



## ***Climatic influences on Quaternary alluvial stratigraphy and terrace formation in the Jemez River valley, New Mexico***

John B. Rogers and Richard A. Smartt

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# CLIMATIC INFLUENCES ON QUATERNARY ALLUVIAL STRATIGRAPHY AND TERRACE FORMATION IN THE JEMEZ RIVER VALLEY, NEW MEXICO

JOHN B. ROGERS<sup>1</sup> and RICHARD A. SMARTT<sup>2</sup>

<sup>1</sup>Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131;

<sup>2</sup>New Mexico Museum of Natural History and Science, 1801 Mountain Road NW, Albuquerque, NM 87104

**Abstract**—Quaternary alluvium preserved within the Jemez River valley of the southwestern Jemez Mountains records net incision punctuated by periods of fluvial aggradation and equilibrium (relative stability). Quaternary incision of at least 192 m yields an average incision rate of at least 12 cm/ka within San Diego Canyon. Incision has been interrupted by 5 major valley-filling events that preceded Qt1-Qt4 terrace formation and includes the alluvium beneath the present valley floor, and by 4 minor aggradation and equilibrium periods preceding Qt5-Qt9 terrace formation. The alluvium beneath Qt1-Qt4 may record similar cycles of climate-driven incision, equilibrium, aggradation, equilibrium and incision. We hypothesize that incision is initiated during interglacial-glacial transitions and continues into glacial times; equilibrium facies (boulder lags) coincide with interglacial and (late) glacial conditions; and aggradation begins during glacial-interglacial transitions. Evidence for this hypothesis is derived from fill stratigraphy, chronology provided by the presence of Lava Creek B ash, paleoecological inferences, and analogy with the modern floodplain of the Jemez River. The hypothesis successfully predicts the stratigraphy beneath the modern floodplain and suggests a more precise way of estimating the age of terraces and terrace deposits based upon correlation with established climate records.

## INTRODUCTION

### Purpose of study

Field research was concentrated near the confluence of the Jemez River and the Rio Guadalupe (hereafter referred to as "the confluence") north of the Village of Cañon, New Mexico (Fig. 1). The major objectives of this study were to identify and map the fluvial units near the confluence, estimate the age of the fluvial deposits/surfaces, and define and interpret possible causes (e.g., base-level change, volcanism, climate, complex-response) for periods of incision, equilibrium and aggradation of the higher-order perennial streams near the confluence.

### Background geology, Jemez Mountains

The Jemez Mountains, situated at the intersection of the Rio Grande rift, Colorado Plateau, and Jemez lineament, are a long-lived volcanic field constructed by middle-Miocene through Pleistocene eruptive activity. Volcanism, which began >13 Ma (Gardner et al., 1986), culminated with two catastrophic caldera-forming pyroclastic eruptions in the early Quaternary. The first of these was the eruption of the lower Bandelier Tuff dated at 1.61 Ma (Izett and Obradovich, 1994). This eruption resulted in the formation of the Toledo caldera and was followed by smaller-volume intracaldera eruptions collectively known as the Cerro Toledo Rhyolite. At 1.22 Ma (Izett and Obradovich, 1994), the second catastrophic eruption blanketed the region with the upper Bandelier Tuff and resulted in the collapse of the magma chamber to form the Valles caldera (Smith and Bailey, 1968). The formation of the 20-km-wide Valles caldera (Fig. 1) largely obliterated the Toledo caldera (Heiken et al., 1986), which may have coincided closely in size and position with the Valles caldera. Following the eruption of the upper Bandelier Tuff, all active volcanic vents in the Jemez Mountains have been restricted to the Valles caldera. The youngest vent extruded the Banco Bonito lava flow (Fig. 1) around 50-60 ka (Toyoda et al., 1995; Reneau et al., 1996). The post-collapse history of the Valles caldera includes early resurgent doming of the central caldera floor (Redondo dome), formation of a caldera lake or lakes, erosional breaching of the caldera wall to drain these lakes, and intracaldera rhyolite volcanism along a ring-fracture zone (Smith and Bailey, 1968).

### Location of study area

San Diego Canyon originates at the breach in the southwest rim of the Valles caldera (Fig. 1). This steep-walled canyon, whose headwaters are within the caldera, has been carved by the Jemez River, a major tributary of the Rio Grande. Approximately 25 km downstream from the breach, the Rio Guadalupe joins the Jemez River. The Jemez River above and below the confluence are informally referred to as the upper and lower Jemez River in this paper. Along the upper Jemez River, canyon walls expose primarily Paleozoic sedimentary rocks capped by thick layers of lower and upper Bandelier Tuff (Smith et al., 1970). At the confluence,

San Diego Canyon widens dramatically. Valley walls below the confluence are composed of Permian to Tertiary sedimentary rocks. The Rio Guadalupe drains the western flanks of the Jemez Mountains and the eastern flanks of the Sierra Nacimiento (Fig. 1). Near the confluence, the Jemez River and the Rio Guadalupe are perennial, bouldery mountain streams with gradients of approximately 0.007. The riparian community is dominated by cottonwoods, willows and grasses. The lower hillslopes and terrace levels are dominated by sparse juniper.

### Terrace and fill terminology

We incorporate the concept of the threshold of critical power in streams (Bull, 1979). The threshold of critical power is defined by the equation **stream power / critical power = 1**, and separates the modes of net deposition and net erosion in fluvial systems. Stream power is the potential for the stream to do work and is controlled by variables including discharge and gradient. Critical power influences a stream's ability to transport and erode and is controlled by variables such as hydraulic roughness and sediment load. When stream power exceeds critical power, incision can occur, creating terraces by abandonment of former floodplains. When critical power exceeds stream power, sediment is deposited and the channel aggrades. When stream power and critical power are equal (i.e., the fluvial equilibrium condition or graded condition), lateral erosion dominates.

Terraces are floodplains that have been isolated from active floodplain processes by subsequent incision and are designated "Q". A *strath* is a bedrock surface beneath a channel formed during periods of fluvial equilibrium when river parameters (i.e., gradient, discharge, roughness) are balanced so that neither aggradation (valley infilling) nor incision (valley deepening) occur (Bull, 1991). During equilibrium, the river migrates laterally to widen the valley and truncates underlying bedrock along a roughly planar surface (strath). Straths are usually overlain by a thin (<4 m in the study area) deposit of bedload alluvium. Subsequent incision creates a strath terrace. *Fills* are deposits formed during times of fluvial aggradation. Fills bury existing topography and therefore may have a non-planar contact with the bedrock below. Subsequent incision creates a fill terrace. A *fill-cut* terrace is underlain by a strath cut into older alluvium (fill) as opposed to bedrock and may be genetically the same as a strath terrace (Bull, 1991). Alluvial units buried beneath Bandelier Tuff have been given the designation 'Qg' (Quaternary gravel). Numerical modifiers give the relative age of buried gravels and terraces, with '1' being the oldest within each category.

## DATA AND RESULTS

### Alluvial units and terraces

Three buried fluvial gravels and nine terrace levels record the geomorphic evolution of San Diego Canyon in the vicinity of the confluence

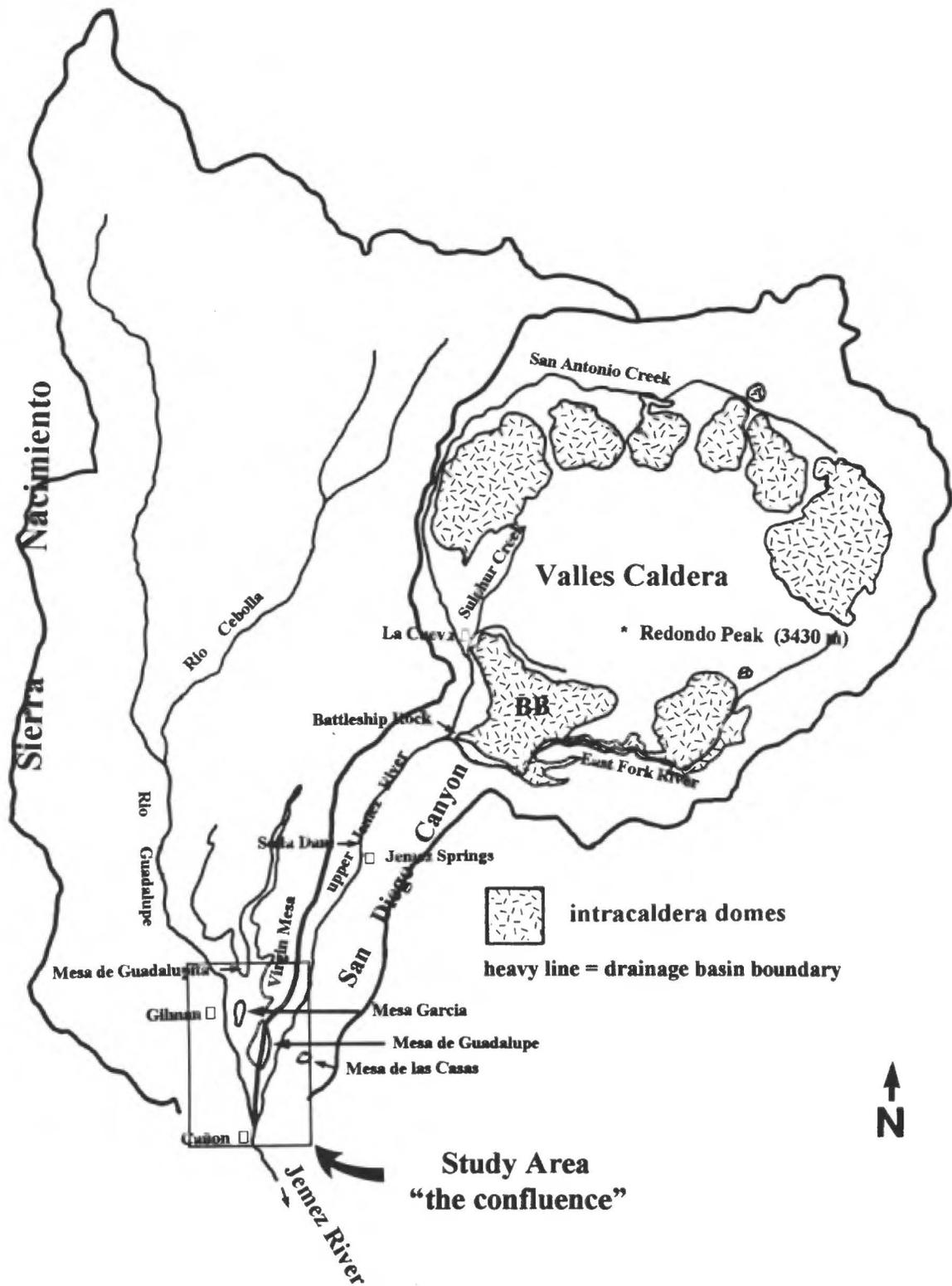


FIGURE 1. Location map outlining the two large drainage basins for the Jemez River upstream from the confluence of the Rio Guadalupe and the upper Jemez River. BB= Banco Bonito lava flow.

(Table 1). Qg1, a 3-m-thick gravel unit, buried beneath the lower Bandalier Tuff and exposed at Virgin Mesa, Mesa de las Casas, and Guadalupe Mesa (Fig. 1), lies approximately 192 m above the modern river (grade). Based on clast count data (Rogers, 1996), this deposit represents the bedload of the ancestral Rio Guadalupe. Burial at 1.6 Ma by the lower Bandalier Tuff provides an average incision rate of 12 cm/ka through the Quaternary.

Qg2 and Qg3 are alluvial units buried beneath the upper Bandalier Tuff and are exposed at the southern end of Mesa de Guadalupe (Fig. 1). Both rest on Permian redbeds (Yeso Formation). The buried surface of Qg2 lies approximately 187 m above grade and was likely the floodplain or a low-lying terrace of the ancestral Rio Guadalupe (Rogers, 1996) at 1.2 Ma. The alluvium of Qg2 is approximately 29 m thick and contains a 2.4-m-thick lens of primary or reworked ignimbrite, which may be Cerro

TABLE 1. Summary of fluvial deposit data near the confluence.

Unit	Surface or Deposit Type	Estimated Age (Ma)	Elevation of top above grade (m)	Deposit thickness (m)	Locations found	Associated tephras/volcanics
Qg1	buried axial gravel	1.6 (d/s)	192	2.7	RG,uJR	lower BT
Qg2	buried fill	> 1.2 (d)	187	26	RG,uJR	upper BT, CTR
Qg3	buried axial gravel	1.2 (d/s)	176	3	RG,uJR	upper BT
Qt1	major fill terrace	0.64/0.62 (d)	111	20	RG,JR,uJR	Lava Creek B ash
Qt2	major fill terrace		81	12-14	RG,JR,uJR	
Qt3	major fill terrace		53	11-15	RG,JR,uJR	
Qt4	major fill terrace		31	<27	RG,JR,uJR	
Qt5	minor strath/fill-cut	<.06 (s)	15	?	JR,uJR	Banco Bonito lava clasts
Qt6	minor fill-cut terrace		9	?	JR,uJR	
Qt7	minor fill-cut terrace		6	?	JR,uJR	
Qt8	fill terrace	late Holocene (d/s)	4	4	JR,uJR	
Qt9	fill terrace	late Holocene (d/s)	<3	<2	RG, JR, uJR	

uncertain, d = deposit age, s = surface age, RG=Rio Guadalupe, JR=lower Jemez River, uJR=upper Jemez River, BT=Bandelier Tuff, CTR=Cerro Toledo Rhyolite

Toledo Rhyolite (F. Goff, personal commun., 1994). Qg3, a 3-m-thick gravel unit approximately 176 m above grade, is believed to be the bedload of the paleo-Rio Guadalupe channel (Fig. 2) at the time of the upper Bandelier Tuff eruption (Rogers, 1996). Prior to burial, the river may have been cutting a strath into Qg2.

Qt1 through Qt4 are major fill terraces preserved near the confluence (Fig. 3). They are considered 'major' fills because they have significant aerial extent and they are considerably thicker (Table 1) than the other terrace deposits. The alluvium underlying Qt1 is approximately 21 m thick and rests in planar contact on Permian redbeds (Fig. 4). The base of the fill is a 3- to 4-m-thick axial-channel boulder bed. Above this is a thick sequence that includes finer overbank silts and sands and channel sands and gravels. These are in turn overlain by another axial-channel boulder bed. The Lava Creek B ash erupted from the Yellowstone area approximately 620 ka (Sarna-Wojcicki et al., 1987) or 640 ka (Sawyer et al., 1995). Lava Creek B ash has been found 95 m above grade within the sediments of Qt1, providing an age for this fill. The positive identification of this ash is based upon microprobe analyses on glass shards. With

the exception of the Lava Creek B ash, the same general stratigraphy is found beneath Qt2 (Fig. 5). In the Española basin, 50 km to the northeast, Dethier and Reneau (1995) described a similar stratigraphy in which two channel gravels are separated by 5 to 10 m of overbank or alluvial fan deposits. Qt3 and Qt4 fills are not as well exposed as Qt1 and Qt2 fills, but, where exposed, show a similar stratigraphy of basal and capping boulder zones. Qt3 has internal axial-channel gravels in addition to the basal and capping beds (Fig. 3). The geometry of the base of Qt4 is highly variable near the confluence and downstream from the study area (M. L. Formento-Trigilio, personal commun., 1996).

Qt5-Qt9 are minor strath, fill-cut, or fill terraces. Qt5 is the highest (~15-18 m above grade), oldest terrace that incorporates river clasts of Banco Bonito lava (Rogers, 1994). This first appearance of Banco Bonito clasts provides a maximum age of approximately 50-60 ka for Qt5 and a minimum age for Qt4. Qt5 is not correlative with the Qt5 terrace (Formento-



FIGURE 2. Qg3 buried by Tsankawi pumice (basal pumice bed of the upper Bandelier Tuff) at the southern end of Mesa de Guadalupe. Arrow points to cross-bedded pumice, evidence for fluvial reworking at the time of the upper Bandelier Tuff eruption. Steve Reneau and Fraser Goff for scale.

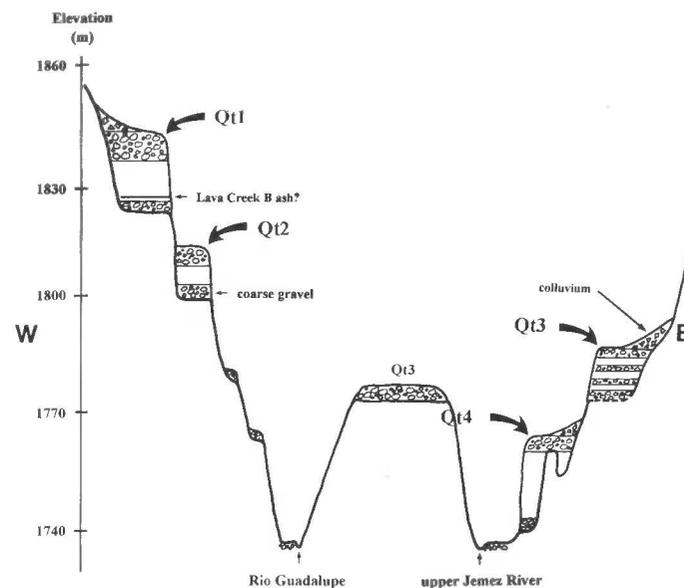


FIGURE 3. Idealized valley cross section above the confluence showing Qt1 through Qt4. Qg1 through Qg3 and Qt5 through Qt9 not shown. The Qt3 gravels between the two rivers cap an unnamed mesa immediately south of Mesa de Guadalupe.

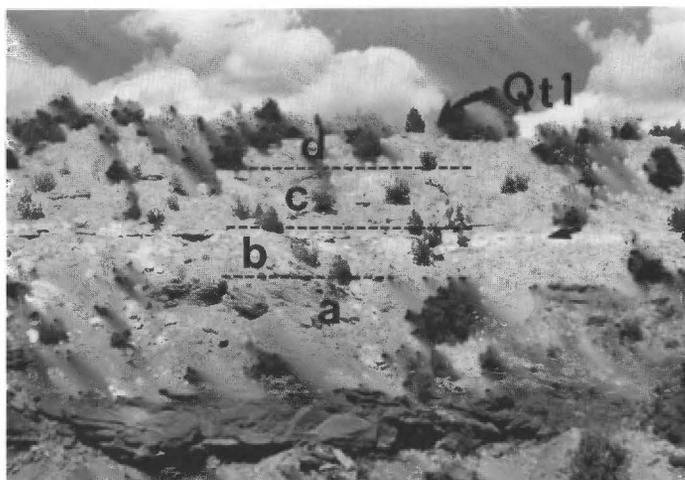


FIGURE 4. Qt1 and its underlying alluvium. a=Permo-Triassic redbeds, b=basal axial-stream gravels with associated overbank sediments, c=finer facies, d=capping axial-stream gravels. Arrow points to probable 1-m-thick Lava Creek B ash layer (white) associated with the overbank sediments above the basal boulder bed.

Trigilio and Pazzaglia, this volume) downstream of Cañon. Qt6 and Qt7 are minor fill-cut or minor strath terraces found only near the confluence along the upper and lower Jemez River. Qt8 and Qt9 are fill terraces of late Holocene age based on archeological evidence (Rogers, 1996).

#### Fossil snails

Several hundred fossil terrestrial gastropods were recovered from the zone between the basal and capping gravels of Qt1 - Qt4, (but excluding the floodplain facies associated with the basal gravel) and from the floodplain and debris-flow deposits immediately overlying the basal axial-channel gravel of Qt3, for the purpose of establishing an aminostratigraphy for the southwestern Jemez Mountains and correlation with deposits/surfaces in the Española basin (Table 2).

Protein membranes play an active role in the construction of the carbonate shells of invertebrates. These proteins, of numerous amino acids, provide the template upon which the calcium carbonate is crystallized. The calcium carbonate protects the protein templates and the relative abundance of specific protein amino acids is a conservative taxonomic trait independent of environmental conditions (Miller, 1989). During life, almost all of a gastropod's amino acids exist as L-isomer configurations.

After death, these L-isomers convert to D-isomers through a complex series of reactions that together are called racemization. Racemization rates are nonlinear and are dependent on time and temperature. Absolute ages cannot be directly derived from D/L ratios (alle/Ile ratios) unless additional geologic age control exists that allows for the construction of local calibration curves. Amino-acid ratios are most often used for relative ages.

Terrestrial gastropods from overbank facies were collected from vertical or sloping exposures at least 3 m beneath the terrace tread. Samples were analyzed in the laboratory of W. D. McCoy, University of Massachusetts, Amherst, using cation-exchange, liquid chromatography to determine the conversion of L-isoleucine to D-alloisoleucine (alle/Ile ratios) in the total hydrolysate (HYD) and free fraction (FREE) of amino acids (Table 2). The total acid hydrolysate measures all detectable amino acids in the sample (naturally free amino acids and formerly peptide-bound amino acids). The free analysis measures the concentrations of the non-peptide bound amino acids. Samples with the same letter (e.g., A, B, C) are from the same fluid (preparation) and should yield the same results. A, B, and C represent separate preparations (i.e., different shells). Rogers (1996) provides a detailed discussion of these data. A correlation exists between the deposits underlying Qt1, Qt2, Qt3 and Qt4, and the deposits underlying Q<sub>2</sub>, Q<sub>3</sub>, Q<sub>4</sub> and Q<sub>5</sub>, respectively, in the Abiquiu embayment and Española basin (Fig. 1), based upon elevation above grade (Dethier et al., 1988; Gonzalez and Dethier, 1991; Dethier and McCoy, 1993; Gonzalez, 1993). Q<sub>2</sub> contains the Lava Creek B ash and is therefore correlative with Qt1. If the elevation correlation is correct, the age estimates used by Dethier and McCoy (1993) of  $310 \pm 70$  ka (Q<sub>3</sub>),  $170 \pm 40$  ka (Q<sub>4</sub>), and  $95 \pm 15$  ka (Q<sub>5</sub>), based on a calibrated amino-acid curve for the Española basin, would be reasonable approximations for the ages of the fills underlying Qt2, Qt3 and Qt4, respectively. Amino-acid data comparisons (Table 2), however, only partially support an elevation correlation. Amino-acid ratios for Qt3 show a strong match with amino-acid ratios for Q<sub>3</sub>, not Q<sub>4</sub>. Plotting *Succinea* (HYD) values for Qt3 (Samples AGL-2517, AGL-2518) and Qt4 (Samples AGL-2523 and AGL-2521) on the amino-acid curve of Dethier and McCoy (1993, fig. 4) yield additional age estimates of  $310 \pm 105$  ka and  $160 \pm 50$  ka, respectively, for the fills underlying Qt3 and Qt4. *Succinea* (HYD) ratios for Qt2 were too high and thus were not used. The reason for these high ratios is not known, but the data for Qt2 *Succinea* is very limited. Tentative correlation with the fills of the Española basin, combined with the aerial extent of the Qt1 through Qt4 fills, is the basis for interpreting the Jemez River valley fills to be of climatic origin. It is important to note that both the Rio Grande and Rio Chama, which flow through the Española

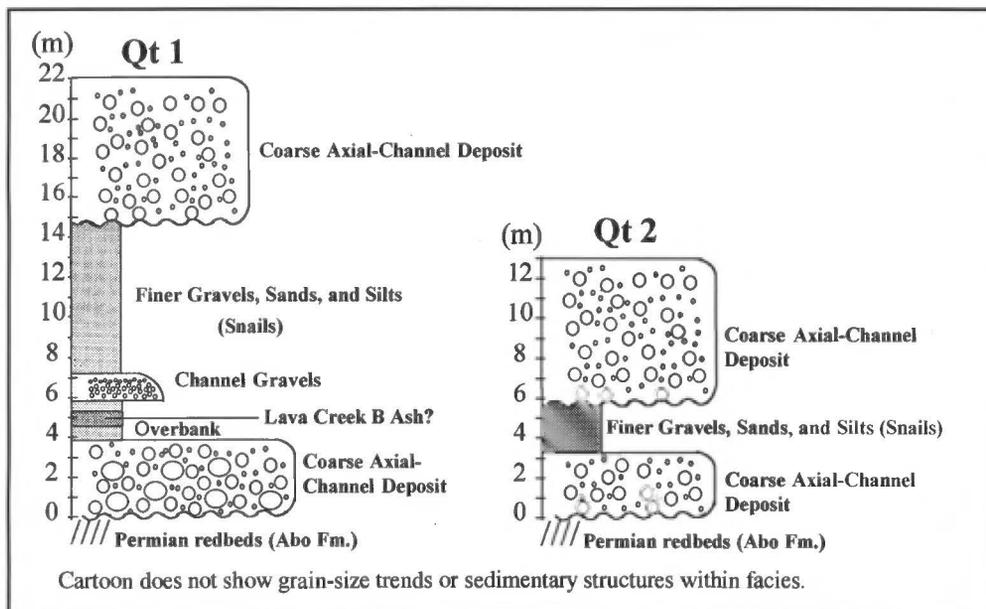


FIGURE 5. Generalized stratigraphy of the deposits underlying Qt1 and Qt2 emphasizing a coarse-fine-coarse pattern.

TABLE 2. Comparison of amino-acid racemization data from the confluence with select amino-acid racemization data from the Española basin. Jemez River samples were processed, identified, and analyzed at the University of Massachusetts, Amherst, in the lab of W. McCoy.

Jemez River Valley						Española basin <sup>1</sup>					
Deposit	Sample No.	Genus	Prep	HYD	FREE	Deposit	Sample No.	Genus	HYD	FREE	
Qt1	AGL-2514	<i>Succinea</i>	A	0.442	1.13	Q <sub>2</sub>	AGL-504	<i>Succinea</i>	0.69 ± 0.03(3)	1.08	
			A	0.445	1.055		AGL-576	<i>Succinea</i>	0.63 ± 0.04(2)	0.99 ± 0.08(2)	
			B	0.6565	na		AGL-506	<i>Succinea</i>	0.65 ± 0.02(2)	1.12(1)	
			B	0.654	na		AGL-1510	<i>Succinea</i>	0.70 ± 0.01	1.02 ± 0.04	
Qt2	AGL-2515	<i>Succinea</i>	A	0.799	0.982	AGL-1332	<i>Succinea</i>	0.69 ± 0.02	1.03 ± 0.04		
			A	na	0.973	AGL-1508	<i>Succinea</i>	0.72 ± 0.0	na		
			B	0.812	na	AGL-954	<i>Succinea</i>	0.93 ± 0.04(3)	1.03 ± 0.02(2)		
			B	0.812	na	AGL-1340	<i>Succinea</i>	0.71 ± 0.05	1.05 ± 0.06(3)		
	AGL-2516	<i>Vallonia</i>	A	0.352	na	AGL-955	<i>Succinea</i>	0.79	na		
			A	0.346	0.886	AGL-1341	<i>Succinea</i>	0.65 ± 0.01	na		
			B	0.459	0.825	AGL-1402	<i>Vallonia</i>	0.53	na		
			B	0.443	na	AGL-1509	<i>Vallonia</i>	0.63 ± 0.01	na		
			C	0.562	0.844	AGL-1404	<i>Vallonia</i>	0.61	na		
			C	0.569	na	AGL-1401	<i>Vallonia</i>	na	0.95 ± 0.02(2)		
			AGL-1395	<i>Vallonia</i>	0.62	na					
			AGL-1083	<i>Catonella</i>	0.83 ± 0.07(2)	1.11 ± 0.01(4)					
Qt3	AGL-2517	<i>Succinea</i>	A	0.472	0.671	Q <sub>3</sub>	AGL-577	<i>Succinea</i>	0.34 ± 0.02(2)	0.70 ± 0.01(2)	
			A	0.492	na		AGL-1333	<i>Succinea</i>	0.49 ± 0.03	0.85 ± 0.03	
			B	0.541	0.674		AGL-1361	<i>Succinea</i>	0.41	na	
			C	0.483	0.675		AGL-1334	<i>Succinea</i>	0.63 ± 0.01	0.95 ± 0.02	
	AGL-2518	<i>Succinea</i>	A	0.499	na	AGL-575	<i>Succinea</i>	0.47	0.85 ± 0.04(2)		
			A	0.485	na	AGL-947	<i>Vallonia</i>	0.4	na		
			B	0.466	na	AGL-1403	<i>Vallonia</i>	0.46	0.83		
	AGL-2519	<i>Vallonia</i>	A	0.4	0.649	AGL-1405	<i>Vallonia</i>	0.54	na		
			B	0.466	0.64	AGL-1406	<i>Vallonia</i>	0.4	na		
			C	0.466	na	AGL-570	<i>Vallonia</i>	0.39 ± 0.05(2)	na		
	AGL-2462	<i>Ashmunella</i>	A	0.458	0.734	AGL-515A	<i>Gyraulus</i>	0.33	na		
			A	0.465	0.72	AGL-509A	<i>Pupilla</i>	0.36	na		
	AGL-2460	<i>Microphysula</i>	A	0.498	0.687	Q <sub>4</sub>	AGL-1362	<i>Succinea</i>	0.33 ± 0.07	0.45 ± 0.01	
			B	0.491	0.691		AGL-1506	<i>Succinea</i>	0.38	NA	
	AGL-2456	<i>Oreohelix</i>	A	0.604	0.777		AGL-569	<i>Succinea</i>	0.17 ± 0.01(2)	0.49 ± 0.01(2)	
			A	0.582	0.772		AGL-505	<i>Succinea</i>	0.20 ± 0.01(3)	0.38 ± 0.02(3)	
	AGL-2457	<i>Oreohelix</i>	B	0.487	0.746		AGL-1393	<i>Succinea</i>	0.25 ± 0.01(2)	0.33 ± 0.02(2)	
			B	0.498	0.74		AGL-1500	<i>Succinea</i>	0.24 ± 0.01	0.35 ± 0.01(3)	
			C	0.457	0.799		AGL-1409	<i>Vallonia</i>	0.33	na	
	AGL-2458	<i>Oreohelix</i>	C	0.463	0.785		AGL-1507	<i>Vallonia</i>	0.29	na	
A			0.546	0.674	AGL-1394		<i>Vallonia</i>	0.16	0.35		
A			0.476	0.666	AGL-1501		<i>Vallonia</i>	0.27	na		
AGL-2459	<i>Oreohelix</i>	A	0.473	na	AGL-1407		<i>Vallonia</i>	0.36	na		
		A	0.486	na	AGL-1408		<i>Gyraulus</i>	0.24	na		
AGL-2461	<i>Zonitoides</i>	A	0.532	0.822	Q <sub>6</sub>		AGL-574	<i>Succinea</i>	0.12	0.27	
		B	0.485	na			AGL-948	<i>Succinea</i>	0.19 ± 0.04(2)	0.27 ± 0.06(2)	
Qt4	AGL-2522	<i>Succinea</i>	A	0.232			na	AGL-1339	<i>Succinea</i>	0.15 ± 0.03(4)	na
			A	0.324			0.418	AGL-1502	<i>Succinea</i>	0.26 ± 0.0	0.18 ± 0.02
			A	0.327			0.434	AGL-1503	<i>Succinea</i>	0.29 ± 0.02	0.15 ± 0.02
			A	0.322			0.388	AGL-1330		0.18 ± 0.01	0.29 ± 0.01
AGL-2520	<i>Vallonia</i>	A	0.314	na			AGL-951		0.33 ± 0.02(2)	na	
		A	0.459	na			AGL-1331		0.16 ± 0.01	0.25 ± 0.04	
Qt5	AGL-2524	<i>Vallonia</i>	A	0.258		na	AGL-956		0.25	na	
			A	0.244		na	AGL-952	<i>Vallonia</i>	0.22	na	
			AGL-1410			0.17	na				
			AGL-1395	<i>Vallonia</i>		0.62	na				
Holocene	AGL-2513	<i>Succinea</i>	A	0.086	~0.13						
			A	na	~0.11						
			B	0.066	0.149						
			C	0.131	na						
			C	0.129	na						

<sup>1</sup>Select Rio Chama data from Dethier and McCoy, 1993, Appendix 1. Q<sub>n</sub> = name of geomorphic surface that overlies deposit.

Snails from the Española basin were collected from floodplain deposits that underlie Jemez-derived fan deposits and overlie axial gravels.

basin, have glaciated headwaters, whereas the Jemez River does not. This difference between the two study areas may significantly influence the timing of fluvial responses to differing discharge and sediment loads.

The large number of fossils collected allowed paleoecological inferences. Fossil snails from fluvial deposits and living snails from the modern riparian habitat near Gilman (Fig. 1) were identified at the species level (Table 3). Following is an annotated list of fossil and living snails found near the confluence with modern habitat and distribution information:

*Ashmunella ashmuni* is a montane species known only in the northern part of the state. Fossil *A. ashmuni* were found in "pods", localized (within 1 ft<sup>3</sup>) deposits of plentiful adults and juveniles, much like the estivating pods or colonies of living, live-bearing *Ashmunella*. *A. ashmuni* are typically found together with *Oreohelix* and are common above 2195 m in

the southwestern Jemez Mountains (Smartt and Metcalf, 1996, in review). We found living *A. ashmuni* in a sheltered marsh environment along a perennial creek in a side canyon along the Rio Guadalupe at 2048 m. This population of *A. ashmuni* demonstrates that the appropriate mixture of conditions can provide livable habitat for snails at unusually low elevations.

*Cochlicopa lubrica* is found in montane, forested habitats throughout New Mexico, generally above 1981 m elevation (Metcalf and Smartt, 1988).

*Discus whitneyi* is a montane species (Smartt and Metcalf, 1996, in review).

*Gastrocopta armifera* has been reported in the Sacramento Mountains in the Transition Life Zone (Ponderosa pine-oak woodland) (Metcalf and Smartt, 1988).

TABLE 3. Fossil and living gastropod assemblages and their modern environments.

Species	Deposit							Modern Range / Habitat
	Qt1	Qt2	Qt3	Qt4	Qt5	HF <sup>1</sup>	Mod <sup>2</sup>	
<i>Ashmunella ashmuni</i>		x	x					montane-wet
<i>Cochlicopa lubrica</i>		x		x			1	montane (ponderosa pine and higher; forest dweller)
<i>Discus whitleyi</i>		x	x		x			montane
<i>Gastrocopta armifera</i>	x	x		x				montane
<i>Gastrocopta cristata</i>				x				not diagnostic
<i>Gastrocopta pellucida</i>				x				upper Sonoran life zone/eastern NM grasslands
<i>Helicodiscus eigenmanni</i>	x	x	x			x		montane
<i>Microphysula ingersolli</i>	x	x	x		x			montane
<i>Oreohelix strigosa</i>			x					montane (7200' plus)
<i>Pupoides albilabris</i>				x	x	x	1	not diagnostic (highly variable; commonly PJ and lower)
<i>Succinea</i> sp.	x	x	x	x	x	x		not diagnostic
<i>Vallonia cyclophorella</i>	x	x						pinon-juniper to montane
<i>Vallonia gracilicosta</i>		x					4	pinon-juniper to montane
<i>Vallonia</i> sp.			x	x		x		not diagnostic
<i>Vallonia</i> sp. (juvenile)	x	x	x		x			not diagnostic
<i>Vertigo gouldi</i>			x					the common <i>Vertigo</i> in Los Alamos area; pine/oak zone and higher
<i>Vertigo ovata</i>				x		x		high montane (slow meandering streams, high meadows)
<i>Zonitoides arboreus</i>	x	x	x	x	x	x		montane

<sup>1</sup>Holocene fill. Relation to Qt8 or Qt9 not known.

<sup>2</sup>Collected from modern riparian habitat near Gilman. Numbers in the Mod column = number of individuals collected.

x=fossil species present, but number of individuals not recorded.

*Gastrocopta cristata* thrives at lower elevations in New Mexico and is usually found along stream valleys, occurring under stones or branches in leaf litter in timbered areas along floodplains (Metcalf and Smartt, 1988). This species is highly adapted to arid conditions (Leonard and Frye 1962). *G. cristata* does not appear to be a species of the montane forests (Metcalf, 1967).

*Gastrocopta pellucida* is common in the Lower and Upper Sonoran Life Zones (i.e., desert through pinon-juniper woodland) in southern and eastern New Mexico, where it is usually found on slopes and bajadas, under some sort of shelter such as large stones, fallen yucca stems or caudices of yucca (Metcalf and Smartt, 1988).

*Helicodiscus eigenmanni* is widespread in New Mexico, being found in mountainous areas, mainly in the upper Upper Sonoran and the Transition Life Zones where woodlands are sufficient to produce leaf litter in which the species is commonly ensconced (Metcalf and Smartt, 1988). *H. eigenmanni* is a species of the lowermost montane or canyon forests of the Florida Mountains, southwest New Mexico (Metcalf, 1967).

*Microphysula ingersolli* is typical of the Canadian Life Zone (i.e., ponderosa pine, spruce and fir) and higher to timberline in New Mexico with reported occurrences typically between 2560 and 3140 m elevation (Metcalf and Smartt, 1988).

*Oreohelix strigosa* is a live-bearing, montane species not known below 2195 m elevation in the southwestern Jemez Mountains (Smartt and Metcalf, 1996, in review). Living specimens were found close to the confluence of the Rio Guadalupe and the Rio Cebolla (Fig. 1) within leaf litter about limestone outcrops. This site, at an elevation of 2195 m, is borderline pine-oak zone/aspenspruce zone. Hoff (1962) noted that *O. strigosa* occurs only where there is considerable moisture in the soil and in litter and that inadequate moisture may be an important factor determining the lower limit of range in elevation. Fossil *O. strigosa* were collected as pods, that included both juveniles and adults from Qt3 at an elevation of approximately 1770 m. Pods were found near the base of a fossil debris flow (part of the Qt3 deposit) that buried the overbank sediments associated with the basal gravels of Qt3 and from the uppermost sediments of the overbank deposit associated with the basal gravels of Qt3. *O. strigosa* likes to dig down under moist rocks or scree slopes. Prior to death, *O. strigosa* populations probably lived within and under the ancient debris flow at Qt3. *O. strigosa* are often found in association with *A. ashmuni*.

*Pupoides albilabris* ranges from Lower to Upper Sonoran Life Zones where it is found under logs and stones and in damp leaf mulch on floodplains, under dead caudices of *Yucca elata* and *Dasyliirion* sp. on dry hillsides bordering floodplains, and in lawns of urban areas. It is of little

value as a paleoecological indicator because of its tolerance of a variety of habitats (Metcalf, 1967).

*Succinea* sp., not diagnostic at the genus level.

*Vallonia cyclophorella* is a common New Mexico species that ranges from pinon-juniper woodlands to montane environments living along the floodplains of mountain canyons and preferring the adjacent wooded, often rocky, canyon slopes (Metcalf and Smartt, 1988). Hoff (1962) reported *V. cyclophorella* from 7 stations in New Mexico ranging from 2255 to 3627 m in elevation. Hoff noted that the microhabitat preference seemed to be leaf litter. In the Sacramento, Capitan, and Sierra Blanca mountains of southeastern NM, Metcalf (1967) collected *V. cyclophorella* from wooded canyons (ponderosa pine, Douglas fir, Gambel oak) as low as 1951 m up to aspen forests at 2743 m elevation. In the Tortugas and Picacho alluviums (southern Rio Grande valley) fossil *V. cyclophorella* are associated with other gastropods characteristically found in the leaf litter of woodlands (Metcalf, 1967).

*Vallonia gracilicosta* is a common New Mexico land snail of pinon-juniper to montane woodlands (Metcalf and Smartt, 1988). *V. gracilicosta* is generally distributed in montane forests of the southern Rocky Mountains (Pilsbry, 1948; Karlin, 1961). Metcalf (1967) found living specimens in the Sacramento Mountains at 2286 m in ponderosa pine forest. Smartt and Hafner (1989) reported that *V. gracilicosta* is more common in the eastern part of the state and tends to tolerate somewhat drier conditions than *Vallonia cyclophorella*.

*Vallonia* sp., not diagnostic at the species level.

*Vertigo gouldi* is the common *Vertigo* in the Los Alamos area and is a snail of the Transition and Canadian Life Zones (Smartt and Metcalf, 1996, in review).

*Vertigo ovata* is a high montane species preferring slow meandering stream systems and high meadows (Smartt and Metcalf, 1996, in review). *V. ovata* inhabits moist or marshy areas, where it is found under sticks, stones, leaf litter and dead grass (Metcalf, 1967). Beetle (1965, in Metcalf, 1967) found *V. ovata* around the periphery of a marshy pond in Grand Teton National Park, Wyoming at an elevation of 2042 m, where it was observed to "...invade the damp moss and mingle with the freshwater forms" as water level dropped in the pond (Metcalf, 1967). Although typically diagnostic of high, moist conditions in New Mexico, *V. ovata* can be found at significantly lower elevations if the appropriate microenvironment exists.

*Zonitoides arboreus* is found in the leaf litter of most of the forested mountains of New Mexico and is especially typical of the Transition and Canadian Life Zones (Metcalf and Smartt, 1988).

## INTERPRETATIONS/DISCUSSION

## Fluvial cycles

The generalized stratigraphy of Qt1 and Qt2 (Fig. 5) suggests a consistent cyclical progression in the processes of incision, equilibrium, and aggradation. The presence of alluvium on bedrock implies incision prior to alluviation. Before the bedrock was beveled and before the alluvial package was deposited, the river had been downcutting. Alluvium in planar contact with bedrock implies that incision was followed by equilibrium, a time when the river migrated horizontally across the valley floor, cutting a boulder-mantled strath with contemporaneous floodplain deposits. In this paper, equilibrium is synonymous with 'relative stability', and the two terms will be used interchangeably hereafter. Following a period of relative stability, the river system entered a period of instability where it was not capable of transporting all of its load and aggraded. This period is represented by the central part of the deposit and is interpreted to be the actual valley-filling interval. The river returned to equilibrium, leaving a boulder-capped strath beveled into the underlying alluvium, in a sense making Qt1 a fill-cut terrace. Subsequent incision created the Qt1 terrace and the sequence repeated itself to form Qt2, Qt3 and Qt4 are not as well exposed as Qt1 and Qt2 but show the same general stratigraphic trends (with the exceptions noted previously).

To refer to the deposits underlying Qt1 through Qt4 as fills may be misleading. Although entirely alluvium, only the central parts of the deposits, those above the floodplain deposits associated with the basal gravels and below the capping gravels, are hypothesized to represent true valley-filling intervals. The Jemez River valley 'fills' are viewed as a combination of aggradation and "equilibrium" (buried "strath" and fill-cut) deposits. A more traditional view would be to interpret the fills as being emplaced during one aggradational cycle. The capping gravels would represent lateral movement of the channel over floodplain deposits during aggradation. The coarse-fine-coarse stratigraphy might represent changes in the aggradation rate (i.e., slow-fast-slow) of a purely aggradational regime. In this alternative scenario, during periods of slower aggradation, fine sediments are winnowed away, leaving boulder lags.

## Climatic inferences

Bull (1991) proposed a hillslope process-response model for more arid parts of the southwest U.S. that associates aggradation with the Pleistocene-Holocene climatic change. In Bull's model, weathering rates exceeded erosion rates during the late Pleistocene because of denser plant cover. As the climate changed to drier or warmer during the latest Pleistocene, hillslope sediment yields were greatly increased due to a combination of decreased vegetative protection and increased rainfall intensities associated with the return of monsoon thunderstorms. By analogy with Bull's model, it is hypothesized that trunk streams begin to aggrade during glacial-interglacial transitions in the southwestern Jemez Mountains. Evidence of glaciations has not been found in the Jemez Mountains. Therefore, reference to continental-scale glacial and interglacial periods in this paper correspond to pluvial and interpluvial conditions locally.

Snail data support this interpretation. Diagnostic fossil species collected from the fill deposits of Qt1, Qt2 and Qt3 are primarily montane varieties (Table 3). We would expect to find these assemblages today thriving at higher, cooler and wetter elevations in the Jemez Mountains compared to the elevations of the fossil deposits. 'Montane' refers to a modern environment that supports oaks (e.g., Gambel oak, *Quercus gambeli*, and not varieties of scrub oak such as the wavy-leaf oak, *Quercus unguolata*) and ponderosa pine at its lower extreme. Largely intact fragile shells with limited abrasion and some still retaining color is strong evidence that fossil snails were not transported from upstream locations. Fossil *Oreohelix strigosa* was recovered from the Qt3 fill at an elevation of approximately 1765 m above sea level, whereas living *Oreohelix strigosa* have not been found in the southwestern Jemez Mountains below 2195 m. Live snails, collected near Gilman (Fig. 1) from the modern riparian environment just below the transition from a pinon-juniper woodland to a pine-oak woodland, included *Cochlicopa lubrica*, *Pupoides albilabris* and *Vallonia gracilicosta*. These species are what one would expect to find in this environment. The mixed snail fauna of Qt4 is not

montane but more appropriately considered as transitional (pinon-juniper woodland to pine-oak woodland). Based on the snail data, we conclude that fluvial aggradation of the trunk streams happened during cooler and wetter times than exist at present. The hypothesis of aggradation during glacial-interglacial transitions is consistent with other studies in the Jemez Mountains region (e.g., Love et al., 1987; Dethier et al. 1988; Dethier et al., 1990; Gonzalez and Dethier, 1991; Gonzalez, 1993; Dethier and Reneau, 1995).

By analogy with the modern river, we hypothesize that interglacial periods include times of fill-cut/strath formation in the vicinity of the confluence. Today these rivers are neither aggrading nor incising but migrating laterally across the valley floor. A bouldery lag lies upon older alluvium (explained below). Today, the active channels of both the upper Jemez River and the Rio Guadalupe just upstream of the confluence are impinging on the bedrock walls of the low unnamed mesa that separates the two rivers. Beveled bedrock is visible in the channels in places. Interglacial periods are not characterized only by lateral erosion. At least two periods of Holocene aggradation briefly interrupted or occurred prior to the current fluvial regime (Rogers, 1996).

We hypothesize that when the climate changes from an interglacial to a glacial period, stream power increases. Cooling and increase in effective moisture may result in an increase in vegetation density on hillslopes. A hypothetical combination of changing precipitation patterns, increasing vegetation density and associated hillslope stability, and a relatively exhausted sediment supply (much of the available sediment was incorporated in the preceding filling event) results in rivers that have sufficient power to both transport available sediment and incise into bedrock. We hypothesize that stream incision near the confluence was initiated during or following the interglacial to glacial transitions.

Glacial periods are long compared to interglacial and transition periods (Winograd et al., 1992), providing the fluvial system with time to balance parameters and return to relative stability. We hypothesize that pluvial periods conclude with a time of strath cutting (Fig. 6) near the confluence. Snail data support this interpretation. The fossil snail community from Qt3 is the most montane of the assemblages, and was collected from overbank sediments associated with the hypothesized late glacial buried strath.

Well data (Fig. 7) several kilometers downstream from the confluence also support this climatically driven fluvial cycle hypothesis, which predicts a late Pleistocene (Wisconsinan) - Holocene transition fill. Based on our hypothesis, this fill lies beneath the modern floodplain and it is the older alluvium upon which the modern Jemez River is eroding a fill-cut. The subsurface stratigraphy (Fig. 7) can be generalized as a sequence of coarse-fine-coarse fine alluvium resting on bedrock, the Miocene Zia Sandstone. Although no subsurface age control is available, we interpret this sequence to represent (1) a basal coarse zone (axial-channel gravel) formed during the late Wisconsinan strath-forming interval; (2) a central zone deposited as a fill during the late Wisconsinan-Holocene transition; and (3) an upper coarse zone coincident with mid-to-late Holocene equilibrium. The capping fine zone is composed of late Holocene fills

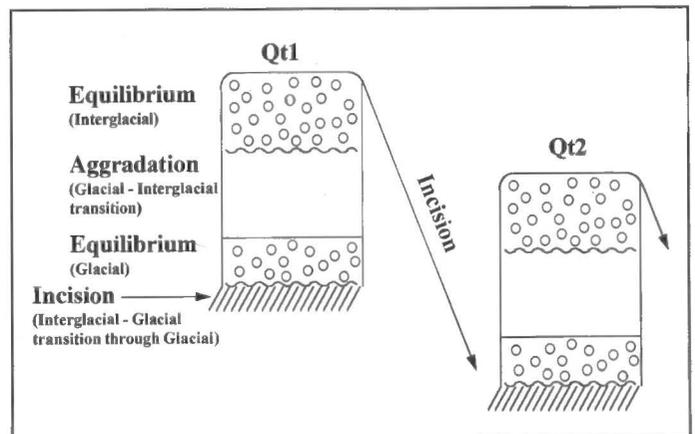


FIGURE 6. A climate-driven fluvial cycle hypothesis.

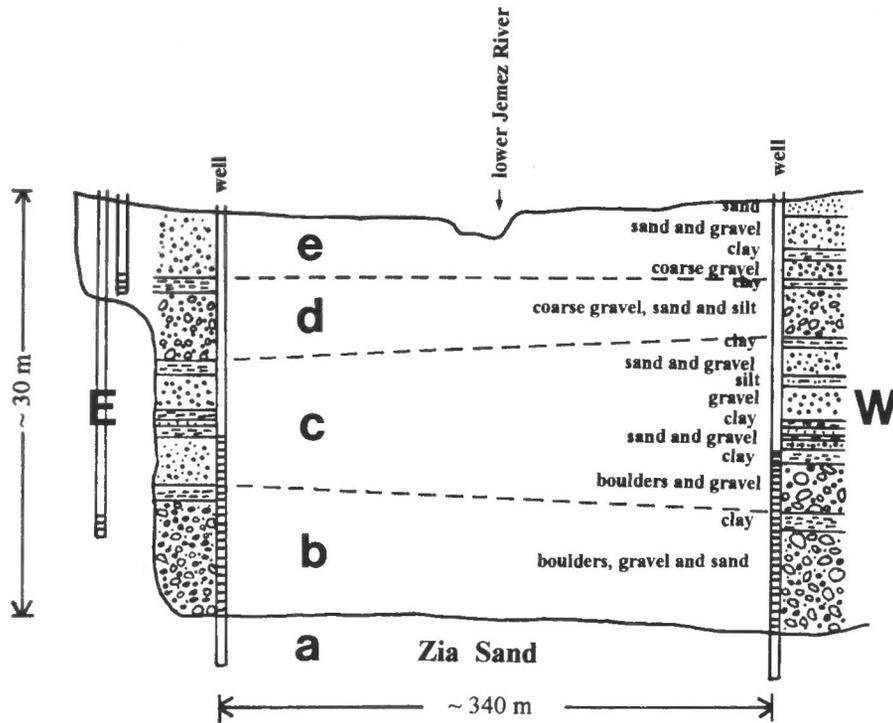


FIGURE 7. Well data from downstream of the confluence. Modified from data provided by W. White, 1994. Interpretation: b = late Wisconsinan strath with boulder lag; c = Wisconsinan-Holocene transitional fill; d = Holocene equilibrium; and e = late Holocene fill. a = bedrock.

(Formento-Trigilio and Pazzaglia, this volume). These overlapping fills are believed to be the result of complex-response or minor climatic perturbations. These fine-grained, unconsolidated fills are subject to rapid erosion and may not remain in the geologic record. In the future, if the southwestern Jemez Mountains pass through an interglacial-glacial transition, then incision should occur and create a new terrace, revealing a coarse-fine-coarse sequence below.

**Age estimates and comparison with the marine-oxygen-isotope curve**

If the climatically driven fluvial cycle hypothesis presented above has merit, it may be possible to correlate the fluvial record near the confluence to a known climate record. We have attempted to correlate the fill stratigraphy near the confluence with the marine oxygen-isotope curve, a proxy for global ice volume. The number of major post-700 ka fills from the Jemez River matches the number of high ice volume to low ice volume shifts as recorded by the marine oxygen-isotope curve between oxygen isotope stage 16 and the present (Fig. 8). These transitions in ice volume follow oxygen isotope stages 16, 12, 10, 6 and 2. If the fills of Qt1-Qt4 and the fill beneath the modern floodplain correlate with these shifts, the marine oxygen-isotope curve provides a third means of estimating ages for the fills beneath Qt2, Qt3 and Qt4 (Fig. 8; Table 4). Lava Creek B ash in Qt1 supports this correlation and provides a temporal pin to the oxygen isotope stage 16/15 timeframe. The position of the ash within the fluvial cycle, however, is not clear. There are two possibilities. The Lava Creek B ash may have been deposited near the base of the filling interval (Figs. 4, 5) suggesting that the Yellowstone eruption occurred during a glacial-interglacial transition. More likely, the ash was deposited on the floodplain associated with the late glacial strath prior to the valley-filling interval, in which case the Yellowstone eruption occurred during a glacial period.

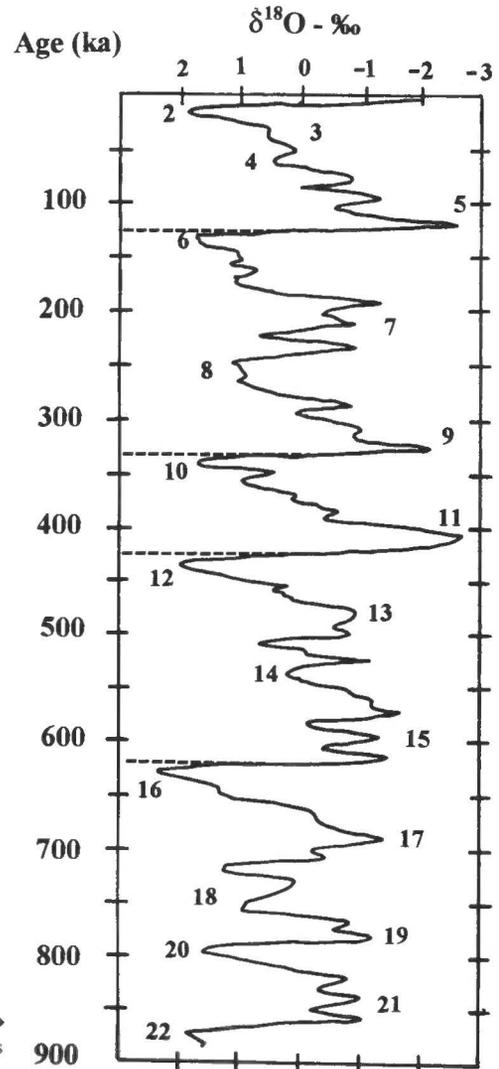


FIGURE 8. Marine oxygen-isotope curve Modified from Bassinot et al. (1994, fig. 7), Numbers beside curve are isotope stages.

TABLE 4. Age estimates for the Jemez River deposits based on elevation correlations, amino-acid ratios, and the marine-oxygen-isotope curve.

Jemez River Deposit <sup>1</sup>	Correlative Española Basin Deposits <sup>1</sup> based on elevation above grade	Est. Age of Española Basin Deposits (yr) (Dethier & McCoy, 1993)	Est. Age of Jemez River Deposits (yr) based on Amino-Acid Ratios <sup>3</sup>	Est. Age of Jemez River Deposits based on Marine Curve (yr) (Bassinot et al., 1994)
Qt1	Q2	620,000	530,000 ± 133,000 <sup>4</sup>	625,000
Qt2	Q3	310,000 ± 70,000 <sup>2</sup>		425,000
Qt3	Q4	170,000 ± 40,000 <sup>2</sup>	310,000 ± 105,000	340,000
Qt4	Q5	95,000 ± 15,000 <sup>2</sup>	160,000 ± 50,000	125,000

<sup>1</sup>Name of geomorphic surface overlying deposit. Española basin deposits include Jemez-derived fans that overlie axial floodplain and channel deposits.

<sup>2</sup>Age obtained from snails within floodplain deposits that underlie Jemez-derived fan deposits and overlie axial gravels.

<sup>3</sup>Estimated from local calibrated amino-acid curve for Española basin using *Succinea* (hydrolysate)

<sup>4</sup>Using Sample AGL-2514-B

## CONCLUSIONS

This paper presents a speculative, climate-driven fluvial-cycle hypothesis for major fill terraces near the confluence of the Jemez River and Rio Grande. The cycle consists of incision-equilibrium-aggradation-equilibrium. The fluvial cycle provides an alternative way of viewing fill terraces with deposits that may be a combination of equilibrium (relatively stable) and aggradational (unstable) stratigraphies. We further propose that these fluvial regimes may be linked to distinct climatic episodes (see also Gonzalez and Dethier, 1991, p. 38; Gonzalez, 1993, p. 198). To better understand valley-filling and terrace genesis near the confluence, we need higher resolution age control for the fills (and surfaces) of Qt1 - Qt4, detailed analyses of the stratigraphy, sedimentology, and provenance of the central parts of the fills, and a better understanding of past and present hillslope processes coupled with paleobotanical data. If the hypothesis is correct, global climate records, such as SPECMAP (marine curve), and regional records, such as the DH-11 (continental curve) core from Nevada, may provide ways of estimating the age of terraces and terrace deposits when better age control is lacking. Amino-acid dating results were also very encouraging, but larger data sets are needed for regional correlations.

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