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UNCOMMON TWENTIETH-CENTURY STREAM BEHAVIOR OF LOWER ABO ARROYO REVEALED BY FLOOD DEPOSITS AND HISTORIC PHOTOGRAPHS

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Abstract—Widely scattered coal and clinker clasts and flotsam, combined with historical photos, and modern observations in the lower Abo Arroyo indicate valley-wide flooding and significant changes in sediment transport and channel erosion during the 20th Century. Coal and clinker granules and pebbles (2- to 40-mm diameter) as well as flotsam of whole juniper trees and other wooden debris along the valley floor of Abo Arroyo show that the valley was inundated by one or more large floods. Aerial photos taken in 1935 show widespread dark deposits along the valley floor. These dark deposits are believed to be coal that came from spills along the Atchison, Topeka and Santa Fe (AT&SF) Railroad through Abo Pass to the east. The railroad was built between 1903 and 1908, when the first timetable for the route was published. Prior to 1935, the most likely period for extensive flooding was in August and September of 1929, when regional storms and flooding occurred on the Rio Puerco, Rio Grande, and other gauged tributaries. The 1935 photographs also show that the lower 10 km of Abo valley had anastomosing unincised channels, gravel bars, and slackwater yazoos along the valley margins. No continuous incised channel existed, although branching short headcuts extended from the arroyo mouth at the Rio Grande, upstream about 2 km, across the valley-mouth Holocene alluvial fan. Aerial photographs taken in 1947 show that channel incision along the valley floor farther east had increased *downstream* and that much of the coal had been remobilized, reworked, and partially buried by later flood deposits. The lowest reach of Abo Arroyo became entrenched by 1954, completing a continuous channel from Abo Canyon westward. Incision by headcutting was, at most, a minor process at the arroyo mouth. This channel behavior along lower Abo valley is unlike most other arroyos in New Mexico because: 1) Abo Arroyo was not incised continuously well into the 20th Century, 2) due to concentration and then dispersion of stream power it incised downstream rather than upstream, 3) it is a bedload stream with a gradient three to seven times steeper than adjacent streams (Rio Grande and Rio Puerco), 4) adjacent sparse vegetation has minimal effect on flows, and 5) it is not evolving (so far) through stages of arroyo development and aggradation.

INTRODUCTION

The late Dr. Stanley A. Schumm published many outstanding articles and books on the behavior of streams. Two publications pertinent to 20th century changes along Abo Arroyo are "Explanation and extrapolation in geomorphology: Seven reasons for geologic uncertainty" (Schumm, 1985) and "To Interpret the Earth; Ten ways to be wrong" (Schumm, 1991; Table 1). Abo Arroyo serves as an example of contrast in stream behavior involving most of the problems listed in Table 1 when compared to the Rio Puerco arroyo system on the opposite side of the southern Albuquerque Basin. The problems of "convergence," "multiplicity," and "systems' response" are addressed using Abo Arroyo behavior illustrated below.

A vast literature covers aspects of "the arroyo problem"—causes and processes of historic entrenchment of many ephemeral and larger streams in the southwestern United States and elsewhere (e.g., Bryan, 1925; Cooke and Reeves, 1976; Graf, 1983; Bull, 1997). Friedman et al. (2015) published a thorough and remarkable study of recent behavior of the Rio Puerco of the east, which joins the Rio Grande 18-km downstream from the mouth of Abo Arroyo. Friedman et al. (2015) summarize the difficulty in determining the dynamics of stream erosion, transport, and deposition because the processes are episodic, spatially complex, not steady state, and scale-dependent. Not only do studies require precise measurements, but spatial and

TABLE 1. Schumm's (1991) "Ten Ways to be Wrong" when interpreting features and processes on Earth.

PROBLEMS OF SCALE & PLACE
Time
Space
Location (place in time & space where observations are made)
PROBLEMS OF CAUSE & PROCESS
Convergence–similar results from different causes and processes
Divergence–dissimilar results from same causes and processes
Efficiency–work done/energy expended
Multiplicity (multiple causes & processes may lead to observed end)
PROBLEMS OF SYSTEMS' RESPONSE
Singularity–or indeterminacy--unexplained variation in a data set
Sensitivity–some systems react and respond more than others in time & space
Complexity–complex response--chain of system alterations beyond the system's ability to return to the way it was

temporal variability require observations over large distances and long times. There is a need to integrate data at points, cross-sections, reaches, and whole river scales. Friedman et al. (2015) have done that along the lower Rio Puerco. By using new quantitative techniques applied over distances of nearly 100 km, they were able to look at: 1) temporal and longitudinal shifts from erosion to deposition, 2) possible waves or pulses of incision and deposition, and 3) cyclic processes of arroyo cuts and fills. Even though the study reach was 87.5 km long, it was not large enough to include changes in upstream factors like exposed bedrock, contributions by large tributaries, valley-margin slopes, land use/land cover (other than riparian vegetation versus vegetation and grazing outside the riparian zone), groundwater, weather/climate, soils, and response times of water and sediment discharge at various scales.

This report concerning lower Abo Arroyo, on the other hand, is much more preliminary and observational. At this stage, we are not able to apply the new, sophisticated, and time-consuming/team efforts necessary to produce an analysis as thorough as that of Friedman et al. (2015). Yet, thanks to historic photographs and ground observations, we can point out significant differences in stream behavior between the two streams and, perhaps, many other ephemeral streams. Some of the contrasts in basic characteristics between the systems are listed in Table 2.

A basic description and map of the Abo drainage basin and its geology are presented in Love and Rinehart (this volume, Abo Arroyo drainage area minipaper; Fig. 1). Here, we look at mid-20th Century stream behavior in the lower 25 km of Abo Arroyo, downstream from the mouth of Abo Canyon. Lower Abo Arroyo does not follow conventional "notions" about arroyo development: not cut in the mid- to late-nineteenth century, not formed by head-cutting upstream from the mouth, and not (so far) passing through stages of an "arroyo cycle" of incision, widening, and then followed by aggradation of an inner floodplain and trapezoidal-wetted-perimeter channel cross section. Descriptive models of drainages that display discontinuous incised channels and "gully mouth" fans (Schumm and Hadley, 1957; Bull, 1997) are not particularly pertinent to the development of Abo Arroyo either. Cadol et al. (2011), though, describe the downstream extension of incision through Canyon de Chelly in the late 20th century, and attribute it to a combination of sediment availability (a pulse of grazing-related sediment increase and decrease downstream) and vegetation changes (the introduction of invasive woody riparian tamarisk and Russian olive).

Abo Arroyo is primarily a bedload-transport ephemeral stream with a much steeper gradient than the Rio Puerco (Table 2). The physics of bedload movement in streams was addressed by Bagnold (1977). He defined stream power as

$$\omega = \rho QS/\text{width} = \tau\bar{u} = \rho YS\bar{u}$$

where ω is total stream power (kinetic power per unit length of channel), Q is discharge, S is the gravity gradient, τ is the mean boundary shear stress, $\bar{u}$ is the mean flow velocity, Y is the flow depth, and ρ is the absolute density mass per volume (water and sediment). Bedload is limited to sliding and saltating within about 0.4 Y above the bed, and the bedload transport rate, i_b, is dependent on the ratio of water depth (Y) to bedload-grain diameter (D), or Y/D, and the power available for bedload transport is ω_b. Bagnold (1977) discussed threshold values for bedload movement, τ_0, u^*_0, ω_0, so the most consistent equation for the bedload transport rate is

$$i_b = 1.6\ (\omega - \omega_0)[(\omega - \omega_0)/\omega_0)]^{1/2} \text{ x } (\bar{Y}/D)^{-2/3}.$$

In the case of Abo Arroyo, the changing geometry of flows between broad shallow flows and concentrated flows in channels implies large downstream variations in Y/D, water losses to the streambed, bedload transport, and deposition.

The preliminary motivation for this investigation was due to ants. While mapping the Black Butte 7.5-minute quadrangle (Rinehart et al., 2014), we found that harvester ants (P*ogonomyrmex* spp.) along the Abo valley floor had gathered abundant granules of subrounded bituminous coal in their ant hills (Fig. 2). Beyond the ant hills we found larger pebbles of coal (fist-sized) and tree-sized flotsam indicating past large floods on the valley floor. This led to questions about the origin of the coal clasts and the geometry of the floods versus the huge size of

TABLE 2. Comparison of Characteristics of Lower Abo Arroyo to Rio Puerco

Characteristic	Abo Arroyo	Lower Rio Puerco
Drainage basin size	1,073 km^2	19,040 km^2
Elevation of headwaters	2,000-3,078 m	2,000-3,445 m
Elevations of studied reaches	1,450-1,625 m	1,440-1,536 m
Gradients of studied reaches	6-10 m/km	3-4 m/km
Water losing/gaining reach	losing	losing
Types of sediment crossed in study areas	Alluvial valley fill on top of basin fill dominated by gravelly coarse sand deposits from the ancestral Abo drainage	Alluvial valley fill on top of basin fill dominated by fine sand, silt and clay deposits from the ancestral Rio Puerco
Length of gage record	1997-2001	Rio Puerco at Bernardo 1947-present; earlier gages
Maximum discharge	227 m^3/sec (1997)	1070 m^3/sec (1929)
Dominant sediment load type	Coarse gravel bedload (silty-clay to boulders)	Suspended fine sand-clay
Vegetation adjacent to channel	Sparse grasses, four-winged salt bush, salt cedar rare except near mouth	Salt cedar forests and sand bar willows
Sinuosity	Low, rare meanders	Moderate with tortured loops
Couplets of tight meanders between straighter reaches	Common	Common
Channel shapes	Very broad with gravel bars, in part anastomosing	Aggrading narrow meandering trapezoidal channel
Floodplain development	Low, sand-covered point bars and gravel bars	Extensive aggrading inner floodplain of fine sand, silt and clay

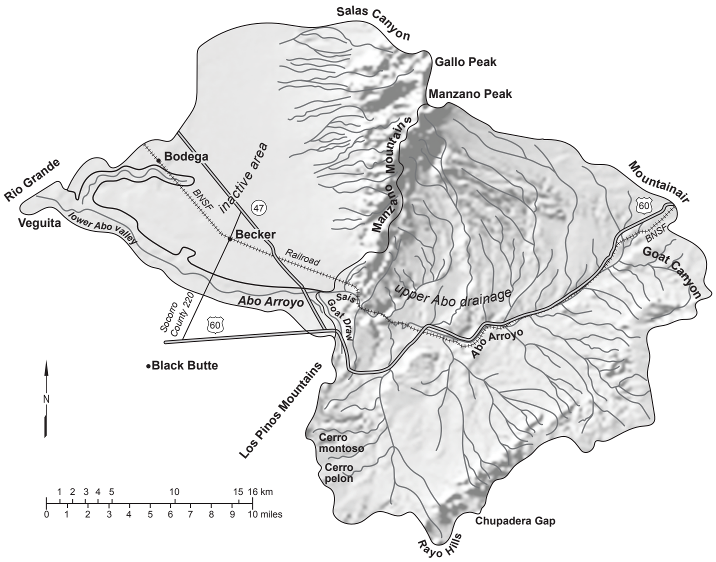


FIGURE 1. Abo Arroyo drainage basin. The boundary between the upper, contributary part of the drainage basin and the lower, transport and distributary section is between NM Highway 47 and Sais, at the mouth of Abo Canyon.

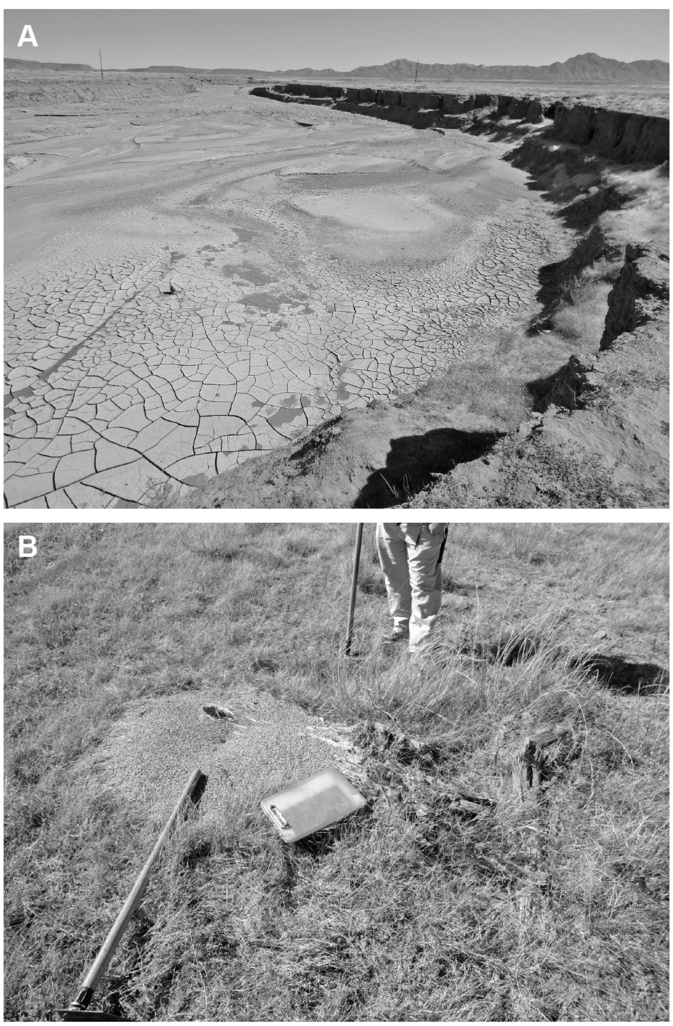


FIGURE 2. Abo Arroyo and valley floor. **A**) Entrenched Abo Arroyo viewed upstream toward Abo Pass. **B**) Ant hill with coal granules built on juniper-tree flotsam on valley floor of Abo Arroyo, west of Socorro County Road 220.

the modern arroyo and the timing of the floods. This in turn led to examination of multiple generations of historic aerial photographs that told an uncommon story about the development of Abo Arroyo and the valley floor.

As indicated by Love and Rinehart (this volume, Abo Arroyo drainage area minipaper), no coal seams crop out in the upper, bedrock drainage basin of Abo Arroyo. The coal must have come from the AT&SF (now the Burlington Northern and Santa Fe [BNSF]) railroad line constructed through Abo Pass between 1903 and 1907 and in continuous use from 1908 to the present (Myrick, 1990; Hall et al., 2009). Although diesel engines replaced coal-burning engines from the 1930s to the 1950s, coal from western New Mexico continued to be hauled through Abo Pass along the main line. Based on the amount of coal found downstream, car-loads of coal must have been lost to Abo Arroyo prior to 1935.

Previous publications found pertinent to the hydrology and development of lower Abo Arroyo are by Stewart-Deaker et al. (2007) and Hall et al. (2009). Their observations are incorporated below. Love and Rinehart (this volume, minipaper) present basic information about the hydrology and geology of the Abo Arroyo drainage basin that is not repeated here.

METHODS

The evidence we present is primarily observational—on the ground and from aerial photographs. After the initial discovery of coal clasts and juniper-tree flotsam, similar evidence was found along the Abo Arroyo valley bottom from 6 km east to at least 20 km east of Veguita. The size and shape of the currently impressive Abo Arroyo was also noted. Locations given below are coordinates based on NAD 83 UTM easting and northing. Along Abo Arroyo channel, some locations are given by easting alone (e.g., 350121 E).

Digitally scanned aerial photographs taken in 1935 and 1947 were obtained from the Earth Data Analysis Center. The 1954 aerial photographs are from Bureau of Geology files. The 1935 aerial photographs were taken on a number of days. The 1947 aerial photographs (approximate scale 1:35,400) were taken on 1/20/1947, and the 1954 aerial photographs (approximate scale 1:54,000) were taken on 1/31/1954. In the following illustrations, parts of the 1935 aerial photographs have east-west and/or north-south lines with minor discontinuities. These are the result of the four-lens camera employed. The 1947 aerial photographs were scanned from 9- x 9-inch prints with circular coverage, so corner edges are dark.

RESULTS

Ground-based Observations

Hall et al. (2009) published photographs from the Kansas Historical Society taken in the early 1900s of Abo Arroyo during construction of the AT&SF trestle at the mouth of Abo Canyon (UTM 361877 E, 3813855 N). The arroyo channel was narrower, with a broad, coarse, well-developed gravelly point bar downstream from the trestle suggesting that incision was extant for perhaps decades. The height of arroyo banks to the valley floor at the trestle appears to be about the same 100 years later—4-5 m. The channel in 2016 is considerably wider (50-60 m) than it was in 1903.

1935 Aerial Photographs

The eastern reach (Fig. 3) downstream of the AT&SF railroad trestle showed that Abo Arroyo was incised and that tributaries had begun to incise. The channel increased its width in multiple low-amplitude meanders downstream to the NM Highway 47 bridge crossing (UTM 357671 E, 3814148 N) and slightly beyond. Low attached bars and braid-bars are developed within the channel. The former valley floor north and south of the incised Abo Arroyo exhibited multiple low-sinuosity shallow channels that were incised at their downstream ends where they joined Abo Arroyo. Many of these channels had dark reaches or patches that could have been either vegetation or coal-bearing flotsam. The valley floor on the south side of Abo Arroyo near the upstream end also had some light-hued deposits, which may indicate some flood deposition after the dark patches formed.

Downstream from the NM Highway 47 bridge, the 1935 incised channel became much narrower, slightly more sinuous, with meander amplitudes slightly larger (Fig. 4; UTM 356430 E, 3814194). A couple of km farther west (UTM 354554 E, 3814212 N), the incised channel appears to have been much shallower, and floods appear to have taken multiple slightly sinuous channels across the valley floor recently (before 1935). Low braid-bars appear to dominate the valley floor. The recent main channel and elevated valley-floor channels continued west of the Socorro County Road 220 crossing (UTM 350121 E, 3815084 N).

West of the Socorro County Road 220 crossing of Abo Arroyo south of Becker, NM, (Fig. 5), the recently incised Abo

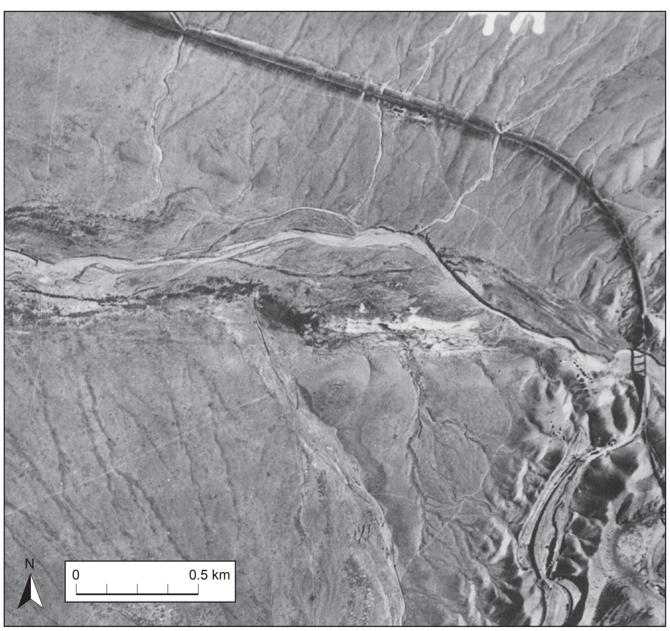


FIGURE 3. 1935 aerial photograph of AT&SF railroad trestle at mouth of Abo Canyon and Sais siding. Note that most tributaries are unincised adjacent to Abo Arroyo and that there are recent anastomosing channels on the valley floor above the arroyo. An example of an attached bar as a point bar is in the shadow of the trestle. Examples of recent diamond-shaped braid bars are seen on the left side of the photo along the channel. Scale is approximate because photograph is distorted, not rectified.

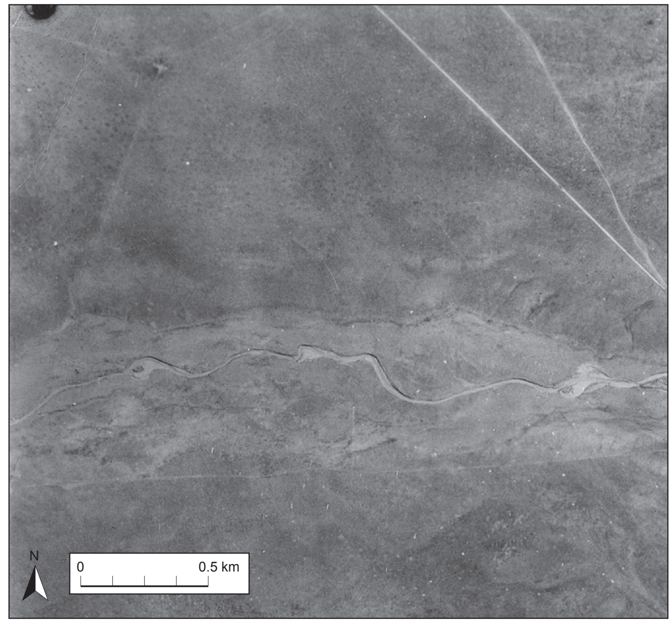


FIGURE 4. 1935 aerial photograph of Abo Arroyo and Abo valley floor downstream from NM 47 bridge. Note narrow meandering channel and evidence of yazoo channels on the valley floor. Scale is approximate because photograph is distorted, not rectified.

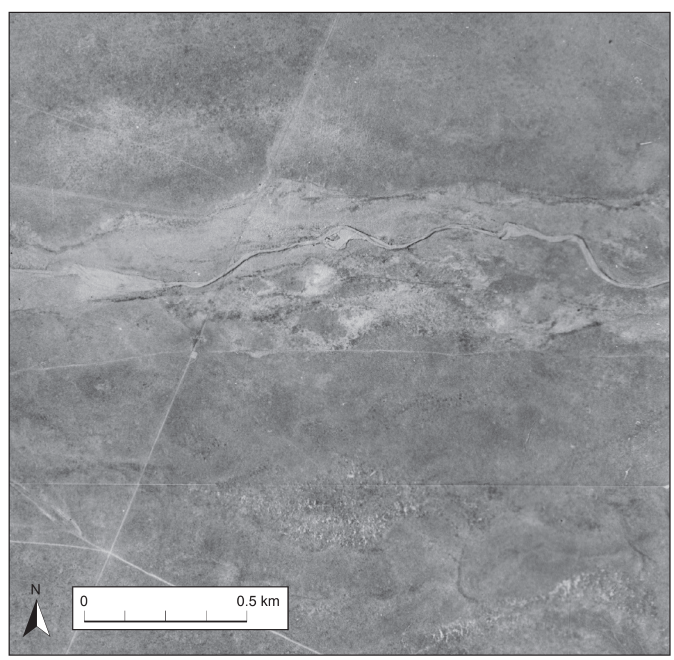


FIGURE 5. 1935 aerial photograph of Abo Arroyo and Socorro County Road 220 crossing. Note narrow incised channel and expanding meander loops. Note fan-like deposit west of road. Scale is approximate because photograph is distorted, not rectified.

channel was very narrow, with very low-sinuosity reaches alternating with arcuate meanders across the valley. Attached bars within the narrow channel were dark, indicating concentrations of coal. Yazoo channels paralleled the main channel and also made arcuate meanders on the valley floor and were incised discontinuously downstream. Between the narrow incised main channel and the yazoos were apparent crevasse splays forming lozenge-shaped bars that spread out on the valley floor (Fig. 6). Dark patches within the yazoos and along the valley margins were coal-bearing in 2012.

Approximately 2.5-km downstream from Socorro County Road 220, the pattern on the valley floor (Fig. 7) showed that the main, presently-incised and narrow, channel had spread out in a broad low fan with anastomosing, unincised channels before 1935 and had spread coal across the valley. The yazoo channel on the north side of the valley floor built broad braidbars before rejoining the main drainage west of a north-south fence. In 1935, the main incised channel continued in a narrow, barely sinuous channel for nearly 400 m, at which point (Fig. 7, valley west of center of photo; UTM 346029 E, 3817057 on Google Earth) the whole drainage spread out in a braided system across the entire valley floor. The drainage gathered again into slightly incised channels (Figs. 8-9). Dark sediment deposits spread out more extensively downstream.

The broad valley floor at the lower end of Abo Arroyo in 1935 (Fig. 10) was covered with dark sediment and an unnamed tributary valley to the north from the vicinity of Bodega siding was flooded with dark sediment. The dark sediment was cut by a human-built levee and by dendritic incised headwalls extending eastward from the Rio Grande floodplain. The dark sediment was reworked into the incised channels at the mouth

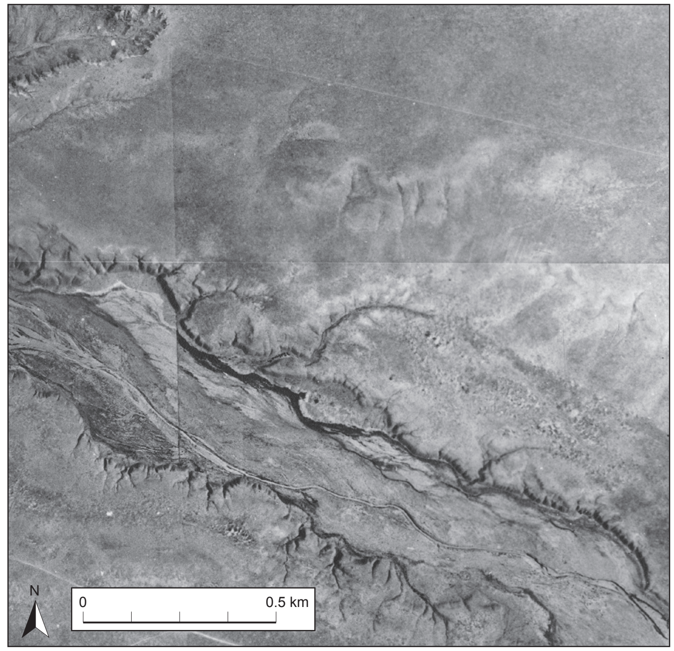


FIGURE 7. 1935 aerial photograph of Abo Valley approximately 9 km east of Veguita, NM. Note multiple channels with fan- or bar-like avulsions spread out on the valley floor. Although the main channel appears to be incised in the eastern part of the photo, it is still shallow and spreading in the western part. Note the dark color in many of the channels. Scale is approximate because photograph is distorted, not rectified.

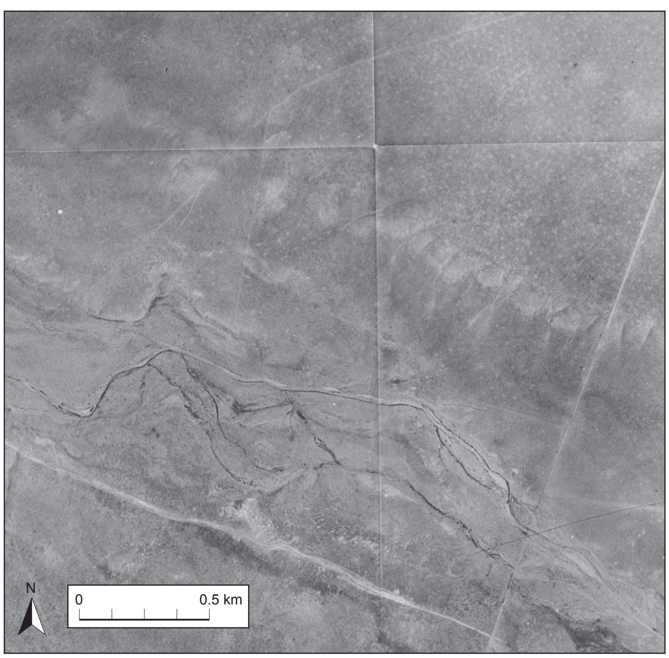


FIGURE 6. 1935 aerial photograph of Abo Valley downstream from Socorro County Road 220. Note several formerly anastomosing channels with dark reaches. These had coal clasts in them in 2012. Scale is approximate because photograph is distorted, not rectified.

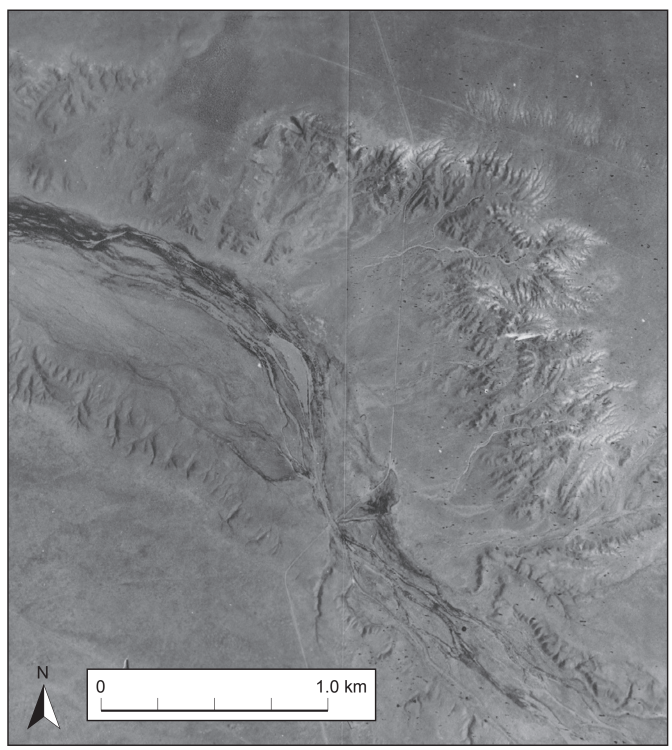


FIGURE 8. 1935 aerial photo showing anastomosing and slightly incised channels with lots of dark clasts along the lower Abo Valley, 6-8 km east of Veguita. Scale is approximate because photograph is distorted, not rectified.

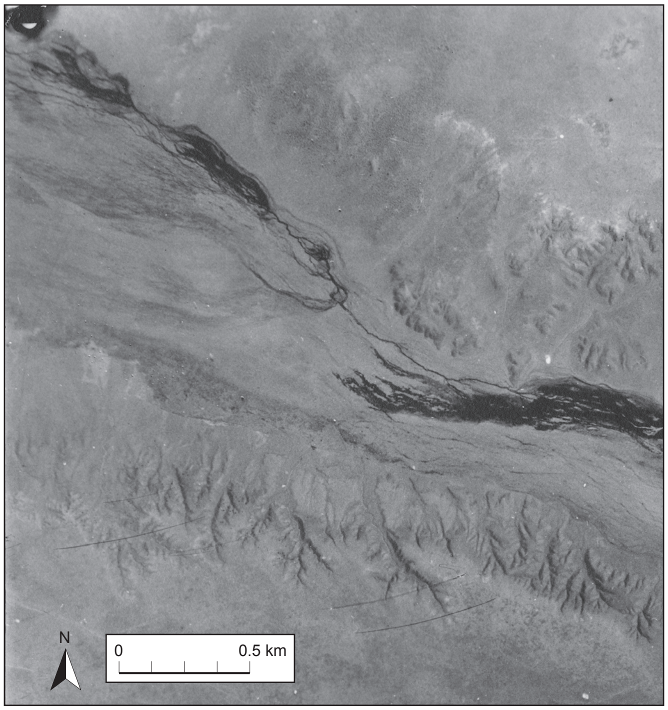


FIGURE 9. 1935 aerial photograph of lower Abo Valley 4-6 km east of Veguita showing multiple small braided channels connected by slightly sinuous reaches. Dark clasts emphasize recent valley-floor deposition. Scale is approximate because photograph is distorted, not rectified.

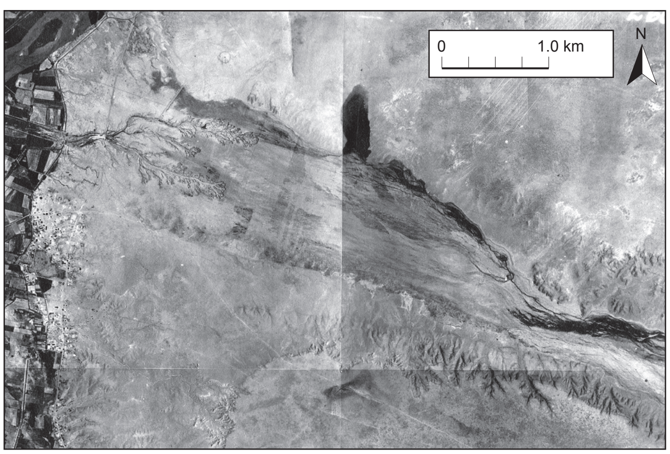


FIGURE 10. 1935 aerial photograph of lower Abo Valley and Veguita. Note fan-like channels across entire valley floor and dark sediments along channels, in back-water areas, and in a tributary valley to the north. Note also extent of head-cutting from the Rio Grande floodplain. Scale is approximate because photograph is distorted, not rectified.

of the drainage, and appeared to be buried by light-colored sediment farther east.

1947 Aerial Photographs

The reach downstream from the trestle showed little change from 1935 except for slight erosion of arroyo walls and tributaries and broadening of meanders to increase sinuosity. Downstream from Highway 47, the local rancher constructed a diversion from the channel into two stock ponds (Fig. 11). North of the stock ponds, a meander formed and was in the process of chute cutoff—a very rapid and ephemeral adjustment. The arcuate reaches between meanders remained narrow.

Farther downstream, between NM highway 47 and County Road 220, the meanders increased their amplitude and cut into the valley floor to widen the arroyo channel. Attached bars and rhomboid bars were visible in broad reaches. The dark sediment/vegetative patterns seen prominently on the valley floor on the 1935 aerial photographs were still visible, but less prominent, possibly, but not likely due to the time of year and differences in cameras. These patterns could also be due to the termination of overland flows across the valley floor following channel consolidation and incision. Some transport of coal and/or burial of coal deposits are possible as well. A short distance east of the county road crossing, differences in shadows along the channel suggest a possible headcut within the arroyo channel (Fig. 12), although the shadow instead may be due to a bank cut down for an old road crossing.

West-northwest of County Road 220, the arcuate channel reaches and broader meanders were similar to those in 1935. In 1947, the channel was much more defined between County Road 220 and the area of Figure 7 than it was in 1935 (Fig. 13); here, it extended downstream across its former fan about 2.5 km (Fig. 13, junction of two channels, left center; 344100 E, 33818875 N). Farther downstream (at 344175 E, 3819104 N), where in 1935, the arroyo had spread out onto the valley floor southwest of the present channel, a pair of tight meanders now occupied a reach that had formerly exhibited very low-sinuosity fan channels. Downstream from there, the channel occupied a former trail or road in a discontinuously incised reach to 340395 E, 3821049 N, where it then spread out as a gully-mouth fan (light sediment, left central part of Fig. 14). Many yazoo areas of dark gray coal/vegetation are still seen on the 1947 aerial photographs, although the fan at (340395 E) appears to bury the older dark gray sediments, and the ponded sediment in the tributary valley to the north appears to be covered with lighter-colored sediment on its south end.

1954 Aerial Photographs

By 1954, the dominant Abo Arroyo channel through the lowermost reach had been established (Fig. 15) and was incised to a headwall 1 km east of the highway at Veguita. Between the headwall and an incised straight reach that seems to follow an old road, the channel appears to be broad and braided with light-colored sand (Fig. 15). Other straight reaches appear to follow human-made structures.

Stream Discharge and Weather Records

As summarized by Love and Rinehart (this volume, Abo Arroyo minipaper), Abo Arroyo had a stream gauge recording discharges for water years 1997-2000, when the U.S. Geological Survey briefly monitored base flow and runoff at a gauge 2-km east of the mountain front (Stewart-Deaker et al., 2007). The highest instantaneous streamflow during their study was 227 m^3/s (7/31/97), and the highest daily mean streamflow was

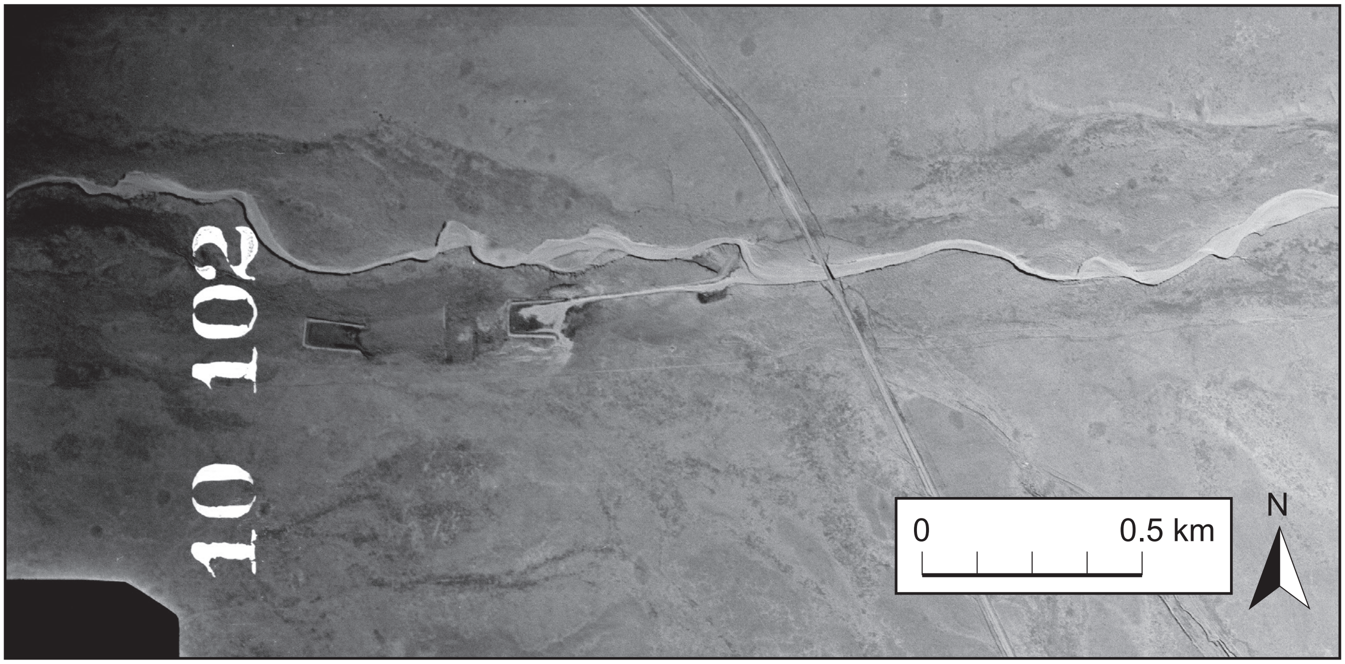


FIGURE 11. 1947 aerial photograph of Abo valley in the vicinity of Highway 47 bridge. Note that stock ponds have been constructed and take water from Abo Arroyo. Note narrow width of Abo Arroyo except in meander bends. Scale is approximate because photograph is distorted, not rectified.

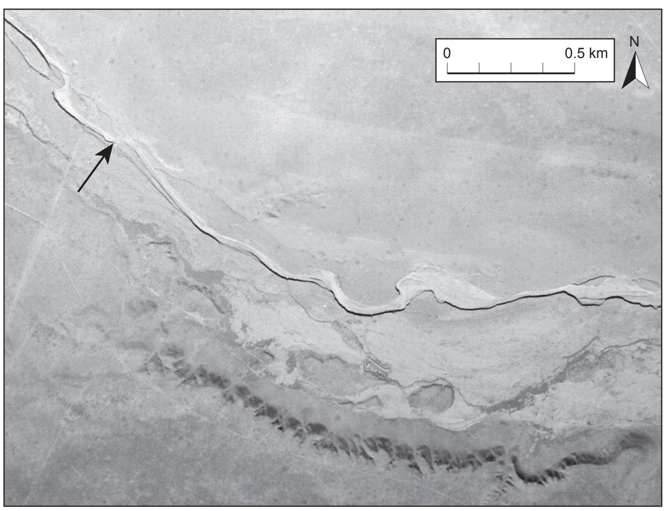


FIGURE 12. 1947 aerial photo of Abo Valley near Socorro County Road 220 crossing. Arrow points to possible headcut within Abo Arroyo. Scale is approximate because photograph is distorted, not rectified.

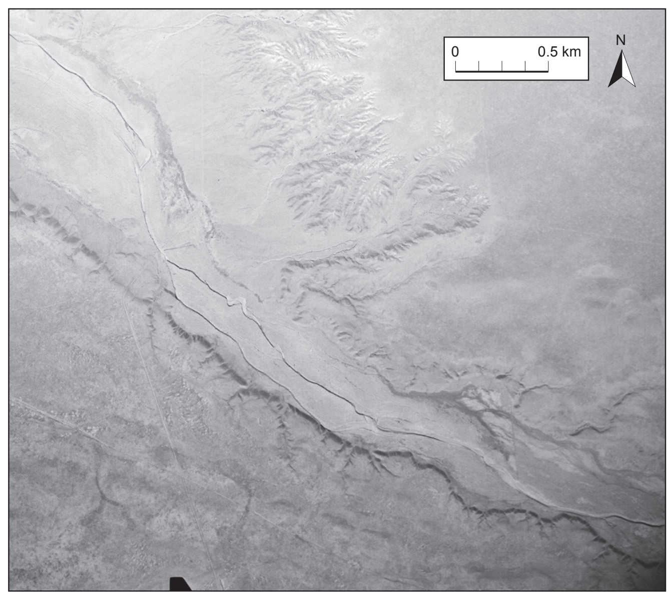


FIGURE 13. 1947 aerial photo of Abo Arroyo channels along the lower Abo Valley (6-10 km east of Veguita) compared with Figures 6 and 7. Channels appear to be deeper and more dominant, although one reach on the west side appears to be shallow and feeds a local headcut downstream. Scale is approximate because photograph is distorted, not rectified.

37.7 m^3/s (6/6/97). Because there are neither long-term stream gauges nor published records of floods along Abo Arroyo, weather records were examined for any large precipitation events that might suggest timing for large floods.

Floods down the Rio Puerco on the western side of the Albuquerque basin took place episodically during the 20th century (New Mexico State Engineer, 1930; Heath, 1983). On August 9th and 10th, 1929, heavy rains had fallen in the upper Rio Puerco and Rio Salado watersheds. Floods reached the Rio Grande on August 12th and flooded the Rio Grande valley beyond San Marcial by August 13th. The State Engineer estimated the Rio Puerco discharge near Bernardo at 867.8 m^3/s. Forty-two days later, on September 21st to 23rd, more heavy rains fell over the entire Rio Grande drainage area north of Socorro, New Mexico. Discharge of the Rio Puerco at Rio Puerco (railroad crossing west of Los Lunas) was estimated at 1,068 m^3/s and 991 m^3/s near Bernardo (New Mexico State Engineer, 1930; Heath, 1983). Smaller floods occurred along the Rio Puerco in October 1913, August 1935, August 1936, and May, September and October 1941.

FIGURE 14. Aerial photo of lower Abo Valley and Veguita in 1947. Note several diversion dams near the headcuts and the distributaries at the mouth of the incised channel. Obviously, part of the incised channel follows a very straight road or trail. Scale is approximate because photograph is distorted, not rectified.

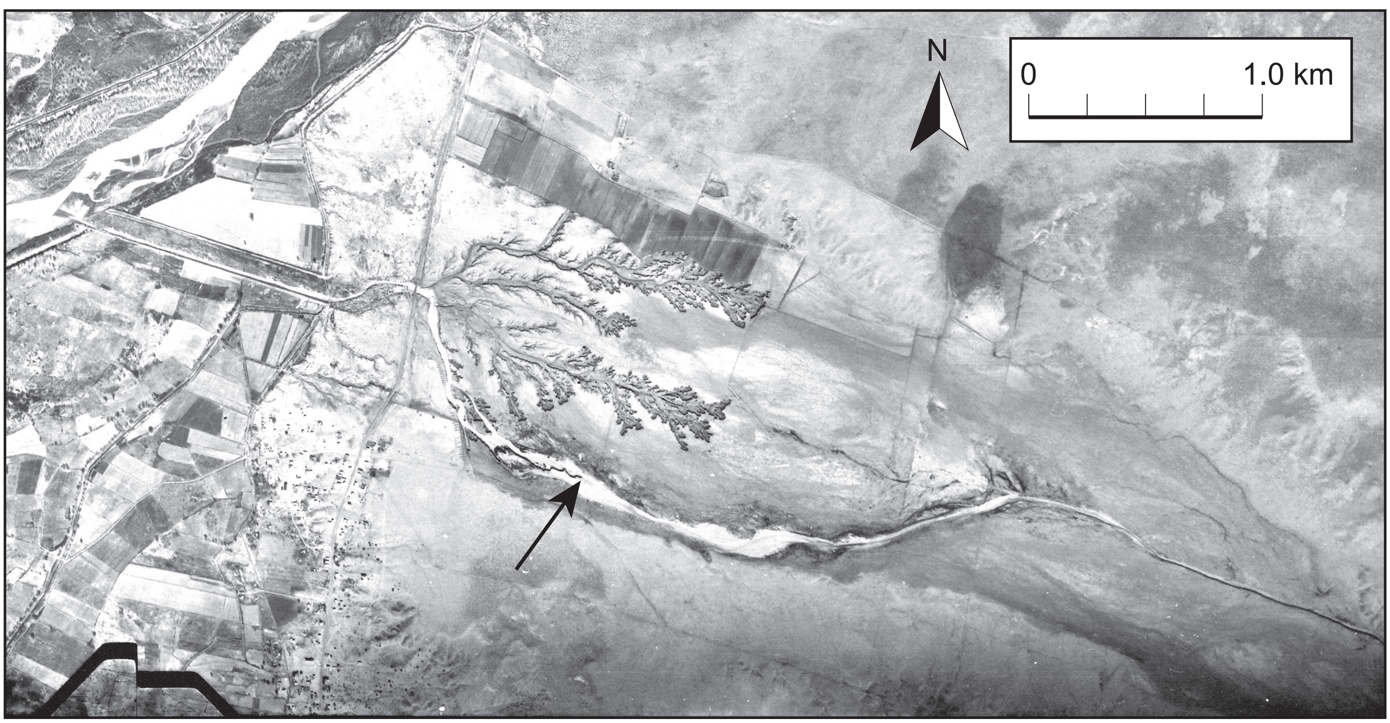


FIGURE 15. Mouth of Abo valley in 1954. Note one channel dominates former distributary fan, but it is not incised between a headcut (arrow) and the eastern straight reach. Scale is approximate because photograph is distorted, not rectified.

Black (1930) compiled precipitation and flood data for the two floods of 1929. His Plate 1 is a map of New Mexico with "isohyetose lines" and interpreted storm tracks for precipitation between August 8th and 11th. The map shows a west-east bulge in the 50.8-mm (2-inch) isohyetal line (a line drawn on a map connecting points having equal rainfall for a given period) and convergence of storm tracks across the southern Albuquerque basin, up the Abo Arroyo drainage, and beyond Mountainair to Duran, NM. Black (1930) reported that for the time period of the second flood in September, Mountainair received 26.2 mm (1.03 inches) of rain between September 21st and 23rd, and received 52.3 mm (2.06 inches) of rain total for September. Los Lunas received 31.0 mm (1.22 inches) of rain in those three days, and 85.1 mm (3.35 inches) for September. To the south, Socorro received only 15.5 mm (0.61 inches) during those three days. The isohyetal lines for precipitation between September 21st and 29th show that the Abo drainage received between 25.4 mm (1.0 inches) and 38.1 mm (1.5 inches).

Black (1930) also listed the 10 greatest flood peaks at San Marcial between 1895 and 1926. Excluding snow-melt spring-runoff peaks in May and June, and excluding peaks that happened before the railroad was completed through Abo Pass, only one flood, in July 1908, could have had a contribution from Abo Arroyo and could have transported coal.

Sheppard and Wiedenhoeft (2007) correlated tree-ring late-wood reflectance and late-wood width from trees in the Manzano Mountains with May-September precipitation in weather region 6 of New Mexico, which includes the Manzano Mountains. They showed several years between 1911 and 1935 when May-September precipitation is calculated to have been between 300 and 400 mm (11.8 and 15.7 inches). Between 1935 and 1954, only four years had precipitation greater than 300 mm (11.8 inches), but 1941 precipitation reached >500 mm (>19.7 inches). Although there is not a one-to-one correlation between relatively wet summers and runoff-generating floods, the probability of floods should increase during relatively wet seasons.

DISCUSSION

As can be seen in the photos and descriptions above, Abo Arroyo was undergoing a process of arroyo extension unlike conventional models of arroyo headcutting (e.g., Bryan, 1925; Schumm and Hadley, 1957; Bull, 1997). Instead, historic data show extended incision from near the mouth of Abo Canyon downstream rather than exclusively from the valley-mouth of the drainage at the Rio Grande upstream by headwall retreat (although that happened near Veguita). Several geomorphic/sedimentologic factors, particularly relating to stream power, wetted perimeter geometry, water loss, as well as land-use-land-cover, and semi-arid climate may help explain this behavior (Table 2). Extension of incision was on-going in 1935 and clearly had been for decades.

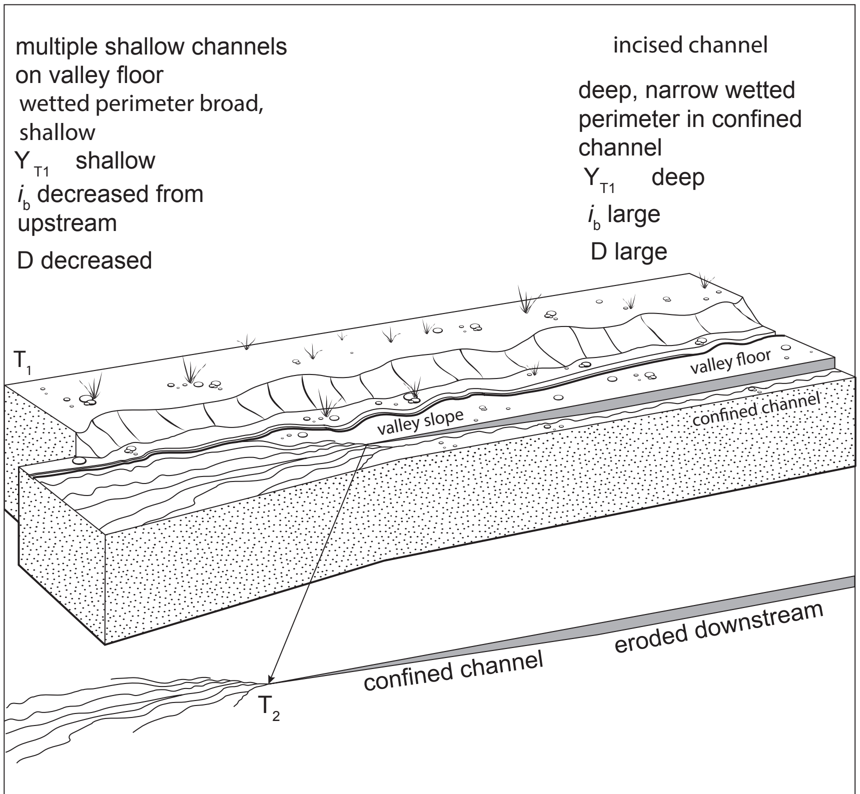
Between 1935 and 1947, the Abo Arroyo channel incised another 2-km downstream, in part by having flow concentrated along shallow channels, roads and/or trails following the valley. It would be tempting, using this one pair of data points, to calculate how many decades it took to advance from upstream to where it was in 1935—similar to Mark Twain's (1883) calculation that the Mississippi River used to stick out into the Gulf of Mexico, but incision may not have been from one point nor in one direction. Some nearly-straight upstream reaches in 1935 may also have followed old roads or trails. The historic aerial photos show possible local points of avulsion of shallow channels upstream that could be interpreted as "fan heads and fan spreads," and incision appears to have increased by removing sediment from the base and sides of the main channel. Except near Veguita, and possibly near Socorro County Road 220, no headcuts were observed.

Presumably as entrenchment began close to the mountain front, and perhaps at the steeper reach noted downstream (Love and Rinehart, Abo Arroyo minipaper), lesser flows could have entrenched as geometry of the incised narrow channel increased flow depth and concentrated stream power; still, greater flows would have been required to counter water-loss to the stream bed in order to extend entrenchment downstream. The photos seem to imply that the entrenchment mechanism was by eroding sediment along the base of channels, or, where there were resistant layers buried within the valley alluvium, local headcuts formed within partially incised channels and were removed by further erosion.

Abo Arroyo, like most ephemeral streams, has flashy flow, with steep rises in discharge, followed by a longer period of waning flow. The shapes of the flood hydrographs probably change slightly with each flow. Stream power decreases during waning flow in any case and water is lost to the channel bed in almost all stages of flow. Bedforms get organized and re-organized during waning flow, leading to localized deposition and erosion. The effects of water loss and waning flow must become more apparent farther downstream as the geometry of the system changes until the time at which all the discharge is confined all the way to the Rio Grande.

The evidence from aerial photographs also suggests that in these bedload streams, entrenchment does not necessarily follow formation of channels. At least locally, perhaps during low flows and water loss to the channel bed, decreasing stream power downstream may cause more load to drop and accumulate temporarily. The gravity slope, S, must decrease over the transitional reaches between confined and unconfined channels. Besides sediment storage in bedforms in the confined channel, sediment storage also occurs along avulsing channels that parallel the main shallow channel or in temporary, thin, channel-mouth fans onto the valley floor. These fans and avulsing channels shift downstream in subsequent decades (Fig. 16). As Bagnold (1977) indicated, bedload transport rate decreases as an inverse function of the ratio of flow depth to bedload grain size, Y/D. This relationship suggests that where floods spread out and Y becomes shallow, larger clasts are deposited (most likely in gravel bars), and that size of transported clasts decreases down valley as Y decreases further (Fig. 16). Because coal has a lower density than most rocks, the absolute density (mass per volume, ρ) is less for the mixture of coal and water, so deposition of coal clasts tends to be in low-energy backwater environments on the margins of the valley floor and in the mouths of tributaries. In the 1935 aerial images, coal appears to have spread out more pervasively in the last few km above Veguita, perhaps as a result of lower energy gradient and shallower depth. In the 1947 aerial image of the same area, light-colored sediments from newer floods appear to bury the coal, or perhaps replace it as the coal was swept farther downstream.

Although there may have been avulsions of multiple channels parallel to a main shallow channel or temporary thin, channel-mouth fans along the lower Abo valley, it is doubtful



S is gravity slope of valley floor; at point where discharge is less confined, depth decreases, power decreases, large clasts deposit, smaller and less dense clasts continue down valley	S decreases as channel merges with valley floor; large flows scour base and sides to extend erosion downstream	S in channel parallels valley floor; along confined channel, lesser flows lose water to base, depth decreases, power decreases, large clasts are deposited and grain-size decreases, channel bedforms aggrade; larger flows along a confined channel have more power to transport more and larger clasts, may scour base and sides of channel

FIGURE 16. Schematic diagram showing changing stream power and transport rates depending on discharge and geometries of wetted perimeter in a bedload stream and its valley floor at times T1 and T2. Y is water depth; bedload-grain diameter is D; the bedload transport rate is ib; the gravity gradient, S, must necessarily decrease between the fully confined channel and the unconfined flows on the valley floor.

that the avulsionis were thick enough, or steep enough to affect incision via headcuts as envisioned by Schumm and Hadley (1957) and Bull (1997; among many others). Rather, the photos show that the valley floor was active in several anastomosing channels for many km before the channel became incised. The detailed topography along various reaches of Abo valley await better control via LiDAR or other survey techniques over a long distance to see whether fan-like deposition and steepened gradients are a possible cause for entrenchment.

Cadol et al. (2011) showed that in Canyon de Chelly between 1935 and 2006, an interplay between a pulse of sediment and spread of introduced and native woody vegetation along the channel led to a down-canyon extension of an incised channel. They attributed the pulse of sediment to increased livestock in the headwaters in the early 1900s. It is likely that there was an increase in grazing throughout the Abo drainage in the 19th century similar to that in other drainages (Denevan, 1967). No data concerning timing and extent of erosion of the upper Abo drainage basin have been located. Hall et al. (2009) showed that Abo Arroyo in Abo Canyon was already entrenched through 4-5 m of alluvium by 1908. It is possible that due to 19th century erosion, there was increased production of sediment in the incised, dendritic channels in the headwaters. The timing of when increased sediment loads reached the lower Abo drainage is not clear. Sediments on the floor of Abo valley had reached the area west of Socorro County Road 220 before 1935, had spread out as described above and perhaps had continued downstream. The impression is that the sediments were not from a single, organized pulse, but more from local adjustments from incised channel to unincised channels.

Tamarisks have invaded the upper part of the drainage from Abo Canyon eastward, and the lowest part near the Rio Grande, but in between, vegetation is not a factor in channel nor channel-margin behavior (cf. Cadol et al., 2011; Friedman et al., 2015).

The historic photos catch the Abo drainage in the process of becoming entrenched, which is quite different from guessing (or creating a descriptive model of) what happened after the processes of incision were completed to form a continuous arroyo. This process is a classic example of Schumm's "problem of convergence," "problem of multiplicity," and "complex response" (Table 1). Abo Arroyo presently looks like many other arroyos in the Southwest, particularly now that the arroyo is continuous for many kilometers upstream. Because there had been widespread valley-floor flooding before or during incision, one might later mistake the fan-like sediments on the valley floor as being fans at the mouths of discontinuous gullies (Thornthwaite et al., 1942; Schumm and Hadley, 1957; Bull, 1997). Except for the marker of short-lived coal-clast introduction and short-term reworking, one might not be able to tell whether longitudinally extensive deposits were contemporaneous or had undergone episodic recycling down-valley over longer periods of time.

CONCLUSIONS

Historic data regarding the behavior of lower Abo Arroyo provide a cautionary tale regarding the formation of continuous arroyos in a semiarid setting. Lower Abo Arroyo is now a broad, steep continuous channel that is dominated by coarse bedload transport. Vegetation plays almost no role in controlling hydraulic parameters. Lower Abo Arroyo was not continuous from the mouth of Abo Canyon to the Rio Grande until 1954. Comparison of aerial photographs taken in 1935, 1947, and 1954 shows that the channel incised and extended downstream rather than by migration of headcuts upstream. The photographic evidence indicates that the arroyo did not cut by integration of multiple headcuts with gully-mouth fans in-between. Extensive coal-clast deposits along the lower Abo valley, still seen on the ground and documented on 1935 photographs, are a short-term time marker for where flooding occurred on the valley floor beyond the confinement of the modern incised arroyo. We interpret the flooding and downstream incision as a necessary result of the geometry of stream power driving bedload transport, beginning in channels of a losing stream and then spreading out across an unincised valley floor.

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Shannon Williams at travertine quarry.
Photo courtesy of Bonnie Frey.