Journal of
Sedimentary
Research

Journal of Sedimentary Research, 2017, v. 87, 880–896
Research Article
DOI: http://dx.doi.org/10.2110/jsr.2017.48

DISCOVERY OF PALEOGENE DEPOSITS OF THE CENTRAL HIGH PLAINS AQUIFER IN THE WESTERN GREAT PLAINS, U.S.A.

JON J. SMITH,[1] GREG A. LUDVIGSON,[1] ANTHONY LAYZELL,[1] ANDREAS MÖLLER,[2] R. HUNTER HARLOW,[3]
ELIJAH TURNER,[1] BRIAN PLATT,[4] AND MICHAEL PETRONIS[5]

[1]Kansas Geological Survey, 1930 Constant Avenue, Lawrence, Kansas 66047, U.S.A.
[2]Department of Geology, The University of Kansas, 1475 Jayhawk Boulevard, Lawrence, Kansas 66045, U.S.A.
[3]Department of Geology, Baylor University, One Bear Place #97354, Waco, Texas 76798, U.S.A.
[4]Department of Geology and Geological Engineering, 120A Carrier Hall, University of Mississippi, University, Mississippi 38677, U.S.A.
[5]Department of Natural Resources Management, New Mexico Highlands University, Las Vegas, New Mexico 87701, U.S.A.

ABSTRACT: **Recent drilling in southwestern Kansas has produced intact cores to investigate the subsurface lithostratigraphy, sedimentary provenance, and chronostratigraphy of strata constituting the central High Plains Aquifer (HPA). In large portions of the HPA, groundwater withdrawals greatly exceed rates of recharge, leading to dramatic water-level declines and growing concerns for long-term sustainability. Two cores, HP1A (98 m) and CMC1 (50 m), are the first and deepest intact cores of the HPA ever collected. The cores show decameter-scale intercalations between suspended-load fluvial deposits composed of fine-grained sands with pedogenically modified overbank deposits, and very coarse-grained sands and gravels consistent with high-energy, bedload-dominated fluvial systems. Six intervals in HP1A and one from CMC1 were analyzed for detrital-zircon U-Pb ages by LA-ICP-MS. The HP1A samples show maximum depositional ages (MDAs) ranging from $\sim$ 27.5 to 36.4 Ma with depth. A MDA of $\sim$ 30 Ma was measured in the CMC1 core. These Paleogene zircons likely originated from explosive volcanism associated with the mid-Cenozoic ignimbrite flare-up (44–18 Ma), which blanketed much of western North America with high-volume air-fall tuffs. We propose that a large evaporite-dissolution basin in southwestern Kansas provided the accommodation space to preserve a record of Paleogene strata. The lack of younger middle–late Miocene zircons from cores in southwestern Kansas is striking given that such grains, likely derived from the Snake River Plain–Yellowstone hotspot volcanic provinces (16.1–0.6 Ma), are readily identified in the Ogallala Formation in north-central Kansas and Nebraska. The MDAs suggest Eocene to Oligocene age deposits that are time-equivalent to the Arikaree and White River groups in Nebraska are also present in Kansas.**

INTRODUCTION

The High Plains Aquifer (HPA) is one of the most important water resources in North America, accounting for nearly 30% of all groundwater withdrawals in the United States and currently supporting an estimated 15.5 million acres of irrigated land in the states of Kansas, Colorado, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (Fig. 1; Dennehy 2000). In large portions of the central and southern HPA, groundwater withdrawals greatly exceed local rates of recharge, and dramatic declines in water levels stoke growing concerns for long-term sustainability (McGuire 2014). In particular, water yields, drawdowns, and estimated useable lifetime of the aquifer is most in question for southwestern Kansas (Butler et al. 2015). Predicting the effects of various groundwater management strategies will depend on continuing improvements in our understanding of the depositional history, stratigraphic framework, and hydrogeologic properties of Cenozoic sediments constituting the aquifer. Acquiring quality stratigraphic information from the HPA, however, has been challenging because of the complex terrestrial stratigraphy, limited surface exposures representing only a small fraction of the total aquifer thickness, and the great difficulty in retrieving intact drill cores from unconsolidated and saturated intervals (Gutentag et al. 1984; Macfarlane 2009). Recent scientific drilling in the formational interior of the central HPA in southwestern Kansas has produced the first intact cores to investigate the lithostratigraphy and chronostratigraphy of this important Cenozoic succession.

This paper reports high-precision U-Pb ages of detrital-zircon populations from core that may provide a means to achieve long-distance correlation of heterolithic continental sedimentary units and to help delineate significant hydrostratigraphic subunits in the HPA system on a regional scale. During much of the Cenozoic, North America experienced geologically frequent super-eruptions with ejecta volumes $>$ 100 km^3 concurrent with deposition of HPA sediments (Fig. 2). The eruptions were associated first with the mid-Cenozoic ignimbrite flare-up (e.g., Chapin et al. 2004; Best et al. 2013a) and subsequently from volcanic fields along the path of the Snake River Plain–Yellowstone hotspot (e.g., Perkins and Nash 2002). These eruptions produced vast welded vitric tuffs and ash-fall deposits containing abundant zircons for U-Pb dating (e.g., Fan et al. 2015; Rowley and Fan 2016). The maximum depositional ages (MDAs) inferred from detrital zircons in multiple cores and core intervals suggest that a

Published Online: August 2017

substantial portion of the HPA in southwestern Kansas may consist of Eocene to Oligocene age deposits equivalent to the Arikaree and White River groups, which form part of the HPA succession in Nebraska and eastern Colorado. These deposits were previously unknown in the central High Plains Aquifer region.

GEOLOGIC BACKGROUND

The HPA is composed of near-surface Cenozoic geologic units that include, in ascending order, volcaniclastic claystones and siltstones of the White River Group (late Eocene–Oligocene), volcaniclastic sandstones of the Arikaree Group (late Oligocene–Early Miocene), terrigenous clastic deposits of the Ogallala Group (Miocene), and unconsolidated Quaternary deposits in hydraulic contact with these older units (Gutentag et al. 1984). The Ogallala Group (Formation status in the central HPA of Kansas) is regionally the principal water-bearing unit of the aquifer and consists mostly of superposed gravel, sand, silt, and clay cut-and-fill deposits; eolian silt and clay; and local lenses of volcanic ash and sparse lacustrine limestones (e.g., Frye et al. 1956; Seni 1980; Gustavson and Winkler 1988; Ludvigson et al. 2009). In addition, paleosols occur with high stratigraphic frequency in the sedimentary deposits of the central HPA and are characterized by abundant carbonate nodules, root traces, vertebrate and invertebrate burrows, and sometimes pervasive paleophreatic calcretes (e.g., Gustavson and Winkler 1988; Smith et al. 2011; Joeckel et al. 2014; Smith et al. 2016). These clastic sediments were eroded and transported eastward from the Rocky Mountains, likely by braided, high-energy streams with periods of local eolian deposition (Gustavson and Winkler 1988; Fielding et al. 2007). Recent studies suggest that subduction-related dynamic rebound during the middle Cenozoic caused several hundred meters of regional uplift centered under the Southern Rocky Mountains (e.g., McMillan et al. 2002; Heller et al. 2003; Liu 2015). The resulting continental tilting and steep paleoslopes along the flanks of the Southern Rockies induced progradation of the Ogallala Group, as opposed to an increase in accommodation space on the Great Plains. The formation was deposited initially in southeast-trending paleovalleys that were incised into pre-Cenozoic strata during the Laramide orogeny (Gustavson and Winkler 1988). Nearly continuous aggradation filled most of the paleovalleys and interfluve areas with an extensive and relatively thin (Fig. 3) blanket of alluvial deposits. Late Cenozoic uplift of the Great Plains region halted deposition of the Ogallala Formation and initiated widespread erosion and deep incision by the Platte, Arkansas, and Canadian rivers and their tributaries that continues to the present (Chapin 2008; Duller et al. 2012).

In Kansas, only the Ogallala Formation and hydraulically connected Pleistocene alluvium were previously recognized as constituting the HPA (Macfarlane 2000). Ogallala deposits have been characterized as heterogeneous, varying widely in facies composition, thickness, and layer continuity over short distances (e.g., Frye et al. 1956; Gutentag et al. 1984). While formations (e.g., Valentine, Ash Hollow, and Olcott formations) with distinct lithofacies associations are recognizable in outcrops of the Ogallala Group throughout Nebraska (e.g., Diffendal 1982; Fielding et al. 2007; Joeckel et al. 2014), similar facies recognized in the central and southern High Plains do not appear to occur in any consistent stratigraphic order and show little regional lithostratigraphic utility (Ludvigson et al. 2009). Likewise, the concept of the Ogallala "cap rock" or "algal limestone," referring to a regionally persistent and ledge-forming terminal petrocalcic horizon, is not supported by more recent stratigraphic studies (Swineford et al. 1958; Diffendal 1982; Gustavson and Winkler 1988; and Joeckel et al. 2014). Instead, these studies show that carbonate-cemented paleosols and petrocalcic horizons are present in numerous stratigraphic positions in HPA deposits.

HPA deposits are typically less than 100 m thick (Fig. 3), and the thicknesses vary greatly due to inherited paleotopography, subsidence due to evaporitic dissolution, and degradation accompanying late Cenozoic uplift and incision (Leonard 2002). In southwestern Kansas, central HPA deposits are up to 230 m thick locally due to faulting and subsidence associated with a massive evaporitic dissolution front working its way northward through Permian strata of the Hugoton embayment—a north-trending extension of the Permian Anadarko Basin (Sorenson 2005; Watney et al. 2013). Multiple evaporite beds 300–600 m below the base of the HPA are involved, including the Middle Permian Blaine Formation, Flowerpot Shale, Stone Corral Formation, and the Hutchinson Salt Member of the Wellington Formation. Dissolution in these units accounts for up to 100 or more meters of accommodation space in the basin (Watney et al. 2013). Such large karst features correlate with deep-seated, basement-rock folds and faults, which likely focused groundwater flow and promoted

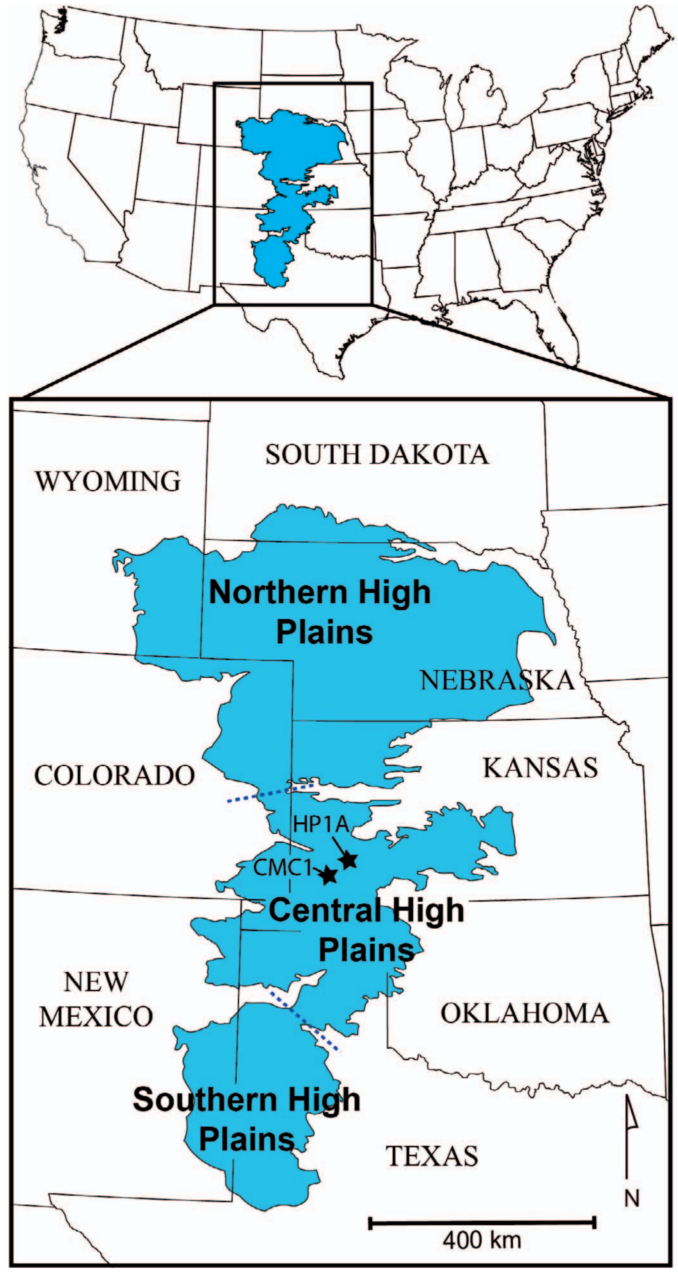

FIG. 1.—Location of the northern, central, and southern regions of the High Plains aquifer (blue polygon, colloquial regions divided by blue dotted lines) and general location of HP1A and CMC1 core sites in the western Kansas (stars). Modified from McMahon et al. (2003).

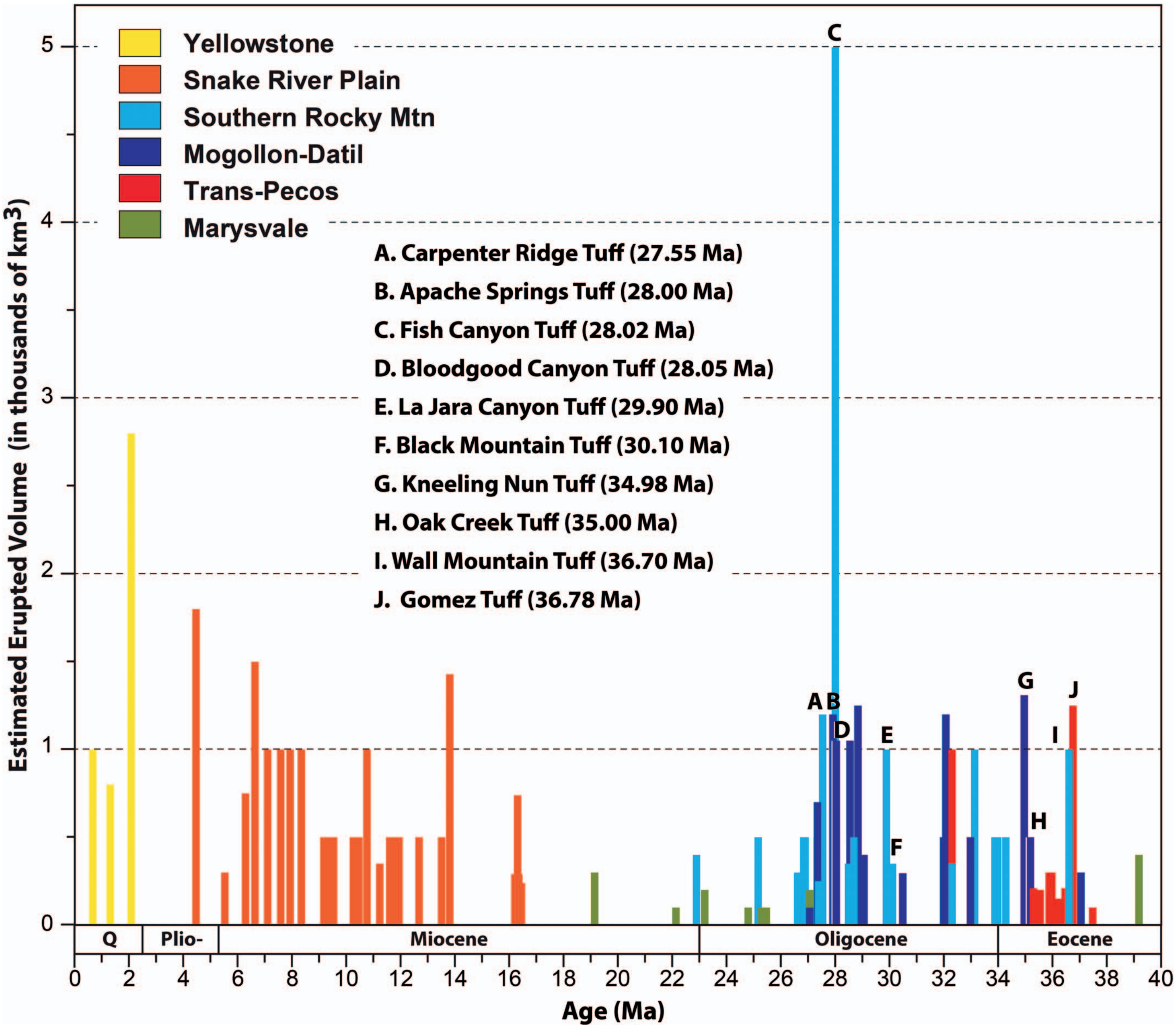

FIG. 2.—Chart showing the age distributions and estimated volumes of known supervolcanic eruptions with ejecta volumes greater than 100 km^3 in western North America over the last 40 million years. Colors denote volcanic fields of origin and lettered eruptions are discussed in the text. Absolute ages and ejecta volumes (estimated with large uncertainties; Mason et al. 2004) were derived from tuffs proximal to source calderas. Data synthesized from Seager (1973); Erb (1979); Ekren et al. (1984); Henry and Price (1984); Rytuba and McKee (1984); McIntosh et al. (1990); Pierce and Morgan (1992); Henry et al. (1994); Rowley et al. (1994); Perkins and Nash (2002); Morgan and McIntosh (2005); and Lipman and Bachmann (2015). See Supplemental Table SV1 for the complete list of known super-eruptions constituting this figure.

evaporite dissolution at depth. The area of subsidence is bounded on the west by the Bear Creek fault and on the east by the Crooked Creek–Fowler fault (Fig. 3) and contains several subbasins, such as the Meade and Ashland basins, which show ongoing evidence for Plio-Pleistocene subsidence (e.g., Frye and Hibbard 1941; Martin and Peláez-Compomanes 2014; Layzell et al. 2015).

Chronostratigraphic Correlations

In Kansas, chronostratigraphy of HPA strata has been constrained principally using fossil mammal and floral assemblages, and tephrochronologic analyses of distal air-fall tuffs (Ludvigson et al. 2009). These investigations are focused mainly in the north-central part of the State, where incision by the Solomon, Saline, and Smoky Hill rivers and their tributaries have dissected and exposed the eastern erosional margin of the HPA (Fig. 3). In this region, numerous fossil mammal assemblages typical to Barstovian (16.3–13.6 Ma), Clarendonian (13.6–10.3 Ma), and Hemphillian (10.3–4.9 Ma) North American Land Mammal Ages (NALMAs) suggest middle to late Miocene depositional ages (e.g., Zakrzewski 1988, 1990; Liggett 1997; Liggett et al. 1998; and references therein). Multiple species in the fossil-grass genus *Berriochloa* are exclusive to either Clarendonian or Hemphillian strata and appear to record a valid biostratigraphic succession in Ogallala deposits in Kansas and Nebraska (Thomasson 1990, 2005).

Ludvigson et al. (2009) presented a comprehensive summary of published reports on volcanic ash beds in HPA strata in Kansas and the

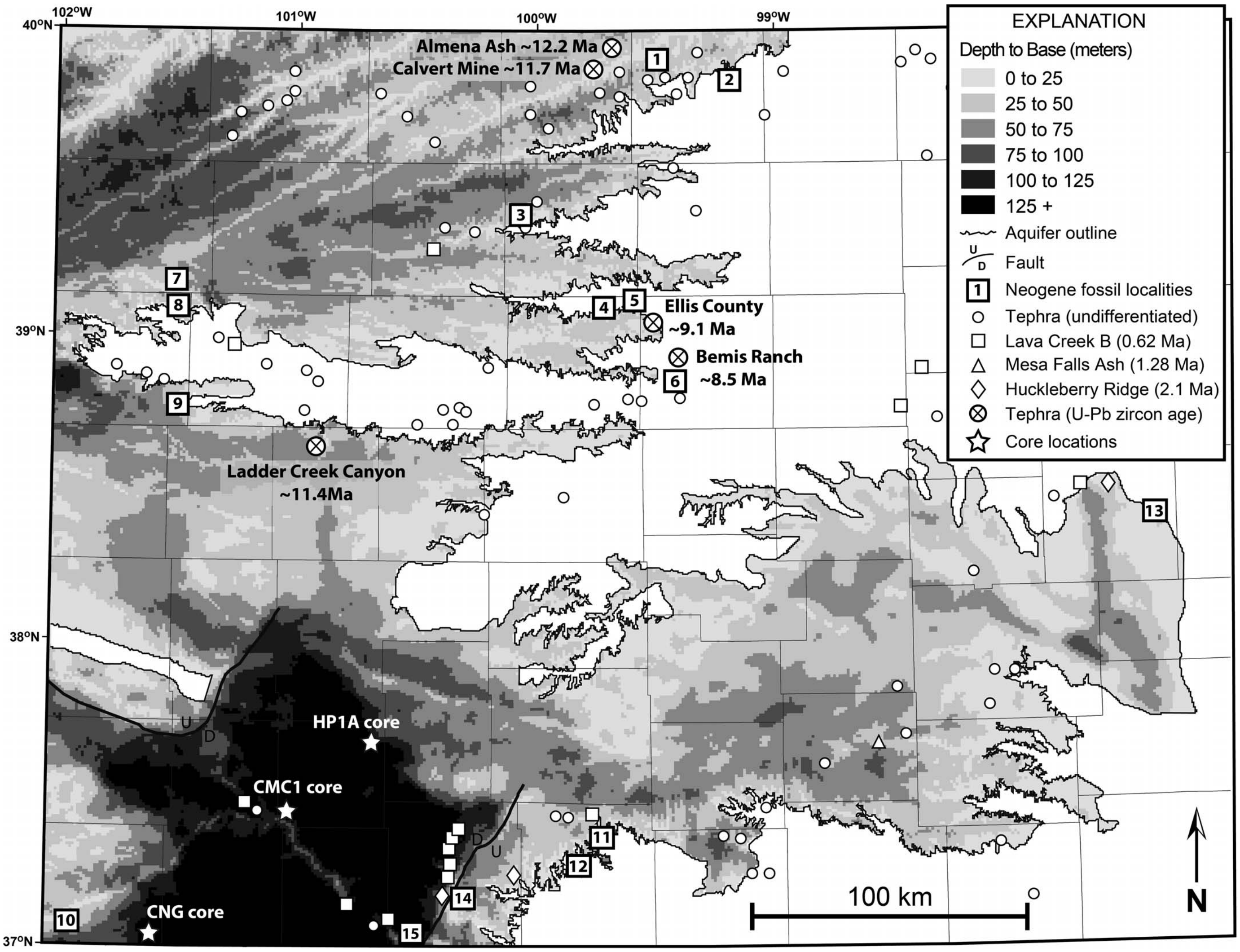

FIG. 3.—Map of western Kansas showing depth to base of the High Plains Aquifer and locations of scientific cores (stars), Neogene fossil sites, and volcanic-ash deposits. Numbered squares show approximate locations of Miocene local faunas: Long Island (1), Greta (2), Minium Quarry (3), Wakeeney (4), Keller and Hamburg (5), Bemis Ranch (6), Edson Quarry (7), Rhinoceros Hill (8), Lost and Found Quarries (9), Fullerton Gravel Pitt (10), Beckerdite Site (11), Swayze Quarry (12) and the "Delmore Formation" (13); modified from Hibbard (1952), Zakrzewski (1988, 1990), Liggett (1997), and Liggett et al. (1998). Pliocene local faunas from Borchers Badlands (14) and Keefe Canyon (15); modified by Martin and Peláez-Compomanes (2014). Locations of currently undifferentiated tephra (circles), 0.62 Ma Lava Creek B (small squares), 1.28 Ma Mesa Falls (triangles), and 2.1 Ma Huckleberry Ridge (diamonds) volcanic ash deposits modified from Swineford et al. (1955), Izett and Wilcox (1982), Ward et al. (1993), and references therein. Tephra with known zircon U-Pb ages (circled x) include the Almena Ash, Calvert Mine, Ellis County, and Bemis Ranch ashes from Hallman (2016); and the Ladder Creek Canyon ash bed from Sitek (2017). See Discussion section for CNG core details. Depth-to-bedrock base map modified from Macfarlane and Wilson (2006).

various attempts to date and correlate these deposits. Age constraints to the ash beds include radiometric fission-track dates from glass shards and zircons (Naeser et al. 1973; Boellstorff 1978; Potter 1991; Ward et al. 1993). Geochemical correlations of distal ash beds in the central HPA to well-dated proximal volcanic tuffs were conducted using rare-earth and other trace-element composition (David 2006) and chemical fingerprinting by electron microprobe analyses (Naeser et al. 1973; Perkins et al. 1995; Perkins 1998). Late Cenozoic volcanic fields along the Snake River Plain–Yellowstone hotspot track produced a voluminous record of silicic volcanism resulting in at least 24 recognizable ashfall tuffs preserved in Neogene deposits of the central Great Plains (Perkins and Nash 2002). Published radiometric and tephrochronologic dates from volcanic ash beds from HPA deposits in Kansas range from 18 to 5 Ma (Ludvigson et al. 2009). However, of the 111 documented tephra deposits in Kansas (e.g., Carey et al. 1952; Swineford et al. 1955; Izett and Wilcox 1982), most have remained largely unexamined using modern dating techniques, or the details of the tephrochronologic analyses are, to date, unpublished (Fig. 3).

METHODS AND MATERIALS

Two cores, HP1A and CMC1, were collected by the Kansas Geological Survey (KGS) from HPA deposits in southwest Kansas (Fig. 3). In the unsaturated zone, cores were drilled using an Acker hollow-stem auger with a wireline, split-spoon core-barrel sampler. From below the water table, core was recovered using an S-27 RotoSonic drill rig with an Aqualock piston sampling system that hydraulically holds both the sediment and pore fluids within the core barrel. The rotary-vibratory drilling technology provides, for the first time, an efficient and cost-effective means of collecting intact cores from unconsolidated and saturated intervals of the HPA with nearly 100% recovery. Lithologic

TABLE 1. *Locations and age constraints of samples used for detrital-zircon geochronology in this study.*

Sample Name	GPS Location			Maximum Depositional Ages		Sample Description
	Lat. (°N)	Long. (°W)	Elev (m)	YC2σ(3+) (Ma)*	Youngest Single Grain (Ma)†	
HP1A 16-17	37.66	–100.66	851	27.4 ± 1.7 (n = 3)	26.2 ± 1.4	Argillaceous fine-grained sand
HP1A 24-26	37.66	–100.66	843	28.0 ± 1.6 (n = 3)	27.2 ± 1.3	Argillaceous fine-grained sand
HP1A 33.5-34.5	37.66	–100.66	833.5	35.4 ± 0.7 (n = 19)	34.1 ± 1.5	Sandy silt
HP1A 40-41	37.66	–100.66	827	35.3 ± 1.0 (n = 5)	31.5 ± 1.1	Medium-grained sand
HP1A 52-53	37.66	–100.66	815	35.6 ± 1.2 (n = 11)	34.1 ± 1.8	Sandy silt
HP1A 86-89	37.66	–100.66	781	36.4 ± 1.2 (n = 6)	30.2 ± 1.1	Argillaceous fine-grained sand
CMC1 23-24	37.41	–101.05	860	29.9 ± 1.6 (n = 3)	23.5 ± 0.8	Argillaceous fine-grained sand

* YC2σ(3+) age is based on the weighted mean of the U-Pb ages of the youngest cluster of three or more overlapping, concordant zircon grains
n = number of youngest grains
† Youngest reported U-Pb grain

descriptions of the cores noted color, bedding features, mineralogy, and pedological and biological features. Quantitative particle-size analyses of the cores at 0.5 m intervals were conducted at the KGS Geoarchaeology and Paleoenvironmental Research Laboratory using the standard pipette method (Soil Survey Staff 1982) based on the Stokes Law of gravitational settling rates to determine texture on particle sizes less than 2000 μm; 2000–63 μm (total sand), 63–2 μm (total silt), and < 2 μm (total clay). Nearly pure sand samples were analyzed separately from the pipette procedure with a Ro-Tap sieve shaker as follows: 63–250 μm (fine sand), 250–500 μm (medium sand), and 500–710 μm (medium-coarse sand), 710–1440 μm (coarse sand), and 1410–2000 μm (very coarse sand).

Six core intervals from HP1A and one interval from CMC1 were sampled for detrital zircon U-Pb geochronology (Table 1). Zircon grains were separated from argillaceous, fine-grained core intervals with evidence for pedogenic modification, the exception being sample HP1A 40–41 m, which was composed of medium-grained sand. Zircon separations were carried out at The University of Kansas Isotope Geochemistry Laboratories (IGL) by a combination of chemical and physical disaggregation and heavy-mineral separation techniques including a disk mill, ultrasonic bath (Hoke et al. 2014), Frantz™ isodynamic magnetic separator, and heavy liquids (methylene iodide). At least 300 grains were randomly handpicked under a binocular microscope, mounted in epoxy resin discs, and polished to half width to expose their internal structures. U–Pb zircon ages were determined by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) using a Photon Machines Analyte G2 193 nm ArF excimer laser ablation system feeding a Thermo Scientific Element2 ICP-MS. Circular 20 μm spots were ablated with the laser at 2.0 J/cm^2 fluency with a 10 Hz repetition rate, and ablated material was carried to the ICP-MS in helium gas with a 1 l/min combined flow rate. Downhole elemental and isotopic fractionation and calibration drift were corrected by bracketing measurements of unknowns with the weighted mean ^{206}Pb/^{238}U age of 600.4 ± 0.65 Ma for the GJ-1 zircon reference material (Jackson et al. 2004). Data were reduced using the VizualAge data reduction scheme (Petrus and Kamber 2012) for the IOLITE software package (Paton et al. 2011). Validity of calculated ages was checked by concurrent measurements of the Plesovice (Sláma et al. 2008) and Fish Canyon Tuff (e.g., Wotzlaw et al. 2013) zircon reference materials.

The ^{207}Pb/^{206}Pb dates are reported for grains older than 900 Ma, and ^{206}Pb/^{238}U dates for grains younger than 900 Ma. Analytical results are presented using plotting and tools available in Isoplot 4.15 (Ludwig 2012). Kernel density estimates (KDEs) were produced using DensityPlotter 7.1 (Vermeesch 2012). Using the DZ Age Pick 2010 program of the Arizona LaserChron Center webpage (www.laserchron.org), maximum depositional ages (MDAs) were calculated from the youngest grouping of at least three or more grains with overlapping U-Pb ages at 2σ (Dickinson and Gehrels 2009c). Cross-correlation coefficients of sample probability density plots (PDPs) were calculated using DZstats (Saylor and Sundell 2016). Analytical results are shown in Supplemental Table HPDZ.

RESULTS

Core Descriptions

HP1A Core.—The HP1A core is the first attempt to recover an intact, scientifically drilled core of the HPA from above and below the water table (Fig. 4). Approximately 98 m of core were retrieved with an average recovery rate of ~ 89%. HP1A consists mostly of fine- to medium-grained sand (67%) to sandy silts and coarse-grained sand and gravel beds. The HP1A core can be divided into four discrete sections based on the stratigraphic distribution of lithofacies.

Section 1 constitutes ~ 11.75 m of the core from the base at 98 m to ~ 86.25 m and consists of nearly equal portions of very fine- to medium-grained argillaceous sand beds and beds of sandy silt and clay. Sand beds are thin, generally < 0.5 m thick, and composed of moderately to poorly sorted, rounded to subangular, silty, very fine- to medium-grained sand. Most sand beds in this section are weakly to well-cemented with carbonate. Sandy silt and clay beds show low-chroma gray to greenish gray colors, reddish brown to purple mottles, common carbonaceous root traces, and rare millimeter-scale carbonate nodules. These are interpreted as hydromorphic paleosols displaying redoximorphic features that formed under conditions of poor soil drainage (Kraus 1999). Interbedded sands and gleyed hydromorphic paleosols in Section 1 are interpreted as a dominantly suspended-load river system with poorly drained overbank conditions and shallow, fluctuating water tables (Miall 2010).

Section 2, from 86.25 m to 37 m, is the thickest interval of the core and is composed of beds of upward-fining gravel and very coarse-grained sand with very few fine-grained intervals. Gravel beds range from 0.5 to 1.5 m thick and are composed of clast-supported, poorly to moderately sorted, rounded to subrounded, pebble- to cobble-size clasts of granite, anorthosite, quartzite, sandstone, and gneiss and armored mud balls. Gravel beds have sharp basal contacts with underlying units where preserved and often fine upwards to coarse-grained sand with gravel-size clasts constituting ~ 10% of the deposit. Sand beds are mostly medium- to very coarse-grained to pebbly, moderately to poorly sorted grains. Finer-grained beds are infrequent (n = 5), relatively thin (< 0.5 m thick), and composed of reddish-brown, clayey silt containing rare, millimeter-scale carbonate nodules and calcareous rhizoliths. Lithologic characteristics suggest that the depositional environment of Section 2 was a high energy, bed-load-dominated fluvial system (Miall 2010).

Section 3, from 37 m to ~ 13 m, consists dominantly of interbedded fine- to medium-grained argillaceous sand and beds of calcareous sandy silt. Sand beds are generally upward fining and range from ~ 0.5 to 2 m

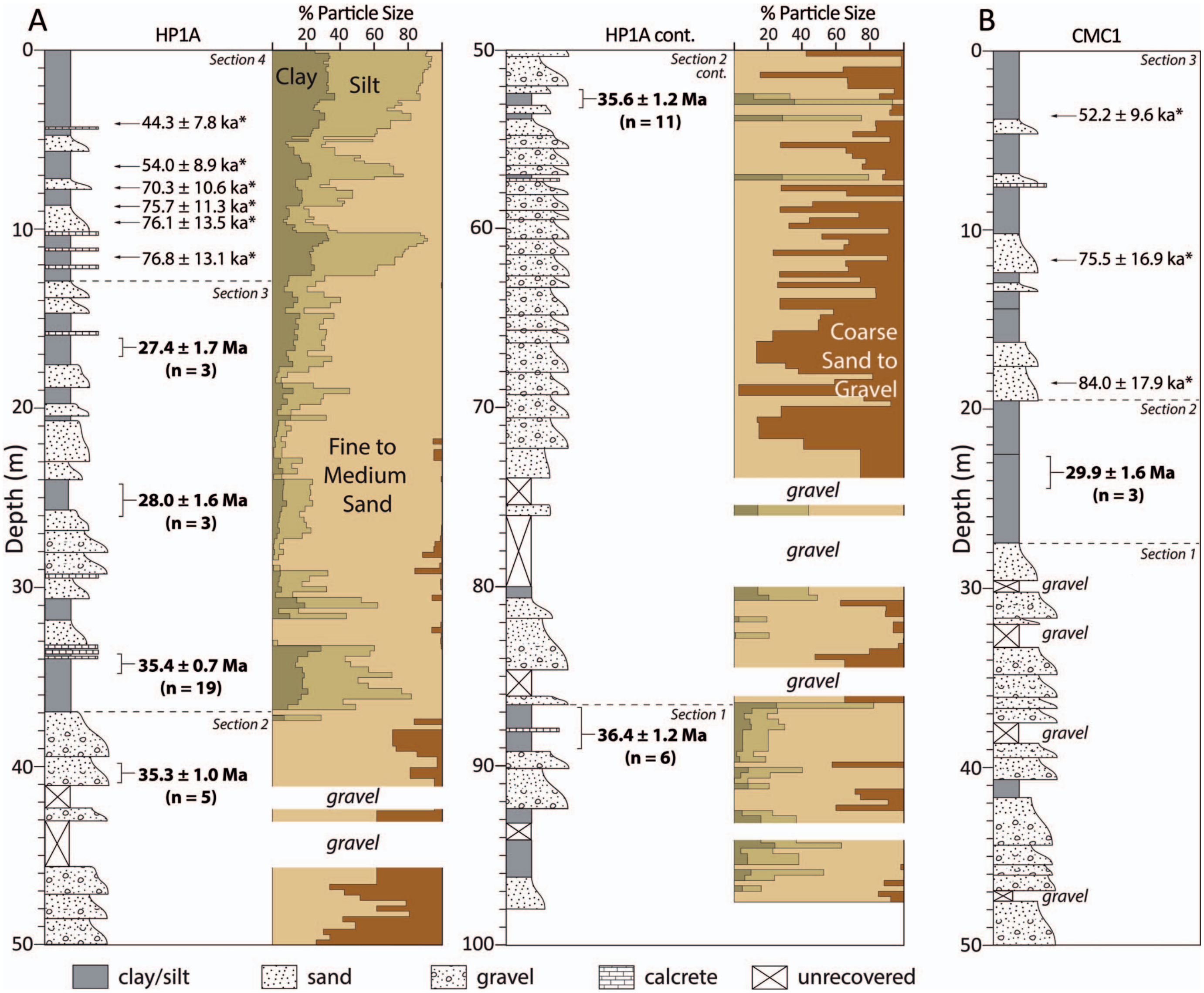

FIG. 4.—Graphic log of **A)** the $\sim$ 98 m HP1A core with particle size distribution and **B)** CMC1 core showing stratigraphic position of samples collected for detrital-zircon analyses. Maximum depositional age in bold based on the weighted mean of the U-Pb ages of the youngest cluster of three or more zircon grains (n = number of youngest zircon grains used for calculated ages). OSL dates (asterisks) reported in Layzell et al. (2016).

thick. These are composed of moderately to well sorted, very well rounded to subangular, fine- to medium-gained sand with rare calcareous root traces and carbonate nodules. Fine-grained beds ranging from $\sim$ 0.5 to 3 m thick are stratigraphically common (n = 22) and composed of reddish-brown to tan, sandy silt with rare gray-green mottles, blocky to prismatic ped structures, distinct slickensides, common calcareous rhizoliths and rhizohaloes, invertebrate burrow traces, and up to centimeter-scale carbonate and iron-oxide nodules. Silt-dominated beds are interpreted as overbank sediments on which relatively mature cumulic paleosols formed (Kraus 1999). The paleosols do not have well preserved A horizons, possibly because of pre-burial erosion or oxidation after burial. Compared with section 1, these paleosols suggest better drainage conditions and increased pedogenic modification with higher-chroma colors and upsection increases in abundances of carbonate nodules, calcrete intervals, rhizoliths, bioturbation and burrows, distinct slickensides, and clay skins on paleosol ped faces. Carbonate is common throughout the core in the form of cement, rhizoliths, and nodules, but indurated beds ($<$ 0.2 m thick) of calcrete are mostly confined to this section of the core. Section 3 lithologies suggest a mixed- to suspended-load fluvial system with relatively stable and moderately well-drained overbank conditions based on paleopedogenic features and maturity (Miall 2010).

Section 4, from $\sim$ 13 m to the land surface, is composed mostly of pedogenically modified beds of sandy silt and clay. Sediments in this section are interpreted as eolian in origin based on stratigraphic correlation, textural characteristics, and landscape position (Layzell et al. 2016). Layzell et al. (2016) report optically stimulated luminescence (OSL) dates from six samples in this section ranging from ca. 76.8 ka at $\sim$ 12 m depth to 44.3 ka at $\sim$ 4 m depth (Fig. 4). These dates indicate that this section comprises a late Quaternary loess–paleosol sequence, which includes the Loveland, Gilman Canyon, and Peoria loesses.

CMC1 Core.—CMC1 is a 50-m-deep core retrieved with an average recovery rate $>$ 90%. The core is composed of nearly equal amounts of coarse-grained sand to gravel and very fine argillaceous sand to sandy silts showing varying degrees of pedogenic modification (Fig. 4). The core can be divided into three sections based on changes in dominant lithofacies.

Section 1 extends from the base of the core at 50 m to 27.5 m and is composed of vertically stacked, upward-fining sequences of coarse gravel to fine-grained sand that are very similar to facies described in section 2 of HP1A. Gravel beds are 0.5–1.5 m thick and composed of clast-supported, poorly to moderately sorted, rounded to subrounded, pebble to cobble-size clasts of granite, quartzite, sandstone, and gneiss. The gravel beds fine upward to moderately sorted, rounded to subrounded, medium- to fine-grained sand. No primary sedimentary structures were observable in the core. A 1-m-thick paleosol at 40.7 m depth shows angular blocky structure, prominent clay films on ped faces, distinct slickensides, powdery carbonate stringers, and prominent gray mottles. The depositional environment was likely a rapidly aggrading, high-energy, braided fluvial system with frequent channel shifting. The paucity of paleosols suggests that periods of landscape stability were either of insufficient duration to form soils or that weakly developed soils formed in the sandy alluvium were eroded before burial or oxidized after burial.

Section 2, from approximately 27.5 m to 19.6 m, is composed of reddish-brown, sandy clay with rare gray-green mottles, well developed angular blocky structure, abundant carbonate nodules ranging in diameter from 0.5 to 2 cm, and strongly cemented by carbonate (up to 53% by weight) throughout. This section is interpreted as at least two paleosols separated at 23.3 m by a relatively thin BCk horizon. The paleosol morphology and magnitude of development imply well-drained soil conditions and long periods of landscape stability (Kraus 1999).

Section 3, from 19.6 m to the land surface, is composed of pedogenically modified beds of sandy silt and clay interpreted as eolian deposits based on stratigraphic correlation, textural characteristics, and landscape position (Layzell et al. 2016). OSL ages from this section (Fig. 4) of the core range from ca. 84.0 ka at 18.7 m depth to 52.2 ka at 4.4 m depth and, as with HP1A, are correlative with the Great Plains Quaternary paleosol–loess sequence (Layzell et al. 2016).

Detrital-Zircon Provenance

Zircon grains from HPA samples produced concordant U-Pb ages ranging from latest Oligocene (23.5 Ma) to Archean (3578 Ma) in age (Fig. 5). Concordant dates were divided into seven age populations (A–G) based on comparisons with other detrital-zircon provenance studies identifying major zircon-generating provinces and magmatic events in North America (Table 2; Fig. 6). The seven populations include Archean and Paleoproterozoic zircons (> 1825 Ma) of Population A, Paleoproterozoic zircons (1800–1635 Ma) of Population B, Mesoproterozoic zircons (1535–1300) of Population C, Mesoproterozoic and Neoproterozoic zircons (1300–920 Ma) of Population D, Neoproterozoic and Paleozoic zircons (750–285 Ma) of Population E, Mesozoic and Paleogene zircons (250–44 Ma) of Population F, and Paleogene zircons (44–18 Ma) of Population G.

The cross-correlation coefficient is the coefficient of determination of a cross-plot of PDPs or KDEs and is used as an indicator of similarity between two or more samples (Saylor and Sundell 2016). The resulting cross-plot is sensitive to changes in the presence or absence of age peaks and the relative magnitude or shape of the peaks. For sample sizes n > 300, PDP cross-correlation is able to consistently distinguish between samples derived from the same parent ($R^2 > 0.5$) and from those drawn from different parents ($R^2 < 0.2$). We used PDPs for this comparison because Saylor and Sundell (2016) demonstrated that KDEs are less reliable indicators of similarity due to over-smoothing of peak shapes. PDP cross-correlation values for the six detrital zircon samples from HP1A and CMC1 are all > 0.40 and have an average $R^2 = 0.68$, suggesting that they were derived from the same depositional source (Table 3). Sample HP1A 86-89 is the most dissimilar to the other six age spectra (average $R^2 =$ 0.51), likely due to greater numbers of zircons in Population F (24% versus 8–15% in the other samples).

Population A: Archean and Paleoproterozoic (> 1825 Ma).— Potential sources for these ages include the Archean (> 2500 Ma) Superior, Wyoming, and Wopmay cratons, and the mid-Paleoproterozoic (2000–1825 Ma) Trans-Hudson orogeny (Hoffman 1989; Whitmeyer and Karlstrom 2007) (Fig. 6). Archean and Paleoproterozoic basement rocks of appropriate age were uplifted and exposed in the Southern Rocky Mountains during the Laramide orogeny (Dickinson et al. 1988), but such grains are also common constituents of Mesoproterozoic to Paleogene sedimentary deposits (e.g., Dickinson and Gehrels 2009a; Fan et al. 2011; Gehrels et al. 2011; May et al. 2013; Smith et al. 2015). Given the relatively small numbers of these oldest-age zircons in the samples (2% of the total population), Population A grains were most likely recycled from Mesoproterozoic–Paleogene sedimentary rocks.

Population B: Yavapai–Mazatzal orogenic belt (1800–1535 Ma).— Zircons of this age range are the most abundant and constitute 34% of the total population. These grains were originally formed in the northeast–southwest-trending Yavapai (1825–1700 Ma) and Mazatzal (1700–1635 Ma) terranes (Fig. 6), which were accreted to the North American continent and formed intrusive granitic bodies (Whitmeyer and Karlstrom 2007). Yavapai–Mazatzal basement rocks were exposed during the early Carboniferous in the core of the Ancestral Rocky Mountains orogenic belt (Kluth 1986) and currently crop out because of the Laramide Orogeny in western Colorado, New Mexico, southern California and Arizona, and southeastern Wyoming (Houston 1993; Shaw and Karlstrom 1999). Zircon grains of this age are well represented in Pennsylvanian to lower Paleogene sedimentary rocks throughout western North America (e.g., Eriksson et al. 2004; Gehrels et al. 2011; Soreghan and Soreghan 2013; Sweet et al. 2013), and it is likely that some Population B grains were recycled from these strata during the Laramide Orogeny (e.g., Dickinson and Gehrels 2003; May et al. 2013; Fan et al. 2015).

Population C: Mid-continental granite–rhyolite province (1535–1300).—Zircons that match this age range (23% of the total population) are likely derived from granitic and rhyolitic magmatism in the North American mid-continent associated with the Mesoproterozoic (1535–1300 Ma) collision of juvenile crust along the Laurentian southeastern margin (Whitmeyer and Karlstrom 2007) (Fig. 6). Similar to Yavapai–Mazatzal source rocks, some of these mid-continental plutons were exposed in the Paleozoic uplift of the Ancestral Rocky Mountains and are common constituents of Pennsylvanian and younger strata (e.g., Dickinson and Gehrels 2003; Soreghan and Soreghan 2013; Sweet et al. 2013; Smith et al. 2015). While HPA deposits likely do incorporate recycled zircons from these older sedimentary rocks, granite–rhyolite-province rocks exposed during the Laramide Orogeny such as the Laramie anorthosite complex (1440 Ma) and the Sherman batholith (1430 Ma; Harlan et al. 1994) are also potential sources of zircons of this age (Fan et al. 2015).

Population D: Grenville province (1300–920 Ma).—These grains constitute 17% of the total population and were likely derived from the Mesoproterozoic basement formed during the Grenville orogeny (1300–920 Ma) along the eastern and southern flank of Laurentia (Dickinson and Gehrels 2003; Whitmeyer and Karlstrom 2007) (Fig. 6). Grenvillian-age zircons are common in Phanerozoic sedimentary rocks in North American (Gehrels et al. 2011) and are the predominant grains reported from Neoproterozoic to Mesozoic strata (e.g., Dickinson and Gehrels 2003; Moecher and Samson 2006; Gleason et al. 2007; Hietpas et al. 2011; Rainbird et al. 2012; and Soreghan and Soreghan 2013). The Pikes Peak

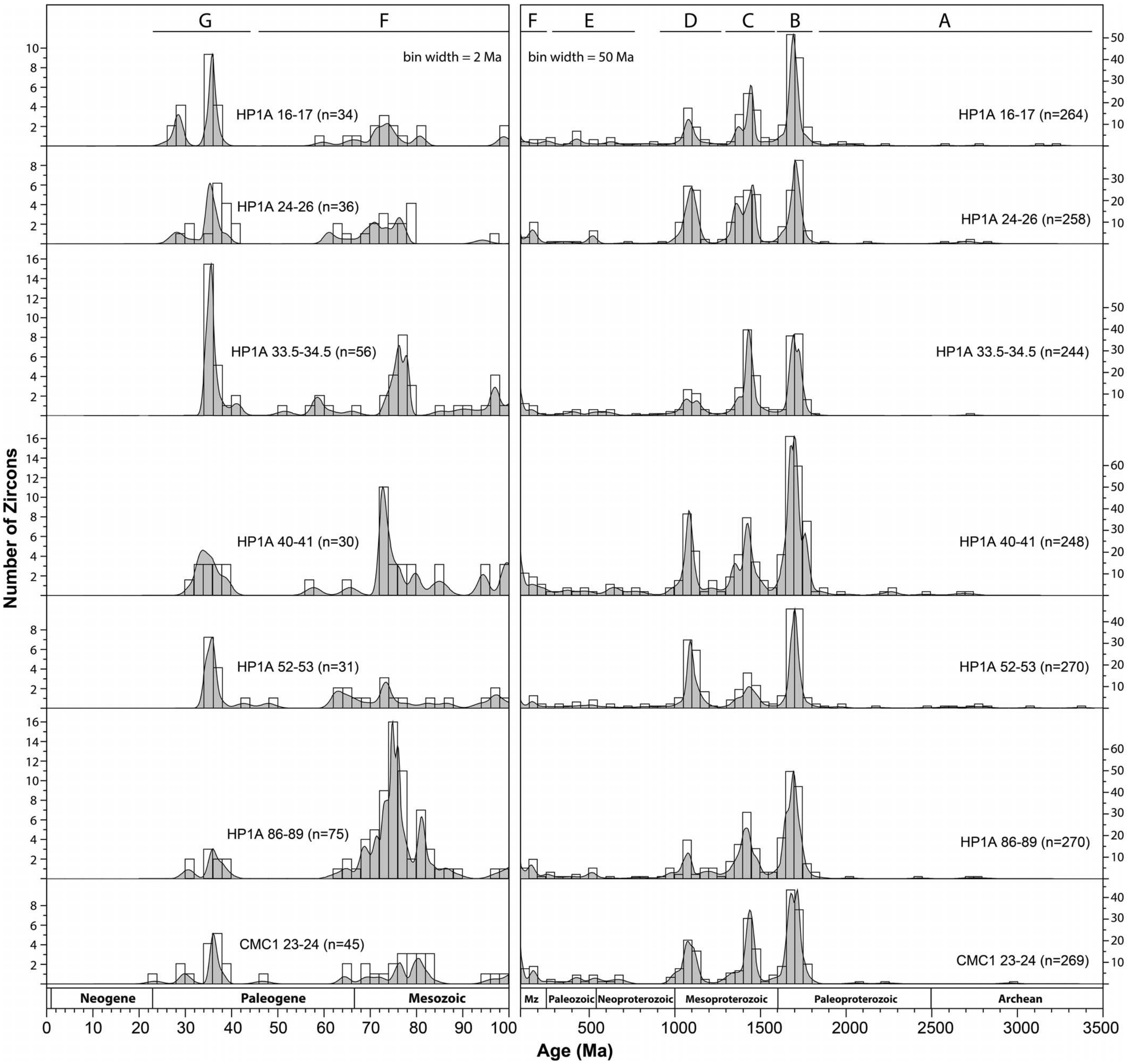

FIG. 5.—Normalized Kernel density plots based on $^{206}Pb/^{238}U$ ages (< 900 Ma) and $^{207}Pb/^{206}Pb$ ages (≥ 900 Ma). Zircon age populations listed at the top. Durations of Populations A–G are shown at the top.

TABLE 2. *Age percentages of detrital zircons in studied samples.*

Population	Inferred Source Terrane	HP1A 16-17 (n = 300)	HP1A 24-26 (n = 292)	HP1A 33.5-34.5 (n = 300)	HP1A 40-41 (n = 277)	HP1A 52-53 (n = 300)	HP1A 86-89 (n = 346)	CMC1 23-24 (n = 281)
G (44–23.5 Ma)	Mid-Cenozoic Ignimbrite Flare-Up	7	5	8	3	4	3	5
F (250–44 Ma)	Cordilleran Orogen	8	11	15	13	9	24	15
E (750–285 Ma)	Peri-Gondwanan/Appalachian–Ouachita	7	3	5	6	5	3	6
D (1300–920 Ma)	Grenville Province	13	23	12	14	26	11	17
C (1535–1300 Ma)	Mid-Continent Province	22	28	28	17	15	22	22
B (1825–1635 Ma)	Yavapai–Mazatzal Terranes	39	27	32	43	36	35	33
A (> 1825 Ma)	Paleoproterozoic–Archean	4	2	1	3	4	1	1

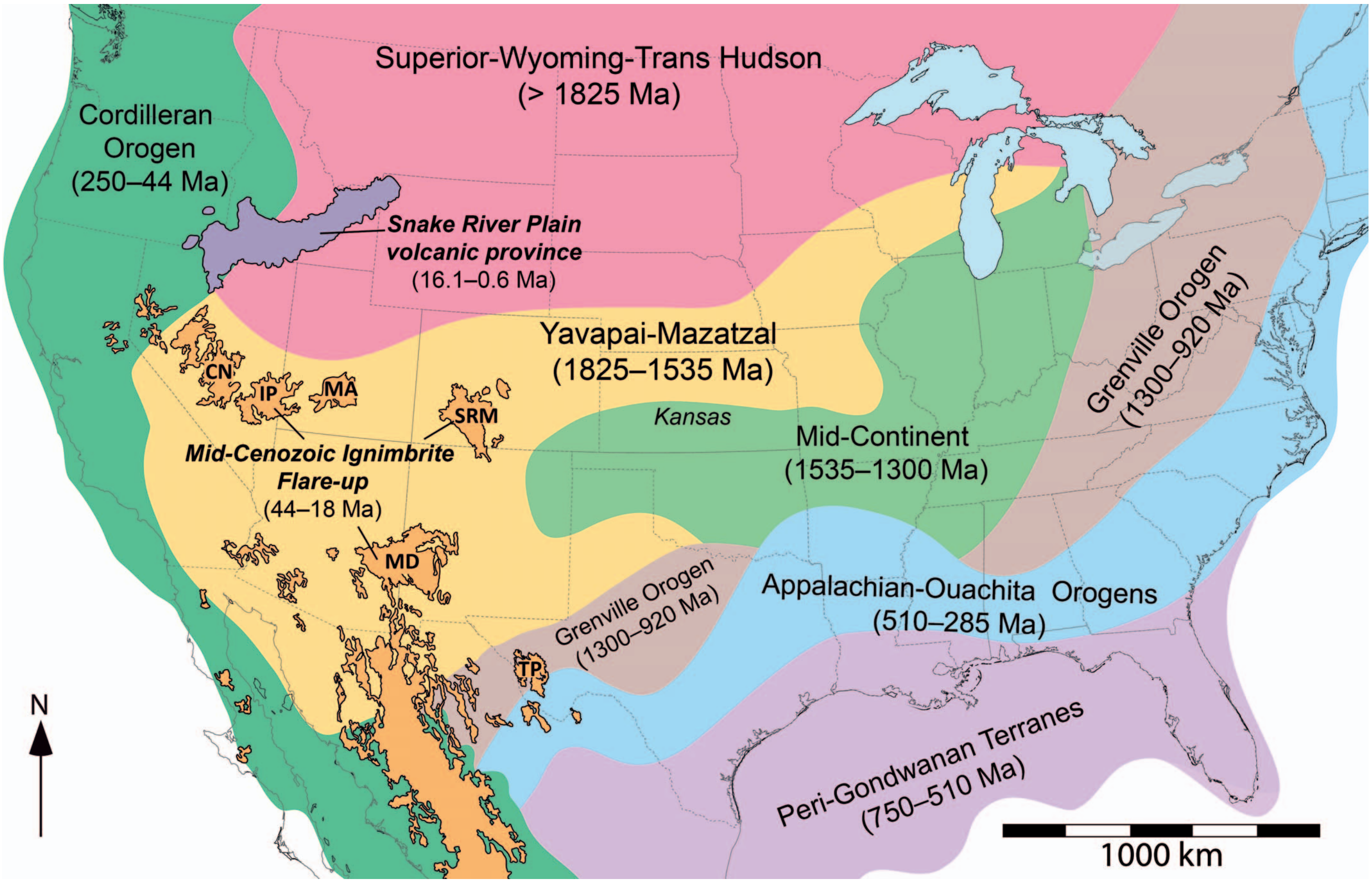

FIG. 6.—Map of North American crustal provinces and magmatic events that may have generated the detrital zircons deposited in High Plains sediments. Major zircon provinces are modified from Dickinson and Gehrels (2009b) and references therein. Distribution of calderas and tuffs associated with the mid-Cenozoic ignimbrite flare-up (orange polygons) include the Southern Rocky Mountains (SRM), Mogollon–Datil (MD), Trans-Pecos (TP), Marysvale (MA), Indian Peak (IN), and Central Nevada (CN) volcanic fields (modified from Best et al. 2013a); purple polygon represents the Snake River Plain–Yellowstone Hotspot track (modified from Perkins and Nash 2002).

Batholith (1115–1066 Ma) in the Southern Rocky Mountain region may also have contributed to this zircon population (Guitreau et al. 2016).

Population E: Peri-Gondwanan and Appalachian–Ouachita provinces (750–285 Ma).—Population E grains (5% of the total population) are widely distributed in North America and have multiple potential source areas along the eastern and southern margin of the continent; mostly associated with Neoproterozoic to Paleozoic continental collisions between Laurentia and Gondwana and subsequent anorthositic–granitic intrusions (Murphy et al. 2004; Soreghan and Soreghan 2013) (Fig. 6). Original sources for Neoproterozoic gains (750–510 Ma) include the peri-Gondwanan terranes of Avalonian–Carolinian (640–580 Ma) and the Suwannee, Sabine, and Yucatan–Campeche (680–540 Ma) terranes (e.g., Thomas et al. 2004; Dickinson and Gehrels 2009a). Paleozoic Appalachian–Ouachita zircons (510–285 Ma) were likely derived from the Potomac (500 Ma), Taconian (500–430 Ma), Acadian (400–350 Ma), and Alleghanian (325–265 Ma) terranes and associated granitic intrusions (e.g., Hatcher 1989; Goldberg and Dallmeyer 1997; Dickinson and Gehrels 2003). Other possible sources include the Antler–Sonoma orogenies (461–225 Ma) in the western U.S.A. (Dickinson 2004) and the Permian–Triassic magmatic arc province (284–232 Ma) in Mexico (Torres et al. 1999; Dickinson and Lawton 2001). These grains were transported to western basins during the Permian and Jurassic by transcontinental fluvial systems (Dickinson and Gehrels 2009b) and recycled into Cretaceous to lower Paleogene sedimentary rocks during the Laramide orogeny (Dickinson and Gehrels 2003, 2009a; May et al. 2013). Population E grains in HPA sediments were likely eroded from Paleozoic to lower Paleogene sedimentary rocks uplifted in the Southern Rocky Mountains (Fan et al. 2015).

Population F: Cordilleran orogeny (250–44 Ma).—Population F zircons constitute 13% of the total population and likely originated from the Cordilleran Magmatic Arc (e.g., Dickinson 2004; Dickinson and Gehrels 2009a; Laskowski et al. 2013; Fan et al. 2015) (Fig. 6). Between the Late Triassic and middle Cenozoic, subduction of the Farallon oceanic plate beneath the western margin of the North American craton resulted in the incremental accretion of exotic island arcs and the generation of nearly continuous continental-arc magmatism (Dickinson and Lawton 2001). A broad spectrum of U-Pb ages are represented in this population, but 75% of the zircons (typically $\sim$ 20 grains) are from the Late Cretaceous (100–66 Ma; Fig. 6). Laramide plutons of Late Cretaceous age (75–44 Ma) are also distributed in western Colorado and New Mexico (Chapin et al. 2004; Chapin 2012), though these plutons are not likely a major source of grains due to their distance from the study area. Population F zircons were deposited originally across the North American west as volcanic ash beds in Late Cretaceous strata, recycled later into lower Paleogene sedimentary rocks, and finally uplifted and eroded along the eastern margins of the Rocky Mountains (Armstrong and Ward 1991; Dickinson and Gehrels 2009a; Fan et al. 2015).

TABLE 3. *Cross-correlation coefficient based on PDPs.*

	HP1A 16-17	HP1A 24-26	HP1A 33.5-34.5	HP1A 40-41	HP1A 52-53	HP1A 86-89	CMC1 23-24
HP1A 16-17	1.00	0.80	0.77	0.70	0.76	0.45	0.82
HP1A 24-26	0.80	1.00	0.76	0.68	0.80	0.51	0.80
HP1A 33.5-34.5	0.77	0.76	1.00	0.58	0.61	0.49	0.79
HP1A 40-41	0.70	0.68	0.58	1.00	0.82	0.55	0.73
HP1A 52-53	0.76	0.80	0.61	0.82	1.00	0.40	0.75
HP1A 86-89	0.45	0.51	0.49	0.55	0.40	1.00	0.65
CMC1 23-24	0.82	0.80	0.79	0.73	0.75	0.65	1.00

Population G: Mid-Cenozoic Ignimbrite Flare-Up (44–18 Ma).— Population G zircons (5% of the total population) were likely formed during a period of late Paleogene explosive silicic volcanism in western and southwestern North America known as the mid-Cenozoic ignimbrite flare-up (Coney 1978) (Figs. 2, 6). Beginning $\sim$ 44 Ma, nearly continuous magmatic activity, associated with rollback of the subducting oceanic Farallon plate, eventually covered large areas of Nevada, Utah, Colorado, New Mexico, Arizona, and northwestern Mexico with a patchwork of volcanic fields composed of calderas, basalt flows, mafic to felsic intrusive rocks, and silicic ash-flow deposits hundreds to thousands of meters thick (e.g., Best et al. 2013a). Ignimbrites from the vast volcanic fields of central and eastern Nevada suggest at least 30 super-eruptions with volumes $>$ 1000 km^3 from $\sim$ 35 to 18.5 Ma, including very large eruptions producing the Lund (29.2 Ma) and Wah Wah Springs (30.1 Ma) tuffs (Best et al. 2013b; Best et al. 2013c). The Marysvale volcanic field (39–19 Ma) in central Utah produced several widespread tuffs with volumes $>$ 100 km^3 (Rowley et al. 1994). Closer to the Great Plains, calderas in the Trans-Pecos (38–32 Ma) and Mogollon–Datil (36–24 Ma) volcanic fields in Texas and New Mexico (McIntosh et al. 1990; Henry et al. 1994; Chapin et al. 2004), and the Central Colorado (37.5–32.5 Ma) and San Juan (29.5–23 Ma) volcanic fields in the Southern Rocky Mountains (Bachmann et al. 2002; McIntosh and Chapin 2004) during the late Eocene and Oligocene (37–23 Ma) produced episodic ignimbrite volcanism (Fig. 2). Among these, the most widespread ($>$ 15,000 km^2) and voluminous ($>$ 4,000 km^3) is the Fish Canyon Tuff (28.02 Ma), centered at the La Garita Caldera in the San Juan volcanic field (Wotzlaw et al. 2013; Lipman and Bachmann 2015). Zircons in Population G may have been derived from direct ash fallout, and ash beds dated to these eruptions occur at least as far as western Nebraska (Fig. 6; Perkins 1998; Fan et al. 2015). Mid-Cenozoic zircons may have also been derived from the erosion of latest Eocene–Oligocene sedimentary deposits in the Southern Rocky Mountains.

Maximum Depositional Ages

Dickinson and Gehrels (2009c) outlined several methods for using the youngest age grains in a larger detrital-zircon population to constrain the maximum depositional ages (MDAs) of sedimentary units. These include the youngest-single-grain (YSG) age, where 1σ is $<$ 10 Myr, though lead loss may produce spuriously young ages in individual zircons. The YC2σ(3+) method uses the weighted mean age of the youngest group of three or more grain ages ($n \geq 3$) overlapping in U-Pb age at 2σ confidence interval. While conservative, the YC2σ(3+) is considered the most statistically robust limit on depositional age, even if there are younger single grains in a population. Both the YSG and the YC2σ(3+) ages from the sampled stratigraphic intervals of HP1A and CMC1 are presented in Table 1, while Figure 7 shows YC2σ(3+), the weighted mean of the youngest grouping of concordant grains in each sample. The six MDAs from the HP1A core occur in a serial order that obeys the stratigraphic law of superposition. MDAs at the 16–17 m and 24–26 m intervals are 27.4 $\pm$ 1.7 Ma and 28.0 $\pm$ 1.6 Ma, respectively. The MDA of samples from intervals 33.5–34.5 m, 40–41 m, and 52–53 m were 35.4 $\pm$ 0.7 Ma, 35.3 $\pm$ 1.0 Ma, 35.6 $\pm$ 1.2 Ma, while zircons from 86–89 m in HP1A were 36.4 $\pm$ 1.2 Ma. Zircons from 23–24 m in the CMC1 core yielded a MDA of 29.9 $\pm$ 1.6 Ma. Also of note, Miocene age grains are lacking from all intervals tested in the HP1A and CMC1 cores.

DISCUSSION

An Innovative Approach to Dating Terrestrial Sedimentary Deposits

Ashfall deposits are among the most reliable geochronological marker horizons because radiometric ages on volcanic minerals and their geochemical correlation with isochronous units can provide high-precision absolute ages of deposition (e.g., Lowe 2011). Volcanic ash beds in terrestrial stratigraphic successions, however, are missing over most of the areal extent of hosting sedimentary deposits and are typically preserved as swale-filling deposits of very limited lateral extent (Diffendal 1982). Are there alternative sedimentary facies that could serve as receptacles for concentrations of datable volcanogenic grains (e.g., zircons) from now-vanished tephra deposits, or are all such grains completely removed by erosional stripping of the landscape?

We propose that time-rich, mature paleosols may function as likely hosts for volcanogenic zircons from ashfalls that temporally overlap with periods of soil formation. Fluvial channel deposits, the traditional target facies for detrital-zircon studies, contain zircon populations in which contemporary volcanogenic grains are likely diluted by mixing with extrabasinal zircon grains from sedimentary source areas. These deposits are therefore well suited for provenance studies. We propose that zircon populations in paleosols, however, could be biased toward higher concentrations of volcanogenic zircon grains from eruptions that overlapped with the period of paleosol formation. This facies difference would be especially pronounced if the active volcanic sources were not located within the fluvial drainage basin.

Abiotic and biotic pedoturbation, including animal burrowing and caching, and the piping of surface sediments through root channels and desiccation cracks, can introduce volcanogenic zircon grains from surficial tephra deposits into the soil matrix (Fig. 8). Halfen and Hasiotis (2010), for example, showed in burrowing experiments with western harvester ants that $\sim$ 55% of all excavated material was incorporated in the nest as backfill or tunnel linings and not, as traditionally thought, transported to the surface or incorporated exclusively in the nest mound. In addition, a significant volume of near-surface material was translocated downward as much as 82 cm below the surface. Therefore, U-Pb ages from the youngest zircons preserved in paleosols may more accurately reflect the true age of the deposit than detrital zircons in fluvial channel deposits.

In cores from southwest Kansas in which obvious ashfall deposits are lacking, we sampled chiefly argillaceous fine-grained intervals containing features indicative of paleopedogenic modification for zircon U-Pb dating, the exception being HP1A 40–41 m (Table 1). The HP1A 40–41 m sample

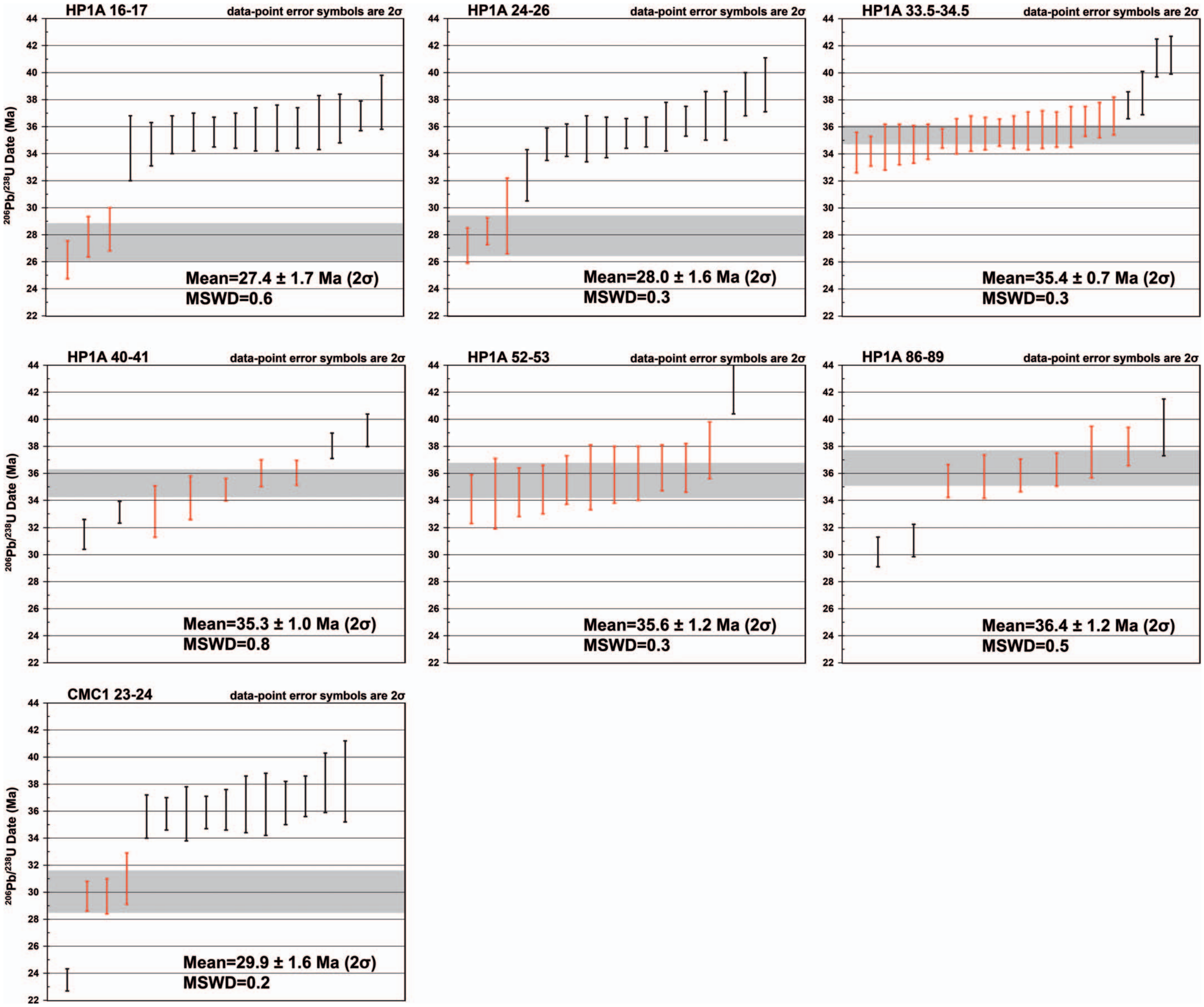

FIG. 7.—YC2σ(3+) maximum depositional ages of sampled intervals from HP1A and CMC1 cores. YC2σ(3+) at 2σ (gray bars) are based on the weighted mean age of the youngest grouping of three or more concordant grains overlapping in age at 2σ (red bars). MSWD = mean square weighted deviation.

comes from a coarser-grained facies more typical of those targeted for detrital-zircon studies. Though the total number of grains recovered from HP1A 40–41 m is slightly less than from the other samples, there are no appreciable differences in the age populations recovered (Fig. 5) or the percent distribution of zircons within those ages (Table 2) in comparison with samples from fine-grained intervals. These comparisons are inconclusive given the small sample size, and more work is needed to test the efficacy of targeting fine-grained, paleopedogenic facies for detrital-zircon studies.

Sedimentary Provenance

The detrital-zircon U-Pb ages from the cores in southwest Kansas show a high degree of similarity between samples because all the major peaks and cumulative curves of the six age spectra are nearly identical, suggesting no major changes in sediment source during deposition (Fig. 5; Table 3). Pre-Paleogene zircon populations were most likely eroded from Precambrian basement rocks and Phanerozoic sedimentary strata uplifted along the Front Range of the Southern Rockies and transported by rivers to southwestern Kansas. Paleogene zircons (Population G) originate from explosive volcanism associated with the mid-Cenozoic ignimbrite flare-up (44–18 Ma) that blanketed large parts of Nevada, Utah, Arizona, Colorado, New Mexico, Texas, and northwestern Mexico in vast ash-flow tuffs and air-fall deposits (e.g., Best et al. 2013a).

The youngest zircons in Population G may have been deposited directly as volcanic fallout on the High Plains paleosurface or were eroded from tephra deposits in Southern Rocky Mountain source areas and transported by rivers or the wind to southwestern Kansas. We propose that the development of a large evaporite-dissolution basin in southwestern Kansas (Fig. 3) and the panhandle regions of Oklahoma and Texas provided the accommodation space to preserve previously unrecognized Paleogene strata in the central HPA (Watney et al. 2013). Paleogene deposition in the central HPA is consistent with continental-scale reconstructions of late Eocene and Oligocene paleodrainage systems in the Great Plains region (Galloway et al. 2011; Sharman et al. 2017; Blum et al. in press). These

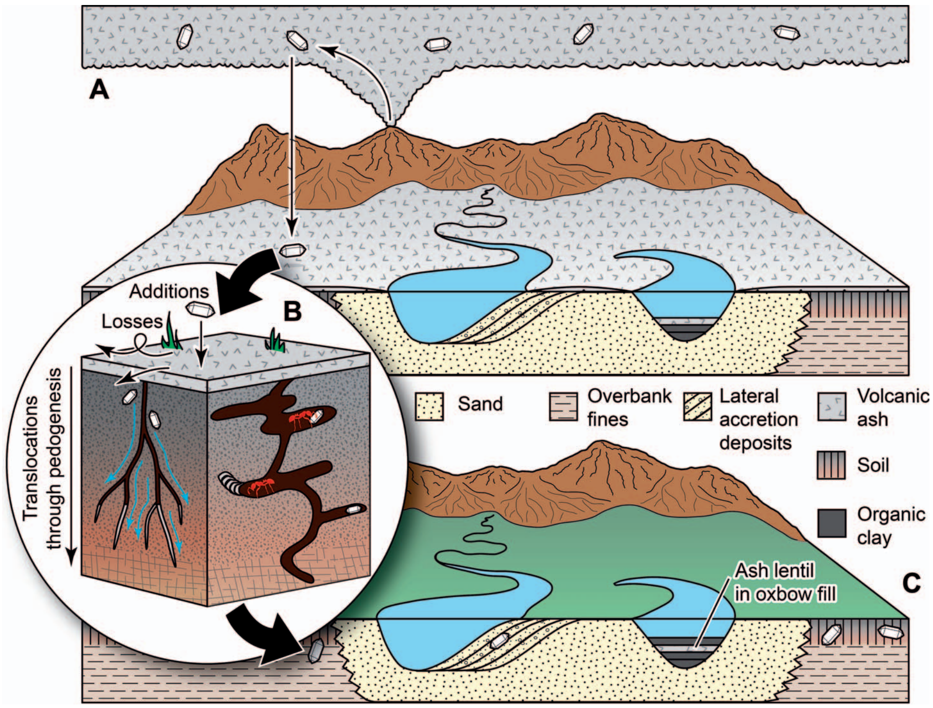

FIG. 8.—Conceptual diagram of **A)** the deposition of primary ash-fall tephra across a landscape, **B)** the incorporation of zircons into a paleosol via pedoturbation, including piping through root channels and desiccation cracks, and translocation by animal burrowing activity, and **C)** the likely locations of zircon grains preserved in paleosols, swales, and fluvial deposits in the post-eruption landscape.

reconstructions suggest that late Eocene to Oligocene paleofluvial systems, ancestral to the modern Arkansas River and with headwaters proximal to eruptive centers in the Southern Rocky Mountains, flowed through southwestern Kansas before turning toward the Gulf of Mexico (Fig. 9). While modern rivers flow eastward across the Great Plains to the Mississippi River, Paleogene rivers in the central U.S. were likely steered south along a broad north–south-oriented lowland of dynamic subsidence that extended to the Texas Gulf Coast (Liu 2015). These reconstructions are supported by the presence of multiple Paleogene fluvial deposits, such as the latest Eocene Castle Rock Conglomerate (Keller and Morgan 2016), having a strongly southeast-trending axis along the eastern flank of the Colorado Front Range.

Magmatic Zircon Provenance

While magmatic activity in western and southwestern North America during the Paleogene was widespread, likely eruptive sources for Population G zircons can be inferred from the supervolcano data summarized in Figure 2 and Supplemental Table SV1. The utility of using volcanogenic zircons to generate highly resolved depositional ages largely depends on the proximity of the sampling location to contemporaneously active magmatic sources, and a sufficiently high frequency of eruptive events generating zircons. Candidate eruptions suggested here are based on the following assumptions: 1) eruptions closest in age to YC2σ(3+) ages of the samples, 2) eruptions from volcanic fields nearest to the High Plains study area, and 3) eruptions that produced the highest estimated volumes of tephra. Given these assumptions, zircons that produced the $\sim$ 36.5 Ma MDA in HP1A at the 86–89 m interval were most likely derived from voluminous (> 1000 km^3) eruptions of the Wall Mountain Tuff (36.70 Ma) in the Southern Rocky Mountains or the Gomez Tuff (36.78 Ma) in the Trans-Pecos volcanic field (Henry et al. 1994; Lipman and Bachmann 2015).

HP1A intervals sampled at the 33.5–34.5 m, 40–41 m, and 52–53 m produced MDAs of $\sim$ 35.5 Ma. Large eruptions in the Mogollon–Datil volcanic field produced the Kneeling Nun (34.98 Ma) and Oak Creek tuffs (35.00 Ma), but this is also a period of frequent, high volume (100–300 km^3) volcanic activity in the Trans-Pecos region of west Texas (Erb 1979; McIntosh et al. 1990; Henry et al. 1994). Given that supervolcanic eruptions are not known from the Southern Rocky Mountain at this time and that late Eocene fluvial systems crossing the central HPA region are not thought to extend to the southwest (Fig. 9), it is possible that the $\sim$ 35.5 Ma age zircons were transported mainly as atmospheric fallout from volcanic sources in New Mexico and western Texas.

The $\sim$ 30 Ma MDA of zircons from the 23–24 m interval of the CMC1 core were likely sourced from eruptions that produced the La Jara Canyon (29.90 Ma) and Black Mountain (30.10 Ma) tuffs of the Southern Rocky Mountain volcanic field (Lipman and Bachmann 2015). There are several candidate sources for the zircons constituting the $\sim$ 27.4–28 Ma MDAs in the HP1A 16–17 m and 24–26 m core intervals. These include the very large (> 1000 km^3) eruptions that produced the Carpenter Ridge (27.55 Ma) and Fish Canyon (28.02 Ma) tuffs in the Southern Rocky Mountain volcanic field and the Apache Springs (28.00 Ma) and Bloodgood Canyon (28.05 Ma) tuffs in the Mogollon–Datil volcanic area (McIntosh et al. 1990; Lipman and Bachmann 2015). Of these, the exceptional (> 5000 km^3) eruption that produced the Fish Canyon Tuff from the La Garita caldera seems the most likely source of youngest grains in the HP1A 16–17 m and 24–26 m intervals.

Chronostratigraphy of Cenozoic Deposits on the Great Plains

In southwestern Kansas, over 3,300 individual zircons from cores have been U-Pb dated, including those in this study and 12 smaller samples from pilot studies of HP1A and other cores (Smith et al. 2013), and yet no Neogene-age grains (< 23 Ma) have been recovered. With a lack of any countervailing geochronologic data (i.e., NALMAs, paleobotanical or tephrochronologic data), the most parsimonious interpretation of the MDAs generated in this study is that previously unrecognized Paleogene (Eocene–Oligocene) deposits, time-equivalent with the White River and Arikaree groups, are present in southwestern Kansas in what had previously been assumed to be the Neogene Ogallala Formation (Fig. 10).

Several lines of evidence lead us to interpret the Paleogene U-Pb ages as the actual ages of the deposits in southwest Kansas. Firstly, the six

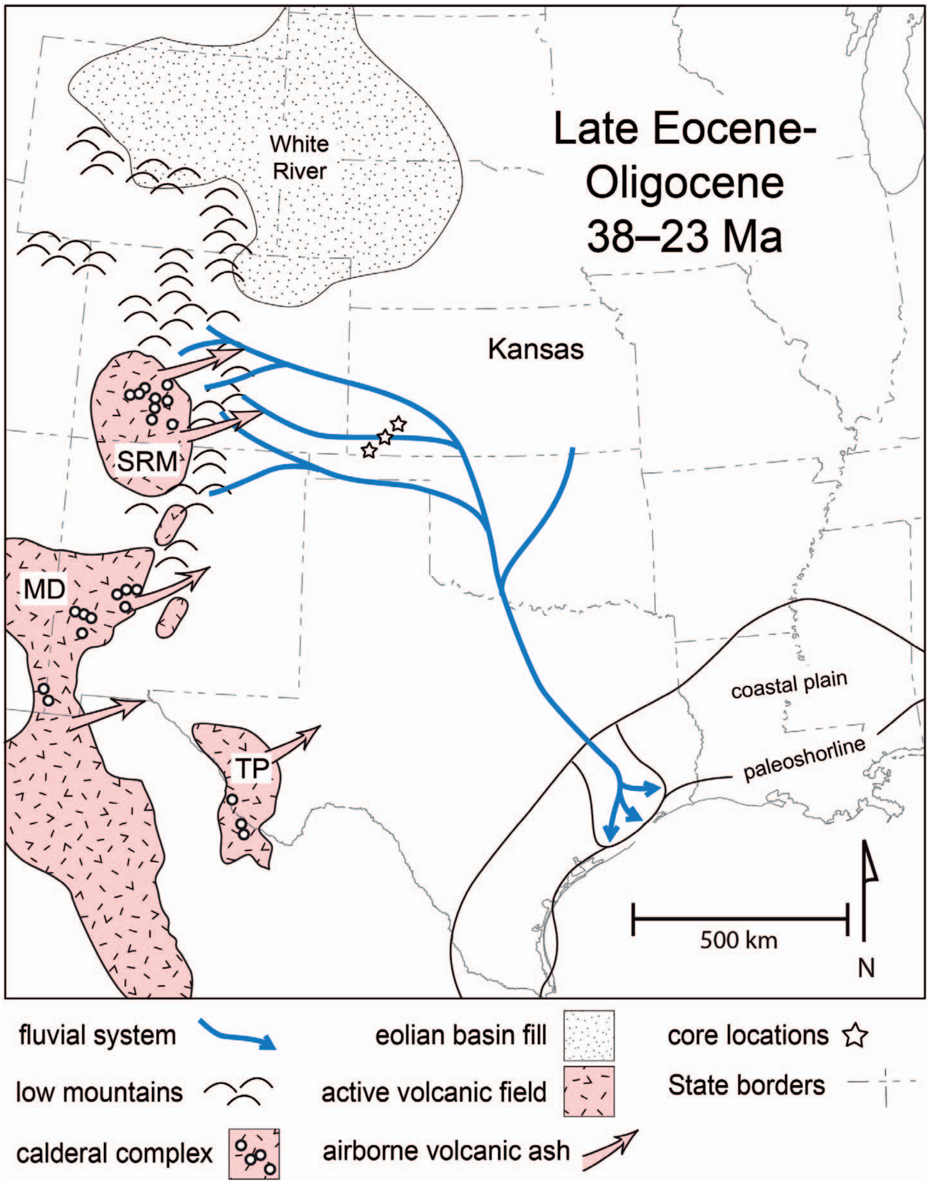

FIG. 9.—Paleogeographic maps of Paleogene (late Eocene to Oligocene) paleodrainage systems and potential volcanic sources of zircons for the HP1A, CMC1, and CNG cores (stars) in southwestern Kansas. Volcanic fields include the Southern Rocky Mountains (SRM, 37.5–23 Ma), Trans-Pecos (TP, 38–32 Ma), and Mogollon–Datil (MD, 36–24 Ma); modified from Galloway et al. (2011) and Chapin et al. (2004).

YC2σ(3+) derived MDAs from the HP1A core occur in a serial order that obeys the stratigraphic law of superposition (Fig. 4). If Population G zircons were mainly detrital, one might expect zircon ages in HP1A to be progressively younger with stratigraphic depth due to the unroofing of successively older tephra deposits in the source area.

Secondly, Miocene and younger age grains are lacking from all zircon samples analyzed in the HP1A and CMC1 cores. There was a preliminary expectation that Miocene-age zircons would be detected in cores from southwestern Kansas given that central High Plains deposits elsewhere record a nearly geologically continuous period of explosive silicic volcanism associated with the Snake River Plain–Yellowstone hotspot (16.1–0.6 Ma) concomitant with deposition of the Ogallala Formation (Fig. 2). Neogene grains are readily identified in relatively large numbers using the same methods and targeting similar facies as the current study from other localities in Kansas and Nebraska. Hallman (2016) examined minimally reworked air-fall tuffs and calcic paleosols from north-central Kansas (Fig. 3) and reported MDAs ranging from 12.2 to 8.5 Ma that correlate well with proximal tuffs in the Twin Falls (10.5–8.5 Ma) and Bruneau–Jarbidge (12.7–10.5 Ma) volcanic fields of the Snake River Plain. In that study, Miocene-age zircons make up 6–14% of the total zircon population in calcic paleosols, and 58–99% of grains in ash beds. Sitek (2017) reported on U-Pb zircon ages from a volcanic ash bed ($\sim$ 11.4 Ma) in exposures of the Ogallala Formation at Ladder Creek Canyon and a succession of overlying paleosols with superposed ages ranging from 10.3 to 6.3 Ma (Fig. 3). Field (2017) examined paleosols in cores of the Valentine Formation (Ogallala Group) from Boyd County, Nebraska, and reported MDAs from youngest zircon populations ranging from 15.8 to 14.9 Ma, which likely originated from the McDermitt caldera of the Snake River Plain. Miocene grains from these deposits constituted 7–28% of the total zircons recovered.

In addition, Vermeesch (2004) described a method for calculating the smallest number of grains that must be dated in a uniformly distributed zircon population to have 95% confidence that a significant fraction of the detrital age spectrum was not missed. Vermeesch (2004) recommends a sample size of at least 117 grains to be certain that no fraction ≥ 0.05 of the population was missed. For sample sizes of $\sim$ 300 or more grains, as is the case in this study, there is 95% confidence that no fraction ≥ 0.023 of the sample was missed. Further, these calculations show that within the

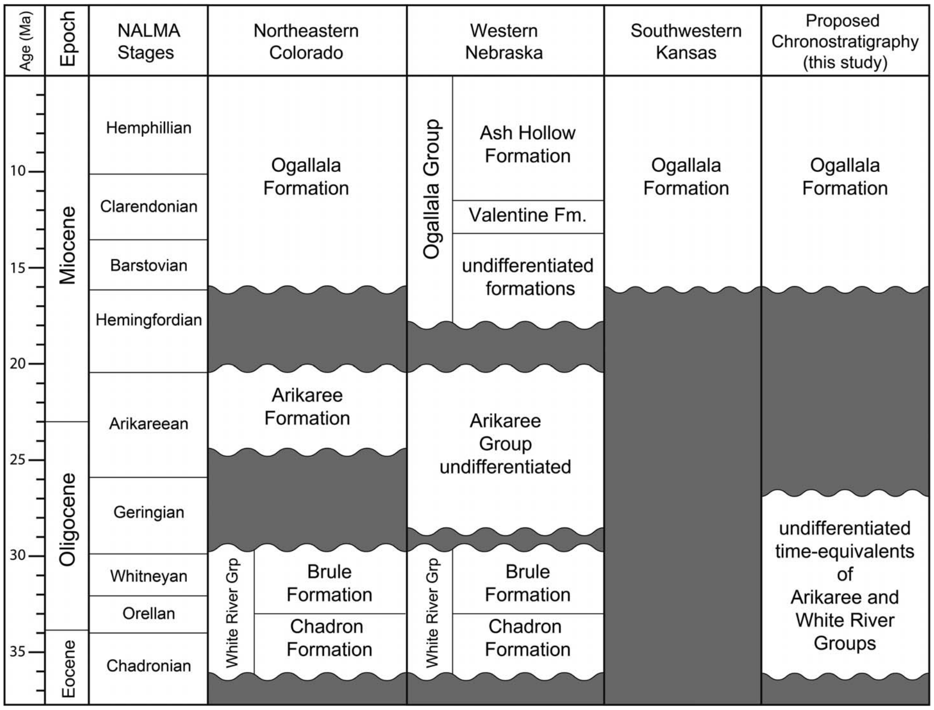

FIG. 10.—Chronostratigraphy of High Plains Aquifer sediments in northeastern Colorado (Tweto 1979), western Nebraska (Swinehart et al. 1985; Joeckel et al. 2014), and southwestern Kansas (Macfarlane 2000) with the proposed addition of Paleogene strata in southwestern Kansas based on U-Pb zircon dating.

aggregate set of > 3300 grains analyzed from southwestern Kansas there is a nearly 0% maximum probability of missing any fraction ≥ 0.01 of the detrital age spectrum. Given the sample sizes analyzed, the statistical likelihood of missing a population of Neogene aged zircons is vanishingly small.

Finally, our results are consistent with zircons analyzed from a 60-m-deep research well (CNG; Fig. 3) drilled in 2000 by the U.S. Geological Survey (USGS) Water Resources Division in eastern Morton County, Kansas (McMahon et al. 2003). CNG was drilled by ODEX air-hammering with the cuttings flushed from the borehole via compressed air in 30 cm increments. While acknowledging possible biases introduced by the drilling method, the youngest single zircon grain from an aggregate set of 288 grains was dated to 26.3 ± 1.9 Ma (Ludvigson et al. 2016).

Implications for Patterns of Cenozoic Deposition on the Great Plains

Paleogene strata in southwestern Kansas raise the question: where is the Miocene Ogallala Formation in this region that make up the bulk of the HPA on the Great Plains? One possibility is that a significant period of regional incision following late Cenozoic uplift of the Great Plains region (Chapin 2008) eroded overlying Miocene sediments and exposed Paleogene strata preserved in the evaporite-dissolution basin in southwestern Kansas. Another hypothesis is that portions of the central High Plains were not active areas of aggradation during the Miocene and the Ogallala Formation was never deposited in the study area. Recent stratigraphic and geochronologic studies of the Ogallala suggest that the formation may have been deposited as a series of temporally distinct and laterally discontinuous lobes of fluvial sediment (Chapin 2008; Galloway et al. 2011; Harlow 2013; Hallman 2016). Stream avulsion in proximal reaches of Miocene fluvial systems may have routed deposition into different areas of a low-accommodation basin. This idea is not inconsistent with the model of deposition hypothesized for distributive fluvial systems (Weissmann et al. 2010). The geographic distribution of these potentially diachronous sediment bodies has important implications for the movement and storage of groundwater in the HPA, so all hypotheses related to their depositional histories and stratigraphic architecture require further examination.

CONCLUSIONS

The results of this research join a growing body of literature using zircon U-Pb geochronology to constrain both the provenance and depositional ages of Phanerozoic strata in western North America (e.g., Dickinson and Gehrels 2009c; May et al. 2013; Sweet et al. 2013; Blum and Pecha 2014; Fan et al. 2015; Smith et al. 2015). Though volcanic tephra is the benchmark for time resolution in sedimentary deposits, recent studies demonstrate that in terrestrial strata from continental sedimentary basins that commonly lack primary air-fall ash beds, the youngest grouping of zircon ages (MDAs) in the unit often correlate with expected depositional ages inferred from biostratigraphic, radiogenic, and other geochronologic techniques (Dickinson and Gehrels 2009c; Fan et al. 2015).

We analyzed detrital zircons from two continuous cores drilled in southwest Kansas (HP1A and CMC1) to better constrain the provenance and chronostratigraphy of deposits constituting the central HPA. The cores show decameter-scale intercalations between suspended-load fluvial deposits composed of fine sands with pedogenically modified overbank deposits, and very coarse-grained sands and gravels suggesting high-energy, bed-load-dominated fluvial systems. A total of 2,102 zircons were analyzed from six core intervals in HP1A and one interval in CMC1, and grouped into seven distinct populations. The youngest population (~ 44–23 Ma) originated from explosive volcanism associated with the mid-Cenozoic ignimbrite flare-up that blanketed large parts of western and southwestern North America in vast ash-flow tuffs and air-fall deposits. The six YC2σ(3+) MDAs from the HP1A core occur in a serial order that obeys the law of superposition, and Miocene age grains are lacking from all samples tested in southwestern Kansas. These results mirror previous analyses of samples from HP1A and additional cores from southwest Kansas showing Eocene to Oligocene maximum depositional ages and suggesting correlation with the Paleogene White River Group in Nebraska, previously unknown from Cenozoic strata in Kansas.

SUPPLEMENTAL MATERIAL

Tables SV1 and HPDZ are available from JSR's Data Archive: http://sepm.org/pages.aspx?pageid=229.

ACKNOWLEDGMENTS

We gratefully acknowledge support from the National Science Foundation Grant EAR-1023285, Kansas Water Office Grant KAN0066607, and the U.S. Geological Survey National Cooperative Geologic Mapping program under the guidance of the Kansas Geological Mapping Advisory Committee. We thank Majie Fan and an anonymous reviewer for their thoughtful reviews that greatly improved the clarity of this manuscript, and Gary Weissmann and Gary Hampson for their editorial assistance. Special thanks to Jay and Jarvis Garetson of Garetson Brothers Farms and the staff of the KGS Exploration Services. We thank colleagues Rolfe Mandel, Matt Joeckel, John Doveton, Joe Thomasson, Lynn Watney, Tammy Rittenour, Randy Stotler, Laura Murphy, and Kathryn Snell; and research assistants Bridgett Sanderson, Adrienne Duarte, Brian Sitek, and the staff of the KGS Geoarchaeology and Paleoenvironment Laboratory.

REFERENCES

Armstrong, R.L., and Ward, P.L., 1991, Evolving geographic patterns of Cenozoic magmatism in the North American Cordillera: the temporal and spatial association of magmatism and metamorphic core complexes: Journal of Geophysical Research, Solid Earth, v. 96, p. 13,201–13,224.

Bachmann, O., Dungan, M.A., and Lipman, P.W., 2002, The Fish Canyon magma body, San Juan volcanic field, Colorado: rejuvenation and eruption of an upper-crustal batholith: Journal of Petrology, v. 43, p. 1469–1503.

Best, M.G., Christiansen, E.H., Deino, A.L., and Gromme, S., 2013a, Introduction: the 36–18 Ma southern Great Basin, USA, ignimbrite province and flareup: swarms of subduction-related supervolcanoes: multicyclic super-eruptions: Geosphere, v. 9, p. 260–274.

Best, M.G., Christiansen, E.H., Deino, A.L., Gromme, S., Hart, G.L., and Tingey, D.G., 2013b, The 36–18 Ma Indian Peak–Caliente ignimbrite field and calderas, southeastern Great Basin, USA: multicyclic super-eruptions: Geosphere, v. 9, p. 864–950.

Best, M.G., Gromme, S., Deino, A.L., Christiansen, E.H., Hart, G.L., and Tingey, D.G., 2013c, The 36–18 Ma Central Nevada ignimbrite field and calderas, Great Basin, USA: multicyclic super-eruptions: Geosphere, v. 9, p. 1562–1636.

Blum, M., and Pecha, M., 2014, Mid-Cretaceous to Paleocene North American drainage reorganization from detrital zircons: Geology, v. 42, p. 607–610.

Blum, M.D., Milliken, K.T., Pecha, M.A., Snedden, J.W., Frederick, B.C., and Galloway, W.E., in press, Detrital-zircon records of Cenomanian, Paleocene, and Oligocene Gulf of Mexico drainage integration and sediment routing: implications for scales of basin-floor fans: Geosphere.

Boellstorff, J., 1978, Chronology of some late Cenozoic deposits from the central United States and the Ice Ages: Nebraska Academy of Science, Transactions, v. 6, p. 35–49.

Butler, J.J., Whittemore, D.O., Reboulet, E., Knobbe, S., Wilson, B.B., Stotler, R.L., and Bohling, G.C., 2015, High Plains Aquifer Index Well Program: 2014 Annual Report: Kansas Geological Survey, Open-file Report 2015-3, 147 p., accessed July 12, 2016.

Carey, J.S., Frye, J.C., Plummer, N., and Swineford, A., 1952, Kansas volcanic ash resources: Kansas Geological Survey, Bulletin 96, Part 1, p. 1–68.

Chapin, C.E., 2008, Interplay of oceanographic and paleoclimate events with tectonism during middle to late Miocene sedimentation across the southwestern USA: Geosphere, v. 4, p. 976–991.

Chapin, C.E., 2012, Origin of the Colorado mineral belt: Geosphere, v. 8, p. 28–43.

Chapin, C.E., Wilks, M., and McIntosh, W.C., 2004, Space–time patterns of Late Cretaceous to present magmatism in New Mexico–comparison with Andean volcanism and potential for future volcanism: New Mexico Bureau of Geology and Mineral Resources, Bulletin 160, p. 13–40.

Coney, P.J., 1978, Mesozoic–Cenozoic Cordilleran plate tectonics, *in* Smith, R.B., and Eaton, G.P., eds., Cenozoic Tectonics and Regional Geophysics of the Western Cordillera: Geological Society of America, Memoir 152, p. 33–50.

David, B.T., 2006, "Chemical fingerprinting" of volcanic tephra found in Kansas using trace elements [M.S. thesis]: Manhattan, Kansas, Kansas State University, 115 p.

Dennehy, K.F., 2000, High Plains regional ground-water study: U.S. Geological Survey, Fact Sheet, FS-091-00, p. 1–6.

Dickinson, W.R., 2004, Evolution of the North American Cordillera: Annual Review of Earth and Planetary Sciences, v. 32, p. 13–45.

Dickinson, W.R., and Gehrels, G.E., 2003, U-Pb ages of detrital zircons from Permian and Jurassic eolian sandstones of the Colorado Plateau, USA: paleogeographic implications: Sedimentary Geology, v. 163, p. 29–66.

Dickinson, W.R., and Gehrels, G.E., 2009a, Insights into North American Paleogeography and Paleotectonics from U–Pb ages of detrital zircons in Mesozoic strata of the Colorado Plateau, USA: International Journal of Earth Sciences, v. 99, p. 1247–1265.

Dickinson, W.R., and Gehrels, G.E., 2009b, U-Pb ages of detrital zircons in Jurassic eolian and associated sandstones of the Colorado Plateau: evidence for transcontinental dispersal and intraregional recycling of sediment: Geological Society of America, Bulletin, v. 121, p. 408–433.

Dickinson, W.R., and Gehrels, G.E., 2009c, Use of U-Pb ages of detrital zircons to infer maximum depositional ages of strata: a test against a Colorado Plateau Mesozoic database: Earth and Planetary Science Letters, v. 288, p. 115–125.

Dickinson, W.R., and Lawton, T.F., 2001, Carboniferous to Cretaceous assembly and fragmentation of Mexico: Geological Society of America, Bulletin, v. 113, p. 1142–1160.

Dickinson, W.R., Klute, M.A., Hayes, M.J., Janecke, S.U., Lundin, E.R., McKittrick, M.A., and Olivares, M.D., 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: Geological Society of America, Bulletin, v. 100, p. 1023–1039.

Diffendal, R.F., Jr., 1982, Regional implications of the geology of the Ogallala Group (upper Tertiary) of southwestern Morrill County, Nebraska, and adjacent areas: Geological Society of America, Bulletin, v. 93, p. 964–976.

Duller, R.A., Whittaker, A.C., Swinehart, J.B., Armitage, J.J., Sinclair, H.D., Bair, A., and Allen, P.A., 2012, Abrupt landscape change post-6 Ma on the central Great Plains, USA: Geology, v. 40, p. 871–874.

Ekren, E.B., McIntyre, D.H., and Bennett, E.H., 1984, High-Temperature, Large-Volume, Lavalike Ash-Flow Tuffs without Calderas in Southwestern Idaho: U.S. Geological Survey, Professional Paper 1272, 76 p.

Erb, E.E., Jr., 1979, Petrologic and structural evolution of ash-flow tuff cauldrons and noncauldron related volcanic rocks in the Animas and southern Peloncillo mountains, Hidalgo County, New Mexico [Ph.D. Dissertation]: Albuquerque, University of New Mexico, 286 p.

Eriksson, K.A., Campbell, I.H., Palin, J.M., Allen, C.M., and Bock, B., 2004, Evidence for multiple recycling in Neoproterozoic through Pennsylvanian sedimentary rocks of the Central Appalachian basin: Journal of Geology, v. 112, p. 261–276.

Fan, M.J., DeCelles, P.G., Gehrels, G.E., Dettman, D.L., Quade, J., and Peyton, S.L., 2011, Sedimentology, detrital zircon geochronology, and stable isotope geochemistry of the lower Eocene strata in the Wind River Basin, central Wyoming: Geological Society of America, Bulletin, v. 123, p. 979–996.

Fan, M., Mankin, A., and Chamberlain, K., 2015, Provenance and depositional ages of late Paleogene fluvial sedimentary rocks in the central Rocky Mountains, U.S.A: Journal of Sedimentary Research, v. 85, p. 1416–1430.

Field, H.L., 2017, Chronostratigraphic Interpretations of Cenozoic Paleosols in Nebraska Using Integrated U-Pb Dating and Carbon Isotope Chemostratigraphy [M.S. thesis]: Lawrence, Kansas, University of Kansas, 78 p.

Fielding, C.R., LaGarry, H.E., LaGarry, L.A., Bailey, B.E., and Swinehart, J.B., 2007, Sedimentology of the Whiteclay Gravel Beds (Ogallala Group) in northwestern Nebraska, USA: structurally controlled drainage promoted by early Miocene uplift of the Black Hills Dome: Sedimentary Geology, v. 202, p. 58–71.

Frye, J.C., and Hibbard, C.W., 1941, Stratigraphy and paleontology of a new middle and upper Pliocene formation of south-central Kansas: The Journal of Geology, v. 49, p. 261–278.

Frye, J.C., Leonard, A.B., and Swineford, A., 1956, Stratigraphy of the Ogallala Formation (Neogene) of Northern Kansas: Kansas Geological Survey, Bulletin 118, 92 p.

Galloway, W.E., Whiteaker, T.L., and Ganey-Curry, P., 2011, History of Cenozoic North American drainage basin evolution, sediment yield, and accumulation in the Gulf of Mexico basin: Geosphere, v. 7, p. 938–973.

Gehrels, G.E., Blakey, R., Karlstrom, K.E., Timmons, J.M., Dickinson, B., and Pecha, M., 2011, Detrital zircon U-Pb geochronology of Paleozoic strata in the Grand Canyon, Arizona: Lithosphere, v. 3, p. 183–200.

Gleason, J.D., Gehrels, G.E., Dickinson, W.R., Patchett, P.J., and Kring, D.A., 2007, Laurentian sources for detrital zircon grains in turbidite and deltaic sandstones of the Pennsylvanian Haymond Formation, Marathon assemblage, west Texas, USA: Journal of Sedimentary Research, v. 77, p. 888–900.

Goldberg, S.A., and Dallmeyer, R.D., 1997, Chronology of Paleozoic metamorphism and deformation in the Blue Ridge thrust complex, North Carolina and Tennessee: American Journal of Science, v. 297, p. 488–526.

Guitreau, M., Mukasa, S.B., Blichert-Toft, J., and Fahnestock, M.F., 2016, Pikes Peak batholith (Colorado, USA) revisited: a SIMS and LA-ICP-MS study of zircon U–Pb ages combined with solution Hf isotopic compositions: Precambrian Research, v. 280, p. 179–194.

Gustavson, T.C., and Winkler, D.A., 1988, Depositional facies of the Miocene–Pliocene Ogallala Formation, northwestern Texas and eastern New Mexico, Geology, v. 16, p. 203–206.

Gutentag, E.D., Heimes, F.J., Krothe, N.C., Luckey, R.R., and Weeks, J.B., 1984, Geohydrology of the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: High Plains RASA Project, U.S. Geological Survey, Professional Paper 1400-B, 63 p.

Halfen, A.F., and Hasiotis S.T., 2010, Downward thinking: rethinking the "up" in soil bioturbation: 19th World Congress of Soil Science, Soil Solutions for a Changing World, 1–6 August 2010, Brisbane, Australia, Published on DVD.

Hallman, J.A., 2016, Spatial and temporal patterns of Ogallala Formation deposition revealed by U-Pb zircon geochronology [M.S. thesis]: Lawrence, Kansas, University of Kansas, 94 p.

Harlan, S.S., Snee, L.W., Geissman, J.W., and Brearley, A.J., 1994, Paleomagnetism of the Middle Proterozoic Laramie Anorthosite Complex and Sherman Granite, southern Laramie Range, Wyoming and Colorado: Journal of Geophysical Research, Solid Earth, v. 99, no. B9, p. 17,997–18,020.

Harlow, R.H., 2013, Depositional and Paleoclimatic Evolution of the Cenozoic High Plains Succession: Haskell Co., Kansas [M.S. thesis]: Lawrence, University of Kansas, 125 p.

Hatcher, R.D., Jr., 1989, Tectonic synthesis of the U.S. Appalachians, *in* Thomas, W.A., Hatcher, R.D., Jr., and Viele, G.W., eds., The Appalachian–Ouachita orogen in the United States: Geological Society of America, The Geology of North America v. F-2, p. 511–535.

Heller, P.L., Dueker, K., and McMillan, M.E., 2003, Post-Paleozoic alluvial gravel transport as evidence of continental tilting in the U.S. Cordillera: Geological Society of America, Bulletin, v. 115, p. 1122–1132.

Henry, C.D., and Price, J.G., 1984, Variations in caldera development in the Tertiary volcanic field of Trans-Pecos Texas: Journal of Geophysical Research, v. 89, p. 8765–8786.

Henry, C.D., Kunk, M.J., and McIntosh, W.C., 1994, ^{40}Ar/ ^{39}Ar chronology and volcanology of silicic volcanism in the Davis Mountains, Trans-Pecos Texas: Geological Society of America, Bulletin, v. 106, p. 1359–1376.

Hibbard, C.W., 1952, Vertebrate Fossils from Late Cenozoic deposits of central Kansas: University of Kansas Paleontological Contributions, Vertebrata, Article 2, p. 1–14.

Hietpas, J., Samson, S., and Moecher, D., 2011, A direct comparison of the ages of detrital monazite versus detrital zircon in Appalachian foreland basin sandstones: searching for the record of Phanerozoic orogenic events: Earth and Planetary Science Letters, v. 310, p. 488–497.

Hoffman, P.F., 1989, Precambrian geology and tectonic history of North America, *in* Bally, A.W., and Palmer, A.R., eds., The Geology of North America—An Overview: Geological Society of America, The Geology of North America v. A, p. 447–512.

Hoke, G.D., Schmitz, M.D., and Bowring, S.A., 2014, An ultrasonic method for isolating non-clay components from clay-rich material: Geochemistry, Geophysics, Geosystems, v. 15, p. 492–498.

Houston, R.S., 1993, Late Archean and Early Proterozoic geology of southeastern Wyoming, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming, Memoir 5, p. 78–117.

Izett, G.A., and Wilcox, R.E., 1982, Map showing localities and inferred distributions of the Huckleberry Ridge, Mesa Falls, and Lava Creek ash beds (Pearlette family ash beds) of Pliocene and Pleistocene age in the western United States and southern Canada: U.S. Geological Survey, Miscellaneous Investigations Series, Map I-3225, scale 1:4,000,000.

Jackson, S.E., Pearson, N.J., Griffin, W.L., and Belousova, E.A., 2004, The application of laser ablation–inductively coupled plasma-mass spectrometry to *in situ* U–Pb zircon geochronology: Chemical Geology, v. 211, p. 47–69.

Joeckel, R.M., Wooden, S.R., Jr., Korus, J.T., and Garbisch, J.O., 2014, Architecture, heterogeneity, and origin of late Miocene fluvial deposits hosting the most important aquifer in the Great Plains, USA: Sedimentary Geology, v. 311, p. 75–95.

Keller, S.M., and Morgan, M.L., 2016, Overview of the Eocene Castle Rock Conglomerate, east-central Colorado: remapping the fluvial system, and implications for the history of the Colorado Piedmont and Front Range: Geological Society of America, Field Guides, v. 44, p. 125–141.

Kluth, C.F., 1986, Plate tectonics of the Ancestral Rocky Mountains, *in* Peterson, J.A., ed., Paleotectonics and Sedimentation in the Rocky Mountain Region: American Association of Petroleum Geologists, Memoir 41, p. 353–369.

Kraus, M.J., 1999, Paleosols in clastic sedimentary rocks: their geologic applications: Earth-Science Reviews, v. 47, p. 41–70.

Laskowski, A.K., DeCelles, P.G., and Gehrels, G.E., 2013, Detrital zircon geochronology of Cordilleran retroarc foreland basin strata, western North America: Tectonics, v. 32, p. 1027–1048.

Layzell, A.L., Mandel, R.D., Ludvigson, G.A., Rittenour, T.M., and Smith, J.J., 2015, Forces driving late Pleistocene (ca. 77–12 ka) landscape evolution in the Cimarron River valley, southwestern Kansas: Quaternary Research, v. 84, p. 106–117.

Layzell, A.L., Mandel, R.D., Rittenour, T.M., Smith, J.J., Harlow, R.H., and Ludvigson, G.A., 2016, Stratigraphy, morphology, and geochemistry of late Quaternary buried soils on the High Plains of southwestern Kansas, USA: Catena, v. 144, p. 45–55.

Leonard, E.M., 2002, Geomorphic and tectonic forcing of late Cenozoic warping of the Colorado piedmont, Geology: v. 30, p. 595–598.

Liggett, G.A., 1997, The Beckerdite local biota (early Hemphillian) and the first Tertiary occurrence of a crocodilian from Kansas: Kansas Academy of Science, Transactions, v. 100, p. 101–108.

Liggett, G.A., Zakrzewski, R.J., and McNinch, K.L., 1998, Geologic and paleontologic investigation of the Cimarron National Grassland, Morton County, Kansas: Dakoterra, v. 5, p. 123–126.

Lipman, P.W., and Bachmann, O., 2015, Ignimbrites to batholiths: integrating perspectives from geological, geophysical, and geochronological data: Geosphere, v. 11, p. 705–743.

Liu, L., 2015, The ups and downs of North America: evaluating the role of mantle dynamic topography since the Mesozoic: Reviews of Geophysics, v. 53, p. 1022–1049.

Lowe, D.J., 2011, Tephrochronology and its application: a review: Quaternary Geochronology, v. 6, p. 107–153.

Ludvigson, G.A., Sawin, R.S., Franseen, E.K., Watney, W.L., West, R.R., and Smith, J.J., 2009, Review of the stratigraphy of the Ogallala Formation and revision of Neogene (“Tertiary”) nomenclature in Kansas: current research in earth science: Kansas Geological Survey, Bulletin 256, Part 2, p. 1–9.

Ludvigson, G.A., Mandel, R., Macfarlane, A., and Smith, J.J., 2016, Capturing the record of Neogene climate change from strata of the High Plains Aquifer in Kansas: research activities and findings: Kansas Geological Survey, Open-File Report 2016-31, 32 p.

Ludwig, K.R., 2012, Isoplot 4.15: a geochronological toolkit for Microsoft Excel: Berkeley Geochronology Center, Special Publication 5, revised January 30, 2012.

Macfarlane, P.A., 2000, Revisions to the nomenclature for Kansas aquifers: Kansas Geological Survey, Bulletin 244, Part 2, p. 1–14.

Macfarlane, P.A., 2009, New insights into the hydrostratigraphy of the High Plains aquifer from three-dimensional visualizations based on well records: Geosphere, v. 5, p. 51–58.

Macfarlane, P.A., and Wilson, B.B., 2006, Enhancement of the Bedrock-Surface-Elevation Map Beneath the Ogallala Portion of the High Plains Aquifer, Western Kansas: Kansas Geological Survey, Technical Series 20, 28 p.

Martin, R.A., and Peláez-Compomanes, P., 2014, Diversity dynamics of the late Cenozoic rodent community from southwestern Kansas: the influence of historical processes on community structure: Journal of Quaternary Science, v. 29, p. 221–231.

Mason, B.G., Pyle, D.M., and Oppenheimer, C., 2004, The size and frequency of the largest explosive eruptions on Earth: Bulletin of Volcanology, v. 66, p. 735–748.

May, S.R., Gray, G.G., Summa, L.L., Stewart, N.R., Gehrels, G.E., and Pecha, M.E., 2013, Detrital zircon geochronology from the Bighorn Basin, Wyoming, USA: implications for tectonostratigraphic evolution and paleogeography: Geological Society of America, Bulletin, v. 125, p. 1403–1422.

McGuire, V.L., 2014, Water-level changes and change in water in storage in the High Plains aquifer, predevelopment to 2013 and 2011–13: U.S. Geological Survey, Scientific Investigations Report 2014–5218, 14 p.

McIntosh, W.C., and Chapin, C.E., 2004, Geochronology of the central Colorado volcanic field: New Mexico Bureau of Geology and Mineral Resources, Bulletin 160, p. 205–236.

McIntosh, W.C., Sutter, J.F., Chapin, C.E., and Kedzie, L.L., 1990, High-precision ^{40}Ar/^{39}Ar sanidine geochronology of ignimbrites in the Mogollon–Datil volcanic field, southwestern New Mexico: Bulletin of Volcanology, v. 52, p. 584–601.

McMahon, P.B., Dennehy, K.F., Michel, R.L., Sophocleous, M.A., Ellett, K.M., and Hurlbut, D.B., 2003, Water movement through thick unsaturated zones overlying the central High Plains aquifer, southwestern Kansas, 2000–2001: U.S. Geological Survey, Water-Resources Investigations, Report 03–4171, 32 p.

McMillan, M.E., Angevine, C.L., and Heller, P.L., 2002, Postdepositional tilt of the Miocene–Pliocene Ogallala Group on the western Great Plains: evidence of late Cenozoic uplift of the Rocky Mountains: Geology, v. 30, p. 63–66.

Miall, A.D., 2010, The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology: Berlin, Springer, 582 p.

Moecher, D.P., and Samson, S.D., 2006, Differential zircon fertility of source terranes and natural bias in the detrital zircon record: implications for sedimentary provenance analysis: Earth and Planetary Science Letters, v. 247, p. 252–266.

Morgan, L.A., and McIntosh, W.C., 2005, Timing and development of the Heise volcanic field, Snake River Plain, Idaho, western USA: Geological Society of America, Bulletin, v. 117, p. 288–306.

Murphy, J.B., Pisarevsky, S.A., Nance, R.D., and Keppie, J.D., 2004, Neoproterozoic–early Paleozoic evolution of peri-Gondwanan terranes: implications for Laurentia–Gondwana connections: International Journal of Earth Sciences, v. 93, p. 659–682.

Naeser, C.W., Izett, G.A., and Wilcox, R.E., 1973, Zircon fission-track ages of Pearlette family ash beds in Meade County, Kansas: Geology, v. 1, p. 93–95.

Paton, C., Hellstrom, J., Paul, B., Woodhead, J., and Hergt, J., 2011, Iolite: freeware for the visualisation and processing of mass spectrometric data: Journal of Analytical Atomic Spectrometry, v. 26, p. 2508–2518.

Perkins, M.E., 1998, Tephrochronologic and volcanologic studies of silicic fallout tuffs in Miocene basins of the northern Basin and Range Province, U.S.A [Ph.D. Dissertation]: The University of Utah, Salt Lake City, Utah, UMI Dissertation Services, Microform No. 9913253, Ann Arbor, Michigan, 206 p.

Perkins, M.E., and Nash, B.P., 2002, Explosive silicic volcanism of the Yellowstone Hotspot: the ash fall tuff record: Geological Society of America, Bulletin, v. 114, p. 367–381.

Perkins, M.E., Diffendal, R.F., Jr., and Voorhies, M.R., 1995, Tephrochronology of the Ash Hollow Formation (Ogallala Group): Northern High Plains [Abstract]: Geological Society of America, Abstracts with Programs, v. 27, p. 79.

Petrus, J.A., and Kamber, B.S., 2012, VizualAge: a novel approach to laser ablation ICP-MS U-Pb geochronology data reduction: Geostandards and Geoanalytical Research, v. 36, p. 247–270.

Pierce, K.L., and Morgan, L.A., 1992, The track of the Yellowstone hot spot: volcanism, faulting and uplift, *in* Link, P.K., Kuntz, M.A., and Platt, L.B., eds., Regional Geology of Eastern Idaho and Western Wyoming: Geological Society of America, Memoir 179, p. 1–53.

Potter, S.L., 1991, Geologic characteristics of the Calvert ash bed, Ogallala Group (Miocene), western Kansas [M.S. thesis]: Fort Hays State University, Hays, Kansas: American Geological Institute, GeoRef Accession No. 1994–056771, 93 p.

Rainbird, R.H., Cawood, P., and Gehrels, G., 2012, The great Grenvillian sedimentation episode: record of supercontinent Rodinia's assembly, *in* Busby, C., and Azor, A., eds., Tectonics of Sedimentary Basins: Recent Advances: New Jersey, Wiley-Blackwell, p. 583–601.

Rowley, J., and Fan, M., 2016, Middle Cenozoic diachronous shift to eolian deposition in the central Rocky Mountains: timing, provenance, and significance for paleoclimate, tectonics, and paleogeography: Geosphere, v. 12, p. 1795–1812.

Rowley, P.D., Mehnert, H.H., Naeser, C.W., Snee, L.W., Cunningham, C.G., Steven, T.A., Anderson, J.J., Sable, E.G., and Anderson, R.E., 1994, Isotopic ages and stratigraphy of Cenozoic rocks of the Marysvale volcanic field and adjacent areas, west-central Utah: U.S. Geological Survey, Bulletin 2071, 35 p.

Rytuba, J.J., and McKee, E.H., 1984, Peralkaline Ash Flow Tuffs and Calderas of the McDermitt Volcanic Field, Southeast Oregon and North Central Nevada: Journal of Geophysical Research, v. 89, p. 8616–8628.

Saylor, J.E., and Sundell, K.E., 2016, Quantifying comparison of large detrital geochronology data sets: Geosphere, v. 12, p. 1–18.

Seager, W.R., 1973, Resurgent volcano-tectonic depression of Oligocene age, south-central New Mexico [Abstract]: Geological Society of America, Abstracts with Programs v. 84, p. 3611–3626.

Seni, S.J., 1980, Sand-body geometry and depositional systems, Ogallala Formation, Texas: University of Texas at Austin, Bureau of Economic Geology, Report of Investigations, no. 105, 36 p.

Sharman, G.R., Covault, J.A., Stockli, D.F., Wroblewski, A.F.-J., and Bush, M.A., 2017, Early Cenozoic drainage reorganization of the United States western interior–Gulf of Mexico sediment routing system: Geology, v. 45, p. 187–190.

Shaw, C.A., and Karlstrom, K.E., 1999, The Yavapai–Mazatzal crustal boundary in the Southern Rocky Mountains: Rocky Mountain Geology, v. 34, p. 37–52.

Sitek, B.C., 2017, Analyzing the Cenozoic Depositional History of Western Kansas: A New Approach Using Paleosol Zircon Geochronology [M.S. thesis]: Lawrence, Kansas, University of Kansas, 49 p.

Sláma, J., Košler, J., Condon, D.J., Crowley, J.L., Gerdes, A., Hanchar, J.M., Horstwood, M.S.A., Morris, G.A., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, B., Tubrett, M.N., and Whitehouse, M.J., 2008, Plešovice zircon: a new natural reference material for U–Pb and Hf isotopic microanalysis: Chemical Geology, v. 249, p. 1–35.

Smith, J.J., Platt, B.F., Ludvigson, G.A., and Thomasson, J.R., 2011, Ant-nest ichnofossils in honeycomb calcretes, Neogene Ogallala Formation, High Plains region of western Kansas, U.S.A: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 308, p. 383–394.

Smith, J.J., Ludvigson, G.A., Harlow, R.H., Doveton, J.A., Zeigler, K., Petronis, M., Möller, A., Feldman, J., Stotler, R., and Rittenour, T.M., 2013, Paleogene strata of the High Plains in western Kansas? Preliminary radiometric dates from volcanogenic zircons in mature paleosols [Abstract]: Geological Society of America, Abstracts with Programs, v. 45, p. 478.

Smith, J.J., Platt, B.F., Ludvigson, G.A., Sawin, R.S., Marshall, C.P., and Olcott-Marshall, A., 2015, Enigmatic red beds exposed at Point of Rocks, Cimarron National Grassland, Morton County, Kansas: chronostratigraphic constraints from uranium–lead dating of detrital zircons: Kansas Geological Survey, Bulletin 261, 17 p., 1 appendix.

Smith, J.J., Layzell, A.L., Lukens, W.E., Morgan, M.L., Keller, S.M., Martin, R.A., and Fox, D.L., 2016, Getting to the bottom of the High Plains aquifer: new insights into the depositional history, stratigraphy, and paleoecology of the Cenozoic High Plains: Geological Society of America, Field Guides, v. 44, p. 93–124.

Soil Survey Staff, 1982, Procedure for collecting soil samples and methods of analysis for soil survey: Soil Survey Investigations Report 1, U.S. Department of Agriculture, Soil Conservation Service, Washington, D.C., 74 p.

Soreghan, G.S., and Soreghan, M.J., 2013, Tracing clastic delivery to the Permian Delaware Basin, USA: implications for paleogeography and circulation in westernmost equatorial Pangea: Journal of Sedimentary Research, v. 83, p. 786–802.

Sorenson, R.P., 2005, A dynamic model for the Permian Panhandle and Hugoton fields, western Anadarko basin: American Association of Petroleum Geologists, Bulletin, v. 89, p. 921–938.

Sweet, A.C., Soreghan, G.S., Sweet, D.E., Soreghan, M.J., and Madden, A.S., 2013, Permian dust in Oklahoma: source and origin for Middle Permian (Flowerpot–Blaine) redbeds in Western Tropical Pangaea: Sedimentary Geology, v. 284, p. 181–196.

Swineford, A., Frye, J.C., and Leonard, B., 1955, Petrography of the late Tertiary volcanic ashfalls in the central Great Plains: Journal of Sedimentary Petrology, v. 25, p. 243–261.

Swineford, A., Leonard, A.B., and Frye, J.C., 1958, Petrology of the pisolitic limestone in the Great Plains: Kansas Geological Survey, Bulletin 130, Part 2, p. 97–116.

Swinehart, J.B., Souders, V.L., Degraw, H.M., and Diffendal, R.F., Jr., 1985, Cenozoic paleogeography of western Nebraska, *in* Flores, R.M., and Kaplan, S.S., eds., Cenozoic Paleogeography of West-Central United States: SEPM, Rocky Mountain Section, p. 209–229.

Thomas, W.A., Becker, T.P., Samson, S.D., and Hamilton, M.A., 2004, Detrital zircon evidence of a recycled orogenic foreland provenance for Alleghenian clastic-wedge sandstones: Journal of Geology, v. 112, p. 23–37.

Thomasson, J.R., 1990, Fossil plants from the late Miocene Ogallala Formation of central North America: possible paleoenvironmental and biostratigraphic significance, *in* Gustavson, T.C., ed., Geologic Framework and Regional Hydrology: Upper Cenozoic Blackwater Draw and Ogallala Formations, Great Plains: University of Texas at Austin, Bureau of Economic Geology, Symposium Publication no. 6, p. 99–114.

Thomasson, J.R., 2005, *Berriochloa gabeli* and *Berriochloa huletti* (Gramineae: Stipeae), two new grass species from the late Miocene Ash Hollow of Nebraska and Kansas: Journal of Paleontology, v. 79, p. 185–199.

Torres, R., Ruiz, J., Patchett, P.J., and Grajales, J.M., 1999, Permo-Triassic continental arc in eastern Mexico: tectonic implications for reconstructions of southern North America, *in* Bartolini, C., Wilson, J.L., and Lawton, T.F., eds., Mesozoic Sedimentary and Tectonic History of North-Central Mexico: Geological Society of America, Special Paper 340, p. 191–196.

Tweto, O., 1979, Geologic map of Colorado: U.S. Geological Survey, Special Map, scale 1:500,000.

Vermeesch, P., 2004, How many grains are needed for a provenance study?: Earth and Planetary Science Letters, v. 224, p. 441–451.

Vermeesch, P., 2012, On the visualization of detrital age distributions: Chemical Geology, v. 312–313, p. 190–194.

Ward, P.A., III, Carter, B.J., and Weaver, B., 1993, Volcanic ashes: time markers in soil parent materials of the southern plains: Soil Science Society of America, Journal, v. 57, p. 453–460.

Watney, W.L., Youle, J., Hedke, D., Gerlach, P., Sorenson, R., Dubois, M., Nicholson, L., Hansen, T., Koger, D., and Baker, R., 2013, Sedimentologic and stratigraphic effects of episodic structural activity during the Phanerozoic in the Hugoton Embayment, Kansas, USA: American Association of Petroleum Geologists, Annual Convention and Exhibition, Article #90163, Pittsburgh, Pennsylvania, May 21.

Weissmann, G.S., Hartley, A.J., Nichols, G.J., Scuderi, L.A., Olson, M., Buehler, H., and Banteah, R., 2010, Fluvial form in modern continental sedimentary basins: distributive fluvial systems: Geology, v. 38, p. 39–42.

Whitmeyer, S.J., and Karlstrom, K.E., 2007, Tectonic model for the Proterozoic growth of North America: Geosphere, v. 3, p. 220–259.

Wotzlaw, J.-F., Schaltegger, U., Frick, D.A., Dungan, M.A., Gerdes, A., and Günther, D., 2013, Tracking the evolution of large-volume silicic magma reservoirs from assembly to supereruption: Geology, v. 41, p. 867–870.

Zakrzewski, R.J., 1988, Preliminary report on fossil mammals from the Ogallala (Miocene) of north-central Kansas: Fort Hays Studies Science Series 10, p. 117–127.

Zakrzewski, R.J., 1990, Biostratigraphy of fossil mammals from the Ogallala (Miocene) of north-central Kansas [Abstract], *in* Gustavson, T.C., ed., Geologic Framework and Regional Hydrology: Upper Cenozoic Blackwater Draw and Ogallala Formations, Great Plains: Bureau of Economic Geology, University of Texas, Austin, p. 98.

Received 10 January 2017; accepted 2 June 2017.