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Regional piedmont incision during base-level rise in the northeastern Sonoran Desert, Arizona, USA

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ABSTRACT

Ephemeral channels incise into the piedmonts (both alluvial fans and pediments) of the northeastern Sonoran Desert, USA. Located around metropolitan Phoenix, this tectonically quiescent region experienced only aggradation in endorheic structural basins throughout the Pliocene. A wave of aggradation then followed Salt and Gila river integration at the start of the Pleistocene. Aggradation of piedmont base levels continued throughout the rest of the Quaternary. This paper explores two hypotheses to explain piedmont incision despite rising base levels. The classic explanation is that incision is part of the evolution of desert mountain ranges as they decrease in size. A new alternative we propose here involves a lateral shift in base level from Pliocene endorheic basin playas to positions kilometers closer to range fronts in response to river integration. We present a thought exercise of modeling a pediment longitudinal profile as a 1D diffusive system, and we also analyze incision into alluvial fans of the Sierra Estrella range. While our 1D modeling results for pediments are consistent with both explanations for range-front incision, Sierra Estrella bajada incision is best explained by the sudden relocation of the base level to the toe of desert piedmonts.

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Introduction

Introductory textbooks (e.g., Christopherson & Birkeland, 2019; Hamblin, 1988; Hess & McKnight, 2005; Schaetzl & Marston, 2021) portray the long-term evolution of the Basin and Range Province (BRP) as a gradual reduction of range size. Horsts start out with range-front faults and extensive coalesced alluvial fans (bajadas). Erosion over millions of

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González, Kelley, and Marvin are co-first authors based on their equal contributions to the content of the entire paper. The order presented is alphabetical. **Tribute** *The fifth author of this paper took a desert geomorphology graduate seminar with Tony Orme in 1983. Part of that seminar involved a field trip to pediments in the Mojave Desert. Being aware that Ron Dorn had T.M. Oberlander as a master's thesis advisor, Tony asked keen questions that challenged Dorn to avoid re-iterating Oberlander's position interpreting pediments as relics of past, wetter Tertiary climates. Tony's questions focused on field observations of contemporary processes modifying the visited pediments and also prefacing the research of Tony Parsons, Athol Abrahams and colleagues on the role of process geomorphology in pediment development. This paper has its origins in that field trip — not to be bound by preconceptions of early learning but to let the reality of the field speak to an open mind. This paper derives from a "desert geomorphology" graduate seminar taught 37 years after the one led by Professor Anthony Orme.*

years transforms ranges into eroded inselberg remnants fronted by bedrock pediments. This portrayal is based on century-old BRP geomorphic scholarship by Davis (1905, 1933a) and Johnson (1932a, 1932b). The timescale of this gradual reduction in range area and relief after tectonic activity subsides was left ambiguous in these early twentieth-century writings. Today, the timescale is known to be on the order of 9–15 million years in the northeastern BRP of Arizona, USA (Fitzgerald et al., 1993; Foster et al., 2012; Spencer & Reynolds, 1989).

This paper concentrates on a corollary research problem of the evolution of bajadas and pediments fronting ranges in Arizona's northeastern BRP, essentially the area in and around metropolitan Phoenix, USA. In particular, we focus on the observation that both types of piedmonts, fans and pediments, are in an incised condition in this area. Even a casual observer taking a "Google Earth tour" of this region will find difficulty identifying a piedmont that lacks incision. Careful scrutiny, however, will reveal that the nature of this incision is not uniform.

Variable base-level change histories occur for pediments and bajadas with similar dimensions in the metropolitan Phoenix area. For example, the pediment in Figure 1(c) experienced a drop of ca. 125 m, but the base level of the pediment in Figure 1(a) rose ca. 90 m in the same time period of the late Quaternary (Larson et al., 2014, 2020, 2016; Skotnicki et al., 2020b). The two alluvial fans portrayed in Figure 1(b,d) have similar dimensions, but the one in Figure 1(d) did not experience base level change in the past 2.5 Ma (Skotnicki et al., 2020a); this contrasts with bajada in Figure 1(b) that experienced both a ~ 90 m rise in base level and a lateral shift of ~ 20 km closer to fan toe (Skotnicki & DePonty, 2020).

The classic explanation for BRP piedmont incision involves a gradual reduction in range size after tectonism ceases. Geomorphic scholarship points to the proximal incision of pediments (Dohrenwend & Parsons, 2009) and "telescoping" of alluvial fans shifting the hydrologic apex in a down-fan direction (Blair & McPherson, 2009). An alternative hypothesis explored here for the first time involves pediment and bajada incision taking place despite ongoing base-level rise, explained by a lateral shift in the location of base level from a distant endorheic playa depocenter to the foot of a pediment or bajada (Figure 2). The remainder of this introduction reviews prior scholarship on these alternative explanations.

Evolutionary hypothesis for piedmont incision in the Basin and Range Province

In his articles on hard rock granitic pediments, W.M. Davis (1905, 1933a, 1933b) interpreted the growth of pediments to be at the expense of mountain ranges, progressing to the point where

> "sooner or later in this past-mature stage a mountain face must meet the opposite face of its block, and its height must thereafter be decreased, for any further retreat will lower the craggy mountain crest. Thus in time, the load of detritus washed down from the face comes to be less than that which the sheet floods can sweep away. They, always efficient workers, thereupon begin to rob the rock floor by taking up some of its deep-weathered detritus, which they have previously been unable to move. (Davis, 1933a, p. 4)"

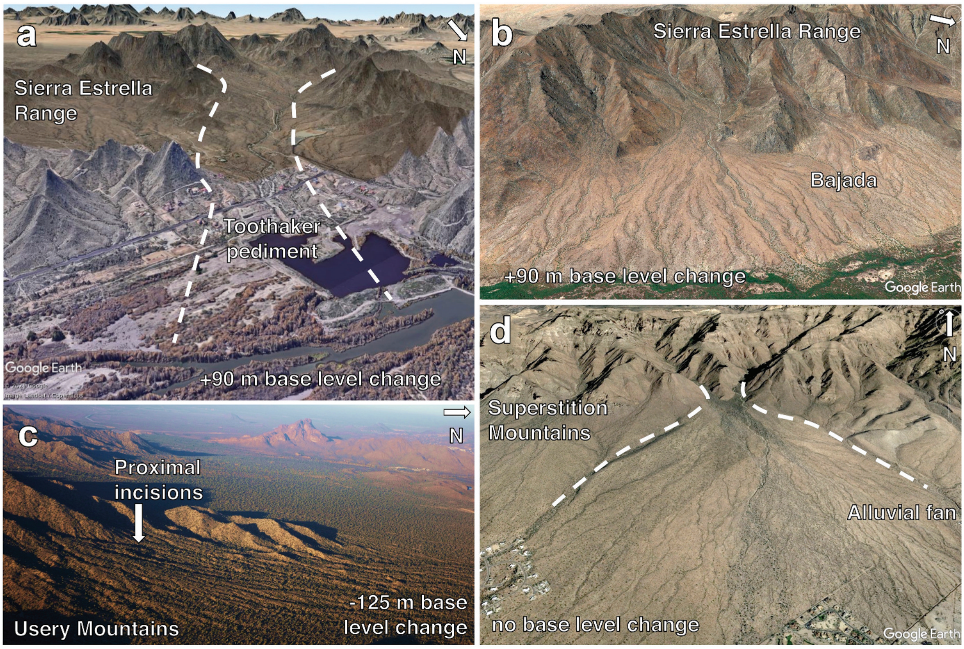

Figure 1. Desert pediments (a and c) and desert alluvial fans (b and d) experience incision in the tectonically quiescent northeastern Arizona BRP. The location of these piedmonts are indicated in Figure 5. Scale information on the length of each piedmont is provided below. A. Toothaker pediment at the northern end of the Sierra Estrella with ~ 90 + m of base-level rise occurring over the past 2.8 Ma years, but with lateral shift of ca. 7 km of base level towards the foot of this km-wide pediment. B. Eastern bajada of the Sierra Estella range with ~ 90 + m of base-level rise in the past 2.5 Ma and a lateral shift of ca.20 km of base level, effectively burying the toe of a bajada that is now ~3.5 km long. Note the distributary nature of incision into the bajada. C. North pediment of the Usery Mountains with proximal incision of the range front (Larson et al., 2014, 2016). The lower end of the ~4 km-long granitic pediment has smoothed after ~125 m of falling base level (Larson et al., 2010, 2014, 2020, 2016 over the last 2.5 Ma (Skotnicki et al., 2020b). D. South bajada of Superstition Mountains with stable base level of Queen Creek for the past ca. 2.5 Ma (Skotnicki et al., 2020a). The ca. 4 km-long bajada shows the typical “telescoping” of alluvial fans associated with a shift in the hydrological apex towards the bajada toe.

Davis observed that the “efficient workers” of small washes on Arizona pediments “openly trenched along most of its streamlines to a depth of 10 to 15 feet (3.0–4.6 m) as if the process of re-degradation to a slightly lower level” (Davis, 1933a, p. 11).

A general view emerged that pediment incision is part of the evolution of pediment and inselberg systems in tectonically quiescent locations like the northeastern Sonoran Desert (Cooke & Mason, 1973; Howard, 1942; Johnson, 1932a, 1932b; Waibel, 1928). Howard (1942, p. 135) explained: “as the mountains dwindle in size, precipitation and the volume of sediment available for streams decrease. The decrease in load more than compensates for the loss of water, so that the dwindling waters are gradually rejuvenated.” The Davisian terminology “rejuvenation” has fallen out of favor in modern geomorphology. Still, it means the same as incision into a planar surface – in this case, a bedrock pediment. A slightly different notion of the long-term evolution of pediments is held by Kesel (1977), who argues that downcutting during a long period of tectonic

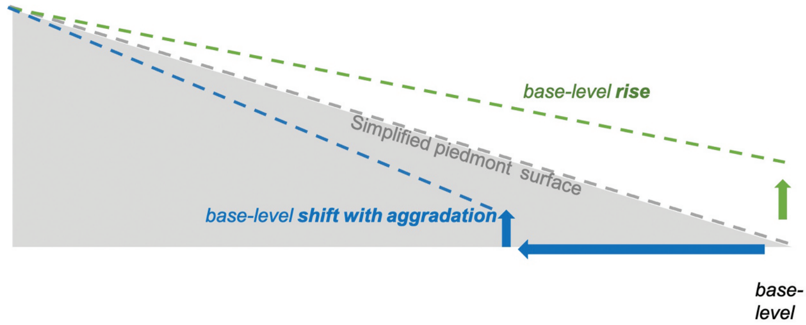

Figure 2. Conceptualization of how base-level rise could influence piedmont aggradation or incision, where the left side of the simplified diagram is the boundary between range and piedmont. Abundant prior research reveals the response of a desert fan or pediment to base-level rise to be aggradation. However, if this aggradation is also associated with a lateral shift closer to the range front, then we propose that the response would be piedmont incision as seen in Figs. 1a and 1b.

quiescence is a requirement that allows the lateral displacement of mountain-front slopes. This notion was held earlier by King (1949, 1955) studying pediments in southern Africa.

The alluvial-fan literature, although much larger and full of debate on the notion, also includes the hypothesis that as fans evolve, they undergo a "telescoping" that inevitably leads to bajada incision (Mabbutt, 1977; Dávila et al., 2012; Gerson et al., 1993; Peterson, 1981; Ritter et al., 2000; Scheinert et al., 2012). The term "telescoping" is different from the backwearing of inselbergs. Telescoping is a term to describe the down-fan movement of the hydrologic apex from the top towards the toe of a fan, as seen in Figure 1(d).

Relocation of base level as an alternative explanation for piedmont incision

A basic concept in physical geography and geomorphology emphasizes that base-level rise leads to river valley infilling (Davis, 1902). This is often exemplified by Mississippi River valley aggradation in response to eustatic sea-level rise (Fisk, 1944). With ongoing Pliocene aggradation (Skotnicki & DePonty, 2020; Skotnicki et al., 2020b) in the Luke and Higley basins (Figure 3), the normal expectation would be to see channel infilling on pediments and alluvial fans entering these basins. However, the exact opposite condition exists for piedmonts fronted by the Salt and Gila rivers (Figures 4–5), including the Papago Buttes, Phoenix Mountains, San Tan Mountains, South Mountains, and Sierra Estrella range (Figure 1(a,b); Figure 6).

The notion that lateral shifts in a trunk stream can lead to tributary incision (Lane, 1955) has been well documented (Brierley & Fryirs, 1999; Faulkner, 1998; Schumm et al., 1987). However, the spatial scale of a shifting river channel has never been explored at the ca. 6000 km^2 scale within the northeastern Sonoran Desert region of Arizona (Figures 3–5).

This research evaluates whether a lateral shift in base level, despite ongoing aggradation, can contribute to the incision of desert piedmonts. We utilize numerical modeling in a thought exercise and also assess bajada incision on two sides of the Sierra Estrella.

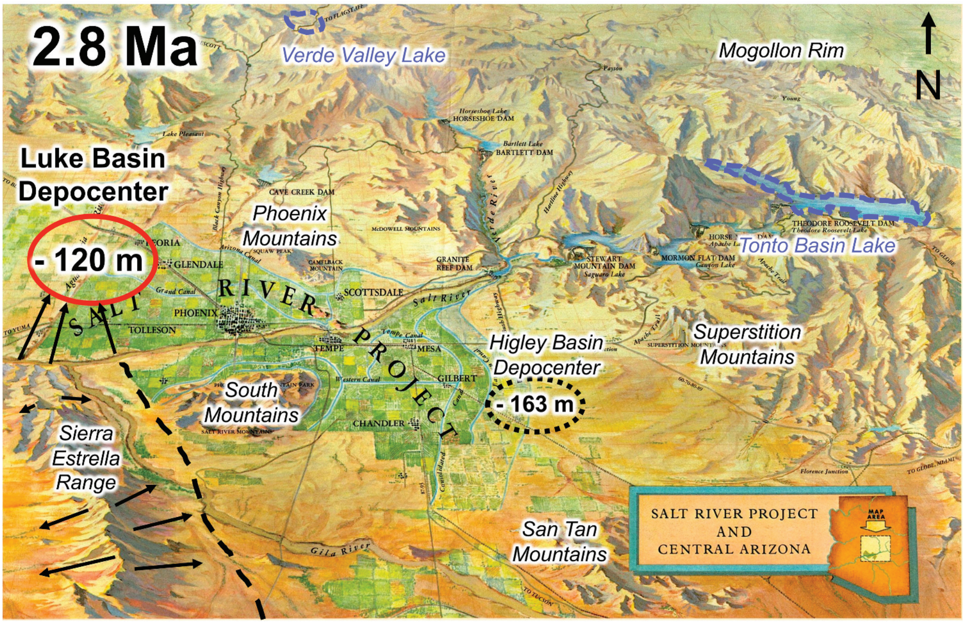

Figure 3. Before Salt River integration (between 2.8 Ma and 2.2 Ma), the Tonto Basin served as its hydrological terminus. Verde Valley Lake was the base level for Verde River waters (Skotnicki et al., 2020b). Well-log analyses by Skotnicki and DePonty (2020) revealed the playa surface in the Luke Basin was 120 m lower than today. Other well log data revealed that the adjacent Higley Basin's playa was 163 m lower (Skotnicki & DePonty, 2020). Note that the Sierra Estrella drainages all had the Luke Basin depocenter as its base level. The text emphasizes the mountain ranges in the Phoenix, USA, area that are highlighted on this public domain historic map produced by the Salt River Project.

The two sides of the Sierra Estrella range have the same tectonics, climate, and geology in their drainage basins. Both sides experienced the same climatic changes, as well as timing and amount of base-level rise. The only difference is in the lateral shift of the position of base level. The east-facing fans experienced rapid sedimentation right at their base as a result of the sudden arrival of the Salt and Gila rivers, while channels of west-facing fans still had to travel kilometers to reach the same rising base level of the Salt-Gila rivers.

In the next section, we present the study area, focusing on what is known about base-level changes in the region and its relevance for the Sierra Estrella piedmont. Methods and results are followed by a discussion of how our findings compare with prior scholarship.

Study area

Base-level changes in Central Arizona

Central Arizona rests within the BRP, a broad region of extension with structural basins thousands of meters deep. Watersheds entering these basins have only experienced base-level rise throughout the late Miocene and Pliocene as extension waned (Fitzgerald et al., 1993; Foster et al., 2012; Reynolds & Bartlett, 2002; Spencer & Reynolds, 1989), and basins filled up with locally-derived sediment (Gootee, 2013; Laney & Hahn, 1986; Richard et al., 2019; Skotnicki & DePonty, 2020; Skotnicki et al., 2020a; Spencer, 2011).

Larson et al. (2014, 2016, 2020) studied the response of pediments to drainage integration processes just to the north and east of our study area. From the perspective of Figure 5, Larson et al. (2014, 2016, 2020) studied pediments upstream of Granite Reef Dam, or upstream of the point at which the ancestral Salt River deposits (ASRD) aggraded a mega-fan floodplain and where the Salt and Gila rivers integrated (Figure 4). Upstream of Granite Reef Dam (Figure 5), the Salt and Verde rivers experienced a complex history of base-level rise and then fall (Larson et al., 2020) leading to pediment incision (Larson et al., 2014, 2016). Downstream of Granite Reef Dam, however, range piedmonts have experienced only continuous aggradation.

The base-level history of the transition from purely endorheic drainage to through-flowing rivers is portrayed in Figures 3–5. Prior to river integration, drainages in the region flowed towards playas or depocenters in the Luke and Higley basins (Figure 3). We stress that these depocenters have only increased in elevation throughout the Pliocene, as recorded by well-log analyses (Skotnicki & DePonty, 2020). The Salt and Verde rivers overflowed the sill of Pliocene lakes (Figure 3) between 2.8 and 2.2 Ma (Skotnicki et al., 2020b). This river integration led to the development of a massive floodplain and aggradation of the ASRD (Figure 4). The Gila River then integrated, also via lake overflow, ca. 2.2–2.1 Ma (Gootee et al., 2021; Jungers & Heimsath, 2016). Well-log data analyzed by Skotnicki and DePonty (2020) reveal a base level rise of ~ 130 m in

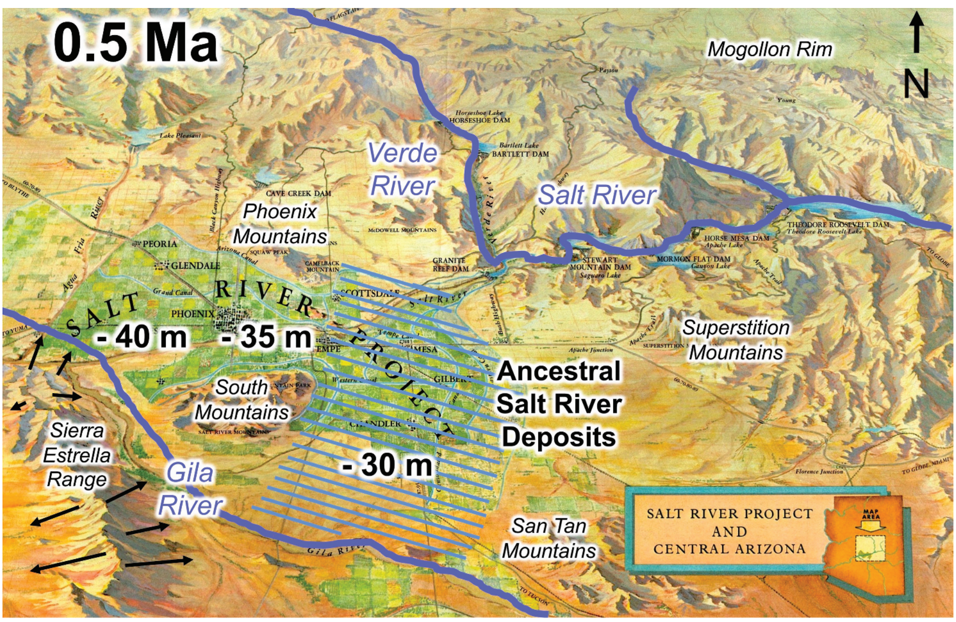

Figure 4. Available well-log data (from Reynolds & Bartlett, 2002; Skotnicki & DePonty, 2020) reveal that the Salt River ca. 0.5 Ma was about 30 m lower than at present, and that ephemeral washes that draining to the Salt River had to have graded to this base level. Note that the Sierra Estrella drainages would have had the Gila River as its base level then, also about −40 m lower in elevation than at present. These data are portrayed on a public domain historic map produced by the Salt River Project.

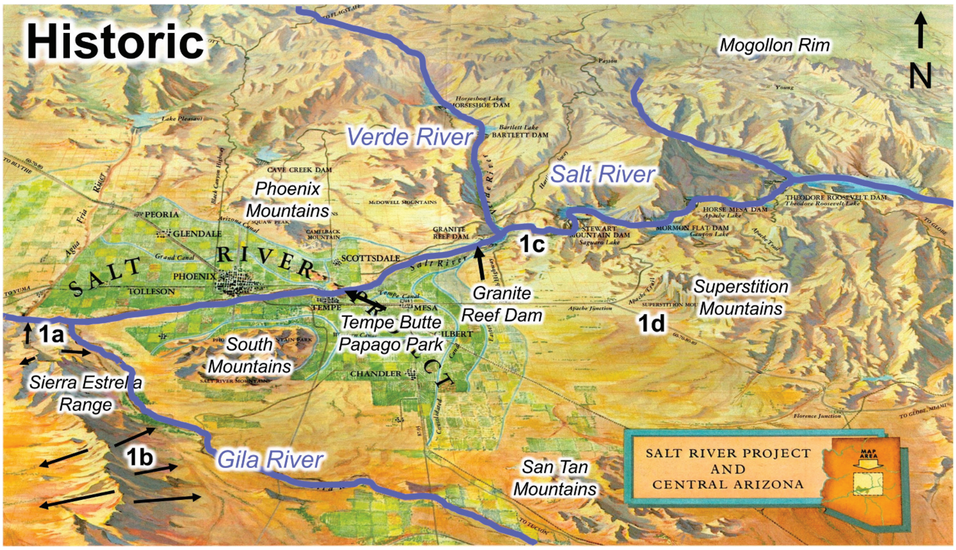

Figure 5. Historic position of the Salt, Verde and Gila Rivers portrayed on a public domain map produced by the Salt River Project in the 1930s. Locations 1a-1d identify the piedmonts shown in Figures 1a-1d. Note that Sierra Estrella drainages have the Gila River as their modern base level, but drainages on the west side of the range have a much further distance to travel to the Gila River than those on the north or east sides.

the ASRD area indicated in Figure 4 over a two million year period (Larson et al., 2020; Skotnicki et al., 2020b).

The next big hydrological event to provide data on paleo-base levels in the region was an avulsion of the Salt River about 460 ka (Skotnicki et al., 2020b). Aggradation of the ASRD led to a stream piracy event (Larson et al., 2020; Skotnicki & DePonty, 2020) just east of "-35 m" in Figure 4. This avulsion site is also identified as Tempe Butte-Papago Park in Figure 5 – a low spot in a bedrock ridge where the river spilled over on a ramp built of its own sediment.

The Salt River's avulsion shifted the location of the Salt River's channel to the north side of South Mountains (Figure 5) ca. 460 ka (Skotnicki et al., 2020b) and led to the abandonment of the ASRD. Well-log data reveals the top ASRD to have been ca 30 m lower just prior to the avulsion (Skotnicki & DePonty, 2020) (Figure 4). Reynolds and Bartlett (2002) used well-logs to discover the impact of this avulsion: the sudden arrival of meter-diameter boulders on top of ephemeral washes and an ancestral pediment.

The relevance of the Salt River's avulsion for understanding base-level change derives from deposition of Salt River gravels on a surface that was 35 m lower than at present (Reynolds & Bartlett, 2002) about 0.46 Ma (Skotnicki et al., 2020b). Salt River gravels from one of these wells was used to establish the ca. 460 age via cosmogenic burial dating (Skotnicki et al., 2020b). This 35 m-lower surface just west of the avulsion site corresponds with other well-log data to the west recording the arrival of these Salt River gravels ca. 40 m lower than present-day elevations (Figure 4). Thus, available well-log

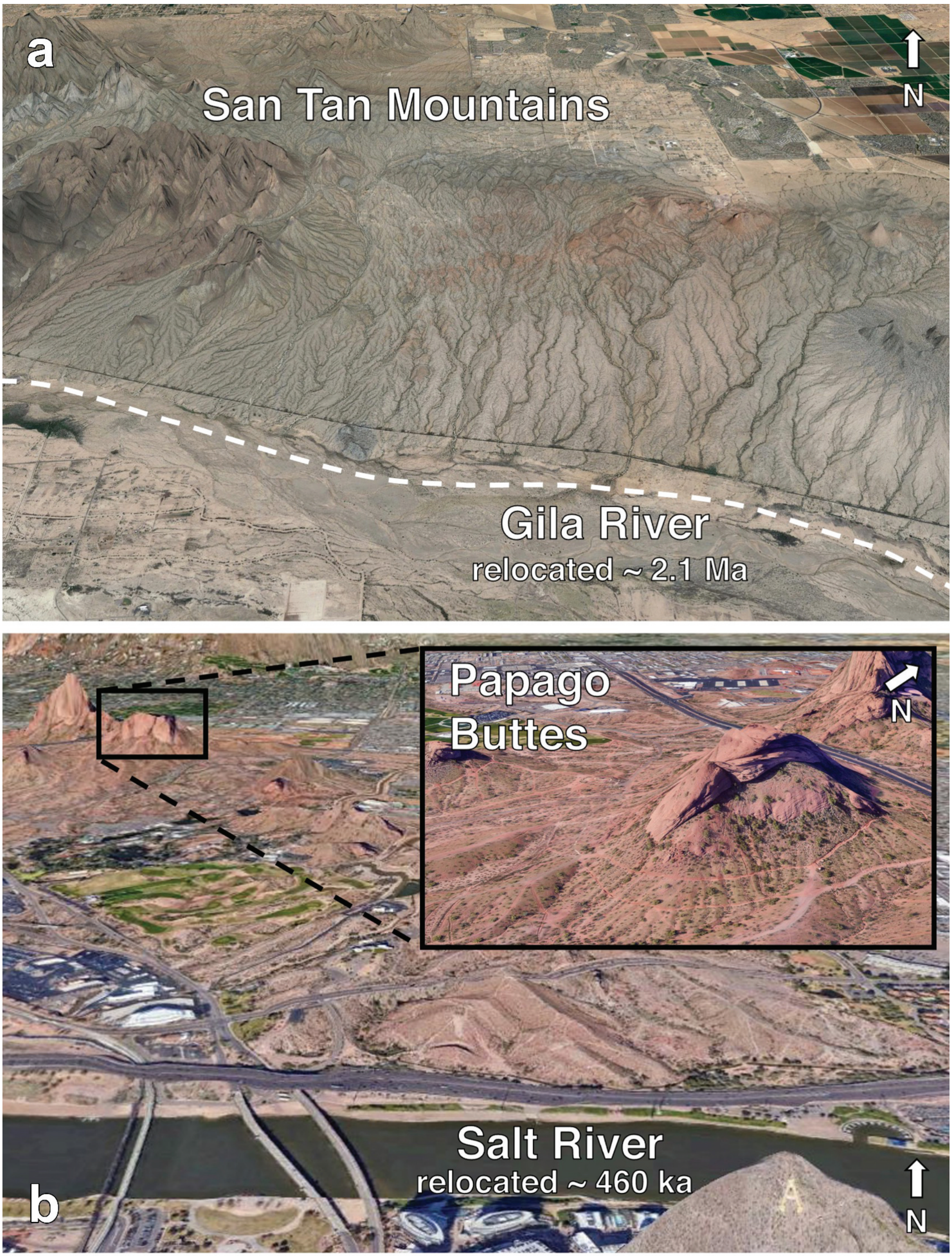

Figure 6. In selecting a study site for morphometric analysis, we considered all ranges fronting the Gila and Salt Rivers. For example, (a) the north-looking Google Earth view of incised San Tan Mountains granitic pediment (width of view ~ 9 km) shows the Gila at its base. In contrast, piedmonts on the side not fronted by the Gila lacks substantial incision. Another example is (b) northwest-looking Google Earth views of Papago Buttes sedimentary pediment (width of views ~0.7 km). Again, the side draining directly to the nearby Salt River shows more incision.

data from the time period of ca. 0.5 Ma (Figure 3) indicates that the base level of Sierra Estrella drainages was ca. 30–40 m lower than at present. The obvious implication is that the late Pleistocene experienced another 30–40 m of base level rise in the area of Salt-Gila river integration – which was the location of base level for the Sierra Estrella range at that time.

One key summary point is that the drainages of the mountains in central Arizona have only experienced base-level rise:

(i) throughout the late Miocene and Pliocene as endorheic basins infilled (Figure 3);

(ii) when the Salt, Verde and Gila rivers integrated and started filling in their new river channels from 2.8 Ma to 0.5 Ma (Figure 4); and

(iii) when the Salt River experienced an avulsion to its present position north of South Mountains about 460 ka (Figure 5).

The second key summary point is that the location of local base level shifted laterally from low spots (playas or depocenters) of the Luke and Higley Basins (Figure 3) to positions right up against several of the mountains (Figures 4 and 5). For the northern and eastern sides of the Sierra Estrella range, this lateral shift brought local base level ~7 km closer to north-end pediments (Figure 1(a)) and ~20 km closer to east-side alluvial fans (Figure 1(b)).

Sierra Estrella east-west asymmetry as a focus of this study

The alluvial fans and pediments that experienced the sudden arrival of the Salt or Gila rivers at their toes have been undergoing incision in central Arizona. For example, Figure 6(a) shows an incised granitic pediment on the south side of the San Tan Mountains; the Gila River's integration placed the aggrading river right next to the San Tan Mountains ca 2.1 Ma (Gootee et al., 2021). Figure 6(b) shows the sedimentary pediment of Papago Buttes next to the Salt River that relocated to its toe about 460 ka (Skotnicki & DePonty, 2020). Figure 1(a,b) show incision into a granitic pediment and alluvial fan, respectively, of the Sierra Estrella where the Gila River relocated base level to their toes. The piedmonts of the Phoenix Mountains and the alluvial fans of South Mountains are also incised where they face the Salt and Gila Rivers (see Figure 5 for locations). Thus, the northeastern BRP of Arizona offers an abundance of potential sites to study the effects of both base-level rise and a lateral shift in base-level position.

Out of all ranges in the Phoenix area fronted by newly-arrived rivers, we settled on the Sierra Estrella Range as our focus for several reasons. (i) The western and eastern bajadas originally had the same base level of the Luke Basin depocenter (Figure 3) and similar routing distances to this base level. (ii) River integration produced a dramatic asymmetry in distance to the new base level of the Gila River, where alluvium buried the toe of the eastern piedmont, but the western piedmont was still routed through the same ephemeral axial drainage of Rainbow Valley draining to Gila River. (iii) Demsey (1989) previously mapped the alluvial fans on the western and eastern sides of the Sierra Estrella. Hence, we could analyze incision into the same "M1" mapping unit of Demsey (1989), judged to be early to middle Pleistocene in age of deposition. In this way, we could compare incision into the same fan unit on the east and west sides, and (iv) prior research on long-term tectonic history of extensional basins in central Arizona (Spencer, 2011) and well-log research (Reynolds and Bartlett, 2002; Skotnicki & DePonty, 2020) provided three time "stamps" to document the history of only base-level rise of Sierra Estrella drainages: the late Miocene-Pliocene period of basin infilling (Figure 3); the early Quaternary arrival of the Salt River and then the Gila River (Figure 4); and the late Pleistocene avulsion of the Salt River (Figure 5).

Methods

We apply two different methodological strategies to analyze piedmont incision. First, we conducted a morphometric analysis comparing the east and west sides of the Sierra Estrella. The east side experienced the greatest lateral base-level shift when Salt-Gila alluvium buried the toe of the eastern bajada; in contrast, the lateral relocation of base level of the western side was much less and still requires ephemeral streams to traverse ~ 30 km to same base level. Second, we explore the mathematical basis of pediment incision by testing the classic and alternative hypothesis with a diffusion model that solves Fick's equation on a simplified pediment-inselberg profile.

Morphometric analysis of bajada incision

Comparing incision of bajadas on the east and west sides requires that we compare drainages with the same rock types. The Sierra Estrella range (Melchiorre, 1992; Richard et al., 2000) contains: (i) Proterozoic granitic rocks that include the full spectrum from granite to gabbro in each mapped unit (Melchiorre, 1992; Richard et al., 2000), (designed as G in Figure 7); and (ii) a mixture of metasedimentary, metavolcanic, and gneissic rocks (designed as M in Figure 7). Contacts between these two basic rock types are conveniently perpendicular to the range crest, allowing similar proportions of rock types on both sides of the range.

Comparing incision on the east and west bajadas also requires that we analyze alluvial-fan deposits that are the same age. This means that the "clock" for incision starts at the same time on both sides. The most aerially extensive alluvial-fan unit on both sides of the range was mapped by Demsey (1989) as the "M1" surface. Thus, the best time constraint for the onset of incision is for this mapped M1 alluvial fan unit of the Sierra Estrella range (Figure 7). Demsey (1989) interpreted the age to be early to mid-Pleistocene, but presented no firm age control. The idea is that the incision into this deposit would have to be after the mid-Pleistocene, and hence concurrent with ongoing base level rise.

As noted above, both sides have always drained to the same approximate base-level elevation: first, for the Pliocene to the Luke depocenter (Figure 3); then, to the Salt/Gila River (Figures 3 and 4). Thus, we only vary the distance to base level of the Gila River.

Figure 7 presents a planimetric view of all transects laid out across the M1 units on the east and west sides of the Sierra Estrella, and Figure 8 presents the topographic profiles of these transects. To lay out these transects on both sides of the Sierra Estrella range across the M1 unit, we first determined bajada orientation using "Minimum Bounding Geometry Tool," from ESRI ArcMap Data Management toolbox, around the east and west fans separately. These were oriented at 130° and 127° on the east and west, respectively. Then, we generated a centroid for each alluvial fan M1 unit. The profile transects were drawn to cross-fan at the ~130°, stay with the M1 polygon, and intersect the centroid. Two M1 units on the west side were moved down from the centroid so the

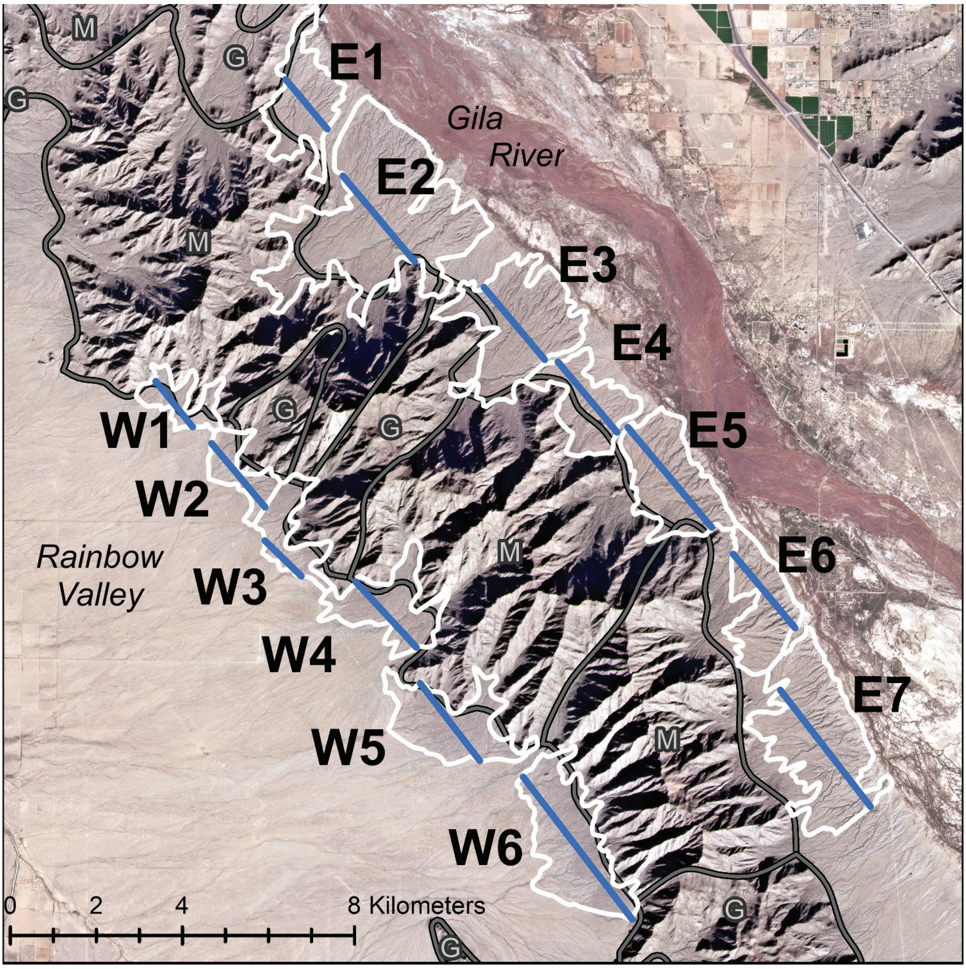

Figure 7. The Sierra Estrella study site of the morphometric analysis. The basic lithologic units (dark grey polygons) are metamorphic (M) and granitic (G) from Melchiorre (1992) and Richard et al. (2000). The white polygons are the M1 mid-Pleistocene alluvial fan mapping unit of Demsey (1989). The blue lines indicate the locations of cross-fan topographic profiles used in our morphometric analysis. The base image is modified from https://www.planet.com/imagery, acquired with an Arizona State University site license. Topographic information comes from 10 m DEM data from the USGS National Elevation Dataset (https://catalog-next.data.gov/dataset/usgs-ned-n34w113-1–3-arc-second-2013-1-x-1-degree-img).

entire profile would remain in the boundary. Then the locations were checked against a slope raster and aerial imagery. Profile lengths and locations were then adjusted (moved a maximum of 50 m) if they crossed or approached the mountain front. The sum of the eastern cross section is 17,310 m and the western is 14,377 m. We then calculated the average slope of each fan that ranges from 2–5°

Alluvial-fan scholarship contains a variety of metrics to analyze fan incision (e.g., Blair & McPherson, 2009; Calvache et al., 1997; Giles, 2010; Harvey, 1984; Silva et al., 1992), but the particular research question and characteristics of the study area led us to develop

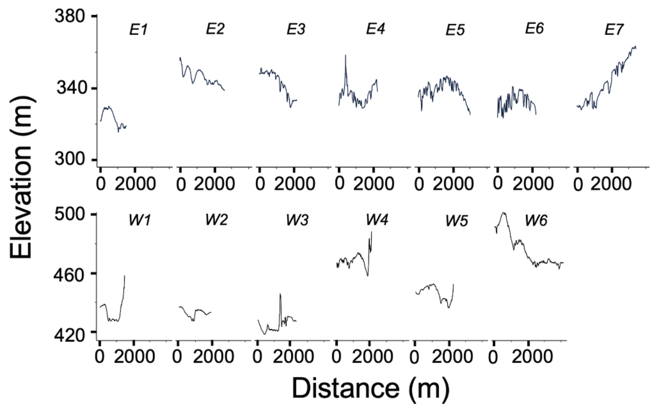

Figure 8. Sierra Estrella cross-fan profiles that correspond to transects shown in Figure 7, with the intent of the reader being able to visually compare the amplitude of the topographic variability with similar horizontal and vertical scales.

a new approach designed to compare an experimental condition where only one condition (base-level distance) varied.

We separated cross-section series into high- and low-frequency parts, i.e., large- and small-scale variations. To do this, we applied a low-pass filter (LPF, moving-average) to the 10 m resolution cross sections (Figure 8) with a 200 m (20 data points) Gaussian smoothing filter. The LPF accounts for fan and bajada geometry and other low-frequency variations (Figure 7). Notice the profiles (Figure 8) include the broad convex nature of alluvial fans with smaller variations, gullies, incised into the overall shape.

After smoothing with the LPF, we ran a high-pass filter (HPF) to isolate higher frequency variations (cf. incisions). We created the HPF profile by subtracting LPF profiles from the original profiles. Lastly, we used a rolling standard deviation function (called the local standard deviation or LSD) on the profiles to characterize gulley incision. The function moves along the profile and calculates the standard deviation within a defined window. We used a window size of 50 m (5 data points) with uniform weighting.

We tested parameters and carefully selected inputs to produce accurate and meaningful results since this method could be sensitive to user error. The LPF window size should be larger than the channel widths but smaller than the overall fans. The weighting system changes whether or not we consider data points closer to the current one more heavily than data points farther away. Lastly, the LSD window should be smaller than most channels.

We acknowledge boundary effects when analyzing spatial data. Thus, we removed data results from the beginning and end of transects if the LSD window was not completely filled. This equated to the first and last four LSD values. Though small changes in individual results do occur when different values are used, the overall results do not change.

Thought exercise on pediment longitudinal profiles as a diffusive system

The evolution of the elevation of a bedrock pediment channel can be thought of as a diffusive system, where sediment flows from places with higher elevation to those with lower elevation. This is another way of saying that the inselberg mountain-pediment system is a "conveyor belt" for sediment transfer (cf. Applegarth, 2004; Mabbutt, 1977; Dohrenwend & Parsons, 2009; Johnson, 1932b; Kesel, 1977; Larson et al., 2014; Pelletier, 2010).

Fick's equation provides one approach to describe such diffusive systems – an approach used previously for similar systems (e.g., Doane et al., 2019; Muto & Swenson, 2005). As a support for our thought exercise, we briefly comment here on what this approach can tell us about the processes that could explain incision of a pediment channel. For one dimension, Ficks´s equation is stated as:

$$\frac{\delta\eta}{\delta t} = D\frac{\delta^2\eta}{\delta x^2} \quad \text{(Eq.1)}$$

where η is the pediment elevation that depends on time (t), on the distance from the mountain divide (x), and on the diffusion coefficient (D).

A simplified surface of a mountain inselberg-pediment system can be thought of as a rectangular triangle with a base of L and height of H. This simplified system can include another smaller triangle inside representing a fault block that could end up as an inselberg. To solve Fick's equation, we assume no-flux occurring at the divide as the first boundary conditions ($\delta\eta/\delta x_{x=0} = 0$). Note that this condition comes from the fact that there is no upper point contributing mass at the divide. The inselberg slope is represented by a coefficient $D = 0$, yielding no-transport in places where the mountain surface reaches fresh bedrock.

For the second boundary condition, we explored different cases: i) base-level elevating at a constant rate; ii) base-level decreasing at a constant rate; iii) base-level with a lateral shift closer to the pediment; iv) simultaneous base-level rise and lateral shift closer to the pediment, examining different ratios of these; and v) fixed base level. The first case represents the influence of an aggrading basin. The second case represents toe erosion produced by a knickpoint created by the sudden arrival of a river at the toe of the piedmont. The third case can be produced by the integration of a river into a basin. The fourth case explores ratios between base-level rise and lateral shift. The last condition is a control case.

The last part of this thought exercise compares simulation results to field observations of different pediment-inselberg systems in broader Phoenix, USA, metropolitan study area (cf. Figures 1(a,c), 5, 6). The field observations are qualitative and seek to identify any study areas that have the same basic longitudinal profile characteristics as those observed in the simulations.

Results

Morphometric analysis of Bajada incision

Our results reveal differences in the amount of incision of alluvial-fan surfaces of the same age, the M1 early to mid-Pleistocene alluvial fan mapping unit of Demsey (1989),

Table 1. Sierra Estrella bajadas display very different amounts of incision on the eastern and western sides, analyzing only the geomorphic equivalent M1 mid-Pleistocene alluvial fan units of Dempsey (1989).

Range side	Source Material	Fan	Average Local Standard Deviation
East	Granite	E1	0.2770
East	Granite	E2	0.2175
East	Granite	E3	0.4602
West	Granite	W1	0.1995
West	Granite	W2	0.1144
West	Granite	W3	0.1918
East	Metamorphic	E4	0.5922
East	Metamorphic	E5	0.7642
East	Metamorphic	E6	1.1754
East	Metamorphic	E7	0.4938
West	Metamorphic	W4	0.5164
West	Metamorphic	W5	0.2604
West	Metamorphic	W6	0.3965
All East M1 Units			0.5777
All West M1 Units			0.3113
East M1 Granite Units			0.3163
West M1 Granite Units			0.1605
East M1 Metamorphic Units			0.7294
West M1 Metamorphic Units			0.3893

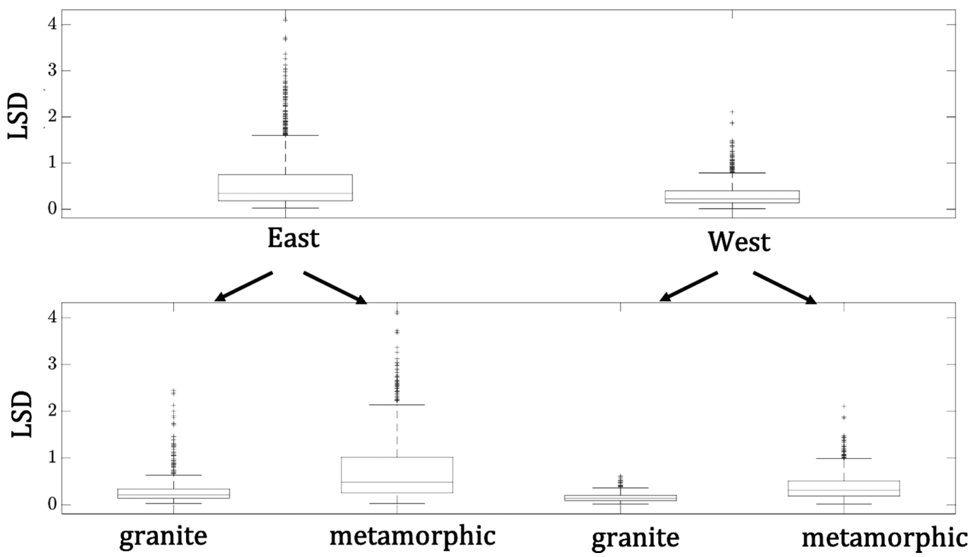

Figure 9. Sierra Estrella bajadas on the east-facing and west-facing sides display very different amounts of incision. Incision data are presented as box plots showing the metric of local standard deviation (LSD) values. (a) Upper plots compare east and west detrended M1 profiles mid-Pleistocene alluvial fan mapping unit of Demsey (1989). (b) The lower plot splits apart the granite and metamorphic drainage basins of the same-age M1 units, identifying the dominant lithology in each basin.

indicated in Table 1 and Figure 9. The general and clear trend in our data reveals that the eastern early/mid-Pleistocene fan units are more incised than the western units. This is true for fans with a mostly granitic drainage basin and also fans with a mostly metamorphic drainage basin (Table 2; Figure 9).

Table 2. Simulation results of pediment-inselberg longitudinal profile changes in response to different base-level change scenarios.

Base-level simulation	Simulation Result	Comparison with Pediment Field Observations
Stable base level (Figure 11(a))	Proximal incision with no change at the toe	northern San Tan Mtn pediments (Figure 6(a))
Rising base level (Figure 11(b))	Proximal incision with toe aggradation	condition not met in study area
Falling Base level (Figure 11(c))	Proximal incision with toe incision	northwestern Usery Mtn pediments (33.521,-111.662)
Lateral shift closer to piedmont toe (Figure 11)	Proximal incision with toe incision	condition not met in study area
Rising base level & lateral shift with $v > u\ tan(\beta)$ (Figure 11(e))	Proximal incision with toe aggradation	southern White Tank Mtns "Skyline" pediment (33.463, −112.553)
Rising base level & lateral shift with $v < u\ tan(\beta)$ (Figure 11(f))	Proximal incision with toe incision	northern Sierra Estrella Toothaker pediment (Figure 1(a)) southern San Tan Mtns pediments (Figure 6(a)) southern Papago Buttes pediment (Figure 6(b)) southern Phoenix Mtns pediments (33.536,-112.024)
Rising base level & lateral shift with $v = u\ tan(\beta)$(Figure 11(g))	Proximal incision with no incision at the toe	condition not met in study area

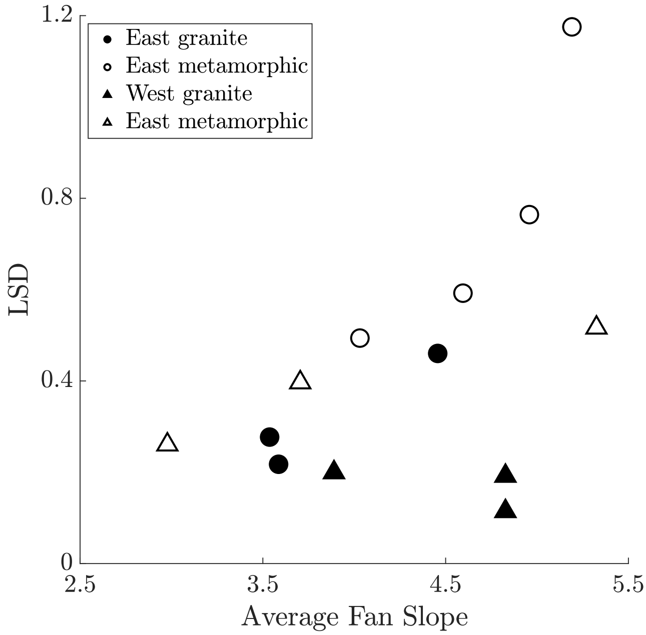

Figure 10. Incision of the Gila River-facing Sierra Estrella bajada depends on the slope of the M1 alluvial fan units mapped as early/mid-Pleistocene by Demsey (1989); in contrast, the west-facing bajada does not seem to be influenced by average fan slope of the M1 unit.

The average local standard deviations on the east side are always larger than those on the west side: 0.5777 vs. 0.3113 (Table 1). This pattern persists when isolating rock types in the source drainage basins. Granite-sourced M1 units on the east side average 0.3163 vs. 0.1605 on the west side. This difference also exists at 0.7294 versus 0.3893 for metamorphic-sourced M1 units on the east and west sides, respectively. Figure 9 presents boxplots of unaveraged data. Figure 9(a) groups profiles by east and west, while Figure 9 (b) shows each individual profile's local standard deviations.

While Figure 9, presents all local standard deviations, Figure 10 plots incision (average local standard deviation) against average fan slope, revealing that fan slope does appear to influence the average amount of incision for east-side granitic and metamorphic fans. In contrast, fan slope does not appear to play a notable role in west-side fan incision. The only major difference in the east- and west-side fans is the distance to base level after river arrival.

Our results are consistent with what is seen visually in the field and on aerial imagery (Figure 7, Figure 1(b)). Western Sierra Estrella piedmonts have a distinctly different morphology in terms of incision compared to the eastern piedmonts fronting the aggraded floodplain of the Gila River. These observations are consistent with the hypothesis that the east-side alluvial fans of the Sierra Estrella have been experiencing increased channel incision due to river arrival burying thefan toes (Figure 1(b); Figure 2).

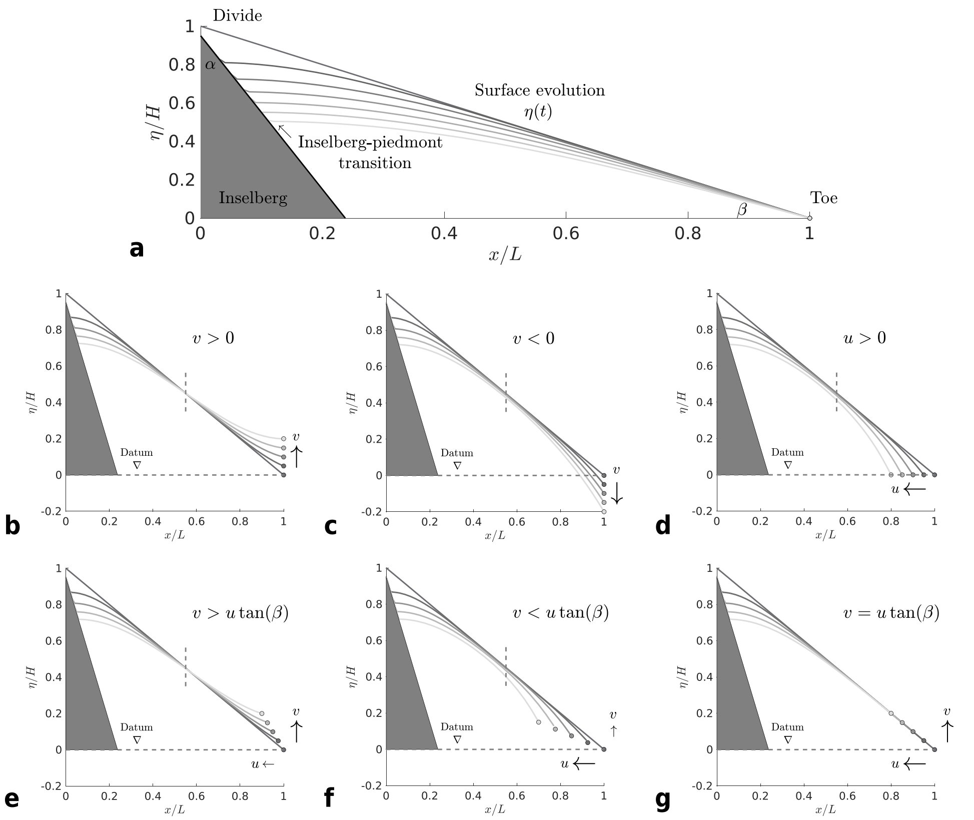

Figure 11. Thought-exercise in pediment dynamics after solving Fick's equation. The time-direction of the profiles is represented by curves that go from dark-gray to light-gray. Profiles evolve due to diffusive effects and toe displacements. Inselberg non-erodibility is represented by $D = 0$. Simulations are for seven different base-level conditions: (a) stable base level; (b) rising base level; (c) falling base level; (d) lateral shift of base level close to the mountain front; (e) base-level rise and lateral shift with $v > u\ tan(\beta)$; (f) base-level rise and lateral shift with $v < u\ tan(\beta)$; and (g) base-level rise and lateral shift with $v = u\ tan(\beta)$. The inflection point in B is highlighted with a dashed line, dividing the profile into two regions. Toe displacements influence the region of the right side. This dashed line is repeated in C, D, E, and F serves as a way to identify toe-influence region to the right of the dashes. Note that incision at the toe of the pediment only occurs in scenarios C, D, and F.

Thought exercise on piedmont longitudinal profiles as a diffusive system

The mathematical approach to modeling the longitudinal profile evolution of pediment-inselberg systems explained in methods reveals a strategy to understand how these systems evolve under different base-level change scenarios. Figure 11 presents scenarios of base-level change to compare with field observations of pediment-inselberg systems in the Phoenix metropolitan region (Table 2).

Discussion

Alluvial fan evolution in relation to drainage integration

Prior scholarship offers a variety of explanations for why alluvial fans experience incision (Bowman, 2019; Ventra & Clarke, 2018). The literature is more worthy of a lengthy review paper or book – far more than we can discuss here. However, we broadly cast this scholarship into the following eight general themes:

· tectonics (A.M. Harvey et al., 2018; L. A. Owen et al., 1997; Bahrami, 2013; Clevis et al., 2003; Guerra-Merchan et al., 2004; Kesel & Lowe, 1987; Pope & Wilkinson, 2005; Rits et al., 2017; Rubustelli et al., 2005);

· different reasons for base-level fall (Bowman et al., 2010; Calvache et al., 1997; Granados and Espejo, 2014; Harvey, 1984, 2002b; Hooke, 1972; Pope et al., 2016; Viseras et al., 2003);

· a threshold response caused by aggradation from tributary drainages near the fan head (Clarke et al., 2010; Clarke, 2015; Hooke & Dorn, 1992; Ventra & Nichols, 2014; Weaver & Schumm, 1974);

· changes in accommodation space (A.M. Harvey et al., 2018; Fidolini et al., 2013; Huerta et al., 2011; Muto & Steel, 2000; Posamentier & Vail, 1988; Weissmann et al., 2005);

· responses to climate change, land cover and pulses of sediment supply (Bartz et al., 2020; Coulthard et al., 2002; Kochel et al., 1997; L.A. Owen et al., 2014; Li et al., 2021; Schmidt et al., 2012; Terrizzano et al., 2017; Wasklewicz & Scheinert, 2016; Wells & Harvey, 1987);

· coupling linkages at different spatial and temporal scales (A.M. Harvey, 2012; Cabré, Aguilar, Mather, Fredes, Riquelme et al., 2020; Harvey, 2002a; Pepin et al., 2010; Rohais et al., 2012);

· changes in a dynamic equilibrium that may involve millennial or longer time scales (Davies & Korup, 2007; Poulos & Pierce, 2018; Tricart & Cailleaux, 1965); and

· high magnitude meteorological/climatological events leading to high magnitude floods (Baker, 2006; Beaty, 1974; Cabré, Aguilar, Mather, Fredes, Riquelme et al., 2020; Gao et al., 2020; Gutiérrez et al., 1998; Kale et al., 2000; Lafortune et al., 2006; Quigley et al., 2006)

Out of the possible explanations in prior scholarship listed above, we can only exclude active tectonism and base-level fall from the aforementioned potential causes of Sierra Estrella fan incision. These simply do not apply to our Sierra Estrella study area.

These explanations do not include the long-term (late Miocene, Pliocene, Quaternary) timescale examined here of a gradual reduction in range relief and drainage basin area that leads to alluvial fan “telescoping” and bajada incision (Mabbutt, 1977; Dávila et al., 2012; Peterson, 1981; Ritter et al., 2000; Scheinert et al., 2012).

Our finding of a more incised eastern flank of the Sierra Estrella (Figures 9 and 10; Table 1) fronting the ca. 2.5 Ma arrival of the Salt River (Skotnicki & DePonty, 2020) and the ca. 2.1 Ma arrival of the Gila River (Gootee et al., 2021) is explained well by the lateral shift in base level, despite ~120 m of base-level rise. The Salt and Gila rivers arrived right at the toe of the eastern Sierra Estrella bajada (Figure 1(b)) and started burying the toe of the bajada. The western Sierra Estrella bajada experienced less incision (Figures 9 and 10; Table 1), we think because base level shift was less than half the distance felt by the eastern side. Figure 2, thus, is not an overly dramatic portrayal of what we think happened to the eastern Sierra Estrella bajada.

The qualitative appearance of incision (e.g., Figure 1(b)) certainly gives the impression of retreating knickpoints generating the east-side Sierra Estrella incision. A retreating knickpoint would produce the tributary pattern observed in the fan incision (Figure 1 (b)). However, we cannot rule out processes that alter relationships between transport- and detachment-limited hillslope systems. Erosive processes have the potential to transition the system between transport- and detachment-limited. Thus, nothing in our observations rule out the possibility that changes in sediment supply could influence incision. We also cannot rule out the role of high magnitude meteorological events resulting in incision. Teasing out the importance of high magnitude precipitation events or top-down sediment-supply shift versus our bottom-up, toe burial hypothesis for the Sierra Estrella piedmonts is beyond the scope of this research project.

Pediment-inselberg profile evolution in relation to drainage integration

Scholarship on bedrock pediments offers far fewer explanations than the alluvial-fan literature for why aggradation or incision occurs. Parallel retreat of inselberg hillslopes (Penck, 1924) is generally thought to lead to an alluvium-mantled bedrock surface on a pediment's distal end called a suballuvial bench (Mabbutt, 1966, 1977; Lawson, 1915). Changes in sediment supply from the drainage basin, such as from climatic changes (Blackwelder, 1931; Oberlander, 1979) might also bury the distal end of a pediment producing a landform called an alluvial slope (Applegarth, 2004). Numerical modeling suggests that suballuvial benches can experience "exhumation" and channel incision from piedmont tilting (Pelletier, 2010). Tilting, however, is something that has not occurred in the Phoenix study area for the time period of our investigation, as evidenced by flat-lying basin sediment fill (Gootee, 2013; Laney & Hahn, 1986; Richard et al., 2019; Skotnicki & DePonty, 2020; Skotnicki et al., 2020a; Spencer, 2011).

Proximal incision of bedrock pediments (Dohrenwend & Parsons, 2009) occurs commonly in inselberg-pediment systems, including in our study area of central Arizona. This top-of-pediment incision also occurs in all simulation conditions upstream of an inflection point (Figure 11; Table 2), produced by diffusive effects. This is consistent with early 20th century thinking that pediments experience incision nearest to the inselberg over geological timescales as a consequence of gradual reduction in range relief and drainage basin size (Cooke & Mason, 1973; Davis, 1905, 1930, 1933a, 1933b; Howard, 1942; Johnson, 1932a, 1932b; King, 1949, 1955; Waibel, 1928). Diffusive effects do depend on the local slope of the longitudinal profile, soil composition, bedrock type and its decay, as well as climate and how it changes (e.g., precipitation rate, infiltration capacity, vegetation). The fixed-base condition of Figure 11(a) reveals that diffusion is a reasonable mechanism to explain proximal pediment incision from the gradual reduction of range size.

All simulations generated a convexity in the upper pediment (Figure 11). However, convexities in proximal wash longitudinal profiles have not been documented in prior scholarship on bedrock pediments. This simulated convexity is because we selected a no-flux condition and a linear diffusion equation. Future research could explore what erosion conditions would generate both observed proximal incision in Figure 11 and also the straight pediment slope of natural pediments (Dohrenwend & Parsons, 2009). We emphasize that the focus of our 1D modeling efforts rested on the toe of pediments. In particular, we wanted to assess if solving Fick's equation on a simplified pediment-inselberg profile could lead to a better understanding of the effects of both base-level rise and lateral shifting.

Pediment scholarship typically refers to incision as dissection of exposed bedrock surfaces (Cooke & Mason, 1973; Dohrenwend & Parsons, 2009; Oberlander, 1989). Our focus on pediment toe incision is unusual in the pediment literature – something that we think reflects the focus in prior scholarship on proximal incision. Pediment toe incision occurs in simulations of (i) a falling base level with no lateral shift in base level position (Figure 11(c)); (ii) a lateral shift in base level position closer to the range front with no change in base level (Figure 11(d)); and (iii) where the ratio of the rate of base-level rise to $u\ tan(\beta)$ is less than 1 (Figure 11(f)); note: u is the rate of lateral shift, and β is the initial elevation-angle of the piedmont.

A lateral shift with no vertical displacement of the toe generating pediment toe incision (Figure 11(d)) is a condition that is not met in the larger Phoenix region, and we are not aware of a pediment location elsewhere to compare with this simulation result. However, lateral shifts in streams do cause tributary stream incision (Brierley & Fryirs, 1999; Faulkner, 1998; Lane, 1955; Schumm et al., 1987), albeit at a much smaller area than pediments.

However, if rising base level occurs with a lateral shift closer to the toe of the pediment, the reaction of the longitudinal profile is conditioned by the ratio of the rate of these displacements. In particular, if v is the rate of base-level rise, u the rate of lateral shift, and β the initial elevation-angle of the piedmont, then near-base incisions only appear if $v < u\ tan(\beta)$ (Figure 11(f)). This condition arises from a geometrical constraint, setting a limit for which it is possible the presence of both base-level rise and near-base incisions.

In this manner, we can define the following parameter:

$$\Gamma = \frac{u\ \tan(\beta)}{v} \tag{Eq.2}$$

where for $\Gamma > 1$, incisions will appear at the toe. If we contrast this vertical/horizontal toe displacement with the classic explanation and the field observations, incisions in the northern Sierra Estrella system (Fig. 1a) could be governed by a lateral shift. If this were not the case, incision (or any other evidence of erosion) should be present only far from the toe.

The condition of $v < u\ tan(\beta)$ is met by four pediment systems in metropolitan Phoenix (Table 2). Granitic pediments on the northern end of the Sierra Estrella (Figure 1(a)), granitic pediments on the southern side of the San Tan Mountains (Figure 6(a)), sedimentary pediments on the southern side of Papago Buttes (Figure 6 (b)), and metamorphic pediments on the southern side of the Phoenix Mountains all once had distant base levels located at the playas of the Luke and Higley basins (Figure 3). The condition in the simulation shown in Figure 11(f) is strongly satisfied, because the lateral shift in base level location resulted in a shift of many kilometers closer through the sudden event of drainage integration. Looking carefully at Figure 11(f), note also that pediment incision occurs throughout the longitudinal profile, including the middle of the profile – a characteristic of all the above Phoenix-region pediments.

Pediment toe aggradation is the main characteristic of what is often called an alluvial slope (Applegarth, 2004; Applegarth & Stefanov, 2006) that has a suballuvial bedrock platform (Applegarth, 2004; Blackwelder, 1931). Blackwelder (1931) thought that climatic changes could result in pulses of sedimentation causing the accumulation of alluvium on a bedrock pediment, but Applegarth (2004) and Applegarth and Stefanov (2006) argued that these forms are simply a transition between bajadas and full bedrock pediments. The simulation approach used here offers an alternative interpretation.

The "Skyline" pediments at the southern end of the White Tank Mountains (ca. 33.463, −112.553) could be explained by the simulation conditions in Figure 11(e) (Table 2). This simulation is the opposite of Figure 11(f) in that the ratio of the rate of base-level rise to *u tan(β)* is greater than 1 (Figure 11(e)). Here, aggradation associated with river integration did take place, as shown in many well logs, but the location of the original base level was a small structural basin whose center was located near the present-day position of the Gila River. Thus, when Salt-Gila river integration occurred, these White Tank southern pediments experienced a lateral shift rate of ~360 m/Ma; this is almost eight times less than the lateral shift rate of ~2800 m/Ma for northern pediments of the Sierra Estrella range (Figure 1(a)).

Pediment toe stability occurs in simulations of no base level change (Figure 11(a)). The condition of no base-level change is met by the northern San Tan Mountains pediment (Figure 6(a)). While this pediment no longer drains to the Higley basin depocenter (Figure 3), it does drain to Queen Creek whose Pliocene and Quaternary history indicates a stable base level (Skotnicki et al., 2020a).

Pediment toe stability also occurs in simulation Figure 11(g), but we are not aware of a location that meets the condition of this simulation, where the ratio of the rate of base-level rise to *u tan(β)* (*u* the rate of lateral shift, and *β* the initial elevation-angle of the piedmont) is equal to 1. It may be possible to find such a location, but the conditions that allowed us to test most of the simulations in Figure 11 required the expenditure of tens of millions of dollars on well drilling operations to acquire samples able to analyze base-level history (Skotnicki & DePonty, 2020).

We now turn to an implication of pediment-inselberg profile simulations (Figure 11): analyzing the effects of diffusion and toe displacement on pediment evolution. To do so, we must analyze their timescales of change. The diffusive timescales reflect how long it takes for a mountain-particle to cross the whole inselberg-pediment domain (L) due to diffusion. This timescale (τ_d) can be expressed as in Equation 3; we assume that the upper angle of the inselberg is small enough, α in Figure 11(a), making its base small compared to the piedmont length.

$$\tau_d = L^2/D \tag{Eq.3}$$

We think of the timescale of toe displacement from the perspective of contributions that base-level rise and lateral shift make to reshape the pediment profile. For the lateral shift, the rate is *u/cos(β)*, whereas the rate o base-level rise is *v/sin(β)*. By adding these rates and considering that the distance from top-to-toe is *L/cos(β)*, a timescale (τ_t) can be defined as follows:

$$\tau_t = \frac{HL}{uH + vL} \tag{Eq.4}$$

A rearrangement of the previous equation yields $\tau_t = (1/\tau_x + 1/\tau_z)^{-1}$, where τ_x and τ_z are the timescales of toe displacement in the horizontal and vertical directions, respectively. This alternative notation allows us to make an analogy with an electrical parallel circuit: τ_t is the equivalent timescale/resistance of a system in which τ_x and τ_z are the timescales/resistances of two parallel ways/paths to erode-the-pediment/cross-the-circuit. Here erode-the-pediment means that the toe moves L horizontally or H vertically.

Other timescales can also be defined. For example, it is possible to define the time it takes to reduce the volume of the pediment by half due to toe displacement (τ_t^*):

$$\tau_t^* = \frac{uH + vL - \sqrt{(uH)^2 + (vL)^2}}{2uv} \tag{Eq.5}$$

Note that τ_t and τ_t^* converge to a trivial timescale when $u \rightarrow 0$ or $v \rightarrow 0$, representing the time when pediment erodes due to toe displacement:

$$\lim_{u\to 0} \tau_t = \lim_{u\to 0} 2\tau_t^* = \frac{H}{u} \quad \lim_{v\to 0} \tau_t = \lim_{v\to 0} 2\tau_t^* = \frac{L}{u} \tag{Eq.6}$$

We choose τ_t for this analysis, although any timescale can be selected. Taking the ratio of τ_d and $\tau_t$yields :

$$\kappa = \frac{\tau_d}{\tau_t} = \frac{L}{D}\left(u + \frac{v}{\theta}\right) \tag{Eq.7}$$

where $\theta = H/L$ the slope of the hill. κ compares the dominance of the diffusive capacity against the toe displacement by aggradation and lateral shift. Note that κ is similar to the Péclet number. The Péclet number characterizes dispersive-advective systems (e.g., Theodoratos & Kirchner, 2020; Wang & Cardenas, 2014).

The parameter κ could help to classify various pediments, where a threshold for this could be proposed to characterize hillslopes evolution. Such a classification is beyond the scope of this work. Nevertheless, we estimate a representative value for the Toothaker pediment, at the northern Sierra Estrella (Figure 1(a); Figure 5), to offer an order of magnitude of κ. This area has a granitic lithology with desert vegetation, similar to that observed, for example, in some places of northern Chile. In those places, diffusion coefficients range from $D = 1 \times 10^{-4}$ to 23×10^{-4} m^2/yr (Callaghan, 2012; Richardson et al., 2019). On the other hand, $D = 18 \times 10^{-4}$ to 40×10^{-4} m^2/yr yields erosion rates of ~12 – 19 mm/ky at the Toothaker hilltop, which matches erosion rates for pediments in the most arid locations in the Phoenix area (Ara Jeong, personal communication). Therefore, we consider $D = 20 \times 10^{-4}$ m^2/yr as a representative value of the diffusion coefficient in the study area. Other estimations for the Toothaker pediment are L = 12,400 m, $\theta = 0.018$, u = 3 mm/yr, Γ= 1.4 mm/yr. These assumptions yield $\kappa \approx 32{,}000$.

A final implication of this research is that our findings contradict a paradigm that pediments are fossil or relict landforms of a wetter Tertiary climate (Oberlander, 1974, 1989; Twidale, 1998, 2002). Our thought exercise and field observations, along with prior observations from central Arizona (Larson et al., 2014, 2016, 2020), indicate that pediments are not fossil or relict landforms. Granitic, sedimentary, and metamorphic pediments all react to ongoing geomorphic processes such as a lateral shift in base level associated with aggradation (Figures 1(a), 6, 11(e)) or base-level fall (Figures 1(c) and 11(c)).

Conclusion

No prior scholarship that we could identify links desert piedmont incision, either alluvial fans or pediments, to a rise in base level. Yet, a rising base level is exactly what incising fans and pediments experienced in the northeastern BRP of central Arizona for the entire Pliocene and Quaternary. Prior to the integration of the Salt River after 2.8 Ma, piedmont base levels were found over 100 m below modern elevations at the depocenters (playas) of the Luke and Higley basins (Figure 3). After arrival of the Salt and Gila rivers, base levels both rose and moved much closer to toes of Phoenix-region piedmonts (Figures 4 and 5). Thus, we hypothesize that a massive lateral shift in base level to the toes desert piedmonts could be a potential explanation for the channel incision. Our 1D diffusion simulations to explain pediment-inselberg longitudinal profiles (Figure 11; Table 2) and morphometric analyses of the Sierra Estrella bajadas (Figures 10 and 11; Table 1) support the hypothesis that a combination of base-level rise and lateral shifting can generate piedmont incision, starting at the toe and working up-piedmont.

At the same time, the results of our research cannot rule out the early 20th century thinking that range-size reduction on the geological timescale of late Miocene through Quaternary could also potentially explain the observed piedmont incision. Similarly, the alluvial-fan literature offers other alternatives for bajada incision that could apply, including a threshold response, changes in sediment supply, changes in accommodation space, climate change, spatial-temporal coupling, or high magnitude climate or meteorological changes.

Our findings are an initial investigation, but if further work confirms our new hypothesis – that the lateral shift in base level as a result of drainage integration is indeed the cause of Quaternary piedmont incision – the broader implications of this research could impact interpretations that fan incision is necessarily a result of basin dissection (Stokes, 2008). Sedimentologists and geomorphologists typically interpret incision of such piedmont systems as a function of active tectonics (Blair & McPherson, 2009; Hussain & Aghwan, 2014; A. M. Harvey et al., 2005; Van Wie, 1976). River integration in extensional tectonic settings like central Arizona are associated with tectonic quiescence (Skotnicki et al., 2020b); our findings, thus, lead to the possibility that some past sedimentological records of alluvial-fan systems could have been misinterpreted.

Another implication of this research involves how base level is taught. We examined how base-level rise is treated in posted course notes from over 30 different colleges teaching Introduction to Physical Geography in Australia, Canada, the USA and UK. All of these course notes teach that base level rise leads to aggradation in fluvial systems. There could be pedagogical value in helping students understand that lateral shifts of base level might lead to incision of mountain piedmonts (alluvial fans and pediments), where the lateral shift in base level can be more important than an overall rise in base level (Figure 2; Figure 11(f)).

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Data availability statement

All available data are presented inside this manuscript.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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