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LAKES, LOESS, AND PALEOSOLS IN THE PERMIAN WELLINGTON FORMATION OF OKLAHOMA, U.S.A.: IMPLICATIONS FOR PALEOCLIMATE AND PALEOGEOGRAPHY OF THE MIDCONTINENT

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ABSTRACT: **Lower to mid-Permian deposits of the Midcontinent (U.S.A.) record a significant and long recognized aridification because they archive the shift from more humid facies (e.g., coal, organic shale) of the Pennsylvanian to widespread redbeds, semiarid to seasonal paleosols (Calcisols, Vertisols), and evaporites by the mid-Permian. The provenance, transport and depositional processes of the voluminous Permian redbeds of the Midcontinent, however, remain largely undefined. The Artinskian Wellington Formation in Oklahoma exhibits high-frequency cycles comprising organic-rich laminated mudstone with thinly laminated (inferred primary) dolomite, variegated laminated mudstone with gypsum, massive, red to gray-green mudstone with pedogenic overprinting, and pale red siltstone. The gypsum exhibits a distinct $^{87/86}$Sr isotopic ratio (0.709199) that is inconsistent with Permian seawater. We suggest that these facies record deposition in ephemeral to perennial lakes during a time of increasing aridity and seasonality, the latter indicated by abundant mudcracks, vertic-type paleosols, conchostracans, and lungfish burrows. The fine and uniform grain size and the geochemistry of the siliciclastic component suggest far-travelled and likely eolian transport that ultimately accumulated in both subaqueous and subaerial environments. Provenance analysis indicates the siliciclastic component was sourced chiefly from the southeastern Ouachita–Appalachian orogen and the Ancestral Rocky Mountains (ARM) or its derivative sediment.**

INTRODUCTION

The late Paleozoic records Earth's "best known" pre-Quaternary ice age characterized by an "extreme" climate (Kutzbach and Gallimore 1989; Crowell 1999; Fielding et al. 2008). Attendant with Pangean assembly, the equatorial Central Pangean Mountains formed and atmospheric circulation shifted from zonal to monsoonal, resulting in cross-equatorial flow and marked seasonality (Kutzbach and Gallimore 1989; Parrish 1993). For reasons that remain debated (Tabor and Poulsen 2008), a significant shift in climate from more humid to arid conditions occurred in the Permian, especially in western equatorial Pangaea. In Midcontinent North America, this aridity shift corresponds to the deposition of the first regionally extensive redbed units by mid-Permian time. The highly weathered nature of these mudstone and evaporite outcrops, however, has hindered attempts to constrain the depositional setting, provenance, and climatic implications (Chaplin 2004).

This study focuses on detailed analysis of a whole core of the Wellington Formation (Fig. 1A) from northern Oklahoma (Fig. 1B), with additional observations from a laterally extensive quarried outcrop (Kay County Quarry) of the same interval. Our objective is to address the depositional environments, source(s) and transport mechanism(s) of the siliciclastic sediment and, thereby, paleoclimatic implications of this regionally extensive unit. Specifically, this study assesses whether 1) the facies reflect principally continental (lacustrine, loess, and paleosol) deposition, rather than the previously interpreted marginal marine environment; and 2) eolian transport was the chief mechanism for the (volumetrically predominant) siliciclastic component of the Wellington Formation. These findings bear on improving constraints on regional paleoclimatic conditions, including atmospheric circulation in this part of western Pangaea, during a time of major climatic transition in the late Paleozoic.

GEOLOGIC SETTING AND CONTROVERSIES

The late Paleozoic Gondwanan–Laurasian plate collision produced the equatorial Central Pangean Mountains (CPM; Scotese et al. 1979; Blakey 2007), expressed in southeastern–mid North America as the Appalachian–Ouachita foldbelt (Fig. 2). This collision was roughly coeval with formation of the intracratonic Ancestral Rocky Mountains (ARM) in western Pangaea (Fig. 2; Kluth and Coney 1981). Between these tectonic domains, the Midcontinent region of the U.S. (central Pangaea) generally formed a low-gradient, low-elevation landscape in nearly equatorial latitudes ($\sim 5°$ S to $\sim 5°$ N; Tabor et al. 2008) during Pennsylvanian through Permian time. Superimposed on this low-gradient paleogeography was the Amarillo–Wichita uplift and adjacent Anadarko basin and (northward) Hugoton embayment to the west and southwest and the Ozark uplift and Ouachita uplifts to the east and southeast (Fig. 2; McKee and Oriel 1967; Johnson et al. 1989). By Permian time, however, several uplifts began to subside (De Voto 1980; Gilbert 1992; Sweet and Soreghan 2010; Soreghan et al. 2012), such that the Amarillo and Wichita uplifts were covered by lower–middle Permian strata (Johnson 1989; Price et al. 1996; Gilbert 2002; Soreghan et al. 2012). Similarly, Upper Pennsylvanian and Permian strata, including the Wellington Formation in parts of Oklahoma, blanket the Precambrian-cored Nemaha ridge

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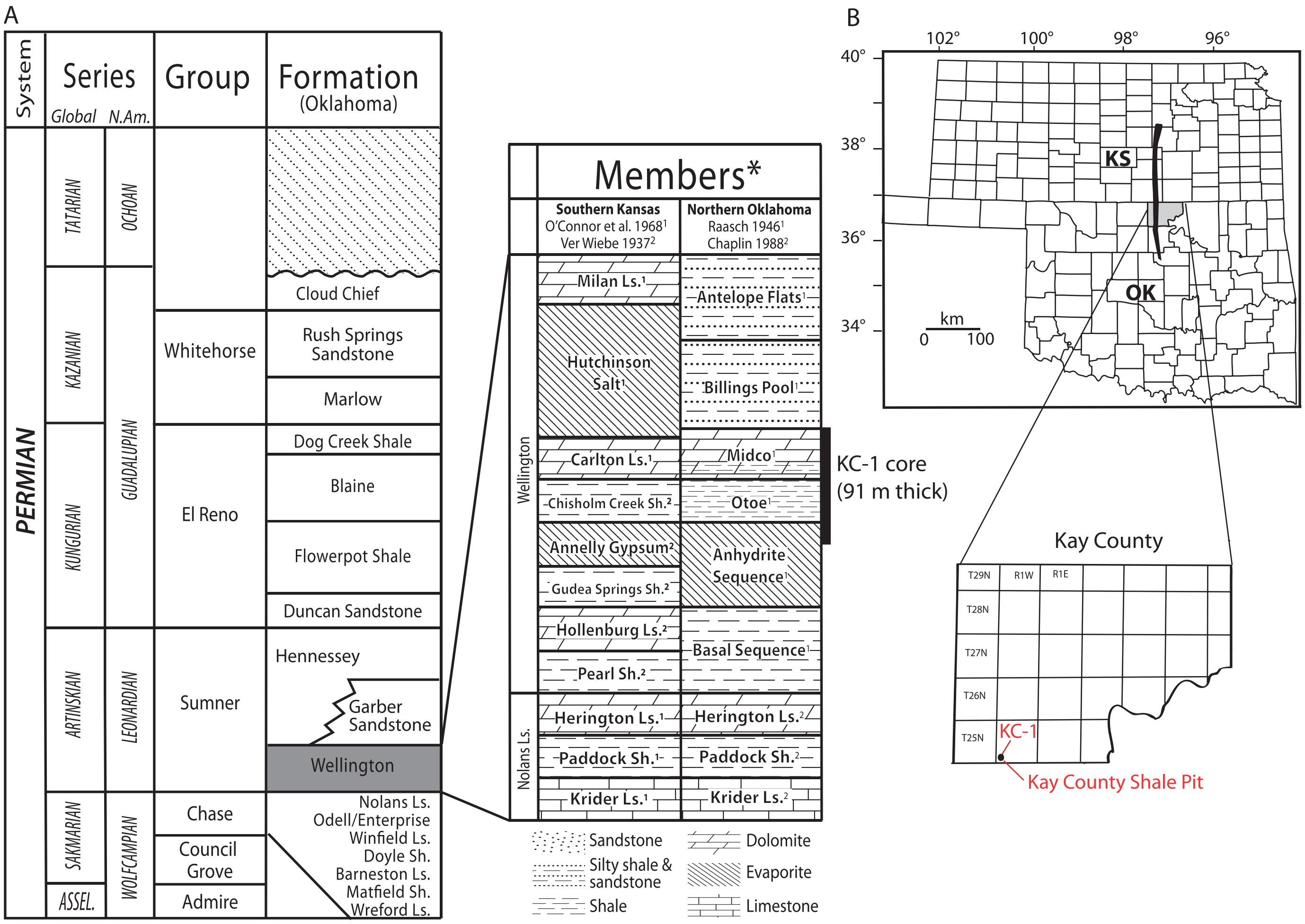


FIG. 1.—**A)** Permian stratigraphy of outcrops in north-central Oklahoma, combined and modified from Dunbar et al. (1960), Wilson (1962), Chaplin (1988), and Johnson et al. (2001). The units and lithology of the Wellington Formation and the Nolans Limestone are shown for Oklahoma and Kansas, based on the work of Ver Wiebe (1937), Raasch (1946), O'Connor et al. (1968), and Chaplin (1988). The superscripts 1 and 2 in the inset column refer to the specific source that defined the units in Kansas and Oklahoma. *Stratigraphic names of Wellington and Nolans are members unless otherwise stated, viz. Anhydrite and Basal sequences. **B)** Study area of Kay County, Oklahoma depicting the location of the KC-1 core and Kay County Shale Pit outcrop (modified from Chaplin 2004).

(Fig. 2; Luza 1978; Chaplin 1988). This region remained equatorial (~ 5° S to ~ 2° N) from Virgilian (Gzhelian) through Leonardian (Kungurian) time (Tabor et al. 2008).

Through much of the late Paleozoic, "icehouse" conditions characterized by repeated waxing and waning of continental ice sheets (Veevers and Powell 1987; Crowell 1999; Fielding et al. 2008; Fischbein et al. 2009) produced pervasive cyclothems at low latitudes (Wanless and Shepard 1936; Heckel 1986; Veevers and Powell 1987). Upper Paleozoic strata of the Midcontinent record both glacioeustasy and the onset of increasing aridity (Tabor et al. 2008). From the Pennsylvanian to the mid-late Permian, deposition in the Midcontinent shifted from limestone–shale cyclothems of the Chase and Council Grove groups to redbeds and evaporites of the Nippewalla and El Reno groups (Fig. 1; Johnson et al. 1989; Golonka and Ford 2000; Heckel 2007). The Leonardian (Artinskian) Sumner Group, including the Wellington Formation described here, marks the transition between the underlying limestone–shale cyclothems and the overlying redbeds and evaporites.

The Wellington Formation of the Sumner Group crops out in a narrow strip from northern Oklahoma into mid-Kansas (Fig. 1B; Mazzullo 1999; Hall 2004). The Wellington Formation is 250 m (820 ft) thick (Raasch 1946) and encompasses six members; this study focuses on the Anhydrite sequence and the Otoe and Midco members (Fig. 1A). Gypsum or anhydrite, siltstone, shale, and mudstone with subordinate dolomudstone and dolomite constitute the lithology of the Wellington Formation in Oklahoma (Fig. 3; Raasch 1946; Boardman 1999; Chaplin 2004). The Wellington and coeval deposits are commonly capped by the coarser-grained Garber Sandstone (Fig. 1A) in Oklahoma, whereas northward (Kansas) evaporites, including bedded halite in the Hutchinson Salt (Fig. 1A; Fig. 2; Swineford and Runnels 1953; Jones 1965; Watney et al. 1988), overlie the Wellington.

Controversy exists over the depositional environment of the Wellington Formation, with older studies suggesting deposition partly in a lacustrine setting (Dunbar 1924; Raasch 1946; Tasch 1961a, 1964) and newer studies postulating marine or marginal marine conditions (Mazzullo 1999; Chaplin 2004; Hall 2004). Most studies inferring a marine origin for the Oklahoma strata focused on the dolomite and evaporite facies, owing to poor outcrop exposures that precluded detailed petrographic descriptions of other facies. Chaplin (2004) provided general interpretations of the Wellington Formation based on newly obtained whole core (including the core used in this study); however, he focused primarily on the underlying Chase and Council Grove formations of unequivocal marine origin. For the Wellington Formation, studies favoring a

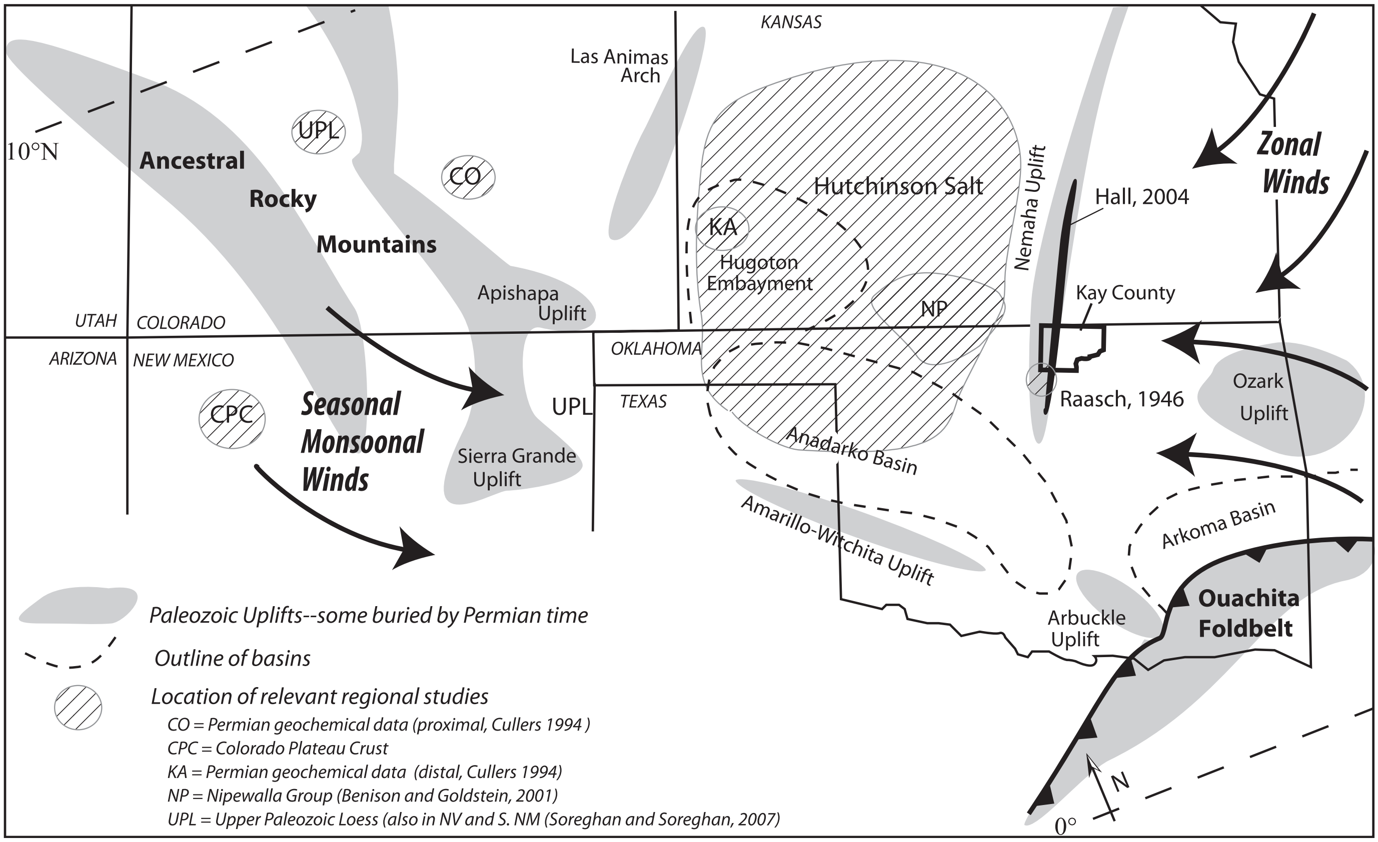


FIG. 2.—Leonardian paleogeography of the Midcontinent showing main features mentioned in text. Arrows show general directions of zonal winds (seasonally shifting from southeasterlies to northeasterlies as intertropical convergence zone migrates) and inferred seasonal monsoonal westerlies. Locations of geochemical datasets from other Permian strata used in this study are indicated on map by diagonal lines. Locations and relative sizes of uplifts and basins are based on Berg (1977), McKee and Oriel (1967), Johnson et al. (1989), Algeo and Heckel (2008), and Soreghan et al. (2012).

continental origin are based on selected paleontological aspects (e.g., insect beds) constrained to certain horizons. Few studies have focused on the siliciclastic strata, which dominate by volume. Finally, recent fluid-inclusion and sedimentology work by Benison and Goldstein (2001, 2002) suggests that the overlying Nippewalla Group in Kansas consists of acid saline lake deposits amid mudflat, eolian, and paleosol siliciclastic deposits. A continental origin for even parts of the Wellington Formation would significantly alter paleogeographic and paleoclimatic reconstructions and attendant depositional and transport pathways for this time and region.

METHODS

This study centers on the KC-1 core from Kay County, Oklahoma (Fig. 1B), drilled by the Oklahoma Geological Survey using freshwater as the drilling fluid. The cored interval begins at the surface and extends ~ 91 m, penetrating the upper Anhydrite sequence, the Otoe Member, and most of the Midco Member of the Wellington Formation, which crops out at the surface (Fig. 3); thus, the Billings Pool and Antelope Flats members were not present in the core. We slabbed intervals of the core and described the entire core at centimeter-scale resolution. Representative samples of all facies were selected for thin-section and geochemical analysis. Additional facies data are based on field observations of the Wellington Formation exposed in the Kay County Shale Pit (36° 35′ 53.31″ N, 97° 21′ 0.85″ W) immediately adjacent to the core site (Chaplin 2004). This quarry exposes the Midco Member of the Wellington in three dimensions over ~ 200 m. This aided in more definitive descriptions of facies contacts and lateral variability of facies.

Four siliciclastic facies and two chemical sediment facies were identified using macroscopic sedimentologic features supplemented by petrographic and SEM observations and geochemical and mineralogical characterization. Thirty-five thin sections were examined. The core description, including facies thicknesses and vertical transitions, was used to calculate facies abundances and determine the most common facies transitions using a transition-count matrix, an approach similar to Markov-chain analysis (Carr 1982; Driese and Dott 1984). Five representative samples were disaggregated using sodium phosphate ($Na_6O_{18}P_6$) and sonication for 10 minutes for grain-size analysis. Although grain-size analysis on lithified rocks can be problematic, the Permian rocks in north central Oklahoma have not been buried very deeply, $<$ 1 km (Carter et al. 1998). The mudstones are poorly indurated, even in core, and petrographic examination indicates that the facies are poorly cemented, such that the sonicated sediment provides a reasonable approximation of the original sediment texture. The measured grain size likely represents a maximum, in the event any weak cements persisted. Analyses of the disaggregated sediment after treatment was performed using a Beckman-Coulter LS-230 laser particle size analyzer. In addition, the mass and grain size of the "acid-insoluble-residue" (siliciclastic fraction) was determined from eight dolomite samples through dissolution in 2N HCL to infer detrital influx during carbonate deposition. Source-rock-analyzer-based TOC and pyrolysis data were collected on 10 dark mudstone samples by Weatherford Laboratories.

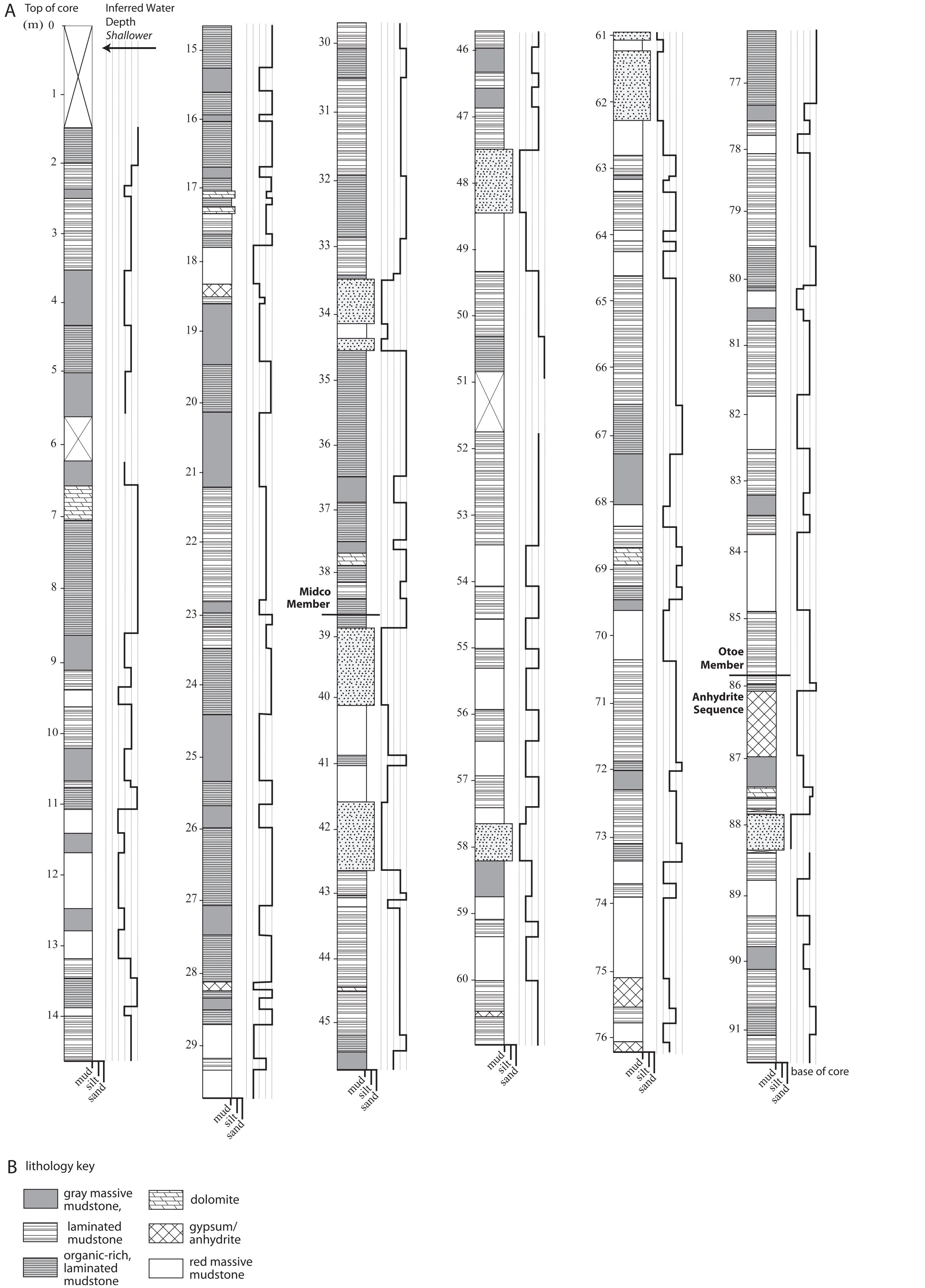
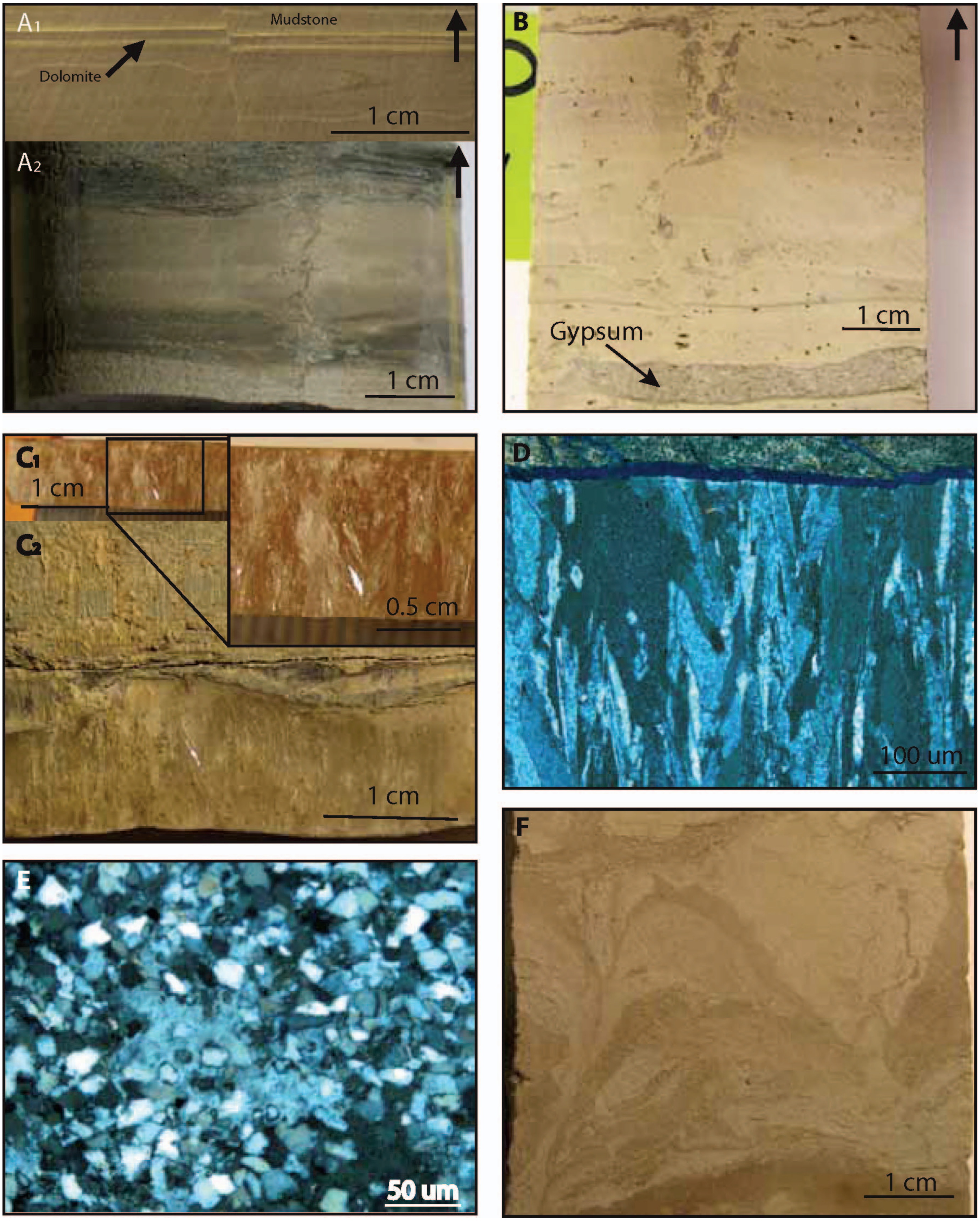


FIG. 3.—Stratigraphic column of the Wellington Formation in the KC-1 core illustrating facies, inferred water level, and the boundary of the members encompassed by the cored interval.

TABLE 1.—*Summary descriptions and interpretations of the main facies in the Permian Wellington Formation.*

	Facies		Grain Size		Lithology	Color	Features	Mineralogy	Environmental Interpretation	
Siliciclastic Facies	Siltstone Lithofacies		fine silt	10 µm (st dev = .6)	Siltstone	Light brown to pale orange	Massive to faintly laminated or chaotic bedding +/− patchy fabric, rare root traces	Primarily subangular to angular quartz; rutile, muscovite, zircon, chlorite, K-feldspar, and pyrite	Subaerial (eolian) suspension deposition; overprinting by pedogenesis, disruption by salt crusts	↑
	Massive Mudstone Lithofacies	Red massive mudstone	very fine silt to clay	4 µm (st dev = .2)	Mudstone; gypsum	Dark red to purple	Massive bedding +/− slickensides & laminae of gypsum; local ped-like structures	Primarily clay (illite and smectite) subangular to angular quartz; chlorite, rutile, K-feldspar	Both subaerial (eolian and minor unconfined flow deposits) and subaqueous suspension deposition. Extensive pedogenesis.	
		Gray massive mudstone	very fine silt to clay	4 µm (st dev = .2)		Lt gray and/or greenish or bluish gray		Primarily clay (illite and smectite) angular quartz, muscovite; quartz, chlorite, rutile, muscovite, and biotite		
	Laminated Mudstone Lithofacies	Variegated mudstone	clay	3 µm (st dev = .3)	Mudstone; dolomite; gypsum	Variable and mixed: red, grey, yellow, brown, white	Laminated (mm-scale) to wavy or chaotic bedding with evaporite and dolomite laminae +/− small slickensides, mudcracks, burrows, root traces, brecciated fabrics, rare conchocostracans, rare cubic casts	Primarily clay (illite and smectite) some angular quartz grains; albite, iron oxides, quartz, muscovite, chlorite, and pyrite	Low-energy, subaqueous suspension settling into perennial lake, likely shallow, some desiccation and pedogenesis	Shallowing-upward "cycle"
		Organic-rich mudstone	very fine silt to clay	4 µm (st dev = .2)	Mudstone; dolomite	Lt gray - black; some yellow and/or green	Laminated (mm-scale) dolomite and dark mudstone	Mudstone: Primarily clay (illite and smectite) Few angular quartz grains; muscovite and pyrite. Dolomitic micrite	Low-energy subaqueous suspension settling in perennial-lake environment. Likely deeper with less evidence for desiccation	
Chemical Facies	Dolomite Lithofacies		n/a	~ 1–5 µm	Dolomite; Ca/Mg = ~1–1.2; ~25% siliciclastics	White - buff	Laminated (mm-scale) or thicker beds +/− desiccation cracks, rare burrows, microcrystalline texture, fenestral fabric	Accessory mineralogy = zircon, quartz, K-feldspar, albite, chlorite, iron oxides, celestite, barite, pyrite	Low-energy subaqueous perennial-lake environment.	
	Gypsum Lithofacies		n/a	n/a	Gypsum; relatively pure	Clear, white, or stained red	Laminated (small-scale) or thicker beds intermixed with mudstone +/− vertically oriented crystals +/− displacive crystals in mudstone.	Gypsum and/or anhydrite	Subaqueous deposition (bottom growth and laminated habits) to penecontemporaneous formation (displacive habits); High-salinity water	


A1
Mudstone
Dolomite
1 cm
A2
1 cm
B
1 cm
Gypsum
C1
1 cm
C2
0.5 cm
1 cm
D
100 um
E
50 um
F
1 cm

Qualitative phase identification on representative samples from each facies was accomplished by backscattered electron imaging coupled with energy-dispersive X-ray analysis (EDXA) using 20 kV accelerating voltage and 10 nA beam current (see details in Pack 2010). In addition, 35 samples from siliciclastic facies throughout the core were powdered, processed to eliminate carbonate-bound Ca (following Soreghan and Soreghan 2007), and analyzed for major and trace elements using combined XRF and ICP-MS. Finally, a Rigaku automated wide-angle X-ray diffractometer (XRD) with a graphite monochromator and copper tube (CuK, 40 kV, 30 mV) was used to characterize clay mineralogy; runs were conducted between 4 and 70° 2θ with step size of 0.05° 2θ and 5 s dwell time. Oriented aggregate mounts for XRD were prepared following Poppe et al. (2002).

For detrital-zircon geochronological analysis, we used a siltstone sample from the middle of the Midco Member of the Wellington collected from the quarry outcrop (to obtain sufficient sample from a specific stratum). For analysis, 2 kg of the siltstone was processed using standard crushing and heavy-mineral separation techniques (Gehrels et al. 2008). The analytical procedures in employing the Micromass Isoprobe at the University of Arizona closely followed those described in detail by Dickinson and Gehrels (2008) except that a spot diameter of 25 μm was utilized because of the fine grain size of the zircon. A crystal of the Sri Lankan zircon (564 ± 4 Ma (2θ error)) was analyzed for calibration every five unknowns. The interpreted age for grains < 1 Ga are taken from $^{206}Pb/^{238}U$ ages whereas grains > 1 Ga are based on $^{206}Pb/^{207}Pb$ ages; these ages are summarized in Appendix 1 (see Acknowledgments). Age uncertainties are reported at the 1-sigma level and include only measurement or analytical errors. Ages were analyzed for discordance by comparing the $^{206}Pb/^{207}Pb$ ages to the $^{206}Pb/^{238}U$ ages for those grains > 1 Ga; a 30% difference was used to filter the data. In total, 79 grains were retained for analysis, and the data are presented as a cumulative probability plot in which the age and associated errors of each grain are summed.

For strontium isotope analyses, gypsum samples were selected representing pristine (unrecrystallized) examples of the various morphologies present (laminated, displacive, and bottom-growth crystals). External surfaces were cleaned and the gypsum was powdered using a drill equipped with an ultra-fine bit. Approximately 2 mg of each sample powder was placed in 4 ml of quartz-distilled water for 1 week until no visible sample remained. Subsequently, 0.8 ml of Seastar 14 molar NHO_3 was added to each vial, to make the solution approximately 3 N HNO^3. The samples were slowly pumped through 50 microliter Sr spec columns equilibrated with 3 N HNO_3. Approximately 1 ml more 3 N HNO_3 was used to wash the other ions from the columns. The Sr was eluted with 2 ml of quartz-distilled water and dried on a hotplate with 1 drop of dilute phosphoric acid. The samples were loaded on Re center filaments with a Ta activator and run at approximately 1400°C in multi-dynamic mode on a IsotopX PhoeniX64. A small correction of 0.000006 was applied to each sample to account for the slight difference between the measured value of NBS987 and the recommended value of 0.710248.

RESULTS

Results are presented in two parts: 1) description and interpretation of facies comprising the KC-1 core (summarized in Table 1), supplemented with outcrop observations; 2) geochemical and detrital-zircon geochronologic characterization of the Wellington siliciclastic facies for inferring provenance.

Facies Analysis

Dolomite

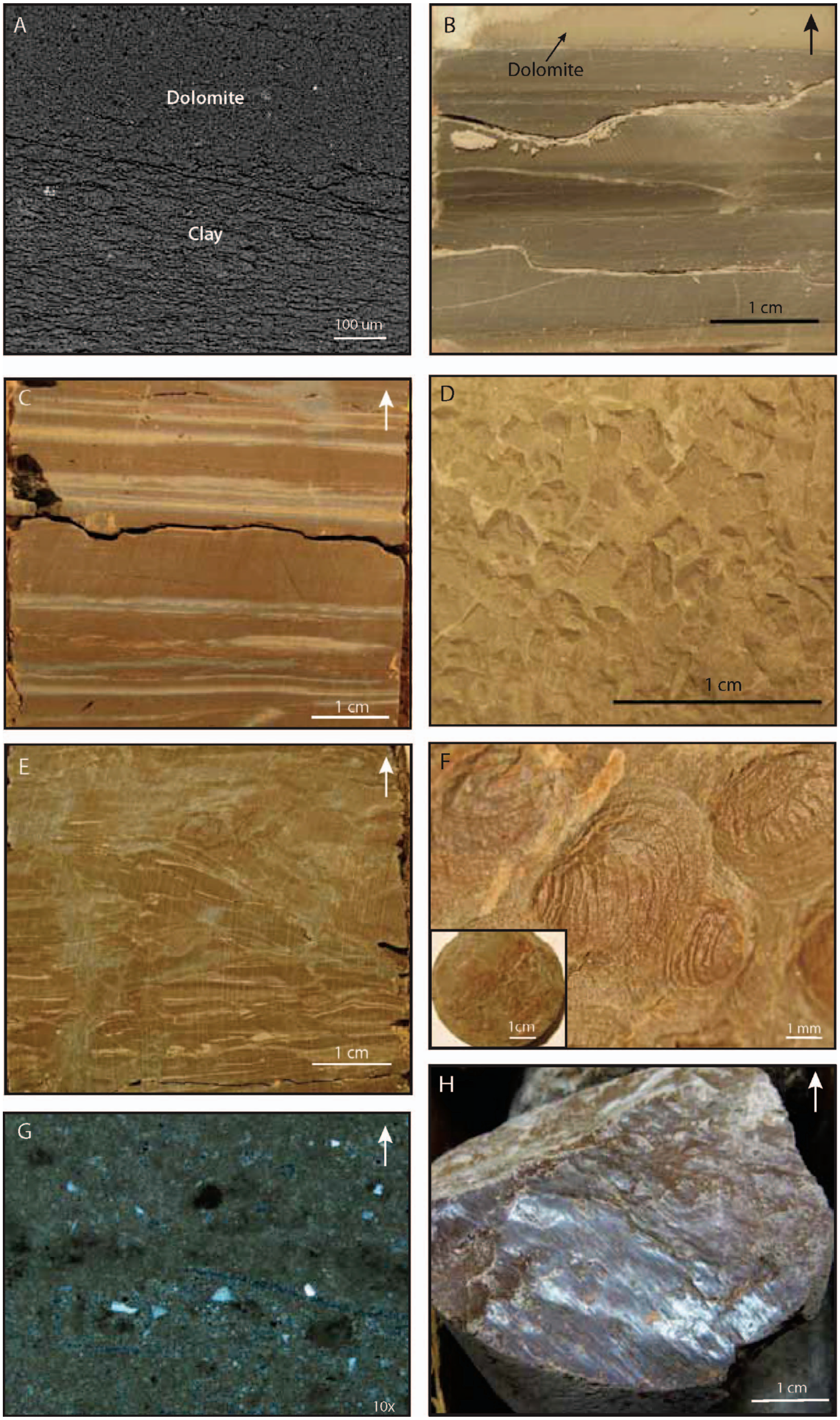
Description.—The dolomite mudstone facies is very fine grained (clay to very fine silt), white to light gray, and occurs as (1) microlaminae intercalated with siliciclastic facies (Fig. 4A1, Fig. 5A), or (2) thicker (4 to 48 cm, average 17 cm), structureless to vaguely laminated beds (Fig. 4A2) that compose 2% of the core. Insoluble residue of the dolomite mudstone averages 25.2% ($n = 5$), and consists predominantly of quartz, potassium feldspar, iron oxides, and pyrite. Microprobe images reveal aggregates of rhombohedral dolomite crystals (~ 1–5 μm) with a Ca/Mg ratio of ~ 1–1.2. Secondary minerals include pyrite and Fe oxides in addition to trace amounts of various silicate minerals. Common thin vertical cracks and/or rare infilled vertical structures occur (Fig. 4B). Gypsum locally occurs as thin interbeds in the dolomite (Fig. 4B). In outcrop, the dolomite is laterally continuous (Fig. 6A), with sharp upper and lower bases (Fig. 6B, C).

Interpretation.—The dolomite is interpreted as primary, because it (1) occurs as discrete beds, particularly as laminae interlayered with siliciclastic mudstone, (2) displays a very fine-grained (micritic) texture (Last 1990), and (3) lacks any petrographic evidence for replacement textures or dolomitization of biogenic calcite or aragonite (Garcia del Cura et al. 2001). Primary dolomite is typically microcrystalline and characterized by a fine (less than about 10 μm) grain size (Folk 1973; von der Borch 1976; Vasconcelos and McKenzie 1997). Dolomite with a larger grain size and a saccharoidal texture is commonly secondary and displays evidence of replacement (von der Borch 1976). Primary dolomite of lacustrine origin is typically very fine grained (< 1–2 μm) and forms aggregates (Last 1990), like the Wellington dolomite. The coexistence of iron oxides and pyrite in the dolomite and associated laminated facies is consistent with dolomite formation from metabolic activity of bacteria (Trudinger et al. 1985; Last 1990; Machel 2004; Sanz-Montero et al. 2009). In low temperatures and anoxic conditions, bacterial sulfate reduction is the main process that produces pyrite (Trudinger et al. 1985; Williams-Stroud 1994; Machel 2004). During bacterial sulfate reduction, metabolic CO_2 and bicarbonate ions are released, providing ideal conditions for carbonate formation in general (Sanz-Montero et al. 2009) and primary dolomite in particular (Vasconcelos and McKenzie 1997; Sanchez-Roman et al. 2008, 2009).

The intercalation of millimeter- to submillimeter-scale laminae of dolomite and siliciclastic material suggests subaqueous suspension deposition into a quiet-water environment. There are no indications of flaser, ripple, or any other type of stratification indicative of traction processes, and individual beds are laterally continuous across the quarry face. There are, however, indications of exposure or shallow, subaqueous conditions superimposed on the dolomite mudstone facies. For example, we interpret the very fine vertical cracks (Fig. 4A2) as mudcracks, indicating that exposure and periodic wetting and drying occurred after the dolomite laminae formed. The larger infilled vertical structures (Fig. 4B) are likely vertical burrows that suggest oxic (shallower-water) conditions existed subsequent to dolomite formation.

←

FIG. 4.—Characteristic sedimentary features of various facies in the Wellington core. **A1)** ~ 1-mm-thick dolomite laminae (227.4 ft, 69.3 m; Otoe), and **A2)** thicker, bedded dolomite (white or light) ~ 1.25 cm thick with desiccation cracks (51.0 ft, 15.5 m; Midco). **B)** Microcrystalline dolomite with evaporite(?) voids, laminations of gypsum, and a burrow (22.5 ft, 6.9 m; Midco). **C)** Gypsum with vertical crystal growth. **C1)** A swallow-tail gypsum crystal (248.0 ft, 75.6 m; Otoe); **C2)** A mud drape over gypsum crystals; both are indicative of subaqueous, primary origin (61.1 ft, 18.6 m; Midco). **D)** Thin section of vertically growing crystals capped by dissolution surface, suggesting subaqueous origin (60.0 ft, 18.3 m; Midco). **E)** Photomicrograph displaying well-sorted angular to subangular quartz grains of siltstone facies (279.3 ft, 85.1 m; Otoe). **F)** Mound-shaped structure within the siltstone facies (128.0 ft, 39 m; Otoe).


A
Dolomite
Clay
100 um
B
Dolomite
1 cm
C
1 cm
D
1 cm
E
1 cm
F
1cm
1 mm
G
10x
H
1 cm

Pure dolomite of stoichiometric composition has a Ca/Mg ratio of 1; therefore, the Ca/Mg ratio of the dolomite here suggests a relatively stoichiometric dolomite (Chilingar 1957; Last 1990; Machel 2004) similar to modern dolomite in saline lakes, although the stoichiometric composition of dolomite remains equivocal as the chief means of distinguishing between marine and lacustrine environments (Last 1990).

Gypsum

Description.—Gypsum occurs in three forms (in order of abundance), 1) thicker beds intercalated with siliciclastic material that display vertically oriented crystals, 2) laminae in mudstone facies (discussed below), and 3) displacive nodular gypsum in mudstone. The thicker gypsum beds compose 3% of the Wellington Group in the core. The vertically oriented crystals widen upward, originate from a common plane, and exhibit a sharp contact with the overlying mudstone (Fig. 4C1, D). The overlying mudstone thickens over depressions and thins over raised gypsum crystal terminations (Fig. 4C2). The transition to overlying mudstone typically consists of a layer of gypsum regrowth over a thin layer of mud or a sharp contact with truncated crystals. Rare nodular beds of gypsum occur with vague remains of vertically twinned gypsum rhombs. No replacement textures have been identified in thin-section or microprobe analysis. Microprobe analysis indicates nearly pure calcium sulfate, with less than 0.1 wt% other (mostly silicate) phases. Strontium isotope data ($^{87}Sr/^{86}Sr$) collected from five gypsum samples, representing all three occurrences of gypsum and lacking any textural evidence of replacement, are listed in Table 2. The values range from 0.708688 to 0.709711 and average 0.709199.

Interpretation.—The vertically aligned (swallow-tail) crystals of gypsum record subaqueous bottom precipitation in saline surface water (Benison et al. 2007). The upward-widening habit of the vertical gypsum crystals and their origination from a common plane support a primary, subaqueous origin as bottom-growth crystals (Gibert et al. 2007). The thickening and thinning of mudstone directly above the vertical gypsum crystals indicates that subaqueous gypsum precipitation occurred prior to deposition of the mud, which infilled microtopography (Spencer and Lowenstein 1990). Sharp contacts with the overlying mudstone that truncate the tops of the underlying gypsum crystals suggest dissolution prior to mud deposition.

The displacive gypsum crystals likely reflect penecontemporaneous formation in the host mud. Similar displacive habits form in the shallow subsurface in both modern saline lakes and sabkhas (Spencer and Lowenstein 1990; Benison et al. 2007). Some of the displacive gypsum beds, however, do appear to have altered from anhydrite to gypsum (or vice versa), which readily occurs at shallow burial depths (Warren 1989; Gibert et al. 2007).

The Sr-isotope data from all gypsum morphologies (laminated, displacive, and bottom growth) are inconsistent with (and significantly higher than) Permian seawater values reported by Korte et al. (2006), indicating that the gypsum did not precipitate from waters directly connected to marine sources. This is discussed in more detail below, but the data indicate a significant continental source for the Sr, and thus, strong evidence for a continental origin rather than a supratidal or sabkha setting for gypsum formation.

Siltstone

Description.—The very fine siltstone facies varies from pale orange to brown to locally white to light gray, and composes 8% of the core. It consists of well-sorted, angular to subangular siliciclastic (mostly quartz) grains (Fig. 4E) of fine silt (10 μm); the clay-size fraction ranges from ~ 19 to 70% (average ~ 34%). The siltstone facies occurs in massive beds 10 cm to 1.2 m thick, with common soft-sediment deformation and chaotic bedding (Fig. 4F). Downwardly bifurcating, vertical traces (2 to 5 cm long) occur locally. Typically, basal contacts are slightly gradational with the underlying massive mudstone facies, whereas upper contacts are typically sharp and capped by the organic or variegated mudstone facies. Although the siltstone facies is present through the middle and lower portion of the core, it is absent in the upper ~ 33 m. In the quarry outcrop, the siltstone appears massive and highly fractured, and is laterally continuous, with mottling, peds, and vertical traces along the upper surface.

Interpretation.—The fine-grained and consistently well-sorted texture suggests eolian transport for this facies (Pye 1987; Tsoar and Pye 1987). The very fine grain size reflects longer-term suspension and, therefore, transport from a relatively distant source (Pye 1987; Smalley et al. 2005). In addition, massive bedding and gradational contacts are most consistent with suspension fallout during eolian transport as opposed to traction deposition (Pye 1987; Johnson 1989). Rare root traces (i.e., rhizoliths) and poorly developed pedogenic overprinting (see below) record exposure and preclude subaqueous deposition. The soft-sediment deformation in this facies could reflect seismites (Montenat et al. 2007) whereas the chaotic bedding may be a result of extensive bioturbation (Smoot and Lowenstein 1991). An alternate method of forming soft-sediment deformation, chaotic bedding, and patchy fabrics, however, is through precipitation of efflorescent salt crusts. These salt deposits are typically very thin, easily dissolved, and rarely preserved (Smoot and Castens-Seidell 1994). In highly permeable sediment, such as silt, the growth of efflorescent salt results in mounds ranging from 2 to 4 cm that deform subjacent structures and create a "popcorn like" texture that can trap silt in depressions, as seen in both modern saline pans (Smoot and Castens-Seidell 1994) and Permian saline deposits (Benison and Goldstein 2000, 2001).

Organic Mudstone Facies

Description.—The organic mudstone facies is predominantly dark gray to greenish black (Fig. 5B, 6B) and composes 23% of the study section. The average grain size is very fine silt to clay (4 μm). Light-colored, thin laminae of subangular to angular coarse silt quartz grains occur commonly. Total organic carbon (TOC) values are 0.78–1.09 wt.%, averaging ~ 0.92 wt%, and Rock-Eval data indicate immature, type IV kerogen. Microprobe (Fig. 5A) and cathodoluminescence imaging indicate (sub-millimeter- to millimeter-scale) planar laminae consisting of alternating dark-colored calcareous mudstone and light-colored dolomite, locally convoluted. Muscovite, pyrite, and quartz occur in the clastic laminae, similar to the mineralogy of the gray massive mudstone. XRD analysis indicates less quartz compared to the red-colored facies and a clay-rich matrix, consisting of micas, kaolinite, and chlorite.

←

FIG. 5.—**A)** SEM-BSE image of dolomite laminae in organic mudstone facies (dolomite produces brighter reflectance in CL; 219.4 ft, 66.9 m; Otoe). **B)** Typical laminae in organic mudstone facies exhibiting color variations of gray, black, and lighter-colored dolomite. Notice possible oil staining (24.9 ft, 7.6 m; Midco). **C)** Typical expression of laminae in the variegated mudstone facies. Notice color variation among laminae (144.8 ft, 44.1 m; Otoe). **D)** Cubic halite casts (11.1 ft, 3.4 m; Midco) in variegated mudstone facies. **E)** Wavy to sinuous complex mudcracks in variegated mudstone facies viewed in cross section (239.5 ft, 73.0 m; Otoe). **F)** Imprints of conchostracans, sizes range from ~ 1–5 mm (179.0 ft, 54.6 m; Otoe). **G)** Photomicrograph showing "floating" quartz grains in clay matrix (153.4 ft, 46.8 m; Otoe) of massive mudstone facies. **H)** Slickensides (205 ft, 62.5 m; Otoe) in massive mudstone facies.

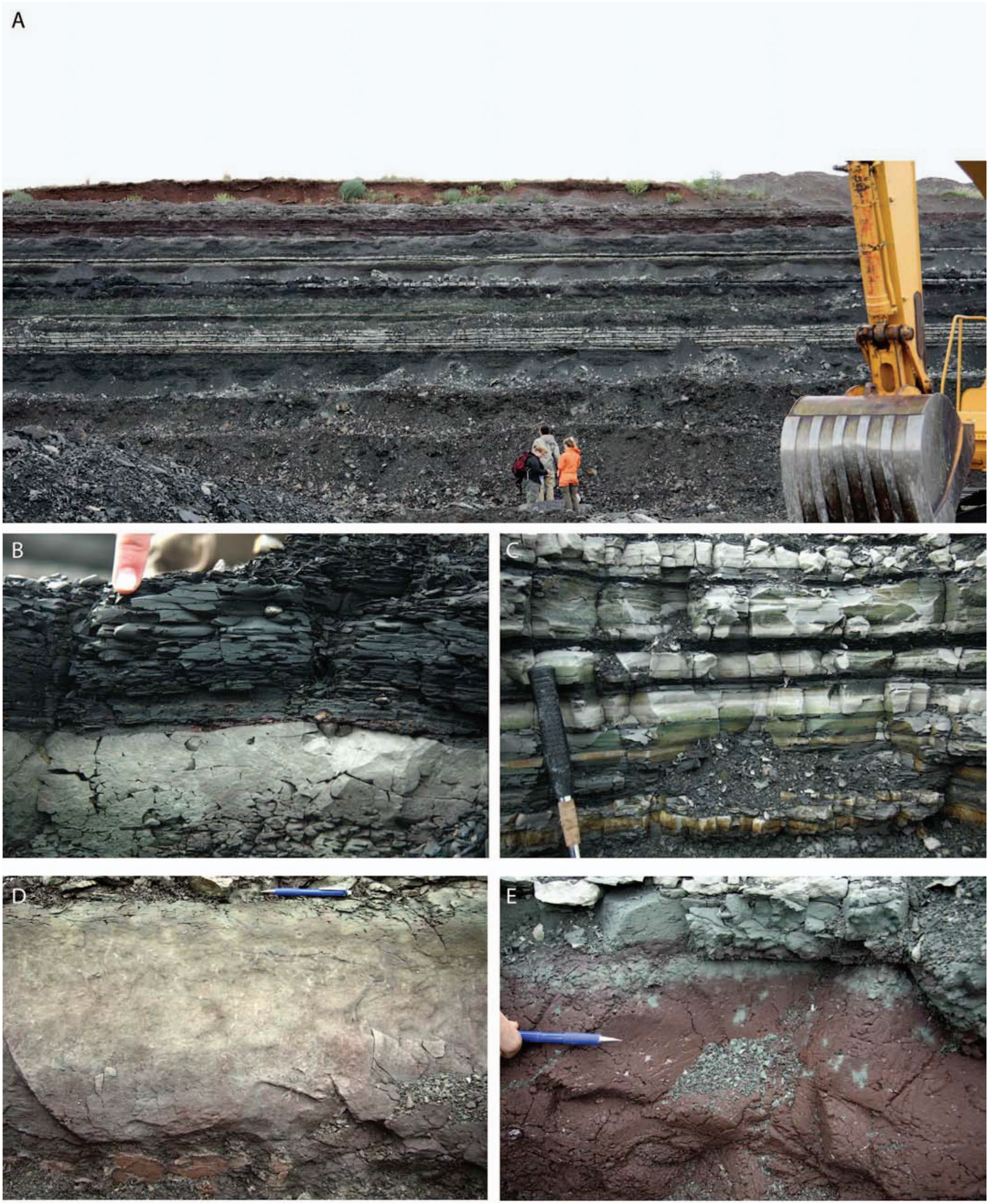


FIG. 6.—Outcrop photos of facies in Midco Member. **A)** Photo across quarry face illustrating the thin-bedded, continuous nature of the facies and lack of scouring. **B)** Organic mudstone facies sharply overlying a thicker dolomite bed. **C)** Interbedded dolomite and organic mudstone. **D)** Outcrop of massive mudstone showing gradational nature at base from underlying variegated mudstone facies. **E)** Blocky peds and reduction features in the massive mudstone facies.

TABLE 2.—*Strontium isotope data from gypsum beds in the Wellington Formation.*

Sample Identifier	Gypsum Growth Habit	$^{87/86}$Sr (raw)	$^{87/86}$Sr (corrected)	2-Sigma Error
Gy26.5	displacive	0.70918	0.709186	0.0004
Gy26.5r	displacive	0.7092375	0.7092435	0.00006
197.1b	bottom growth	0.709244	0.70925	0.0001
KCl60.1	displacive	0.709094	0.7091	0.00009
Gy92.4	laminated	0.708682	0.708688	0.00008
197.1a	bottom growth	0.709705	0.709711	0.00007

Dolomite laminae are abundant in this facies, occurring as either laminae, beds up to 8 cm thick, or small round clasts (Figs. 5A, B, 6C). In contrast to the abundant mudcracks in the laminated mudstone facies (described below), this facies rarely exhibits vertical cracks. Overlying facies are mainly the laminated mudstone or locally the massive mudstone or siltstone facies. Basal contacts are typically sharp from the underlying massive mudstone or siltstone facies or rarely the variegated mudstone.

Interpretation.—The dark color, elevated TOC values, and planar lamination indicate a low-energy, low-oxygen, subaqueous environment. Although such conditions are commonly associated with deep water, they can also occur in shallow basins if salinity gradients are sufficient to reduce vertical mixing (e.g., Great Salt Lake, Utah; Hardie et al. 1978). The convolute laminae could reflect seismic activity (Montenat et al. 2007), or perhaps mass-flow processes (Benison and Goldstein 2001), although the regional, low-relief setting argues against the slopes necessary for the latter. The alternating high- and low-TOC mudstone laminae suggest seasonality during deposition (Allen and Collinson 1986), whereas the dolomite laminae represent increased carbonate input (Last 1990). As noted above, the fine-scale, relatively pure laminae of dolomite interlaminated with the organic mudstone suggests subaqueous, suspension settling.

Laminated Mudstone Facies

Description.—Laminated, variegated mudstone is the most common facies in the core, composing 30% of the section. Individual beds of very fine silt to clay (3–4 μm) laminae average ~ 50 cm thick. Various colors, chiefly red with less common orange, white, brown, yellow, and gray occur, varying among millimeter scale laminae (Fig. 5C). Planar to wavy laminae at the sub-millimeter to millimeter scale are most common, but chaotic and/or brecciated intervals also occur. Lamination typically fines upward and consists of light-colored very fine silt, dolomite, or red or gray mud; rare laminae of peloids also occur. Dolomite appears in the form of small-scale (~ 0.1–6 cm) planar laminae, small rounded clasts, or disseminated within the mudstone laminae. Gypsum is common in this facies and occurs as planar beds 1–2 cm thick, or as displacive crystals. Rare cube-shaped casts occur on bedding planes in the upper 3.5 m of core (Fig. 5D).

Rare, downwardly bifurcating traces occur in this facies along with thin vertical cracks (1–3 mm wide), randomly oriented slickensides, and chaotic bedding (Fig. 5E). Rare imprints of whole branchiopod crustacean conchostraca (~ 1–5 mm in diameter; identified by Dr. P. Murry, Tarleton State University, personal communication, 2010; Dr. R. Scott, University of Tulsa, personal communication, 2010) occur on bedding planes (Fig. 5F); these conchostraca are whole and unfragmented and exhibit well-developed growth lines. Generally, the organic or (rarely) massive mudstone facies underlies this facies, whereas the massive mudstone or siltstone facies gradationally overlie this facies.

Interpretation.—The millimeter scale laminae and conchostracans indicate deposition in a low-energy subaqueous environment (Tasch 1964; Smoot 1993). In the Permian, conchostracans typically lived in continental environments and tolerated a range of salinities (Tasch 1964; Swanson and Carlson 2002; Park and Gierlowski-Kordesch 2007; Scott 2010). The taphonomy (unabraded and unfragmented) of these bioclasts indicates little transport prior to death. Tasch (1961a, 1961b, 1962) and Swanson and Carlson (2002) noted that conchostracans are common in the Wellington Formation on bedding planes of dolomite–mudstone intervals.

The laminae of dolomite are similar in texture and grain size to the thicker laminated (inferred primary) dolomite. The presence of very fine-grained, laminated dolomite supports subaqueous deposition of the laminated mudstone facies. Also, the thin, planar laminae of gypsum with vertically oriented crystals are likely primary, further supporting a subaqueous origin. The cubic casts record halite casts (Benison and Goldstein 2001); the alignment of these cubes along bedding planes suggests that the halite formed in the water column and settled to the bottom.

Although the evidence suggests a predominance of subaqueous deposition, periodic subaerial exposure is indicated by 1) root traces and slickensides, which reflect pedogenesis (Retallack 1990), and 2) mudcracks and brecciated fabrics, which further indicate subaerial exposure. The irregular (wavy) shape of the mudcracks is consistent with highly saline environments (Hardie et al. 1978), whereas the brecciated fabric could indicate incipient pedogenesis.

Massive Mudstone Facies

Description.—The massive mudstone facies is variably dark red to purple or light gray to greenish with reddish to purple hues more common in the Otoe Member and drab gray colors more common in the younger Midco Member (Fig. 6D). Regardless of color, all display massive bedding with well-developed, randomly oriented slickensides and blocky peds (Fig. 6E), rare laminae of gypsum, local brecciated fabrics, and local, floating subangular to angular quartz grains within the muddy matrix.

Dark red to pale purple mudstone composes 19% of the core and generally forms beds about 0.5 m thick. Gray to greenish massive mudstone forms beds about 35 cm thick on average and composes 16% of the study section. The massive mudstone is composed of very fine silt to clay grains (3–4 μm) of mica and clay minerals (illite, kaolinite, and smectite) and rare dolomite. Petrographic observations also reveal a clay-rich matrix with local outsized silt grains of subangular to angular quartz (Fig. 5G). XRD data reveals that the grayer mudstone contains less quartz and a higher percentage of clay minerals than the redder mudstone.

Vertical, bifurcating traces (centimeter scale) are rare, whereas well-developed slickensides are abundant (Fig. 5H), and autobrecciated fabric occurs locally in which the clasts exhibit an angular shape. Planar laminae of gypsum with vertically oriented crystals, 0.1–2 cm thick, locally occur in these facies with sharp contacts against the massive mudstone. Generally, the base of this facies grades upward from underlying variegated mudstone facies with a transition zone consisting of complex mudcracks and brecciated fabric whereas it is either sharply overlain by the organic or variegated mudstone or more gradationally by the siltstone facies.

Interpretation.—The fine-grained and well-sorted texture and massive bedding is most consistent with eolian deposition (Pye 1987; Tsoar and Pye 1987). Typical far-traveled eolian "clayey" loess is of mud size and enriched in mica and clay minerals (Junge 1969; Clemmensen 1979; Pye 1987). Abundant slickensides, ped-like features, and root traces record pronounced pedogenic overprinting in a subaerial setting. The local brecciated fabric and its angular texture suggests an *in situ* autoclastic origin formed from wetting and drying (Benison and Goldstein 2001) rather than erosion and traction transport of intraclasts, and no other evidence of traction currents are present. The vertically aligned crystals in the gypsum interbeds, however, suggest bottom precipitation from occasional subaqueous conditions (Vandervoort 1997). This is evidence for ephemeral saline surface waters.

Paleosols

Description.—Prominent, randomly oriented slickensides, blocky peds, downwardly bifurcating vertical traces, and homogenized bedding occur in discrete horizons throughout the core, and although most common to the massive mudstone facies, are not limited to a single facies, and thus, are summarized here. The slickensides are very pronounced, forming shiny, subvertical planes in the mudstone that crosscut the entire core (Fig. 5H) and are visible in outcrop forming high angles to bedding. Blocky ped structures are also pervasive in these intervals. Microfabrics include highly birefringent clay, exhibiting two preferred directions. Intervals throughout the core exhibiting these features have a sharp upper boundary and a gradational basal boundary. Rare downwardly bifurcating traces occur, but gray reduction spots are more common. XRD analyses indicate illite and smectite as the most prominent clay minerals.

Interpretation.—The presence of (downwardly bifurcating) root traces, abundant slickensides, and blocky peds record pedogenesis, specifically development of Vertisols (Retallack 1990). Slickensides form from shrinking and swelling of clay, particularly smectite during wetting and drying (Retallack 1990), and the basal gradational boundary and sharp upper boundary are consistent with pedogenesis. The structureless bedding and lack of horizonation reflect pedoturbation as a result of the shrinking and swelling (cf. Goebel et al. 1989). The oriented microfabric is defined as clinobimasepic fabric (Retallack 1990) and commonly occurs in Vertisols due to stress produced from shrinking and swelling of clays (Nettleton and Sleeman 1985). Pedogenic overprinting is most common in the massive mudstone facies and, subordinately, variegated mudstone facies.

Geochemical Analysis

Whole-Rock and Trace-Element Geochemistry.—Whole-rock geochemistry of the Wellington provides information on potential provenance of the sediment and chemical processes during deposition and early diagenesis. In the following we compare the chemical data to several reference compositions to ultimately test hypotheses of provenance but also depositional processes. These reference datasets include: upper continental crust (UCC; Taylor and McLennan 2001), average shale (SH; Taylor and McClennan 1985), Quaternary loess (QL; Taylor and McClennan 1985), upper Paleozoic loessite (UPL; Soreghan and Soreghan 2007), Colorado Plateau crustal model (CPC; Condie and Selverstone 1999); Ouachita flysch (OAU; Gleason et al. 1995; Sutton and Land 1996; Totten et al. 2000), and roughly coeval Permian redbeds from western Kansas (KA; Cullers 1994). The locations of these regional datasets are shown in Figure 2.

The SiO_2 values (Fig. 7A) for the siltstone facies are higher (58 to 88.5 wt.%) and more variable than the mudstone facies (~ 58 to 60 wt.%); the siltstone SiO_2 values are also higher than upper continental crust (UCC), but similar to upper Paleozoic (UPL) and Quaternary loess (QL) values. The mudstone facies samples are enriched in Al_2O_3 compared to the siltstone facies, UCC, UPL, and QL, but are similar to average shale (SH) and Ouachita flysch (OAU). The difference in the ratio of SiO_2/Al_2O_3 between the mudstone and siltstone likely reflects grain-size effects rather than differences in weathering or provenance owing to the higher concentration of clay minerals in the mudstone (Taylor and McClennan 1985; Cullers 1994).

The crossplot of total alkali metal oxides ($Na_2O + K_2O$) vs. SiO_2 (Fig. 7B) shows a depletion relative to UCC in alkalis and no trend in the mudstone facies, further reflective of a uniform composition of the various mudstone facies. The siltstone facies displays a negative trend (Fig. 7B), with values similar to UPL and QL. The Wellington mudstone samples are relatively uniform and depleted in Na_2O compared to the siltstone samples when normalized to Al_2O_3, whereas the siltstone facies is more variable (Fig. 7C). The mudstone samples are again more similar to SH and OUA, while the siltstone samples are more similar to QL, KA, and UPL in the normalized plot. Na_2O and K_2O ratios in sediments are typically controlled by source rock (Garrels and MacKenzie 1971), but also can reflect weathering either prior to deposition or *in situ* (McLennan et al. 1993; Qiao et al. 2009).

Differences in trace-element composition exist among the Wellington facies. A plot of Th/Sc vs. Cr/Th (Fig. 7D) illustrates that the mudstone samples uniformly lie between ratios for UCC (Th/Sc = 1), which is enriched in incompatible elements, and more mafic sources (Th/Sc = 0.6; Totten et al. 2000). In contrast, the siltstone samples exhibit a more variable Th/Sc ratio, typical of a continental signature (Fig. 7D). The siltstone samples plot similar to KA and UCC, whereas the mudstone samples plot similar to the SH and OUA values.

Finally, there are a number of other differences in trace-element composition of the mudstone compared to the reference data (Fig. 7E). For example, the mudstone facies are enriched in Cr, Ni, and V compared to UCC but depleted in Sr compared to UCC. The mudstone facies also exhibits differences in trace-element pattern compared to average shale (SH; Fig. 7E).

Detrital-Zircon Geochronology.—The Wellington Formation contains zircons with U-Pb ages that range from Archean in age to ~ 350 Ma (Appendix 1; Fig. 8). A large number of zircon grains (n = 14) fall into a group that spans early Paleozoic (530–370) ages (Fig. 8). There are a few grains in the age range of 570–740 Ma; however, the dominant mode are grains (n = 31) of mostly Mesoproterozoic age that cluster within the ranges of 900–1360 Ma. Finally, there is also a population of grains (n = 11) that yield ages between 1610 and 1800 Ma and a few scattered Archean ages (> 2500 Ma, n = 4).

Provenance Interpretations of Geochemistry

The composition of the Wellington sediments differs significantly from UCC. Multiple cross plots of the geochemistry data of the Wellington sediments, including Na_2O/Al_2O_3 vs. K_2O/Al_2O_3, Th vs. Sc, Th/Sc vs. Cr/Th, and Th/U vs. Th, all show that the composition reflects mixed felsic and mafic provenance, suggesting derivation from multiple sediment sources.

The mudstone composition plotted on Na_2O/Al_2O_3 vs. K_2O/Al_2O_3 (Fig. 7C) and Th/Sc vs. Cr/Th (Fig. 7D) empirically suggests the Ouachita Mountains (OAU) as a possible sediment source. The composition of the Ancestral Rocky Mountains (ARM) is represented in this study through derivative sediments, i.e., upper Paleozoic loess (UPL; proximal) and Kansas shale (KA; distal) and is also similar to the composition of the Wellington sediments. Overall, both KA, which represents distal ARM sediment (Cullers 1994), and the Ouachita

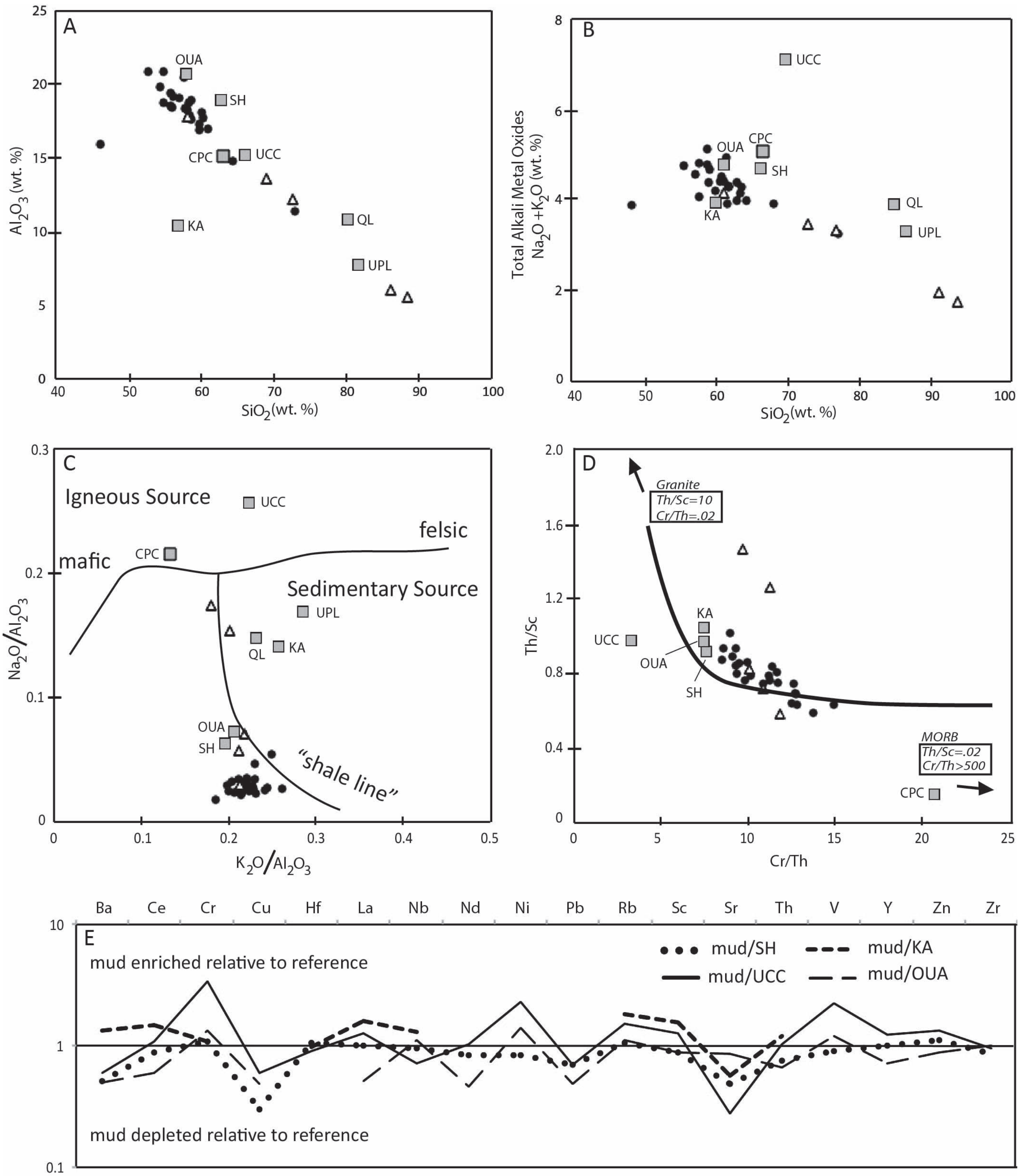


FIG. 7.—Geochemical plots of Wellington mudstone (circles) and siltstone (triangles) compared to various geochemical reference datasets: UCC upper continental crust; OUA Ouachita-derived sediments; KA Permian shales in Kansas; UPL upper Paleozoic loessite; SH average shale. See text for references. **A)** Crossplot of Al_2O_3 vs. SiO2, **B)** crossplot of Na_2O + K_2O vs. SiO_2. **C)** Plot of Na_2O/Al_2O_3 vs. K_2O/Al_2O_3. Mudstones plot between mafic and felsic compositions. Igneous, sedimentary, and shale lines are from Garrels and MacKenzie (1971). **D)** Plot of Th/Sc vs. Cr/Th, with the bold line representing an idealized signature of a mixing line between granite and MORB (mid-oceanic-ridge basalt) sources. The Wellington mudstone facies plots along the mixing line, while the Wellington siltstone facies trend toward a more felsic composition. After Totten et al. (2000). **E)** Spider plot of average trace-element value of mudstone facies compared to various reference datasets.

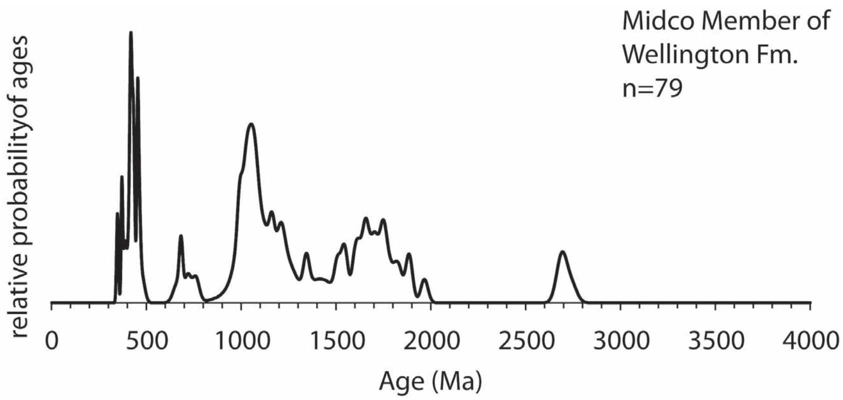


FIG. 8.—Cumulative probability plot of U-Pb ages of detrital zircons from the outcrop sample of the Midco Member of the Wellington Formation. The curve represents the sum of individual radiometric ages and associated errors of the analyzed zircons. The significance of the age peaks are discussed in the text.

Mountains detritus (OAU) both seem to best fit the relative proportion of the trace elements in the Wellington mudstones (Fig 7E), particularly when compared to average shale or upper continental crust. Although the ARM contains higher silica content than the Ouachita Mountains flysch, both are composed mainly of felsic-derived rock types (Cullers 1994; Totten et al. 2000) and exhibit similar compositions.

In contrast, the Wellington siltstone facies differs in composition from the mudstone facies and trends toward a more felsic source. The Wellington siltstones consistently plot similar to Paleozoic sediments derived from the ARM, although a few siltstone samples overlap the mudstone samples. Thus, overall the siltstone geochemistry signals primary derivation from the ARM or its derivative sediments, with either some secondary mixing with mudstone during pedogenic overprinting or periodic sediment input from the Ouachita Mountains.

Another characteristic of the geochemical data is the uniform composition of the different mudstone facies, which may indicate sediment derivation from similar, well-mixed, distal source(s). Totten et al. (2000) interpreted multiple sources for the Pennsylvanian Stanley Group based on two distinct clusters in plots of Th vs. Sc and Th/Sc vs. Cr/Th (Fig. 4 and 5 in Totten et al. 2000). In contrast, the Wellington mudstone samples cluster tightly, typically between compositions of felsic and mafic source rocks. Similarly, Cullers (1994) inferred a homogeneous, well-mixed sediment source for distal mudstone deposits compared to a heterogeneous, less-well-mixed source in more proximal coeval deposits.

The detrital-zircon ages of the single sample analyzed are consistent with interpretations of a mixed source. Although forming the most abundant population, zircons with ages ranging from ~ 900 to 1300 Ma (Fig. 8) are a common signature in upper Paleozoic deposits (Dickinson and Gehrels 2003) that reflect contribution from Grenville basement and do not necessarily suggest a unique source region for detrital grains in the Wellington Formation. Grenville basement and derivative sediment with grains of these ages lies both east (Becker et al. 2005) and south (Gleason et al. 2007) of the study site. The population of grains in the 1600–1800 Ma range (Fig. 8) likely were derived from the Ancestral Rocky Mountains or derivative deposits to the west of the study site, where basement terranes (Yavapai–Mazatzal) of that age were exposed throughout the Pennsylvanian and earliest Permian (Van Schmus et al. 1993), and zircons of these ages are a common component of slightly older loessite deposits (M. Soreghan et al. 2002; Soreghan et al. 2008a). Zircons of mid-Paleozoic age have been reported from terranes in the Appalachian–Ouachita systems, and particularly terranes of Mexico and Central America then situated south of the Ouachita system (Weber et al. 2006; Martens et al. 2010; Soreghan and Soreghan 2013). This suggests a south-southeast source direction for the mid-Paleozoic detrital zircons.

DISCUSSION

Depositional Setting for the Wellington Formation

Since the original studies of the Wellington Formation, the depositional setting of this unit has been debated (Dunbar 1924; Raasch 1946; Tasch 1964; Schultz 1975; Chaplin 2004; Hall 2004). Virtually all workers have noted that there is definite evidence for continental deposition, but a number of workers still favor a marine or marginal marine origin for most of the Wellington, and attempt to reconcile the mixture of signals by calling on either a tidal or sabkha environment or invoking numerous transgressions and regressions at various temporal scales. Our facies, petrographic, and geochemical data strongly suggest that the Permian Wellington Formation of north-central Oklahoma formed in continental environments, including saline and freshwater perennial lakes, playas, wind-blown silt fields (loess), and soils. There is no diagnostic evidence for marine or marginally marine paleoenvironments in the Anhydrite sequence, the Otoe Member, and the Midco Member present in the KC-1 core and nearby outcrop.

The KC-1 core contains numerous paleosols, most of which are inferred to be Vertisols. Paleosols in the Wellington were also documented by Raasch (1946) and Hall (2004). Vertisols unequivocally reflect extensive subaerial exposure and pedogenic overprinting of the underlying sediment. If this underlying sediment is interpreted as marine, or even intertidal, however, then superposition of these pedogenic features necessitates numerous and very abrupt fluctuations in sea level. For example, in Pennsylvanian cyclothems, paleosols commonly occur at each cycle top, commonly on the 10 m (100–400 ky) scale in subsiding cratonal regions (e.g., Heckel 1986; Davydov et al. 2010), whereas paleosols occur on average every 3–5 m in the Wellington. In a lake basin, however, abrupt changes of lake level, from relatively deep to dry, can occur on the order of 10^4 years or less, even in very large tropical lakes (e.g., Lake Victoria; Johnson et al. 1996).

Evaporites form in a wide range of environments, including marine, marginal marine, and continental, which has obfuscated interpretations of the Wellington Formation. The Sr isotope composition of the gypsum, however, indicates a continental origin. The $^{87}Sr/^{86}Sr$ composition of Permian seawater is well characterized and drops through the early Permian (Korte et al. 2006) from ~ 0.7080 at the start of the Permian to ~ 0.7070 in the Kungurian, then rises to 0.7077–0.7074 during the Artinskian. The data from the Wellington, averaging 0.7092, indicate a (mainly) continental source. Given that some of the gypsum records subaqueous formation, the most likely environment is a saline perennial lake, whereas the gypsum that precipitated displacively likely reflects a playa environment. We use the terms saline lake to refer to continental basins with input of both groundwater and surficial water from continental sources; playa to refer to continental basins with

TABLE 3.—*General summary of paleontology found in the Wellington Formation. Note that brackish to marine environmental indicators are most common in Kansas.*

Fossil Type	Location (County)		Member	Interpreted Environment from Source	Source
	Oklahoma	Kansas			
Conchostracans	Noble and Kay	Sumner, Sedgwick, Harvey, Marion, Dickinson	basal Billings Pool	Continental	Tasch 1964; Swanson and Carlson 2002; Park and Gierlowski-Kordesch 2007; Scott 2010; Kay County Core
Lungfish burrows	Noble	none reported	basal Billings Pool	Continental	Carlson 1999; Chaplin 2004
Insect beds	Noble	Dickinson	basal Billings Pool (OK); Carlton Limestone (KS)	Continental	Beckemeyer and Hall 2007
Stromatolites	Noble and Kay	Dickinson	basal Midco (OK); basal Carlton Limestone (KS)	Brackish to Marine	Hall 2004
Vertebrate ichonofauna	Noble	Dickinson	basal Billings Pool	Continental	Swanson and Carlson 2002
Eurypterus sellardsi	none reported	Dickinson	basal Carlton Limestone	Brackish to Marine	Dunbar 1924; Hall 2004
Horseshoe crabs (*Paleolimnus signatus*)	none reported	Dickinson	basal Carlton Limestone	Disagreement between authors: Continental or Brackish	Dunbar 1924; Babcock et al. 2000; Hall 2004
Pelecypods	none reported	Dickinson	basal Carlton Limestone	Brackish to Marine	Dunbar 1924; Hall 2004
Lingula	none reported	Dickinson	Annelly Gypsum/basal Carlton Limestone	Brackish to Marine	Dunbar 1924; Hall 2004

mainly meteoric groundwater input; and sabkha to refer to arid shorelines with periodic input of surficial marine water (Yechieli and Wood 2002).

Since the dolomite is intimately associated with the gypsum, then the setting of the dolomite formation is more consistent with a continental environment rather than a sabkha or lagoonal setting. Specifically, the fine grain size and laminated character is consistent with a perennial, saline lake in which the dolomite formed as a primary precipitate. Dolomicrite, commonly interlaminated with siliciclastic material, is common in the geologic record in units interpreted as offshore lake facies (Desborough 1978; Deckker and Last 1988; Last 1990; Calvo et al. 1999). Indeed, the precipitation of gypsum could be one factor in elevating the Mg ratio of the solution from which the dolomite ultimately formed. A perennial-lake origin for the laminated dolomite is also consistent with its co-occurrence with the organic-rich mudstone facies, which further suggests low-oxygen, perennial lake conditions.

In addition to those attributes suggestive of a perennial lake, several intervals in the study section display features more consistent with periodic exposure in a playa environment, such as common desiccation features, displacive gypsum, and mudstone displaying disrupted bedding (autobrecciation and inferred efflorescent crusts; Spencer and Lowenstein 1990; Benison and Goldstein 2001). Although a number of these sedimentary features are characteristic of a range of environments, their interbedding with the inferred perennial-lake deposits, and the presence of interbedded gypsum, with its continental chemical signature, suggests a playa setting rather than sabkha, supratidal, or lagoonal setting.

The paleontologic evidence from the Wellington suggests a continental signature for the study area with more brackish conditions to the north in Kansas. The only fossils observed in the core are conchostracans found on bedding planes of the laminated mudstone facies, which appear pristine and *in situ*. By the Permian, conchostracans were common in continental environments (Tasch 1964; Swanson and Carlson 2002; Park and Gierlowski-Kordesch 2007; Scott 2010); however, some conchostracan species, commonly Triassic in age, may indicate brackish conditions (Kozur and Weems 2010). In outcrops of the Wellington, the ranges of fossils vary depending on location. Fossils reported in Oklahoma (Table 3) outcrops indicate more freshwater conditions, including conchostracans (Tasch 1961; Hall 2004), lungfish burrows (Carlson 1999; Chaplin 2004), vertebrate ichnofauna (Swanson and Carlson 2002), occasional stromatolites (Hall 2004), and insect beds (Beckemeyer and Hall 2007). In contrast, fossils reported in Kansas outcrops (Table 3) may indicate more brackish to marine conditions, including eurypterids (*Eurypterus sellardsi*; Dunbar 1924), horseshoe crabs (see below; Dunbar 1924; Hall 2004), stromatolites (Carlson 1968; Hall 2004; Bolhar and Van Kranendonk 2007), *Lingula* (Dunbar 1924; Hall 2004), and pelecypods (Dunbar 1924; Hall 2004). Stratigraphically, the Oklahoma outcrops are reported as younger, including the Midco through basal Billings Pool members, whereas the slightly older Kansas outcrops include the upper Annelly Gypsum through the Carlton Limestone (Midco equivalent) members (Table 3). Therefore, the paleontology alone suggests that the stratigraphically older Wellington fossils of Kansas indicate more brackish conditions, while the younger Wellington fossils of Oklahoma suggest more continental conditions.

Finally, albeit negative evidence, the Wellington strata examined in this study lack characteristics that generally define a sabkha or tidal environment. For example, characteristic features such as, e.g., "chicken-wire" and enterolithic evaporites (gypsum or anhydrite), widespread fenestral fabrics, flat-pebble intraclast conglomerates, and tepee structures (Warren and Kendall 1985) are rare to absent in the study strata. In addition, sabkha deposits are typically interbedded with shallow subtidal deposits (Schreiber 1978), whereas the Wellington lacks associated normal marine deposits. Finally, no evidence occurs for the peritidal "trinity," i.e., subtidal, intertidal, and supratidal subenvironments (Warren and Kendall 1985), marked by facies and features such as peloidal, oolitic, and skeletal grainstone, burrowed carbonate mudstone, flaser bedding, and ripple cross-stratification.

Transport Processes of Wellington Formation Siliciclastics

The commonly accepted mode of transport for Pennsylvanian–Permian clastics occurring in Oklahoma is fluvio-deltaic, with ultimate preservation in environments interpreted to range from fluvial and lacustrine to deltaic and tidal flat (Twenhofel 1926; Wilson 1927; Fay 1964; Johnson 1990; Mazzullo 1999). These interpretations are based in part on evidence such as the presence of cross-bedded sandstone, which occurs in the Garber Sandstone immediately overlying the Wellington Formation (Raasch 1946; Elrod 1980) and the presence of inferred marine evaporites in the enclosing formations (Twenhofel 1926; Wilson 1927; Fay 1964;

Johnson 1990). Some researchers, however, have postulated an eolian origin for the mudstone in the Wellington and younger Flowerpot formations (Raasch 1946; Yang 1985; respectively). In the Midco and Otoe members of the study area, evidence for fluvio-deltaic deposition does not occur: the siliciclastic strata exhibit a narrow (clay–silt) grain size and lack evidence for erosional scouring or any channels. Cross-bedding does occur in the Billings Pool Member in outcrop (above the study interval) and oscillation ripple marks have been identified in thin siltstones in the Midco Member (Hall 2004), yet the predominant stratification type in the clastic facies is either laminated or massive.

The predominant facies in the Midco and Otoe members, the laminated mudstone facies, reflects subaqueous deposition as indicated by very continuous laminae and interlaminated dolomite and bottom-growth gypsum. If the siliciclastic mud discharged as a strong overflow current (hypopycnal flow) from one or more point sources in a density-stratified lake the sediment would spread horizontally and ultimately sink as a suspension deposit (e.g., Lake Turkana, Cohen 1989). This requires considerable depth of the lake body to create the density gradient required to buoy the sediment plume. The laminated mudstone facies, however, contains numerous horizons of mudcracks, suggesting numerous desiccation events. Thus, if the mud laminae were deposited as a result of a series of overflow discharge events, then large-magnitude lake-level fluctuations must have also been very abrupt and very common. If, conversely, the mud discharged into the lake as a strong underflow current (hyperpycnal flow) from one or more point sources, then distinct sedimentary features should occur, e.g., laminae that exhibit grading, and association with silty and at least fine sandy beds (Soyinka and Slatt 2008), which are absent.

A third possibility is that the clastic sediment was introduced into the lake system via eolian processes. In the study section, grain-size averages are in the very fine- to fine-silt range, typical for distal eolian dust (Pye 1987; Smalley et al. 2005), and dust deposition in lakes and playas is a common phenomenon, particularly downwind of arid to semiarid regions (e.g., southwestern U.S., Reheis et al. 1995; Lake Biwa, Xiao et al. 1999; Lake Chad, Evans et al. 2004; man-made Lake Volta, Breuning-Madsen and Awadzi 2005; northwest China, Qiang et al. 2007; Dead Sea, Haliva-Cohen et al. 2012). In most of these modern systems, the eolian component is of very fine silt to clay size and occurs as laminae in the lake sediment or in more massive beds disturbed by biogenic reworking. Dust transport and settling into a shallow, saline lake subject to occasional desiccation, would produce mudcracked surfaces. Taking into consideration the bulk of the evidence, including the lack of channels or sediment thickening and coarsening indicative of point-source inputs of the siliciclastic component to the lacustrine system, we favor eolian transport as the chief mechanism of delivery of siliciclastic grains to the depositional site. This process resulted in formation of the laminated mudstone facies through subsequent suspension settling of the sediment in a perennial lake that experienced periodic desiccation that formed the millimeter scale laminae and mudcracks, respectively.

As noted above, the massive mudstone facies is also interpreted as eolian in origin. The similar texture of the laminated and massive mudstone, transitional contacts, and lack of erosional scours or lag features between the facies suggest a similar transport mechanism. The massive character and association with Vertisols could be interpreted to reflect unconfined flow in which mud aggregates were carried in traction (Wright and Marriott 2007). The massive mudstones in this case, however, lack almost all of the common macroscopic attributes of such traction-flow deposits as defined by Wright and Marriott, such as 1) erosional bases, 2) intraclast lenses or lags, 3) related facies associations (e.g., conglomeratic lenses, pedogenic carbonates), and 4) lenticular stratification of interbedded calcrete clasts. Thus, we favor a mainly eolian transport interpretation, in which the mud settled onto a playa or shallow lake system, and was subsequently further homogenized pedogenically. This still allows the possibility of occasional unconfined flow events associated with storms to remobilize and locally transport previously deposited mud (Alonso-Zarza et al. 2009). This also does not eliminate the presence of aggregates, and the microscopic observation of quartz clasts floating in mud matrix (Fig. 5G) suggests that aggregates might have existed. However, we suggest that if the mud did form aggregates, these were transported via eolian processes and might be similar to Quaternary eolian deposits documented in Australia (parna). Butler (1956) suggested that these massive, clayey, pedogenically altered deposits (1–3 m thick) were formed by wind transport of silt-size clasts of clay aggregates, although this process remains obscure (Hesse and McTainsh 2003).

Finally, the siltstone facies are interpreted as loess(ite) deposits that accumulated over the playa system during phases when no standing water occurred. The massive texture, well-sorted silt grain size, and provenance are all consistent with an eolian origin, and no features occur consistent with traction flow, whether confined or unconfined (e.g., lateral-accretion surfaces, or planar or ripple cross lamination). The provenance, reflected in both the geochemical and detrital zircon attributes, indicates a mixed source that reflects regions both east and west of the study area, consistent with a seasonally changing wind regime.

Wellington Lake Model and Regional Paleoclimatic Implications

The climate-sensitive sediments composing arid, closed-basin lakes record high-frequency variations in regional short-term climates and are useful for paleoclimate interpretations (Smith et al. 1983; Olsen 1986; Smith and Bischoff 1997; Lowenstein et al. 1999; Lowenstein et al. 2003). No evidence exists for major changes in tectonic regime during deposition of the Wellington Formation; thus, deposition was chiefly influenced by regional climate changes and should be considered an "optimal" reflection of paleoclimate (Smith and Bischoff 1997; Lowenstein et al. 2003). The facies in the Wellington Formation appear to reflect at least two different temporal scales of climate change. First, the facies stacking suggest repeated, upwardly shallowing events (detailed below). Second, a more detailed examination of the facies transitions suggests that, in the upwardly shallowing successions, small-scale fluctuations indicative of higher-frequency wetting and drying occurred, evinced by juxtaposition and overprinting of facies and features, including: 1), the syncopated pattern of facies, for example the organic and laminated mudstone facies; 2) specific features, such as Vertisols containing slickensides; 3) alternating laminae of evaporites (dry) and clastics (wet); and 4) complex mudcracks reflecting seasonality. In addition, the presence of conchostracans indicates seasonality, as their eggs are laid in ephemeral water bodies (Tasch 1958; Swanson and Carlson 2002); similarly, lungfish, reported from the Wellington, aestivate in burrows during dry episodes (Carlson 1968; Hasiotis et al. 1993; Swanson and Carlson 2002).

Vertical facies transitions in the study section indicate a preferred vertical stacking pattern of, from base to top: (1) organic mudstone with dolomite, (2) laminated mudstone with gypsum, (3) dark red or gray massive mudstone, and (4) fine-grained siltstone. Using the organic mudstone as a base for each, the study interval records at least 30 deepening and subsequent shallowing episodes (Fig. 3) that likely reflect longer-term climatic change during Wellington Formation deposition.

Perennial Freshwater Lake Stage.—This stage represents the "flooding stage" and the most humid interval as groundwater, direct precipitation, and related runoff filled the basin and deposited the organic mudstone facies (Fig. 9). It is typical in tropical lake systems that direct precipitation and evaporation dominate the local hydrology, for example, even in modern Lake Tanganyika, the second largest freshwater lake in the world by volume, the main contribution to water input is direct

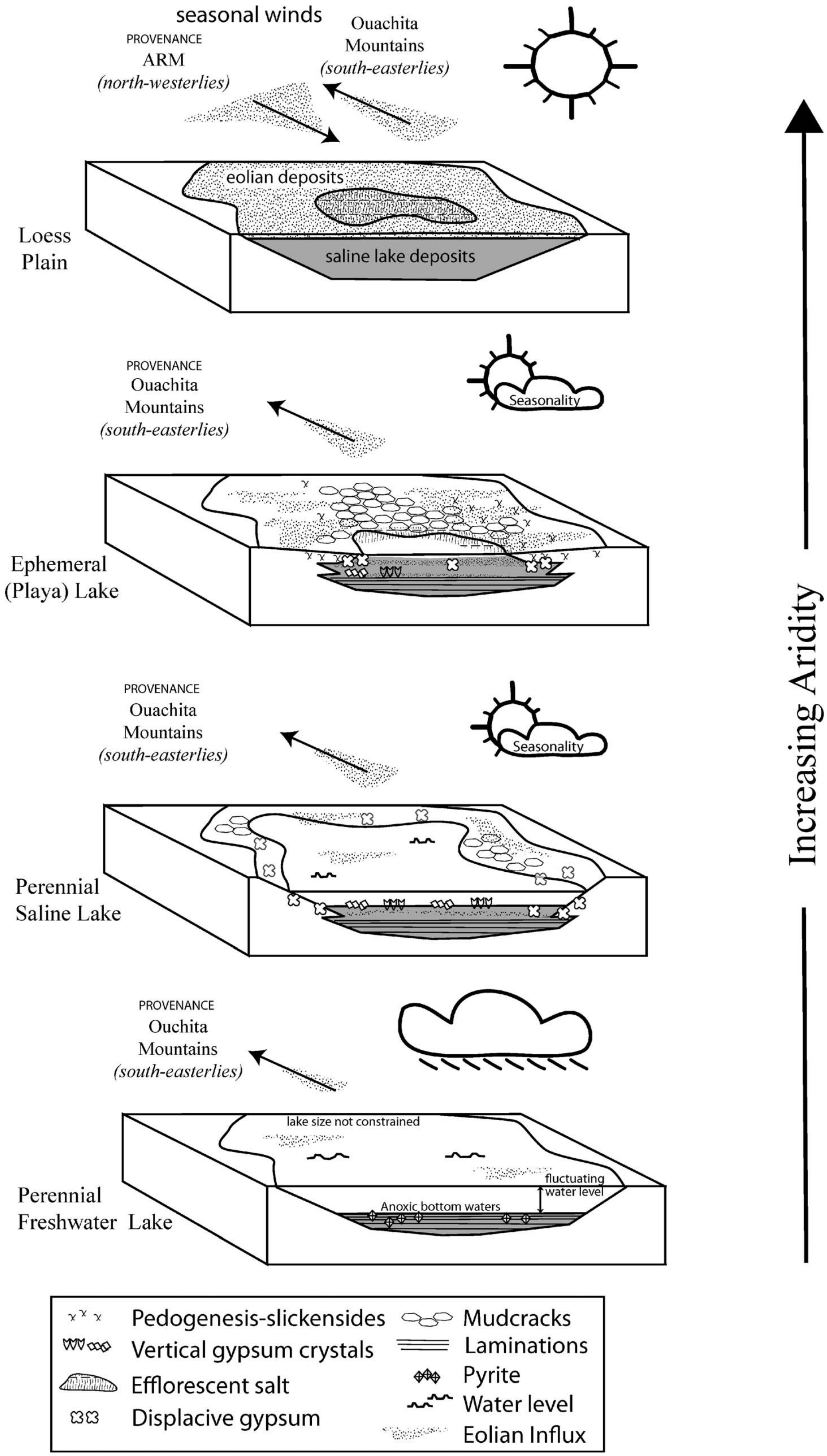


FIG. 9.—Depositional model for the Wellington Formation. Each stage depicted in the diagram is generalized; high-frequency fluctuations likely occurred, creating heterogeneous facies. Perennial-lake stage is represented by the organic mudstone and laminated dolomite. (2) Perennial lake, but with increasing evaporation, causing an overall decrease in water level and formation of the variegated mudstone facies and thicker gypsum and dolomite units, though seasonality and short-term fluctuations allowed occasional return of deposition of organic mudstone. (3) Playa or mudflat stage, during which desiccation features are common and the variegated (or rarely the organic) mudstone was pedogenically overprinted, creating Vertisols. Additional eolian transport of clayey loess coupled with pedogenesis formed the massive mudstones. (4) Loess deposition.

precipitation (Nicholson 1999). This stage represents in aggregate ~ 25% (by thickness) of the study interval, and thus, a significant part of the paleogeography. The lake was likely stratified and possibly anoxic, enhancing sulfate reduction and dolomite formation, and preservation of laminations and organics (Trudinger et al. 1985; Last 1990; Machel 2004; Sanz-Montero et al. 2009). Seasonality or short-term changes in hydrology likely caused fluctuations in salinity and water level as evidenced by variable thicknesses of dolomite deposits, some with desiccation features, and rare gypsum laminations in the organic mudstone facies. Rare periods of increased salinity and evaporation would trigger subaqueous gypsum growth on the lake bottom and within the sediment, analogous to other examples of evaporites forming contemporaneously with high rates of organic deposition along a lateral salinity gradient (e.g., Nury and Schreiber 1997). Arid episodes may have also resulted in eolian transport of silt-size clastics into the lake, creating rare organic-poor (lighter-colored) silty laminae.

Perennial Saline Lake Stage.—This stage represents increasing aridity leading to greater evaporation rates and higher salinity, and consequent deposition of the laminated variegated mudstone (Fig. 9). Although this stage represents a shallower, less anoxic lake, evidence for strong seasonality and a fluctuating water chemistry includes: 1) local dolomite laminations, 2) abundant desiccation features, including complex mudcracks penetrating throughout each mudstone bed and at the top of the interbedded dolomite beds, 3) small pedogenic slickensides, 4) brecciated layers and chaotic bedding thinly interbedded between laminated intervals, and 5) variegated colors (Chaplin 2004). Pulses of eolian silt and clay entered the lake and formed the discrete silty laminations. Most of the gypsum in the core formed during this stage, with both subaqueous vertical crystal precipitates and intra-sediment precipitates. The presence of both of these forms of gypsum vertically juxtaposed further indicates abrupt fluctuations in water level (Benison and Goldstein 2001). Conchostracans occur during this stage and were able to tolerate the high-stress environment of a saline lake (Tasch 1961a), but they occur in beds lacking evaporites and thus probably represent periods of slightly decreased salinity.

Ephemeral (Playa) Stage.—During this stage, much of the water covering the basin evaporated, exposing the laminated variegated mudstone (Fig. 9). Transitional contacts between the variegated mudstone and overlying massive mudstone (Vertisols) facies support a similar (initial eolian) origin for these clastics, with the massive mudstone reflecting both ultimate deposition as loess, rather than subaqueous settling, and pedogenic overprinting. Several authors suggest that the exposed surfaces in saline lake environments experience almost constant pedogenic overprinting (Bowler 1986; Smoot and Lowenstein 1991; Gierlowski-Kordesch and Rust 1994). Seasonal wetting and drying of mudstones during pedogenesis led to development of Vertisols. The geochemical similarity between the massive and laminated mudstones lends additional evidence for the genetic relationship between these two facies.

Loessitic Stage.—The final stage is represented by eolian deposition of the siltstone facies, reflecting the most prolonged arid phases (Fig. 9). Rare pedogenic overprinting in the siltstone (indicated by root traces) may reflect periods of decreased sediment influx. Trapping of loess requires moist ground and thus, seasonal wetness (Pye 1987). As saline groundwater evaporated from these silt deposits, efflorescent salts formed, resulting in the patchy fabric, and chaotic bedding, analogous to modern examples in Saline Valley and Death Valley (Gierlowski-Kordesch and Rust 1994; Smoot and Castens-Seidell 1994).

Throughout deposition of the Wellington Formation, an even longer-term shift in climate is inferred based on a significant change in the relative proportion of facies between the Midco Member and underlying Otoe Member and Anhydrite sequence. The lower part of the interval (~ 50 m, Otoe Member and Anydrite sequence; Fig. 3) contains a substantially larger percentage of facies reflecting arid conditions, specifically the very fine siltstone, red massive mudstone, laminated variegated mudstone, and gypsum beds. In contrast, the upper part of the interval (~ 40 m, Midco Member; Fig. 3) is composed of a markedly higher percentage of facies reflecting more humid conditions, including the gray massive mudstone, organic mudstone, and dolomite. Thus, the study section overall reflects a shift from more arid conditions in the Otoe and Anhydrite members to more humid (relative) conditions in the Midco Member (Fig. 3).

This model suggests a generally semiarid but highly seasonal climate for the mid-continent in late Early Permian time. Many have inferred that zonal circulation in western and central tropical Pangea during the Pennsylvanian shifted to increasingly monsoonal and thus, increasingly seasonal climate in the Permian (Parrish 1993; Gibbs et al. 2002; G. Soreghan et al. 2002; Tabor and Montañez 2002). The provenance data from the Wellington suggest that sediment emanated from both the west-northwest (ARM) and south-southeast (Ouachita Mountains; in paleo-coordinates). This implies northwesterly and south-southeasterly winds (Fig. 9) if: 1) the Wellington sediments were eolian-sourced and 2) the dust source remained proximal to the original basement source. Relating these interpretations to the depositional model of the Wellington, the laminated and massive (paleosols) mudstones represent more humid periods associated with wetter times accompanied by south (easterlies), whereas loess deposits (very fine siltstone facies) represent drier conditions with increased aridity and seasonal westerlies.

The temporal and lateral extent of this lake system is difficult to constrain based on the core and associated outcrops of this study. Delineating the size of this inferred lake system is also hindered by the lack of other detailed sedimentologic studies of the Wellington that would define potential lacustrine deposits. Nevertheless, previous workers have correlated individual marker beds in the Midco and Otoe members of the Wellington between northern Oklahoma and central Kansas, over 220 km (Fig. 1; Raasch 1946; Hall 2004). Employing the simplifying assumption that this outcrop belt represents the minimal diameter of a circular lake, this suggests a single lake of over 37,000 km^2. This speculative but supportable calculation paints a paleogeographic portrait of the Early Permian Midcontinent that differs substantially from previous interpretations and provides testable hypotheses for future studies.

CONCLUSIONS

1. The lithologic and geochemical data presented in this study, coupled with data from earlier studies, suggest that the Lower Permian Wellington Formation of Oklahoma records continental (lacustrine and loess) deposition rather than marginal marine (sabkha, tidal). The chemical facies forms only 10% of the Wellington and comprises 1) predominantly fine-grained laminated dolomite interlaminated with organic-rich mudstone that records subaqueous suspension deposition and 2) gypsum that consists of several primary morphologies reflecting deposition in subaqueous and shallow subsurface (displacive) environments, but exhibit Sr isotope compositions inconsistent with Permian seawater. Siliciclastic facies make up most of the Wellington and reflect both subaqueous suspension and eolian deposition but overall eolian transport. The clastic facies shows no indication of tidal or sabkha features. Common overprinting by Vertisol pedogenic features also points to a continental setting.
2. Deposition of the Wellington Formation occurred in a range of related environments that included perennial freshwater lacustrine, perennial saline lacustrine, ephemeral lacustrine (playa), and loess accumulations. These fluctuations suggest strong climatic control on the facies successions on various scales. Seasonality in climate is suggested by alternations of laminated sediment, Vertisols, and

fossils (e.g., conchostraca). Longer-term climatic change is indicated by facies successions that reflect transitions from a perennial freshwater lake with primary dolomite growth to a shallower, saline lake with subaqueous gypsum growth and laminated mudstone to a dry saline pan with development of mudcracks (desiccation stage), pedogenic overprinting, and loess accumulation.
3. Geochemical and detrital zircon data indicate a mixed provenance for the volumetrically predominant siliciclastic component, with both south-southeastern (Ouachita and possibly Mexico) and western (ARM) sources.
4. Evidence from this study is consistent with the interpretations of Benison and Goldstein (2001) suggesting that a large area of shallow lakes existed in the Midcontinent during the Permian. Other coeval deposits should be re-examined for possible alternate interpretations, which could fundamentally shift our view of the Permian in the Midcontinent.

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Appendix 1 contains the U-Pb geochronologic analyses of detrital zircons in the Wellington Formation siltstone and is available from JSR's Data Archive: http://sepm.org/pages.aspx?pageid=229.

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