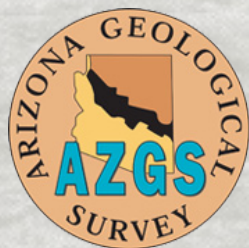


Geology and Geomorphology of the San Pedro River, Southeastern Arizona



Riparian zone along the San Pedro River flanked by deeply dissected alluvium derived from the Galiuro Mountains near San Manuel, Arizona.

P.A. Pearthree & J.P. Cook
Arizona Geological Survey



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Arizona Geological Survey

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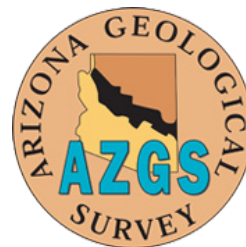
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Geology and Geomorphology of the San Pedro River, Southeastern Arizona

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Introduction

The San Pedro River flows through the rugged landscape of San Pedro Valley from the U.S. – Mexico border to its confluence with the Gila River at Winkelman (Figure 1). The river has incised (downcut) moderately to deeply into the valley floors that were accumulating sediment until the past few million years or less. River incision has in turn driven incision of all of its tributaries and erosion of the surrounding landscape. The inception of river incision resulted in a dramatic narrowing of the extent of river deposits, and this trend has continued to the present. As the river has incised, it has carved an erosional trough in older basin-fill deposits and bedrock, and has left behind remnants of older river deposits (river terraces) that record previous levels of the river. During the Holocene (the past ~10,000 yrs) the river has operated within a relatively narrow corridor bounded by eroded basin deposits, older river terrace deposits, tributary deposits, and bedrock, so all Holocene river deposits are restricted to this corridor. The primary purpose of this paper is to summarize the geologic setting and the geomorphic development and evolution of San Pedro River during the middle and late Quaternary. The latter point is particularly important for understanding the physical setting of Holocene San Pedro River deposits. This work was undertaken to assist Arizona Department of Water Resources staff in their efforts to delineate areas associated with river subflow in the San Pedro River Watershed.

Geographic Setting and Geologic History of the San Pedro River

The San Pedro River flows north for about 125 miles through the Basin and Range province of southeastern Arizona from the U.S. – Mexico border to its confluence with the Gila River near Winkelman. The San Pedro is a large regional watershed of approximately 4,720 mi². The uppermost part of the river in Arizona is flanked by the Huachuca and Mule

Mountains, the next reach downstream is flanked by the Whetstone, Dagoon, Little Rincon, and Rincon Mountains, and the lower San Pedro Valley is flanked by the Rincon, Santa Catalina, and Tortilla Mountains on the west and the Galiuro Mountains on the east.

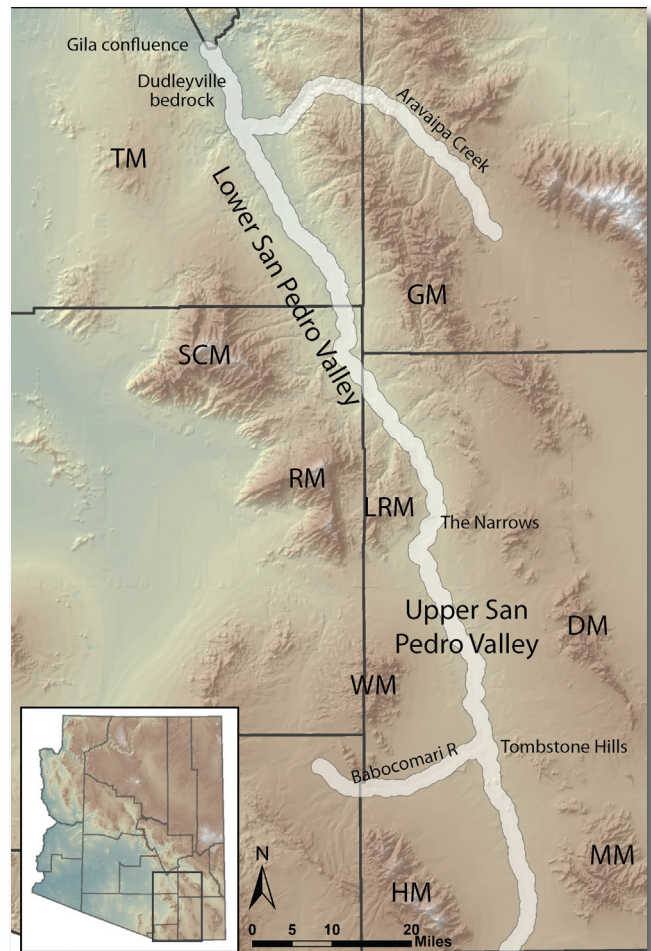


Figure 1. Location map for the San Pedro Valley. The river is within the light-colored corridor from the U.S. – Mexico border to the Gila River confluence; the paths of Babocomari River and Aravaipa Creek are also outlined. Labels identify the Huachuca (HM), Mule (MM), Whetstone (WM), Dagoon (DM), Little Rincon (LRM), Rincon (RM), Santa Catalina (SCM), Galiuro (GM), and Tortilla (TM) mountain ranges.

For most of its length, the San Pedro River course is formed in eroded late Cenozoic basin-fill deposits.

Bedrock bounds the river in 3 relatively short reaches, the Tombstone Hills in the Fairbank-Charleston area, the area of the Narrows between the Rincon and Little Rincon Mountains north of Benson, and near Dudleyville above the Gila confluence (Figure 1). The San Pedro is fed by many tributaries that vary greatly in size, from tiny watersheds that drain short and steep catchments to the largest tributaries, the Babocomari River and Aravaipa Creek. Each of these largest tributaries has extensive sedimentary and bedrock-lined reaches. Although the San Pedro River is the axial drainage or trunk stream throughout its length in Arizona, the size of the watershed and the diversity of rock types within the watershed increase dramatically from the upper to lower reaches.

The general trend of San Pedro Valley is governed by the strong north to northwest structural and topographic grain of the adjacent mountain ranges. The sedimentary basins through which the river flows are more complicated, as the San Pedro River links multiple basins that were partially or completely separate drainage and depositional systems prior to development of the river. Some of the basins began to subside with the onset of extension and normal faulting as much as 30 million years B.P. (before present) (Dickinson, 1991), but others probably began to form more recently (Menges and Pearthree, 1989). Most faulting and basin subsidence in the region probably ceased by ~ 5 million years B.P. (Menges and Pearthree, 1989), although some faulting has continued into the Quaternary (Pearthree, 1998). In terms of nomenclature for the deposits that filled these basins, the San Pedro Valley has historically been divided into upper and lower sections at the Narrows (Heindl, 1952), with deposits of the upper San Pedro Valley to the south called the St. David Formation (Gray, 1967), and deposits of the lower San Pedro Valley to the north called the Quiburis Formation (Heindl, 1963). The distribution of bedrock reaches along the river and variations in the estimated depth to bedrock, however, imply that several topographically low areas were loci of deposition prior to the development of the through-flowing San Pedro River (Figure 2). The uppermost basin in the Hereford area south of the Tombstone Hills and Fairbank is the deepest structural basin in San Pedro Valley (Richard et al., 2007). The lowest part of the next basin to the north was near the southern flank of the Rincon Mountains in the area of Tres Alamos. These upper basins were probably part

of the same drainage system linked by a north-flowing “proto-San Pedro River” by the middle Pliocene, ~3.5 million years B.P. (Lindsey et al, 1990; Smith, 1994). Based on estimated depth to bedrock, another center of deposition may have existed north of the Narrows in the Redington area, and a larger depocenter certainly

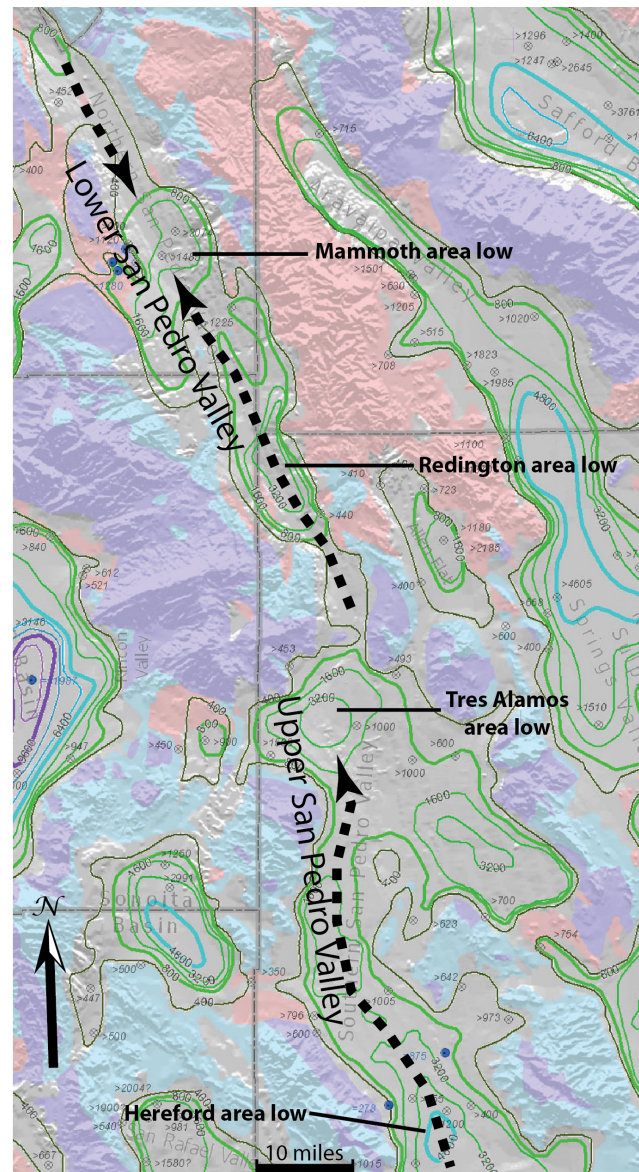


Figure 2. A portion of the Depth-to-Bedrock Map of Arizona (Richard et al, 2007) covering the San Pedro Valley. Contours are in feet below the surface. Each of the labeled lows was certainly filling with sediment from surrounding mountain ranges for most of the past 20 million years. Bold dashed lines show inferred surface drainages that linked the Hereford and Tres Alamos depocenters in the middle Pliocene (Lindsay et al, 1990), and the Redington area drained north to the Mammoth depocenter throughout the Pliocene (Dickinson, 2003), prior to incision of the modern San Pedro River.

existed farther north in the greater Mammoth area (Heindl, 1963; Dickinson, 2003; Richard et al, 2007). These latter two basins were probably linked by surface drainage throughout the Pliocene (Dickinson, 2003), but it is not clear whether there was a through-flowing river linking all of the upper and lower basins in the late Pliocene to early Quaternary.

The well-studied deposits of the St. David Formation in upper San Pedro Valley pre-date, and thus provide a maximum age constraint on, the Quaternary incision of the upper San Pedro River. Sedimentary characteristics of the lowest exposures of the St. David Formation north of Benson are consistent with deposition in a playa-like environment (analogous to modern Willcox Playa) prior to about 3.5 million years B.P. Exposures of stratigraphically higher and younger deposits from the Benson area south to near the U.S.-Mexico border are interpreted as primarily river floodplain and channel deposits that accumulated from 3.5 million to less than 770,000 yrs B.P. (Gray, 1967; Johnson et al, 1975; Lindsay et al., 1990; Smith, 1994). These upper deposits are evidence for a proto- San Pedro River that was slowly aggrading in the upper San Pedro Valley. Alluvial fans from tributary drainages were feeding into the ancestral San Pedro from the east and west, and the uppermost exposures of the St. David Formation on the east side of the valley consist solely of tributary alluvial fan deposits (Lindsay et al, 1990). Presumably these alluvial fans were graded to the highest level of axial valley deposits, which have been almost completely removed by erosion in the Benson-St. David area. Relatively high, planar alluvial surfaces preserved in the southern ½ of the upper San Pedro Valley may approximate this maximum level of valley aggradation on top of the St. David deposits (Figure 3). Each surface remnant is higher than all river terraces and tributary fans and terraces in their vicinity, and they all have strong petrocalcic soil development (caliche) attesting to their antiquity. They extend discontinuously for about 25 miles on the west side of the San Pedro River, from the Hereford area to north of the Babocomari Creek confluence, and their altitudes decrease from 4265 ft in the south to 4110 ft at the northernmost remnant. This is consistent with an axial valley drainage system that flowed north at a very gentle 0.0012 gradient prior to the initiation of river incision.

The first major period of incision in the upper San Pedro, which occurred sometime after the last major geomagnetic reversal at 770,000 years B.P. (Johnson



Figure 3. Relatively high, old surface remnants near the axis of upper San Pedro Valley that may approximate the pre-incision valley floor. Sites are labeled in feet above sea level. View is oblique from the U.S. – Mexico border to Benson. Base image from Google Earth.

et al., 1975), also caused substantial incision of tributary valleys. This incision was followed by a major aggradation period recorded by the “Granite Wash” tributary deposits (probably equivalent to map unit Qi1 of Cook et al, 2009), which filled tributary valleys that had developed during the initial incision (Johnson et al, 1975; Lindsay et al, 1990). The river and tributary drainages re-incised after deposition of the Granite Wash deposits, and have remained below the maximum level of middle Quaternary aggradation ever since. Quaternary incision is greater downstream along the upper San Pedro River; if the old surfaces discussed above accurately record the pre-incision axial valley floor, then net river incision varies from <100 feet in the south to >300 feet in the Benson area.

The spatial distribution of different facies of the Quiburis Formation in lower San Pedro Valley indicates that the largest and presumably lowest center of deposition prior to river incision was in the greater Mammoth area. In this area, a playa environment existed in the late Miocene and possibly into the Pliocene; at times, parts of this area sustained small lakes (Dickinson, 1998; 2003). Tributary alluvial fans fed into this depocenter from the east, west, and north. A broad axial valley drainage fed into the playa from the south, and tributaries on both sides of the valley fed into the axial valley (Dickinson, 2003).

The timing of river incision in lower San Pedro Valley is less well constrained, but downcutting along the axial drainage may have begun earlier there than in upper San Pedro Valley. Volcanic tephra fairly high in the Quiburis Formation in the Mammoth area have been dated at ~5 million years B.P. (Scarborough, 1975), implying that most of the Quiburis deposits there are late Miocene in age. Cosmogenic age estimates obtained for high alluvial fan remnants on the margins of San Pedro Valley indicate that they date to at least 1 million years B.P. (Matt Jungers, Arizona State University, oral communication, 2014). These paleofan surfaces pre-date most of the valley incision, so it is likely that incision of the lower San Pedro Valley began prior to 1 million years B.P.

The distribution and character of basin-filling deposits prior to development of the modern San Pedro River have implications for the form of the modern valley. As the basins were dropping down due to faulting they were synchronously being filled with sediments eroded from adjacent mountain blocks (Heindl, 1963; Menges and Pearthree, 1989; Dickinson, 1991). Similar deposition patterns persisted for a few million years after faulting waned and before axial valley incision commenced (Menges and Pearthree, 1989; Smith, 1994). These basin-filling sediments are predominantly fairly coarse alluvial fan gravel near the mountains, transitioning to finer gravel and sand deposits farther from the mountains. Much finer-grained sand, silt, clay and minor gravel was deposited in the valley axes. The finest-grained sediments accumulated in the playa or lake-like environment in the lowest parts of these valleys. In general, the coarser-grained alluvial fan deposits are substantially more resistant to erosion than are the finer-grained basin axis deposits. Because younger Quaternary alluvial fan deposits

mantle most areas where basin-fill sediments were deposited, the character of sediment supplied from adjacent mountain ranges in more recent times is also a critical factor in resisting erosion. Generally, the course of the San Pedro River is formed in late Cenozoic basin axis deposits that are fairly susceptible to erosion, but areas adjacent to the river are much more extensively eroded where deposits are very fine-grained, such as the greater Benson area (Figure 4A). In areas where the San Pedro River course is formed in coarser Miocene, Pliocene or Quaternary alluvial fan deposits, older, more indurated basin deposits (both of these factors are important in the lower San Pedro Valley), or bedrock, the river corridor is narrower and the surrounding landscape is less pervasively eroded (Figure 4B).

Late Quaternary Valley Development

The valley erosion in both lower and upper San Pedro Valley has ultimately been driven by incision of the river. In the past million or more years for the lower San Pedro, and in the past ~600,000 years in the upper San Pedro, the river has incised far below the former valley floors. This river incision has caused all of the tributaries to incise as well, because the river is the base level to which the tributaries are graded. Base-level fall is transmitted efficiently upstream through easily erodible materials by knickpoint migration and bed erosion, depending primarily on the resistance of the material forming the stream bed to erosion and the amount of stream power available to do work (Bull, 1979). Thus, larger tributaries flowing over easily erodible material will respond most quickly and completely to river incision, whereas small tributaries flowing over resistant strata may have steep gradients and obvious knickpoints not far upstream. Incision along the channel network in turn drives erosion of adjacent hillslopes over a much longer time frame. In the eroded landscapes of San Pedro Valley, most of the material that has been removed was initially eroded from hillslopes into adjacent channels via sheetflow or gullies, then on down the drainage network to the Gila River. Thus, direct erosion by the river is a minor component of landscape denudation, but it is critical because it ultimately drives tributary and hillslope erosion.

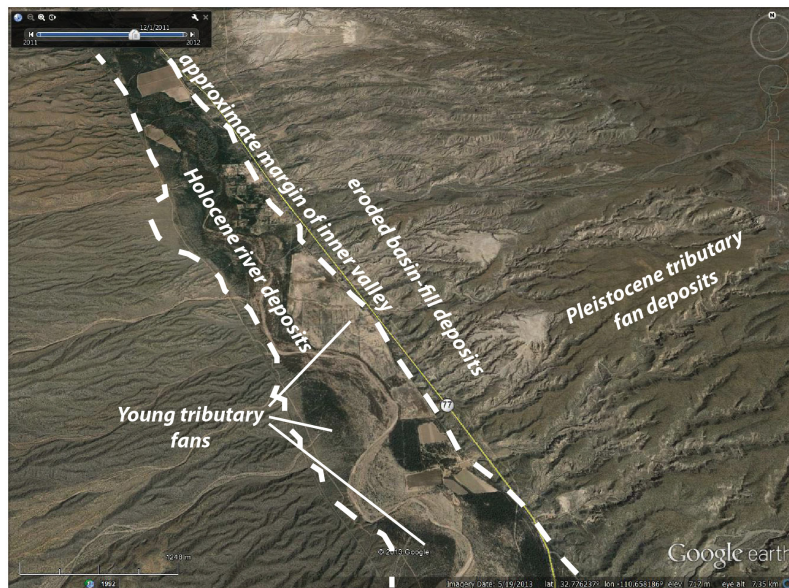
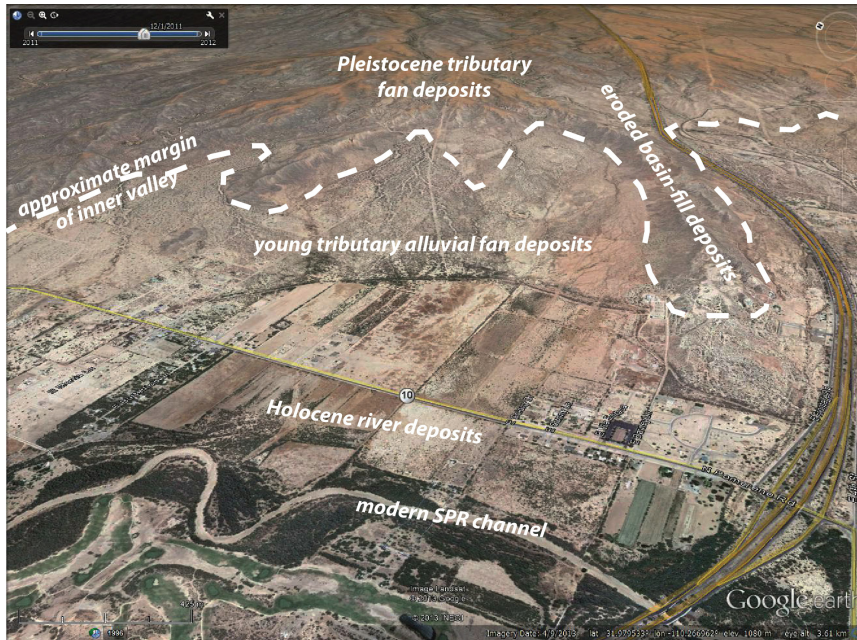


Figure 4. Inner valley morphology. (A) highly eroded basin-fill deposits and wide inner valley just north of Benson. (B) relatively narrow and well-defined inner valley south of Mammoth. Base images-Google Earth.

River deposits of all ages are obviously limited to areas that the river has occupied since it began to erode into basin deposits. Old river terrace deposits perched high above the modern river record past levels of the river as it progressively downcut after river incision began in the early or middle Quaternary. The oldest of these terrace deposits (geologic map unit Qi1r) are found high above the modern river and thus predate most of the river incision (Cook et al., 2009) (Figure 5). Progressively lower and younger Pleistocene river

terrace deposits (map units Qi2r, Qi3r) are more abundant, and record past river levels during the long-term trend of downcutting by the river. These terrace deposits record (1) periods when river incision diminished and lateral erosion was predominant; (2) periods when the river switched from incision to aggradation; or (3) combinations of these phenomena, i.e., cessation of incision, then aggradation combined with lateral erosion, followed by renewed incision.

The topographically lowest part of the San Pedro Valley (the “inner valley”), which contains the modern river channel and all of the Holocene floodplain alluvium of the San Pedro River, began to form in the late Pleistocene. The youngest Pleistocene river terraces that are preserved along the river (map unit Qi3r; Cook et al., 2009) may record one or more intervals of river aggradation that partially filled an inner valley that was incised as low as or lower than the modern San Pedro River. The age of the Qi3r deposits is not directly constrained, but stratigraphic evidence from several well-studied tributary valleys provides some clues to their age. Coro Marl deposits associated with long-lived springs in 4 different tributary drainages near the San Pedro River are of particular importance (Pigati et al, 2009; Figure 6). Three of these sites (Lehner Ranch, Horsethief Draw, and Murray Springs) are in upper San Pedro Valley, and the fourth site (Cerro Negro) is located south

of Mammoth in lower San Pedro Valley.

The marl deposits are from 2 to 12 ft thick and are found at or slightly higher than the modern incised arroyo channels in these tributaries. They rest on tributary sand and gravel deposits in valleys eroded into older basin-fill deposits. Thus, the Coro Marl deposits began to accumulate in tributary valleys that were at levels close to the modern valley bottoms and which gradually aggraded above the modern levels.

Based on extensive radiocarbon and luminescence dating, these deposits accumulated from ~50,000 to 15,000 years B.P., depending on the site (Pigati et al., 2009). Because the San Pedro River is the level to which each of these tributary washes is graded, the fact that tributaries had carved valleys as deep or deeper than the modern valleys prior to the beginning of marl deposition implies that the altitude of the river was as low as, or possibly lower than, the modern river bed in prior to 50,000 years B.P.

Marl deposition records a period when the water table

dates to about 13,000 years B.P. (Waters and Haynes, 1987). The channel of the modern arroyo is incised in a broad tributary valley that has been eroded 30 to 45 ft below planar eroded surfaces formed on St. David Formation deposits to the north and south (Figure 7). Historical arroyo incision exposed a complex series of late Quaternary deposits in this valley. At this site, the Coro Marl is about 3 ft thick and has been dated at between 15,000 and 25,000 years B.P. The marl rests on up to 8 ft of gravel, sand, silt and clay of the Millville alluvium, which accumulated in the valley

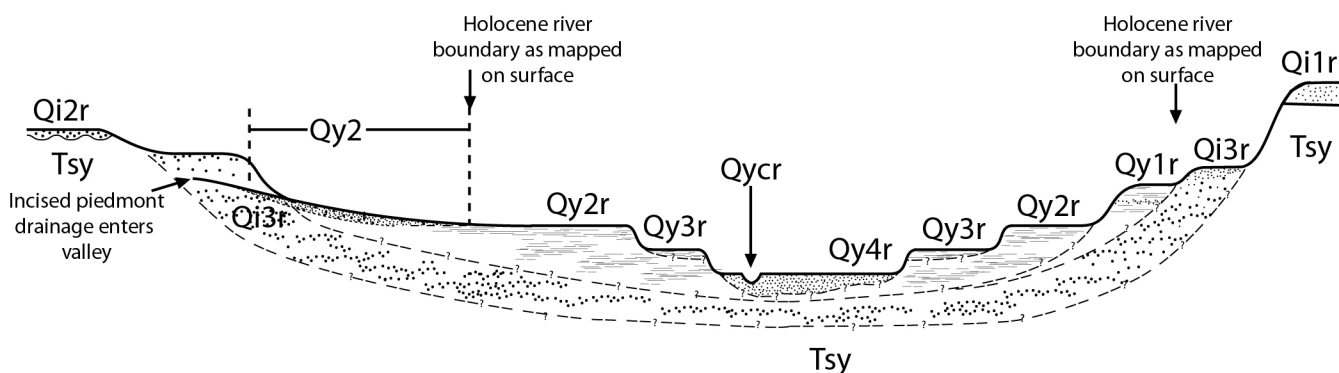


Figure 5. Schematic topographic cross-section showing Holocene and Pleistocene river deposits and terraces. Base of deposits shown in subsurface is uncertain. Modified from Cook et al (2009).

was high and relatively stable, and the absence of erosional unconformities in these units indicates that they were deposited more or less continuously over tens of thousands of years (Pigati et al, 2009). This precludes substantial local incision during this time, because incision would have lowered the local water table and resulted in erosion of the marl deposits. Nearly continuous spring deposition is consistent with stable or gradually rising base level (e.g., Leopold and Bull, 1979), so it may be that deposits were gradually accumulating in the inner valley and tributary valleys during this period. Marl deposition ended at all sites shortly after 15,000 years B.P. when the water table fell due to local incision and regional climate change (Pigati et al., 2009).

The topographic and stratigraphic relationships of late Quaternary deposits (including the Coro Marl) along several tributaries of the upper San Pedro River shed further light on the timing of river incision and aggradation. The age and nature of late Quaternary deposits at the Murray Springs site, about 2 miles upstream from the inner valley along Curry Draw (Figure 6), have been studied in great detail because of the presence of a Clovis mammoth-kill site that

bottom prior to the beginning of marl deposition and thus must be older than 25,000 years B.P. Based on lack of success in radiocarbon dating, Waters and Haynes (1987) inferred that the Millville alluvium is >50,000 years B.P. Multiple intervals of latest Pleistocene and Holocene erosion have cut into the Millville alluvium, but the floor of the modern arroyo channel is very close to the level of the bottom of the Millville alluvium (Waters and Haynes, 1987). Thus, the general erosional form of the tributary valley was established prior to 25,000-50,000 yrs B.P., and Curry Draw had eroded to a level similar to the modern wash at that time.

Two other archaeological sites provide similar insights into the depth and timing of tributary valley incision. The Coro Marl overlies the Millville alluvium at Horsethief Draw, just south of Curry Draw (Figure 6) and about 0.9 miles upstream from the inner valley. The vertical extent of the Millville alluvium is less well described at this location, but apparently the contact between the Millville alluvium and the underlying St. David Formation was at or below the maximum arroyo incision during the Holocene. The Coro Marl in Horsethief Draw has been dated

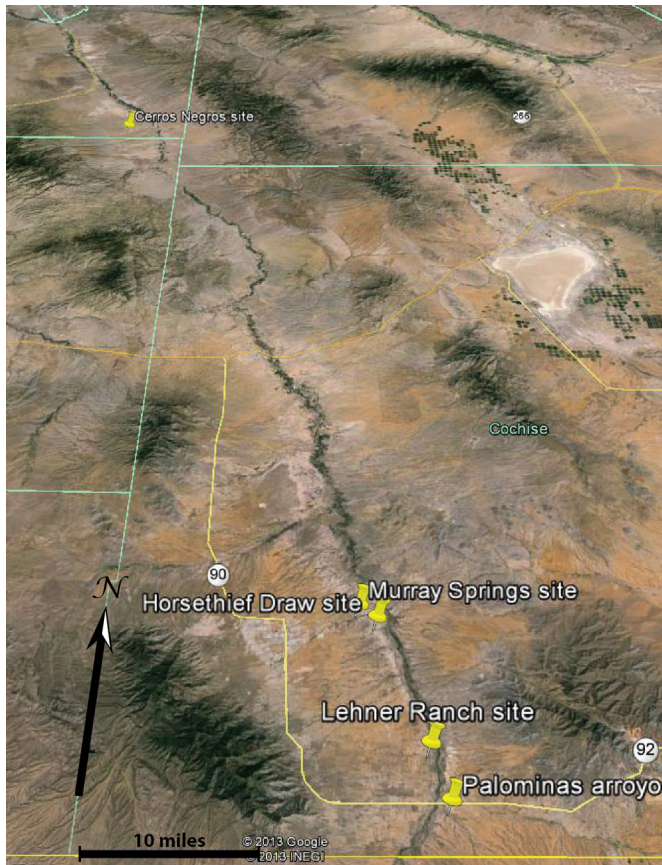


Figure 6. Locations of sites along tributaries of the San Pedro River with dated late Pleistocene deposits referred to in the text. View is oblique to the north from the U.S. – Mexico border to the Mammoth area. Base image from Google Earth.

from 15,000 to 50,000 yrs B.P. (Pigati et al., 2009), which requires that the tributary valley was eroded to a level at or below the modern arroyo channel prior to 50,000 yrs B.P. A similar situation exists farther south at the Lehner Ranch site (Figure 6), where Clovis mammoth-kill remains were discovered near the level of the modern arroyo channel (Haury et al., 1959). In addition, pre-Clovis mastodon remains were discovered in reddish-brown silt, sand and gravel of the underlying Millville alluvium (Mead et al., 1975). At this site, the Coro Marl has been dated at 17,000–20,000 yrs B.P. (Pigati et al., 2009), but based on a radiocarbon date from a nearby site, Mead et al. (1975) estimated the age of the Millville alluvium at >30,000 yrs B.P. The base of the Millville alluvium is below the modern depth of exposure along the arroyo (Haynes and Haury, 1982); thus, the tributary valley was likely graded to a river level below the modern river channel when Millville deposition began > 30,000 yrs B.P. This site is particularly significant because it is only about 0.2 miles upstream from the inner valley along an unnamed tributary.

Based on the evidence from tributary valleys summarized above, the San Pedro River valley bottom was likely lower than the modern river channel prior to 50,000 yrs B.P., when the Millville alluvium began to be deposited in eroded tributary valleys.

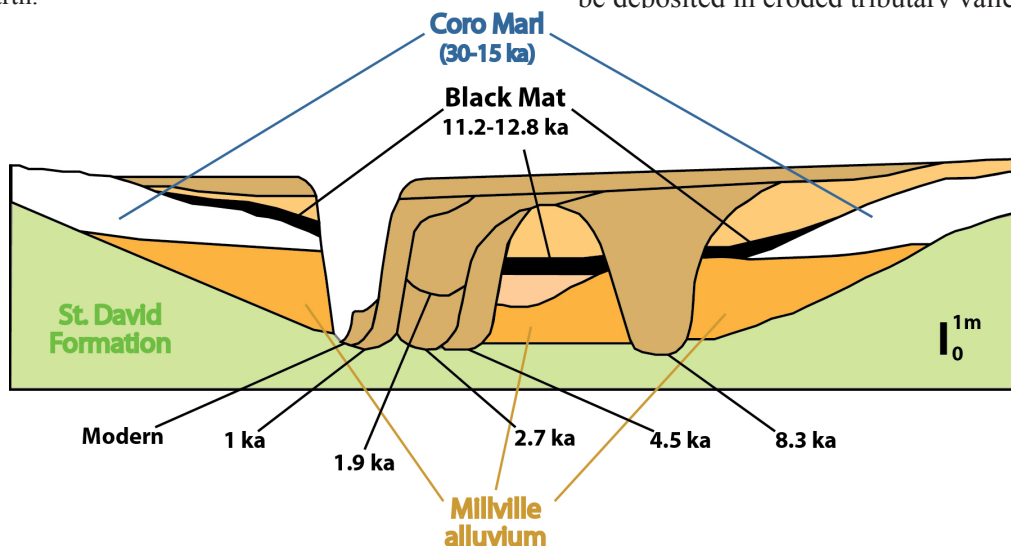


Figure 7. Diagram of late Quaternary stratigraphy exposed in Curry Draw. Deposits of the St. David Formation underlie the valley. The late Pleistocene Millville alluvium and Coro Marl accumulated in a valley eroded into the St. David Formation that was about as deep as, but much wider than, the modern valley. A shallower valley was cut into these deposits after 15 ka (thousands of years before present), which was subsequently filled by deposits including the latest Pleistocene “Black Mat” by about the beginning of the Holocene (shown in pink, black and yellow). Waters and Haynes (2001) found evidence for 6 periods of arroyo formation and subsequent back-filling of the valley between 8.3 ka and the present (shown in brown). Ages are recalibrated to calendar years using the calibration from Fairbanks et al. (2005). Five of these arroyos cut down to levels very similar to the modern arroyo, at or slightly into the contact with the underlying St. David Formation. Age ranges for the Coro Marl and Black Mat are from Pigati et al. (2009). Figure modified from Waters and Haynes (2001). For purposes of this Special Paper, this figure was colorized and the caption expanded.

The youngest Pleistocene river terrace surfaces (unit Qi3r; Cook et al, 2009) are 10 ft or more higher than adjacent Holocene river deposits. In most places we know little about the thickness of the Qi3r deposits because of lack of exposure, but locally they are at least tens of feet thick. The Qi3r deposits commonly contain abundant pebbles and cobbles and thus appear to be coarser than Holocene river deposits, although Qi3r deposits that are preserved as terraces may be more coarse-grained than “average” because coarser deposits are more likely to resist erosion. Qi3r deposits are generally equivalent in age to the Millville alluvium (late Pleistocene), and the terrace surfaces may record the maximum level of Millville aggradation in the river valley. In this scenario, Millville alluvium / Qi3r deposits filled the inner river valley from a level below the modern river channel to the level of Qi3r terraces over a period of tens of thousands of years, providing a stable or slowly rising base level for tributary streams and allowing for the accumulation of Millville alluvium and Coro Marl in those tributaries.

The San Pedro River likely incised into Qi3r deposits / Millville alluvium in the latest Pleistocene, making space in the valley bottom for the multiple generations of Holocene deposits that currently are exposed there. There is clear evidence for modest incision in the tributaries in the latest Pleistocene (15,000 to 13,000 yrs B.P.) that contributed to the cessation of deposition of the Coro Marl (Waters and Haynes, 1987; Waters and Haynes, 2001; Waters, 2008; Pigati et al, 2009). In Curry Draw, this erosion partially removed the Millville deposits in the valley bottom, but did not result in significant incision into the underlying St. David Formation deposits (Waters and Haynes, 1987). From this evidence, we infer that the river did not erode substantially below the level of the modern channel at that time. A recent geological investigation near the confluence of Palominas arroyo and the San Pedro River (Figure 6) documented organic-rich deposits about 40-45 ft below the surface of Palominas wash prior to historical incision (20-25 ft lower than the modern arroyo channel). These deposits date to ~13,000 years B.P. (Ballenger, 2010). The altitude of the organic-rich deposits is essentially the same as the modern incised channel of the river, which is currently about 0.5 miles to the west. Ballenger (2010) interpreted the organic-rich deposits as having accumulated in a wetland on the margin of the San

Pedro River, presumably at or near its confluence with Palominas wash. Thus, the river channel in that area in the latest Pleistocene was at least as low as the modern incised river channel. Deposits interpreted to be St. David Formation were encountered at the bottom of one borehole about 30 ft lower than the Palominas arroyo channel, and Ballenger (2010) inferred that the lowest part the incised valley was as deep as 40 ft below the modern arroyo channel. Because this valley was graded to the nearby San Pedro River, the altitude the river channel prior to 13,000 yrs B.P. must have been lower than the current channel.

Stratigraphic relationships and dating of deposits in the tributary valleys mentioned above indicate that the Holocene has been characterized by multiple periods of aggradation punctuated by episodes of downcutting. The most obvious example of this pattern is the historical period, when the San Pedro River and most of its tributaries switched dramatically from unincised, or discontinuously incised, systems in the 1800s to deeply and continuously incised channels in the late 1800s and early 1900s (Cooke and Reeves, 1976; Hereford, 1993; Huckleberry, 1996; Woods, 1997; Hereford and Betancourt, 2009). River incision has been sufficient along most reaches to isolate the early historical floodplain from inundation in river floods, creating a new river terrace. Subsequent to initial historical river incision, the incised channel widened by bank erosion and multiple terrace levels have developed within the incised valley (Hereford, 1993; Cook et al, 2009; Hereford and Betancourt, 2009; Huckleberry et al, 2009). Most tributary washes have incised in response to the base-level fall of the river channel and have developed new alluvial fans at the margins of the incised channel. Latest Holocene tributary fan deposits (Teviston alluvium; Waters and Haynes, 1987) that were graded to the historical river floodplain have also been isolated from further inundation and deposition.

Holocene deposits exposed at the Murray Springs site on Curry Draw have been dated and interpreted to indicate that there have been at least 5 prehistoric periods of incision beginning 7500 yrs B.P. (Waters, 2008). Each period of incision was followed by aggradation that filled the incised gully or arroyo and spread out over the valley floor, forming in an unincised valley bottom until the next period of incision occurred. A similar chronology of incision and

aggradation has been reconstructed for the Santa Cruz River near Tucson (Waters, 2008). Although it is not clear that the incision and aggradation history of the San Pedro River itself is well established, researchers have inferred a similar histories of incision and aggradation for the river and tributary valleys (Waters and Haynes, 2001; Waters, 2008). The geologic and geomorphic settings of archaeological sites and features within or on top of Holocene San Pedro River deposits have recently been evaluated (Cook et al., 2009; Onken et al., in press 2014). Numerous buried sites dating to 2000 to 3000 yrs B.P. have been found within deposits mapped as Qy2r, but nearly all sites dating to the period of ~1000-700 yrs B.P. have been found on the surface. This implies that river floodplain aggradation was underway by 3000 yrs. B.P. and that most Qy2r deposits are older than 1000 yrs B.P.

Changes in altitude of the tributary channels and presumably the river itself have been dramatic at times during the Holocene, but the net effect of these periods of incision and aggradation on the level of the river apparently has been minor. For example, in Curry Draw four of the prehistoric incision events cut down to similar levels as the modern arroyo, and subsequent aggradation periods filled the valley to similar levels. The details of past incision events and periods of aggradation on the San Pedro River itself are not constrained in this way, but the general situation may be similar. In that case, the river has accumulated sediment on its floodplain and eroded vertically and laterally into those deposits several times during the Holocene. There is no direct evidence that the river has downcut deeply below the level of the modern channel at any time in the Holocene, however.

Development and Maintenance of the Bounding Topography of the Inner Valley

The inner valley within which Holocene San Pedro River deposits are confined has been shaped by multiple processes in the late Pleistocene and Holocene. The inner valley is the lowest part of San Pedro Valley, and it includes relatively young river and tributary deposits. It is bounded laterally by hillslopes formed in eroded basin fill, older Pleistocene river deposits, and locally bedrock. In the subsurface, the inner valley presumably is cut into basin-fill deposits and bedrock. As we discussed earlier, the inner valley

began to form in the late Pleistocene and probably reached its deepest level of incision more than 50,000 years B.P. The form of the inner valley that we observe today has been shaped since then by geomorphic and geologic processes that are at times complementary and at other times are opposing. The important processes are (1) vertical incision and lateral erosion by the river; (2) river aggradation; (3) vertical incision and lateral erosion by tributaries near their confluences with the river; (4) tributary deposition; and (5) erosion of adjacent hillslopes. Some of these processes are closely linked, such as river and tributary erosion. Other processes tend to operate in opposition to one another, such as river and tributary erosion vs. river and tributary aggradation, and thus represent different modes of fluvial behavior. In this section, we consider how the interactions of these various processes have shaped the inner valley during the late Pleistocene and Holocene.

Vertical incision of the river during the Quaternary period is the most fundamental process, as it has provided the base-level fall that has driven the erosion of San Pedro Valley and provided space for the inner river valley to develop. River incision has initiated incision by tributaries, and ultimately has driven erosion of hillslopes throughout San Pedro Valley. Although vertical river incision has been the long-term trend since the early to middle Quaternary, abundant evidence from the late Quaternary described earlier indicates that the history of river downcutting and aggradation is complex in detail. Intervals of river incision may be followed by periods of stability or aggradation. As has been demonstrated by the historical period of arroyo development, an interval of downcutting by the river is readily transmitted upstream along tributaries. This results in more erosion throughout the valley, which increases the sediment supply to the river corridor. If the power of the river is not sufficient to transport this increased sediment supply, then a period of river incision might be followed by aggradation. Long-term changes in regional climate are well-documented (e.g., Pigati et al., 2009), and these changes have certainly affected runoff and erosion in the watershed. The river almost certainly had a different hydrologic and hydraulic regime under the wetter climate of the late Pleistocene. Certain climate changes may have resulted in increased runoff and available stream power, which could lead to river incision. These same changes may

have resulted in increased erosion in the watershed over a longer period, increasing sediment supply to the drainage system and resulting in aggradation along the tributaries and the river.

Vertical river incision was required to form the inner valley, but lateral river erosion has been more important in shaping the inner valley. The importance of lateral river erosion is illustrated by the historical record of arroyo development and subsequent channel changes. When continuous incised channels began to form along the river in the late 1800s, vertical incision and associated headcut propagation were the dominant processes (Cooke and Reeves, 1976; Hereford and Betancourt, 2009). The incised channel subsequently widened substantially by lateral bank erosion in a series of floods through the mid-1900s. Rates of channel widening since that time have been much lower due to the wider channel (more space for the river) and more sediment in the incised channel (Hereford, 1993). In addition, for San Pedro River upstream of the Aravaipa Creek confluence, the 1926 flood peak was 2 to 4 times larger than any subsequent floods (Pope et al, 1998; USGS Surface Water Data, <http://waterdata.usgs.gov/az/nwis/sw/>). The absence of any really large floods along most of the river may also have contributed to the decrease in rates of lateral erosion. Nonetheless, the modern incised channel is quite sinuous along much of its length, and bank erosion continues to occur around outside channel bends (Figure 8). Even though most of the modern channel is incised into Holocene river or tributary deposits, there are many locations where the channel directly abuts bounding basin-fill or older river deposits (Figure 9). These examples demonstrate that lateral river erosion continues to modify the boundaries of the inner valley.

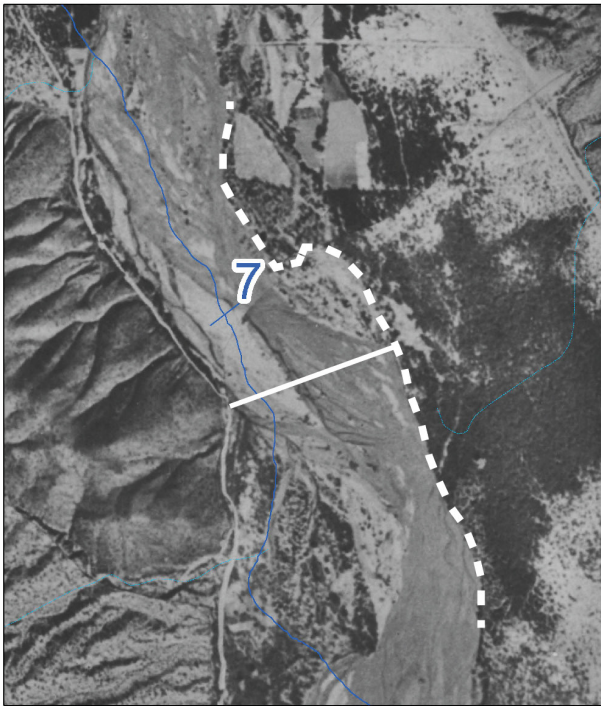
The distribution of exposed Holocene river deposits also indicates that lateral river erosion has been an important process shaping the bounding topography of the inner valley throughout the late Holocene. Along most of the margins of the inner valley, Holocene tributary deposits of varying widths separate Holocene river alluvium from the bounding deposits. Late Holocene river floodplain alluvium (unit Qy2r; Cook et al., 2009) has been deposited directly against older bounding deposits in about 60 separate areas along the San Pedro River, however (Figure 9). In these areas, essentially all tributary deposits must have been removed by lateral river erosion to make space

for deposition of river alluvium against the bounding geologic units. In the process of removing tributary deposits the bounding topography was almost certainly eroded as well.

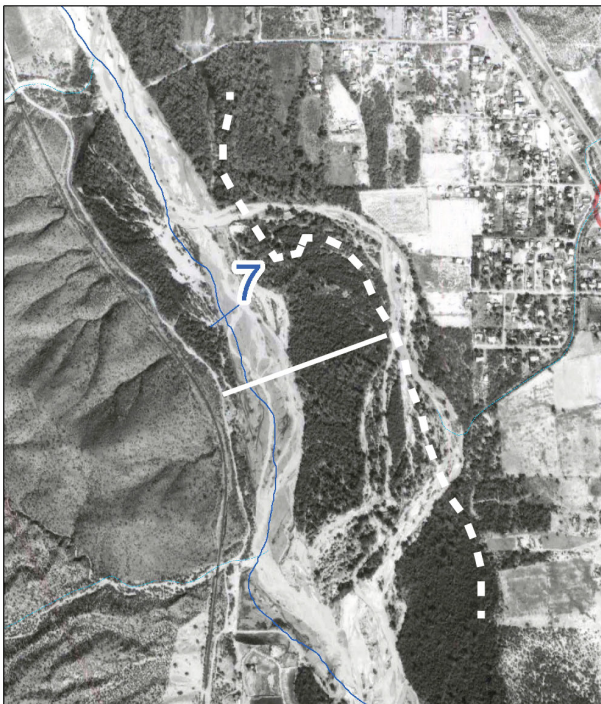
Based on these relationships, we infer that many instances of lateral river erosion trimming of bounding hillslopes have shaped the form of much of the inner valley throughout the Holocene. Lateral river erosion likely has been especially effective immediately after vertical incision, as during the historical period, but it may also occur as the river is aggrading after periods of incision. Although each instance of lateral river erosion tends to trim the bounding topography perpendicular to the general trend of the inner valley, many instances of lateral erosion summed over thousands of years tends to form fairly well-defined inner valley bounding topography that parallels the general trend of the river. Some deviation from linearity is likely due to variations in lateral river erosion, but much of it is probably a function of how long it has been since the river eroded laterally at that particular place.

Erosion by tributaries of all sizes has also modified the form of the inner valley. In fact, these processes have sculpted the bounding topography along virtually the entire inner valley to a lesser or greater degree. Vertical incision and lateral erosion by tributaries tends to carve the bounding topography back from the river corridor to form tributary valleys, thus making the bounding topography more crenulated (having an irregularly wavy or serrate outline in map view). Any sizable tributary has the potential to do its own lateral erosion; if lateral river erosion has not occurred at a particular reach for thousands of years, then lateral tributary erosion will widen tributary valleys and form increasingly larger crenulations in the base of the bounding inner valley topography. Vertical incision is likely predominant on smaller tributaries, as they respond to long-term or episodic downcutting by the river. Larger tributaries have more erosive power and thus have much more potential to achieve reasonably graded profiles and then erode their valleys laterally, so in general bounding topography is more deeply crenulated where they join the inner valley (Figure 10). Obviously, the erodibility of the geologic units is another critical factor in how effectively tributaries can modify the bounding topography (see Figure 10 for example). As was discussed previously, lateral river erosion may contribute some amount to the sinuosity

Lateral Erosion RM7: 1935



Lateral Erosion RM7: 1984



Lateral Erosion RM7: 1955

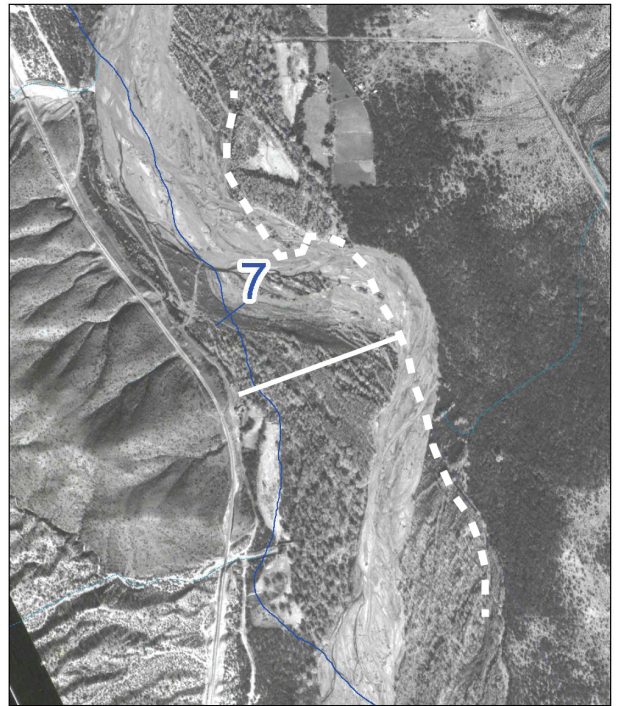


Figure 8. An example of progressive bank erosion around an outside river bend and other channel changes in the Dudleyville area, lower San Pedro Valley. The solid line is the approximate width of the channel in 1935, about 1400 ft; the dashed line is the location of the channel margin in 1935. Both are in the same location on the 1955 and 1984 images.

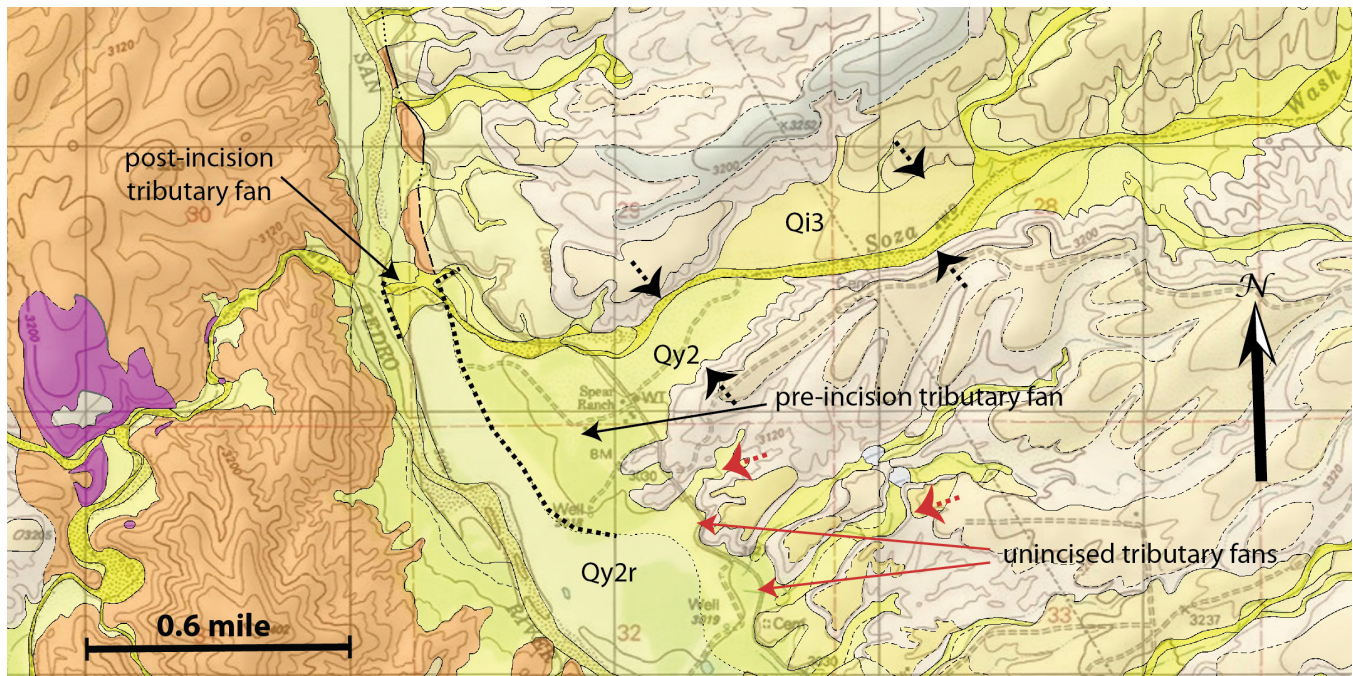


Figure 10. Geologic map of the confluence of Soza Wash with the San Pedro River (Cook et al, 2009). Soza Wash is a large tributary, and it has eroded a wide and long valley into basin-fill deposits (margins highlighted by black arrows with dashed lines). The floor of the tributary valley is covered with Holocene and late Pleistocene (Qi3) deposits. Some much smaller valleys eroded by tributaries are highlighted by red arrows. Prior to historical river incision, Soza Wash deposited a large alluvial fan onto the margin of the river floodplain. The post-incision Soza fan is much smaller and closer to the center of the inner valley. The alluvial fans associated with the small drainages highlighted by red arrows are not incised, because of limited tributary discharge and the fact that the incised river channel is on the opposite side of the inner valley. The floors of these valleys are covered by Holocene tributary deposits. Soza Canyon, which enters the San Pedro River from the west, is also a large tributary. It has carved a narrow valley, however, because the deposits on the west side of the river are older, coarser, and more indurated.

tributary deposition in these areas, some of the ridges and spines that are exposed at the surface may extend farther toward the river in the subsurface. Thus, it is likely that the river did not directly shape the bounding topography by lateral erosion in these areas.

There clearly is a relationship between the width of the inner valley, the erodibility of the bounding geologic units, the linearity of the bounding topography, and the known and inferred distribution of Holocene river deposits. Where the bounding topography is formed in bedrock or basin-fill deposits that are resistant to erosion, the inner valley is relatively narrow, bounding slopes are relatively steep, and the topographic slope breaks that form the margins of the inner valley are linear to curvilinear with relatively small and narrow tributary valleys. Where the inner valley is narrow, the chance of the lateral river erosion impinging on the bounding units over thousands of years is high, and tributary deposits along the river are periodically modified or removed by river erosion. In these

areas, vertical and lateral erosion by the river are the dominant processes that shaped the inner valley in the late Quaternary, and it is likely that river alluvium has been deposited in essentially every part of the inner valley sometime during the Holocene. Tributary erosion and deposition have been far more important processes in areas where the inner valley is wide and the bounding topography is highly crenulated. In these areas, the bounding geologic units are less resistant to erosion, and thus have been eroded both vertically and laterally by tributaries and to a lesser degree by hillslope erosion. In addition, Holocene tributary aggradation has partially or completely buried eroded topography formed on the bounding units due to high sediment supply from the surrounding landscape. In these areas, topographic breaks that mark the boundary of the inner valley are the product of several complex geomorphic processes and have not necessarily been formed by directly by river erosion. The form and character of the inner valley varies between these end-members, but the better-defined and more linear the

bounding topography, the greater likelihood that entire width of the inner valley contains some young river deposits.

Tributary Depositional Environments and Interaction with River Deposition and Erosion

River and tributary deposition in the inner valley involves interactions between tributary and river sediment supply, stream power to transport sediment, and changing river channel morphology and position in the inner valley. Tributaries of all sizes have deposited alluvial fans in the inner valley. There is abundant evidence in the historical aerial photo record (the past ~80 years) that interactions between these fans and river erosion and deposition are dynamic. Large river floods have eroded river and tributary deposits, and have trimmed or removed tributary alluvial fans built out onto the floodplain. Lateral river erosion into tributary deposits also occurs during more modest flow events. Tributary washes transport abundant sediment into the inner valley when they flood, building fans onto river deposits and encroaching onto the river floodplain or channel. Floods on the river and its tributaries are typically not synchronous, which results in complex temporal and spatial patterns of decrease and increase in the areas of tributary fan deposition in the inner valley (see Figure 11 for example).

Changes in river mode have also impacted the distribution of tributary and river alluvium in the inner valley. In the historical period, major shifts in the distribution of tributary and river deposits occurred as a result of arroyo development on the river and adjacent tributaries. Extensive tributary alluvial fans on the margins of the river floodplain have been isolated from further deposition due to channel incision, and tributary deposits have been transported farther into the axis of the inner valley to the incised modern river floodplain (Figure 10). Thus, changes between river aggradation and incision dramatically impact the distribution of tributary and river deposits through time, and it is reasonable to presume that changes such as these have occurred several times previously in the Holocene (Waters, 2008). Stratigraphic exposures along incised tributary channels in areas that formerly were active tributary

alluvial fans provide abundant evidence for interaction between tributary and river deposition through the middle and late Holocene. Beds of tributary gravel deposits are commonly found between beds of finer-grained deposits, which are probably river floodplain deposits (Cook et al, 2014). In nearly all of these areas, tributary sand and gravel deposits that were deposited along the margin of the river floodplain prior to historical river and tributary incision cap the exposures. These sequences of fine- and coarse-grained deposits record tributary and river aggradation on the flanks of the inner valley, and likely accumulated when both the river and tributary fluvial systems were aggrading. River aggradation in the inner valley causes local base-level rise for the tributaries where they join the river floodplain, which encourages tributary fan deposition. This is the situation that existed along most tributaries prior to historical river incision.

Exposures along Palominas arroyo reveal that the river channel occupied a position near the eastern margin of the inner valley, about 0.5 miles east of the modern river channel, in the middle Holocene. In this area, almost the entire area between the edge of the inner valley and the river channel is covered by the young Palominas alluvial fan (Figure 12). An approximately north-south oriented paleochannel filled with pebbles and cobbles of a variety of lithologies is exposed on the right (north) bank of the arroyo at the margin of the inner valley (Figure 13). The orientation of the channel is roughly parallel to the trend of the inner valley, and it is cut into somewhat older tributary and possibly river deposits. We interpret this feature to be a paleochannel of the San Pedro River that was eroded into tributary deposits and filled with river deposits during a period of river aggradation during the Holocene. Farther upstream along the arroyo at approximately the same stratigraphic level, Ballenger (2010) dated archaeological features at 4,500 and 3,500 yrs B.P. These dates provide a rough estimate for the age of the paleochannel. We conclude that the San Pedro River channel was at the eastern margin of the inner valley a few thousand years ago, and the Palominas fan has encroached substantially onto the floodplain since that time. Thus, the entire inner valley that is currently covered by Palominas fan deposits has been occupied by the river sometime in the past few thousand years.

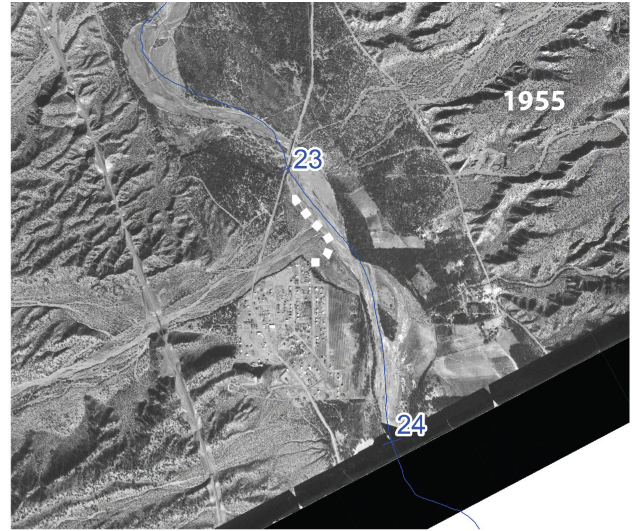
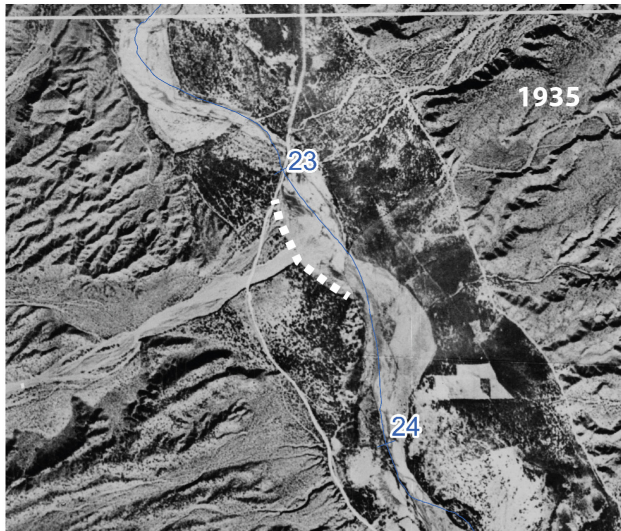


Figure 11. Sequence of aerial photos of the Tucson Wash – San Pedro River confluence illustrate the dynamic interaction between river floods and tributary floods. White dashed lines illustrate the approximate boundary between river and tributary deposits at each photo date. The large river flood of 1926 substantially eroded the Tucson Wash fan, which was still evident in 1935. By 1955, Tucson Wash alluvial fan had prograded over the former river channel. This trend has continued to the present, as the Tucson Wash fan has forced the river channel to the east and has covered most of the 1926 flood channel. North is up. Base imagery from the Soil Conservation Service (1935), Army Map Service (1955), Google Earth (1992), and National Agricultural Imagery Program (2103).

Changes in climate over thousands to tens of thousands of years have also influenced trends in tributary and river deposition. Beginning in the early late Pleistocene, the river incised below the level of the modern channel, then gradually aggraded to a level above the Holocene floodplain ~15,000 years B.P. The river then incised to a level at or below the modern channel at the end of the Pleistocene, and this latest Pleistocene inner valley has partially filled with Holocene deposits. The incision in the latest

Pleistocene, at least, coincides with the transition from glacial to interglacial climate and changing vegetation patterns (Pigati et al., 2009). This complicated history has undoubtedly resulted in the formation of a complex 3-dimensional pattern of river and tributary deposition in the inner valley. Thus, the extent of tributary and river alluvium in the inner valley mapped in any short interval (e.g., Cook et al., 2009) is geologic snap-shot, subject to change over decades to millennia.

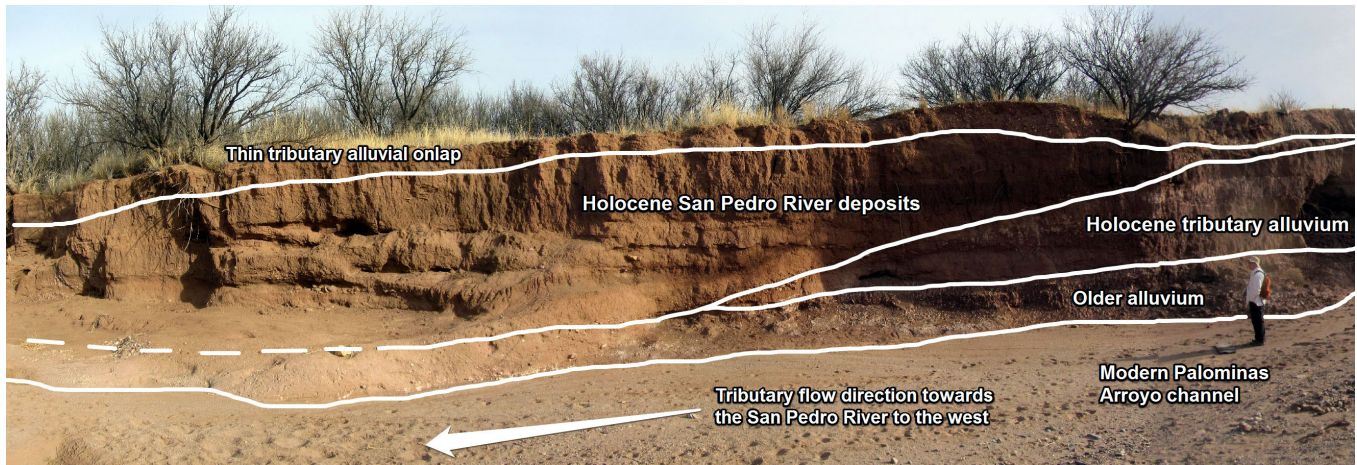


Figure 13. Interpretation of a stratigraphic exposure of a paleochannel of the San Pedro River along Palominas arroyo. View is looking NE, approximately perpendicular to the modern Palominas arroyo and parallel with the trend of the paleochannel and the inner valley margin.

Small tributaries have deposited relatively small alluvial fans on the margins of the river floodplain, and the floors of tributary valleys commonly are covered with young tributary deposits (Cook et al., 2009). Some small tributaries have linked directly to the incised modern river channel, in which case modern tributary deposition has migrated to the margin of the modern river channel; others have not incised and continue to deposit fans on the margin of the early historical river floodplain (Figure 10). Prior to the past 100 years or so, all of these tributaries were graded to the stable or slowly aggrading river floodplain. Even with historical arroyo development, the modern river channel is probably still higher than the lowest level of late Pleistocene river erosion in most reaches. This net river aggradation likely drove tributaries to aggrade near their confluences with the river and partially back-fill valleys that initially formed when the river channel was at its lowest (see Figure 10). Thus, the young tributary deposits that have accumulated in these valleys mantle some amount of erosional topography on the bounding geologic units. Because small tributary fans have formed all along the river corridor, the potential for them to be removed by river erosion depends on the form and width of the inner valley. In areas where the bounding topography is linear and the inner valley is narrow, small tributary fans almost certainly have been subject to temporary removal by lateral river erosion during the past 10,000 years. After they are eroded away, tributaries soon begin to build new fans out over young river deposits when the river migrates away from the tributary mouth. In areas where the bounding topography is

eroded well back from the river and is crenulated, tributary deposits in the inner valley are far less likely to have been removed by river erosion.

Larger tributaries transport larger amounts of sediment, and many have deposited large, well-defined individual alluvial fans and fan complexes into the inner valley. Because they are large features, substantial lateral river erosion is required to significantly alter or remove them. For that reason, they might be considered to be more permanent features in the inner valley. However, because these fans are large features, they typically protrude well out into the inner valley, which makes them more subject to river erosion. Large fans are also demonstrably dynamic features in the historical record, as they occasionally experience large floods and transport abundant sediment in these floods. In the absence of large river floods or persistent lateral river erosion, large tributaries have the potential to prograde rapidly over areas that were formerly part of the river floodplain. In the example of Tucson Wash near Mammoth (Figure 11), the large tributary fan had been trimmed by river erosion recently before 1936, the earliest aerial photo date, most likely in the flood of 1926. By 1992, the fan had prograded ~550 ft over the former floodplain, forcing the river channel to the northeast. By 2013, the fan had prograded ~825 ft, continuing to move the river to the northeast.

In areas where the inner valley is relatively narrow and well-defined topographically, it is likely that even large tributary fans can be eroded and those areas

temporarily incorporated into the river channel or floodplain. The confluence of Alder Wash, Kielberg Canyon, and the San Pedro River in lower San Pedro Valley illustrates the dynamic nature of tributary fan and river interaction (Figure 15). Both Alder and Kielberg washes are relatively large, heading in the

The river bends to the east, north and west around this fan and the former floodplain. A very small active fan is exists on the east side of the river at the Kielberg Wash confluence – there is essentially no space for such a fan to accumulate. This relationship has been similar throughout the historical photo record, with

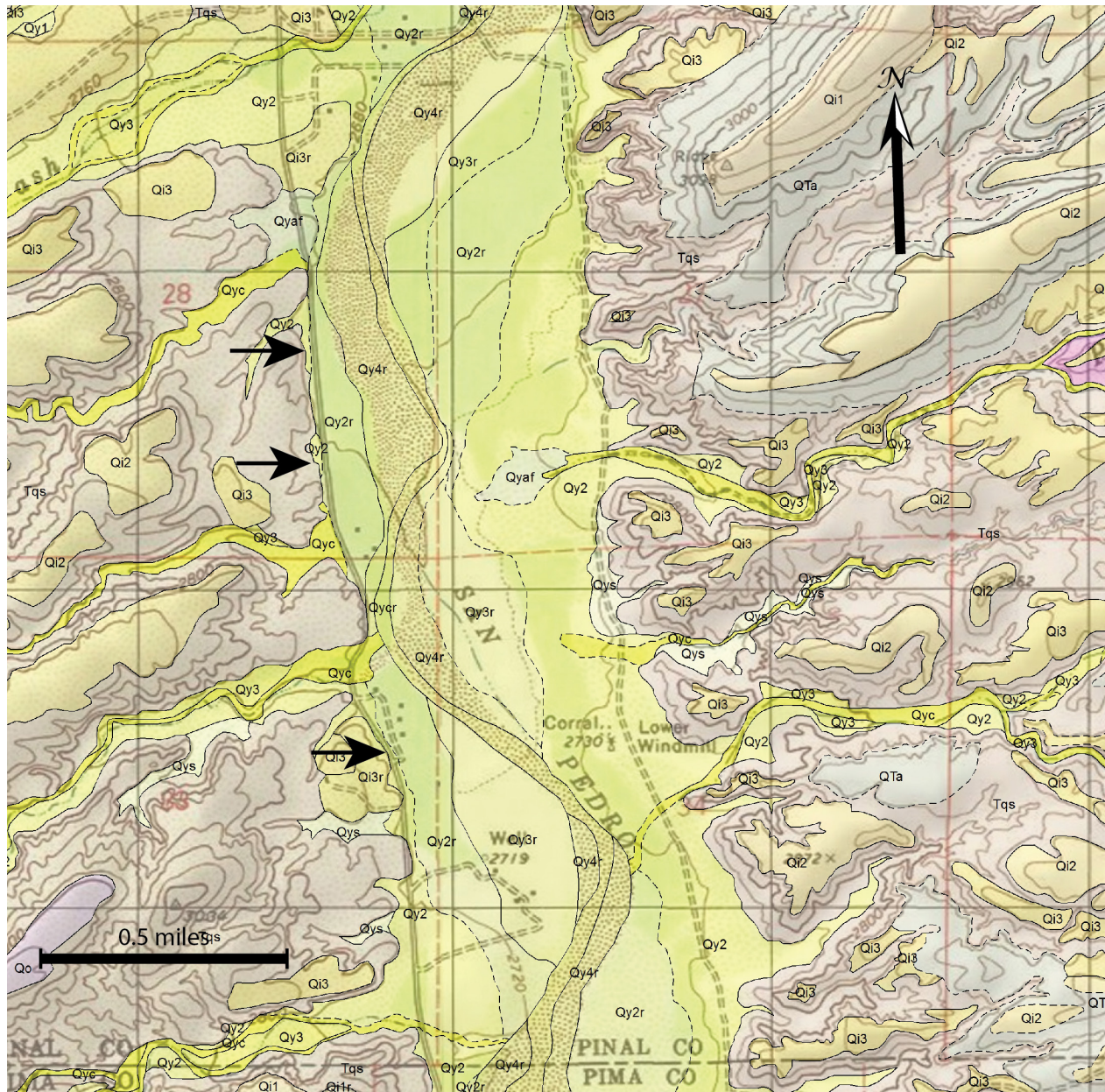


Figure 14. Black arrows point to areas where only a thin apron of young deposits separates the bounding geologic units on the west side of the inner valley from Holocene river alluvium. Holocene tributary deposits are completely absent in places where Holocene river alluvium abuts basin-fill deposits. Geologic map from Cook et al (2009).

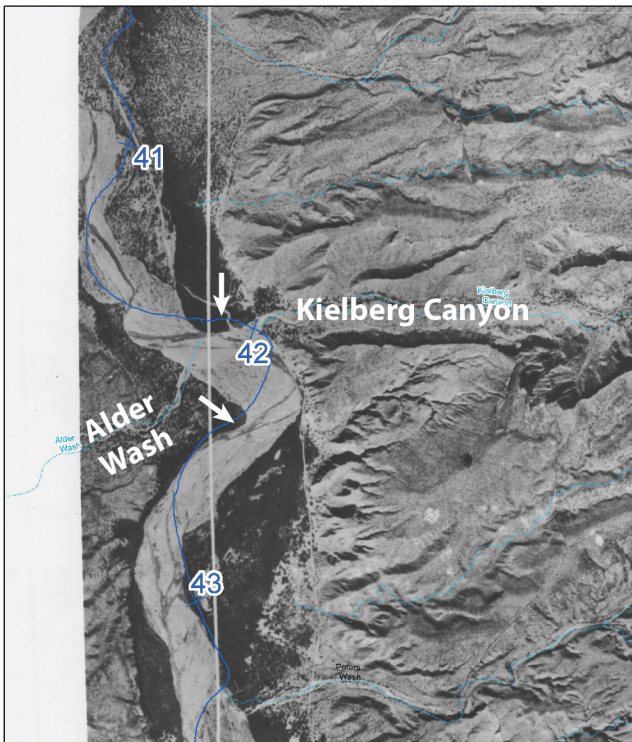
Santa Catalina and Galiuro Mountains, respectively, and they join the river at essentially the same location. Alder Wash deposited a moderately large fan onto the western margin of the pre-incision river floodplain.

minor bank erosion. Given that Kielberg Wash has a large drainage area, it very likely that this is a temporary situation, and eventually Kielberg Wash will rebuild its alluvial fan in a large flood and that will

force the river channel back to the west. In addition, continued lateral erosion around the outside river bends will tend to erode into the Alder fan and provide additional space for the Kielberg fan as meanders migrate downstream. When this occurs, part of what is now the Alder fan will become part of the river floodplain, and part of the river floodplain will become part of Kielberg fan.

is certainly some unknown amount of interfingering of fan and river deposits in the subsurface in these areas, but the lateral extent cannot be readily determined from the geomorphology. While some amount of erosion of fan toes by the river would be expected over thousands of years, it is highly unlikely that these entire features could be modified by river erosion and deposition, and thus incorporated into the river floodplain. The Palominas Wash area

Alder Wash Kielberg Canyon Confluence: 1935



1620 ft

Alder Wash Kielberg Canyon Confluence: 2013

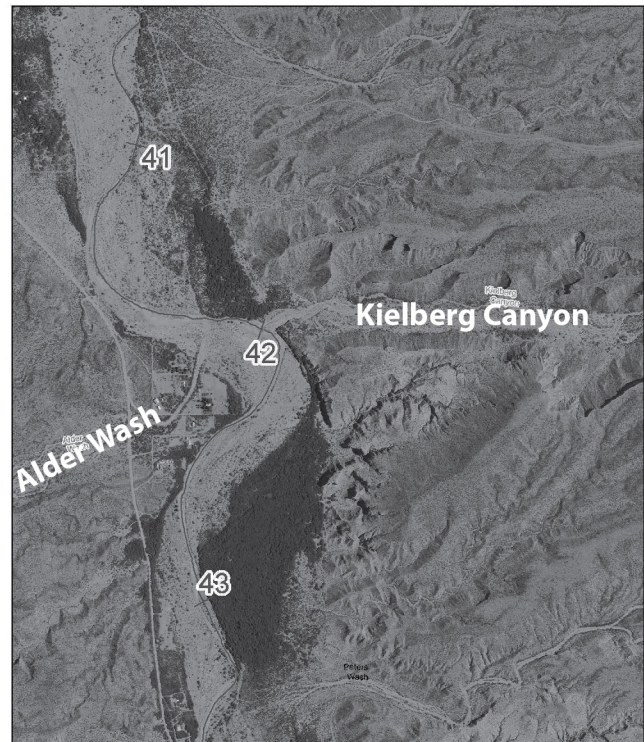


Figure 15. Confluence of Alder Wash, Kielberg Canyon, and the San Pedro River illustrating fan and river dynamics. Because of its location relative to river meanders, the Alder Wash alluvial fan and adjacent young river terrace deposits have persisted through the historical aerial photo record. The Kielberg Canyon alluvial fan has been persistently trimmed by river erosion, beginning prior to the historical photo record. White arrows point to areas where minor lateral erosion has occurred on outside meander bends. Continued lateral river erosion may trim the Alder Wash fan, and possibly will provide more space for deposition of a Kielberg Canyon fan. Base imagery is from the Soil Conservation Service (1935) and the National Agricultural Imagery Program (2013).

In areas where the inner valley is wide, it is likely that large tributary fans are more permanent features that are only subject to some modification near the river. Fans in these settings are relatively large, and their apexes are located far from and substantially higher than the river. Prior to historical river incision, the slopes of these large fans typically transitioned almost imperceptibly onto the river floodplain. There

discussed previously illustrates, however, that even in areas where the inner valley is moderately wide and tributary fans are fairly large, the distribution of river and fan deposits may change dramatically over thousands of years.

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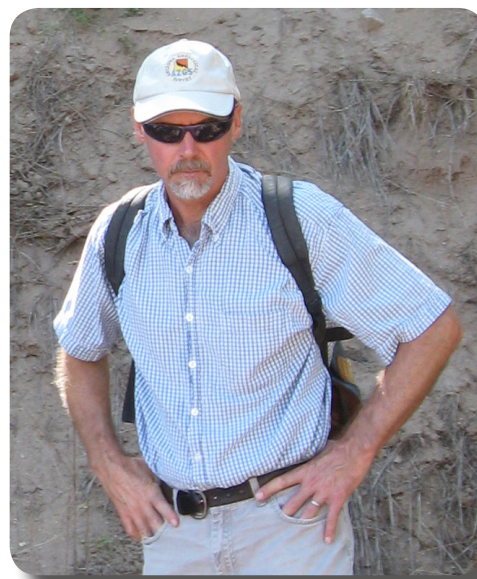
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