Radiocarbon and fossil vertebrate ages of Late Pleistocene and Holocene sediments imply rapid rates of evaporite deposition in the northern Tularosa Basin, south central New Mexico

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RADIOCARBON AND FOSSIL VERTEBRATE AGES OF LATE PLEISTOCENE AND HOLOCENE SEDIMENTS IMPLY RAPID RATES OF EVAPORITE DEPOSITION IN THE NORTHERN TULAROSA BASIN, SOUTH CENTRAL NEW MEXICO

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ABSTRACT—Rates of accumulation from four distinct depositional environments in the northern Tularosa Basin are estimated using radiocarbon ages from various depths and some simplistic assumptions. Deposition of gypsum, other evaporites, and siliciclastic dust builds marshes, elevated pond and stream margins, and conical spring mounds. Two radiocarbon ages in young Holocene alluvium along Salt Creek show differing amounts of accumulation during the past few hundred years depending on evaporite deposition. Three samples determine the age and rapid accumulation (180–330 cm/10^3yr) of an extensive gypsum wetland along Salt Creek during the Younger Dryas climatic event 11–12 ka. Burned grass at the buried edge of the Carrizozo Malpais lava flow provides the first estimate of the radiocarbon age of the lava flow and may be used to estimate accumulation rates of several gypsiferous features in the vicinity. Two radiocarbon ages show that the large gypsum spring mounds at the Mound Springs complex grew to heights of 5 m or more in one or more episodes during the past 3,000 years. Stream and fan alluvium without evaporite preservation appears to accumulate on the order of 16–33 cm per thousand years whereas evaporite accumulation in different depositional environments ranges from 33 to 330 cm per thousand years.

INTRODUCTION

Several radiocarbon ages were determined and fossil remains of large and small vertebrates, gastropods, and micro-organisms were collected while investigating depositional systems of the northern Tularosa Basin with regard to three of the four extant populations of White Sands pupfish (*Cyprinodon tularosa* of Miller and Echelle, 1975). The pupfish habitats extend from the southern Oscura Mountains to Big Salt Lake (Fig. 1) in springs, marshes, and Salt Creek. Diverse, relatively young geologic deposits and rather unique geomorphic features dominate this landscape (Love et al., 2010; Love et al., this guidebook). Some of the geologic units include small fish remains as well. Allen et al. (2009) presented many radiocarbon-age results from the context of the margins of Lake Otero. The authors have reported some radiocarbon ages at conferences (Allen et al., 2005, 2006; Love et al., 2007, 2010, 2011, 2012a, 2012b). This report is a compilation of radiocarbon-age data and recently found vertebrate fossils, and summarizes the related geologic contexts for the northern Tularosa Basin. These ages are the basis for estimating rates of deposition in different deposits. This brief report is modified and updated from Love et al. (2010) and an unpublished report to White Sands Missile Range (WSMR) that contains more details of our work and more extensive references.

METHODS

Geologic mapping included identification, description, extent, and tentative assignments of possible ages of the geological deposits. The deposits were mapped and investigated on the ground and located using aerial photographs and global positioning system (GPS) measurements. Outcrops of many of the map units were found along eroded bluffs or in gullies. Bucket augers were used to obtain subsurface samples in deposits likely to contain stratigraphic records of past processes or climatic episodes. Discovery of megafaunal remains was part of the observational and descriptive process in the field.

Samples obtained for radiocarbon-age determination and/or microfossil identification were disaggregated with sodium hexametaphosphate in water, sieved, and the dried residues examined using a binocular microscope. Samples of organic carbon picked from sieve residues were sent to Beta Analytic and analyzed using standard accelerator mass spectrometry (AMS) procedures. The ages of the samples are reported as radiocarbon years before present (BP) or as calibrated ages (calendar years before present), in some cases as BC (before Christ) or AD (Anno Domini). The conversion from radiocarbon years before present to calendar age depends on an established calibration curve, based on comparisons between radiocarbon ages and an independent estimate of calendar ages (radiocarbon dating of tree wood and dendrochronology for the time period depicted here). The reported analytical error is based on statistical analysis of sample, background, and reference standard results.

Megafossil specimens were either collected or received by Gary Morgan for identification and curation at the New Mexico Museum of Natural History and Science (NMMNH). For comparison, previous collections of fossil vertebrates from the Tularosa Basin are described by Morgan and Lucas (2002; 2005).

OVERALL QUATERNARY GEOLOGICAL CONTEXT OF THE NORTHERN TULAROSA BASIN

The floor of the northern Tularosa Basin is a gently southward-sloping gypsum-alluvial-discharge plain (Fig. 1; Love et al., this guidebook). The basin is closed with regard to surface drainage, but leaks southward to the Hueco basin in the subsurface. The depositional system consists of coalescing clastic distal alluvial fans from the surrounding mountains; alluvial channels and valley

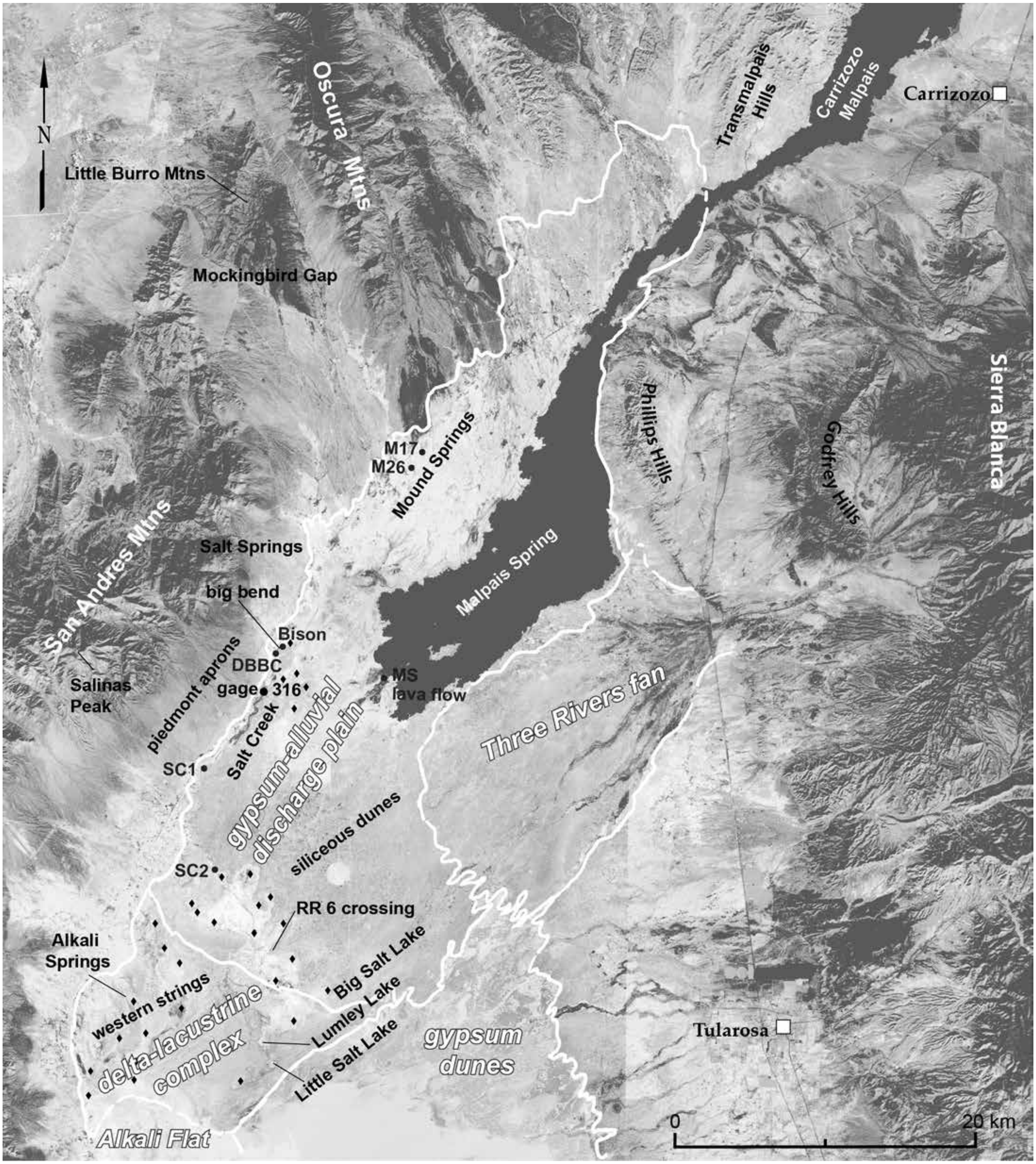

FIGURE 1. Composite image from space of northern Tularosa Basin showing extent of gypsum-alluvial discharge plain, Mound Springs, Salt Creek, Carrizozo Malpais lava flow, Big Salt Lake, Alkali Flat, and gypsum and siliceous eolian deposits. Black diamonds indicate numerous significant deflation basins (blowouts). Radiocarbon sample localities are indicated by their abbreviations listed in Table 1. Base image modified from digital file of David A. Sawyer, U.S. Geological Survey (ret.). (See also Color Plate 4)

floors in low, connected, inter-slope reaches; gypsum springs, streams, marshes, and ponds; and eolian blowouts, lunettes, and loess. Much of the plain is underlain by shallow, perched groundwater. The slope of the plain is generally north-south, from 1,480 m elevation in the north to 1,200 m near Big Salt Lake with gradients decreasing southward from 8 to 1.2 m/km. In the past, this plain was graded to late Pleistocene Lake Otero, with a maximum level of about 1204 m elevation (Allen et al., 2009). The lowest features include the blowout areas from 5 km north of Range Road 6, where Salt Creek enters a large blowout complex on the valley floor, to Big and Little Salt Lakes. Farther south are the vast blowouts of Alkali Flat and Lake Lucero. Salt Creek has cut a broad valley below the top of the local basin fill. Exposures of older (pre-late Pleistocene) basin fill yielded tusk fragments of large proboscideans, probably *Mammuthus columbi* (Columbian mammoth). Deflated surfaces within basin fill reveal trackways similar to proboscidean trackways examined along the edges of Pleistocene Lake Otero (Lucas et al., 2002; 2007; Allen et al., 2009). Salt Creek is incised 4–8 m below late Pleistocene deposits that now form a broad terrace of gypsum. The base level of Salt Creek is controlled by large eolian blowouts, particularly from 5 km north of Range Road 6 south to Big Salt Lake.

The Carrizozo Malpais lava flow followed the large alluvial channel and adjacent valley floor of the northern and northeastern Tularosa Basin that was the axial drainage from the Oscura, northern San Andres, Jicarilla, Carrizo, Sierra Blanca, and northern Sacramento Mountains watersheds, but the lava stalled on the low-gradient, groundwater-related discharge plain.

The present areas of active discharge of shallow groundwater include the Mound Springs complex, Malpais Spring and adjacent marshes, reaches of perennial stream flow in Salt Creek, and small spring mounds adjacent to Salt Creek. Past areas of groundwater discharge were much more extensive across the northern Tularosa Basin (Love et al. 2010).

RADIOCARBON AND FOSSIL AGE RESULTS

Radiocarbon ages from four different depositional environments in the northern Tularosa Basin are presented in Table 1, along with their UTM coordinates. These include (1) extensive gypsum marsh deposits exposed along Salt Creek, (2) moist, partially cemented (“evaporite affected”), fine-grained alluvium along Salt Creek, (3) accumulations of several types of gypsiferous deposits at the distal margins of the Carrizozo Malpais lava flow, and (4) accumulations of gypsum spring mounds in the Mound Springs area. Included is a new date from a layer enriched with organic carbon (“black mat”) exposed in alluvium along arroyos on the western margin of Alkali Flat.

Gypsum marsh deposits

Fossiliferous gypsum marsh deposits ranging to a thickness of 2.9 m (Fig. 2) occur along the incised banks of Salt Creek from Range Road 316 south to the deflation basins south of Range Road 6. The marsh covered at least 50 km^2 and probably more (Fig. 2A). Beneath the gypsum are reddish-brown and gray-green, fine-grained, siliciclastic alluvial deposits and local pebble-gravel

TABLE 1. List of radiocarbon ages obtained in this study.

Radiocarbon Age[1]	Lab Number	Material[2]	$\delta^{13}C$ ‰[3]	Locality[4]	UTM[5] east	UTM[5] north	Depth[6] cm
Salt Creek paleo-wetland deposits							
10900 (50)	Beta 210310	macrophytes	-14.7	SC2	366505	3671311	450
10600 (40)	Beta 204416	"	-12.5	SC1	366046	3677710	295
10130 (40)	Beta 210309	ostracodes	-4.8	SC1	366046	3677710	140
Salt Creek big bend alluvial deposits							
260 (30)	Beta 318311	charred material	-12.3	SC-DBBC	380607	3685641	30
500 (30)	Beta 314768	bone collagen	-9.8	SC bison	371036	3685816	100
Spring-mound deposits (M17, M26) and present-day Malpais Spring (MS)							
2850 (40)	Beta 222440	macrophytes	-24.4	M17	380607	369518	415
1590 (40)	Beta 277074	charred material	-23.0	M26	379564	3696721	610
Modern[7]	Beta 222441	macrophytes	-26.7	MS	377993	3683980	na
Lake Otero Margin paleo-wetland deposits							
10640 (50)	Beta 319443	macrophytes	-13.7	LOM-WP2-BM	358817	3641244	>200
Burned grass adjacent to Carrizozo Malpais lava flow							
4680 (40)	Beta 277075	macrophytes	-26.3	Lava flow	377873	3683971	277

1. Radiocarbon ages determined by accelerator mass spectrometry; 1-sigma error reported by the lab in parenthesis.
2. Plant materials were subjected to standard acid-base-acid pretreatment.
3. Carbon isotopic ratios in delta notation (relative to the PDB standard); used to correct for isotopic fractionation.
4. Locality designations
5. UTM locations NAD83, zone 13.
6. Depth below top of measured section at each locality.
7. Radiocarbon activity was 104% of the reference standard, indicating the material was living within the last 50 years.

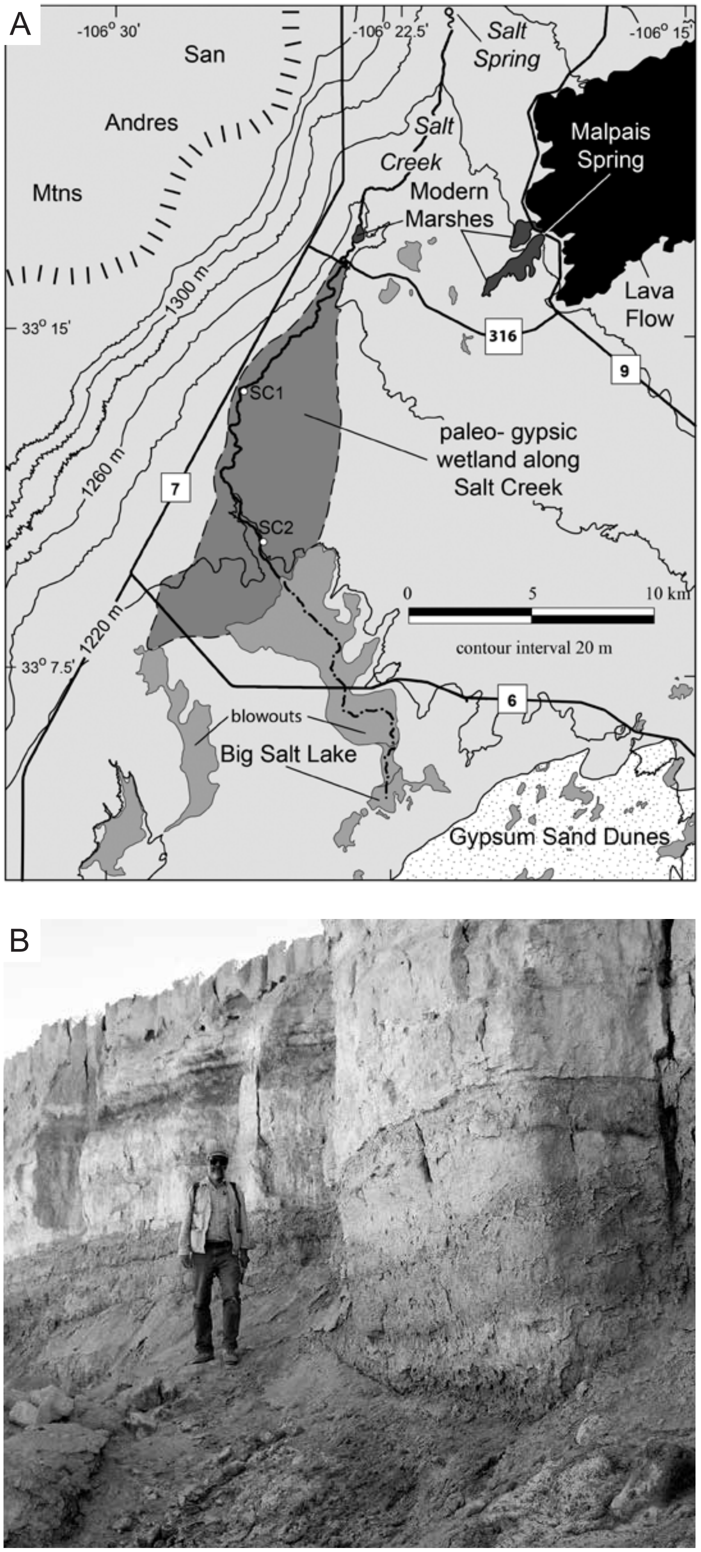

FIGURE 2. Gypsiferous marsh deposits. A. Map showing the 50 km^2 extent of the gypsum marsh. Locations SC1 and SC2 show where sections were measured and carbon samples were taken. B. Incised bank of Salt Creek at SC1 showing gypsum marsh deposits with dark gray bands of organic matter overlying red and grayish green layers of siliceous silt and clay. Radiocarbon ages from two localities are 10,900 BP, 10,600 BP, and 10,130 BP. Fragmentary fossil bones of *Equus conversidens* were found in a fallen block of alluvium near person's feet.

channels containing fragmentary remains of *Equus conversidens* (Pleistocene horse) and a right humerus of a *Camelops hesternus* (Pleistocene camel; NMMNH catalog number 63860). Marsh deposits predominantly consist of bedded gypsum with bands of siliceous mud and organic matter (Fig. 2B). Fossils in the marsh deposits include large gastropods (*Stagnicola* and *Planorbella*), fish bones and scales, amphibian bones, possible underprints of megafauna tracks, and many ostracods and foraminifera. Three radiocarbon ages of organic matter were obtained: 10,900 ±50 BP at the base of the gypsum marsh deposit, 10,600 ±40 BP in the middle of the marsh deposit, and 10,130 ±40 BP near the top (Table 1). The marsh and fossils all indicate a relatively wet environment during the Younger Dryas climatic episode in the northern Tularosa Basin.

Alkali Flat-margin black mat

The western margin of late Pleistocene Lake Otero (Allen et al., 2009) has been modified by Holocene erosion and deposition of medial-distal piedmont alluvium that is graded to the deflated levels of Alkali Flat. A bed of dark gray, fine-grained alluvium enriched in organic carbon (i.e. black mat deposit) is intercalated in the alluvium and is exposed in a few places in arroyo cuts in the alluvium (Fig. 3). A radiocarbon age of 10,640 ±50 BP was obtained at one such locality where the black mat is about 172 cm below the land surface (Table 1). This age correlates with the extensive gypsum marsh deposits found farther north. A relative abundance of organic matter including plant fragments in the black mat suggests an abundance of vegetation and wetter conditions than indicated by underlying and overlying alluvium.

Evaporite-affected (partially cemented) alluvial deposits near the big bend of Salt Creek

Salt Creek turns westward and then sharply south as it goes around a high bluff of older gravelly basin fill 2 km north of the stream gage on Range Road 316 ("gage 316" on Fig. 1). The banks of Salt Creek at the big bend are as high as 5 m consisting of partially cemented, moist, fine-grained alluvium exhibiting shallow, subtle cross-bedded channels (Fig. 4). "Evaporite-affected" deposits within the alluvium are horizons cemented with gypsum and calcium carbonate and locally the surface of the deposits has a hard, fine-grained gypsum crust up to 20 cm thick. A mineralized partial skeleton of *Bison bison* (NMMNH catalog number 63859) with articulated leg and foot bones buried horizontally about 100 cm below the surface yielded a calibrated age of AD 1600–1660. Charcoal in similar less-affected (almost no amount of precipitated sulfate and carbonate) alluvium 20–30 cm below the surface in the same area produced a calibrated age of AD 1400–1440. Downstream from this locality, near the exposed base of the thin-bedded, fine-grained alluvium, are small conispiral gastropod shells and fish scales. Modern gastropods (*Juturnia tularosae*, Hershler et al., 2002) with similar shells are known to play host to parasites that infect modern pupfish.

FIGURE 3. Dark wetland alluvium ("black mat"; darker gray band above and to left of rod) and Holocene fan channel (on right side of photograph) and sheet alluvium exposed in an arroyo on the western side of Alkali Flat. Rod is 1.5 m long, marked with 10-cm intervals.

Carrizozo Malpais lava flow near Malpais Spring

Several estimates of the age of Carrizozo Malpais lava flow have been made using unconventional methods (Salyards, 1991; Anthony et al., 1998; Dunbar, 1999). A pollen profile to a depth of 2.8 m near Malpais Spring was determined by Hafsten (1961), but no age estimate was attempted. Previously, no carbon for a radiocarbon age of the flow had been found. Salyards (1991), using secular variation magnetostratigraphy, estimated an age for the lava flow of roughly 5,000 years. Anthony et al. (1998) used ^{3}He to determine a surface exposure age of 4,800 ±1700 years on the upper Carrizozo flow unit of Renault (1970). Dunbar (1999) used ^{36}Cl to determine a surface age for the lava flow of 5,200 ±700 years. Several auger holes were completed in this study to determine that the southwestern edge of the lava flow has been buried by up to 4 m of eolian and gypsum-seep deposits (Fig. 5). At one locality near the edge of the lava flow at a depth of 2.77 m, burned grass stems were recovered from the basal few centimeters of gypsum-seep deposits, directly overlying greenish-gray siliciclastic alluvium that probably pre-dates the lava flow. These burned grasses produced a ^{14}C age of 4,680 ±40 BP, providing the first radiocarbon estimate for the age of the lava flow (Table 1). Figure 6 shows the calendar age range (x-axis) for the given radiocarbon age (y-axis), i.e., the "calibration curve" for converting ^{14}C ages to calendar years. This ^{14}C age, with 2-σ error bars, and the corresponding calendar ages and errors are indicated. For

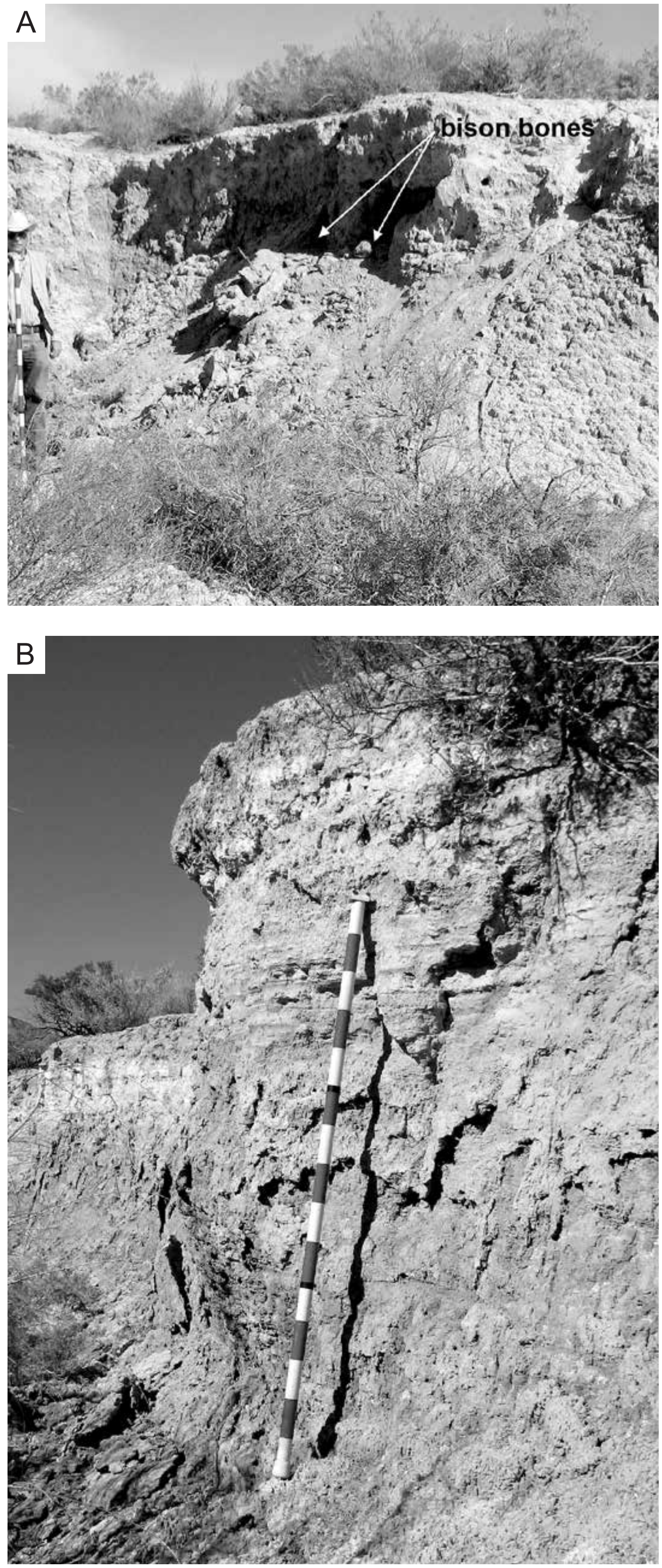

FIGURE 4. Views of evaporite-affected fine-grained alluvium near the big bend of Salt Creek. A. Location of fossilized bison bones in arroyo wall. B. Exposure illustrating fine-grained nature of clastic sediments and evaporite deposits and crust. Rod is 1.5 m long.

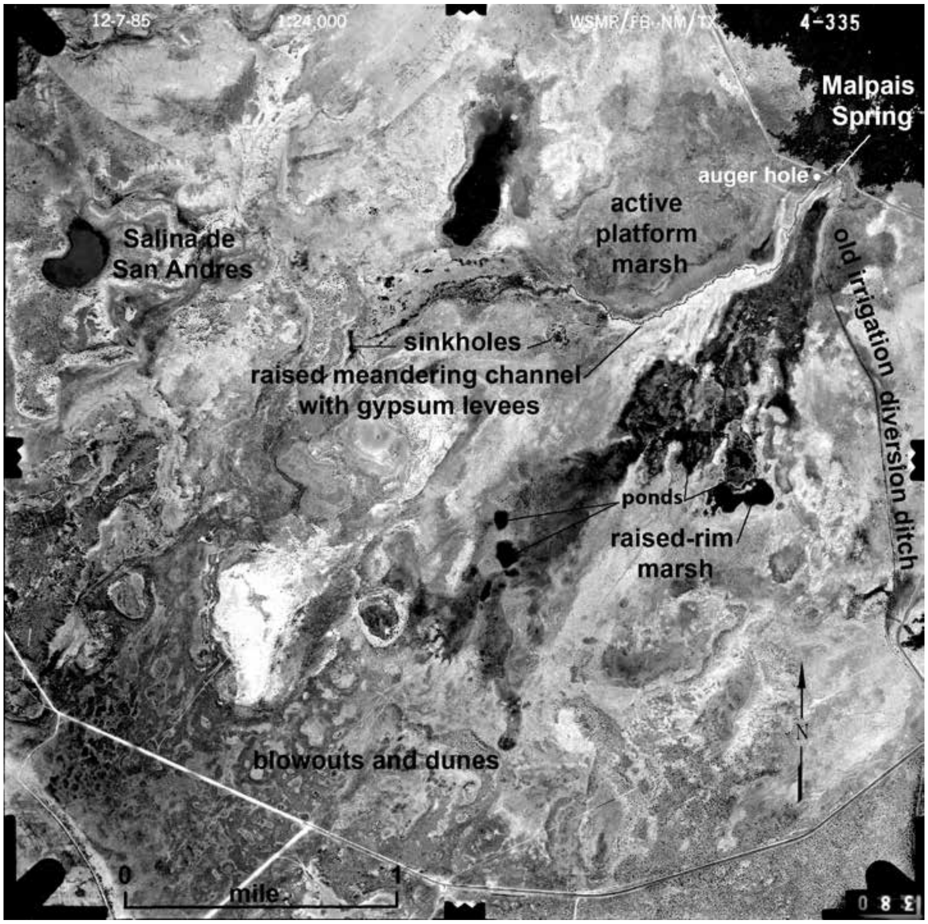

FIGURE 5. Aerial photograph of the area southwest of Malpais Spring marking location of auger hole penetrating burned-grass horizon, Photo also illustrates uncommon geomorphic features (see Love et al., this volume). Photograph from Stewart Technologies, 12/7/85, 1:24,000 scale (9-inch by 9-inch image). (See also Color Plate 5)

this radiocarbon interval, there are two possible calibrated ages of BC 3,630 to 3,580 or BC 3,530 to 3,360 years.

Gypsum Spring Mounds

Springs that deposited gypsum are common on the valley floor in the northern Tularosa Basin (Love et al., 2007). Most mounds are not active now, but many exhibit stacked deposits of different morphology, indicating that the mounds were active more than once in the recent past. The largest spring mounds are four to five meters high and have basal diameters more than 200 m across. At the top of the mounds are water-holding craters a few meters across and commonly less than 1 m deep. Smaller spring mounds have gypsum rims less than 1 m high (called "minimounds"), but still have craters 4–5 m across. The rims and slopes of the mounds consist of consolidated granular gypsum with minor amounts of siliceous dust and pedogenic calcium carbonate in fissures.

To understand the substrate (deposits below the craters of the mounds) of the springs, augered holes were completed in several inactive (no water present) gypsum spring mounds and one active mound. Meinzer Mound (active; mound 17 of Meinzer and Hare, 1915) is more than 5 m high and has an estimated volume exceeding 30,000 m^3. Geologic deposits in the crater-fill show distinct wet and dry episodes (Fig. 7). Ostracodes and foraminifera help delineate these episodes. American bulrush achenes (*Schoenoplectus americanus*) at a depth of 5 m in spring-related deposits yielded a radiocarbon age of 2,850 ±40 BP (Table 1). Because water in the springs may be depleted in radiocarbon relative to atmospheric concentrations (Cruz, 1982), modern bulrush achenes were compared from similar waters in the area to ensure there is no depletion in ^{14}C (they are not; Table 1 "modern"). These data suggest that Meinzer Mound grew to more than 5 m high during two active episodes in less than 3,000 years.

Based on this information, another augered hole was completed in a large mound, Mound 26, south of South Mound. Mound 26 is 4.78 m high, 160 m across at the base, and has a similar profile to Meinzer Mound. The spring (in the crater) is not active and the entire mound is dry. The spring deposits within the crater are bioturbated to a depth of about 3 m and are uniformly fine-grained and gray with an abundance of gypsum silt and sand. At a depth of 5.4 m, the auger encountered a chalcedony flake (archaeological) in the fine-grained sediment. At a depth of 5.5 m, a sherd of El Paso brown ware was caught in the auger (identified by archaeologists Jim Bowman and Trevor Kludt). Below the sherd, fire-cracked lava fragments, small sandstone slabs, flakes, and charcoal continued to a depth of 6.7 m at which level augering ceased. Charcoal fragments from a depth of 6.1 m yielded a ^{14}C age of 1,590 ±40 BP (2-σ calibrated age of AD 390 to 560).

DISCUSSION AND SUMMARY

Ideally, to determine rates of sedimentation or recurrence intervals (as with fault offsets; McCalpin 2009), multiple ages within and at the top of the deposits are necessary. Except for the three ages determined for levels within the gypsum marsh, such data are not available. Even so, single ages combined with modern tops of accumulation allow estimations of rates. The problem is that the modern tops of some of the deposits are not a "zero" age as deposition stopped at some unknown time in the past. A second problem is that one age does not address fluctuating rates of deposition or hiati within deposits. Thus, the rates discussed below are considered crude at best, but worth consideration.

The gypsum marsh deposits exposed along Salt Creek range from 50 cm to more than 2 m thick, consisting of bedded gypsum, with bands of siliceous mud, organic matter, and fossil snails, fish scales, and other biota. As given above and in Table 1, the three

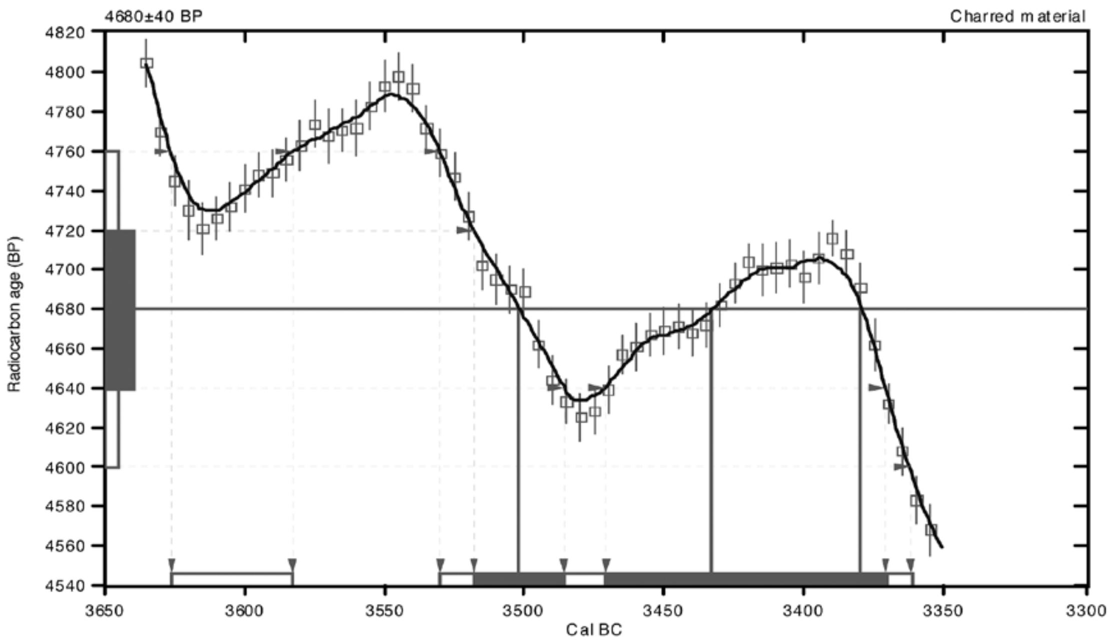

FIGURE 6. Plotted curve of calibrated calendar dates versus radiocarbon age (4680 ±40 BP) for burned grass recovered at 2.77 m depth next to the buried edge of Carrizozo Malpais lava flow. Although the radiocarbon deviation number is small, the calibration curve shows two possible ranges in calendar dates.

radiocarbon ages on organic matter in stratigraphic order from base to top are 10,900, 10,600, and 10,130 BP. The middle and youngest ages are from the same vertical section and are 155 cm apart. At that site, the vertical accumulation rate for the marsh was about 330 cm per thousand years. The oldest date came from a different locality. Separating the older age and youngest age are 140 cm of sediment; thus, the rate is estimated as 182 cm per thousand years.

Two estimates for accumulation rates of partially cemented fine-grained alluvium forming banks up to 5 m high at the big bend of Salt Creek are based on a calibrated age of AD 1600–1660 from leg bones buried about 100 cm below the surface and a calibrated age of AD 1400–1440 from charcoal in nearby alluvium 20–30 cm below the surface. Assuming that the alluvial surface adjacent to the present incised arroyo channel of Salt Creek has zero age or perhaps is continuing to accumulate some sediment, the alluvium with few evaporites had a depositional accumulation rate of 33 cm per thousand years whereas the section with more evaporites accumulated at a rate of 250 cm per thousand years.

For comparison, the alluvium within the alluvial apron above the black mat on the west side of Lake Otero has a wide range in thickness down slope and fills channels excavated into older lake deposits. Because of channel scours cut into the black mat, alluvium near the sample ranges in thickness from 172 cm to 312 cm. Although it is unwise to assume that there are no hiati in alluvial deposition and that the top of the alluvium has zero age, the alluvial deposition rate is estimated to range from 16 cm to 29 cm per thousand years.

The distal end of the Carrizozo Malpais lava flow overrode existing alluvium, spring evaporites, and loess, all of which continued to aggrade and bury the lava. The radiocarbon age of

FIGURE 7. Schematic cutaway into Meinzer Mound (M 17) showing stratigraphy beneath the spring crater and the gypsum crust at the rim and along the outer slopes. Note age of 2850 BP at 5 m below the crater floor. (See also Color Plate 5)

4680 BP was obtained from a depth of 2.77 m. This depth implies a rate of 60 cm per thousand years at this spot. Malpais Spring flows from beneath the snout of the lava flow and has established the course of a meandering stream to the southwest. The stream flow has deposited gypsum and trapped dust to create a raised-gypsum-levee and channel that ends in sinkholes (Love et al., this guidebook). The levees are as much as 1.7 m above the surrounding plain, with a vertical depositional rate of about 36 cm per thousand years. This assumes that the plain did not erode or aggrade during the same time interval. A separate diffuse area of discharge to the southwest established a broad (1 km^2) marsh that deposited a raised evaporite platform as high as 3 m above the surrounding plain. If the platform began to be developed after the lava flow, the vertical accumulation rate would be on the order of 64 cm per thousand years.

Gypsum spring mounds 4 to 5 m high have built rapidly in late Holocene time and may undergo episodic growth depending on local discharge conditions. Active spring mound 17 ("Meinzer Mound") shows two episodes of open-water gypsum spring deposition, growing to 5 m high (volume > 30,000 m^3) since 2,850 BP. The average rate of vertical accumulation is about 17.5 cm per thousand years, but the hiatus between open-pond episodes implies much faster rates when springs are active. Inactive spring mound 26 grew 4.78 m high and 160 m in diameter on top of an archaeological site that yielded charcoal at a depth of 6.1 m with a radiocarbon age of 1590 ±40 years BP (calibrated age of AD 390–560). This implies a vertical build up of 39 cm per thousand years.

The radiocarbon ages presented here provide a basis for much more study of the deposits of the northern Tularosa Basin. The rapid accumulation of alluvial and gypsiferous wetland deposits, some with definite hiati, suggests the possibility of obtaining more detailed records of overland flow and groundwater discharge from these environments. The wet and dry cycles of Mound 17 may indicate episodes of wet and dry climate during the late Holocene. Determining these episodes may lead to better understanding of climate and cultural sequences regionally.

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