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Impact of drainage integration on basin geomorphology and landform evolution: A case study along the Salt and Verde rivers, Sonoran Desert, USA

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The Salt and Verde rivers, Sonoran Desert, USA, integrated multiple endorheic extensional basins near the start of the Quaternary. Integration began via spillover on both rivers. Spillover resulted in headward erosion in upstream basins, leading to basin-wide incision and excavation of large volumes of sediment transported into downstream basins. As a result, the Verde River aggraded to what is now the highest terrace in the lower Verde River valley (LVRV), the Lousley Hills terrace. Evidence suggests deposition of the Lousley Hills terrace fill led to aggradation and backfilling of adjacent pediments. Ancestral Salt River Deposits (ASRD) of the combined Salt and Verde rivers deposited an extensive alluvial fan in the Higley Basin, raising local base level for over 2 million years. Eventually, this led to aggradational piracy of the Salt River (~0.46 Ma) that integrated the Higley and Luke basins. Consequently, this shortened and steepened the Salt River, resulting in ~30 m of aggradation downstream and headward incision upstream. Headward incision abandoned the ASRD and created the Sawik stream terrace. Piedmont pediment and alluvial fan systems that were formerly adjusted to the ASRD incised in response. Since abandonment, the ASRD floodplain has accumulated a sheet of silt and fine sand from aeolian and local fluvial processes. Sedimentary, metamorphic, and granitic pediments that developed in slowly aggrading endorheic basins display evidence of response to base-level adjustments resulting from drainage integration processes. Classic ballena landforms (eroding alluvial fans) began to form in the LVRV only after drainage integration — providing the first known maximum age for the ballena form. Drainage integration of the Salt and Verde rivers clearly demonstrates the impact of base-level fluctuations on basin-scale geomorphology. However, integration led to very different geomorphic responses in different extensional basins, revealing the difficulty of a one-size-fits-all conceptual model of geomorphic response drainage integration.

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1. Introduction

Drainage integration occurs when former hydrologically closed (endorheic) or disconnected drainage basins merge to form a new hydro-geomorphic system (Hilgendorft et al., this issue). Much of drainage integration research has focused on the evolution of main-stem river systems within a drainage basin, resulting in a burgeoning understanding of processes that drive integration (Oberlander, 1965; Meek, 1989; House et al., 2005; Douglass and Schmeeckle, 2007; House et al., 2008; Reheis and Redwine, 2008; Douglass et al., 2009; Gunnell and Harbor, 2010; Lee et al., 2011; Pearthree and House, 2014; García-Castellanos and Larrasoana, 2015; Repasch et al., 2017; Geurts et al., 2018; Geurts et al., this issue; Skotnicki et al., this issue). Despite this, comparatively few studies have investigated the variety and significance of landforms that experienced a basin-scale response to integration processes. Recent studies investigating these basins have begun to illuminate basin-wide, dynamic responses (Geurts et al., 2018; Geurts et al., this issue) of those landscapes — including pediment adjustment (Larson et al., 2010; Larson et al., 2014; Larson et al., 2016) and tributary response (Jungers and Heimsath, 2019). These studies reveal the potential for aiding in the development of conceptual models of basin and landform evolution during and post integration (Menges and Pearthree, 1989) – with significance that goes beyond geomorphology to basin evolution (Roberts et al., 1994), basin sedimentation (Richard et al., 2007), carbon dioxide sequestration (Gootee, 2013), groundwater resource management (Laney and Hahn, 1986; Reynolds and Bartlett, 2002; Skotnicki and DePonty, this issue), and natural hazard mitigation (Jeong et al., 2018).

This paper attempts to shed light on basin-scale adjustment and the landforms resulting from drainage integration. We do this by presenting a variety of landforms, observed and interpreted over >20 yr of field investigation throughout the spatial extent of formerly closed, endorheic basins along the now through-flowing lower Salt and Verde rivers, Arizona, USA (Figs. 1–3).

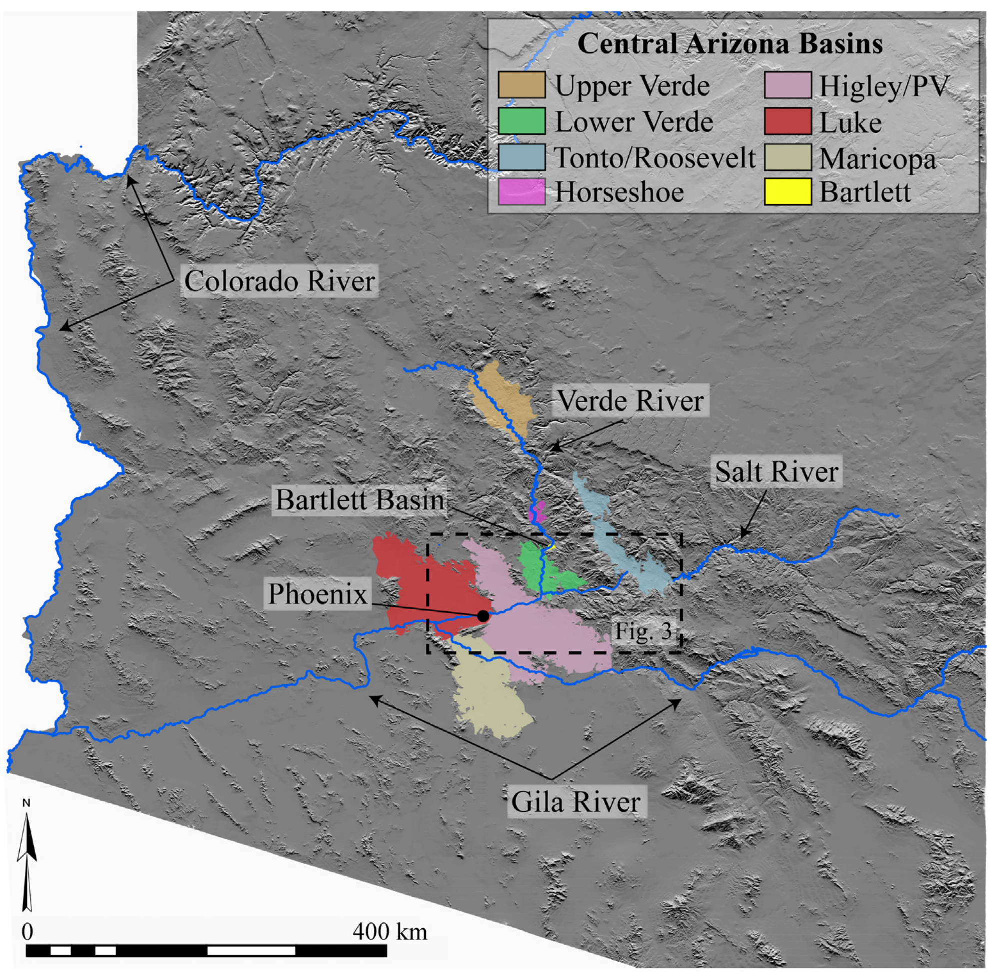

Fig. 1. The rivers and basins of Arizona, USA, that are the focus of this study. The basins depicted here were formerly endorheic, but integrated within the last ~2.2–2.8 Ma (Jungers and Heimsath, 2016; Skotnicki et al., this issue). The integration of these basins resulted in the modern through-flowing drainage networks of the Salt, Verde, and Gila rivers of central Arizona. The Salt River is not shown as continuous through the Tonto/Roosevelt Basin because there is a large reservoir in that basin today.

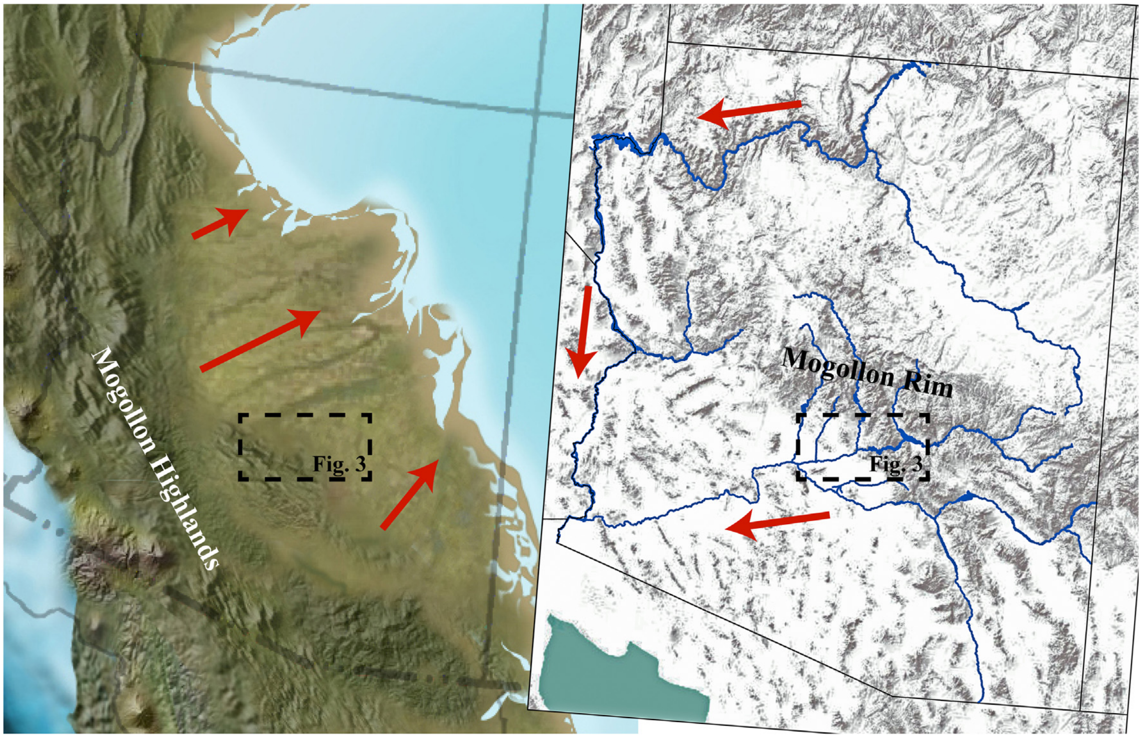

Fig. 2. The change in tectonic forces acting on Arizona over the past ~100 Ma set the stage for drainage-network reversal and geologically more recent drainage integration. (Left) Northern Arizona University Emeritus Professor Ronald Blakely's ca. 92 Ma reconstruction of Arizona paleogeography (used with permission) illustrates regional northeasterly flowing drainages in the Late Cretaceous. The generalized flow direction is indicated by red arrows. The Mogollon Highlands, created by compressional tectonics occurring at that time, are to the south-southwest where exoreic streams flowed to a Cretaceous Inland Seaway in the North American continental interior. (Right) The modern Verde and Salt rivers, along with all through-flowing drainages in Arizona, now flow in the opposite direction - to the southwest. The generalized flow direction of the regional drainage is indicated by the red arrows. Nearly all through-flowing rivers in central Arizona originate from the Mogollon Rim and flow southwest where they transverse numerous formerly internally drained basins that they once had to integrate to become a through-flowing stream. A black dashed box in each figure notes the location of the map in Fig. 3 for reference. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Source imagery: ESRI, USGS, NOAA, and with permission of Ronald Blakey.

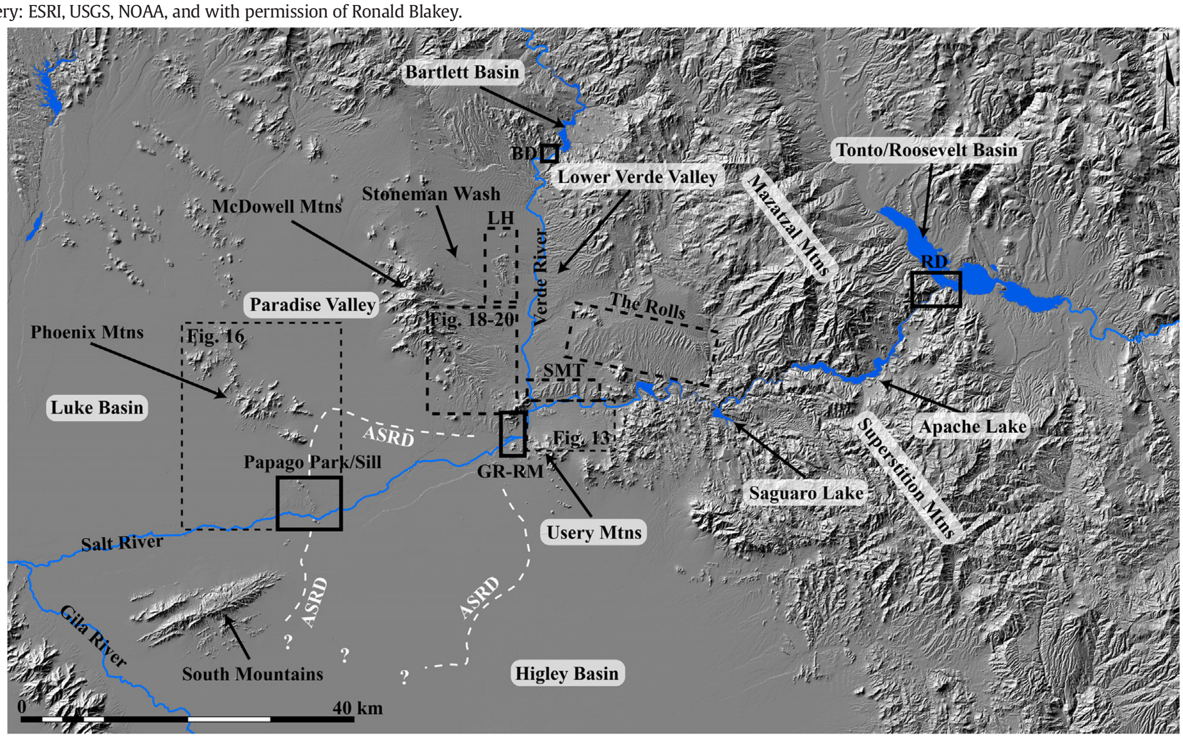

Fig. 3. The Salt and lower Verde rivers, central Arizona, USA. See Figs. 1 and 2 for spatial context. This map displays the key geomorphic and geologic features discussed throughout the remainder of this paper. Basins through which these rivers have integrated are labeled and their full extent can be observed at a smaller scale in Fig. 1. Dashed boxes indicate the locations of important landforms discussed within the text. Bold boxes indicate locations of key features and sites where basin integration occurred. RD = Roosevelt Dam. BD = Bartlett Dam. GR-RM = Granite Reef – Red Mountain. LH – Lousley Hills. SMT – Stewart Mountain Terrace (Larson et al., 2010). ASRD – Ancestral Salt River Deposit (Skotnicki and DePonty, this issue; Skotnicki et al., this issue). The white dashed line indicates the estimated approximate boundary of the ASRD based on the extent mapped by Laney and Hahn (1986) and Skotnicki and DePonty (this issue). Question marks beyond this boundary represent the uncertainty of the southern extent of the ASRD.

2. Study area: the Salt and Verde rivers of central Arizona

Decades of research in central Arizona have led to estimates for the timing and hypothesized potential mechanisms, supported by abundant evidence, of integration of the Salt, Verde, and Gila rivers through the Phoenix metropolitan area (Pope, 1974; Péwé, 1978; Skotnicki, 1996; Skotnicki and Leighty, 1997; Skotnicki and Spencer, 2001; Skotnicki et al., 2003; Block, 2007; Douglass et al., 2009; Larson et al., 2010; Jungers and Heimsath, 2016; Larson et al., 2016; Jungers and Heimsath, 2019; Dorn et al., this issue; Skotnicki and DePonty, this issue; Skotnicki et al., this issue). The Salt and Verde rivers became fully integrated through formerly endorheic basins near the Pliocene-Pleistocene boundary (~2.2–2.8 Ma) (Fig. 2; Skotnicki et al., this issue). In addition, other studies in these drainage basins have shown them to be an ideal setting to examine the geomorphic evolution of formerly endorheic basins that have transitioned to integrated, exoreic systems (Larson et al., 2014; Larson et al., 2016; Seong et al., 2016). Within this study we investigate geomorphic features in basins of the Salt and lower Verde river systems that include the Tonto/Roosevelt basin, lower Verde Valley basin, Higley-Paradise Valley basins, and Luke Basin (Figs. 1 and 3).

2.1. Setting the stage for the modern landscape: drainage integration in central Arizona

Before proceeding to the remainder of this paper that focuses on highlighting landform evidence of geomorphic response to integration events, we provide an overview of the process of drainage integration along these rivers — presented in greater detail elsewhere (Skotnicki et al., this issue).

The last time in geologic history that through-flowing streams traversed central Arizona (Elston and Young, 1991) was during the Cretaceous and early Tertiary (Fig. 2). These rivers existed in a very different tectonic context where convergence and compression stresses were active in southwestern North America (Sales, 1968). This resulted in uplift of the Mogollon Highlands (Bilodeau, 1986) — a northwest- to southeast-trending mountain range in southern Arizona (Fig. 2). Northeast-flowing drainages originated from the Mogollon Highlands and flowed towards the Cretaceous interior sea until the late Paleogene (Potochnik, 1989; Potochnik and Faulds, 1998; Potochnick, 2001). Uplift of the Colorado Plateau during the Laramide orogeny (Sales, 1968) coupled with later structural extension and basin subsidence in central and southern Arizona, disrupted this regional drainage pattern. Closed-basin endorheic systems were commonplace south of the Mogollon Rim (Fig. 2) during the Oligocene (Spencer and Reynolds, 1989). The Salt and Verde rivers (Fig. 1) of central Arizona preserve abundant evidence of the geologically recent establishment of through-flowing rivers (Fig. 3) (Laney and Hahn, 1986; Menges and Pearthree, 1989; Pearthree, 1993; Douglass et al., 2009; Larson et al., 2010; Skotnicki and DePonty, this issue; Skotnicki et al., this issue).

Based on paleomagnetic studies of the lacustrine units within the Verde Formation (Bressler and Butler, 1978), and Verde River incision of approximately 300 m into the Verde Formation, it is likely that "dramatic downcutting … began after ca. 2.5 million years ago and most likely signals the development of a through-going Verde River" (Pearthree, 1993, p. 23). A ca. 2.5 Ma age for the initiation of top-down integration of the Verde River from the upper Verde Valley into what are now downstream basins (Fig. 1; e.g., Horseshoe, Bartlett, lower Verde) is consistent with the presence of a 3.3 Ma volcanic tephra deposited within closed-basin playa deposits downstream in the lower Verde River valley (LVRV) that was deposited prior to river integration (Dorn et al., this issue).

The Salt River likely originated from a top-down drainage integration process (Hilgendorft et al., this issue), possibly from overflow of a lake in the Tonto/Roosevelt Basin (Fig. 1) (Douglass et al., 2009; Dorn et al., this issue). This hypothesized overflow process occurred near the present-day position of Roosevelt Dam (Fig. 3). The timing of this event is constrained by cosmogenic burial ages from ancestral Salt River deposits (ASRD) ca. 2.2–2.8 Ma, an alluvial deposit representing the arrival of and aggradation of the Salt River. The ASRD abruptly overlies locally-sourced, endorheic basin fill in much of the Higley Basin near Phoenix, AZ (Figs. 1 and 3) (Skotnicki and DePonty, this issue; Skotnicki et al., this issue). Basalt clasts from the Verde and Salt rivers occur together at the base of the ASRD deposits in well cuttings collected with a 3-m sampling interval. In addition, based on strontium isotopic, geochemical, SEM, and microprobe chemistry studies of basalt clasts collected from well cuttings near the base of the ASRD and outcrop positions where the Salt and Verde first entered the LVRV, we hypothesize that these two rivers integrated within close temporal proximity and are chronologically indistinguishable at present (Dorn et al., this issue).

Aggradation of the ASRD continued for about 2 million years across the Higley Basin (Fig. 3) (Skotnicki et al., this issue). This long-term aggradation raised base level of the Higley-Paradise Valley basins and gradually lowered the gradient of the Salt River's longitudinal profile in the Higley and LVRV basins. Eventually, aggradation filled the Higley/Paradise Valley basins to the point where the ancestral Salt River reached the elevation of the Papago bedrock sill at ~326 m (1070 ft) (Fig. 3) (Skotnicki and DePonty, this issue). It is likely that this initiated an aggradational spillover process (Hilgendorft et al., this issue) that integrated the Luke Basin (Fig. 1) across the Papago Park bedrock ridge (Fig. 3) and resulted in Salt River alluvium being deposited on top of locally derived sediments at Papago Park (Fig. 3) (Reynolds and Bartlett, 2002). Ultimately, this spillover event rerouted the Salt River to the north side of South Mountain where it exists today (Fig. 3). Skotnicki et al. (this issue) present a single cosmogenic burial age of 0.46 $\pm$ 0.02 Ma, best treated as a maximum limit, for the onset of Salt River gravel deposition in a new river course west of the Papago bedrock sill. Other maximum age constraints for this aggradational spillover event come from burial ages towards the top of the ASRD: a single burial age of 0.55 $\pm$ 0.12 Ma, and an isochron age of 0.54 $\pm$ 0.12 Ma (Skotnicki et al., this issue). The newly positioned Salt River flowed into the Luke Basin and then met the Gila River on the west side of South Mountain (Fig. 3), the course it follows today.

In summary, the sequence of events reviewed in this section provides the sequential context for the evolution of the Salt and Verde rivers. We hypothesize that drainage integration fundamentally drives much of basin-wide geomorphic response and has resulted in the variety of landforms visible in the region today (Figs. 1–3).

3. Methods

Though much of the contemporary study of geomorphology is tied to quantitative measurement and modeling, the origin of the field of geomorphology in natural history has meant that observation and interpretation have always been a fundamental part of a geomorphologist's research (Rhoads and Thorn, 1996). Indeed, the complexity of geomorphic systems and unique suite of conditions within a given landscape-system fundamentally requires observation and field investigation to understand natural variability and to verify more reductionist models developed in the laboratory (Church, 2013). Therefore, our approach in this paper is largely focused on observation and interpretation through the lens of extensive field investigations. We systematically examine and present the findings of our collective years of field work on the landforms in the basins of the lower Salt and Verde rivers (Figs. 1 and 3). We estimate that the authors have spent over three decades in this study area analyzing and interpreting the geomorphology, in addition to mapping the geology (Skotnicki and Ferguson, 1995; Ferguson and Skotnicki, 1996; Skotnicki, 1996; Skotnicki and Ferguson, 1996; Skotnicki and Leighty, 1997; Ferguson et al., 1998; Skotnicki and Spencer, 2001; Skotnicki et al., 2003; Larson et al., 2010; Larson et al., 2014; Larson et al., 2016). Therefore, given the paucity of research that has investigated the basin-wide geomorphic response to integration, and given the variety and character of landforms in integrated basins, we present this paper to provide initial insight to aid in expanding our holistic understanding of the geomorphology of drainage integration. We integrate and compare our field investigations and interpretations presented here with results from physical models of integration processes (Douglass and Schmeeckle, 2007). In addition, we incorporate and build off the results of new research in this special issue that focuses on the processes of main-stem drainage integration of the Salt River (Dorn et al., this issue; Skotnicki and DePonty, this issue; Skotnicki et al., this issue). Although an enormous variety of geomorphic features exist within the basins the lower Verde and Salt river transverse, we narrow our selection of landforms discussed to those explicitly relevant to both drainage basin integration and in classic desert geomorphology research.

4. Landforms as evidence of and response to drainage integration

Basin-scale adjustment to integration processes is largely driven by base-level change, which, itself, is a result of integration. Table 1 summarizes our analysis of how base level changed throughout the late Pliocene and Quaternary in response to drainage integration. In what follows, we first present a variety of landforms tied directly and specifically to basin landscape evolution driven by integration processes along specific reaches of the Salt and Verde rivers. We then highlight classic landforms in desert geomorphology that have been impacted by drainage integration processes, including a variety of pediments, alluvial fans and ballena forms, forms that result from inverted topography, and sandsheets.

4.1. Geomorphic impact of lake overflow at Roosevelt Dam site and in the Tonto/Roosevelt Basin

Douglass et al. (2009) hypothesized that a lake in the Tonto/Roosevelt Basin (Lance et al., 1962; Anderson and Piety, 1988) spilled over the bedrock sill near present-day Roosevelt Dam (Figs. 1 and 3). More recent studies have provided evidence that is consistent with this hypothesis (Dorn et al., this issue; Skotnicki et al., this issue). Based on physical (Douglass and Schmeeckle, 2007; Douglass et al., 2009) and conceptual (Meek, 1989; House et al., 2005; Pearthree and House, 2014; Meek, in press; Hilgendorft et al., this issue) models of this process, overflow would have generated a knickpoint that would have retreated back into the Tonto/Roosevelt Basin and resulted in incision of the tributaries of the Salt River upstream of the overflow location (RD in Fig. 3).

Following this initial integration, the longitudinal profile of the Salt River would have continued to extend headward through time as it adjusted to a new, ~350 m lower, base level of the LVRV (Fig. 3). This must have resulted in a lowered basin-wide base level in the Tonto/Roosevelt Basin and would have resulted in excavation of sediment from this upstream basin and transport of this sediment into the downstream basin. Eventually, aggradation in the downstream basin ceased as much of the stored sediment was excavated from upstream. Ultimately, incision of the Salt River would then begin as the sediment supply was reduced (Douglass and Schmeeckle, 2007; Douglass et al., 2009; Larson et al., 2010). The impact of this post-overflow adjustment can be observed in remote imagery as an extensively dissected landscape throughout the Tonto/Roosevelt Basin (Fig. 4). This basin-wide phenomenon is also observed in the field and exemplified by locations like "the narrows" (Fig. 5A) and Hell's Gate (Fig. 5B) along Tonto Creek, a major Salt River tributary in the Tonto/Roosevelt Basin (Figs. 1 and 3).

4.2. Canyon topography, entrenched meanders, and a high terrace along the Salt River between the Mazatzal Mountains and Higley Basin

When the Salt River spilled across the Mazatzal Mountains near Roosevelt Dam (Figs. 3 and 4), it eventually cut through underlying bedrock and two small basins (currently occupied by Apache Lake and Saguaro Lake; Fig. 3). Aerial photographs in Fig. 6 illustrate the canyon topography and entrenched meanders of the Salt River. We hypothesize that the sinuous course of the Salt River's incision into resistant bedrock is likely the result of the Salt River originally flowing across weakly consolidated sediments in these small basins that later allowed for superimposition onto the underlying bedrock.

We originally expected to find a deposit analogous to the Bullhead Alluvium of the lower Colorado River (Howard et al., 2015) along the Salt River within the LVRV (Figs. 1 and 3). Along the lower Colorado, headward incision driven by top-down drainage integration resulted in upstream excavation of sediment that was then deposited in basins downstream - most notably in a unit called the Bullhead Alluvium (Howard et al., 2015). Larson et al. (2010) originally identified tens of meters of alluvium within the LVRV that forms a prominent fluvial terrace they named the Stewart Mountain Terrace (SMT in Fig. 3). They noted that the subrounded gravels at the surface of the SMT were larger on average and had a distinctly different clast assemblage than the lower Salt River terraces. They suggested the SMT could have a similar significance to the Bullhead Alluvium, but stated that further work was necessary to verify. Skotnicki et al. (this issue), linked the SMT alluvium to The Rolls Formation, a fanglomerate sourced from the southern Mazatzal Mountains (Fig. 3). However, although the sedimentology of gravels present at the surface of the SMT is largely similar to the Rolls Formation, the SMT also contains clasts of the Mescal Limestone. The nearest outcrop of Mescal Limestone is found near Roosevelt Dam (Fig. 3), indicating it was transported there by an integrated Salt River. We support the hypothesis of Larson et al. (2010) and Skotnicki et al. (this issue) that the SMT is a fluvial terrace, but go further to say that it may represent: (1) a strath terrace where relatively sediment-poor water flowed across an older Rolls Formation surface upon initial overflow breaching the sill at Roosevelt Dam, or (2) the newly integrated Salt River reworked upstream Rolls Formation sediments and deposited them at SMT with the Mescal Limestone incorporated. Unfortunately, an adequate exposure useful in examining internal terrace fill to test these hypotheses does not exist. Despite the ambiguity of the genesis of SMT, it is a prominent feature within this landscape and further work is necessary to determine its significance.

4.3. Landforms as evidence of geomorphic response to Verde River integration in the LVRV

It is important to note that there is a Bullhead Alluvium analogous deposit for the Verde River downstream from Bartlett Dam called the Lousley Hills (Fig. 3).When the upper Verde Valley basin was breached and the Verde River began integrating downstream basins, sometime after ca. 2.5 Ma (Bressler and Butler, 1978; Pearthree, 1993), its waters would have entered Horseshoe, then Bartlett, before entering the LVRV basin (Figs. 1 and 3). Based on established criteria for identifying transverse drainage mechanisms (Douglass and Schmeeckle, 2007; Douglass et al., 2009), Skotnicki et al. (this issue) hypothesized, similar to the Salt River, that Bartlett Basin experienced a spillover event into the LVRV.

The location where the integration occurred, about 1 km west of Bartlett Dam (Fig. 3), consists of a very strongly cemented mudflow containing basalt boulders, the Needle Rock Formation (Skotnicki, 1996). Waters from this Bartlett Basin spillover exited the Needle Rock Formation and flowed directly into the LVRV onto a playa. This playa's existence is observed today by remnants of extensive deposits of the Pemberton Ranch Formation preserved at the surface, capped by younger, more resistant sedimentary units (Figs. 7 and 9). It is also found in well logs throughout the center of the LVRV (Skotnicki et al., 2003).

In contrast to the Salt River in the LVRV, we hypothesize that the Lousley Hills terrace and its alluvial fill is a Bullhead Alluvium (Howard et al., 2015) analogous deposit. It forms the high stream

Table 1
Base-level change in the Salt River watershed during the late Pliocene and Quaternary.

Portion of watershed	Base-level change(s)	Summary of possible geomorphic impact
Verde and Salt watersheds above lake overflow locations at Bartlett and Roosevelt dams (refer to Fig. 3)	Knickzone migration upstream from the overflow locations resulted in base-level lowering	Lowering has been the consistent base-level trend throughout the Pleistocene. The lowering, however, was punctuated, as is evidenced by progressively lower pediments and stream terraces in the Tonto Basin of the upper Salt River drainage (Royse and Barsch, 1971; Barsch and Royse, 1972; Anderson and Piety, 1988). Certainly, local effects such as landsliding and process response influences could have produced local aggradation.
Along the Salt River between Stewart Mountain and Roosevelt dams (see Fig. 4)	Base level first quickly rose upon spillover and then fell progressively, with filling and overspilling small basins in this stretch.	The overflow event might have produced a deposit analogous to the Bullhead Alluvium, raising base level downstream from the spillover at Roosevelt Dam. However, the authors have not found definitive evidence of such a deposit in this reach. It is possible that base level periodically stabilized generating strath terraces (Péwé, 1978) that could either be Sawik or Mesa terrace equivalent ages.
Lower Verde River valley (Fig. 3) upstream of the confluence of the Verde River with the Salt River	Stable for the Pliocene as the LVRV experienced an overfill condition, and then lowered from the Stewart Mountain terrace to the Sawik terrace for the early and mid-Pleistocene. Then, after the 0.46 Ma aggradational piracy event (Fig. 12), base level dropped to progressively lower terraces in Fig. 13.	The alluvial fans of Mazatzal and southeast McDowell Mountains would have had to respond to river incision starting in the early Pleistocene, with episodic lowering again during the late Pleistocene. The Mazatzal alluvial fans show the greatest variation in geomorphic resistance to erosion, with the Rolls Formation fanglomerate being the most resistant and featuring relief inversion of “The Rolls” and “Stewart Mountain terrace”, where former topographic lows (loci of debris flow deposition) became topographic highs. Fans debauching the southeastern McDowell Mountains and Black Mesa area exemplify a ballena form that would have initiated in the early Pleistocene. The granitic pediments on the north side of the Usery Mountains would have experienced rapid base-level fall from the Stewart Mountain to the Sawik levels (Fig. 13) at the start of the Pleistocene.
McDowell Mountain eastern pediment to the west of the Lousley Hills gravels (Figs. 3, 7, 8, 9A)	With Verde River overflow west of Bartlett Dam, base level initially lowered and then rose quickly until ca. 1.6 Ma when they started lowering. Verde River stream terraces mostly match the Salt River sequence (Fig. 13) of lowering base levels.	The granitic pediment had a stable base level for the late Pliocene of the playa surface because the LVRV was in an overfill condition. Then, with overflow of the Verde across the Needles Formation and knickzone recession, the Lousley Hills gravels deposited (Bullhead Alluvium analogous) along the length of the Verde River's initial position in the LVRV. Presently, only remnants exist along the west side in the LVRV. The sediment discharge from the eastern McDowell Mountain granitic pediment took ca. 1 million years to aggrade a sediment wedge to superimpose themselves across the Lousley Hills, and thus the base level of the pediment rose slowly from overflow to ca. 1.6 Ma. Then, base level started slowly lowering with subsequent knickzone recession into the pediment (Fig. 11).
Adjacent to the Salt River between Granite Reef and Papago bedrock sills (Fig. 3).	Late Pliocene slow base-level rise with aggradation of Rolls Formation, and then a more rapid rise with ASRD deposition. Then, about <0.46 Ma, base level fell to the Mesa, then by 0.86 ka to the Blue Point, by 0.31 ka to the Lehi and modern floodplain levels (Fig. 13)	Three pediments would have been influenced by the Salt River's rise in base level with ASRD deposition and then rapid fall in the late Pleistocene: the west-facing Usery Mountain granitic pediment; the south-facing Red Mountain (official name of Mt. McDowell) sandstone/breccia pediment, and the southeastern sandstone/breccia pediment of Papago Park. These pediments experienced about 2 million years of slow aggradation, with remnants preserved in the form of old channels (now inverted relief) on the Red Mountain pediment and find sand in embayments of the Usery Mountain pediments. Then, base-level fall led to pediment incision (Larson et al., 2016)
Western Higley Basin occupied by the ASRD portrayed in Fig. 1	Late Pliocene slow base-level rise with aggradation of Rolls Formation. ASRD deposition led to more rapid base-level rise. With piracy of the Salt River at the Papago bedrock sill (Fig. 12), slow aggradation from aeolian and fluvial inputs.	Pediments on the south-facing side of the Usery Mountains would have experienced the greatest effects of base-level rise because they were closest to the ASRD and would have experienced aggradation burying formerly exposed bedrock. The remainder of the pediments and small stream systems could have been influenced by shifts in the position of the Salt River as it aggraded in different locations over the ASRD. After the ASRD was abandoned ca. <0.46 Ma, source-bordering dunes of the Gila River moved north and mixed with fluvial sediment from Queen Creek and other smaller bordering drainages.
Southeastern Luke Basin, west of Papago Park and between South Mountains and Phoenix Mountains (Figs. 2–3)	For the late Pliocene until the late Pleistocene, either slow aggradation (if an overfill condition did not exist) or stable base level (if an overflow condition existed). At ca. <0.46 Ma, rapid base-level rise of ~30 m (Reynolds and Bartlett, 2002). No data then until at 12 ka with a period of lowering, followed by mid-Holocene rising, and lowering at ca. 1 ka (Huckleberry et al., 2013).	South Mountain experienced pedimentation along its drainages (Larson and Dorn, 2014) during the period of base-level stability, and then substantial aggradation in response to the Salt River's arrival. All the aggraded fluvial systems have since incised, but the timing and reason(s) for this incision are not known. The Phoenix Mountains' metamorphic pediments have experienced asymmetric amounts of incision, with those facing the Salt River showing a stronger response of incision and those facing away from the Salt River showing little incision. Again, the timing and reason(s) for the incision of the pediments is not known.

Fig. 4. Satellite imagery of the Tonto/Roosevelt Basin (see Fig. 1) revealing the heavily dissected landscape that has been adjusting since integration occurred sometime before 2.2–2.8 Ma (Skotnicki et al., this issue).
Imagery Source: Esri, Maxar.

terrace along the Verde River (Fig. 3). Lousley Hills terrace fill rests unconformably atop the playa deposits in the basin (Figs. 6–9). The unconformity here is interpreted as an erosion surface whereby small streams exiting the McDowell Mountains (Fig. 3) were flowing to a newly integrated Verde River as it also incised into the playa, lowering the base level in the LVRV. The initial arrival of the Verde River would have been relatively sediment-poor flow (Douglass and Schmeeckle, 2007), resulting in incision into the playa. Subsequently, headward erosion and elongation of the Verde River's longitudinal profile into the upstream Bartlett Basin would have excavated stored sediment and transported it into the LVRV.

The Lousley Hills terrace likely represents aggradational filling of the LVRV and supports a spillover hypothesis for integration of these basins. In the modern landscape, the terrace is predominantly preserved along the west side of the Verde River just downstream of Bartlett Dam (Fig. 3), but likely would have filled much of the valley, perhaps resembling an alluvial fan. Throughout the lower 20 m of the terrace fill (Fig. 7), clasts of the well-cemented matrix of the Needle Rock Formation

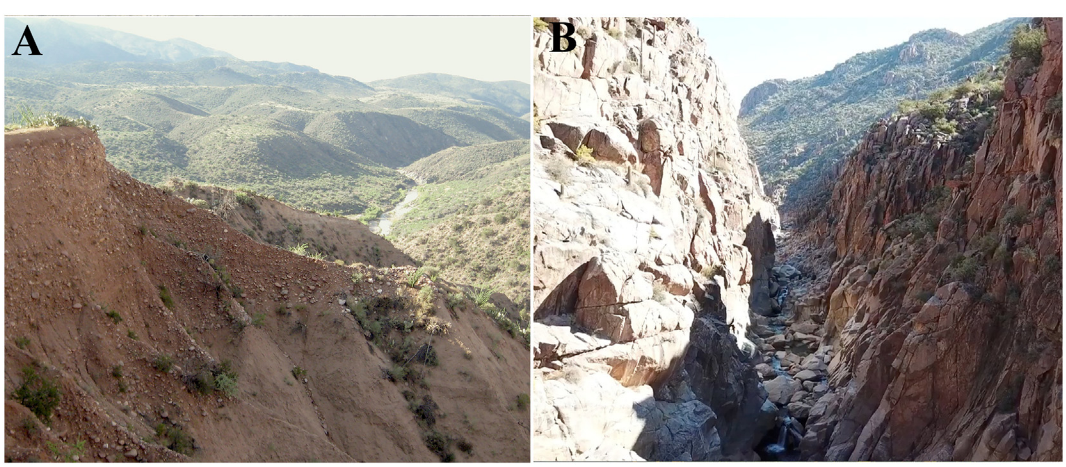

Fig. 5. Evidence of regional landscape incision and canyon topography can be seen throughout the drainage basin upstream of Roosevelt Dam, a location of drainage integration within the Salt River watershed (Figs. 3 and 4). This is exemplified by field-scale investigations along Tonto Creek. (A) Incision of "the narrows" of Tonto Creek as viewed from the highest terrace deposit of unknown age that occurs ~187 m above the creek. Location: N 33.9912913, W 111.2825457. (B) Hell's Gate along Tonto Creek as imaged by drone, where the depth of incision in this view is ~150 m. Location: N 34.1391502, W 111.187114.

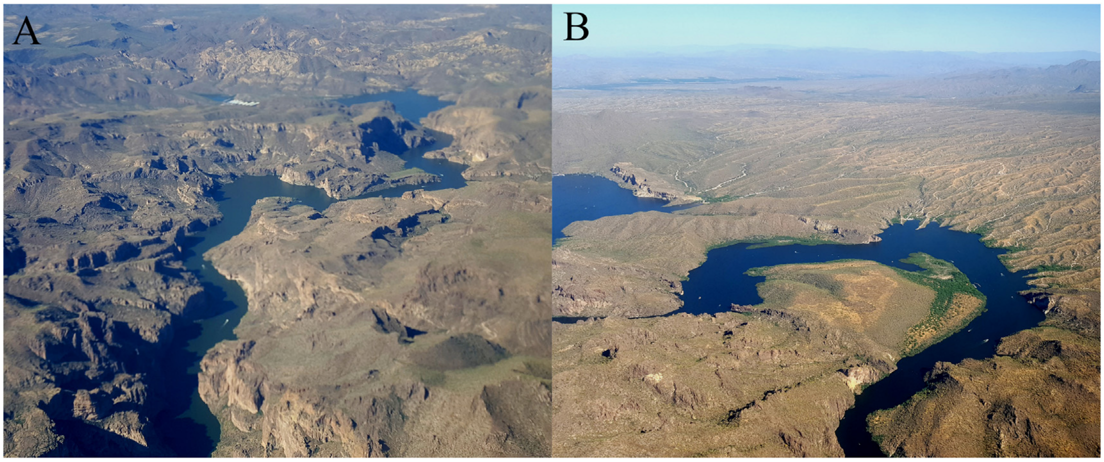

Fig. 6. Canyons created by the Salt River crossing small basins between the Tonto/Roosevelt Basin and the lower Verde River Valley. (A) Apache Lake is a reservoir along the Salt River that occupies a small basin. When the newly arrived Salt River integrated this small basin, it created the canyon topography seen in this oblique aerial photograph. The base of this image is approximately ~2 km for scale. (B) Saguaro Lake is a reservoir of the Salt River in the LVRV, and the lower part of this reservoir was a small basin; when the Salt River integrated this small basin it resulted in a small canyon with a sinuous pattern later filled in by the reservoir. The base of this image is ~2 km for scale. The location of both Apache and Saguaro Lakes are shown in Fig. 3.

can be found. Also, basalts in the lower ~5 m of the gravels have been sourced to Needle Rock Formation basalt clasts sampled from outcrop positions ~100 m west of modern-day Bartlett Dam (Dorn et al., this issue).

To further support the interpretation of the Lousley Hills terrace as a Bullhead Alluvium-like feature, geochronologic data reported by Skotnicki et al. (this issue) reveal a single cosmogenic ($^{26}Al/^{10}Be$) burial age of ca. 2.18 Ma from quartz cobbles collected near the contact of the Lousley Hills alluvium and the underlying playa deposits. This age postdates upper Verde Valley integration (ca. 2.5 Ma) and the endorheic LVRV-dated tephra (ca. 3.3 Ma), thus fitting the known chronology. To further bracket the timing of aggradation of the Lousley Hills terrace fill, a second cosmogenic burial age sample was collected from a separate but related landform and alluvial deposit behind the Lousley Hills terrace. This deposit is composed of predominantly sand-sized grains of quartz and feldspar (grus sand) transported locally from the pediment surface flanking the McDowell Mountains (Figs. 3, 8–10). A single cosmogenic burial age of 1.65 $\pm$ 0.08 Ma for quartz was obtained from a sample just above contact between the Lousley Hills and the truncated playa (Fig. 10D; Skotnicki et al., this issue). The latitude and longitude of this sample location is N 33.683542, W 111.7361244. We interpret this sample to be taken from a deposit that is a wedge of grus alluvium that aggraded in response to the main stem Verde River aggrading the Lousley Hills terrace fill. This wedge of sediment lies atop the playa as well (Figs. 8–10).

Aggradation of the Lousley Hills alluvium eventually ceased as the longitudinal profile's gradient decreased and upstream sediment excavation slowed (Douglass and Schmeeckle, 2007; Douglass et al., 2009), but aggradation of the grus sediment wedge continued behind the Lousley Hills terrace. We speculate that this sediment wedge may have overtopped the Lousley Hills. Upon doing so, the tributary streams were then controlled by the base level of the Verde River. At some point after Lousley Hills aggradation had ceased, the Verde River incised, lowering the basin-wide base level within the LVRV. These McDowell Mountains-

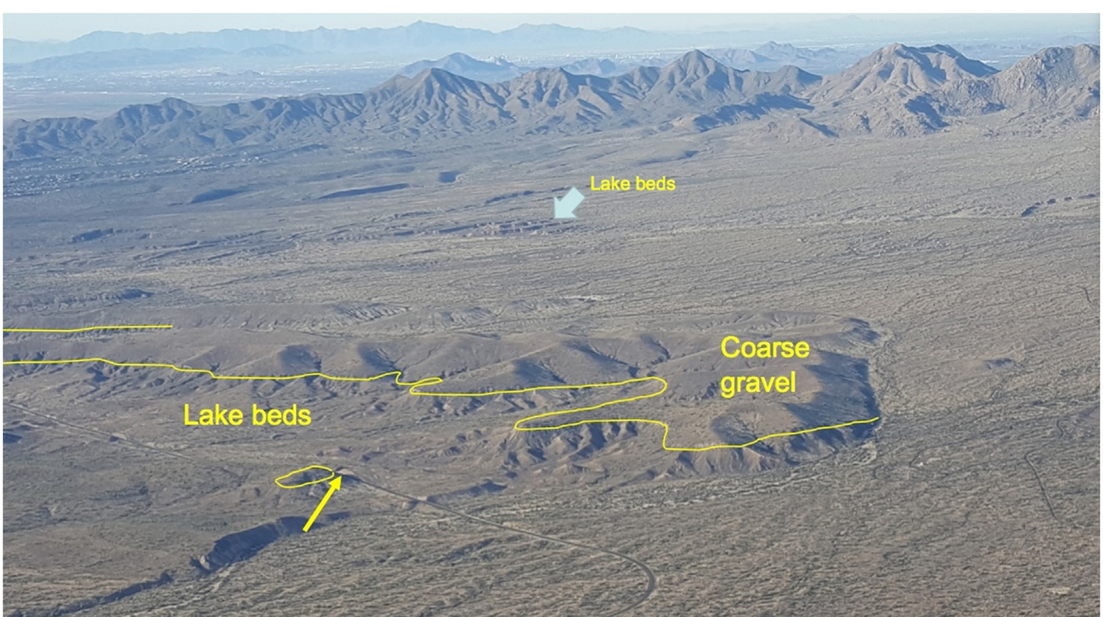

Fig. 7. Aerial photograph of the Lousley Hills (Fig. 3) looking southwest towards the McDowell Mountains. The Lousley Hills terrace consists predominantly of gravels and boulders that were deposited directly on a playa (labeled "lake beds" in this photo). This view shows the location where the most extensive remnants of Lousley Hills terrace are preserved. Additional preserved remnants are scattered on both sides of the modern Verde River in the lower Verde River valley.

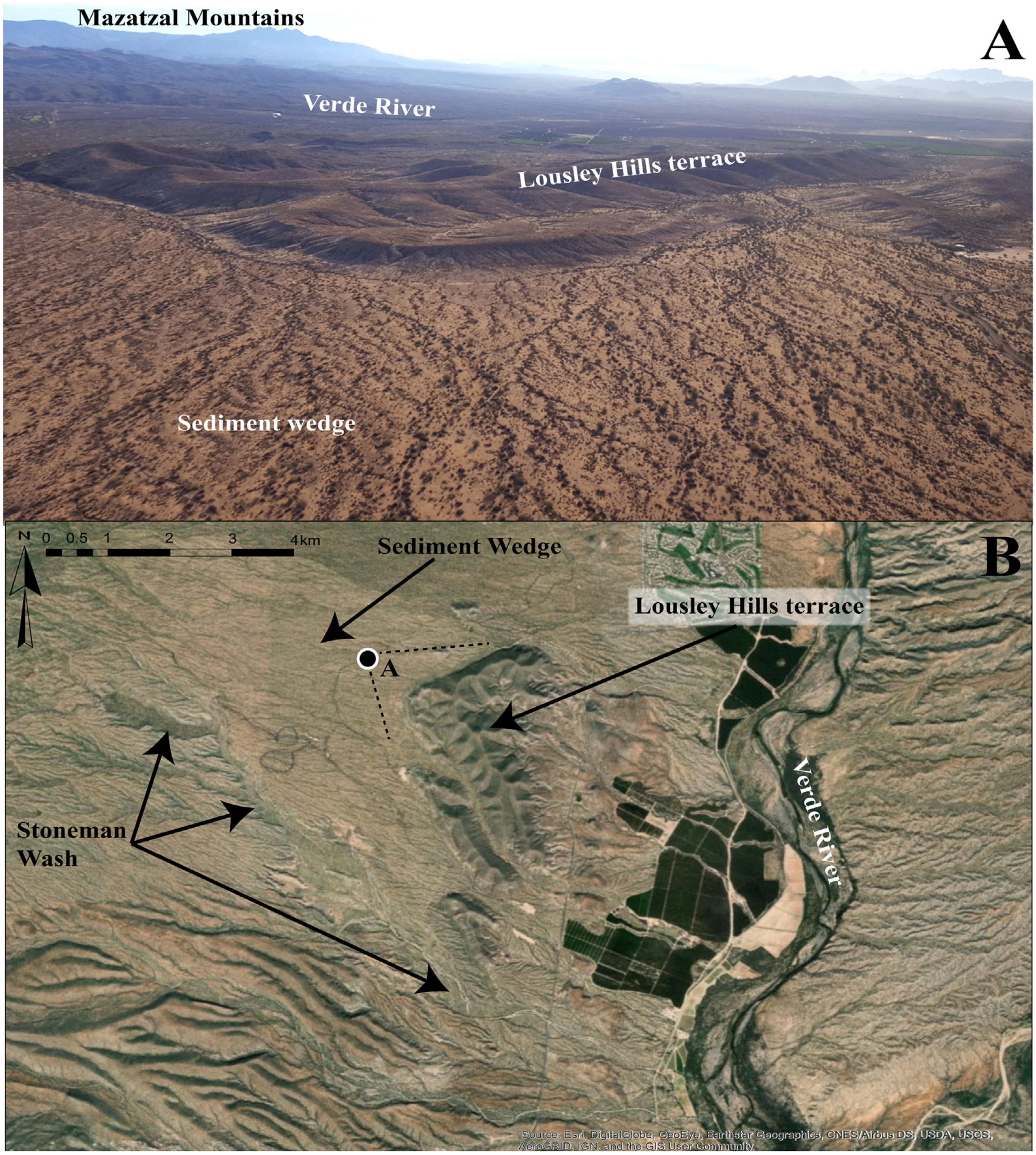

Fig. 8. The grus-sediment wedge of the LVRV aggraded behind the Lousley Hills terrace sometime after ca. 2.18 Ma (Skotnicki et al., this issue). The Lousley Hills terrace is an aggradational fill terrace that is hypothesized to represent initial integration of the Verde River from the Bartlett Basin with the LVRV (Figs. 1 and 3). As aggradation commenced in the LVRV during integration, local pediment streams derived from the McDowell Mountains would have been "backed up" by these aggrading sediments. The result is a large grus-sediment wedge behind the Lousley Hills seen here. (A) The approximate location of this northwest to southeast view aerial photograph is N 33.708958, W 111.738202. Note the grus sediment wedge trapped behind the darker Verde River alluvium of the Lousley Hills terrace. Ephemeral drainages dominating the surface of this sediment wedge are incising into this wedge at present – some more significantly than others (e.g., Stoneman Wash, see Panel B). (B) Satellite view for perspective of what is seen in the aerial photograph in A. The location and photographic viewshed of A is marked with a dot and dashed lines. One of the most significantly incised drainages through the sediment wedge is Stoneman Wash, denoted here with black arrows for reference.

sourced tributary streams then also incised, becoming superimposed transverse drainages across the Lousley Hills terrace (Fig. 8). The present-day position of knickpoints retreating upstream in these ephemeral tributary drainages can be observed in a drainage network evolving in one of the largest of these local drainages, Stoneman Wash (Figs. 8B and 11). Stoneman Wash has retreated through the sediment wedge and into the granitic pediment on the eastern side of the McDowell Mountains (Figs. 8B, 10A, 11), also resulting in pediment incision in response.

4.4. Landforms indicative of geomorphic response to aggradational spillover of the Salt River at Papago Park: integration of the Higley and Luke basins

Skotnicki and DePonty (this issue) document the Salt River gradually aggrading within the Higley Basin while depositing the ASRD (Fig. 3). They estimate that this lowered the gradient of the ancestral Salt River from ~6 to 4 m/km. Aggradation occurred over an ~2 million year period (Skotnicki et al., this issue). Skotnicki and DePonty (this issue) speculated that the top elevation of the ASRD near Papago Park (Fig. 3) matched the surface elevation of this bedrock sill (at ~326 m) and proposed aggradational spillover, a form of piracy stream capture (Douglass and Schmeeckle, 2007; Hilgendorft et al., this issue), as the process that integrated the Salt River into the Luke Basin (Figs. 1, 3, and 12).

This process rerouted the southerly course of the Salt River in the Higley Basin to the west (Laney and Hahn, 1986; Block, 2007; Skotnicki and DePonty, this issue) around the north side of South Mountains (Figs. 3 and 12). This change shortened the river length by ~35 km. The combination of shortening and a steeper local

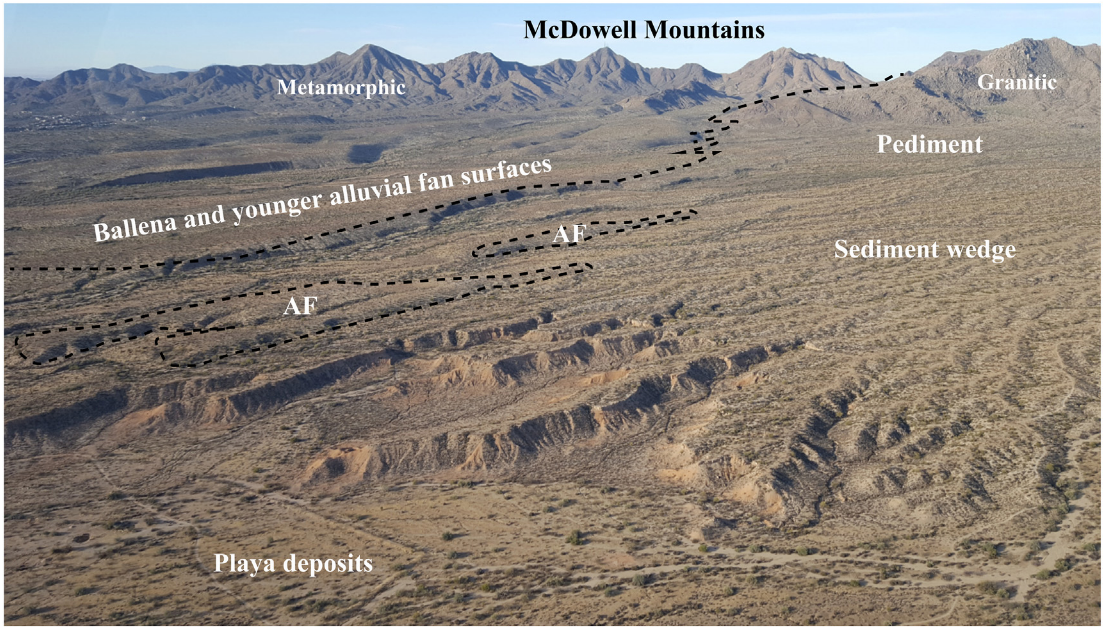

Fig. 9. The approximate location of this northeast to southwest view aerial photograph is N 33.697369, W 111.704953. This is taken from directly over the Lousley Hills and looking towards the McDowell Mountains (Fig. 3).The originally flat-lying playa/lake deposits were truncated as McDowell Mountain washes incised in response to the newly arrived Verde River. Then, the Lousley Hills gravels were deposited, and in response, a sediment wedge was deposited behind the Lousley Hills. Subsequent incision allows mapping of the truncated erosion surface of the lake beds with a slope from the McDowell Mountains towards the Verde River of 0.1–0.2°. The alluvial-fan deposits in the background pre-date the arrival of the Verde River and are graded to the original Pemberton playa.

gradient of ~10 m/km likely led to the creation of a new knickpoint or knickzone that then propagated eastward, upstream along the Salt River. Skotnicki et al. (this issue) and we hypothesize that the propagation of this knickzone led to abandonment of the ASRD as a depositional surface and the formation of the modern Sawik terrace (Péwé, 1978).

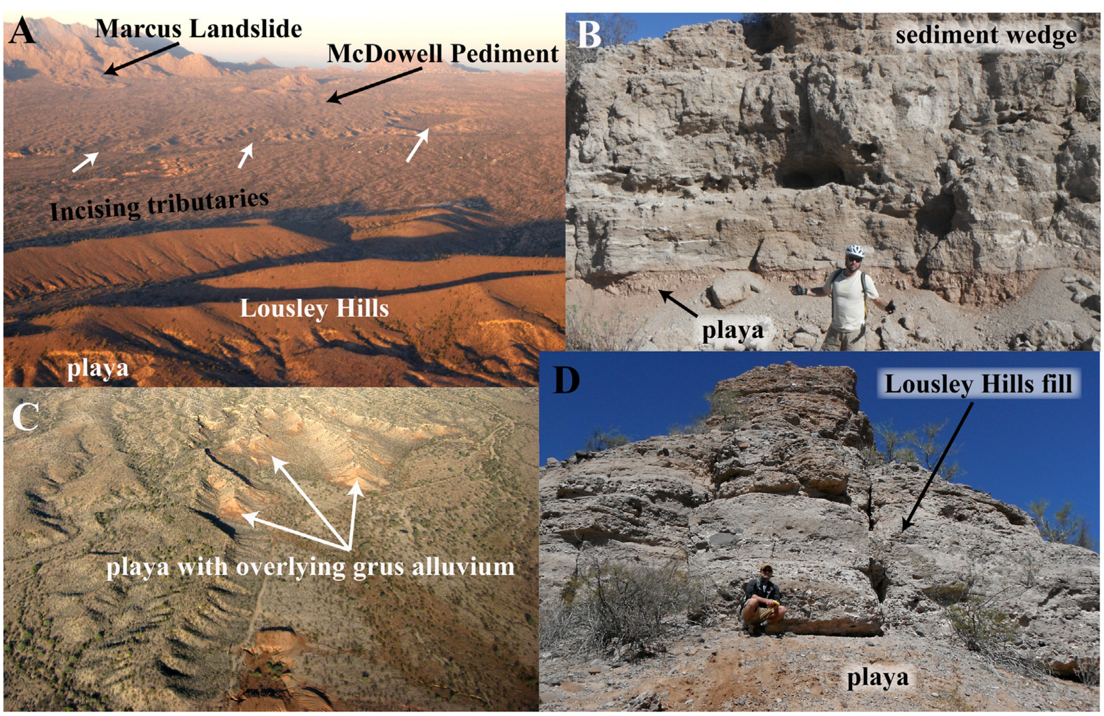

Fig. 10. Oblique aerial and ground photographs illustrating geomorphic processes associated with the Lousley Hills, the Verde River's analogous deposit to the Bullhead Alluvium of the lower Colorado River (Howard et al., 2015). (A) This image taken over the present-day Verde River, showing the Lousley Hills terrace in the foreground and looking directly west towards the McDowell Mountains and McDowell Pediment. In this photograph the sediment wedge behind that extends up to the McDowell Pediment and a local sturzstrom named the Marcus Landslide (Douglass et al., 2005) can be seen. Incising ephemeral tributary streams upon the grus sediment wedge are annotated and white arrows mark locations of the most extensive headward retreat of these systems into the McDowell Pediment, where pediment incision is also now occurring. (B) Exposure of the grus sediment wedge behind the Lousley Hills. A major ephemeral channel, Stoneman Wash, exposes the sediment wedge on top of the playa sediments here (Fig. 8). Sediment wedge resting unconformably on truncated Pemberton playa sediments with a cosmogenic burial age of ca. 1.6 Ma (Skotnicki et al., this issue). (C) Aerial perspective of playa deposits resting underneath the sediment fill, characteristic of this area. (D) Lousley Hills gravels resting unconformably on truncated Pemberton playa sediments with a cosmogenic burial age of ca. 2.2 Ma (Skotnicki et al., this issue).

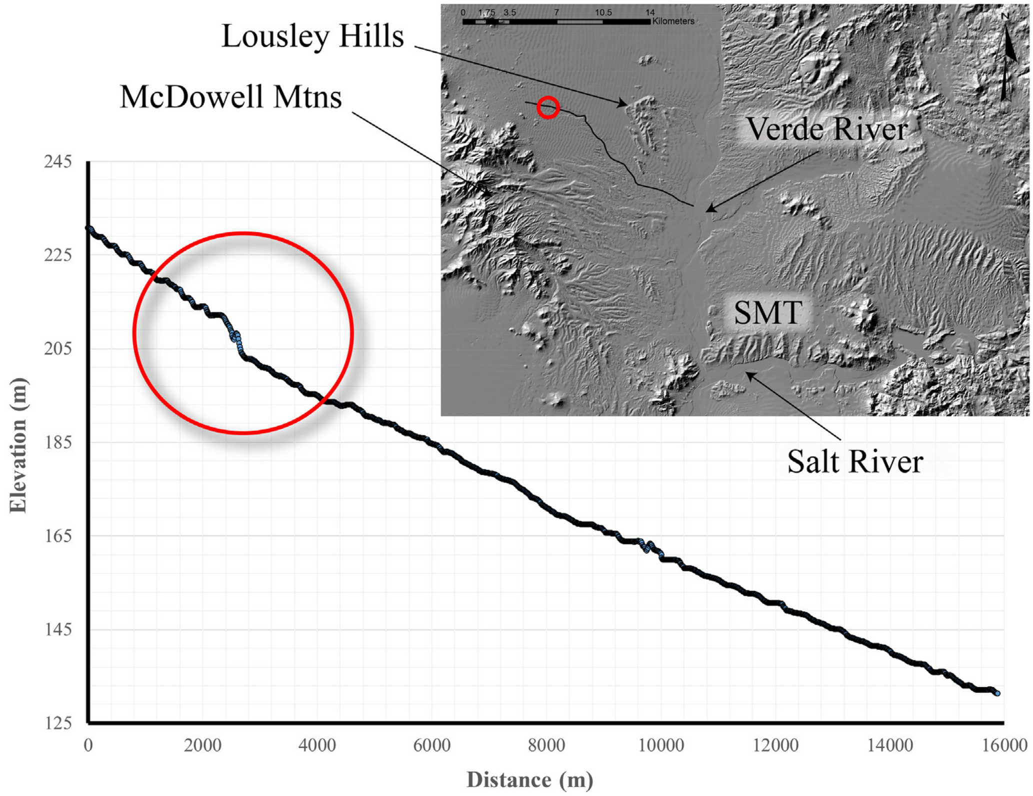

Fig. 11. The longitudinal profile of Stoneman Wash, a tributary stream to the Verde River in the LVRV. Stoneman Wash flows eastward to the Verde River from the McDowell Mountains (Fig. 3), traverses the McDowell Pediment, and cuts through the grus sediment wedge (Figs. 8–10) behind the Lousley Hills fill terrace (Figs. 3 and 8). The circles along the longitudinal profile and in the hillshade DEM in this figure represent the location of the knickpoint of Stoneman Wash as it has now eroded through the grus sediment wedge and into the granitic McDowell Mountains pediment (Fig. 10). The Verde River, Stewart Mountain terrace (SMT), Lousley Hills, and McDowell Mountains are labeled in this figure for spatial reference (see Fig. 3). The longitudinal profile was created using a 1/3 arc-second (~10 m) DEM acquired from National Map via the United States Geological Survey.

The best-preserved remnants of the Sawik terrace occur where the ancestral Salt River flowed over the narrow bedrock sill near present-day Granite Reef Dam (Fig. 3). These remnants are strath terraces cut into sedimentary and granitic pediments. Salt River gravels ~2.5 m underneath a Sawik terrace remnant have a single cosmogenic burial age of 692 ± 35 ka (Seong et al., 2016). This age represents aggradation of gravels before abandonment of the Sawik terrace surface. This age of Sawik terrace sediments is within the margin of error with an isochron burial age of 547 ± 120 ka for gravels near the top of the ASRD (Skotnicki et al., this issue). Therefore, both estimates support the interpretation that the Sawik terrace represents the top of the ASRD before it was abandoned by aggradational spillover processes.

Furthermore, the age estimates for the Sawik terrace fill and upper ASRD sediments representing a not-yet-incised ancestral Salt River fit the chronology of aggradational spillover at the Papago Park sill (Fig. 3). There, a single burial age of 460 ± 23 ka in sediments of the Salt River (Reynolds and Bartlett, 2002) records the arrival of Salt River gravels in the Luke Basin (Reynolds and Bartlett, 2002; Skotnicki et al., this issue). Thus, we hypothesize that knickpoint recession on the Salt River, as a result of aggradational spillover, led to an incision event that created the Sawik terrace and also abandoned the ASRD depositional surface of the Salt River upstream of the integration location (Granite Reef Dam) of the LVRV and Higley Basins (Figs. 1 and 3).

Additional Salt River terraces (Fig. 13) occur below the Sawik terrace (Kokalis, 1971; Pope, 1974; Péwé, 1978; Larson et al., 2010; Larson et al., 2016) and represent ongoing adjustment of the Salt and Verde systems after the Papago Park sill aggradational spillover event. Based on physical models of the aggradational spillover process, we hypothesize that incision driven by this spillover event created the Sawik terrace and progressed through the Salt River system. Ultimately, the longitudinal profile of the Salt River stabilized for some time at what is now the Mesa terrace level. This surface was abandoned ~86 ka (Larson et al., 2016). Subsequent incision at ~86 ka commenced to the Blue Point terrace level but it, too, was ultimately abandoned at ~31 ka (Larson et al., 2016). The reason for these incision events below the Mesa terrace level are not known at present, but are not related to integration processes.

4.5. Pediment response to drainage integration

The granitic pediments of the Usery Mountains (Fig. 3) responded to base-level change differently depending on whether they were connected to the LVRV or to the Higley Basin as their base level (Table 1). Larson et al. (2016) focused on the pediments (Fig. 14) that had ephemeral drainages directly tied to the level of the Mesa River terrace in both basins (Fig. 13). By examining these pediments, they interpreted the Mesa terrace level to represent a long-occupied period of landscape stability, possibly between ca. 460 ka to ca. 86 ka (see Section 4.4). Cosmogenic exposure ages for the Mesa and Blue Point terraces of the Salt River (Fig. 13) provided age control for their study of the response of pediments to base-level change in order to assess the control of base level on the adjustment of pediments. Using GIS modeling to reconstruct remnant pediment surfaces that had been adjusted to different Salt River terraces, Larson et al. (2016) found that the larger pediments (e.g., labeled “adjusted” on Fig. 14) with larger drainage areas were able to completely adjust and form a pediment surface in ~50 ka, developing the same classic pediment-inselberg profile of pediments that topographically transition to the Mesa terrace surface (e.g., labeled “Mesa terrace base level” in Fig. 14). In contrast, pediment complexes with smaller drainage areas (e.g., labeled “adjusting to modern base level” in Fig. 14) are still adjusting. They also suggest this may be, in part, influenced by the degree of weathering of the underlying substrate through

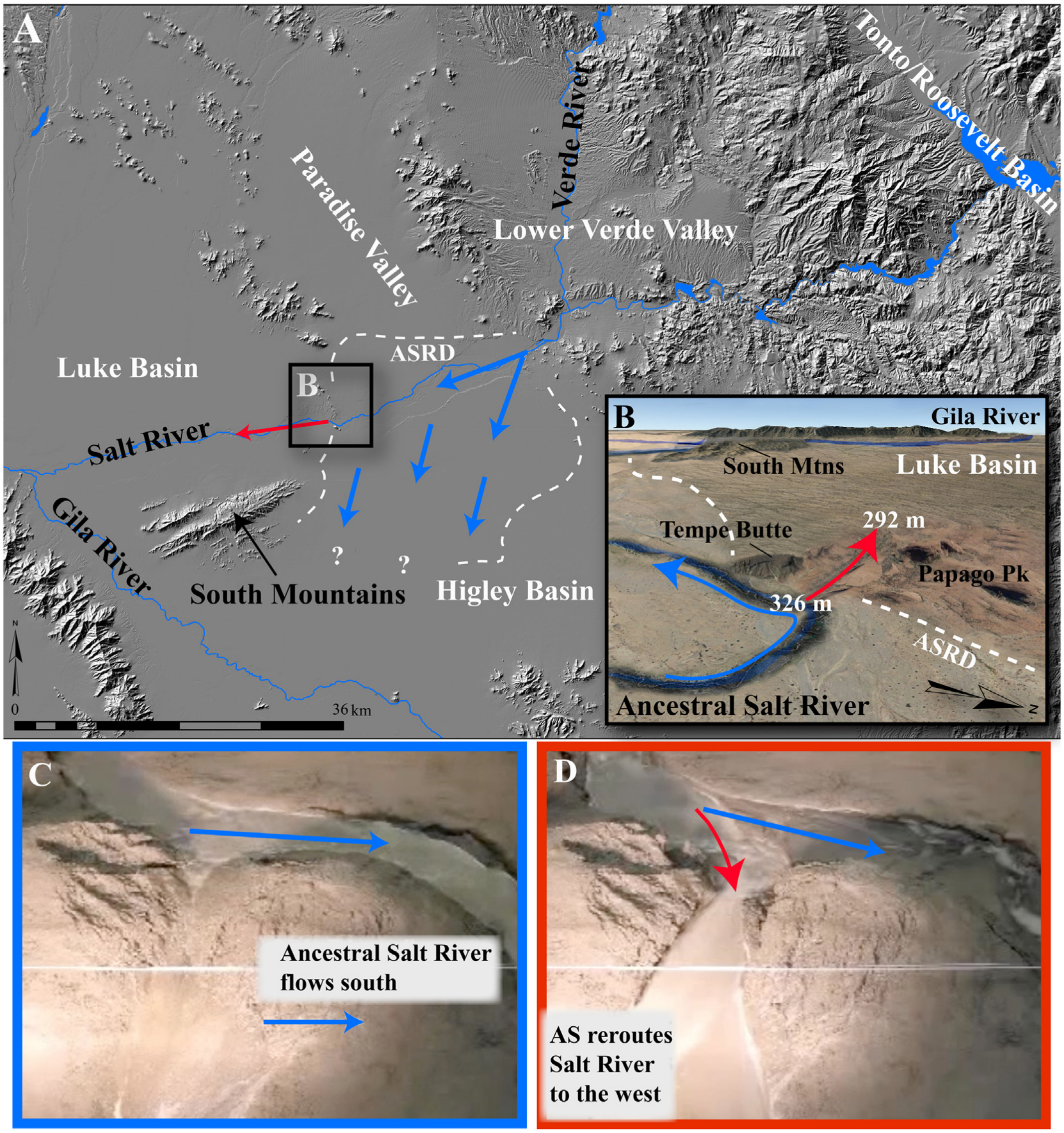

Fig. 12. For ~2 million years, the ancestral Salt River aggraded within the Higley Basin, after integrating the lower Verde Valley basin and the Tonto/Roosevelt Basin (Fig. 1; Skotnicki et al., this issue). It is hypothesized that aggradation reached a sill in the Higley Basin and spilled over near Papago Park (Fig. 3) into the Luke Basin. This aggradational spillover event redirected the Salt River's position from flowing south to its present, more westerly course. (A) The map contains blue/light arrows indicating the generalized flow direction of the ancestral Salt River before this integration event. Red/dark arrows indicate the redirected flow path upon integration with the Luke Basin. (B) An artistic reconstruction from a northeast to southwest perspective view of the location of integration between Papago Park and Tempe Butte. A smaller box labeled B in A shows the location of this image. Blue/light arrows indicate the ancestral Salt River's flow direction. Red/dark arrows indicate the rerouted path into the Luke Basin. (C) and (D) are photographs from physical modeling experiments of aggradational spillover, showing the process hypothesized to occur in B (Douglass and Schmeeckle, 2007). "AS" in (D) refers to aggradational spillover. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

which the pediment drainages are trying to adjust (Wahrhaftig, 1965; Larson and Dorn, 2014).

A breccia pediment of Red Mountain (GR-RM in Fig. 3), on the north side of the Salt River, is across from the Usery Mountain granitic pediments seen in Fig. 14. This sedimentary pediment (Fig. 15) was originally topographically linked to a base level near the Granite Reef bedrock sill (Fig. 3) that was likely stable during the late Pliocene before the arrival of the Salt River. The assumption of stability is based on the observations of Skotnicki et al. (this issue) that the LVRV was in a condition of overspill of sediment into the Higley Basin during the late Pliocene.

Upon arrival of the Salt River and initial deposition of the ASRD ca. 2.2–2.8 Ma, the base level would have started rising as the ASRD aggraded. This would have caused an aggradation of sediment carried by local washes on the pediment, similar to the grus sediment wedge observed near the Lousley Hills terrace today (Figs. 8–10). Remnants of the aggrading washes can be seen in Fig. 15B. As aggradational spillover occurred near the Papago Park sill ca. <0.46 ka (see Section 4.4), the Salt River began incising and remnants of pediment aggradation were abandoned. The angular clasts in the breccia bedrock of the pediment consist of granitic cobbles and boulders (Fig. 15B). Thus, these washes now stand out as an example of relief inversion tied to drainage integration of the Salt River (Fig. 15A) as the former channels are more resistant to erosion than the adjacent sedimentary pediment now responding to more recent base-level lowering driven by the Salt River.

Another group of pediments influenced by drainage basin integration are those flanking the Phoenix Mountains and Papago Park (Figs. 3 and 16). These pediments experienced varying degrees of incision by their ephemeral washes and are the most perplexing with respect of drainage integration. At this time, the best we can do is speculate about this incision. During the Pliocene, as well as the early and middle Pleistocene, the endorheic Luke Basin served as a slowly rising base level as it gradually filled with internally sourced sediment. Then, <460 ka, as a result of

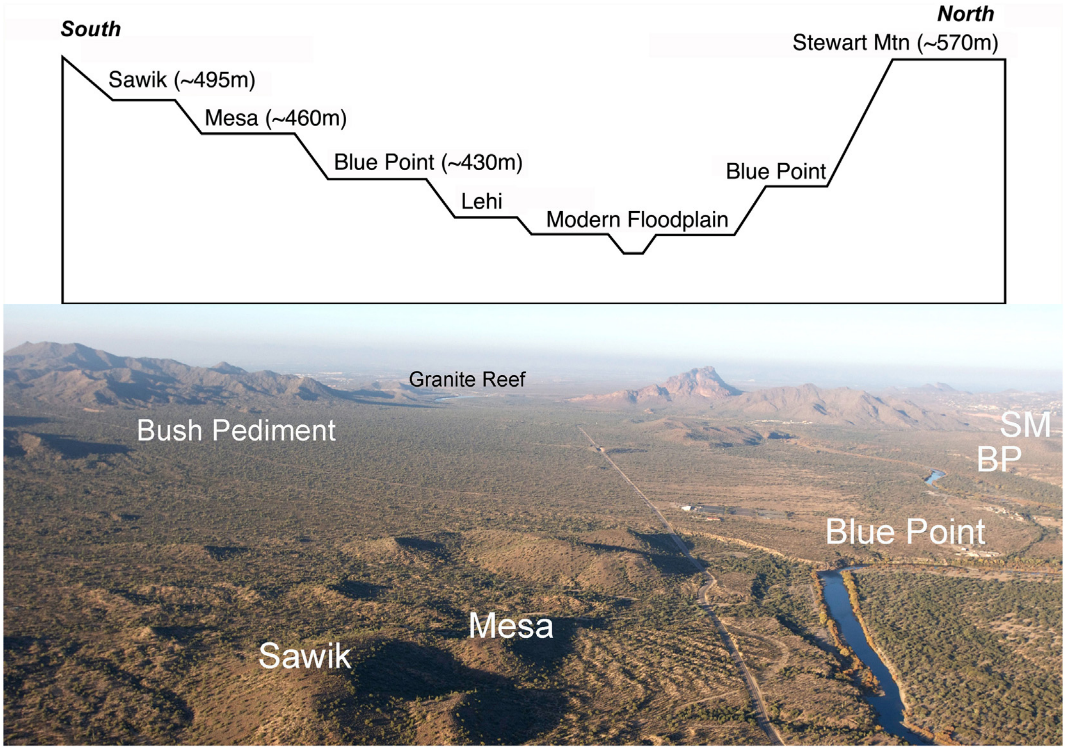

Fig. 13. This east to west perspective aerial photograph of the Salt River valley, within the LVRV, shows the Salt River terraces just east of the Granite Reef Dam (Fig. 3). The Bush Pediment, seen here, is on the north side of the Usery Mountains (Fig. 3) and contains ephemeral streams that flow across and incise into pediments that drain to the Salt River. However, it and the other Usery Mountain pediments have undergone significant adjustment in response to progressive base-level lowering of the Salt River (Larson et al., 2016). SM = Stewart Mountain terrace. BP = Blue Point terrace. Elevations in this figure correspond to terrace tread surfaces within this photograph. Tread elevations decrease in the downstream direction and converge within the Higley Basin (Fig. 3; Péwé, 1978; Larson et al., 2010). The approximate location of this aerial photograph is N 33.543895, W 111.585207.

the Salt River's aggradational spillover (Section 4.4) at the Papago bedrock sill (Figs. 3 and 12), more than 30 m of aggradation of Salt River alluvium occurred in well logs (Reynolds and Bartlett, 2002). Thus, the base level of the Salt River-facing (south-facing) pediments of the Phoenix Mountains and those at Papago Park would have experienced base-level rise. However, downstream of the Salt River's spillover at Papago Park, there is no evidence of any base-level fall along the Salt River until ca. 12 ka, and even then, it was just a few meters (Huckleberry et al., 2013).

It is possible that a lateral shift of base level from the center of the Luke Basin tens of kilometers away to the newly-arrived and aggrading Salt River <460 ka played a role in the observed pediment incision (Fig. 16). Consider the granitic pediments bounding the Gila River just to the southeast of the study area, on the fringes of the Phoenix metropolitan region (Fig. 17), where the Gila River flows between the San Tan Mountains and the Sacaton Mountains. While the Gila River likely experienced base-level changes in the late Quaternary (Huckleberry, 1993; Huckleberry, 1994; Huckleberry, 1995; Waters, 2008; Gootee, 2019), the two granitic pediments graded to the Gila shown in Fig. 17 would have experienced the same changes. Yet, pediments of the San Tan Mountains are clearly much more incised than those of the Sacaton Mountains. The only clear distinction is that the Gila now flows along the base of the San Tan Mountains. Thus, we hypothesize that when the Gila River shifted towards the

Fig. 14. This aerial photograph showing a southwest-view of the Usery Mountains near Granite Reef Dam (Fig. 3) and the Salt River (foreground) shows the Usery Mountain granitic pediments that have been influenced by base-level changes of the Salt River's integration and ongoing post-integration adjustment. Larger pediment drainage areas have fully adjusted to base-level lowering (on the left), while pediments with the smallest drainage areas are still incising. Those on the far right (west-facing) are still stable with the Mesa River terrace as their base level. The latter have not yet been influenced by post-Mesa incision that started ca. 86 ka (Larson et al., 2016).

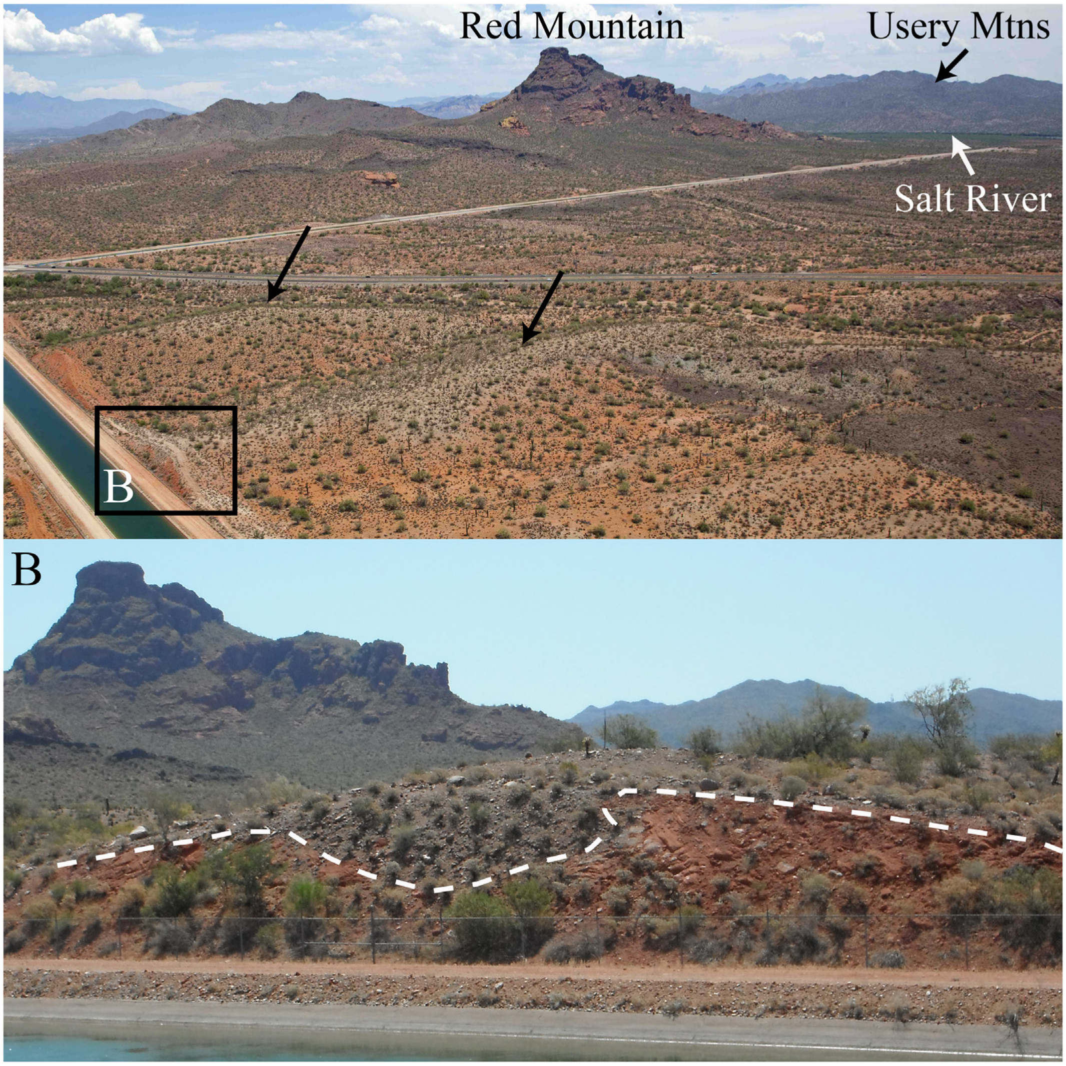

Fig. 15. The sedimentary pediments of Red Mountain (Fig. 3; formally named Mt. McDowell) were first influenced by drainage integration when the Salt River integrated the LVRV and Higley Basins and began aggrading the ASRD (Figs. 3 and 12) in the Higley Basin. This would have raised the local base level of the basin, including pediment washes. This aerial image, viewing to the southeast, reveals buff-colored sinuous ridges that are relict pediment drainages that are an equivalent morphostratigraphic surface to the Sawik terrace tread (top of ASRD). (B) The granitic alluvium seen in a channel cross section is more resistant to erosion than the sedimentary pediment that is dominated by a sandstone matrix. The result is inverted topography driven by Salt River base-level fluctuations. The location of this exposure is marked in box B in the aerial image above. The location of these images is ~N 33.548206, W 111.728420. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

San Tan pediment, the foreshortening of the longitudinal gradient resulted in the observed incision. Thus, it is possible that the shift of base level from the center of the Luke Playa (Fig. 1) to just south of the pediments of Fig. 16 resulted in the observed pediment incision.

4.6. Alluvial fan response to drainage integration

An issue that has eluded analysis involves understanding the age and longevity of evolution of a rounded ballena form (Peterson, 1981). Drainage integration of the Verde River offers a way to obtain a maximum age constraint in the LVRV (Fig. 3). Drainage integration began lowering the base level of the local alluvial fans in the LVRV (Fig. 18) when the Salt and Verde rivers began to incise, abandoning the Stewart Mountain terrace (Figs. 3 and 18; see Section 4.2). Our analysis (Table 1) suggests that this would have lowered LVRV base level ca 2.2 to 2.8 Ma (Skotnicki et al., this issue) in a time frame consistent with the origin of the Verde River (Bressler and Butler, 1978; Pearthree, 1993). Hence, a maximum estimated age for the ballena form seen in Figs. 18B and 19A is the beginning of the Quaternary.

The McDowell Mountains' (Fig. 3) southern end contains a mixture of metamorphic rock types, and alluvial fans debauch on the western, southern, and eastern sides. Similar to granitic pediments of Usery Mountains (Fig. 14), the southern McDowell Mountains alluvial fans experienced very different base-level histories depending on the basins into which they flow. In particular, a dramatic contrast can be seen between ballena forms observed both in the field (Fig. 19A) and in DEMs (e.g., Fig. 19A in Fig. 18) flowing from the McDowell Mountains to the west and largely unincised fans at the south-southwestern end of the McDowell Mountains (Figs. 18 and 20). The metamorphic materials of the ballena form (Figs. 18B and 19A) and south-southwestern draining McDowell fans (Figs. 18B and 20) contain a similar mixture of rock types. Fig. 20 shows an example of southwestern McDowell Mountain fan, "Shadow fan" (named for a subdivision on the fan), in 1991 prior to development and 1995 during development. The surface of Shadow fan is flat and contained well-developed desert pavements prior to development; a few washes have incised ~2–4 m, but only along the dotted lines in Fig. 20A.

The base-level history of the Shadow fan has been very different from the ballena forms on the eastern side of the McDowell Mountains. The Shadow fan's base level used to be the same as the Red Mountain pediment (see Fig. 15), where base level started lowering ca. <460 ka. The dotted ephemeral washes in Fig. 20A all now flow to the Blue Point terrace level (Fig. 13) of the Salt River. The ballena forms of the

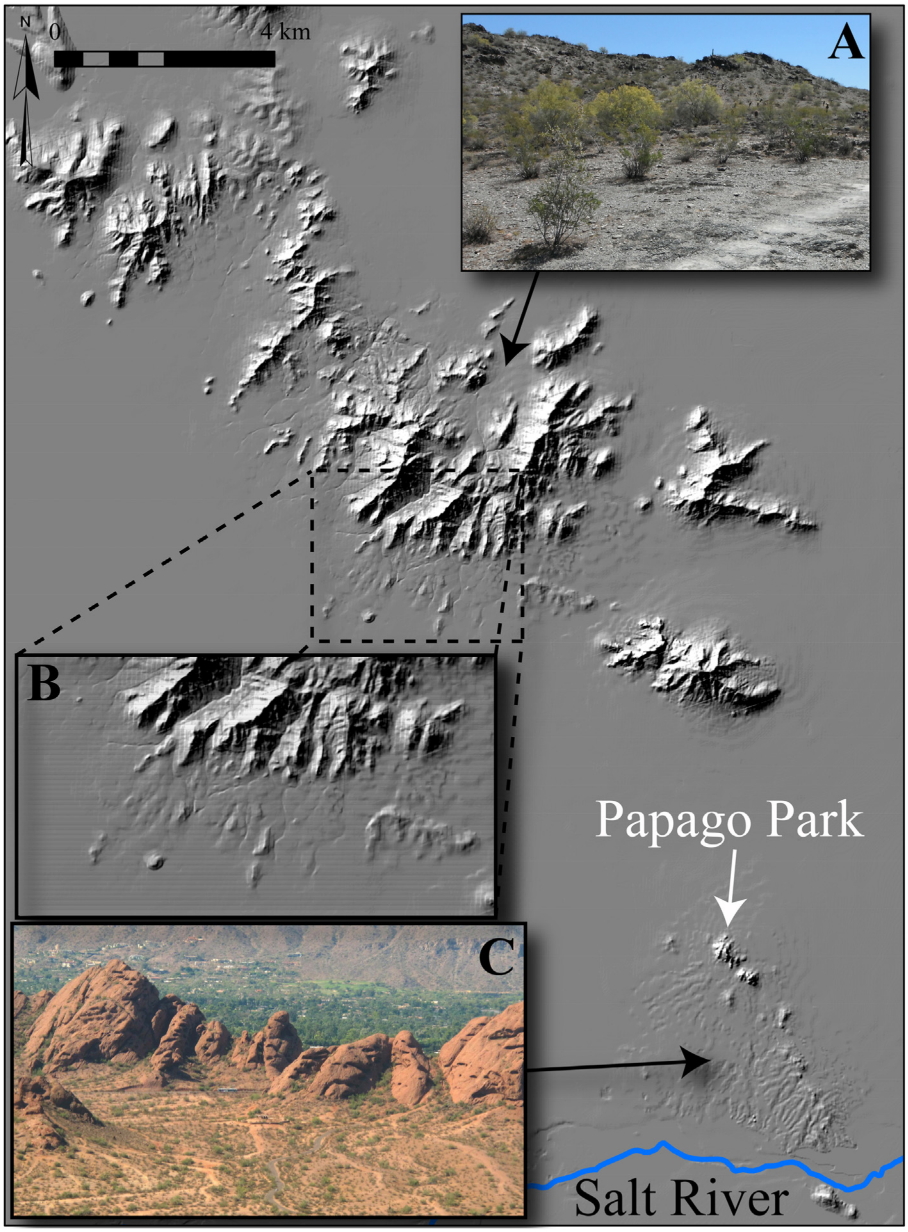

Fig. 16. Pediments of the Phoenix Mountains and Papago Park (Fig. 3). (A) Pediments on the north side of the Phoenix Mountains have substantially less incision than those on the south side, nearer to the Salt River. (B) Pediments on the south of the Phoenix Mountains have several meters of incision into pediment surfaces and drain to the Salt River. (C) Papago Park's pediments have all been incised by small washes flowing across their surface. This incisional asymmetry between north- and south-facing pediments is likely because of proximity to the Salt River and it being the base-level control for the ephemeral washes that flow across these pediments.

alluvial fans flowing into the LVRV, shown in Fig. 19A, experienced an additional two million years of base-level lowering, which likely explains the significantly more dissected fan form (Fig. 18B).

4.7. Relief inversion in response to drainage integration

Fig. 15 illustrates relief inversion of ephemeral washes on the Red Mountain pediment that resulted from drainage integration lowering the base level of a sedimentary pediment. A much more extensive example of relief inversion associated with drainage integration is "The Rolls" (Fig. 3). Skotnicki et al. (this issue) identified a Pliocene alluvial-fan system originating in the southern Mazatzal Mountains that includes debris-flow transported clasts, often meters in diameter. "The Rolls", clasts within the Stewart Mountain terrace (SMT), and sediments underlying the ASRD (Fig. 21; see Section 2.1) in the Higley Basin are consistent with a hypothesis that these deposits are part of a connected sedimentary unit, the Rolls Formation (Fig. 3).

Streams that transported the Rolls Formation sediments flowed through the topographically lowest points in the Pliocene landscape and across Granite Reef sill into the Higley Basin (Fig. 21A). Today, The Rolls stand out as high topography (Fig. 21B and C) because the weaker fanglomerate and pediment material surrounding it has eroded more rapidly. The sedimentology of The Rolls contains debris-flow deposits with boulders locally larger than a meter in diameter that are difficult for erosive processes to transport.

4.8. Abandonment of ancestral Salt River deposits and sandsheet deposition

The Salt and Verde river's arrival into the Higley Basin resulted in aggradation of the ASRD (Fig. 3). When the Salt River shifted its course at the Papago bedrock sill (Figs. 3 and 12) ca. <0.46 Ma, the entire surface area of the ASRD was abandoned (Figs. 3 and 12; Section 4.4). Since abandonment, very little alluvial sediment has been deposited on the ASRD. Most

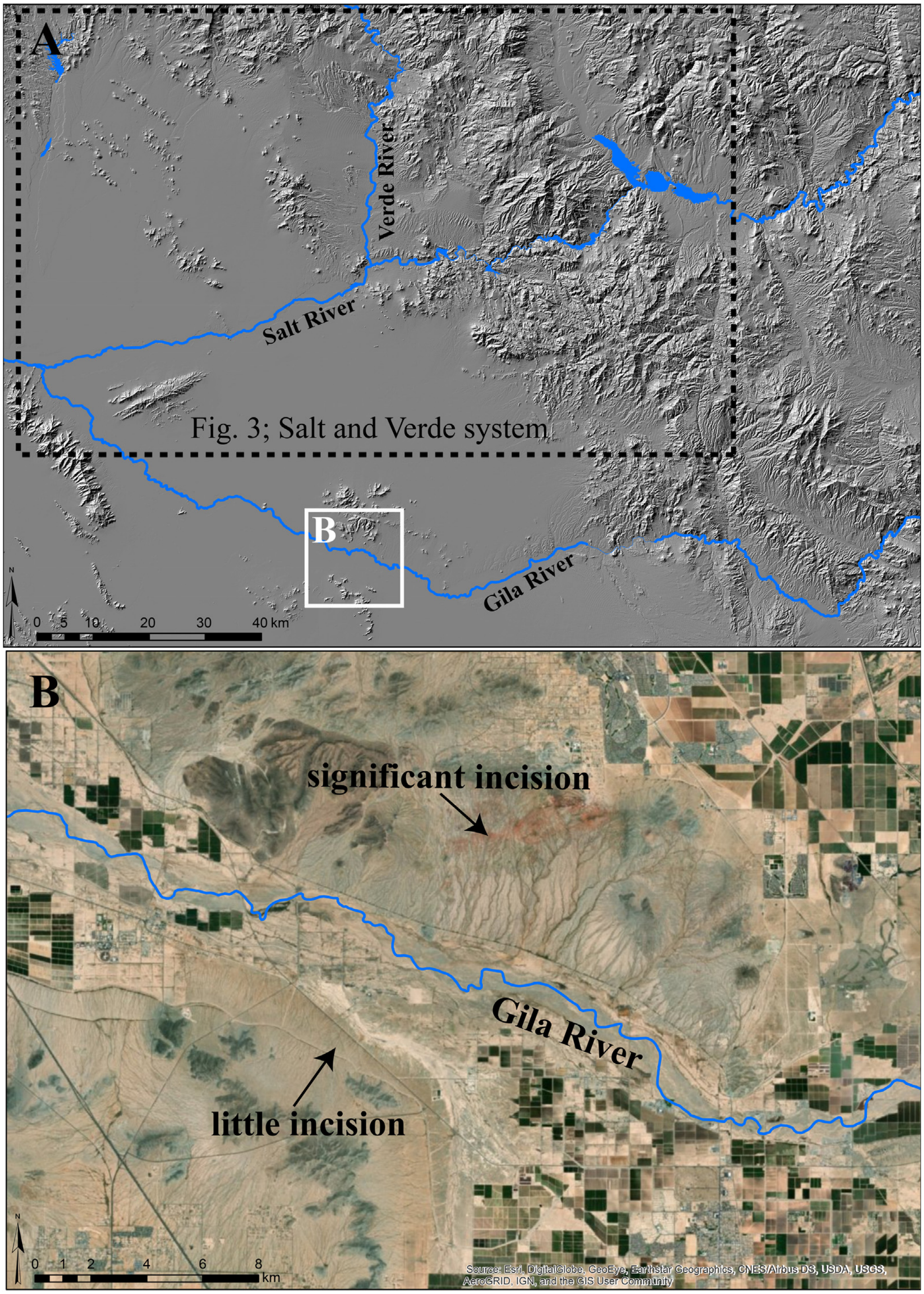

Fig. 17. The Gila River and adjacent granitic Sacaton (south of Gila River) and San Tan (north of Gila River) pediments. The Sacaton Mountains, south of the Gila River in this figure, are flanked by pediments, as are the San Tan Mountains, north of the Gila River in this figure. Whereas the Sacaton pediment shows "little incision", the San Tan pediment shows evidence of a lot more ephemeral wash downcutting (labeled "significant incision"). Since both granitic pediment complexes would have experienced the same vertical base-level changes, we hypothesize the difference in incision is related to the horizontal position of the Gila River, which defines the base level of these tributary streams.

of what has been input comes from small ephemeral washes draining the mountain ranges bounding the basin. Periodically, some large flooding events have come from the Queen Creek drainage on the eastern margin of the ASRD area, where it interfingers with a sandsheet-like deposit at the surface of the basin (Skotnicki and Gootee, this issue).

This sandsheet is a silt and fine sand covermass on top of the ASRD seen in both field observations and in well log cuttings (Skotnicki and DePonty, this issue). It is likely derived from a mixture of aeolian fine sand and silt blown northward from the Gila River floodplain, along with locally-sourced low-energy ephemeral washes flowing from South Mountain to the west and the San Tan Mountains to the east.

Source-bordering dunes exist north of the Gila River (Fig. 22). The sediments accumulated on top of the ASRD are a mixture of locally-derived aeolian and fluvial deposits that are the consequence of Salt River integration processes abandoning the ASRD surface. This sandsheet likely reflects geomorphic processes that dominate post-integration basins after the fluvial system has adjusted.

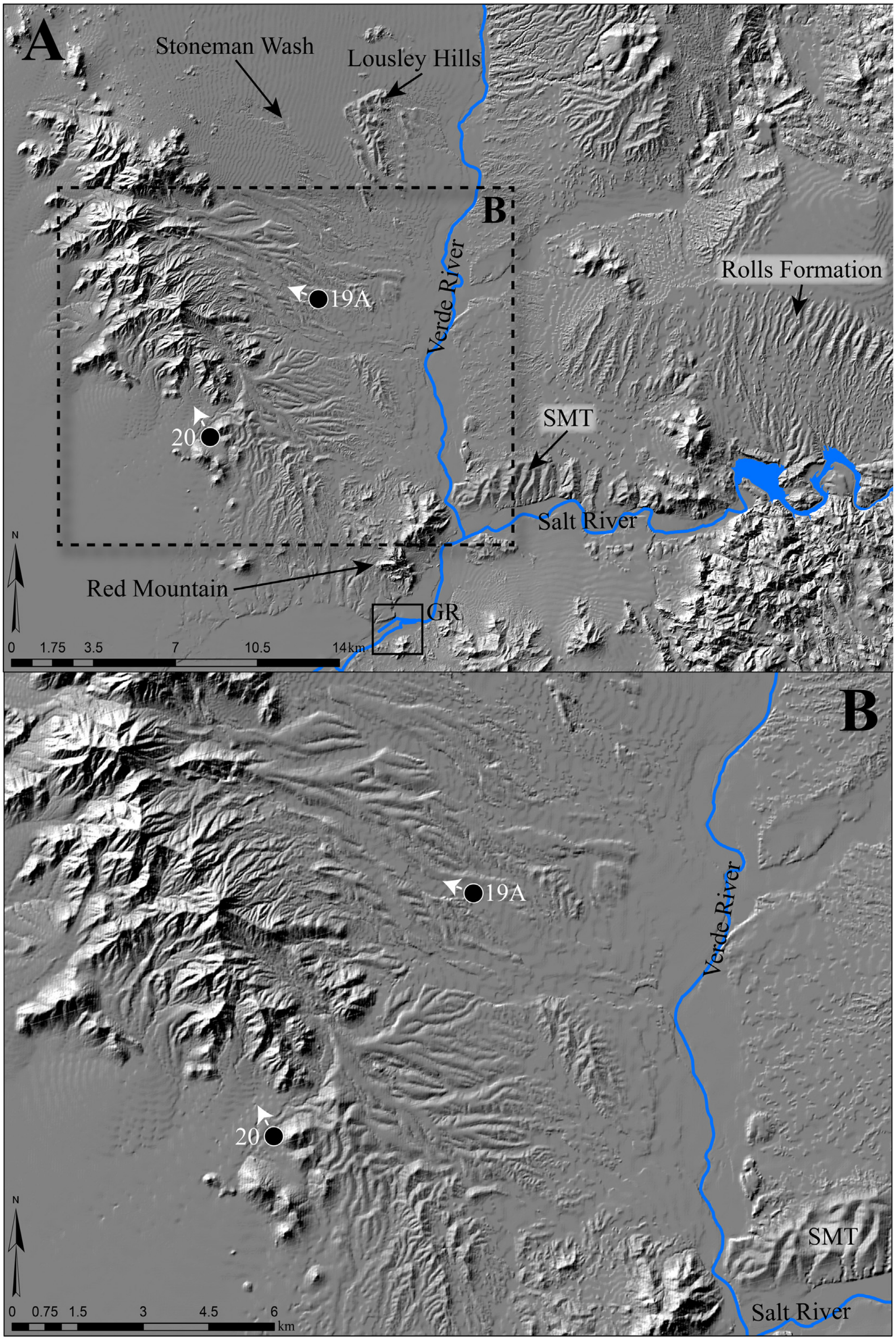

Fig. 18. Alluvial fans and ballenas of the LVRV (Fig. 3). (A) The McDowell Mountains form the western boundary of the LVRV. The metamorphic lithologies of the McDowell Mountains produce alluvial fans that flow towards the Verde River to the east and the Salt River to the south and west. The current landscape contains modern alluvial fans and ballena (relict incised fan) that have responded to base-level fluctuations of the Salt and Verde rivers caused by drainage integration and post-integration basin adjustment. The rolling topography of these forms can be seen in the box labeled B. (B) DEM hillshade of the ballena and alluvial fan forms of the McDowell Mountains. Locations of photographs in Figs. 19A (ballena form) and 20 (Shadow fan) are marked by dots in both A and B with arrows showing the view direction. GR = Granite Reef. SMT = Stewart Mountain terrace.

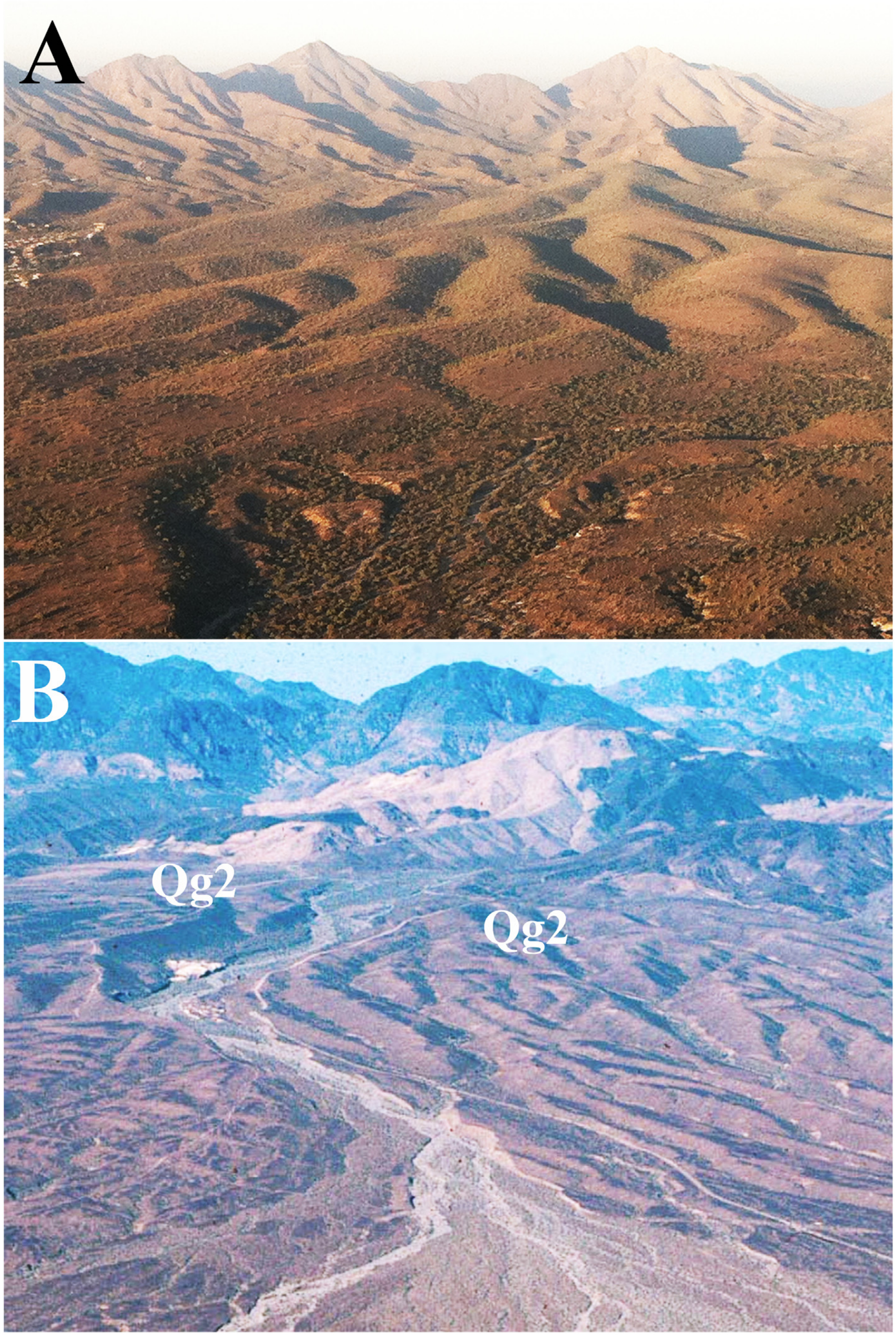

Fig. 19. Ballena forms of (A) the lower Verde River Valley coming out of the southeastern McDowell Mountains (Figs. 3 and 18B) and (B) Warm Springs alluvial fan in Death Valley (Duhnforth et al., 2017).

5. Discussion

The location of much of the study area (Figs. 1 and 3) in the Sonoran Desert means that classic desert landforms such as pediments (Kesel, 1977; Péwé, 1978; Parsons and Abrahams, 1984; Pelletier, 2010) and alluvial fans (Melton, 1965; Bull, 1984; Huckleberry, 1994; Melton, 1965; Bull, 1984; Huckleberry, 1994) evolved as a product of drainage integration processes that established through-flowing drainages throughout central Arizona. Our analysis (Table 1) indicates that extensive pediments of the granitic Usery Mountains (Fig. 14), breccia Red Mountain (Fig. 15), breccia Papago Park (Fig. 16), and metamorphic Phoenix Mountains (Fig. 16) developed during the Pliocene under conditions of slowly rising base level or base-level stability. The analysis presented in Larson et al. (2014) suggests that the original development of these large pediments requires the slow slope retreat of inselbergs (Penck, 1924) at a steady base level through active slope processes reviewed elsewhere (Dohrenwend and Parsons, 2009).

The evidence presented in Section 4.5 supports analyses presented in Larson et al. (2014, 2016) that pediments respond to geomorphic perturbations such as base-level fluctuations. This happens regardless of rock type — no matter whether the pediment-inselberg complex is granitic, sedimentary, or metamorphic. Fig. 15, for example, presents remnants of pediment aggradation, whereas Fig. 14 illustrates re-adjusted pediments within the last 81 ka. Lateral shifts in positions of the integrated exoreic streams likely also influence pediment incision by shifting the base level horizontally, thereby lengthening or shortening the

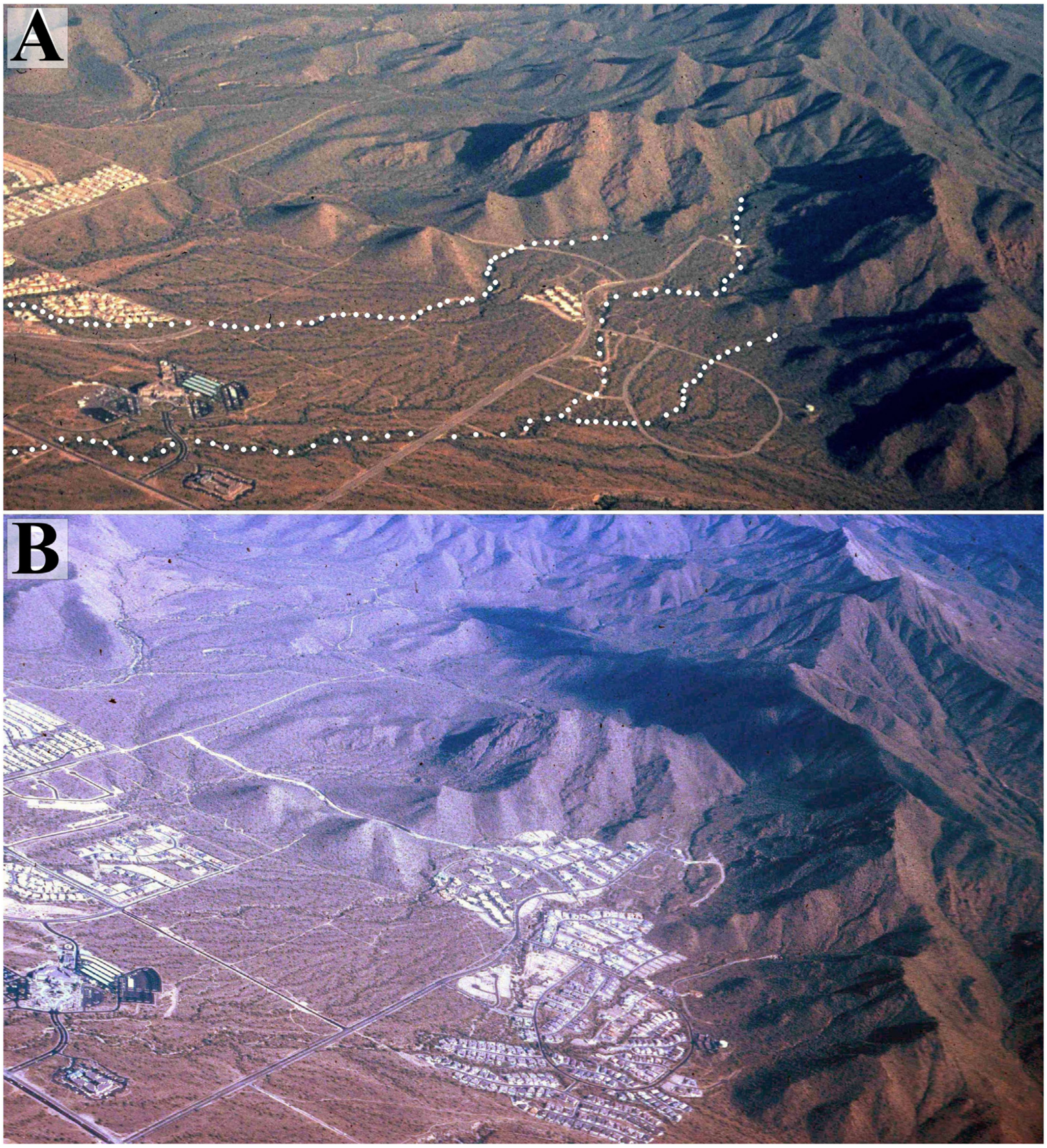

Fig. 20. Shadow alluvial fan of the McDowell Mountains in 1991 (A) and 1995 (B). The dots identify the major ephemeral washes that have incised between 2 and 4 m, although the surface of the fan used to contain well-developed desert pavements prior the housing developments. See Fig. 18 for spatial context.

longitudinal profile of pediment streams (Figs. 16 and 17). Nothing that we have encountered supports previous notions that the pediments in the Sonoran Desert are some sort of fossilized or inherited landform (Oberlander, 1974; Twidale, 1983; Oberlander, 1989; Twidale and Bourne, 2013), but instead are continuously changing landforms fundamentally tied to base level.

The ballena landform is an almost universal aspect of alluvial-fan evolution in the Basin and Range Province of North America (Peterson, 1981) and in many other settings as well. As an alluvial fan shifts its loci of deposition in the down-fan direction, the morphology of the fan closest to the mountain range eventually rounds through ongoing surface erosion. Hundreds of geological quadrangle maps show this form with various age estimates typically ranging from late Tertiary to mid-Quaternary; a detailed analysis of this geological mapping literature (Dibblee, 1964; Dickey et al., 1980; Swadley and Hoover, 1989) is, however, beyond the scope of this paper. However, all age assignments on these maps were estimates. Alluvial-fan researchers sometimes made specific age estimates, without any analytical support, or assumed that desert fans responded to the metronome of climatic changes, as revealed within oxygen isotope stages (Bull, 1991).

One of the few places with a solid age constraint for the ballena form of an eroding alluvial-fan surface comes from the use of rock varnish microlaminations (Liu, 1994) and cosmogenic ^{10}Be and ^{Al}26 for surfaces of the Warm Springs alluvial fan, Death Valley, California, USA (Duhnforth et al., 2017). The limit of rock varnish microlaminations is about 300 ka (Liu, 2020), which corresponds to an early minimum surface exposure age (Nishiizumi et al., 1993). Duhnforth et al. (2017), however, obtained much older minimum surface exposure ages between 990 ka and 630 ka for the ballena form (named Qg2) of the Warm Springs Death Valley fan seen in Fig. 19B.

The integration of the Salt and Verde systems through the LVRV (Fig. 3) allows us to place a maximum age for the evolution of the ballena form. Our conclusion is that these alluvial fans started to erode at the onset of the Quaternary ca. 2.5 Ma because of base-level lowering (Table 1) associated with the arrival of the Verde River, providing evidence that ballenas can be exclusively Quaternary in origin.

In addition, an array of landforms exists along the Salt and Verde rivers that record the integration process itself. Understanding the character and evolution of these landforms helps to both test hypotheses regarding the integration process in a basin and to also comprehend the impact

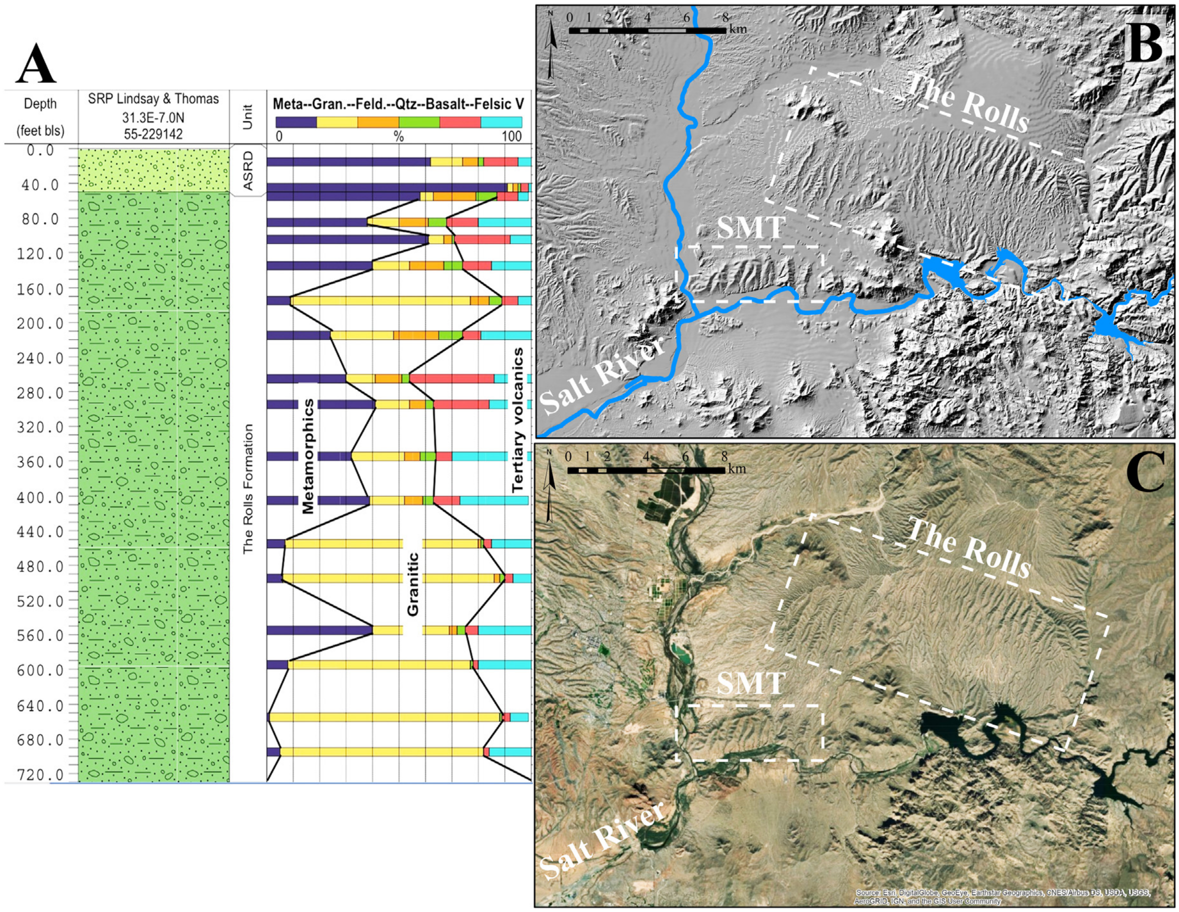

Fig. 21. Relief inversion represented in the topography of "The Rolls" (Fig. 3). (A) Well drilled in the Higley Basin that shows similar sediments to those found at "The Rolls" underneath the ASRD sediments of the Salt River. (B) and (C) show the inverted relief of The Rolls in both hillshade DEM and satellite imagery.

integration has on basin's geomorphic systems. House et al. (2008) and Howard et al.'s (2015) research on the sedimentology and "Bullhead Alluvium" along the lower Colorado River provides an iconic case study of how drainage integration can produce enormous quantities of sediment that are deposited downstream of a drainage integration location where a spillover event has occurred. We interpret an analogous landform in the LVRV along the Verde River (Section 4.3), the Lousley Hills terrace. In addition, the combination Salt and Verde river system in the Higley Basin contains the ancestral Salt River gravels (Fig. 3; Skotnicki et al., this issue). Physical models suggest deposits like this must occur during an overflow integration process (Douglass and Schmeeckle, 2007; Douglass et al., 2009). Thus, the geomorphic features of the Lousley Hills terrace and ASRD strongly support an overflow hypothesis for integration of the Verde River through the Bartlett and LVRV basins and the Salt River from the Tonto/Roosevelt Basin to the Higley Basin.

Lower relief at the sill where integration occurred between the Bartlett and LVRV basins may have been important in preserving evidence of the sequence of geomorphic events associated with drainage integration along the Verde River (Figs. 1 and 3). Just as the low relief of the potential Bartlett spillover onto a playa likely influenced preservation the Verde River's Bullhead Alluvium-analogous deposit (i.e., the Lousley Hills), a very different geomorphic setting downstream of the Salt River's lake overflow might explain the lack of a Bullhead Alluvium analogous deposit in the LVRV just downstream of its overflow location. Upon overflow near the present-day position of Roosevelt Dam (Figs. 3 and 4), the Salt River flowed across an extensive bedrock landscape and two small basins represented today by Saguaro lake and Apache Lake (Fig. 3). No evidence exists of the original deposits in these basins. Today, we see a topography dominated by canyons and entrenched meanders (Fig. 6) that is likely the result of superimposition and headward retreat of the Salt River's longitudinal profile from the LVRV into the Tonto/Roosevelt Basin (Fig. 3). We hypothesize that the substantial relief between the Tonto/Roosevelt Basin and LVRV along the Salt River, in comparison to the LVRV and Bartlett Basin for the Verde, allowed for greater erosion and capacity for sediment transport thereby flushing most of the Salt River sediment farther downstream into the Higley Basin as deposits of the ancestral Salt River (Fig. 3).

The genesis, aggradation, and abandonment of the ASRD is a significant player in the geomorphic evolution of the Higley and LVRV basins. Its importance may have its origins in the tectonic setting of central Arizona. Faulting in this study area largely ceased before ca. 9 Ma (Fitzgerald et al., 1993). The cessation of faulting within the Higley Basin allowed the necessary stability for sediment to accumulate over ~2 million years, driving basin geomorphic systems to respond to a long-term, gradually rising base level. Ultimately, this would impact pediments and alluvial fans bounding this basin. Eventually, the Higley Basin would reach its capacity to store sediment and spillover into the Luke Basin, initiating a wave of incision that propagated through the basins drained by the Salt and Verde rivers (Fig. 3). This left the Sawik terrace as a landform along the Salt River and resulted in pediments and fans incising into their former surfaces and responding to a lowering basin-wide base level. Thus, analogous deposits to the ASRD, if observed in other basins in other integrated systems, can help to understand the origin and evolution landforms we observe in integrated basins.

Skotnicki and DePonty (this issue) present the first compilation of the thickness and nature of fine sediments, mostly silt and fine sand, that have accumulated on top of the abandoned ASRD. An initial microscope study of this these deposits indicate that these sediments may derive from both locally sourced aeolian and fluvial sources (Jeong et al.,

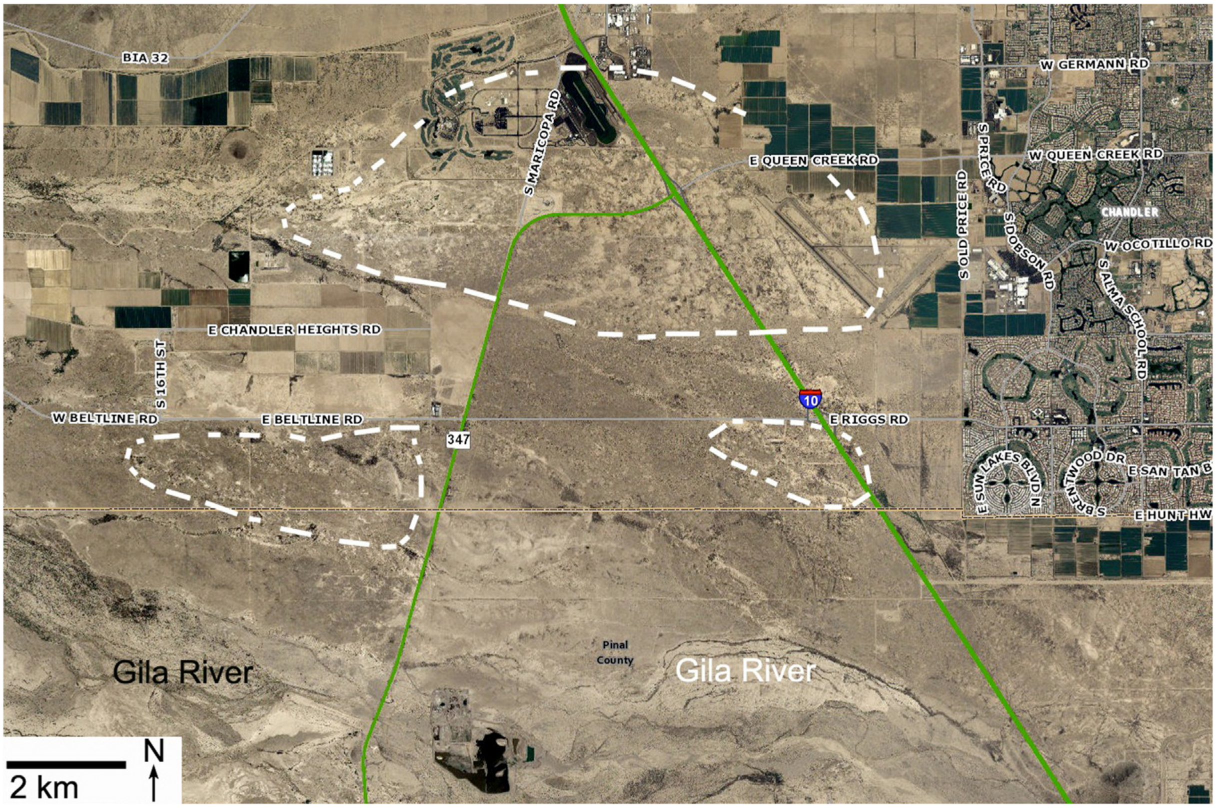

Fig. 22. Source-bordering dunes near the Gila River in the southern margin of metropolitan Phoenix. Areas surrounded by dashed lines indicate the presence of distinct dune forms. In contrast, the rest of the area north of the Gila River is a deposit of fine sediments that mix aeolian and fluvial materials, all on top of the ASRD (Skotnicki and DePonty, this issue).

2018). With ASRD deposition ceasing <460 ka, very little is known about the nature of this sediment cover with the exception of Skotnicki and Gootee (this issue), who present evidence for pulses of alluvial sediment coming from the Queen Creek drainage and interfingering with this overlying fine-grained unit in the eastern portion of the Higley Basin.

Research related to the archeology of the area has shed additional insight into the late Quaternary history of the area of the abandoned ASRD. In the last 5000 yr, for example, there were four events where aeolian sands and silts were deposited (Wright et al., 2011). At least during the last 18 ka, the channel of the Gila River has changed from accumulating sand and gravel to fine-grained sediment more than once, with a major pulse occurring approximately 5000 yr ago (Waters and Ravesloot, 2000). Sand dunes on the southern fringe of the ASRD, thus, originated from the Gila River in the Higley Basin. Exposure of fines during periods of low flow allowed deflation of the fines that were transported from south to north and we think very likely played a role in covering the ASRD with fines seen in well cuttings, along with low-energy ephemeral washes from bounding ranges (Skotnicki and DePonty, this issue).

We interpret these fine sediments to represent a stage of basin geomorphic system evolution in integrated systems that has not yet been identified and deserves more detailed study. As integration-driven base-level fluctuations stabilize, local drainages derived from the mountains surrounding the basin, as well as aeolian processes, provide the only new sediment input into the basin, thereby becoming the dominant geomorphic processes altering the basin landscape.

6. Conclusion

The establishment of a through-flowing river system in a setting formerly occupied only by endorheic drainage can dramatically alter the geomorphology of an integrated basin. The Salt River and Verde River systems of central Arizona cross the Basin and Range extensional tectonic setting and likely established their present course sometime between ca. 2.2–2.8 Ma. A series of drainage integration events occurred that connected the basins through which they now flow. Landforms (e.g., stream terraces, canyons, entrenched meanders, inverted topography, aggradational sediment wedges, pediments, alluvial fans, etc.) throughout these basins provide supporting evidence for hypotheses regarding the processes responsible for integrating these basins and for the impact integration has on the basin-wide geomorphic systems.

The processes resulting in integration of the basins also resulted in a complex sequence of base-level changes that drove landform evolution in those basins. Because these rivers flow through the Sonoran Desert, drainage integration also impacted classic desert landforms like pediments and alluvial fans. Base-level fluctuations impacted granitic, sedimentary, and metamorphic bedrock pediments — indicating that this classic desert geomorphic landform is not a fossil landform, but responds to ongoing geomorphic forcing. The classic erosional alluvial-fan landform, a ballena, has eluded efforts to pin down a maximum age of landform evolution; drainage integration processes provide a maximum age. Ballenas in the lower Verde River valley developed from Verde River drainage integration and have a maximum-limiting age of ca. 2.5 Ma — revealing that this classic desert landform can develop entirely in the Quaternary.

Declaration of competing interest

In regards to the research and findings reported in this paper:

1) The authors of this manuscript have no competing financial interests or investments.
2) Nor do they have personal relationships or conflicts of interest.

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