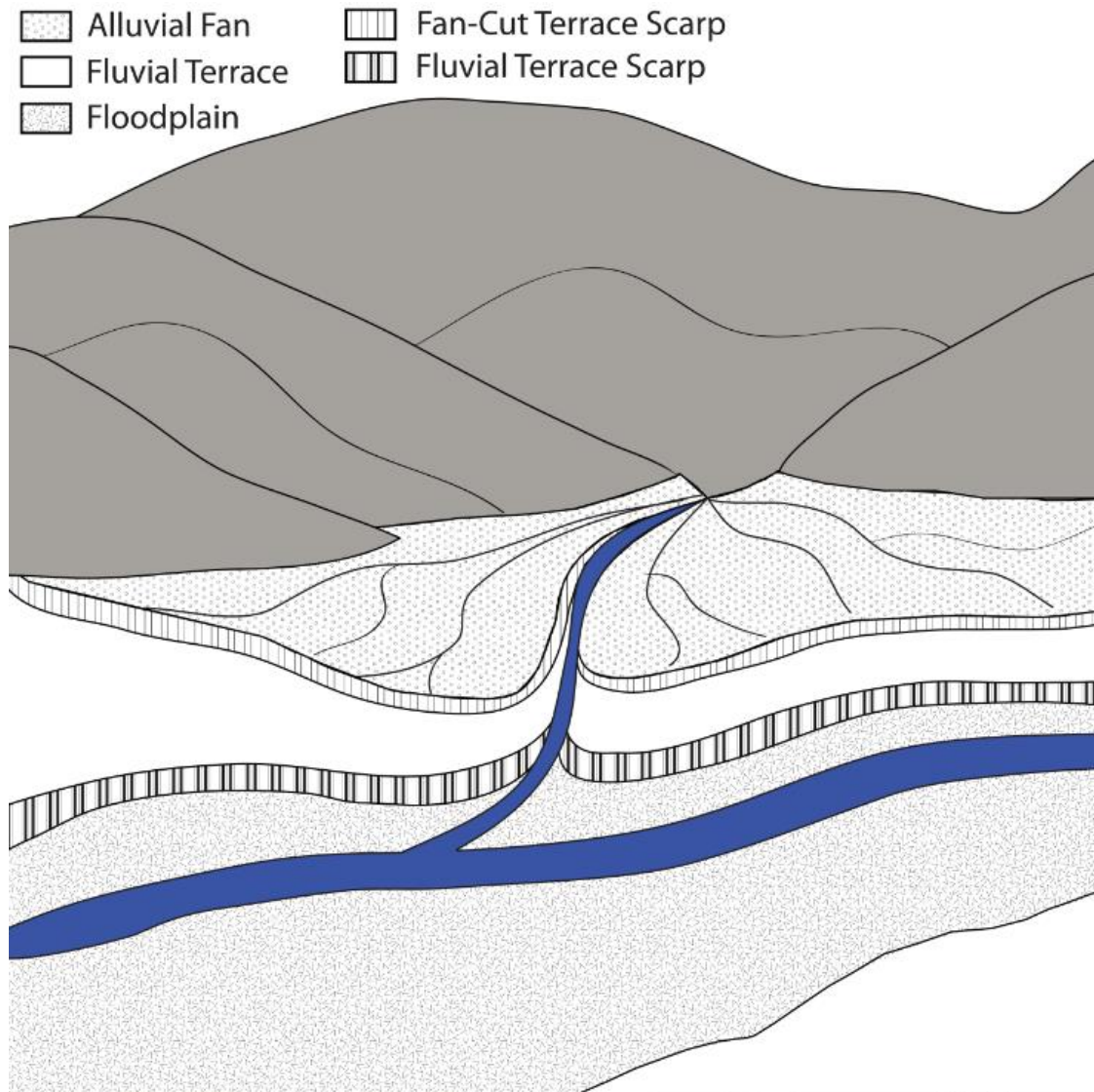
Fig. 1. Idealized diagram of morphologic relationship between a fluvial terrace and a fan-cut terrace. While the fluvial terrace scarp remains parallel to the axial drainage, the fan-cut terrace scarp bounds both the tributary and the edge of the fan, which has been truncated by the axial drainage. Viewed from the channel, a fan-cut scarp appears to parallel the axial stream.

Within geomorphic scholarship the term 'fan-cut terrace' is predominantly used in

research conducted in India (Bedi 1980, Chatterjee and Sarkar 1982, Chopra 1990, Jana

and Dutta 1996, Kumar and Aravindan 2007, Uniyal, et al. 2010, Kesari 2011). In

addition, we have found five other descriptions used to describe this landform: toe-cut

alluvial fans (Mack and Leeder 1999, Leeder and Mack 2001, Florsheim 2004, Suresh, et

al. 2007, Mack, et al. 2008, Blair and McPherson 2009, Harvey 2010), toe-trimmed

alluvial fans (Al-Farraj and Harvey 2005), truncated alluvial fan (Young, et al. 1986,

Manville 2010, Sanchez-Nunez, et al. 2012), the eroded distal end of alluvial piedmonts

(Pederson, 1981), and alluvial terraces (Colombo, et al. 2000, Colombo 2005, Gao, et al.

2005). No single accepted term, however, exists for the basic landform (**fig. 1**). We, thus,

suggest that *fan-cut terrace* be the commonly accepted term — defined as follows: an

abandoned alluvial surface that forms by the truncation of tributary alluvial fans by an

axial drainage flowing obliquely or perpendicular to the alluvial fan surface.
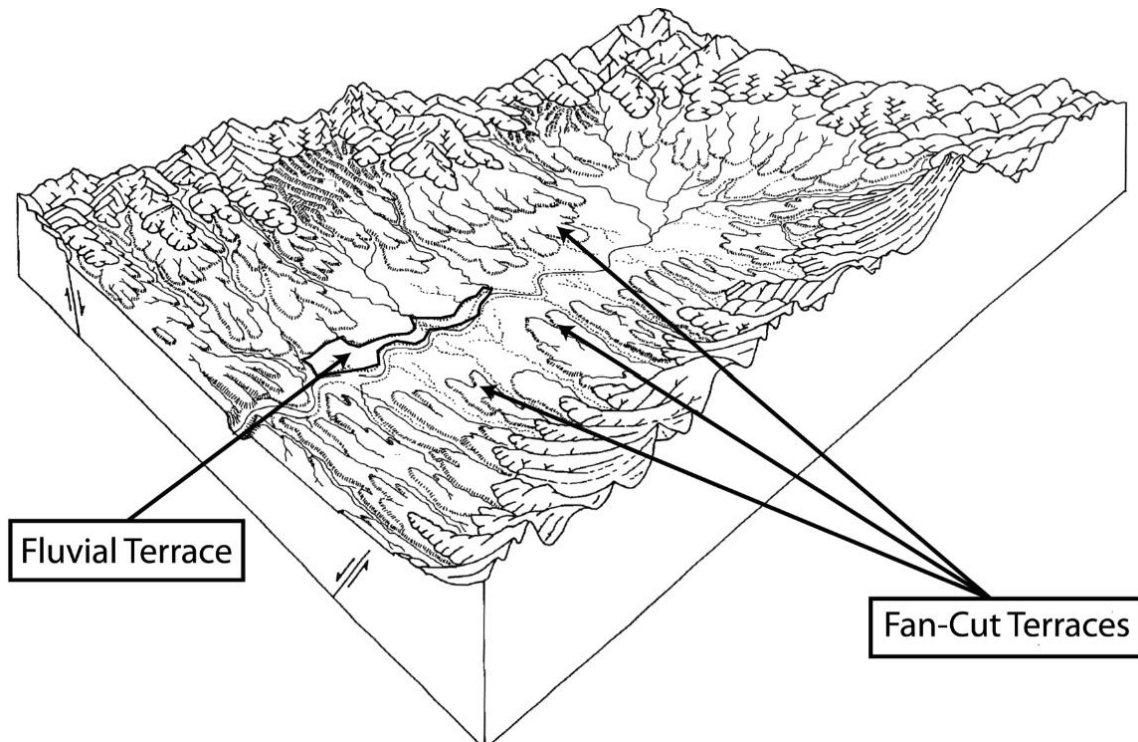
Fig. 2. Pederson (1981, p. 35) diagrammed several "cycles" of dissection and deposition in a typical basin within the Basin and Range, North America. This adaptation of Pederson's original diagram emphasizes the distinction between small isolated true fluvial terraces and the more dominant alluvial fans that have been truncated by an

incising main wash. The truncation of alluvial fans results in fan-cut terrace formation.

The lack of a commonly accepted term may have led to potentially confusing wording in Colombo et al.'s (2000) research on the Rio San Juan of Argentina. Flights of abandoned alluvial and fluvial benches sit as markers of the geomorphic landscape evolution of this area. Tributaries of the San Juan Valley empty into the Rio San Juan, resulting in alluvial fans that have been progressively incised (**fig. 3**). Cycles of alluvial-fan sedimentation blocking or intruding into the Rio San Juan has been followed by subsequent overtopping and down-cutting by the river (Colombo, et al. 2000, Colombo 2005); this axial stream incision then lowered the base level of the tributary alluvial fans. The authors collectively refer to "alluvial terraces" to describe the treads above the Rio San Juan — landforms that are clearly fan-cut terraces. Although correctly identifying the alluvial nature of the sedimentology, we think the term *alluvial terraces* is often used synonymously with fluvial terraces and leads to potential confusion.
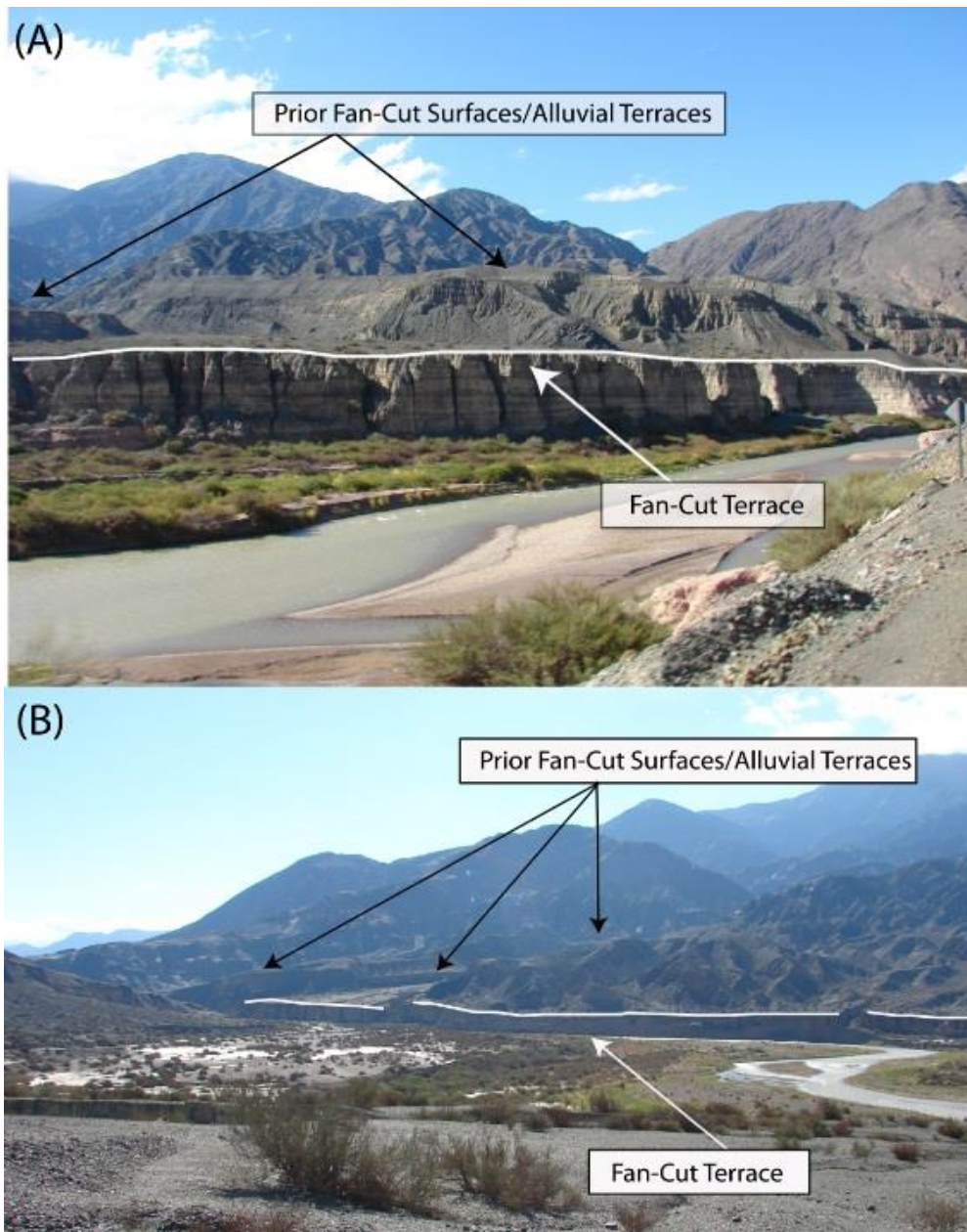
Fig. 3. The Rio San Juan Valley, Argentina exhibits classic examples of the truncation of alluvial fans, creating fan-cut terraces through the process of axial stream incision lowering the base level of the tributary fans (Colombo et al., 2000). (A) Two separate incision events by the Rio San Juan formed two distinct fan-cut terraces, with the younger one (white line) inset an older fan-cut terrace (black arrows. (B) A broader view where fan-cut terraces appear to form a laterally continuous riser that looks strikingly similar to a fluvial terrace. In reality, these are coalesced fans have been truncated by the Rio San Juan (Colombo et al., 2000). Photos by Phil Larson.

A more serious issue is that the process of an axial stream truncating the distal end of a tributary alluvial fan can sometimes produce a landform that looks like an abandoned floodplain, or a fluvial terrace. It is possible that the lack of an accepted terminology for fan-cut terraces led to a basic misinterpretation of landforms above the Mojave River system at Afton Canyon, Mojave Desert, California. Meek (1989) proposed that Afton Canyon underwent a rapid incision as a result of the basin overflow of Pleistocene Lake Manix. In contrast, others (Wells and Enzel 1994, Enzel, et al. 2003) identified features inside Afton Canyon as fluvial terraces that would suggest a slow down cutting of the Mojave River. Some of these features along Afton Canyon, in reality, are fan-cut terraces. The existence of these claimed fluvial terraces was then used as evidence that Afton Canyon did not undergo a rapid incision (Enzel 2003). Meek rejected this view and argued that the surfaces identified in Afton Canyon are all below the level of the lake basin floor and hence have no relevance to how fast Lake Mojave drained (Meek 2004). Meek's interpretation of the various surfaces inside Afton Canyon, as the explanation of lake overflow to cut Afton Canyon, was later verified by U.S. Geological Survey research (Reheis and Redwine 2008). Similarly, the lack of a clear definition could have generated the misidentification of fan-cut terraces as wave-cut recessional terraces (Wells and Enzel 1994). Research by the U.S. Geological Survey (Reheis, et al. 2007) explained that the "scarps are not at a constant elevation, making another suggested interpretation of the scarps as wave-cut features (Wells and Enzel, 1994) unlikely" (p. 20).

The confusion over terminology, the ease of incorrectly identifying fan-cut terraces, and the potential complications misidentification can cause in understanding drainage basin history all highlight the need for a retrospective analysis of this basic landform. The

second section of this paper starts this analysis by reviewing the literature on fan-cut and fluvial terraces. The third section of the paper presents well-known criteria to be used in distinguishing *fan-cut terraces* from fluvial terraces. We then use these criteria in a case study from a non-controversial central Arizona drainage, where the basic landform looks very much like a fluvial terrace at first glance – but is truly a fan-cut terrace.

THE TERRACE FORM

Fluvial Terraces.– Since fan-cut terraces have been confused with fluvial terraces, any literature review must start with fluvial terraces. The history of fluvial terrace literature spans approximately two centuries where Miller (1883) suggested that Playfair (1802) was likely first to recognize their importance. The modern framework of fluvial terraces, however, largely stems from the fundamental works of G.K. Gilbert and W.M. Davis (Gilbert 1877, Davis 1902, Pazzaglia 2013). Fluvial terraces represent the former floodplain of the current river that has been abandoned at a level higher than the modern channel (Leopold, et al. 1964, Schumm 1977, Petts and Foster 1985, Bull 1990, Ritter, et al. 2002, Hugget 2003, Harden 2004, Charlton 2008).

The surface of the former floodplain is known as the terrace tread, while the slope that rises to the tread is generally referred to as the terrace scarp, berm, or riser (Campbell 1929, Ritter, et al. 2002).   Fluvial terraces are mapped/correlated as either paired or un-paired terraces. Paired terraces match elevation and theoretically have the same geochronologic significance on both sides of the river valley (Leopold, et al. 1964, Schumm 1977, Ritter, et al. 2002). Paired terraces occur when vertical stream incision is greater than lateral migration of the stream channel (Schumm 1977). These terraces can

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record a single incision event or multiple events that lead to uniform incision and terrace formation. Un-paired terraces do not match in elevation on either side of the river valley. They often have a staggered topography from valley side to valley side and likely form when lateral migration coincides with some degree of vertical incision (Leopold, et al. 1964, Schumm 1977, Charlton 2008). These terraces can represent a combination of episodic incision and lateral planation, being created as the river both incises slowly and migrates laterally through its valley. It is also possible to have unpaired terraces as the result of the erosive lateral migration of the river, obliterating remnant surfaces, very similar to the 'toe-cutting' processes altering alluvial fans (Leeder and Mack, 2001).

Terraces can be classified as either depositional or erosional. The most common depositional terraces are fill terraces, and they require an aggradational event within the stream valley, a period of floodplain formation and subsequent incision of the stream channel abandoning that floodplain. Another form of a depositional terrace is a nested-fill terrace.

Erosional terraces include strath (Bucher 1932) and fill-cut terraces. Bull (1990) suggests that beveling of bedrock straths and the strath terrace are the "fundamental tectonic stream-terrace landform" and they are often found where streams have tectonically induced downcutting. However, more recent research suggests strath terraces form through lateral planation of weakened or highly erodible banks (Montgomery 2004) leaving behind a thin veneer of alluvium overlying a beveled bedrock surface. Formation of the erosional strath is followed by channel incision, leaving behind the strath terrace (Mackin 1937). Fill-cut terraces are similar although they do not bevel the bedrock "strath." The stream valley has filled with alluvium and the alluvium is first eroded to

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form an erosional surface, followed by incision into this floodplain. It is important to note that the highest terrace in a valley filled with alluvium is likely a fill terrace and is depositional in origin. Fill-cut terraces are inset within the fill terrace and represent further incision events within a stream valley.

Incision Mechanisms.– Incision mechanisms resulting in the fluvial terrace form — as well as subsequent incision of tributary alluvial fans —can result from changes in intrinsic or extrinsic variables in the fluvial system, ultimately influencing the balance between sediment discharge (Qs) and stream fluid discharge (Q). Working under the paradigm that streams tend towards grade (Gilbert 1877, Davis 1902, Mackin 1948, Schumm 1977, Bull 1990), a steam's Q transports all Qs in a state of equilibrium (Mackin 1948, Baker and Ritter 1975, Schumm 1977, Bull 1979). A concave-upwards graded longitudinal profile is a function of the Q/Qs relationship, or competence of the stream (Gilbert, 1877), as the fluvial system tends to steadily increase in discharge and bed load grain size decreases downstream. For grade to establish, base level must remain stationary (Gilbert 1877, Knox 1975, Leopold and Bull 1979, Bull 1991). However, graded streams rarely occur in natural settings, because of the truly dynamic and variable nature of streams (Fonstad and Marcus 2010, Marcus and Fonstad 2010). For the purpose of understanding terrace formation, however, a major alteration of grade can generate a response of aggradation or incision of the channel.

Tectonism, uplift and/or subsidence can significantly alter grade and result in terrace formation. Stream terraces, therefore, have the potential to generate insight into the tectonic history of a drainage basin (Pewe 1978, Leopold and Bull 1979, Bull 1990, Merritts, et al. 1994, Maddy 1998, Holbrook and Schumm 1999, Berryman, et al. 2000,

Hsieh and Knuepfer 2001, Westaway 2003, Westaway, et al. 2004, Peters and Balen van 2007, Carcaillet, et al. 2009, Zuchiewicz 2011). When tectonism alters the streams gradient (or slope), it influence the ability the stream to move sediment downstream. For example, tectonic uplift in the headwaters increases stream gradient, giving that stream a greater ability to transport sediment. If the sediment load does not change, the stream incises into its channel, abandoning its former floodplain as a terrace. Base level subsidence generates a similar effect, increasing the stream gradient and causing incision that results in terrace formation. A drop in base level can result from tectonic subsidence or eustatic sea level lowering.

Climatic oscillations have long been recognized as an important factor in stream incision (Leopold, et al. 1964, Knox 1983, Bull 1990, Bull 1991, Molnar, et al. 1994, Knox 1995, Bestland 1997, Fuller, et al. 1998, Tebbens, et al. 2000, Hsieh and Knuepfer 2001, Houben 2003, Brigland and Westaway 2008, Kock, et al. 2009). Changes in precipitation influence the streams ability to transport sediment. Vegetation change alters the sediment input into a stream as well (Huntington 1907, Quinn 1957, Wells, et al. 1987, Bull 1991, Throckmorton and Reheis 1993, McDonald, et al. 2003). Climate also influence eustatic sea level change, that raises and lowers base level of an entire drainage basin (Blum and Tornqvist 2000, Tebbens, et al. 2000).

Lithologic differences also impact incision (Colombo, et al. 2000, Ritter, et al. 2002). As a drainage basin evolves it often erodes headward and laterally across a landscape. This may alter the materials mined by a stream and its tributaries. For example, changes that produce larger or smaller clasts can result in aggradation or incision. Changes in particle size can also impact the autogenic processes within a

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drainage network, where streams originating in mountains have a steeper gradient and higher elevation than neighboring tributaries that may originate over softer lithologies in the piedmont. This can lead to drainage captures by the lower elevation/gradient piedmont stream, that would cause aggradation; subsequently incision into the channel results from readjustment of the longitudinal profile (Ritter 1972).

Fan-cut terraces.– In contrast to the extensive literature on fluvial terraces and mechanisms of their formation, relatively little scholarship exists on processes responsible for fan-cut terraces. Most literature that references the term 'fan-cut terrace' deals with mapping research in India (Bedi 1980, Pederson 1981, Chatterjee and Sarkar 1982, Chopra 1990, Jana and Dutta 1996, Kumar and Aravindan 2007, Uniyal, et al. 2010, Kesari 2011). More extensive research covers the truncation of alluvial fans through a conglomeration of terms and processes responsible for their truncation, with less attention paid directly to fan dynamics or how fan-cut terraces relate to other depositional landforms (**Table 1**).

Leeder and Mack (2001) stress that research on this landform has been neglected. They use the term 'toe-cutting' to explain one process responsible for the development of the fan-cut terrace form: an axial drainage migrating laterally erodes the distal end of tributary fans. They point to three allocyclic mechanisms - climatic oscillations, tectonic tilting, and fault propagation - as possible processes to cause an axial drainage to overtake distal fan aggradation. They also differentiate toe-cutting from axial stream incision, that can also result in fan-cut terrace formation. They point to numerous examples in Gile et al. (1981) and Bull (1991). The causes of axial stream incision, thus, are treated here as similar to those that create fluvial terraces.

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TABLE 1

Literature discussing alluvial-fan truncation organized into different processes.

Process of Truncation	Summary	Citation
Glacial	The role of glaciers is directly inferred, but not explicitly.	(Carryer 1966)
Fluvial	Large flooding events initiated by natural dam failure causes drainage incision and truncation of the fan surface.	(Colombo, et al. 2000, Colombo 2005, Le Roux, et al. 2008)
	Erosion of the distal reach of tributary alluvial fans by lateral migration (and/or incision) of main drainage	(Pederson 1981, Leeder and Mack 2001, Knudsen, et al. 2002, Given 2004, Al-Farraj and Harvey 2005, Sanchez-Nunez, et al. 2012)
Coastal	Erosion of alluvial fans by wave action from a transgressing sea or land subsidence	(Rudberg 1986)
	Erosion of the distal ends of alluvial fans by wave action in a coastal/lacustrine setting.	(Young, et al. 1986, Nemec and Postma 1993, Harvey, et al. 1999)
Outburst Floods	Sudden outbursts that spill out of their constraining basin erode the base of alluvial fans	(Knudsen, et al. 2002, Wolfe and Beget 2002, Manville 2010)
Faulting/ Tectonics	Faulting offsets the fan surface, creating a truncation of fan aggradation and the abandonment of that surface.	(Ritter, et al. 1995, Ginat, et al. 1998, Dudash 2006, Kargaranbafghi, et al. 2011)

The fluvial system of the axial stream can generate both fluvial terraces and fan-cut terraces through toe-cutting or through lowering the base level in a drainage basin. The focus here rests in drawing a distinct difference between fan-cut terraces and fluvial terraces and how these differences manifest in a field setting.

CRITERIA-BASED APPROACH TO DISTINGUISH FLUVIAL AND FAN-CUT TERRACES

We propose several criteria to help field researchers distinguish fluvial terraces from fan-cut terraces in locations like the Basin and Range Province of western North America. While these criteria are not new, we believe that there is a need to compile them in one place to help future field investigators distinguish these very different, but potentially similar looking, landforms.

Shape of the surface.– One of the most efficient ways to distinguish between fan-cut terraces and fluvial terraces is by reconstructing the tread of the terrace back to the alluvial fan tributary. These surfaces can be reconstructed through aerial photograph interpretation, remote sensing techniques, ground truthing via differentially corrected global positioning systems and other ground survey approaches. However, Reconstructing these deposits on a morphological basis may prove initially difficult in areas of relatively low relief.

Consider the fan-cut terrace in **figure 4**. While the fan-cut terrace looks similar to the fluvial terrace as it parallels the axial drainage at the distal end of the fan, this riser wraps around the corner and is a topographically continuous surface that rises in relief towards the head of the fan. **Figure 4** illustrates a case where a tributary wash has eroded a portion of the fanglomerate, a process that helps produce the illusion of a fluvial terrace form. Alluvial fans may have been dissected since deposition by subsequent erosive processes, but an abandoned surface should not be assumed as a fan-cut terrace unless the surface can be reconstructed back to an original alluvial fan tributary.

Form of deposition on the surface.– Where debris-flow processes dominate alluvial fan aggradation, the morphology of the fan surface can differ substantially from terraces deposited by fluvial processes. Bar-
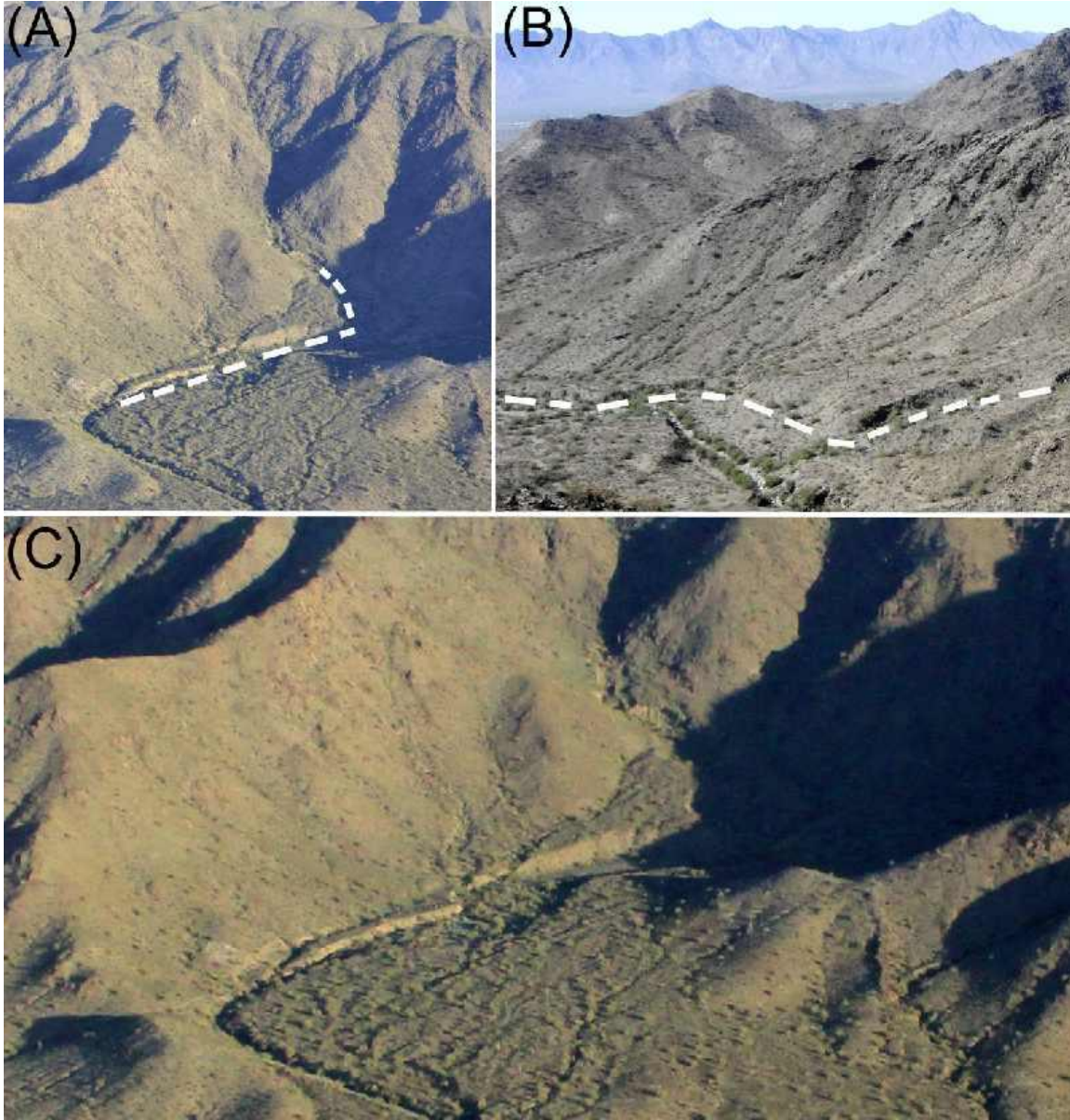
Fig. 4. The topography of the fan-cut terrace (identified above the dashed line) parallels the trunk stream where the toe has been cut by the axial wash. However, riser of the fan-cut terrace also parallels the incised tributary wash — as exemplified by two different perspectives (A and B) of the Pyramid trail fan, South Mountain. Image C provides an oblique aerial view unencumbered with annotations.

and-swale topography (**fig. 5A**) is often the morphological result of debris flows on

alluvial fans (Frankel and Dolan 2007). This contrasts with a relatively smoother topography resulting from fluvial deposition (**fig. 5B**). While desert pavement-forming processes (Dixon 2009) will tend to obscure these distinctions in pre-Holocene deposits, this basic morphological distinction provides one way to distinguish fan from fluvial deposits.

   Sedimentology of the deposit.‑If the underlying alluvial sediments are fanglomerate in nature and show no interruption by the truncating stream, then it is likely that the landform is a fan-cut terrace (fig. 6C). There may be a few emplaced fluvial clasts from the axial drainage an exposure, but fanglomerate deposits should be the dominant form and are usually distinguished by coarser clasts within a finer-grained matrix. The coarse clasts are subangular to subrounded and more poorly sorted than normal fluvial deposits. The surficial expression of fanglomerate deposits results in a bar and swale topography (fig. 6A). In contrast, fluvial deposits tend to be better sorted and more rounded if they are boulders and cobbles (fig. 6B) or will show sorting between sandy and gravel facies (fig. 6D).
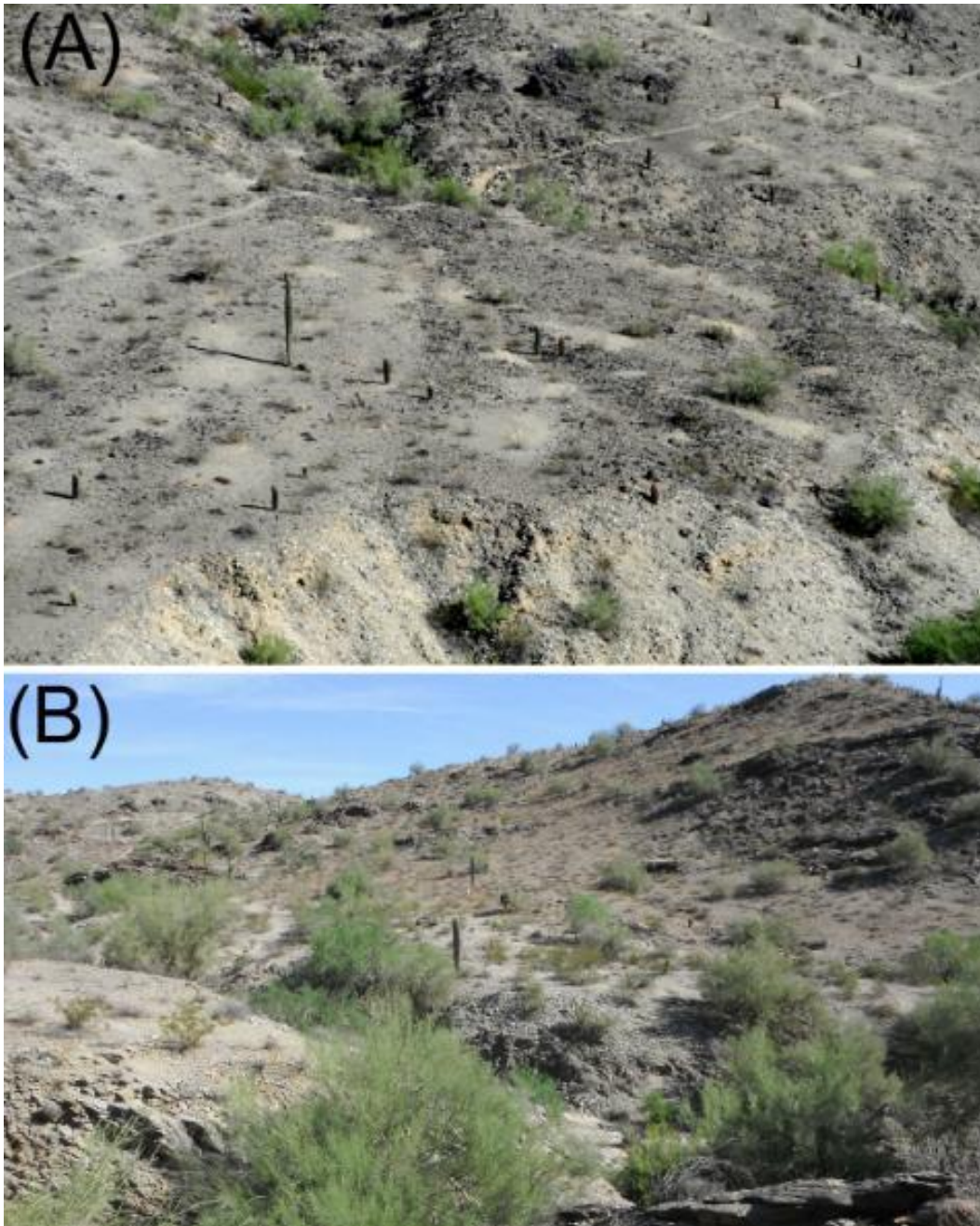
Fig. 5. The surface morphology of an ambiguous landform can be compared to nearby features. For example, (A) The alluvial fans at South Mountain, Arizona, are characterized by pronounced heavily varnished bars separated by lower and less varnished swales. Debris flows produce this basic topography of alternating bars and swales. (B) In contrast, the stream terraces at South Mountain are typified by low relief and relatively planar surfaces. Saguaro (*Carnegiea gigantea*) and Paloverde (*Parkinsonia microphylla*) trees provide scale.
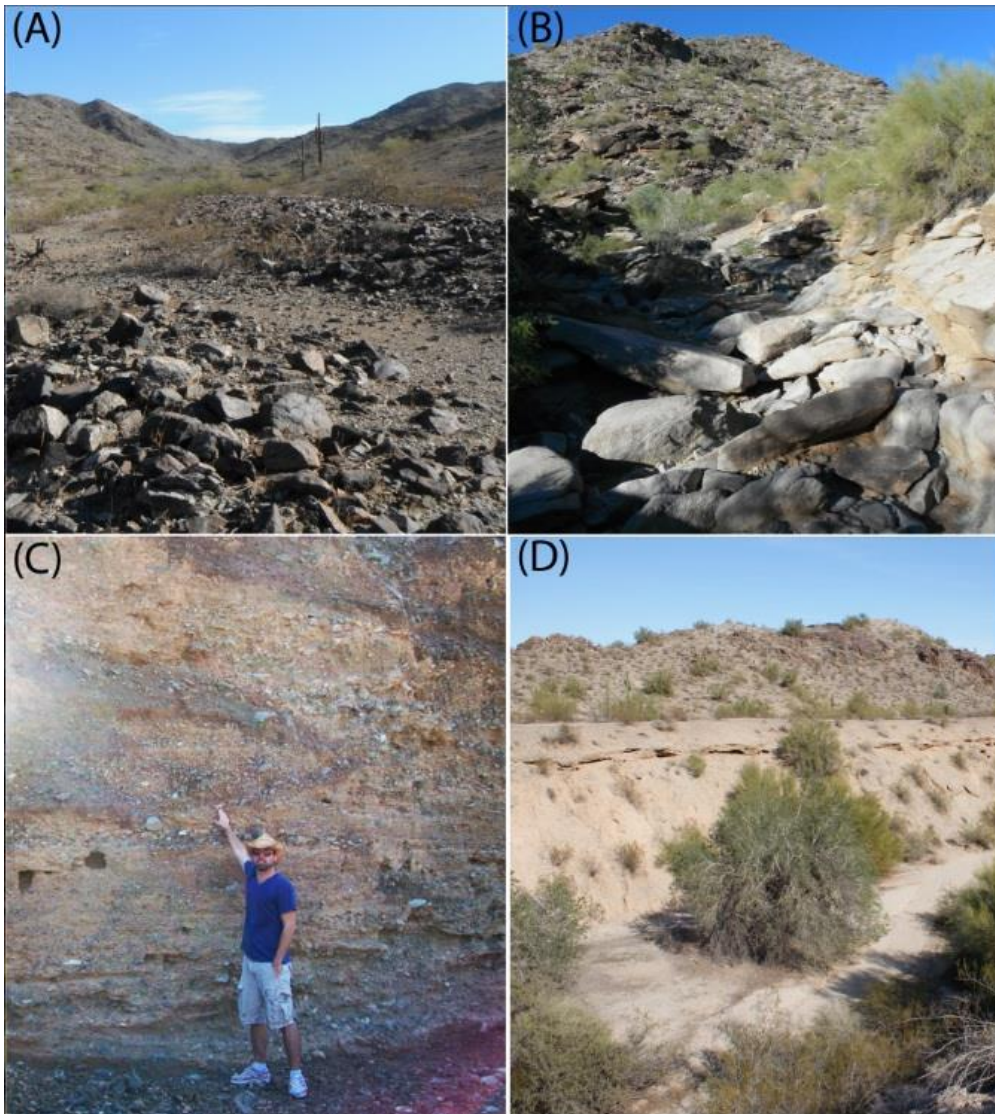
Fig. 6. Alluvial fan and fluvial terraces are often strikingly different in regards to their surface morphology and sedimentological characteristics. In a surficial setting, fanglomerate often takes the shape of bar and swale deposits (A), while river boulders and cobbles tend to show rounding and imbrication (B). In exposed cuts, fanglomerate exhibits poor sorting and more angular clasts (C), whereas fluvial deposits exhibit sorting, such as sandy lenses and gravel lenses of rounded clasts (D). All images from South Mountain, Arizona.

Provenance.– Provenance can sometimes serve as a useful tool in distinguishing

the landforms. This is particularly significant in large drainage basins like those

investigated by Colombo et al. (2000). Alluvial fan sediments entering a drainage from a

tributary basin derive from a local source (Brierley, et al. 1993, Hereford, et al. 1996). On the other hand, the major trunk drainage will host a mix of rock types from throughout the upstream portions of its drainage basin. Sedimentological provenance is best applied with larger drainage basins or if the geology of a tributary drainage is particularly complex/unique (Mather 2000, Duk-Rodkin, et al. 2001).

Longitudinal profiles.– A common method for investigating fluvial terraces compares the longitudinal profiles of terraces to the modern fluvial channel. This comparison reveals insight into the nature of incision, local tectonics, and underlying bedrock (e.g. Merritts, et al. 1994, Pazzaglia, et al. 1998, Zuchiewicz 2011). Long profiles can also prove useful in distinguishing fan-cut from fluvial terraces. Convexities may exist along the long profile. If these convexities correspond with the physical location of tributary drainages, then they could represent the topographic effect of alluvial fan material derived from side tributaries.

Another way that long profiles may distinguish a fan-cut from a fluvial terrace involves whether profiles of the modern channel converge downstream or remains parallel to the terrace form. In many drainages in the Basin and Range of the western USA, the long profiles of contiguous fan-cut terraces merge with the modern channel. The reason has to do with the width of the valley form. As the axial valley widens, progressively more distal fan sediments reach the trunk drainage. If the valley widens enough, the fan surfaces merges with the modern channel. In contrast, fluvial terraces remain parallel and topographically above the modern channel. The one caveat in using this criteria involves uplift of the range that will also produce downstream convergence; however, if tectonic activity can be ruled out based on independent geoscience studies,

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then convergence would indicate that the abandoned alluvial surface is likely a fan-cut terrace.

Comparisons with adjacent drainages.– Drainages rarely exist in isolation. The forms found in the basin under study typically exist next to adjoining drainages. Examination of these adjacent drainages can help provide a broader perspective, in that a slightly wider or narrower adjacent drainage could display more classic fan-cut or fluvial terrace forms. The clarity of forms in nearby drainages with similar lithologies and slightly different geometries can provide a fresh perspective to clarify the basin under study.

Another strategy involves comparing the chronology of events between drainages, either through relative (i.e. superposition, fossils, etc) or more quantitative chronometric techniques (i.e. optical stimulated luminescence, radiocarbon dating, cosmogenic nuclide burial dating). Fluvial terraces may have a very different chronology than fan-cut terraces, and a comparison of ages in a local range or region can help distinguish fluvial from alluvial fan deposits.

CENTRAL ARIZONA CASE STUDY AT BURSERA VALLEY

Physical Geography setting of the study area.– The Bursera Valley at South Mountain (**fig. 7**) rests entirely within the South Mountain Metamorphic Core Complex (SMCC) of central Arizona. South Mountain stretches approximately 29 km and is a city preserve located in south Phoenix, Arizona. Metamorphic core complexes are early extensional structures that stretch in a discontinuous band of mountain ranges from north to south through the North American Cordillera (Coney 1980, Armstrong 1982, Coney

and Harms 1984, Reynolds 1985). South Mountain is almost entirely dominated by two distinct rock types that divide the range, physiographically, into two separate units. The western half consists predominantly of Precambrian gneiss, while the eastern portion consists of mid-Tertiary plutonic rock types.
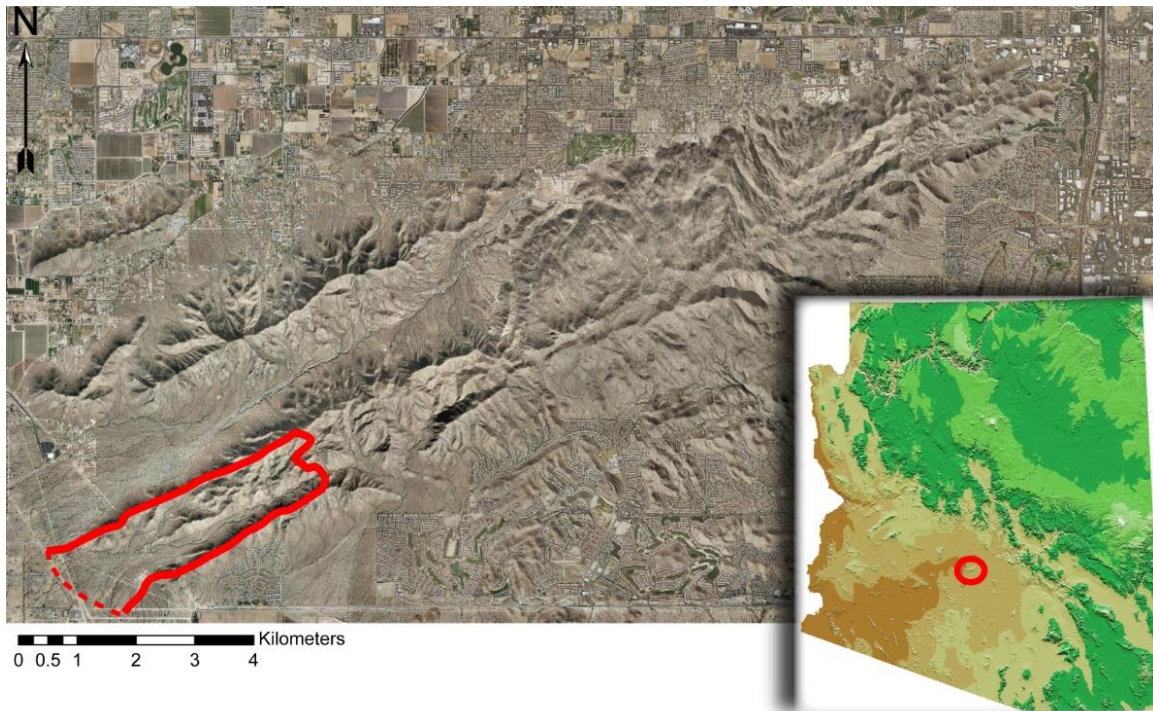
Fig. 7. The studied Bursera drainage basin rests within the Gila Range of South Mountain Park, the largest city park in the USA (circled location in inset map of Arizona). Precambrian metamorphic gneiss dominates all tributaries entering this drainage. The city of Phoenix, Arizona, completely surrounds this natural preserve.

Typical of most metamorphic core complexes, this mountain exhibits classic elongated drainages that flow out from the center of the range (Pain 1985, Pain 1986, Spencer 2000, Pelletier, et al. 2009). The Bursera Valley resides within one such structural drainage called a corrugation — analogous to the corrugations in some roof styles. The western corrugated drainages contain only alluvial fans, while the eastern corrugations host semi-continuous fluvial terrace surfaces (**fig. 8**).

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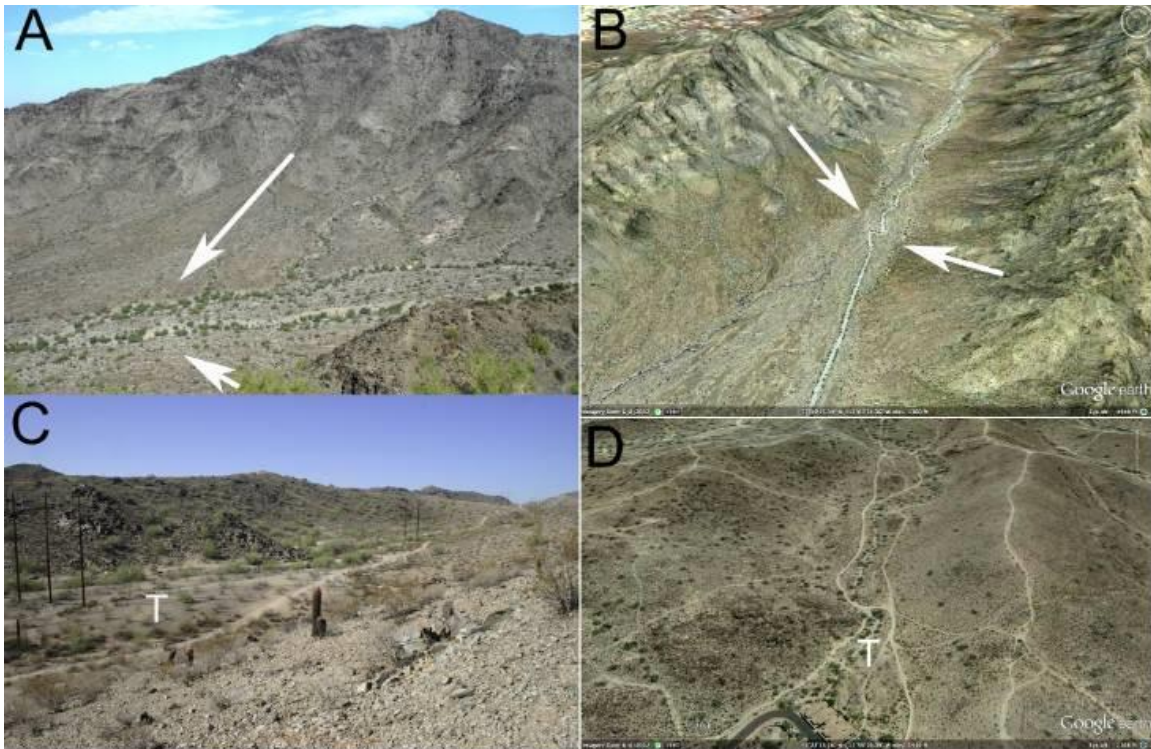
Fig. 8. Drainage basins in the western portion of the SMCC (A,B) are elongated, structurally confined drainages, but are developed over gneissic rocks and host alluvial fans. In contrast, drainage basins on the eastern portion of the SMCC (C,D) developed over granitic lithologies. These basins contain fluvial terraces as the dominant alluvial landform.

This Bursera Valley case study is part of ongoing broader research investigating the geomorphological significance of alluvial landforms within South Mountain. Bursera Valley was selected for this case study because the terrace forms in the valley look very much like fluvial terraces (**fig. 9**). This is despite previous work (Dorn 2010, Dorn 2011, Moore, et al. 2012) that studied the dominance of alluvial fans within eastern gneissic portion of South Mountain.

Just as in the Pederson (1981) idealized model of landforms in the Basin and Range (**fig. 2**), fluvial terraces exist along the axial channel (**fig.10**). The two lowest fluvial terraces occur towards the topographically lower western end of the Bursera drainage — named by convention T1 for the lowest abandoned floodplain, and then T2 for the next

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highest fluvial terrace (**fig. 9A**). Isolated remnants of a topographically higher fluvial

terrace T3 exist in the middle section of the drainage (**fig. 10B**). The issue of contention

rests with the genesis of the terrace forms that exists above these fluvial terraces (**fig. 9,**

11 and 13).

Fig. 9 Bursera Canyon displays abandoned alluvial surfaces that look very much like
fluvial terraces upon first inspection. The linear dashes show the position of the axial
stream. The sinuous dashes identify the incised wash of a tributary alluvial fan that
actually produced the fan-cut terrace above the axial stream.

APPLYING CRITERIA TO BURSERA VALLEY

All but one of the aforementioned criteria could be used to analyze the high

Bursera Valley surface. Provenance could not be used, because the Bursera basin has the

same Xm (Precambrian metamorphic) gneissic lithology throughout.

Shape of the surface.‑ Perspective matters a lot in viewing landforms. Bottom-up,

side-ways, and top-down views reveal different perspectives.

In many views, fan-cut terraces can look like fluvial terraces (for example, fig. 11A).

However, a different perspective can reveal the origin of a tread and rise derives from a

tributary drainage (fig. 11B and 10C). Following surfaces around the corner, and tracing

them up an alluvial fan, however, is not always possible.
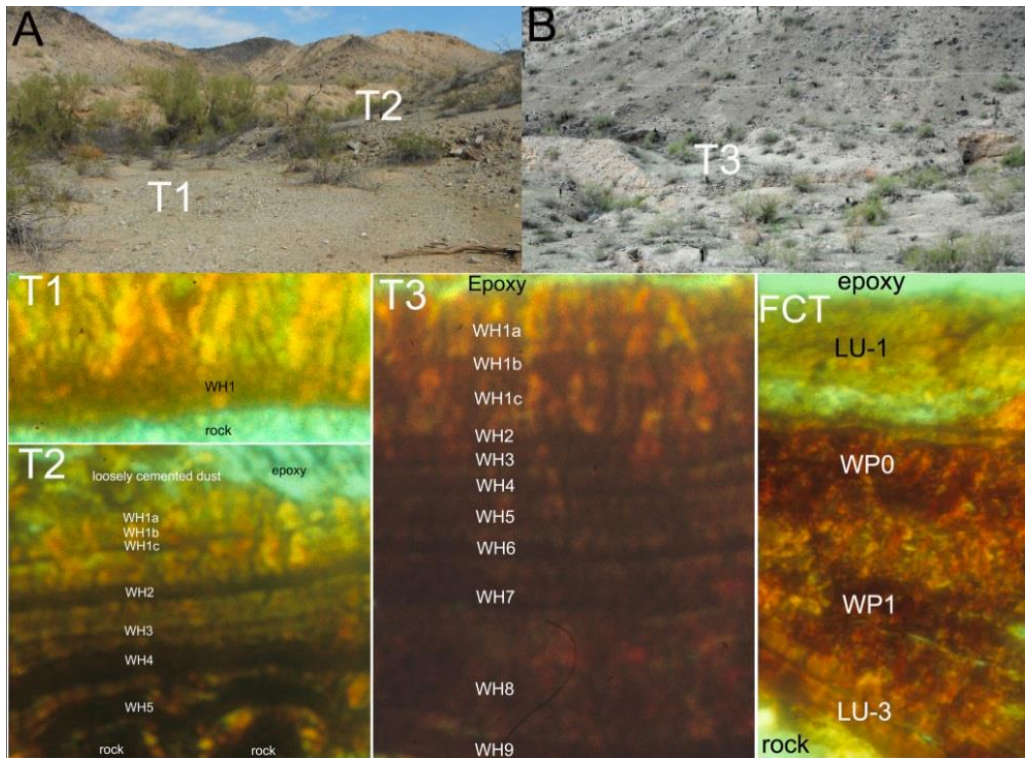
Fig. 10. The Bursera Valley contains both fan-cut and fluvial terraces. The fan-cut terrace surface clearly creates the prominent high terrace surface within the valley, while T3 (B), T2 and T1 (A). These terraces are spatially isolated to the lower half of the Bursera Valley where valley width and increased discharge allows for more lateral migration of the axial stream. The abandonment of the fan-cut terrace within Bursera Valley also corresponds with the abandonment of alluvial fans found elsewhere within South Mountain (FCT) and is chronologically older than the terrace surfaces inset within it.
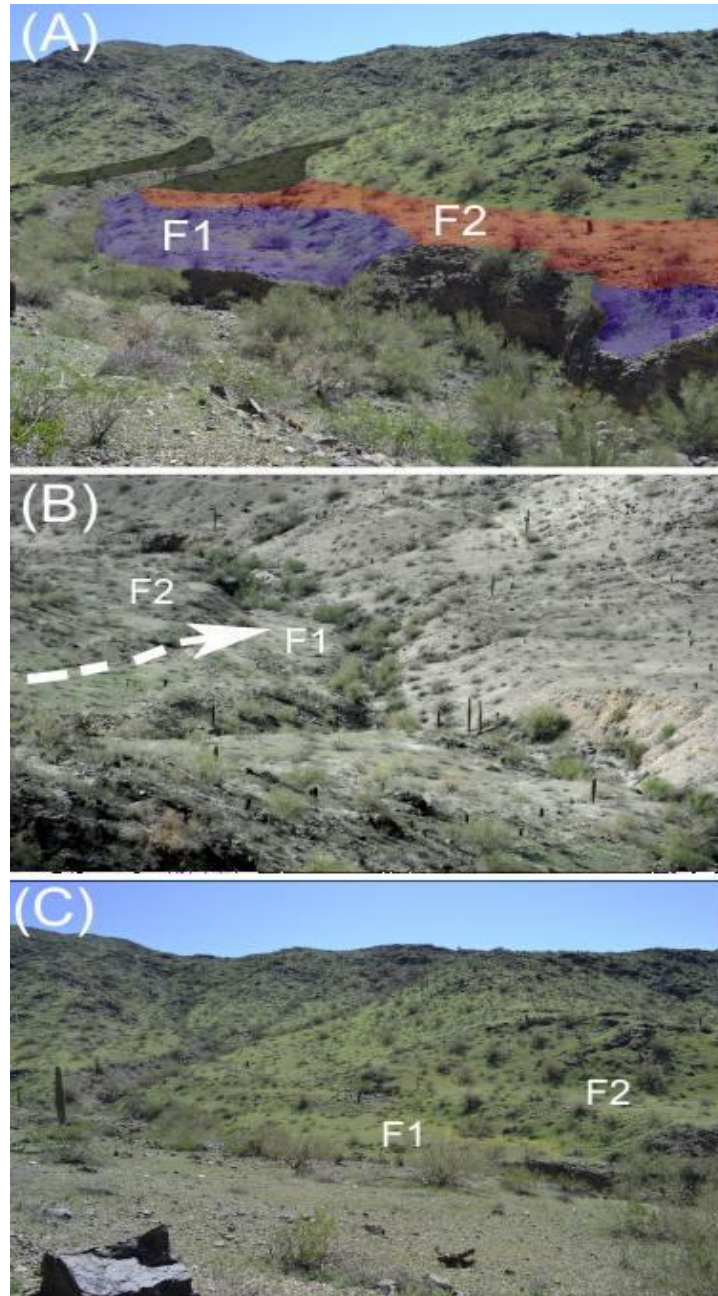
Fig. 11. The terrace surfaces marked by F1 and F2 both appear to fluvial terraces, while the gray shading presents an incised alluvial fan in Image (A). A different perspective (B) shows the F1 surface to be the result of a small side drainage that generated a small inset alluvial fan. The higher F2 surface is contiguous with the alluvial fan, better seen in the perspective in image C.

One of the conundrums associated with the terrace forms in Bursera Valley is that many

surfaces do not wrap around a fan-head trench and follow the shape of an alluvial fan —

as presented in **figure 4**. Instead, the forms exist as risers and treads plastered on the side

of Bursera Valley (**fig. 12A**). Thus, the terrace-like feature must have been a part of the

alluvial fan seen in **figure 12B**. When the axial stream incised, this piece of the alluvial

fan became a fan-cut terrace.
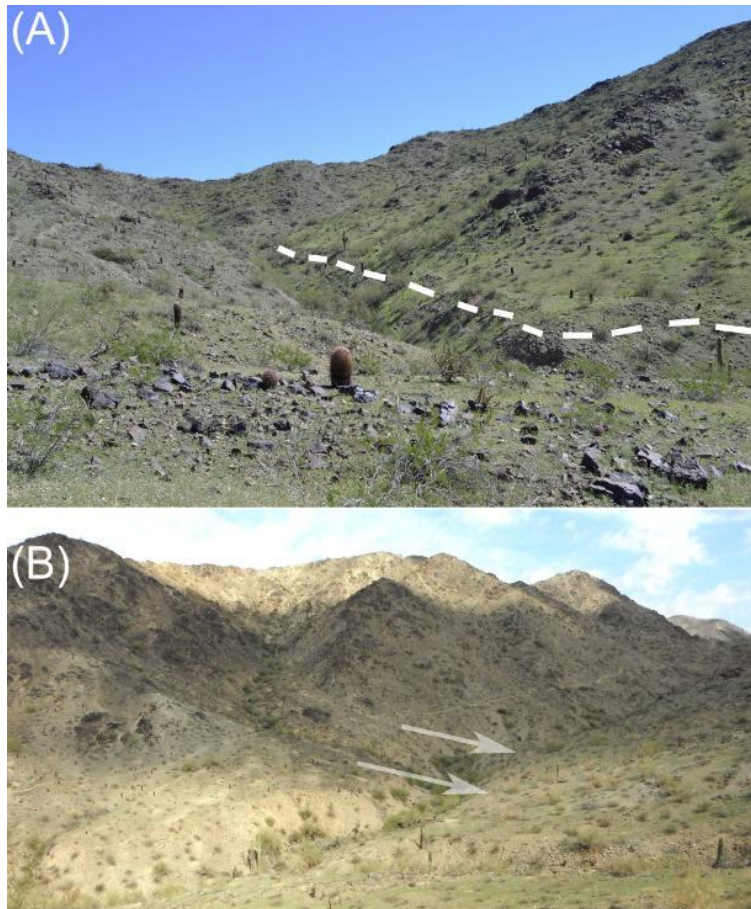
Fig. 12. The terrace surface above the dashed line in image A on the south side of the
valley, appears to be a fluvial terrace from this perspective. In reality, however, the
alluvial fan on the north side of the valley seen in image B once reached across the
unincised valley and deposited fanglomerate against the south side of the valley. Then,
once the axial wash incised, the terrace form emerged.

Form of deposition on the surface.– The T1 fluvial terrace surface of Bursera Valley consists of a smooth sandy surface with isolated pebbles (**fig. 10A**). Desert pavements comprised of mostly gravels and pebbles rest atop the T2 (**fig. 10A**) and T3 (**fig. 9B**) fluvial terraces. In contrast, the surface of high terrace form (**fig. 9, 11, and 13**) contains a bar-and-swale topography (**fig. 6**) that mimics the bar-and-swale forms seen on tributary canyon alluvial fans (**fig. 5**).

Sedimentology of the deposit.– Unlike the sorted sandy and gravel lenses that occur in the fluvial terrace T1, T2 and T3 deposits (**fig. 10A and 10B**), the higher terrace form consists of classic sequences of fanglomerate deposition (**fig. 13**). While it is certainly possible that the upper Bursera basin generated debris flows, the orientation of the fanglomerate bedding planes are consistent with origins in side tributary canyons.

Fig. 13. This fanglomerate is typical of most cut exposures within the Bursera Valley. Note the poor sorting and subangular clasts within this 5 m high exposure.

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Longitudinal profiles.– A Trimble GeoXH differential corrected global

positioning system (dGPS) measured elevation data to compile longitudinal profiles of

both the high terrace feature and the modern channel. The high terrace is a semi-

continuous surface that appears to continue the entire reach of Bursera Valley.

The convergence of the high terrace with the modern channel low down in the

drainage basin (**fig. 14**) could have a tectonic cause. However, tectonic uplift is no longer

active in this region (Reynolds 1985, Reynolds and Bartlett 2002). An alternative

explanation for convergence could be that Bursera Valley widens progressively

downstream. Valley widening allows the distal sections of alluvial fans to converge with

the modern channel. In contrast, a narrower valley in the upper reaches means that toe-

cutting occurs upon lowering of the base level.
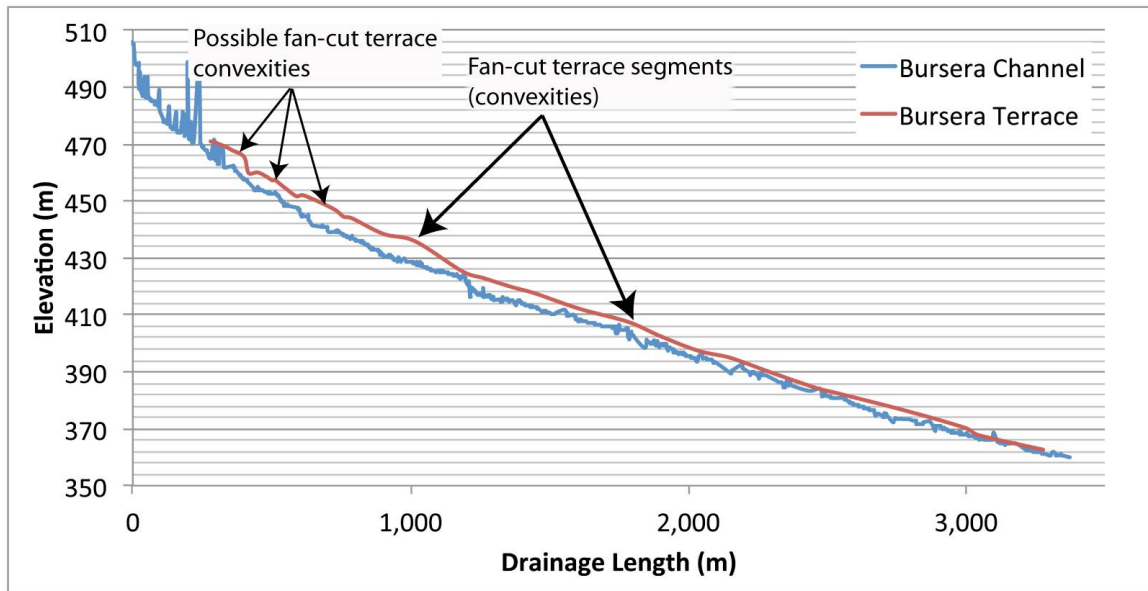
Fig. 14. A detailed longitudinal profile revealing convexities related to tributary alluvial
fans. Those noted as "possible" correspond to locations where tributary streams input into
the axial drainage, but the dGPS precision was slightly above the mean PDOP used to
collect data. The variability in the channel profile in the upper most portion of the
Bursera Valley is also a result of high deviations in PDOP.

Another set of features associated with the longitudinal profile of the terrace also support the fan-cut terrace genesis of the high terrace. The terrace profile reveals five prominent convexities (**fig. 14**) associated with the larger tributary valleys that feed alluvial fan material towards the valley axis.

Comparisions with adjacent drainages.– Alluvial fans appear to be the dominant form throughout the western half of South Mountain. A parallel valley, San Juan Valley, displays large alluvial fans that debouch from the Ma Ha Tuak and Gila Ranges (**fig. 15**). These alluvial fans are In turn eroded at their toe by the main San Juan modern channel. The strikingly similar morphology of the San Juan and Bursera drainages certainly would not disprove a fluvial origin for the Bursera drainages. Instead, the contextual point is that the patterns in adjacent drainages can aid in determining whether or not the feature is a fan-cut or fluvial terrace.

Another available tool would be to apply chronometric tools. Varnish microlamination dating (VML) reveal that the abandoned upper alluvial surface within Bursera Valley host a pattern identified as LU-3 – deposited between 16.5 ka and 24 ka (**fig. 10**). This LU-3 VML signal is the most common age for extensive alluvial fan deposits found at South Mountain (Dorn 2010, Moore, et al. 2012). In contrast, the fluvial terraces in Bursera Valley are progressively younger. The T3 highest fluvial terrace surface was abandoned before or during VML event WH9 (8100 cal yr BP); the middle T2 terrace was abandoned before or during WH5 (4100 cal yr BP); and the lowest T1 terrace was abandoned during the Little Ice Age's WH1 event (300-650 cal yr BP).

These ages correlate regionally with other fluvial terraces, such as the post-Lehi incision event of the Salt River between 940 and 300 cal yr BP (Huckleberry, et al. 2012). The older T2 and T3 terrace VML ages match up with events in the cumulative probability density function (CPDF) plot for rivers with the southwestern USA (Harden, et al. 2010).

Fig. 15. The San Juan Valley is a classic setting for fan-cut terraces. Alluvial fans emerge from tributary fans on both sides of the axial drainage. San Juan wash has both incised and 'toe-cut' the distal reach of these fans resulting in fan-cut terraces. Bursera Canyon has a similar lithology of metamorphic gneiss and small steep basins that generate alluvial fans. This east-looking perspective reveals that the similar gneissic lithologies and a similar geologic setting to an adjacent canyon would be one piece of evidence in favor of a fan-cut interpretation. The image follows Google Earth usage guidelines [http://www.google.com/permissions/geoguidelines.html].

In summary, the ages of the fluvial terraces in Bursera Valley correspond with other fluvial terraces in the region. In contrast, the age similarity of the Bursera terrace form with other alluvial fans in the range (Dorn, 2010; Moore et al., 2012) does not prove

a fan-cut origin. However, the age similarity provides one more type of evidence that aligns with a fan-cut terrace interpretation.

Analysis of adjudicating criteria.– In the context of the Bursera Valley study site, all available criteria pointed to the fluvial terrace forms (**fig. 9, 11, and 12**) being fan-cut terraces. Despite appearances to the opposite, none of the criteria support a fluvial terrace interpretation.

These fan-cut terraces formed as a result of first, aggradation of an alluvial fan surface, followed by base level lowering of the axial wash. This base level change then resulted in a wave of fan incision. Some small toe cutting has occurred; for example the cut exposing the fanglomerate in image **figure 5A** likely involved some lateral erosion by the axial wash. However, the fan-cut terrace form's genesis relates mostly to base-level lowering by the incising axial drainage.

CONCLUSION

Alluvial fans commonly feature scarps at their distal end produced when a stream erodes into the fan. Researchers currently use six different terms to describe an abandoned alluvial surface that forms by the truncation of tributary alluvial fans by an axial drainage flowing obliquely or perpendicular to the alluvial fan surface. Thus, we propose that future research employ the term 'fan-cut terrace'. This terminological confusion may have been responsible for misinterpretations of fan-cut terraces as fluvial terraces. To help minimize the potential for future problems, we propose several criteria to help distinguish between fan-cut and fluvial terraces within a drainage basin. Employment of these criteria in the Bursera Valley, central Arizona, illustrates their

potential in the context of landforms that look very much like a fluvial terrace, but in

reality are fan-cut terraces.

Chapter 3

STRATH DEVELOPMENT IN SMALL ARID WATERSHEDS: CASE STUDY OF

SOUTH MOUNTAIN, SONORAN DESERT, ARIZONA

ABSTRACT. Analyses of modern straths and strath terraces in small arid drainages

of <5 km^2 reveal two previously undocumented processes that appear to be

responsible for carving bedrock erosional floodplains in granitic lithologies of the

South Mountain metamorphic core complex, central Arizona. The first process

involves an asymmetry of erosion due to enhanced rock decay along channel banks,

compared to channel beds. Ephemeral washes flowing in topographic lows between

bedrock pediments cut straths through lateral migration into the pediment's

weathering mantle, a process observed during several flash floods. This process is

further facilitated by bedrock decay through abiotic processes like biotite oxidation

that is subsequently enhanced by mycorrhizal fungi associated with the roots of

plants growing along stream banks. A second process of strath formation relates to

aggradational piracy along the margins of the range. Piracy leads to an increase in

drainage area and regrading of the stream's longitudinal profile. The increased

drainage area accessed during long profile adjustment forms a bedrock strath

immediately downstream of the capture point, while post-piracy adjustments form

straths upstream of the capture through headward knickpoint migration. Erosional

floodplains produced by these processes experience subsequent incision, forming

strath fluvial terraces. The mechanisms for incision, however, remain unclear.

Those drainages flowing into the Salt River incised at the onset of the last glacial maximum, according to ^{14}C and VML ages, and this could relate to a shift in the position of the Salt River towards South Mountain or incision of the Salt River itself. In contrast, the pirated drainage flows south towards the Gila River and incised into its highest strath between Heinrich Events 1 and 2 — suggesting a possible link to climatic change. The causes of Holocene strath incision events ~4100 cal BP and ~300-650 cal BP possibly correlate with regional fluvial adjustments seen in larger Southwestern USA rivers.

INTRODUCTION

The scholarly literature examining the varied processes resulting in fluvial terraces dates back more than 150 years (for example, Hitchcock, 1824; Hitchcock, 1833; Darwin, 1846; Hitchcock, 1857; Gilbert, 1877; Lesley, 1878; Dana, 1881; Miller, 1883; Nelson, 1893; Davis, 1902; Born and Ritter, 1970; Schumm, 1977; Bull, 1990; Merritts and others, 1994; Ritter and others, 2002; Pazzaglia, 2013). Still, the fundamental observation of Asher P. Schick, nearly 40 years ago, remains true today: "the study of fluvial terraces of small watersheds in the arid zone seems to have been neglected" (Schick, 1974). This is not meant to infer that our understanding of arid rivers is lacking, as an abundance of research focuses on fluvial systems in drylands (for example, Bull and Schick, 1979; Graf, 1982; Graf, 1988; Genxu and Guodong, 1999; Flerchinger and Cooley, 2000; Graf, 2000; Yair and Kossovsky, 2002; Lange, 2005; Ma and others, 2005; Taylor and Hudson-Edwards, 2008; Chowdhury and Sharma, 2009). However, Schick's (1974, p. 81) observation becomes increasingly relevant when investigating processes responsible for

strath carving and strath terrace formation in the arid environment (for example, **fig. 1**).

Fig. 1. Downtown Phoenix, Arizona, serves as a distant backdrop for Kiwanis Canyon, South Mountain. A thin veneer of gravels cap a typically small strath terrace cut into Tertiary granite. Paloverde trees (*Parkinsonia microphylla*) ~3m in height provide scale.

Despite eight decades of 'strath' (Bucher, 1932) terrace research, there exists an ongoing struggle to understand processes responsible for the formation of beveled strath floodplains (Formento-Trigilio and Slingerland, 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."

Major strath carving (Bull, 1990) occurs when rates of lateral erosion exceed rates of

vertical incision, during a period of vertical stability (Gilbert, 1877; Mackin, 1937; Yokoyama, 1999; Hancock and Anderson, 2002; Montgomery, 2004; Wohl, 2008; Pazzaglia, 2013). Strath terraces form once vertical incision resumes, abandoning the strath above the modern channel. When both vertical incision and lateral erosion coincide, unpaired, minor-strath terraces can result (for example, Garcia, 2006). An adequately thick veneer of resistant alluvium may be necessary to preserve the strath as a terrace (Montgomery, 2004; Garcia, 2006; Garcia and Mahan, 2009). Processes leading to strath floodplain formation have long been thought to occur when a stream reaches a graded condition, where it drains to a static base level, and 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) indicates that straths develop when the stream has achieved either a profile of steady state or grade, drawing a careful distinction between the two. Steady state profiles do not change in elevation even when extrinsic properties, like base level, fluctuate. Steady state streams strive to incise synchronously with uplift in tectonically active regions (Pazzaglia and others, 1998; Pazzaglia and Brandon, 2001). This does not necessarily require a lengthy period of a static longitudinal profile. In the case of the Truckee River, Nevada, a suite of six erosional terraces formed within a 44 year time span as the result of minor fluctuations in base level (Born and Ritter, 1970).

Controls on the oscillations to and from grade/steady-state include: 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, in Press)

Once a stream reaches a steady-state or grade, recent research suggests different conditions can facilitate strath formation: (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; Wohl, 2008); and (4) inherent instability triggered by meander growth and cutoffs (Finnegan and Dietrich, 2011).

An increase in sediment supply may be a dynamic control on channel behavior, resulting in an alluvial cover that, in effect, armors the channel and protects the bed from vertical incision (Hancock and Anderson, 2002; Fuller and others, 2009). This is further supported by research that indicates erosion of bedrock through plucking, abrasion and cavitation (Hancock and others, 1998; Whipple and others, 2000; Chatanantavet and Parker, 2009) and channel slope largely depend on rates of channel bed exposure to erosion (Sklar and Dietrich, 2001; Stock et al, 2005). A change in the nature of sediment flux may also allow for channel morphology to shift to a braided form, thus facilitating widening of its valley and these two processes may work in harmony.

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 et al. (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 piracy can increase the drainage area sufficiently to facilitate the formation of straths over graded time scales. Drainage evolutionary processes associated with basin overflow (for example, Meek, 1989a; Meek, 1989b; Reheis and others, 2007; Reheis and Redwine, 2008; Larson and others, 2010) may also result in the creation and subsequent incision of straths.

The influence of channel slope on strath formation may be controlled, to a large degree, by the resistance of the underlying lithology (Gilbert, 1877). Because streams flowing over resistant rocks form steepened, narrow channel reaches and those flowing over a weak substrate form wide, low sloped channel reaches, weak substrate allows for 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 found that perennial streams flowing over weak sedimentary lithologies developed a distinct "asymmetry in bedrock erodibility" (p.464) resulting from mechanical weathering via wetting and drying (or freeze-thaw) of the channel banks over time. Montgomery (2004) specifically noted that strath formation did not require a bed protected by alluvium if this asymmetry exists – but a positive feedback would occur where alluvium covers the strath. Others have

suggests that bedrock discontinuities (i.e. horizontal/subhorizontal jointing and shear zones) could also facilitate bank erosion and strath development in more resistant lithologies (Wohl, 1998; Wohl, 2008).

Understanding processes that create a strath and subsequent strath terrace have become increasingly relevant as numerous studies have employed straths to determine uplift rates, climatic driven sediment variability, erosion rates, incision rates, drainage basin evolution, and more (for example, Burnett and Schumm, 1983; Pazzaglia and Gardner, 1993; Merritts and others, 1994; Burbank and others, 1996; Chadwick and Hall, 1997; Pazzaglia and others, 1998; Reneau, 2000; Barnard and 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). Thus, understanding strath development is not only pertinent to fluvial geomorphology, but to other earth systems as well.

The purpose of this paper rests in proposing and evaluating two new process models responsible for fluvial strath terrace formation observed in small arid drainages within an isolated, tectonically quiescent mountain range in the Basin and Range. The next section of this paper provides the geological setting of the South Mountain study area and introduces our hypotheses for strath formation in small arid watersheds. The methods and results from this case study will then be used to evaluate the hypothesized mechanisms of strath and strath terrace formation.

GEOLOGIC SETTING AND STUDY AREA

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South Mountain metamorphic core complex (SMCC) stretches approximately 29 km and is located within a city preserve in south Phoenix, Arizona. 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 has covered such topics as drainage-basin evolution (Pain, 1985; Pain, 1986; Spencer, 2000), hillslope stability (Applegarth, 2002), debris flows (Dorn, 2010; Dorn, 2012), and joint exploitation, tectonic tilting, and structurally controlled knickpoints influencing drainage development (Pelletier and others, 2009), we have not found prior research on strath floodplain and strath terrace formation in MCCs.

Additionally, SMCC was investigated because previous research (Reynolds, 1985) had suggested: (1) the presence of fluvial terraces within structurally controlled drainages; (2) that the SMCC is relatively 'geologically simple'; (3) SMCC has been tectonically quiescent for over ~8 ma; (4) and SMCC is almost entirely dominated by two types of lithology (**fig. 2**). The western half of SMCC consists mainly of Precambrian gneiss where alluvial fans are the predominant alluvial landform. In contrast, the eastern portion consists of mid-Tertiary plutonic lithologies that host isolated and semi-continuous strath terraces. The drainages in which the strath terraces reside have drainage areas <5km^2. Thus, the entirety of SMCC serves as a natural laboratory to contribute to Schick's (1974) challenge of better understanding fluvial terraces in small arid drainage basins. SMCC also enables the testing of strath terrace process models in a field setting

with somewhat limited overall variability (i.e. limited tectonism and lithologic variation) in these drainages.
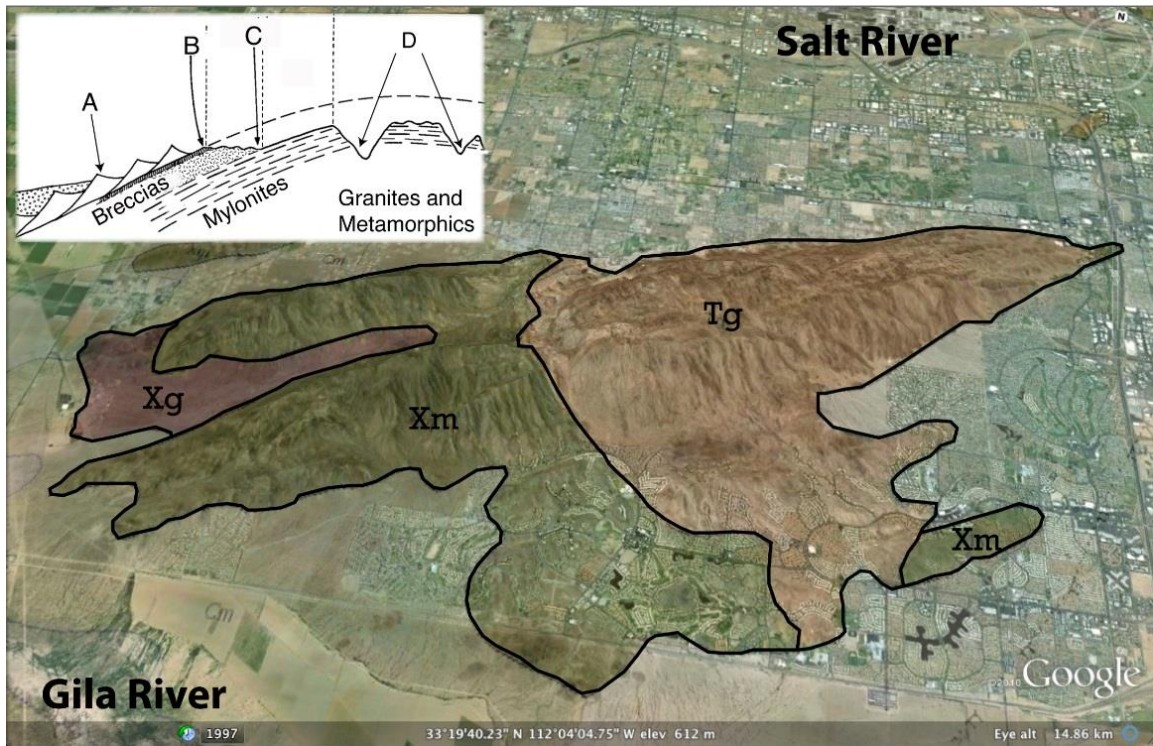
Fig. 2. A simplified geologic map of South Mountain Metamorphic Core Complex, with a distinct contrast of Tertiary granitic lithologies (Tg) in the eastern section of the range and the Precambrian metamorphics and rarely exposed granitiods (Xm, Xg) in the western half. The inset diagram is an idealized cross-section in granitic rocks of the SMCC, connecting geological features to topography with the following annotations: A) zone of upper plate rocks-sometimes covered with alluvium; B) microbreccia ledge; C) mountain front rising to dome facets; and D) deeply incised valleys following axial structural-corrugations. Corrugations are incised into a broad low-relief upland in plutonic lithologies, while incising into high relief narrow uplands in the metamorphics (modified from Pain, 1985). The base image is used following permission guidelines for Google Earth [http://www.google.com/permissions/geoguidelines.html]

HYPOTHESES OF STRATH FORMATION

Field observations carried out over hundreds of site visits to SMCC led to two different hypothesized mechanisms of bedrock strath formation (**fig. 3**). The two hypothesized processes are, as far as we can surmise, not previously discussed in the literature regarding arid/desert watersheds.

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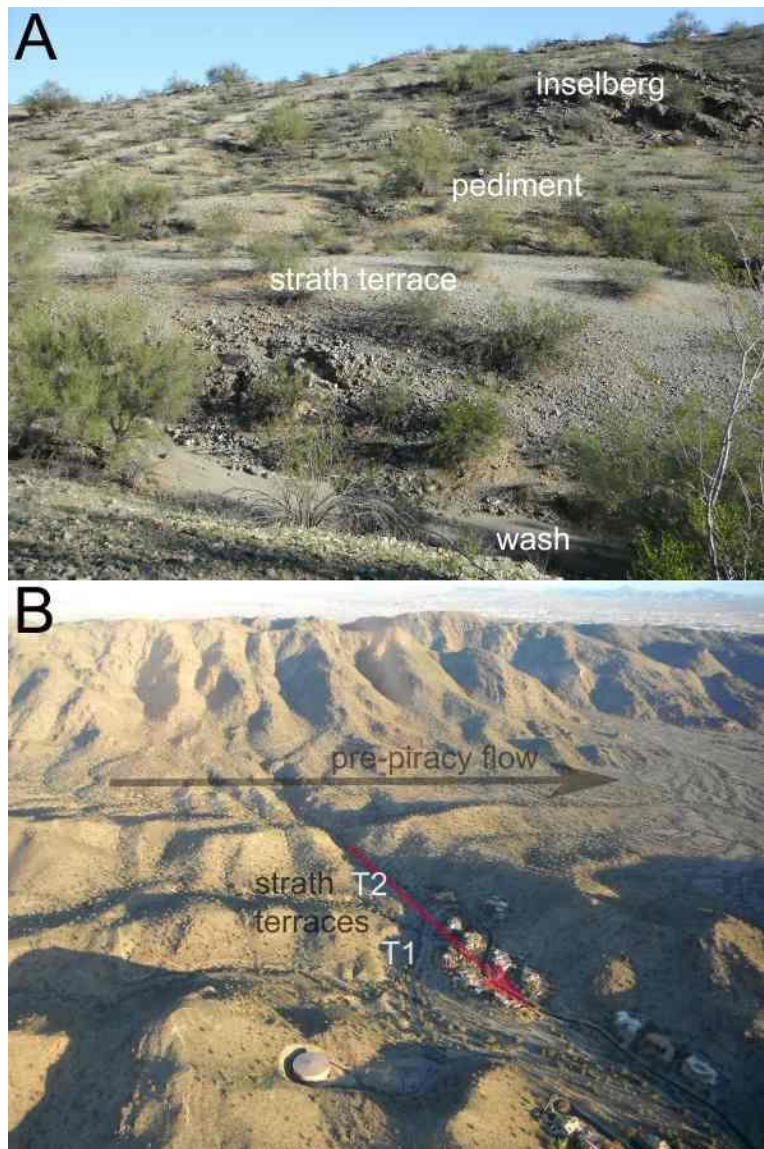
Fig. 3. This paper presents two hypothesized mechanisms of strath formation in small granitic drainages of South Mountain, central Arizona: (A) lateral migration eroding adjacent pediments, facilitated by enhanced rock decay on strath margins; and (B) aggradational drainage piracy leading to a sequence of straths and strath terraces generated through ongoing adjustment of the longitudinal profile. The original the drainage flowing west to east (gray arrow) aggraded in response to an earlier piracy event, causing the drainage to flow over its former bounding bedrock range (red arrow). The increase in drainage area allowed for strath carving downstream of the point of capture similar to that of Garcia (2006). Meter-tall Creosote (*Larrea tridentata*) bushes provide scale in A, and mansions provide scale in B.

Hypothesis #1 Enhanced rock decay along stream banks fosters strath widening.– The

literature on stream erosion of granitic materials contains the conceptual model of

stepped topography (Wahrhaftig, 1965). Thus, we start with Wahrhaftig's (1965) premise

that small stable washes carrying grus erode vertically into relatively unweathered

granitic rock at very slow rates. This is due to the inability of grus to serve as an erosional

tool on fresh granite. Our hypothesis is that the floodplains of small ephemeral washes

widen straths during flash floods at the expense of decayed granitic rock present in

channel banks (**fig. 4**). This hypothesis expands on research conducted in Taiwan that

revealed high magnitudes floods have a larger impact on channel widening than vertical

incision (Hartshorn and others, 2002) and on Montgomery's (2004) asymmetry of

erodibility in strath formation. During high magnitude precipitation events, the decayed

granitic rock is stripped from the exposed bank and transported downstream. These

widening locations occur where the channel bed consists of relatively fresh granite often

overlain by thin accumulations of grus bedload.

The presence of decayed granitic rock in the channel banks is the function of two

processes. First, pediments and associated inselberg slopes are a common piedmont

landform in Arizona and the Basin and Range (Tuan, 1959; Kesel, 1977; Oberlander,

1989; Applegarth, 2004; Dohrenwend and Parsons, 2009). Central Arizona pediments

form in granitic rocks, schist, breccia and ignimbrite. They are most commonly studied at

the scale of kilometers fronting isolated ranges typical of the Basin and Range. However,

pediments also occur on the scale of meters in small arid drainages like those in SMCC

(Reynolds, 1985). Washes flow down the topographic low in these small arid basins at

the intersection of adjoining pediments.

Granitic pediments are typified by the existence of a variably thick weathering mantle at the surface formed by subaerial weathering processes interacting with the rock surface (Mabbutt, 1966; Twidale, 1968; Cooke and Mason, 1973; Moss, 1977). These pediments grade to the base level of the main axial drainage, and the weathering mantle is exposed in channel banks. Ephemeral washes are able to migrate laterally into their banks and erode the weathered distal end of these small pediments forming bedrock straths — that later form strath terraces after an episode of vertical incision (**fig.** 3A).

Lateral widening at the expense of an already decayed bedrock pediment is enhanced further through decay on channel banks resulting from root and mycorrhizal fungi weathering. Additional decay may result from water storage in channel silt and sand deposited at the foot of banks, taken from concepts of granite landform evolution proposed by Oberlander (1972; 1974; 1989). Subsurface water flow, trapped by the silt/sand, enhances contact time between capillary water and the bedrock granite accelerating grussification.
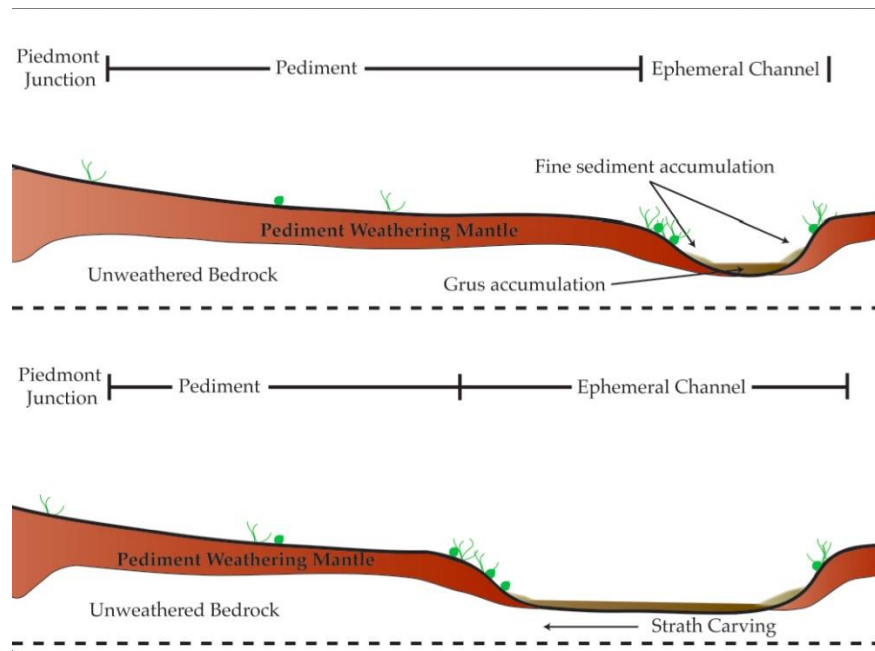
Fig. 4. Hypothesis of strath formation via lateral erosion into granitic pediments. Bedrock straths form due to an erosional asymmetry in ephemeral channels underlain by a granitic substrate. Pediments bound ephemeral channels in these drainages and the partially decayed granitic rock of the pediment mantle is exposed along channel banks. Ongoing contact with capillary water under a cover of silt/sand, as well as the biochemical action of roots and associated mycorrhizal fungi, lead to further decay of channel banks. Over time, ephemeral streams erode laterally into the relatively weaker channel banks, where the channel bottoms consist of relatively fresh granite. Strath continue to widen at the expense of the pediment until vertical incision results in strath terrace formation.

Hypothesis #2 Aggradational drainage piracy leading to strath development.–

Studies of drainage evolution in MCCs suggest that stream piracy is a common intrinsic

process that plays an important role in drainage reorganization over time (Pain, 1985;

Pain, 1986; Spencer, 2000; Douglass, 2012). Pain (1985) explained the general process at

SMCC: drainages initially form in structural corrugations that parallel the axis of the

range. Eventually younger drainages flowing off the steeper flanks of SMCC erode

headward and capture the older, structurally controlled drainages. Similarly, low-

elevation drainages along the margins of SMCC are confined by smaller bedrock

structures that determine flow direction, paralleling the upland SMCC corrugations.

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Aggradational piracy along these marginal drainages starts when the flanks of SMCC, hosting steeper drainages, capture headwaters of the elongated structurally-controlled drainages (**fig. 5**). Capture of segments of the larger axial drainage then leads to a wave of alluvial fan aggradation on the flanks of SMCC. Aggradation resulting from fan growth on the SMCC margins raises the bed of lowland channels high enough to spill over the lowest point of the confining bedrock structure, similar to a hypothesis originally suggested by John Douglass (personal comm.) in alluvial fans in the metamorphic lithologies of SMCC.

We hypothesize that a fan aggradation event at the current location of the Warpaint Fan resulted in aggradational piracy at three different locations (**fig. 5**). The initial phase in capture resulted in knickpoint migration through the bounding range, resulting in small strath floodplain development just downstream of the point of capture in Piracy Canyon (**fig. 3B**), further facilitated by the substantial increase in drainage area (Garcia, 2006; Stamm and others, in Press). Subsequent headward knickpoint migration into the pre-capture drainage excavated the accumulated grus, leading to dynamic downstream aggradation filling the valley and burying the strath. As the knickpoint progressed upstream, the pre-capture floodplain was abandoned resulting strath terrace development behind the point of capture (Seidl and Dietrich, 1992; Seidl and others, 1997; Finnegan and Dietrich, 2011). The middle spillover became a windgap, as a result of its relatively small drainage area. However, the Warpaint spillovers had a sufficient drainage area to maintain headward knickpoint migration and drainage reorganization resulting in a series of small bedrock straths behind the point of capture.

We note that aggradational piracy is a singular triggering event, while the proposed pediment erosion and enhanced decay of channel banks represent a long-term ongoing process inherently tied to base level fluctuation. Thus, we propose our first hypothesis leads to subsequent strath formation inset below the straths formed during capture adjustment within pirated drainages.
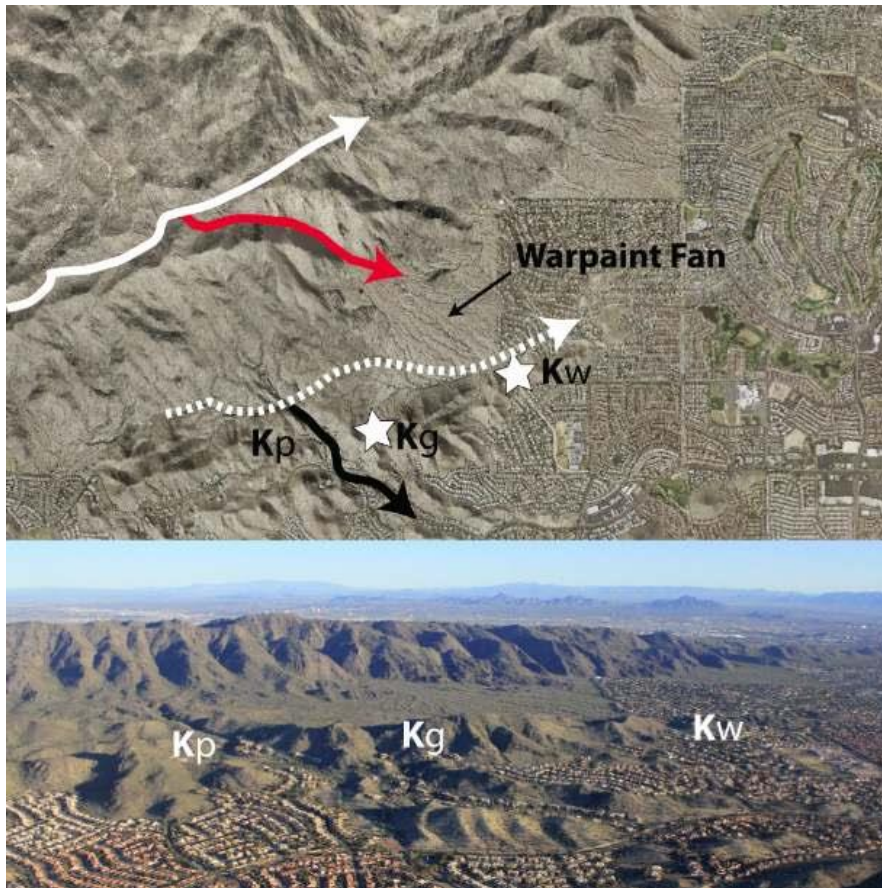
Fig. 5. Pain (1985) proposed that headward eroding streams on the flanks of the SMCC eventually capture (red arrow) larger, structurally controlled drainages flowing along the axis of the range (solid white arrow). In this example near the Warpaint trailhead, the resulting aggradation of the Warpaint fan raised the bed of the original flank drainage (dashed white arrow), resulting in three aggradational piracy events from spillovers across the small bounding range. Knickpoints (K) were thus created at Warpaint wash (Kw), a windgap (Kg), and Piracy Canyon (Kp). The upper image is used following permission guidelines for Google Earth.
[http://www.google.com/permissions/geoguidelines.html]

METHODS

Assessing enhanced bank decay and aggradational piracy as strath and strath terrace forming mechanisms required a mix of different methods: field mapping; direct field observations of flash flooding and its effect on bed and bank stability; digital image processing of electron microscopy to measure porosity and to observe the biochemical processes taking place along bed and bank; and radiocarbon and varnish microlamination dating to constrain the timing of strath incision.

Mapping and Topographic Profiles.– Because no comprehensive geomorphic landform map exists for SMCC, field mapping of semi-continuous fluvial terraces involved field observations, aerial reconnaissance, and data collection utilizing differentially corrected global positioning systems (dGPS). dGPS provides both spatial and topographic data, the latter consistently displaying resolutions of sub half-meter accuracy (average accuracy of 33 cm).

The mapping of isolated strath terraces is complicated by varying degrees of uncertainty as to whether a planar bedrock landform was once a part of the floodplain of a desert wash — as opposed to the alternative of a truncated pediment (**fig. 6A and 6B**). We placed isolated terraces in three categories. Isolated straths were mapped in the category of high confidence if: they contain gravels with a provenance that occurs up-basin (**fig. 6D**); they exhibit morphological floodplain evidence (for example, a chute cutoff in **fig. 7A**); or if they exhibit geochemical evidence of being in a floodplain position, such as presence of groundwater calcrete at the contact with the strath surface (**fig. 7B**). Isolated straths were assigned a medium confidence if there exists a clear

morphological break between the strath terrace and the adjoining pediment (for example,

fig. 3A). Low confidence straths morphologically merge into the adjacent pediment (**fig. 6C**). These low confidence sites are likely strath terraces, but the evidence is not absolute. These isolated terraces often exist in the most upstream portions of the drainage basin where valley width and drainage area dramatically decreases.
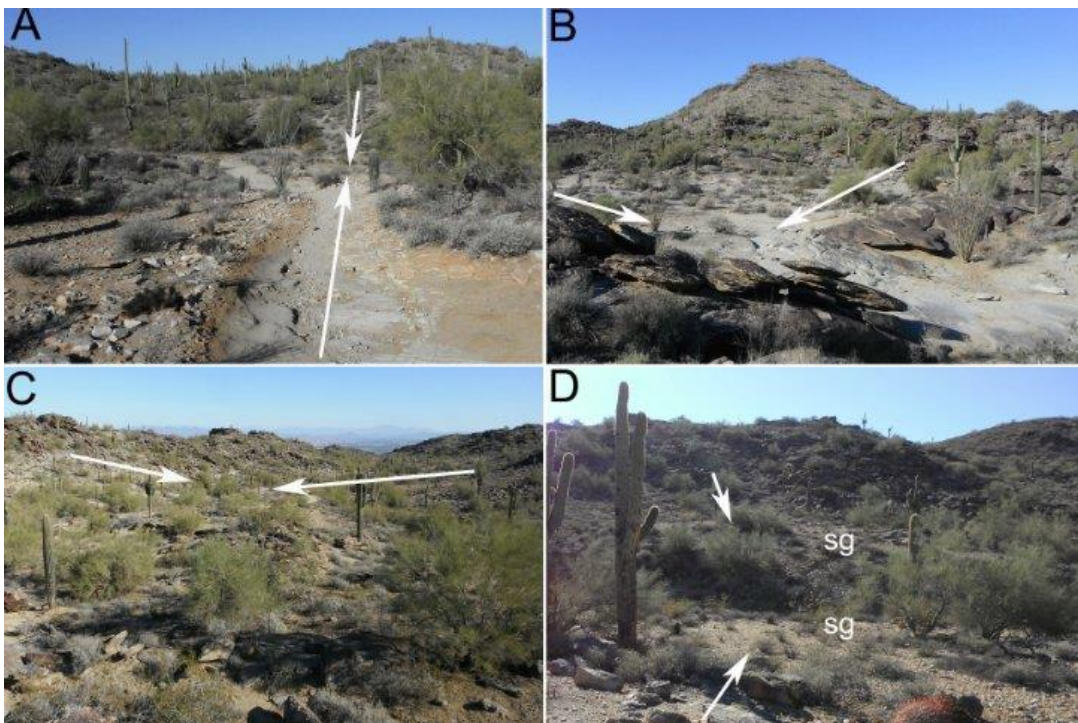
Fig. 6. Images from the same area of an upland corrugation of SMCC illustrate the difficulty of distinguishing a truncated pediment from a strath fluvial terrace. In each image, arrows indicate the direction of overland flow down the pediment towards the wash. In image A, the colluvial cover has been stripped by trail erosion, revealing the bedrock platform of the pediment as it slopes gently towards the axial wash. Image B presents the same site but from a different angle (the left arrow in B is the same position as the lower arrow in A). Image C shows this upland corrugation with a broader view, where the position of the incised axial channel exists in the topographic low between pediments. We are confident that the terrace form in image D is fluvial, indicated by 'sg' for surface gravels that have a provenance up-basin. The particular patterning of epidote and quartz veins is distinctive and can be traced to a bedrock outcrop several hundred meters upstream.
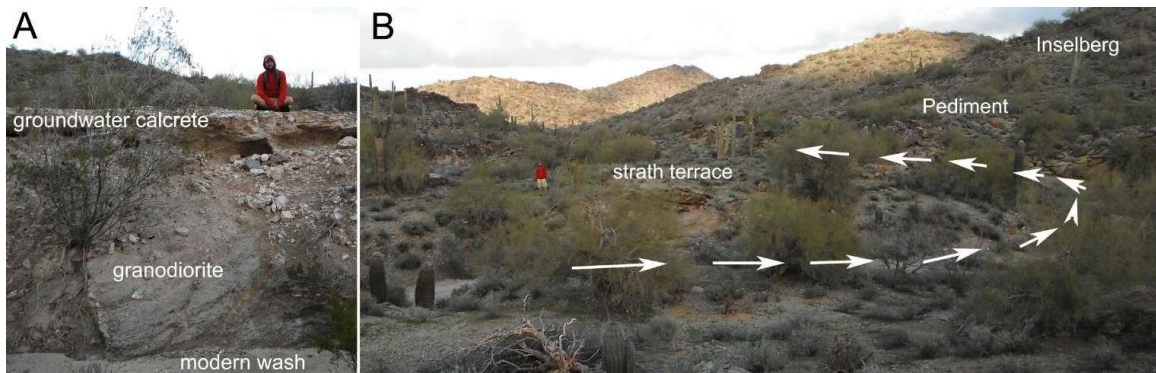
Fig. 7. Certain features provide convincing evidence that a beveled bedrock platform above a modern wash is a fluvial strath terrace and not a truncated pediment. (A) Groundwater calcrete forms along the wash bottoms in small ephemeral drainages with very low relief — allowing groundwater to pond on top of the bedrock. Its preservation records evidence that the location once supported a wash. (B) A meandering wash (arrows) isolate a strath terrace with an abandoned chute cutoff (where the first author stands).

To better understand the morphologic distinction and genetic relationships between pediment and strath we collected data on cross-sectional topographic profiles of strath terraces, adjacent pediments, and inselberg slopes — similar to the classic "pediment association" (Cooke, 1970). We only gathered these data in locations where we could observe and map the exposed bedrock surface. This is possible where anthropogenic activity (for example, abandoned roads or trails) stripped the colluvial cover.

Field observations of strath widening.– Direct observations of the widening of straths in modern ephemeral wash floodplains took place during flash floods at single-site locations 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) washes. Poor lighting conditions, unfortunately, did not facilitate clear photography.

Direct observations were possible because of the small travel time between Arizona State University and field sites, when it became clear that an extensive Arizona monsoon mesoscale convective complex was likely heading to SMCC. Each site was surveyed prior to the initiation of flow. Automated rain gauges operated by the Flood Control District of Maricopa County (2012) are within a kilometer of each observation site. Pre-flood surveying consisted of fixing a meter stick perpendicular to the bedrock bank of the wash, carefully marking the edge of the bank prior to flow initiation. In addition, the channel bottom was spray painted in spots prior to flow initiation.

Despite a large number of storms experienced in the field without observed flow, three events enabled direct observation of the process of strath widening through bank erosion: a precipitation event of 5.4cm in 6 hours on 8/03/05 with return interval of 32 years; an event of 3.6cm in 3 hours on 7/24/11 with a return interval of 8 years; and 2.1cm 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 accurately reflects the exact precipitation received in each of the studied drainages, available gauge data provide an approximation and valuble insight into the intensity of each observed event.

Rock decay as a limiting process on strath widening. – 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. However, samples were first impregnated in the field with epoxy

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prior to collection in order to preserve *in situ* relationships for the 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 adjacent to a channel; depths of sample collection into the bank ranged from 80 cm to 100 cm.

The samples were polished for study with backscattered electron (BSE) microscopy. Using methods detailed elsewhere (Dorn, 1995), digital image processing of BSE imagery at a scale of 1000x determines 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.

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.

Radiocarbon analysis of pedogenic carbonate to constrain the age of strath incision.– Exposures of terrace edges were dug back 0.5 m to extract course cobbles that occur in a Stage 2 Bk soil horizon. Stage 2 starts when the cobbles are coated on the top

and the bottom with calcium carbonate, and carbonate is starting to fill in the interstices (Gile and others, 1966). Extracted cobbles from Pima, Javelina, and Beverly Wash terraces were sectioned and polished as cross-sections normal to the carbonate coating. BSE evaluated the textures of the carbonate coatings on the undersides of cobbles. Most of the cobbles had a non-laminated texture for the innermost rind; these were discarded. All of the cobbles collected from the Pima Canyon terrace lacked a laminar texture for the innermost rind. Further processing continued only for the Javelina and Beverly Canyon samples.

Those cobbles with a laminar texture in BSE for the innermost rind were prepared in three stages. First, a Dremel drill with a tungsten-carbide needle mechanically removed the non-laminated outer texture. Second, the drill then slowly removed carbonate until the color of the underlying rock could be seen through the rind. Third, this lowermost laminar carbonate was then extracted, and it is this innermost carbonate rind that was counted by conventional radiocarbon dating.

Varnish microlaminations to constrain the age of strath incision.– Rock varnish is a mixture of manganese, iron and clay minerals that darkens exposed rock surfaces (Potter and Rossman, 1977). Varnish in drylands contain a layered microstratigraphy in so long as acid-producing organisms, eolian abrasion and other erosional processes do not affect varnish processes. Slowly accreting coatings forming at rates of microns/ka display relatively simple varnish microlaminations (VML), and those varnishes accreting in more mesic locates can accrete at rates of tens of μm/ka to produce detailed VML sequences.

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Both slow and more rapidly formed VML sequences have been calibrated for the Great

Basin (Liu and others, 2000; Liu, 2003; Liu and Broecker, 2007; Liu and Broecker,

2008b; Liu and Broecker, 2008a). Subsequently, VML has been used at various sites

globally (Diaz and others, 2002; Lee and Bland, 2003; Dietzel and others, 2004; Zerboni,

2008) and in the Sonoran Desert (Dorn, 2010; Dorn, 2012; Dorn and others, 2012).

VML samples were collected from bedrock (for example, **fig. 8**) exposed by

fluvial terrace incision. VML samples were then turned into polished ultra-thin sections

(5-10 μm thick), because the typical way of making geological sections produces thin

sections too thick to reveal VML microstratigraphy. The VML thin sectioning technique,

developed by Tanzhuo Liu and described elsewhere (Liu and Dorn, 1996) reduces failure

rates and facilitates inter-comparisons. The VML sections were then compared to the

Holocene and Pleistocene calibrations established by Liu and colleagues (Liu and others,

2000; Liu, 2003; Liu and Broecker, 2007; Liu and Broecker, 2008b; Liu and Broecker,

2008a).

Fig. 8. This Javelina Canyon VML collection site consists of resistant fine-grained and quartz-rich granitic body surrounded by grussified granodiorite containing more biotie. This site was exposed to varnishing only after incision abandoned the strath terrace. Since the sampling location is slightly below the height of the terrace tread, exposure to varnishing would not have occurred until after the start of incision. The channel is bedrock with locations of contemporary strath widening.

RESULTS

Mapping strath terraces and adjacent pediment topographic profiles.– Strath

terraces occur in the majority of drainages within the granitic lithologies of SMCC. The

terraces are most continuous in the downstream portion of the largest drainages in terms

of drainage area (**fig. 9**).
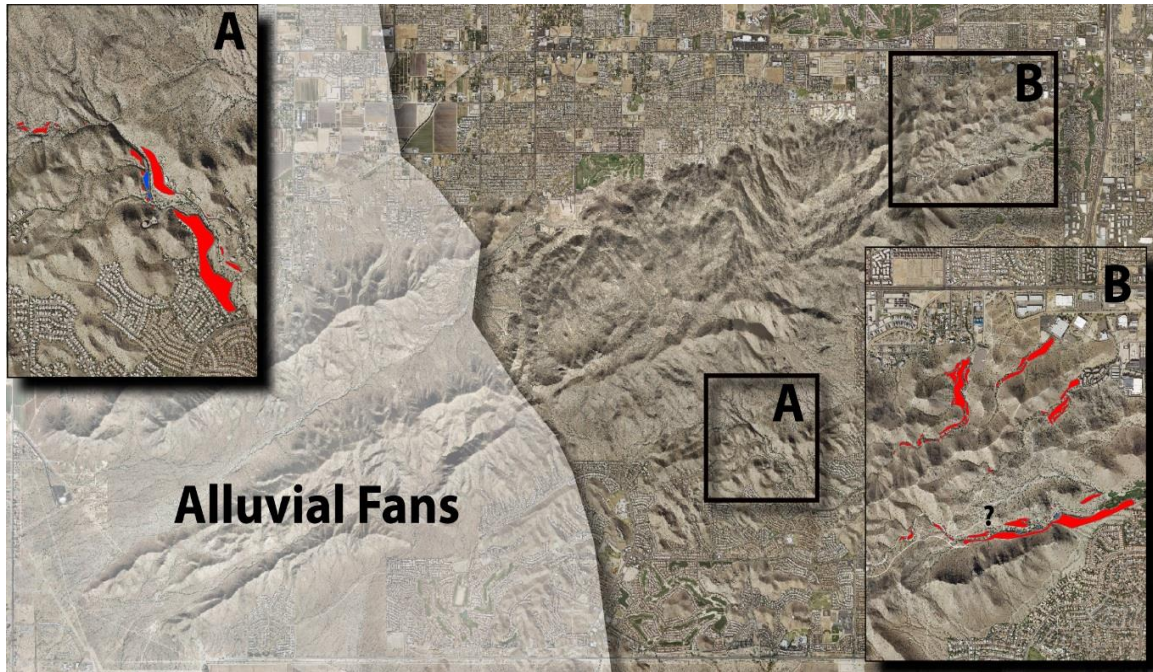
Fig. 9. The eastern granitic portion of SMCC contains the most extensive fluvial terraces, while the western portion is dominated by alluvial fans. Inset A (Piracy Canyon) and B (Javelina, Unnamed, Beverly, and Pima Washes) display the most extensive terraces. A predominant high terrace (red colored T2) exists in each drainage with a lower inset strath terrace (blue colored T1).

The headwaters of the largest drainages and the downstream portions of smallest watersheds contain dozens of isolate strath terraces (for example, **fig. 1 and 10**), suggesting a drainage area threshold exists (for example, Merritts and others, 1994) although analysis of this is beyond the scope of this research and being combined with ongoing work elsewhere by the authors. Over 60 locations of isolated strath terraces were identified and their locations are indicated in the local vicinity of each pin displayed in **figure 10**. This map has been formatted as a KML file for ease of access (**fig 10;** temporary location for KML file:

http://alliance.la.asu.edu/temporary/strath/Larson_Figure10.kml). This map is our most complete effort to map all strath terrace remnants within SMCC. Although we explored these drainages over hundreds of investigations, it is probable that we missed several

locations of isolated strath terraces. That said, the broader pattern evident in **Fig. 10** is

that while isolated strath terraces are ubiquitous in the granitic eastern portion of SMCC,

they are spatially sporadic and often exist in isolation. They are also most often preserved

on the inside of meander bends within these drainages. Often the most continuous strath

terrace sequences are those in the distal portion of the largest drainage basins, which

typically are those developing within the structural corrugations (i.e. Pima, Javelina, and

Beverly Washes).

The more extensive terrace surfaces (fig. 9) and isolated terrace remnants (fig. 10)

typically abut small pediments (for example, figs. 3A, 6D, 7B, 11). The presence of

eroded old roads and trails (for example, fig. 6A) make it possible to study how bedrock

topography and the gradational relationship between hillslope (inselberg), pediment and

strath terrace pertains to overall landscape development. Fig. 11 illustrates a typical

bedrock cross-sectional profile. The steep inselberg face merges into the gently sloping

pediment, which then transitions into the beveled strath terrace. The topography seen on

the strath terrace in fig. 11 comes from the incision of small washes cutting down in

response to local base level lowering of the trunk drainage during incision.
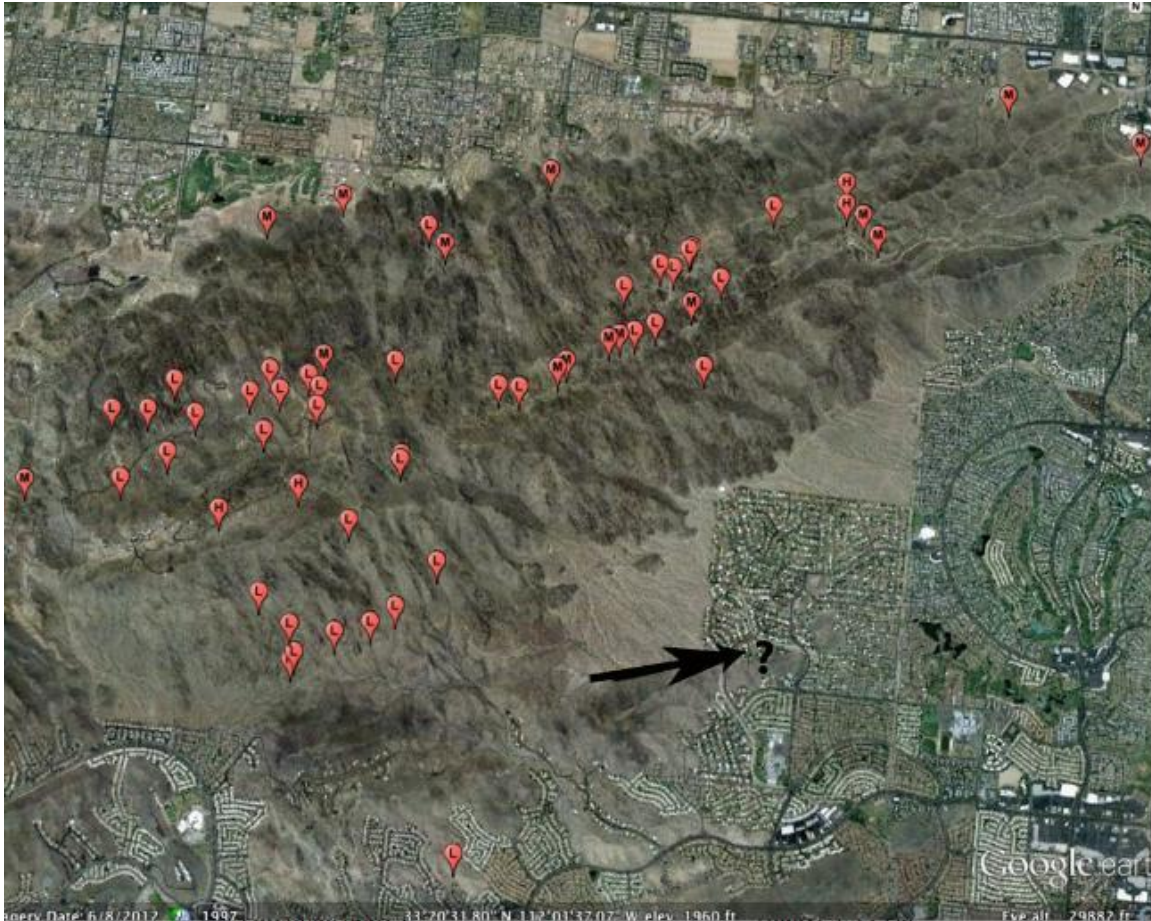
Fig. 10. Locations of identified isolated strath terrace remnants in SMCC in a Google Maps format, where a supplemental .kml file (temporary location http://alliance.la.asu.edu/temporary/strath/Larson_Figure10.kml) allows the reader to explore locations at the resolution of Google Earth. H identifies the isolated remants where we have a high confidence that the terrace form represents a former floodplain, M symbol a medium confidence level, and L simple a lower confidence. The arrow on the south side of the range indicates the location of Warpaint wash that hosts a series of discontinuous strath terraces; the question mark is where the aggradational piracy event would have overflowed the bounding range perhaps producing a downstream strath where houses were built. The base image is used following permission guidelines for Google Earth [http://www.google.com/permissions/geoguidelines.html]
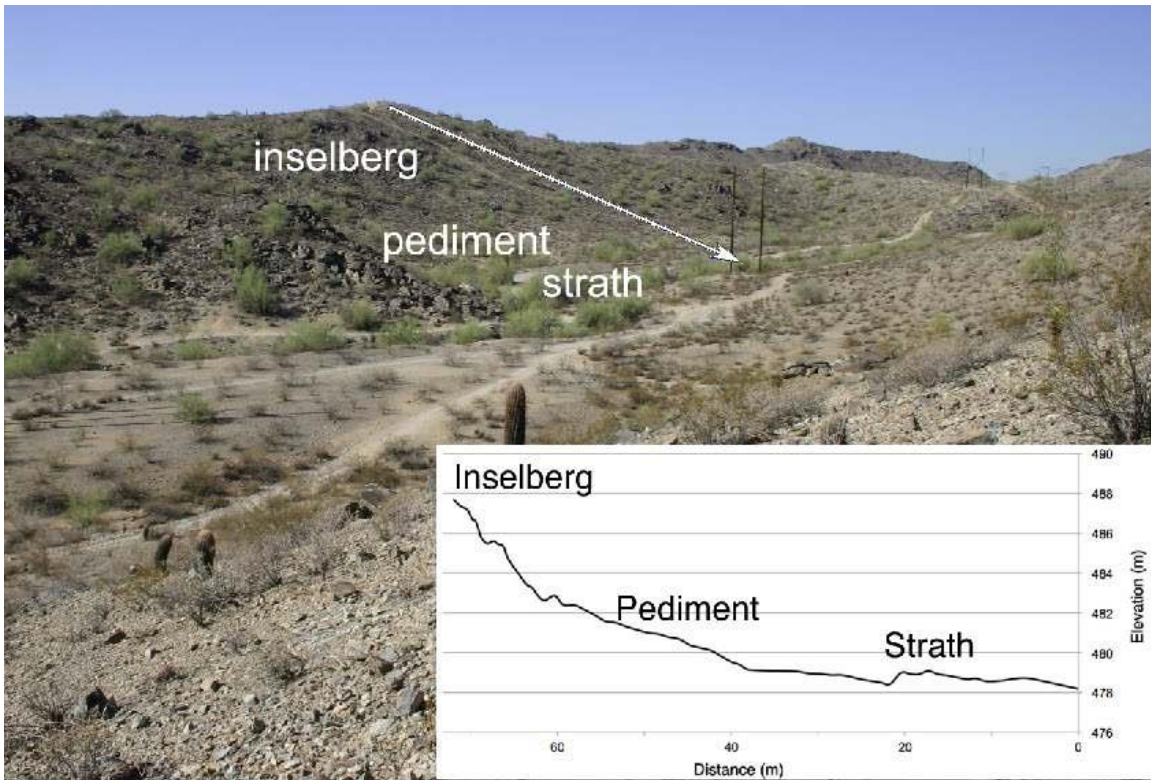
Fig. 11. An abandoned road at Beverly Canyon (to the left of the arrow) led to stripping of the colluvial cover. This facilitated measurement of a cross-sectional topographic profile along the bedrock surface from the strath terrace up to the top of the inselberg. Slope breaks between the strath, pediment and local inselberg are consistent with the hypothesis that ephemeral washes widen straths through lateral migration into banks composed of more highly decayed rock.

Direct observations of strath widening during flash floods.– The upper Corona del Loma, Warpaint and Pima Wash banks eroded laterally 21 mm, 12 mm and 5 mm, respectively in response to the 8/03/05 storm. The Kiwanis and Beverly wash banks eroded laterally 6 mm and 4 mm respectively during the 7/24/11 event. The Javelina wash bank experienced 9 mm of channel widening during the 6/20/00 event (**table 1**). In contrast, isolated fragments of the spray paint on the exposed bedrock of the channel bed could be seen at each of these sites after each flash flood. The presence of spray paint fragments on the channel bed indicates that no detectable bedrock incision occurred

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during these ephemeral flows. In each case, the ephemeral flow saltated medium sand grains (grus) that abraded most of the spray paint off the channel bedrock and wear exposed the granite often appear polished, likely from this process. Grussified grains were ejected into the flow through the impact of saltating grains on the grus covered portions of the channel bed. In contrast, each of the bedrock channels were widening through erosion of thoroughly decayed granite. Although these observations of six flash floods are anecdotal, the observed process of preferential widening of strath floodplains in each wash (at the expense of highly decayed bedrock bank material) is undoubtedly prevalent.

TABLE 1

Field observations of strath widening during high magnitude precipitation events

Wash	Precipitation Event	Bank Erosion	Strath Incision	Event Date
Corona del Loma	5.4 cm/6 hr	21 mm	not detectable	08/03/05
Warpaint	5.4 cm/6 hr	12 mm	not detectable	08/03/05
Pima	5.4 cm/6 hr	5 mm	not detectable	08/03/05
Kiwanis	3.6 cm/3 hr	6 mm	not detectable	07/24/11
Beverly	3.6 cm/3 hr	4 mm	not detectable	07/24/11
Javelina	2.1 cm/15 min	9 mm	not detectable	06/20/00

Rock decay as a limiting process on strath widening.– The granitic bedrock banks of the six small washes that experienced erosion during ephemeral flooding show double to triple 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 2**).

These porosity measurements combine intra-grain and inter-grain pores that are visible in 1000x BSE images. The direct inference is that chemical decay processes that occur along the bedrock banks of ephemeral washes aid in the decomposition and disintegration of the granitic bedrock — turning the material into friable grus.

TABLE 2

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
Upper 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
Javelina	13.0	4.6	5.1

Electron micrographs provide a visual sense of the greater degree of rock decay found along the banks of these dry washes (**fig. 12**). Whereas the mid-channel (**fig. 12A**), and bedrock interior (**fig. 12D**) do show evidence of some porosity from ongoing discongruent dissolution, these positions are much less decayed than samples collected along the wash banks (**fig. 12B and 12C**) where there exists minimal physical contact between different pieces of decayed minerals.
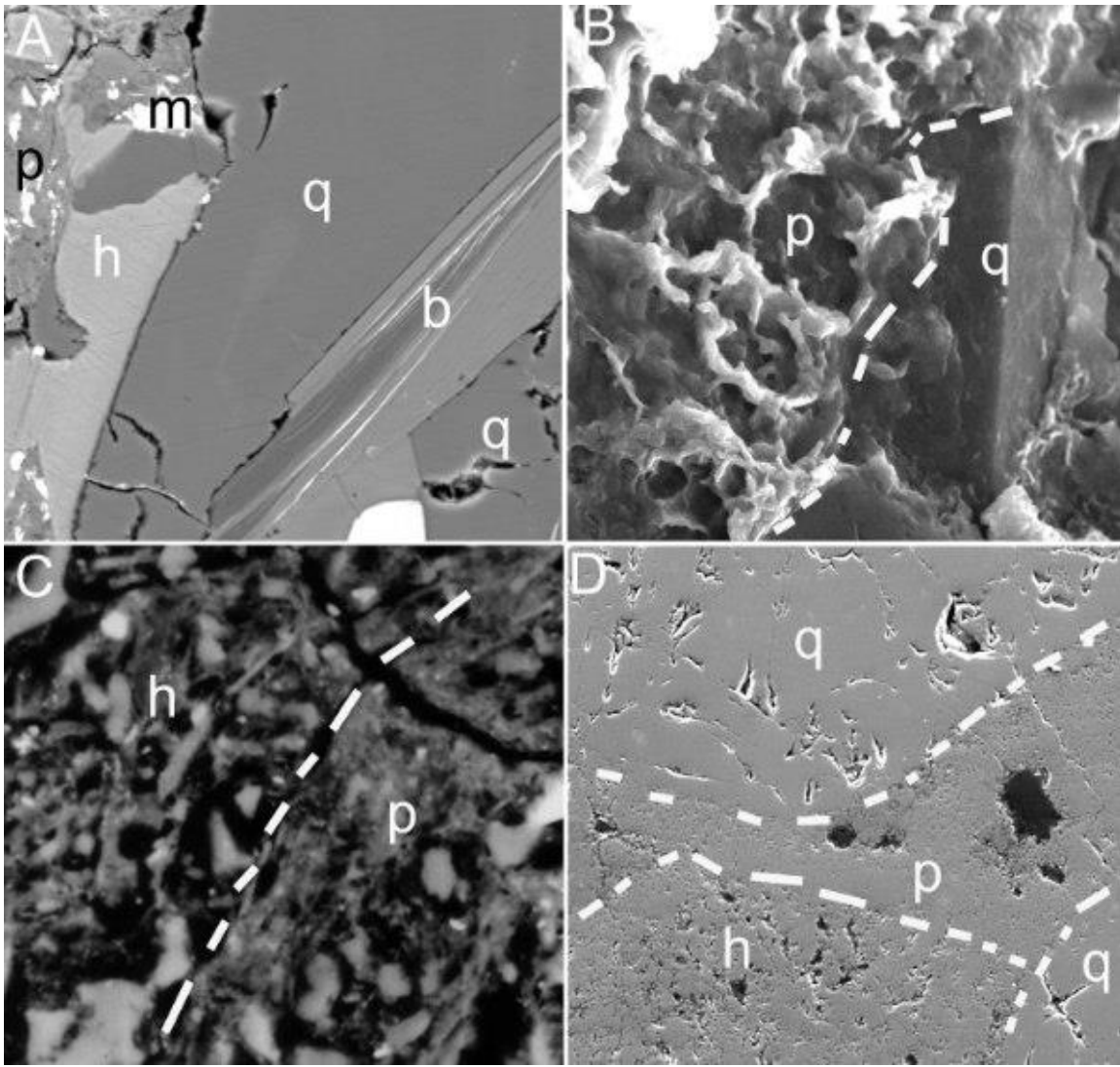
Fig. 12. Backscatter (A&C) and secondary (B&D) electron microscope imagery of granitic weathering associated with the widening of a strath at Pima Wash, South Mountain. Energy dispersive X-ray spectroscopy aided mineral identification of quartz (q), biotite (b), hornblende (h) plagioclase (p) and magnetite (m). Dashed lines in B, C, and D identify mineral boundaries. All images are 400μm in width. 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.

The net effect of the greater porosity along channel banks can be seen in **fig. 13**, where the gray relatively fresh granitic strath contrasts with the 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; Oberlander, 1989). However, our direct electron microscope observations also point to another process — root decay associated with the enhanced growth of vegetation along wash banks.

Fig. 13. 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.

The banks of washes at South Mountain logically display a more extensive vegetation coverage than adjacent hillslopes because of proximity to water. 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. 14**). 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 micro-analytical techniques, reveals the power of roots and their associated fungi to decay bedrock (Landeweert and others, 2001; Hoffland and others, 2004; Bonneville and others, 2009; Smits and others, 2009; McMaster, 2012; Viles, 2013).
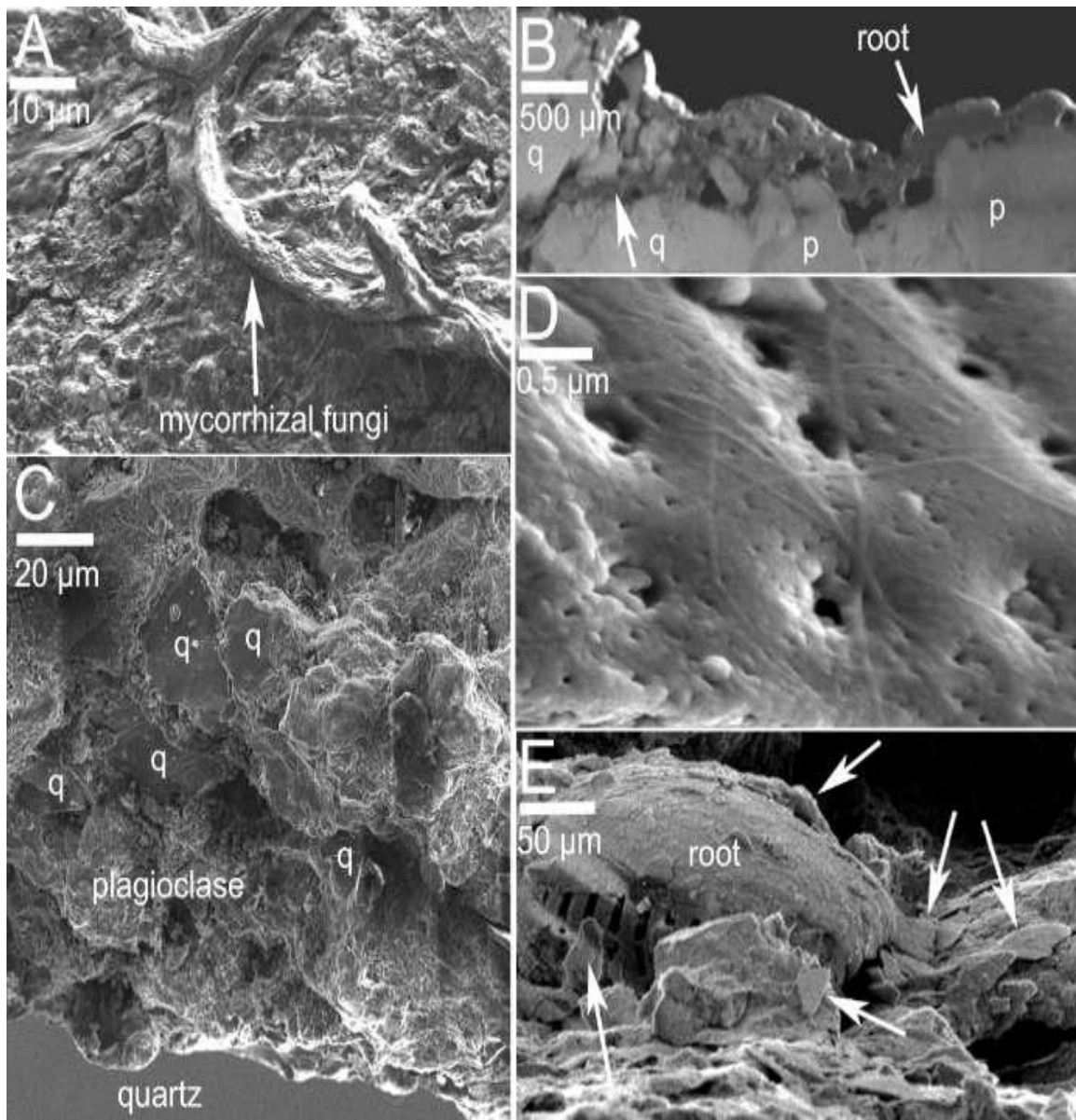
Fig. 14. Secondary electron images of rock decay along banks fronted by hard-rock straths. The images all show the effects of mycorrhizal fungi (image A) and roots (B). Mineralogy (q= quartz; p=plagioclase) is based on EDX analyses. Most of the effect appears to be the decay plagioclase grains to the 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.

Radiocarbon dating of pedogenic carbonate.– The Javelina strath terrace innermost laminar rind yielded a conventional radiocarbon age of 30140±150 BP (Beta 322777) yielding a calibrated 1 sigma age range of 34820 to 34680 cal BP. The strath Beverly terrace innermost laminar rind yielded a conventional radiocarbon age of 30140±150 BP (Beta 322778) yielding a calibrated 1 sigma age range of 35310 to 35060 cal BP. The Pima strath terrace samples did not have a laminar-textured rind appropriate for radiocarbon dating in our sampling.

It is certainly possible that some older carbonate moved into the pedogenic system in the form of dust. Soil carbonate studies from Southwestern USA found atmospheric deposition of $CaCO_3$ to be a major source of pedogenic carbonate (Capo and Chadwick, 1999). If this dust was simply cemented together on the undersides of the cobbles, some older carbon could have contaminated these ages.

However, a more likely issue involves the open nature of the pedogenic carbonate system. Radiocarbon dating of pedogenic carbonate is notoriously difficult and fraught with uncertainties (Callen and others, 1983; Stadelman, 1994; Wang and others, 1994) associated with the remobilization of carbonate giving ages that are younger than the geomorphic deposit. Thus, because of the open nature of the carbonate system, we think these ^{14}C results are best interpreted as minimums and must be correlated with VML dating to be considered accurate.

VML dating.– **Table 3** summarizes the VML minimum age estimates for the different SMCC strath fluvial terraces discussed in the paper. **Figures 15-22** provide examples of both the geomorphic context and VML ultrathin section results. Note in **figures 15-17** how the strath terrace merges topographically into the adjacent pediment.

TABLE 3

VML pattern and minimum age ranges for South Mountain incision events discussed in the paper. T2 is the higher strath terrace, and T1 refers to the lower inset strath terrace.

Landforms and Locations	Minimum Calibrated Calendar Age	Related Figures
Piracy Cyn Upstream Inset Terrace N 33.32466 W 112.04377	WH1, 300-650 years ago (Little Ice Age)	Fig. 20
Pima Cyn T1 N 33.36237 W 111.98821	WH5 (4.1 ka)	Fig. 17
Piracy Cyn T1 N 33.32357 W 112.03212	WH5 (4.1 ka)	Fig. 19
Piracy Cyn T2 N 33.32325 W 112.03220	LU-3, 24-16.5 ka	Fig. 19
Beverly Cyn T2 N 33.36690 W 111.99080	Between WP3 and WP4, 39-30 ka	Fig. 11
Pima Cyn T2 N 33.36319 W 111.99732	Between WP3 and WP4, 39-30 ka	Fig. 16
Javelina Cyn T2 N 33.37186 W 111.99374	Between WP3 and WP4, 39-30 ka	Fig. 8, 15
Piracy Cyn Wall N 33.32309 W 112.03273	LU-5, >74 ka, recording a minimum age for the piracy event	Fig. 18

Fig. 15. Granitic Javelina Canyon on the eastern end of South Mountain incised into its former floodplain and exposed resistant bedrock. This event exposed bedrock that was then coated by varnish with a VML signal between the WP3 and WP4 (Wet Pleistocene) events. The period between WP3 and WP4 has a calibrated age range between 39-30 ka.
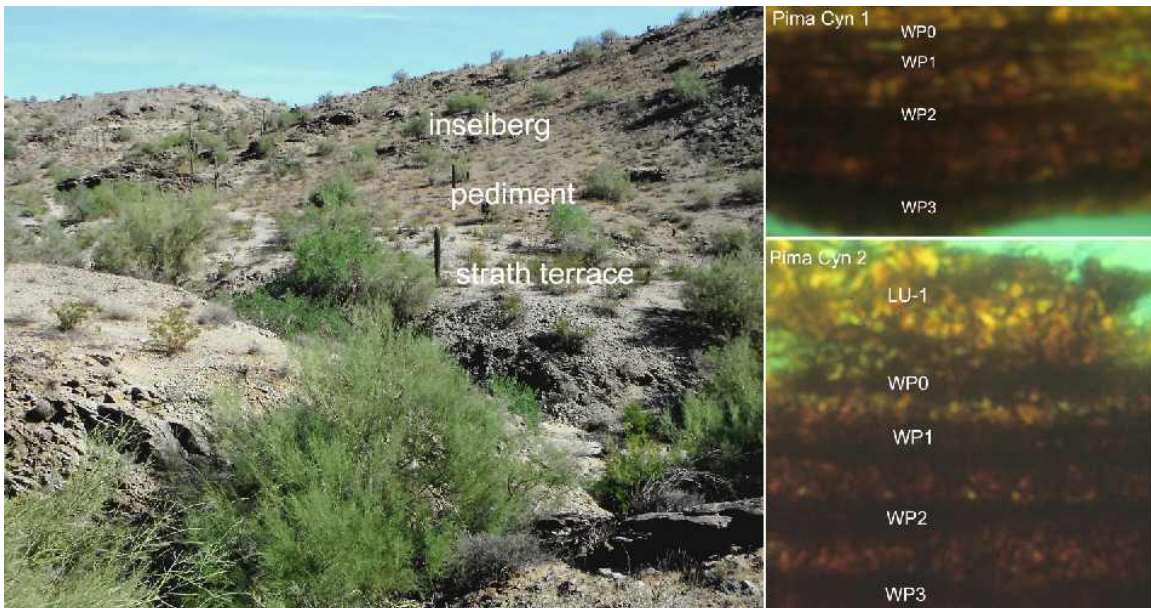
Fig. 16 Pima Canyon is the largest drainage in the granitic eastern end of South Mountain that contains the most extensive terraces that are the highest elevations above the current wash. Incision into this terrace exposed bedrock that has a VML signal between WP3 and WP4 or between 39-30 ka.
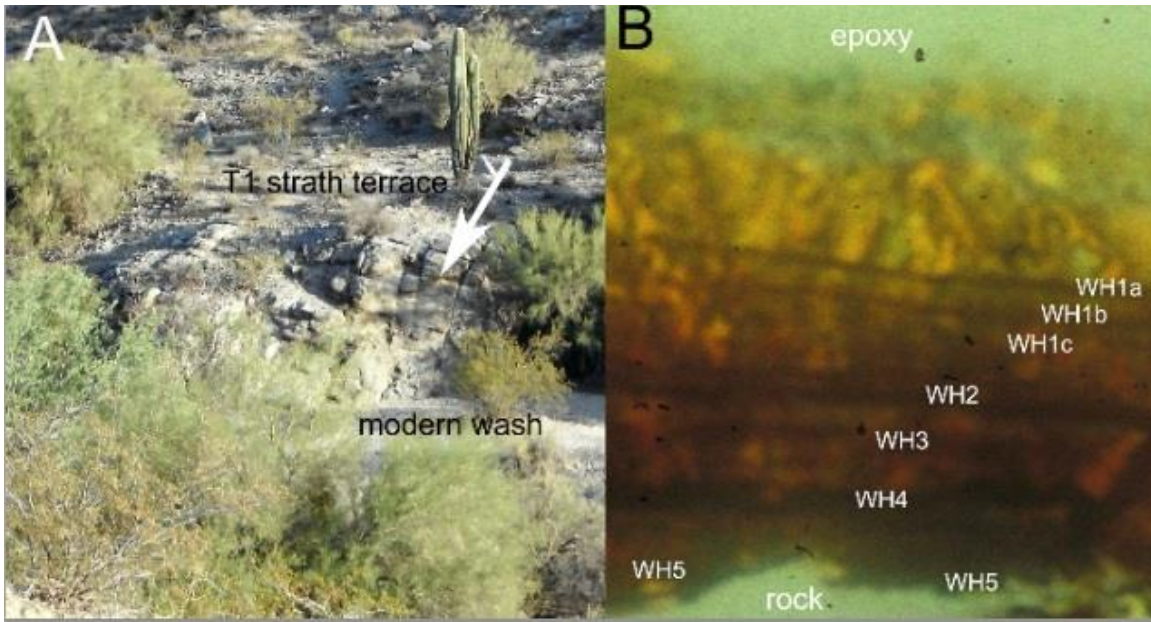
Fig. 17. Pima Canyon's inset T2 strath terrace exists sporadically along the lower reaches of the drainage. The VML pattern formed on the bedrock face just underneath the strath surface, of WH5 establishes a minimum age of WH5 (4.1 ka) for the incision event.
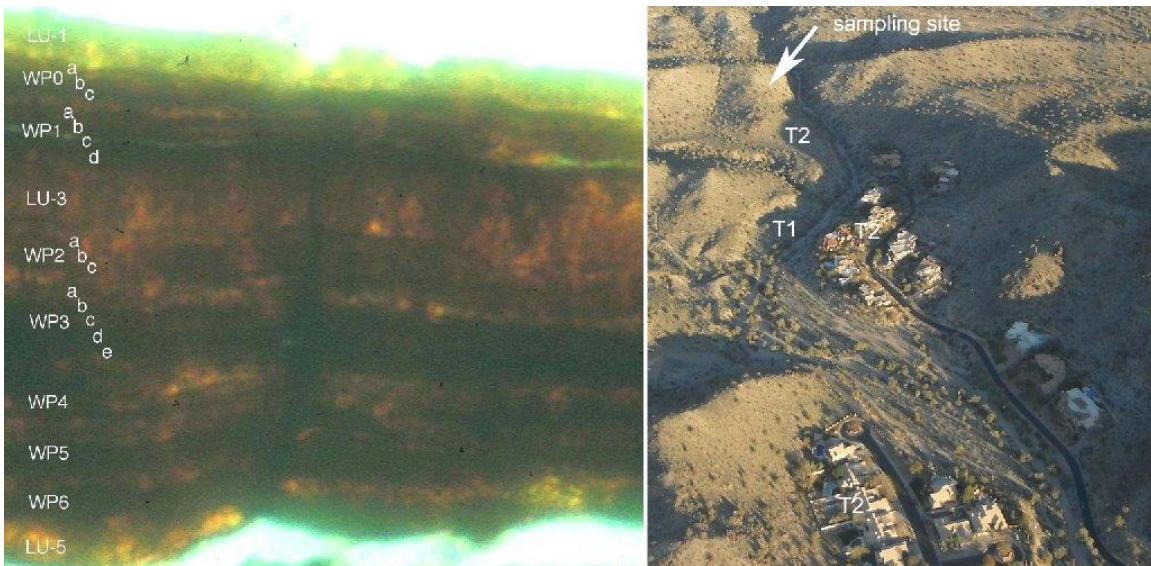
Fig. 18. The eroded hillslope at the overflow point at Piracy Canyon (sampling site) displays a VML sequence with an age of >75 ka. This is a minimum age for the piracy event, because the hillslope continues to erode. While homes occupy most of the higher strath terrace (T2), unconstructed locations exist for study of the T2 and T1 strath terraces.

Fig. 19. Piracy Canyon hosts two strath terraces. The lower T1 strath terrace has course boulders with a VML signal that is older than WH4. The ultrathin VML section was a bit too thick to clearly discriminate WH4 (2800 cal BP) from WH 5 (4100 cal BP), but it is likely that the very lowest laminae is WH5. The upper strath T2 terrace hosts varnish with a basal layer of LU-3, calibrated to be between 24 and 16.5 ka
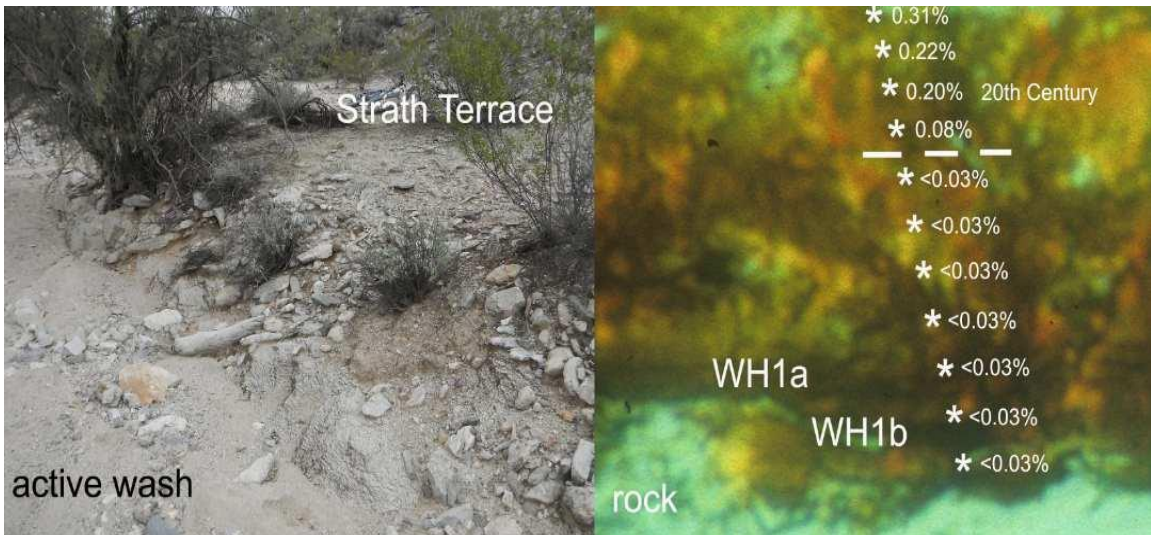
Fig. 20. Small isolated strath terraces occur upstream of the capture location. In this particular location, the terrace was abandoned during the Little Ice Age, calibrated to be between 300 and 650 years before present. Rock varnish shows the pollution signal from the 20th century in the uppermost portion, and end microlaminations that formed at the end the Little Ice Age microlaminations (WH1a and 1b) form the basal layer of the varnish and represent a minimum age for terrace abandonment.

DISCUSSION

The discussion starts with an evaluation of the proposed new hypotheses for strath formation in arid/desert granitic terrains: the first hypothesis of enhanced rock decay along bedrock banks; and the second hypothesis of the increase in drainage area and adjustment of the longitudinal profile associated with aggradational piracy. Then, we speculate on possible causes of strath incision at South Mountain, leading to strath terrace formation. The last portion of the discussion section turns more broadly to the issue of strath terrace formation in arid/desert granitic terrains and metamorphic core complexes.

The pediment-strath relationship and strath widening by enhanced rock decay along bedrock banks.– Granite's tendency to decay to grus through biotite decay (Isherwood and Street, 1976; Hoskin and Sundeen, 1985), discongruent dissolution (**fig. 12**), and biotic processes (**fig. 14**) means that granitic terrains tend to produce biomodal sediment: core stones of boulder size that are not easily transportable by ephemeral desert washes and sand-sized grus. This means that streams carrying only grus are able to erode into beds of undecayed granite only at very slow rates (Wahrhaftig, 1965). Thus, when a small arid wash encounters undecayed granite (for example, **fig. 13**) rates of vertical incision slow, especially when a stream is near a steady-state (Pazzaglia, 2013) or graded (Leopold and Bull, 1979) condition that is not conducive for vertical incision.

While no prior published data are available on incision rates of small granitic desert washes in undecayed bedrock, direct observations of erosive processes during ephemeral flooding reveal that flash flooding preferentially erodes grussified banks and not bedrock channels. This is also supported by research in Taiwan by Hartshorn et al.,

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(2002) who note that high magnitude, low frequency floods are more significant in increasing bedrock channel width than in vertical incision. High magnitude precipitation events, 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 2**).

As a proxy for the degree of rock decay, porosity was measured in the channel banks, channel floor, and bedrock interior. An asymmetry between bed and bank resistance to erosion (Montgomery, 2004) exists in all study sites, where channel banks are nearly 2-3x more porous than control positions in the bedrock interior and channel bottom (**table 2**). This enhanced mineral decay reduces grain-to-grain contact (**figs. 12 and 14**) that appears to have facilitated the observed strath widening during flash flooding. Thus, the relative efficiency of bank decay as compared to that of the channel floor/interior of the bedrock (80-100 cm into the bank) and the topographic/morphologic relationships observed in the study reach lend support to the strath forming mechanisms proposed in hypothesis #1.

Therefore, three general factors in our study area would facilitate strath carving in granitic terrains in arid regions: 1) the *pediment-strath relationship*; 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.

The existence of small pediments within the SMCC has been noted for some time (Reynolds, 1985). These small pediments are morphologically related to strath terrace remnants, as they grade smoothly to a strath terrace surface. We, herein, suggest the term *pediment-strath relationship* to describe this association. We observed the *pediment-*

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strath relationship in nearly all drainages underlain by granitic rocks (for example, **figs. 3A, 6D, 7B, 11, 16**). Furthermore, sites in SMCC where strath terrace remnants are not present contain pediments that grade to approximate to the modern strath channel (**figs. 6A and 6B**). 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 relationship throughout central Arizona. This suggests that both pediment development and strath formation are conducive to conditions of geomorphic stability, where the control of base level may be highly significant.

The relevance of *pediment-strath relationship* to this dicussion rests in preparing the landscape for strath carving in two ways. First, pediments already have very gradual slopes (Cooke, 1970). Therefore, it does not take a significant excavation of mass to develop a strath across this surface. Second, pediments in granitic terrain often contain a highly decayed regolith/soil layer, or 'weathering mantle' (Mabbutt, 1966; Cooke and Mason, 1973; Moss, 1977). The weathering mantle exposes highly decayed granitic rocks in the channel banks that are susceptible to channel bank erosion.

The prevalence of bank-side vegetation (for example, **figs. 1, 8, 13, 15, 16, 20**), due to a greater abundance of water in desert washes, results in enhanced bank decay through biochemical and biophysical processes acting on the granitic rocks exposed. 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

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cohesion; mycorrhizal fungi even pit quartz (**fig. 14**). When combined with the abiotic processes of biotite oxidation and plagioclase discongruent dissolution (**fig. 12**) 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 2**) and further enables the strath widening observed directly during ephemeral storms (**table 1**).

We speculate that a third factor might be important to the development of straths in arid granitic terrains: the temporary storage of silt and fine sediment deposited at the base of channel banks. Dry desert washes store silt at the contact of the strath and adjacent channel bank (**fig. 21A-D**). Our direct observations of flooding events at SMCC reveal that this silt deposits on the margin of a channel as an ephemeral flood pulse recedes. We speculate that this silt behaves 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; Oberlander, 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 annual events.
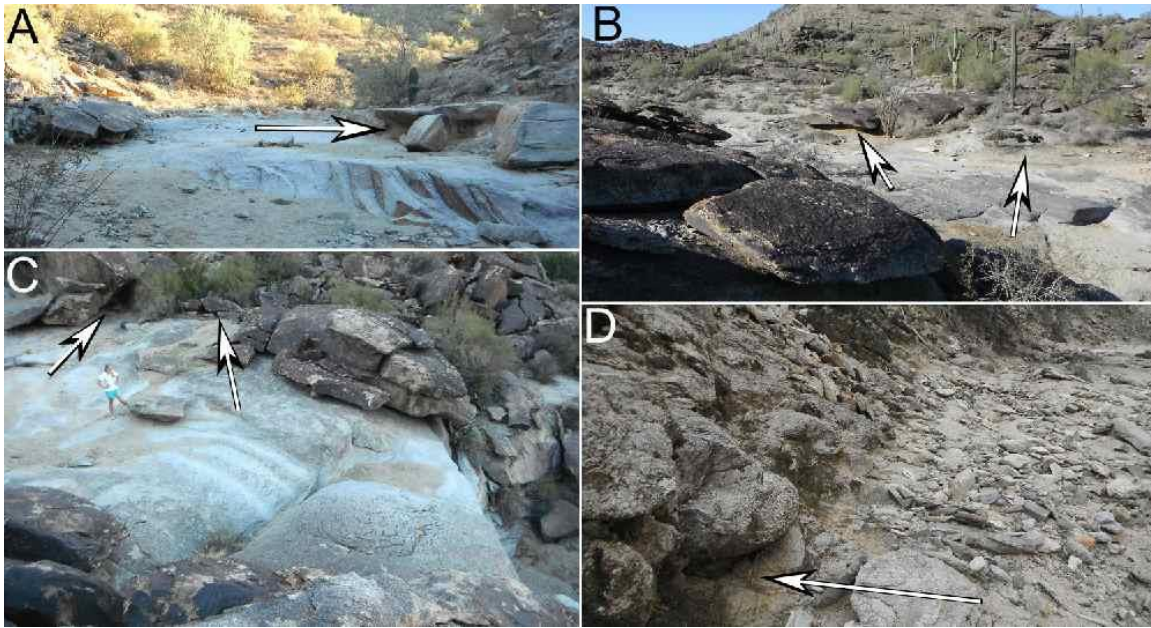
Fig. 21. Strath widening could be enhanced through water retention in silt that deposits at the bottom of the bank (arrows in images A-D). The growth of lichen and bryophuyte lithobionts in image D also likely play a role in enhancing rock decay along banks. Scale in images A-C can be inferred from the 3 m tall Paloverde trees (Parkinsonia microphylla). The width of image D is approximately 6 m.

We hypothesize that the erosional asymmetry (for example, Montgomery, 2004) observed at SMCC may be relevant to other locations in the Sonoran Desert portion of the Basin and Range province. For example, the much larger Verde River (Pope, 1974) and Salt River (Kokalis, 1971; Pewe, 1978; Larson and others, 2010) terraces are often strath cut into granitic bedrock and the remnants of these strath terraces rest above modern pediments graded to the local base level of these rivers. We suggest these straths form the base level of the pediments that have graded to terrace levels — representing the *pediment-strath relationship* (Larson, in Prep). Sufficient drainage area has commonly been invoked as being important to the formation of strath terraces (for example, Merritts and others, 1994; Garcia, 2006). Since the SMCC research reported here illustrates that small arid drainages (<5 km^2) are of sufficient size to develop strath terraces, we hypothesize that drainages underlain by granitic rocks throughout the Sonoran Desert,

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and perhaps in other arid regions, could develop straths and strath terraces in this fashion. While our anecdotal observations in the region confirm the existence of the *pediment-strath relationship* in regards to strath terraces in other drainage basins, a full treatment of the extent of arid straths in granitic terrains is beyond the scope of this research.

  Strath formation through drainage piracy.– Merritts et al. (1994*)* concluded that strath formation may depend on a sufficient drainage area upstream; within their study reach straths reside sufficiently downstream of the headwaters where a large enough drainage area exists to provide the stream power needed to laterally incise. Garcia (2006) tested this hypothesis using a case study of Pancho Rico Creek, California; a capture event greatly increased the drainage area and, in part, resulted in strath development downstream of the elbow of capture. Piracy and its corollary of drainage area also influences strath development within the Missouri River watershed (Stamm and others, in Press).

  Piracy is a common process at South Mountain (Pain, 1985; Pain, 1986; Douglass, 2012). Piracy Canyon (**fig. 3B**) displays many of the criteria indicative of drainage piracy (Douglass and others, 2009a; Douglass and others, 2009b). **Figure 3B, 5 and 22** present oblique aerial imagery where a paleoflow direction, elbow of capture, and the low sill controlling the location of the capture all indicate aggradational piracy as the cause of the transverse drainage. Notably, gravels preserved just behind the sill reflect the paleo-flow direction (**fig. 22B**).
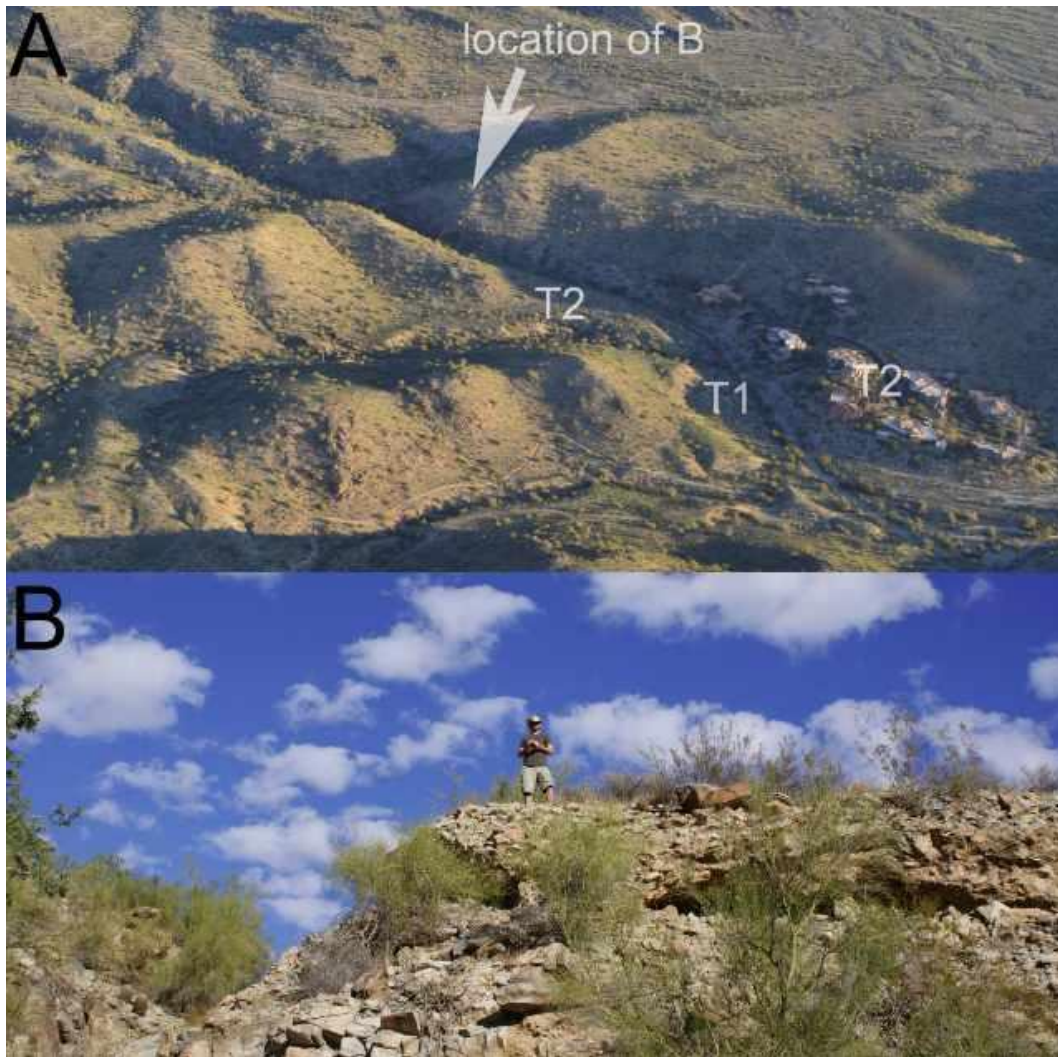
Fig. 22. Piracy Canyon. The arrow in image A indicates the location of image B, that illustrates ~1m of fluvial gravels preserved at the elbow of capture — providing evidence of the paleo-flow direction parallel with the bedrock ridge. Image A also presents T2 strath and T1 strath terraces of the drainage that cuts a transverse path through a bedrock ridge.

Aggradational piracy occurs in watersheds when drainage capture within the SMCC results in significant fan aggradation on the margins of the range. Fan aggradation raises the bed of marginal, low-elevation washes paralleling the range axis (**fig. 5**). When the channels reach the height of the foothill ranges that control their flow direction, they spill over, resulting in capture by a much smaller drainage.

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The increase in drainage area following the spillover may provide sufficient stream power to initially carve the strath floodplain downstream of the point of capture (**fig 9A**). In the case of Piracy Canyon, the capture more than doubled the drainage area from the pre-capture drainage (1,769,700 m^2) to the post-capture drainage (4,109,900 m^2).

After capture the knickpoint created at the capture point erodes headward through the transverse range — excavating an increasing amount of stored sediment. This leads to a substantial wave of aggradation downstream — capping the strath surface and preserving it. The headward erosion of the knickpoint upstream also results in strath terrace formation upstream of the capture point (**fig. 9A**) during longitudinal profile adjustment — through processes described elsewhere (Seidl and Dietrich, 1992; Seidl and others, 1997; Finnegan and Dietrich, 2011).

Evaluating Causes of Strath Incision.– The techniques used to estimate the age of strath terrace formation include relative dating based on inset morphologic relationships, radiocarbon dating of laminar calcrete on cobble rinds, and varnish microlamination (VML) dating. The ^{14}C and VML techniques only provide minimum ages for strath abandonment. Thus, it is not possible to make clear correlations between strath formation and paleoclimatic records. These data, however, do permit speculation about plausible relationships between our data and chronologies for incision events collected by other researchers in the region.

The oldest recorded incision event involves the T2 terraces along the largest drainages of Pima, Javelina and Beverly canyons, in the eastern portion of SMCC (**fig.**

9B). The broad time frame for T2 incision in Pima, Beverly, and Javelina Canyons is 39-30 ka based on the VML age and ~35 ka for the innermost laminar calcrete ^{14}C calibrated ages (**table 3**). These minimum ages indicate that incision occurred after major eustatic sea level decline at ~32 ka (Lambeck and others, 2002). However, the ~330 km distance to the Gulf of California suggests that eustatic sea level lowering is unlikely as a cause of incision of the T2 terraces.

One hypothesis explaining terrace formation involves incision of the Salt River in this time frame. Javelina, Beverly and Pima drainages all empty northeastwards into the Salt River (**fig. 2**), that forms the local base level control for these drainages. Incision creating the Blue Point (Pewe, 1978) terrace east of Phoenix likely occurred ~33 ka based on a single ^{14}C age from laminar calcrete on Blue Point Terrace cobbles (Larson and others, 2010). However, there is no evidence that the Blue Point terrace existed along the Salt River in this area. Thus, incision of the Salt River is not a testable hypothesis at this time.

Another explanation for incision into the T2 terraces of Pima, Beverly and Javelina Canyons would involve lateral migration of the Salt River shifting closer to South Mountain. The current distance to the Salt River is ~5 km (**fig. 2**), but little relief exists for about 2 km south of the present-day Salt River channel. Southward movement of the Salt River would have steepened the longitudinal profile drainages flowing from South Mountain, especially in the lower sections of the drainages. Unfortunately, the city of Phoenix encroached on most of the northern flank of SMCC, making it impossible to trace profiles continuously to the Salt River in the area where we would predict the greatest divergence between terrace and wash. This explanation would predict that the

middle sections would show roughly parallel profiles of wash and terrace, and that the uppermost part of the profile would begin to merge. The portion of the Javelina T2 terrace and channel available for dGPS surveying is consistent with a lateral shift of the Salt River. Longitudinal profiles of the Javelina Terrace and its modern channel in South Mountain reveal roughly parallel profiles that appear to coalesce in the upstream direction (**fig. 23**).
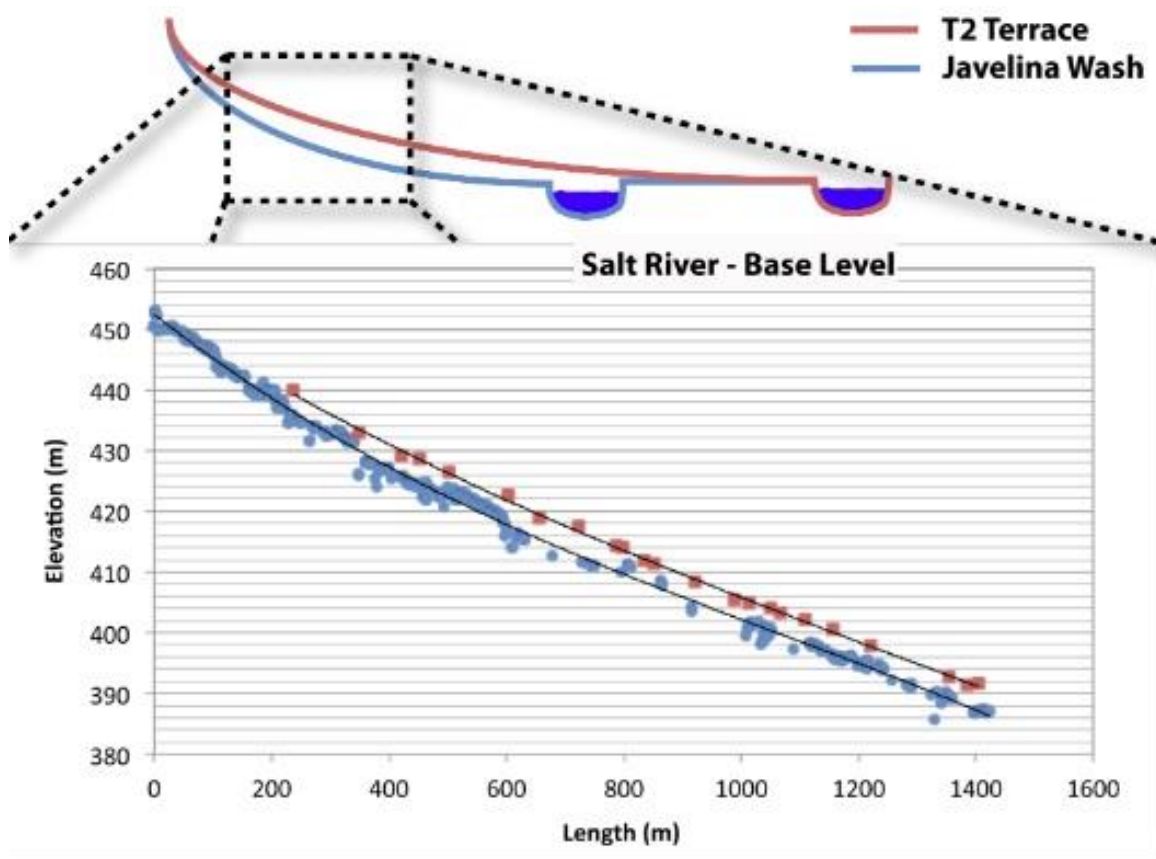
Fig. 23. A shift in the position of the Salt River towards South Mountain could explain the observed longitudinal profiles, exemplified here for Javelina Canyon.

Incision of the Salt River, or its lateral shift closer to South Mountain, are both consistent with the observed asynchrony of the oldest terraces on the north and south sides of the range. Piracy Canyon drains south towards the Gila River (**fig. 2 and 9A**).

Javelina, Pima, and Beverly canyons drain north to the Salt River (**fig. 2 and 9B**). The T2 terraces of the south and north draining canyons do not have the same age, which is consistent with the notion that changes to the Salt River would not have influenced Piracy Canyon's behavior.

The next strath incision event observed at SMCC resulted in the T2 terrace of Piracy Canyon (**fig. 19; table 3**), falling in the broad time range between 24 and 16.5 ka. The basal layer of varnish on the T2 terrace at Piracy Canyon has the LU-3 VML pattern that falls between Heinrich Events 2 and 1. This same minimum age is found on the most extensive abandoned alluvial fan deposits in the western portion of SMCC (Dorn, 2010; Moore and others, 2012). While a major climatic or meteorological event could have led to incision at Piracy Canyon (and the alluvial fans on the western end of South Mountain), there exists no evidence in either the available pollen or packrat midden literature that a major climatic change — wet, dry, transition from wet to dry or from dry to wet —clearly correlated with the T2 incision at Piracy Canyon.

The pollen and packrat midden evidence for the Sonoran Desert and adjacent uplands suggests the region was cooler and wetter during this time frame (Van Devender, 1990; Anderson and Shafer, 1991; Anderson and others, 2000; Lozano-García and others, 2002). Pollen records in northern Baja California remained similar from 44 to 13 ka —a combination of pines, junipers and sagebrush in that area indicating more humid and cooler conditions (Lozano-García and others, 2002). This is consistent with pollen records from Potato lake on the Mogollon Rim, Arizona (Anderson and Shafer, 1991) a mixed forest of Engelmann Spruce and other conifers existed from 35 to 21 ka indicating a climate that was as much as 5°C degrees cooler than modern; cooling was even more

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pronounced 21 – 10.4 ka when Engelmann Spruce dominated (Anderson and Shafer, 1991). Packrat midden sequences in the Sonoran Desert suggest that dwarf conifer vegetation of Juniper osteosperma and Pinus monophylla grew in the lower Sonoran Desert with elevations similar to South Mountain in this same late Pleistocene time range (Van Devender, 1990; Allen and others, 1998; McAuliffe and Van Devender, 1998). Thus, the paleoclimatic data available this region between 24 and 16.5 does not contain evidence of a major change that could explain the incision into the T2 terrace at Piracy Canyon. It is more likely that incision is the result of ongoing knickpoint propagation following stream capture.

The third observed strath incision event took place before ~4.1 ka recorded by the WH5 VML pattern (**figs. 19; table 3**). The T1 strath terraces at Pima and Piracy Canyons have the same minimum age. The 4.1 ka time frame corresponds to proposed episodes of enhanced flooding in the Southwest from 4550-3320 cal BP (Harden and others, 2010). A climatic control would be consistent with penecontemporaneous incision of drainages flowing towards the Salt (Pima) and the Gila (Piracy Canyon) Rivers.

The youngest strath incision event took place towards the end of the Little Ice Age (**fig. 20; table 3**). If ongoing adjustment of Piracy Canyon's topographic profile has been very inefficient, it is possible the Little Ice Event could be caused by headward migration of a knickpoint retreating upstream. Still, the relative youth of this terrace makes us extremely skeptical of a mechanism related to drainage evolution. We think it more likely that this minor incision relates to climatic oscillations. A period of intense regional flooding at 300 cal BP in the southwestern USA may be the mechanism of this incision (Harden and others, 2010). This period also corresponds to incision along the

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Salt River between 940 cal BP and 300 cal BP (Huckleberry and others, 2012).

In summary, the various incision events causing strath abandonment at South Mountain have no clear cause. Longitudinal profile adjustments from intrinsic changes in a drainage, base level change, and climatic change could be invoked for different terrace-forming events. However, we have not found compelling evidence to explain any strath terrace.

Connection South Mountain and other drainages within the Basin and Range.– The two proposed mechanisms of strath formation at South Mountain may have broader implications for future fluvial research in metamorphic core complexes, as well as granitic terrains within the broader Basin and Range province.

The tendency of granitic rocks to undergo grussification (Isherwood and Street, 1976) and to develop pediments in arid climates (Dohrenwend, 1984; Dohrenwend and Parsons, 2009) suggests that the proposed erosional asymmetry mechanism of greater bank erosion in the decayed granite would not be unique to metamorphic core complexes. It may be a process facilitating strath widening in any arid Basin and Range drainage underlain by granitic lithologies. In particular, the occurrence of isolated strath terraces (for example, **fig. 10**) could be a product of the way that granite decays; accidental exposure (cf. Warhaftig, 1965) of the subsurface weathering front creates a fresh granitic channel bottom that facilitates strath widening at the expense of decayed granite along channel banks (**fig. 4**). Anecdotally, we have observed spatially sporadic granitic straths in small and large drainages throughout central Arizona — a research agenda beyond the scope of this paper.

Drainage capture events within drainages facilitate strath formation from

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increases in drainage area after capture (Garcia, 2006; Stamm and others, in Press). The research conducted at South Mountain documents the first known case of aggradational piracy leading to strath formation in a small desert drainage. Since South Mountain is a metamorphic core complex (MCC) undergoing extensive drainage piracy as a part of its drainage evolution (Pain, 1985; Pain, 1986; Spencer, 2000; Douglass, 2012), it is distinctly possible that small deserts drainages in other MCCs could similarly contain straths and strath terraces.

CONCLUSION

Nearly 40 years ago Asher P. Schick (1974) challenged desert and fluvial geomorphologists to develop a better understanding of terraces in small arid watersheds; in the intervening four decades research has largely been lacking on strath terrace development along small desert washes. This study, thus, analyzes the formation of strath terraces in small watersheds (<5 km^2) within an isolated mountain range of South Mountain in the Basin and Range province of central Arizona. Two proposed mechanism facilitate strath formation within these watersheds – 1) aggradational piracy and 2) an asymmetry of erosion in ephemeral channels underlain by granitic lithologies.

Aggradational piracy occurs within low-elevation drainages flowing across the margins of the South Mountain metamorphic core complex (MCC). Fan aggradation derived from sediment transport off the flanks of the range raises the bed of these marginal drainages. Subsequently, the marginal drainages overtop their constraining ranges at the lowest point and are captured. The increase in drainage area after capture facilitates strath carving downstream of the point of capture. Headward propagating knickpoints abandon strath floodplains behind the point of capture as the longitudinal

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profiles adjusts to capture. Since MCCs occur widely in the desert southwestern USA, we think it unlikely that South Mountain is unique in drainage capture generating straths in small arid drainages.

An asymmetry of erosion in the ephemeral channels of South Mountain results from more highly decayed granitic rocks exposed on the channel banks as compared to largely fresh granitc rocks of the channel floor. The asymmetry exists as a result of the bounding pediment weathering mantle 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 think that the process of strath formation by erosional asymmetry should be widespread in places like the Sonoran and Mojave Deserts.

Chapter 4

THE INFLUENCE OF BASE LEVEL LOWERING ON GRANITIC ROCK PEDIMENT DEVELOPMENT

ABSTRACT.   The scholarly research on granitic rock pediments includes very little discussion on the role base level fluctuations. This study investigates the controls of base level on granitic rock pediments flanking inselberg mountain ranges in south-central, Arizona. When base level is lowered, terrace incision occurs and pediments respond by regrading to strath floodplains of the Salt and Verde rivers. Pediments regrade through different mechanisms working in concert: headward erosion; stream piracy; and lateral migration. Headward erosion of pediment drainages begin at the base of the pediment in response to base level lowering. The largest drainages erode headward more efficiently and create a local base level on the pediment surface. The largest pediments respond with the greatest erosion rate (averaging ~90mm/ka) while the smallest pediments have erosion rates an order of magnitude lower (~ 7-8mm/ka). Tributaries retreating from these master drainages incise into the remnant pediment surfaces and can capture pediment streams on the former surface. Stream piracy processes resulting from headward eroding drainages work to increase drainage area of the capturing stream and lowering the relict pediment surface over time. Finally, lateral erosion occurs predominantly in the distal reach of the master pediment drainges. It also occurs when large

pediment drainages converge, suggesting a drainage area relationship facilitating lateral erosion. Each of these processes resulting in planation down to a new pediment surface adjusted to a lowered base level.

INTRODUCTION

William Morris Davis helped found the Association of American Geographers (AAG) and was its first president in 1904 and 1905 (Daly 1944). Davis' initial and most extensive research focused on the importance of base-level change (Powell 1875) in setting off a "cycle of erosion" (Davis 1902, Davis and Snyder 1898). Later in his life Davis developed a fascination with granitic rock pediments as a desert landform (**fig. 1**) and their development (Davis 1933). Ironically, base-level change was one of the few potential factors affecting pediments not addressed by Davis (1933). For more than 100 years, AAG journals have published numerous papers on pediments and related processes (Twidale and Mueller 1988, Friend 2000, Von Engeln et al. 1940, Meyerhoff 1940, Ongley 1974, Tuan 1962, Rahn 1967, Tator 1952, Tator 1953, Ruhe 1964), but with little concern over the influence of base-level change. Similarly, the role of base level has received very little examination in the larger pediment literature; the only explicit attention relates to the numerical modeling research of Strudley et al., (2006) and Strudley and Murray (2007).

Figure 1. The Bush pediment, grading to the modern-day Salt River in central Arizona, presents the classic rock pediment form described throughout the literature. However, this field site demonstrates that the Bush pediment once graded to several different base levels in the past: T4 (Stewart Mountain terrace, age unknown), T3 (Sawik terrace, age > 1.2 ma), T2 (Mesa terrace, age ca. 440 ka), and T1 (Blue point terrace, age ca. 33 ka).

In this chapter, I postulate that base level lowering can play a vital role in granitic rock pediment development. I formally address the following questions:

1. What landforms characterize granitic rock pediments in central Arizona, where substantial base-level lowering has taken place in the last half-million years?
2. What factors influence pediment adjustment to base-level lowering?
3. What processes appear to be involved in pediment adjustment to base-level lowering?
4. How does this case study of base-level lowering shed light on prior theoretical discussions about pediments?

I posit that granitic rock pediments are not landforms 'inherited' from a past wet climate, as advocated by many. Rather, granitic rock pediments actively adjust to base-level lowering, displaying a wide array of landforms associated with processes of stripping the former pediment mantle, regolith carbonate, and tors. Then, after a period of active erosion, the graded pediment form develops — all during the Quaternary period of relative aridity, as opposed to a wet tropical climate during some period in the Tertiary.

This research also tests the modeling result that pediments respond to base level incision (Strudley and Murray 2007, Strudley, Murray and Haff 2006), but I propose they will regrade when base level is stable in a cyclical process tied to strath floodplains and the major river controlling basin wide base level. I further posit that lateral erosion by pediment drainages and headward drainage piracy on the pediment surface (Cooke, Warren and Goudie 1993, Gilbert 1877, Howard 1942, Johnson 1932, Sharp 1940, Rahn 1967, Warnke 1969) play a significant role in the process of pediment regrading. The next section briefly summarizes the pediment literature, revealing the need to evaluate role of base level change.

THEORETICAL BACKGROUND

G.K. Gilbert analyzed planation surfaces in the Henry Mountains, Utah (1877). Ever since, geomorphologists have exhibited a fascination over the pediment landform of beveled bedrock (**fig. 1**) and it's genesis (for example, Twidale 1981, Oberlander 1989, Dohrenwend 1994, Dohrenwend and Parsons 2009, Twidale 1978b, Oberlander 1997, King 1953, Whitaker 1979, Cooke and Warren 1973, Tator 1952, Tuan 1959, Birot and Dresch 1966, Weise 1978). Despite an expansive body of work, last thoroughly reviewed by Dohrenwend and Parsons (2009), pediment formation remains unclear. Oberlander (1989: p. 56) and Nichols et al. (2002: p. 122) call this uncertainty the 'pediment problem'.

As with most lengthy academic debates, classification systems vary (Cooke and Mason 1973, Bourne and Twidale 1998, Twidale 1982, Oberlander 1989), which tends to cloud discussions. Pediment types include: apron pediments (Cooke and Warren 1973,

Cooke 1970); pediment domes (Davis 1933), exposed crystalline rock pediments (Twidale 1978a); mantled pediments, allochthonous debris-covered pediments (Twidale 1982, Twidale 1983, Bourne and Twidale 1998); terrace pediments (Cooke and Warren 1973, Plakht, Patyk-Kara and Gorelikova 2000); and rock pediments that have a uniform lithology with the mountain front (Oberlander 1989, Oberlander 1997).

In particular, this research focuses on the classic (Davis, 1933) "rock pediment" form (**fig. 1**) (Oberlander, 1989; Pelletier, 2010) that is a low gradient ($<0.2\degree - 11.3\degree$, Strudley and Murray 2007) piedmont. While fluvial transport dominates, pediments host only relatively (Applegarth 2004) thin (max 2-4m, Strudley and Murray 2007) veneers of alluvium. While they develop in a variety of climatic and lithologic conditions (Oberlander 1989, Dohrenwend and Parsons 2009, Ritter, Kochel and Miller 2002, Twidale 1982, Strudley and Murray 2007, Pelletier 2010, Cooke 1970), the granitic pediments explored here are found in region explored in the classic literature: the Sonoran Desert.

An abundance of core concepts have emerged in the thirteen decades of pediment scholarship. **table 1** assembles many of key ideas debated in the granitic rock pediment literature. In summary, pediments are fluvial transport surfaces that balance sediment supply and transport. Granitic rock pediments exist between small ranges (inselbergs) and a local base level (**fig. 2**). They tend to occur in regions of relative tectonic quiescence or where vertical erosion rates roughly equal uplift or isostatic rebound. A dramatic slope break exists at the inselberg-pediment interface, and some argue that this piedmont junction is a relic of formation during a wetter period of time. Still others present compelling evidence of active processes operating on inselberg debris slopes supplying

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sediment to the top of the pediment, and that the sudden slope break results from the

particle-size transition from large spheroidally weathered boulders on inselberg slopes to

sandy grus on the pediment. Early scholars tended to favor sheet flooding or lateral

stream migration as beveling processes, while researchers in the latter half of the 20th

century stressed the importance of subsurface weathering at the base of the inselberg in a

moist (non-desert_ climate as a basic cause of the sudden slope break.
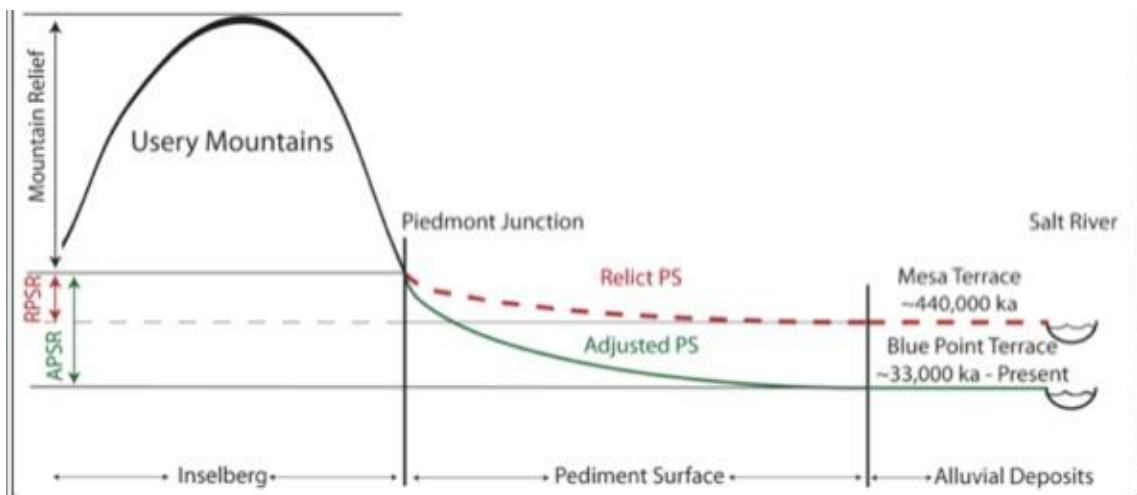
Fig. 2. Pediment surfaces exist in a continuum of associated landforms (Dohrenwend and Parsons, 2009). In the field context of this study (**fig. 1**), a former pediment surface once graded to the Mesa strath terrace level ~440ka. The adjusted pediment has since regraded to the Blue Point strath terrace that was abandoned ~33ka. Thus, we add the concept of a relict pediment surface (RPSR) and adjusted pediment surface (APSR).

TABLE 1
Core concepts discussed in scholarship on rock pediments.

Concept	Brief Explanation
Balancing sediment supply and transport	Pediments display a balance between critical power and stream power (Bull 1979), that may be necessary to maintain the pediment form (Cooke and Warren 1973). For example, a high sediment supply may sufficiently bury the erosional pediment surface (Applegarth, 2004) to the point where it can no longer be classified as a pediment (Pelletier 2010). Pediments tend to occur where relatively small catchments exist (Applegarth,

	2004), and this is likely relates to a sediment transport/supply relationship (Dohrenwend and Parsons 2009).
Stability-Steady State	The common perception is that extensive pedimentation requires vertical stability or relative tectonic quiescence (Dohrenwend 1994, Pelletier 2010, Dohrenwend and Parsons 2009, Dohrenwend et al. 1991, Dohrenwend et al. 1996, Blackwelder 1929). The issue of base level has received attention in recent modeling research (Strudley and Murray 2007, Strudley et al. 2006), however little is discussed regarding pediment response to progressive fluctuations in base level. Many researchers (Dohrenwend, 1994; Pelletier, 2010; Dohrenwend and Parsons, 2009; Dohrenwend et al., 1991; Dohrenwend et al., 1996; Blackwelder, 1929) point to geomorphic stability as necessary for pediments to form, thus it must be implied that base level and tectonics must be stable for pediments to form.
	In a steady state condition, vertical erosion roughly equals uplift or isostatic rebound (for example, Pazzaglia 2013). This relationship is consistent with the spatial distribution of pediments within the Basin and Range — predominantly bounding smaller, low relief ranges with small drainage areas (Lustig 1969). This contrasts with ranges of relief that host depositional piedmonts of alluvial fans (Pelletier 2010, Bull 1977, Bull and McFadden 1977).
Hillslope/Hydraulic Processes	In granitic lithologies, weathering produces bimodal detritus within the pediment association and this relationship may explain the sharp contrast in slope at the piedmont junction – hillslopes will break down into boulders, thus requiring a steep slope for transport, while the pediments weather into grus (or sand) sized sediment requiring a low slope for transport. Abundant research has shown that processes acting on the hillslopes and mountain mass are active processes (Parsons and Abrahams 1987, Parsons and Abrahams 1984)
Inselberg-Pediment Linkage	Many pediment formation models connect processes of degradation in the mountain mass and pediment development (Dohrenwend and Parsons 2009) because of the abrupt change in angle at the mountain front. Some suggest the problem lies in understanding 'parallel rectilinear slope retreat' (Oberlander 1989). Although linear mountain fronts exist in some locations, most mountain fronts undulate as a result of the varying degree of drainage development within the mountain mass and pediment (Parsons and Abrahams 1984). Furthermore, the sinuosity of the mountain front increases with time in a geomorphically stable system (Bull and McFadden 1977).
Isostacy	The idea of exhumation of a suballuvial bench (Paige 1912, Lawson 1915, Cooke 1970) has been recently rejuvenated by

	(Pelletier 2010) invoking flexural-isostatic uplift as an explanation for the tilting involved in pediment exhumation around the pediment/inselberg boundary.
Lateral migration of streams	Those favoring beveling of the pediment surface via erosion of laterally migrating streams (Gilbert 1877, Johnson 1932, Howard 1942, Warnke 1969, Sharp 1940, Johnson 1931) often point to sheet floods (Howard 1942), weathering, rain splash, and rill wash (Johnson 1932) that erode the mountain front (Parsons and Abrahams 1984). Still others argue that rectilinear escarpments cannot be explained by this process (e.g. Ruxton 1958, Ruxton and Berry 1957, Mabbutt 1966), because lateral erosion would require streams to flow parallel the piedmont junction (Lustig 1969, Strudley et al. 2006, Pelletier 2010, Ritter et al. 2002) and cannot explain the distinct piedmont angle (Oberlander 1989). While it is 'unrealistic' (Cooke and Warren 1973) that lateral erosion is an exclusive process (Parsons and Abrahams 1984), the anastomosing to braided nature of many pediment channels could have a laterally erosive effect, especially in an erodible substrate (Denny 1967, Sharp 1940).
Pediment Association	Cooke (1970) and Dohrenwend and Parsons (2009) note that pediments exist in a continuum of associated landforms (**fig. 2**), where they typically exist in the zone of fluvial transport (Dohrenwend 1994, Strudley et al. 2006).
Pediment mantles	Mantles of decayed granitic material and soils can extend up to a few meters in depth on active pediment surfaces. Mantles have a fairly planar surface, but the contact with bedrock is usually irregular suggesting differential subsurface weathering (Cooke and Warren 1973, Mabbutt 1966). Numerical modeling (Strudley and Murray 2007, Strudley et al. 2006) applied Heimsath et al's soil production models (Heimsath et al. 2000, Heimsath et al. 1999) suggests that mantles are in an equilibrium where erosion rates, soil production, and bedrock weathering are in balance. The rate of bedrock weathering is inversely proportional to soil production; where bedrock weathering is greatest with thin soil. In this model, pediments form when an appropriately thin soil is present. Any shift from this equilibrium would result in deviation from the pediment form.
Piedmont Junction	A large body of research focuses on the piedmont junction (**fig. 2**) in an attempt to determine how pediments extend and mountains degrade over time (e.g. Ruxton 1958, Ruxton and Berry 1957, Twidale 1967, Twidale 1968, Mabbutt 1966, Kirkby and Kirkby 1974, Denny 1967, Selby 1982, Parsons and Abrahams 1984). Working in badlands, Schumm (1962) found that the piedmont junction is not a zone of deposition and that the slopes of the mountain front and pediment are able to transport the supplied

	sediment size; the pediment extends as the steep upland slope retreats. Similar processes may work in granitic lithologies (Cooke and Warren 1973). Granitic rocks tend to form a distinct, sharp increase in slope where the pediment meets the inselberg mountain front. This thin zone of drastically increased slope could be a function of structural and lithologic controls (Denny 1967, Twidale 1967, Cooke and Reeves 1972).
Relict form	Many have suggested that pediments and associated landscapes are forms inherited from previous periods of different climatic/geomorphic regimes (Oberlander 1989, Oberlander 1972, Oberlander 1974, Mabbutt 1965, Moss 1977). Oberlander (1989), for example, argued that Mojave and Sonoran Desert pediments primarily formed under Miocene vegetative and climatic regimes (Oberlander 1974). Quaternary periods of aridity then stripped a former cover of soil and regolith, exposing the pediment erosion surface and tors.
Sheet flooding	Early researchers emphasized the role of sheet flooding (McGee 1897, Davis 1938, King 1949), where this process may be a consequence of the pediment rather than its cause (Cooke and Warren 1973, Lustig 1969, Rahn 1967).
Subsurface weathering	Enhanced subsurface weathering at the piedmont junction may aid slope retreat (e.g. Twidale 1968, Twidale 1967, Mabbutt 1965, Mabbutt 1966). Some argue that enhanced rock decay at the base of the inselberg is a primary pediment forming process (e.g. Twidale 1968, Twidale 1967, Mabbutt 1965, Mabbutt 1966, Bryan 1925).

Given disparate observations from a wide variety locations (**table 1**), no single

formative model seems to apply to all granitic rock pediments. Thus, our approach starts

with the premise that location-dependent factors could yield new insight into pediment

processes. In particular, we work in the classic arid climate of the Sonoran Desert, with

the classic granitic lithology, and in a classic geological setting of tectonic quiescence in

central Arizona. What we vary is base level — a topic only previously explored in

numeral modeling (Strudley and Murray 2007, Strudley et al. 2006). Certainly, many

prior pediment studies note the occurrence of "incised pediments" (e.g. Davis 1933,

Oberlander 1989, Tuan 1962, Dohrenwend and Parsons 2009, Young 1992, Amoroso and

Miller 2012), but the connection between incised pediments and base-level change has not yet received systemic study in the rock pediment literature.

SETTING OF THE STUDY AREA

The purpose of this section is to provide an overview of the geological history near the junction of the Salt and Verde rivers. This history is speculative, because it is based on preliminary research. Still, this background sets the stage for the base level change that is being studied here.

Central Arizona, near the junction of the Salt River and Verde River (**fig. 3**), formerly hosted the Pemberton closed basin with extensive playa deposits that intercalate red clays and gypsum (Pope 1974, Skotnicki et al. 2003). The Pemberton basin originated from Basin and Range faulting that terminated approximately eight million years ago. Still, the basin remained closed throughout the Miocene and Pliocene as alluvial-fan deposits debouching from the Mazatzal Mountains deposited at rates faster than playa aggradation (**fig. 3**). Thus, the Pemberton playa formed the original base level of the eastern McDowell and Usery pediments.
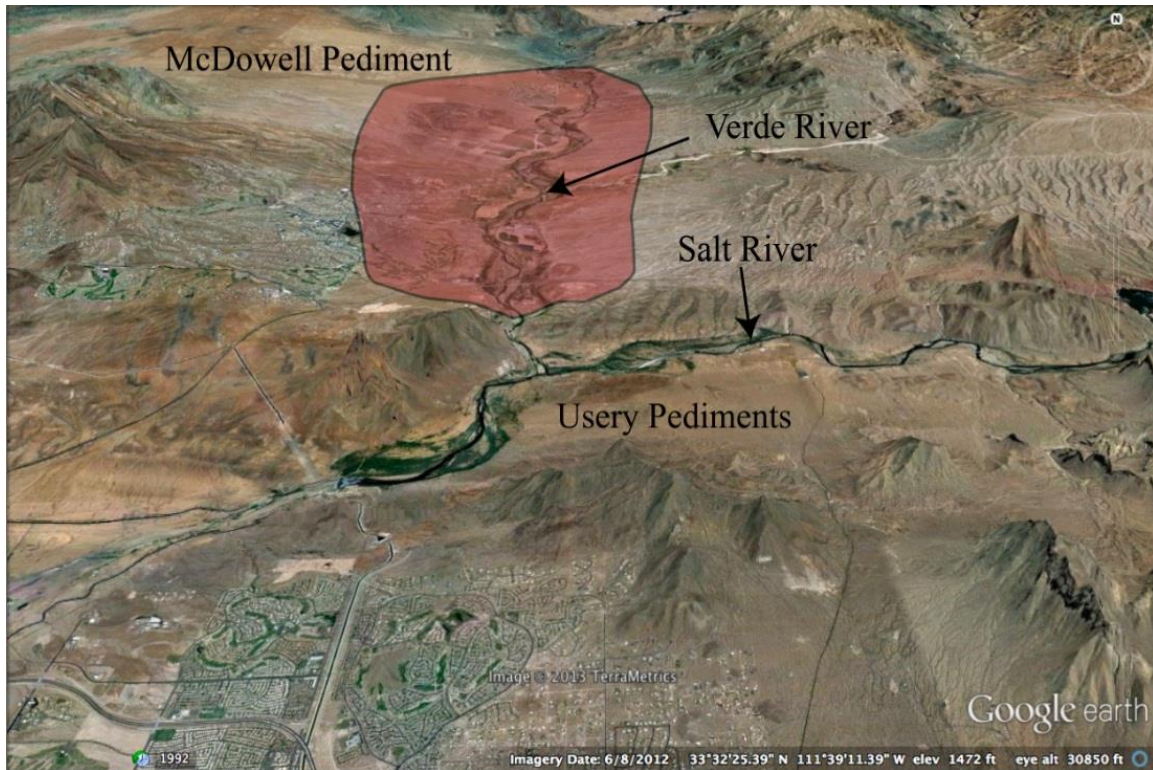
Fig. 3. The Salt and Verde watersheds supply a major portion of the water supply for metroPhoenix. The two incising pediment systems are just upstream of the junction of these rivers. The Usery Mountain pediments are to the south of the Salt River, and the McDowell Mountains pediment is to the west of the Verde River. The Pemberton playa shifted in position as it slowly accumulated in a closed basin created by Basin and Range faulting, but most of the red clays of the Pemberton formation can be found in the shaded area. Sediments deriving from the Matazal Mountains in the east dominated the basin's sediment budget — pushing the playa towards the McDowell Mountains and closing off the basin's southern side.

The sill of the Pemberton closed basin breached when a paleolake in the position of present-day Tonto Basin overflowed (Douglass et al. 2009a, Douglass et al. 2009b). Subsequent knickpoint recession and excavation of sediment resulted in aggradation of the massive Stewart Mountain terrace of the Salt River (Larson et al. 2010). The timing of this overflow event that produced an integrated the Salt River is not known, although it before the >1.2 ma aged Sawik Terrace of the Salt River (Larson et al. 2010).

The Salt River's integration dramatically changed the composition of sediment accumulating in Phoenix, according to research near the Phoenix airport.

"The contact between the Salt River Gravels and the underlying basin fill is generally very sharp in the logs, cores, and cuttings… There is a surprising lack of soil development along the contact, which can be explained by (1) no large age difference between the two units, or (2) scouring of the contact by the Salt River prior to deposition of the lowest Salt River Gravels" (Reynolds and Bartlett 2002).

The lake overflow model (Douglass et al. 2009a, Douglass et al. 2009b) would be consistent with a scouring event by a newly formed Salt River, following by deposition of the observed gravels.

Integration of the Salt River dropped the base level of piedmont washes flowing into the Salt River from the Usery Mountains. Usery-sourced washes first adjusted to the base level of the >1.2 ma aged Sawik terrace (**fig. 1**). At the same time, lowering of the Salt River resulted in dissection of the Pemberton Playa by local washes derived from the eastern McDowell Mountains. That incision continued until the Lousley Hills gravels were deposited on top of the eroding playa (**fig. 4**). Gravels derived from the eastern McDowell Mountains then deposited on top of the truncated playa, in response to the sudden rise in base level to the level of the Lousley Hills. **Figure 5** illustrates a location west of the Lousley Hills along Stoneman Wash (see **fig. 4**), where gravels were sampled for cosmogenic burial dating.

Fig. 4. The lower Verde River displays a complex sequence of events. First, the playa sediments eroded in response to integration of the Salt River (white line). Second, the Lousley Hills gravels deposited — forming a fill terrace. Third, gravels derived from the McDowell Mountains began to accumulate behind the Lousley Hills terrace. Fourth, transverse drainages crossed the Lousley Hills terrace. Fifth, these drainages adjusted to the Mesa River terrace (identified by M), and the eastern McDowell pediment graded to this terrace. Then lowering of the Verde river resulted in a pediment that is undergoing erosion due to knickpoint recession of washes (identified by white arrows).

Fig. 5. The top of the Pemberton playa deposit is now an unconformity, where locally derived gravels preserve the landscape after the Lousley Hills terrace raised the base level of these washes. This is a collection site for burial cosmogenic nuclide dating, where the truncated top of the playa sediment is informally named the "Pewe Surface".

Cosmogenic burial dating samples along the Verde River reveal some insight into the timing of events, even though these ages are preliminary. The gravels collected at **figure 5** at ~1.3 ma (**fig. 6**) reflect a McDowell Mountains-derived drainage that is undergoing active incision in response to lowering of the Verde River's base level. Larson et al. (2010) speculated that the Sawik Terrace's >1.2 ma age does not reflect a stable base level, but rather ongoing incision of the Salt River. Thus, it is possible that as the Salt River incised during "Sawik time", the Verde responded in turn — and the ~1.3 ma age for the Pewe Surface gravels (**fig. 6**) provides a minimum age for Lousley Hills deposition and also this ongoing adjustment to the lowering base level of the Salt River.
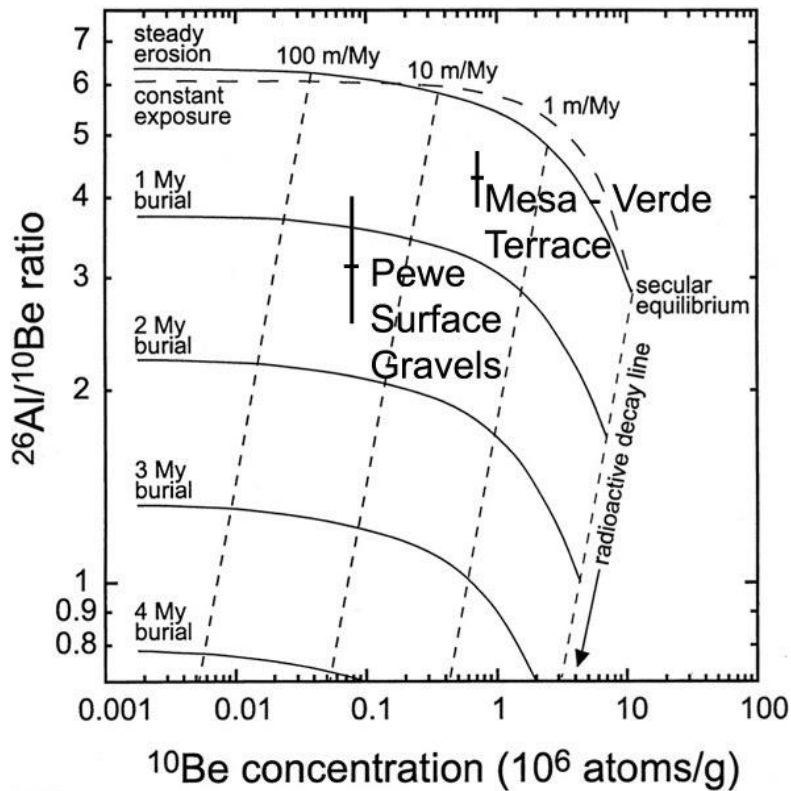
Fig. 6. Burial dating ages for the Pewe Surface gravels (see **fig. 5** and Mesa terrace gravels (**fig. 4**). These ages are preliminary.

In summary, the gradual base level lowering of the Salt River from the Stewart Mountain terrace to the Sawik terrace and then to the Mesa terrace (**fig. 1**) resulted in a corresponding lowering of the base level of the Verde River eventually to the Mesa terrace equivalent (**fig. 4**). This period of adjustment to the strath floodplain appears to have been sometime between ~1.3 ma and the ca. 440 ka age for the Mesa terrace. **Figure 7** diagrams this adjustment along both the Verde and Salt rivers.

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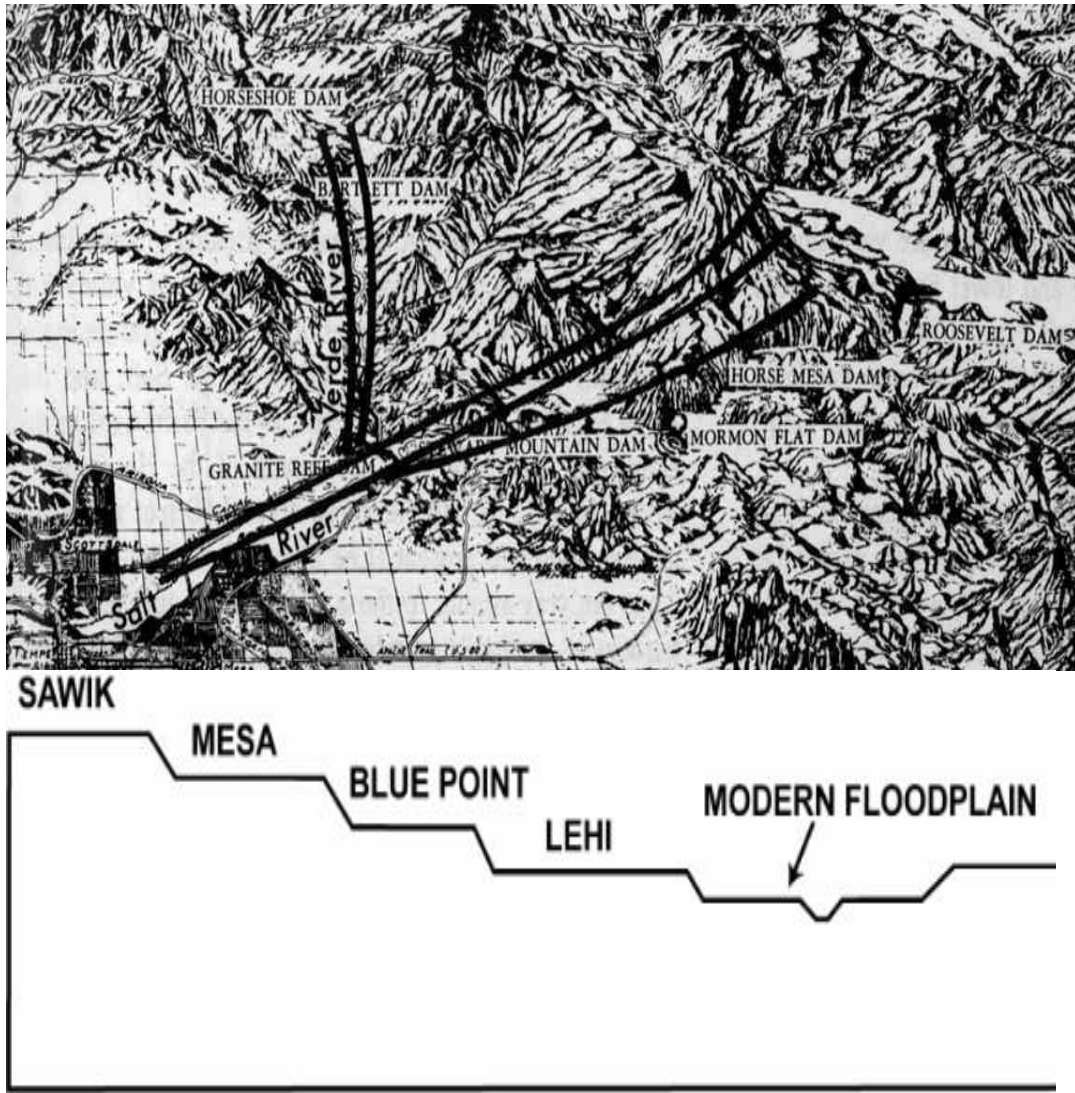
Fig. 7. A physiographic diagram produced by the Salt River Project, on which Péwé (1978) indicated the three strath terraces of Sawik, Mesa, and Blue Point along the Salt River. Two terraces were drawn for the Verde River. Note that Péwé pinches out the Blue Point terrace in east Mesa, Arizona. The lower diagram shows the idealized Salt River terrace system as envisioned by Péwé (1978).

Pewe (1978) suggested that the Salt River's Mesa terrace (~440 ka) represented a long-term period of base level stability for local tributaries and bounding pediments (Larson et al. 2010). I agree that the Salt River system reached the level of the Mesa terrace fairly quickly, because the basin fill— derived from the Matzatzal Mountains — consists of fanglomerate gravels that have very little cementation.

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Thus, it is possible that the pediments of the eastern McDowell Mountains (**fig. 8**) and Usery Mountains (**fig. 9**) had several hundreds of thousands of years to adjust to the base level of what is now the Mesa river terrace. Thus, the starting point for the research presented here is formation of the pediments that are graded to the Mesa river terrace level (e.g. Mesa pediment in **fig. 9**).

Pewe's (1978) sequence of Salt River terraces (**fig. 7**) provides a record of episodic incision and periodic base level stability as controls for the tributaries flowing into the Salt River basin (Larson et al. 2010, Scarborough 1981). Thus, our test of base level control in this study is tied directly to fluctuations of vertical incision and relative stability in areas with well-established geomorphic relationships. Of particular importance is the relationship between the Mesa terrace and the pediment transition in response to base level lowering to the lower terraces (Blue Point) and the modern floodplain/Lehi terrace. Since the formation of the Mesa terrace the Salt River lowered to the Blue Point terrace level and then again to the Lehi/Modern floodplain.

The Mesa river terrace level was abandoned ca. 440 ka according to ^{36}Cl burial ages for the Mesa terrace of the Salt River (439±63 ka minimum age; Campbell, 1999). The preliminary Al-Be burial age for the Mesa terrace along the Verde River at ca. 500 ka (**fig. 6**) is consistent with the age for the Mesa terrace along the Salt River. This research utilizes the incision event ~ 440 ka that resulted in the abandonment of the Mesa river terrace level down to the Blue Point terrace (**figs. 1 and 7**).

Fig. 8. East McDowell Pediment. The arrows correspond with the arrows in Figure 5. The collection site for the Pewe Surface gravels roughly corresponds with the right arrow.
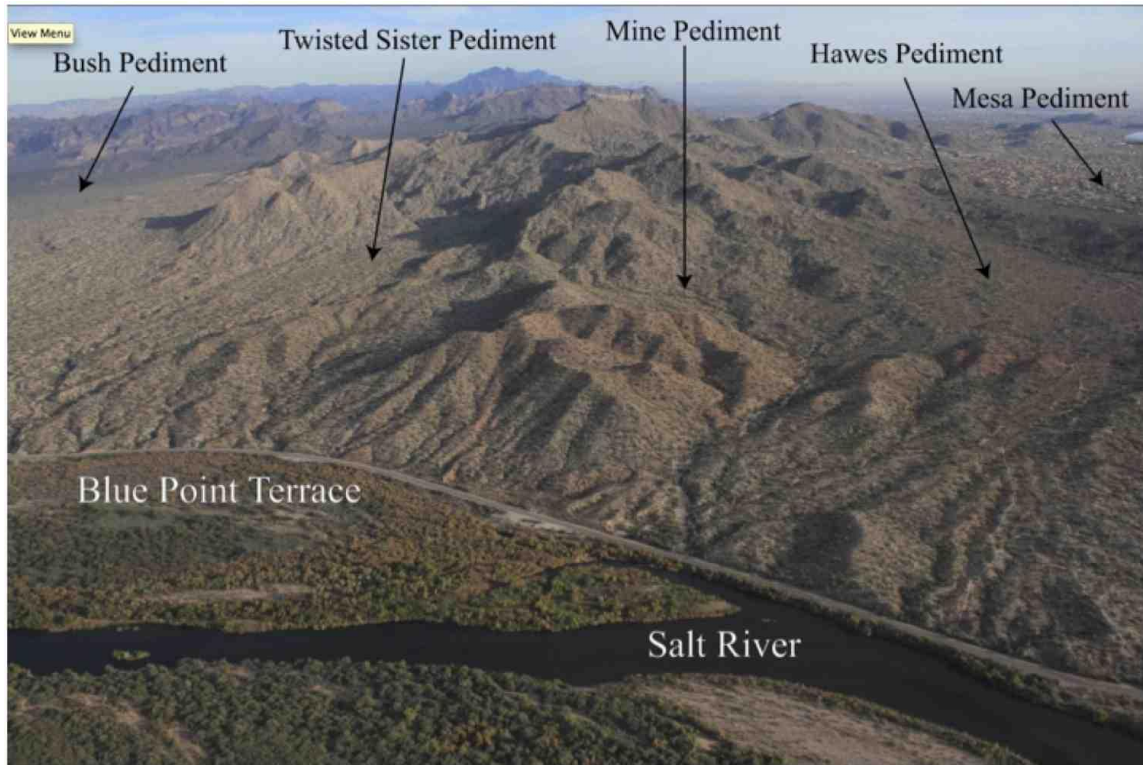
Fig. 9. Low angle aerial photograph of five Usery pediments: Bush, Twisted Sister, Mine, Hawes and Mesa. Note the varied topography on each pediment with varying levels of incision and regrading in response to the base level lowering of the Salt River. The Mesa pediment grades to the Mesa terrace level west of this photograph. The other pediments have responded to the base level lowering of the Salt River and have varying degrees of incision, with the Bush pediment being almost completely regraded to the Blue Point terrace. Also, note the escarpment at the base of the pediments resulting from lateral migration of the Salt River into the pediment basins.

Since this research focuses on the Usery pediments, the basic geology of the

Usery Mountains provides useful background information. The Usery Mountains, an

approximately east-west trending range (Willis 1934), uplifted during late-Cenozoic

extensional orogenic events in Arizona. Although two narrow shear zones exist within

the Usery Mountains, they are relatively simple geologically. Two mineralogically

similar lithologic units of early to middle Proterozoic age dominate the Usery Mountains.

The first is a porphyritic coarse-grained granite to quartz monzonite and the second is a

coarse-grained granite to syenite (Skotnicki and Ferguson 1996). These lithologies form

the majority of the substrate upon which the pediments have developed. In the far distal portions of the Mine and Hawes drainages isolated outcrops of metamorphosed granitic rocks constrain channels.

METHODS

The methods employed in this study occurred in four stages. The first stage identified and delineated four different pediment systems around the Usery Mountains. The second stage documented landforms associated with an eroding granitic pediment system that would provide minimum heights of the pediment graded to the Mesa terrace. The second stage then mapped features that provide minimum elevations of the Mesa pediment system. Third, the relict Mesa pediment systems had to be reconstructed for the different pediments through GIS. The fourth stage measured longitudinal profiles of the different pediment systems. Lastly, volumes of sediment lost between the reconstructed Mesa pediment and the present-day surface allowed calculation of erosion rates for the different pediments around the Usery Mountains.

Identifying and Delineating the Pediment Basins.– Delineating the boundaries between adjacent pediments is not a straight forward task and is fraught with difficulties (Cooke and Warren 1973). This is due to the fact that pediments surrounding a mountain mass can have indistinct boundaries without any clear morphological distinction. Fortunately, the pediment basins in this study (**fig. 9**) tend to have quite clear morphological boundaries. This is because they are incising to adjust to the lowered base level.

Still, for the modern pediment basins in this study we used the suggestion of Cooke and Warren (1973) to map them in relation to the *Pediment Association*. Fluvial

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processes and sediment transport drive this association from the mountain mass to the zone of accumulation, therefore, longitudinal constraints on pediment surface mapping were between the zone of degradation (mountain mass) and zone of aggradation (base level). Latitudinal boundaries were constrained by drainage pattern breaks and morphologic contacts. If sudden hydrologic breaks in pediment wide flow direction existed we would map a boundary at that location. For example, running north and south between the Salt River and Usery Mountains (N 33.52895 W 111.64298), between the Bush and Twisted Sister pediments, an area of high, undulating relief exists from which pediment drainages appear to flow in opposing directions. For lack of a better term, we have described this as a pediment interfluve. This pediment interfluve location delineated the westernmost boundary of the Bush pediment (**fig. 9**).

Documenting Forms Associated with Eroding Pediments.– Since little research on pediments focuses on the influence of base-level change, no prior research has documented the basic sorts of forms associated with eroding granitic pediments. The exception is the numerical modeling work (Strudley and Murray 2007, Strudley et al. 2006) that appropriately uses the exposure of tors as evidence of base level fall.

The identification and documentation of forms associated with eroding pediments involved several very different types of methods: electron microscopy to analyze the nature of carbonate deposits and the characteristics of granitic mineral decay; field observations; and low-angle aerial photography.

The process of sample preparation for imaging with back-scattered electrons (BSE), high resolution transmission electron microscopy (HRTEM), and analysis with energy dispersive X-rays (EDX) started with a polished cross-section. Polished cross-

sections imaged with BSE facilitate an understanding of both carbonate textures and granitic mineral decay, because atomic number is imaged by contrast. EDX helps identify likely minerals through identification of elemental peaks. HRTEM helps understand the detailed nature of mineral decay at the nanoscale.

Fieldwork involved over forty different trips to the McDowell-Verde and Usery-Salt field areas. Fieldwork included the use of dGPS to locate different geomorphic features and measure longitudinal profiles of washes with spatial and vertical resolutions of sub-half meter accuracy. Much of the fieldwork, however involved just thinking about the various geomorphic features and how they might relate to the relict pediment graded to the Mesa terrace and also base level adjustment of the Salt and Verde Rivers. The fieldwork was complemented by low-angle aerial photography that generated a different perspective on field-identified forms.

Reconstructing Paleo-Pediment Surfaces.– Kriging techniques generated the relict pediment surfaces that once graded to the Mesa river terrace, where the ArcGIS Geostatistical Analyst toolbox facilitated clipping of the digitized boundaries of each drainage basin. Kriging techniques generate a continuous surface by using known points of reference and associated attribute values (e.g., elevation), and interpolation values between these known points (Oliver and Webster 1990).

The Mesa river terrace forms the lower boundary of each Mesa-aged reconstructed pediment. Because the Mesa terrace is discontinuous, some pediments required interpolation between terrace remnants. In these cases, Mesa terrace elevations were estimated by using longitudinal slope profile analysis of the Mesa terrace tread and verified by dGPS measurements of the nearest Mesa terrace remnant.

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The remainder of the data used to reconstruct the Mesa-age pediment only provides minimum elevations for the relict surface. This is because remnants of the former pediment were all buried when the Mesa-age pediment was active. For example, remnants of the original pediment mantle have been eroding. In another example, the regolith calcrete forms at the contact between the inselberg and the very top of the pediment mantle — and the regolith calcrete remants mapped in this study formed under a completely eroded pediment mantle. Thus, the reconstructed surface provides only a minimum height for the Mesa-age pediment. This minimum-height reconstruction was generated at a 10 m resolution. This matches the existing digital elevation model (DEM) of the present-day topography.

Several Kriging techniques in ArcGIS Geostatistical Analyst generate different types of surfaces. Each option provides slightly different outputs that would change calculated volumes lost and erosion rates. The goal of the interpolation rested in standardizing interpolation surfaces for all basins to the greatest degree possible. This is to maintain a simplistic model of the relict pediment. Thus, three key criteria had to be met before accepting a surface for later analysis.

1. The surface must represent a minimum erosion rate. This conforms to nature of the evidence.
2. The surface must be as smooth as possible, minimizing unnecessary transverse undulations. This is because the present-day Mesa pediment (**fig. 9**) has a relatively smooth surface. Furthermore, pediments typically have little internal relief ($<0.2°-11.3°$, Strudley and Murray 2007).
3. The surface must minimize areas of volume "gain" between old surface and new. This is because no area should truly have a gain in elevation.

Pediment Longitudinal Profiles.– Pediments are fluvial transport surfaces
(Dohrenwend 1994, Strudley et al. 2006). As such, long profiles can provide useful
insights into fluvial processes (e.g. Merritts, Vincent and Wohl 1994, Pazzaglia, Gardner
and Merritts 1998, Snyder et al. 2000). Thus, longitudinal profiles were created along
transects that bisected both the relict and modern pediment surfaces in all pediment
basins investigated. These profiles were taken from the exact center of the pediment
surface across both the relict and modern DEMs. Data used to generate the longitudinal
profiles came from the modern 10m DEM and relict surface 10m DEM.

Calculating Minimum Erosion Rates.– The first step in calculating minimum
erosion rates for each pediment involved first calculating the volume of material between
the present-day topography and the reconstructed Mesa-age pediment. This volume
would be a minimum value. Then, volume divided by area provides an average minimum
amount of erosion for a pediment system. Lastly, this minimum erosion value is divided
by the age of the Mesa terrace.

Previous research (Campbell 1999) analyzed ^{36}Cl gravels on the surface of a Mesa
terrace remanant and then at depth — revealing a minimum exposure age of 439,000 +/-
63,000. This age is consistent with the Al-Be burial dating age for the Mesa terrace along
the Verde River (**fig. 6**).

Dividing a minimum erosion value in mm by the minimum age for a terrace
yields an erosion rate of mm/ka that requires an error analysis. Certainly, the 2 sigma
error associated with the ^{36}Cl age of ± 63ka (or 14%) should propagate into the overall
erosion rate. Because the reconstructed surface is most certainly below the elevation of
the original Mesa-age pediment, the calculated erosion rate is likely less than the true

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erosion rate. However, the cosmogenic ages are also minimums; thus, since the true age *could be* older, the calculated erosion rate *could* be higher than the true erosion rate. There is no way to know the magnitude of these off-setting effects given available data. Thus, erosion rates are presented with just the error of 14%. However, the true error is larger. I speculate that the erosion rate is probably a minimum, because the cosmogenic age could be correct; however, the reconstructed Mesa-age pediment surface is most definitely lower than the original.

RESULTS

Forms associated with eroding granitic pediments.– The emergence of tors from mantle stripping during readjustment to a lowered base level has been previously identified landform associated with pediment erosion (Strudley et al. 2006). Certainly, tors are ubiquitous in the eastern McDowell pediment (**fig. 8**) and Usery pediments (**fig. 9**) that are undergoing erosion. However, tors can occur well beneath the former pediment surface. Consider the current knickpoint of Stoneman Wash in the eastern McDowell Pediment (**fig. 10**). This knickpoint is retreating into the Mesa-age pediment (**fig. 4, 8, 10A, 10B**). The pediment surrounding this knickpoint still has a mantle of grus sand that is underoing erosion, and stripping of this mantle reveals the presence of tors (**fig. 10C, 10D**). Another reason why tors provide a problematic source of elevation for a paleo-pediment surface is that they can stick out of contemporary pediments adjusted to a base level.

In contrast, the pediment mantle (Mabbutt 1966) of transported and decayed grus (**fig. 10C and 10D**) does provide a reliable minimum height for the paleo-surface. Furthermore, remnants of pediment mantles can stretch for several hundred meters from the base of an inselberg to partway down a pediment (**fig. 11**). This preservation is possible between incising washes, because the sandy nature of the mantle promotes infiltration as opposed to runoff. Thus, where they occur, former pediment mantles provide minimum heights for a paleo-pediment surface.

Geomorphologists working the western USA most commonly associate carbonate accumulates with pedogenesis. In particular, they most often identify stages of calcrete development as a relative age indicator (Gile, Hawley and Grossman 1981). However, there are many other forms of carbonate that occur outside of a pedogenic environment. One particular type of regolith carbonate is particularly useful in reconstructing a paleo-pediment surface; laminar carbonate forms along the contact between the pediment mantle and the bedrock inselberg (**fig. 12**). This laminar regolith carbonate has been preserved in many locations in the eastern McDowell and Usery pediments. However, the best circumstance for pediment reconstruction is where the laminar carbonate reaches its highest extent: right at the base of the inselberg (**fig. 12**).
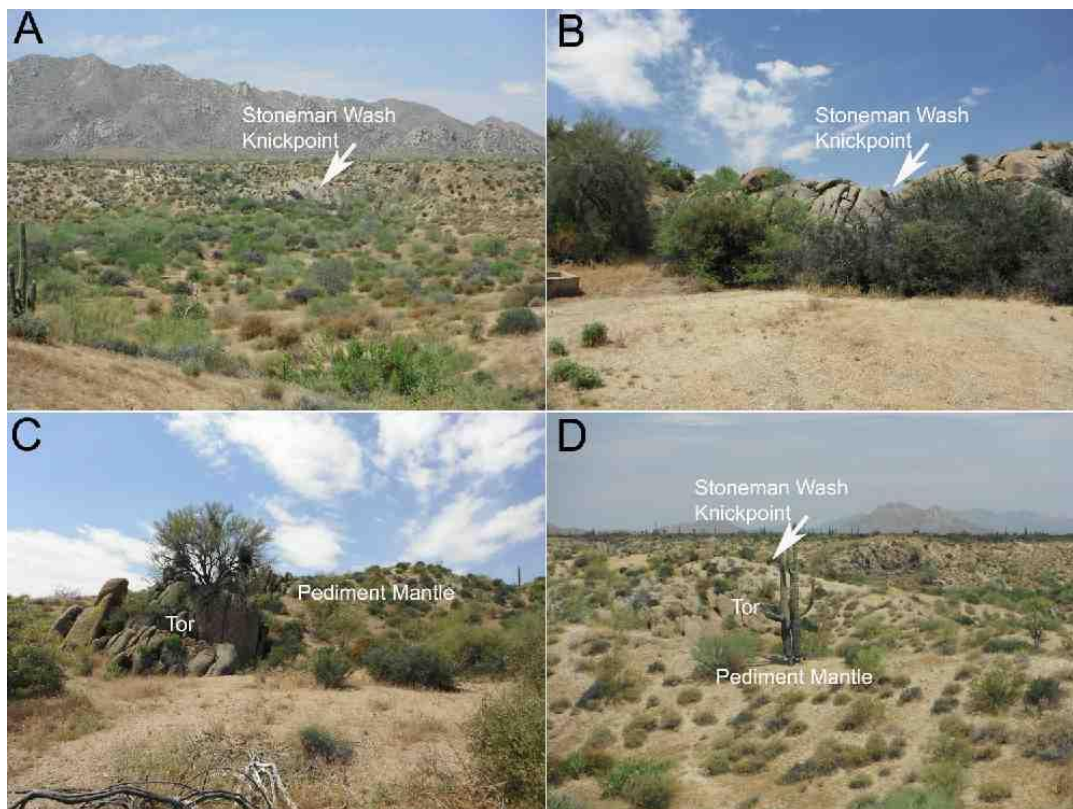
Fig. 10. Stoneman Wash incises into the Mesa-age pediment of the eastern McDowell Mountains. The right arrow in **figures 5 and 9** identify the position of the knickpoint identified in images A, B and D. As the pediment surrounding this knickpoint erodes, the pediment mantle of grus erodes into a series of washes and interfluves. Erosion of this mantle then leads to the exposure of formerly buried tors, as seen in image C.

Fig. 11. The Usery Mine pediment (**Figure 10**) still retains a remnant of its mantle cover. This 4 m thick remnant stretches over 100 m and almost reaches the base of the present-day inselberg.

One particular type of regolith carbonate is particularly useful in reconstructing a paleo-pediment surface; laminar carbonate forms along the contact between the pediment mantle and the backing bedrock inselberg (**Figure 12**). This laminar regolith carbonate has been preserved in many locations in the eastern McDowell and Usery pediments. However, the best circumstance for pediment reconstruction is where the laminar carbonate reaches its highest extent: right at the base of the inselberg (**fig. 12**).

Fig. 12. A remnant of laminar regolith carbonate occurs a few meters north of the remnant of pediment mantle (**fig. 12**). This is at the top of the Usery Mine pediment (**fig. 10**). This laminar carbonate forms where water flowing down the inselberg slope infiltrates into the sandy pediment mantle. Even though the granitic bedrock can be thoroughly decayed, the sandy pediment mantle is much more porous and permeable. Thus, gravity water seeps down to the base of the sandy mantle, and water flows along the mantle-bedrock contact. Laminar carbonate precipitates under these conditions. A remnant of this regolith carbonate can be seen, just above the zone of enhanced decay.

Highly decayed granitic rock is another form associated with an eroding pediment system. Intense zones of decay commonly occur at a current piedmont junction (Twidale 1967, Twidale 1968, Oberlander 1989). Stripping of the former mantle cover exposes this zone of intense decay at the base of an inselberg (e.g. **fig. 12**). In some cases, as in **figure 12**, the laminar regolith carbonate is preserved above this zone of enhance decay. In such circumstances, the regolith carbonate provides a closer minimum elevation for the paleo-pediment. However, sometimes, the regolith carbonate has eroded — leaving behind just the zone of enhanced decay. Of course, these zones of decay are often not preserved, because they are more susceptible to erosion. Thus, where they are seen, they are most often capped and preserved by the laminar regolith carbonate.

In summary, three different forms provide minimum elevations for paleo-pediment reconstruction: the tops of pediment mantles; the highest elevation of an exposure of regolith carbonate at the pediment/inselberg piedmont angle; and zones of enhanced decay at the base of an inselberg. Tors are not used, because they occur both above and well below the surface of a pediment.

Field Mapping Paleo-elevation Indicators.– The use of dGPS and high resolution, low angle aerial photography facilitated detailed mapping of forms that provide minimum elevations of a relict pediment surface. Where pediment mantles are continuous, transects of elevation points could be gathered. However, regolith carbonate occurrences are typically not continuous, resulting in specific points. **Figure 13** provides an example of such mapping for the Twisted Sister pediment. Similar maps exist for the other Usery pediments.
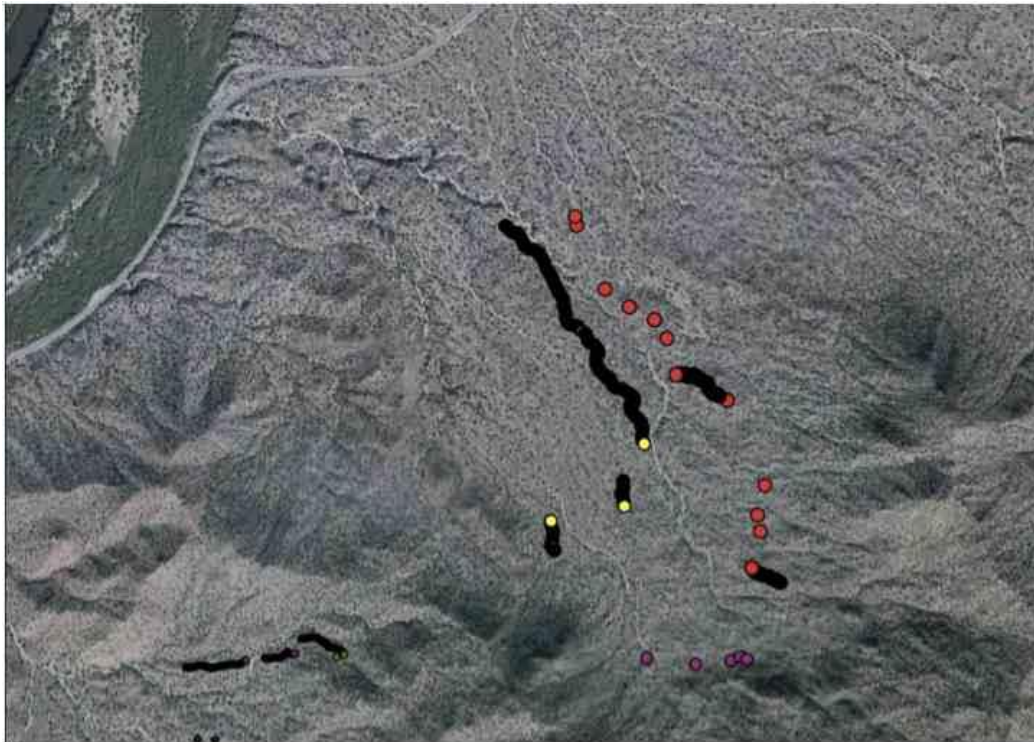
Fig. 13. Points and lines identify locations of regolith carbonate (purple) and pediment mantle (red and yellow) sites in the Twisted Sister pediment. The present-day Salt River floodplain is in the upper left corner, and the Bush Highway road provides a sense of scale. Smaller points in the lower left are on the neighboring Mine Pediment.

Delineation of the Pediments and Kriging Relict Surfaces.– **Figures 14 and 15** present the boundaries of the four Usery pediments that are adjusting to the lowered base level of the Salt River. Only the Mesa pediment is not shown (see **fig. 9**), because it represents the 'control' condition of a pediment still graded to the Mesa river terrace.
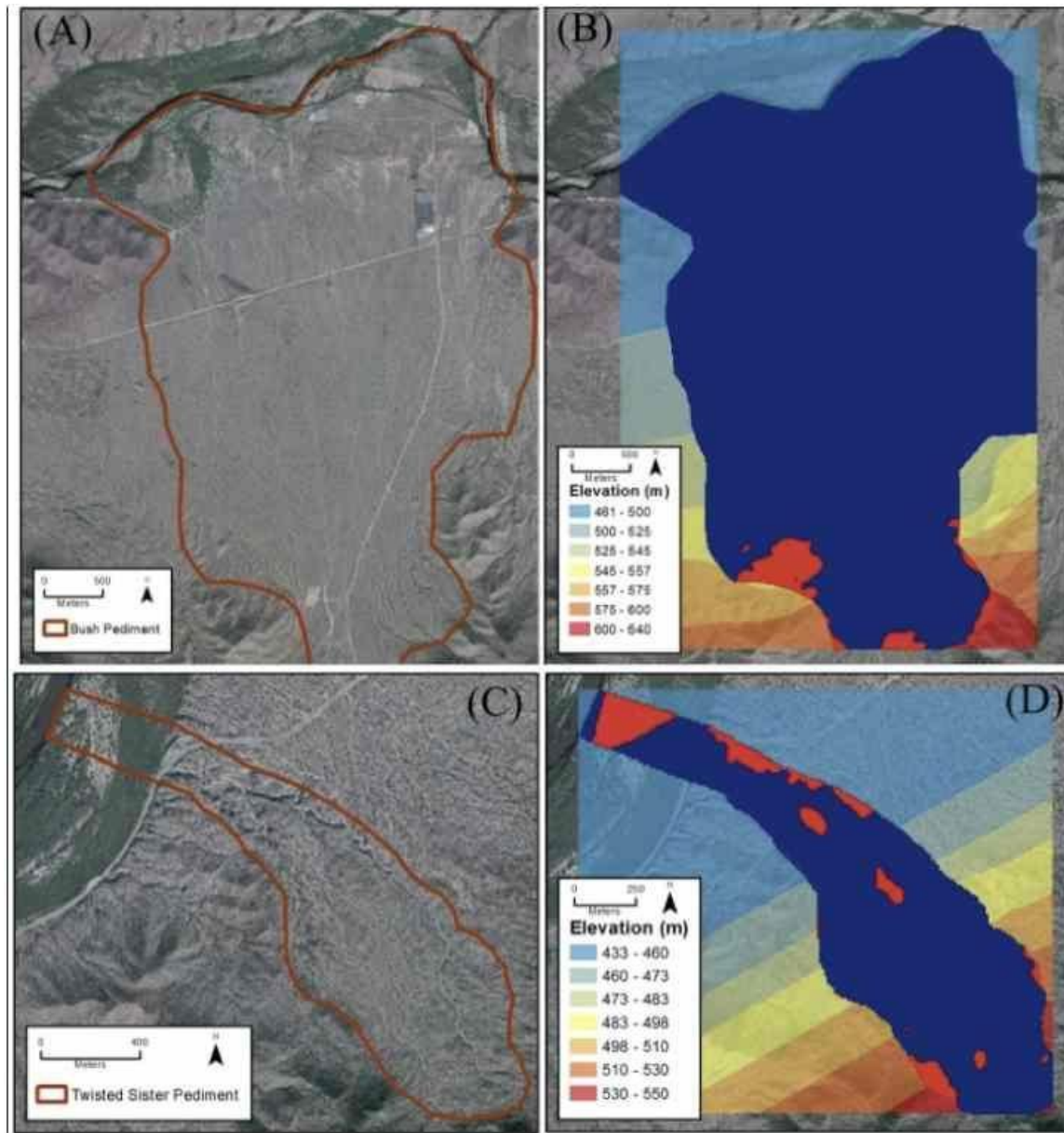
Fig. 14. Red lines delineate the Bush (A) and Twisted Sister (B) pediments. In mapping the paleo-surfaces, red areas indicate locations where the Kriging generated elevations higher than the present-day topography. Blue colors map out the most reasonable paleo-surface for the Bush (C) and Twisted Sister (D) pediments that fits the three criteria specified in the methods section.

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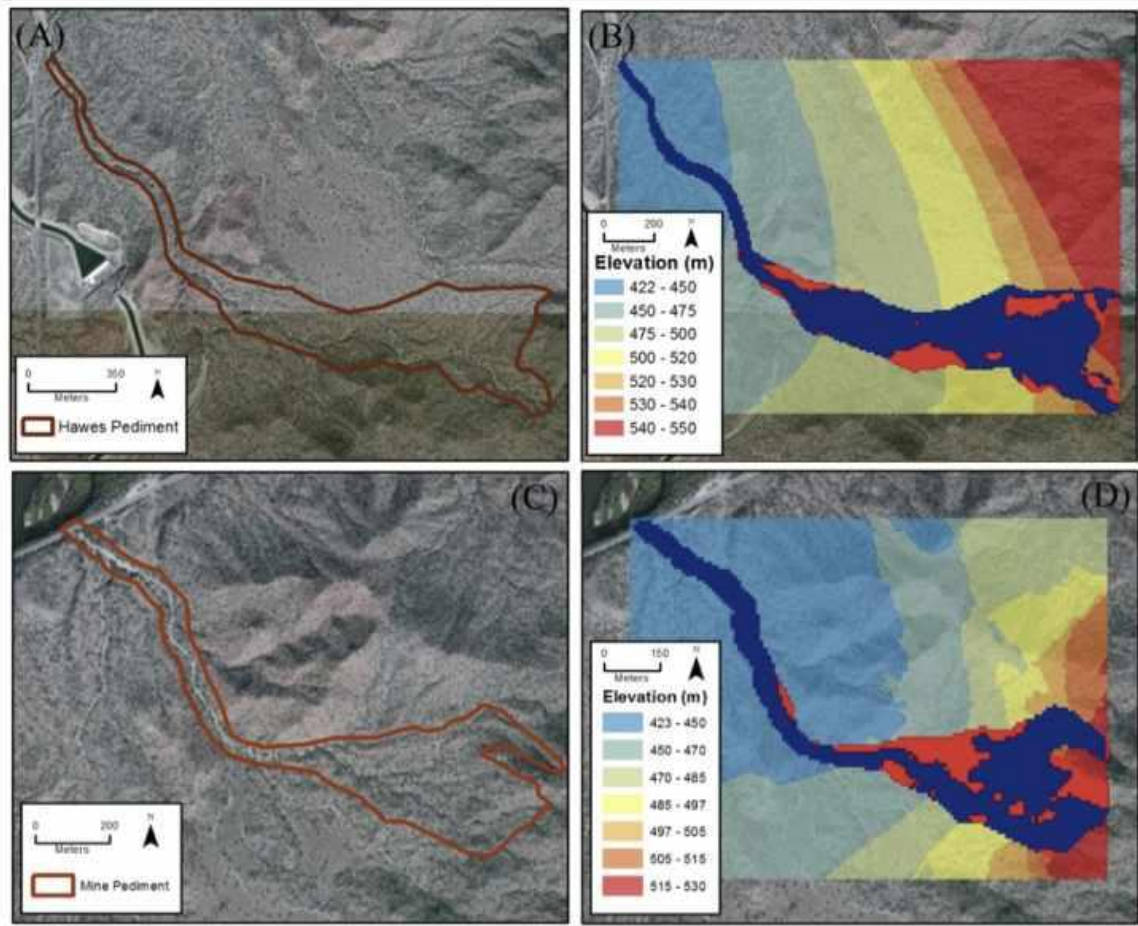
Fig. 15. Red lines delineate the Hawes (A) and Mine (B) pediments. In mapping the paleo-surfaces, red areas indicate locations where the Kriging generated elevations higher than the present-day topography. Blue colors map out the most reasonable paleo-surface for the Hawes (C) and Mine (D) pediments that fits the three criteria specified in the methods section.

Pediment Longitudinal Profiles and Observations of Varied Incision.– The

longitudinal profiles for each incising Usery pediment (**fig. 16**) reveal a concave upward

profile for both modern and paleosurfaces. The relatively smooth paleo-long profiles is

probably an artifact of distribution of the data — even if the paleo-surface was probably

fairly smooth. The much greater variability of the modern profiles reflects an abundance

of knickpoints at various locations. In contrast, the Mesa pedment (**fig. 17**) is the

'control' for this study. It still grades to the Mesa river terrace. The pre-construction 10 m

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DEM shows a relatively smooth profile, interrupted only by such features as large

inselbergs that dot the pediment. I note a variety of specific observations on the

longitudinal profiles of the four Usery pediments:

- The Mine pediment has a dramatic concave-upward profile. This sharp increase in slope in the proximal portion of the pediment correlates to the location of pediment relict surfaces where little adjustment has occurred.

- The modern Bush pediment is experiencing significant incision only in the far distal end, around the Blue Point terrace. This incision results from lowering base level from the Blue Point terrace level to the modern floodplain or the historically flooded Lehi terrace (**fig. 21**).

- The Mesa-time reconstruction of the Bush pediment dips beneath the present-day mountain front. This is a result of the kriging models interpolation. Relatively few remnant data points were observed at the top of the Bush pediment, and most of the Mesa age relict surface has been eroded. Thus, interpolation of this surface is less certain.

- The modern surface sometimes undulates above the reconstructed Mesa-time reconstruction in the Mine and Bush pediments. This is due to the interpolation methods used and the resolution of the 10 m DEM surfaces utilized.

- The Twisted Sister pediment appears to have the least divergence of any pediment profile. This is the result of the strongly undulating topography on the modern surface as a result of incision. The undulations are clearly seen in the modern profile where it often contacts the reconstructed relict pediment level. In these locations it is often a location of the preserved pediment relict that is incorporated into the modern profile.
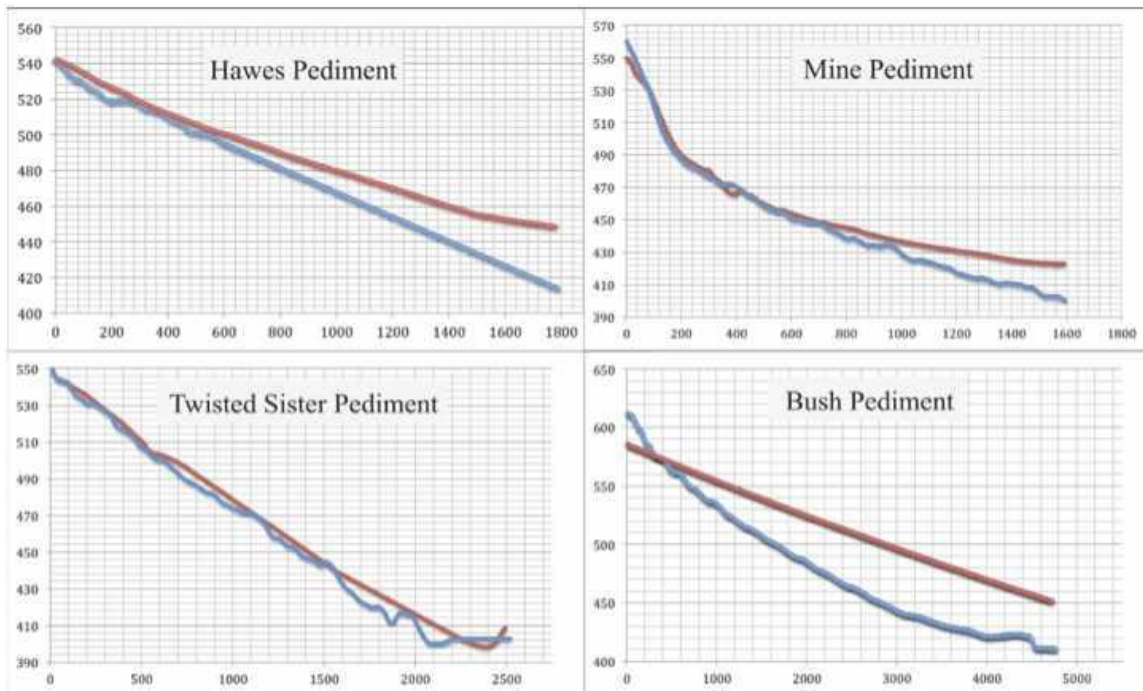
Fig. 16. Longitudinal profiles of Usery pediment systems that are adjusting to the lowered base level of the Salt River. Red lines delineate the paleo-pediment surface reconstructed to grade to the Mesa river terrace. The blue lines indicate the modern 10 m DEM.
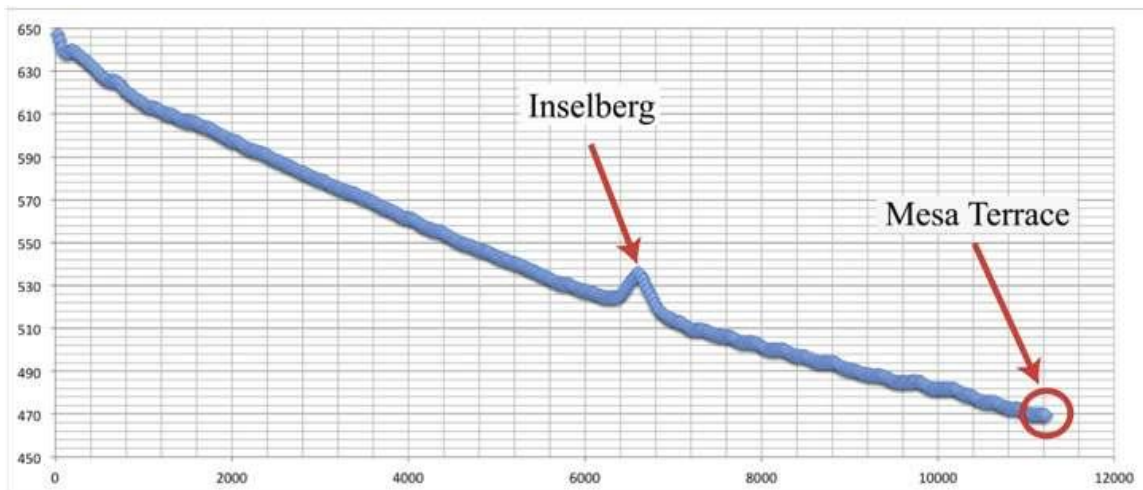
Fig. 17. The smooth longitudinal profile of the Mesa pediment, generated from the pre-construction 10m DEM, accords with the reality seen in the aerial photograph. The Mesa pediment does not exhibit the incision morphology that is typical of the other pediments. There are no relict pediment surface remnants in this basin and it grades to the Mesa river terrace. The topography comes from isolated inselbergs. The Mesa terrace grades westward into the Mesa river terrace.

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Erosion Rates and Pediment Morphometry.– **Table 2** summarizes the basic length and area dimensions of the four incising Usery pediments. **Table 2** also presents the calculation of the mass of granitic bedrock eroded between the reconstructed Mesa-time pediment and the modern surface. The average erosion rate for each pediment system is based on the cosmogenic ^{36}Cl age for the Mesa River terrace and its statistical 2 sigma uncertainty.

This is not to infer that the average erosion rate reflects the rate at any given point along a pediment. The minimum erosion rate for the entire pediment integrates the entire area. Still, it is useful to compare the overall rate with particular locations. For example, at the ^{36}Cl sampling site, the erosion rate is about 39±5 mm/ka (**fig. 18**). Put more conservatively, this particular site has a half the erosion rate of the entire pediment system – likely because of its relative proximity to an inselberg of resistant metamorphic rocks just to the northwest.

Fig. 18. This road cut through a remnant of the Mesa strath terrace is the sampling site

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for [36]Cl dating of the Mesa terrace (Campbell, 1999). At this particular site, the erosion rate is 39±5 mm/ka.

TABLE 2

Pediment morphometry and erosion rates for different pediment basins of the Usery Mountains. The uncertainty term is based only on the 2 sigma error for the cosmogenic age of the Mesa river terrace.

Basin	Length	Area	Volume Eroded	Minimum Erosion Rate
Hawes	1785m	443,000 m^2	1,306,395 m^3	6.7±0.9 mm/ka
Mine	1593m	209,800 m^2	759,891 m^3	8.3±1.2 mm/ka
Twisted Sister	2519m	1,005,200 m^2	12,559,758 m^3	28.1±3.9 mm/ka
Bush	4764m	13,182,100 m^2	518,789,589 m^3	89.7±12.6 mm/ka

An apparent correlation occurs between both pediment area (Log10) and

pediment length (Log10) and average erosion rate of the four studied pediment systems

(**fig. 19 and 20**). Higher erosion rates are associated with more extensive pediments.
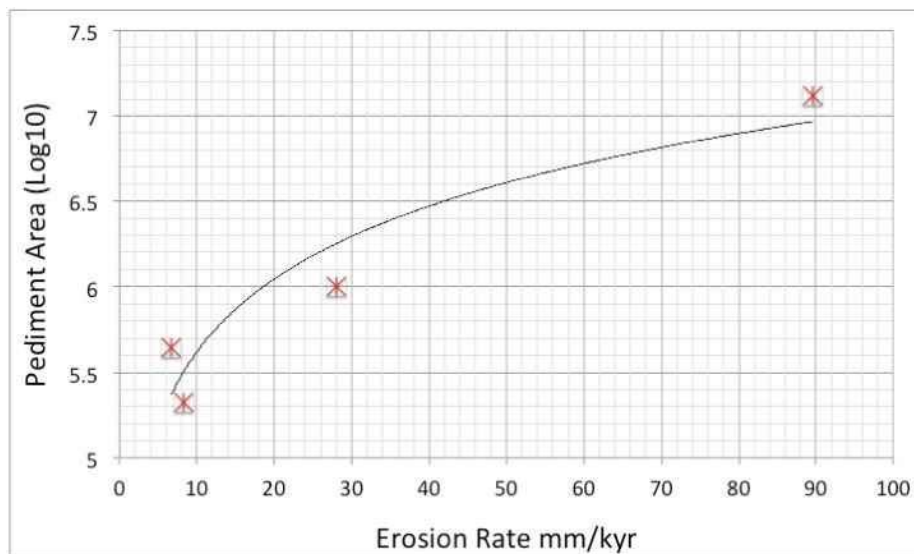
Fig. 19. A linear-log plot of erosion rate and drainage area of the four Usery pediments suggests a basic linear relationship.   A logarithmic "best fit" line emphasizes an apparent correlation between pediment area and erosion rate.

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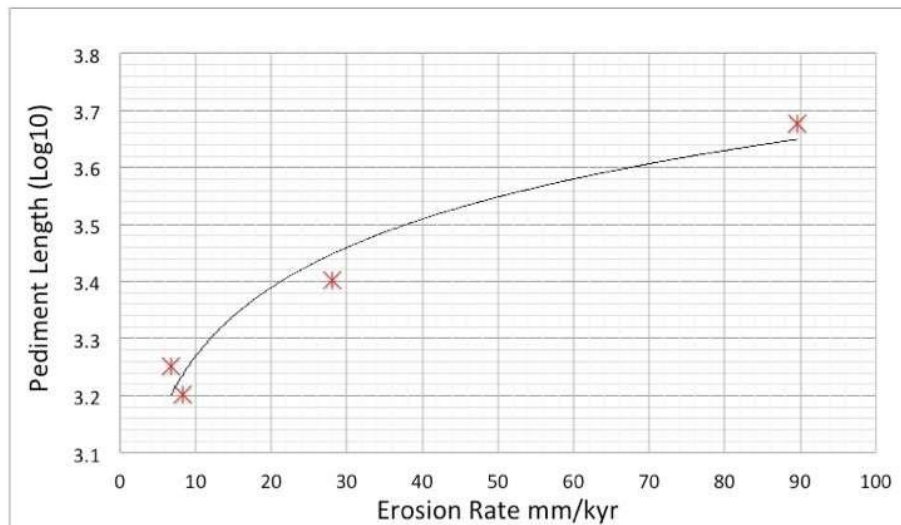
Fig. 20. A linear-log plot of erosion rate and length of the four Usery pediments suggests a basic linear relationship. A logarithmic "best fit" line emphasizes an apparent correlation between pediment and erosion rate.

DISCUSSION

The organization of this discussion section is structured to transition from some of the broader issues in the granitic rock pediment literature towards insights that are more focused on the specifics of the Usery and McDowell field areas of the Sonoran Desert.

Active or Relict?– The contention that rock pediments are landforms inherited from a past climate of greater moisture (Oberlander 1989, Oberlander 1972, Oberlander 1974, Mabbutt 1965, Moss 1977) is incompatible with the results gathered here. Four lines of evidence support this position: (a) regrading of the Bush pediment in ~400 ka during the Quaternary period of relative aridity; (b) regrading of 5% of the Bush pediment since incision into the Blue Point terrace in the last ~33 ka; (c) active modification of the piedmont angle in adjusting pediment systems; and (d) the range of erosion rates that depend on pediment size being consistent with active pedimentation processes.

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The Bush pediment has the classic pediment form (**fig. 1**), even though its longitudinal profile is more concave upward (**fig. 16**) than the Mesa pediment (**fig. 17**). This classic granitic rock pediment completely regarded in about ~400ka. The last 400 ka in the southwestern USA has seen a mixture of climatic periods slightly more arid than today (e.g., Medieval Warm Period) and slightly more moist (e.g. during last full glacial). Thus, pedimentation did not take place during some Tertiary tropical climate (Oberlander 1989, Oberlander 1972, Oberlander 1974, Mabbutt 1965, Moss 1977).

The lowest end of the Bush pediment has been actively responding to the lowering of base level from the Blue Point terrace in the last ~33ka (Larson et al. 2010), as seen in the longitudinal profile (**fig. 21**). Headward erosion has regarded about 5% of the Bush pediment to the modern floodplain of the Salt River. This headward erosion also involves subsequent channel widening by washes with the largest drainage areas.

The piedmont angle is the slope transition between inselberg and pediment. For those favoring the position that pediments are relicts, the piedmont angle should simply represent stripping of the former weathered regolith (Oberlander 1989, Oberlander 1972, Oberlander 1974, Mabbutt 1965, Moss 1977). **Figure 22** contrasts the uppermost headward extending parts of the Hawes pediment system with the Mesa pediment. The extensive gullying that takes place at the top of pediments that flow to the modern Salt River's floodplain suggests that the piedmont angle is not a relict landform.

Yet another perspective on why the relict conceptual model for granitic pediments is inconsistent with these results comes from a comparison of the four pediment systems. The log-linear relationship between drainage area (or pediment length) and erosion rate

(**fig. 19 and 20**) should not exist pediments were relict systems. There should be minimal erosion of the pediment, and the only process would be a slow transport of grus.

The remaining pediments have all experienced differential responses to incision and have felt pronounced base level impacts due to their proximity to the Salt River. The Bush pediment surface is largely graded to the Blue Point terrace level, inset below the Mesa surface (**fig. 3**), and very few remnants of the Mesa level remain. This indicates that the Bush pediment was able to nearly 'repedimentize' the entire surface between ~440 ka and 33 ka (Blue Point terrace age). The surface of the Bush pediment largely consists of alluvial anastomosing channels dominated by grus (medium sand) sized sediment, all of which are characteristic of the classic pediment form in granitic lithologies (**fig. 1**). The efficiency of the Bush pediment's re-pedimentation is not only evident through its surface appearance (**fig. 1**), but also a significantly higher erosion rate (**table 2**).

In contrast, the other studied Usery pediments still retain substantial portions that are remnants of the Mesa pediment, graded to the Mesa terrace. Mantle remnants and degrading interfluves that have yet to be beveled by pedimentation processes mean that these smaller pediments have lower average erosion rates. **Figures 19 and 20** suggest that the thoroughness of re-pedimentation is a function of the size of pediment drainages — whether measured by pediment basin area and pediment basin length. Larger pediment systems appear to be more efficient at reestablishing a pediment surface.

That pediments with different morphometric characteristics respond so differently to the base level change speaks to the importance of the usual controls on fluvial systems as opposed to some relict climatic condition.
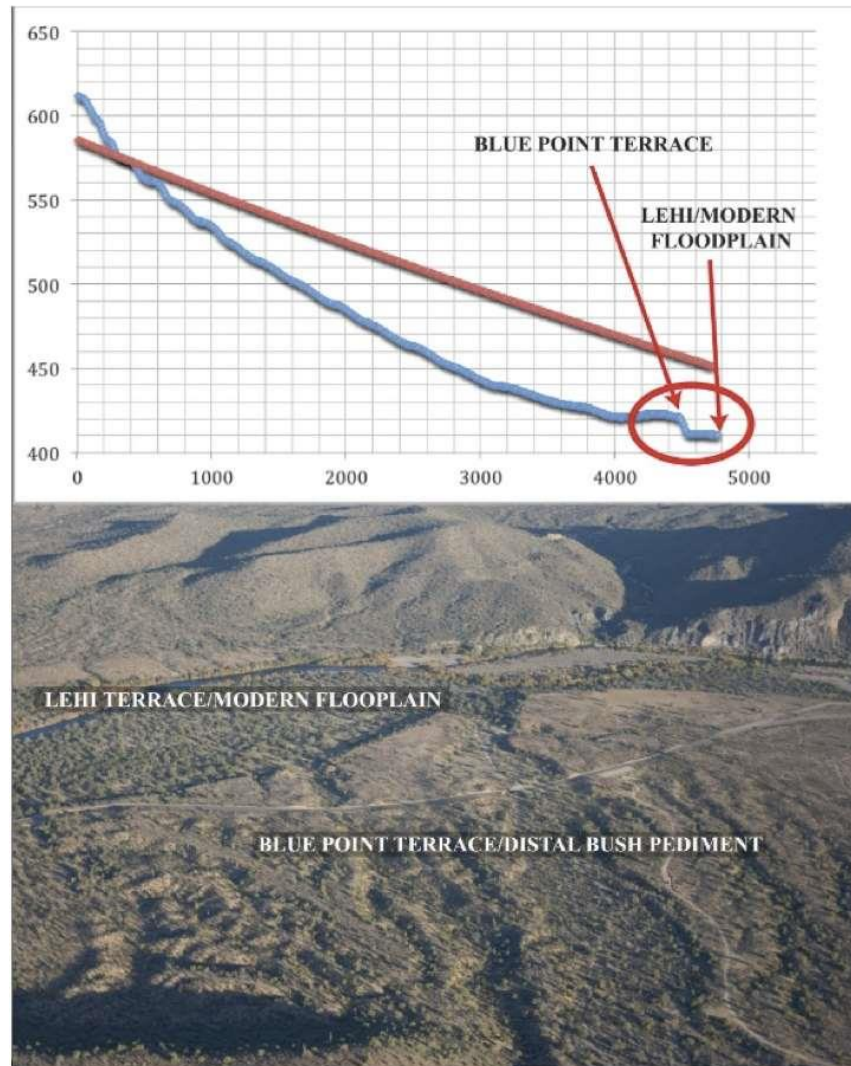
Fig. 21. The upper 95% of the modern Bush pediment grades to the Blue Point strath terrace. However, the incision event ~33ka that created the Blue Point terrace resulted in a base level drop of the lower 5% of the Bush pediment. A combination of knickpoint headward erosion and drainage expansion is beveling the Blue Point strath and associated pediment surface.

Fig. 22. The pediment-inselberg junction for the Hawes pediment system and the Mesa pediment presents a contrast in terms of the degree of gullying. The upper image juxtaposes the uppermost portion of the Hawes pediment drainage area with the piedmont angle of the Mesa pediment. The lower image illustrates an abundance of gullying at the top of the Hawes system, where the gullying is accessing intensely decayed granite – in accordance with prior thinking that water flows down the inselberg and into the former pediment mantle (cf. Oberlander, 1989). This contrasts with the more classic piedmont angle seen in **figure 17**.

Pediments and Base Level.– Base level remains a fundamental control on streams

(e.g. Schumm 1977, Leopold and Bull 1979, Harvey 2002, Begin, Meyer and Schumm

1981, Ouimet, Whipple and Granger 2009, Mather 2000b, Mather 2000a, Yoxall 1969),

including small desert washes (Schick 1974). While fluvial transport occurs across rock

pediments (Dohrenwend 1994, Strudley et al. 2006) and pediments are a "fundamental

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component of a drainage basin" (Cooke et al. 1993), no prior empirical research has explored rates of change when base level lowers. Certainly, numerical modeling research suggests that tors can emerge as base level lowers (Strudley and Murray 2007, Strudley et al. 2006), and this is consistent with our observations (**fig. 10**). The exception is Pewe (1978), who argued that the Bush pediment of the Usery Range once graded to the stable Mesa level and subsequently responded to base level lowering. Otherwise, base level has not received much attention in the pediment literature. Unlike many of the granitic rock pediment systems in the Mojave Desert that grade to playa in a closed basin, those in the Sonoran Desert largely grade to integrated drainages such as the Gila, Salt, Aqua Fria, Verde, and others. Thus, ongoing stream incision throughout the Sonoran Desert has led to a lowering of base level of corresponding pediments washes.

Figures 4 and **9** present broad aerial views of the eastern McDowell and Usery pediments illustrating how knickpoints associated with larger drainages on a pediment system retreat faster towards the inselberg than smaller washes. **Figure 9** (aerial) and **figure 10** (ground) illustrate how the knickpoint of Stoneman Wash — the largest drainage on the eastern McDowell pediment — retreated most rapidly. As base level falls the pediment drainages respond by incising into the current pediment surface due to the increase in gradient. This generates a wave of knickpoints that retreat headward into the pediment.

Small drainages that are tributary to the headward eroding drainages also develop knickpoints, which erode back into the channel walls capturing drainages on the relict surface and neighboring headward eroding drainages. **Figures 23 and 24** illustrates for the Usery pediments that smaller washes then respond to incision of the larger pediment drainage with knickpoint retreat.
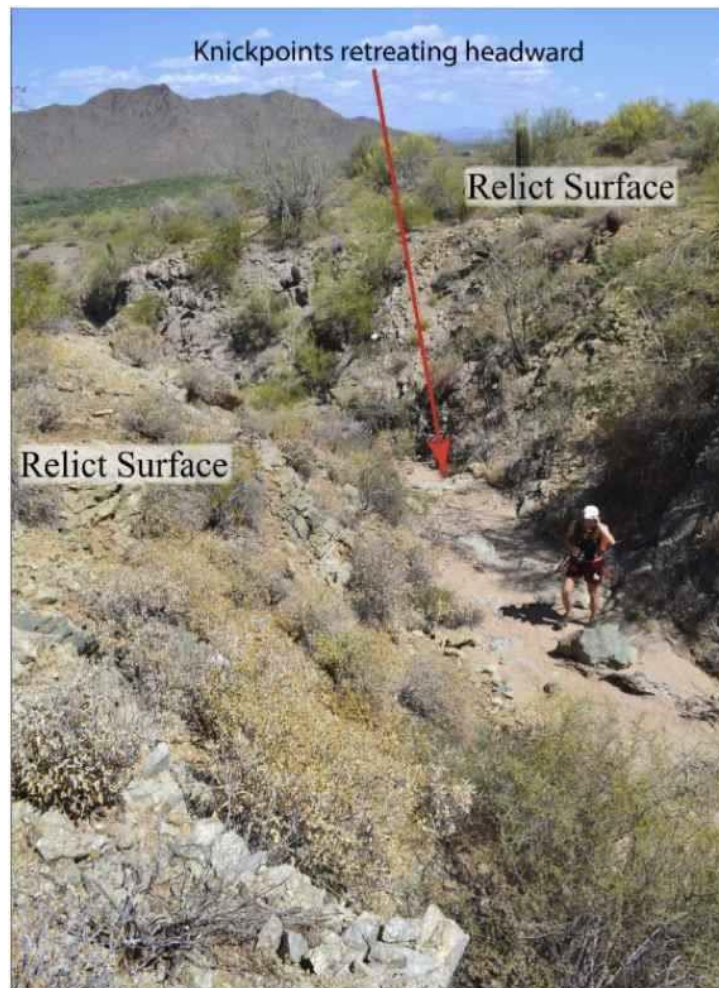
Fig. 23. As the larger pediment drainage responds to lowering base level, its tributaries washes respond in turn. This image shows a tributary on the Twisted Sister pediment eroding headwards by means of knickpoint retreat.
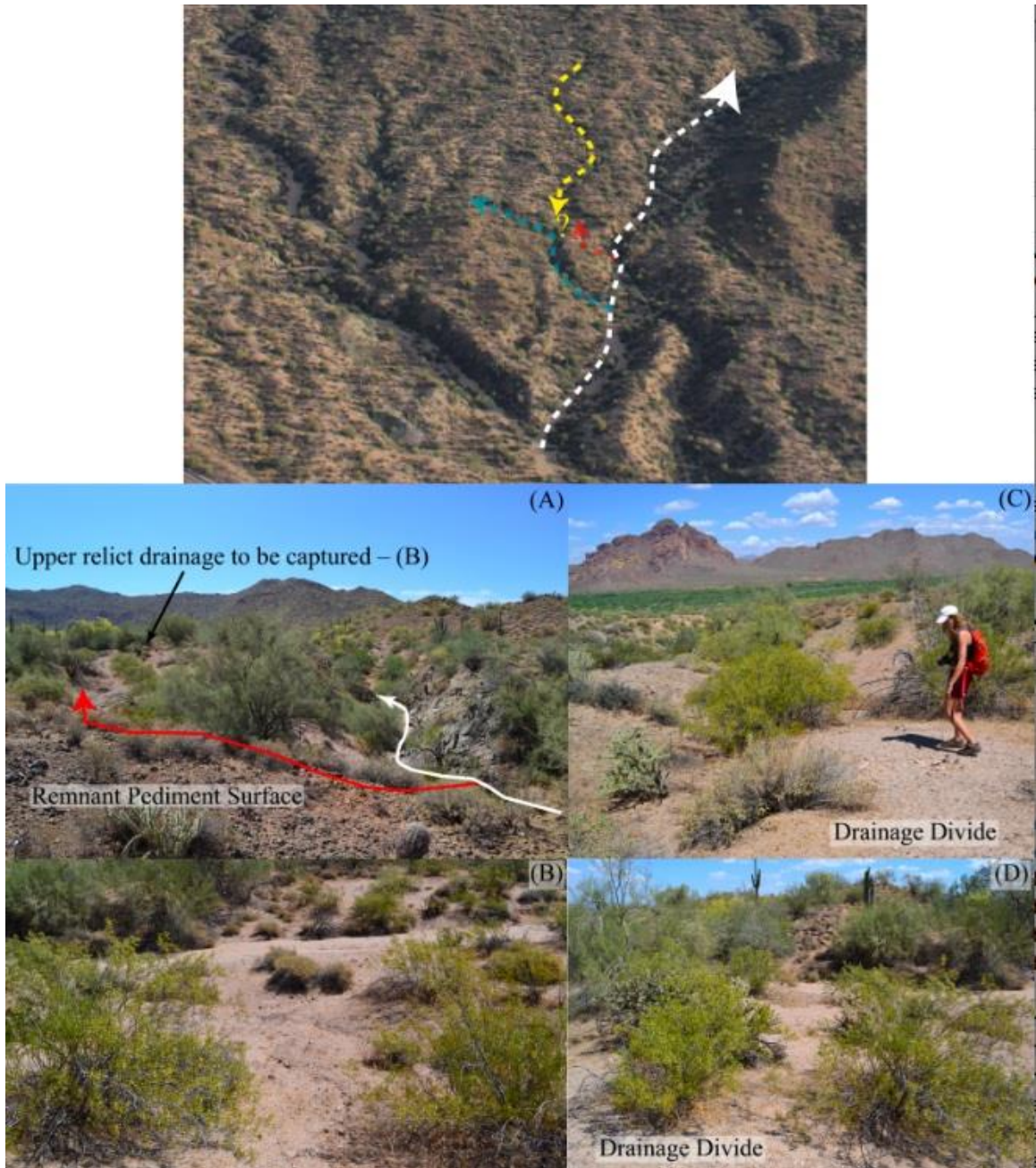
Fig. 24. The lower Twisted Sister pediment illustrates one site of typical headward erosion and knickpoint retreat — incising and elongating the profiles of larger drainages on the pediment. In response, tributaries then erode back in to the remnant pediment surface (A and C). Often this results in capture of a drainage flowing on the remnant pediment surface (B and D). In (A) the white arrow delineates the master drainage and its significant incision, while the red arrow represents the retreat of a tributary drainage, which will possibly capture the low gradient drainage in (B). The white and red arrows in A correspond to those on the oblique aerial photograph. The yellow dashed line represents the drainage being captured in (B). The blue dashed line is another tributary drainage eroding headward from the master drainage (white line).

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The Role of Piracy.– Recently published research on pediments developed in "soft basin rocks" reveal that incised pediments readjust to a new equilibrium condition based on drainage capture processes intrinsic in the fluvial system (Pastor et al. 2012). Similarly, drainage piracy appears to be endemic to the Usery pediments, occurring near the inselberg (**fig. 25**), in the middle of a pediment (**fig. 26**), and nearer to the base level of the Salt River (**fig. 19 and 27**).

Fig. 25. Upper drainages of the Usery pediments, in this case the Bush pediment, have several examples of a headward retreating knickpoint being at a lower elevation a small drainage divide. Such a location appears to be a future elbow of capture.

Fig. 26. The largest area of preserved pediment mantle occurs between the Mine and Hawes pediments. A rolling topography of incised washes currently drains to a larger wash on the Hawes pediment (lower dashed line). However, the upper dashed line identifies a wash with a steeper gradient that has pirated the upper sections of this rolling topography.

Two different types of drainage piracy appear to dominate. One is driven by steeper-gradient washes (**fig. 25-28**). Another, less common process, occurs where extensive areas off former pediment mantle once covered bodies of rock less resistant to grussification. Most of these in the Usery pediments are metamorphics that do not decay to grus. The pediment mantle formed a ramp over these resistant lithologies, leading to superimposition (**fig. 28**).

Fig. 27. The lower Twisted Sister pediment once flowed northwestward towards the Salt River floodplain (dashed line). An incising drainage's knickpoint detached this section of wash from its headwaters on the relict pediment surface.
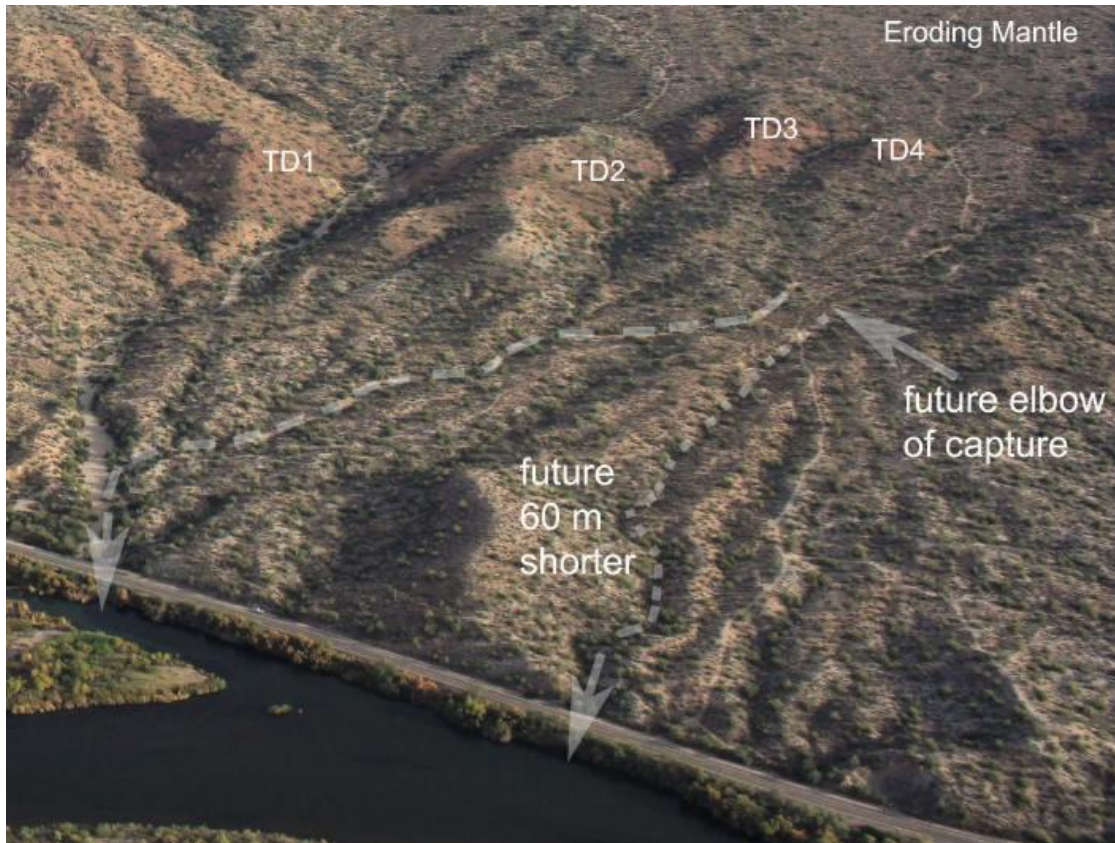
Fig. 28. The relict eroding mantle of the Mine pediment served as a covermass on top of a relatively resistant body of reddish metamorphic rock. Several superimposed transverse drainages (to the right of TD1, TD2, TD3, and TD4) used the mantle as a ramp. Transverse drainage TD1 is in the process of capturing the headwaters of TD2, TD3 and TD4, because of its steeper gradient. Also, below the metamorphics, small washes appear to be in the middle of a small drainage capture.

Pediment-Strath Relationship.– Research presented in a previous chapter

documented the *pediment-strath relationship* in small granitic rock pediments of South

Mountain, central Arizona. A similar morphologic relationship occurs along the Salt

River. **Figure 21** reveals the gradational form of the Bush pediment and Blue Point strath

floodplain. The Blue Point terraces served as the base level for the Bush pediment, until

incision generated the Blue Point strath terrace (**fig. 29**). **Figure 30** illustrates the same

process for the Twisted Sister pediment.

This relationship demands understanding of the dynamics of the axial drainage that created the fluvial terraces in order to investigate the dynamics of base level control on pediment systems. Some researchers have invoked base level as a control in numerical models (Strudley and Murray 2007, Strudley et al. 2006). Others have investigated "terrace pediments" that are defined by their formation in soft, or weak sedimentary lithologies (Plakht et al. 2000, Royse and Barsch 1971, Barsch and Royse 1972, Howard 1942) controlled by a major base level (Cooke et al. 1993). However, little research has focused on field sites investigating the role of base level in crystalline lithologies. **Figure 31** generalizes how the pediment-strath relationship along large through-flowing streams influences landscape evolution of the adjacent pediment system.

Fig. 29. The Usery pediment that once graded to the Mesa strath terrace, regarded to the Blue Point (BP) strath terrace. The arrow annotated on the aerial photo identifies the strath cross-section in the lower image at Blue Point along the Salt River.

Fig. 30. A morphologic relationship observed at South Mountain in small granitic rock pediment systems, termed *pediment-strath relationship* in a previous chapter, also occurs along the much larger Salt River. The labeled mantle remnants rest on a pediment that graded to the Mesa strath terrace. Incision down to the level of the Blue Point led to a readjustment of the pediment to this lowered base level. At this 'Blue Point time', the Salt River enlarged its strath floodplain by lateral migration and the Twisted Sister pediment graded to the Blue Point strath floodplain. Subsquent incision of the Blue Point strath at ~33 ka led to a corresponding incision of small washes.
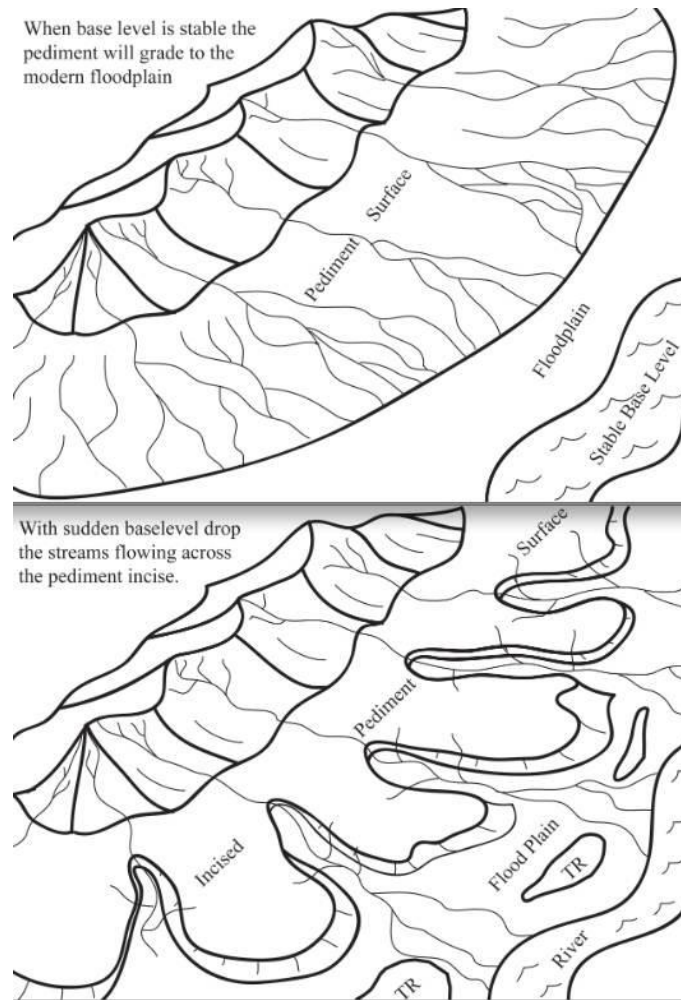
Fig. 31. The base level of drainages flowing through basins containing granitic rock pediments exert a major influence on the level of activity on a pediment. A stable base level of a strath fosters a relatively flat pediment surface, often hosting chaotically arranged washes. A declining base level generates strath stream terraces remnants (TR) and causes the pediment to incise, with faster rates of knickpoint retreat occurring along washes accessing larger drainage areas. Remnants of the former pediment are best preserved in smaller pediment drainages. **Figure 1** and **figure 29** displays this idealized landscape in the context of the Usery pediments.

I speculate that pedimentation processes are inherently tied to strath floodplain and strath terrace development. Yoxall (1969) showed that drainages elongate and establish a profile near equilibrium lateral migration subsequently commenced in the distal channel reach. Consider **figure 21**, and note how washes graded to the modern flooplain have widened greatly at the expense of the strath terrace remnants. This

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widening can also be seen in **figure 22**. Pediment drainages in lower reaches have wider

channels and begin to develop braided-anastomosing channel networks that are

recognized morphological characteristics of laterally migrating streams. In a study of a

very different setting in Taiwan, Hartshorn et al. (2002) noted that "rare large floods are

more important in widening the bedrock channel than they are in driving down the base

level" (p. 2038). Bank-weakening processes may also aid channel widening. I

hypothesized in a precious chapter that an erosional asymmetry exists, where banks

decay and erode faster than channels similar to those discussed in nearby ephemeral

granitic drainages.

Strath floodplain development may occur as a result of lateral erosion of the Salt

River into to pediment surface (**fig. 30**). A previous chapter discussed similar processes

in granitic rocks based on the *pediment-strath relationship*. It is clear that pediments are

being laterally eroded into in many locations (for example, **fig. 9, 28, 30**) and that strath

terraces reside both on (**fig. 18**) and at the base (**fig. 29**) of pediments. I hypothesize that

the Salt River migrates laterally into the pediment when the river is near graded

conditions. At a graded or steady state, the Salt River's rates of vertical incision is

inhibited by stability and also by the coarse bedload on the channel floor. Thus, stream

power is not focused on the channel bed, but on the channel banks. Since the Salt River is

a perennial stream with a much larger drainage area then those discussed in Larson and

Dorn (Submitted), a slightly different mechanisms needs to be invoked to explain this

process.

I hypothesize that a combination of wetting and drying (e.g. Montgomery 2004) of the exposed pediment channel bank, bank undercutting and ground water return flow weaken the banks and facilitate lateral erosion, although more research is necessary to verify these mechanisms.

Relative Role of Base Level and Isostacy.– Isostacy has been hypothesized to play a role in pediment development in the Sonoran Desert, where isostatic uplift generates exhumation at the pediment-inselberg junction (i.e. Pelletier 2010). The Usery Mountains offer new insights into this hypothesis. **figures 17 and 32** present two examples where the graded Mesa pediment contains proximal incision at the piedmont junction. It is distinctly possible that this minor proximal incision could relate to isostatic uplift. Alternatively, it is also possible that the proximal incision in **figure 17 and 32** could have been produced by extreme meteorological events, leading to incision of the inselberg. I do not believe it is possible to falsify either isostacy or an extreme storm event.
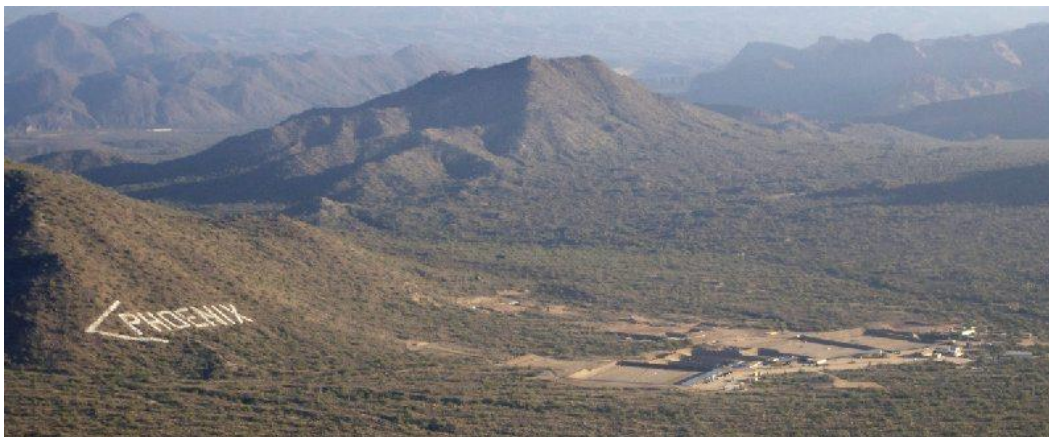
Fig. 32. The northern side of the Usery Mountains grade towards the Mesa River terrace. This view of the gun club pediment shows relatively minor proximal incision at the inselberg-pediment piedmont junction.

However, this study reveals that base level causes far greater proximal incision than either isostacy or an extreme storm event. **Figures 22 and 25** illustrate that far

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greater mountain front incision occurs in pediments impacted by the base level declines

of the Salt River. A broader view of this issue can be seen in **figure 33**, where the

proximal incision associated with base level change of the Hawes pediment contrasts the

Usery inselberg fronted by the Mesa pediment. These examples suggest that uplift and

exhumation (i.e. Pelletier 2010) is at most a minor pedimentation mechanism — at least

for the eastern McDowell and Usery pediments impacted by the base level fall of the Salt

and Verde rivers.

Fig. 33. The Mesa pediment grades to the Mesa fluvial terrace. However, knickpoints are retreating headward towards the Mesa pediment. Distance from the Salt River has delayed its inicision. White arrows in the oblique aerial photograph correspond to the small red arrows identifying incising washes. The lower image follows Google Earth usage guidelines: [http://www.google.com/permissions/geoguidelines.html]

Pelletier (2010) notes that the treatment of uplift and base level lowering as a

value independent of pediment processes (in the Strudley models) does not hold true in

the Sonoran Desert. He argues that tectonic activity has largely ceased and uplift is now

the result of flexural-isostasy due to erosional unloading of the mountain mass. Although

Pelletier's argument about uplift may be correct and may be producing minor proximal

incision, base level in this portion of the Basin and Range is often controlled by basin axial drainages, that have integrated endorheic basins through which they flow — for example, the Salt River, Verde River, Gila River, Agua Fria River, and San Pedro River. In these integrated drainages, base level should be considered an extrinsic variable in explaining proximal incision.

Revisiting the Role of Lateral Stream Migration.– Numerous researchers have invoked erosion via lateral migration of pediment streams as a mechanism responsible for pediment formation (Gilbert 1877, Johnson 1932, Howard 1942, Warnke 1969, Sharp 1940, Johnson 1931). Criticism of lateral stream processes stem from Lustig (1969) who suggested that drainages would have to debouche the mountain front and swing laterally, against gravity, in order to abut the mountain front to explain the characteristic piedmont angle (Oberlander 1989). This opposition continues into recent literature where lateral stream migration is largely ignored (Pelletier 2010, Strudley et al. 2006). However, Parsons and Abrahams (1984) discovered that 3 to 51 percent of the piedmont junction at classic Mojave Desert pediments are being influenced by channel processes, while the remainder of the inselberg front results from hillslope processes. Howard (1942) and Johnson (1931, 1932) did explain that the piedmont junction evolution may be modified by rillwash, sheetwash, and rainsplash. It has also been suggested that weathering at the piedmont junction may be important (i.e. Twidale, 1968). Thus, these works collectively suggest lateral stream erosion should not be discarded from future modeling and should not be treated as mutual exclusive to any other processes acting on the piedmont junction.

Fig. 34. Washes along the northern front of the Usery Mountains, at the western end of the Hawes pediment, illustrate flowing somewhat parallel to the mountain front. Washes to the upper right of the double arrows exemplify this tendency. The mountain front parallel orientation is being controlled by the lowered base level locking these drainages in place.

Based on observations made at the Usery pediments (for example, **fig. 34**), I support the hypothesis that lateral erosion can influence repedimentation. Base level induced knickpoint migration in these systems leads to narrowly incised channels that retreat headward in an attempt to establish stable longitudinal profiles. Experimental modeling shows that streams will continue to grow headward as a result of base level lowering until an equilibrium profile can be established (Yoxall 1969, Leopold and others 1964). Elongation of the long profile will retreat to the mountain front increasing local slope and enhancing hillslope processes and embayment growth. This would increase sinuosity of the mountain front where larger pediment drainages would command the largest drainage areas and thus, the largest embayments. Once a stream approaches

equilibrium conditions headward erosion ceases and lateral erosion begins downstream (Yoxall 1969), as vertical incision is no longer the focus of stream power at stable base level.

In the actively adjusting Usery pediments the widest portions and most significant areas of re-pedimentation often occur where: 1) the largest pediment drainages coalesce (**fig. 35**) and/or 2) in the far distal reach of the largest drainages (**fig. 36**). Wider areas occur Immediately down stream drainage convergence. This suggests a positive relationship between drainage area and the efficiency of lateral erosion. Progressive capture processes and the increased elongation of the drainages may supply sufficient drainage area allowing for adequate stream power to erode laterally in the distal portion of regrading pediments. Research presented in an earlier chapter on South Mountain shows that an erosional asymmetry, based on differential weathering characteristics between the channel bed and banks, can facilitate lateral erosion in granitic rocks. It is possible that a similar phenomenon facilitates lateral erosion in the distal portion of these pediments.

Fig. 35. Locations immediately downstream of where large pediment drainages convergence often have significantly wider channels. The larger in drainage area leads to higher stream power and more efficient lateral erosion, that in turn results in planation of the pediment. Two different views of the same site offer an example on the Twisted Sister pediment. Red arrows point to the same location.

Fig. 36. In this view of the upper end of the Mine pediment, the black arrows identify locations where significantly wider and planar channel reaches are actively responding to base level lowering. These black arrows reside in areas where the largest (in terms of drainage area) pediment drainages flow. Direct evidence of cut banks and anastomosing channel reaches are observed in these areas. The red dotted line outlines the boundary of incised and actively adjusting portions of the Mine Pediment.

CONCLUSIONS

The majority of research on granitic rock pediments has focused on understanding the piedmont junction and degradation of the mountain mass. Very little research, other than numerical modeling, has focused on the quantitative and qualitative aspects of base level change on granitic rock pediments.

The granitic rock pediments of the Usery and McDowell Mountains show a strong linkage to base level fluctuations. Pediments that have not yet experienced base level impacts are still graded to older terrace and basin fill surfaces, while pediments proximal to the Salt River have experienced varying degrees of incision and re-pedimentation. The degree of pediment adjustment (via erosion rate) correlates directly to the pediment area and pediment length. This suggests that drainage area may control the efficiency of pedimentation processes.

Pediments regrade, in the study site, through differential headward propagation of knickpoints. Small pediment drainages are controlled by larger master drainages that incise more efficiently and become the local base level control on the pediment. Tributary drainages will erode headward into the relict pediment surface and capture other drainages upstream or neighboring headward eroding drainages. This results in an overall widening of a planar pediment surface and a lowering of the relict surface to the master drainage.

Lateral migration and erosion by the distal portions of headward eroding streams facilitate pedimentation. The far distal reaches of pediment drainages have wider channels that begin to take an anastomosing form. This also occurs where the largest pediment drianages coalesce. Recent research (Larson and Dorn, Submitted) in nearby ephemeral drainages shows that an erosional asymmetry can exist facilitating lateral erosion in granitic rocks. Similar conditions exist in this study suggesting lateral migration may be responsible for the efficiency of pedimentation in the distal pediment reach.

An earlier chapter proposed the *pediment-strath relationship.* This relationship suggests pediments grade to fluvial strath surfaces within the Sonoran Desert. These pediments contain the classic weathered mantle discussed in pediment literature. The weathered mantle is exposed in the channel walls of the main basin axial stream, which creates a less resistant bank that facilitates lateral erosion. In the case of the Salt River, the river laterally erodes at the expense of the bounding pediments. Since the Salt River is perennial and a significantly larger drainage, periodic wetting and drying of the channel walls, undercutting of the exposed pediment, and ground water return flow may further enhance the weakness of the channel banks and facilitate lateral erosion. Many of the older terrace remnants now lay upon active pediment surfaces. This morphological relationship suggests that previous straths were carved upon the pediment surface. I suggest that the strath terraces of the Salt River were carved at the expense of these pediments and subsequently abandoned when the Salt River incised, similar to the model proposed in a previous chapter for small ephemeral drainages at South Mountain.

Chapter 5

STEWART MOUNTAIN TERRACE: A NEW SALT RIVER TERRACE WITH
IMPLICATIONS FOR LANDSCAPE EVOLUTION OF THE LOWER SALT RIVER
VALLEY, ARIZONA.

**ABSTRACT. Stream terraces of the Salt River form the interpretive backbone of
Plio-Pleistocene landscape evolution of central Arizona, because they represent the
base level of all tributary streams. This paper presents a new addition to T.L.
Péwé's Salt River Terrace sequence (in decreasing topographic position and age:
Sawik, Mesa, Blue Point, and Lehi) that has been unrefined for the last thirty years.
The existence of an older, higher terrace was predicted by research suggesting that
the lower Salt River originated by lake overflow from an ancestral Pliocene lake in
the Tonto Basin. Field reconnaissance, aerial photo interpretation, and
sedimentological analysis revealed this terrace on the north side of the Salt River,
named here the Stewart Mountain Terrace (SMT). Where exposed, the fluvial
sediments of SMT overlay Tertiary basin fill unconformably. SMT sediments are
characterized by ~50 m thick fluvial gravels found more than 70 meters above
remnants of the Sawik Terrace. Although the gravels are distinctly Salt River in
origin, Stewart Mountain gravels differ from the lower and younger Salt River
Terraces. The clast sizes are much larger on average and host a significantly
different lithology. Because of these differences the SMT has profound implications**

for the understanding of regional drainage reorganization after basin and range extension. The existence of this terrace and its distinct gravels are consistent with, but do not prove, a lake overflow mechanism for the initiation of through flowing drainage in the Salt River valley.

INTRODUCTION

Fluvial or stream terraces are remnants of ancient floodplains that rest topographically above modern floodplains to create relatively flat bench-like landforms. The former floodplain surface, or terrace tread, represents a period of relative stability within the fluvial system. The abandonment of that surface is represented by incision into the former floodplain. A stream can incise as the result of any combination of several processes: 1) a drop in base level (lowest point in a fluvial system) to which all the drainages respond, 2) an increase in discharge generating an increase capacity for stream erosion, 3) tectonic and/or isostatic uplift in the headwaters that increase stream gradient resulting in incision, and/or 4) a reduction in sediment load into the stream. Because terraces represent a shift from periods of stability and floodplain formation to a period of instability and steam incision, each terrace and incision event records key geomorphic and geo-chronologic evidence of how the fluvial landscape has changed over time (Leopold and Bull, 1979; Pazzaglia et. al 1998; Ritter et. al 2002; Schumm, 1973).

Recognizing the significance of stream terraces, Professor Troy L. Péwé and his students at Arizona State University mapped and analyzed Plio-Pleistocene stream terraces along the Salt River of central Arizona in the 1970s (**fig. 1**; Kokalis, 1971; Pope, 1974; Péwé, 1978). They documented four former floodplains that were successively

abandoned each time the Salt River incised (**fig. 2**). The oldest three (Sawik, Mesa, and

Blue Point) are strath stream terraces. The term strath connotes that a river incised in its

floodplain and into the underlying bedrock, leaving behind only a few meters of alluvial

gravel cover. The Lehi Terrace, is a fill terrace, reflecting the Salt River's incision into

its own fluvial deposits.
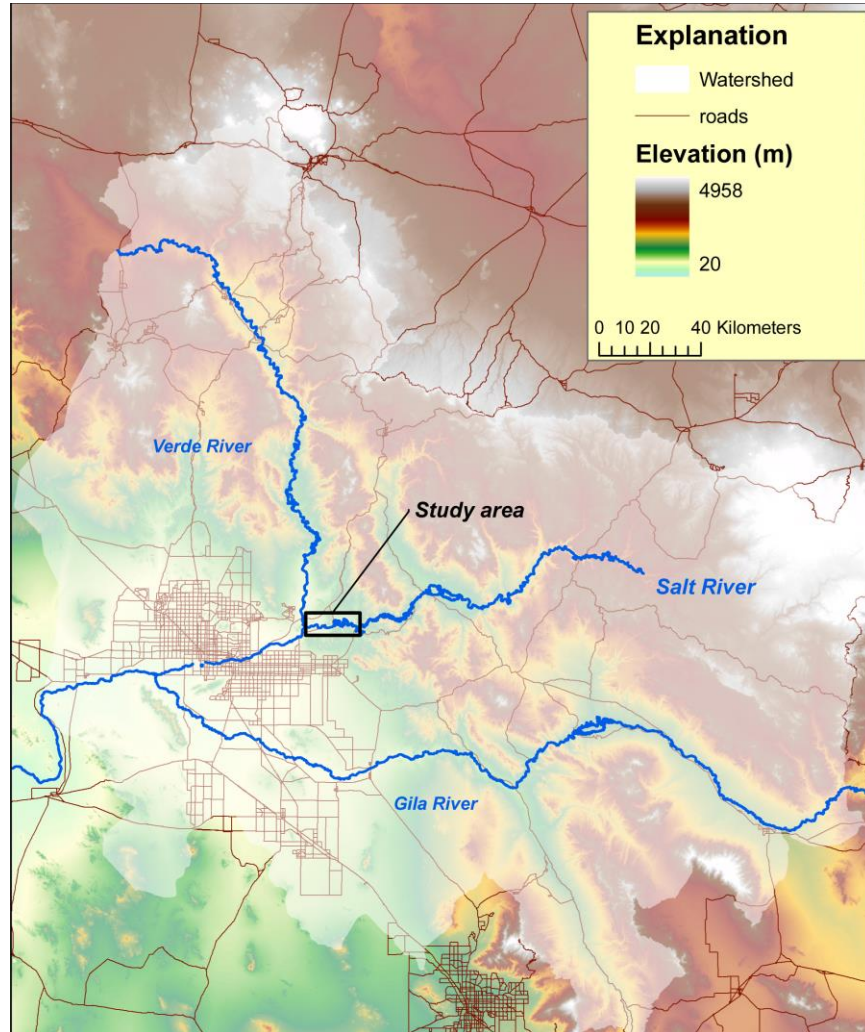
Fig. 1. *Digital elevation model of Maricopa County, Central Arizona and the location of the Stewart Mountain Terrace study reach within.*

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Little data exist as to when the Salt River eroded into its former floodplains leaving behind the sequence of stream terraces. Campbell (1999) analyzed the accumulation of cosmogenic ^{36}Cl in multiple cobbles from one Sawik Terrace location near the TRW plant in Mesa (N 33.49030 W 111.70840). Campbell (1999) found that cobbles from the Sawik Terrace are close to or at secular equilibrium. Thus, the sampled strath Sawik Terrace exposure was eroded into bedrock and then abandoned more than 1.2 million years ago. Péwé (personal communication) thought the Sawik was as old as 2.2 Ma because of its apparent correlation with a terrace surface on the Gila River that is overlain by a 2.2 Ma basalt flow. More dating is needed to determine the precise age of the Sawik Terrace. The Sawik-age course of the Salt River did not mirror its modern day course, but instead flowed on the southern side of the South Mountains, Phoenix, AZ (Hoyos-Patino, 1985; Arrowsmith, 2001; Block, 2007).
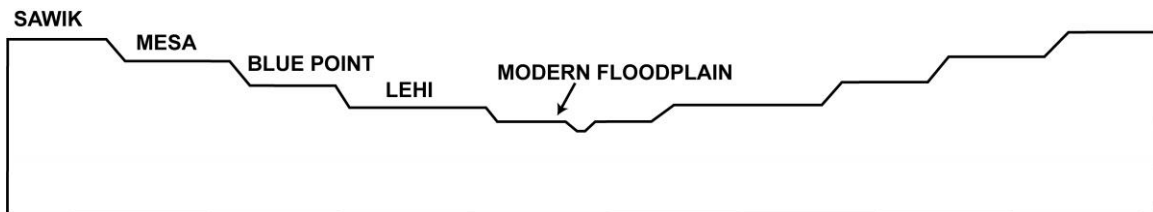
Fig. 2. Diagrammatic profile view of terraces of the lower Salt River Valley, after Péwé (1978). This depicts the previously known sequence of four paired terraces within the Salt River Valley.

The Mesa River Terrace is the most extensive of all four known terraces. It forms a continuous surface from west of the Arizona State University's Campus in Tempe, AZ, eastward into the city of Mesa, with more sporadic remnants continuing up the Salt River Valley (Péwé, 1978; **fig. 3**). The Mesa River Terrace represents a period of base level stability in the Salt River system after incision into the Sawik Terrace. As such,

numerous pediments and local tributary streams were graded to this surface (Péwé, 1978). Campbell (1999) analyzed ^{36}Cl in multiple cobbles from a road cut along the Bush Highway (**Marked A on fig. 5)** and calculated a minimum exposure age of 439± 63 thousand years for the Mesa Terrace gravels. This half-million year estimate is roughly consistent with the Stage III-IV soil carbonate development observed at multiple locations in Mesa Terrace soils (Péwé, 1978).
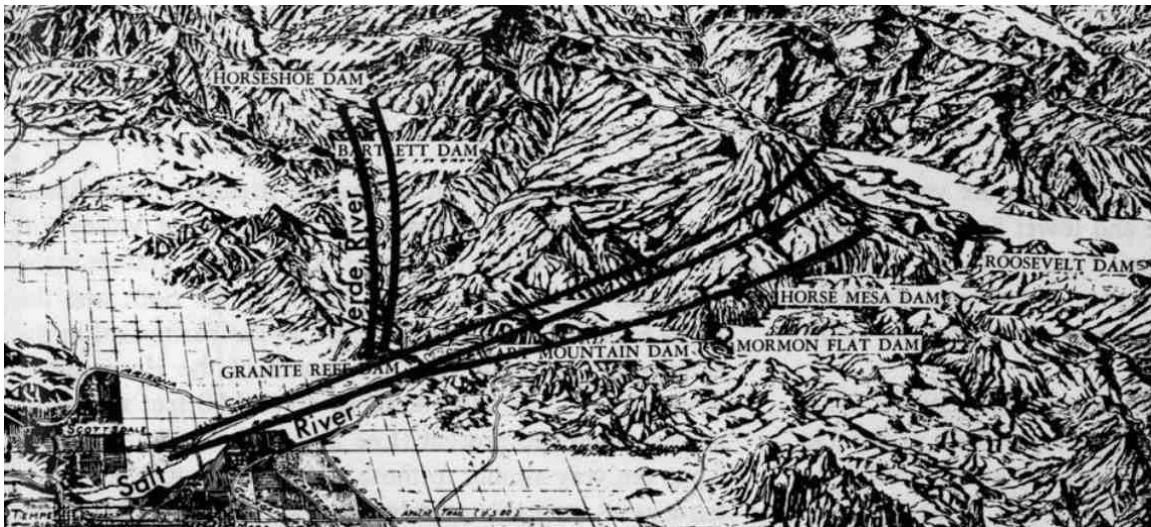
Fig. 3. A physiographic diagram produced by the Salt River Project, on which Péwé (1978) indicated the three strath terraces of Sawik, Mesa, and Blue Point along the Salt River. Two terraces were drawn for the Verde River. Note that Péwé pinches out the Blue Point terrace in east Mesa, Arizona. Péwé also used this figure to indicate his assumption of regional correlation of the terraces in each of the tributary watersheds of the Salt-Gila system, central Arizona.

Radiocarbon dating of pedogenic carbonate is notoriously difficult and fraught with uncertainties (Callen and others, 1983; Wang et al., 1994; Stadelman, 1994), but a radiocarbon age on the innermost carbonate rind around Blue Point terrace cobbles yielded a calendar age of 33,100 ± 380 years (14C age of 30,980±290) (Beta 51401). This age is roughly consistent with the Stage I soil carbonate development seen in Blue Point soils (Péwé, 1978).

Fig. 4. Southwest-looking photograph taken from approximately 1860'on the north side of the Salt River (**Marked as B on fig. 5**), looking down at remnants of the Sawik and Mesa terraces on the south side of the River. The newly recognized terrace is identifiable by the rounded gravels seen here. Rounded gravels reflect fluvial transport and subsequent deposition of alluvium, preserved as the oldest and highest stream terrace of the Salt River.

The Lehi Terrace is just above the modern floodplain and has been historically flooded (Péwé, 1978). Unlike the other terraces, the Lehi was not eroded into bedrock and consists of alluvium deposited by the Salt River floods. The presence of an early Holocene turtle shell, reported by Péwé (1978) and Archer (1989) suggests the Lehi Terrace is approximately 5-10 thousand years old. Lehi Terrace fill represents a long sequence of Holocene flooding deposits confined by the higher Blue Point Terrace remnants.

METHODS: A DEDUCTIVE APPROACH

Transverse drainages are streams that cut across mountain ranges or significant topographic barriers to flow. A transverse drainage represents a dramatic change in the fluvial system that can be attributed to only four possible processes: antecedence, superimposition, piracy, and overflow (Douglass et al., 2009a). Antecedent streams drain across and erode a channel into a bedrock structure that uplifts beneath the stream, thus the stream is older than the uplifted structure. Superimposed streams originate flowing atop a covermass of easily erodible material. As the stream incises into the covermass it is essentially locked in place by the underlying bedrock structure. Pirated streams are captured by another drainage that has a steeper stream gradient. Streams that result from lake overflow are originally ponded in endoheic, or interior-drained, basins that eventually overspill at the sill, or lowest point of the basin rim, eroding a canyon across the bedrock structure downstream of overflow apex.

The Salt River flows across several mountain ranges and topographic barriers, hence it contains many transverse sections. The most dramatic transverse section starts at the location of today's Roosevelt Dam, where the Salt River tranverses the Mazatzal Mountains (**Fig 3**). Recent research developed a new methodology to analyze the origin of transverse drainages. This research suggests the Salt River's presence downstream of today's Roosevelt Dam is likely due to overflow of an ancestral Lake Roosevelt that existed in the Tonto Basin (**see Fig. 3**; Douglass et al., 2009a; Douglass et al., 2009b: Pp. 49-51). This conclusion was based on matching geological and geomorphological evidence against objective criteria developed through physical modeling.

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As suggested in Douglass et al. (2009b; p. 49-51), a lake overflow event would have distributed Salt River gravel downstream of the overflow apex into basins that formerly lacked deposits from this major river. Concomitantly, Reynolds and Bartlett's (2002) examination of subsurface sediment near Sky Harbor Airport, Phoenix, AZ, records the sudden arrival of "Salt River Gravels" which suggests the possibility of an overflow origin to the through flowing Salt River (cf. Reynolds and Bartlett, 2002, their figure 19).

However, a key piece of evidence for a lake-overflow origin of the lower Salt River was missing. A lake overflow event should have produced large gravel deposits on top of an ancestral landscape that would have lacked a major through-flowing drainage prior to this overflow event. This would be analogous to events that occurred during the birth of the lower Colorado River (House et al., 2005). The ancestral landscape of the area now occupied by the Salt River Valley consisted mostly of fanglomerate deposits derived from the Mazatzal and other local mountain ranges. These fanglomerates were previously mapped as "Valley Fill Sediments" (Pope, 1974; Péwé, 1978) just north of the Salt River (**Fig. 3**). These were similarly mapped as "younger sedimentary basin-fill deposits" of late Tertiary age by Skotnicki and Leighty (1997). Mazatzal Mountains-derived valley-fill fanglomerate sediments can be seen in cliffs along the north side of the Salt River.

The methodological approached here practiced deduction. The first step involved field reconnaissance investigating sites for the predicted overflow gravels. Once the predicted gravels were identified, comprehensive mapping of all locations of previously unidentified Salt River gravels was conducted. Also, particle sizes were measured and

compared between the predicted gravels and the gravels of the younger Salt River

terraces along randomly-located line transects. This data was then placed in the context of

prior research to begin to reinterpret the drainage evolution of the Salt River.

RESULTS

The largest deposit of previously unmapped Salt River gravels occurs at

the topographically highest exposures of previously mapped "valley fill sediment". The

highest gravels are found at 1870' on the north side of the Salt River (**Fig. 5**). Clasts

consist of gravel, cobbles and boulders with the largest boulders exceeding 2 meters in

the intermediate axis— significantly larger than those on the lower Salt River Terraces.

Rock types include granite, quartzite, Proterozoic meta-conglomerate, basalt(s), schist,

and other lithologies found in the Salt River basin. These gravels occur approximately 60

m above the Sawik Terrace on the south side of the Salt River (**Fig. 4**).

This deposit, herein called the Stewart Mountain terrace (SMT), is named after

the nearby prominent bedrock mountain that may have played a role in preservation of

the terrace remnants. The same gravel deposit exists on top of the valley fill on preserved

terraces for about 6 kilometers along the north side of the Salt River (**Fig. 5**).
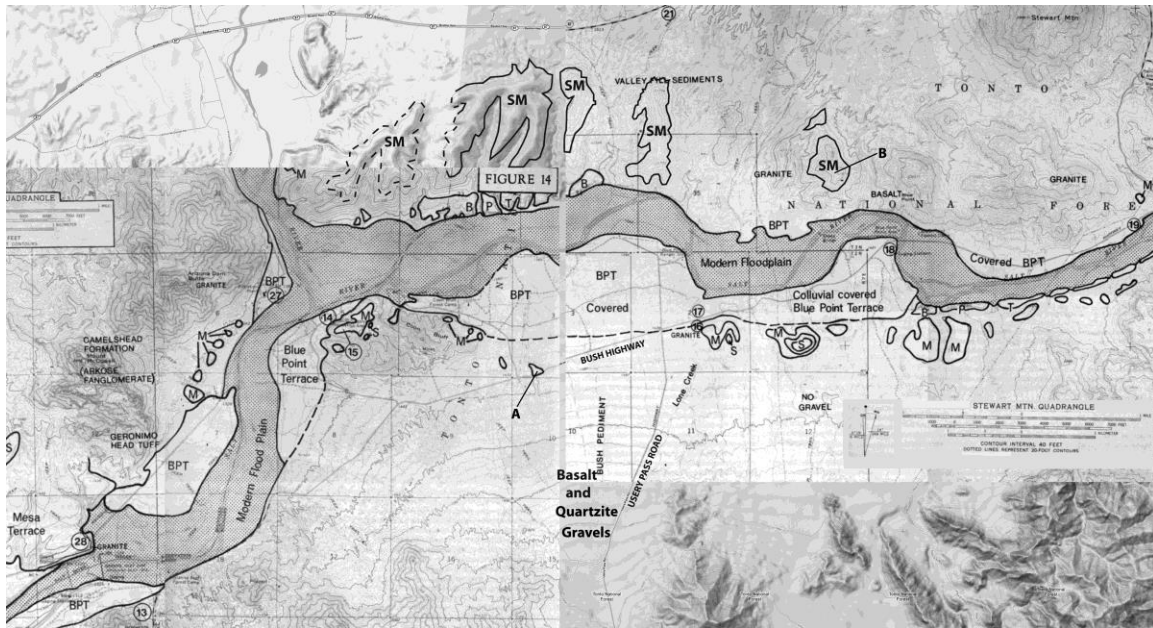
Fig. 5. Map of the locations of Stewart Mountain terrace remnants (SM) on the north side of the Salt River, and of rounded quartzite and basalt gravels on the south side of the Salt River — all previously unrecognized. The dashed line indicates the likely boundary of the Stewart Mountain terrace on the Fort McDowell Indian Reservation, as inferred by topography, examination of aerial photographs and binocular examination. Location A marks a [36]Cl date on the Mesa Terrace. Location B marks the location of **fig. 4**. The base map consists mostly of figures modified from Péwé (1978) showing the locations of Sawik (S), Mesa (M) and Blue Point Terrace (BPT) remnants.

Currently, the age of SMT is unknown. Its topographic prominence in relation to the other terraces (**fig. 6 and 7**) indicates that it is the oldest in the Salt River terrace sequence. One gully exposure reveals a Stage IV+ calcrete underneath the terrace gravels, but the presence of a calcrete duricrust is not diagnostic of any particular age beyond a half-million years. Resolving its age will require cosmogenic nuclide analyses.

The thickness of the SMT gravels is difficult to determine because of the lack of a clean exposure at the base of the deposit. The best insight comes from the easternmost terrace remnant, because gravels are found directly on top of granite bedrock and on top

of >3 meter diameter granite core stones that could potentially have been moved by flooding. This contact appears to be about 50 meters underneath the top of the gravels.
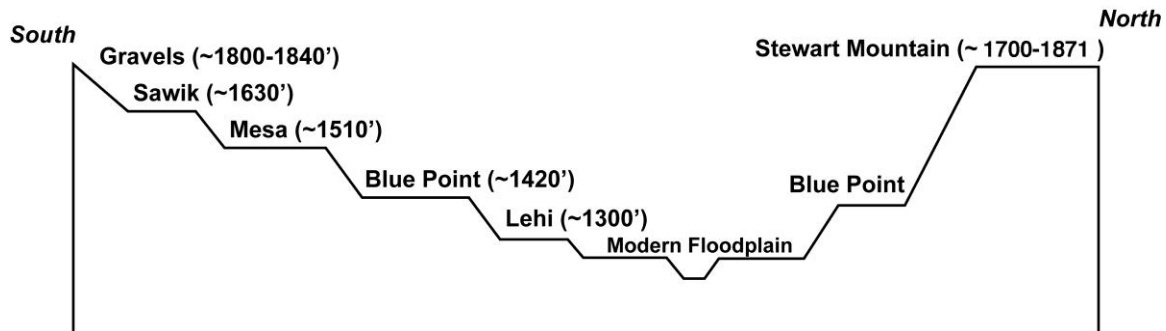
Fig. 6. Generalized profile of the revised Salt River terrace sequence, from South to North, approximately where Usery Pass Rd. meets the Bush Highway. The lower boundary of the Stewart Mountain terrace is a rough estimate. The Lehi terrace does not exist this far east, so the indicated elevation is where Péwé (1978) mapped this inset fill terrace a few kilometers to the west.

Péwé (1978) and Kokalis (1971) concluded that the basic rock types and size distributions of the Sawik, Mesa and Blue Point terrace gravels were virtually indistinguishable. In contrast, the SMT gravels − while clearly Salt River in provenance − are much larger (Table 1). In addition, the lithologies of the SMT gravels are substantially different from the younger terrace gravels. Kokalis (1971) undertook an extensive study of clast lithology on the different terraces of the Salt River in the area of Figure 5, where Kokalis examined hundreds of clasts. A video of the collection process has been archived:

(http://www.azgs.az.gov/VISUALIZE/VIDEO/Pewe%20Collection/pewe2.mp4).

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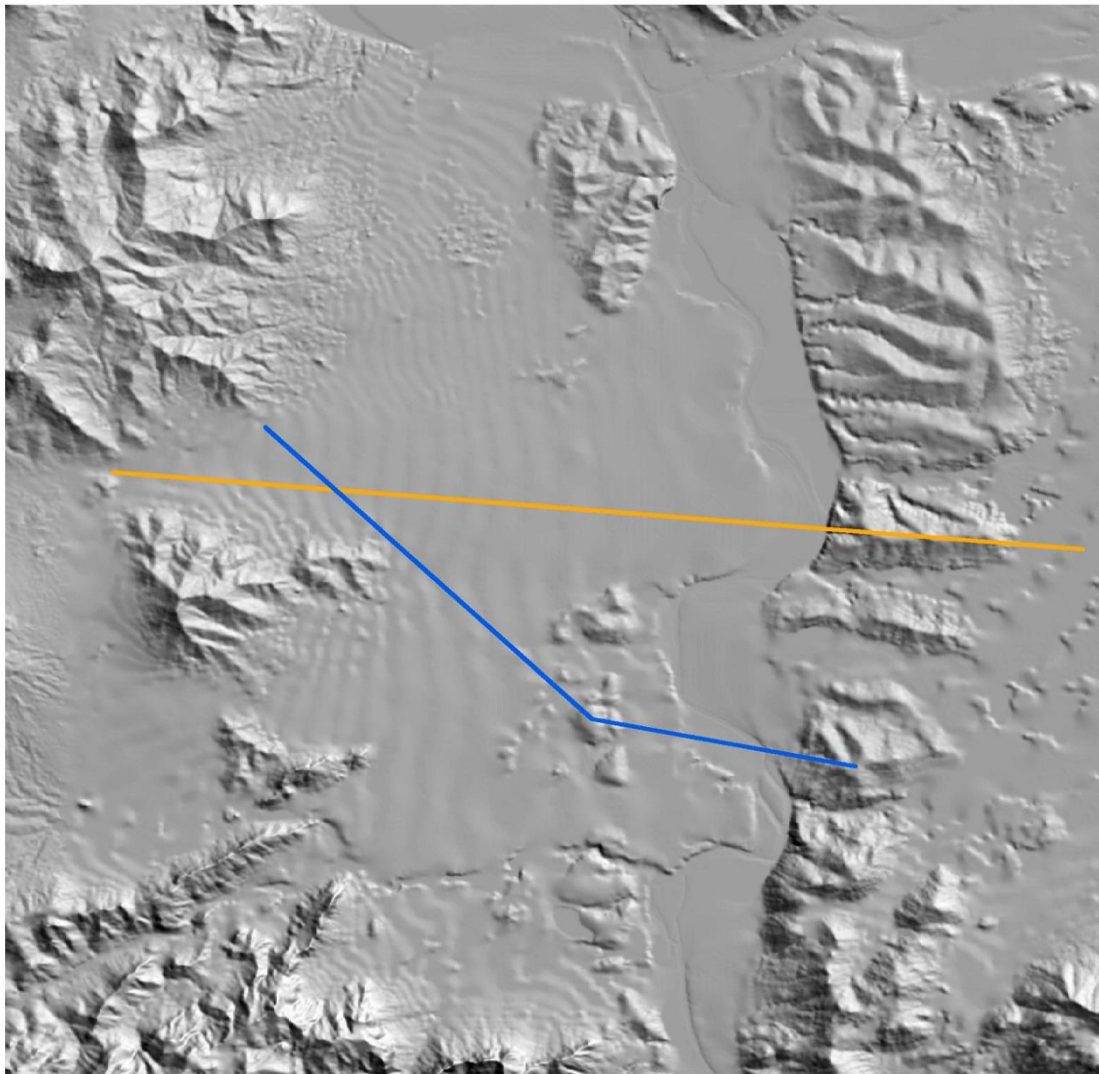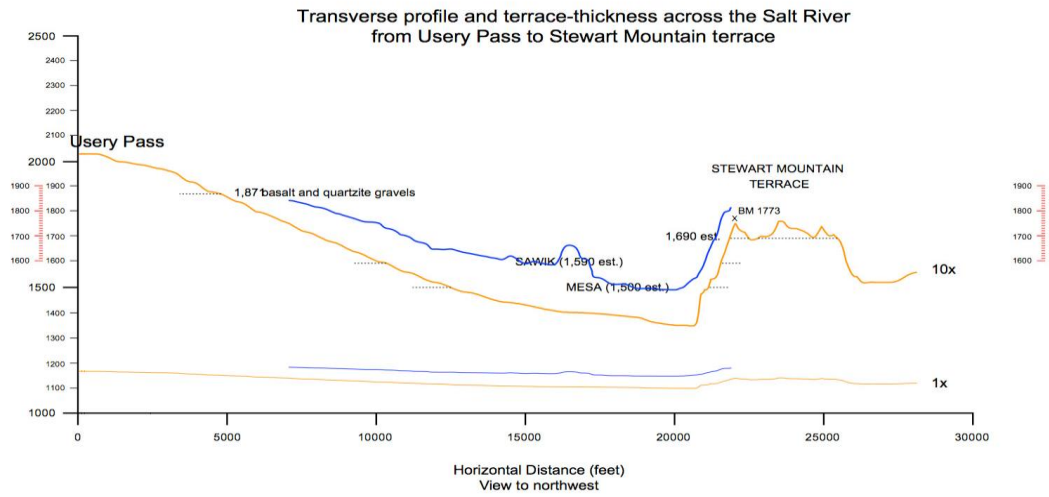
Figure 7. Two topographic profiles across the new terrace sequence. The profiles have

been exaggerated 10x and were created in ArcMap using high-resolution DEM elevation.

In addition, Kokalis also examined the composition of clasts in a location he
identified as valley fill — but we identify as a remnant of SMT. We are perplexed why
Kokalis did not correctly identify this geomorphic feature as belonging to the Salt River
terrace sequence. Still, it is significant that the composition of the Sawik and Stewart
Mountain terraces are distinct and significantly different from the younger surfaces
(**Table 1 and Fig. 8**).

TABLE 1

*Particle sizes and percent lithology of randomly sampled clasts on different Salt River
Terrace. Particle sizes were measured as a part of this study, but the lithology data
derives from Kokalis (1971).*

Particle sizes		Blue Point	Mesa	Sawik	Stewart Mountain
Number of clasts		314	354	360	160
Average (cm)		3.5	3.7	4.9	77.1
Median (cm)		3	3	3	66.5
Largest (cm)		22	21	34	258

Rock Type	Lehi	Blue Point	Mesa	Sawik	Stewart Mountain
Andesite	5	1	4	1	4
Arkose sandstone	3	4	3	15	3
Basalt	9	8	3	0	3
Dacite	3	3	2	6	1
Diabase, vein quartz and others	13	12	8	1	2
Granite	9	12	10	0	2
Meta-basalt	3	2	1	0	3
Meta-sedimentary	13	14	13	3	6
Orthoquartzite	14	18	24	43	21
Quartz monzonite	5	3	4	1	9
Rhyolite	6	8	8	10	40

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Siltstone and shale	10	7	10	13	3
Subarkose sandstone	8	6	10	7	3

Because river terraces can have pairs on the other side of a valley, we investigated the reach between 1600' and 1900' parallelling SMT on the south side of the Salt River and found only one location that contains anomalous quartzite and basalt cobbles. This location lies between 1600' and 1820' just west of the Usery Pass Road (labeled basalt and quartzite gravels; **Fig. 5** and **Fig. 7**). These clasts do not form a river terrace, but represent the base of an anomalous old gravel deposit resting on granodiorite bedrock.

Fig. 8. The Stewart Mountain terrace hosts an abundance of boulders with intermediate axes larger than 2 meters in diameter. In contrast, it is difficult to find boulders with the axis more than a half-meter in diameter on the lower Salt River terraces.

DISCUSSION

The general model (e.g., Péwé, 1978 and personal communication) for the past

thirty years has been that the lithology, and hence source areas, of the Salt River terrace

gravels has remained relatively similar. This model also suggested that the slope of the

terraces, which decreases from Sawik to Lehi, reflects epeirogenic uplift of the transition

zone in Arizona and possibly subsidence of the Phoenix Basin, resulting in the passive

rotation of the terrace surfaces over time (**fig. 9**).
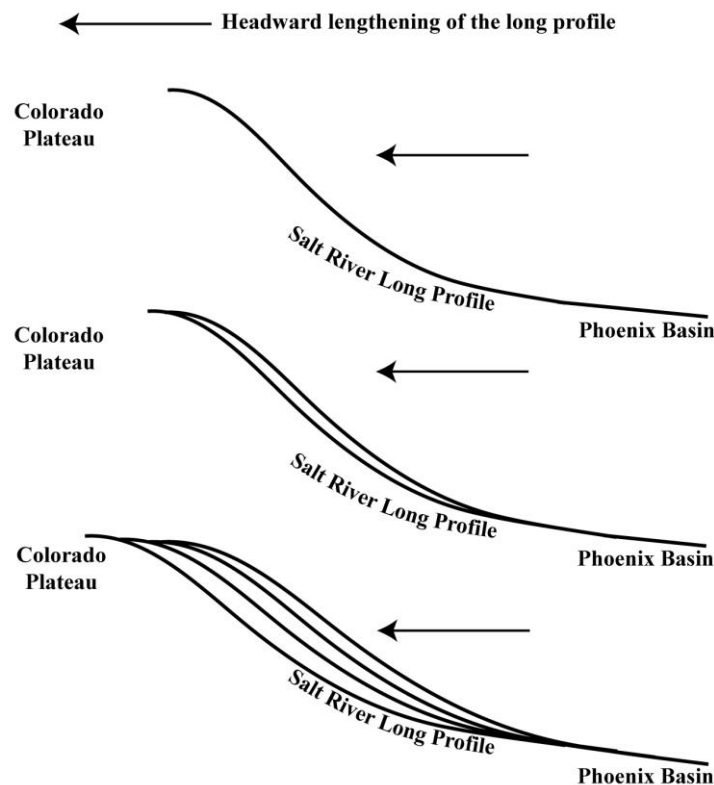
Fig. 9. Model of neotectonic uplift resulting in present terrace slope and morphology
along the Salt River, based on ideas presented by Péwé (1978, personal communication).
This model would produce similar rock types for each terrace, since the source areas
would be similar. This model also reflects the characteristic change in slope that can be
observed in Salt River terraces. As suggested, uplift of the transition zone and subsequent
subsidence of the Phoenix Basin may have allowed for the terraces to passively rotate
establishing their present change in slopes. This diagram is modified from Block (2007).

Following Péwé (1978, personal communication), available data are consistent with similar source areas for the Lehi, Blue Point, and Mesa terrace gravels. However, the Sawik and SMT gravels appear to have somewhat different lithologies, a finding that indicates a shift in the provenance of Salt River gravels (**table 1**). A full understanding of the potential source areas of these gravels is a project beyond the scope of this research; however, at this point, the substantial change in observed gravel rock types justifies reinvestigating the Salt River terraces **fig. 9**.

The observed change in terrace slope over time (Péwé, 1978, personal communication; **fig. 3**) and the change of rock types would be consistent with an alternative explanation for the older terraces having progressively steeper longitudinal profiles. Enlarging the drainage area of the Salt River would alter its longitudinal profile (**fig. 10**). At any given location along the Salt River, the gradient would be lowered every time the Salt River's drainage area increased. Headward extension of the Salt River could be relatively rapid, through the initiation of through-flowing drainage by lake overflow (e.g. Douglass et al., 2009a, 2009b). Alternatively, headward extension of the drainage up into the Mogollon Rim could also be gradual. Either process of headward extension could produce the observed change in lithology and progressively increasing slopes of older terraces.
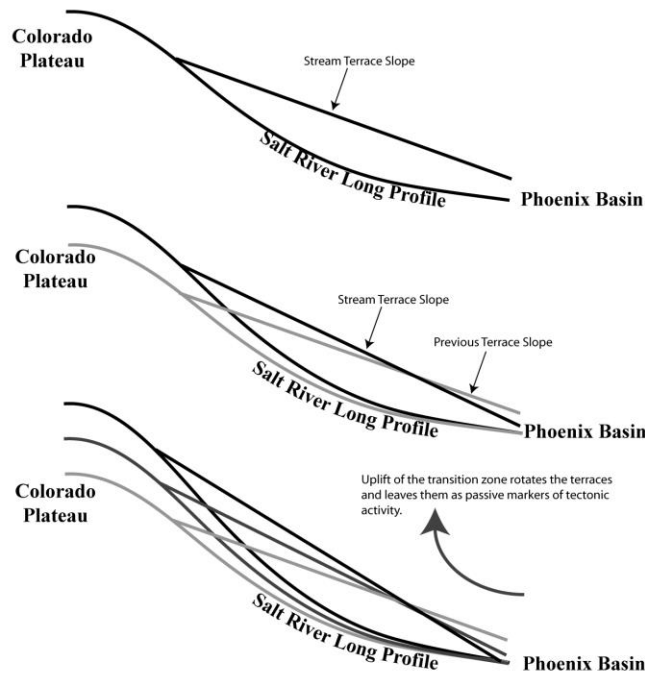
Fig. 10. Enlargement of the Salt River's drainage area generates increasingly steep slopes of older Salt River Terraces through headward extension of the Salt River's long profile. Extension of the long profile would result in a decrease in local slope at any given location. In this conceptual model, the initiation of through-flowing drainage would lengthen the long profile of the Salt River over time.

The model, tentatively favored here, for initiation/localization of through flowing drainage of the Salt River and the occurrence of the SMT is the overflow hypothesis of Douglass et al. (2009a, 2009b). Further supporting this model is previous research suggesting lacustrine sediments from a large Pliocene lake exist in the Tonto Basin upstream from the SMT (Peirce, 1984). Using the analog of the inception of the Lower Colorado River (House et al., 2005), lake overflow first results in extensive erosion of the preexisting fanglomerate fill, followed by river aggradation (possibly the SMT gravels) and finally punctuated by dramatic incision until a new base level is reached. The meter-plus diameter gravels of the SMT and underlying calcrete have formed an effective caprock that has preserved the underlying valley-fill sediments. The presence of these

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large erosion resistant gravels and calcrete could potentially explain the prominent topographic ridge that extends westward from the granite bedrock of Stewart Mountain that separates the lower Salt and lower Verde River valleys (**fig. 11**).

Because the SMT gravels represent the highest known position of the Salt River, a corollary question is how much fanglomerate eroded from the basin before the SMT gravels were deposited. The highest recorded position of basin-fill deposits come from Skotnicki and Leighty (1997, p. 11) who write:

"Projection of the basin-fill deposits on the north side of the [Salt] river southward suggests that the piedmont south of the river was also once buried by basin-fill deposits. South of the map area in the Apache Junction quadrangle, a high remnant of these deposits rests on the northeast side of Pass Mountain about 2400 feet (T2N, R7E, S25). This means that at least 1000 feet of basin-fill sediments were removed prior to deposition of the Sawik terrace -- prior to about the latest Pliocene."

We have not yet been able to confirm this observation, but there is only about 161 m between the highest SMT position and this remnant. Thus, the overflow event would have had to remove about 161 m of prior valley fill before the onset of aggradation and gravel deposition. Such initial incision is an expectation of the lake overflow process (e.g. House et al., 2005).

Lake area and height of retreating knickpoints determine the severity of the initial overflow event. Initially the overflow water only transports sediment sourced downstream from the lake, as upstream sediment is trapped in an endorheic basin. If an overflow event occurred it would start out by eroding a channel in the pre-existing rocks, because the pre-existing lake would have to be drained completely before a through-

flowing stream could transport up-basin gravels. We speculate that erosion of these pre-existing rocks could possibly explain the substantially different lithology of SMT gravels. Floodwaters rapidly incising into pre-existing bedrock and channels would accelerate removal of valley fill sediment.
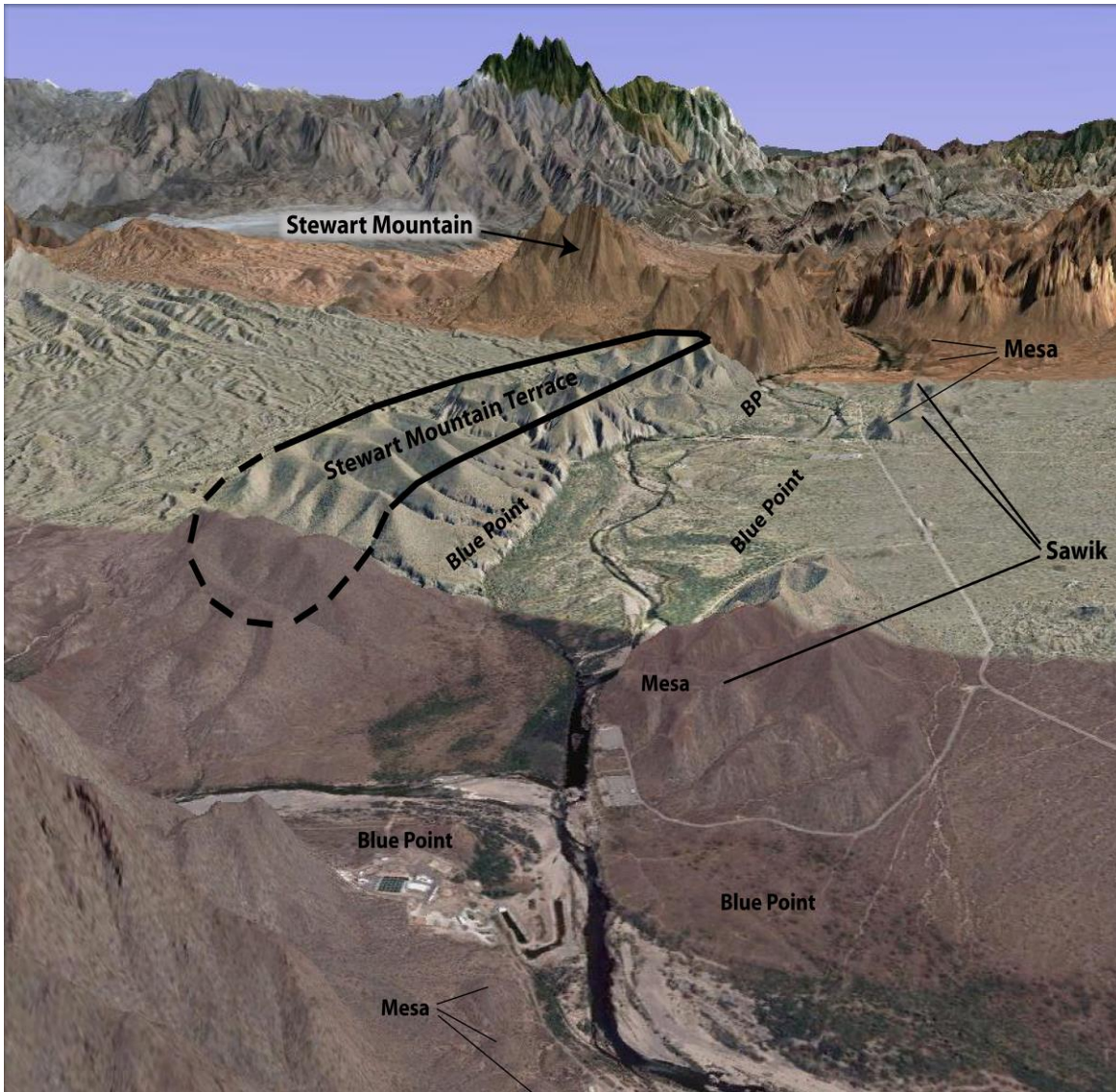
Fig. 11. East-looking Google Earth view of the Salt River Terraces mapped in Figure 4. The Stewart Mountain gravels rest on top of a prominent ridge. The image is used following permission guidelines for Google Earth.
[http://www.google.com/permissions/geoguidelines.html]

Following the hypothesized overflow event, accumulated sediment stored in the previously closed Tonto Basin would mobilize along the newly lengthened Salt River. The high sediment discharge forces the river to rapidly aggrade in order to steepen the channel and increase the river's slope. The Stewart Mountain gravels could represent this aggradational event. The steeper slope supplies the shear stress or stream power necessary to move the large influx of sediment (Ritter, 2002; Bagnold, 1973; Bagnold, 1977). As the amount of stored sediment supplied to the Salt River wanes, the river no longer requires the steeper slope and will then more gradually establish a shallower gradient approaching a graded state through periodic incision (Schumm, 1965; Schumm, 1977).

We speculate that the Mesa Terrace may represent this return toward equilibrium, and we speculate that the Sawik gravels could represent the Salt River's slow adjustment towards this equilibrium. It is also possible that SMT gravels did not herald the breaching of the Tonto Basin and that the Stewart Mountain Terrace similarly represents the Salt River's adjustment towards equilibrium however the existence of the SMT is strongly consistent with the overflow hypothesis, but neither is proof of the other.

CONCLUSION

Stream terrace sequences provide vital evidence in studies of the evolution of drainage basins. The newly discovered Stewart Mountain Terrace, introduced here, represents a significant addition to scholarship on the Salt River's drainage. The unique position, lithology, and particle sizes of Stewart Mountain gravels suggest that the

previous neotectonic uplift model proposed by Péwé (1978) and modified by Block (2007) may require revision. The existence of the Stewart Mountain terrace reveals a need to reinterpret the Plio-Pleistocene evolution of Salt River fluvial system in central Arizona. Although chronometric studies will be needed to analyze the newly discovered sequence of events in the landscape evolution of the Salt River Valley, we note that lake overflow model proposed by Douglas et al. (2009a, 2009b) predicted the occurrence of a feature such as the Stewart Mountain Terrace. While available data are consistent with lake overflow as the process responsible for initiating the through-flowing Salt River fluvial system, many questions surrounding a lake-overflow mechanism remain to be answered.

Chapter 6

CONCLUSION

> "the study of fluvial terraces of small watersheds in the arid zone seems
> to have been neglected." (Schick 1974)

Summary.- This dissertation assembles four field-based case studies of drainage basins containing fluvial terraces within the Sonoran Desert, south-central Arizona. Each studies purpose contributes insights that perhaps will help lead to a broader conceptual model regarding the formation and distribution of fluvial terraces in arid environments. These studies were conducted at varied drainage basin scales, over different lithologies, and in hydrologically different fluvial systems.

The "alluvial fan-cut terrace: A review and criteria to differentiate from fluvial terraces," was the first study in this work. This research was conducted to determine the relationship between fluvial terraces and alluvial fans in a single basin. Alluvial fans and fluvial terraces often form within a single drainage basin within the Basin and Range. These forms can often be misinterpreted from one another toward the axis of a drainage basin, where basin axial drainage incision can leads to incision into a floodplain or into distal alluvial fan deposits graded toward the basin center. The confusion that can result can also be compounded by the lack of a single definition for the incised fan unit. In this study, it is purposed that the term fan-cut terrace be used and a criteria is established for future researcher to differentiate this form from fluvial terraces. This criteria was then applied to a case study in the Bursera Valley of South Mountain, Arizona, and using these criteria a fan-cut surface was discovered as well as isolated inset fluvial terrace remnants.

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The second study, "Strath development in small arid watersheds: Case study of South Mountain, Sonoran Desert, Arizona," was conducted to shed light on the nature of small drainage basins that contained abundant strath terrace remnant surfaces. Within these drainages two mechanisms are responsible for strath development: piracy and strath cut at the expense of weathered bounding pediments. Strath grow at the expense of pediments due to an asymmetry of erosion with greater weathering concentrated on the channel banks, compared to channel bottoms. This process was observed in several flash floods. Aggradational piracy along the margins of the range also can result in strath formation. Piracy leads to an increase in drainage area and regrading of the stream's longitudinal profile. The increased drainage area accessed during long profile adjustment forms a bedrock strath immediately downstream of the capture point, while post-piracy adjustments form straths upstream of the capture. This is later followed by incision abandoning the strath as a terrace. The timing of this incision is discussed in Chapter 3 and the various incision events are possibly tied to climate and base level fluctuations.

The third study conducted, "The control of base level on pediment processes, a case study from the lower Salt River Valley, central Arizona," investigated the interaction of pediments, terraces and the major basin drainage (i.e. the Salt River) to see determine how piedmont surfaces respond to fluctuations in base level, indicated by fluvial terraces. The scholarly research on granitic rock pediments includes very little discussion on the role base level fluctuations. This study investigates the controls of base level on granitic rock pediments flanking inselberg mountain ranges in south-central, Arizona. When base level is lowered, terrace incision occurs and pediments respond by

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regrading to strath floodplains of the Salt and Verde rivers, this morphologic relationship

is termed the pediment-strath relationship. Beginning with headward knickpoint

regression, pediments regrade through different mechanisms working in concert:

headward erosion; stream piracy; and lateral migration. The effectiveness of re-

pedimentation is tied to the size and length of the pediments. Stream piracy processes

resulting from headward eroding drainages work to increase drainage area of the

capturing stream and lowering the relict pediment surface over time. Finally, lateral

erosion occurs predominantly in the distal reach of the master pediment drainages when

drainage area is sufficient. It also occurs when large pediment drainages converge, also

suggesting a drainage area relationship facilitating lateral erosion.

The last study, "Stewart Mountain Terrace: A new Salt River terrace with

implications for landscape evolution of the lower Salt River valley, Arizona, " was

conducted in order to investigate the nature of integration processes and fill terraces

within this regions. Troy Pewe's work on the Salt River established the backbone of

this research. This study builds upon his classic terrace sequence. A topographically

higher, sedimentologically different terrace was discovered along the lower Salt River. It

is hypothesized herein that initial integration and overflow of the Salt River from the

Tonto Basin is reflected in this Stewart Mountain Terrace (SMT). SMT sediments are

characterized by ~50 m thick fluvial gravels found more than 70 meters above remnants

of the Sawik terrace. Because of sedimentological difference of the SMT, the SMT has

profound implications for the understanding of regional drainage reorganization after

basin and range extension. The existence of this terrace and its distinct gravels are

consistent with, but do not prove, a lake overflow mechanism for the initiation of through flowing drainage in the Salt River valley.

Future Research.- South-central Arizona is a region of the Basin and Range physiographic province with particular significance, because it represents the future of the province that has not yet experienced drainage integration. The case studies within this dissertation, thus, provide a conceptual framework for fluvial terrace development and drainage basin evolution within this region. To verify whether or not these phenomenon are Basin and Range wide processes in reaction to basin evolution and responsible for fluvial terrace development, future research will be conducted on integrated drainages (i.e. Verde River and Mojave River) to see if similar processes can be identified and described.

Using the Verde River as an example, Mapping strath terraces will further assess of the validity of the pediment-strath relationship using aerial photography, differentially corrected global positioning systems, and remote sensing techniques. Cosmogenic nuclide analyses on terrace deposits and on incised pediment surfaces will establish a geochronology of these processes. Ground penetrating radar will examine the subsurface sedimentological contacts within the Verde Basin. Detrital zircons will be applied to the terraces within the Verde River to understand the nature of the integration and post-integration deposits. Further analysis of pediments bounding the Verde River will facilitate a further understand the dynamics of pediment surfaces.

In all, the research herein combined with the proposed future work should paint a picture for how drainage basins evolve post-integration within the Basin and Range. The

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far reaching goal is to develop a detailed hypothesis that fully describes these processes, along with numerical and physical models to test this hypothesis.

Intellectual Merit.- Ultimately, this dissertation advances theoretical understanding about four fundamental topics within geomorphology. First, the nature of fill terraces discussed in Chapter 4 (Lousley Hills) and Chapter 5 (Stewart Mountain terrace) in this region appear to be tied to process and recording processes of lake overflow integrating drainages in the Basin and Range. Although the hypothesis proposed by House et al. (2005) is for a much different river system, the lower Colorado, I hypothesize that lake overflow and integration is the key mechanism by which drainages integrate in the Basin and Range province.

Hypotheses developed in this work on strath terraces represent the second major contribution to geomorphology. Asher Schick (1974) suggested that a theoretical understanding of arid stream terraces in small drainage basins is largely lacking . Montgomery (2004) stated that the understanding of strath terraces is far inferior to that of their fill terrace counterparts. Therefore, I investigated strath terraces at two varied scales of drainage size in this dissertation- one large (Salt River-Chapter 4 and 5) and one small (South Mountain-Chapter 3).

I observed a morphologic and genetic relationship between strath terraces and the pediments that bound them termed here the pediment-strath relationship. Strath terraces form at the expense of the adjacent pediments through the erosion by a laterally migrating stream. This relationship was observed in both scales: along the Salt River and in drainages less than five square kilometers in area. A weathering asymmetry in these systems facilitates the lateral erosion. For the small drainages of South Mountain,

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channel banks were much more highly weathered than channel floors. Based on a few observations, this weathering asymmetry appears to exist along the Salt River, although future research will be needed to test this hypothesis.

A third theoretical contribution relates to the minimal research previously conducted on the impact of base-level fluctuations on pediment development. Since the pediment-strath relationship requires pediments that roughly grade to strath surfaces, pediments must respond to changes in the river level over time. I, thus, hypothesized that pediments actively respond as alluvial landforms, both aggrading and degrading in response to base level change. Base level lowering results in suite of headward eroding processes that bevel the pediment over time including: capture, lateral planation, and knickpoint recession. The efficiency of the pedimentation processes roughly correlates to pediment basin size and length. Using field evidence, relict pediments were reconstructed using kriging methodologies in ArcGIS; the volume of material between these reconstructed ancient surfaces and the modern surface were used to estimated erosion rates.

These first three contributions (fill terraces as a response to basin integration, the pediment-strath relationshiop, the importance of base level on pediment evolution) all tie into the much larger contribution of this work - to begin to understand the connection between drainage basin evolution and landform development in the Basin and Range province.

Broader Impacts.- In addition to the intellectual merits of this dissertation, there are several far reaching impacts for society. First, local Arizona residents, winter snowbirds, and visitors to the Sonoran Desert exhibt basic intellectual curiosity about the

natural history of south-central Arizona and the Sonoran Desert. Visitation to parks, trails, and natural history museums exhibit this interest. This area is a mecca for outdoor recreation enthusiasts. From campers, mountain bikers, rock climbers, boaters, and hikers, these many visitors are curious about the unique landscape they see here. This work can help provide background information to those who visit these areas. For example, county parks like the McDowell Mountains Regional Park sits within the lower Verde Valley and display many of the features seen in this dissertation. The thousands of users of the lower Salt River valley float by many of the terraces and pediment features I discuss.

Engineering and construction projects could benefit from this research. Engineers developing roads and other infrastructure projects may not realize the nature of the pediment-strath relationships or the active nature of the pediment form and channel banks. For example, construction along the banks of rivers bounded by pediment surfaces may not be a safe housing choice given that the formation of strath floodplains occurs at the expense of bounding pediments. The same holds true for bridge construction and roads where erosion can cause failure or collapse of these structures. Sedimentary basins are often utilized as sources of ground water, fossil fuels and mineral resources. Use of these resources connects to the history of how these basins evolved. The hypothesis tested here on how basins evolve over time could lead to advancements in the search for resources within the Basin and Range province.

Lake overflow appears to be a common process at many locations across the globe, whether the lake forms by landslide dam, by volcanic action, or artificially. This research supports the hypothesis that lake overflow is a prominent mechanism by which

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basins integrate. The previous research conducted by House et al. (2005) and the research

I conducted here could lead to insights into the risk potential and landscape response

associated with lake overflow processs. Furthermore, the removal of dams produces an

effect similar to lake overflow; thus the landscape response to lake overflow in the

Sonoran Desert could help develop a better understanding of the future of drainages

impacted by dam removal.

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