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Abstract

La Mesa geomorphic surface, in the floor of the Jornada del Muerto Basin (shortened to Jornada Basin) in southern New Mexico, is termed JER La Mesa and is intermediate in age between lower and upper La Mesa in the nearby Desert Soil–Geomorphology Project. Based on pumice dated at 1,600,000 yrs, stage V carbonate, and totals of pedogenic carbonate, the bulk of JER La Mesa is thought to be about 1,600,000 yrs old. In the central part of the basin floor, the soil with dated pumice and stage V carbonate has 1,861 kg/m^2 of pedogenic carbonate. In contrast, in the eastern part of the basin floor, two pedons with eolian sediments that bury JER La Mesa average only 858 kg/m^2 of pedogenic carbonate. Because the deposits at these sites occupy about the same span of time, carbonate totals at the two sites with buried soils should be much closer than they are to carbonate totals at the site without buried soils. It is believed that a major displacement along the Jornada fault, which forms the southwestern structural boundary of the Jornada Basin, created an intermittent lake, here termed Lake Jornada, that inundated the eastern part of the basin floor (so that soils could not form in sediments of JER La Mesa) and that the lake deposited a layer of gypsum on drying. This gypsum is believed to be the source of gypsum that accumulated in the soils of JER La Mesa and in layers buried by sediments of the piedmont slope that borders the basin floor. A rough estimate, using the amount of missing carbonate and the stratigraphic position of the gypsum, is that Lake Jornada could have existed from about 1,040,000 to 325,000 yrs ago. However, data are sparse, especially considering the extensive area involved. Much more data are needed for soils of JER La Mesa, both at the surface and buried by younger deposits and their soils.

Introduction

Several questions arose during recent soil-geomorphic investigations in the Jornada Basin floor in southern New Mexico. One question concerned the very substantial amounts of pedogenic carbonate missing from parts of La Mesa geomorphic surface. Another involved the widespread distribution of a thin deposit of buried gypsum that extends far south of its source in the San Andres Mountains. A third concerned the chronological relations between La Mesa in the Jornada Basin and upper and lower La Mesa at the nearby Desert Soil–Geomorphology Project (informally termed the Desert Project; Hawley, 1975; Gile et al., 1981, 1995b). Objectives of this

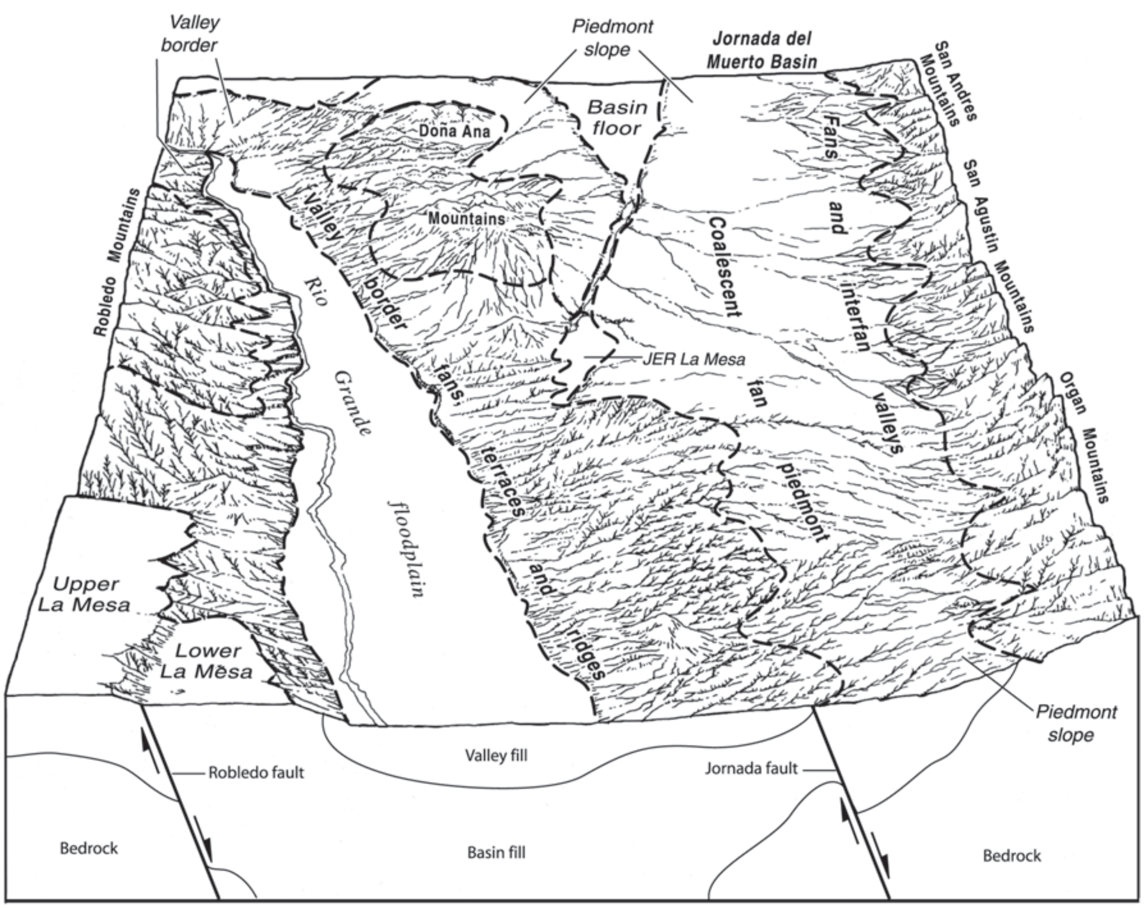

FIGURE 1—Major physiographic features of the Desert Soil–Geomorphology Project in southern New Mexico (modified from Gile, 1975). JER (Jornada Experimental Range) La Mesa is present in both the northern and southern parts of the basin floor; the northern part not labeled. This diagram and Fig. 2 show only some of the southern part of the very extensive Jornada Basin floor. The Robledo and Jornada faults follow Seager et al. (1987).

TABLE 1—Geomorphic surfaces and stages of carbonate accumulation for soil of the valley border, piedmont slope, and the basin floor north of US–70.[1]

Geomorphic surface			Carbonate stage		Estimated soil age
Valley border	Piedmont slope	Basin floor	Nongravelly materials	Gravelly materials	(years B.P. or epoch)
Coppice dunes	Coppice dunes	Whitebottom			Historical (since 1850 A.D.)
		Lake Tank			present to 150,000
Fillmore	Organ		0, I	I	middle and late Holocene 100 –7,000
	III		I	I	100(?)–1,000
	II		I	I	1,100–2,100
	I		I	I	2,200–7,000
Leasburg	Isaacks' Ranch		II	II, III	latest Pleistocene (10,000–15,000)
Late Picacho	Late Jornada II		III	III	late Pleistocene (15,000–75,000)
Picacho	Jornada II	Petts Tank	III	III, IV	late to middle Pleistocene (75,000–150,000)
Tortugas			III	IV	late middle Pleistocene (150,000–250,000)
Jornada I	Jornada I	Jornada I	III	IV	middle Pleistocene (250,000–400,000)
	Doña Ana			IV	>400,000
Buried surfaces and soils					(400,000–780,000)
Lower La Mesa			III, IV		middle to early Pleistocene (780,000)
JER La Mesa			IV, V		early Pleistocene to late Pliocene (780,000–2,000,000)
Upper La Mesa			V		late Pliocene (2,000,000–2,500,000)

[1]Geomorphic surfaces after Ruhe (1967), Hawley and Kottlowski (1969), and Gile et al. (1995b). Materials genetically related to constructional phases of a geomorphic surface are designated by the geomorphic surface name (e.g., Fillmore alluvium; Hawley and Kottlowski, 1969). Lower and upper La Mesa and JER La Mesa are not formally considered a part of the valley border but are included here because they form part of a stepped sequence with the valley border surfaces. The late phases of Jornada II and Picacho are relatively minor in extent and have not been separately mapped. They are included here because they occupy a highly significant part of the soil chronology. Coppice dunes have not been formally designated a geomorphic surface but are considered separately here because of their extent and significance to soils of the area. Buried surfaces and soils refer to surfaces and soils that are stratigraphically between the Jornada I soil and alluvium of the ancestral Rio Grande, north and south of Tortugas Mountain.

study were to determine: (1) the amounts of pedogenic carbonate in the soils and its relation to soil age and to the chronology of the several La Mesa surfaces; (2) to determine the reasons for substantially less pedogenic carbonate in soils of the eastern side of the basin floor, as compared to the central part; and (3) to present evidence of a former lake that once occupied the eastern part of the basin floor.

The study area is in the broad floor of the Jornada Basin (Figs. 1, 2). La Mesa geomorphic surface, of middle Pleistocene to late Pliocene age, is on the basin floor, which was once occupied by the ancestral Rio Grande; most soils have formed wholly or partly in its deposits, the fluvial facies of the Camp Rice Formation (Ruhe, 1967; Hawley et al., 1969; Seager et al., 1971, 1976; Hawley, 1975; Gile et al., 1981; Mack et al., 1993; Table 1). These sediments contain very little or no carbonate, and all or nearly all of the pedogenic carbonate must have been derived from atmospheric additions (Gile et al., 1981; Capo and Chadwick, 1999).

Paleomagnetic data bracket the age of La Mesa in the Jornada Basin between 780,000 and 900,000 yrs (Mack et al., 1993). However, several factors indicate that parts of La Mesa in the Jornada Basin are much older, with La Mesa as a whole having an age range of about 780,000–2,000,000 yrs. Soils about 1,600,000 yrs old occupy the bulk of La Mesa in the Jornada Basin, as indicated by dated pumice, the very extensive areas with stage V carbonate, and totals of pedogenic carbonate. Much of the younger part of the age range for La Mesa in the Jornada Basin is near the valley in the western part of the basin floor, where the latest pre-incision fluvial sediments were deposited. La Mesa in the Jornada Basin is here termed JER La Mesa because so much of the Jornada Experimental Range is located on it (Fig. 2).

Soil classification is according to the second edition of *Soil taxonomy* (Soil Survey Staff, 1999). The stages of carbonate accumulation are according to Gile et al. (1966) and Birkeland et al. (1991; Table 2). Laboratory analyses were done by the National Soil Survey Laboratory at Lincoln, NE; methods are given in Tables 3 and 4.

Pedogenic carbonate as a chronological tool

The total amount of pedogenic carbonate in a soil may be used to estimate its age (Gile et al., 1981; Machette, 1985; Mayer et al., 1988; Marion, 1989). If the age of a soil is not known, its age may be estimated by using the formula shown in Table 3 and the same rate of carbonate accumulation determined from a soil of known age. According to Machette's (1985) model, soils older than about 100,000 yrs should have similar average accumulation rates that can be used to correlate soils locally and to estimate ages of soils that are older than about 100,000 yrs. All soils discussed in this report meet this requirement.

In some soils of JER La Mesa there is a large disparity between the maximum paleomagnetism age of 900,000 yrs (Mack et al., 1993) and the estimated age by totals of pedogenic carbonate. This is indicated by a comparison of carbonate totals for soils of lower La Mesa and JER La Mesa. Lower La Mesa is good for such comparisons because its age is constrained by several factors. One concerns magnetostratigraphy, which for an area of lower La Mesa at the Desert Project has been identified as Matuyama (reversed polarity, older than 780,000 yrs; Mack et al., 1998). South of the Desert Project, another area of lower La Mesa has been identified as Brunhes (normal polarity, younger than 780,000 yrs;

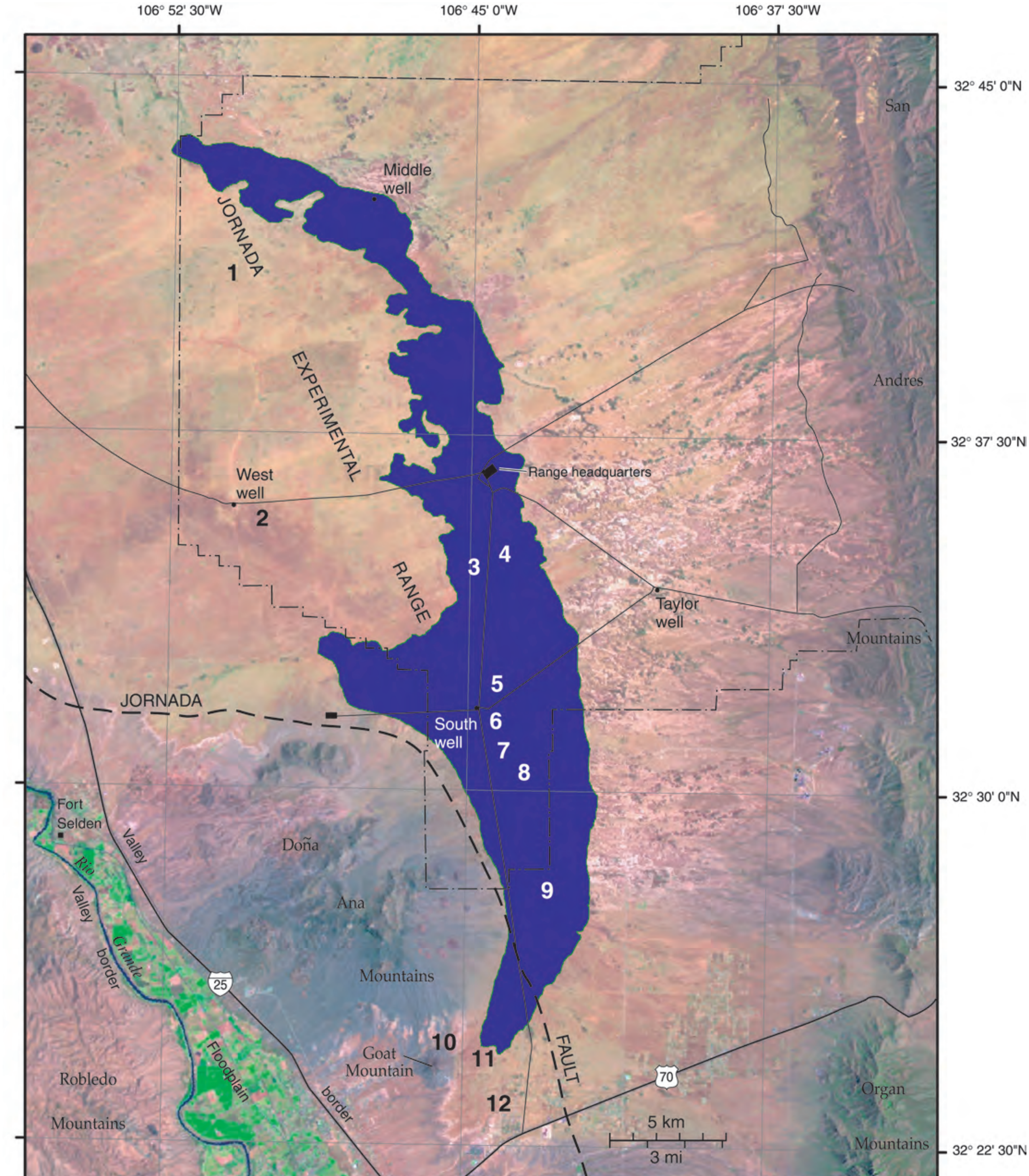

FIGURE 2—Jornada Experimental Range and part of the Desert Project (modified from Herbel and Gile, 1973). **1**, locates pedon 94–1; **2**, pedon 95–4; **3**, pedons 95–2, 95–3, and 99–1; **4–9**, study sites that have gypsum buried (sites 4, 5, and 9) or in the land-surface soil (sites 6, 7, and 8); **10**, the scarp north of Goat Mountain; **11**, the northern end of JER La Mesa sediments, which extend northward from east of Goat Mountain, and the southern margin of Lake Jornada; **12**, pedon 65–7 on the JER La Mesa surface. The heavy dashed line east and north of the Doña Ana Mountains locates the Jornada fault as shown by Seager et al. (1987). Isaacks Lake playa is just east of the fault and south of site 9. Landsat thematic map of New Mexico with lake shoreline derived from national elevation dataset by Mark M. Mansell. The dark blue area shows a possible extent of Lake Jornada.

TABLE 2—Stages of carbonate accumulation in gravelly and nongravelly materials.[1]

Stage	Diagnostic carbonate morphology: Gravelly materials	Nongravelly materials
I	Thin pebble coatings, continuous in the last part of the stage.	Few filaments and/or faint coatings.
II	Continuous pebble coatings, some interpebble fillings.	Few to common nodules.
III	Many interpebble fillings, forming a K horizon;[2] horizon is plugged in the last part of the stage.	Many nodules and internodular fillings, forming a K horizon;[2] horizon is plugged in the last part of the stage.
IV	Laminar horizon overlying the plugged horizon.	Laminar horizon overlying the plugged horizon.
V	Laminar layer and platy structure are strongly expressed; incipient brecciation and pisolith (thin, multiple layers of carbonate surrounding particles) formation.[3]	
VI	Brecciation and recementation (multiple generations), as well as pisoliths, are common.[3]	

[1]"Gravelly" materials contain more than about 50% rock fragments (fragments 2 mm or larger in diameter, such as pebbles). "Nongravelly" materials contain less than about 20% rock fragments. Materials with intermediate (20–50%) contents of rock fragments have intermediate morphologies.
[2]Gile, L. H., et al., 1965.
[3]Birkeland et al., 1991.

Vanderhill, 1986). Thus, the true age of lower La Mesa could be very close to 780,000 yrs, the boundary between Brunhes and Matuyama. This interpretation agrees with the conclusion of Mack et al. (1998) that downcutting of the Rio Grande at Rincon Arroyo in the Jornada Basin began very near or at the Matuyama–Brunhes boundary. This would initiate soil development in the abandoned lower La Mesa floodplain at about that time.

Totals of pedogenic carbonate are available for two pedons on lower La Mesa at the Desert Project. One is the Curtis Monger study site (Monger et al., 1991), which has 992 kg/m^2* of pedogenic carbonate. The other is pedon 61–8 (Gile and Grossman, 1979), which has 1,168 kg/m^2 of pedogenic carbonate. Both sites are level and not subject to run-in. Averaging the totals of the two pedons gives a value of 1,080 kg/m^2. Using this value and the estimated age of 780,000 yrs for lower La Mesa, as discussed above, gives an average accumulation rate of 1.4 kg/m^2/1,000 yrs, and this figure has been used in a chronological comparison with soils of JER La Mesa in the following section.

Pedogenic carbonate for JER La Mesa

Carbonate data for soils of JER La Mesa are scarce, especially considering the vast area involved (Fig. 2). Data illustrating the complete carbonate profiles for these ancient soils are available for only five pedons: 94–1, 95–2, 95–3, 95–4, and 99–1. Pedons 94–1 and 95–4 are in the central part of the basin floor, whereas the other three are in the eastern part (Fig. 2).

Sites 1 and 2—central part of the basin floor and a remarkable soil about 1,600,000 yrs old

Pedon 94–1 (site 1) is in the Cruces series, a loamy, mixed, superactive, thermic, shallow Argic Petrocalcid; pedon 95–4 (site 2) is in the Hueco series, a coarse-loamy, mixed, superactive, thermic Argic Petrocalcid. Pedons 94–1 and 95–4 have pedogenic carbonate totals of 2,296 and 1,861 kg/m^2 respectively (Table 3). Pedon 94–1 is on the lower part of a 2% slope, and its carbonate could have been increased by runoff from the soils upslope. Thus pedon 95–4 (which is level) is used for comparison purposes with soils of lower La Mesa. Applying the same carbonate-accumulation rate as for soils of lower La Mesa (1.4 kg/m^2/1,000 yrs) gives an estimated age of about 1,330,000 yrs. Pedon 95–4 also has the distinctive stage V morphology, typical in JER La Mesa but seldom found in lower La Mesa, which is dominated by stages III and IV. Also, laminar linings of pipes in lower La Mesa soils are thin or absent, whereas pipes of JER and upper La Mesa commonly have thick, often multicyclic laminar linings.

An estimated age of about 1,330,000 yrs for pedon 95–4 would not be unreasonable because pumice dated at 1,600,000 yrs is present at a depth of only 228 cm (7.25 ft; Table 3; Mack et al., 1996). However, transport of the pumice down river by the ancestral Rio Grande is estimated to have been very rapid, probably a few days or weeks (Mack et al., 1996). Thus, if sedimentation above 228 cm (7.25 ft) continued at about the same rate as for the thick layer with pumice, pedon 95–4 could be about 1,600,000 yrs old. The accumulation rate for pedon 95–4 was calculated to check this. Using an age of 1,600,000 yrs and 1,861 kg/m^2 of pedogenic carbonate, the accumulation rate is 1.2 kg/m^2/1,000 yrs. This is very close to the accumulation rate of 1.4 kg/m^2 for lower La Mesa and is strong evidence that pedon 95–4 is, indeed, about 1,600,000 yrs old.

Soils of several ages with stage V morphology are present along and above fault scarps. Some of these soils may be older than 1,600,000 yrs, and an overall age range of 780,000–2,000,000 yrs has been tentatively assigned for soils of JER La Mesa (Table 1). Some of the soils in this ancient plain may even be of upper La Mesa age (e.g., see site 8, discussed later).

Site 3—eastern part of the basin floor

Pedons 95–2, 95–3, and 99–1 are in the eastern part of the basin floor (Figs. 2, 3), where there is abundant evidence of burial of the Camp Rice fluvial sediments by Pleistocene eolian deposits (Gile, 1999). These eolian deposits are thought to be eolian analogs of alluviums that were caused by major changes to drier climates, leading to landscape instability and associated severe erosion (Gile et al., 1981).

Pedons 95–2, 95–3, and 99–1 have buried soils formed in Camp Rice fluvial deposits that are buried by Pleistocene eolian sediments (Fig. 4). All soils have argillic horizons and stage III calcic horizons. The three pedons are coarse-loamy, mixed, superactive, thermic, Typic Calciargids, and all three are in the Yucca series or its analogs. Pedon 99–1 is Yucca; pedon 95–3 is a calcareous analog; and pedon 95–2 is a deep analog (the calcic horizon is below a depth of 1 m [3 ft]). Pedon 95–3 is on a ridge side; the other two pedons are on a ridge crest that is windward of the ridge side (Fig. 4). Laboratory data are in Table 4.

Boundaries of the buried K/Bt horizons can only be approximate because some of the Bt material has been engulfed by carbonate. Carbonate in the buried K/Bt horizons is included with the overlying soil for calculations of pedogenic carbonate because this carbonate descended from the horizons above.

Pedon 95–3. Pedon 95–3 (Fig. 4) is on the west-facing, wind-eroded side of a gentle ridge and slopes 1% to the west. Data for the land-surface soil, formed in Pleistocene eolian sediments, have been discussed (Gile, 1999). Table 4 presents these data along with data for deeper horizons analyzed for this study.

The land-surface soil in the post-La Mesa eolian deposit has a discrete carbonate maximum (Table 4) with a total of pedogenic carbonate similar to that of Jornada II soils of late Pleistocene age (Gile, 1999). Also, the size and morphology of pipes are typical of pipes of late Pleistocene soils (see fig. 5 in Gile, 1999).

Some horizons of the buried soil contain much more silt, reflecting the fluvial origin

*Editor's note: To obtain lb/ft^2, multiply kg/m^2 by 0.2048.

TABLE 3—Complete carbonate profiles for two soils of JER La Mesa.

The Argic Petrocalcid Hueco 95–4

Horizon	Depth cm	$CaCO_3$ <2mm %	Pedogenic $CaCO_3$ kg/m^2	Bulk density g/cm^3
A	0–6	TR	–.9	1.5
BAt	6–15	TR	–1.4	1.5
Bt1	15–28	–	–2.1	1.6
Bt2	28–43	TR	–2.6	1.7
Bt3	43–57	TR	–2.4	1.7
Btk1	57–74	4	8.7	1.7
Btk2	74–83	7	9.2	1.7
Btk3	83–89	21	21.6	1.8
K21m	89–104	90	280.4	2.1
K22m	104–114	88	182.7	2.1
K23m	114–122	88	139.2	2.0
K24m	122–134	70	154.8	1.87
K25m	134–153	73	262.7	1.92
K26m	153–175	89	329.1	1.70
K31	175–202	22	96.4	1.7
K32	202–228	14	57.5	1.7
Bqk1	228–261	4	17.8	1.8
Bqk2	261–282	17	57.1	1.7
Bqk3	282–301	1	0.0	1.7
Bqk4	301–317	9	21.8	1.7
Kqm	317–327	55	97.2	1.8
Bqk	327–335	TR	–1.4	1.7
Bq	335–351	TR	–2.6	1.6
K/C	351–361	52	86.7	1.7
C1	361–373	1	0.0	
C2	373–391	TR	–1.6	1.6
Ck1	391–401	49	28	1.7
Ck2	401–409	3	1	1.6
Ck3	409–429	21	24	1.7
C1'	429–434	TR	0.0	
C2'	434–475	–	0.0	
C3	475–515	TR	0.0	
C4	515–545	TR	0.0	
			1,860.9 total	

The Argic Petrocalcid Cruces, overblown phase 94–1

Horizon	Depth cm	$CaCO_3$ <2mm %	Pedogenic- $CaCO_3$ kg/m^2	Bulk density g/cm^3
C	0–10	–		
BAtb	10–16	2	2.6	1.6
Btk1b	16–26	4	4.8	1.6
Btk2b	26–36	4	5.1	1.7
Btk3b	36–42	4	3.1	1.7
K1b	42–51	63	10.0	1.8
K21mb	51–61	74	153.3	2.1
K22mb	61–72	71	161.7	2.1
K23mb	72–88	56	176.0	2.0
K24mb	88–114	60	289.6	1.9
K25b	114–122	69	97.9	1.8
K26mb	122–150	53	276.6	1.9
K27b	150–173	28	111.18	1.8
K28b	173–195	24	86.0	1.7
K29mb	195–212	40	119.3	1.8
K31b	212–230	43	128.5	1.7
K32b	230–253	45	112.0	1.7
K33b	253–302	52	407.7	1.6
Cb	302–322	TR	–2.0	1.6
Ckb	322–352	1	0.0	
			2,296.3 total	

$CaCO_3$ equivalent by method 6E1g (Soil Survey Investigations Staff, 1996). **TR** = trace, either not measurable by quantitative procedure used or less than 0.5%. For bulk density, figures given in tenths are estimates from previous work (Gile and Grossman, 1979), using soil texture and consistence; the others are measured. The C1 horizon of 95–4 is mostly noncalcareous but contains about 10% carbonate-cemented zones of ground-water origin that analyze 58% carbonate, not included in the totals of pedogenic carbonate. The Ck1, Ck2, and Ck3 horizons of 95–4 contain a mixture of pedogenic and ground-water carbonate. About half of this mixture is estimated to be of pedogenic origin and is included in the totals of pedogenic carbonate. The C2' horizon of 95–4 is mostly noncalcareous but contains about 20% indurated, rounded plates of ground-water origin that analyze 58% carbonate, not included in the totals of pedogenic carbonate. The platy ground-water carbonate formed horizontally along sedimentary strata, deposited from ground water moving laterally along them before the floodplain was abandoned by the downcutting Rio Grande. In contrast, the pedogenic carbonate can be traced downward in the soil as an illuvial feature, deposited from the downward-moving soil solution. Both pedons contain very little or no > 2 mm (> 0.08 inch) material, with the following exceptions for pedon 95–4, in which the percentage by volume of > 2 mm material follows each horizon: Bqk (4%), Bq (1%), K/C (2%), C1 (7 %), C2 (5%), Ck2 (1%), Ck3 (8%), C4 (1%). Fragments of pumice dated at 1.6 million years old (Mack et al., 1996) extend from 228 cm (7.5 ft) to at least 545 cm (18 ft), the bottom of the sampling trench. The calculation for pedogenic carbonate is for a volume element one square meter in horizontal cross section and of variable thickness, according to the formula **$CaCO_3$ (kg/m^2) = (L x Db x [1 – > 2 mm vol. %]/100 x $CaCO_3$)/10** where **L** is the thickness of the horizon in cm, **Db** is the bulk density of the fine-earth fabric, **(1 – > 2 mm vol. %)/100** is a correction for the volume occupied by the >2 mm material, and **$CaCO_3$** is carbonate content of the horizon minus the carbonate content of the parent material.

of the parent materials, than overlying horizons deposited by the ancestral Rio Grande. An accumulation of gypsum and a marked change in particle size occur beneath the carbonate accumulation (Table 4). The Bkyb horizon has 39% gypsum, and the Byb horizon contains 72% gypsum. The latter horizon is mostly clear gypsum (selenite variety of $CaSO_4 \cdot 2\ H_2O$); it is underlain by three horizons, all of which contain 60% or more clay (Table 4). Observations to approximately 5.5 m (18 ft) below the lowermost sampled horizon show substantial variations in texture, ranging from fine sandy loam to silty loam. Only a minor amount of gypsum is present at a depth of approximately 5 m (16 ft).

The gypsum is thought to have been derived from deposits of Lake Jornada (discussed later) as it dried and finally disappeared. Position of the gypsum below the carbonate is typical for pedogenic gypsum because it is more soluble than carbonate. After the lake dried, the gypsum it contained must have been deposited on the lake bottom, in this case the fluvial deposits of the ancestral Rio Grande. However, some of the gypsum moved downward in the soil by pedogenic processes and could have accumulated in the gradually lowering water table and then deposited in the uppermost saturated (ground-water) zone and capillary fringe as the water table dropped. Deposition of gypsum by evaporation as the water table gradually lowered would therefore continue during dry times when precipitation was insufficient for pedogenic movement of gypsum. Thus the gypsum could have been partly of pedogenic and partly of ground-water origin.

Pedogenic carbonate for the land-surface soil, from 0–151 cm (0–59 inches), totals 314 kg/m^2 (Table 4). Pedogenic carbonate for the buried soil totals 556 kg/m^2 (Table 4); the total for the pedon as a whole is 869 kg/m^2. This is considerably less than the 1,861 kg/m^2 for pedon 95–4 in the central part of the basin floor (Table 3).

Pedon 99–1. Pedon 99–1 (Fig. 4) is in an area of Historical deposition on the ridge crest. Historical erosion and deposition have been widely documented in the Jornada Experimental Range (e.g., Buffington and Herbel, 1965; Gibbens et al., 1983; Gile, 1999).

An accumulation of cemented gypsum, from 30 to 50 cm (1 to 2 ft) thick, is at a depth of approximately 5.7 m (19 ft) in the

TABLE 4—Characteristics of the Typic Calciargids, pedons 95–3, 99–1, and 95–2.

Horizon	Depth (cm)	Dry color	Texture	Particle size (mm) Sand 2–0.05 %	Silt 0.05–0.002 %	Clay <0.002 %	$CaCO_3$ equiv. < 2mm %	Pedogenic $CaCO_3$ kg/m²	Estimated bulk density g/cm³
Pedon 95–3 (Yucca, calcareous analog)									
A	0–5	5YR 5.5/4	fsl	78	11	10	4	2.4	1.6
Btk1	5–18	5YR 5.5/3	ls	81	11	9	5	8.3	1.6
Btk2	18–31	5YR 5.5/3	fsl	77	11	12	8	14.6	1.6
K21	31–48	7.5YR 9/3	scl	63	16	21	25	69.4	1.7
K22	48–65	7.5YR 8/2	fsl	67	14	19	22	64.3	1.8
K31	65–85	7.5YR 7.5/3	fsl	71	14	16	17	54.4	1.7
K32	85–114	7.5YR 7/3	fsl	73	14	13	12	54.2	1.7
K33	114–141	5YR 7/3	fsl	74	12	13	9	36.7	1.7
K34	141–151	7.5YR 7/4	fsl	69	15	16	15	23.8	1.7
								313.5 total	
Btk1b	151–160	5YR 6/6	ls	86	10	4	2	1.3	1.5
Btk2b	160–171	5YR 6/3	cl	41	30	29	7	9.2	1.5
Btk3b	171–191	5YR 5.5/5	vfsl	54	30	17	1	0.0	1.4
Btk4b	191–203	7.5YR 7/3	fsl	64	26	10	7	10.8	1.5
K21b	203–221	7.5YR 9/1	vfsl	56	32	13	28	82.6	1.7
K22b	221–239	7.5YR 8/2	vfsl	63	26	10	18	55.1	1.8
K23b	239–256	7.5YR 8/2	1	49	39	12	26	76.5	1.8
K24b	256–289	7.5YR 8/3	vfsl	47	47	6	29	166.3	1.8
K25b	289–321	7.5YR 8/2	vfsl	56	33	11	8	39.3	1.7
K26b	321–335	7.5YR 8/3	sil	40	55	5	39	85.1	1.6
Ckb	335–355	8YR 8/2	sil	45	51	5	7	15.6	1.3
Bkyb	355–376	8YR 8/2	sil	33	59	8	1	0.0	1.3
Bylb	376–381			54	39	8	1	0.0	1.3
By2b	381–401	7.5YR 6/3	c	1	40	60	TR	555.5 total	
By3b	401–421	5YR 4.5/4	c	5	30	64	1		
Cb	421–446	7.5YR 6/3	c	5	34	61	6		
								869.0 total for pedon	
Pedon 99–1 (Yucca)									
C	0–17	5YR 5/5	fs	89	5	6	1	0.0	1.5
Ab	17–22	5YR 5/4	ls	81	9	10	TR	-0.8	1.6
Btb	22–37	5YR 5.4	fsl	80	7	13	TR	-2.4	1.6
Btk1b	37–51	5YR 5/4	sl	74	10	17	4	6.7	1.6
Btk2b	51–70	5YR 5/5	fsl	74	11	16	4	8.5	1.5
Btk3b	70–88	5YR 5/5	fsl	75	10	15	4	8.1	1.5
K1b	88–101	7.5YR 7/4	sl	71	13	17	12	22.9	1.6
K21b	101–115	7.5YR 8/2	fsl	63	17	20	24	54.7	1.7
K22b	115–138	7.5YR 8/2	scl	60	17	24	24	95.2	1.8
K23b	138–162	7.5YR 8/2	scl	57	19	24	25	103.7	1.8
K24b	162–178	7.5YR 8/3	scl	60	18	23	23	63.4	1.8
K25b	178–216	7.5YR 8/3	scl	59	19	22	28	174.4	1.7
K/Btb2	216–228	7.5YR 8/3	fsl	66	18	17	15	25.2	1.5
								559.6 total	
Kb2	228–251	9YR 9/1	sl	63	23	14	21	64.4	1.4
Ck1b2	251–281	7.5YR 7/3	ls	80	11	9	7	22.7	1.3
Ck2b2	281–306	10YR 7/3	s	94	4	3	1	0.0	1.2
Ck3b2	306–324	10YR 7/2	s	94	4	2	3	3.7	1.2
Ck4b2	324–374	10YR 7/2	s	97	1	2	TR	-6.0	1.2
Ck5b2	374–399	10YR 7/2	cos	96	2	1	1	0.0	1.2
								84.8 total	
								644.4 total for pedon	

fluvial sandy sediments below the sampled horizons. The cemented gypsum would have been somewhat more than 3 m (10 ft) below the surface of the fluvial sediments, easily reachable by wetting fronts in these sandy sediments, early in soil history. That moisture reached these depths is also shown by calcareous root channel fillings, 1–4 mm (0.04–0.16 inches) in diameter, just above the gypsum. The gypsum consists mostly of angular and bladed forms (selenite) cemented together and is probably a lateral equivalent of the selenite associated with clay at pedon 95–3, previously discussed.

Beneath the Historical deposit the total of pedogenic carbonate for the pedon as a whole is distinctly less than for pedon 95–3 (644 vs 848 kg/m²) and also less than for pedon 95–2, to be discussed next. This relatively low carbonate total for pedon 99–1 is attributed to its position on the margin of the ridge crest, where infiltration rates would be expected to be lower than for stabler areas away from the margin. For these reasons the carbonate total for pedon 99–1 is thought to be anomalously low and is not used in comparison with pedon 95–4 in the central part of the basin floor.

Pedon 95–2. Pedon 95–2 is on the crest of the ridge (Fig. 4). Three buried soils are beneath the Historical sediments. The K/Btb3 horizon, at a depth of 345–375 cm (11–12 ft), is underlain by gravelly sediments of fluvial origin. The selenite found at pedons 95–3 and 99–1 was not found here, possibly because the fluvial sediments were so deeply buried by eolian sediments that our backhoe could not reach

TABLE 4, continued.

Horizon	Depth (cm)	Dry color	Texture	Particle size (mm) Sand 2–0.05 %	Silt 0.05–0.002 %	Clay <0.002 %	$CaCO_3$ equiv. < 2mm %	Pedogenic $CaCO_3$ kg/m²	Estimated bulk density g/cm³
Pedon 95-2 (Yucca, deep analog)									
C1	0–6	5YR 5/4	s	88	5	7	1	0.0	1.5
C2	6–19	5YR 5/4	s	89	5	6	TR	-2.0	1.5
BAtb	19–29	5YR 5/4	fsl	81	7	12	TR	-1.6	1.6
Bt1b	29–43	4YR 4.5/4	fsl	81	6	14		-2.2	1.6
Bt2b	43–61	4YR 4.5/4	fsl	78	7	14		-2.9	1.6
Btk1b	61–70	4YR 4.5/4	fsl	76	8	15	1	0.0	1.6
Btk2b	70–83	5YR 5.5/4	sl	73	9	18	3	4.2	1.6
Btk3b	83–101	5YR 6/4	fsl	74	7	19	2	2.9	1.6
Btk4b	101–118	5YR 6/4	fsl	77	6	17	2	2.7	1.6
Btk5b	118–138	5YR 6/5	fsl	79	5	16	2	3.2	1.6
K1b	138–155	7.5YR 9/4	sl	73	11	16	16	43.4	1.7
K21b	155–177	7.5YR 9/2	sl	70	13	17	22	83.1	1.8
K22b	177–203	7.5YR 8/2	fsl	71	13	16	20	88.9	1.8
K/Btb2	203–222	5YR 7/3	fsl	78	10	12	11	32.3	1.7
								252.0 total	
K1b2	222–239	7.5YR 8/2	scl	63	16	21	25	69.4	1.7
K21b2	239–256	7.5YR 9/2	scl	58	19	23	32	95.1	1.8
K22b2	256–292	7.5YR 9/2	scl	58	18	24	32	189.7	1.8
K31b2	292–317	7.5YR 8/2	scl	67	12	21	16	63.8	1.7
K32b2	317–345	7.5YR 7/4	fsl	71	11	18	15	62.7	1.6
K/Btb3	345–375	7.5YR 7/3	ls	86	10	4	18	86.7	1.5
								567.4 total	
Ck1b3	375–396	7.5YR 7/3	ls	86	7	7	6	14.7	1.4
Ck2b3	396–432	7.5YR 7/3	s	91	6	4	5	17.3	1.2
Ck3b3	432–460	10YR 7/2	s	97	1	2	TR	-3.2	1.2
								28.6 total	
								848.0 total for pedon	

The term "variant" has been discontinued (Soil Survey Division Staff, 1993) and is here replaced by "analog" for informal use. Colors given are the dominant ones; smaller volumes of other colors are present in some horizons. The By1b horizon of pedon 95–3 is mostly clear gypsum, parts of which are stained and/or separated by colors of adjacent horizons. The Bkyb, By1b, By2b, and Cb horizons in pedon 95–3 contain 39, 72, 1, and 2% gypsum respectively. Particle size on carbonate-containing basis by method 3A1; $CaCO_3$ equivalent by method 6E1g (Soil Survey Investigations Staff, 1996). **TR** = trace, either not measurable by quantitative procedure used or less than 0.5%. Particle size data are reported in tenths of percent, rounded to whole numbers in this table. The calculation for pedogenic carbonate is given in Table 3. Bulk density estimated from previous work (Gile and Grossman, 1979), using soil texture and consistence. The three pedons contain very little or no >2 mm material, with the following exceptions, in which the percentage by volume of >2 mm material follows the horizon. Pedon 95–2: Ck1b3 (9%), Ck2b3 (5%), and Ck3b3 (4%). Pedon 99–1: Ck1b2 (3%), Ck2b2 (2%), Ck3b2 (15%), Ck4b2 (1%), and Ck5b2 (2%). Abbreviations for the texture follow the Soil Survey Staff (1951).

them. Total pedogenic carbonate for the pedon as a whole is 848 kg/m² (Table 4).

Mystery of the missing carbonate

Pedon 95–4 of JER La Mesa in the central part of the basin floor has 1,861 kg/m² of pedogenic carbonate (Table 3). But pedons 95–2 and 95–3, in eolian deposits underlain by buried soils of JER La Mesa in the eastern part of the basin floor, have much less carbonate; when totals of the buried and unburied soils are combined, they average only 858 kg/m². This indicates that approximately 1,000 kg/m² of pedogenic carbonate is missing. Carbonate totals for the two pedons with buried soils should be much closer to the carbonate total for pedon 95–4, because deposits at the two areas occupy about the same span of time. A lake that formed early in the history of JER La Mesa may be responsible for the difference in carbonate content.

Formation of Lake Jornada

Herrick (1904) proposed an ancient lake, named Lake Otero, in the Tularosa Basin just east of the Jornada Basin, to explain the extensive gypsum beds in that area. That conclusion was supported by Kottlowski (1958), Weber and Kottlowski (1959), and Hawley (1993). Weber and Kottlowski (1959) indicated that the whole west-central part of the Tularosa Basin was probably an intermittent lake during the latest Pleistocene pluvial episode. Gypsum in playas north of the JER headquarters (Fig. 2) may also be lacustrine. In addition, there is evidence, to be discussed, of a lake much larger than suggested by the playas alone.

North of the Doña Ana Mountains, extensive displacement along the Jornada fault (Seager et al., 1987; Fig. 2) has offset La Mesa sediments approximately 45 m (148 ft; Mack et al., 1994). Precise age of the displacement is not known. However, prominent stage V horizons along some of the fault scarps (which have been buried in many places by deposits and soils dating from various times in the Pleistocene and Holocene) indicate that the displacement must have taken place early in the history of JER La Mesa.

A remnant of JER La Mesa and its stage V horizon are preserved at approximately 1,329 m (4,360 ft) elevation north of Goat Mountain (#10, Fig. 2). Beneath the sediments of Isaacks Lake playa (Fig. 2), La Mesa sediments are at approximately 1,305 m (4,280 ft) elevation. This indicates that displacement of the JER La Mesa sediments east of the Jornada fault and the Doña Ana Mountains was at least 24 m (78 ft) at Isaacks Lake playa.

In addition to the main Jornada fault (Fig. 2), branches extend from it in various places. One of these branches extends to the vicinity of West well (Fig. 2; Seager et al., 1987; Bill Seager, pers. comm. 1995; see also fig. 6 in Gile, 1999). No evidence has been found that would indicate substantial later displacement along the Jornada fault. Thus, areas adjacent to the fault probably have been little affected or unaffected by faulting since that displacement.

Evidence to be presented indicates that an intermittent lake, here named Lake Jornada, must have formed soon after the displacement created the north-south topographic low just east of the Doña Ana Mountains (Fig. 2). In addition to the displacement, formation of the lake would

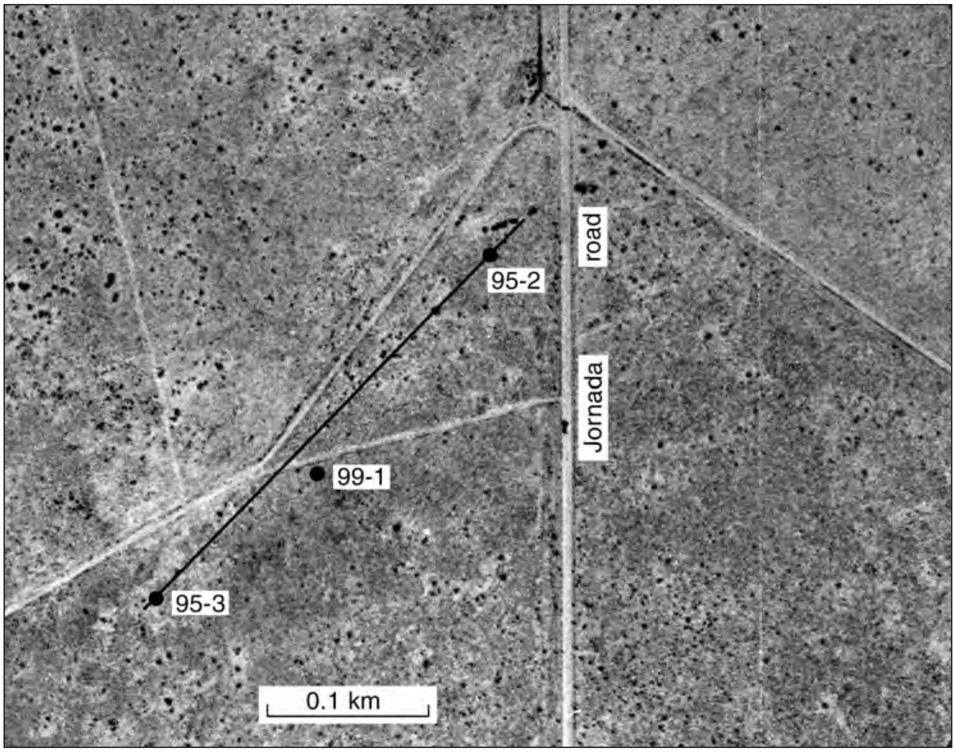

FIGURE 3—Aerial photograph locating cross section (Fig. 4) and pedons 95–3, 99–1, and 95–2, just west of the Jornada Road. Aerial photograph taken in 1974.

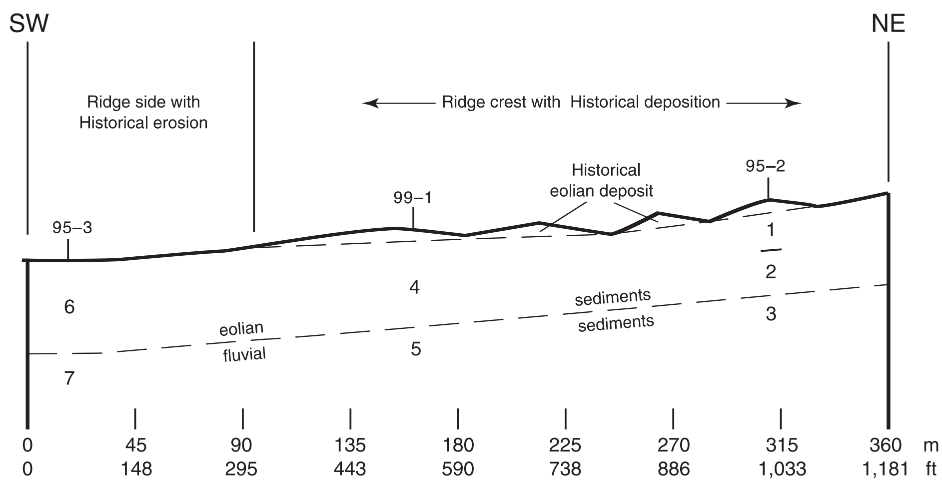

FIGURE 4—A cross section of the land surface from pedons 95–3 to 95–2 at site 3 (Fig. 2). West of the Historical deposit on the ridge crest is a wind-eroded ridge side that slopes 1% to the west. No vertical scale (soil depths follow): **1**, 0–203 cm (0–7 ft); **2**, 203–345 cm (7–11 ft); **3**, 345–460 cm (11–15 ft); **4**, 0–228 cm (0–8 ft); **5**, 228–399 cm (8–13 ft); **6**, 0–151 cm (0–5 ft); **7**, 151–446 cm (5–15 ft). The lower dashed line separates Pleistocene eolian sediments from fluvial sediments of JER La Mesa (Table 1).

have been stimulated by the high water tables that must have existed at the time; entrenchment of the Rio Grande valley to the west was only slight as compared to today. Thus, the effect of the valley in lowering water tables in the Jornada Basin floor must have been nil east of the Doña Ana Mountains and similar areas far to the east. Water to form and maintain the lake would have been provided by the Doña Ana Mountains to the west and by the Organ and San Andres Mountains to the east. Even under present conditions and the current interpluvial climate, in some years enough runoff water accumulates during the summer rainy season to form a lake that lasts for a period of several months in Isaacks Lake playa.

Stratigraphic position of gypsum as a signature for Lake Jornada

The stratigraphic position of gypsum is a valuable chronological marker for establishing the time of existence for Lake Jornada. Parts of the basin floor have been buried by sediments from the adjacent piedmont slopes. Gypsum is at the surface of some of the playas north of the range headquarters (Fig. 2), but to the south it is both in buried position and in soils of JER La Mesa. These relationships are illustrated by sites 4–9 discussed from north to south in the following sections (see the cited references for more detail).

Site 4—burial of gypsum by Petts Tank and Jornada I sediments

Site 4, elevation 1,317 m (4,320 ft), is in a playa 1.3 km (0.8 mi) north of site 3 (Fig. 2). In this playa Petts Tank sediments of late Pleistocene age (Table 1) extend to a depth of 2.2 m (7.2 ft) and are underlain by a buried soil of Jornada I age. Beneath the Jornada I soil, layers of gypsum, some of which are cemented, extend from 4.4 m (14 ft) to at least 5.5 m (18 ft), the bottom of the trench (Gile et al., 1997, pp. 54, 55).

Site 5—burial of gypsum by Petts Tank sediments

Site 5, elevation 1,315 m (4,313 ft), is on the toeslopes of the alluvial-fan piedmont approximately 1.9 km (1.2 mi) northeast of South well (Fig. 2). In pedon 91–10, sediments of Petts Tank age (Table 1) extend to 170 cm (14 ft) depth, where the parent materials change markedly from high-carbonate sediments from the San Andres Mountains to the low-carbonate river sediments deposited by the ancestral Rio Grande. A Bt horizon and stage II carbonate have formed from 170 to 277 cm (5.6 to 9.1 ft) in depth in these fluvial sediments. A discontinuous gypsum hardpan is present from 227 to 277 cm (7.4 to 9.1 ft) in depth. From 277 to 475 cm (9.1 to 15.6 ft) layers of discrete crystals and bands of gypsum alternate with layers of fine and very fine sand and silt. From 475 to 498 cm (15.6 to 16.3 ft) the materials are soft and loose sandy river sediments without gypsum. Lateral continuity of gypsum in this area is shown by a second study trench 65 m (213 ft) east of the first, main trench. Gypsum at this site differs from the first in having an extremely hard, root-turning layer of cemented gypsum at a depth of 3.3 m (11 ft; Gile et al., 1995a, pp. 147, 148).

Site 6—gypsum in soils of JER La Mesa

Site 6, elevation 1,314 m (4,310 ft) is in a slight ridge in the central part of the Jornada Basin floor, approximately 0.8 km (0.5 mi) east of South well (Fig. 2). The extensive belts of eolian sands to the north are not found in this area because the Doña Ana Mountains are to the windward (Fig. 2). Pedon 61–2 is in the ridge and has 569 kg/m^2 of pedogenic carbonate (Gile et al., 1981, table 25). This is considerably less than the average of 858 kg/m^2 for two pedons at site 3 (Table 4).

Gypsum is present as small selenite

crystals from 112 to 185 cm (3.6 to 6.1 ft) in depth, in amounts ranging from 18% to 34%. It is thought to have accumulated by a combination of illuvial and ground-water processes as described at site 3. The base of the gypsum accumulation was not determined (Gile and Grossman, 1979, pp. 846, 847; Gile et al., 1981, pp. 188–191).

Site 7—gypsum in soils of JER La Mesa

Site 7 and pedon 68–6, elevation 1,314 m (4,310 ft), are in a slight depression in the basin floor south of site 6 (Fig. 2). Pedon 68–6 has 795 kg/m^2 of pedogenic carbonate (Gile et al., 1981, table 25). Carbonate gradually decreases to 1% $CaCO_3$ at a depth of 231–249 cm (7.6–8.2 inches). The gypsum occurs as crystals, with none being present above 160 cm (63 inches). The percentage of gypsum gradually decreases with depth, as would be expected in an illuvial horizon, and it also occurs in typical position, below the carbonate maximum. The percentages of gypsum are 20, 11, and 5 at depths of from 160 to 203 cm (5.25 to 6.66 ft), 203 to 231 cm (6.66 to 7.58 ft), and 231 to 249 cm (7.58 to 8.16 ft), respectively.

Site 8—gypsum in soils of earliest JER La Mesa or upper La Mesa

Pedon 61–1 at site 8, elevation 1,314 m (4,310 ft), is in a slight ridge in the basin floor. Pedon 61–1 has a thick complex horizon of carbonate accumulation; its lower horizons were not sampled. The sampled horizons total 1,090 kg/m^2 of pedogenic carbonate; the lowermost horizon sampled, from 173 to 196 cm (5.7 to 6.4 ft), contained 29% $CaCO_3$. Thus, the total amount of carbonate for this pedon would be substantially greater. The relatively high total (compared to soils at sites 6 and 7, just to the north) indicates that this soil probably dates from earliest JER La Mesa or even upper La Mesa time (Table 1). The K21 horizon, although not continuously cemented, consists of extremely hard, indurated plates that may once have been part of a continuously cemented horizon. Long-term submergence by the waters of Lake Jornada may have been responsible for the fractured horizon.

Analyses show traces of gypsum at a depth of only 33 cm (13 inches); gypsum is present continuously in the horizons below, culminating with 30% gypsum at 173–190 cm (5.7–6.4 ft) depth. This provides continuous tracking of illuvial gypsum downward in the soil and is additional evidence of gypsum accumulation partly, if not primarily, by illuviation from gypsum deposited on the soil surface by the drying of Lake Jornada.

Site 9—burial of gypsum by Organ, Jornada II, and Jornada I sediments

Pedon 66–6 is at site 8, elevation 1,311 m (4,300 ft), on a coalescent fan piedmont sloping 1% to the west. Pedon 66–6 is 2.4 km (1.5 mi) east of the Jornada Road, just southeast of the southeast corner of the JER. At this site the deep study trench extended progressively downward through Organ, Jornada II, and Jornada I sediments; gypsum; and then into fluvial deposits of the ancestral Rio Grande. Fine-grained gypsum is present throughout the zone from 437 to 518 cm (14.3 to 17 ft) in depth. The two horizons in this zone, from 437 to 457 cm and 457 to 518 cm (14.3 to 15 ft and 15 to 16.9 ft) depths, contain 80% and 70% gypsum, respectively. With increasing depth the fine-grained gypsum grades into selenite, which (at about 594 cm [19.5 ft] depth) overlies fluvial sediments without gypsum (Gile and Grossman, 1979, pp. 894, 895; Gile et al., 1981, pp. 183–185).

The cited studies strongly suggest that a continuous sheet of gypsum, mostly pure but commonly mixed in part with associated sediments, extends from the vicinity of site 9 to north of the JER headquarters (Fig. 1). Gypsum south of site 9 will be discussed later.

Evidence of a smaller late Pleistocene lake at site 9

In addition to the gypsum deposits at site 9, Jornada II sediments above the gypsum have a distinctive zone high in silt, informally termed the "silt zone," that extends from 208 to 325 cm (6.8 to 10.7 ft) in depth (see fig. 5 in Hawley and Kottlowski, 1969, and Gile et al., 1981, pp. 184, 185). A very similar zone is in pedon 70–7 approximately 3 km (1.9 mi) to the south, despite this soil having formed in low-carbonate parent materials instead of the high-carbonate parent materials at site 9. This silt zone is thought to have been deposited in a lake that flooded the basin floor during a pluvial episode in the late Pleistocene. This lake could be analogous to a late Pleistocene lake that formed in playas near the JER headquarters to the north (see discussion at site C in Gile, 1999).

Pedons 66–6 and 70–7 are both at 1,311 m (4,300 ft) elevation, and the lake margin is estimated to have been slightly above this. The lake could have extended as far north as South well (elevation 1,312 m [4,305 ft]), but because of higher elevations north of South well, it probably did not join with the late Pleistocene lake at the JER headquarters. This interpretation agrees with the morphology and data for horizons associated with the silt zones of pedons 66–6 and 70–7, which show no gypsum (Gile and Grossman, 1979, pp. 894, 895, 956, 957).

Soils of JER La Mesa and gypsum south of site 9

Site 10—scarp exposure of JER La Mesa and the associated slope to the east

North of Goat Mountain (#10, Figs. 2, 5) the JER La Mesa sediments and soils are well exposed in a scarp caused by erosion associated with entrenchment of the Rio Grande valley to the west. The prominent stage V horizon indicates that this soil must date from the early part of the age range for JER La Mesa. Just east of the scarp remnant, which is level or nearly level, is a 2% slope to the east. It is uncertain whether this 2% slope represents downwarping or colluvial slope associated with downdropping along the Jornada fault. If the latter, this slope represents a younger surface cut into the JER remnant along the scarp, illustrating that stage V horizons form in soils of at least two ages in the JER La Mesa age range.

Site 11—soils of the JER La Mesa basin floor and the southern margin of Lake Jornada

Two possibilities exist for formation of the basin floor below the 2% slope east of Goat Mountain (#11, Fig. 2). The basin floor could be a constructional surface of JER La Mesa, formed on Camp Rice sediments, deposited by a south-flowing ancestral Rio Grande, which was subsequently downfaulted by the Jornada fault. Or, alternatively, this segment of the ancestral river poured northward into a pre-existing structural depression caused by the fault. Stage V horizons are in slight ridges of the basin floor below the 2% slope discussed at site 10. Stage V formation in ridges is expedited by erosion, which reduces depth to carbonate maxima in the soils, speeding evolution of the carbonate horizon (Gile, 1999). Topographic lows adjacent to the ridges are dominated by stage IV horizons; instead of losing sediment the lows are receiving it, lifting the wetting fronts and thus slowing evolution of the carbonate horizon in the lows. In addition, soils in the lows are finer textured than those in the ridges. This also slows the wetting fronts, reducing their depth of penetration.

In contrast to sites 3, 6, 7, and 8 (Fig. 2), no evidence was found indicating that the soils at site 11 were covered by Lake Jornada. However, observations in pole holes dug for power lines showed selenite to be present beneath the prominent carbonate horizons in these soils (John Hawley, pers. comm. 1967). This indicates that, although the soils were not covered by Lake Jornada, they must have been very close to the edge of its waters. Thus, the lowest occurrence of JER La Mesa soils in the basin floor, about 1,318 m (4,325 ft), is taken as reflecting the approximate surface of Lake Jornada.

With increasing elevation southward (to about 1,323 m [4,340 ft]) the distinct stage V ridges are commonly replaced by an undulating basin-floor terrain that is dominated by stage IV and plugged or near-plugged stage III horizons, as illustrated by the next section.

FIGURE 5—A scarp along the JER La Mesa geomorphic surface, an ancient relict basin floor north of Las Cruces. This is a view of the scarp at site 10. The scarp cuts sediments of an ancestral Rio Grande that once flowed far above the present floodplain. The scarp was caused by erosion associated with entrenchment of the Rio Grande valley to the west; the slopes at left of the scarp extend toward the Rio Grande floodplain. The Doña Ana Mountains are on the skyline. The view is north. Photo by the author.

Site 12 and the extension of JER La Mesa to the south

Pedon 65–7 at site 12, elevation about 1,321 m (4,335 ft), is in the JER La Mesa basin floor southeast of Goat Mountain (Fig. 2). Pedon 65–7 has two carbonate maxima, one with 32% $CaCO_3$ at 46–61 cm (18–24 inches) in depth and the other in a plugged or near-plugged horizon with 59% $CaCO_3$ at 122–137 cm (4–4.5 ft) in depth. Such distinct and widely separated maxima are not common in deposits of the same age, suggesting the possibility of a younger deposit that buried the soil of JER La Mesa. Such a deposit could have been eolian because no mountains are to the windward.

The sampled horizons totaled 1,370 kg/m^2 of carbonate (Gile et al., 1981, table 25). Lower horizons of this soil were not sampled; the lowest horizon sampled, from 274 to 307 cm (9 to 10 ft), contains 14% $CaCO_3$. Additional carbonate from these lower horizons would substantially increase the total pedogenic carbonate for pedon 65–7. No gypsum was found in this pedon. Consult Gile and Grossman (1979, pp. 882, 883) for laboratory data and a description of pedon 65–7. However, gypsum is reported in the sample log of the George Garcia well (elevation 1,327 m [4,355 ft]), which is located approximately 1.1 km (0.7 mi) to the northeast. Common to abundant selenite was reported between 6 and 15 m (20 and 50 ft) below the ground surface in the basal part of the distal piedmont facies of the Camp Rice Formation. However, no gypsiferous zones were reported in the underlying fluvial facies to its base approximately 58 m (190 ft) below the ground surface, except for a single cluster of selenite crystals noted at approximately 46 to 49 m (151 to 161 ft; King et al., 1971, pp. 36–38).

Soils and sediments of JER La Mesa extend to the basin-floor remnant south of Goat Mountain (Fig. 2), where elevations range from approximately 1,320 to 1,323 m (4,330 to 4,340 ft). Stage V horizons also are in this area, where depths to carbonate maxima are shallower due to erosion associated with entrenchment of the Rio Grande valley. These stage V horizons are not as prominent and extensive as those at site 10, supporting the interpretation that soils of more than one age are in JER La Mesa.

Atmospheric and alluvial inputs to Lake Jornada[1]

It was noted earlier that pedogenic carbonate was derived from atmospheric additions to the soils. After formation of Lake Jornada, atmospheric additions of carbonate and other components from the atmosphere fell into the lake during its pluvial episodes. Long-term studies of dustfall in the Desert Project showed other components to be mostly clay, silt, finer sand fractions, and organic carbon (Gile and Grossman, 1979). These most common components of dustfall would also be the most readily eroded by wind. During its pluvial episodes Lake Jornada would also have received alluvium from areas upslope of the lake. Because the bordering slopes in the basin-floor position are very gentle, the alluvium would contain high percentages

[1]Bill Seager (pers. comm. 2001) has noted two possibilities of additional lakes associated with gypsum north of Lake Jornada. One is near the Point of Rocks and the other is near Fleck Draw.

of clay, silt, and the finer sand fractions. These sediments would also be readily picked up by the wind. Thus, soon after the lake dried during an interpluvial period, virtually all of the lacustrine sediments would have been eroded away with the notable exception of gypsum accumulations the size of coarse sand and larger. This material would have been abundant, and later would be a source of gypsum accumulations in the soils of JER La Mesa.

Why and when did Lake Jornada dry up?

As the Rio Grande valley progressively deepened during its entrenchment, the water table beneath the Jornada Basin floor must have begun to lower markedly (Gile et al., 1981, p. 51, figs. 6, 7, and 9). Water that formerly maintained the lake moved downward toward the water table, which today is far below the present land surface; at pedon 95–2 (site 3), for example, elevation of the water table is approximately 1,238 m (4,060 ft; King et al., 1971), whereas the land surface elevation at the same point is 1,320 m (4,330 ft).

Several factors suggest an approximate time when the lake dried up. One is the amount of pedogenic carbonate that is missing. According to carbonate totals for the studied pedons, roughly 1,000 kg/m^2 of carbonate is missing as previously discussed. This amount of carbonate would require about 715,000 yrs to accumulate, according to the rate discussed earlier. Thus, an intermittent lake could have occupied the eastern part of the basin floor for about 715,000 yrs. For much of this period, water tables must have been high, even during the interpluvial episodes. Thus it seems doubtful that much if any carbonate would have moved downward into the soils during the interpluvial periods.

Another factor reflecting the time that the lake existed is the stratigraphic position of gypsum, as discussed in previous sections. The gypsum must be older than Jornada I because it is present beneath Jornada I sediments and its soils. Assuming that the sediments of Jornada I were deposited immediately after the gypsum was deposited, and averaging the time estimated for Jornada I (250,000–400,000 yrs; Table 1) give an average age of 325,000 yrs. This figure, plus 715,000 yrs to account for the missing carbonate, gives a total of 1,040,000 yrs. Thus, Lake Jornada could have existed from about 1,040,000 to 325,000 yrs ago. But it should be stressed that this is only a very rough estimate, and that much more data are needed for soils of JER La Mesa, both at the surface and buried by younger deposits and their soils.

Discussion and summary

In the Jornada Basin a combination of paleomagnetism, dated pumice, totals of pedogenic carbonate, and carbonate morphology indicate that much of La Mesa surface is about 1,600,000 yrs old, with an estimated age range of about 780,000– 2,000,000 yrs. Thus La Mesa in the Jornada Basin is intermediate in age between upper and lower La Mesa in the Desert Project and is termed JER La Mesa (Table 1).

The ancestral Rio Grande once flowed in the basin floor east of the Doña Ana Mountains (Figs. 1, 2). Although buried in places, the sediments of JER La Mesa may be continuously traced along the basin floor to the vicinity of Goat Mountain, where they may be compared to sediments of lower and upper La Mesa in the Desert Project (Fig. 1).

Elevations of 1,323 m (4,340 ft) east and south of Goat Mountain compare with elevations of approximately 1,280 m (4,200 ft) at lower La Mesa on the west side of the valley (Fig. 1). These elevation differences alone would not be evidence for an age difference between lower La Mesa and JER La Mesa because of possible differences in elevation due to movement along the Robledo fault in the west side of the valley and along the Jornada fault on the east side (Seager et al., 1987). However, the stage V carbonate in soils of JER La Mesa (compared to only stages III and IV on lower La Mesa) and their higher totals of pedogenic carbonate are clear evidence that JER La Mesa is in fact older, and that some or all of the differences in elevation are due to two different floodplain elevations and ages. Thus, there must have been at least three different elevations of ancient floodplains associated with the La Mesa surface in the Desert Project area (Fig. 1), from oldest to youngest as follows: upper La Mesa, JER La Mesa, and lower La Mesa (Fig. 1; Table 1).

Lower La Mesa is highly significant genetically because it shows the morphological transition between the plugged stage III horizon and initial development of the stage IV laminar horizon. JER La Mesa is genetically significant in a similar way—its soils show the transition between stages IV and V. In soils of JER La Mesa, stage V first occurs in soils of ridges where erosion has brought carbonate maxima closer to the soils surface, causing breakup and eventual recementation that characterizes stage V. In contrast, some soils of topographic lows adjacent to the ridges show stage IV morphology because they have received sediment instead of losing it; in addition, soils of the lows are finer textured, reducing the penetration and depth of wetting fronts.

Evidence discussed at site 11 indicates that the surface of Lake Jornada would have been at approximately 1,318 m (4,325 ft) elevation. The lake would have extended from the vicinity of site 11 northward to the northern part of the Jornada Experimental Range (Fig. 2). When the lake was full, it would have been approximately 14 m (46 ft) deep at Isaacks Lake playa (Fig. 2). At South well, elevation 1,314 m (4,310 ft), the lake would have been approximately 4 m (13 ft) deep. At site 3, elevation at pedon 95–2 on the ridge crest is approximately 1,320 m (4,330 ft). But when the lake was there, elevation at pedon 95–2 would have been only approximately 1,316 m (4,318 ft) because the upper 3.5 m (11 ft) is a Pleistocene eolian deposit that accumulated after the lake was gone. Thus the sediments of JER La Mesa would have been covered by approximately 2 m (6 ft) of water when the lake was there.

When Lake Jornada dried, a thin deposit of gypsum derived from the San Andres Mountains would have accumulated on the floor of the lake. The gypsum deposit is buried in many places along the lower piedmont slopes that border the basin floor. But where not buried, the gypsum deposit would have been readily weathered, broken up, and moved into the soils of JER La Mesa by precipitation. As the water table lowered and the soil material dried, some of the gypsum could have been deposited in the uppermost saturated (ground-water) zone and capillary fringe as the water table dropped. Thus the gypsum is thought to have accumulated by both pedogenic and ground-water processes.

Figure 2 shows a possible extent of Lake Jornada. However, its true extent cannot be shown at present because in many places, variable thicknesses of alluvial and eolian sediments buried the sediments of JER La Mesa after the lake dried. Much more work is needed on the stratigraphy and chronology of deposits in the Jornada Basin. It should also be stressed that the estimated duration of Lake Jornada is highly tentative, pending further work.

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