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THE OTERO FORMATION, PLEISTOCENE LACUSTRINE STRATA IN THE TULAROSA BASIN, SOUTHERN NEW MEXICO

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ABSTRACT.—The Otero Formation is gypsiferous clay and sand, gypsite, and associated fluvial-deltaic facies deposited in and adjacent to Pleistocene Lake Otero in the Tularosa Basin of south-central New Mexico. This lithostratigraphic unit, which excludes Holocene eolian and playa sediments of the White Sands-Lake Lucero-Alkali Flat area, forms much of the surficial basin fill at elevations below 1220 m. The formation's areal extent is a least 2100 km²; and, it is widely exposed in parts of Doña Ana, Otero and Sierra Counties. Originally named by C. L. Herrick in 1904, the term Otero Formation has never been used by subsequent workers. The Tularosa Formation, also named by Herrick, comprises strata that we include in the upper part of the Otero sequence. We define a lectostratotype section for the Otero Formation and review its lithotypes, distribution, thickness and age. Further study is needed to (1) decipher climatic and geomorphic history recorded by these lacustrine and fluvial-deltaic sediments, and (2) better define the formation's lateral and basal (subsurface) boundaries.

INTRODUCTION

The Tularosa Basin covers an area of almost 17,000 km² in Socorro, Sierra, Lincoln, Doña Ana and Otero Counties in southern New Mexico (Fig. 1). Bordered to the west by the Oscura, San Andres, Organ and Franklin Mountains, and to the east by the Sierra Blanca, Sacramento Mountains and Otero Mesa, the Tularosa Basin is one of the few Rio Grande rift basins with internal drainage (Hawley, 1975, 1986, 1993; Orr and Myers, 1986; Lozinsky and Bauer, 1991). Two north-trending half grabens separated by the Jarilla uplift and fault zone (Fig.1) are the major structural components (Seager et al., 1987, sections A-A' to C-C'). In the western half graben, as much as 2000 m of Neogene sediments are basin fill (Zohdy, 1969; Doty and Cooper, 1970); and a 1833-m stratigraphic test well near White Sands Missile Range (WSMR) Headquarters (T-14: NE 1/4 sec. 15, T22S, R5E) penetrated mostly fine-grained lake beds to a depth of at least 1585 m (McLean, 1975). Almost all of this sequence has been referred to the upper Cenozoic Santa Fe Group (Hawley et al., 1969; Seager et al., 1987; Johnson et al. 1989), but the basin fill remains essentially unstudied in most of the Tularosa Basin.

Emphasis here is on the Otero Formation of C. L. Herrick (1904, see below), a middle to upper Pleistocene (post-Santa Fe) lacustrine and fluvial-deltaic unit that is a major component of surficial basin fill below an elevation of 1220 m. This elevation is the approximate topographic-closure level of the Tularosa Basin, which merges southward with the Hueco Bolson floor near the New Mexico-Texas Stateline (Fig. 1). Basin closure can be attributed to three mechanisms: (1) differential uplift/subsidence along range/basin-boundary faults, (2) progradation of terminal distributaries of the ancestral Rio Grande at the basin's southern end during the final phase of Santa Fe Group deposition in that area (Seager, 1981; Seager et al., 1987; Mack et al., 1997), and (3) episodic basin-floor deflation during the middle and late Quaternary.

Work to date suggests that the ancestral upper Rio Grande terminated in the southern Tularosa Basin and central Hueco Bolson during much of the late Pliocene (~2.5 and 1.8 Ma: Gile et al., 1981, 1995; Seager et al. 1984, 1987; Vanderhill, 1986; Mack et

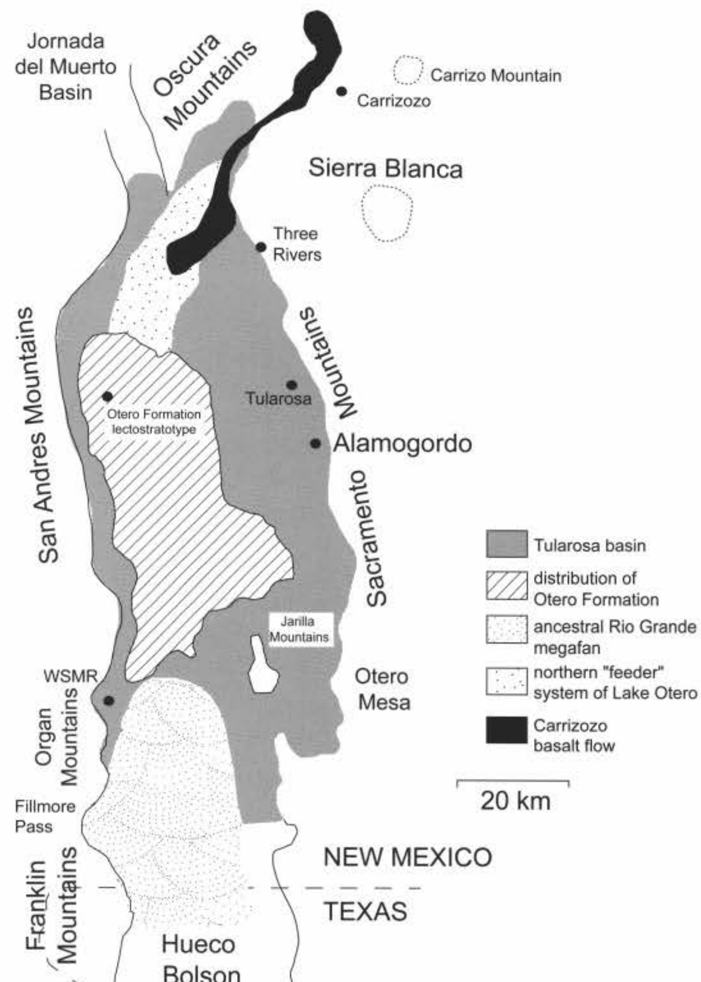

FIGURE 1. Map of the Tularosa Basin (after Seager et al., 1987; Anderson et al., 1997) showing inferred distribution of Otero Formation and location of lectostratotype section.

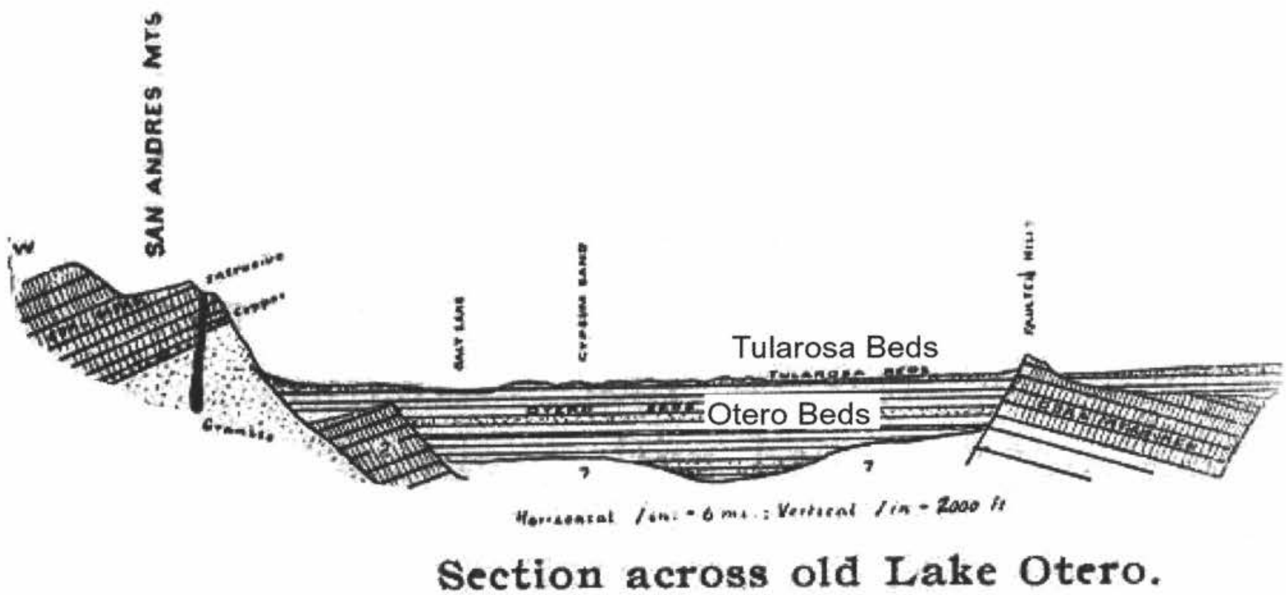

FIGURE 2. C. L. Herrick's cross section of Lake Otero (from C. L. Herrick, 1904, p. 179).

al., 1996, 1997). The large, low-gradient fluvial fan (megafan: Fig. 1) constructed during this interval forms the bulk of the Camp Rice Formation in the area (Strain, 1966; Hawley et al., 1969; Hawley, 1975, fig. 2). The apex of the fluvial distributary system is in Fillmore Pass (gap between Organ and Franklin Mountains). Fan area is at least 900 km^2; and Camp Rice Formation thicknesses are as much as 200 m in hanging-wall basin blocks of the transition zone between the Tularosa and Hueco half grabens (Seager et al., 1987). The extensive playa-lake complex that formed the inferred terminal sink for the entire ancestral upper Rio Grande has been designated Lake Cabeza de Vaca by Strain (1966, 1971); lacustrine and deltaic deposits of this "lake" basin (estimated sill elevation of about 1125 m) in the northwestern Hueco Bolson are correlated with the Fort Hancock Formation of Strain (1966; Gustavson, 1991).

The most visible lacustrine and associated fluvial–deltaic beds in the Tularosa Basin are interbedded evaporites (mostly gypsum), clay, sand and gravel that crop out along the floor and margins of Lake Lucero and the Alkali Flat to the north. All well-documented lake and playa deposits of late Quaternary age occur below an elevation of 1205 m and have a surface area of at least 2100 km^2 (Hawley, 1983, 1993). C. L. Herrick (1904) originally described these strata as the Otero and Tularosa formations, names ignored by subsequent workers. Here, we re-evaluate Herrick's lithostratigraphy of the Lake Lucero area and formally establish his Otero Formation.

PREVIOUS STUDIES

C. L. Herrick (1904) first concluded that an ancient lake much greater in extent than present Lake Lucero covered most of the current floor of the Tularosa basin. He called this ancient lake "Lake Otero" (Fig. 2) and observed that:

"....it may be regarded as certain that the great basin north of the Jarilla mountains and extending northward to east of the Oscuros was for a very long period covered by a salt lake in which gypsum, salt, and saline alkalis were deposited with intermittent regularity. Thus were formed the great saline beds which we venture to call the *Otero marls*. This formation has been penetrated by wells to a depth of some 200 feet in many places and everywhere reveals a succession of gypsum and saline beds intercalated in gypsiferous marls. It is impossible to guess at the thickness of the formation. It may very possibly prove to be of Tertiary age, at least in part, as it seems to pass undisturbed under the lava beds at the north end of the valley. The upper surface, where exposed, is a plane and the superposed sandy marls (Tularosa Formation) are distinctly differentiated.

The upper or *Tularosa Beds* are rarely over twenty-five feet thick and in many places contain fresh-water lacustrine shells. It would appear, therefore, that the line between the upper and lower beds marks a period of transition to a time when more water and more sediments entered the lake from the sides" (C. L. Herrick, 1904, p. 179-180).

Herrick went on to use the terms "Otero Formation" (p. 186-187), "Otero saliferous formation" (p. 187) and "Tularosa Formation" (p. 187). He also reiterated that the two units could be distinguished by the topographic break at the Alkali Flat (Otero Formation below the break, Tularosa Formation above: Fig. 2) and the presence of freshwater gastropods in the Tularosa Formation.

Meinzer and Hare (1915, p. 24) cited C. L. Herrick's (1904) article, even noting that it recognized "the valley fill and divides it into formations called Otero marls and Tularosa beds." However, as the quote indicates, Meinzer and Hare (1915) referred to these strata by the informal term "valley fill" (see especially their p. 64-72 and fig. 10), to which they assigned a Quaternary and Tertiary(?) age. Careful comparison of C. L. Herrick (1904) and Meinzer and Hare (1915) indicates that Herrick's Otero and Tularosa formations correspond to the subdivision of "valley fill" that Meinzer and Hare (1915) termed "gypsum deposits." They mapped the outcrops of these strata (pl. 17) and described them (p. 69-70) as follows:

Gypsum underlies the southern part of the large alkali flat, all of the white sands area, and a section of the low desert plain extending southward to T. 22 S., Rs. 5 and 6 E., eastward to Dog Canyon and within a few miles of Alamogordo and Tularosa, and northwestward to a point beyond Malpais Spring.....

The gypsum seen in outcrops has several different forms, indicating corresponding differences in origin.

In the banks of the large alkali flat from the vicinity of Ritch's ranch to the southern extremity, and in outliers that project above this part of the flat, outcrops about 20 feet deep generally show gypsum with distinct horizontal bedding indicating deposition from the concentrated waters of an ancient lake (Pl. XV, *B*)....

In the mid-slope arroyos and in the wells of the gypseous plain the section in downward succession is commonly as follows: (1) Soil, composed of impure gypsum or gypseous clay, from less than 1 foot to several feet thick; (2) hard massive gypsum resembling the bedrock ledges from 1 to several feet thick; (3) soft, homogeneous gypsum—in only a few places showing horizontal bedding similar to the gypsum deposits adjacent to the alkali flat (Pl. XIV, A)—ranging in thickness from less than 5 feet to more than 10 feet; (4) red homogeneous gypseous adobe, to bottom of exposure.

They concluded that "it seems probable that the main mass of gypsum was deposited in an ancient lake, the clay deposits gradually giving way to the gypsum deposits as the lake waters became concentrated" (Meinzer and Hare, 1915, p. 70). Although Meinzer and Hare (1915) acknowledged an outcrop thickness of the gypsum deposits of 20 ft or more, their well data suggest these strata are no more than 100 ft thick.

Many subsequent workers have, in passing, mentioned the existence of Pleistocene Lake Otero and its gypsiferous sedimentary fill (e.g., Meinzer, 1922; Jicha, 1959; Schmidt and Craddock, 1964; Kottlowski et al., 1965; Hawley and Kottlowski, 1969; Hawley, 1975; King and Harder, 1985; Lozinsky and Bauer, 1991). Indeed, these strata have long been identified, beginning with C. L. Herrick (1900), as the proximal source of the gypsum in the dunes of the famous White Sands. Kottlowski (1958, p. 1734) noted, "the 280 square miles of dunes and other parts of Tularosa Basin below 4000 feet are underlain by bedded gypsum 5-25 feet thick—deposits of Lake Otero, named by Herrick (1904)." However, neither he nor the other workers used C. L. Herrick's lithostratigraphic names Otero and Tularosa formations; and Seager et al. (1987) most recently mapped these strata as the informal units "gypsiferous lake deposits in the Tularosa basin" (Qlg) and "older gypsiferous basin-floor deposits and lake beds" (Qbfg).

A major impediment to stratigraphic research since 1942 simply relates to the fact that much of the Tularosa Basin has been dedicated to national defense programs, and accessibility to many sites of interest continues to be difficult if not impossible. With a few exceptions (e.g., Doty and Cooper, 1970), most studies focus on water-supply and saline-groundwater issues, without much attention being paid to details of basin-fill stratigraphy and sedimentology (e.g., Hood, 1959; McLean, 1975; Bedinger et al., 1989; Orr and Myers, 1986). A few prior studies have simply dealt with economic-resource and genetic aspects of the area's vast gypsum reserves (e.g., H. N. Herrick, 1904; Talmage, 1932, 1933; Kottlowski, 1958; Weber and Kottlowski, 1959; Allmendinger and Titus, 1973), while others emphasize the gypsum dune complex and geologic setting of White Sands National Monument (e.g., Vandiver, 1936; McKee and Moiola, 1975). Starting with Meinzer (1922), there have also been several studies of more regional scope that cover aspects of the "pluvial-lake" record and paleoecology in this part of the American Southwest. Of special relevance are investigations of late Quaternary paleoenvironmental conditions, archaeological records, and soil-geomorphic relationships within the Tularosa Basin and nearby areas (e.g., Gile et al., 1981, 1995; Miller, 1981; Hawley, 1983, 1993; Van Devender and Toolin, 1983; Van Devender et al., 1984; Williams and Bedinger, 1984; Smith and Miller, 1986; Blair et al., 1990; Harris, 1997).

OTERO FORMATION

Definition

C. L. Herrick's (1904) use of the terms Otero Formation and Tularosa Formation provides as precise a definition of lithostratigraphic units as many names proposed during the early twentieth century and still used today. Therefore, his names need to be considered as potentially valid names for lithostratigraphic units. Nevertheless, our observations suggest that C. L. Herrick's Tularosa Formation is not a mappable lithostratigraphic unit distinct from his Otero Formation. Indeed, the Tularosa Formation of C. L. Herrick is composed of the same lithotypes as his Otero Formation, so we view it as little more than the upper 5-10 m of the Otero Formation. Therefore, only one formation need be recognized, and one name, Otero Formation, is adequate.

Lectostratotype Section

C. L. Herrick designated no type section for his Otero Formation, so we designate a lectostratotype section (Figs. 3-4). As Salvador (1994, p. 28) stated, a lectostratotype is "a stratotype for a previously described stratigraphic unit selected later in the absence of an adequately designated original stratotype (holostratotype)." This section is at the northern end of the Alkali Flat, ~ 1.5 km east of Range Road 7, on the southeastern face of a long, southwest-northeast-trending escarpment (see the Appendix for the map coordinates). The lectostratotype section is one of the thickest exposed sections of the Otero Formation. Furthermore, it well exposes characteristic lithotypes of the formation, is relatively accessible, contains age-diagnostic fossils and includes an unambiguous upper contact of the Otero Formation with overlying gypsum sands. The lectostratotype is thus an excellent type section, though it has one drawback—the base of the Otero Formation is not exposed. Nevertheless, the base of the formation is nowhere exposed in the Tularosa Basin, so no section with an exposed base is available for a lectostratotype.

At the lectostratotype section, the Otero Formation is ~ 10 m thick, and consists of variegated (principally yellowish gray and red) gypsiferous clay, gypsiferous sand and gypsite (Figs. 3-4). All beds are poorly indurated and very calcareous. A single bed in the section (bed 11: Fig. 3) consists of trough crossbedded volcaniclastic sands and gravel. It contains bones of late Pleistocene

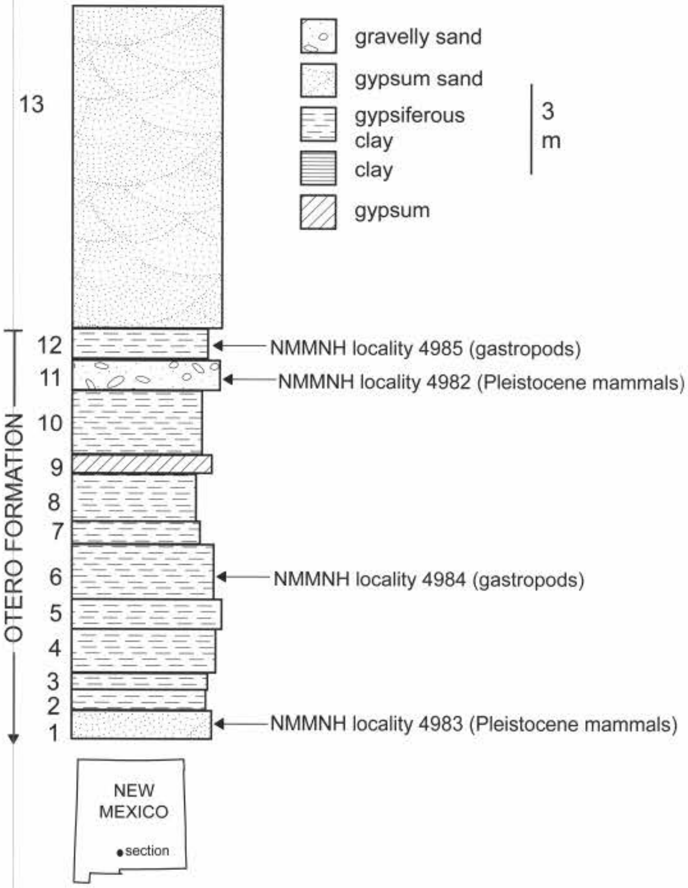

FIGURE 3. Lectostratotype section of the Otero Formation. See Appendix for description of numbered lithologic units.

mammals (*Equus, Camelops*), as does the lowest bed in the section (Fig. 3) (Morgan and Lucas, this guidebook). Two beds in the section contain fossils of freshwater gastropods (Fig. 3).

The base of the lectostratotype section is at the surface of the Alkali Flat, and clearly the Otero Formation continues downward, below the surface. The top of the Otero Formation is a sharp surface of truncation overlain by friable gypsum sands, which apparently are Holocene (?) eolian sediments that have recycled gypsum from the underlying Otero Formation.

Lithotypes, Distribution and Thickness

The Otero Formation is exposed and underlies a large area of the Tularosa Basin below an elevation of about 1220 m, and documented lacustrine facies of late Pleistocene age are all below 1205 m (Fig. 1). Throughout its outcrop area, Otero lithotypes closely resemble the lectostratotype section—gypsiferous clays, sands, gypsite and minor pebble gravel. Gravel-clast composition at and north of the lectostratotype section is dominated by intermediate-igneous rock types rather than consisting of a local (Proterozoic and Paleozoic) clast assemblage from the nearby San Andres Range (Hawley, 1983). Near Alkali Spring (at UTM zone 13, 360630E, 3659984N, NAD 27), ~ 5 km northeast of the lectostratotype section of the Otero Formation, a section of Otero Formation ~ 8 m thick is exposed and contains two beds

FIGURE 4. Photograph of lectostratotype section of the Otero Formation.

of volcaniclastic sand/gravel. The lower bed is 0.5 m thick, and the upper, which is 3 m thick, displays trough crossbed axes that indicate paleoflow toward the southwest.

This indicates that the fluvial-deltaic system at the northwestern margin of Lake Otero tapped into a relatively distant source terrane in the Lincoln County porphyry belt (Allen and Foord, 1991), which includes the Carrizo Mountain and northern Sierra Blanca intrusive centers with peak elevations approaching 3000 m (Fig. 1). Valley fill of the primary feeder stream to this northern fluvial-deltaic-lacustrine complex can be traced northward to the point where it is buried by the Carrizozo basalt flow (T11-12S, R6E); and about 60 km of the ancestral valley floor to the northeast is now occupied by the mid-Holocene flow (see age control discussion below).

The northernmost outcrops of well-documented lacustrine and fluvial-deltaic facies in southeastern Sierra County are located about 3.2 km north of the type section. These fossiliferous beds (including a mammalian fauna) are exposed in the walls of a small subbasin south of Alkali Spring (Hawley, 1983, fig. II-1). Other outcrops extend southward along the western side of the Tularosa Basin into Doña Ana County south of Lake Lucero to just east of Antelope Hill (T21S, R5E). To the east, the Otero Formation crops out in places along US-70 to west of US-54 in a basin-floor area surrounding Lone Butte (T19S, R9E). Because of the extensive Holocene cover in the White Sands dune field, the formation is poorly exposed in the White Sands National Monument area and adjacent, eastern parts of the basin as far north as the mouth of Three Rivers (sec. 9, T14S, R6E). Based on reconnaissance mapping by Seager et al. (1987) and an unpublished map of Quaternary deposits in the northern Tularosa Basin by Hawley in 1986 (Tularosa 2° Sheet), the total area of outcrop and inferred subsurface distribution of the Otero Formation is at least 2100 km^2 (Fig. 1).

Maximum thickness of the Otero Formation, based on the water well data of Meinzer and Hare (1915, see above), appears to be about 30-35 m. Maximum exposed thickness is the ~10 m at the lectostratotype section.

Age

Fossil mammals from the Otero Formation indicate its upper, exposed portion is of Late Pleistocene age (Morgan and Lucas, this guidebook). However, direct evidence of its oldest age is not known, though it is certainly in the middle to late Pleistocene age range. This is because strata of the Camp Rice Formation (Strain, 1966) underlie the Otero Formation (Seager et al., 1987). In the Jornada del Muerto and northern Mesilla basins west of the San Andres-Organ range, the Camp Rice Formation is no younger than about 0.73 Ma (Mack et al., 1993). Mack et al. (1996) also report an age of about 2 Ma for pumice in the Camp Rice Formation about 10 m below the surface of the megafan apex in the Doña Ana Range Camp area of eastern Fillmore Pass (Fig. 1). In the southern Mesilla and northern Hueco Bolson, however, uppermost Camp Rice beds may be slightly above the Brunes/Matuyama (magneto-stratigraphic) boundary, which marks the base of the middle Pleistocene (Vanderhill, 1986; Gile et al., 1995, p. 36). If this chronology applies to the top of the Camp Rice Formation in the Tularosa Basin, then strata of the Otero Formation cannot be older than middle Pleistocene.

A precise minimum age of the Otero Formation is more difficult to determine. It is definitely older than the Carrizozo lava flows that overlie it, which are now considered to be about 5000 years old (Salyards, 1991; Dunbar, 1999). And, the upper part of the lectostratotype section contains fossils of late Pleistocene mammals (Fig. 3). Therefore, it is most likely no younger than late Pleistocene (Wisconsinan), but its precise minimum age within the late Pleistocene remains to be determined.

The possibility that at least the upper part of the Otero Formation was deposited during a single glacial-pluvial cycle (Pinedale-Tahoka: late Wisconsinan [marine oxygen-isotope-stage 2]) has been suggested (Kottlowski et al., 1965; Hawley et al., 1976; Gile et al., 1981). Recent work by Hall (2001) in the type area of the Tahoka Formation documents a middle to late Wisconsinan age (<40 ka) for the bulk of that unit; and he also demonstrates a close correlation of late Pleistocene lacustrine cycles in a region extending from the Texas High Plains to the Estancia Basin of central New Mexico (Allen and Anderson, 2000). Considering the proximity of the Estancia and Tularosa basins (about 80 km separation), synchrony of Late Pleistocene lacustrine deposition in both basins is probable. Recent dating of late Wisconsinan lacustrine features in the lower Sacramento River and Salt basins of southeastern New Mexico and Trans-Pecos Texas (pluvial Lakes Sacramento and King) also shows excellent correlation with the Estancia and Southern High Plains record (Wilkins and Currey, 1997).

A Late Wisconsinan age for much of the exposed Otero Formation is, therefore, consistent with all available chronologic and paleoclimatic information on pluvial lakes of this region. It is also quite possible, however, that the poorly exposed, lower part of the formation may be as old as Middle Pleistocene and include deposits correlative with the penultimate glacial-pluvial cycle. In the Southern Rocky Mountain to Sierra Blanca region, this cycle includes at least one major Bull Lake-glacial advance and interval of valley incision by the ancestral Rio Grande (Hawley et al., 1976; Gile et al. 1981; Richmond, 1986).

DISCUSSION

Much of what we know today about the Otero Formation was already known to C. L. Herrick (1904)—its lithotypes, general distribution and origin. We only recently discovered evidence that confirms previous suggestions that it is mostly (or entirely) of Late Pleistocene age (Morgan and Lucas, this guidebook).

The Otero Formation represents a significant event in the geologic history of the Tularosa Basin—inundation and evaporation of a large, closed, saline playa basin during the later part of the Pleistocene. A similar, smaller and probably contemporaneous lake, Lake Trinity, also developed in the northern Jornada del Muerto basin, just northwest of Lake Otero (Neal et al., 1983; Kirkpatrick and Weber, 1996). It, too, has a gypsiferous basin fill that is locally at least 30 m thick.

An important but unstudied record of climate change and possible local tectonic events is recorded in the Otero Formation. Alternating layers of gypsiferous clay and sand probably represent wet-dry cycles of climate. The gravelly bed at the type section, and thicker sand and gravel at the Alkali Spring area 3-5 km to the northeast, provide the only good record of fluvial-deltaic deposition in this general lake-floor environment. Subsurface sections near the edges of Lake Otero must preserve more complexly interbedded clastic and evaporite facies of the lake margin and lake basin. Further study, particularly of subsurface data, is needed to understand better the climatic and tectonic events that drove deposition in Lake Otero and produced its evaporitic basin fill, the Otero Formation.

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REFERENCES

Allen, B.D. and Anderson, R.Y., 2000, A continuous, high-resolution record of late Pleistocene climate variability from the Estancia basin, New Mexico: Geological Society of America Bulletin, v. 112, p.1444-1458.

Allen, M.S. and Foord, E.E., 1991, Geological, geochemical and isotopic characteristics of the Lincoln County porphyry belt, New Mexico: Implications for regional tectonics and mineral deposits: New Mexico Geological Society, Guidebook to 42nd Field Conference, p. 97-113.

Allmendinger, R. J. and Titus, F. B., 1973, Regional hydrology and evaporative discharge as present-day source of gypsum at White Sands National Monument, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 55, 26 p.

Anderson, O.J., Jones, G.E., and Green, G.N., compilers, 1997, Geologic map of New Mexico: U.S Geological Survey, Open-File Report OF-97-52, scale 1: 500,000.

Bedinger, M. S., Sargent, K. A. and Langer, W. H., eds., 1989, Studies of geology and hydrology in the Basin and Range Province, southwestern United States, for isolation of high-level radioactive waste: Characterization of the Rio Grande region, New Mexico and Texas: U.S. Geological Survey, Professional Paper 1370-C, 42 p.

Blair, T. C., Clark, J. S. and Wells, S. G., 1990, Quaternary continental stratigraphy, landscape evolution, and application to archeology: Jarilla piedmont and Tularosa graben floor, White Sands Missile Range, New Mexico: Geological Society of America Bulletin, v. 102, p. 749-759.

Doty, G.C. and Cooper, J.B., 1970, Stratigraphic test well T-14, post area, White Sands Missile Range: U.S. Geological Survey, Open-file Report, 34 p.

Dunbar, N. W., 1999, Cosmogenic ^{36}Cl-determined age of the Carrizozo lava flows, south-central New Mexico: New Mexico Geology, v. 21, p. 25-29.

Gile, L.H., Hawley, J.W. and Grossman, R.B., 1981, Soils and geomorphology in the Basin Range area of southern New Mexico—guidebook to the Desert Project: New Mexico Bureau of Mines and Mineral Resources, Memoir 39, 222 p.

Gile, L. H., Hawley, J. W., Grossman, R. B., Monger, H. C., Montoya, C. E., and Mack, G. H., 1995, Supplement to the Desert Project Guidebook, with emphasis on soil micromorphology: New Mexico Bureau of Mines and Mineral Resources, Bulletin 142, 96 p.

Gustavson, T. C., 1991, Arid basin depositional systems and paleosols: Fort Hancock and Camp Rice Formations (Pliocene-Pleistocene) Hueco Bolson, West Texas and adjacent Mexico: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations No. 198, 49 p.

Hall, S.A., 2001, Geochronology and paleoenvironments of the glacial-age Tahoka Formation, Texas and New Mexico High Plains: New Mexico Geology, v. 23, p. 71-77.

Harris, A. H., 1997, Geographic and chronologic patterns in Late Pleistocene vertebrate faunas, southern New Mexico: New Mexico Museum of Natural History and Science, Bulletin 11, p. 129-134.

Hawley, J. W., 1975, Quaternary history of Doña Ana County region, south-central New Mexico: New Mexico Geological Society, Guidebook 26, p. 139-150.

Hawley, J.W., 1983, Quaternary geology of the Rhodes Canyon (RATSCAT) Site; *in* Eidenbach, P. L., ed., The prehistory of Rhodes Canyon, New Mexico: Tularosa, Human Systems Research, Inc., p. 17-32.

Hawley, J.W., 1986, Physiographic provinces [and] landforms of New Mexico; *in* Williams, J. L., ed., New Mexico in maps (2nd edition). Albuquerque, The University of New Mexico Press, p. 23-31.

Hawley, J.W., 1993, Geomorphic setting and late Quaternary history of pluvial-lake basins in the southern New Mexico region: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 391, 28 p.

Hawley, J. W. and Kottlowski, F. E., 1969, Quaternary geology of south-central New Mexico border region: New Mexico Bureau of Mines and Mineral Resources, Circular 104, p. 89-115.

Hawley, J.W., Bachman, G.O. and Manley, K., 1976, Quaternary stratigraphy in the Basin and Range and Great Plains provinces, New Mexico and western Texas; *in* Mahaney, W.C., ed., Quaternary stratigraphy of North America: Stroudsburg, Dowden, Hutchinson, and Ross, Inc., p. 235-274.

Hawley, J.W., Kottlowski, F.E., Seager, W.R., King, W.E., Strain, W.S. and LeMone, D.V., 1969, The Santa Fe Group in the south-central New Mexico border region: New Mexico Bureau of Mines and Mineral Resources, Circular 104, p. 52-76.

Herrick, C. L., 1900, The geology of the White Sands of New Mexico: Journal of Geology, v. 8, p. 112-128.

Herrick, C. L., 1904, Lake Otero, an ancient salt lake in southeastern New Mexico: The American Geologist, v. 34, p. 174-189.

Herrick, H. N., 1904, Gypsum deposits in New Mexico: U.S. Geological Survey, Bulletin 223, p. 89-99.

Hood, J.W., 1959, Ground water in the Tularosa Basin, New Mexico; *in* Pray, L. C. et al., eds., Guidebook for joint field conference in the Sacramento Mountains of Otero County, New Mexico: Midland and Roswell, Permian Basin Section SEPM and Roswell Geological Society, p. 236-250.

Jicha, H. L., Jr., 1959, The White Sands—a short review; *in* Pray, L. C. et al., eds., Guidebook for joint field conference in the Sacramento Mountains of Otero County, New Mexico: Midland and Roswell, Permian Basin Section SEPM and Roswell Geological Society, p. 285-291.

Johnson, W. D. Jr., Hawley, J. W., Stone, W. J., Kottlowski, F. E., Henry, C. D. and Price, J.G., 1989, Geology, *in* Studies of geology and hydrology in the Basin and Range Province, southwestern United States, for isolation of high-level radioactive waste; characterization of the Rio Grande region, New Mexico and Texas: U.S. Geological Survey, Professional Paper 1370-C, p. C7-C19.

King, W. E. and Harder, V. M., 1985, Oil and gas potential of the Tularosa basin—Otero platform—Salt basin graben area, New Mexico and Texas: New Mexico Bureau of Mines and Mineral Resources, Circular 198, 36 p.

Kirkpatrick, D. T. and Weber, R. H., 1996, Quaternary geology and archaeology of Lake Trinity basin, White Sands Missile Range, New Mexico: The Archaeological Society of New Mexico, Bulletin 22, p. 109-127.

Kottlowski, F. E., 1958, Lake Otero-second phase formation of New Mexico's gypsum dunes: Geological Society of America Bulletin, v. 33, p. 541-552.

Kottlowski, F. E., Cooley, M. E. and Ruhe, R. V., 1965, Quaternary geology of the Southwest; *in* Wright, H. E., Jr. and Frey, D. G., eds., The Quaternary of the United States: Princeton, Princeton University Press, p. 287-298.

Lozinsky, R. P. and Bauer, P. W., 1991, Structure and basin-fill units of the Tularosa Basin: New Mexico Geological Society, Guidebook 42, p. 7-8.

Mack, G.H., Love, D.W. and Seager, W.R., 1997, Spillover models for axial rivers in regions of continental extension: The Rio Mimbres and Rio Grande in the southern Rio Grande rift, USA: Sedimentology, v. 44, p.637-652.

Mack, G. H., Salyards, S. L. and James, W. C., 1993, Magnetostratigraphy of the Plio-Pleistocene Camp Rice and Palomas formations in the Rio Grande rift of southern New Mexico: American Journal of Science, v. 293, p. 49-77.

Mack, G.H., McIntosh, W.C., Leeder, M.R., and Monger, H.C., 1996, Plio-Pleistocene pumice floods in the ancestral Rio Grande, southern Rio Grande rift, USA: Sedimentary Geology, v. 103, p. 1-8.

McKee, E.D., and Moiola, R.J., 1975, Geometry and growth of the White Sands dune field, New Mexico: U.S. Geological Survey, Journal of Research, v. 3, p. 59-66.

McLean, J.S., 1975, Saline ground water of the Tularosa Basin, New Mexico: New Mexico Geological Society, Guidebook 26, p. 237-238.

Meinzer, O. E., 1922, Map of the Pleistocene lakes of the Basin and Range Province and its significance: Geological Society of America Bulletin, v. 33, p. 541-552.

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., 1981, Coevolution of deserts and pupfishes (Genus *Cyprinodon*) in the American Southwest; *in* Naiman, R. J. and Soltz, D. L., eds., Fishes in North American deserts: New York, John Wiley and Sons, p. 39-94.

Neal, J. T., Smith, R. E. and Jones, B. F., 1983, Pleistocene Lake Trinity, an evaporite basin in the northern Jornada del Muerto, New Mexico: New Mexico Geological Society, Guidebook 34, p. 285-290.

Orr, B. R. and Myers, R. G., 1986, Water resources in basin-fill deposits in the Tularosa Basin, New Mexico: U. S. Geological Survey, Water Resources Investigations Report 85-4219, 94 p.

Richmond, G. M., 1986, Stratigraphy and correlation of glacial deposits of the Rocky Mountains, the Colorado Plateau, and the ranges of the Great Basin; *in* Sibrava, V., Bowen, D. Q. and Richmond, G. M., eds., Quaternary glaciation in the northern hemisphere: New York, Pergamon Press, p. 99-127.

Salvador, A., ed., 1994, International stratigraphic guide. Trondheim and Boulder, International Union of Geological Sciences and Geological Society of America, 214 p.

Salyards, S. L., 1991, A possible mid-Holocene age of the Carrizozo Malpais from paleomagnetics using secular variation magnetostratigraphy: New Mexico Geological Society, Guidebook to 42nd Field Conference, p. 153-157.

Schmidt, P. G. and Craddock, C., 1964, The geology of the Jarilla Mountains, Otero County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 82, 55 p.

Seager, W.R., 1981, Geology of Organ Mountains and southern San Andres Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 36, 97 p.

Seager, W.R., Hawley, J.W., Kottlowski, F.E., and Kelley, S.A., 1987, Geology of the east half of the Las Cruces and northeast El Paso 1 degree x 2 degree sheets, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 57, scale 1:125,000, 5 sheets.

Seager, W. R., Shafiqullah, M., Hawley, J. W. and Marvin, R. F., 1984, New K-Ar dates from basalts and the evolution of the southern Rio Grande rift: Geological Society of America Bulletin, v. 95, p. 87-99.

Smith, M. L. and Miller, R. R., 1986, The evolution of the Rio Grande Basin as inferred from its fish fauna; *in* Hocutt, C. H. and Wiley, E. O., eds., Zoogeography of North American freshwater fishes: New York, John Wiley and Sons, p. 457-485.

Strain, W. S., 1966, Blancan mammalian fauna and Pleistocene formations, Hudspeth County, Texas: Texas Memorial Museum, Bulletin 10, 55 p.

Strain, W. S., 1971, Late Cenozoic bolson integration in the Chihuahua tectonic

belt: West Texas Geological Society, Publication No. 71-59, p. 167-173.
Talmage, S.B., 1932, Origin of the gypsum sands of Tularosa Valley: Geological Society of America Bulletin, v. 43, p. 185-186.
Talmage, S. B., 1933, Source and growth of the white sands of New Mexico: Pan-American Geologist, v. 60, p. 304.
Vanderhill, J. B., 1986, Lithostratigraphy, vertebrate paleontology, and magnetostratigraphy of Plio-Pleistocene sediments in the Mesilla Basin, New Mexico [Ph. D. dissertation]: Austin, The University of Texas, 311 p.
Van Devender, T. R. and Toolin, L. J., 1983, Late Quaternary vegetation of the San Andres Mountains, Sierra County, New Mexico; *in* Eidenbach, P. L., ed., The prehistory of Rhodes Canyon, New Mexico: Tularosa, Human Systems Research, Inc., p. 33-54.
Van Devender, T. R., Betancourt, J. L. and Wimberly, M., 1984, Biogeographic implications of a packrat midden sequence from the Sacramento Mountains, south-central New Mexico: Quaternary Research, v. 22, p. 344-360.
Vandiver, V.W., 1936, White Sands geological report; *in* Southwestern monuments, supplement for May, 1936: Coolidge, Arizona, U.S. National Park Service, p. 379-400.
Weber, R. H. and Kottlowski, F. E., 1959, Gypsum resources of New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 68, 68 p.
Wilkens, D.E., and Currey, D.R., 1997, Timing and extent of Late Quaternary paleolakes in the Trans-Pecos closed basin, west Texas and south-central New Mexico: Quaternary Research, v. 47, p. 306-315.
Williams, T. R. and Bedinger, M. S., 1984, Selected geologic and hydrologic characteristics of the Basin and Range province, western United States—Pleistocene lakes and marshes: U.S. Geological Survey Miscellaneous Investigations, Series Map I-1522-D, scale 1:2,500,000.
Zohdy, A.A.R., 1969, Geophysical survey for ground water at White Sands Missile Range, New Mexico: U.S. Geological Survey open-file report, 144 p.

APPENDIX

Lectostratotype section of the Otero Formation. Strata are flat lying. Section base at UTM 13, 358703E, 3655295N and top at 13, 358742E, 3655392N, NAD 27.

Gypsum sand:

13. Gypsum sand; grayish orange pink (5 YR 7/2), very fine to fine grained; calcareous; friable; base is sharp, truncated surface. **10.1**

Otero Formation:

12. Gypsiferous clay; light olive gray (5 Y 5/2); some red mottles; calcareous; contains gastropods (NMMNH locality 4985). **0.7**
11. Gravelly sand; pale yellowish brown (10 YR 6/2) and medium light gray (N6); medium to very coarse grained; volcanic litharenite; trough crossbedded; fossil mammals (NMMNH locality 4982). **0.8**
10. Gypsiferous clay; variegated same colors as units 6 and 8. **2.0**
9. Gypsiferous clay; very pale orange (10 YR 8/2); very calcareous; a few sand grains. **0.6**
8. Gypsiferous sandy clay; yellowish gray (5 Y 7/2); very calcareous. **1.2**
7. Gypsiferous sandy clay; dusky yellow (5 Y 6/4); very calcareous. **0.8**
6. Gypsiferous clay; pale reddish brown (10 R 5/4); calcareous; contains gastropods (NMMNH locality 4984). **1.4**
5. Gypsiferous sandy clay; same color and lithology as unit 8. **0.6**
4. Gypsiferous clay; same color and lithology as unit 6; numerous large selenite crystals. **1.1**
3. Gypsiferous sandy clay; dusky yellow (5 Y 6/4); calcareous. **0.3**
2. Gypsiferous clay; same color and lithology as unit 6. **0.2**
1. Gypsiferous sandy clay; same color and lithology as unit 8; contains fossil mammals (NMMNH locality 4983); base not exposed. **0.5+**

The edge of the gypsum sand dunes as it migrates toward the east on the White Sands National Monument. In the heart of the dunes, the sand dunes are moving approximately ~10 feet (~3 meters) per year. Dunes near Lake Lucero move at a rate of over ~30 feet (~10 meters) per year. The Sacramento escarpment is in the background. Photograph by Virgil Lueth.