**Erosional history and soil development on Quaternary surfaces, northwest Espanola Basin, New Mexico**

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INTRODUCTION

Extensive late Cenozoic fans and pediments form surfaces that flank the Rio Grande River along much of its course in New Mexico. The surfaces record pauses during general downcutting by the Rio Grande, as well as episodes of aggradation. Surface formation is likely linked with tectonic control of base level, but climate change may also be important. Where ages can be determined for pediments and fans, these features can be used to help constrain local uplift and denudation histories. However, easily dated material is uncommon in the arid and semiarid regions of the West, and radiometrically dated Quaternary sequences are rare.

Arid and semiarid basins with axial drainage display a general sequence of landforms outward from flanking mountain ranges: mountain front, pediment or fan, coalescing pediments or fans, and stepped alluvial terraces along the major drainage. In most semiarid regions, pediments and adjacent alluvial fans have similar gradients and transport similar material by flow in one or more channels (Moss, 1977). Surfaces are more likely to be erosional near the mountain front and depositional near the axial drainage, but any surface may display evidence for contemporaneous erosion and deposition. Grain size in many active alluvial fans decreases away from the mountains (Bull, 1964), and preservation of stratigraphic relations and soils is more likely downslope. However, once a surface is abandoned by base-level lowering, lateral erosion may proceed more rapidly in downslope areas where surfaces are covered by finer material. Preservation of a complete stratigraphic record is thus unlikely at any point, but comparison of morphostratigraphic and soil relations on several surfaces aids in reconstruction of geomorphic history.

Soil Development

Available water and organic matter are sparse and rates of chemical weathering are slow in arid regions. Carbonate accumulates in dry soils because eolian sources, precipitation, and slow weathering of soil minerals result in high concentrations of calcium (or magnesium) carbonate in evaporating soil solutions. Dry fallout and precipitation constitute a series of cut and fill surfaces formed as the Rio Grande eroded down the mountain front, affording additional protection for underlying carbonate horizons. Arid and semiarid basins with axial drainage display a general sequence of landforms outward from flanking mountain ranges. As arid soils increase in age, B horizons become increasingly clay-rich, and color hues become redder and chromas darker. The clay and iron content begin to provide some cementation in perhaps 10-20 ka.
FIGURE 1. Map showing location of the Rio Grande rift and geographic features of the Española Basin (after Manley, 1979). Field area is shown as a square near Chilil.
Climate in most of the Espanola Basin is semiarid. Mean annual precipitation averages 25 cm at Espanola, 36 cm at Santa Fe (Spiegel and Baldwin, 1963), and 46 cm at Los Alamos (Griggs, 1964). Significant understory vegetation and soil organic matter are present only above 2,200 m. Detailed information about paleoclimate in the Espanola Basin is sparse, but general inferences about Quaternary climates can be drawn from studies in nearby areas (Van Devender and Spaulding, 1979). Full "glacial" climates in northern New Mexico were probably expressed by greater effective moisture. Cirque and small valley glaciers formed in the Sangre de Cristo Range and vegetative cover likely increased in lowland parts of the Espanola Basin. Interglacial climates, by analogy to the Holocene, were warmer and drier than glacial climates and the change to interglacial climates likely resulted in landscape instability, erosion, and sedimentation. Holocene climate was initially warm and dry (Martin and Mehringer, 1965), but in the past 4,000 years has become more variable (Leopold, 1951).

Pliocene and Quaternary Geology

High pediments correlative with the Ortiz are preserved in the Penasco embayment and slope WNW toward the top of Black Mesa. The lowest of the high pediments (Truchas surface of Manley, 1976) predates deposition of the lower Bandelier Tuff (1.4 m.y.), which is preserved on a surface cut about 35 m below the Truchas level. A basalt flow that caps Black Mesa was dated at 2.8 m.y. (Manley, 1979); it overlies cobble gravel deposited by the ancestral Rio Grande, giving a close approximation for base level above the present channels at 3 m.y. ago. A lower surface, termed the Santa Cruz (Manley, 1976), is preserved as isolated remnants in the eastern Espanola Basin. Kelley (1979) suggested that the surface is a pediment near the mountains and a fan down-gradient. Manley (1976) noted upper Pleistocene terrace deposits at two levels as much as 50 m above present channels.

Surface remnants west and northwest of Espanola cannot be traced laterally to surfaces east of the Rio Grande. However, basal Puye Formation is a channel gravel deposited by the Rio Grande at grade with the Ortiz surface about 3 m.y. ago (Manley, 1979). Base level rose from 3 to 2 m.y. ago and probably 1.4 m.y. ago as the Puye, flows, and mara deposits from the Cerros del Rio volcanic field, and finally the lower Bandelier Tuff periodically dammed the Rio Grande at White Rock Canyon. Base level lay about 180 m above the present level when a basalt flow entered an extensive lake in Los Alamos Canyon some 2 m.y. ago (Manley, 1979). We know of little specific evidence for relative base-level changes between 1.4 and 1.1 m.y. ago. Smith, Bailey, and Ross (1970) noted that deep canyons were cut into the lower Bandelier and filled by upper Bandelier Tuff, but published maps and reconnaissance fieldwork suggest that much of the distal upper Bandelier covered a surface of low relief. Upper Bandelier Tuff exposed at similar elevation east and west of White Rock Canyon strongly suggests that base level did not change dramatically until after 1.1 m.y. ago.

Late Quaternary base-level changes on the axial drainage must have been controlled by relative motion between the Santo Domingo Basin and the Espanola Basin along the La Bajada fault, and by resistance to erosion provided by the basalt flows and tuff in the 10 km upstream from the fault. After the volcanic rocks were removed, headward erosion doubtless occurred rapidly in the poorly consolidated Santa Fe Group. We also recognize the importance of deformation along late Quaternary faults to individual drainages, but concentrate here on the influence of Rio Grande base level.

METHOD

We mapped surfaces and deposits along Rio del Oso in detail, and described and sampled soils in this area from surfaces south of the Rio del Oso and from one exposure in the Santa Cruz surface. All soil samples were analyzed for bulk density (Chleborad and others, 1975), carbonate content, and gravel/sand ratios. We performed complete granulometric analyses on selected samples and determined extractable iron (Jackson, 1973) for all B horizons and for selected samples of parent material. Our carbonate analyses followed a CO$_2$ generation technique using Chittick apparatus as proposed by Dreimanis (1962) and modified by Machette (written comm., 1982). Precision of carbonate analyses was ± 6%, whereas replicate analyses for bulk density and extractable iron gave a precision of about ± 8%.

We calculated total carbonate content for each horizon (c) using methods suggested by Machette (1982). Initial carbonate content was estimated using parent material beneath soil profiles, or assuming an initial carbonate value of 1% (Gile and others, 1981) where unaltered parent material was absent. We calculated total secondary carbonate in a soil profile (cS) by summing c values for all horizons. For undisturbed soils and constant accumulation rates, cS should be directly related to age. Machette and others (1982) suggested that carbonate-accumulation rates have averaged 0.5 gm cm$^{-2}$ ka$^{-1}$ for the past 50 ka and 0.25 gm cm$^{-2}$ ka$^{-1}$ prior to 50 ka.

Two samples were submitted to Beta Analytic, Inc., for C$^14$ analyses. Sample K D-29 consisted of charcoal fragments disseminated in silty sand beneath an alluvial surface some 3 m above the modern Rio del Oso. The second sample (KD-8) consisted of an overthickened A horizon buried by some 5 m of alluvium and colluvium and overlying a poorly developed soil. The surface above the buried soil lies some 26 m above the Rio del Oso in an erosional zone dissected by many small gullies.

RESULTS

Surfaces and Deposits Along the Rio del Oso

Five surfaces could be consistently distinguished above the active channel of the Rio del Oso and in adjacent areas along the Arroyo del Palacio (Fig. 3). The highest surface, designated Q 1, is exposed as isolated remnants in the western part of the Chili and eastern part of the Vallecitos quadrangles. The surface is generally cut into a stratigraphic sequence consisting of Santa Fe Group truncated and overlain by Puye deposits which underlie the lower Bandelier Tuff. Overlying the tuff are deposits of basaltic cobbles and boulder gravel that display stripped stage-IV soils overlain by stage-III soils. The Q2 surface is more widely exposed at lower elevations and is cut across basaltic cobbles and boulder gravel that fills channels in Santa Fe sediment near the mountain front. Deposits beneath the Q2 surface are finer and soils are better preserved east of the Vallecitos quadrangle. Surfaces Q3 and Q4 overlie arkosic sand and basaltic gravel from one to more than 20 m thick that fill channels cut into the Ojo Caliente Sandstone. The Q3 surface truncates an aggradational sequence near the Rio Chama. Deposits beneath the Q3 surface contain buried soils at a number of locations and surface-boulder cover is minimal. Deposits beneath the Q4 surface contain less gravel than those beneath the Q3 surface. Qal represents low, alluvial terraces near modern channels.
FIGURE 3. Map showing surfaces of the Rio del Oso area, northeast Jemez Mountains.
Gradients on surface remnants along Rio del Oso (Fig. 4) are similar to the river with the exception of Q1, which appears to steepen toward the mountain front. Easterly segments of Q1 project to an elevation of -2,000 m at the Rio Chama. The present channel of the Rio Chama at Black Mesa lies at an elevation of 1,735 m, whereas the Pliocene gravels beneath the capping flow on Black Mesa crop out at about 2,010 m.

**Soils**

Laboratory analyses of carbonate in 21 soil profiles generally support field descriptions of soils (Demsey, unpubl. data 1983) and clearly show the influence of erosion on the accumulation of soil carbonate. Soil ages calculated from carbonate content give minimum age for surface stabilization ranging from about 200 to 20 ka (Table 1). Bulk densities ranged from 1.2 to 2.1 g cm\(^{-3}\), whereas dithionite-extractable iron ranged from 0.4 to 1.04% in B horizons and from 0.16 to 0.28% in parent material, but the data show no clear trend related to surface position or inferred age.

Carbonate content of typical profiles on each surface ranges from a maximum of 60% (Q1) to about 25% for a stage-II soil on the Q4 surface (Fig. 5). The strongest K horizon on the Q1 surface displays stage-IV morphology, and several soils elsewhere on the surface expose two or more stripped and buried K horizons of at least stage-III development. Maximum carbonate content of the Q2 soils is about 40%, typical of "strong" stage-III field descriptions. Soils on several Q2 surfaces expose weak Holocene B horizons overlying stronger argillic or carbonate-cemented buried B horizons. Soils on Q3 and Q4 surfaces along the Rio del Oso are more poorly developed than those on adjacent higher surfaces.

Approximate minimum ages for Rio del Oso surfaces were estimated using the soil-carbonate stage (tile and others, 1981) and values listed in Table 1. Soils on the Q1 and Q2 surfaces have carbonate contents that suggest ages of about 150-250 ka. However, the stripped stage-IV carbonate which underlies stage-III soils on the Q1 surface probably took at least 200 ka to develop, and the surface probably formed at least 400-500 ka ago. Comparable stages of surface soils on the Q1 and Q2 suggest that both stabilized at about 200 ka. Maximum profile stage suggests Q3 soils are slightly older than Q4 soils, but the surfaces are of broadly similar age. A buried A horizon beneath an eroding, low Q3 surface gave a radiocarbon date of 10,590± 150 yrs B.P. (Beta-8359), and soil development and carbonate content suggest it was about 5 ka when it was buried. This evidence shows that at least portions of the Q3 surface were active at about 15 ka, implying complex erosional and depositional events in latest Pleistocene time. Tree-ring counts on the Q4 surface suggest it was abandoned at least 100 yrs ago; soil development is modern. Charcoal in deposits beneath the surface gave a date of 280 ± 90 yrs B.P. (Beta-7821).

**DISCUSSION**

**Rio del Oso Surfaces**

Our data and those of Manley (1976, 1979) indicate that the late Pliocene and Quaternary landscape northwest of Española was generally stable until after deposition of the upper Bandelier Tuff, and downcutting which isolated Q1 surfaces did not occur until mid- to late Pleistocene time. Once erosion began, denudation of areas east of Lobato Mesa occurred rapidly, dropping local arroyo levels at least 150 m and average landscape elevation more than 80 m. No evidence is preserved for periods of significant aggradation between at least 200 and 50 ka before present. Deposits beneath the Q3 surface near the Rio Chama record...
Surfaces along the Rio del Oso and in nearby areas stabilized between about 250 and 500 ka before present. The surface of pediment Q1 was an aggradational area until after 1.4 m.y. ago, and probably until after 1.1 m.y. ago, assuming surfaces are similar to those exposed 8 km to the south of Rio del Oso. Carbonate stage and total-profile carbonate suggest that colluvium which slopes from Q1 surfaces has been stable for more than 200 ka. After erosion removed most of the Q1 surface and cut through into underlying Miocene sediment, the Q2 surface formed some 40 m lower and was abandoned at about 200 ka. Although the Q1 surface formed more than 400 ka ago, soil development implies that erosion slowed on the Q1 and Q2 surfaces at similar times. Total soil carbonate suggests that parts of the Q3 surface stabilized at 25–40 ka, carbonate stage indicates latest Pleistocene, and a single radiocarbon date demonstrates that portions of the surface were active at about 10 ka. Carbonate stage on Q4 soils suggests that they are slightly younger than Q3 soils, and Cs values and absolute elevations of the surfaces overlap. Both surfaces must have been abandoned in latest Pleistocene or earliest Holocene. Periods of aggradation and erosion probably characterized much of Holocene time, but the Rio del Oso area records evidence only for 3–5 m of aggradation followed by erosion in historical time.

For most of their length, surfaces in the study area are pediments carved by streams during high-energy, episodic transport in systems of shallow channels that sloped toward Black Mesa. Dethier and Martin (this guidebook) mapped a north-trending fault at the west edge of the Chili sheet that displays at least 5 m of Quaternary motion. Activity of this fault and others along the mountain front could have influenced deposits beneath the Q1 surface and local stream gradients, but our field studies give no positive evidence. None of the younger surfaces show gradient changes or offsets that can be attributed to faulting.

The depositional nature of the distal Q3 surface and latest Pleistocene aggradation along major rivers in northern New Mexico was probably a response to latest Pleistocene climatic changes or to slowing of regional uplift. Aggradation in Q3 time along the Arroyo del Palacio, Rio del Oso, and Arroyo de la Presa produced terraces at the mouths of these drainages and other terraces along the west side of the Rio Grande. Local evidence is not sufficient to decide whether the Rio Grande produced aggradation by decreasing gradients or whether the tributaries aggraded in response to excessive loads from their catchments. 

**Surfaces of the Northern Espanola Basin**

Late Quaternary dissection is most complete and surfaces youngest in the northwest Española Basin. South of Española, canyons are narrow and steep-walled, and dissection of the surface cut across the Bandelier Tuff (the Pajarito Plateau) has apparently occurred more slowly than in the Rio del Oso area because unconsolidated Miocene sediment is covered with tuff and thick Puye gravels. Gradients for the high pediments (Q1) and lower surfaces are comparable north and south of Española (Fig. 6). However, lower surfaces are principally terrace deposits near the Rio Grande, and there are no low pediments parallel to stream channels. The high surfaces of Manley (1976) probably correlate with the Ortiz pediment and have gradients similar to that plotted in Figure 6. The late Pliocene surface that corresponds to the Ortiz is buried beneath the Puye Formation west of the Rio Grande and is displaced by north- and northeast-trending faults.

Our reconnaissance investigations and analyses of soils developed on the Santa Cruz surface are not sufficient to establish its age. Soil carbonate is at least stage III, and clay and iron accumulation are greater than in any of the soils we examined in the Rio del Oso area. Kelley’s (1979) reconstruction of the surface from isolated remnants (see Fig. 6) shows that it is much lower than the Ortiz and grades toward a Rio Grande level close to, or lower than, the present level. Because soil development suggests that the Santa Cruz formed prior to latest Pleistocene time, and its gradients suggest modern base levels, the Santa Cruz event does not correlate with surfaces preserved in the northwest Española Basin.

We believe evolution of surfaces in the northwest Española Basin resulted primarily from base-level control by the Rio Grande, but apparent west-to-east asymmetry suggests at least some local tectonic influence. Once White Rock Canyon was cut through the resistant volcanic rocks into unconsolidated sediment, river grade probably responded to regional erosion and deposition controlled by tectonism and climatic change. We have sketched base-level changes from late Pleistocene to the present for an area near Española, assuming minimal tectonic influence over short intervals (Fig. 7). The graph shows inferred, relative local changes and should be used as a guide for discussion. Integration of the Rio Grande in late Pliocene resulted in cutting of widespread erosion surfaces graded to a base level some 35 m higher than the present level about 2 m.y. ago. Afterwards the base level in the NW Española Basin rose as a result of damming and aggradation by Jemez Mountain rocks, reaching levels some 350 m above the present level about 1 m.y. ago. Erosion followed, lowering the base level 200 m by at least 200 ka and perhaps by as much as 400 ka.

Bachman and Mehnert (1978) suggest that slowing of regional-uplift rates caused cutting of the Llano de Albuquerque surface at about 500 ka ago, and formation of the Llano de Manzano by coalescing fans some 200 or 300 ka ago. Surfaces Q1 and Q2 may broadly correlate...
with these Albuquerque Basin surfaces, which would imply regional base level during most of the 3-1 m.y.B.P. interval was controlled locally. The upper Pliocene to mid-Quaternary deposits in White Rock Canyon provided local-base level, and understanding their evolution is a key to advancing our knowledge of Quaternary geomorphic evolution of the Espanola Basin.

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Narrow-gauge yard at Antonito. This is now the eastern terminus of the Cumbres and Toltec Scenic Railroad. It was formerly the point where the branch lines to Santa Fe and Durango separated.