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GEOMORPHOLOGY OF THE NORTHERN TULAROSA BASIN, SOUTH CENTRAL NEW MEXICO, WITH PARTICULAR ATTENTION TO UNCOMMON SURFICIAL FEATURES

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ABSTRACT—The floor of the northern Tularosa Basin between the Oscura Mountains and Alkali Flat consists of a south-sloping gypsum-alluvial discharge plain with distal alluvial fans, stream valleys, springs and marshes, eolian blowouts, loess, and the Carrizozo Malpais lava flow. Episodic deflation of large blowout basins as much as 8 m deep and several km long are a major influence on base levels and the resulting geomorphology of the northern basin. Holocene blowouts have expanded and deepened as shallow (perched) ground water levels have declined. The surficial expression of clastic depositional and erosional features ("clastic world") is typical of the semiarid Basin and Range, and includes features such as multi-level piedmont slopes, and bolson floor and eolian deposits.

In contrast, large areas of the northern Tularosa Basin are underlain by gypsum ("gypsum world"). The gypsum accumulates by evaporation of brackish- to brine-saturated groundwater discharge and by input of eolian gypsum and siliciclastic dust. Gypsum build-up and erosion creates rare surficial features perhaps unique to the northern basin. The surficial features include (1) gypsum spring mounds from 1 to 5 m high with basal areas from tens to hundreds of square meters, (2) gypsum megamounds more than 13 m high and 1.5 km across, (3) gypsum marsh deposits 0.5 to >2 m thick covering an area of more than 50 km^2 (4) raised-rim active and extinct gypsum ponds and marshes, (5) active and inactive gypsum platform marshes, and (6) a raised gypsum-levee meandering stream. Dissolution of former buildups of gypsum produces sinkholes in the gypsum megamounds and in gypsiferous basin fill.

INTRODUCTION

Two distinct environments with contrasting modes of deposition--"clastic world" and "gypsum world" were mapped while investigating evidence of the broad, long-term ecosystems and geological contexts 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 primary focus was to produce geologic maps of the area that include pupfish habitats extending from the southern Oscura Mountains to Big Salt Lake (Fig. 1). The fish presently occupy springs, marshes, and Salt Creek. Diverse recent geologic deposits and rather unique geomorphic features dominate this landscape. Some of the geologic units preserve fossil fish remains (probably *C. tularosa*) showing that the fish have occupied the area for thousands of years. The northern Tularosa Basin is considered to be north of Alkali Flat. The purpose of this paper is to summarize the geomorphology and origins of features in this unique area of Tularosa Basin.

Tectonically, the northern Tularosa Basin is surrounded on three sides by tilted fault-bounded ranges (Fig. 1). Fault-block ranges to the west and north include the northern San Andres Mountains, Little Burro Mountains (Mockingbird Gap Hills), Oscura Mountains, and Transmalpais Hills. To the east are the Phillips Hills, Godfrey Hills, and higher Sierra Blanca and Sacramento Mountains. Gravity models suggest more than 2.3 km of offset and subsequent fill basinward of the range-bounding normal faults (Peterson and Roy, 2005). Although fault scarps with large topographic expression and latest Pleistocene-Holocene movement cut alluvial aprons farther south along the San Andres, Organ, and Sacramento Mountains, the fault scarps north and west of the study area are obscured by erosion and burial, indicating that they were not active in late Quaternary time. Bachman (1968) suggested that an intra-basin horst connects a smaller fault block (Little Burro Mountains) in Mockingbird Gap with Tularosa Peak and the half-horst extending south to the Jarilla Mountains, bounded by the down-to-the-west Jarilla normal fault (Lozinsky and Bauer, 1991). No surficial expression of the Jarilla Fault is observed in the study area.

"Clastic world" includes typical mountain-front piedmont slopes with fault scarps, coalescing alluvial fans, several levels of inset channels and fan-segments (commonly higher surfaces are older; lower surface are younger), and interfan alluvium and incised arroyos. Siliceous eolian sand dunes, coppice dunes, and sand sheets are common on distal fan toes. The seemingly normal inset fan and channel features raise a puzzling aspect of the clastic piedmont slopes here. The northern Tularosa Basin is closed--no streams remove eroded sediment from the basin to lower base level through time-- instead, aggradation and burial of older features should dominate. Possible explanations are presented below.

"Gypsum world," is dominated by deposits due to groundwater discharge in local springs or across more areally extensive wetlands. The origin of these features and deposits are referred to as "krenegenic[1]" from a Greek word pertaining to being generated by springs. The features and deposits related to discharge of gypsiferous waters are extensive, covering nearly half of several 7.5-minute quadrangles. The calcium sulfate and other dissolved constituents are recycled from Permian rocks in the uplifts to the north, where thick evaporites of the Yeso, San Andres, and Artesia Formations are exposed to descending groundwater. Present spring waters away from Salt Creek have total dissolved solids (TDS) of approximately 4,000 mg/L and are close to being saturated with gypsum. Salt Creek has TDS of approximately

[1]**Krenegenic** (from *krene*', gr. spring; *genic*, gr. generated by; similar to biogenic, pedogenic) of or generated by spring processes; includes spring mounds, other spring orifices, wetlands, cienegas, seeps, pits, pots, necks, sapping features, hydromorphic concentrations, and cements.

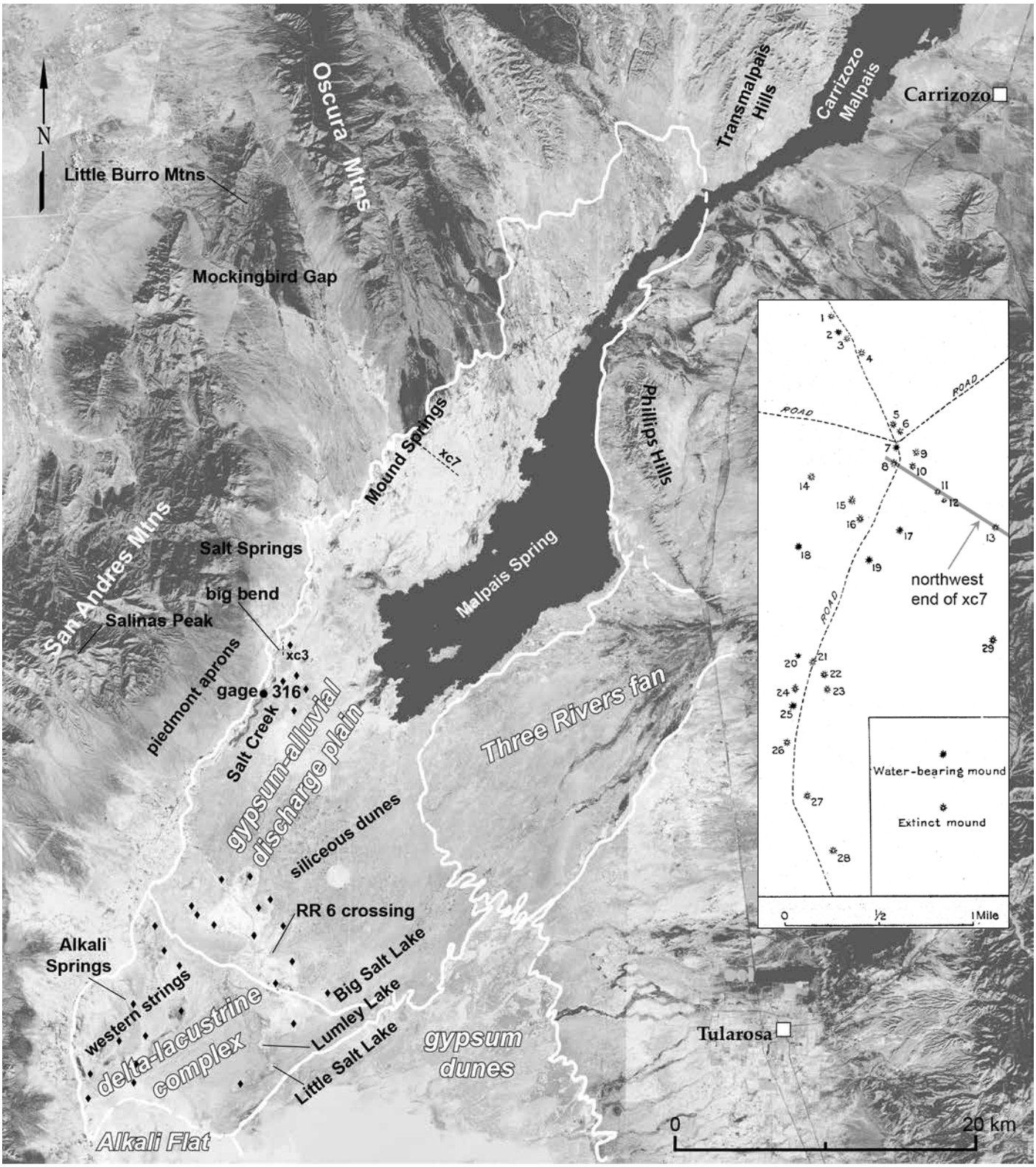

FIGURE 1. Composite image from space of the northern Tularosa Basin showing extent of the gypsum-alluvial discharge plain, Mound Springs, Salt Creek, Carrizozo Malpais lava flow, Three Rivers fan, Big Salt Lake, Alkali Flat, and siliceous and gypsum dunes. Black diamonds indicate numerous significant deflation basins (blowouts). Dashed lines xc 3 and xc 7 show where the cross section of Figure 3 and profile of Figure 7 are located. Base image modified from digital file of David A. Sawyer, U.S. Geological Survey (ret.). Inset map of numbered spring mounds by Meinzer and Hare (1915).

125,000 mg/L and is dominated by sodium chloride, but is close to saturation with other evaporites as well.

Historically and prehistorically, springs in the northern Tularosa Basin, particularly the Mound Spring complex and Malpais Spring, have been important stopping points and geographic landmarks for travelers. In 1911, Dr. O.E. Meinzer of the U.S. Geological Survey was the first geologist to describe many of the features and geology of the northern Tularosa Basin (Meinzer and Hare, 1915). Our investigation is an extension of his excellent work, nearly a century later. The numbering system from Meinzer and Hare (1915) is used to identify the spring mounds in the vicinity of the Mound Springs complex. Other geologic maps in the vicinity are by Bachman (1968), Bachman and Harbour (1970), and Weir (1965).

METHODS

Geologic mapping included identification and description of geological deposits and geomorphic features on the ground, mapping their extents, and tentative assignments of possible ages. The deposits and features were located using aerial photographs, orthophoto and topographic map quadrangles, and global positioning system (GPS) coordinates, including differential GPS surveying across individual spring mounds. Outcrops of some of the map units were found in excavated pits, along eroded bluffs, or in gullies. Bucket augers were used to obtain subsurface samples in a few deposits likely to contain strata of different sedimentary facies, organic matter, or depositional proxies reflecting past climates.

Gypsum, carbonate, and insoluble residue percentages for representative sediment samples were determined using the methods described by Nelson et al. (1978) and Dreimanis (1962). X-ray diffraction analysis was used to identify mineralogical constituents in samples of both new evaporite crusts and hardened Holocene and late Pleistocene deposits.

Samples obtained for radiocarbon-age determination and/or micro-fossil identification were sieved and the residues examined using a binocular microscope. Radiocarbon ages are discussed in a separate article (Love et al., this volume). Conventional radiocarbon ages are indicated using the suffix "BP," calibrated (calendar) ages are provided for a few of the younger dates.

SUMMARY AND DISCUSSION OF GEOMORPHOLOGY

The overall geologic context of the floor of the northern Tularosa Basin is a gently southward-sloping, gypsum-alluvial-discharge plain (Fig. 1). Geomorphic features reflect the "clastic world" depositional system of the extensive Three Rivers fan, smaller coalescing alluvial fans from the surrounding mountains, alluvial channels in low, inter-fan reaches and shallowly incised stream valleys. Fault scarps basinward from the San Andres and Oscura mountains commonly are small and degraded, where present at all. Relatively steep and tall scarps are found at the western base of the Phillips Hills. "Gypsum world" features include gypsum springs, streams, marshes, and ponds. Eolian blowouts, lunettes, sheet sands, coppice dunes, and loess may be clastic, gypsiferous, or a combination. The slope of the plain is generally north-south, from 1,480 m elevation in the north to 1200 m near Big Salt Lake, with gradients decreasing southward from 8 to 1.2 m/km. The lowest features include the blowout hollows (diamond symbols on Fig. 1) 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. The path from the playas farther south to Alkali Flat is blocked by Holocene sand dunes. A sub-parallel set of blowouts to the west leads from Alkali Springs to Alkali Flat. In the past, Pleistocene Lake Otero occupied the area from Big Salt Lake and Alkali Springs to south of Lake Lucero (Allen et al., 2009). Blowouts east of Salt Creek in the vicinity of Range Road 316 ("gage 316" on Fig. 1) form sloping depressions followed by local tributaries and playa lakes such as Salina de San Andres.

Salt Creek has cut a broad valley below the top of the local basin fill (Fig. 1). Perennial and ephemeral stream flow in Salt Creek is from base flow of shallow, brackish to saline groundwater and fresher runoff from precipitation on the valley margins. The perennial reach of Salt Creek begins at Salt Springs. Discharge gradually increases downstream and the stream incises into partially cemented alluvium to form banks up to 5 m high at the big bend of Salt Creek. Flow decreases downstream from Range Road 316 ("gage 316" on Fig. 1) except during large flood events, and commonly is ephemeral from Range Road 6 crossing ("RR 6" on Fig. 1) to Big Salt Lake. South of Range Road 316, 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 eolian blowouts, particularly from 5 km north of Range Road 6 to Big Salt Lake. Two inset terraces show that the blowouts and Salt Creek increased levels of incision in steps rather than in a single episode of erosion.

The Carrizozo Malpais lava flow followed the valley floor southward and buried an alluvial channel. The axial drainage, termed the "Carrizozo" channel, was fed by streams originating in the Oscura Mountains, and other highlands to the north and east. The lava stalled on the low-gradient, groundwater-related discharge plain (or ponds and marshes) before reaching the valley of Salt Creek. A radiocarbon age of 4680 ±40 yr was obtained from buried grasses in front of the lava flow (Love et al., this volume). This translates to two ranges of calibrated ages: BC 3630 to 3580 or BC 3530 to 3360 years. Details of the topography of flow lobes are described by Garry et al. (2008).

Clastic alluvial features and deposits

The dominant clastic features of the northern Tularosa Basin are the piedmont slopes below the ranges, Salt Creek valley, the valley of the former Carrizozo drainage, and the westward-directed Three Rivers fan from the base of Sierra Blanca. The ranges surrounding the northern Tularosa Basin have steep, but deeply embayed mountain fronts that produce very coarse clastic sediments on proximal fan slopes. The piedmont slopes exhibit several levels (commonly four--rather than the generic three of Fig. 2) of alluvial deposits, with younger deposits and channels

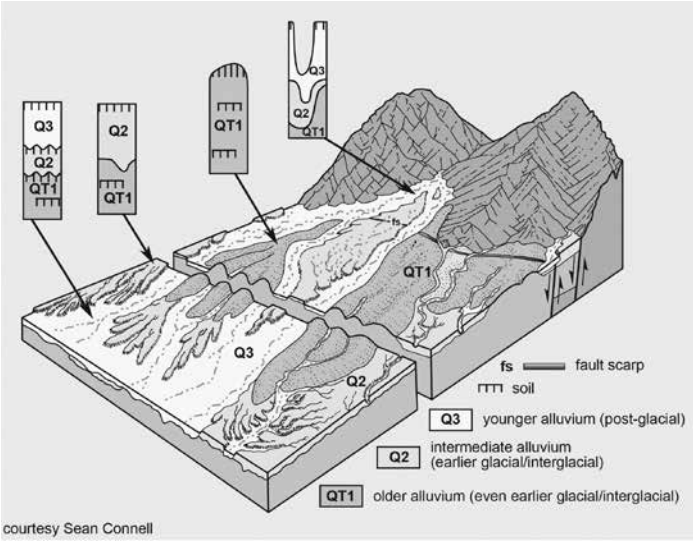

FIGURE 2. Schematic cut-away block diagram showing typical features of Basin and Range piedmont slopes. These include the dissected range front, three levels and ages of piedmont alluvium descending away from the mountains, and soils developed, buried, or eroded on the alluvial surfaces. Note that the fault scarp dies out across the fan. In the northern Tularosa Basin, more than three tiers of alluvium are present, and some younger alluvium buries older alluvium at medial positions on the piedmont. Diagram modified from Peterson (1981) by Sean Connell and Leo Gabaldon.

inset below older deposits (Love et al., 2007; 2012). Exceptions are seen east of Salinas Peak where young alluvial deposits cover at least two levels of older, previously higher, eroded surfaces. In that area, one historically active stream channel has aggraded several meters above the surrounding landscape to form a raised alluvial channel (cf. Love and Seager, 1996). Further basinward, older piedmont deposits form small "mesitas" elevated above younger (Holocene) fine-grained alluvium. Adjacent to the channel of Salt Creek through blowouts, distal fan alluvium grades to former levels of stream terraces and blowout floors.

As mentioned in the introduction, the past and present gradients of the clastic piedmont aprons are puzzling. Older fan remnants are topographically higher than younger surfaces, as is common elsewhere in the Basin and Range province (Fig. 2). The inset surfaces, in turn, tend to be incised by topographically lower channels and deposits. The inset levels are basinward of visible degraded fault scarps. Because the aprons grade to the basin, which is essentially "closed," why should there be topographic relief between older fan remnants, intermediate alluvial surfaces, and lower active alluvial fan surfaces and channels? In a closed basin, should not the basin continue filling and older piedmont deposits be buried by younger sediments? Five possible hypotheses are suggested:

1) Uplift of the ranges may involve more than one fault, so older fan remnants may have been uplifted along basinward faults that are subsequently inactive and buried.
2) Piedmont slopes may have been rotated basinward between normal faults so that older proximal slopes have been rotated up and raised toward the mountains.
3) Dramatic changes in discharge from mountain channels to piedmont slopes due to changing climates may shift loci of incision and deposition back and forth on piedmont aprons.
4) Even without changing conditions of discharge, complex response and internal adjustments (e.g. Schumm, 1977) may shift loci of incision and deposition back and forth on piedmont aprons.
5) The basin has deflated repeatedly, so stream gradients have steepened and gentled repeatedly through time. Steeper gradients would lead to incision on the piedmont, while aggradation on the bolson floor would decrease gradients on piedmont slopes (if discharge conditions were equal).

Similar elevated and inset levels of fan deposits are present in separate drainages, suggesting that climate and possible tectonism are the two most likely causes.

Clastic Late Quaternary alluvium of the Salt Creek valley and the Three Rivers alluvial fan is a major component of the local geomorphology. Exposures within the incised course of Salt Creek exhibit coarse gravelly channels interfingered with sand, silt, and reddish-brown clay (Fig. 3) within the sediments beneath at least two terrace treads. They contain bones and tusks of extinct megafauna. At about the same topographic level, the Three Rivers fan crosses much of the northern Tularosa Basin east to west, south of Malpais Spring (Fig. 1). The alluvium consists of channels of pebbly sand inter-bedded with silt, clay, and gypsum crusts.

Evaporite-affected alluvium (i.e. alluvium containing significant evaporites and/or seasonally saturated with brackish, saline, and brine water) is common along the borders and floor of Salt Creek valley, particularly the alluvium emanating from the drainage sloping from the northern edge of the Carrizozo lava flow toward Salt Creek and alluvium at the bend of Salt Creek. The alluvium commonly is moist during at least three seasons of the year and supports saline-tolerant shrubs and grasses such as *Allenrolfea occidentalis* and *Distichlis spicata*. Puffy white and pale yellow crusts develop along the surface when evaporation is high and conditions are dry (Fig. 4A). Along Salt Creek from Salt Springs to the big bend, fine-grained, partially cemented, brown-to-gray alluvium with small, shallow cross-bedded channels forms banks 1.5–5 m above the channel (Fig. 3).

Evaporite features and deposits

Evaporites deposited at the surface in "gypsum world" are mostly gypsum, but x-ray diffraction showed that halite and hexahydrite are also common. Historically halite was harvested from Salinas de San Andres and a battle was waged between Texan claimants and local long-time salt harvesters over ownership of the salt (Wessel, 2010). Mirabilite-crystal-shaped laths were noted in playas in cold weather, but did not survive sampling and transport to the x-ray lab. Seasonal evaporites tend to be "puffy" on the ground and on adjacent vegetation at the capillary fringe, whereas year-round gypsum crusts and subsurface strata are "rock-hard" and resistant to runoff and eolian erosion (Fig. 4 B, C, D). Fine-grained gypsum "loess" tends to develop a crust but remains loose beneath the crust. Many gypsum deposits

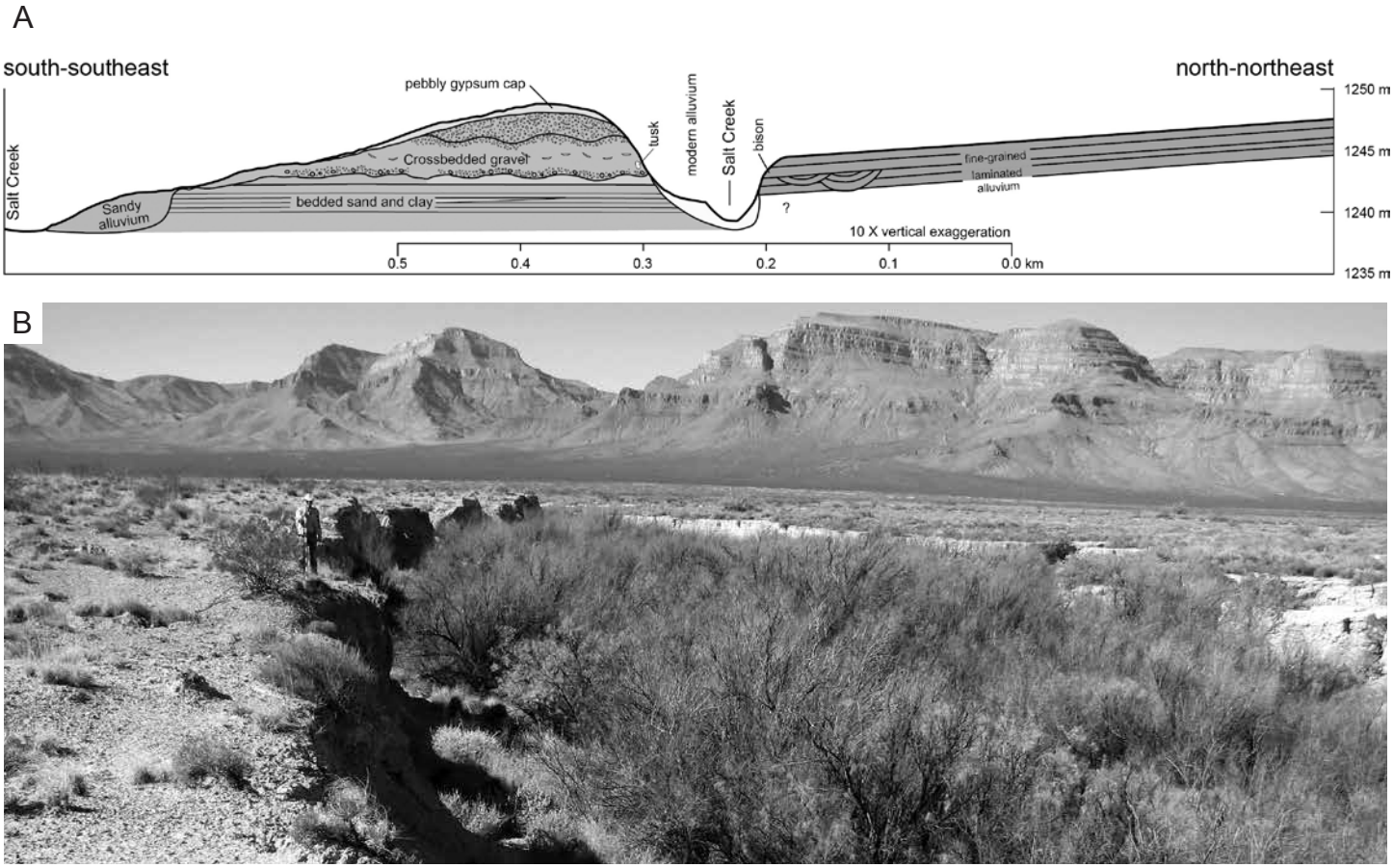

FIGURE 3. Cross section and photograph of exposures east of the big bend of Salt Creek. A. Cross section along line xc 3 of Figure 1 illustrating older clastic basin fill and younger fine-grained alluvium with bones of modern bison. B. Bluffs overlooking Salt Creek.

develop polygonal cracks 0.5 to 2 m across that may extend down at least 1 to 2 m. These cracks are commonly lined with bands of gypsum and pedogenic calcium carbonate.

Geomorphic features developed in gypsum result from constructional accumulations, eolian deposits, and by later partial dissolution. Besides the well-known gypsum spring mounds are newly named features (by the authors): "minimounds," "megamounds," "platforms" and "platform marshes," a "raised-levee" meandering stream with evaporite levees, "raised-rim" ponds and marshes, and areally extensive thick gypsum marsh deposits. All the features with "raised rims" share similar origins by deposition of gypsum around the margins of open water springs, ponds, or streams.

Erosional features include aligned and unaligned sinkholes developed in gypsum megamounds and in basin-fill alluvium. Erosional features primarily caused by eolian processes are discussed separately below.

Gypsum spring mounds

The historic area of "Mound Springs" has obvious gypsum spring mounds 4 to 5 m high with basal "footprints" more than 200 m across (Figs. 4, 5). There are dozens of mounds of various sizes on the valley floor in the northern Tularosa Basin north of Range Road 6 (Love et al., 2007). Active springs adjacent to Salt Creek have pools 4–12 m across with raised rims approximately 0.5 to 1 m high and outer crusts sloping gently away from the rims. Similar features reflecting inactive or extinct springs were mapped as "minimounds," many of which are in the same area as larger mounds and along Salt Creek. Most large mounds are not active at this time, but many show that the mounds were active more than once in the recent past. The tops of the mounds have water-holding craters a few m across and commonly less than 1 m deep. The rims and outer slopes of the mounds consist of consolidated granular gypsum with minor amounts of siliceous dust and pedogenic calcium carbonate in fissures.

Several inactive (no water present) gypsum spring mounds and one active mound were augered to understand the springs' development and substrate. 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. 6). Microfossils help delineate these episodes. American bulrush achenes (*Schoenoplectus americanus*) at a depth of 5 m in spring-related deposits yielded a radiocarbon age of 2850 BP (Love et al., this volume). These data suggest that Meinzer Mound grew to more than 5 m high during two active episodes in less than 3000 years. An auger hole in a similar-sized, but inactive mound (Meinzer number 26, south of "South Mound") produced charcoal fragments from a depth of 6.1 m that yielded an age of 1590 BP

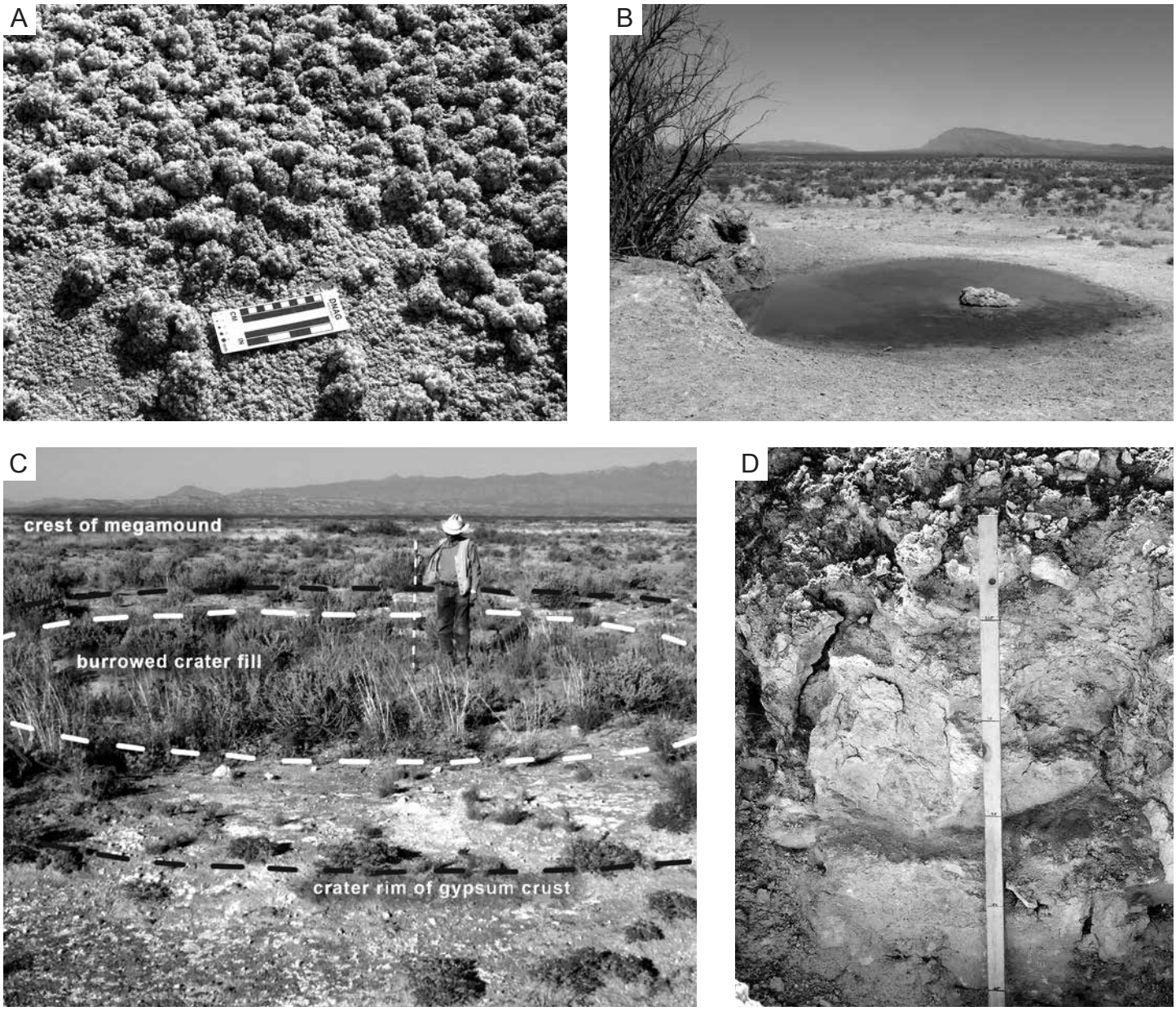

FIGURE 4. Features of "gypsum world." A. Puffy accumulations of halite, gypsum, and perhaps hexahydrite on moist mud flat of Salt Creek. B. Artificially breached side of Mound 19 ("Dead Oryx Spring"); pale, shield-like mounds 15 and 16 in middle distance. C. Inactive minimound illustrating loess-filled crater and low rim on south side of crest of megamound. D. Hard, polygonally fractured gypsum exposed in backhoe trench on west side of Mound 12. Marks on staff are 25 cm apart.

(2-σ calibrated age of AD (Anno Domini) 390 to 560; Love et al., this volume). This age suggests that Mound 26 grew to more than 5 m high in less than 1,600 years.

Megamounds

Megamounds are broad, low, shield-like deposits of gypsum up to 14 m high, 1.5 km across (Fig. 4C, 7), and as much as several kilometers long. The two largest megamounds appear to be composite accumulations of spring-related gypsum, perhaps generations of small spring mounds (minimounds) on top of a broad platform of marsh deposits and/or thick gypsum loess-like accumulations. The megamounds consist of poorly consolidated silt- to sand-sized granular gypsum lenticules and densely consolidated, light brown to gray to white gypsum. The uppermost exposed crust is generally consolidated platy gypsum broken into sub-meter columnar polygons, further broken into cobble- and pebble-sized angular blocks and sub-horizontal plates 2–5 cm thick at the surface. The indurated surface crust commonly is underlain by as much as several decimeters of relatively loose, powdery, gypsiferous, silt and sand. Siliciclastic loess and thin pebbly alluvium locally cover the crust. Beneath the surface are crudely bedded, semi-consolidated, and consolidated gypsum layers and local pebbly alluvium overwhelmed by secondary gypsum.

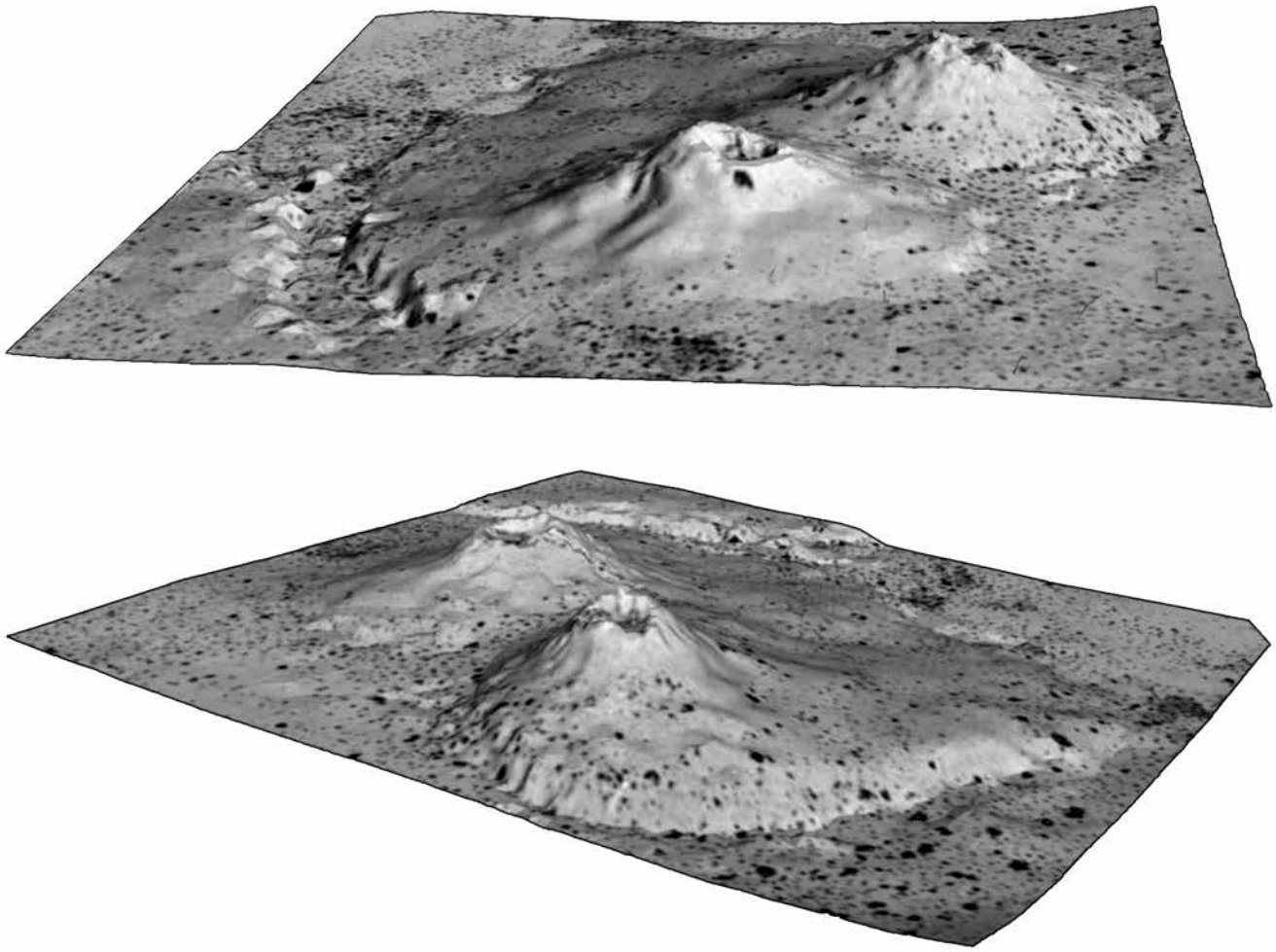

FIGURE 5. Oblique views of mounds 11 and 12 generated by draping a digital orthophoto over a digital elevation model (DEM). The DEM was constructed using closely spaced differential GPS data. Vertical exaggeration approximately x 7.

Geomorphic features at the lower margins of Carrizozo Malpais

Several different kinds of geomorphic features are developed at the snout of the Carrizozo lava flow (Fig. 8). The major features with readily explainable origins are described below. Other minor features are elevated gypsum crusts 1–2 m above surrounding alluvial slopes west of the Carrizozo lava flow and have as yet undetermined origins. The most notable krenegenic feature associated with the lava flow is Malpais Spring, which discharges from the edge of the flow. The resulting stream wandered southwestward across a low-gradient, playa-like plain before it was diverted in the 20th century. The stream is a major habitat for White Sands pupfish. The spring flows at 18 to 75 L/s with rare peak flows of 122 L/s (Myers et al., 2008). The spring probably began to discharge from beneath the lava after the flow was emplaced. Spring discharge probably has been less variable than other drainages in the northern basin because the spring has no direct surface connection to precipitation runoff from stream valleys or distal portions of alluvial aprons. The spring flow does respond to precipitation-runoff events in the watershed (Myers et al., 2008). As a result,

FIGURE 6. Schematic trench cut into Meinzer Mound showing stratigraphy beneath the spring crater and the gypsum crust at the rim and along the outer slopes. Note age of 2,850 BP at 5 m below the crater floor.

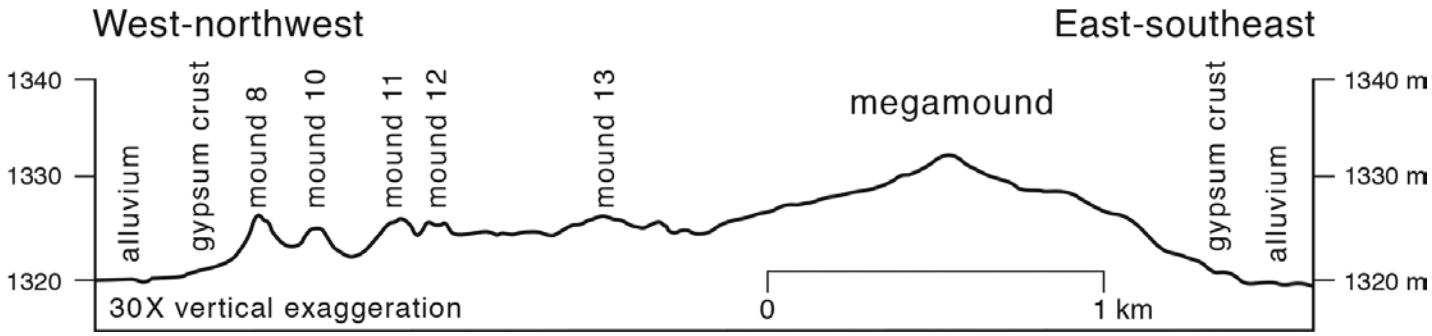

FIGURE 7. Cross profile of megamound along line xc 7 of Figure 1. Note vertical exaggeration.

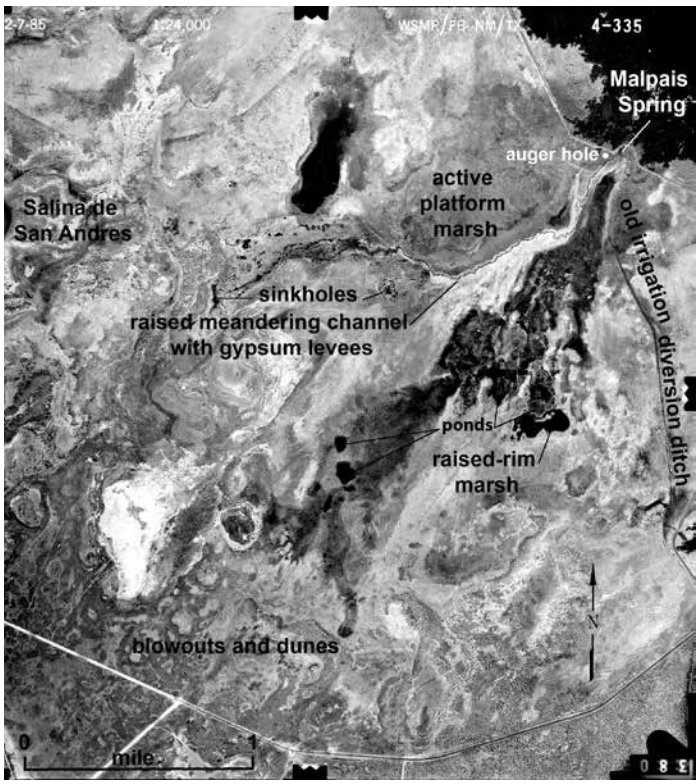

FIGURE 8. Aerial photograph of the area southwest of Malpais Spring illustrating uncommon geomorphic features developed by precipitation of granular gypsum and accumulation of gypsic and siliceous dust. These include a raised meandering channel with gypsum levees downstream from Malpais Spring, raised-rim marshes, an active platform marsh, and sinkholes. The playa, Salina de San Andres, a historical salt supply locale is on the west side of the photo. Photograph from Stewart Technologies, 12/7/85, 1:24,000 scale (9-inch by 9-inch image). (See also Color Plate 5)

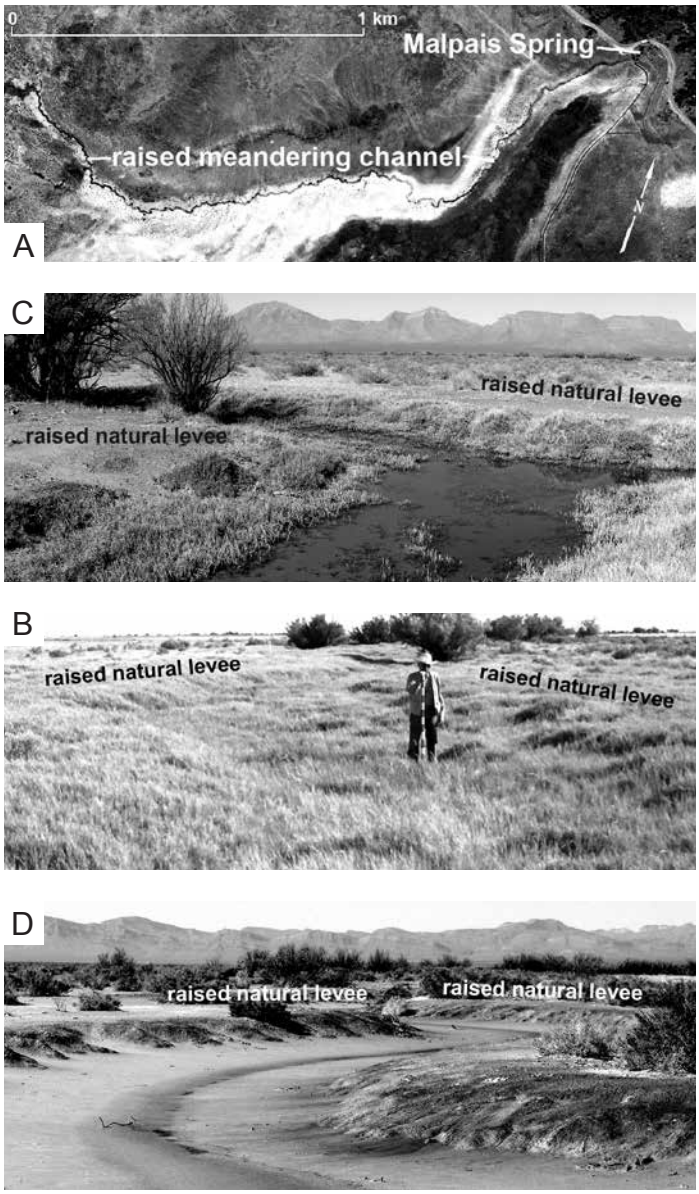

FIGURE 9. Photographs of raised meandering channel with levees of precipitated gypsum 0.7–1.5 m above the surrounding landscape (probably post-lava flow). A. Enlarged portion of Figure 8 aerial photograph showing meandering channel. B. Channel and levees near spring, covered with saltgrass (*Distichlis spicata*). C. Channel and levees approximately one hundred meters downstream. D. Channel and levees farther downstream.

the stream channel and meanders were established and remained in their consistent place across the adjacent plain for perhaps five thousand years. Natural levees and the channel aggraded by a combination of precipitated granular gypsum and by accumulation of eolian siliceous and gypsum dust. These processes raise the levees and channel above the surrounding landscape on the order of 0.7 to 1.2 m during that period of time (Figs. 8, 9). The meandering channel ultimately is blocked by eolian lunettes to the southwest and now ends in small sinkholes.

South of the lava flow and east of the raised channel, other seeps and springs create ovoid ponds and marshes over an area about 2 km long (Figs. 8, 10). Evidence of similar (now dry) channels and ponds extend even farther south (Fig. 10). Individual ponds are as much as 400 m long and 200 m wide with abundant pupfish. Like the minimounds and mounds, these marshes have raised rims on the order of 0.7 to 1.5 m high and long, gradual outer slopes similar to stoss sides on dunes (Fig. 10).

West of the raised-levee meandering channel is a broad platform of wetland-deposited gypsum and other evaporites ("platform marsh") approximately 1 km^2 in area and up to 1.7 m above the surrounding landscape (Figs. 8, 11). Clumps of gypsophile and halophile vegetation make hummocks on the surface. In dry months, evaporites, such as gypsum, halite, and hexahydrite form puffy crusts around the vegetation. Tall (2 m) reeds (*Phragmites*) grow along the eastern and western margins. In the winter, water up to 25 cm deep seeps from the top of the platform through the reeds and down the sides. Other broad, nearly flat buildups of granular gypsum persist on the nearby landscape, suggesting that platform marshes were more common in the past during episodes of wide-spread gypsum accumulation from broader areas of discharge and evaporation.

A subtle, but extensive geomorphic feature on the south and west (up-wind) edges of the lava flow is a plain consisting of gypsum-dominated eolian and spring deposits with minor alluvial channels. These deposits aggraded about 3 m and buried the margins of the lava flow. Many fissures, hollows, and vugs within the margins of the lava flow are filled with gypsum crusts to heights of at least 1 m above the surrounding plains. These crusts are probably from reprecipitation of eolian gypsum cycled downward from the surface of the lava flow and capillary fringe evaporation coming up from beneath the lava flow.

Extensive Gypsum Marsh Deposits

Fossiliferous gypsum marsh deposits, ranging up to 2.9 m thick (Fig. 12) 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. Beneath the gypsum are reddish-brown and gray-green, fine-grained, siliciclastic alluvial deposits and local pebble-gravel channels. Marsh deposits predominantly consist of bedded gypsum with bands of siliceous mud and organic matter. Fossils include large gastropods (*Stagnicola* and *Planorbella*), fish bones and scales, amphibian bones, possible underprints of megafauna tracks, and many ostracodes and foraminifera. Three radiocarbon ages on organic matter were obtained: 10,900 BP at the base of the gypsum marsh deposit, 10,600 BP in the middle of the marsh deposit, and 10,130 BP near the top (Love et al., this volume). The marsh and fossils all indicate a relatively wet environment during the Younger Dryas climatic episode in the northern Tularosa Basin.

Sinkholes

Rows of sinkholes and individual karst features are developed in the megamounds (Figs. 13, 14). The largest sinkhole is more than 100 m across and 7 m deep (Fig. 14). The megamound east-southeast of the Mound Springs complex has two strings of sinkholes (Fig. 13). One string of at least 34 depressions is oriented down slope at S 45° W. The other string of eleven depressions is oriented S 45° E. A spring mound farther southeast is aligned with this row of sinkholes, suggesting a subsurface connection of discharge rather than recharge at some time in the past, but not necessarily during the same time.

Sinkholes also formed downslope (southwest) from the raised channel of Malpais Spring (Fig. 8). These sinkholes may have formed when fresher (not saturated with gypsum) water occasionally reached the lower, eolian-disrupted parts of the drainage.

Eolian features and deposits

The most prominent features of eolian origin in the northern Tularosa Basin are blowout basins and lunettes. Coppice dunes, distended arms of parabolic dunes, linear dunes, and planar areas of loess cover much of the basin floor. The largest string of blowouts north of Alkali Flat include Little Salt Lake, Lumley Lake, Big Salt Lake, and the extended connection upstream along Salt Creek (Fig. 1). The blowouts are as much as 8 m deep below the level of the alluvial-gypsum discharge plain and are as much as 14 km long. Two separate strings of blowouts along the western margin of the basin between the junction of Range Roads 6 and 7 and Alkali Flat are 4 and 8 km long respectively and 1.5 to 2 km wide. The blowouts adjacent to Salt Creek have intermediate "terraces" of alluvium and eolian sand and loess that reflect episodes of deflation and partial backfilling of deflated blowout floors. These intermediate levels, along with sequences of lunettes, show that both eolian and stream incision happened episodically during the Holocene and not all at once in the late 19th century (e.g., Bryan, 1925).

Blowouts south and west of Malpais Spring form small closed basins with playas such as Salina de San Andres (Fig. 8), and broad valleys for tributaries to Salt Creek. Blowouts in this area probably furnish fine sand and dust to the plains and to the raised-rim features closer to the malpais.

In the areas of blowouts incised into the basin-floor deposits and in lesser blowouts on the upwind (southwest) side of the Three Rivers fan, single meandering gravelly channels and multiple gravelly anastomosing channels are exposed as low, distinct ridges where the inter-channel finer-grained sediments have been blown away (Fig. 15).

Lunettes and distended parabolic dunes are common downwind from the blowouts. A sequence of at least eight lunette crests are preserved as curved forms northeast of the blowout south of Range Road 6 (Fig. 16). The most recent lunette (z of Fig. 16) is

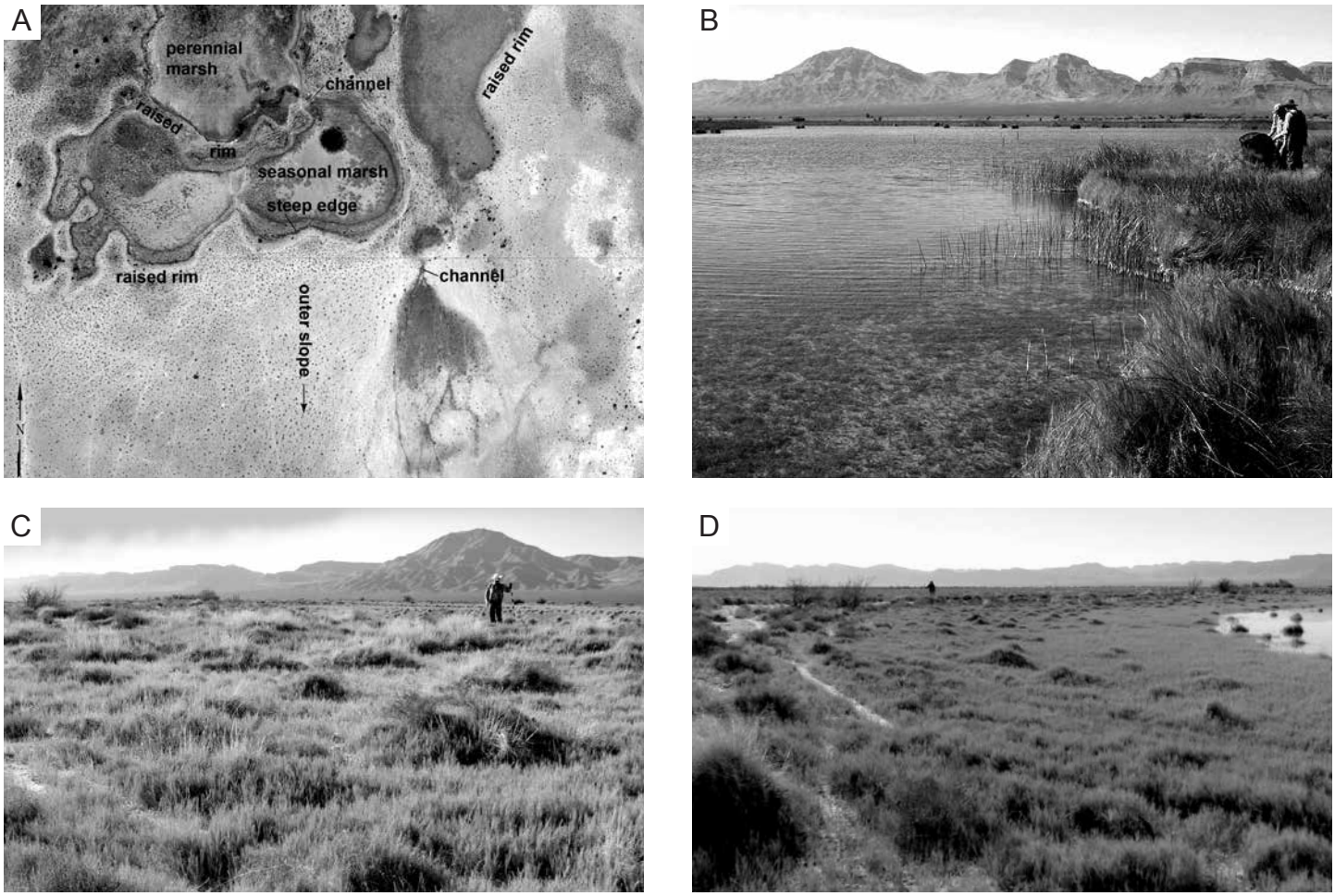

FIGURE 10. Illustrations of raised-rim marshes. A. Aerial photograph showing present marshes and inactive raised-rim features; image from digital orthophoto. Note extensive outer slopes and steep margins facing open water. B. Ground-based photograph of open water in marsh. C. Grassy outer slope of raised-rim marsh. D. Steeper inner edge of raised-rim marsh.

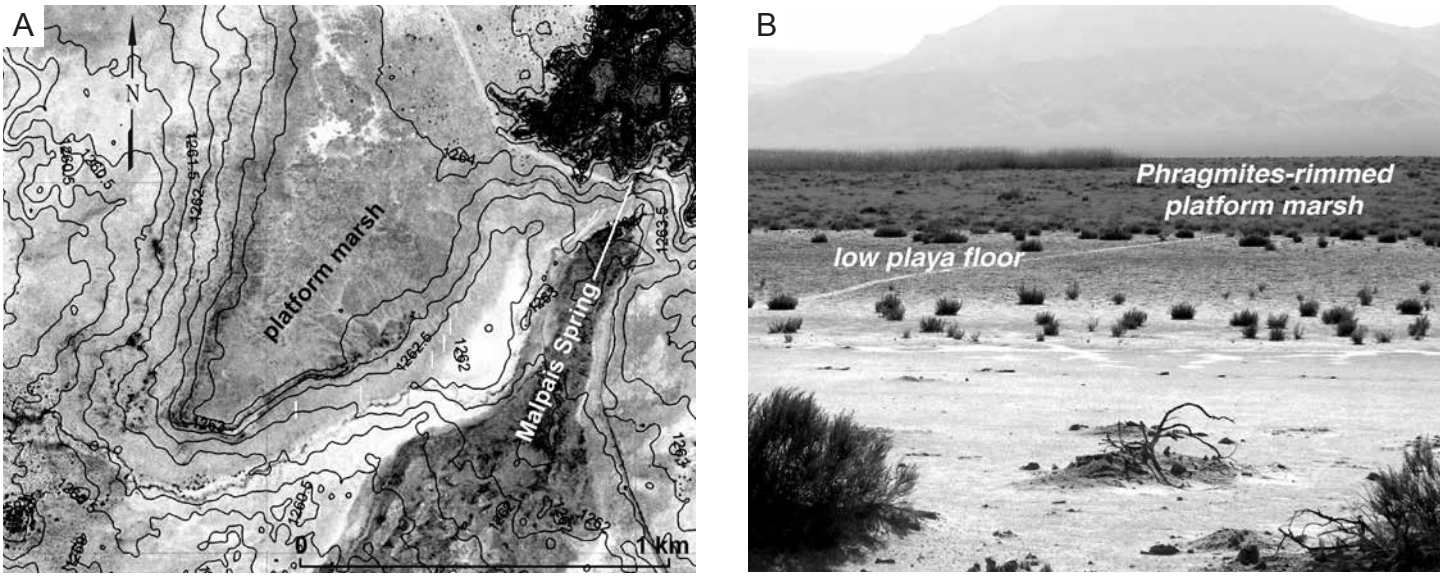

FIGURE 11. Images of platform marsh. A. Digital orthophotograph with superimposed 1/2-m contour lines (elevation data from Intermap®) outlining platform marsh elevated above surrounding blowouts, Carrizozo Malpais lava flow, and other features near Malpais Spring. B. Photograph of eastern edge of platform marsh with reeds (*Phragmites*) along the slope below the top of the marsh.

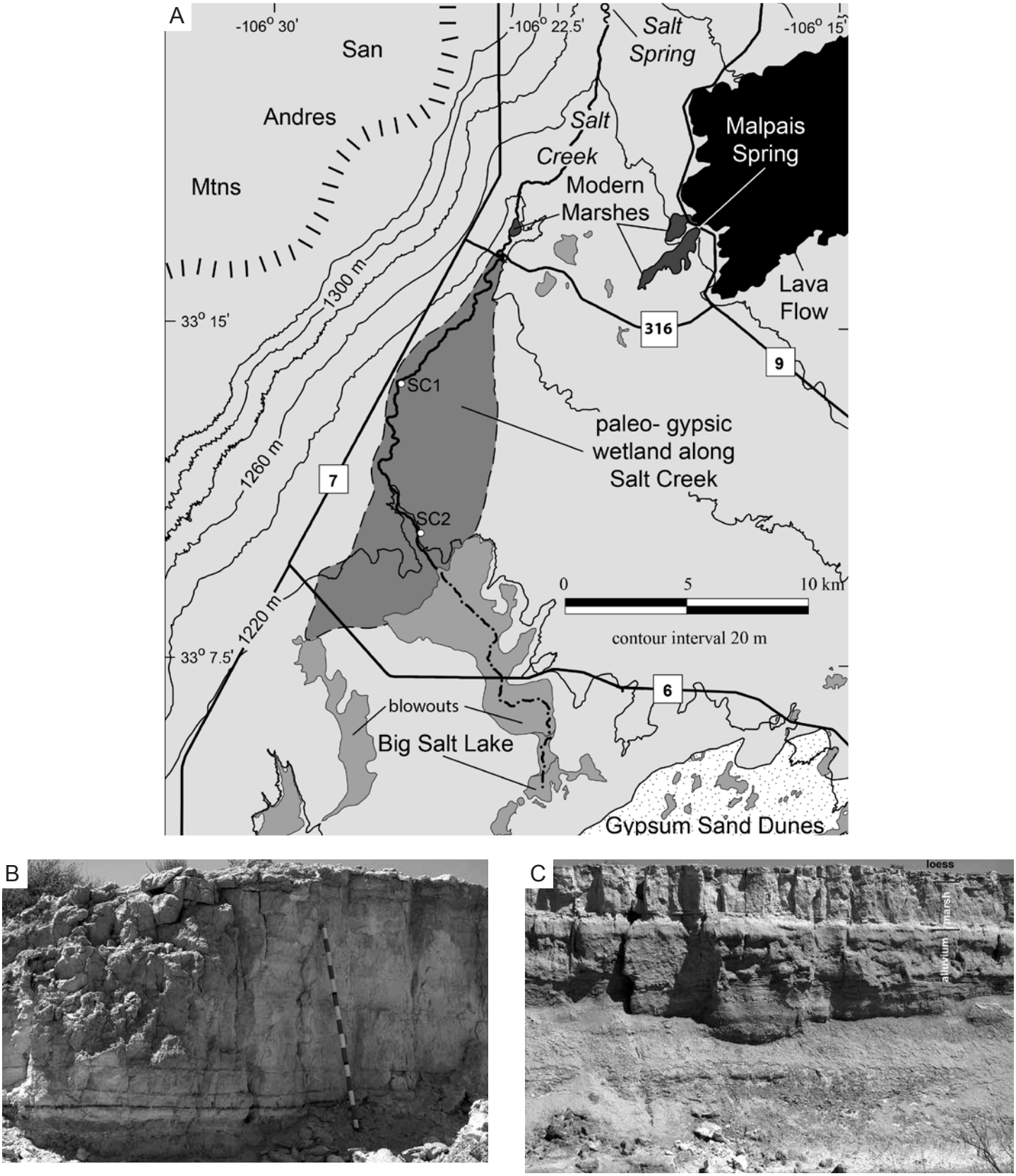

FIGURE 12. Extensive gypsiferous marsh deposits. A. Map of extent of late Pleistocene marsh in contrast to modern wetlands. SC 1 and 2 are sites of measured sections for radiocarbon samples (Love et al., this volume). Radiocarbon ages from the deposits are 10,900, 10,600, and 10,130 BP. B. Photograph of gypsiferous marsh deposits with dark gray bands of organic matter. Rod is 1.5 m long with 10-cm intervals. C. Exposure along Salt Creek illustrating gypsiferous loess at top, gypsum marsh deposits, and red and grayish green layers of siliceous silt and clay and red alluvium.

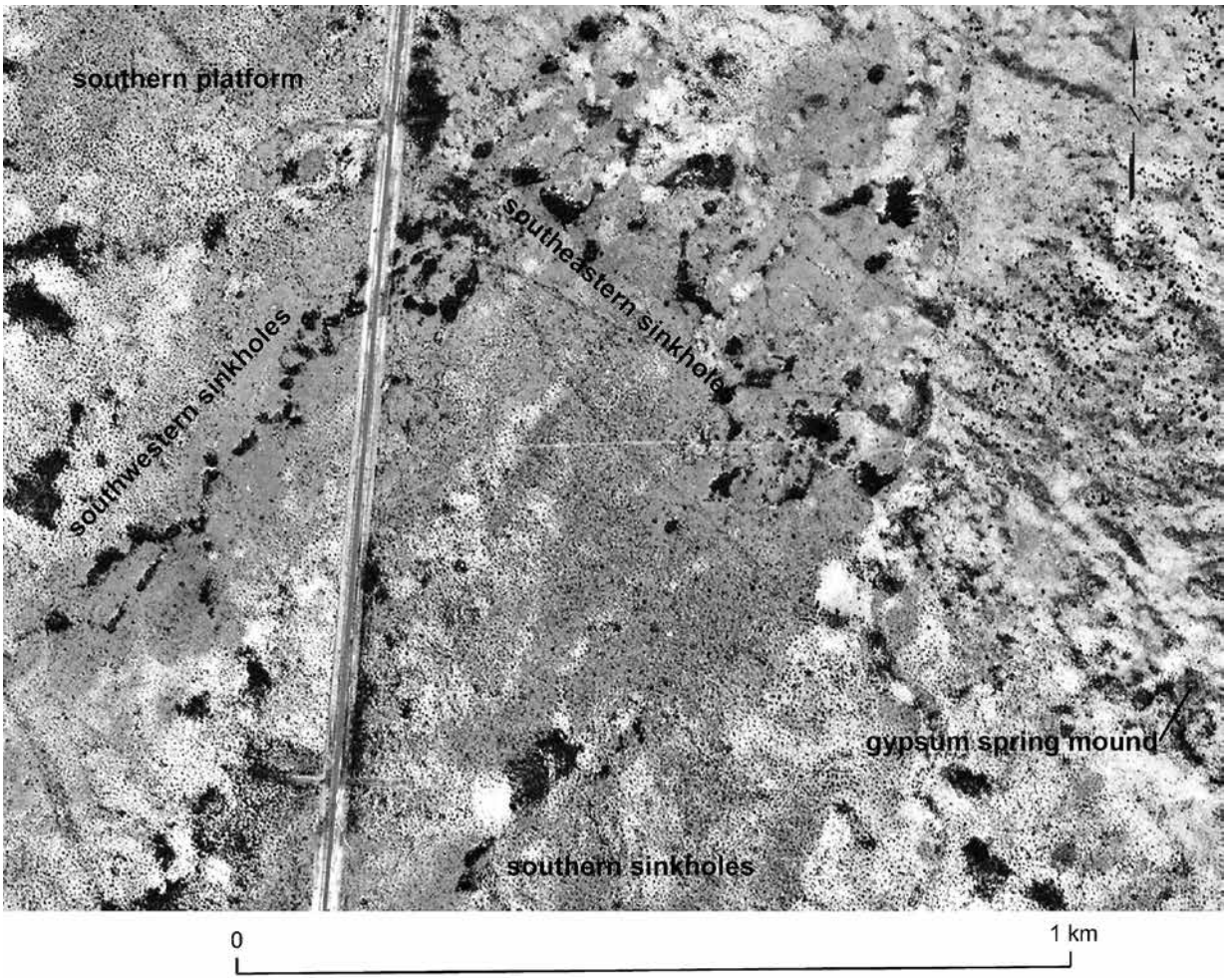

FIGURE 13. Enlarged portion of aerial photograph showing aligned and oriented sinkholes approximately 3 km southeast of Mound Springs complex. Aerial photograph from Stewart Technologies, 12/7/85, 1:24,000 scale.

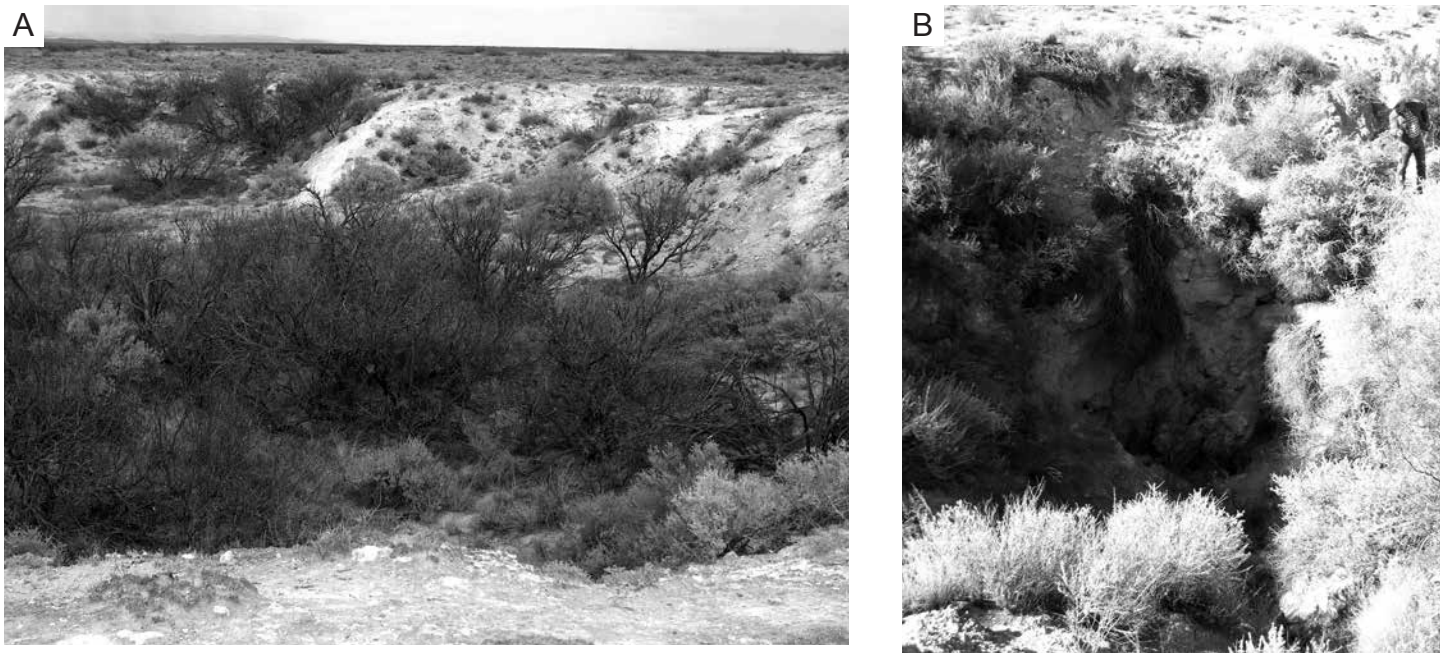

FIGURE 14. Photographs of sinkholes developed in Quaternary gypsum deposits. A. Large sinkhole with crest of megamound in view to northeast. B. Narrow, deep sinkhole developed south of the main group of aligned sinkholes.

accumulating on the slope adjacent to the present blowout floor. Older lunettes form arcuate ridges with stoss sides partially filled in by alluvium and loess. As seen in Figures 15 and 16, the intermediate levels of alluvium and loess commonly develop distinctive patterned vegetation.

Meinzer delineated a separation of siliciclastic dunes to the north of Big Salt Lake from larger gypsum sand dunes to the south, derived from Alkali Flat and Pleistocene Lake Otero. The dunes north of Big Salt Lake and Range Road 6 continue to be dominated by gypsum. Reddish staining by clay along with some siliciclastic grains imparts a more siliceous look to the dunes. The siliciclastic dunes commonly form on distal alluvial fans such as Three Rivers fan and the alluvial aprons of the San Andres Mountains (Fig. 1).

CONCLUDING REMARKS

The geomorphic features of the northern Tularosa Basin stem from a unique combination of clastic piedmont deposition and erosion, stream deposition and erosion, eolian erosion and lesser amounts of deposition, and discharge and deposition of evaporites from shallow groundwater to form gypsum-rimmed springs, marshes, streams, and larger features of gypsum accumulation. The floor of the basin is a south-sloping gypsum-alluvial discharge plain cut by Salt Creek and eolian blowouts. Superimposed across this plain is the Carrizozo lava flow. Holocene blowouts and eolian deposition affect the stream gradients of Salt Creek, its tributaries, and piedmont slopes. Past episodes of deflation appear to have affected stream and piedmont gradients repeatedly as well. Holocene features developed in response to processes in a semiarid climate, whereas relict features such as the extensive gypsum marsh deposit suggest responses to wetter and cooler climatic conditions.

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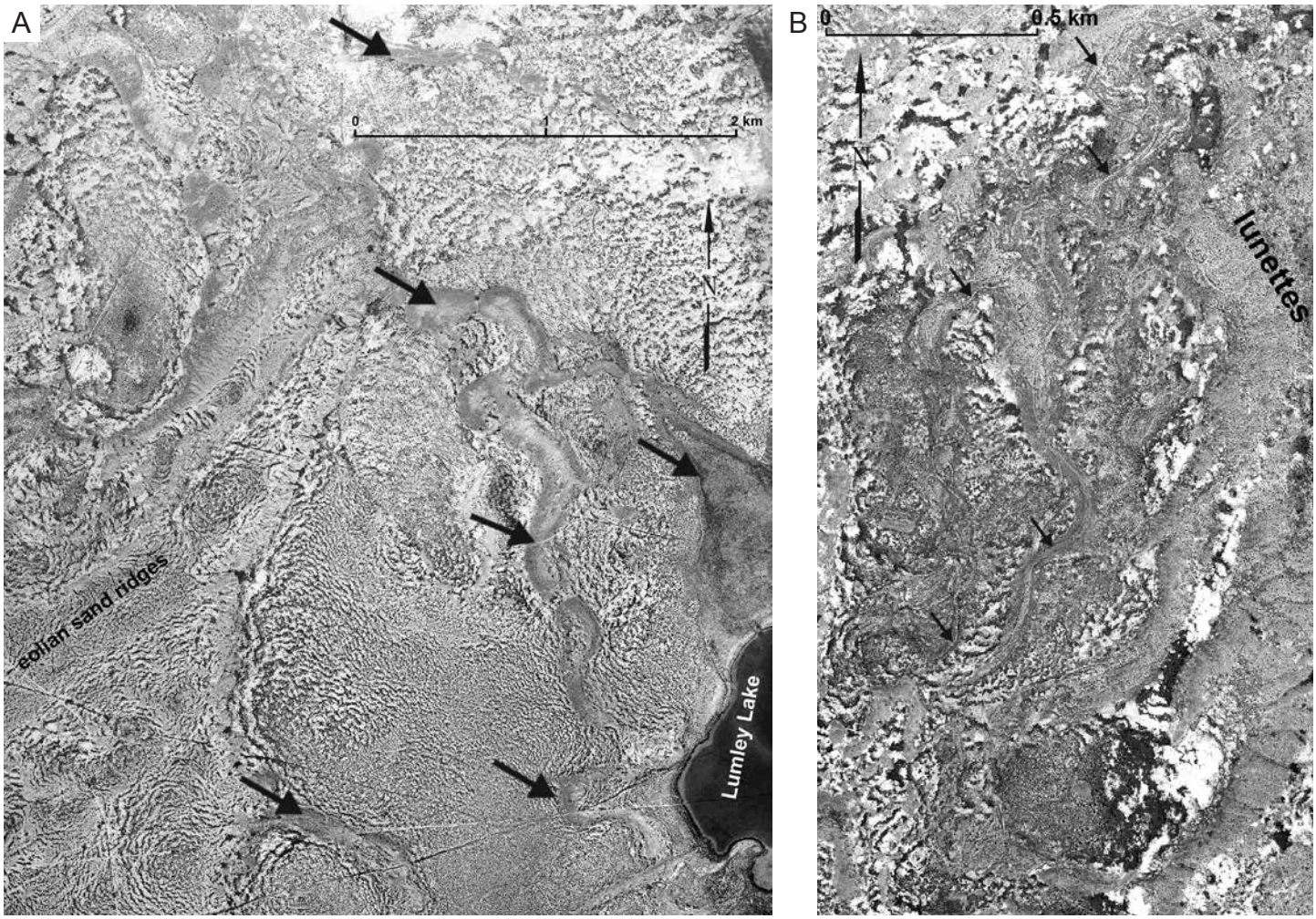

FIGURE 15. Aerial photographs of exhumed gravelly channels in deflated areas of the gypsum-alluvial discharge plain. Black arrows point to gravelly ridges. A. Enlarged aerial photograph of area west and north of Lumley Lake. B. Enlarged aerial photograph of southern flank of Three Rivers fan approximately 12–15 km north of Big Salt Lake. Note central parts of channels are visible between levees. Aerial photographs from Stewart Technologies, 12/8/85, 1:24,000 scale (9-inch by 9-inch images).

FIGURE 16. Enlarged portion of aerial photograph of multiple lunettes (lettered s through z) downwind from large blowout approximately 10 km northwest of Lumley Lake. Aerial photograph from Stewart Technologies, 12/8/85,1:24,000 scale (9-inch by 9-inch images).

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REFERENCES

Allen, B.D., Love, D.W., and Myers, R.G., 2009, Evidence for late Pleistocene hydrologic and climatic change from Lake Otero, Tularosa Basin, south-central New Mexico: New Mexico Geology, v. 31, p. 9–25.

Bachman, G.O., 1968, Geology of the Mockingbird Gap quadrangle, Lincoln and Socorro Counties, New Mexico: U.S. Geological Survey, Professional Paper 594-J, 43 p.

Bachman, G.O., and Harbour, R.L., 1970, Geologic map of the northern part of the San Andres Mountains, central New Mexico: U.S. Geological Survey, Miscellaneous Investigations Map I-600.

Bryan, K., 1925, Date of channel trenching (arroyo cutting) in the arid southwest: Science, v. 62, p. 338–344.

Dreimanis, A., 1962, Quantitative gasometric determination of calcite and dolomite by using the Chittick apparatus: Journal of Sedimentary Petrology, v. 32, p. 520–529.

Garry, W.B., Zimbelman, J.R., and Bleacher, J.E., 2008, Morphology and emplacement processes at the distal end of the Carrizozo lava flow, New Mexico: Implications for Martian flow sheets (abs.): Abstracts of Papers Submitted to the Lunar and Planetary Science Conference, 39th Lunar and Planetary Science, March 10–14, 2008; Houston, TX, United States Abstract 1734.

Love, D.W. and Seager, W.R., 1996, Fluvial fans and related basin deposits of the Mimbres drainage: New Mexico Geology, v. 18, p. 81–92.

Love, D., Allen, B., and Myers, R., 2007, Preliminary geologic map of the Mound Springs quadrangle, Lincoln, Sierra, Socorro, and Otero counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 163, 1:24,000 sheet.

Love, D.W., Allen, B.D., and Myers, R.G., 2012, Geologic map of Quaternary deposits on the Capitol Peak SE and Sheep Mountain quadrangles with illustrations of uncommon surficial features, northern Tularosa Basin, south-central New Mexico (abs.): Geological Society of America, Abstracts with Programs, v. 44, no. 6, p. 13.

Love, D.W., Allen, B.D., Morgan, G.S., and Myers, R.G., 2014, 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: New Mexico Geological Society, Guidebook 65.

Lozinsky, R.P., and Bauer, P.W., 1991, Structure and basin-fill units of the Tularosa Basin: New Mexico Geologic Society, Guidebook 42, p. 7–9.

Meinzer, O.E., and Hare, R.F., 1915, Geology and water resources of Tularosa Basin, New Mexico: U.S. Geological Survey Water-supply Paper 343, 317 p.

Miller, R.R., and Echelle, A.A., 1975, Cyprinodon tularosa, a new cyprinodontid fish from the Tularosa Basin, New Mexico: The Southwestern Naturalist, v. 19, no. 4, p. 365–377.

Myers, R.G., Allen, B.D., and Love, D.W., 2008, Malpais Spring and Malpais salt marsh, northern Tularosa Basin, New Mexico: New Mexico Geology, v. 30, p. 59.

Nelson, R.E., Klameth, L.C., and Nettleton, W.D., 1978, Determining soil gypsum content and expressing properties of gypsiferous soils: Soil Science Society of America, Journal, v. 42, p. 659–661.

Peterson, C., and Roy, M., 2005, Gravity and flexure models of the San Luis, Albuquerque, and Tularosa basins in the Rio Grande Rift, New Mexico and Southern Colorado: New Mexico Geologic Society, Guidebook 56, p. 105–114.

Peterson, F.F., 1981, Landforms of the basin and range province, defined for soil survey: Nevada Agricultural Experiment Station, Bulletin 28, 52 p.

Schumm, S. A., 1977, The fluvial system: New York, John Wiley and Sons-Interscience, 338 p.

Weir, J.E., Jr., 1965, Geology and availability of ground water in the northern part of the White Sands Missile Range and vicinity, New Mexico: U.S. Geological Survey, Water supply Paper 1801, 78 p.

Wessel, R.L., 2010, Tejeños, salteros, and land-use conflict: Historic qualities of the Salina de San Andres Salt Trail through the Tularosa Basin, Chapter 3 *in* Greenwald, D.H., ed., 2009 Tularosa Basin Conference Proceedings: Basin Exploration, Settlement, Entrepreneurs and Development, 14 p.