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Late Holocene behavior of small drainage basins on the Colorado Plateau: Influences of lithology, basin form, and climate change

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LATE HOLOCENE BEHAVIOR OF SMALL DRAINAGE BASINS ON THE COLORADO PLATEAU: INFLUENCES OF LITHOLOGY, BASIN FORM, AND CLIMATE CHANGE

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ABSTRACT.—In the semiarid landscape of the Colorado Plateau in northeastern Arizona, small basins associated with the “Blue Gap” escarpment have been rapidly aggrading over the last millennium. The mode of operation of the fluvial systems in a few sub-basins, however, has changed since the late 19th century from net aggradation to net erosion as shown by the formation of deeply incised, discontinuous arroyos. Detailed study of stratigraphy and soils in the upper reaches of some of the basins, along with radiocarbon dates and dendrochronology, shows that sediment in these portions of the basins, sometimes as thick as 3-4 m, is roughly 1000 years old. Sediment that is older than a millennium is not stored in the upper reaches of the basins. Additionally, the soil-stratigraphic record shows that during this period, aggradation has generally been the consistent mode of channel behavior in this area. The lack of paleochannels shows that until the 19th century arroyos formed, there were no previous episodes of deep channel incision. The observed rapid aggradation is partly attributable to the highly erodible Jurassic sandstones, siltstones, and mudstones that make up the cliffs and slopes of the escarpment, including the Bluff Sandstone of the San Rafael Group, and the Salt Wash Member of the Morrison Formation. The recent change from aggradation to incision in some of the basins could be attributed to the effects of late Holocene climate change. The timing of this change (late 19th century) suggests that the change could be associated with the end of the Little Ice Age (LIA ca.1200-1850AD). The modern geomorphic processes acting in adjacent basins today are inconsistent across the field area. This inconsistency is attributed to the lag time between climate change and basin response, and to subtle variations in basin characteristics such as slope, aspect, and vegetation that would affect surficial processes. This study reinforces previous studies (Bull, 1991; McFadden and McAuliffe, 1997) recognizing lithology as a key factor in dictating rates and processes of hillslope sediment production and sediment deposition. In this case, the weakly cemented sandstones of the Blue Gap field area are likely more sensitive to minor climatic changes of the Holocene than are more resistant lithologies.

INTRODUCTION

Researchers including Hack (1949), Karlstrom and Karlstrom (1986), Wells et al. (1987), Bull (1991), and Reneau et al. (2000) have documented the presence of latest Pleistocene to early Holocene terrace and piedmont deposits throughout much of the American southwest. The alluviation is often hypothesized to be a response to the Pleistocene-Holocene climate change, when the degradation in hillslope plant canopy composition and cover lead to an increase in sediment supply (Bull, 1991). In more recent studies, some researchers have proposed that aggradational events during the Holocene in arid and semiarid regions of the United States may have also been triggered by climate changes (Kochel, et al., 1997; Eppes, 2002). For example, McFadden and McAuliffe (1997) attributed middle and post-middle Holocene alluvial fill deposits, developed in landscapes associated with the Bidahochi formation of northern Arizona, to such changes. They noted, however, that the alluviation was not likely due to hillslope vegetation changes. They cite numerous studies, based on available paleobotanical proxy records, that demonstrate little post-early Holocene plant community changes in these areas. They proposed an alternative hypothesis, suggesting that the magnitude of the aggradation was a consequence both of increases in precipitation amounts or annual patterns of precipitation, and of the high erodability of the Bidahochi formation that forms the basins in their study area. Eppes (2002) draws similar conclusions for the easily eroded granites that crop out in the San Bernardino Mountains of Southern California. The McFadden and McAuliffe study, as well as many other studies in this region (e.g., Waters and Haynes, 2001) indicate that channel cut-and-fill cycles occur on millennial to centennial time scales. These and other researchers have

increasingly focused on the question of how and why basins in these dryland areas respond to climate change at various scales as a function of lithology, basin area, and other geomorphic variables (Hereford, 2002; Reneau, 2000; Patton and Schumm, 1980).

Research on sediment production on hillslopes (particularly in granite bedrock: Pavich, 1986; Nesbitt and Markovics, 1997), and on slope erosion and sediment yield (Langbein and Schumm, 1958; Yair et al., 1980) usually focuses on attempts to derive rates of sediment production from measurements of sediment yield (see review in Clapp et al., 2000). Such studies often assume a steady state between sediment yield and sediment production with no change in the volume of sediment stored within a basin, which in some cases may be a questionable assumption (Clapp et al., 2000).

Recently, some researchers (e.g., Clapp et al., 2000; Pederson, 2000) have more carefully investigated the link between hillslope processes and valley floor behavior. An improved understanding of this link would enable an understanding of the relative influences of climate, aspect and lithology on hillslope and valley floor processes. The ideal landscape that would enable such a study would be characterized by datable valley floor deposits and easily erodible slope materials.

We have located such a study area within the “Blue Gap” area of northeastern Arizona. This area is characterized by small basins whose valley floors contain from one to five meters or more of alluvium. The relief, rock types, general plant communities, and climate of basins in the field area are similar. Trees that now or in the past have colonized the valley floors or channels have been buried by different fill events, so that valley floor alluvium is easily datable by tree ring analysis or radiocarbon dating. Also, the bedrock materials throughout the Blue Gap field area are highly friable rock types that may be especially sensitive to Holocene

climate changes (McFadden and McAuliffe, 1997). The purpose of this project was to study the late Holocene alluvial valley floor deposits and soils in the study area in the attempt to understand the nature and timing of sediment deposition in these small basins.

Blue Gap Study Area

The Blue Gap field area (named for its proximity to the Blue Gap trading post) is located on the Colorado Plateau, 10 miles west of Chinle, Arizona (Fig. 1). Blue Gap is located in the central part of the Navajo Reservation and is characterized by a semiarid climate with 22 cm average annual precipitation and seasonably warm (19.9°C) average annual maximum temperature. On the average, 52% of the total rainfall occurs during July, August, September, and October. Average annual snowfall is 29.7 cm, 75% of which falls during December, January, and February (climate data from NOAA). Elevation in the study area ranges from 1910 m (6260 ft) in the lowest areas of the Blue Gap wash to 2050 m (6700 ft) at the highest elevation.

The Blue Gap field area covers approximately ten square kilometers of highly dissected piñon/juniper woodlands along the Black Mesa upwarp on the Colorado Plateau. The field area is characterized by a 150 m high northeast-southwest trend-

ing escarpment facing to the southeast and cut into the easily erodible, clay-cemented Jurassic sandstones and mudrocks of the Bluff Sandstone of the San Rafael group and the Salt Wash Member of the Morrison Formation. Several ca. 1 km-wide basins drain off a segment of the escarpment that is less than 3 km long. These basins are designated zero, 1, 2, and 3, from north to south. These basins are further subdivided into first and second-order sub-basins that are designated with letters from north to south within each larger basin (i.e., basin 1B).

METHODS

Field Analysis

Several arroyos, some over 4 m deep, provide excellent exposures of the stratigraphy of valley fill in the Blue Gap Field area. For this study, eighteen high-resolution stratigraphic sections of valley fill sediments and intercalated soils were measured and recorded as exposed in the walls of four arroyos (Fig. 2). Data was combined with ^{14}C dates and dendrochronologic dates, where available, to

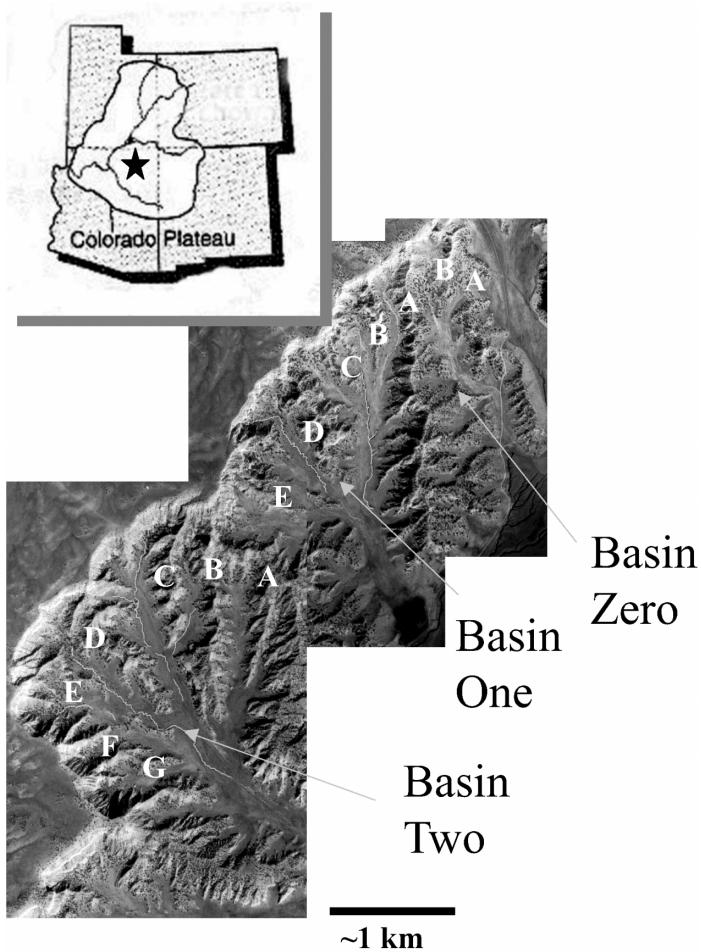


FIGURE 1. Location of Blue Gap Field area and designation of basins.



FIGURE 2. Example of stratigraphy exposed in arroyo walls in basin 2E.

constrain the ages of the various surfaces identified in measured sections. (For detailed information on application of dating methods see Tillery, M.S. thesis, unpubl.). In addition to the arroyo stratigraphic information, detailed field observations were also made in each of the sub-basins on the vegetation composition, age of the valley floor alluvial surface, and arroyo geometry (if present).

Map Analysis

Portions of the bedrock escarpment and pediments in the field area are covered by a mantle of weathered regolith ranging in thickness from 5 to 30 cm. Slope surfaces were mapped into two units: regolith-covered or bare bedrock. This mapping was done in the field on black and white aerial photos. The areas of bedrock and regolith were then calculated using a digital planimeter and totaled for percent bedrock versus regolith for each basin. These data were analyzed for incised basins, aggrading basins, and basins that are currently exhibiting both responses.

A number of studies show that sediment yield is related to drainage basin morphology including basin area and basin relief (Schumm, 1963; Milliman and Meade, 1983). Drainage basin area was measured using a planimeter. This information was combined with the bedrock/regolith slope analysis to establish a ratio of basin slope area to total basin areas for incising, aggrading, and combination basins.

RESULTS

Field Observations

The vertical aerial photo (Fig. 1) shows the boundaries of key basins and sub-basins of the study area. Detailed mapping and other field studies of these basins (Tillery, unpubl. M.S. thesis) indicate that the ridges that serve as basin and sub-basin divides likely represent the remnants of a spatially extensive bedrock pediment after the definition of Ritter et al. (1995). If the basin divides at Blue Gap are pediment remnants, then the present basins in the study area formed following vertical incision by tributaries after abandonment of the pediment. Thus, many of the slopes of the lower part of the escarpment and those along the valley floor have formed following pediment abandonment.

There is a remarkable dichotomy of geomorphic processes acting on the most proximal parts of the small sub-basins in the field area. Among 25 sub-basins analyzed, ten are presently aggrading and nine are incising. The aggradation in some of the basins is occurring so quickly that living trees are buried meters deep in alluvium (Fig. 3). In none of the incised basins do the incised sections extend as far as the main channel (Fig. 4).

Occasionally incision and aggradation occur simultaneously in the same small basin. For example, much of the floor of Basin 1D is cut by a long arroyo, but in the lower parts of the basin floor the arroyo is beginning to aggrade. Finally, some basins seem to be in a state of quasi-equilibrium, showing no recent aggradation or incision (i.e. Basin 2C). This highly variable behavior is unexpected, given that all of the sub-basins are cut into essentially the same formations, occur at the same elevation, have generally



FIGURE 3. View of partially buried Juniper trees and very recent aggradation in basin 1C.

small areas (less than one square kilometer), the same climate, and generally similar vegetation.

Although in Blue Gap there is no evidence of paleochannels of the same magnitude as the present incised arroyos, one shallow paleochannel was observed in Basin 1B, approximately 1 km southwest of the main escarpment. The shallow depth of this paleochannel (1.5 m below present surface and ca. 1m thick) shows that it did not incise nearly as deeply as modern arroyos (typically 2-4 m deep). If the modern channel is reoccupying the same path as older arroyos, then recently undercut mature (300 yr old) trees and carcasses of long-lived trees also give evidence that the older channels did not reach the magnitude of the modern arroyos. In the uppermost parts of a few arroyos, the presence of large headcuts (2 to 3 m high) and recent bank collapses suggest continued headcutting and arroyo extension. Comparison of the present locations of these active headcuts with their locations ten years ago on the vertical area photos, however, indicates that the headcuts are progressing quite slowly. Additionally, the presence of small inset terraces and channel berm sediment in most reaches of the arroyos at Blue Gap suggests that many of the arroyos have also passed the stage of rapid vertical incision.

Initial observations in the Blue Gap Field Area show that the weathering of sandstone and mudstone bedrock exposed along



FIGURE 4. View of recent incision in Basin valley floors, from basin 1D.

the escarpment varies subtly both vertically and laterally between basins. The same weathering characteristics are observed on outcrops of the Salt Wash and the Bluff, indicating that the two different units are essentially weathering in the same manner. In many places on the escarpment slopes the bedrock is covered with a mantle of weathered bedrock that is up to 30 cm thick, while in other places the bedrock lacks this mantle and is completely exposed. Presumably, this weathered mantle represents a key source of sediment supplied to the basin valley floors. When bare bedrock is exposed, there is a thin resistant crust with weakly-cemented bedrock beneath. Currently, in these places where hillslopes are weathering limited, hillslope sediment production is outstripped by sediment transport off the slopes. In other places, where the mantle is currently present, the hillslopes are transport limited. In many places, the weathering-limited and transport-limited sections along the cliff are exactly juxtaposed. These spatially abrupt changes in sediment storage on the slopes often are observed where there is no other obvious change in the character of the bedrock or in some cases in the slope morphology (Fig. 5).

As the red mudstone units in the Salt Wash Member of the Morrison Formation and the Bluff Sandstone erode, they yield red, clay-rich sediment. On sandstone bedrock immediately below such units, a fine-grained red coating, or crust, is produced that tends to armor the surface of the otherwise relatively friable sandstones. Removal

of this protective crust presumably increases the ease of erodibility of the newly exposed sandstone bedrock by diffuse, overland flow.

Deposits of red clay crusts are also observed on the surfaces of recent alluvial units on the valley floor, producing a similar armoring effect. Such reddish clay-rich layers (0.2 cm thick) are also visible in the stratigraphy of older valley floor deposits exposed in the arroyo walls. In some respects these layers resemble pedogenic B horizons. However, although the reddish material may be redistributed vertically by pedogenic processes, these layers clearly represent deposition of fine-grained sediment derived from red mudrock units exposed on the adjacent hill-slopes during the low-energy stage of channel flow events.

Active, shallow (less than 1/2 m deep) channels with sloping sides occur in the uppermost reaches of some of the sub-basins. These younger channels are sometimes truncated after short distances (i.e., 0.25 km) by very recent channel fan deposits. In most cases channel fan deposits are topographically positive features, within which the vegetation, though slightly buried, appears to be considerably more green and healthy than the surrounding vegetation. Often a channel will change from incision to aggradation several times as it progresses downstream. This results in incised channel sections punctuated by channel fans. The behavior of these discontinuous channels is the same as those described by Bull (1996). The bright green color of the vegetation growing on the channel fans provides evidence that moisture, occasionally accompanied by very young sediment from the channelized flow upstream, continues to be concentrated in these areas.

Morphometric Analysis of Subbasins

Despite the presumably differing effects of rainfall on regolith versus that of rainfall on exposed bedrock, the ratio measurements of exposed bedrock areas versus regolith-covered bedrock areas on the slopes of each basin (Fig. 6) did not indicate a correlation between basin slope morphology and basin floor behavior (i.e., incision or aggradation). The average ratio of weathered regolith to bedrock was 5.56 in aggrading basins, 5.33 in incising basins, and 3.24 in basins exhibiting both behaviors. There is also no obvious relationship between basin size and geomorphic response. Aggrading basins have an average basin area of 0.17 km², incising basins average 0.147 km², and basins exhibiting both behaviors have an average area of 0.172 km². The correlation between geomorphic processes and the ratio of basin slope area to total basin area was also ambiguous. In the study area, an average ratio of 0.54 km² was calculated for basins characterized by active aggradation in their most proximal area, 0.62 km² for basins characterized by incision, and 0.53 km² for basins exhibiting both behaviors.

Alluvial Stratigraphy

Basin-floor alluvium consists mainly of fine sands with silt and clay-sized particles, derived from the clay-cemented sandstone bedrock in the area. The percentage of fine particles versus sand-sized particles varies with different units within the fill. In the sedimentary basin fill, five dominant facies can be defined: 1) massive, sand-dominated (with or without clasts); 2) laminated,

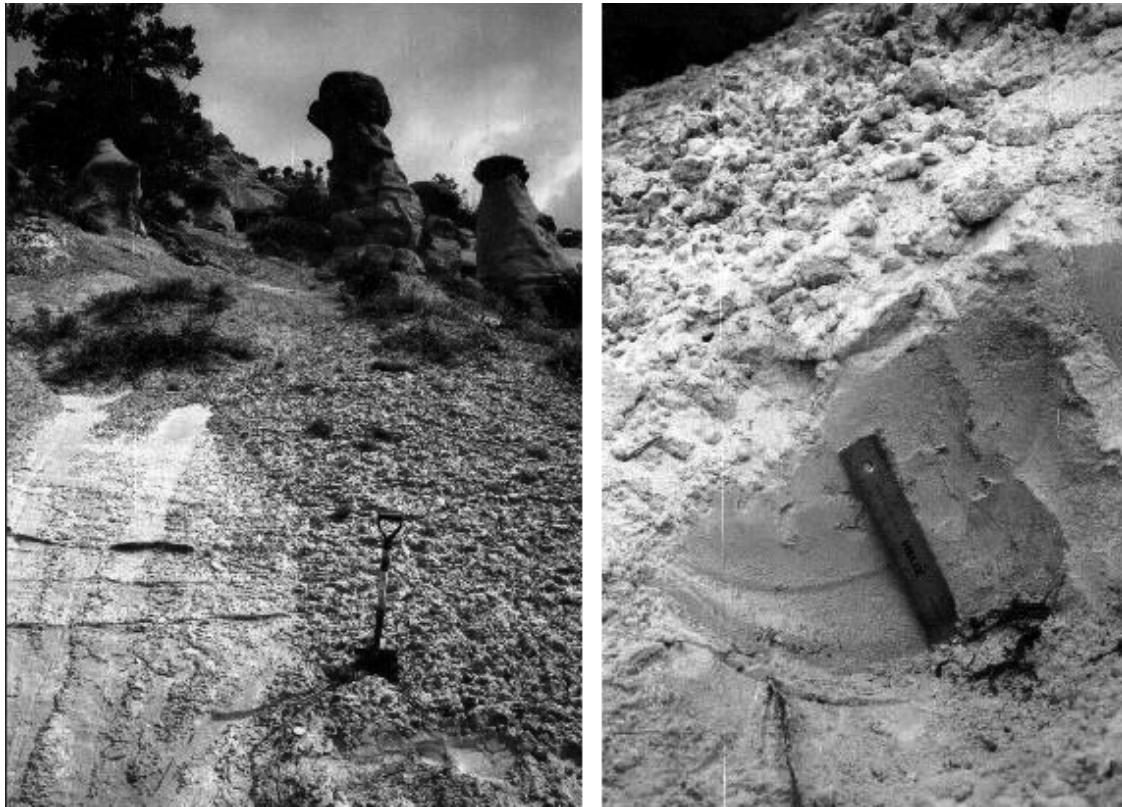


FIGURE 5. View of insitu regolith on slopes of basin 2 C, ruler on right is 20 cm.

sand-dominated; 3) massive, clay-rich; 4) laminated, clay-rich, and 5) gravel lenses. Weak soils are also identified throughout the valley floor alluvium.

Sand-dominated units generally have color values in the 10 YR range (Munsell Soil Color Chart). Sand-dominated units can be up to 1 m thick and usually tend to be thicker than the clay-rich units. Where present, laminations range from being only faintly visible to being very clear with frequent fining-upwards sequences in the sand-dominated units. Fining-upward sequences are usually capped by thin (<1 cm) red clay lenses.

The clay-rich units generally are characterized by hues of 7.5 YR due to the redder colors of the clay portions of the sediment. As discussed above, the source of the red clay can be easily traced to red shale layers in the Salt Wash member of the Morrison Formation. Some thicker, reddened bands within the strata exhibit weak soil development including loss of sedimentary structure, krotovina, mottling, vesicles, carbonate stringers on clasts, or

weak ped structure.

Shallow, gravelly, channel-fill deposits with clasts up to 4 cm or rare sand and clay matrix-supported deposits with clasts up to 40 cm are observed less frequently. The rare gravel lenses exposed in the arroyo walls usually exhibit some imbrication indicating down-valley channelized flow.

Characteristics of Individual Basins

The three basins that were used for the stratigraphic section descriptions were chosen because of the stratigraphy exposed in arroyo walls. The headcut morphology varied in each of these incised channels. However, in each case, the incised channels become increasingly shallow at the downstream end until they are completely buried in a series of channel fans. Table 1 describes some of the characteristics of the arroyos used in this study.

TABLE 1. Characteristics of arroyos studied and number of stratigraphic sections.

Arroyo	Beginning Elevation (m)	Ending Elevation (m)	Length (km)	Total Relief (m)	Slope (m/km)	Number of stratigraphic sections described
1B	1955	1932	1.37	23	16.8	6
1D	1973	1930	1.92	43	22.4	6
2D	1958	1921	2	47	17.9	5

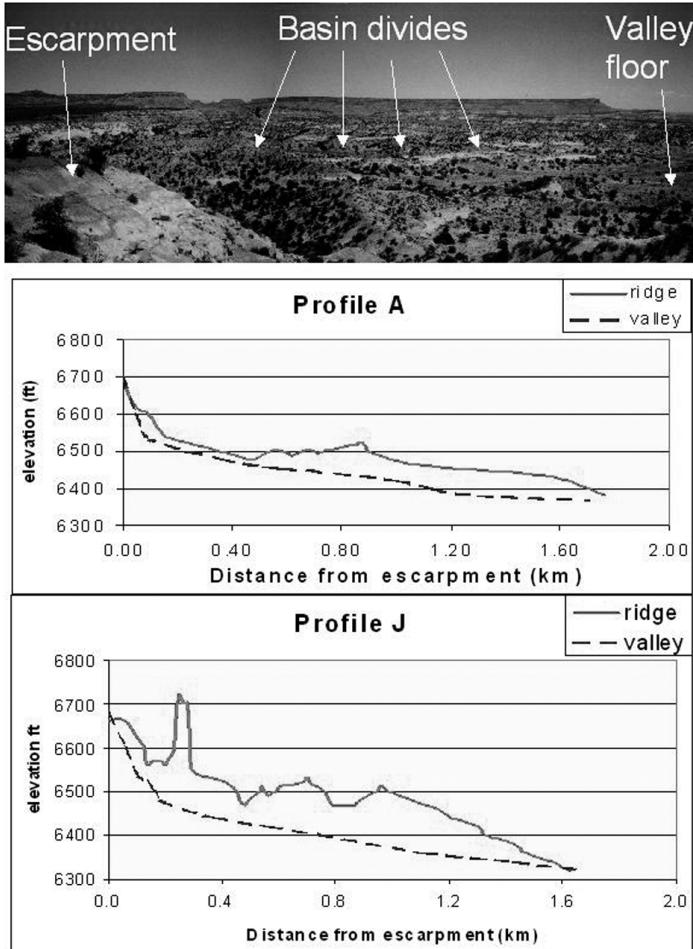


FIGURE 6. Basin 1D mapping of regolith cover, exposed bedrock and recent alluvial aggradation including channel fans.

Basin 1B

Recent periods of aggradation are evident in the lower stretches of basin 1B. In many places, living trees have been stressed or killed as a result of burial by as much as 2 m of sediment, and much younger trees (less than half a meter tall) have germinated on this new surface. Channel fans within 0.1 kilometer of the head of the arroyo are expressed as topographically positive slugs of sediment deposited where a channel has died out. These features are subtle, usually less than 1 meter in total relief, and likely contribute to the variability in the valley floor stratigraphy downvalley. The upper reaches of this valley show very little recent aggradation. Here, the valley floor has only minor accumulations of fill and the pediment remnants dominate the landscape. The depth of alluvium in the lower reaches of the basin combined with the lack of valley fill in the upper reaches of the basins support a diachronous model of basin valley filling. The arroyo in basin 1B begins abruptly with a two-meter deep head cut near where the northern and southern lobes of the basin meet (Figs. 7, 8). The stratigraphic sections of basin 1B proved to be the most difficult to correlate and interpret. Age control in this basin is poorly constrained and the stratigraphy is variable. Even though five of the stratigraphic section descriptions were

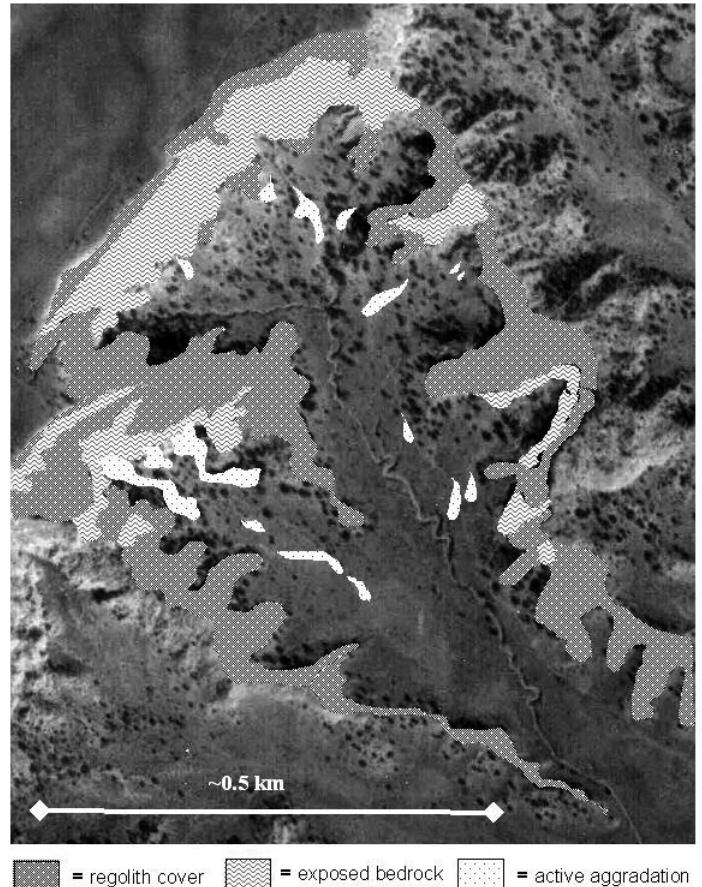


FIGURE 7. Locations of stratigraphic sections described and trees dated in basin one.

carried out within 1.3 km of each other, there was wide variability in stratigraphic units and soils, including degree of soil development, number of soils, and depth to soils. It proved impossible to trace any one individual soil down the length of the valley. This variation likely results in part from the varying effects of input from side basins and channels, along with local and subtle variations in the surface topography of the valley floor as it is observed today. For example, a topographic swell could be responsible for trapping moisture during wetter periods, or eolian deposits in drier periods. This trapping would preclude deposition further down basin. These types of processes have been documented in other studies where topographic variations on a single geomorphic surface were shown to result in great soil-stratigraphic spatial variability (Birkeland, 1999; Eppes and Harrison, 1998).

The radiocarbon date (Table 2) obtained in this basin was from a piece of charcoal found in the uppermost soil of arroyo section 1B-4 (approximately 1.5 m below the surface, sample collected by McFadden, see table 21). This sample gave a date of 509 +/- 38 radiocarbon years before present and therefore indicates at least 1.5 m of burial in ca. 500 years.

Basin 1D

Field observations for this basin indicate more recent surface antiquity than that observed in basin 1B. In the northern lobe, there



FIGURE 8. Stratigraphic sections described in basin 1B.

is some evidence of stability on the valley surface and the recent valley fill shows only moderate aggradation (less than 1 m). Trees have medium ages (50-100 years) and become younger down-valley. Aggradation also decreases downchannel. The main channel that runs the length of the valley is 3 m deep and 2-3 m across. This channel is backfilling as evidenced by inset terraces and sloping walls in some sections. There is also a large and healthy tree (V-2) growing directly in the channel near the base of the escarpment.

The southern lobe shows aggradation appearing to be sufficiently recent that no vegetation is growing on it. This lobe is not incised until it joins up with the arroyo coming out of the northern lobe. The pediment slopes are very steep and mostly free of mantle. Recent slugs of sediment have buried sagebrush and have no new vegetation growing on their surfaces. As in basin 1B, recent aggradation almost always occurs at the end of a shallow channel and is topographically raised above the surrounding terrain by up to 0.5 m. Any vegetation that is growing in the area of this young sediment is very bright green and healthy. This is in contrast to the surrounding vegetation, which is gray and dry. Again, this variability in vegetation health suggests that the processes that bring sediment to the valley floor have also recently brought water along the same path.

The arroyo in this basin begins at the base of a gully on the face of the escarpment at an elevation of 1973 m. It is therefore slightly longer than the channel in basin 1B. The stratigraphic sections described in this arroyo that show that the stratigraphy of basin 1D is distinct from that in basin 1B (Fig. 9). Basin 1D contains an incipient cambic B (weak color structure B horizon) buried soil, a relatively well-developed soil for this study area. This unit is more consistent and easily traceable up and down the valley than any of the soils in basin 1B. It is found 75 cm below the present surface near the head of the basin and steadily progresses to a depth of 110 cm in the downstream most stratigraphic section. This progressive downvalley burial, combined with geomorphic and vegetation observations made in the basin, is consistent with a diachronous model of basin valley aggradation.

In the third stratigraphic section at the major bend in the channel (Fig. 7), the roots of a large piñon tree (V-1) extend into the arroyo. From the stratigraphic position of the tree roots exposed in the arroyo, it is clear that the tree germinated on the buried surface represented by the cambic B soil mentioned above. This tree reached a large size and branched out before it was buried by over a meter of alluvium by subsequent valley aggradation events. Dendrochronology indicates that this tree is probably close to 300 years old (McAuliffe et al., unpubl., 2003). The age of the tree combined

TABLE 2. Radiocarbon dates – Blue Gap Basins 1B and 1D. (from McAuliffe et al., unpubl, 2003)

ID	Sample #	Basin	^{14}C date	Calibrated		Calibrated calendar ranges ± 2 sigma
				Intercept	± 1 sigma	
B	MB1B	1B charcoal	509 ± 38	AD 1421	AD 1406-1437	AD 1330-1343 AD 1395-1445
C	2-Oct-99-P1	1D Pinyon	650 ± 80	AD 1300	AD 1280-1400	AD 1240-1430
D	JR-Oct-99-1	1D Juniper (mid channel)	384 ± 38	AD 1479	AD 1446-1517	AD 1437-1532 AD 1597-1619 AD 1542-1636
D	J2-Oct-99-2	1D Juniper (tributary channel)	384 ± 36	AD 1518 AD 1596 AD 1621	AD 1480-1533 AD 1540-1636	AD 1449-1645
E	3-Oct-99-J1	1D Juniper (deeply buried base)	520 ± 40	AD 1420	AD 1410-1430	AD 1320-1340 AD 1390-1440

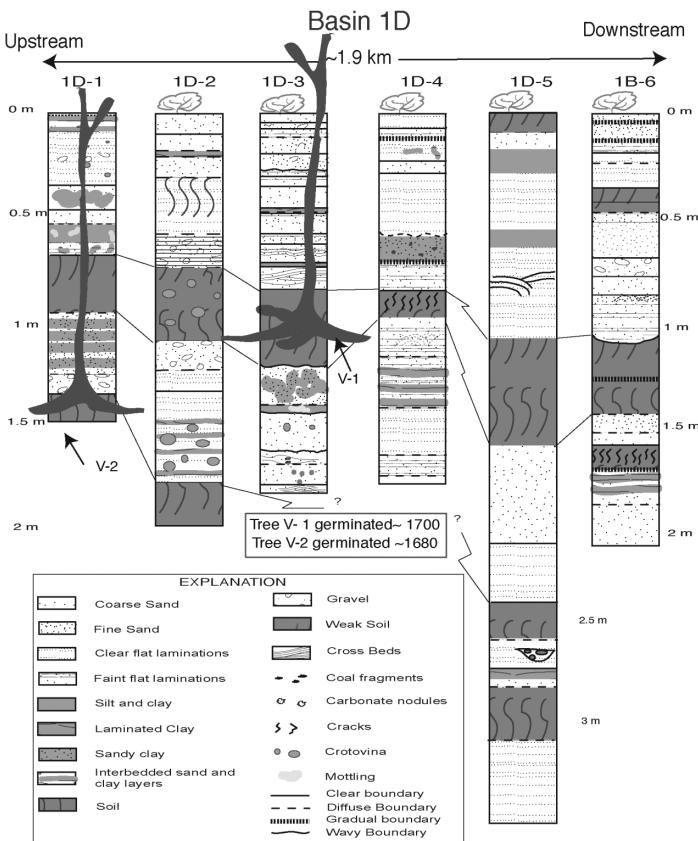


FIGURE 9. Stratigraphic sections described in basin 1D.

with the depth to the soil at this point shows slightly more than 1 m of alluvium deposited in this part of the valley in roughly 300 years. The date of arroyo incision was inferred to be the early 1930s by an abrupt decline in growth recorded in the tree rings.

Another buried surface was dated by the method described above in the uppermost reaches of the arroyo. The surface on which the mature tree (V-2) germinated (Fig. 7) was identified by the stratigraphic position of tree roots visible in the arroyo exposure. This tree, growing near the floor of the current arroyo, allowed us to date a second weakly developed buried soil, 0.7 m below the most prominent soil listed above. This tree is somewhat older than 320 years (McAuliffe et al., unpubl., 2003). This would seem to separate the two buried soil surfaces by a minimum of 20 years.

Basin 2D

The upper reaches of this basin exhibit characteristics of a fairly stable landscape. There are no indications of rapid burial of trees or recent aggradation although there is some evidence of previous back-filling of the valley bottom. Basin 2D is characterized by a ca. 2 km stretch of incised channel which begins in the uppermost areas of basin 2D and passes basins 2E, 2F and 2G before it ceases to be incised (Fig. 10). The arroyo is less than 2 m deep in the uppermost section and becomes more deeply incised downstream. Toward the head of basin 2D the arroyo is not actively incising and is in a stage of backfilling as evidenced by the wide, shallow morphology of the channel, with sloping sides. The channel is divided into multiple branches as it approaches

the escarpment. In the upper reaches of the arroyo, bedrock is sometimes visible in the floor of the arroyo.

The arroyo reaches over 4 m deep as it cuts near the pediment remnant in the lower portion of basin 2E (between sections 2E-4 and 2E-5 in Fig. 10). At this point, the arroyo is bounded on the east side by bedrock and on the west side by alluvium. Bedrock does not crop out again downstream of this section, despite the fact that, in general, the arroyo cut is much deeper downstream. Locations of the bedrock exposures within the arroyo, combined with the increasing depth of the arroyo downstream, indicate that the valley fill is shallower in upstream reaches of the valley. As with the other arroyos, the channel ends in a wide series of channel fans that occur over the last 0.5 km.

The stratigraphy in this basin was similar to that of basin 1B in that it is difficult to correlate soils down valley (Fig. 10 and 11). The most strongly developed soil in any of the basins is in the uppermost reaches of this arroyo 56 cm below the present surface. It is the only soil in the field area that exhibited carbonate nodules. This soil (soil A) can be characterized as an incipient soil with Bw/Bk horzonation. The carbonate nodules are approximately 2 mm in diameter. There are also weak pedogenic carbonate accumulations on clasts in the lower horizon. No other soil down slope exhibited a similar morphology. Dendrochronology on a tree (sample # 9-16-011) that germinated on a soil surface 0.6 m below soil A yielded a age of germination of 1000 yr BP and death at 740 yr BP. This age represents the oldest Holocene surface dated anywhere in the Blue Gap alluvium. The death date might represent the age of the aggradational event, which killed the tree and sup-

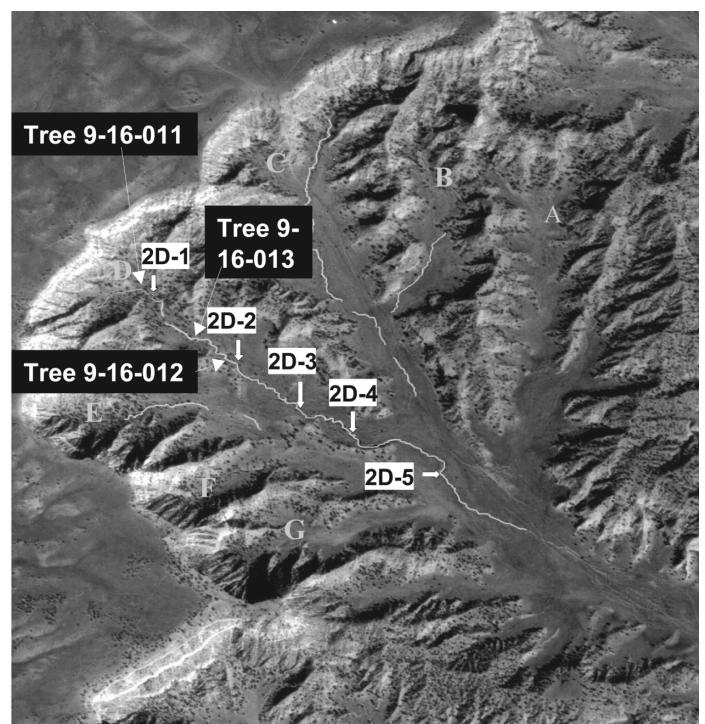


FIGURE 10. Locations of stratigraphic sections described and trees dated in basin 2E.

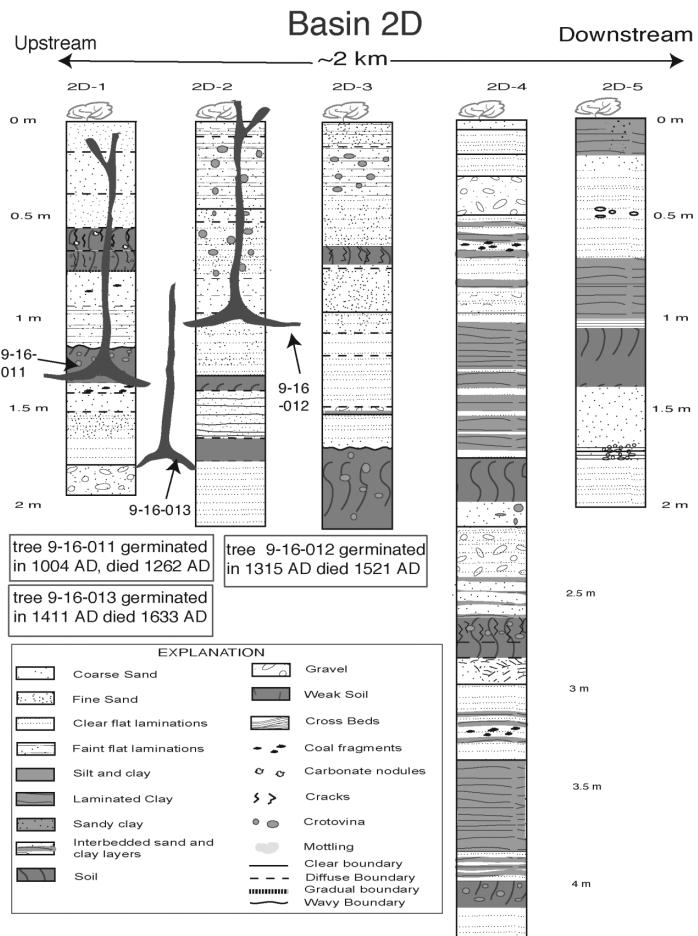


FIGURE 11. Stratigraphic sections described in basin 2E.

plied the 0.6 m of alluvium on which soil A developed. If so, that would give a maximum age of 740 yr for the soil.

Near the second stratigraphic section, a juniper tree (sample # 9-16-012) that germinated 0.95 m below the present surface yielded an age of germination of 677 yr BP and a death at 481 yr BP. Although the root position relative to the present surface is only 6 cm above the root position of 9-16-011 listed above, the actual horizon that it is rooted on is probably several horizons above that of the previous tree. This is impossible to verify because soil A was not traceable to this point and the soil development where # 9-16-012 germinated is much less apparent. However, the dates do correlate well.

The third date acquired in this basin was from a juniper located halfway between sections 1 and 2, and rooted on a surface 276 cm below the present surface (below the floor of the channel). This tree (# 9-16-013) yielded a germination date of 591 yr BP and a death at 370 yr BP.

DISCUSSION

Facies Model

Arroyo exposures of alluvium combined with observations of the processes active in the basin valley floors today allow

development of a depositional facies model for the Blue Gap Field Area. Bedrock is occasionally visible in the floors or walls of the arroyos, particularly in the tributaries or when arroyos cut close to pediment remnants. In most places, the valley fill does not extend significantly deeper than what is already exposed in the arroyos, perhaps only a meter or two. The dates acquired on buried living trees and tree carcasses show that most of the valley fill visible at present has accumulated only within the past several hundred years or a millennium at most.

Detailed stratigraphy of the valley fill exposed in the arroyo walls shows that there have been repeated pulses of rapid alluviation and net aggradation punctuated by brief periods of surface stability. The periods of aggradation are represented by the thick accumulations of buff-colored fine to medium sand that frequently contain flat laminations and fining-upwards sequences. These fining-upwards sequences are sometimes capped with clay lenses, which in some cases have been slightly flushed through the unit below giving an initial appearance of pedogenic clay accumulation. Sedimentary bedding is still evident on freshly exposed surfaces, however, and there are no other signs of pedogenic processes. Periods of stability are marked by the thicker reddened beds in the strata that exhibit weak soil development. Studies have demonstrated that at least 500-1000 yr may be required to attain stage I carbonate morphology in such parent materials (Gile and others, 1981; Machette, 1985; Birkeland, 1999). This information along with available ¹⁴C and tree ring dates require that these incipient soils had at most a few decades to a century to form.

A diachronous process of valley floor aggradation can explain the apparent discrepancy for the buried trees dated in basin 2E, with deposition beginning at the mouth of the basins and migrating up valley towards the heads of the basins. Figure 12 shows the complex relationships evident in the basin fill in Basin 2E. Tree 9-16-011 germinated first at 1000 yr BP in the upper reaches of the valley floor as the valley floor was filling in from the lower reaches. Tree 9-16-012 germinated 677 yr BP on a higher surface in lower reaches of the valley that had been affected by diachronous aggradation. Finally, tree 9-16-013 germinated 591 yr BP down valley from tree 9-16-011, but not far enough down valley to be on a surface that was affected by the subsequent valley floor fill. Therefore, it is on a surface that projects below the germination surface of tree 9-16-012.

If the 740 yr BP death date of tree 9-16-011 represents the timing of the aggradation that killed the tree, and the maximum age for soil A noted in the uppermost stratigraphic section in basin 2, it is reasonable that another tree would germinate 55 years later on that surface or on one stratigraphically close to it. The 55 yr difference could explain why the soil development described in soil A in section one is not evident 0.25 km downstream at section two. Perhaps continued downstream aggradation prevented the downstream surfaces from developing the soil characteristics noted upstream.

There is no significant record of any period of previous arroyo incision in the last 1000 years in the exposures of valley fill in the Blue Gap Field Area. In the 5 km of valley fill stratigraphy exposed, no paleochannels of significant size are visible. This leads us to believe that the present arroyos are recently formed

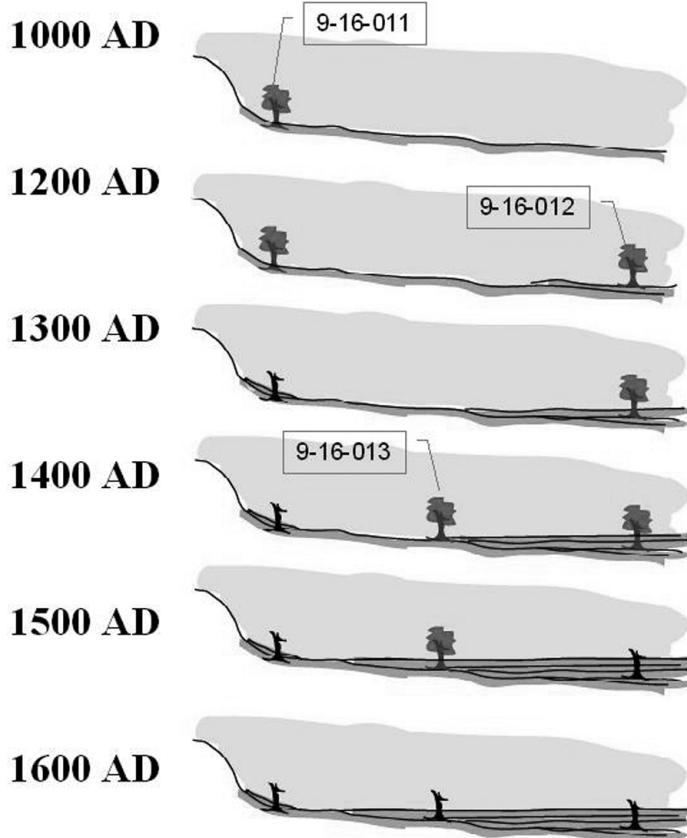


FIGURE 12. Model for diachronous filling of basin 2. See text for explanation.

features and that arroyos did not develop in this area during the 1000 yr stratigraphic record of the valley fill. Additionally none of the incised arroyos extend as far as the main channel. This is an important observation because it can eliminate base level fall associated with the Blue Gap Wash as the main contributing factor to up-stream incision.

Significance of Hillslope Regolith and Valley Floor Channel Behavior

Although the planimeter analysis conducted in this study does not indicate an immediately obvious connection between present basin valley behavior and percentage of regolith-versus-bedrock in the basin slopes, the locally variable areal extent of regolith is likely to be important as a factor affecting sediment supply and other variables that influence stream channel behavior in the study area. The extent to which the bedrock is exposed or covered with regolith affects hydrologic characteristics and consequently the sediment supply to channels in the basins. For example, precipitation falling on a thick layer of regolith is more likely to infiltrate than that which falls on exposed bedrock. Precipitation falling on bedrock will likely result in overland flow across the protective crust. Researchers have observed that weathering of bedrock results in development of hillslope colluvial mantles and transport of sediment to basins by fluvial systems, most recently

shown by the studies of Clapp et al. (2000) and Pederson (2000). Runoff flowing over bare bedrock, however, entrains little sediment and therefore carries minimal sediment to the basin floor. Presumably, the larger water discharge to sediment discharge ratios in these areas would generally favor incision, or at least limit aggradation, in a manner described by Bull (1991). In some areas, this is observed in the study area. For example, the cliffs and many of the associated slopes that lack abundant regolith, at the head of basin 1D, presumably almost entirely weathering limited, are associated with an arroyo that has deeply incised immediately up to the base of the cliffs.

The results of the regolith versus bedrock planimeter mapping were difficult to analyze for several reasons. Other studies (Burnette et al., unpubl., 2003; Tillery et al., 2001; McAuliffe et al., unpubl., 2003) document the variable thickness and changes in character of the regolith with slope position and aspect so that the initial regolith versus bedrock evaluation may be insufficient to capture the link of slope material and behavior associated with valley floor responses. Many of these basins are aggrading in one location and simultaneously incising in another location. This often occurs back and forth along the length of the basin or within distances that are too small to be captured with the scale of the aerial photos. Therefore, the categorization of the basins into the three groups of incising, aggrading, or both is based largely on generalities for the individual basins. In addition, given the rapid evolution and dynamic behavior of discontinuous ephemeral streams, it is difficult to attribute current behavior of channels to slopes that reflect evolution over millennia.

Climate connections

Many researchers have documented asynchronous drainage basin response to climate change (Graf et al., 1987; Patton and Schumm, 1980) although they disagree on why the responses are so varied. Hereford (1987) states that discontinuous streams alternate between deposition and erosion independently of external controls such as climate. This is in contrast to Bull (1991) and Waters and Haynes (2001) who assert that climate change processes affecting entire fluvial systems at the same time may have more sudden impact and greater effect than base-level falls migrating upstream from a point source.

The relatively recent arroyo incision in a few basins in the Blue Gap study area has occurred subsequent to perhaps as much as a thousand years of net aggradation throughout the study area. Given the nature of the channel slopes, observed patterns of grazing, and the timing of incision of some channels (this study; McAuliffe et al., unpubl., 2003), we do not attribute this change from aggradation to incision in a few of the basins in the last one or two centuries to grazing effects (see McFadden and McAuliffe, 1997). It seems more likely that this significant change in the behavior of some of the channels might be attributed to another cause.

The timing of the recent change from aggradation to incision in some of the basins (late 19th century) suggests the possibility that this change in channel behavior may be linked to changes in climate at the end of the Little Ice Age (LIA ca. 1200-1850 AD). Recently, Hereford (2003) has also suggested the behav-

ior of channels in other areas of the Colorado Plateau may have been strongly affected by such late Holocene climate changes. The geomorphic expressions we see across the basins may have varied, however, because of the lag time between the climate change and the basin response. They may also be inconsistent because responses are likely subject to subtle variations in basin characteristics such as aspect and vegetation.

CONCLUSION

This study reinforces other studies (McFadden and McAuliffe, 1997; Bull, 1991; Eppes, 2002) recognizing lithology as a key factor in dictating rates and processes of hillslope sediment production and sediment deposition. Ephemeral streams that are subject to episodes of back filling and entrenchment characteristically occur where hillslope erosion provides abundant sand, silt, and clay, largely because they are so easily eroded. The geology of the Jurassic sedimentary beds of the escarpment fits this model nicely.

Active burial of juniper and piñon trees in the basin valley floors at Blue Gap along with pedestalled old trees on the slopes above demonstrate recent accelerated slope erosion and associated valley floor aggradation. Valley floor aggradation has been the primary mode of operation in most of the study area for nearly all of the past millennium. Initiation of arroyo incision in Blue Gap is inferred to have been at the beginning of the 20th century, based on tree ring analysis of trees undercut by arroyo incision. The correlation between the timing of the change from aggradation to incision in some of these basins and the end of the Little Ice Age suggests a connection between these two events. The variable and somewhat complex geomorphic behavior of the sub-basins, however, indicates that the actual impact of such climate changes may be somehow modulated by the slope regolith, vegetation, aspect, and other geomorphic variables that are not yet well understood.

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Dutton's (1885, fig. 25) woodcut photograph of El Tintero.