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ORIGINAL PAPER

The paleoclimatic and geochronologic utility of coring red beds and evaporites: a case study from the RKB core (Permian, Kansas, USA)

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Abstract Drill core is critical for robust and high-resolution reconstructions of Earth's climate record, as well demonstrated from both marine successions and modern long-lived lake systems. Deep-time climate reconstructions increasingly require core-based data, but some facies, notably red beds and evaporites, have garnered less attention for both paleoclimatic and geochronologic analyses. Here, we highlight studies from the Rebecca K. Bounds (RKB) core, a nearly continuous, >1.6 km drill core extending from the Cretaceous to the Mississippian, recovered from the US Midcontinent by Amoco Production Company in 1988, and serendipitously made available for academic research. Recent research conducted on this core illustrates the potential to recover high-resolution data for geochronologic and climatic reconstructions from both the fine-grained red bed strata, which largely represent paleo-loess deposits, and associated evaporite strata. In this case, availability of core was instrumental for (1) accessing a continuous vertical section that establishes unambiguous superposition key to both magnetostratigraphic and paleoclimatic analyses, and (2) providing pristine sample material from friable, soluble, and/or lithofacies and mineralogical species otherwise poorly preserved in surface exposures. The potential for high-resolution paleoclimatic reconstruction from coring of deep-time loess strata in particular remains severely underutilized.

Keywords Red beds · Core · Paleoclimate · Permian · Loess · Evaporites · Pangaea

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Introduction

Drill core is well recognized as a key data set for reconstructing climate records. Drilling marine sediments has been long exploited to clarify climate dynamics and atmospheric-oceanic linkages, especially for the Neogene, but extending even to the Cretaceous (e.g., IODP 2008). Continental climate reconstructions also benefit greatly from drill core data, and core from modern, long-lived lacustrine systems in particular have facilitated major advances in understanding climate dynamics of Earth's recent record, from the tropics to the poles (e.g., Lowenstein et al. 1999; Scholz et al. 2007; Cohen 2011; Melles et al. 2012).

Despite these significant advances, the need remains for highly resolved (orbital-forcing-scale) records that can shed light on continental climate in Earth's deep-time record and reveal the full depth of the dynamic range of Earth's climate system (NRC 2011; Soreghan and Cohen 2013). The orbital-scale record recovered from Triassic–Jurassic strata of the largely lacustrine Newark basin system (Olsen et al. 1996) exemplifies the potential for obtaining highly resolved deep-time records from continental successions, as does the promise of emerging results from Mesozoic and lower Cenozoic strata of the Colorado Plateau Coring Project (Olsen et al. 2010), and Bighorn Basin Coring Project (Clyde et al. 2013), respectively. However, continuous coring of continental red beds is relatively uncommon, as these facies have little economic value, and have been long dismissed as of little use for paleoclimatic reconstruction, despite limited detailed study. Many of the proxies most commonly applied to paleoclimatic reconstructions in, e.g., modern/recent, organic-rich lacustrine units (e.g., organic biomarkers, pollen, and redox-sensitive transition metals) are considered to be compromised in oxidized systems. Yet examples of remarkable preservation in red bed strata do occur, such as the presence of (1) superparamagnetic magnetite and the accompanying magnetic susceptibility record in Permian red beds (Soreghan et al. 1997) and (2) pristine pollen and spores in Cenozoic and Pennsylvanian red beds (Benison et al. 2011; Oboh-Ikuenobe and Sanchez Botero 2013; Sánchez Botero et al. 2013). Moreover, in red bed—evaporite successions, the evaporites—if protected from dissolution and alteration caused by post-depositional infiltration of dilute waters—can yield a variety of high-resolution quantitative and qualitative paleoclimate data (e.g., Benison and Goldstein 1999; Sánchez Botero et al. 2013; Zambito and Benison 2013). In addition, sedimentary structures and primary fluid inclusions in Cenozoic and Permian bedded halite can represent arid climate flooding-evaporation-desiccation cycles and air temperature proxies, respectively (Benison and Goldstein 1999; Lowenstein et al. 1999; Zambito and Benison 2013). Paleoclimate reconstructions from such strata, however, are dependent upon obtaining cores drilled using methods suitable for extracting intact evaporites and (commonly friable) fine-grained red beds. To date, such specialized coring has been rare, but yields remarkable data when accomplished.

The purpose of this contribution is to highlight the importance of continuous core to develop a detailed geochronologic framework and paleoclimatic record from generally overlooked facies—in this case fine-grained red beds and associated evaporites, even from deep-time successions. Fortuitous access to drill core in this case enabled study of (1) a stratigraphically complete section, key for assessing a magnetic reversal stratigraphy, and (2) an unaltered section, containing phases (evaporites, clays) otherwise easily dissolved or compromised by traditional drilling methods and by late-stage near-surface diagenesis. Obtaining a continuous vertical section that establishes unambiguous superposition is particularly critical for this expansive, low-relief region characterized by severely limited outcrop exposures. Furthermore, the fine-grained red beds highlighted here record an example of paleo loess, a facies type with the potential to rival deep-sea and laminated lacustrine sediments in their ability to archive high-resolution paleoclimatic data (Liang et al. 2012), but little exploited for Earth's deep-time climate record. Hence, we also highlight the vast paleoclimatic potential offered by coring deep-time loess.

Geologic setting

Midcontinent North America during the Permian was bordered by a series of orogenic systems associated with the final assembly of Pangaea: the Ouachita-Marathon system southward, the Appalachian system eastward, and remnant uplifts of the Ancestral Rocky Mountains to the west, southwest and northwest (Johnson 1978; Kluth and Coney 1981; Slingerland and Furlong 1989; Fig. 1). This greater region, extending from southern Saskatchewan to Texas (north–south) and Wyoming through Kansas (west–east), preserves a variable but commonly thick (10^2–10^3 m) Lower-Middle Permian section (McKee and Oriel 1967;

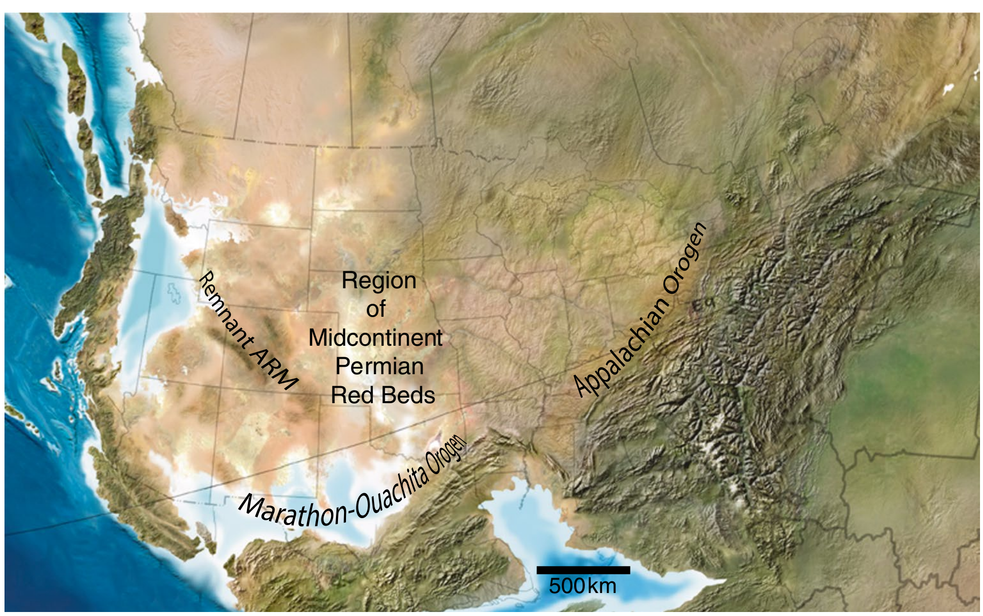


Fig. 1 Paleogeographic map of North America for Middle Permian (265–255 Ma) time, from Blakey (Colorado Plateau Geosystems, http://cpgeosystems.com), modified to show orogenic belts of the Appalachian, Ouachita-Marathon, and ARM (Ancestral Rocky Mountains) systems. Permian red bed strata are preserved across a broad region of Midcontinent North America (see Fig. 2). *Note* paleoequator line and paleoequator

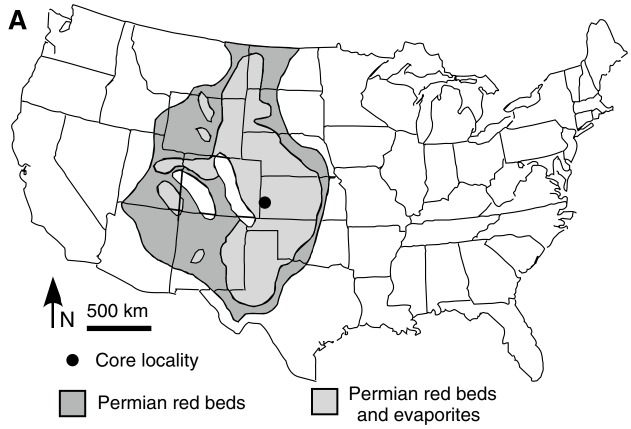
Walker 1967) that extends across various basins and positive areas and reflects as-yet poorly understood subsidence that is perhaps related to post-orogenic and/or far-field effects (Soreghan et al. 2012).

Lithofacies in the Midcontinent Permian range from red beds interbedded with marine limestone low in the section, to entirely continental red beds and evaporites high in the section (McKee and Oriel 1967). This transition reflects a well-documented eustatic and climatic shift driven by (1) the evolution from the Permo-Carboniferous icehouse climate to full greenhouse conditions in the Permo-Triassic (Frakes 1979), with attendant high-frequency glacioeustasy detectable predominately low in the section (e.g., Heckel 2008) and (2) the gradual emergence of the Pangaean supercontinent, as relative sea level reached its Phanerozoic minimum near the end of the Permian (Ross and Ross 1988, 1994, 1995). The latter trend resulted in the predominance of continental over marine deposition through most of the Permian in the Midcontinent and indeed globally (e.g., Golonka and Ford 2000).

The Midcontinent USA was situated in the western equatorial region (~5–15°N; e.g., Golonka et al. 1994; Scotese 1999; Kent and Muttoni 2003; Loope et al. 2003) of Pangaea throughout Permian time, yet the climate was generally arid, and inferred to have become increasingly arid from Pennsylvanian through Permian time (e.g., Parrish 1993), although the forcing for this trend remains debated (Tabor and Poulsen 2008, and references therein). Both models and data indicate the onset of monsoonal circulation across Pangaea by early Permian time (e.g., Robinson 1973; Parrish and Peterson 1988; Kutzbach and Gallimore 1989; Parrish 1993; Soreghan et al. 2002; Tabor and Montanez 2002).

Within the greater study region of Kansas and Oklahoma, the Permian interval includes, from base to top, the Council Grove, Chase, Sumner, and Nippewalla, groups (and three post-Nippewalla Formations in Kansas that are likely equivalent to the Quartermaster Group in Oklahoma; Fig. 2). Zambito et al. (2012) presented the detailed stratigraphy of the studied interval and difficulties regarding correlation in the region. Regionally, the Council Grove and Chase groups consist generally of lithologically mixed (marine) carbonate and (continental) siliciclastic "cyclothems", whereas the overlying groups consist predominantly of red siliciclastic strata and bedded and displacive evaporite strata. The loss of a marine signal up section in this stratigraphy, together with laterally discontinuous outcrops that are poorly preserved owing to late-stage meteoric dissolution has long stymied efforts of stratigraphic dating and correlation. Compounding this, few complete (and well preserved) cores exist, owing to the limited economic interest in this shallow section. Hence, detailed study of environments and paleoclimate of the Midcontinent Permian, and—by extension—the record of greater western equatorial Pangaea—remains severely hampered.

A



B

Period	Series	Age (Ma)	Stage	Kansas Lithostratigraphy
Permian	Lopingian	252.2	Changhsingian	
		254.1	Wuchiapingian	
	Guadalupian	259.8	Capitanian	Big Basin Day Creek & Whitehorse Fms
		265.1	Wordian	Nippewalla Group
		268.8	Roadian	
	Cisuralian	272.3	Kunguria n	Sumner Group
		283.5	Artinskian	Chase Group
		290.1	Sakmarian	Council Grove Group (part)
		295.0	Asselian	
		298.9		

Fig. 2 **a** Simplified map showing areal extent of Permian red beds of the Midcontinent US (modified from Benison and Goldstein 2001; originally from Walker 1967) and **b** chronostratigraphy for the RKB core. Age designations for the Sumner and older groups are from Sawin et al. (2008) and West et al. (2010; originally Norton 1939), converted to international timescale designations using the most recent Permian timescale (Gradstein et al. 2012 for the conversion of stages; and Shen et al. 2013 for the latest dates). Chronostratigraphy for the Sumner Group and above reflect new magnetostratigraphic age assignments (Foster et al. 2014) discussed in the text, and detailed in Figs. 4 and 5

Background and methods

The Rebecca K. Bounds No. 1 (RKB) core was drilled by Amoco Production Company in 1988, in westernmost

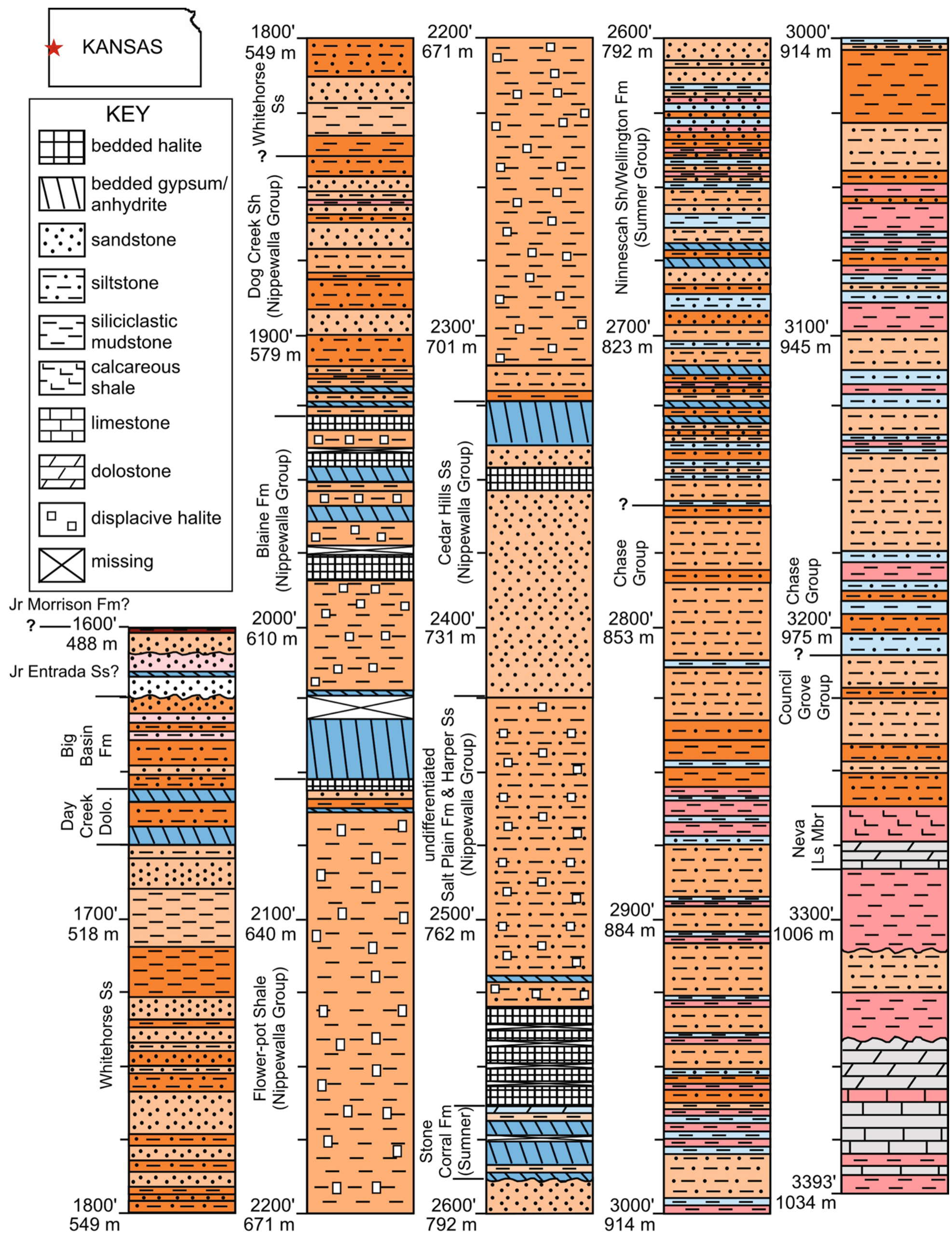


Fig. 3 Location and summarized stratigraphic column for the Amoco Rebecca K. Bounds No. 1 core, Greeley County, Kansas. Red star on inset map in upper left shows approximate core location. See Zambito et al. (2012) for a more detailed lithological log

Kansas, USA (Figs. 2, 3). The core was drilled as an experimental project, primarily to test the capabilities of Amoco's (then) newly developed "SHADS" (Slim-Hole Advanced Drilling System) rig (Walker and Millhein 1989), and secondarily to buttress biostratigraphic work on composite standards for the Paleozoic and Mesozoic. The SHADS technology included not only the capability of drilling and coring rapidly and continuously, but significant on-site core analysis using a modular, portable facility. The drilling of the RKB core required 38 days and US$ 591,000, and resulted in recovery of 1,656 m of continuous core extending from the Cretaceous nearly through the Mississippian, with >90 % recovery overall (Dean and Arthur 1998; Dean et al. 1995; Wahlman pers. commun. 2014). Amoco subsequently analyzed the core primarily for Mississippian-Pennsylvanian foraminiferal and fusulinid biostratigraphy (Wahlman and Groves pers. commun. 2014). According to Amoco internal reports on the RKB core, the youngest biostratigraphically significant marine fossils from the Paleozoic interval were latest Pennsylvanian (Gzhelian) fusulinids (Wahlman pers. commun. 2014). The typically cyclic upper Pennsylvanian section exhibits a gradual loss of normal marine deposition, with much of the uppermost Pennsylvanian composed of dolomitic to anhydritic restricted-marine facies. Buijs and Goldstein (2012) and Dubois et al. (2012) conducted petrographic observations and well log analyses on the Carboniferous-Lower Permian section. Several publications have focused on the Mesozoic strata of the RKB core (e.g., Arthur 1993; Dean et al. 1995; Dean and Arthur 1998). As oil prices continued to fall through the late 1980s and 1990s, the SHADS technology was ultimately abandoned (Wahlman pers. commun. 2014). Splits of the core are now housed at the Kansas Geological Survey core repository in Lawrence, Kansas, as well as the US Geological Survey in Denver, Colorado.

The Permian section of the core consists predominantly of fine-grained red beds with varying amounts of intergranular and displacive halite cement, as well as bedded evaporite strata (Fig. 3). Core recovery in this interval (~488 to ~1,034 m subsurface) is 99.1 %, reflecting the effective use of a drilling fluid engineered for water-sensitive facies (Zambito et al. 2012; Benison et al. 2013). Despite the excellent recovery, this interval remained virtually unstudied until very recently (Benison et al. 2013; Zambito et al. 2012; Foster 2013; Kane 2013, Zambito and Benison 2013; Foster et al. 2014), as the facies are barren of marine fossils typically used for biostratigraphic zonation in this interval, and the fine-grained red bed and evaporite facies were ignored for other detailed analyses.

Beginning in 2011, the section of the core from ~1,034 to 488 m (Middle Permian) was measured, logged, and sampled to establish lithostratigraphy through the targeted intervals (~Lower Permian–Middle Permian; see Zambito et al. 2012 for detailed stratigraphy). In addition, description and sampling were conducted at cm-scale resolution through several intervals chosen to focus on (1) fine-grained red beds of selected units and (2) pristine evaporite strata. For magnetostratigraphic analysis, samples marked with their stratigraphic "up" direction were collected at ~75 cm intervals (avoiding apparent bio- or pedoturbated samples) through the upper 105 m of the Permian interval and subjected to thermal demagnetization. Inclination data were used to track changes in inclination to assess magnetic reversals (see Foster 2013 for details of the magnetostratigraphic analysis). Two hundred and thirty thin sections were made using vacuum impregnation of epoxy. Care was taken not to heat samples or use water during thin section preparation. Thin sections were examined with transmitted, reflected, polarized, and UV–Vis light at magnification up to 2000x. Halite was prepared for fluid inclusion analyses by cleaving to mm-scale chips with a razor blade. Fluid inclusion heating runs were conducted on a USGS-modified gas-flow fluid inclusion stage (Benison and Goldstein 1999) and a Linkam THMSG600 fluid inclusion stage (Zambito and Benison 2013). Twenty-six additional samples representative of facies throughout the study interval were analyzed by X-ray diffraction for general mineral identification. Continuous core scans (e.g., XRF) were not performed as no facilities nor funding were available for such work.

Data acquisition enabled by coring

Data collected as part of the research on the Permian of the RKB core include, to date, petrography, sediment geochemistry, detrital zircon geochronology, magnetostratigraphy, isotope geochemistry, fluid inclusion microthermometry, and preliminary clay mineralogy (e.g., Benison et al. 2013; Zambito and Benison 2013; Foster 2013; Kane 2013; Foster et al. 2014). Our goal here is to highlight selected data collections enabled uniquely by drill core acquisition, together with their chronologic or paleoclimatic utility, and data acquisitions key to paleoclimatic reconstructions in paleo-loess successions that could be done in the future on this or analogous systems in optimally located sites. From the RKB core specifically, we highlight results from magnetostratigraphy and fluid inclusion microthermometry. Critically, none of the results could have been put into an unambiguous stratigraphic succession without the aid of such a high-recovery, well-preserved drill core.

Magnetostratigraphy

Magnetostratigraphy of the Permian part of the RKB core reveals a robust reversal stratigraphy (Fig. 4a). The Zijderveld diagrams (Fig. 4b) show the presence of two magnetic components: a low-temperature component (0–250 °C) representing a modern viscous remanent magnetization (VRM), and a higher-temperature (typically ~550–675 °C, or ~450–550 °C) component. Based on abundant unblocking temperatures above 580 °C, we infer the DRM/CRM (detrital remanent magnetization, chemical remanent magnetization) resides in hematite. Analysis of these data reveals a robust reversal stratigraphy; the presence of this sequence of reversals suggests the magnetization is either a DRM or an early CRM. That is, in either case, the magnetization had to be early in order to record the reversal stratigraphy. Additionally, the magnetic inclination data are consistently low (Foster 2013; Foster et al. 2014), and thus most consistent with early acquisition of the magnetization. The oldest reversal occurs near the contact between the Dog Creek Shale and the Whitehorse Formation at a depth of ~560 m, where the inclination changes from reversed to normal (Fig. 4). Altogether, three reversed polarity events (from bottom to top; event 1: avg. inclination = −15.8°, SD = 9.3°; event 2: avg. inclination = −24.4°, SD = 17.8°; and event 3: avg. inclination = −7.9°, SD = 9.3°) and two normal polarity events (event 1: avg. inclination = 16.5°, SD = 8.9°; and event 2: avg. inclination = 12.3°, SD = 7.6°) occur through the ~105 m of core leading up to the end Permian, clearly

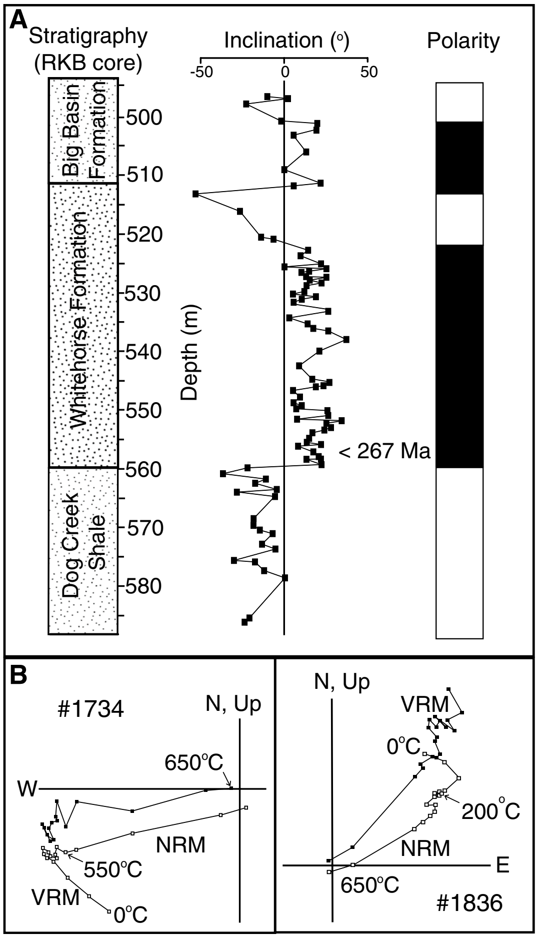


Fig. 4 **a** Stratigraphy of middle Permian red bed strata of the RKB core sampled for magnetostratigraphy, showing resultant magnetic inclination data, and magnetic polarity data of middle Permian red beds from western Kansas. *Black* represents normal polarity and *white* represents reversed polarity. **b** Typical Zijderveld demagnetization plots of normal (*left*) and reversed (*right*) polarity. Present-field magnetization, *VRM* viscous remanent magnetization, *NRM* natural remanent magnetization

placing the Whitehorse and Big Basin Formation in post-Kiaman time (Figs. 4, 5). In addition, an average inclination of 16.3° throughout the sampled interval is consistent with inclination values for the middle to late Permian seen in the variation of inclination with time for the study site (Fig. 6), providing further support for a post-Kiaman age. Combining these data with previous work on chronostratigraphy of the section (Denison et al. 1998; Foster et al. 2014) substantially refines the previously proposed chronostratigraphic placements for the midcontinent region (Fig. 5). In addition to revising the timing and duration of deposition, paleomagnetic data were used to identify paleolatitude estimates. Consistently, low inclination values throughout the sampled interval indicate an average paleolatitude of 6–10°N (Fig. 6; van der Voo (1993), confirming the lower end of previously cited ranges.

Evaporite paleothermometry

Cores of Permian red beds and evaporites throughout the US Midcontinent from a depth window of ~300–2,100 m are well preserved. In contrast, outcrops and deposits within ~300 m of the surface have undergone late-stage dissolution and alteration from recent groundwaters (Benison and Zambito 2013) such that detailed petrography can only be accomplished well with the aid of drill core. The recognition of unaltered bedded halite, displacive halite, and halite cements in red beds (Fig. 7) yields complete and well-preserved core necessary for assessing high-resolution depositional and early diagenetic conditions. For example, the displacive halite lithology (aka “chaotic halite” in some older literature), composed of red mudstone with randomly oriented large halite crystals, forms syndepositionally in groundwater-saturated saline mudflats adjacent to ephemeral saline lakes in arid climates (Benison and Goldstein 2001; Benison et al. 2007; Lowenstein and Hardie 1985). This lithology is the most abundant lithology in the Flowerpot Shale in the RKB core (Benison et al. 2013). However, in outcrop, the displacive halite crystals have been dissolved during late-stage, near-surface diagenesis by low-salinity groundwaters. Therefore, this saline mudflat lithofacies appears as massive mudstone, with only rare halite hopper crystal casts, molds, and pseudomorphs as evidence of the original depositional environment.

Primary fluid inclusions in bedded halite and displacive halite from the RKB core are well-preserved remnants of Permian surface waters and groundwaters. They can be tested with microthermometric methods and various geochemical analyses to yield temperatures, water salinities, and even water pH (Benison 2013). Homogenization of artificially nucleated vapor bubbles in primary fluid inclusions in chevron halite measure the temperature of Permian shallow (less than ~0.5 m) saline water at the time that the halite was growing. Because shallow surface waters have approximately the same temperature as local air temperature, these homogenization temperatures can be considered proxies for ancient air temperatures. Primary fluid inclusions in chevron halite define daily growth bands (Roberts and Spencer 1995; Benison and Goldstein 1999). Careful petrography enables high-resolution stratigraphic control of air temperature proxies at daily scales. This yields diurnal temperature ranges over days to weeks.

Zambito and Benison (2013) measured homogenization temperatures from primary fluid inclusions from 15 beds of chevron halite from the undifferentiated Salt Plan Formation/Harper Sandstone, the Cedar Hills Sandstone, and the Blaine Formation in the RKB core. Temperatures ranged from 7 to 73 °C. The maximum diurnal temperature range was 32° C. Trends in homogenization temperatures from base to near the top of the Nippewalla Group showed

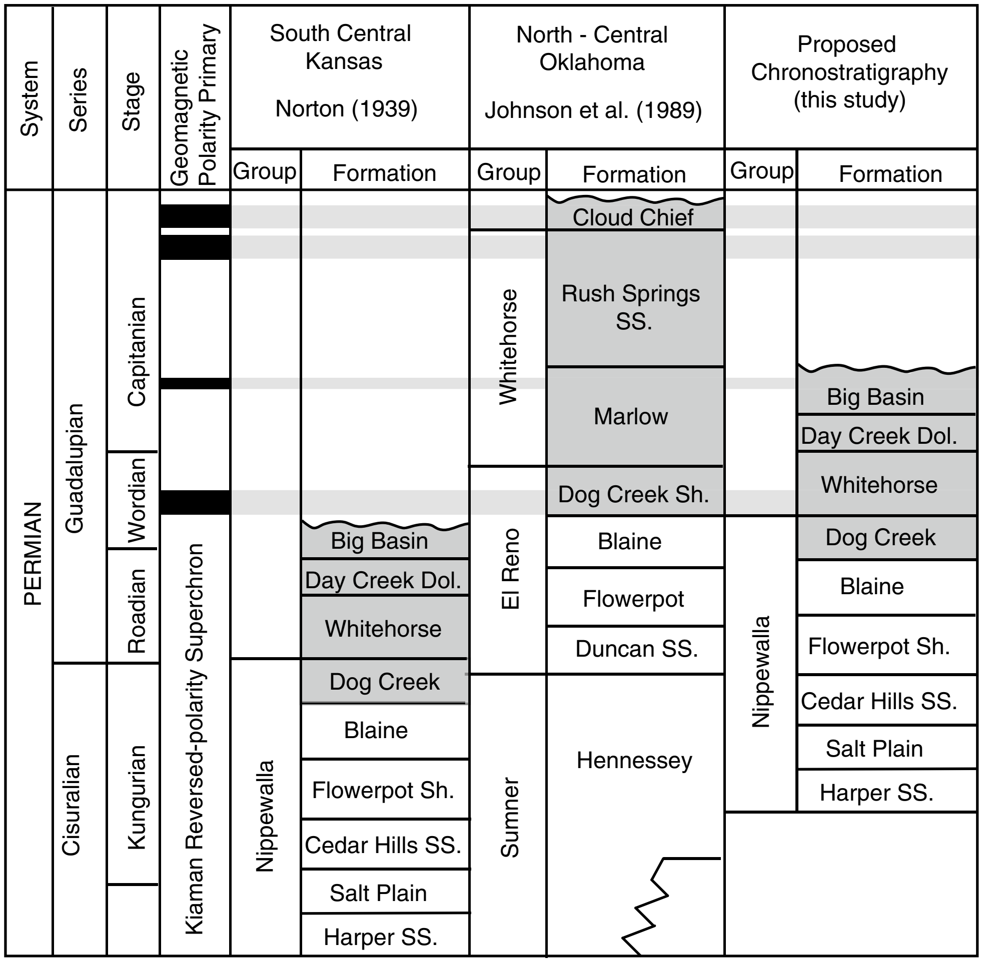


Fig. 5 a Chronostratigraphy and (new) magnetostratigraphy of middle Permian red beds from western Kansas. *Black* represents normal polarity and *white* represents reversed polarity. South Central Kansas column is from Norton (1939; see also West et al. 2010), Swineford (1955), Ham (1960), and Baars (1990). For comparison, we also show north central Oklahoma stratigraphy (Johnson 1989a, b). Shaded area represents ~105 m of red beds sampled for palaeomagnetic data. *Note* that the Kansas Geological Survey places this interval entirely within the Kiaman Superchron (i.e., >267 Ma). Shaded bars displays the positions of normal polarity events found in the RKB core

warming and then cooling. This is quantitative, high-resolution paleoweather and paleoclimate data that strongly suggests extremely warm temperatures in western Pangea during the mid Permian.

Discussion: Why core continental red beds and evaporites?

The problem of time

Midcontinent Permian red beds are predominantly fine-grained, and poorly lithified, owing to generally shallow burial (Carter et al. 1998; Hemmerich and Kelley 2000; Foster et al. 2014). Moreover, the low relief of the region in combination with the commonly low stratigraphic dips (~0.5°) has stymied outcrop-based studies of these units. Widely dispersed outcrops throughout the region expose only a few meters to a few tens of meters of section, and tend to be highly weathered and unstable owing to the friable, fractured, fine-grained, and evaporitic character of the facies (Fig. 8). Moreover, a fundamental obstacle that has prevented detailed study of the red bed-dominated section of the RKB core, and indeed outcrop systems throughout the North American midcontinent, is lack of a reasonable age model, owing to the paucity of biostratigraphically significant fauna. The resulting dearth of temporal resolution has impeded progress in regional and global correlations, and thus integration of the vast amounts of data preserved in these strata.

Magnetostratigraphy, although of limited use for the Early Permian, provides a potentially powerful dating

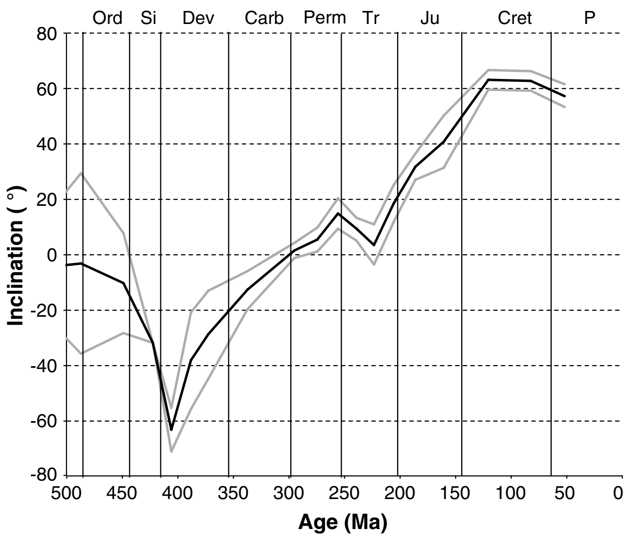


Fig. 6 Plot of the expected inclination through time for the northern study site. The *gray lines* represent error. Data from van der Voo (1993)

and correlation tool for the Middle-Late Permian, as the first reversal after the Kiaman Superchron occurred in the Wordian (~267 Ma; Steiner 2006; stratigraphy.org; Fig. 5). Building a magnetostratigraphic framework, however, requires acquiring samples that are (1) sufficiently indurated and free of surface weathering to enable effective sampling and thermal demagnetization and (2) collected in a long, continuous section with unambiguous superposition to enable construction of a robust reversal stratigraphy. This cannot be done in the Midcontinent Permian without core, owing to the limits of the surface exposures.

Detrital zircons of volcanic origin, however, can be used to constrain the depositional ages of sedimentary units that are otherwise poorly dated (e.g., Dickinson and Gehrels 2009; Soreghan et al. 2008, 2014) driven in part by advances in geochronologic methodology. For example, the ability to screen the U–Pb ages of a large number of grains through laser-ablation methods, followed by ID-TIMS (Isotope-Dilution Thermal Ionization Mass Spectrometry) analysis of the youngest grains in the sampled population can provide high-precision ages of grains that may correspond to the depositional age of the deposit. The derived age of the grain represents a maximum age of deposition; i.e., the grain must be as old as the sampled horizon, although the sampled horizon could be younger. This has been done on outcrop studies, but this method can be used with additional benefit in studies of continuous core as it allows the determination of maximum age of deposition at various horizons, eliminating the need to sample formations from spatially disparate outcrops where relative age information is not known a priori. The only potential drawback to this method is that the volume of sample needed from the core can be substantial; however, in our work (Kane 2013), a core split (half of 8.5 cm diameter core) of ~50 cm length of sandstone, siltstone, or mudstone yielded a sufficient number of zircons, and still enabled preservation of the archival half, as well as discrete sampling for auxiliary (e.g., thin section) analyses.

Red is not dead: the paleoclimatic value of red beds—especially paleo-loess

Lake systems have long been considered an ideal environment to tap for paleoclimatic reconstructions, as (permanent) lakes archive a continuous or near-continuous record that enables analysis at high temporal resolution of multiple metrics of paleoclimate, including proxies reconstructed from lithology, magnetism, geochemical and isotopic signals (e.g., Brigham-Grette et al. 2007; Cohen 2011). In recognition of this, research drilling for continental paleoclimatic reconstructions has focused in many

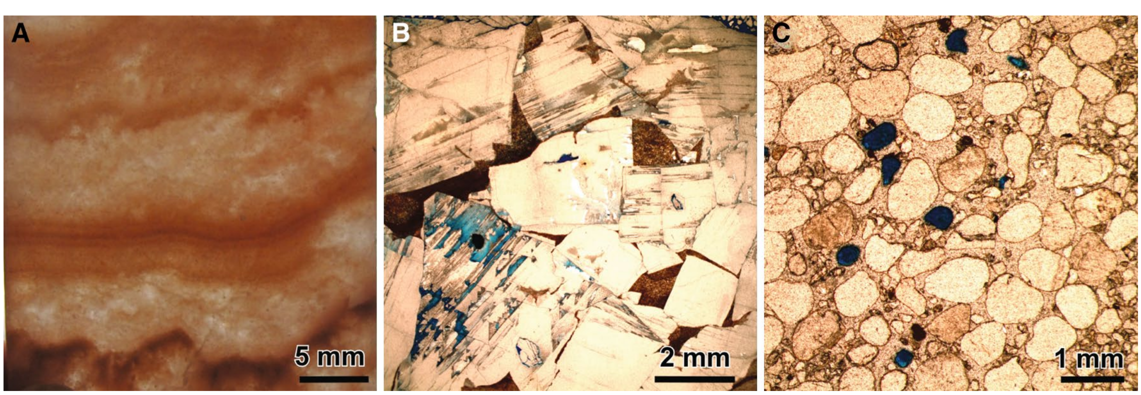


Fig. 7 The three main types of halite in the Rebecca K. Bounds core. **a** Bedded halite with abundant red mud, (714.4 m; 2,344′; thick section, transmitted light), **b** Displacive halite (773.3 m; 2,537′; thin section, transmitted light). **c** Intergranular halite cement in sandstone (738.2 m; 2,422.25′; thin section, transmitted light)

Fig. 8 Photographs of the studied Permian section in surface exposures, illustrating the character of outcrop. **a** Permian Dog Creek Shale exposed in central Oklahoma. **b** Permian Flowerpot Shale exposed in central Oklahoma. **c** Permian Flowerpot Shale exhibiting outcrop dissolution of evaporites

cases on coring of modern, long-lived lake systems (e.g., Lake Malawi, Lake El'gygytgyn, Lake Titicaca, Lake Peten Itza) with records extending in some cases to the Pliocene and even late Miocene (Cohen 2011). The time continuum of the deposits is particularly useful, but lake sediments also offer the potential to utilize several different types of organic carbon-based proxy analyses, such as compound-specific carbon isotopic ratios, and tetraether-based proxies (e.g., TEX-86 and isoprenoid glycerol dialkyl tetra ether; e.g., Tierney 2010).

Red beds occur in both marine and continental settings, but are far more common in the continental record. The red color primarily reflects (oxidized) hematite content, meaning little to no organic carbon may remain, and thus minimal potential for measurement of climate proxies based on such material. Some studies on red beds associated their presence with particular paleoclimatic conditions (review in Dubiel and Smoot 1995; Hu et al. 2014), such as warm arid settings, but other work has demonstrated that red beds form in a variety of climatic settings, from tropical to desert, suggesting caution in paleoclimatic interpretations of a red color (Dubiel and Smoot 1995; Sheldon 2005). Dubiel and Smoot (1995) noted that red bed formation reflects several conditions, including the presence of (1) small amounts of precursor organic matter (Myrow 1990), (2) abundant labile material such as mafic minerals and lithic fragments (e.g., Walker 1967, 1976), and (3) oxidizing conditions (Walker 1967; Turner 1980) Although the red color is not necessarily indicative of paleoclimate, various types of sedimentologic, geochemical, magnetic, and paleontologic criteria support detailed paleoclimatic reconstruction from red beds (details below).

Particularly critical for paleoclimatic reconstruction is preservation of a continuous record of surface paleoenvironments. Although challenging for some types of continental red beds (e.g., fluvial), paleo-loess systems are particularly well suited in this regard. The Chinese Loess Plateau (CLP) is considered an excellent archive of continental paleoclimate—directly comparable in resolution to ice-core and deep-marine archives (e.g., Liu 1985; Kukla and An 1989; Bloemendal et al. 1995; Liu et al. 1999; Ding et al. 2002). In many settings, loess accumulates very quickly, producing high temporal resolution (e.g., 1 m/ky in Rhine Valley) (Hatte et al. 2001; Lang et al. 2003) that rivals or exceeds any other continental depositional system, and responds directly to atmospheric conditions.

Study of loess as a high-resolution paleoclimate archive has long been conducted for the Quaternary record, but loess remains an under-utilized archive for Earth's deep-time record, despite increasing recognition of deep-time loess deposits (e.g., Johnson 1989a, b; Soreghan 1992; Evans and Reed 2007; Soreghan et al. 2008). The Late Carboniferous-Permian record appears to be particularly rich in occurrence and preservation of thick and widespread loess deposits (Soreghan et al. 2008), and many of the fine-grained red beds of this age in the North America midcontinent and elsewhere have been recently reinterpreted as paleo-loess deposits (e.g., Sweet et al. 2013; Dubois et al.

2012; Giles et al. 2013), including units of the RKB core (Foster 2013; Foster et al. 2014). In addition to loess (and associated paleosol) deposits, these facies include lake deposits as well—but shallow and ephemeral saline lakes, rather than deep, oxygen-poor systems.

Recognition of the widespread occurrence of loess and (saline) lake deposits over a broad region of the midcontinent promises the potential of very high-resolution climatic reconstruction, given the possibility of continuous sampling enabled by coring. Loess and associated deposits (e.g., paleosols, saline lake deposits) house enormous potential for paleoclimatic reconstruction. Analogizing again to the CLP, various attributes of loess (e.g., grain size, magnetic susceptibility, and geochemistry) have been mined to reconstruct climatic parameters that include atmospheric circulation (wind velocity and direction), seasonality, and precipitation (e.g., Zhou et al. 1990; An et al. 1991; Bloemendal et al. 1995; Liu et al. 1995; Ding et al. 2002; Sun 2002; Balsam et al. 2004; Vandenberghe et al. 2004; Hao and Guo 2005; Chen et al. 2006), at resolutions extending to millennial. Many of these same metrics are preservable and measurable in deep-time loess deposits and have enabled climate reconstructions ranging to sub-precessional scales (Soreghan et al. 2014).

As an example, the Maroon Formation, a Permian loessite-paleosol succession in central Colorado is well exposed along road cuts and has been extensively sampled (Johnson 1989a, b; Soreghan et al. 1997; Tramp et al. 2004; Soreghan et al. 2014). Tramp et al. (2004) noted that the alternating loessite-paleosol couplets exhibit similarities to the CLP both in lithologic character and in apparent temporal patterns of magnetic susceptibility. Sub-meter sampling of the 700 m section showed that magnetic susceptibility values are higher in deeply red-colored, finer-grained beds, whereas values are lower in orange, silty units. These changes are interpreted to reflect alternating wet-dry phases linked to climate swings within the late Paleozoic icehouse. To further explore these patterns, Soreghan et al. (2014) sampled a 12 m interval of this same section of the Maroon Formation on a 10-cm scale for geochemical, grain size, and magnetic susceptibility trends. They documented a robust negative correlation ($r^2 = 0.9$) between grain size (inferred from image analysis of quartz grains; Soreghan and Francus 2004), and magnetic susceptibility values (Fig. 9). The variations in quartz grain size are interpreted to record changes in wind intensity (and/or source proximity) with finer, more iron-rich sediment deposited during times of reduced winds (or from further distances) and coarser, more quartzose (less iron-rich) sediment deposited during times of stronger, seasonal winds (Soreghan et al. 2014). The finer-grained beds show evidence of pedogenesis and are interpreted to represent wetter conditions that grade downward into the coarser, orange units inferred to be loessite deposited during more arid times. However, the nature of the transitions and the internal stacking of these loessite-paleosol couplets suggest that they represent high-frequency fluctuations in wind patterns and wind intensity. The thicker loessite units, capped by thicker, well-developed paleosols show an abrupt fining in grain size with the coarsest sediment at the transition; thinner loessite-paleosol couplets show a more gradual fining and less variation overall. These alternations, and their nested variability, typical of the entire exposed 700 m of the Maroon Formation may reflect sub-Milankovitch variability. However, attempting to create a continuous record using surface exposures is untenable at the resolution necessary to delineate this variability. A continuous core, bolstered by further refinement of the grain size to magnetic susceptibility correlation, would facilitate reconstruction of a very high-resolution record of wind regimes and thus atmospheric circulation from deep time.

Furthermore, continuous acquisition of metrics such as magnetic susceptibility, XRF-based geochemistry, spectral reflectance, and other data readily acquired from core using rapid core scanning and/or high-resolution point sampling are ideal for quantitative assessments of cyclostratigraphy, which further improves age models and potentially enables resolution of climatic evolution down to the 10 ky scale (e.g., Olsen et al. 1996; Sur et al. 2010).

Paleoclimatic information can also be determined from rocks lacking typical easily interpretable sedimentological features based on changes in clay mineralogy. Such paleoclimatic interpretations from clay mineralogical signatures must first be assessed for influence of non-climatic influences such as extreme water chemistry, as well as changes in source area, tectonic forcing, and sedimentological sorting processes on detrital clays, and diagenetic processes. The climatic signal can potentially be interpreted from very subtle changes in the ratios of clays representing physical weathering (illite/chlorite), seasonal chemical weathering (smectite), and persistent wet conditions (kaolinite) (Arostegi et al. 2011). Clay mineralogy from drill core ensures that surface weathering has not degraded the signal.

Climate and weather revealed in evaporites

Well-preserved ancient evaporites, accessible only in cores, provide paleoclimate data in two distinct ways. Petrographic documentation of halite and gypsum crystal types and sedimentary features lead to informed interpretations of depositional environments. Because most evaporite depositional environments are sensitive to climate, petrographic observations provide qualitative information about paleoclimate, such as relative aridity (i.e., Benison et al. 2007; Lowenstein and Hardie 1985). Secondly, fluid

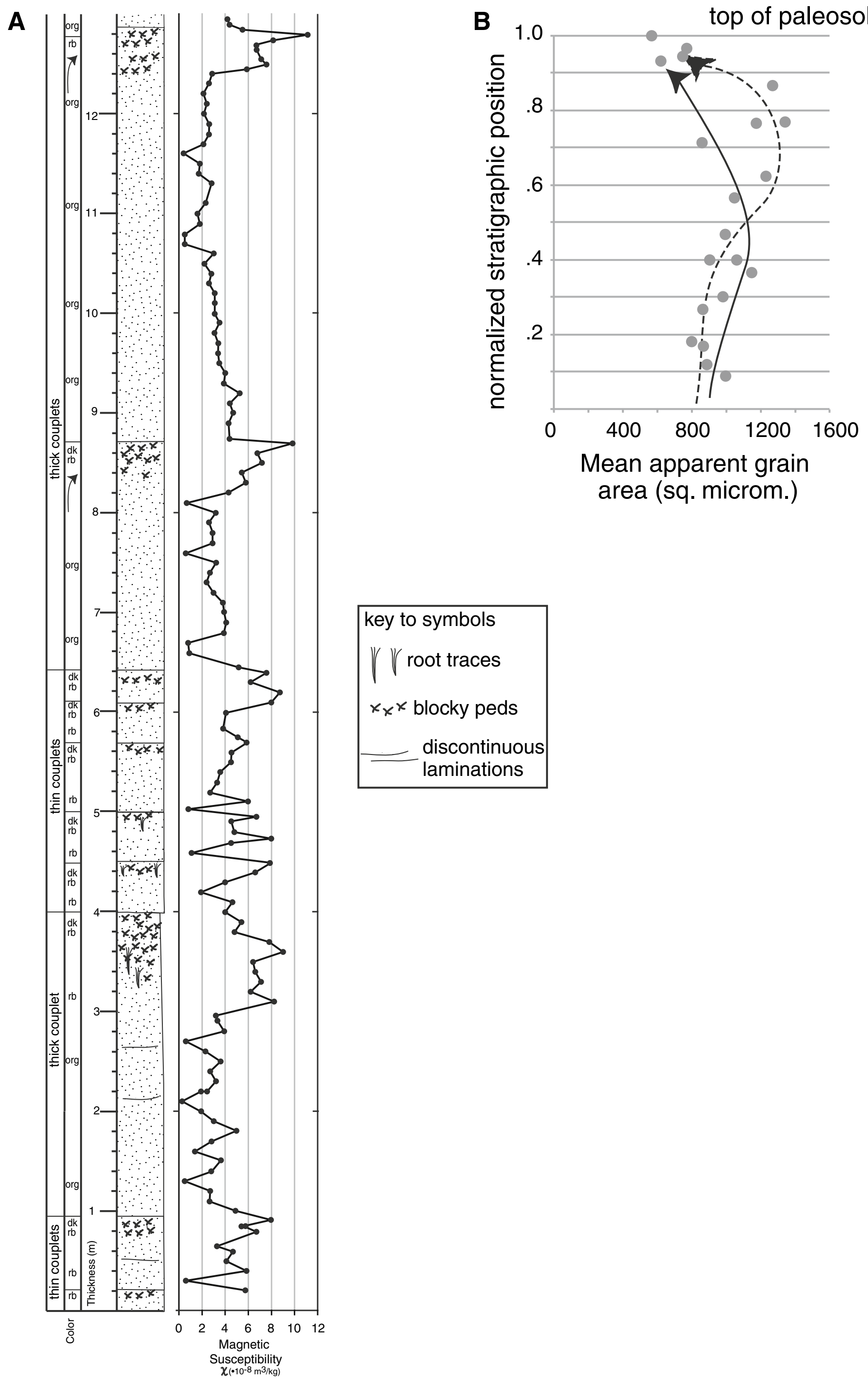


Fig. 9 **a** Detailed measured section of a 12 m interval of the Permian Maroon Formation near Basalt, Colorado (see Soreghan et al. 2014 for location). Bulk magnetic susceptibility values consistently increase at the deeper red (*rb*= "red-brown") horizons bearing lithologic indicators of pedogenesis (blocky peds, root traces) and decrease within the orange-colored (*org*= "orange") non-pedogenically altered loessite horizons. **b** Apparent grain area based on image analysis of ~800 quartz grains per sample normalized to their stratigraphic position relative to inferred paleosol tops within four loessite-paleosol couplets targeted within the measured section. The samples from the thickest couplets exhibit a marked increase in apparent grain size just below the paleosol top, then fine abruptly at the paleosol horizon (*dashed line* with *arrow*), whereas samples from thinner couplets exhibit a more gradual decrease from loessite to paleosol (*solid line* with *arrow*). These appear to reflect changes in the variability of monsoon circulation on sub-Milankovitch scales (see Soreghan et al. 2014). Modified from Soreghan, et al. 2014

inclusion data from bedded halite yield high-resolution, quantitative records of paleoclimate. Homogenization of artificially nucleated primary fluid inclusions are proxies for past air temperatures (Roberts and Spencer 1995). Homogenization temperatures measured from base to top of individual growth bands in chevron halite allows for interpretation of minimum daily temperature ranges, whereas homogenization temperatures from successive chevron growth bands suggest diurnal temperature ranges (Benison and Goldstein 1999). Longer-scale trends in air temperatures can be resolved by comparison of homogenization temperatures among individual beds of halite. In addition, chemical compositions of primary fluid inclusions in ancient halite can document past surface and groundwater chemistry. This chemical data can provide information about weathering processes that may be dependent upon climate. Furthermore, sampling from continuous core confers unambiguous superposition, such that these valuable paleoclimatic data can be placed into a proper temporal context.

Caveats and future opportunities

The mere existence of a core like the RKB offers abundant opportunities, but much more could be done given core scanning. Amoco acquired standard oil industry (well-bore) logging during drilling, but no additional scans were ever conducted on the core. For the purposes of high-resolution environmental reconstruction, multi-sensing core logging techniques (MST) offers a relatively low-cost means to rapidly and nondestructively characterize core samples. Such data include neutral gamma radiation, gamma density, P-wave velocity, magnetic susceptibility, electrical resistivity, and imaging. Data acquired from MST can significantly improve the ability to characterize changes in lithology that can then direct more detailed and time-consuming analyses to follow. Density and P-wave velocity measurements can be used to generate a synthetic seismogram to enable correlation of the core to seismic records. MST also enable continuous digital imaging (color spectrophotometry) of the core for archival as well as image analyses.

Finally, although access to core provides unrivaled opportunities to sample fresh material in unambiguous superposition, the one-dimensionality of a core is clearly limiting relative to the multi-dimensionality of expansive outcrops. Where permitted by the geologic setting, therefore, a coring program that combines drilling with outcrop studies remains the ideal approach. This is particularly true for characterizing linked environmental and paleobiological change, where outcrop studies may provide more access to fossil material, and core provides the context of continual environmental change. The challenge then remains to correlate these records at high resolution, using geochronological and magnetostratigraphic approaches. An excellent example is the current attempt to catalog the possible environmental drivers to human evolution in East Africa, where the fossil and artifact record has long been pursued in isolated outcrops. Tying this record to an archive of continuous environmental change is now occurring through a large-scale coring program (Cohen et al. 2009). Several of the drilling sites for this project were chosen in direct proximity to well-studied outcrops to facilitate direct correlation of the (outcrop-based) fossil and artifact record to the (core-based) paleoenvironmental record.

Conclusions

The RKB core, drilled with the primary intent of testing a drilling methodology, serendipitously aided preliminary chronostratigraphic, and paleoclimatic refinements for the Permian of the North American Midcontinent. The studied units consist entirely of red bed and evaporitic strata, commonly dismissed as being of little utility for chronostratigraphic and paleoclimatic work. Yet fine-grained red beds are ideal for magnetostratigraphic analysis and house the potential to yield a wealth of high-resolution data for paleoclimatic reconstructions, especially if these strata record paleo-loess deposition. Furthermore, contained evaporite strata, pristine in core, can provide quantitative paleoclimatic and even paleo-weather data. Such paleo-loess and evaporite deposits characterize much of the Permian record in many regions globally as well as many regions plagued by low relief and poor outcrop exposure. In these successions, drill core is essential for (1) accessing a continuous vertical section that establishes unambiguous superposition key to both magnetostratigraphic and paleoclimatic analyses and (2) providing pristine sample material from friable, soluble, and/or lithofacies and mineralogical species otherwise poorly preserved in surface exposures. Our work on the RKB core illustrates a fraction of the potential that coring in such units can offer. The ability to drill in key regions representing the most continuous sections and conduct continuous core scanning and auxiliary types of proxy analyses would shed abundant light on a critical icehouse–greenhouse transition in Earth history.

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