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ALLUVIAL FAN STRATIGRAPHY ALONG THE SOUTHERN SACRAMENTO MOUNTAINS, N.M., AND INFERENCES REGARDING LATE QUATERNARY PALEOCLIMATE, SOILS, AND SEDIMENTATION

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ABSTRACT.—Geomorphic and sedimentologic studies of proximal alluvial fans along the western Sacramento Mountain front near Alamogordo, New Mexico, indicate four distinct stratigraphic units consisting predominately of pebbly to bouldery alluvium. The oldest unit, Qf1, is over 10 m thick and extends upward into canyon mouths as a thick fill. Unit Qf1 is composed of several stacked allostratigraphic subunits that are typically bounded by buried soils. Qf1 is late middle to late Pleistocene in age based on two C-14 dates together with sedimentologic and pedologic similarities with the Jornada II alluvium and older alluvial units of the Camp Rice piedmont facies of the Desert Project near Las Cruces. Unit Qfoi is a very local, buried inset gravel unit that may indicate general alluvial fan incision during the latest Pleistocene. Qf2 is 2-5 m thick, generally coarser than Qf1, and lacks buried soils. This unit commonly transitions upward from clast-supported, fluvial pebbles and cobbles to debris-flow deposits containing boulders. Three C-14 dates constrain the age of Qf2 as early Holocene. Unit Qf3 is typically inset into Qf1 and Qf2 near the mountain front and is 1-2 m thick. Soil, stratigraphic, and surface characteristics of Qf3 are consistent with a mid to late Holocene age.

Sedimentologic and soil data for these alluvial fan units, and identification of specific gastropod species in colluvium overlying Qf1, allow for generalized interpretations concerning paleoclimate and soil and sedimentation processes. The identified gastropod species in local colluvium imply that piñon-juniper-oak woodlands extended to the foot of the Sacramento Mountains during the latest Pleistocene, probably because of cooler temperatures and higher effective moisture. Abundant debris-flow deposition at 7.5-9.0 ka is interpreted to reflect a climate change from wetter to drier conditions and/or the arrival of intense summer monsoonal precipitation. Drier conditions in the middle and late Holocene were conducive to calcium carbonate and gypsum precipitation in the soil on fan surfaces, which masked Bt or Bw soils horizons and/or possibly inhibited their development.

INTRODUCTION

Past studies have indicated that relatively cooler and wetter conditions were present in the southwest United States during the latest Pleistocene (Spaulding et al., 1983; Van Devender et al., 1984, 1987; Hall, 1985; Spaulding and Graumlich, 1986; Waters, 1989; Van Devender, 1990; Mensing, 2001). For example, Lake Estancia of central New Mexico was at its highest level ca. 20 to 15 ka, after which the lake level lowered and finally dessicated after 12 ka (Allen and Anderson, 2000). The climate was still relatively cool with greater effective moisture, compared to the present, between 12 and 7-9 ka, after which there was a dramatic change to dryer and possibly warmer conditions (Van Devender et al., 1984, 1987; Hall, 1985; Waters, 1989; Buck and Monger, 1999).

Detailed study of the proximal alluvial fans along the western front of the southern Sacramento Mountains was conducted in order to characterize the activity and behavior of the Alamogordo fault (Koning and Pazzaglia, this volume). This study has resulted in sedimentologic, pedologic, and biologic data that are consistent with known late Quaternary climate changes. In this paper, these data are presented in the context of the alluvial fan stratigraphy and are used to offer some generalized interpretations regarding the relationship of late Quaternary paleoclimate to sedimentation and soil processes.

STUDY AREA

The alluvial fans along the Sacramento mountain-front near Alamogordo lie along the eastern margin of the fault-bounded, internally drained Tularosa Basin (Fig. 1). The eastern-bounding fault of this basin, the Alamogordo fault, separates deep basin fill from the uplifted Paleozoic carbonate strata that comprise the Sacramento Mountains. Rising as a footwall uplift east of the Alamogordo fault, these mountains range in elevation from 1340 m (4400 ft) to 2955 m (9695 ft) and are generally steep on their western side.

The Tularosa Basin supports Chihuahua Desert vegetation communities and has an arid to semiarid climate. The center of the basin is characterized by playas and sand dunes of both quartzose and gypsum composition; annual precipitation here averages 20-28 cm (8-11 in) (Houghton, 1981). Up to 64 cm (25 in) of precipitation can be expected for the highest parts of the Sacramento Mountains (Mclean, 1970). Most of the precipitation occurs in the late summer-early fall via convective storms. Wind direction is generally from the west or southwest; in late winter and spring, these winds commonly carry considerable dust due to relatively drier conditions (Houghton, 1981).

METHODS

Proximal alluvial fan depositional units were mapped at a scale of 1:24,000, and the alluvium was described using measured sections of exposures. Soils were described in the field using hand-excavated pits or hand-excavations of arroyo cut banks. Textural classification of gravelly alluvium follows Folk (1954), and soil nomenclature and descriptions follow the Soil Survey Staff (1992) and Birkeland et al. (1991). Abbreviations of relevant soil proper-

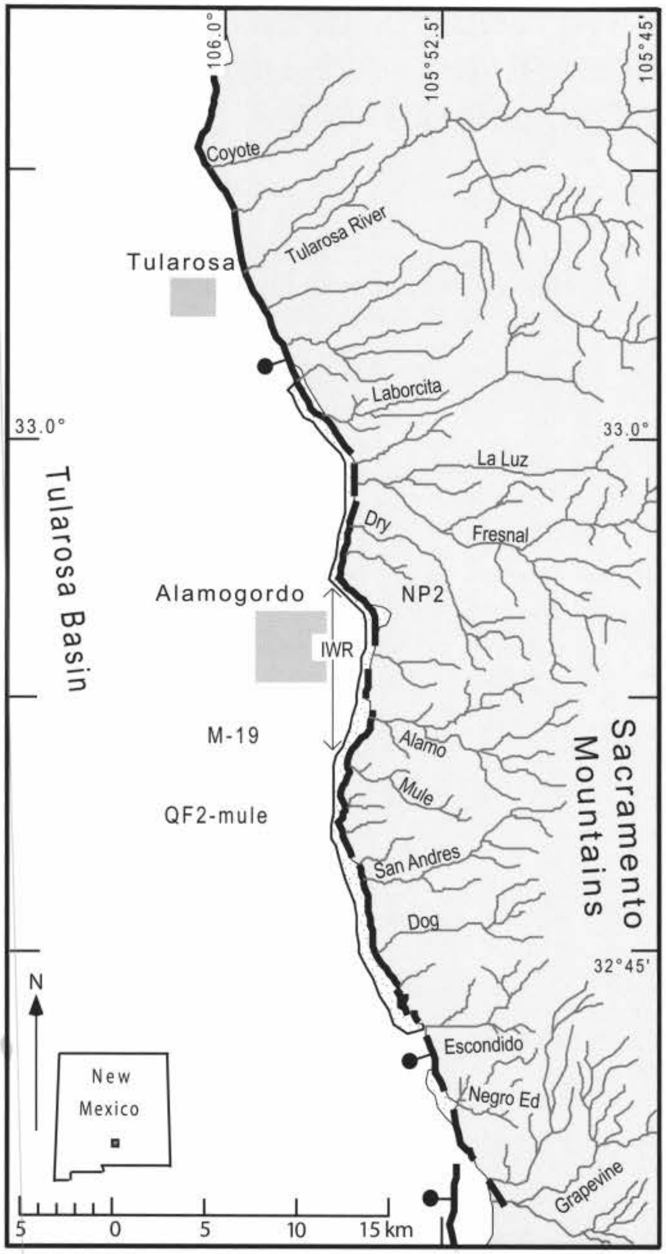

FIGURE 1. Map of study area. Sacramento Mountains shown by shaded area and canyons draining their west front are labeled. Stippled area is the approximate extent of mapped portions of alluvial fans (refer to Koning, 1999, for more detail of mapped area). Key exposures discussed in text are labeled (i.e., M-19, Qf2-mule, NP2). Surface trace of the Alamogordo fault (shown by bold black line) is based on this work and Michael Machette (personal commun., 1997). IWR = Indian Wells mountain-front reentrant.

ties and horizon nomenclature are listed in Table 1. Samples of organic material were collected for radiocarbon dating of specific deposits or horizons, and were analyzed by Beta Analytic Inc.

DATA

The alluvial fan deposits generally consist of poorly to moderately sorted, subangular to subrounded, silty-sandy gravel derived from the Sacramento Mountains. Three extensive alluvial fan depositional units can be distinguished and mapped based on sedimentologic and spatial (e.g., inset) relationships; these are labeled Qf1, Qf2, and Qf3, from oldest to youngest (Table 2; Koning and Pazzaglia, this volume, fig. 4). The three units also have unique surficial and soil characteristics, which are useful as relative age correlation criteria where exposures are lacking. An additional unit, Qfoi, represents older inset gravel intermediate in age between Qf1 and Qf2; this unit is buried, only recognized at two exposures, and was not mapped — which is why we give it a unique label. Three important localities exhibiting these depositional units are described below, followed by discussion of their age constraints.

Alluvial Fan Stratigraphy at Mouth of Mule Canyon

Qf1

The spatial distribution of unit Qf1 on the Mule Canyon fan is similar to that of other fans in the study area. For example, the unit is locally preserved in the proximal and medial regions of the alluvial fans, whereas in the distal regions of the fans it is generally buried by younger deposits. Also, the unit commonly extends into the lower reaches of mountain canyons as a thick (>10 m) alluvial fill (Fig. 2).

Qf2 and Qfoi

At the Qf2-mule exposure, 3.0-3.5 m of unit Qf2 unconformably overlies unit Qfoi (Figs. 2-3; Appendix 1). The lower ~1.5 m of Qf2 consist of clast-supported, imbricated pebbles and cobbles that are in channels or lenticular beds 1-10 m wide. Most of the upper ~1.5 m of Qf2 consists of a massive, matrix-supported debris-flow deposit with abundant cobbles and boulders. Both units Qf2 and Qfoi are inset beneath the higher surface of Qf1 located 250-300 m to the south (Fig. 2).

This outcrop reflects the distinctive sediment characteristics found in Qf2 across the study area. For example, Qf2 commonly transitions upward from fluvial pebbles and cobbles to debris-flow deposits containing large boulders. The unit is typically about 2-5 m thick. Compared to Qf1, Qf2 is slightly coarser and lacks prominent buried soils (i.e., soils with carbonate morphology greater than a weak stage I).

Consisting mostly of cobbles and pebbles, unit Qfoi exhibits vague lenticular bedding (Appendix 1). The base of this unit is not exposed, so the total thickness is unknown. The soil developed on unit Qfoi is marked by >60 cm of illuviated clay and calcic horizons having a stage II carbonate morphology (Appendix 1).

Approximately 5 m northwest (downstream) of site Qf2-mule is an in-filled swale deposit whose sharp lower contact truncates a soil with stage II carbonate morphology that has developed on the Qf2 deposit (Fig. 4). The swale was originally 40-50 cm deep but now is completely filled in by gravelly mud. The swale was originally part of the Qf2 surface, and the later swale-infill is distinguished from the underlying Qf2 deposit by its sedimentologic characteristics, sharp contact, geometry, and finer gravel size (2-3 cm compared to 5-6 cm-diameter). The top of the in-filled swale stands about 2 m above the current floor of the fan-head trench. The soil developed on this infill swale deposit has a stage I carbonate morphology and no clay films.

TABLE 1. Soil properties that are described in this study and their associated abbreviations

Structure	Texture	Consistence	Clay films	Lower Boundary
Grade:		Dry:	Amount:	Distinctness:
sg = single grain	S = sand	lo = loose	n.o. = not observed	a = abrupt
1 = weak	LS = loamy sand	so = weakly coherent	v1 = very few (<5% of relevent surface)	c = clear
2 = moderate	SL = sandy loam	sh = slightly hard	1 = few (5-25% of relevent surface)	g = gradual
3 = strong	SiL = silty loam	h = hard	2 = common (25-50% of relevent surface)	d = diffuse
Size:	L = loam	vh = very hard	3 = many (>50% of relevent surface).	
vf = very fine	SCL = sandy clay loam	Wet:	Distinctness:	Topography:
f = fine	SiCL = silty clay loam	so = nonsticky	f = faint	s = smooth
m = medium	CL = clay loam	ss = slightly sticky	d = distinct	w = wavy
c = coarse	SC = sandy clay	s = sticky	p = prominent	I = irregular
Type:	SiC = silty clay	vs = very sticky	Location:	b = broken
gr = granular	C = clay	po = nonplastic	pf = ped faces	
pl = platy		ps = slightly plastic	po = pores	
sbk = subangular blocky		p = plastic	br = bridges	
abk = angular blocky		vp = very plastic	co = colloid coats on mineral grains	

Other Properties:

Color described using a Munsell soil color chart; (d) = dry; (m) = moist.

Gravel % includes grains > 2 mm diameter.

Carbonate stages for gravelly parent material are summarized below and follow Birkeland et al.'s (1991) modification of Gile et al. (1966); Bachman and Machette (1977); Shroba (1982, written commun. to Birkeland et al., 1991); and Machette (1985).

Stage I: Thin, discontinuous clast coatings; some filaments; matrix can be calcareous next to stones."

Stage I+: Many or all clast coatings are thin and continuous.

Stage II: Continuous clast coatings; local cementation of a few to several clasts; matrix is loose and calcareous enough to give a somewhat whitened appearance.

Stage II+: Same as stage II except that carbonate in the matrix is more pervasive.

Stage III: Horizon has 50-90% of grains coated with carbonate, forming an essentially continuous medium; color is mostly white; "carbonate-rich layers more common in upper part; ~20-25% $CaCO_3$.

Stage III+: Thick carbonate coats; matrix particles continuously coated with carbonate or pores plugged by carbonate; cementation is more or less continuous; > 40% $CaCO_3$.

Stage IV: Upper part of horizon is nearly pure cemented carbonate (75-90% $CaCO_3$) and has laminar depositional layers of carbonate; the rest of the horizon is plugged with carbonate (50-75% $CaCO_3$).

Horizons: A, B, and C denote master soil horizons: Bk= accumulation of $CaCO_3$; By= accumulation of gypsum; Bky= both $CaCO_3$ and gypsum present but $CaCO_3$ dominates; Byk= both gypsum and $CaCO_3$ present but gypsum dominates; Bt= accumulation of silica clay that has formed in situ or is illuvial; Btk= Bt horizon with $CaCO_3$ accumulation; Bw= development of color or structure. For more info, see Birkeland (1999).

TABLE 2. Summary of alluvial fan depositional units.

Unit	Characteristic sediment features	Characteristic surficial features	Characteristic soil features	Interpreted age
Qf3	Stream-flow deposits > debris-flow deposits. No significant buried soils. 1-2 m thick.	Bar and swale topography.	Stage I to I+ carbonate.	Late to mid Holocene (0-7 ka)
Qf2	Overall coarsening-upward texture. Debris flows common near top. No prominent buried soils. 2-5 m thick.	Surface is typically very bouldery. Where the surface is not bouldery, bar and swales are not present.	Stage II carbonate.	Early Holocene (7.5-10 ka)
Qfoi	Clast-supported, sandy pebbles and cobbles inset beneath Qf1 at fan-head. Unknown thickness.	Unit is buried.	20-50 cm of Btk horizons locally underlain by Bky horizons.	Latest Pleistocene (10-25 ka)
Qf1	Stacked allostratigraphic subunits. Subunits bounded by buried soils and composed of debris flows and clast-supported stream-flow deposits. At least 10 m thick.	Lack of original bar and swale surface morphology. Dissected by drainages up to 2 m deep.	Surface soil usually has stage II+ to IV carbonate & lacks distinct Bt horizons. Buried soils may have distinct Bt or Bw horizons overlying whitish calcic and gypsic horizons.	Late to late middle? Pleistocene (25 to 300? ka)

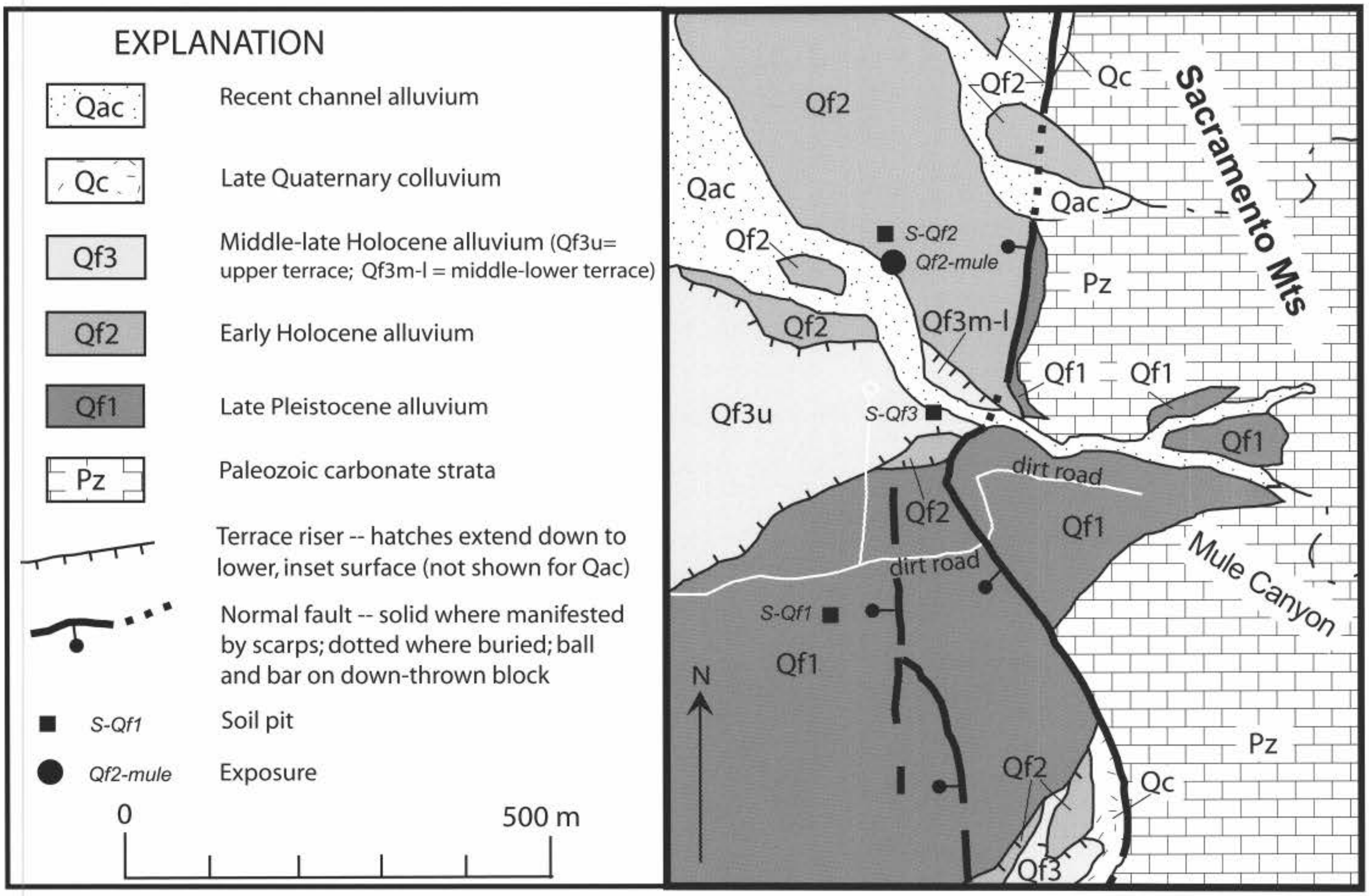

FIGURE 2. Map of proximal alluvial fan at the mouth of Mule Canyon. Fault does not offset Qf2 surface but the pre-Qf2 fault scarp may form a depositional boundary for the unit.

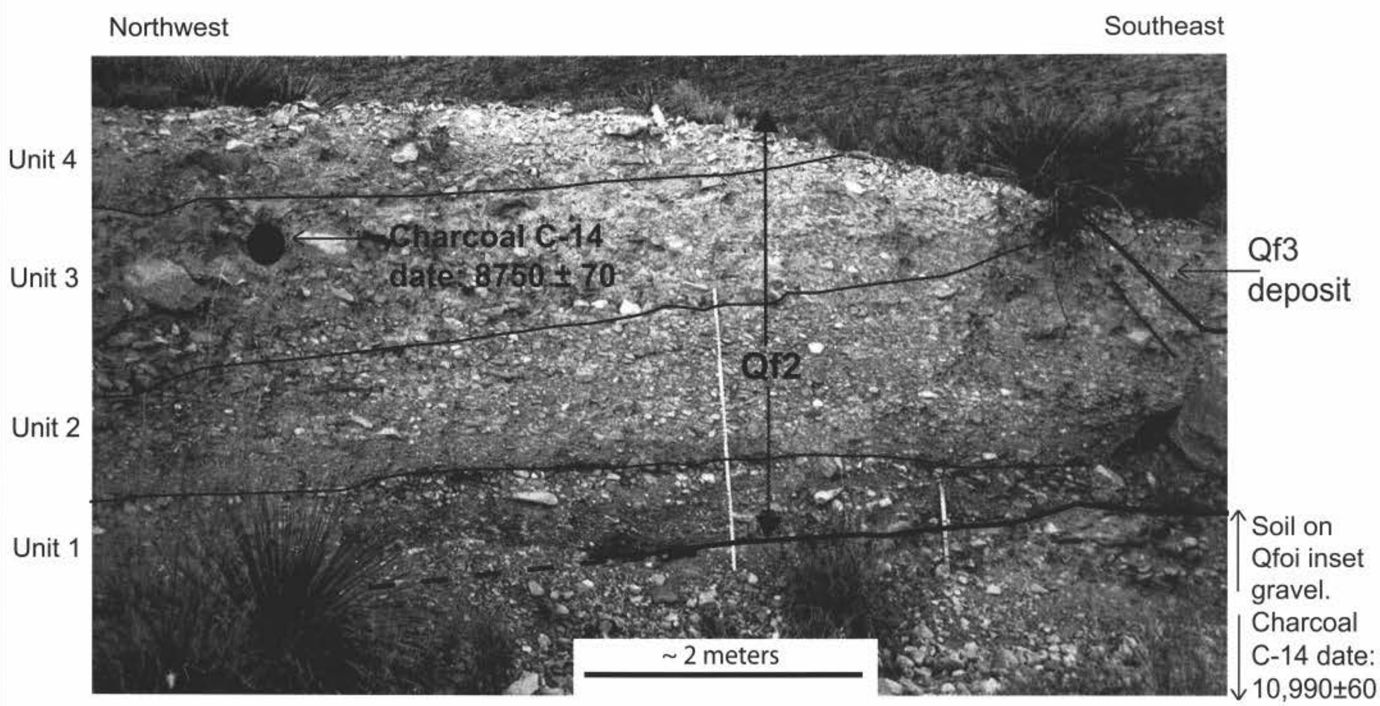

FIGURE 3. Qf2 deposit at site Qf2-mule near mouth of Mule Canyon. Refer to Appendix 1 for description of Qf2. White rod at center of photo is ~2 m long and rests on colluvium that covers Qfoi gravel. C-14 dates given in radiocarbon years.

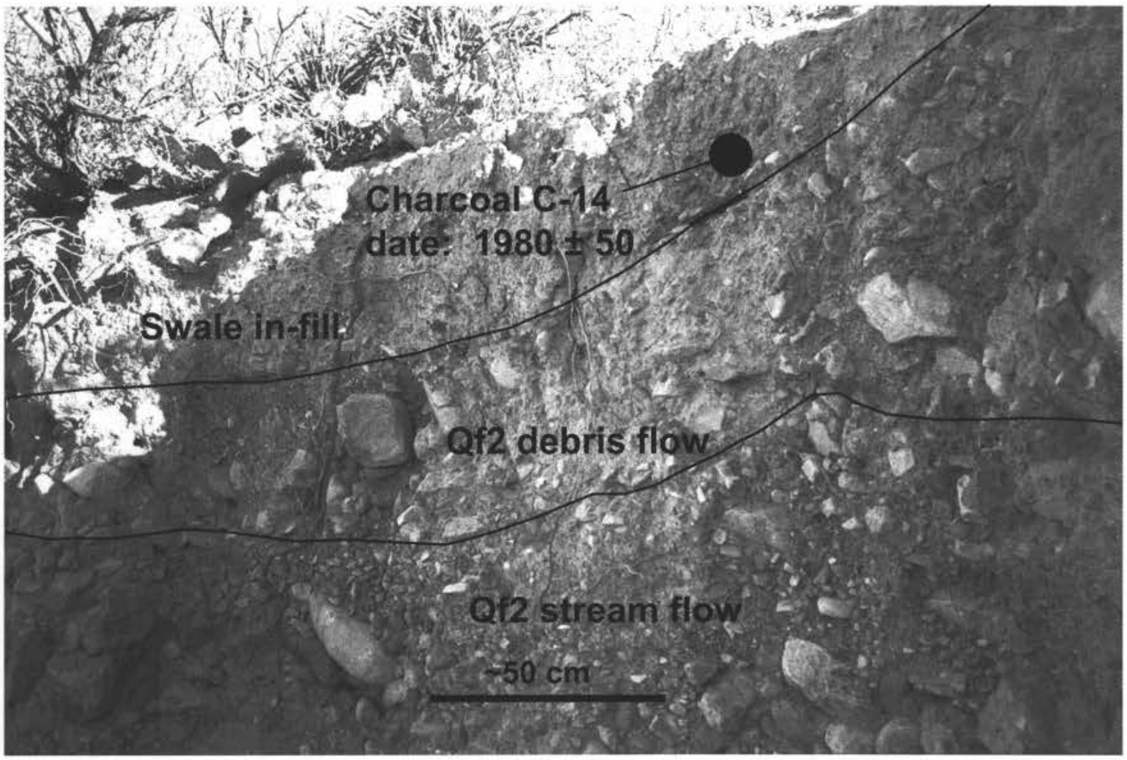

FIGURE 4. Infilled-swale deposit exposed on arroyo wall 5 m northwest of site Qf2-mule.

At site Qf2-mule, relatively abundant charcoal lies scattered within the upper 9 cm of soil developed on unit Qfoi. Charcoal is also present as disseminated small pieces (< 2mm diameter) in the Qf2 debris-flow deposit 0.9 m beneath the present-day surface (Fig. 3, Appendix 1). These two samples yielded radiocarbon ages of 10,990 ± 60 ^{14}C yrs. B.P. and 8,750 ± 70 ^{14}C yrs. B.P., respectively (samples Beta-123568 and Beta-123569). Disseminated charcoal was sampled 30 cm below the surface of the in-filled swale 5 m to the northwest of site Qf2-mule (Fig. 4). This charcoal returned a C-14 date of 1980 ± 50 radiocarbon years (sample Beta-119270).

Qf3

In the proximal portion of the Mule Canyon alluvial fan, Qf3 is inset into Qf1 and Qf2 (Figs. 2 and 3) and is approximately 1-2 m thick. In the distal region of the alluvial fan, Qf3 overlies the older units. These stratigraphic relationships are observed in other alluvial fans in the study area. The tread of the highest Qf3 terrace and the top of the ~ 2 ka in-filled swale deposit discussed above are both about 2 m above the modern channel. Qf3 commonly consists of clast-supported, stream-flow deposits and lesser amounts of debris-flow deposits. Buried soils are very sparse in Qf3 deposits. Three separate terrace treads are identified at this site, but it is unclear if these treads reflect separate cut-and-fill events or successive beveling of a single deposit.

Soils of units Qf1 through Qf3

Soils were described on units Qf1, Qf2, and Qf3 (Fig. 2), and the degree of development varies according to the unit. The soil on unit Qf1 is the most developed, showing a stage II to III carbonate morphology at a depth of 46-87 cm (Table 3, pit S-Qf1). Two calcic horizons with minor clay accumulation or clay films (Btk) are present at 2-46 cm depth, but the clay films may be overprinted by calcium carbonate precipitation. In the upper Btk horizon (2-21 cm depth), calcium carbonate coats on clasts are chipped and broken.

Soils on units Qf2 and Qf3 are less developed compared to the soil on unit Qf1. The soil on unit Qf2 exhibits 45-50 cm of calcic horizons (Bk and Bky) whose carbonate morphology ranges from stage I to II (Table 3, pit S-Qf2). At pit S-Qf3u, there is a maximum of stage I+ carbonate morphology (Table 3).

Soil development on Qf2 and Qf1 deposits exhibits spatial variability in the study area, particularly with regard to gypsum concentration. For example, soils developed on Qf2 alluvium south of Mule Canyon are characterized by having stage II calcium carbonate horizon(s) with minor visible gypsum, whereas the soil observed in pit S-Qf2 shows somewhat weaker calcium carbonate morphology and more visible gypsum accumulation (Table 3). The amount of gypsum observed in the sediment and soil of units Qf2 and Qf1 gradually increases north of Mule Canyon, and it is particularly abundant north of Marble Canyon near Alamogordo. Because of a change in bedding attitude, gypsiferous Permian sediments occupy a higher proportion of mountain front strata north of Marble Canyon. North of Mule Canyon, there may also be more eolian input of gypsum from the White Sands dune field.

M-19 exposure

Qf1

Perhaps the most complete exposure of unit Qf1 in the study area is located where the Alamogordo fault crosses the mouth of a small canyon about 1 km northeast of the mouth of Mule Canyon (site M-19 on Fig. 1). Site M-19 is illustrated and described by means of a map (Fig. 5), a profile of the hanging wall sediment adjacent to the Alamogordo fault (Fig. 6), and a composite stratigraphic section (Fig. 7). A detailed description of the stratigraphic section is found in Koning (1999, appendix C).

The Qf1 deposits at M-19 consist of 14 m of sandy and muddy gravel (Fig. 7) and are representative of Qf1 deposits found at other exposures in the study area. The sediment consists of clast-supported stream-flow deposits with subordinate matrix- to clast-supported debris-flow deposits. Subunits A1, A2, and X1 through X4, each marked by a buried soil on their upper contact, exemplify stacked allostratigraphic subunits that are common depositional features of Qf1. Subunits X1 through X4 are in the lower west footwall exposure and are the oldest exposed Qf1 alluvium (Fig. 7). The lowest ~20-50 cm of subunits X2 through X4 consist of moderately sorted, clast-supported, imbricated sandy pebbles and cobbles. This relatively coarse gravel is interpreted to be deposited by fluvial processes in main-stem (axial) channels similar to those found on the modern fan. Within subunits X2 through X4, the basal stream-flow deposits are overlain by poorly sorted, matrix-supported pebbles, cobbles, and local boulders that are interpreted to be debris-flow deposits. The matrix of these debris flows is generally sandy mud to muddy sand. The debris-flow sediment extends to the top of the subunit. Locally incised into the debris-flow sediment are moderately sorted, pebbly channel deposits approximately 20-40 cm deep and 0.5-2.0 m wide. The fine gravel size of these shallow channels suggests deposition by local reworking of the alluvial fan surface. The soil that marks the top of the subunit is typically continuous across both the debris-flow deposit and the upper, shallow channel deposit. Note that calcic and gypsic (Bky and Byk) soil horizons are common in the Qf1 deposits, but illuviated clay (Bt) soil horizons are observed in

TABLE 3. Descriptive data for soils developed in alluvial units in proximal Mule Canyon alluvial fan.

Soil pit (refer to Fig. 2)	Horizon[1]	Depth (cm)	Color (dry)	Texture (< 2 mm size fraction)	Structure	Consistence wet/dry/plast	Clay films	Gravel (% vol.)	$CaCO_3$ stage	Clast coverage by coats of $CaCO_3$ or $CaSO_4$ (%)[2]	Thickness of clast coatings (mm)
S-Qf1@ mule	A	0-2	10YR 6/3	SL	2m-csbk	ss/sh/po	v1fpf	30[3]	n/a	n/a	n/a
	Btk1	2-21	10YR 6/3.5	SL	1csbk	ss/sh/ps	n/a[4]	40-50	I to I+	50-80[5]	0.2-0.5
	Btk2	21-46	10YR 6/4	SL	1m-csbk	ss/sh/ps	2fpo&1fpf	65	I to I+	50-80	0.2-0.4
	Bky1	46-71	10YR 8/3	SL	1mabk	ss/vh/po	n.o.	60-65	II to III	65-100	0.2-5.0
	Bky2	71-87	10YR 7/3	SL	sg	ss/lo/po	n.o.	65-70	II	50-75	0.2-3.0
	Byk	87-105	10YR 7/3	SL	1mabk	ss/h/ps[7]	n.o.	70	n/a[6]	70-80[7]	n.n.
	Cy	105-115	10YR 6/4	LS	sg	ss/lo/po	n.o.	80	n/a[6]	30-40	n.n.
S-Qf2@ mule	Av	0-2	10YR 5/3	SL	1fsbk	ss/so/ps	n.o.	50	n/a	n/a	n/a
	Bk	2-30	10YR 6/3	SCL	2csbk	s/sh/ps	n.o.	30-35	I+ to II[8]	70-75	<0.2
	Bky1	30-48	10YR 6/3	SCL	1msbk	s/sh/ps	n.o.	65-70	I to II[8]	65	<0.2
	Byk2	48-72	10YR 7/3	SCL	1msbk	ss/h/ps	n.o.	65	n/a[6]	50	1-3
	Cy	72-90	10YR 6/3	SL	sg	ss/lo/po	n.o.	75-80	n/a[6]	5-40	1-3
	Byb9	90-110	10YR 6/4	SL[9]	2m-csbk	ss/sh/ps	n.o.	60	n/a[6]	30-50	<0.2
S-Qf3u@ mule	A	0-4	10YR 5/3	SL	1f-msbk	ss/so/ps	n.o.	70-75	n/a	n/a	n/a
	Bky1	4-32	10YR 6/3	SCL	2m-csbk	ss/sh/p	v1fpf[10]	60-65	I to I+	75-100	<0.2
	Bky2	32-69	10YR 6/3	SL	sg	ss/lo/ps	n.o.	75-80	I	75-80	<0.2
	By	69-112	10YR 5/3	SCL	1f-msbk	s/sh/p	v1fpf[10]	60-65	I	15-20	<0.2
	Cy	112-150	10YR 5/3	LS	sg	ss/lo/po	1dco[10]	60	I	<10%	<0.2

Notes:
n.o. = not observed; n/a = not applicable; n.n. = not noted
1 See Table 1 for explanation of descriptive symbols; see Koning (1999) for specific site-related info.
2 Relative abundance of $CaCO_3$ vs $CaSO_4$ estimated in the field; dominant one listed before subordinate one.
3 Gravel percentage does not include surface armor.
4 Clay films present but masked by $CaCO_3$.
5 Some clasts have broken/chipped $CaCO_3$ coats or have more $CaCO_3$ on top than bottom of clast, implying reworking of surface.
6 Not applicable because mostly gypsum.
7 $CaSO_4$ and $CaCO_3$ form a hard but breakable horizon; clasts are cemented together.
8 Although not continous clast coverage by $CaCO_3$, horizon is calcareous enough to give a whitened appearance.
9 Parent material may be a debris flow deposit.
10 Clay films probably related to initial sedimentation.

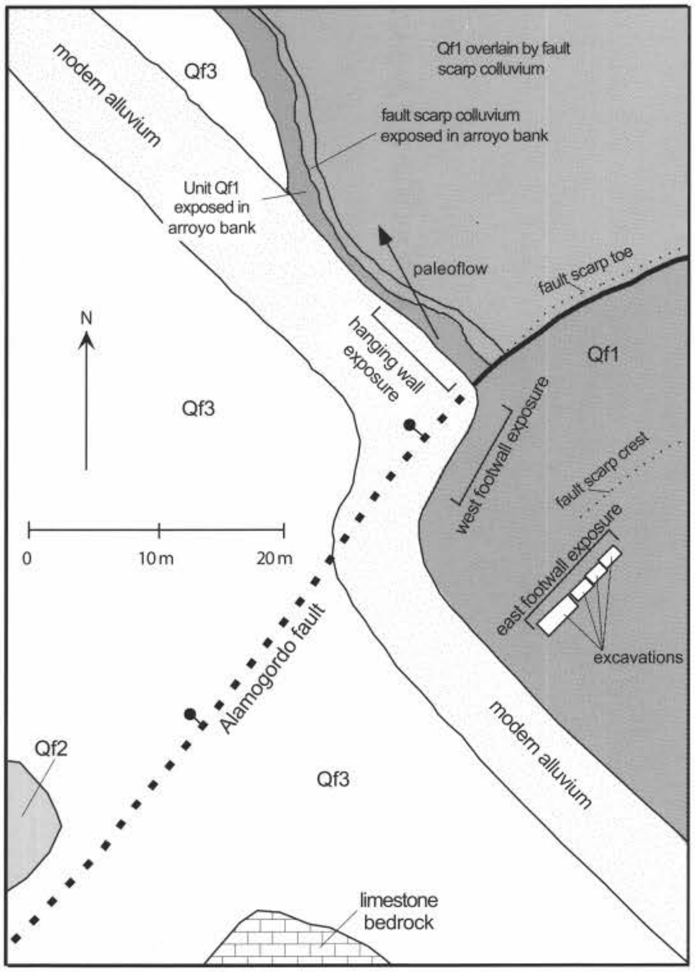

FIGURE 5. Map of site M-19. Described exposures used to construct the composite stratigraphic section of Fig. 7 are labeled. Qf1 flow direction at the hanging wall exposure obtained using imbricated clasts. Fault trace solid where manifested by fault scarps and short-dashed where concealed beneath non-faulted alluvium. Modern channel is generally inset more than 2 m below top of unit Qf3. Map constructed using a total station survey in February, 1998.

subunits X4 and X3 together with three soils in the upper 5 m of the hanging wall exposure (Fig. 7).

Gastropod shells

Gastropod shells are present in the lower part of colluvium derived from erosion of the fault scarp at site M-19 (Fig. 6). Examination of these shells by Richard Smartt indicate that they belong to the species *Glyphyalinia identata, Pupoides albilabris, Hawaiia minuscule*, and *Microphysula ingersoll*. The present habitat distribution of these gastropods is presented in Table 4. Two of these shells, together with a charcoal sample, were dated by C-14 methods. The shells returned radiocarbon ages of 12,610 ± 40 and 12,760 ± 50 (samples Beta-119268 and Beta-119269), and the charcoal returned a radiocarbon age of 12,600 ± 80 (sample Beta-117016).

NP2 exposure

Qf1 and Qf2

At site NP2, located east of Alamogordo in the Indian Wells mountain-front reentrant (Fig. 1), greater than 4 m of Qf1 lies beneath 4.6 m of Qf2 sandy gravel (Figs. 8-9). Qf2 is inset into Qf1, and its surface lies about 2 to 3 m below the Qf1 surface located 110 m to the south and northwest. Thus, the Qf2/Qf1 contact at this exposure is about 7 to 8 m below the top of nearby Qf1. The Qf1 at site NP2 differs from other Qf1 deposits in that it is dominantly mud. This sediment is extensively bioturbated and contains no observed scour surfaces. The mud may be locally derived from an adjacent bedrock knob composed primarily of gypsiferous mudstone and sandstone, or else it may represent bioturbated eolian deposits. Charcoal collected from a stratigraphic horizon about 7.2 m below the top of the exposure and about 10.2 m below the Qf1 surface to the south yielded a date of 41,320 ± 1000 ^{14}C yrs. B.P. (sample Beta-115160). The muddy sediment is correlated to Qf1 because it clearly underlies Qf2 across an unconformable contact and is at least 6 m below the top of the Qf1 surface to the south. Alternatively, this fine-grained sediment may possibly have filled a deep channel inset into Qf1 and correlate to unit Qfoi. However, it differs from other Qfoi deposits in that it contains significant buried soils below the top of the unit and lacks the characteristic clast-supported gravel of unit Qfoi. Also, there is no evidence for a buttress unconformity along the arroyo wall.

Ages of Alluvial Fan Units

Qf1

Two C-14 dates constrain the age of Qf1. As presented above, C-14 analyses of the charcoal dispersed in Qf1 sediment at site NP2 returned an age of 41 ± 1 ka (radiocarbon years). At site M-19, charcoal was collected from a distinct Bt soil horizon located on the top of a large, toppled block of sediment that fell from the crest of the adjacent fault scarp. This block is interpreted to be uppermost alluvium of Qf1 that was deformed by offset along the Alamogordo fault (Fig. 6, subunit A2'). The soil developed on this alluvium would thus post-date the deposition of Qf1. The charcoal collected from the soil returned a C-14 date of 12,990 ± 150 radiocarbon years, and this provides a minimum age constraint for unit Qf1 at this location.

We interpret that Qf1 was generally deposited prior to 25 ka. In addition to C-14 data, this interpretation is based on the presence of well developed soils found on top of Qf1 throughout the study area, and comparison of the soils and sediment characteristics to the Desert Project near Las Cruces. It is justifiable to compare soils between the study area and the Desert Project in order to infer temporal similarities because both have similar vegetation, climate, and relief (Jenny, 1941). Although parent material may differ, particularly with regards to carbonate, there are areas in the Desert Project with high amounts of carbonate bedrock, and these areas were emphasized in this comparison. Soils developed on Qf1 typically possess calcic horizon(s) with stage II+ to IV calcium carbonate morphology (Table 2; Koning,

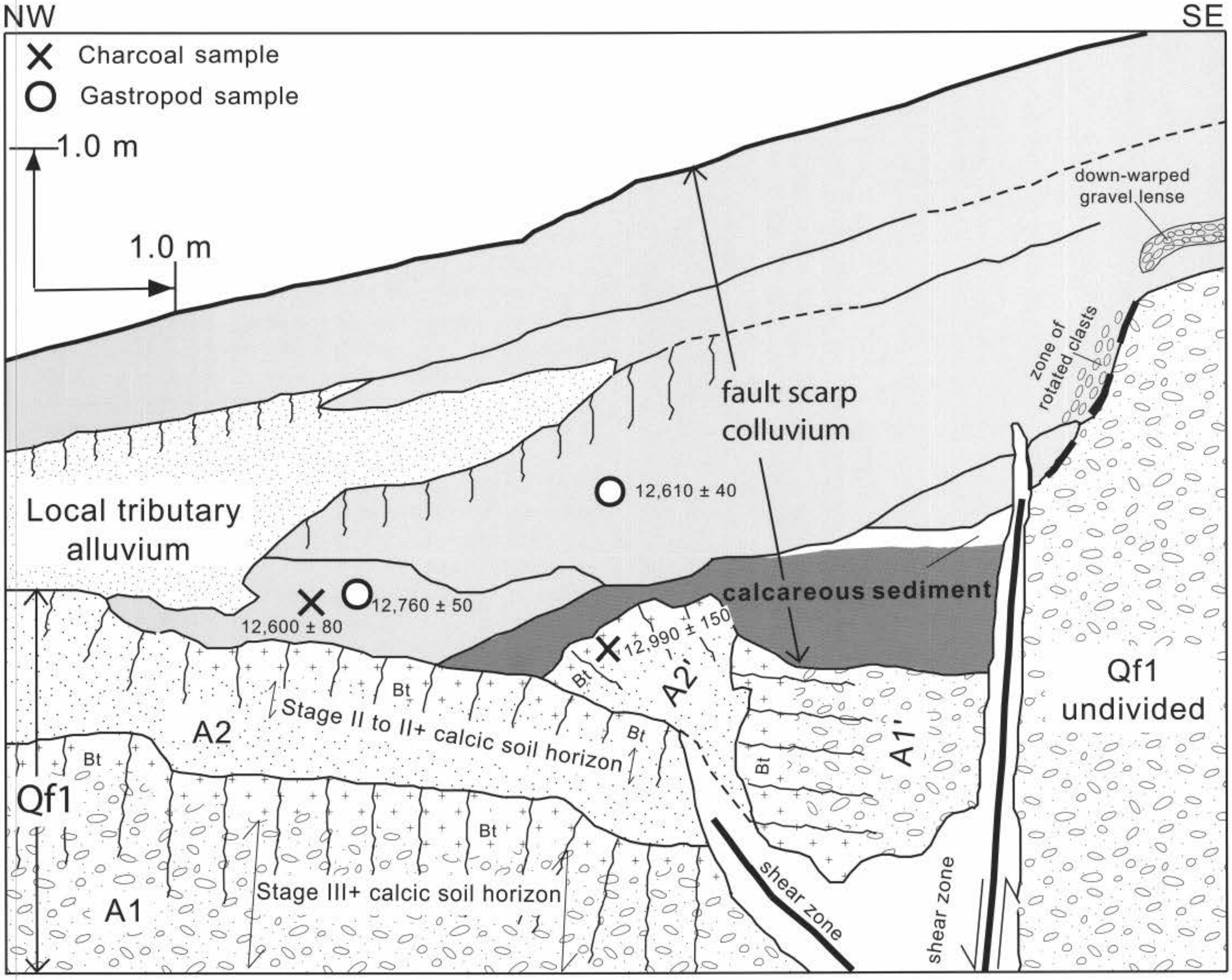

FIGURE 6. Profile of hanging-wall exposure at site M-19. Numbers next to gastropod and charcoal sample locations are radiocarbon dates reported in ^{14}C yrs B.P. Heavy black lines correspond to faults. A1 and A2 are Qf1 alluvial subunits that have well-developed soils. Wavy lines denote buried soils; these lines do not mark depth of soil. The pattern composed of small crosses, labeled "Bt," marks prominent Bt soil horizons in subunits A1 and A2; these are underlain by calcic horizons. A1' and A2' correspond to units A1 and A2 that have toppled from a former fault scarp free face immediately following a rupture event. Shaded units are colluvium derived from the adjacent fault scarp. Local tributary alluvium is derived from arroyo to the northeast and may correlate to unit Qf2. Brief descriptions of units are in Koning and Pazzaglia (this volume); full descriptions given in Koning (1999).

1999). Even where buried by fault scarp colluvium at site M-19, the soils developed on subunits A2 and A1 are 60-150 cm thick and contain Btk soil horizons underlain by calcic horizons with stage II to III+ calcium carbonate morphology (Figs. 6-7). The soil on the Qf1 surface at the mouth of Mule Canyon also exhibits relatively strong calcic horizons with up to II or III calcium carbonate morphology (Table 3). The stacked sequence of depositional units and buried soils of Qf1 is similar to that described for the Jornada II alluvium and older alluvial units of the Camp Rice piedmont facies of the Desert Soil-Geomorphology Project (Gile et al., 1981). Additionally, soils developed on Qf1 resemble those on the Jornada II alluvium, especially with respect to calcic

FIGURE 7. Composite stratigraphic section for Qf1 at site M-19. Shown are sedimentologic facies (e.g., debris flows), soils, important subunits, and tentative correlations across the Alamogordo fault. Shallow, non-axial channel pebbles probably represent local reworking of the fan surface. There is about 1-2 m of error in stepping from the east to west footwall exposures. Reference numbers correspond to descriptions in Koning (1999, appendix C). Extent of right margin of graphic column represents visually estimated average clast size. Soil horizon abbreviations follow Table 1.

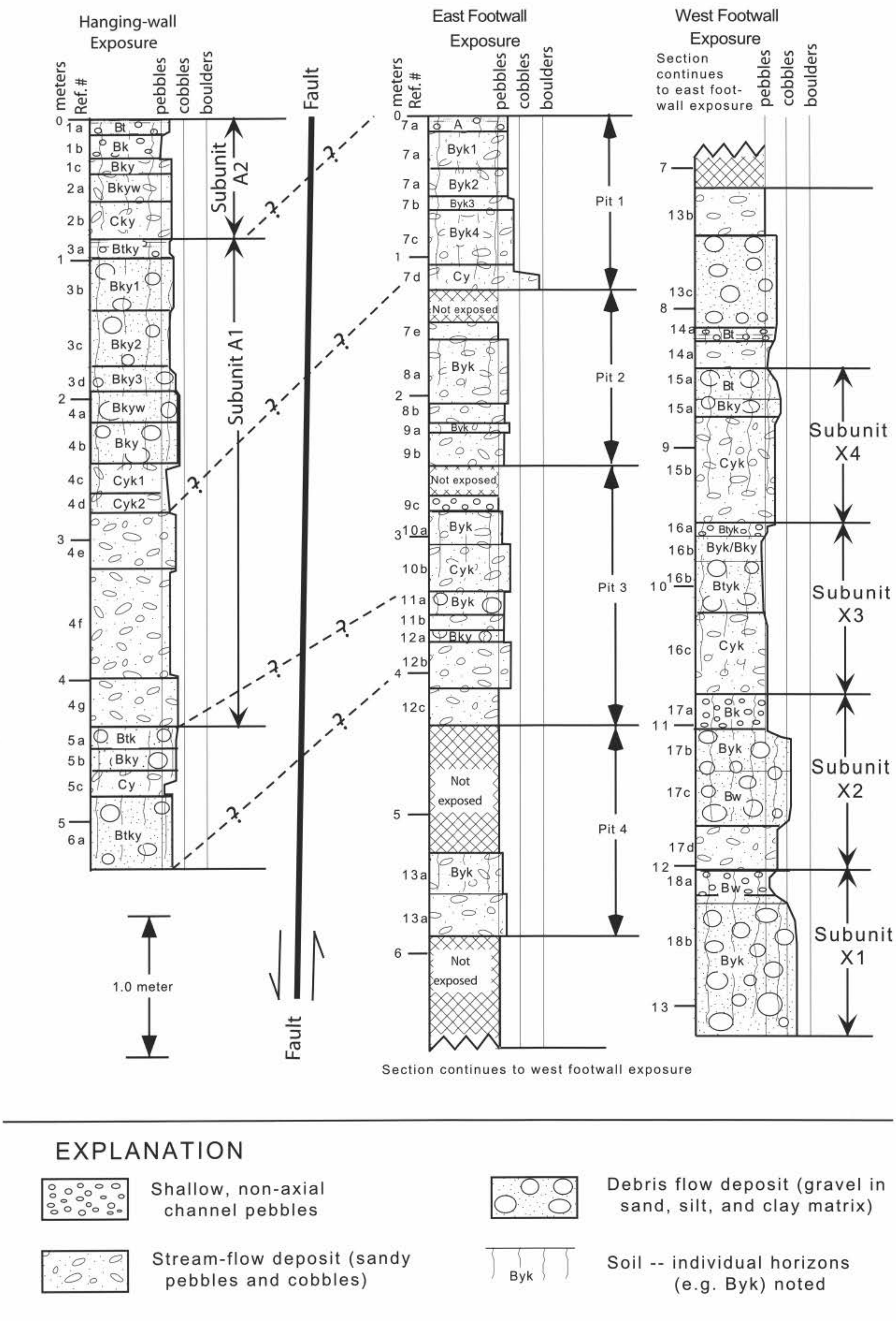
Hanging-wall Exposure
meters
Ref. #
pebbles
cobbles
boulders
Subunit A2
Subunit A1
Bt
Bk
Bky
Bkyw
Cky
Btky
Bky1
Bky2
Bky3
Bkyw
Bky
Cyk1
Cyk2
Btk
Bky
Cy
Btky
1.0 meter
Fault
East Footwall Exposure
A
Byk1
Byk2
Byk3
Byk4
Cy
Not exposed
Byk
Byk
Not exposed
Byk
Cyk
Byk
Bky
Not exposed
Byk
Not exposed
Pit 1
Pit 2
Pit 3
Pit 4
Section continues to west footwall exposure
West Footwall Exposure
Section continues to east foot-wall exposure
Bt
Bt
Bky
Cyk
Btyk
Byk/Bky
Btyk
Cyk
Bk
Byk
Bw
Bw
Byk
Subunit X4
Subunit X3
Subunit X2
Subunit X1
EXPLANATION
Shallow, non-axial channel pebbles
Debris flow deposit (gravel in sand, silt, and clay matrix)
Stream-flow deposit (sandy pebbles and cobbles)
Soil -- individual horizons (e.g. Byk) noted

TABLE 4. Habitat distributions for gastropods sampled at site M-19.

Gastropod species	Modern habitat distribution*	Modern life zone distribution*
Glyphyalinia identata	piñon-juniper to spruce-fir woodlands	Upper Sonoran to Canadian life zones
Pupoides albilabris	desert scrub to piñon-juniper woodlands	Lower to Upper Sonoran life zones
Hawaiia minuscula	piñon-juniper to spruce-fir woodlands	Upper Sonoran to Canadian life zones
Microphysula ingersolli	spruce-fir woodlands	Canadian Life Zone

* note: habitat distributions and life zones are from Metcalf and Smartt (1997).

horizon development. The Jornada II alluvium is thought to be at least 25 ka (Gile et al., 1981). Thus we interpret general alluvial fan stability from 25 ka to 10 ka in order to allow the observed degree of soil development on unit Qf1.

Qfoi

At site Qf2-mule, charcoal sampled from the soil developed on unit Qfoi returned a C-14 date of 10,990 ± 60 radiocarbon years. This is similar to a C-14 date of 11,240 ± 70 radiocarbon years from charcoal sampled in soil developed on a Qfoi deposit at Laborcita Arroyo (Koning and Pazzaglia, this volume). Based on the stage II carbonate morphology and 25-30 cm of Btky horizons present in this soil (Appendix 1), the surface of Qfoi was stable for a significant period of time and was above the active stream (the latter probably being confined in a former fan-head trench). Being inset into Qf1, this unit post-dates the highest aggradation surface of Qf1. We consequently interpret that Qfoi is latest Pleistocene in age (10-25 ka) and may mark a time of general incision of the alluvial fan surface.

Qf2

Qf2 is constrained to be early Holocene in age based on the three C-14 dates at site Qf2-mule, alluvial fan stratigraphic relationships, and comparison to the alluvial fan stratigraphy of the Desert Project. Because prominent buried soils (i.e., soils with carbonate morphology greater than a weak stage I) have not been observed within Qf2 deposits anywhere in the study area, Qf2 was probably deposited over a relatively short time interval. The small pieces of disseminated charcoal in the upper Qf2 debris-flow deposit at site Qf2-mule were probably transported with the debris flow from somewhere in Mule Canyon (i.e., this charcoal is detrital). The charcoal returned a C-14 date of 8,750 ± 70 radiocarbon years, and this gives a maximum age constraint for the debris flow (Fig. 3). The soil developed on unit Qfoi, which underlies unit Qf2 at site Qf2-mule, contains abundant charcoal in its upper Btky horizon that has been dated at 10,990 ± 60 radiocarbon years. This date provides a maximum age limit for the base of Qf2 (Fig. 3; Appendix 1). Charcoal collected from an in-filled swale deposit unconformably overlying the top of Qf2 returned a value of 1,980 ± 50 ^{14}C yrs. B.P. (Fig. 4). This age provides a minimum age limit for Qf2 and a maximum age limit for the 2 m of incision by the current fan-head trench.

The soil developed on top of Qf2 is generally marked by a stage II carbonate morphology (particularly south of Mule Canyon), which is similar to that found on the Isaacks' Ranch alluvium in the Desert Project (Gile et al., 1981). The age of the Isaacks' Ranch alluvium is not well-constrained but is thought to be older than 7 ka and post-dates the late Pleistocene Jornada II alluvium (Gile et al., 1981). Soils developed on alluvium younger than Isaacks' Ranch (younger than ~ 7 ka) do not have stage II carbonate horizons, even in high-carbonate parent material (e.g., Study Area 16 of the Desert Project). However, the Isaacks' Ranch alluvium near Las Cruces is much more discontinuous compared to unit Qf2 in this study. Based on the above data and discussion, Qf2-associated aggradation is interpreted to have occurred over a relatively short time interval during the early Holocene (7.5-10 ka).

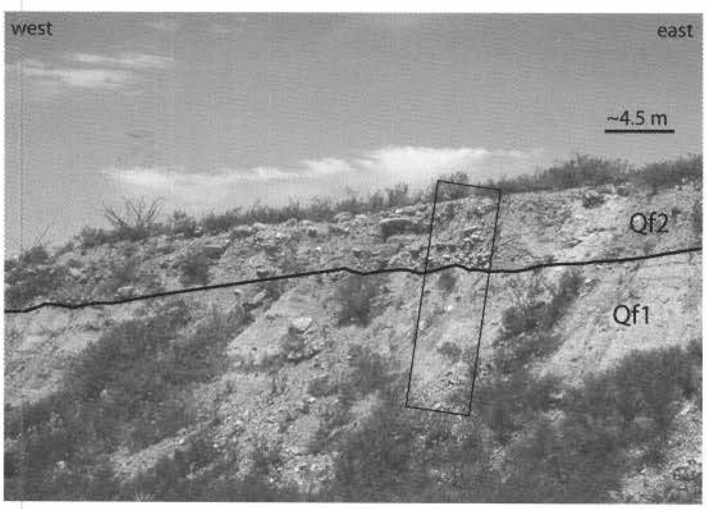

FIGURE 8. Exposure of Qf1 and Qf2 at site NP2 (in the Indian Wells mountain-front reentrant). Rectangle encloses described area of stratigraphic section shown in Fig. 9.

Qf3

The degree of soil development on Qf3 is weak (i.e., stage I to I+ carbonate morphology) and comparable to the soil developed in the Organ alluvium of the Desert Project (Gile et al., 1981). Based on several C-14 dates, the Organ alluvium is thought to post-date 7 ka (Gile et al., 1981). The similarity of the soils of Qf3 with the soils developed in the Organ alluvium, in addition to the early Holocene age assignment to Qf2, indicate that Qf3 is middle to late Holocene in age. At the mouth of Mule Canyon, the similar height of the upper Qf3 terrace tread and the dated in-filled swale deposit suggest that deposition of the highest terrace of Qf3 occurred prior to ~2 ka and that the incision of the present fan-head trench occurred after ~2 ka.

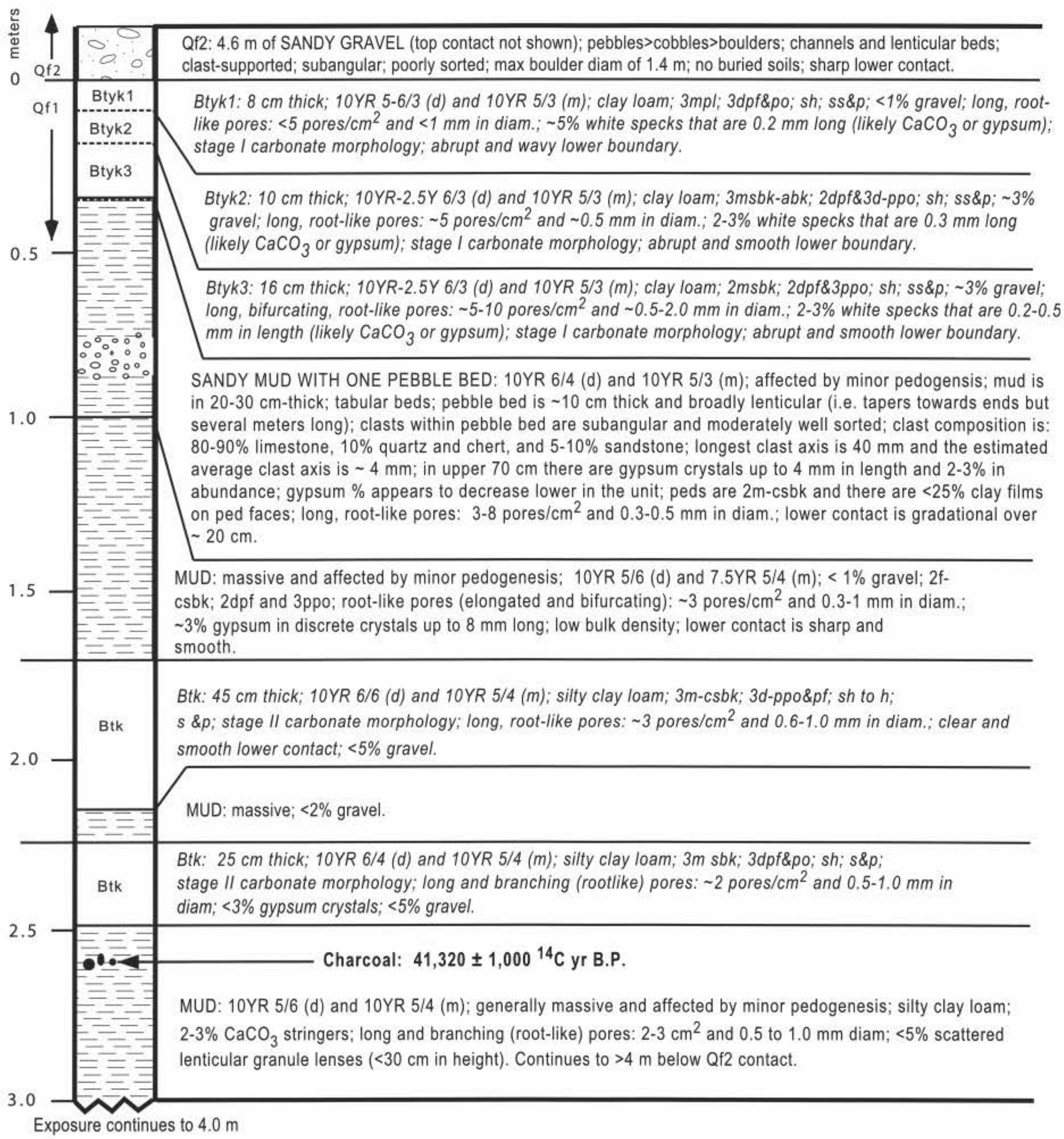

FIGURE 9. Stratigraphic section of site NP2. Numbers left of the graphical column represent depth in meters below the Qf2/Qf1 contact. Location of dated charcoal is shown at 2.6 m depth. Soil property abbreviations follow Table 1. Section located at N: 3,641,500±60 m, E: 414,580±60 m (UTM zone 13, NAD 27).

DISCUSSION

Latest Pleistocene Paleoclimate

None of the four species of gastropods identified in the lower colluvial units at site M-19 (Fig. 6; Table 4) occur together in the same modern habitat. However, three species presently occupy piñon-juniper-oak woodlands habitat (Upper Sonoran Life Zone) and three species presently occupy spruce-fir forest habitat (Canadian Life Zone). We favor the interpretation of a piñon-juniper-oak woodland habitat based on the results of a local packrat midden study by Van Devender et al. (1984). The gastropod shells and charcoal sampled from these lower colluvial units return C-14 dates in the range of 12.5-12.8 ka, so at this time the elevation of the piñon-juniper-oak woodland was depressed by at least 600 m below where it occurs today (600 m being the difference in elevation between site M19 and the approximate lower limit of modern piñon-juniper-oak woodland). Presumably, this depression of the woodland boundary was a result of cooler temperatures and higher effective moisture than the modern; this agrees with interpretations by Van Devender (1984) of cool summer temperatures and winter-spring dominated precipitation during pluvial conditions in the latest Pleistocene.

Late Pleistocene vs. Holocene Soils

The main difference between soils found in Holocene Qf2 and Qf3 deposits versus late Pleistocene Qf1 deposits is that distinct Bt horizons appear to be restricted to buried soils in the Qf1 deposits. Although Bt soil horizons may locally be found on the present surfaces of Qf1 deposits, these are commonly obscured or masked by later (probably Holocene-age) calcium carbonate precipitation and are not readily apparent in the field. Because parent material and slope position (i.e., top of proximal alluvial fans away from terrace risers) is approximately constant for the studied soils south of Alamogordo, this difference in soil characteristics can be attributed to time, vegetation, or climate factors (Jenny, 1941). Perhaps there were longer periods of surface stability during the late Pleistocene, compared to the Holocene, and this allowed sufficient time for distinct Bt horizons to form. Alternatively, it is possible that soils forming in upper Qf1 deposits during the latest Pleistocene developed Bt horizons relatively quickly because of higher soil moisture and weathering rates (Birkeland, 1999). Higher eolian input of clays could also lead to more rapid Bt horizon development (Gile et al., 1981; McFadden, 1982), but this is probably unlikely considering latest Pleistocene pluvial conditions.

The lack of Bt horizons on subaerial Qf1 surfaces (or the masking of them by later precipitation of calcium carbonate), in addition to the lack of Bt horizons in soils on Qf2 or Qf3 deposits, suggest that the dominant Holocene pedogenic process was the accumulation of calcium carbonate and salts. Assuming a stable surface, carbonate overprinting of Bt horizons could be due to less precipitation or possibly higher input of eolian clay (the latter presumably due to drier conditions and less vegetative cover). Higher eolian clay input could increase the water-holding capacity in the uppermost part of a soil and decrease soil water infiltration below (Birkeland, 1999; Chadwick et al., 1995). A decrease in soil water penetration, either from a decrease in precipitation or from higher eolian clay input, would raise the depth of calcium carbonate precipitation (McFadden, 1988; Birkeland, 1999). Once the carbonate content of a soil is sufficiently high, Bt horizon formation is inhibited (Gile, 1975). However, for Qf1 soils it is possible that calcium carbonate precipitation moved upward due to progressive plugging of soil pores by calcium carbonate in a well-developed calcic (K) horizon, which effectively perches soil water above this horizon (Gile et al., 1981). More quantitative and detailed soil work is necessary to elucidate the role of paleoclimate in the formation of these soils.

Sedimentation Response to Early Holocene Climate Change

Qf2 is a distinctive coarsening-upward deposit in which stream-flow gravel is overlain by debris-flow sediment with large boulders. The interpreted age of Qf2 (7.5-10 ka) approximately coincides with an important early Holocene-middle Holocene climatic change in the southwestern United States, in which conditions became drier (Van Devender et al., 1984, 1987; Hall, 1985; Waters, 1989; Davis and Shafer, 1992; Buck and Monger, 1999), but intense summer monsoons also may have developed (Kutzbach, 1981, 1983; Van Devender et al., 1984; Davis and Shafer, 1992; Jahren et al., 2001). We interpret that this climate change is reflected in the sediment characteristics of unit Qf2. A change to a drier climate in the early part of the Holocene would have probably decreased the effective vegetation cover on the hill-slopes, particularly if grassland was replaced by desert-scrub (Buck and Monger, 1999). Consequently, any colluvium and soils that accumulated on these slopes during pluvial conditions of the latest Pleistocene were then more susceptible to erosion (Bull and Schick, 1979; Gile et al., 1981; Bull, 1991). The hypothesized arrival of intense summer monsoonal precipitation, in addition to a drier climate and presumably less vegetative cover, probably destabilized hill-slopes and favored mass-wasting processes. This resulted in abundant debris-flow deposition consistent with that observed in the upper Qf2 deposit. These widespread debris flows occurred in the latter early Holocene (7.5-9 ka) because stream-flow gravel is characteristic of the lower part of Qf2 deposits.

Middle to Late Holocene Sedimentation

After Qf2 deposition, there was general net incision of the proximal alluvial fans in the middle to late Holocene. However, one to three aggradation events occurred during this time to produce the inset terraces associated with unit Qf3. It is not known whether these filling events were related to climate or complex response behavior of the drainages. In the medial and distal portions of the alluvial fans, there was significant aggradation of Qf3 similar to what is observed for the Organ alluvium near Las Cruces (Gile et al., 1981).

CONCLUSIONS

Four distinct stratigraphic units consisting predominately of pebbly to bouldery alluvium are identified in the study area, three of which (Qf1 through Qf3) form extensive, mappable units. Qf1 generally predates 25 ka and records a long period of alluvial fan aggradation. Unit Qfoi appears to have been deposited in fan-head trenches during a time of proximal alluvial fan incision during the latest Pleistocene (25-10 ka). A major event of coarse aggradation in the early Holocene formed unit Qf2. In the middle and late Holocene, the bulk of aggradation associated with unit Qf3 shifted to the medial and distal portions of the alluvial fans, whereas the proximal alluvial fans generally witnessed net incision and the formation of three terraces.

Gastropod shell identification together with soil and sediment field data are used to offer some generalized interpretations regarding the relationship of past climates to alluvial fan sedimentation and soil processes during the latest Pleistocene and Holocene. At 12.5-12.8 ka, gastropod shell data indicate that piñon-juniper-oak woodlands were present along the base of the Sacramento Mountains. This is consistent with cooler temperatures and higher effective moisture during the latest Pleistocene. A significant change to drier conditions occurred during the latter early Holocene. These drier conditions raised the depth of precipitation of calcic and gypsic soil horizons, resulting in overprinting of Bt horizons and possibly inhibiting Bt horizon development. A climate change is also indicated by the prevalent debris-flow deposits in the upper part of unit Qf2 that commonly overlie stream-flow gravel throughout the study area. These debris flows may reflect intense precipitation events associated with the arrival of the summer monsoons and/or a possible decrease in vegetation density, due to drier climate conditions, that resulted in a destabilization of hill-slopes.

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APPENDIX 1. Qf2 and Qfoi exposure at the mouth of Mule Canyon (site Qf2-mule)

Unit	Description[1]	Interpretation
Qf2 unit 4	GRAVEL: 0.5 m thick; 10YR 6/3 (d) and 10YR 4/4 (m); pebbles ~ cobbles > boulders; 20% sandy loam matrix; faint imbrication; no observed internal structures; mostly clast-supported; max clast size of 33 cm, avg clast size of 5-8 cm; mostly subrounded clasts, some subangular; generally moderately sorted.	Stream-flow deposit
Qf2 unit 3	MUDDY SANDY GRAVEL: 1.1 m thick; 10YR 6/3 (d) and 10YR 4/4 (m); 30-35% cobbles; 25-30% boulders; 20% pebbles; 20-25% sandy loam matrix; massive; no imbrication; matrix-supported; max clast size of 63 cm and avg clast size of 7-8 cm; mostly subrounded clasts, some subangular; poorly sorted; gypsiferous. Charcoal occurs as small (< 2 mm), disseminated pieces; C-14 date of 8750 ± 70 ^{14}C yrs B.P.	Debris flow
Qf2 unit 2	GRAVEL: 1.2 m thick; 2.5Y 7/3 (d) and 10YR 4/4.5 (m); 70% pebbles; 10-15% cobbles; 10-15% sandy loam matrix; 5-10 m wide lenticular beds; clast-supported; gravels are imbricated; max clast size of 19 cm, avg clast size of 4-6 cm; mostly subrounded clasts, some subangular; generally moderately sorted.	Stream-flow deposit
Qf2 unit 1	GRAVEL: ~ 0.4 m thick; 10YR 6/3 (d) and 7.5YR 3 /4 (m); 30% cobbles; 3% boulders; 40% pebbles; clast-supported with 10-15% loamy sand matrix; channels and lenticular beds 1-3 m wide; clasts are generally imbricated; max clast size of 30 cm, avg clast size of 2-3 cm; mostly subrounded clasts, some subangular. Top 12 cm of unit is mostly cobbles that are coated by a laminated, 2-3-cm-thick mud to silty sand; a prominent brown clay coats 5% of clast surfaces. Bottom 9 cm of unit is clay-coated pebbles and cobbles with 25% matrix of sandy clay loam; lower 9 cm is slightly altered by pedogenesis (10% clast coverage by <0.2 mm-thick coats of $CaCO_3$, root-like pores, 2vf-f sbk-abk ped structure).	Stream-flow deposit Lower 9 cm stable for short time to allow minor pedogenesis. Clay coats are from percolating stream water.
Qfoi	GRAVEL: 77 cm thick; 35% cobbles; 3% boulders; 40% pebbles; ~22% matrix; vague lenticular bedding; max clast size of 35 cm, avg clast size of 6 cm; mostly subrounded clasts, some subangular; moderately sorted clasts. SOIL (described from top to bottom): Btky1: 9 cm thick; sandy clay loam; 10YR 5/3 (d) and 10YR 3.5/3 (m); 2m-vc sbk structure; 2-3(50%)f pf and 3f po clay films; 55-70% gravel; h-sh; ss and p; c and w lower contact; 50-100% clast coverage by <0.2 mm-thick coats of $CaCO_3$ and gypsum. Abundant charcoal seen. Charcoal date at ~10,990 ± 60 ^{14}C yrs B.P. Btky2: 18 cm thick; loam to sandy loam; 10YR 6/3 (d) and 10YR 4/3 (m); 1m-c sbk structure; v1f pf and 1f po clay films; 75-80% gravel; sh; ss and ps; 80-100% clast coverage by <0.2 mm-thick coats of $CaCO_3$ and gypsum; c and w lower contact. Stage II carbonate morphology. Byk/Bky: 50 cm thick; clay loam; 10YR 6/3 (d) and 10YR 4/3 (m); 1vf-f sbk structure; no clay films; 80-90% gravel; lo; ss and p; >75% of clast surface covered by ≤ 0.4 mm coats of gypsum and $CaCO_3$. Stage II carbonate morphology. Abundant snail shells. This was probably near the surface in the latest Pleistocene. *This soil can only be traced ~10 m horizontally. The Bk/By horizons weaken southward and then are truncated by a channel.	Fluvial terrace deposit related to channel entrenchment in the latest Pleistocene (this unit is ~3 m lower than the Qf1 surface 250-300 m to the south). Soil formed on deposit; depth of carbonate precipitation raised after the lower portion of Qf2 unit #1 was deposited.

Note:

[1] Refer to Table 1 for explanation of soil descriptive symbols.