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Pediment response to drainage basin evolution in south-central Arizona

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The Sonoran Desert portion of the Basin and Range physiographic province contains a number of streams that now flow across once-closed basins. We explore here the research questions of if and how granitic rock pediments respond to the transition from rimming endorheic basins to bordering through-flowing streams. Granitic rock pediments of the northern Usery and eastern McDowell Mountains once graded to the closed Miocene–Pliocene Pemberton basin that occupied the present-day location of the confluence of the Salt and Verde Rivers. The process of lake overflow, which integrated these rivers, first aggraded fill terraces that, in turn, caused aggradation of a mantle of transported grus on bedrock pediments. Subsequent episodic incision of the Salt and Verde rivers lowered the base level; this led to the development of erosional features such as rolling topography of a degrading pediment mantle; exposure of the former piedmont angle and its associated zones of enhanced bedrock decay and regolith carbonate; and exposure of spheroidally weathered bedrock and emerging tors, some of which experienced 20th century erosion. The granitic pediments of the former Pemberton Basin, which now transport grus to the Salt and Verde rivers, have actively adjusted to aggradational and degradational events associated with drainage integration and do not appear to be inherited from an ancient wet climatic interval.

Keywords: drainage basin evolution; pediment; Basin and Range; fluvial terrace; carbonate; landscape evolution; granitic landscapes; Sonoran Desert

Introduction

Extensional faulting in the Sonoran Desert portion of the Basin and Range physiographic province, southwestern USA, led to a landscape of endorheic basins surrounded by bedrock pediments and alluvial fans (e.g., Christiansen & Hamblin, 2007). Unlike more active tectonic portions of the Basin and Range, the Sonoran Desert experienced the disappearance of closed basins, as through-flowing streams like the Gila, Salt, Verde, San Pedro, Queen Creek, and Agua Fria Rivers integrated. The last quarter century of research has started to point to a common mechanism responsible for drainage integration in the Basin and Range: the process of lake spillover, or overflow (e.g., Dickinson, 2013; Douglass, Meek, Dorn, & Schmeeckle, 2009a, 2009b; House et al.,

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2005; Jungers, 2012; Jungers & Heimsath, 2013; Larson, Dorn, Douglass, Gootee, & Arrowsmith, 2010; Meek, 1989, 2004; Menges & Pearthree, 1989; Reheis, Miller, & Redwine, 2007; Spencer et al., 2013).

Scholarly research on granitic rock pediments focuses on a variety of factors responsible for pediment evolution and formation – discussed in depth in numerous reviews (e.g., Cooke & Warren, 1973; Dohrenwend & Parsons, 2009; Oberlander, 1989). We have not found, however, prior research on the response of pediments to hydrologic integration – a process that involves dynamic base-level fluctuations (Douglass et al., 2009a, 2009b). Only a small segment of the pediment literature concerns the role of base-level change in pediment development. Even Davis (1933) did not consider the role of base-level fluctuations on pediment evolution, nor is base-level change considered in some contemporary modeling (Pelletier, 2010). This is not to indicate that base level has been completely neglected; Koschmann and Loughlin (1934, p. 374), for example, suggested that pediment dissection may be connected to the lowering of "streams that drain … basins." It is clear that pediments often experience "dissection," but the complexities of drainage pattern development and mechanisms for dissection are not well understood (Dohrenwend & Parsons, 2009). The minimal attention paid to the topic of how pediments respond to base-level change may be due, in part, to a focus of the previous literature on pediments as relict landforms inherited from deep-seated weathering during previous wet/humid climatic regimes (e.g., Mabbutt, 1965; Moss, 1977; Oberlander, 1972, 1974, 1989; Twidale, 1968).

We focus here on two interrelated research questions: (1) how do pediments respond to drainage integration and associated base-level changes?; and (2) how does this response inform the debate over whether pediments are relict landforms? This paper presents the results of a pilot investigation into the response of granitic pediments to drainage basin evolution and episodic base-level adjustment in the Sonoran Desert, where pediments are ubiquitous (Applegarth, 2004; Parsons & Abrahams, 1984). We focus here on the lower Salt and Verde rivers, south-central Arizona (Figure 1).

Using fieldwork, supplemented by aerial photography and electron microscope studies, we present evidence that the observed granitic rock pediments are not inherited landforms from an ancient wet period of time, as some have suggested. Instead, these pediments respond actively to post-integration base-level changes.

Geomorphic setting of the study area

The confluence of the Salt River and Verde Rivers occurs approximately 40 km northeast of the heart of the Phoenix Metropolitan area (Figure 1). This location formerly hosted the endorheic Pemberton basin. The Pemberton playa deposits consist of intercalated red clays with thin gypsum beds (Pope, 1974; Skotnicki, Young, Goode, & Bushner, 2003). This thick playa deposit aggraded during a semi-arid climate into a deep structural basin. The playa surface once served as a slowly aggrading base level for pediments and alluvial fans draining the surrounding McDowell, Usery, and Mazatzal Mountains (Figure 1). Like other endorheic basins within the Basin and Range, the Pemberton basin originated from regional extension; in this case, extension largely terminated approximately eight million years ago (Menges & Pearthree, 1989). The basin remained closed throughout the Miocene and Pliocene (Pope, 1974).

Sometime in the late Tertiary or Quaternary, a paleolake in the position of present-day Tonto Basin overflowed into the Pemberton basin (Douglass et al., 2009a, 2009b; Larson et al., 2010). This integration event also led to breaching of the southwestern

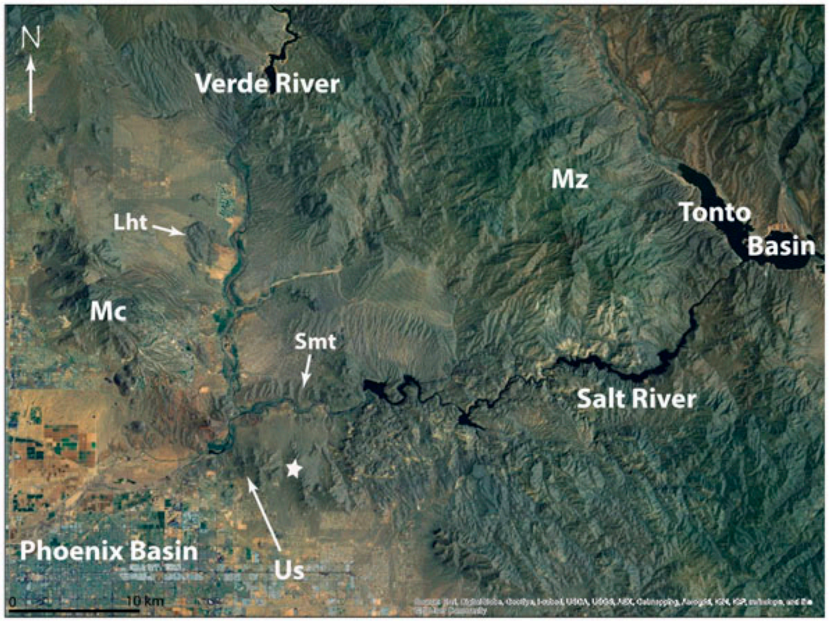

Figure 1. The Salt and Verde watersheds supply a major portion of water to metropolitan Phoenix. The two incising pediment systems under study are just upstream of the junction of these rivers. The northern Usery Mountain (Us) pediments flank the Salt River to the south, and the McDowell Mountains (Mc) pediment forms a western boundary of the Verde River. The Pemberton playa formed in a closed basin, bounded by the Mc, Us, and Mazatzal (Mz) mountains, created by Basin and Range faulting. Sediments deriving from Mz in the east dominated the basin's sediment budget, pushing the playa towards the Mc and closing off the basin's southern boundary. The highest terraces marking the integration-related aggradational episode are noted on this map as Smt (Stewart Mountain terrace – Salt River) and Lht (Lousley Hills terrace – Verde River). The star marks the location of Pass Mountain, the site of our long-term erosion rate estimations.

sill of the Pemberton basin and resulted in a westward hydrologic extension into closed basins occupying what is now metropolitan Phoenix (Figure 1). Subsequent knickpoint recession and excavation of sediment stored in the upstream Tonto Basin resulted in aggradation of boulders and cobbles in the Stewart Mountain fill terrace of the Salt River (Larson et al., 2010). These Salt River clasts are also recorded in wells throughout the Phoenix Basin as a rapid event, aggrading directly on top of ephemeral desert washes:

> 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 surprisingly 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 & Barlett, 2002)

Little is understood about the timing of these events within the lower Salt and Verde Basin (Figure 1). However, mapping projects by the Arizona Geological Survey, a field trip guide book (Péwé, 1978) and research on the Salt and Verde fluvial terraces (Block, 2007; Kokalis, 1971; Larson et al., 2010; Pope, 1974; see Figure 2), provide a basic understanding of fluvial terraces that represent the former base levels of the ephemeral pediment washes.

Figure 2. Pediments have adjusted to episodic incision along the Salt and Verde Rivers within this field area, where incision is marked by the existence of pronounced fluvial terraces along both rivers. This map of the Salt River terraces, modified from Larson et al. (2010), identifies, in order from highest to lowest, the Stewart Mountain fill terrace (SM), Sawik strath terrace (S), Mesa strath terrace (M), and Blue Point strath terrace (BP). A similar sequence of terraces exists along the Verde River.

The lower Salt and Verde Rivers are bounded by granitic ranges of the Usery Mountains to the south and northern McDowell Mountains to the west. While the southern McDowell Mountains and Mazatzal Mountains to the east (Figure 1) generate coalescing alluvial fans, the Usery and northern McDowell Mountains are flanked by gently sloping granitic rock pediments hosting ephemeral drainages transporting predominantly sand-sized grus (e.g., Figure 3).

Methods

Field observations, measurements, and aerial photography

Field work in the study area involved ground and aerial perspectives to assess spatial relationships of pediment landforms and drainage patterns developed within piedmont systems. Aided by differentially corrected global positioning systems (dGPS), we collected topographic data to study the morphological relationships between pediments and base-level changes of the Salt and Verde rivers. We also measured sediment thicknesses in the field to compare aggradational and degradational sequences. High resolution, oblique, low-light aerial photography, imaged during two flights, provided an alternative perspective for understanding spatial relationships.

Electron microscopy

We conducted electron microscope studies of regolith carbonate and of the weathering of granitic rock at the piedmont angle to assess whether a relict pediment surface, graded to a higher base level, once existed in the study area. Water flows down the bedrock surface of an inselberg into the grus cover on a pediment; carbonate is deposited under the mantle of grus, as water flows along the grus/bedrock contact (Hill, 2005; McQueen, Hill, & Foster, 1999). The regolith calcrete is seen at the surface only where the former mantle of sediment has been eroded. To assess the hypothesis that the exposed carbonate is regolith and not pedogenic carbonate, we analyzed textures using electron microscopy (cf. Dart, Barovich, Chittleborough, & Hill, 2007; Holbeche, Gilkes, & George, 2010; Jacobson, Arakel, & Yijian, 1988; Mann & Horwitz, 1979; McQueen et al., 1999; Nash & McLaren, 2003). If the observed carbonate is regolith, and not pedogenic, then subaerial exposure of the regolith carbonate would record the minimum height of a former pediment surface.

Granitic bedrock experiences enhanced grus formation at the piedmont angle. Oberlander (1989) explained that water flowing down bedrock inselberg slopes tend to collect at the base of the slope where the water infiltrates into joints and grus (Oberlander, 1989). With base-level lowering promoting dissection of a pediment, a zone of exposed enhanced weathering near the base of an inselberg slope could reflect the former presence of this piedmont angle. Thus, we evaluated four zones in the northern Usery Mountains of what appears visually to have experienced enhanced weathering. These zones were compared using electron microscopy on samples collected 2 m above and below the base.

The process of sample preparation for imaging with back-scattered electrons (BSE), high-resolution transmission electron microscopy (HRTEM), and energy dispersive X-rays (EDX) analyses starts with polished cross-sections. 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.

Microlaminations and lead-profile study of rock varnish on inselberg surfaces

Thirty varnish microlamination (VML) samples were collected from different bedrock surfaces in the Usery and McDowell Mountains. VML was used to test the hypothesis that well-varnished surfaces of inselbergs reflect a very stable landscape (Oberlander, 1974). The inselberg-pediment system is known as the pediment association and is considered a reflection of the processes operating across the entire piedmont (Cooke, 1970). We used VML to evaluate whether or not these inselberg-pediment systems are active or "paralyzed" (Oberlander, 1989, p. 73). VML samples collected from 30 randomly selected locations and polished as ultra-thin sections were compared to the Holocene and Pleistocene calibrations established by Liu and colleagues (Liu, 2003; Liu & Broecker, 2007, 2008a, 2008b, 2013; Liu, Broecker, Bell, & Mandeville, 2000). Since varnish forms after an erosional event, the VML sequence provides an approximate age for when the surface last eroded.

In a third of the randomly selected locations, only millimeter-scale dots of varnish could be observed in the field. In these cases, we employed lead-profile dating. This method can identify whether or not varnish started to form in the 20th century when emissions from leaded gasoline interacted with the iron and manganese in varnish. Chemical profiles through the varnish that contain lead contamination throughout indicate formation during the 20th century (Dorn, 1998; Dorn et al., 2012; Hoar, Nowinski, Hodge, & Cizdziel, 2011; Spilde, Melim, Northrup, & Boston, 2013). Depth profile in which lead concentrations in the upper few microns are anomalously high, but lead concentrations below drop to natural background levels, indicate that varnish formation started prior to lead use in gasoline and continued into the 20th century (Dorn, 1998; Spilde et al., 2013).

The goal of both VML dating and varnish lead-profile methods is to evaluate when erosion last occurred on randomly selected bedrock surfaces as a means to assess the hypothesis that the pediment-inselberg systems are inherited from a previous wet period of time (Mabbutt, 1965; Moss, 1977; Oberlander, 1972, 1974, 1989),

Long-term erosion rates

A unique aspect of the study area is the presence of a 20.5 ± 1.5 Ma welded tuff deposit of the superstition volcanic field (McIntosh & Ferguson, 1998) that serves as a temporal marker. The welded tuff stands out as a light stripe at Pass Mountain of the Usery Mountains (e.g., Figure 4(A)). The base of the welded tuff includes granitic core stones on a planar erosion surface that we interpret as an ancient pediment. Below this buried erosion surface, the piedmont on the southern side of Pass Mountain (Figure 1) consists of pediments that slope downward to an elevation roughly approximate to the Mesa terrace level on the Salt River (Péwé, 1978).

To obtain a long-term approximation of erosion rates, we established 50 topographic profiles from the ancient granitic erosion surface to the top of modern pediments (Figure 4(B)). We located these profiles at positions where the contact between the base of the ignimbrite and the underlying erosion surface was not obscured by talus. Relief at each location was divided by 19 Ma (the younger end of the two sigma $^{40}Ar/^{39}Ar$ error reported by McIntosh & Ferguson, 1998). If no tilting, flexural isostacy, or normal faulting occurred at this site, then the entire relief would be a product of erosion. However, because no independent data exist to quantify rates of geological processes in generating the relief, the measured rate of meters per million years (or mm/ka) is a value best interpreted as a maximum limit for the long-term erosion rate of pediments along the margins of Pass Mountain.

Results

Field observations, aerial photography, and topography

One of the more notable features throughout the study area is a variably thick deposit of pediment-derived sediment found overlying almost every pediment (Figure 5). Preservation of this pediment mantle varies spatially. A wedge-shaped deposit of pediment mantle extends as far as 4 km upslope from the Lousley Hills fill terrace, with thicknesses exceeding 15 m in places. Anthropogenic activity along pediments on the south side of the Usery Mountains allowed for measurements of exposed thicknesses of up to 8 m of pediment mantle. Pediments on the northern side of the Usery Mountains also include fragments of this mantle, but maximum thicknesses only reach 4 m at present.

Pediments that drain to the modern-day Salt and Verde rivers display a wide range of different morphological features indicative of ongoing erosion. Five stand out: (1) rolling topography where a pediment mantle of deposited grus once accumulated, but is now eroding (Figures 6 and 7(B) and (C)); (2) subaerial exposure of zones of enhanced bedrock decay at the base of inselberg slopes (Figure 7(A)); (3) subaerial exposure of regolith carbonate where the former pediment mantle has been stripped away (Figure 7(D)); (4) incised pediments where the former bedrock surface remains relatively planar, topped with just a thin veneer of the pediment mantle (Figure 6); and (5) a topography of emergent tors where the mantle cover has been completely stripped exposing spheroidally weathered bedrock and tors (Figure 8).

A few Usery Mountain pediments do not topographically grade to the modern Salt and Verde rivers. Instead, these pediments (e.g., Las Sendas, southern Usery) transition to the Mesa terrace level and have very little relief (Figure 9). The only observed relief results from proximal drainage incision at the mountain front. Pediments topographically graded and draining to the Blue Point terrace (Figure 10) or modern Salt and Verde River channels (Figure 6) contain variable degrees of pediment dissection best seen in Figure 3.

Electron microscope study of regolith carbonate and pediment mantle

Electron microscope observations of regolith carbonate sampled from positions that could have been a piedmont junction graded to the Mesa terrace reveal textures similar to those observed for non-pedogenic regolith carbonates in arid regions. A great variety of textures exist in regolith carbonate (Dart et al., 2007; Holbeche et al., 2010; Jacobson et al., 1988; Mann & Horwitz, 1979; McQueen et al., 1999; Nash & McLaren, 2003). Mixtures of silica along with carbonate (Figure 11(A)) (Jacobson et al., 1988), fungal filaments encrusted with calcium carbon (Figure 11(B)) (Nash & McLaren, 2003), micrite pore-filling cement (Figure 11(C)), and laminar carbonate impregnating pore spaces (Figure 11(D)) (Nash & McLaren, 2003) exemplify textures seen in the Usery carbonates that formed when there was a cover of grus. These textures reflect SEM textures found in regolith carbonates elsewhere and are interpreted as having formed at or beneath a former piedmont angle (Figure 7(A) and (D)), at the contact between the now-eroded grus mantle and the underlying bedrock.

Electron microscope study of granitic decay at the piedmont angle

Zones of highly decayed granodiorite are seen at the base of inselberg slopes, typically in association with regolith carbonate (Figure 7(A)). Electron micrographs of decayed granodioite collected from what we interpret as a former piedmont angle (Figure 12(A)) reveal a state of little internal cohesion. The most decayed samples did not survive transport to the laboratory, and thus, micrographs presented here show only most cohesive material**.** Figure 12(A) presents the most cohesive material that also had the lowest porosity. Figure 12(B) shows the typical state of plagioclase decay. Biotite had completely decayed in most of the samples examined, as grussification has progressed beyond the initial stage of biotite decay (Isherwood & Street, 1976). Figure 12(C) exhibits one of the few pieces of samples where biotite fragments still exist, and even this sample is highly decayed. Figure 12(D) reveals that even the surface of quartz grains undergo decay through a process that could involve nanoscale hydration (Pope, 1995). Pope (1995) noted that the outer few nanometers of quartz loses its crystalline structure, and that is what we observe under high resolution transmission microscopy imagery (Figure 12(D)).

In contrast, samples collected 2 m above and below the former piedmont angle reveal evidence of much less weathering, showing extensive intact contacts between interlocking mineral grains. In summary, the micrographs reflect a state of decay where the granodiorite crumbles easily with just light fingertip compression, and these zones of intense decay occur at a former piedmont angle (e.g., Figure 7(A)) where water once infiltrated into a cover of grus (cf. Oberlander, 1989).

Figure 3. East-looking view of the Usery Mountains, which host several different pediment systems. The Bush, Twisted Sister, Mine, and Hawes pediments drain to the floodplain of the Salt River. However, the pediments on the southern side (e.g., Las Sendas) drain to the Mesa terrace elevation and hence have not yet experienced the last half-million years of adjustment to incision.

VML and lead-profile study

Thirty VML samples from random locations on the Usery and McDowell inselbergs display a range of minimum ages for when the bedrock surfaces last experienced erosional (Figure 13). The oldest preserved surface is a bornhardt dome's pressure release shell located above the top of the McDowell pediment (seen to the right of the Marcus landslide in Figure 14). The second oldest preserved surface is a boulder in a debris flow levee above the top of a pediment at the western end of the Usery Mountains. Nearly half of the surfaces were exposed in the Holocene. Almost a third of the ages have just a lead signature, indicative of a surface exposed in the 20th century (Dorn, 1998; Dorn et al., 2012; Hoar et al., 2011; Spilde et al., 2013). Thus, we found no

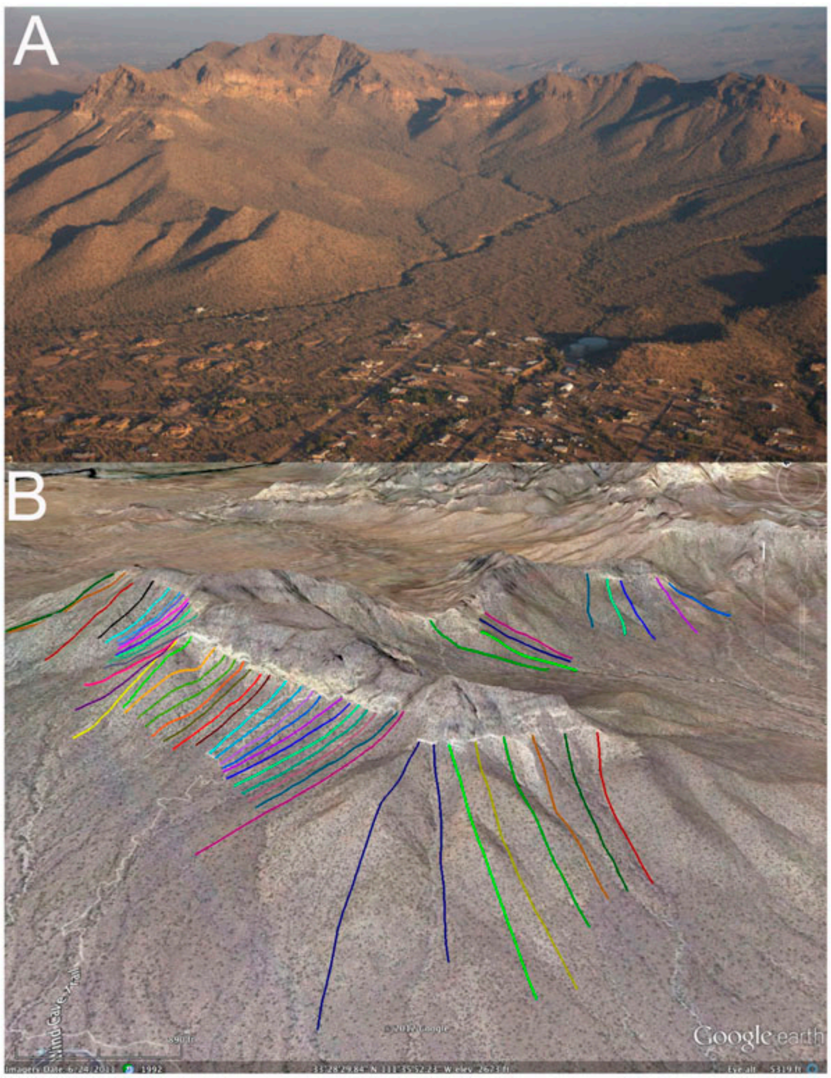

Figure 4. (A) An ancient granitic pediment rests underneath the oldest Superstition volcanic field eruption (McIntosh & Ferguson, 1998) (19–22 Ma). This basal eruption forms the bright cliff face towards the top of the Pass Mountain in the aerial photograph. The houses rest on a pediment graded to the Mesa River terrace. (B) The 50 topographic profiles shown in a Google Earth view provide a measure of relief generated by a combination of erosion, normal faulting, tilting, and flexural isostasy.

Figure 5. The top of the Pemberton Playa deposit is now an unconformity, where locally derived gravels preserve the landscape. These gravels at 619 m were deposited after the Lousley Hills aggraded, raising the base level of small washes derived from the adjacent McDowell Mountains.

evidence that inselberg slopes are paralyzed. Slope activity, instead, reflects mass wasting and ongoing hydraulic erosion of grussified granite throughout the latest Pleistocene, Holocene and into the 20th century (cf. Abrahams, Parsons, Cooke, & Reeves, 1984; Abrahams, Parsons, & Hirsch, 1985; Abrahams, Soltyka, Parsons, & Hirsch, 1990; Parsons & Abrahams, 1984, 1987).

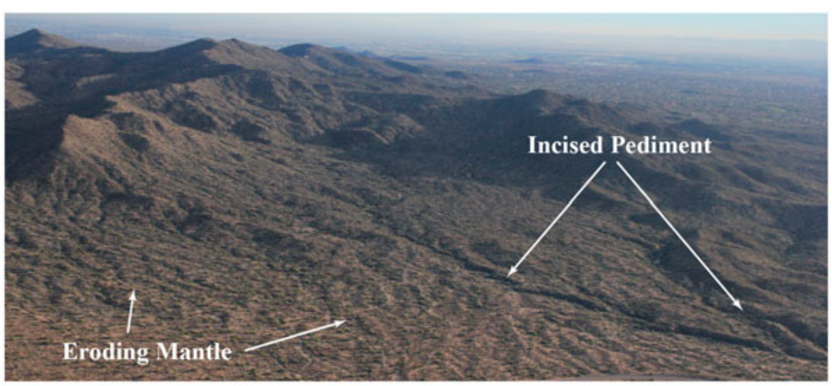

Figure 6. The Usery Pediments draining to the Salt River show two types of response to incision along the Salt River: (1) Pediment incision down to the modern river level, where only a thin mantle remains above the bedrock pediment surface; and (2) a rolling topography where the mantle cover is beginning to be dissected.

Long-term erosion rates

Welded tuff buries an ancient pediment at Pass Mountain in the Usery Mountains. The present-day relief between this ancient pediment and the top of modern-day pediments ranges from 63 to 174 m (Figure 4). Relief at this location is the result of several possible processes including: erosion, tilting, normal faulting, and/or flexural isostasy over the ca. 20.5 Ma time frame (McIntosh & Ferguson, 1998). If no tectonic activity occurred, all of the relief would be a product of erosion. However, since it is not possible to obtain rates on any one of these processes, the data presented in the box-and-whisker plot of Figure 15 only provides the maximum rate of pediment erosion at this one site from 20.5 Ma to the present.

Discussion

Pediments as active, not inherited landforms

One of the many unresolved issues regarding granitic rock pediments concerns the hypothesis that pediments and their backing inselbergs are fossil landforms inherited from a previous wet period of time (Mabbutt, 1965; Moss, 1977; Oberlander, 1972, 1974, 1989), an idea linked to the research of French and German geomorphologists

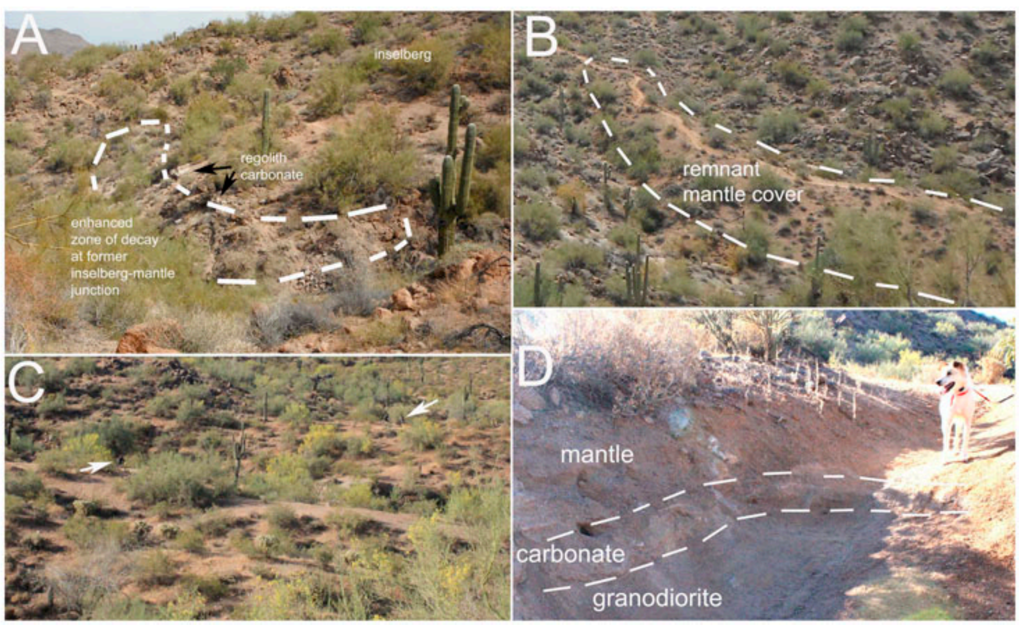

Figure 7. Ground images of the upper Mine pediment. (A) A zone of enhanced mineral decay occurs at the top of the Usery Mine pediment. We find these zones at the locations predicted by Oberlander (1989) who hypothesized that water moving down the inselberg face would seep into the ground, resulting in a zone of enhanced granitic rock decay. In addition, regolith carbonate forms where water flowing down the inselberg slope infiltrates into the sandy pediment mantle. (B) This 4-m thick remnant stretches over 100 m and almost reaches the base of the present-day inselberg. (C) Ongoing erosion of the pediment mantle produces topography of gently rounded ridges. Note the tors that are emerging in areas where the mantle has been completely eroded. Scale is provided by mountain bikers at the arrows. (D) Even though the granitic bedrock is thoroughly decayed, the sandy pediment mantle is still more porous and permeable. Thus, gravity water seeps down to the base of the sandy mantle, and water flows along the mantle-bedrock contact – depositing the regolith carbonate.

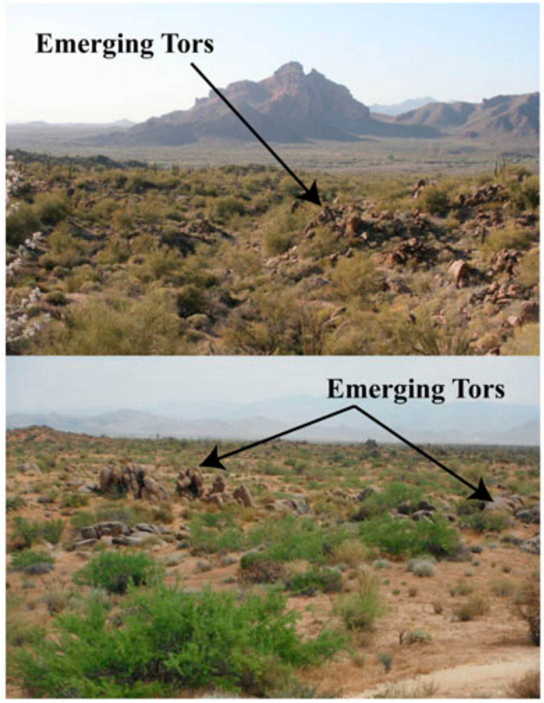

Figure 8. Both the Twisted Sister (top) and McDowell (bottom) Pediments serve as examples of tor emergence exposed by eroding pediments. We interpret the emergence of tors as the result of the adjustment of pediments to lowering.

(e.g., Büdel, 1982; Tricart & Cailleux, 1973). This view often accompanies the perspective that intense subsurface weathering during an ancient wet past plays a key role in creating the basic pediment-inselberg form (Bryan, 1925; Mabbutt, 1965, 1966, 1977; Twidale, 1967a, 1967b, 1968). In this view, the modern surface results from stripping decayed granitic rock, and this stripping took place within the increased aridity of the Quaternary (Oberlander, 1974, 1989).

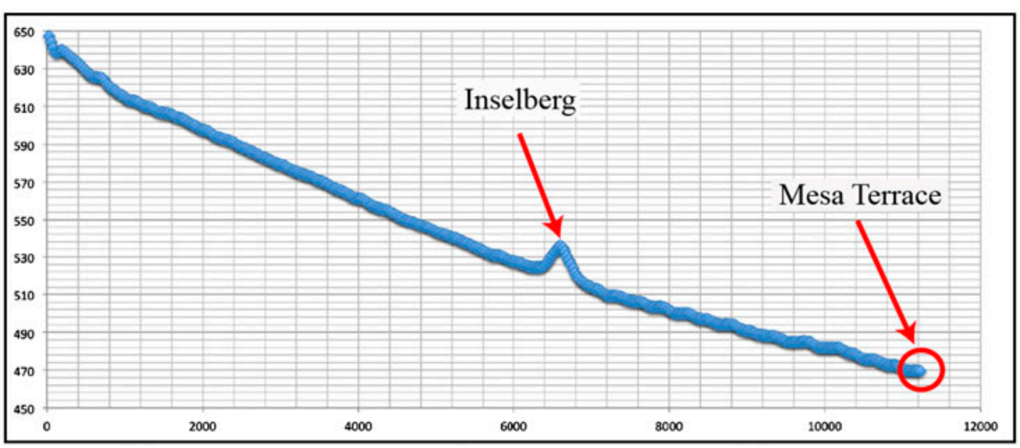

Figure 9. The Las Sendas Pediment longitudinal profile (in meters). The Las Sendas Pediment gently slopes to the Mesa terrace level along the Salt River. The pediment surface has very little relief, as seen in the longitudinal profile data collected using dGPS and local digital elevation models.

We have, however, found no evidence in support of the inherited hypothesis in our study area. Instead, our observations are consistent with other research demonstrating active processes associated with the evolution of pediments and their inselberg slopes (Abrahams et al., 1984, 1985, 1990; Parsons & Abrahams, 1984, 1987). Considered over a perspective of the last 20.5 Ma, vertical erosion rates could be as high as ~5 mm/ka (Figure 15). We note that long-term erosion includes observed proximal drainage incision at the mountain front, the result of drainage elongation and slow mountain front erosion (cf. Vincent & Sadah, 1996).

The young ages of inselberg debris and bedrock slopes (Figure 13) reveal that bedrock slopes undergo active erosion during the Holocene with a third of the random sites experiencing 20th century surface erosion. The idea that these pediment-inselberg systems are active is further supported by research using sediment retention basins operating from 1986 to 2000 (Henze, 2000). Henze's measurements revealed that the

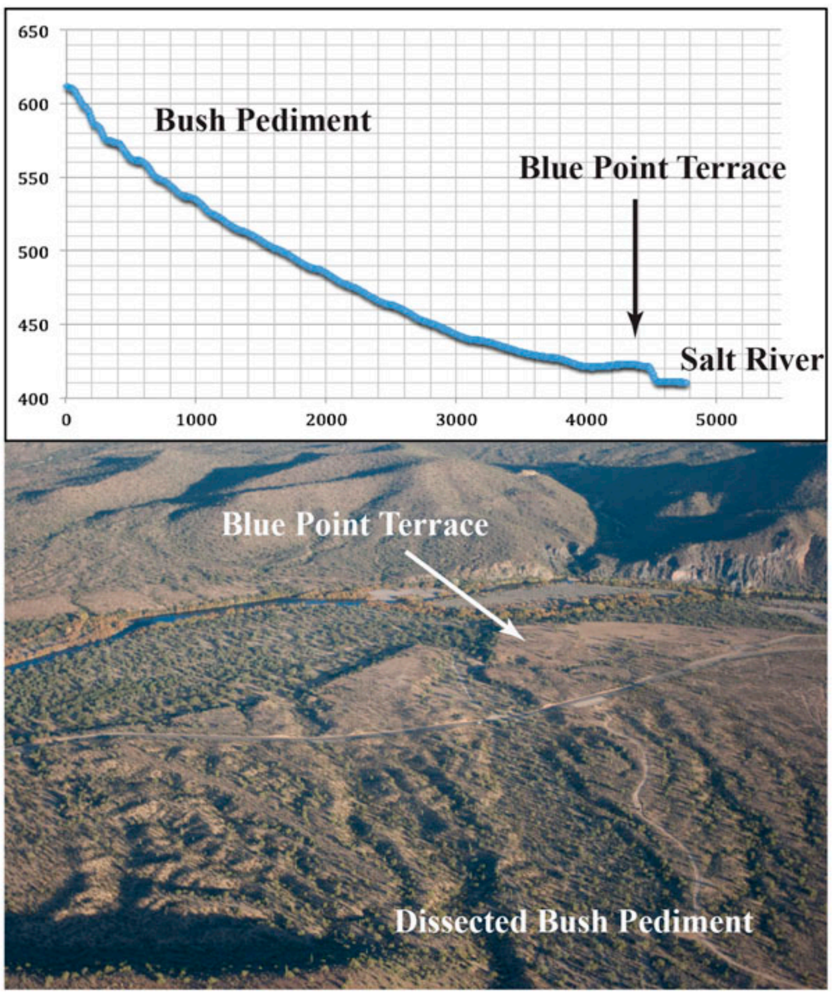

Figure 10. The Bush Pediment longitudinal profile (in meters). Unlike the Las Sendas Pediment, (Figure 9) the Bush Pediment has been actively responding to incision of the Salt River. This has resulted in a longitudinal profile that transitions downslope into the Blue Point terrace. More recent incision of the Salt and pediment response is reflected in dissection of the distal pediment surface.

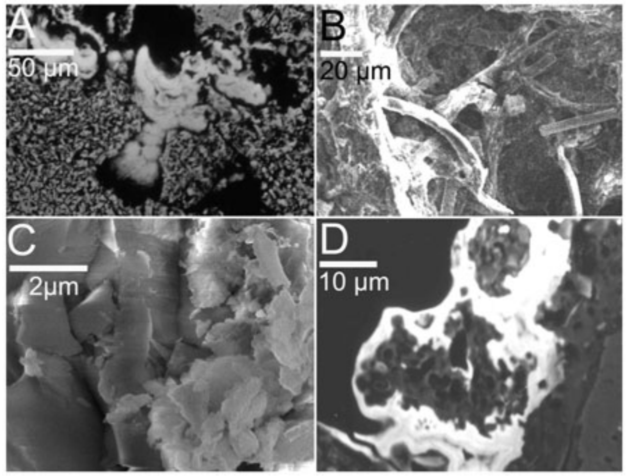

Figure 11. Different types of textures observed in the regolith carbonate on the Usery pediments are similar to regolith carbonate textures formed from groundwater seen in the literature. (A) In this backscattered electron (BSE) microscope image, pure calcite is bright white, and the speckled gray areas are a mixture of carbonate and infilling silica – collected from Figure 7(A). (B) Secondary electron (SE) micrograph of biological activity during cementation, similar to fungal filaments encrusted with calcium carbon seen in Kalahari valley calcrete (Nash & McLaren, 2003) – collected from site shown in Figure 7(D). (C) SE image of a quartz grain of the underlying granite (left side), where micrite pore-filling cement occurs in the abundant pore space (right side), similar to textures in the Kalahari valley (Nash & McLaren, 2003). (D) BSE image of carbonate impregnation into the pore spaces of the underlying granite, with a laminar texture similar to observed SE textures in southwest Australia (Holbeche et al., 2010).

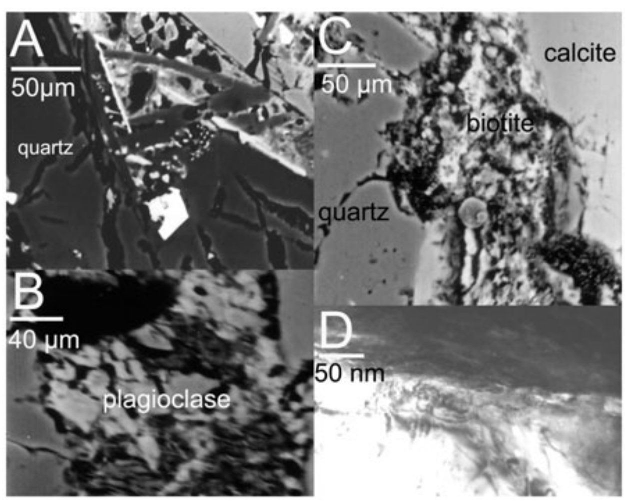

Figure 12. Electron micrographs of strongly decayed granite collected from the former piedmont angle of the Mine pediment (Figure 7(A)). Images (A)–(C) are BSE images. (D) is s high resolution transmission electron microscope image.

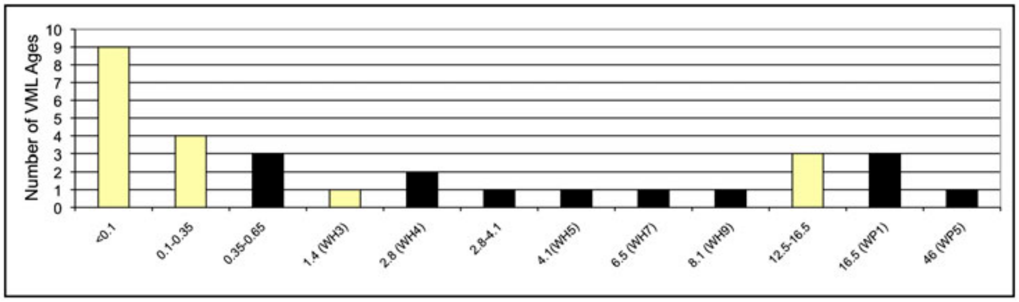

Figure 13. Histogram of VML and lead-profile ages – presented in thousands (ka) of calendar years before present – for 30 randomly selected locations in the McDowell and Usery Mountains.

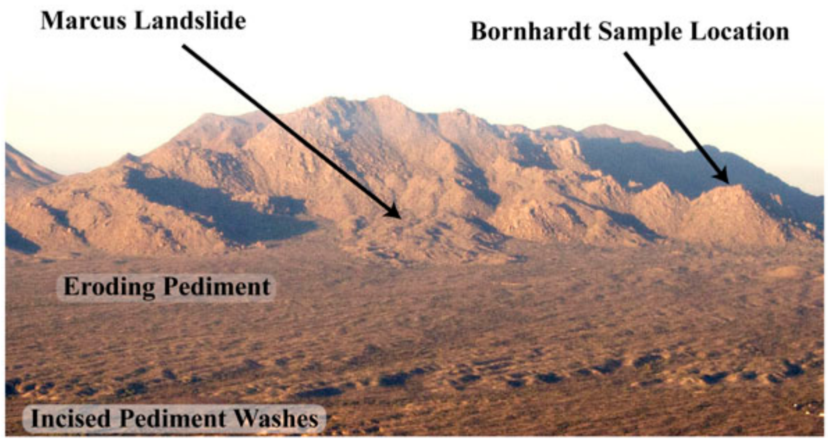

Figure 14. The Marcus Landslide resting on ancient pediment surface of the McDowell Mountains. Prior to drainage integration, the Marcus Landslide deposited on top of a pediment surface that drained to the Pemberton Playa. Since integration, this pediment has been eroding in response to episodic incision of the Verde River to which it drains. Pediment drainages have deeply incised into the ancient pediment surface on which they previously flowed. The bornhardt sample location highlighted in this image is the location of the oldest surface sampled for VML in this study reach.

Las Sendas pediment, graded to the Mesa terrace (Figures 3 and 9), eroded in the late 20th century at a rate of ~61 mm/ka.

The sandy "pediment mantles" on top of bedrock pediments (Figure 7(B)–(D)) show none of the evidence of interlocking grains seen in electron micrographs of decaying bedrock (Figure 12) and show evidence of fluvial transport in clean exposures. This indicates that the pediment mantles in our study area are not deep weathering features. Instead, we interpret these mantles as aggradation in response to a higher base level, and these mantles are now undergoing stripping in response to episodic base-level lowering.

We do not intend to infer that studies of pediment inheritance in other locations are incorrect, or other pediment formation mechanisms are not important. Still, our observations support the paradigm shift started by Abrahams, Parsons, and co-workers (Abrahams et al., 1984, 1985, 1990; Parsons & Abrahams, 1984, 1987). This view

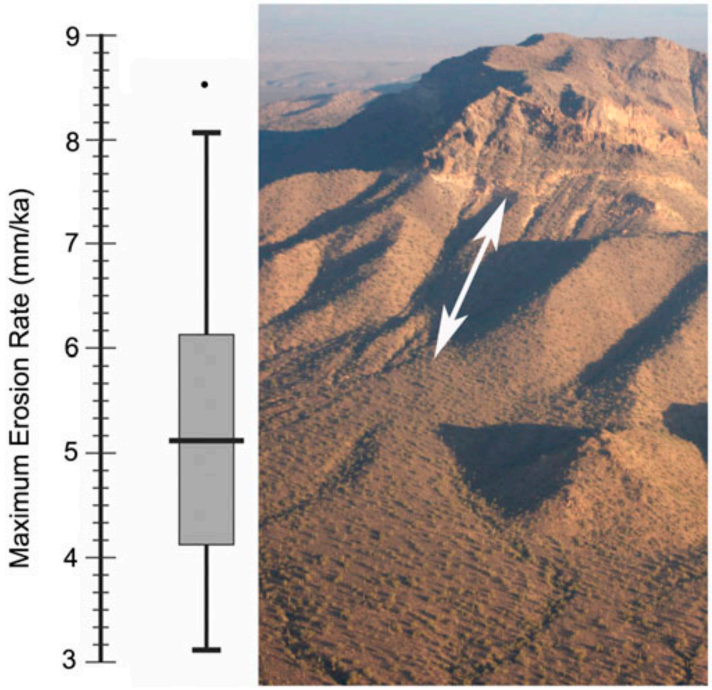

Figure 15. Box and whisker plot of the maximum erosion rate between the ancient pediment buried underneath tuff and the top of the modern pediment. These measurements were taken from 50 locations where the basal member of the Superstition eruptive sequence is clearly exposed. The rate is a maximum for long-term erosion, because an unknown amount of the relief – illustrated by the double arrow at one location – was caused by erosion, normal faulting, tilting, and isostasy. Unfortunately, no independent data exist for rates of faulting, tilting, or isostasy at this location.

suggests that granitic rock pediments and their backing inselbergs experience ongoing rock decay and erosion in response to extrinsic forcing.

Pediments and drainage basin evolution

Initial integration of the Pemberton basin through overflow resulted in a significant episode of aggradation along the Salt and Verde rivers (Douglass et al., 2009a, 2009b) – observed in the Stewart Mountain (Larson, 2013; Larson et al., 2010) and Lousley Hills fill terraces. The rapid arrival of integration gravels, noted by Reynolds and Bartlett (2002), would not only have caused aggradation within the Pemberton Basin, but also rapid infilling of downstream basins underlying present day metropolitan Phoenix (Block, 2007; Péwé, 1978; Reynolds & Bartlett, 2002).

The pediments bounding the Salt and Verde rivers reacted to this aggradation by backfilling their ephemeral drainages. We observe this process in the variably thick pediment mantles of transported grus in varying degrees of preservation. The northern Usery pediment hosts a mantle that can exceed 4 m in places (Figure 6). The southern Usery pediment has up to 8 m of aggraded grus on top of bedrock – observable in construction excavations. The eastern McDowell pediment is buried by a wedge-shape deposit that extends 4 km up slope from Lousley Hills terrace, with thicknesses exceeding 15 m (Figure 5).

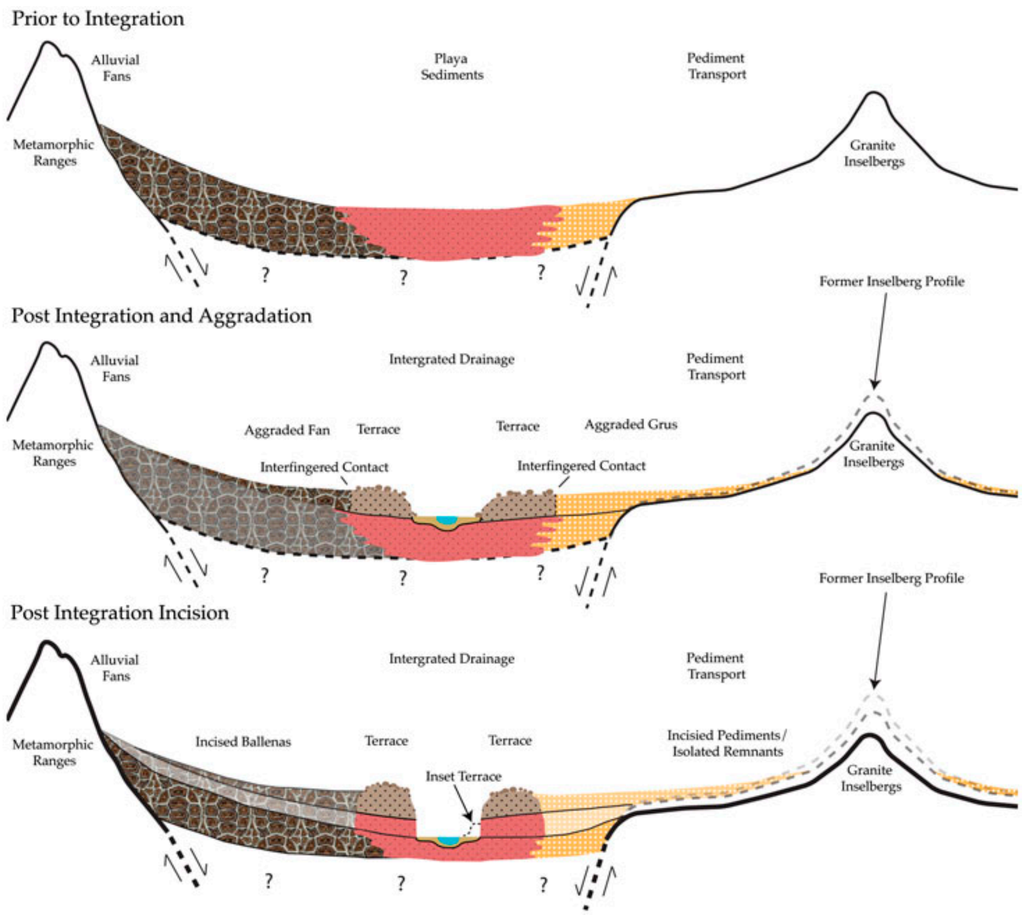

Figure 16. Idealized diagram indicating the response of pediment systems to drainage integration of an endorheic basin.

Once integration had established through-flowing drainage, the Salt and Verde rivers episodically incised marked by four distinct strath terraces. The elevations of these terraces served as the base level of the ephemeral pediment washes through time (Figures 9 and 10). Episodic lowering (Figure 2; Péwé, 1978; Larson, 2013) greatly impacted the evolution of pediments in our study area. We note five general erosional forms associated with ongoing adjustment to base-level lowering: (1) rolling topography where a pediment mantle appears to have aggraded during a time of aggradation along the Salt and Verde, but is now eroding following incision (Figures 6 and 7(B)); (2) the exposure of zones of enhanced bedrock decay at the base of inselberg slopes (Figure 7(A)); (3) the exposure of regolith carbonate where the former mantle has been stripped away (Figure 7(D)); (4) incised pediments where the former bedrock surface remains relatively planar, topped with just a thin veneer of the pediment mantle (Figures 3 and 6); and (5) a topography of spheroidally weathered bedrock and emergent tors where the mantle cover has been stripped (Figure 8). We speculate that future numerical modeling studies could help explain the spatial variability of these forms.

Figure 16 depicts a general conceptual model of how pediments respond to drainage integration. First, pediments grade to the playa surface of a closed basin. Second, integration through lake overflow generates a fill terrace that leads to aggradation of grus that forms an aggradational mantle over bedrock pediments. Third, episodic incision of the through-flowing stream – punctuated by strath stream-terrace formation during times of periodic base-level stability – erodes the pediment mantle and also the underlying bedrock. Although Figure 16 is designed to fit our study area, where granitic pediments exist side-by-side with metamorphic ranges that generate alluvial fans, the idealized sequence in Figure 16 could serve as a model to be tested through future research along the Gila (Jungers, 2012; Jungers & Heimsath, 2013), Mojave (Meek, 1989), lower Colorado (House et al., 2005; House, Pearthree & Perkins, 2008; Spencer et al., 2013), Queen Creek, Cave Creek, and Aqua Fria rivers, which have experienced drainage integration within the Basin and Range.

Conclusion

Granitic rock pediments ringing small mountain ranges in central Arizona are active landforms that adjust to large-scale drainage basin evolution events. Like other integrating systems in the Basin and Range (Douglass et al., 2009a, 2009b; House et al., 2005, 2008; Meek, 1989, 2004; Meek & Douglass, 2001; Reheis et al., 2007; Roskowski et al., 2010; Spencer et al., 2013), the Salt and Verde rivers breached formerly closed basins through the process of lake overflow (Douglass et al., 2009a, 2009b; Larson et al., 2010). The granitic rock pediments near the junction of the Salt and Verde rivers first experienced aggradation of a mantle of transported grus in response to deposition of fill terraces. Then, episodic incision of the Salt and Verde Rivers lowered the base level of the pediments and resulted in erosion of the pediment mantle and underlying bedrock. The studied pediments are actively adjusting forms, not inherited from an ancient wet climatic interval. Future research in other drainages that have experienced integration could test our conceptual model (Figure 16) of the response of pediments to drainage integration.

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