

Age and effects of the Odessa meteorite impact, western Texas, USA

Vance T. Holliday* Department of Anthropology and Department of Geosciences, University of Arizona, Tucson, Arizona 85721, USA

David A. Kring Lunar and Planetary Sciences and Department of Geosciences, University of Arizona, Tucson, Arizona 85721, USA

James H. Mayer Department of Geosciences, University of Arizona, Tucson, Arizona 85721, USA

Ronald J. Goble Department of Geosciences, University of Nebraska, Lincoln, Nebraska 68588, USA

ABSTRACT

The Odessa meteorite craters (Texas, United States) include a main crater (~160 m diameter, ~30 m deep) plus four smaller meteorite craters. The main crater was sampled by coring (to 22 m depth) to better understand its origin and history. Dating by optically stimulated luminescence indicates that it was produced immediately prior to ca. 63.5 ± 4.5 ka. Sediment filling the crater includes impact breccias produced at the time of impact; wind-dominated silts with minor amounts of pond sediments deposited ca. 63.5 ka, probably just after the impact, and ca. 53 ± 2 ka; wind-dominated silt ca. 38 ± 1.7 ka; and playa muds with a wind-blown silt component younger than 36 ka. The environment was arid or semiarid at the time of impact based on characteristics of soils on the surrounding landscape. The impact caused severe damage within 2 km and produced >1000 km/hr winds and thermal pulse. Animals within a 1–1.5-km-diameter area were probably killed. This is only the second well-dated Pleistocene hypervelocity impact crater in North America.

Keywords: Odessa, meteorite, impact, southern High Plains.

INTRODUCTION

The Odessa meteorite craters (southern Great Plains, western Texas, United States; 31°E 45'N, 102°E 29'W) compose an impact site known since the late 1920s (Sellards, 1927; Barringer, 1929). Over the ensuing decades, the main crater, four smaller surrounding craters, and thousands of iron meteorites have been subjected to a variety of investigations. Our investigations from 2001 to 2004 include three components. The primary goal was to estimate the age of the craters by dating the fill contained within the main crater. Determining the age of this impact will aid in establishing the chronology and recurrence interval of crater formation on the Earth's surface. Because small impacts like Odessa are the most common cratering events, their frequency is important in assessing hazards posed to human populations. Another goal was to calculate the environmental effects of the impact. A third and related goal was to investigate the history of filling in the crater to provide clues to the regional postimpact environmental evolution.

The craters are near the southwest margin of the southern High Plains, a broad level plateau bounded to the west by the Pecos River Valley. In the Odessa area the bedrock is limestone and shale of the Fredericksburg Group, underlain by sandstone and shale of the Ant-

lers Formation (both Lower Cretaceous and representing the northwestern extent of Cretaceous units composing the Edwards Plateau) (Eifler, 1976; Evans and Mear, 2000). On top is the Blackwater Draw Formation, the principal surficial deposit of the southern High Plains, including the Odessa area. The Blackwater Draw Formation is composed of layers of Pleistocene eolian sediments heavily altered by pedogenesis, and includes the regional surface soil (Reeves, 1976; Holliday, 1989). All of these Mesozoic and Cenozoic units are exposed along the High Plains escarpment 5 km to the southwest.

The craters were subjected to intensive field study from 1939 to 1941, and from 1958 to 1960 (Sellards and Evans, 1941; Evans, 1961; Evans and Mear, 2000). This work included surface and subsurface mapping, trenching and coring of the main crater and one of the smaller craters, and excavation of a shaft through the crater fill and into the underlying bedrock (Evans and Mear, 2000). Our study focused on the stratigraphy of the main crater, as little information is available for the other four craters.

A topographic high of upturned limestone of the Fredericksburg Group defines a structure 152–183 m in diameter. Erosion was not severe and probably did not enlarge the structure by more than 30 m because the rim is still uplifted relative to the preimpact surface

and is still covered with ejecta that extends onto the surrounding plain. The depth above the bedrock floor to the preimpact surface is 26 m and the depth to the crater rim is 30 m. The crater contains ~27 m of postimpact debris. Through the center of the basin, the fill includes a basal zone (zone 1 of Evans and Mear, 2000) at ~27–24 m consisting of “ejecta fall-back material” (Evans and Mear, 2000, p. 26); an overlying zone (part of zone 2 of Evans and Mear, 2000) at ~24–20 m with interbedded gravel, silt, and clay; and, from 20 m depth to the surface, sand, silt, clay, mud, and some lenses of limestone pebbles (all comprising upper zone 2 and zone 3 of Evans and Mear, 2000). Vertebrate fossils were collected from zone 3 (Fig. 1). Other deposits associated with the impact include ejecta on the uplands around the crater. The ejecta deposit is >1 m thick immediately adjacent to the crater and thins to nothing away from the crater. The ejecta buries the Blackwater Draw Formation, which locally is ~1 m thick and is characterized by a distinct Bt/Bk soil profile.

Our research included field examination of exposures on the crater rim, coring of the crater fill, and sampling of the cores for physical characterization and dating of the deposits. Field and laboratory methods are discussed in Appendix 1 (GSA Data Repository¹) and the results are presented in Tables DR1–DR4 in the Data Repository. A summary of dating results is presented in Table 1.

CRATER STRATIGRAPHY

The fill exposed in the cores includes (from bottom to top): pink shale, yellow calcareous silt, and dark gray mud (Tables DR1, DR2 [see footnote 1]; Fig. 1). The pink shale (lowest zone 2 of Evans and Mear, 2000) was encountered at 21.7–20.7 m. It probably represents fragments of shales from the Fredericksburg Group that were deposited as a breccia.

¹GSA Data Repository item 2005185, Appendix 1 and Tables DR1–DR6, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

*E-mail: vhollid@email.arizona.edu.

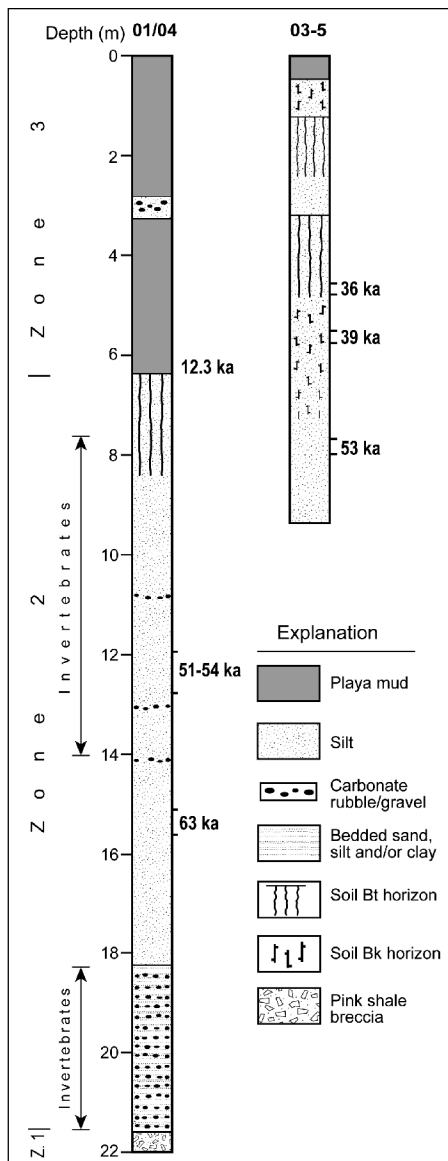


Figure 1. Stratigraphy of fill in main crater of Odessa meteorite craters. 01/04 is composite stratigraphic record of two cores. Previous investigations show that breccia (zone 1) extends to ~27 m depth.

cia (ejecta fall-back) within the crater immediately after the impact. The yellow calcareous silt (zone 2) represents the bulk of the fill observed in cores. The zone is largely a mix of calcareous silt and clay with common secondary carbonate (Tables DR1, DR2). Coarse carbonate clastics with manganese coatings were encountered throughout the zone from 20.7 to 18.75 m, considered equivalent to bedded gravel and silt noted by Evans and Mear (2000, p. 27) in the shaft excavations. From ~6.40 m to 18.75 m below the surface the silt is unstratified except for a few lenses of carbonate rock rubble (Fig. 1). Above ~10 m depth, the silt was heavily altered by pedogenesis (Table DR1). In cores 01/04 the soil is >3 m thick and consists of

TABLE 1. LUMINESCENCE AND RADIOCARBON AGES FROM THE MAIN ODESSA METEORITE CRATER

Lab Number	Depth, m	Age, ka (\bar{A} one sigma)
<i>¹⁴C Ages</i>		
AA44167	6.3	12.28 \pm 1.26
<i>OSL Ages</i>		
UNL714	4.7	36.33 \pm 2.28
UNL715	5.6	39.86 \pm 2.57
UNL716	7.9	53.15 \pm 3.40
UNL957	12.3	53.74 \pm 3.43
UNL958	12.5	50.89 \pm 3.33
UNL959	15.8	63.46 \pm 4.45
UNL960	15.9	51.30 \pm 6.47
UNL960		58.37 \pm 5.28*

Note: Reliable ages only; see Tables DR3 and DR4 (see footnote 1) for geochemical details on all reliable and unreliable age estimates. OSL—optically stimulated luminescence.

*Recalculated age after removal of two low D_e values (see Table DR3).

a deep reddish-brown Btk/Bw profile. The soil is buried beneath ~6.4 m of the gray mud. In core 03-5, the silt was encountered within 1 m of the surface. From that depth to ~10 m, three soils were encountered, welded together forming a pedocomplex of Bt, Btk, and Bk horizons (Table DR1).

Evans and Mear (2000, p. 27) noted that “pond snails and bivalves were collected from 64 to 75 feet [19.5–22.9 m]” in the zone of bedded gravel, silt, and clay in lower zone 2 (Fig. 1). Aquatic snails are also reported from the interval 25–48 ft (7.6–14.6 m) in zone 2 (Evans and Mear, 2000, p. 27) (Fig. 1), though quantities and specific sample intervals are unknown. They interpreted zone 2 above the coarse breccia as lacustrine, owing to the presence of pond (aquatic) invertebrate fossils. The crater undoubtedly held water at times because it was a large, deep basin. Above the zone of manganiferous bedded silt and clay, however, we saw no obvious lacustrine or pond deposits, such as marl, diatomaceous earth, bedded clays, or organic-rich mud, which characterize late Quaternary lake, pond, and playa deposits of the region today (Reeves, 1976; Gustavson et al., 1991; Holliday, 1995), nor did we see other indicators of standing or fluctuating water such as redoximorphic features. Rather, this section is dominated by yellow-brown silt. The physical properties of the yellow silt are very similar to those of loess (pale yellow-brown, silty, calcareous, and massive). Loess is very rare in the region, however, and unknown as a regional deposit (e.g., Holliday et al., 1994). One source could be dust formed when the meteoroid pulverized the Cretaceous limestone. Such material must have blanketed the landscape after the impact. Occasional remobilization by wind and deposition in the crater would be likely. The carbonate rock rubble in the silt was derived from the limestone form-

ing the rim of the crater. The contacts between rubble lenses and underlying silt are very abrupt, suggestive of erosion (by wind) followed by deposition of the rubble, then resumption of silt sedimentation. A related silt source could be the same Cretaceous limestone and shale units exposed along the High Plains, 5 km to the west and southwest (i.e., upwind).

Dark gray mud (zone 3 of Evans and Mear, 2000) overlying on the silt is ~6.4 m thick in cores 01/04, but <1 m thick in core 03-5 (Fig. 1). The mud is blocky and unstratified except in the thicker section, where several lenses of sand and gravel were observed (Fig. 1). Evans and Mear (2000, p. 27) considered zone 3 to be of eolian and colluvial origin. The gray mud (especially below 3.6 m) is physically identical to muds deposited in the many small playa basins that dot the Great Plains landscape around and north of Odessa (i.e., medium to dark gray or gray brown, high in silt and clay, and blocky) (Holliday et al., 1996). In the playas the mud represents accumulation of eolian fines trapped on the floor of moist, heavily vegetated basins (Gustavson et al., 1995). Such sediment is likely and expected on the floor of a depression such as the impact crater. The zone 3 fines likewise were probably blown in, settling on a moist basin floor. The bedded sand and gravel clearly were washed in. Our coring data, plus exposures in the shaft excavations (Evans and Mear, 2000, Fig. 29), indicate that the mud fills a depression located in the northwest quadrant of the crater floor.

AGE OF THE IMPACT AND CRATER FILL

Previous investigators recovered remains of an “elephant tooth” and *Equus* between 6 and 3 m below the surface (Evans and Mear, 2000, p. 28, 38), indicating that the upper fill was late Pleistocene in age (Evans, 1961, p. D-6). Cosmogenic carbon extracted from meteorite fragments was dated to ca. 11,000 ka or older (Goel and Kohman, 1962) and cosmogenic ³⁶Cl/¹⁰Be provided an upper age limit of 100 ka (Chang and Wänke, 1969). Both dating methods were in their infancy, however, and the resulting ages are difficult to evaluate. Age estimates of 50 ka and younger were published (e.g., Grieve et al., 1995), based partly on a date of 49 \pm 3 ka for the Barringer Meteorite Crater (also known as Meteor Crater) in Arizona (Sutton, 1985). Barringer (1967) proposed that both the Barringer and Odessa impact sites were produced by the same event, which is consistent with similarities between the meteoroids that produced the craters (both are Group IAB irons).

Our new age control for sediment in the

main Odessa crater indicates that it filled episodically. Optical ages on the yellow silt fall into three groups: 36–40 ka (UNL714–715) from within the pedocomplex identified in upper core 03–5, overlapping at 1σ (average [ave.] 37.88 ± 1.71 ka); 51–54 ka (UNL716, UNL957–958) also overlapping at 1σ (ave. 52.56 ± 1.95 ka); and 63.46 ± 4.45 ka (UNL959) (Table 1; Table DR3 [see footnote 1]). The optical age for UNL960 is in the 51–54 ka group, but is not considered reliable because of the small number of aliquots and large scatter in the determined equivalent doses (DE) (Table DR3); only a limited quantity of dateable material was recovered, and it is strongly affected by two aliquots with anomalously low DE values. There is no statistical reason for discarding these values, but they are well outside the distribution for this and the other samples. Omitting them increases the calculated age for UNL960 to ca. 58 ± 5 ka (Table 1; Table DR3), within the calculated 1σ error of UNL959.

Among the radiocarbon ages from the gray mud, we consider only AA44167 as a reliable age estimate, providing a calibrated age of ca. 12.28 ka (Table 1; Table DR4 [see footnote 1]). The $\delta^{13}\text{C}$ values indicate that the upper three radiocarbon ages are problematic (Table DR4). Even if the majority of soil organic matter was derived from a pure C4 biomass, values no greater than $\sim -10\%$ are expected (Cerling and Quade, 1993). Measured values between -6.1% and -5.3% from the gray mud likely indicate the persistence of detrital carbonate in the upper three samples after pretreatment, thus explaining the age reversal between AA44166 and AA44167.

IMPACT AND POSTIMPACT ENVIRONMENTS

The environment of the southern Great Plains at the time of the Odessa impact is poorly known, but a few clues are available. Spring tufas dated as 75–55 ka suggest conditions somewhat wetter than today (Rich et al., 2003), but still semiarid based on the presence of secondary calcium carbonate in soils of the upper Blackwater Draw Formation, including the buried section at the crater. The fauna at 35 ka included grassland species such as *Mammuthus columbi*, *Equus* sp., *Camelops hesternus*, and *Bison* sp. (Holliday and Johnson, 2005; see also Dalquest and Schultz, 1992, p. 75–79). The Odessa area was probably an open, semiarid grassland, not significantly different from the modern environment, though perhaps cooler with higher effective precipitation (Holliday, 1991).

This environment was disturbed when the Odessa impact crater field was produced by an iron meteoroid that fragmented as it

punched its way through the atmosphere. The fragment that produced the main crater was estimated to be ~ 4 m diameter and to weigh 315 (Baldwin, 1963). The pattern of craters in the field suggests an impact inclination of 35° – 55° (if fragmentation occurred at an altitude >50 km) or 10° – 20° (if fragmentation occurred at an altitude <5 km) (Passey and Melosh, 1980). The lack of any strong asymmetries in the ejecta blanket of the main crater suggests that the higher inclinations are more likely than the lower ones. Orbital dynamics also indicate that the most probable inclination of any impact event is 45° (Shoemaker, 1962). Using these inclinations and typical impact velocities of 11.2–17 km/s, we derive a diameter of 1.6–4.0 m using pi-scaling techniques (Schmidt and Housen, 1987). Small meteoroids can be significantly decelerated in the atmosphere, which is consistent with an unusually low depth/diameter value for the main crater (0.16 rather than 0.27 for an ~ 160 m crater; e.g., Grieve and Theriault, 2004). A ground-impacting velocity of 7 km/s, however, still implies a 3–4 m projectile. These values correspond to explosive energies equivalent to 0.5–5 kt of TNT (Table DR5; see footnote 1), although alternative older scaling methods based on nuclear explosions (Nordyke, 1977) suggest energy values as high as 50–100 kt. Because the meteoroid was fragmenting and decelerating, the object may have hit the top of the atmosphere with an order of magnitude more energy than that released on impact (e.g., Bland and Artemieva, 2003).

The environmental effects were limited to the vicinity of the impact and dominated by a shock wave, air blast, possibly thermal radiation, and burial beneath ejecta (Kring, 1997). Conservative energy estimates suggest that the cratering event generated peak overpressures of 100 psi (690 kPa) and wind velocities of nearly 2300 km/hr from the crater rim (0.5 kt) to 180 m (5 kt) from the point of impact (Table DR5; see footnote 1). Peak overpressures and wind velocities decreased with distance, declining to 1 psi (6.9 kPa) and 60 km/hr at 930 m (0.5 kt) to 2000 m (5 kt). Any trees or shrubs within several hundred meters of the impact would have been destroyed or damaged (Table DR5). Fatalities among animals living in the area were concentrated within ~ 600 m, although animals farther away could still have been seriously injured. A ballistic shock wave along the trajectory of the impacting asteroid extended the zone affected by 50%–100% to the NNW of the craters, based on the distribution of surviving meteorite fragments.

Models of impact-generated fireballs, scaled to the Tunguska impact event (Toon et al., 1997), suggest that fires may have been ignited

over an area of 0.17 km^2 (a radial distance of 220 m) for a 0.5 kt impact or an area of 0.73 km^2 (a radial distance of 480 m) for a 5 kt impact. A low abundance of impact melt at the crater (Smith and Hodge, 1997) indicates that the volume of severely shocked material was small, which is consistent with a short radial range of fireball damage. The seismic magnitude of the impact was 2.4–3.1 (for 0.5–5 kt, using a corrected form of scaling equation of Melosh, 1989).

Astronomical estimates of impact events with the energy of Odessa suggest that they occur once per 1–10 yr (e.g., Chapman, 2004), yet Odessa is only the ninth well-dated small impact crater produced during the past 100 k.y. (Table DR6; see footnote 1) and only the second well-dated Pleistocene impact crater in North America (after Barringer), or the third example if one includes the Haviland impact pit (Table DR6). Even accounting for the impacts that occur at sea, there is a large discrepancy between the geologic record of recognized craters and astronomical estimates of the impact flux. This probably reflects poor preservation and/or recognition of small impact craters. It also reflects the ability of the atmosphere to prevent small impacting asteroids from reaching the surface with energy sufficient for cratering. The Gold Basin meteoroid, for example, catastrophically fragmented in the atmosphere (Kring et al., 2001), as would other stony and even some iron meteoroids with the energy of the Odessa event (Bland and Artemieva, 2003).

Immediately following the Odessa impact, after the coarse breccia settled in the crater, lenses of gravel, sand, silt, and clay (lowermost zone 2) were washed in. The floor of the crater held some standing water at that time, based on invertebrate fauna. The stratified deposits were buried by massive yellow silts ca. 63 ka, derived from the pulverized limestone that must have surrounded the crater. This deposition was just after the stratified sediments were laid down, based on the absence of weathering in the stratified material. Thus, the crater probably formed ca. 63 ka, indicating that it was not produced by the same impact that generated Barringer Meteorite Crater. The landscape then stabilized as vegetation recovered from the impact. Secondary carbonate in the lower yellow silt is indicative of subaerial weathering under relatively dry, well-drained conditions, but no obvious soil horizons were identified in the lower silts. Several discontinuities suggest, however, that the basin fill was eroded; the most likely mechanism in a small closed basin is wind erosion. Another phase of silty eolian sedimentation took place ca. 51–54 ka, but the deposits have a higher sand content. This suggests wind deflation of

the regional sandy soils (i.e., the surface of the Blackwater Draw Formation) as well as deflation of the ejecta in proximity to the crater. The floor of the crater stabilized after ca. 51–54 ka, as indicated by the thick Btk soil in cores 01/04. Localized episodic silt and sand deposition continued in some areas of the crater during and after ca. 36–39 ka, shown by the multiple buried soils in core 03–5. These periods of eolian activity ca. 53 ka to before 36 ka broadly correlate with phases of loess deposition and sand deposition (in lunettes) elsewhere on the Great Plains (Holliday, 1997; Busacca et al., 2004), though a direct relationship cannot be shown. Eolian sedimentation in the crater, particularly the increase in sand content, also implies regional aridity. Drying, and resulting reduction of the vegetation cover, is an effective and common mechanism for wind erosion and remobilization of eolian deposits throughout the region (Holliday, 1987, 2001).

ACKNOWLEDGMENTS

This work was carried out with support from the National Science Foundation (NSF) ESH grant 9807347 to Holliday and an Integrative Graduate Education and Research Traineeship fellowship to Mayer, the University of Arizona (UA) NSF–Accelerator Mass Spectrometry facility (for radiocarbon dating), funds from the Graduate School of the UA (to Holliday), and funds donated by Tom and Nancy Rodman of Odessa. Tom Rodman has long championed the preservation and interpretation of the craters and supplied all manner of logistical support and enthusiasm for our work; we thank both of the Rodmans and the many other citizens of Odessa for their gracious hospitality. The manuscript benefited from reviews by B. Bottke, G. Collins, and C. Koeberl. This paper is dedicated to Glen L. Evans for his considerable research efforts at the Odessa Meteorite Craters.

REFERENCES CITED

Baldwin, R.B., 1963, *The measure of the Moon*: Chicago, University of Chicago Press, 488 p.
 Barringer, B., 1967, Historical notes on the Odessa Meteorite Crater: *Meteoritics*, v. 3, p. 161–168.
 Barringer, D.M., Jr., 1929, A small meteor crater in Texas: *Engineering and Mining Journal Press*, v. 121, p. 932.
 Bland, P.A., and Artemieva, N.A., 2003, Efficient disruption of small asteroids by Earth's atmosphere: *Nature*, v. 424, p. 288–291.
 Busacca, A., Begét, J.E., Markewich, H.W., Muhs, D.R., Lancaster, N., and Sweeney, M.R., 2004, Eolian sediments, in Gillespie, A.R., et al., eds., *The Quaternary Period in the United States*: New York, Elsevier Press, p. 275–310.
 Cerling, T.E., and Quade, J., 1993, Stable carbon and oxygen isotopes in soil carbonates, in Swart, P.K., et al., eds., *Climate change in continental isotopic records*: Washington, D.C., American Geophysical Union, p. 217–231.
 Chang, C., and Wänke, H., 1969, Beryllium-10 in iron meteorites, their cosmic-ray exposure and terrestrial ages, in Millman, P.M., ed., *Meteorite research*: Dordrecht, The Netherlands, D. Reidel, p. 397–406.
 Chapman, C.R., 2004, The hazard of near-Earth as-

teroid impacts on Earth: *Earth and Planetary Science Letters*, vol. 222, p. 1–15.
 Dalquest, W.W., and Schultz, G.E., 1992, *Ice Age mammals of northwestern Texas*: Wichita Falls, Texas, Midwestern State University Press, 309 p.
 Eifler, G.K., 1976, *Geologic atlas of Texas*, Pecos sheet, Austin, University of Texas, Bureau of Economic Geology, scale 1:250,000.
 Evans, G.L., 1961, Investigations at the Odessa meteor craters, in Nordyke, M.D., ed., *Proceedings of the Geophysical Laboratory/Lawrence Radiation Laboratory Cratering Symposium*: Washington, D.C., p. D1–D11.
 Evans, G.L., and Mear, C.E., 2000, The Odessa meteor craters and their geological implications: Waco, Texas, Baylor University, *Occasional Papers of the Strecker Museum* 5, 50 p.
 Goel, P.S., and Kohman, T.P., 1962, Cosmogenic carbon-14 in meteorites and terrestrial ages of “finds” and craters: *Science*, v. 136, p. 875–876.
 Grieve, R.A.F., and Theriault, A.M., 2004, Observations at terrestrial impact structures: Their utility in constraining crater formation: *Meteoritics and Planetary Science*, v. 39, p. 199–216.
 Grieve, R., Rupert, J., Smith, J., and Theriault, A., 1995, The record of terrestrial impact cratering: *GSA Today*, v. 5, p. 189, 194–196.
 Gustavson, T.C., Baumgardner, R.W., Jr., Caran, S.C., Holliday, V.T., Mehnert, H.H., O'Neill, J.M., and Reeves, C.C., Jr., 1991, Quaternary geology of the southern Great Plains and an adjacent segment of the Rolling Plains, in Morrison, R.B., ed., *Quaternary nonglacial geology: Conterminous U.S.*: Boulder, Colorado, *Geology of North America*, v. K-2, p. 477–501.
 Gustavson, T.C., Holliday, V.T., and Hovorka, S.D., 1995, Origin and development of playa basins, sources of recharge to the Ogallala Aquifer, Southern High Plains, Texas and New Mexico: Austin, University of Texas, Bureau of Economic Geology, *Report of Investigations* 229, 44 p.
 Holliday, V.T., 1987, Eolian processes and sediments of the Great Plains, in Graf, W., ed., *Geomorphic systems of North America*: Boulder, Colorado, *Geological Society of America, Centennial Special Volume 2*, p. 195–202.
 Holliday, V.T., 1989, The Blackwater Draw Formation (Quaternary): A 1.4-plus m.y. record of eolian sedimentation and soil formation on the southern High Plains: *Geological Society of America Bulletin*, v. 101, p. 1598–1607.
 Holliday, V.T., 1991, The geologic record of wind erosion, eolian deposition, and aridity on the Southern High Plains: *Great Plains Research*, v. 1, p. 6–25.
 Holliday, V.T., 1995, Stratigraphy and paleoenvironments of late Quaternary valley fills on the southern High Plains: *Geological Society of America Memoir* 186, 136 p.
 Holliday, V.T., 1997, Origin and evolution of lunettes on the High Plains of Texas and Mexico: *Quaternary Research*, v. 47, p. 54–69.
 Holliday, V.T., 2001, Stratigraphy and geochronology of upper Quaternary eolian sand on the southern High Plains of Texas and New Mexico, United States: *Geological Society of America Bulletin*, v. 113, p. 88–108.
 Holliday, V.T., and Johnson, E., 2005, Paleoenvironments of the Llano Estacado, in Lee, J., *The Llano Estacado*: Lubbock, Texas Tech University Press (in press).

Holliday, V.T., Haynes, C.V., Jr., Hofman, J.L., and Meltzer, D.J., 1994, Geoarchaeology and geochronology of the Miami (Clovis) site, Southern High Plains of Texas: *Quaternary Research*, v. 41, p. 234–244.
 Holliday, V.T., Hovorka, S.D., and Gustavson, T.C., 1996, Lithostratigraphy and geochronology of fills in small playa basins on the southern High Plains, United States: *Geological Society of America Bulletin*, v. 108, p. 953–965.
 Kring, D.A., 1997, Air blast produced by the Meteor Crater impact event and a reconstruction of the affected environment: *Meteoritics and Planetary Science*, v. 32, p. 517–530.
 Kring, D.A., Jull, A.J.T., McHargue, L.R., Bland, P.A., Hill, D.H., and Berry, F.J., 2001, Gold Basin meteorite strewn field, Mojave Desert, northwestern Arizona: Relic of a small late Pleistocene impact event: *Meteoritics and Planetary Science*, v. 36, p. 1057–1066.
 Melosh, H.J., 1989, *Impact cratering: A geologic process*: New York, Oxford University Press, 245 p.
 Nordyke, M.D., 1977, Nuclear cratering experiments: United States and Soviet Union, in Roddy, D.J., et al., eds., *Impact and explosion cratering*: New York, Pergamon Press, p. 103–124.
 Passey, Q.R., and Melosh, H.J., 1980, Effects of atmospheric breakup on crater field formation: *Icarus*, v. 42, p. 211–233.
 Reeves, C.C., Jr., 1976, Quaternary stratigraphy and geological history of the Southern High Plains, Texas and New Mexico, in Mahaney, W.C., ed., *Quaternary stratigraphy of North America*: Stroudsburg, Pennsylvania, Dowden, Hutchinson and Ross, Inc., p. 213–234.
 Rich, J., Stokes, S., Wood, W.W., and Bailey, R., 2003, Optical dating of tufa via in-situ eolian sand grains: A case example from the Southern High Plains, USA: *Quaternary Science Reviews*, v. 22, p. 1145–1152.
 Schmidt, R.M., and Housen, K.R., 1987, Some recent advances in the scaling of impact and explosion cratering: *International Journal of Impact Engineering*, v. 5, p. 543–560.
 Sellards, E.H., 1927, Unusual structural features in the plains region of Texas [abs.]: *Geological Society of America Bulletin*, v. 28, p. 149.
 Sellards, E.H., and Evans, G.L., 1941, Statement of progress at Odessa meteor craters: Austin, University of Texas at Austin, Bureau of Economic Geology, 13 p.
 Shoemaker, E.M., 1962, Interpretation of lunar craters, in Kopal, Z., ed., *Physics and astronomy of the Moon*: New York, Academic Press, p. 283–359.
 Smith, T.R., and Hodge, P.W., 1997, Discovery of impactite at the Odessa meteorite crater: *Meteoritics and Planetary Science*, v. 32, p. A122.
 Sutton, S.R., 1985, Thermoluminescence measurements on shock-metamorphosed sandstone and dolomite from Meteor Crater, Arizona: 2. Thermoluminescence age of Meteor Crater: *Journal of Geophysical Research*, v. 90, p. 3690–3700.
 Toon, O.B., Zahnle, K., Morrison, D., Turco, R.P., and Covey, C., 1997, Environmental perturbations caused by the impacts of asteroids and comets: *Review of Geophysics*, v. 35, p. 41–78.

Manuscript received 20 May 2005
 Revised manuscript received 27 July 2005
 Manuscript accepted 10 August 2005

Printed in USA