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2007, pp. 433-440. https://doi.org/10.56577/FFC-58.433

in:

Geology of the Jemez Region II, Kues, Barry S., Kelley, Shari A., Lueth, Virgil W.; [eds.], New Mexico Geological Society 58 th Annual Fall Field Conference Guidebook, 499 p. https://doi.org/10.56577/FFC-58

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HOLOCENE SOILS, GEOMORPHIC SURFACES, AND MORPHOMETRY OF TWO LOW-ORDER DRAINAGE BASINS IN THE WESTERN JEMEZ MOUNTAINS, NEW MEXICO

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Abstract--The two main tributaries of the Rio Cebolla were the focus of a geomorphologic study to illuminate how their canyons have evolved during the Quaternary. Calaveras Canyon and the Upper Rio Cebolla began developing after the cataclysmic eruption ~1.22 Ma of the Tshirege Member of the Bandelier Tuff that resulted in the formation of the Valles caldera. Spatial variations in the resistance of these volcanic units to erosion, and increased runoff potential in the Upper Rio Cebolla due to the probable capture of a high-altitude tributary basin, likely enhanced incision and widening of the axial valley in the Upper Rio Cebolla. Meanwhile, Calaveras Canyon developed a knickpoint in its long profile. Consequently, the tributaries of Calaveras Canyon possess relatively smooth, concave profiles, better adjusted to the axial channel base level than those in the Upper Rio Cebolla. Additionally, hypsometric analysis of the slopes in the Upper Rio Cebolla tributary basins indicates relatively recent steepening of the slopes in the lower parts of these basins. These differences in bedrock incision have led to differences in valley-bottom morphology. A date of ~ 4800 ^{14}C yr BP provided by charcoal excavated from ~ 2 m beneath the oldest terrace mapped in Calaveras Canyon provides a maximum age for the terraces and the tributary fans that grade to this surface. Dendrochronological methods indicate a time period of the mid-1700s to the late 1800s for the incision of a relatively fine-grained terrace surface to the boulder bar surfaces very near the level of the modern channel. Subsequent flooding events deposited a series of inset flood bar surfaces in the valley-bottom of Calaveras Canyon dated at approximately 1750 to 1870, 1941, and 1958 AD.

INTRODUCTION

The slopes and tributaries of the Rio Cebolla basin (drainage area ~ 120 km^2) drain part of the Jemez Plateau, located immediately west of the Valles caldera in northern New Mexico. The two main higher order channels or "forks" of the Rio Cebolla drainage basin (Fig. 1), Calaveras Canyon (west fork) and the Upper Rio Cebolla (east fork), possess markedly different valley-bottom morphology and hydrologic controls, despite sharing many similar geomorphologic factors. With the exception of a relatively small area of the Upper Rio Cebolla (underlain by the Tschicoma Formation), both basins are underlain by the same volcanic units (the Tshirege and Otowi Members of the Bandelier Tuff) and are similar with respect to their drainage areas, drainage patterns, orientations, elevation ranges, and vegetation types. However, the channel of Calaveras Canyon is dominantly ephemeral and is associated with a group of inset stream terraces ranging from approximately 2 to 4 m above the current channel, and a series of flood bar deposits possessing many large surface boulders. In marked contrast, terraces are absent from most of the valley bottom of the Upper Rio Cebolla. Its channel is perennial and characterized by a spring system along most of its length, and the channel also is dominated by a more extensive, well-developed floodplain that consists of dominantly finer-grained deposits.

This research focuses on the Quaternary evolution of the canyons and the Holocene landscape and soil evolution in the Rio Cebolla drainage basin, with an emphasis on the mid- to late Holocene fluvial surfaces preserved in the valley bottoms, and with the principal goal of understanding the basic causes of the contrasting geomorphic features of the Upper Rio Cebolla and Calaveras drainages. The results were derived by a multidisciplinary approach analyzing many different aspects of the canyons. Analysis of basin morphometry provided insight into the long-term Quaternary development of the canyons. Investigation of the

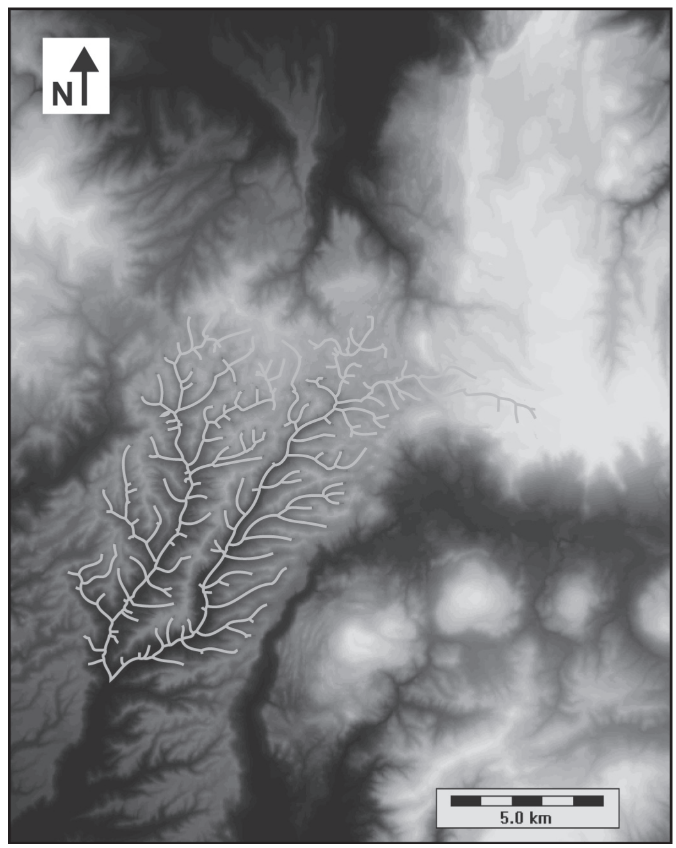

FIGURE 1. Elevation map of the northwest Jemez Mountains with the drainage network of the study basins shown in gray. The small, high-elevation basin in the Upper Rio Cebolla is drained by the two forks running east-west near the north rim of the caldera. Elevation is represented by shade, with black representing the lowest elevation (approximately 2000 m) and white representing the highest elevation (approximately 2900 m). Image generated from USGS 10-m DEMs using RiverTools software.

geomorphic surfaces present in the valley bottoms, including the mapping and description of these surfaces, description of soil profiles developing beneath these surfaces, and dendrochronology of the trees growing on these surfaces, provided data regarding the Holocene landscape evolution in the canyon bottoms.

GENERAL MORPHOLOGY

Calaveras Canyon

Calaveras Canyon lies west of the Upper Rio Cebolla drainage, covers an area of approximately 43 km^2, and possesses approximately 1.7 km of relief from the northern basin rim to the confluence with the Upper Rio Cebolla (Fig. 1). The drainage pattern of this basin is dominantly dendritic, with the largest of the tributary basins located west of the axial channel. As indicated above, the valley bottom of Calaveras Canyon is dominated by a series of inset stream terraces. Observations in the field reveal that the alluvial fans emanating from the tributary basins grade to the uppermost (oldest) terrace segments. Spires and cliff faces of Bandelier Tuff are commonly present near the axial channel, increasingly so in the lower reaches of the basin. The axial channel is floored by bedrock in some places. The near-channel surfaces have a dominantly bar-and swale topography with longitudinal bars possessing many surface and subsurface clasts up to 40 cm in diameter.

Upper Rio Cebolla

The Upper Rio Cebolla, located immediately east of Calaveras Canyon, covers an area of approximately 49 km^2 and possesses approximately 2.2 km of relief from the highlands in the northeast (north of the Valles caldera) to the confluence (Fig. 1). The drainage pattern of this basin is dominantly dendritic, possessing a subtle trellis signature, with virtually all of the largest of the tributary basins located east of the axial channel. The valley bottom in the lower half of the Upper Rio Cebolla is much more open than that of Calaveras Canyon and is dominated by large tributary alluvial fans grading to the approximate level of the modern, fine-grained floodplain. Parts of the upper reaches of the trunk valley possess a similar, yet more subdued, terrace sequence as that observed in Calaveras Canyon. The valley is also more confined in the upper reaches and the axial channel is commonly bedrock, including small waterfalls and cascades.

A relatively small (<6 km^2), high-altitude tributary basin located north of the Valles caldera is the dominant contributor to the 0.5 km of additional relief in the Upper Rio Cebolla as compared to Calaveras Canyon. Qualitative analysis of the topography in this part of the Upper Rio Cebolla suggests the possibility that this high-altitude tributary previously drained north to the Rio Puerco basin prior to its capture caused by headward erosion of the Upper Rio Cebolla (Fig. 2 shows hypothesized capture points). Other possible capture points exist west of Cerro Pelon, and future capture of a small drainage north of the northern hypothesized capture point seems likely.

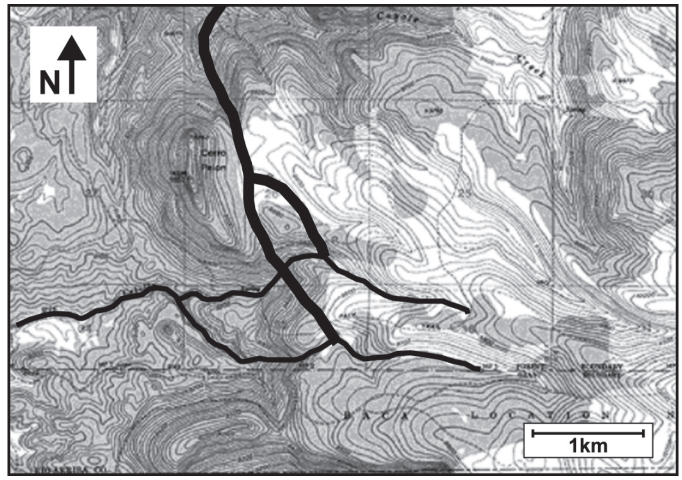

FIGURE 2. Map of hypothesized capture points in the Upper Rio Cebolla. Thin lines are the current stream channels; thick lines indicate hypothesized precapture flow direction to the Rio Puerco basin. Base map taken from USGS 7.5-minute Cerro del Grant, NM, quadrangle.

BASIN MORPHOMETRY

Longitudinal profiles

Long profiles of the two axial channels and their tributaries were plotted using Digital Elevation Models (DEMs) with 10-m resolution (Figs. 3, 4) to examine differences in their channel gradients. In the Jemez Mountains, Aby (1997) and Reneau (2000) have shown that these profiles are most sensitive to lithologic changes. The graphs show that over the majority of its profile at the same distance from their confluence, the main trunk of Calaveras Canyon is approximately 30-60 m higher than the main trunk of the Upper Rio Cebolla. Although on some reaches the profile of the Upper Rio Cebolla (with the exception of the part in the high-altitude tributary basin) is weakly to moderately convex, it is dominantly linear to concave. Conversely, while the profile of the channel of Calaveras Canyon contains a few reaches that are concave, its profile is dominated by an area of convexity culmi-

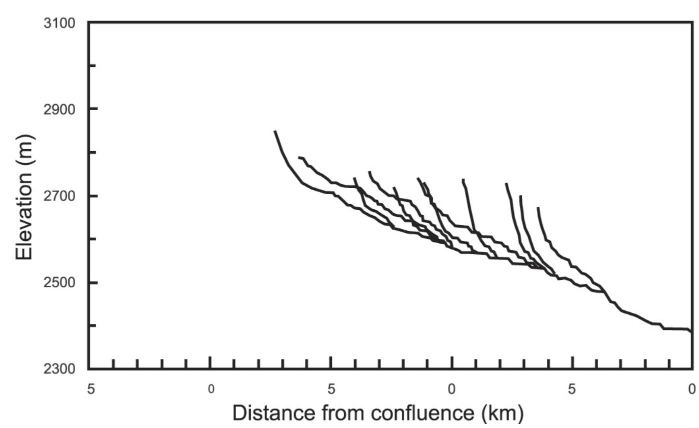

FIGURE 3. Long profiles of Calaveras Canyon and its tributary channels. Small scale steps in the profiles are due to limitations of the DEM data (10-meter resolution).

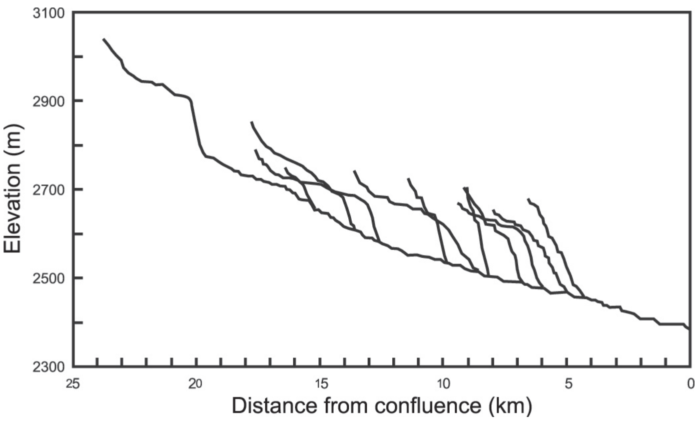

FIGURE 4. Long profiles of the Upper Rio Cebolla and its tributary channels. Small scale steps in the profiles are due to limitations of the DEM data (10-m resolution).

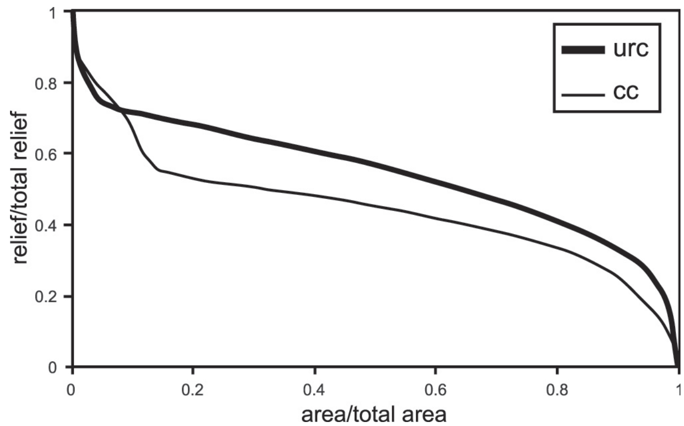

FIGURE 5. Hypsometric curves for the Upper Rio Cebolla (urc) and Calavaras Canyon (cc).

nating at a relatively large knickpoint approximately 3.5 km from the confluence. Both profiles possess a less pronounced knickpoint at approximately 2700 m elevation.

Long profiles were also plotted for the 10 largest tributaries of each basin, enabling interpretation of the long-term behavior of the tributary channels and their associated axial channel. Again, the profiles of these two sets of tributaries exhibit strikingly different characteristics. The tributary channels of Calaveras Canyon (Fig. 3) are dominantly concave and are presumably better adjusted to the base level provided by the axial channel. These profiles increase in convexity as they enter the axial channel at increasingly higher elevations. In contrast, the tributary channels of the Upper Rio Cebolla (Fig. 4) are dominantly convex and drop steeply to the axial channel. This observation suggests that the axial channel of the Upper Rio Cebolla has experienced a relatively recent period of substantial incision such that its tributary basins have yet to adjust completely to this base-level fall.

Hypsometry

Hypsometric curves for Calaveras Canyon and the Upper Rio Cebolla were plotted (Fig. 5) so that the distribution of elevations within each basin could be investigated. The curve for Calaveras Canyon is highly concave in the upper part and just as highly convex in the lower part, with only a very limited area of slopes with gradients between these two areas. In more quantitative terms, this curve shows that 90% of the total basin area is located in the middle 40% of the total elevation range of the basin. The uppermost 25% of the total relief is represented by less than 5% of the total basin area. Similarly, the lowest 20% of the elevation range is represented by just over 5% of the total basin area. The curve of the Upper Rio Cebolla is very similar to that of Calaveras Canyon with one major exception: the steep part of the curve in the upper relative relief ranges represents twice as much of the total relief of the basin as that of Calaveras Canyon. As a result, the relative relief values are approximately 10-15% lower for the Upper Rio Cebolla across most of the total basin area. This difference in the two curves is mostly due to the slope area associated with the high-elevation basin, which as noted above, is hypothesized to have been captured by the Upper Rio Cebolla. The high-altitude basin represents approximately 12% of the total area of the Upper Rio Cebolla and constitutes much of the uppermost 20% of the total relief of this basin.

In order to see if there were smaller scale differences in elevation distribution that were masked by the presence of the high-altitude basin, hypsometric curves were plotted for the 10 largest tributaries in each basin (Figs. 6, 7). The curves for the Calaveras Canyon tributaries, on average, are fairly linear, showing an even distribution of elevation across the basins. The curves for the Upper Rio Cebolla tributaries, however, are dominantly convex with 90% of the basin area above 40%, and 80% of the basin area above 50%, of the elevation range of the basin. This provides additional support for the proposed recent period of axial channel base level fall discussed above, as presumably the slopes in the lower parts of these basins would have responded initially to steepening of the tributary channel.

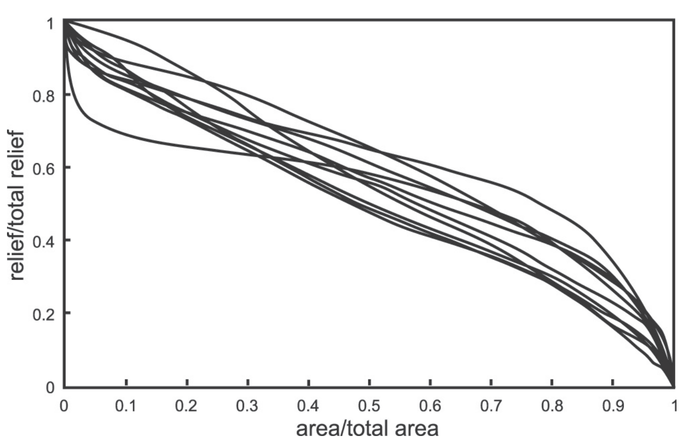

FIGURE 6. Hypsometric curves for the tributary basins in Calaveras Canyon.

GEOMORPHIC SURFACES AND DEPOSITS

Geomorphic surfaces

Calaveras Canyon

For this study the surfaces in Calaveras Canyon were divided into three main mapping units based on field observations, including height above the modern axial channel and type of deposits present at the surface and in the shallow subsurface (see Gere, 2006, for additional morphologic data). Figure 8 shows an idealized topographic cross-section across the valley-bottom of Calaveras Canyon including all mapped surfaces.

Qt1 is preserved as fill terrace segments approximately 4 m above the axial stream channel. Alluvial fans emanating from the tributary basins grade to Qt1 remnants, which are commonly undulating and densely forested. The upper 2 m of the deposits underlying this surface are dominated by sand and silt with dark, fine-grained layers below a depth of 1 m. These occur at approximately 1 m below the Qt1 surface as two wavy, dark, clay-rich bands, approximately 1-2 cm thick and separated by approximately 3-6 cm of sandier material, and a thicker (11 to 30 cm observed) deposit at approximately 1.3 m below the surface. Small pieces of charcoal are commonly found at, or near, the base of the darker clay-rich layers and we infer that the dark color of these deposits is due to the presence of burned organic material.

Qt2 is preserved as occasionally nested, cut-and-fill terrace segments approximately 2-3 m above the axial stream channel. This unit is subdivided into Qt2a and Qt2b, with the former representing the uppermost of the two surfaces. In some areas there is a clear distinction between the two surfaces, with a relatively sharp slope representing approximately 0.25 m vertical separation between them. However, because of the small elevation difference between these two surfaces, distinguishing between them is difficult in areas where only a terrace remnant is present. The Qt2 surface is commonly less forested than Qt1, with the former supporting mostly grasses. The deposits underlying these surfaces are similar to those of Qt1. They are dominantly sand and silt, with an increase in size and amount of sand, and increased occurrence of subsurface boulders observed in the more downstream sites.

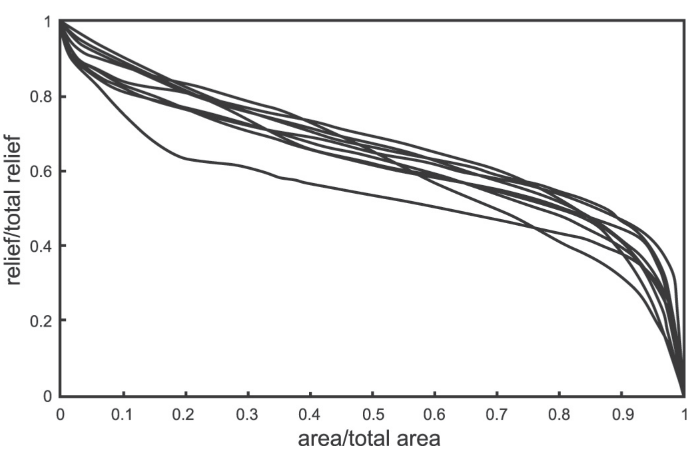

FIGURE 7. Hypsometric curves for the tributary basins in the Upper Rio Cebolla.

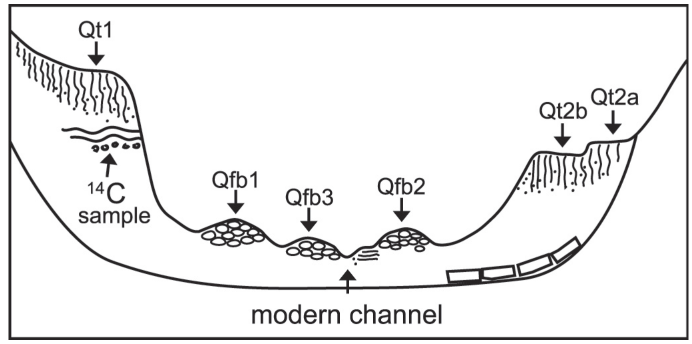

FIGURE 8. Idealized cross-section depicting all surfaces mapped in Calaveras Canyon and their relative relationship to the modern channel. Approximate vertical scale is 5 m.

Qfb is the youngest of the three mapped surfaces. Three subdivisions (Qfb1, Qfb2, and Qfb3) represent the varying heights (approximately 0.3 to 0.8 m) of the longitudinal flood bars present on both sides of the modern axial channel. Typically, the surfaces in the downstream reaches of the canyon are more clearly distinguishable as compared to upstream areas. These surfaces currently support sparse grasses and scattered groups of young trees and are dominated by large surface clasts up to, and occasionally exceeding, 40 cm in diameter (intermediate axis). The deposits beneath these surfaces are dominantly sand, but with occasional large clasts and clay-rich layers also present in most locations.

Upper Rio Cebolla

The fluvial terrace segments in the Upper Rio Cebolla are much less aerially extensive and terrace heights are lower than those in Calaveras Canyon. Also in contrast to Calaveras Canyon, alluvial fans emanating from tributary canyons and a relatively broad floodplain dominate the valley floor. Fill terrace segments approximately 1.5 to 1.7 m above the axial stream channel were, however, observed in the upper reaches of the Upper Rio Cebolla, and alluvial fans emanating from the tributary basins in these reaches grade to the terrace remnants. This surface is not present below an elevation of approximately 2600 m in this basin. Only the upper meter of the deposits underlying this surface was observed. The deposits are dominated by sand and silt with occasional dark, clay-rich layers below approximately 0.75 m. Small pieces of charcoal were commonly observed at, or near, the base of the darker clay-rich layers and we infer that the dark color of these deposits is due to the presence of burned organic material.

A fluvial surface consisting of flood bar deposits, typically less than 0.3 m above the active channel, was also observed in the upper reaches of the canyon. Longitudinal bars containing large gravels are occasionally present on both sides of the modern axial channel and at one location bury a part of a barbed-wire fence. In the middle reaches of the basin, this surface grades to the broad floodplain underlain by finer-grained deposits and is typically dissected by abandoned channels. These surfaces currently support a variety of grasses and woody shrubs, but very few trees.

Soil properties in Calaveras Canyon

Qt1/Qt2 soils

Soils forming beneath the terrace surfaces in both basins exhibit similar characteristics. There is, however, spatial variability in soil development caused by localized bioturbation by small mammals blurring soil horizons, vegetation density and type providing organic material to the surface, and the texture of the sedimentary deposits present in the immediate vicinity of the soil described. Here we focus on the soil properties observed in Calaveras Canyon (see Gere, 2006 for additional morphologic and textural soil data).

Qt1 and Qt2 soils in Calaveras Canyon possess organic-rich A horizons ranging from approximately 10 to 20 cm thick with massive to weak, very fine to medium, granular to subangular blocky structures. A/B horizons in these soils reach as deep as 55 cm below the surface with weak, fine to medium, subangular blocky structures. As mentioned above, spatial variability was witnessed in thickness and development of these horizons that can be explained by localized variability in the type and availability of surface organic matter, particularly grasses versus trees and grasses, with trees presumed to contribute an additional source of organic material via surface litter production.

Soil development beneath the A-AB horizons typically reflects varying degrees of oxidation. Bw horizons reach depths exceeding 1.5 m below the surface and possess massive to weak, fine to medium, granular to subangular blocky structures. Cobbles, where present, commonly possess Stage 1 silt caps (Birkeland, 1984). The variability in the degree of oxidation and development of structure in these horizons is attributed to the varying textures and associated effects on soil water percolation and soil water-holding capacity of the deposits they are forming in. In particular, the sandier layers have developed more pronounced oxidation, and the more silt-rich layers typically possess a better developed structure. Bioturbation has also influenced soil development in some areas by the translocation and mixing of subsurface deposits and soil horizons.

Approximately 1 m below the Qt1 surface are two wavy, dark, clay-rich bands, approximately 1-2 cm thick and separated by approximately 3-6 cm of sandier material. Below this, the deposits contain more silt and sand and also contain small pieces of charcoal. At approximately 1.3 m below the surface, a thicker (11 to 30 cm) clay-rich deposit, also dark in color was observed. One of the soil pits excavated in this surface contained a distinct thin layer of small (<3 mm, commonly <0.5 mm) pieces of charcoal near the base of this dark, clay-rich layer. A sample of this charcoal was collected and submitted for radiocarbon dating. No charcoal was observed in the oxidized sand and silt beneath the lower clay-rich layer. The conventional radiocarbon age provided by the AMS analysis for the charcoal sample is 4780±40 ^{14}C yr BP. The calibration of this radiocarbon age to calendar years provided by the laboratory as the 2 sigma calibrated uncertainty (95% probability) range is 5600 to 5460 cal yr BP and 5370 to 5340 cal yr BP.

Qfb soils forming above the influence of groundwater

Soils forming beneath the Qfb surfaces in the perennial part of Calaveras Canyon are very weakly developed. They typically possess a weak AB horizon up to approximately 10 cm thick, and weakly oxidized Bw horizons forming in the sedimentologically complex channel and near-channel deposits beneath these surfaces. These deposits commonly contain large amounts of gravel and cobbles at the surface and beneath the surface, with the amount and size of these clasts typically decreasing upstream.

Qfb soils forming under the influence of groundwater

In the lower reaches of Calaveras Canyon, specifically in and near the ephemeral part of the canyon, the presence of redoximorphic features show that these soils have been influenced by the shallow, seasonally fluctuating water table (often referred to as the "hyporheic zone"). Soils described in this area commonly contain horizons of gleyed soil as well as areas of mottling, indicating where the fluctuation of the water table has caused alternating oxidizing and reducing conditions so that the iron and manganese present in the system have alternated between their mobile reduced states and their precipitated oxidized states (Birkeland, 1984). This fluctuation between oxidizing and reducing conditions has been documented in the Rio Calaveras study site as a function of seasonal influxes from the atmosphere (providing oxygen for biological and abiotic oxidation reactions) and the vadose zone (providing a source of reductive compounds, specifically organic carbon, for microbially mediated biogeochemical processes) (Groffman and Crossey, 1999). Soils in this area typically possess a more distinct, yet still weakly developed, A horizon as opposed to the typical AB horizon described in Qfb soils further removed from the ephemeral part of the canyon.

DENDROCHRONOLOGY

Age constraint for geomorphic surfaces

The results of ring counts performed on the cores collected from trees growing on the terrace and flood bar surfaces in Calaveras Canyon provide estimated minimum ages for the relative stabilization of these surfaces. Two to ten of the taller and larger-diameter trees established on each of these surfaces were cored to locate the oldest trees. An ecesis period of 5-10 yrs, consistent with ecesis periods documented by Sigafoos and Hendrix (1969), Helley and LaMarche (1973), McCarthy and Luckman (1993), and Meyer (2001), was used to estimate calendar years for the floods that deposited the boulder bars. The oldest trees cored on the Qfb3 surface are estimated to have been established in the mid-1960s. These trees are commonly found growing in small communities of up to 30 trees on a single gravel bar, and show little, if any, bending along the trunk. The oldest trees cored on the Qfb2 surface are estimated to have been established around 1950.

These trees commonly show bending low in the trunk and occasionally have some exposed roots indicating lateral erosion by the channel has occurred subsequent to tree establishment. When the ecesis period is added, it seems likely that these surfaces were deposited during the flood peaks recorded by the Jemez River and Rio Guadalupe gauges in 1958 and the peak recorded by the Rio Guadalupe gauge in 1941, respectively.

The oldest trees observed in the axial valley-bottom (below the Qt1 and Qt2 terraces) are growing on the Qfb1 surface and are estimated to have been established around 1870. The very few trees of this age are mostly firs in poor health, so that the center rings of the tree are rotten and were not recovered, providing a less precise minimum age estimate for the Qfb1 surface. A fir growing on the Qfb surface in the Upper Rio Cebolla near the current stream channel also yielded an estimated time of establishment around 1870, indicating that the channels in both canyons have been at or very near their current elevation since around that time.

The oldest tree cored was a large ponderosa pine growing on the Qt2 surface in Calaveras Canyon, estimated to have been established around the early 1500s. As ponderosa pines in this area do not tend to live much longer than this (L. Scuderi, personal commun.), this age is potentially a very conservative minimum age estimate for the Qt2 surface.

Tree morphology and type as indicators for Recent geomorphic processes

In order to estimate the timing of tributary incision into the Qt2 surface observed at the edges of fans and terraces adjacent to large tributaries in Calaveras Canyon, a fir tree growing in the tributary channel cutting the Qt2 surface just above the head of the ephemeral part of the canyon was cored. We estimate it to have become established around 1910, providing a minimum age for the tributary to have graded to the Qfb surface.

Farther up canyon, a ponderosa pine estimated to be 350 yrs old growing on the Qt1 surface, showing no apparent bending in the trunk, has roots protruding horizontally over an erosional scarp cut by the axial channel. Using a conservative estimate of 100 yrs for this tree to become well established on a relatively level surface before being undercut, this provides a maximum age constraint for incision of the axial channel to the Qfb level of approximately 250 yrs. These data, coupled with data collected from the oldest trees on the Qfb surface, provide at least general constraints for the timing of the incision of the axial channel from the level of Qt2 to the level of Qfb, specifically between the mid-1700s to the mid- to late 1800s.

VOLCANIC ROCK UNITS

Bandelier Tuff

The Otowi and Tshirege Members of the Bandelier Tuff have a complex stratigraphy that varies across the Jemez volcanic field. As the focus of this study was not on the volcanic units in the study area, differentiation of these units beyond the mapping of Smith et al. (1970) was not attempted, and variability of welding and the resulting geomorphic expression are the main focus of this discussion.

The Tshirege Member generally forms spectacular, light-colored cliff faces with dominantly vertical jointing across the study area. The Otowi Member is a darker, more highly welded unit that possesses a platy-fracture pattern and generally forms slopes below the cliffs of the Tshirege Member. In Calaveras Canyon this unit often forms what appear to be cutbanks on alternating sides of the valley-bottom, carved into bedrock as the stream has incised into this unit. These features possess vertical faces (up to 10 m high) on their upstream side and form rounded slopes on their downstream side.

A concealed, down-to-the-southeast, normal fault was mapped by Smith et al. (1970) in the axis of the upper part of the Upper Rio Cebolla basin. The presence of this fault was confirmed in the field by a densely welded tuff (presumably an upper unit of the Otowi Member) that is present at the channel level on the east side of the valley, but is exposed no lower than approximately 15 m above the creek on the west side of the valley.

Tschicoma Formation

The area of the Upper Rio Cebolla that is underlain by rocks of the Tschicoma Formation possesses a lower drainage density and a much less rugged topography than is expressed in the Bandelier Tuff. The exception to this muted topography is present in the relatively steep slope on its western edge above the contact with the younger Bandelier Tuff. All other drainage basins in this part of the Tschicoma Formation drain to the north. The significance of these rocks to this study is their resistance to erosion, which has favored the development of a plateau at elevations exceeding 0.5 km above the rest of the study area.

INFERRED QUATERNARY EVOLUTION OF THE CALAVERAS CANYON AND UPPER RIO CEBOLLA BASINS

The evolution of Calaveras Canyon and the Upper Rio Cebolla basins began following the deposition and cooling of the Tshirege Member of the Bandelier Tuff, ejected approximately 1.22 Ma (Spell et al., 1989) in the cataclysmic eruptions that resulted in the formation of the Valles caldera. Sometime after these units cooled, a normal fault displaced the volcanic units east and west of the current axial valley of the Upper Rio Cebolla. As the fault trace follows the arc of the caldera rim and a complex of caldera-circumferential normal faults mapped in the northwest part of the caldera rim, it is likely that this down-towards-the-caldera motion of this fault is related to the formation of the caldera itself. Therefore, it is likely that this rupture occurred early in the Quaternary and has affected the development of the Upper Rio Cebolla over the entire evolution of the basin. Erosion associated with the development of these basins likely was favored in weaker areas in the bedrock associated with local variations in fracturing and differences in the degree of welding in various units of the Bandelier Tuff. Despite these differences, however, they both developed fairly dendritic drainage patterns, typical of basins forming by random headward erosion in relatively homogeneous, horizontally bedded, bedrock (Easterbrook, 1993).

Analysis of the topography, long profiles, and hypsometry of the basins provide evidence for a relatively recent capture of the high-elevation tributary basin in the Upper Rio Cebolla. No relevant geochronologic data is available to ascertain when the high-altitude tributary basin of the Upper Rio Cebolla was captured. Nevertheless, we infer that subsequent to the capture, the increased runoff potential (and thus stream power) associated with a larger drainage area increased the ability of the Upper Rio Cebolla to incise the bedrock. We also propose that this increased runoff and discharge, coupled with weakened bedrock in the vicinity of the fault, allowed the channel of the Upper Rio Cebolla to adjust rapidly to changes in base-level conditions. In contrast, the long profiles of the axial channel of Calaveras Canyon, and to some extent the tributaries of both study basins, are controlled by resistant rock types in the Otowi Member of the Bandelier Tuff, as shown most clearly by the development of knickpoints in their long profiles. Ultimately these differences in channel behavior have substantially affected the development of the two basins during much of the Quaternary, as expressed by the observed differences in the general morphology of the bedrock canyons. These differences are most clearly exemplified by the much wider valley-bottom of the lower reaches of the Upper Rio Cebolla, and the development of bedrock cut-banks in the valley-bottom of Calaveras Canyon.

Based on the age estimate of ca. 5500 cal yr BP from deposits beneath the oldest terrace in Calaveras Canyon, as well as the characteristics of soils developed on terraces in the study area, the alluvial and fluvial surfaces preserved in the valley-bottoms of Calaveras Canyon and the Upper Rio Cebolla range from mid-Holocene to late Holocene in age. The causes of the associated basin-wide aggradation in Calaveras Canyon are not known, but we speculate that such widespread alluviation (associated with both the fluvial-fill terraces and the tributary fans) may reflect former times of significant increases in sediment flux from basin slopes. Such increases may reflect periods of reduced vegetation in the basins during drier periods in the Holocene (Bull, 1991), or perhaps periods of increased fire severity causing hillslope erosion and alluvial aggradation, as proposed by Meyer et al. (1995) and Pierce et al. (2004) . In the Sacramento Mountains of New Mexico, Frechette et al. (2006) and New and Meyer (2006) identified major periods of alluvial-fan and valley-floor aggradation ca. 5800-4300 and 1000-500 cal yr BP that were promoted by severe fires, in watersheds generally similar to those of this study. Nonetheless, due to either the increased runoff potential or the wider, more-well graded valley-bottom in the lower reaches of the Upper Rio Cebolla (or likely a combination of both), this part of the basin was able to more readily accommodate this influx of sediment without significant aggradation of the stream channel. In contrast, the narrower valleys of Calaveras Canyon and the upper reaches of the Upper Rio Cebolla were choked with sediment and aggraded, and fill-cut terraces subsequently developed during alternating periods of incision and floodplain widening.

Age estimates based on dendrochronological data collected in Calaveras Canyon provide information on the timing of relatively recent large floods that continue to shape the valley floor. The abandonment of the Qt2 terrace in Calaveras Canyon occurred through rapid incision by the axial channel within the past 250 yrs. Subsequent flooding events deposited a series of inset flood bar surfaces in the valley-bottom of Calaveras Canyon dated at approximately 1750 to 1870, 1941, and 1958 AD.

These mid- to late Holocene terraces are less pronounced in the upper part of the Upper Rio Cebolla, and not all of the surfaces mapped in Calaveras Canyon were recognized in this area. These terraces are absent from the majority of the Upper Rio Cebolla, and floodplain development through lateral migration of the stream channel, commonly cutting into the toe-slopes of the large tributary fans, appears to have dominated the mid- to late Holocene development of the valley-bottom of this basin.

ACKNOWLEDGMENTS

We thank Grant Meyer, Lou Scuderi, and Gary Smith for thoughtful reviews of this research. Thanks for help in the field go to Ivan Erchak, Missy Eppes, Peter Castiglia, Nichole Bailey, Alexis Lavine, and Peter Dudley. This work was financially supported, in part, by grants from the New Mexico Geological Society, the Geological Society of America, and the Department of Earth and Planetary Sciences at the University of New Mexico.

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