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SOIL-FORMING PROCESSES ON THE PAJARITO PLATEAU: INVESTIGATION OF A SOIL CHRONOSEQUENCE IN RENDIJA CANYON

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Abstract—Soils formed on alluvial terraces in Rendija Canyon, near Los Alamos National Laboratory, provide a stratigraphic framework in which to evaluate time-dependent soil-forming processes. Soils formed on three Holocene terraces, ranging in age from about 0.5 ka to 7.0 ^{14}C ka, typically have weakly developed Bw horizons that increase in thickness from 20 to >60 cm with increasing soil age. Soils formed on two of the Pleistocene terraces that are >13.8 ^{14}C ka have moderately to strongly developed Bt horizons that typically increase in thickness from about 150 to 250 cm. The oldest soil formed on a third Pleistocene terrace has been severely truncated by erosion. Many of the soils have been influenced by the subsequent addition of alluvium and/or colluvium. Addition of silt and clay from eolian sediment has probably also occurred. The Soil Development Index was used to provide preliminary numerical comparisons of soil development and to develop a soil chronofunction capable of providing ages for the undated Pleistocene terraces. The resulting soil chronofunction suggests that soils on the two youngest Pleistocene terraces began forming at about 70–80 and 105–180 ka, respectively. Although these age estimates are preliminary and will undergo revision as soil-forming processes on the Pajarito Plateau become better understood, the results of this study are encouraging and indicate the potential for using soils to greatly improve understanding of local geomorphic history.

INTRODUCTION

Investigations of soils on the Pajarito Plateau in the vicinity of Los Alamos National Laboratory (LANL) have dramatically increased in the past few years in response to Environmental Restoration and Seismic Hazards Investigation project goals. Recent investigations have generally centered on the distribution of soils across the landscape, soil stratigraphy, and soil characterization to evaluate the distribution of trace elements in soil projects (Longmire et al., in press), uranium contamination in soils (Watt et al., 1994; Watt unpubl., 1996), geomorphic and seismic history (Wong et al., unpubl. report for LANL, 1995; Reneau et al, this volume; Kolbe et al., 1994; Wilcox et al., in press), and origin of fracture-fill materials in the Bandelier Tuff (Davenport et al., 1995). Previously, the only extensive soil study in the Los Alamos area was the development of a soil survey for Los Alamos County (Nyhan et al., 1978).

Fundamental to all these studies is a basic understanding of the systematic time-dependent changes in soil properties, but a study focused on temporal changes in soil-forming processes has not been previously conducted. Soil chronosequence studies provide a means by which to examine time-dependent changes in soils by comparing changes in soil properties among soils formed on surfaces or deposits that vary systematically in age (Birkeland, 1984). The conceptual foundation for soil chronosequence studies is based on Jenny's (1941) state factor approach which states that the dominant soil forming processes are largely driven by five major factors: biology, topography, climate, parent material, and time. Within a soil chronosequence, time is the only major variable, whereas the other soil-forming factors are largely constant relative to time. Although other variables such as vegetation and climate may change over time, a fundamental assumption is that temporal changes in these factors will affect all soils in a similar fashion and/or that the passage of time is the dominant driver of progressive changes in soil properties. The soil chronosequence, therefore, provides a natural laboratory in which to evaluate temporal relations of soil-forming processes. Here, we present preliminary results of an investigation of soils formed on alluvial terraces along Rendija Canyon, and evaluate the use of soils for providing local age control in geomorphic investigations on the Pajarito Plateau.

GEOMORPHIC SETTING

Rendija Canyon is located on the northern Pajarito Plateau, draining the Sierra de los Valles and emptying into Guaje Canyon (Fig. 1). Lithologic variations along the canyon strongly influence the longitudinal profile of the stream and the distribution of stream terraces. The part of the canyon examined in this study lies between two relatively steep reaches where the channel is incised into resistant rocks. Upstream, the channel has cut a narrow canyon through Miocene-Pliocene dacites of the Tschicoma Formation and downstream the channel steepens where it incises into bouldery fanglomerates of the Plio-Pleistocene Puye Formation (bedrock units from Griggs, 1964, and Smith et al., 1970). Between these steeper reaches is a relatively broad canyon where the stream has cut laterally into nonwelded tuffs of the Otowi and Tshirege Members of the Bandelier Tuff and into intervening early Pleistocene pumice beds and alluvium of the Cerro Toledo interval. Roughly half of the drainage basin upstream of the knickpoint in the Puye Formation is underlain by Tschicoma Formation dacites, which provide most of the pebble-to-boulder-sized gravel carried by the stream. Erosion of the Bandelier Tuff and the Cerro Toledo beds along the rest of the watershed provides much sand and pumice to the channel. The reach discussed in this paper includes the north-south-trending Guaje Mountain fault zone, a down-to-the-west normal fault with its most recent movement estimated at between 4 and 6 ^{14}C ka (Gardner and Reneau, this volume).

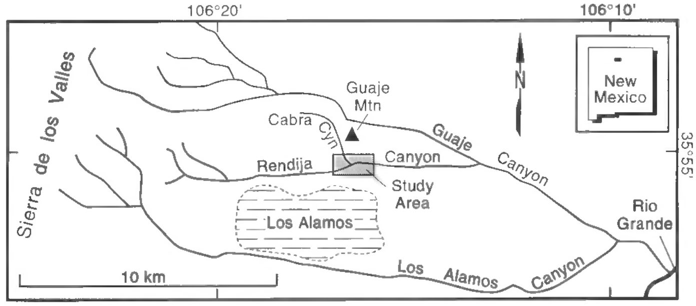

FIGURE 1. Location map for Rendija Canyon and soil characterization sites. Most sites are located in the general vicinity of the Los Alamos Sportsmans Club.

Alluvial terraces

Rendija Canyon possesses the best flight of stream terraces on the Pajarito Plateau within Los Alamos County, in terms of numbers and quality of their preservation and exposure including at least three Pleistocene surfaces and four Holocene surfaces (Fig. 2). These terraces were first examined by Gonzalez and Gardner (unpubl. report for LANL, 1990), and later by Kelson and colleagues as part of a seismic hazards evaluation of the Los Alamos area (Wong et al., unpubl. report for LANL, 1995). The terrace nomenclature used in this paper is based on that developed by Kelson and modified following our more recent mapping and radiocarbon dating (Table 1). The Holocene terraces (Qt5–Qt8) are primarily strath terraces overlain by 0.5–3 m of channel and floodplain deposits of variable thickness and may in part record minor aggradation. In contrast, the Pleistocene terraces (Qt1–Qt4) have at least 4–10 m of channel gravel overlying a strath surface cut into the Bandelier Tuff and record significant aggradational episodes. The ages of the Holocene alluvial deposits are well constrained by 25 radiocarbon dates (Reneau, unpubl., 1995), but no firm radiometric ages are available for the Pleistocene terraces.

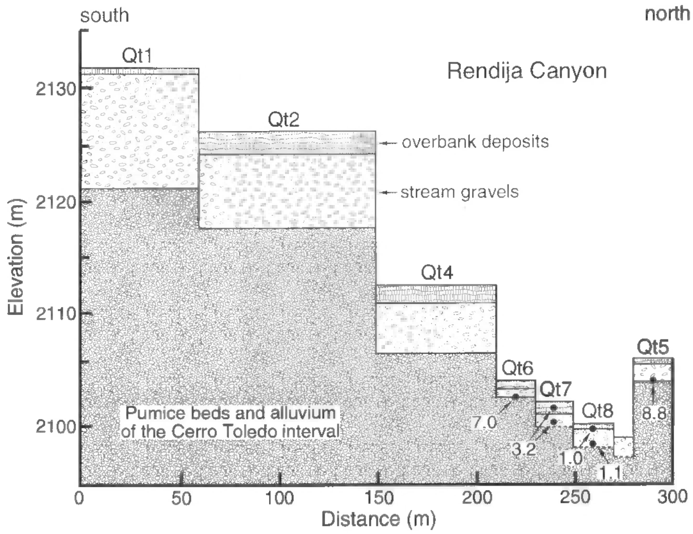

FIGURE 2. Schematic diagram of alluvial terrace sequence in Rendija Canyon. Distribution and height of terraces generally depicts sequence along terraces in upper portion of canyon (soil sites: RCT8-1, RCT7-1, RCT6-1, RCT4-1, RCT2-1 and RCT1-1). Radiocarbon ages (solid circles) shown are for gravelly stream deposits. The Qt5 terrace is poorly preserved with most of the original soil removed from erosion or deeply covered with colluvium.

Soil-forming environment

Modern vegetation along terrace surfaces largely consists of Ponderosa Pine woodland with an understory of annual grasses and forbs. Historic (1911–1986) annual precipitation is about 48 cm and annual mean daily air temperature is about 9°C (Bowen, 1992). Modern precipitation largely occurs biannually, with most precipitation falling between May and October from summer convective storms and between November and March from winter frontal storms. Parent material for these soils mainly consists of alluvium derived from Tschicoma dacite and Bandelier Tuff, as described above, partially augmented by eolian deposition and localized colluvium and/or alluvium. All soil sites are located between 2050 and 2110 m elevation and along nearly level terrace surfaces.

METHODOLOGY

Soil profiles were described according to standard methods and nomenclature of the Soil Survey Staff (1981). Partial soil descriptions for representative soils found on each stratigraphic unit are presented in Table 2. Particle-size distribution was determined using a standard pipette method for representative bulk samples collected from each horizon. Reported volumetric gravel (>2 mm) contents were estimated in the field using standard percentage of composition/cover charts.

Soil morphology was quantified using the Soil Development Index (SDI) procedures according to Harden (1982) and Harden and Taylor (1983). Calculation of SDI values is based on a conversion of soil morphology (e.g., color, structure) into numerical data to enable semiquantitative comparisons of the degree of soil development. Points are assigned to each property based on the difference between the described soil property and the parent material. Points for each property are normalized to a percentage scale of maximum property development based on comparison of each property to a published or conceptual maximum value of development for each particular property. Maximum soil property values from Taylor (1988) were used to normalize soil property values in this study. Normalized property values are summed for each horizon and averaged yielding a Horizon Development Index (HDI) value, which provides an estimate of overall horizon development relative to a conceptual idea of maximum possible horizon development. HDI values are multiplied by horizon thickness and summed for each profile yielding a Profile Development Index (PDI) value for that profile. PDI values provide a means of relative comparison among soils within a given sequence and can be used to develop soil chronofunctions. Index values were calculated for all described soils using morphologic properties of

TABLE 1. Radiocarbon dates from Rendija Canyon soil sites.

Laboratory Number	Field Number	^{14}C Date (yr B.P.)	Sample Depth (m)	Notes
Soil Pit RCT8-1, 1.3 m high Qt8 terrace				
Beta-84730	GM-32	1010 ± 50	0.7	stream sands
Beta-84729	GM-30	1070 ± 50	1.7	gravelly stream deposit
Soil Pit RCT8-2, 1.7 m high Qt8 terrace				
Beta-84734	GM-39	490 ± 60	0.3	sandy floodplain deposit
Beta-84733	GM-38	510 ± 60	0.7	gravelly stream deposit
Beta-84735	GM-40	1580 ± 60	1.9	buried floodplain deposit
Soil Pit RCT7-1, 3.2 m high Qt7 terrace				
Beta-84736	GM-41	3220 ± 60	0.6	floodplain deposit
Beta-84728	GM-29	3200 ± 60	1.5	gravelly stream deposit
Soil Pit RCT6-1, 5.7 m high Qt6 terrace				
Beta-84737	GM-43	720 ± 60	1.1	floodplain deposit; believed to be too young
Beta-84727	GM-28	6950 ± 80	1.6	gravelly stream deposit
Soil Pit RCT6-2, 4.8 m high Qt6 terrace				
Beta-84496	GM-25	5980 ± 40	2.5	gravelly stream deposit
Soil Pit RCT6-3, 5.0 m high Qt6 terrace				
Beta-59672	GM-5	2140 ± 65	0.5	floodplain sediments, sampled in stream bank near pit RCT6-2; believed to be too young
Beta-84732	GM-35	5280 ± 60	1.0	uppermost stream deposit
Beta-84731	GM-34	5920 ± 50	1.7	gravelly stream deposit
Bank exposure, buried colluvial soil above >7 m high Qt4 (?) terrace				
Beta-84726	GM-24	11,480 ± 50	1.0	colluvium; maximum-limiting age for overlying Holocene colluvial deposit
Soil Pit RCT4-1, ~9 m high Qt4 terrace				
Beta-84728	GM-46	13,820 ± 60	0.8	buried soil; maximum-limiting age for overlying Holocene colluvial deposit

Notes:
* All radiocarbon dates are AMS analyses on disseminated charcoal fragments, and are corrected for $\delta^{13}C$. Uncertainties are 1σ values reported by laboratory. This table only includes dates relevant to sampled soils.

TABLE 2. Summary of soil morphology for representative soil profiles developed on alluvial terraces in Rendija Canyon and in sediment overlying the El Cajete Pumice. Notations for soil morphology from Soil Survey Staff (1981) and Birkeland (1984).

Terrace (Soil #)	Horizon	Depth (cm)	Dry Color (Matrix)	Moist Color (Matrix)	Txt.[a]	Structure	Consistence			Argillans	% >2mm	CS[b]	% wt. Sand	% wt. Silt	% wt. Clay
							Dry	Moist	Wet						
Qt8	A1	0--9	10YR 4/3	10YR 2/2	l	1 m sbk:1-2 m,f crb	sh-so	vfr	so, po		3--8		60	32	8
(RCT8-2)	A2	9--14	10YR 4/2	10YR 2/1	sl	1 m sbk:1 m,f crb	sh-so	vfr	so, ps		3--8		77	17	6
	BA	14--26	10YR 4/2	10YR 3/2	sl	1 m,f sbk	so	vfr	so, ps		5--10		77	18	5
	Bw	26--39	10YR 4.5/2	10YR 3/2	ls	1 m sbk	sh-so	vfr	so, vps		5--10		83	19	3
	CB	39--54	10YR 5/3	10YR 4/2	ls	sg	so-lo	lo	so, vps		10--20		90	8	2
	C1	54--85	10YR 5.5/2	10YR 4/2	s	sg	lo	lo	so, po		25--40		98	2	1
	C2	85--140	10YR 6/3	10YR 4/2	s	sg	lo	lo	so, po		25--40		97	2	1
Qt7	C	0--8	10YR 5/4	10YR 4/3	l	1 m,f pl	sh	fr	vss, ps		2--4		39	50	11
(RCT7-1)	A	8--17	10YR 3/2	10YR 2/1	sl	1 m,f sbk	sh-so	vfr	vss, ps		5--15		72	22	6
	Bw1	17--26	10YR 5/2.5	10YR 3/3	sl	1 c,m sbk	so	vfr	vo, pss		10--25		77	19	4
	Bw2	26--69	10YR 5/2.5	10YR 3/2.5	sl	1 c,m sbk	so	vfr-lo	vo, pss		15--25		76	21	4
	CB	69--95	10YR 5/3	10YR 3/2.5	sl	m + 1 c,m sbk	so	vfr-lo	vo, pss		15--25		77	20	4
	C	95--155	10YR 5/3	10YR 3/3	ls	sg	lo	lo	so, po		40--60		86	12	2
Qt6	A	0--8	10YR 5.5/3	10YR 3/2	sil	1 m pr:1c,m,f sbk	so	vfr	ss, ps		3--8		40	51	9
(RCT6-3)	BA	8--15	8.75YR 5/3	8.75YR 4/2	sil	2 m pl:1 m sbk	sh	vfr	s-ss, p-ps		3--8		19	64	16
	Bw1	15--27	10YR 5/3	10YR 4/2	sil	1 m sbk	h	fr-vfr	ss, ps		3--8		60	30	11
	Bw2	27--60	10YR 5/2	10YR 3/2	l	1 c,m sbk	sh	vfr	ss, ps-vps	vf f br	20--30		66	25	9
	Bw3	60--79	10YR 6/3	10YR 4/2	sl	1 c,m sbk	sh	vfr	so, vps		25--40		81	14	5
	Bw4	79--116	10YR 5.5/3	10YR 4/3	ls	sg	so-lo	vfr-lo	so, vps-po		35--50		80	15	5
	C1	116--165	10YR 6/2	10YR 4/2	s	sg	lo	lo	so, po		50--70		86	13	1
	C2	165--205	10YR 6/2	10YR 4/2	s	sg	lo	lo	so, po		5--15		98	2	0
Qt4	A	0--8	10YR 5.5/3	10YR 4/3	sil	2 m,f pl:1 m sbk	sh	vfr	ss, ps		3--8		34	57	9
(RCT4-1)	Bw1	8--34	8.75YR 6/4	8.75YR 4/3	sil	1-2 m pr:1-2 c,m,f sbk	sh	vfr	ss, ps		3--8		34	51	15
	Bw2	34--52	8.75YR 5/3	8.75YR 4/3	sil	1-2 m pr:1-2 c,m,f sbk	sh-so	vfr	ss, ps		3--8		29	55	15
	Bw3	52--69	10YR 5/3	10YR 4/3	sil	1-2 m pr:2-1 c,m sbk	sh	fr	ss, ps-p		3--8		28	57	15
	Bt1b	69--90	7.5YR 6/3	7.5YR 4/3	sil	1-2 m pr:1-2 c,m,f sbk	h	fi-dr	ss, ps-p	3npr:pf, 2npo, 1nsbk:pf	5--10		34	53	13
	Bt2b	90--109	7.5YR 6/3	7.5YR 4/3	sil	1-2 m pr:1-2 c,m,f sbk	h	fr	ss, ps-p	3n-mkpo, 1npr:pf	10--15		38	54	7
	Btk1b	109--126	10YR 4/3	10YR 5/3	l	1-2 m pr:1-2 c,m sbk	vh-h	fi-fr	s-s, ps	3npo, 1npf	5--15	II-	44	46	10
	Btk2b	126--162	10YR 5/3	10YR 4/3	l	2-1 m pr:1-2 c,m sbk	vh-h	fi-fr	ss, ps-p	3npo	5--10	I	51	39	9
	Btk3b	162--172	8.75YR 5/4	8.75YR 4/3	sl	1 m pr:1 c,m sbk	vh-h	fr	ss, ps	3n-mkpo	15--20	I-	63	29	9
	Btk4b	172--198	10YR 5/3.5	8.75YR 4/3	sl	1 m pr:1 c,m sbk	h	fi-fr	s-ss, ps	2npo, 1npf	15--20	I-	70	21	9
	Btb	198--226	8.75YR 6/3	7.5YR 4/3	sl	sg	so	vfr-lo	so, ps	2nco	45--55		65	24	11
	BCb	226--274	8.75YR 5/4	8.75YR 4/3	ls	sg	so	vfr	so, ps	1nco	45--55		80	12	9
Qt2	A	0--10	10YR 5/3	10YR 3.5/2	sil	1 m sbk	so	vfr	s, ps		2--5		18	68	13
(RCT2-2)	BA	10--28	10YR 5/3	10YR 3/2	sil	1-2 c,m sbk	sh	fr	ss, ps		2--5		17	66	16
	Bw1	28--49	10YR 5/3	8.75YR 3/3	sil	1-2 m pr:2-1 c,m sbk	sh	fr-vfr	ss, ps		3--8		19	67	15
	Bw2	49--63	10YR 5.5/3	10YR 3/2	sil	1-2 m pr:2-1 c,m sbk	sh	fr-vfr	ss, ps		3--8		19	67	14
	Bw3	63--77	10YR 6/3	10YR 4/3	sil	1-2 m pr:2 c,m sbk	h	fr	s, ps	v1nco + po	3--8		24	63	13
	Bt1b1	77--90	10YR 6/3	8.75YR 4/3	sil	1-2 m pr:1-2 m pl+1-2 c,m sbk	h	fr-fi	s, p	3n-mkpf, 3n-mkpo	2--5		24	58	18
	Bt2b1	90--107	10YR 6/3	10YR 4/3	sil	2-1 m pr:2 c,m abk+sbk	h	fi	ss, p-ps	4mkpf + po	2--5		28	58	13
	Btk1b2	107--123	10YR 6/3	10YR 4/3	sil	1 c,m pr:1-2 c,m abk	vh	fi	ss, p-ps	4mkpf + po	2--5	I	33	57	10
	Btk2b2	123--143	10YR 6/3	10YR 4/3	sil	1 c,m pr: 1-2 c,m abk	vh	vfi	ss, ps	4n-mkpo, 4npr:pf	2--5	I	36	55	9
	Bt1b2	143--177	7.5YR 5/4	6.25YR 4/3	sil	2-1 m,f pr:3-2 c,m abk	h	fr	s-ss, p	4mkpf + po	10--20		28	50	22
	Bt2b2	177--214	7.5YR 5/4	6.25YR 4/3	sil	2 m pr:2 c,m abk+sbk	h	fi-fr	ss, p	4mkpo, 4n-mkpr:pf, 3n-mkbk:pf	15--25		33	50	16
	Bt3b2	214--257	7.5YR 5.5/4	7.5YR 4/4	l	1 m pr:2-1 c,m sbk	h	fi-fr	ss, p-ps	4n-mkpo, 3n-mkpr:pf, 1nbk:pf	10--20		38	49	14
	Bt4b2	257--278	7.5YR 6/4	7.5YR 4/4	l	1 c,m sbk	h-sh	fr	s, ps-vps	3n-mkpo, 2nbr, 1npf	10--20		43	44	13
	Bt5b2	278--319	10YR 6/4	8.75YR 4/3	l	1 c,m sbk + m	h-sh	fr-vfr	ss, p	3npo, 2nbr	25--40		47	40	12
	BCb2	319--348	10YR 6/4	10YR 4/4	sl	m	h	fr-vfr	ss, vps	2fpo	15--25		64	30	6
Qt1	A	0--6	8.75YR 5/3	7.5YR 3/3	l	1-2 m pl:1-2 m,f sbk	sh	vfr	ss, ps		2--5		48	43	9
(RCT1-1)	BA1	6--19	8.75YR 5/4	7.5YR 3/3	l	1-2 m,f pl:1-2 m,f sbk	so	vfr	ss, ps		2--5		37	49	14
	BA2	19--41	7.5YR 6/4	7.5YR 4/3	l	1-2 m pl:1-2 c,m sbk	sh	vfr-fr	ss, ps	1npr:pf	2--5		41	46	14
	Bt1	41--51	7.5YR 6/4	7.5YR 4/4	l	1-2 c,m sbk	sh-h	fr	ss, ps	2n-mkpf	2--5		45	39	16
	Bt2	51--68	7.5YR 6/4	7.5YR 4/3	sil	1-2 m pl:1-2 c,m abk + sbk	h	fr	ss, ps	3n-mkpo, 3n-mkpf	5--10		32	50	17
	Btkqm	68--85	8.75YR 6/3	7.5YR 4/3	sil	1-2 c,m pr:2-1 c,m pl	vh	efi	ss, ps	3npo, 3npr:pf	10--30	II	38	51	11
	Btk1	85--96	6.25YR 4/4	5YR 4/4	sl	1 c,m sbk	h	fr-vfr	ss-s, ps	4n-mkbr, 4n-mkbr	30--40	I	59	27	14
	Btk2	96--111	6.25YR 4/4	5YR 4/4	sl	1-2 c,m sbk	h	fr-vfr	ss-s, ps	4mkpo	35--45	I	58	24	17
	Btk3	111--137	7.5YR 6/4	7.5YR 4/4	ls	m	h	fr-vfr	ss, ps	1nbr, lam:3n-mkbr	25--35	I	78	21	1
	Btk4	137--190	7.5YR 6/4	7.5YR 3.5/4	ls	m	h	fr-vfr	ss, ps	1nbr, lam:3n-mkbr	25--40	I-	80	13	7
	BC	190--217	8.75YR 6/4	7.5YR 4/4	ls	m	sh-h	fr-vfr	vss, vps	1npo	2--5		84	16	1
	CB1	217--245	8.75YR 6/4	7.5YR 5/4	s	m	sh	vfr	so, po	1nco	30--40		89	9	2
	CB2	245--290	10YR 6/4	10YR 5/4	s	m	sh	vfr	so, po		10--15		86	10	3
Post EC[c]	A	0--4	10YR 4/2	10YR 2/3	sil	2-1 m,f pl:1-2 m sbk	sh-so	vfr	ss, ps		2--5				
(WJR-5)	Bw	4--23	10YR 6/3	10YR 4/3	sil	1 c,m sbk	sh-h	vfr	ss, ps		2--5				
	Bt1	23--39	10YR 6/3	8.75YR 4/3	sil	1 m pr:1-2 c,m sbk	h-sh	fr	ss, ps	3npr:pf, 1npf	2--5				
	Bt2	39--61	7.5YR 6/4	7.5YR 4/4	sil	2-3 m,f pr:2.- m abk+sbk	h	fr-fi	ss, ps	4mk-npr:pf, 3n-mkbk:pf, 3n-mkpo	5--10				
	Bt3	61--84	7.5YR 6/3	7.5YR 4/3	sil	2 m pr:2 c,m sbk+abk	h-sh	fr	ss, p	3n-mkpr:pf, 3n-mkpo, 2mk-nbk:pf	5--15				
	Bt4	84--106	7.5YR 6/4	7.5YR 4/4	sil	2-1 m pr:2 c,m sbk	h	fr	ss, ps-p	4n-mkpo, 3mk-npr:pf, 1nbk:pf	10--20				
	Bt5	106--132	10 YR 6/3	7.5YR 4/3	sil	1 m pr:2-1 c,m sbk	h-sh	fr	ss-s, ps-p	3n-mkpr:pf, 3n-mkpo, 1n-mkbk:pf	10--20				
	2Bt1	132--148	10 YR 8/2	10 YR 7/4	ls	sg	so-lo	vfr	vss-ss, vps	1-v1fco+br, lam:3mk-nco+br	30--50				
	2Bt2	148--203	10 YR 8/3	10 YR 7/4	ls	sg	so-lo	fr-lo	vss, vps	1-v1fco+br, lam:4mk-nco+br	30--50				
	2Bt3	203--221	10 YR 5/4	10 YR 4/4	ls	sg	so-lo	vfr-lo	vss-ss, vps	1-v1fco+br, lam:4mk-kco+br	30--50				

[a]Soil textural class
[b]Secondary carbonate stage (Gile *et al*., 1966)
[c]Soil formed in sediments overlying the 50 to 60 ka El Cajete Pumice.

rubification, texture, structure, dry and moist consistence, and argillans (clay skins).

An important consideration in applying the SDI is determining the soil parent material values. Parent material values for each profile were adjusted to reflect vertical changes in texture, consistence, and color of parent material that correspond to vertical stratification and fining of alluvial sediments due to overbank deposits and/or subsequent colluvial deposition.

RESULTS AND DISCUSSION

Soils formed on Holocene stream terraces

Holocene soils show progressive thickening and development of the Bw horizon as the most systematic change with increasing age (Fig. 3). Soils developed on the Qt8 surface consist of a weakly developed profile that has an Ochric epipedon overlying a thin (<20 cm) Bw horizon with weakly developed subangular blocky structure, no cutans, and a matrix color that has a slightly higher chroma than that of the parent material (Table 2). Radiocarbon dates from two of these Qt8 soils ranged from 0.5 to 1.0 ka (Table 1). A soil developed on a Qt7 surface, which yielded radiocarbon ages of about 3.2 ^{14}C ka, is generally similar to those on the Qt8 except that total Bw horizon thickness has increased to 52 cm. Mean PDI values for the Qt8 are 4.2 and a single Qt7 soil yielded a value of 7.4 (Table 3).

Textures within the Qt7 and Qt8 soils generally become finer upward. The soil matrix within the upper 25 to 40 cm in Qt8 and Qt7 soils is largely sandy loam to loam with a clay content usually between about 5 to 10 wt% and a gravel content (>2 mm) of less than about 20% volume. By comparison, C horizons are generally loamy sand to sand and have a clay content less than about 5 wt% and gravel content of greater than 20% volume. The finer texture within the upper profile is largely attributed to greater deposition of fine sediments associated with overbank deposition, with contributions also from either eolian and local colluvium, rather than in situ weathering of soil matrix. Enhanced eolian deposition during the Holocene has been recognized in other places on the Pajarito Plateau and several soils within this study contain evidence of local colluvial sedimentation (e.g., RCT7-1, Table 2).

Radiocarbon ages from charcoal in gravely Qt6 stream deposits yielded ages from about 5.3 to 7.0 ^{14}C ka (Table 1). Soils developed on the Qt6 surface demonstrate progressive thickening of the Bw horizon, with a total Bw thickness of 64 to 99 cm (Fig. 3, Table 3). Soil structure, rubification, and consistence are also slightly greater in the Qt6 soils than in the Qt7 and Qt8 soils (Table 2). Progressive development of the Bw horizon in Qt6 soils relative to younger soils is also reflected in depth plots of HDI values (Fig. 4). Clay and silt content are slightly increased in Qt6 soils relative to soils formed on younger terraces (Table 2). This increase is probably due to addition of fine sediments from either eolian or local colluvial deposition rather than mineral weathering because of a lack of associated features of mineral weathering such as an increase in rubification. The RCT6-1 soil has a thin (13 cm) weakly developed Bt horizon and overall better structure and rubification than other studied Ot6 soils. This soil, however, has formed on a small terrace remnant that lies at the foot of a Qt4 terrace riser and is covered with a 20 to 40-cm-thick colluvial wedge. Additions of fine-grained sediment from this wedge have apparently increased the rate of soil development relative to other Qt6 soils. Increases in the rate of soil formation in soils along terrace risers has been documented elsewhere (Harrison et al., 1990). A mean PDI value for the three Qt6 soils is about 15.0; however, this average may be too high because a PDI value of 19.7 for the RCT6-1 soil may not be representative of a typical soil formed on Qt6 terraces.

Soils were not analyzed for the Qt5 terrace because poor preservation has resulted in nearly complete stripping or burial of soils on this terrace.

Soils formed on Pleistocene stream terraces

Soils formed on the Qt4 and Qt2 surfaces have been buried in places by a thin (<1 m) layer of sediment generally associated with the distal deposition of small alluvial fans that are derived from nearby higher terraces or hillslopes (A and Bw horizons in Fig. 3). Low sand content and high silt and clay contents for this layer also suggest possibly significant

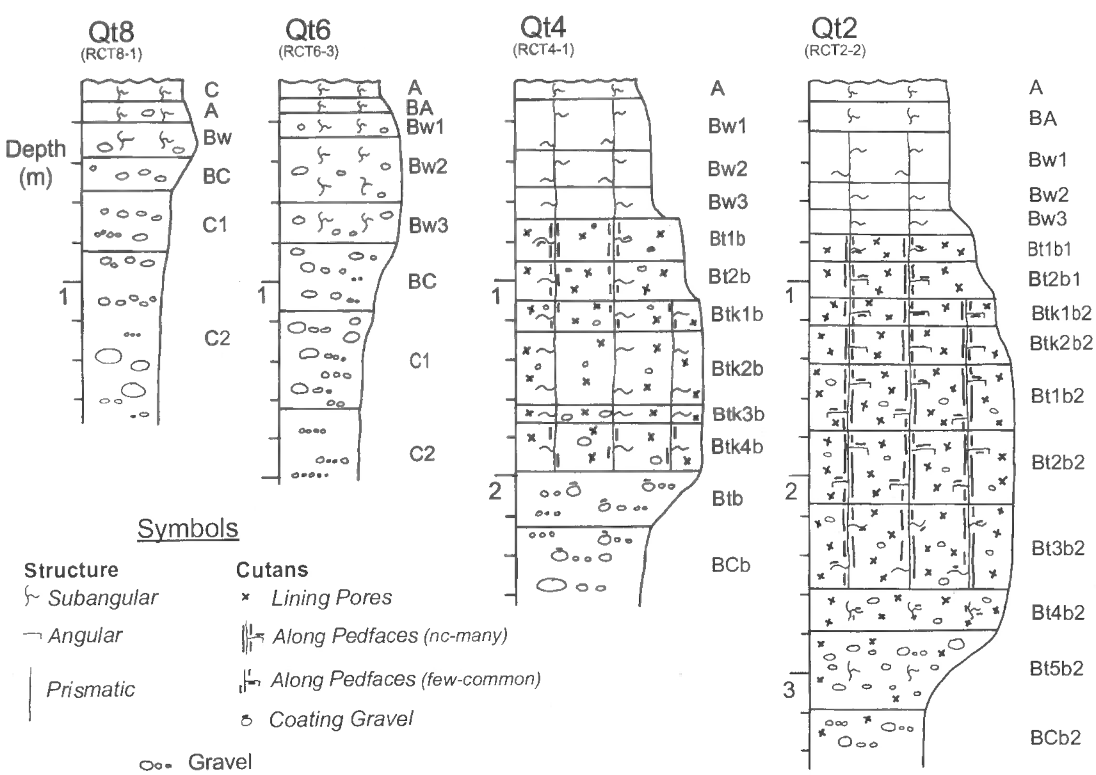

FIGURE 3. Schematic diagram of dominant soil morphology of soil profiles formed on four of the terraces in Rendija Canyon. Sequence represents systematic increases in B horizon development and thickness, especially development of structure and argillans along pedfaces and pores. Note the difference in soil morphology between soils formed in alluvial cap and underlying buried soils on the Qt2 and Qt4 terraces. Symbols for abundance of cutans on pedfaces represent either nearly-continuous (nc) to many or few to common.

TABLE 3. Summary of B horizon thickness, Profile Development Index, and soil ages.

Soil	Soil #	Bw Thickness (cm)	Bt Thickness (cm)	PDI	Mean PDI	Site Specific Age (ka)[a]	Age Range (ka)[b]	Estimated Age (ka) Using PDI[c]
Qt8	RCT8-1	16		3.9		1.0-1.1	0.5-2.1	
	RCT8-2	12		4.1		0.49-0.51, <1.5	0.5-2.1	
	RCT8-3	19		4.7	4.2±0.4		0.5-2.1	1.6
Qt7	RCT7-1	52		7.4	7.4	3.2	2.6-4.0	
Qt6	RCT6-1	67	13	19.7		7.0	5.3-6.9	
	RCT6-2	64		14.3		6.0	5.3-6.9	
	RCT6-3	99		10.9	15.0±4.4	5.3-6.0	5.3-6.9	
HCW[d]	RCT4-1-H	61		17.1			<11.5-13.8	
	RCT4-2-H	85		21.2		<13.8	<11.5-13.8	
	RCT2-1-H	45		15.5			<11.5-13.8	
	RCT2-2-H	49		19.6	17.9±2.4		<11.5-13.8	
Post EC[e]	WJR-5	23	182	70.3	70.3	50-60	50-60	
Qt4	RCT4-1		157	76.4			20-100	75.8
	RCT4-2		124	73.5	75.0±2.1	>13.8	20-100	71.8
Qt2	RCT2-1		276	97.0			100-200	105.5
	RCT2-2		291	129.6			100-200	157.7
	RCT2-3		202	111.9	112.0±16.3		100-200	128.7
Qt1	RCT1-1	41	149	71.7			150--300	>71.7
	RCT1-2		189	97.0	84.4±17.9		150--300	>97.0

[a]Radiocarbon dates from Table 1.
[b]Range for: (1)Qt8-Qt6 from 25 radiocarbon dates from Rendija Canyon (Reneau, unpubl., 1995), (2) HCW from Table 1, (3) Qt4-Qt1 from Wong et al.(unpubl., 1995) based on relative comparisons of soil development.
[c]Soil ages calculated from linear regression results in Fig 5.
[d]Soils formed in Holocene (<11.5-13.8 ka) colluvial wedge overlying QT2 and Qt4 soils.
[e]Soil formed in collium and loess overlying the ca. 50-60 ka El Cajete Tephra. Date for El Cajete from Reneau et al. (1995)

contributions from eolian deposition (Table 2). Charcoal from the upper part of a Qt4 soil underlying the alluvium yielded an age of about 13.8 ^{14}C ka; charcoal from the base of colluvium above a truncated, buried soil that appears to be stratigraphically equivalent to the Qt4 yielded an age of about 11.5 ^{14}C ka (Table 1). Soils formed in the thin layer of alluvium that caps the Qt2 and Qt4 terrace soils have very similar morphology, consisting of well developed Bw horizons with prismatic structure that parts to subangular blocky structure, and color hues that are up to 8.75YR. Clay content in the Bw horizons generally ranges from about 12 to 16 wt% and is generally greater than that of soils formed on Holocene terraces. A lack of obvious evidence of eluviation or in-situ weathering suggests that these high clay contents largely reflect parent material texture; however, abundant evidence of bioturbation from burrowing fauna (possibly cicadas and earthworms) may have resulted in enough mixing of the soil matrix to prevent accumulation of oriented clays and silt along pedologic features. Development of extensive argillans along pores and pedfaces within the upper horizons of the underlying, buried soil indicates that downward translocation of clay must be occurring within the overlying Bw horizons.

The overall degree of development for soils formed in the alluvial cap, reflected by PDI values that range from 15.5 to 21.2, is greater than that displayed by soils formed on the Qt6 (except RCT6-1) and younger terraces indicating that deposition of the alluvium probably began before about 6.0 ka. In addition, strong similarities in profile morphology among the soils formed in the alluvial cap indicates that deposition of this alluvium was probably contemporaneous across both the Qt4 and Qt2 terrace surfaces. Best age estimates for soils formed in this layer suggests that deposition probably began after about 11.5 to 13 ^{14}C ka with soil formation occurring throughout the Holocene.

Soils formed on the Qt4 and Qt2 deposits and that underlie the alluvial layer show considerably greater development than soils formed in Holocene deposits (Fig. 3, Table 2). Soils formed in Qt4 deposits have prismatic structure that parts to subangular blocky structure, 7.5YR to 10YR hues, discontinuous and moderately thick to thin argillans along pedfaces and pores, and a total Bt thickness of about 150 cm. Clay content in Qt4 soil Bt horizons average about 7 to 13 wt%, which is less than the overlying soils formed in the alluvial cap. Soils formed in Qt2 deposits show significantly better development relative to soils formed in the Qt4 alluvium. Qt2 soils have prismatic structure that parts to angular and/or subangular blocky structure, 6.25YR to 10YR hues, moderately thick to thin argillans along pedfaces and pores that are nearly continuous in the strongest Bt horizons, and a total Bt thickness of about 215 cm. Clay content in Qt2 soil Bt horizons range from about 8 to 24 wt%. An increase in clay content in both Qt4 and Qt2 Bt horizons may be due largely to additions of clay from eolian sources and overlying alluvium because most of the argillans occur along pores and vertical pedfaces, indicating substantial illuviation of clay into the Bt horizons. State I to weak state II secondary calcium carbonate has accumulated within a few of the Bt horizons in both Qt2 and Qt4 soils (Table 2). This carbonate is largely superimposed over argillans along prismatic pedfaces, suggesting a more recent (Holocene?) increase in soil aridity or at least a decrease in the downward flux of soil water through the upper Bt horizons.

Mean PDI values for the Qt4 and Qt2 soils (including soils formed in the alluvial cap) are 75.0 and 112.6, respectively. Because soil profile descriptions could not be extended to the unaltered C horizons due to limitations of soil pit depth, these PDI values may be about 2 to 5 points too low depending on the depth to the C horizon. Depth plots of HDI values demonstrate the significantly greater development of the Qt4 and Qt2 soils relative to soils formed in Holocene deposits (Fig. 4). A significant increase in HDI values at about 75 cm reflects the contact between the buried Qt4 and Qt2 soils and overlying soil and alluvium.

Soils formed on the Qt1 surface are spatially variable, with laterally discontinuous B horizons indicating that at least part of the original soil is missing due to truncation by surface erosion. Furthermore, most of the Qt1 has been eroded, leaving only scattered remnants. Some preserved Bt horizons show an overall greater degree of development than Bt horizons in the Qt2 soils, although the Bt horizon is substantially thinner than that in Qt2 soils. Soils formed in Qt1 deposits have prismatic structure that parts to subangular and angular blocky structure, 5YR to 10YR hues, moderately thick to thin argillans along pedfaces and pores, and Bt horizon thickness of about 160 cm. PDI values for the Qt1 average 84.4 and are lower than those for Qt2 soils, reflecting the decrease in profile thickness of the Qt1 soils due to the probable loss of well-developed Bt horizons from erosion.

Soil formed in sediments overlying the El Cajete pumice

A soil (WJR-5, Table 2) formed in a layer of sediment that overlies the ca. 50 to 60 ka El Cajete Pumice (Reneau et al., 1996) provides additional information for soils formed within late Pleistocene time. This soil is located about 12 km southwest of Rendija Canyon along the western boundary of the Pajarito Plateau (2330 m elevation and just southwest of the gate to LANL TA-16), and has formed under vegetation and climate that is generally similar to that for soils formed in Rendija Canyon. Soil parent materials appear to have been loamy sediments derived

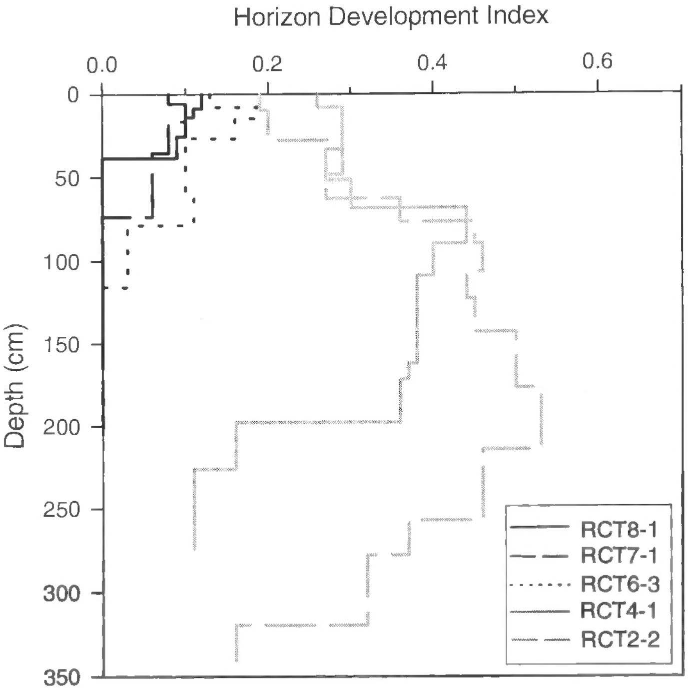

FIGURE 4. Depth plot of HDI values for soils shown in Table 2 (except RCT8-1). HDI values are the average of normalized property values for each horizon and provide a relative indicator of horizon strength.

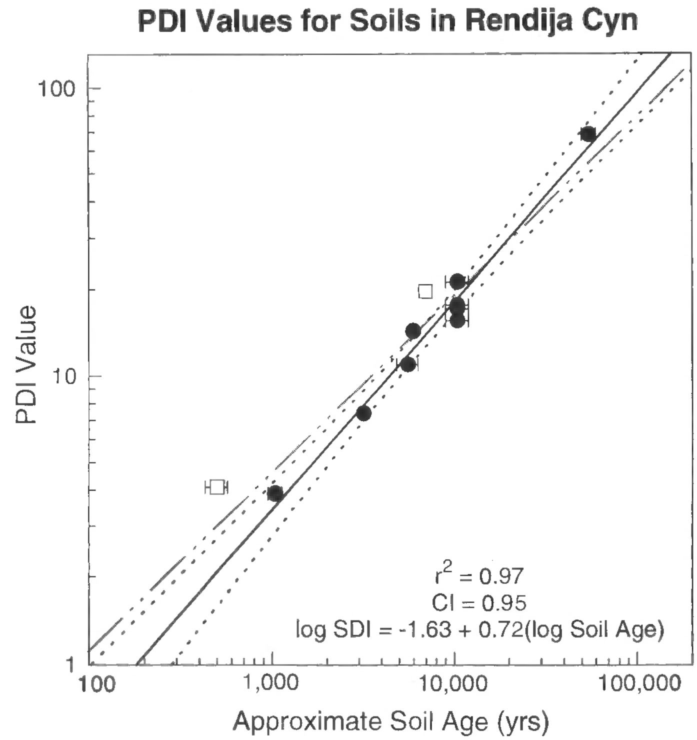

FIGURE 5. Soil chronofunction (solid line) developed using linear regression of dated soils (solid circles) used in this study. Dotted line represents the 95% confidence interval (CI) for regression line. Two soils were excluded from data set (open boxes) due to possible inconsistencies between PDI values and soil dates. A second chronofunction (dash-dot-dot line) reflects the impact that inclusion of the 0.5 ka RCT8-2 soil has on the slope of the line.

from alluvium from nearby hillslopes of Bandelier Tuff and probably supplemented from eolian deposition, with pumice largely restricted to depths below 132 cm. The El Cajete at this site is nearly 100 cm thick and consists of primary fallout pumice with little evidence of reworking. The pumice overlies an older, gently sloping alluvial fan surface. Although this soil formed under slightly different conditions (i.e., elevation, parent material) than soils formed in Rendija Canyon, the overall similarity of the soil-forming environment and the fact that the initial texture of the parent material is generally similar (i.e., loamy sand to silt loam) indicates that the WJR-5 soil can provide a good approximation of soil-forming processes for soils developed in Pleistocene sediments in Rendija Canyon.

The soil formed in the post-El Cajete deposits has prismatic structure that parts to subangular blocky structure, 7.5YR to 10YR hues, moderately thick to thin argillans along pedfaces and pores, and a total Bt thickness of about 200 cm (including 100 cm of pumice). The pumice is largely unweathered but is covered with moderately thick to thin argillans that coat and bridge pumice and form lamellae in places. A PDI value of 70.3 was calculated for total soil formation in both the sediment and underlying pumice. Because the top of the pumice is only slightly bioturbated and lacks significant weathering, the pumice was quickly buried by the overlying sediments. As a result, this soil probably provides a good indication of the extent of soil formation that can occur within the study area over the last 50 to 60 ka.

Development of soil chronofunction for Rendija Canyon soils

Soil ages can be estimated based on a systematic increase in soil profile morphology using simple linear regression analysis of logarithmic relationships between PDI values and ages of dated soils (Fig. 5). Several different methods of linear statistical analyses have been employed for evaluating rates of soil development based on SDI values and to account for poor age control of studied soil surfaces (Switzer et al., 1988; Harden, 1990; Harden et al., 1991). For this study, simple linear regression was used to develop a soil chronofunction based on temporal increases in PDI values and to provide age estimates for non-dated surfaces.

The nine best dated soils were used to develop the soil chronofunction shown in Figure 5. Because of the relatively large range of ages for Holocene terraces (Table 3) only PDI values from soils that were directly dated were used. PDI values from soils developed in the alluvial cap that overlies the Qt4 and Qt2 soils and the post-El Cajete soil were also included in the data set. Two dated soils were excluded from development of the soil chronofunction. The RCT8-2 soil has a radiocarbon age about half that of the other dated Qt8, but a similar PDI value (Tables 1, 3). Inclusion of this soil within the data set resulted in a correspondingly large shift in the chronofunction (Fig. 5). We decided to omit the RCT8-2 soil from our best estimate of the soil chronofunction for Rendija Canyon because better linear agreement among all other soils results when the RCT8-2 soil is omitted; a 500-yr difference in dates for the Qt8 has such a large impact on the resulting soil chronofunction; and because of the relatively low PDI values for very young, weakly developed soils that are insensitive to slight differences in soil age. Likewise, the RCT6-1 soil was omitted because of a possible increase in the rate of soil formation due to colluviation relative to the other Qt6 soils.

The soil chronofunction can be used to calculate approximate ages for each soil not directly dated by radiometric means (Table 3); however, given the uncertainties in both calculation of PDI numbers and in the slope of the soil chronofunction these ages are at best general approximations. A PDI value of 4.7 suggests that the undated RCT8-3 may be about 1.6 ka, which is older than the other two dated Qt8 soils but within the range of radiocarbon dates for apparent Qt8 deposits in Rendija Canyon. Best approximate age estimates for the Qt4 soils range from about 71.8 to 75.8 ka and for the Qt2 soils range from about 105.5 to 157.7 ka. Soils formed on the Qt1 must be older than soils formed on the Qt2; however, because of profile loss from erosion, the approximate age estimates for the remaining soil only range from >71.7 to >97.0 ka.

Regional incision and formation of strath terraces apparently occurred in the Española Basin between 80 and 130 ka, possibly in response to increased stream power due to regional changes in climate associated with periods of glaciation (Dethier et al., 1988). Stream incision and formation of strath terraces along the eastern flank of the San Luis Basin in northern New Mexico may also have been related to some aspect of climate change associated with glacial climate (Pazzaglia and Wells, 1990). General age estimates of about 70–80 and 105–180 ka (each range based on mean and standard deviation) for soils developed in the Qt4 and Qt2 terraces suggest a possible linkage between stream incision and stabilization of the terrace surface and increased stream power associated with middle to late Pleistocene periods of glaciation. However, much remains unknown regarding how fluvial systems along forested drainage basins in northern New Mexico respond to temporal fluctuations in climate. In addition, further work is required to substantiate and improve the preliminary age estimations for the Qt4 and Qt2 deposits based on the soil chronofunctions reported in this study.

CONCLUSIONS

Soils formed on alluvial terraces in Rendija Canyon display progressive and systematic patterns of profile development. Soils formed on Holocene surfaces show progressive thickening and development of Bw horizons. Soils formed in Pleistocene deposits show a considerable increase in development with soils that have thick Bt horizons and well developed structure and argillans along pores and pedfaces. Additions of soil matrix from colluvial, alluvial, or eolian sources has probably enhanced overall soil development and provides additional complications for evaluating temporal changes in the development of these soils.

Quantification of soil morphology using the Soil Development Index provides a means to use systematic increases in profile morphology of dated soils to estimate ages of non-dated soils and related deposits. The overall purpose of our study was to determine if soils can provide a viable means of dating surficial deposits across the Pajarito Plateau for environmental and seismic hazard investigations. The preliminary results presented here indicate that development and use of a soil chronofunction can provide important age control for these studies. Additional PDI values for dated Holocene soils, soils formed in other post-El Cajete deposits, or other late Pleistocene soils, supplemented with additional age control for terraces in Rendija Canyon using other dating methods, will provide a means to verify or adjust the soil chronofunction developed in this study.

Application of PDI values for estimating ages of soils and associated deposits requires additional points of discussion. First, each soil should be evaluated to determine if other geomorphic or environmental processes (e.g., deposition, erosion) have influenced either the rate of soil formation or the character of the soil profile. Second, an adequate number of well-dated soils is required to develop a viable soil chronofunction. Third, careful evaluation of the initial properties of the soil parent material throughout the profile is important to adequately estimate the degree of soil development. The application of PDI values for providing geologic age estimations, therefore, like any geochronologic method, requires a strong understanding of the systematics of the time-dependent process being used to provide age relations. In other words, the use of soils as a chronologic tool requires adequate knowledge of soils and geomorphology to separate systematic (i.e., time-dependent) changes in soil properties from random changes in soil properties (e.g., erosion, deposition).

Many questions remain regarding some of the chemical processes involved with formation of these soils. Investigations are underway that focus on the accumulation of secondary silica and oxyhydroxides of aluminum, and iron and the distribution and development of phyllosilicate minerals. Questions also remain regarding the possible influence of silt- and clay-size particles derived from eolian sources on soil formation in contrast to the possible in situ production of secondary clay and silt minerals due to breakdown of easily weatherable glass in the Bandelier Tuff debris that comprises much of the alluvial deposits these soils have formed from. Resolving these uncertainties will allow improved understanding of soil-forming processes on the Pajarito Plateau and improve confidence in our resultant age estimates.

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