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Colorado Plateau Coring Project, Phase I (CPCP-I): a continuously cored, globally exportable chronology of Triassic continental environmental change from western North America

Paul E. Olsen[1], John W. Geissman[2], Dennis V. Kent[3,1], George E. Gehrels[4], Roland Mundil[5], Randall B. Irmis[6], Christopher Lepre[1,3], Cornelia Rasmussen[6], Dominique Giesler[4], William G. Parker[7], Natalia Zakharova[8,1], Wolfram M. Kürschner[9], Charlotte Miller[10], Viktoria Baranyi[9], Morgan F. Schaller[11], Jessica H. Whiteside[12], Douglas Schnurrenberger[13], Anders Noren[13], Kristina Brady Shannon[13], Ryan O'Grady[13], Matthew W. Colbert[14], Jessie Maisano[14], David Edey[14], Sean T. Kinney[1], Roberto Molina-Garza[15], Gerhard H. Bachman[16], Jingeng Sha[17], and the CPCD team*

[1] Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA
[2] Department of Geosciences, University of Texas at Dallas, Richardson, TX 75080, USA
[3] Earth and Planetary Sciences, Rutgers University, Piscataway, NJ 08854, USA
[4] Department of Geosciences, University of Arizona, Tucson, AZ 85721, USA
[5] Berkeley Geochronology Center, 2455 Ridge Rd., Berkeley CA 94709, USA
[6] Natural History Museum of Utah and Department of Geology & Geophysics,
University of Utah, Salt Lake City, UT 84108, USA
[7] Petrified Forest National Park, Petrified Forest, AZ 86028, USA
[8] Department of Earth and Atmospheric Sciences, Central Michigan University,
Mount Pleasant, MI 48859, USA
[9] Department of Geosciences, University of Oslo, P.O. Box 1047, Blindern, Oslo 0316, Norway
[10] MARUM Center for Marine Environmental Sciences, University of Bremen, Bremen, Germany
[11] Earth and Environmental Sciences, Rensselaer Polytechnic Institute (RPI), Troy, NY 12180, USA
[12] National Oceanography Centre, Southampton, University of Southampton, Southampton, SO17 1BJ, UK
[13] Continental Scientific Drilling Coordination Office and LacCore Facility, N.H. Winchell School of Earth
Sciences, University of Minnesota, Minneapolis, MN 55455, USA
[14] University of Texas High Resolution X-ray CT Facility, The University of Texas at Austin,
Austin, TX 78712, USA
[15] Centro de Geociencias, Universidad Nacional Autónoma de México (UNAM), Boulevard Juriquilla No.
3001, Querétaro 76230, México
[16] Martin-Luther-Universität, Halle-Wittenberg, Institut für Geowissenschaften, Von-Seckendorff-Platz 3,
06120 Halle (Saale), Germany
[17] State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Paleontology and
Center for Excellence in Life and Paleoenvironment, Nanjing 210008, China
[*] A full list of authors appears at the end of the paper.

Correspondence: Paul E. Olsen (polsen@ldeo.columbia.edu)

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Abstract. Phase 1 of the Colorado Plateau Coring Project (CPCP-I) recovered a total of over 850 m of stratigraphically overlapping core from three coreholes at two sites in the Early to Middle and Late Triassic age largely fluvial Moenkopi and Chinle formations in Petrified Forest National Park (PFNP), northeastern Arizona, USA. Coring took place during November and December of 2013 and the project is now in its post-drilling science phase. The CPCP cores have abundant detrital zircon-producing layers (with survey LA-ICP-MS dates selectively resampled for CA-ID-TIMS U-Pb ages ranging in age from at least 210 to 241 Ma), which together with their magnetic polarity stratigraphy demonstrate that a globally exportable timescale can be produced from these continental sequences and in the process show that a prominent gap in the calibrated Phanerozoic record can be filled. The portion of core CPCP-PFNP13-1A for which the polarity stratigraphy has been completed thus far spans ∼215 to 209 Ma of the Late Triassic age, and strongly validates the longer Newark-Hartford Astrochronostratigraphic-calibrated magnetic Polarity Time-Scale (APTS) based on cores recovered in the 1990s during the Newark Basin Coring Project (NBCP).

Core recovery was ∼100 % in all holes (Table 1). The coreholes were inclined ∼60–75° approximately to the south to ensure azimuthal orientation in the nearly flat-lying bedding, critical to the interpretation of paleomagentic polarity stratigraphy. The two longest of the cores (CPCP-PFNP13-1A and 2B) were CT-scanned in their entirety at the University of Texas High Resolution X-ray CT Facility in Austin, TX, and subsequently along with 2A, all cores were split and processed at the CSDCO/LacCore Facility, in Minneapolis, MN, where they were scanned for physical property logs and imaging. While remaining the property of the Federal Government, the archive half of each core is curated at the NSF-sponsored LacCore Core Repository and the working half is stored at the Rutgers University Core Repository in Piscataway, NJ, where the initial sampling party was held in 2015 with several additional sampling events following. Additional planned study will recover the rest of the polarity stratigraphy of the cores as additional zircon ages, sedimentary structure and paleosol facies analysis, stable isotope geochemistry, and calibrated XRF core scanning are accomplished. Together with strategic outcrop studies in Petrified Forest National Park and environs, these cores will allow the vast amount of surface paleontological and paleoenvironmental information recorded in the continental Triassic of western North America to be confidently placed in a secure context along with important events such as the giant Manicouagan impact at ∼215.5 Ma (Ramezani et al., 2005) and long wavelength astronomical cycles pacing global environmental change and trends in atmospheric gas composition during the dawn of the dinosaurs.

1 Context and motivation

Bracketed between two of the largest mass extinctions, the Triassic Period (ca. 252–202 Ma) saw the evolution of the major elements of modern animal communities on land, had arguably the highest atmospheric CO_2 concentrations of the Phanerozoic (Foster et al., 2017) (>4000 ppm: Schaller et al., 2015), and has the longest recovered continuous records of orbitally paced climate change (Olsen and Kent, 1996; Ikeda and Tada, 2014; Kent et al., 2017) – one that bears the fingerprint of the chaotic evolution of the Solar System (Olsen and Kent, 1999; Ikeda and Tada, 2013) (Fig. 1). By the Late Triassic, continental tetrapod associations were remarkably segregated into latitudinal zones, and although dinosaurs had evolved by the beginning of that epoch, herbivorous forms were restricted to high latitudes, while in tropical communities carnivorous dinosaurs remained a relatively minor part of communities, tending also to be rather small (Whiteside et al., 2015). In the oceans, during this time, calcareous nanoplankton made their appearance (Bown et al., 2004), modern reef-forming corals evolved (Stanley, 1981), and archaic forms such as conodonts declined (Tanner et al., 2004).

But despite the pivotal role of the Triassic, the period is characterized by very poor chronologic constraints. This has been especially true for the longest age (stage) of the Triassic, the Norian (∼206–228 Ma), arguably the acme of Triassic life and the longest age of the Phanerozoic. As of 2011, there were only three U-Pb zircon dates over the 22 Myr time interval available to constrain the stage (see Olsen et al., 2011), and even its boundary ages and especially marine to continental correlations have remained hotly contested (Muttoni et al., 2004; Ogg et al., 2012). The Late Triassic–Early Jurassic astrochronology and associated paleomagnetic polarity stratigraphy from the largely lacustrine Newark Basin based on cores mostly from the NSF-funded Newark Basin Coring Project (NBCP) completed in the mid-1990s served as the basis of a high-resolution timescale and has been broadly accepted (e.g., Walker et al., 2013; IUGS/ISC, 2017). However, because it was pinned by radioisotopic dates only at the top of the Triassic age section, its accuracy has been questioned from a number of fronts (e.g., Hilgen et al., 1997; Tanner and Lucas, 2015), including largely biostratigraphically based assertions of the presence of cryptic but significant gaps in the upper part of the Triassic age section that would separate the dated levels from 1000s of meters of the underlying section (Gallet et al., 2003; Kozur and Weems, 2005; Tanner et al., 2004).

Progress in past Earth system science fundamentally depended on being able to measure time at appropriate levels of resolution and also being able to link contemporaneous events, fossil occurrences, and environmental records across geography, and this ability has been sorely lacking for many time intervals in Earth's history. To address

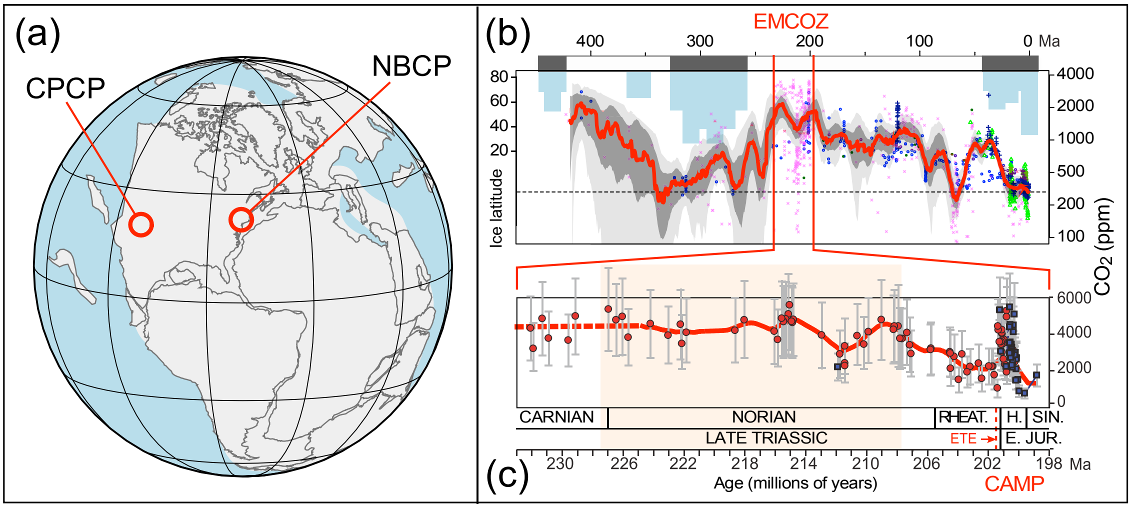

Figure 1. Context for the CPCP cores. **(a)** Late Triassic–Early Jurassic Pangea showing the positions of CPCP cores and Newark Basin Coring Project (NBCP) APTS (based on Whiteside et al., 2010). **(b)** Compilation of CO_2 proxy data and extent of continental ice modified from Foster et al. (2017) with latitudinal extent of ice (light blue bars) and ice-house conditions (grey bars). Proxy symbols are leaf stomata, blue open circles; pedogenic carbonate, pink crosses; boron isotopes, green triangles; liverworts, blue filled circles; and alkenones, blue crosses – red line is fit through the data and 68 % and 95 % confidence intervals are dark and light grey bands. **(c)** The Early Mesozoic CO_2 Zenith (EMCOZ), based on the pedogenic CO_2 proxy from the Newark and Hartford basins, modified from Schaller et al. (2015): red circles are from the Newark Basin and blue circles are from the Hartford Basin; light orange area is interval encompassed by the Chinle Formation in CPCP cores; red line is the smoothed fit through the data; and the dashed red line mean for the points without astrochronologic time control.

this cross-cutting issue for the Triassic, we launched the Colorado Plateau Coring Project (CPCP) as an interdisciplinary multiphase coring experiment in a geologic setting where there was sufficient background information to know there would be abundant zircon U-Pb datable deposits and a recoverable paleomagnetic polarity record that together would allow for a meaningful, globally exportable timescale. Also, deemed highly desirable, would be the selection of a target where cores would leverage, and allow for correlation with, a large amount of previously collected surface information. The CPCP was an outcome of the 1999 US NSF- and ICDP-funded "International Workshop for a Climatic, Biotic, and Tectonic, Pole-to-Pole Coring Transect of Triassic-Jurassic Pangea" (http://www.ldeo.columbia.edu/~polsen/nbcp/westpangea.html, last access: September 2018) that recognized "Western Equatorial Pangea (Colorado Plateau)" as a key coring target. Subsequent CPCP workshops held in 2007 and 2009 (funded by the US NSF, ICDP, and DOSECC) narrowed down the optimal site for the first phase of the CPCP to Petrified Forest National Park, in northern Arizona (Fig. 2) (Olsen et al., 2008; Geissman et al., 2010; http://www.ldeo.columbia.edu/~polsen/cpcp/CPCP_home_page_general.html, last access: September 2018), where strata of the ?Early–Middle Triassic age Moenkopi Formation and Late Triassic Chinle Formation are well represented and have been comparatively very well studied in previous projects, some of which demonstrated that zircon U-Pb geochronologic information (Riggs et al., 2003) and paleomagnetic polarity stratigraphies (Steiner and Lucas, 2000; Zeigler et al., 2017) could be recovered. Furthermore, long-term study (Parker and Martz, 2011) of the superb exposures of Petrified Forest National Park (PFNP) had resulted by that time in a well-characterized physical stratigraphy (Woody, 2006; Martz and Parker, 2010; Martz et al., 2012), into which rich assemblages of vertebrates (Long and Murry, 1995; Parker and Irmis, 2005) and plants (Ash, 1972, 1989; Fisher and Dunay, 1984; Litwin, 1991), and their environments (Therrien and Fastovsky, 2000) were registered (Parker, 2006). These outcrops also have the best record of what is arguably the most prominent continental biotic transition of the Late Triassic (prior to the end Triassic extinction), the Adamanian–Revueltian Biozone boundary (Parker and Martz, 2011; Martz and Parker, 2017) that seems plausibly linked to the great Manicouagan bolide impact (Ramezani et al., 2005; Parker and Martz, 2011; Olsen et al., 2011). Proposals were submitted in 2010 and funding was secured from both the US NSF and ICDP by 2013 to recover a continuous cored record of the Triassic record in PFNP. The CPCP, Phase I scientific coring experiment designed to explicitly test competing Triassic stratigraphic, temporal, climatic and biotic hypotheses took place during November and December of that same year, and involved drilling at northern and southern locations in Petrified Forest National Park (Figs. 2, 4).

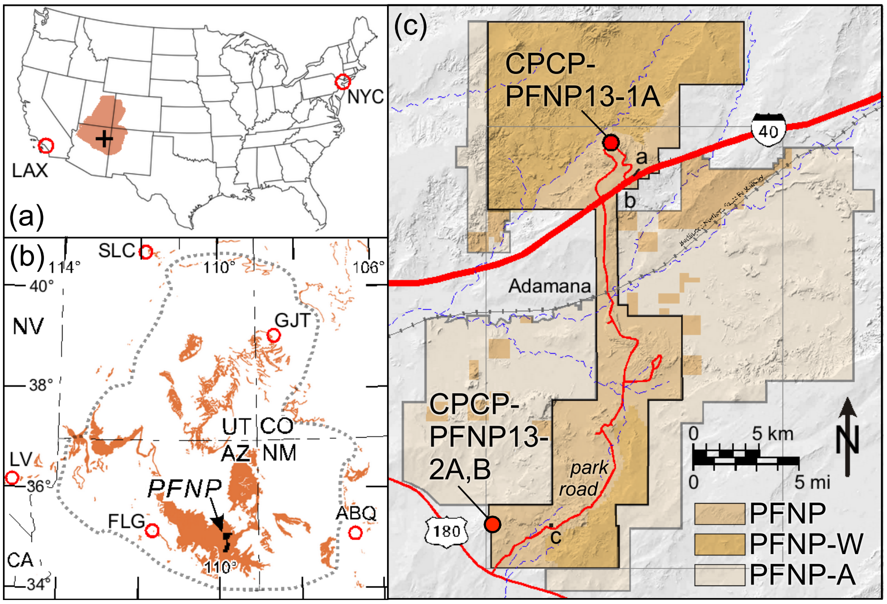

Figure 2. Location of CPCP cores. **(a)** Location of the Colorado Plateau (red-brown area) in the United States with the cross marking the location of the coring sites in Petrified Forest National Park: LAX, Los Angeles, California; NYC, New York City, New York, which is just to the east and south of the location of the Newark-Hartford APTS (NBCP cores and outcrops). **(b)** outline of the Colorado Plateau (dotted line) and Triassic outcrop area (red brown) showing the location of Petrified Forest National Park (PFNP): ABQ, Albuquerque, New Mexico (NM); FLG, Flagstaff, Arizona (AZ); GJT, Grand Junction, Colorado (CO); LV, Las Vegas, Nevada (NV); SLC, Salt Lake City, Utah (UT); CA, California. **(c)** Map of PFNP with location of the coring sites: PFNP, Petrified Forest National Park; PFNP-A, Private or State Trust land; PFNP-W, Petrified Forest National Park, Wilderness area; a, park headquarters; b, park entrance off I-40; c, Rainbow Forest Museum; PFNP-CPCP13-1A, core site at Chinde Point; PFNP-CPCP13-2A, 2B, core site at "West Bone Yard".

1.1 The need to core

Despite the superb outcrops of Triassic strata in parts of the American Southwest, a scientific drilling experiment was essential because most continuous sections in outcrop are either inaccessible in vertical cliffs or are weathered and geochemically altered, making observations and sampling at the appropriate level of detail impossible. Furthermore, the characteristic shallow bedding attitudes in combination with lateral facies changes typical of these largely fluvial systems compromise the ability to determine superposition in sections compiled over long geographic distances. This is especially clear at PFNP, where there are two main outcrop areas, a northern area with the stratigraphically higher parts of the sections and a southern area with the stratigraphically lower Chinle sections. These outcrop areas are separated by about 20 km of no exposure; although the sections have been individually quite well studied, no two analyses of the combined stratigraphic column published in 20 years agreed, some compilations differing by as much as 30 % in total thickness. Additionally, the lowermost parts of the Chinle Formation and underlying Triassic Moenkopi Formation do not crop out in the park. The situation is worse in other areas of the American Southwest.

1.2 Tectonic environment

The overall tectonic context of early Mesozoic strata in the American Southwest is uncertain, because, compared to the relatively simple Triassic–Jurassic extension and continental rifting of central Pangea, including eastern Laurentia, models of the western North American Cordillera are complex, involving exotic terranes, magmatic arcs, oceanic-plate subduction, and intense crustal deformation lasting until the early Cenozoic, with most of the pertinent tectonic geometry being so strongly deformed as to be inferable only by indirect means. Since the 1970s the leading hypothesis for the tectonic context of the mostly continental Triassic–Jurassic sequences was that they developed during eastwardly directed oceanic-crust subduction of the Farallon Plate beneath North America with a magmatic (Cordilleran) arc over the subducting slab and west of the backarc, back-bulge, backarc tectonic furrow, or foreland retroarc basins in which the Triassic–Jurassic deposits accumulated (Burchfiel and Davis, 1972; Lawton, 1994; Gehrels et al., 2000; Barth and Wooden, 2006; Sigloch and Mihalynuk, 2017; Dickinson, 2018) (Fig. 3). An alternative and controversial model based on geologic and geophysical (tomographic) data postulates that western North America was a passive continental margin from the Paleozoic until the Cretaceous with westward-

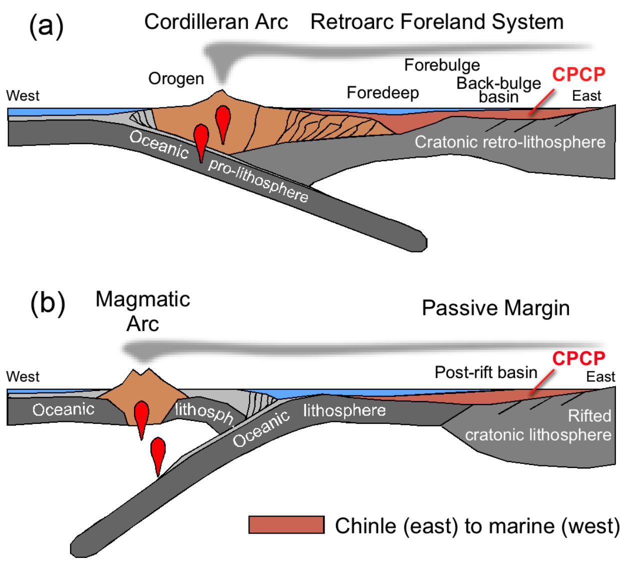

Figure 3. Generalized cartoons of end-members of the alternative tectonic models for the Chinle basin (at position of CPCP in red). **(a)** Conventional model of a Triassic Cordilleran arc with a retroarc basin with Chinle and marine strata (modified and generalized from Eriksson et al., 2008; DeCelles and Giles, 1996). **(b)** Passive margin model for Triassic western North America (modified from Chemenda et al., 1997) which is consistent with Hildebrand (2013). Note that realistic, empirically based cross sections for these end-member models have yet to be published and that these are cartoons based on possible analog situations, with the additional caveat that the significant possibility of large strike–slip components (non-plane strain) is not addressed in this figure. Note also that Chinle was probably in a belt of easterly (trade) winds at the time.

dipping subduction (Hildebrand, 2009; Sigloch and Mihalynuk, 2013). Despite the extreme differences, both models are consistent with having most of the sediment of the Triassic–Jurassic sequences derived from northwesterly flowing fluvial systems, with a persistent slope from the interior of Pangea as well as closer topographic remnants of the Ancestral Rocky Mountain orogen, toward the Cordilleran margin (Riggs et al., 1996). The sources of the fluvial and eolian transport systems during the Triassic–Jurassic time have been documented using detrital zircons (Dickinson and Gehrels, 2008a, b). In both eastward and westward subduction models a southwestern source of silicic volcanic debris is generally identified with the postulated Cordilleran arc or Mogollan Highlands (Howell and Blakey, 2013; Riggs et al., 2013, 2016; Dickinson, 2018). Although the active margin, backarc–retroarc models have basin depocenters and syndepositional deformation localized by proximal active compressive and flexural forces of the approaching arc, or slab-related dynamic subsidence, there is ample evidence that much local deformation and localized subsidence was controlled by early Mesozoic halokenesis (salt tectonics) (Shoemaker et al., 1958; Hazel, 1994; Matthews et al., 2007; Trudgill, 2011; Banham and Mountney, 2014; Hartley and Evenstar, 2017) that might, in fact, prove more important than either basement-involved tectonics or eustasy in structuring much of the stratigraphy (P. E. Olsen et al., 2016). An additional, generally overlooked consideration is that the southern and eastern edges of the western US Triassic–Jurassic sequences lie against the projection of the Central Atlantic rift system, and changes in the uplift of the northwestern rift shoulders related to extensional pulses are plausible factors in modulating rates of supply of sediments to the deposits of the American Southwest (Huber et al., 2016).

The more recent history and origin of the Colorado Plateau itself remains somewhat enigmatic and debated as well, with useful recent reviews of the history being Flowers (2010) and Liu and Gurnis (2010). The plateau is characterized by relatively undeformed crust and is almost entirely surrounded by strongly shortened and subsequently highly extended regions. Apparently prior to and after the Late Cretaceous to early Cenozoic formation of the Central and Southern Rocky Mountains, the region was relatively low-lying, but during the medial Cenozoic extension that formed the Basin and Range physiographic province to the west and the Rio Grande rift to the east, the plateau was uplifted by at least a kilometer and originally east-flowing streams and rivers that deeply incised parts of the plateau and reversed their course, resulting in the more modern version of the Grand Canyon of the Colorado River and associated erosional features. The combined effects of the shortening and extension was a clockwise rotation of the Colorado Plateau about a vertical axis of perhaps up to a net ∼ 10° (see Hamilton, 1981; Steiner, 1986; Kent and Witte, 1993; Bryan and Gordon, 1986; Steiner and Lucas, 2000; Wawrzyniec et al., 2002; McCall and Kodama, 2014). In the late Neogene and Quaternary localized mafic volcanism has taken place, indicating ongoing tectonic evolution of the plateau with the geodynamic origin and timing of the events shaping the plateau remaining hotly debated.

1.3 Climatic context and stratigraphy

In the broadest sense, the stratigraphic sequence on and close to the plateau remained continental to marginal marine through its entire early Mesozoic history. The Colorado Plateau part of Laurentia was near the Equator in the Early Triassic, moved north through the Triassic from more humid latitudes ∼ 7° at 220 Ma into arid tropics at ∼ 16° around 200 Ma (close to the Triassic–Jurassic boundary), continued into the arid sub-tropics at ∼ 27° through the rest of the Early and Middle Jurassic, and then moved into the temperate latitudes ∼ 47° by ∼ 150–140 Ma (and the Jurassic–Cretaceous boundary) and remained approximately at this latitude for nearly 100 Myr (e.g., Kent and Irving, 2010). The plateau and surroundings then moved south to the present latitude of ∼ 37° (Fig. 4). Apart from the Moenkopi Formation, which remains anomalous in being so “arid-looking” despite being

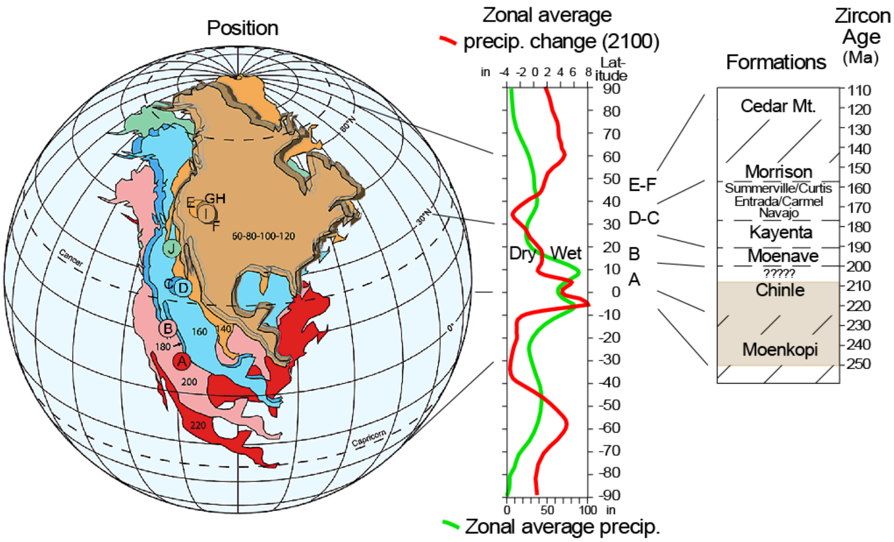

Figure 4. Position of North America (from Kent and Irving, 2010) and the Colorado Plateau (circles) from 220 Ma to Present with comparison to zonally averaged precipitation for today (1950–2000, from https://www.gfdl.noaa.gov/will-the-wet-get-wetter-and-the-dry-drier/, last access: September 2018), change in precipitation for 2100 (ibid.), and the zircon ages for formations (from core CPCP-PFNP13-1A for the Moenkopi and Chinle formations; Suarez et al., 2017 for the Moenave Formation; Marsh et al., 2014 for the Kayenta Formation; Trujillo et al., 2014 for the Morrison Formation; and Mori, 2009 for the Cedar Mountain Formation), with the interval spanned by the CPCP-PNF13 cores shown in tan (hachures indicate hiatuses). This shows how relatively small northward translation of western North America during the Triassic could result in strong changes in climate sensitive facies.

deposited at or near the Equator, the Late Triassic though Cretaceous climate-sensitive sedimentary facies all track latitude, assuming a simple zonal climate (e.g., Kent and Tauxe, 2005), with the giant sand sea of the Early to ?Middle Jurassic age Navajo Sandstone deposited in the subtropics near 30° N, and much less arid facies developing during Late Jurassic and Early Cretaceous times (Fig. 2).

Although characterized by overall very high $p\mathrm{CO}_2$, there are a number of significant fluctuations documented for the Late Triassic (Fig. 2) and Early Jurassic (Schaller et al., 2011, 2015). Although apparently not related to the overall trend in Colorado Plateau climate-sensitive facies, these would be expected to have global change consequences that should be recognizable once the latitudinal shift in the North American Plate is accounted for. At least one of these shifts in the late Norian (Fig. 2) should have been encountered in the CPCP cores.

The oldest Triassic age strata in the PFNP area are part of the nominally Early to Middle Triassic age Moenkopi Formation, its age having been inferred using marine fossils found in distant areas to the west and local tetrapod biostratigraphy (Morales, 1987; Lucas and Schoch, 2002). There are, however, no fossils known from very low in the formation, and therefore its base could conceivably be as old as Late Permian or considerably younger, its top could be as young as early Late Triassic (Carnian) based on admittedly sparse available geochronology (Dickinson and Gehrels, 2009). The Moenkopi could also be of different ages in different areas of the plateau and surroundings. One of the goals of the CPCP is to better constrain the age of these important, paleo-tropical vertebrate assemblages by independent, non-biostratigraphic means.

Most of the rest of Triassic time in the Colorado Plateau is recorded by the continental, largely fluvial Chinle Formation, of which the oldest dated strata are early Norian in age (Olsen et al., 2011; Ramezani et al., 2011) and the youngest late-, but perhaps not latest-Rhaetian in age. The Chinle Formation has provided one of the richest Pangean tropical plant and vertebrate assemblages of Norian and Rhaetian age in the world. In addition, recent advances based on inspection of outcrops have demonstrated that U-Pb detrital zircon geochronology (Ramezani et al., 2011, 2014) provides effective and accurate time control. Putting these outcrop studies in a context where superposition is undoubted, and directly registered to the geochronologic data was another goal of the CPCP.

2 Scientific goals and questions

Based on discussions during the 2007 and 2009 CPCP workshops and preparation for the 2010 proposals, a series of principal guiding questions were recognized. Workshop participants concluded these questions could be best addressed by the environmental and U-Pb calibrated magnetic polarity stratigraphic records of a PFNP core experiment. The questions included the following.

Table 1. Summary data for CPCP drilling sites and cores.

Site	Drill hole	Dates cored	Lat (N)	Long (W)	Elev. (m)	Hole inclination	Azimuth (deg.) dc	Core depth scaled (m)	Core recovery (m)	Stratigraphic depth (m)	Core recovery (%)
Chinde Point	CPCP-PFNP13-1A	11/07/13–11/24/13	35.085933	109.795500	1764	60.2	137.3	519.90	538.10	451.15	103.50
Bone Yard	CPCP-PFNP13-2A	11/27/13–11/29/13	34.822853	109.894091	1711	59.1	200.7	80.77	85.51	69.27	105.87
Bone Yard	CPCP-PFNP13-2B	12/02/13–12/07/13	34.822853	109.894118	1711	75.6	202.9	252.89	262.19	244.95	103.68

1. Is the Newark Basin astrochronostratigraphic polarity timescale (APTS) for the Late Triassic consistent with independent radioisotopic dates and magnetic polarity stratigraphy from the Chinle Formation?

2. Were marine and continental biotic turnover events in the Triassic synchronous? Specifically, as the apparent largest magnitude faunal turnover event on land during the Late Triassic (Mid-Norian, Adamanian–Revueltian boundary) synchronous with the giant Manicouagan bolide impact, independent of it, or an artefact of a condensed section or hiatus, and does it correlate with the marine turnover?

3. There is an apparent pattern of latitudinal biotic provinciality reported in the Late Triassic. Is it supported by high-resolution independent (i.e., non-biostratigraphic) correlations, and is that provinciality correlated with climate-related environmental proxies?

4. Is the orbitally paced (Milankovitch) cyclical climate change recorded in the Newark basin lacustrine facies reflected in the largely fluvial Chinle and Moenkopi formations?

5. Do CO_2 proxies in the western US track those from the eastern US, and how do they relate to the records of environmental change seen in the cores and other areas?

3 Drilling summary

The overall drilling plan was formulated and PFNP was selected as the coring location for Phase One of the project during the 2009 CPCP Workshop at the New Mexico Museum of Natural History and Science in Albuquerque, New Mexico (Geissman et al., 2010). After funding from ICDP was approved in 2010, and from NSF in 2013, the first (Chinde Point) of two specific coring sites was finalized in June and August 2013 after two visits to PFNP to meet with park personnel, representatives of the drilling contractor, and the drilling project manager (D. Schnurrenberger) (Figs. 5 and 6; Table 1). Less than 2 weeks into the coring of the Chinde Point hole, at a depth of over 400 m, it was clear that core recovery through most of the Triassic sequence was excellent and progressing at a rapid and very successful rate. It quickly became clear that we would finish ahead of schedule and under budget. Consequently, we requested a small amount of additional funding from ICDP to leverage our setup to core a second site, which was approved in late November (Figs. 5 and 6; Table 1). The rational for a second coring site in the southern part of the park was that it would allow us to assess the lateral variation and completeness in physical and paleomagnetic polarity stratigraphy. Site 2 selection commenced immediately and set up and coring at site 2A began on 26 November 2013 (Fig. 5), with the planned total depth of core

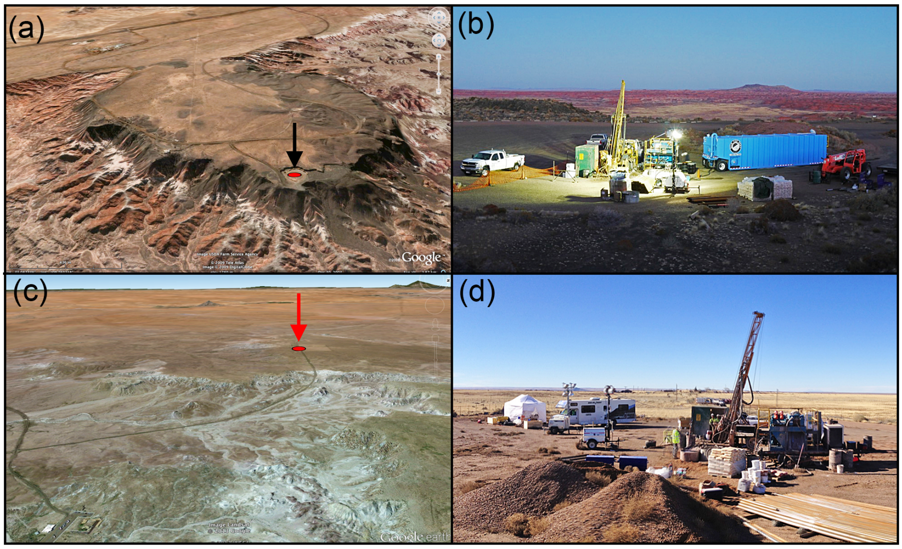

Figure 5. CPCP coring sites: **(a)** Chinde Point (GoogleEarth image) looking south with CPCP-PFNP13-1A coring site in the foreground (red dot and arrow) on mesa capped by Bidahochi Formation lava and lake strata overlying basal Owl Rock Member and Petrified Forest Member of the Chinle Formation with the prominent white band being the ash-rich Black Forest Bed of the upper Petrified Forest Member – Park Headquarters is at upper left; **(b)** CPCP-PFNP13-1A coring site at Chinde Point, looking north at dusk, during coring; **(c)** "West Bone Yard" (GoogleEarth image) site of CPCP-PFNP13-2A and -2B (red dot and arrow) looking west – hills in the distance are Hopi Buttes Bidahochi Formation mares and buildings in the foreground; left are parts of the Rainbow Forest Museum; **(d)** CPCP-PFNP13-2B site at "West Bone Yard" during coring, looking west.

1A (bottoming in Early Permian age Coconino Sandstone) having been reached on 24 November 2013. Site 2A was terminated on December 2 because of problems with hole collapse, and the rig was moved over about 4 m and coring at site 2B commenced on 2 December and total depth was reached on 7 December 2013 (again bottoming in Early Permian age Coconino Sandstone) (Table 1). The additional core processing and associated science for these two additional cores required a supplement from NSF that was approved in December 2015.

Ruen Drilling, Inc. was the coring operator, having also been the operator for the Bighorn Basin Coring Project (BBCP) in very similar lithologies (Clyde et al., 2013). As was the case for the BBCP, a truck-mounted Atlas Copco CS1500 wireline diamond coring rig, with HQ3 tooling was used to recover the cores (6.1 cm diameter) in polycarbonate liners. Liners were used because of the extremely crumbly nature of the Chinle mudstones that have long been known to have a high expanding clay component of probable volcanic origin (e.g., Allen, 1930; Schultz, 1963). As coring proceeded it became obvious that without liners, recovery in the mudstones (comprising a large proportion of the section) would have been substantially reduced and/or disrupted by drilling and core handling, rendering such cores much less useful for high-resolution analyses and scans. Drilling fluids were water, with minimal additives similar to those used by the BBCP (for core BBCP-PCB11-2B), specifically bentonite powder, polymer, and soda ash due to the necessity of an inclined corehole to avoid rod damage and hole collapse (core hole PFNP13-2A was in fact abandoned because of hole collapse). An AMC Solids Removal Unit centrifuge extracted the cuttings from the drilling fluid during drilling, allowing fluid recycling and cuttings disposal off-site.

Core handling and documentation were led by D. Schnurrenberger and members of the NSF LacCore/CSDCO facility (K. Brady and R. O'Grady), who served as a drilling-science liaison ("company representative") while working on opposite shifts and with support of the science team. After coring, the holes were logged by Century Wireline Services (CWS) (Fig. 5). Down-hole logs were taken to virtually the bottom of holes 1A and 2B, and included magnetic susceptibility, natural gamma ray, resistivity, spontaneous potential, acoustic borehole imaging, and dipmeter surveys, the latter of which are consistent with the Reflex EZ Shot survey data, used to track orientation of the hole during drilling. After logging the holes were filled with heavyweight mud and sealed with cement near the surface.

Because the paleomagnetic polarity stratigraphy of the cores was an essential part of the project, core azimuthal orientation was critical, and we employed three strategies towards that end. First, because bedding is nearly flat in PFNP, the core holes were planned to deviate from vertical, inclining 60° or 75° to the SE or SSW depending on the core (Table 1). Inspired by Baag and Helsley (1974) in core recovered from the Moenkopi Formation of Colorado, this allows bedding, or some physical proxy of bedding, to serve for core

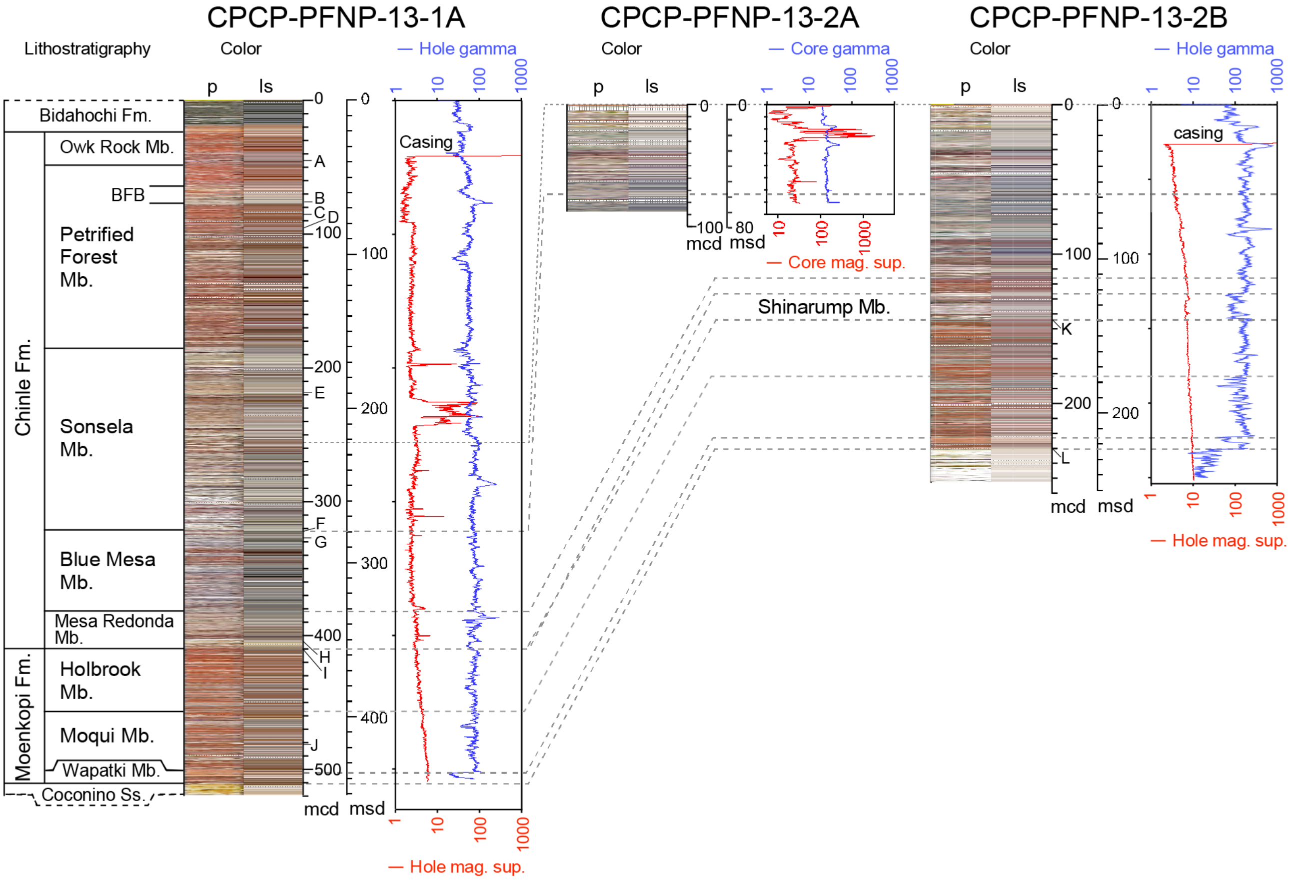

Figure 6. Lithologic logs, compressed photographs (p), line-scan images (ls), natural gamma, and magnetic susceptibility, for each of the cores and holes drilled during the CPCP. Letters A–K refer to core segment photographs in Fig. 8. Abbreviations for the core depths are mcd, meters core (or hole) depth; msd, meters stratigraphic depth of a core or hole with msd = 0.866 · mcd in 1A, msd = 0.858 · mcd in 2A, and msd = 0.969 · mcd in 2B.

orientation (Fig. 7). This was necessary because during the Triassic the Colorado Plateau was at low latitudes as indicated by paleomagnetic inclinations being close to horizontal (e.g., Molina-Garza et al., 1991) meaning that the polarity could not be assessed from inclination values alone. Second, core orientation was tracked using a REFLEX ACT II/III tool that employs an accelerometer to record the core orientation, with the down side of the inclined hole being marked on the bottom core surface after each run based on the device's data. That mark was then extended to the core liner as a white line marked down the entire length of the liner (or core). A similar tool was used at the Hominin Sites and Paleolakes Drilling Project (HSPDP) (Cohen et al., 2016). Third, after drilling ended, cores 1A and 2B were CT-scanned in their entirety at the University of Texas at Austin's CT-Scanning US NSF Facility (Fig. 8), to assure that we would have images to check bedding, which we could not see through the transparent plastic liners because of the opacity of the drilling mud, colored by the red beds. These scans will also provide a wealth of three-dimensional sedimentologic details otherwise not visible (Fig. 8). The nominally 1.5 m core runs were cut on site into roughly 0.7 m (actual average of 71 cm) segments so that they would fit into the CT-Scanner (not to exceed 76.2 cm). The up/down orientation of the core segments is maintained with blue endcaps on tops and red endcaps on bottoms of liners, hand-drawn arrows marked on the plastic tube pointing up-core, and T (top) and B (bottom) labels near the endcaps.

The PNFP cores were labeled and cataloged in the field by Schnurrenberger, Brady, and O'Grady, with support from the science team, and were named using the LacCore convention, which is an extension of the IODP and ICDP syntax. For this project, the naming convention is as follows, using CPCP-PFNP13-1A as an example: CPCP, is the expedition name (Colorado Plateau Coring Project); PFNP, is the overall location (Petrified Forest National Park); 13, is the year drilled (2013); 1, is the coring site (site 1, at Chinde Point); and A, is the hole at site (in this case only 1 hole). The cut core segments are labeled continuing with the LacCore protocol, for example for CPCP-PFNP13-2B-108Y-1-A: 108, is

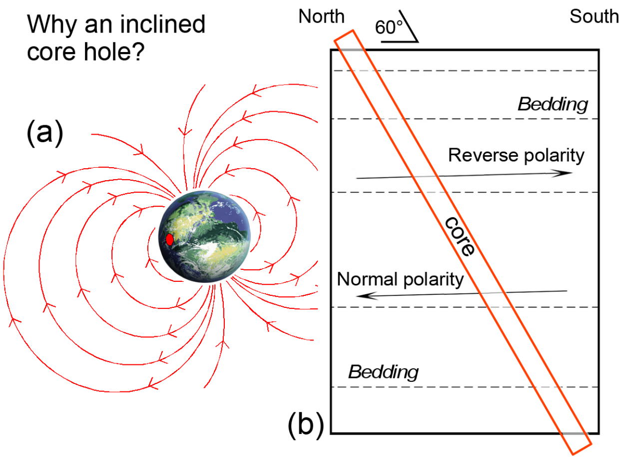

Figure 7. The nearly horizontal bedding in PFNP was used for orientation by inclining the corehole nominally 60° for 1A and 2A and 75° in approximate southerly directions (see Table 1). **(a)** Earth's magnetic field line (normal polarity) with Earth with Triassic Pangea and location of Colorado Plateau (red dot) – note the field lines near horizontal near the Equator. **(b)** Diagram of inclined core hole at 60° with normal and reverse polarity field lines near horizontal due to low latitude position of the Colorado Plateau during the Triassic. The cores were intended to be split along the perpendicular to the inclined core so that bedding is seen to dip 30° , for 1A and 2A, or 15° for 2B, relative to the long axis of the core (compare with Fig. 8).

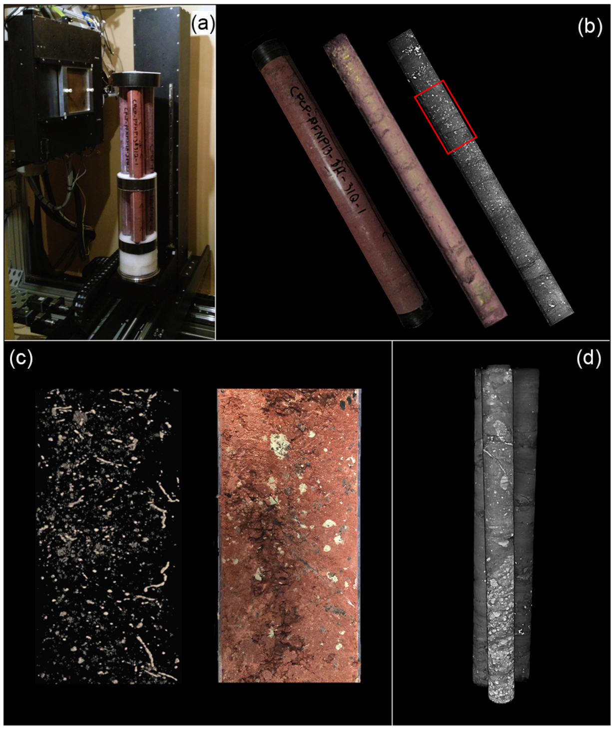

Figure 8. CT scans of CPCP-PFNP13-1A core: **(a)** three core segments bundled with aluminum rod at center in the 450 kV GE Titan X-ray source and Perkin Elmer flat-panel detector at the University of Texas High Resolution X-ray CT Facility, Austin, TX – visible in the front is CPCP-PFNP13-A1-31Q-1 (cores are approximately 0.7 m long); **(b)** four images of core segment CPCP-PFNP13-A1-31Q-1 at core depths 37.5 to 38.2 m is equivalent to 32.5 to 33.1 m stratigraphic depth in the basal Owl Rock Member of the Chinle Formation (left image is in visible light with core in its liner, middle image is a colorized CT volume with liner digitally stripped off; right image is a CT volume with an addition 2 mm stripped off to digitally clean off drilling mud – red box is interval shown in **c**); **(c)** enlargement of CT volume shown in red box in **(b)**, left image is CT volume filtered to highlight carbonate-rich rhizoliths (root traces) and right image is digital photograph of the same interval in the slabbed core (core is ∼ 6.35 cm in diameter) (see https://www.youtube.com/watch?v=T05S7R7dP7M, last access: September 2018); **(d)** bundle of three core segments of Owl Rock Member of the Chinle Formation from CT animation of CPCP-PFNP13-1A-25Q2 (foreground); CPCP-PFNP13-1A-26Q2; CPCP-PFNP13-1A-27Q1 with CPCP-PFNP13-1A-25Q2 volume showing conglomerate and clear bedding inclined to left (cores are approximately 0.7 m long) (see https://www.youtube.com/watch?v=ynM-H8_Qu7A&feature=youtu.be, last access: September 2018).

the core barrel run (run 108); Y, is the code for the coring tool used; 1, is the core segment (uppermost segment cut off the core run); and A, is the designation of the archive half (with W, designating the working half. This code applies to all of digital descriptive data as well (e.g., digital photographs).

3.1 Site 1: Chinde Point

Chinde Point, in the northern part of the PFNP (Fig. 5; Table 1), was selected as the main site (for CPCP-PFNP13-1A) because the zircon U-Pb dated Black Forest Bed (Riggs et al., 2003; Ramezani et al., 2011) outcrops directly adjacent to the site providing an important fiducial, and it allows for coring the highest stratigraphic level in the Chinle Formation accessible using a truck-mounted rig. The location picked also consists of an easily accessible parking lot in the floor of an old barrow pit that could be drilled into thus minimizing disturbance – a key consideration of the Park. Total depth was 519.9 m yielding a total stratigraphic depth of 451 m (Table 1).

Chinde Point is on the northern edge of a mesa capped by Miocene (∼ 8.7–6 Ma) "middle" Bidahochi basalt flows of the Hopi Buttes volcanic complex (White, 1990), into which core 1A was spudded. The basalt is underlain by "lower" Bidahochi gypsiferous Neogene (Miocene) lacustrine pale red mudrock, which locally overlies the Triassic age section. The knowledge that there is a remnant of a possible vent (Ouimette, 1992) on the northwestern side of the mesa only 700 m southwest from the drill site, and that the vent and lavas might be the remnants of a maar with associated faults, stocks, and phreatic breccias, prompted us to select an azimuth of ∼ 135° (Table 1) as opposed to due south, which would be more nearly optimal from a paleomagnetic perspective. Fortunately, no such features were intersected by the core, and there is no obvious magnetic overprint of Miocene age (Kent et al., 2018), and therefore we conclude the strata recovered in this core were minimally affected by the Neogene igneous activity.

Triassic rocks encountered in PFNP13-1A comprised 335 m of Late Triassic (Norian) Chinle Formation mudstones, sandstones, and conglomerates that overlie 88 m of nominally Early and Middle Triassic age Moenkopi Formation. The hole reached a total depth of 451.0 m after penetrating 7 m of Early Permian age Coconino Sandstone (Fig. 6: Table 3) (in stratigraphic thickness all rounded to the nearest meter). The recovered core represents the first time both the lower and upper parts of the Chinle Formation, as can be seen in the area of the PFNP, can be inspected and sampled in undoubted superposition.

3.2 Site 2: West Bone Yard

To leverage the new information from coring at Chinde Point, site 2 was selected to be in the southern part of the park, about 30.6 km from site 1. Initially, we had hoped to site it about 2 km farther to the east, which would have been at a higher stratigraphic position; however, the weather conditions did not permit the drilling truck and support equipment to access that area. Instead we drilled in an equipment storage area called the "West Bone Yard", again minimizing additional disturbance. Unlike the Chinde Point site, bedrock drilling commenced immediately in Triassic strata. Two cores were acquired at site 2: CPCP-PFNP13-2A and CPCP-PFNP13-2B. Our intention was to again core at an inclination of about 60°. However, coring of PFNP-2A (inclined at $\sim 60°$) was terminated at a total depth of 81 m (69 m stratigraphic depth) because of hole collapse, and we decided to site PFNP13-2B about 3 m to the west and drill at an inclination of about 75° for the entire hole (Table 1). Far fewer problems were encountered coring PFNP13-2B and total depth was reached at about 253 m, comprising about 245 m of stratigraphic section (Table 1). Despite the shortness of core PFNP13-2A, it duplicates the upper part of the Chinle in PFNP13-2B and thus provides a useful replicate, complementing the minor core loss in both cores.

Core PFNP13-2B spans more than one-quarter of the section recovered at Chinde Point (a total of about 144 m), but it is invaluable because it is adjacent to the most data-rich parts of the park sequence. Approximately 87 m of the Moenkopi Formation was cored along with 22 m of Coconino Sandstone. Therefore, data from core PFNHP13-2B will permit clear calibration of the fidelity and completeness of the lower Chinle and Moenkopi sections.

4 Core analysis and initial post-drilling science

From PFNP, the cores were shipped to The University of Texas at Austin High-Resolution X-ray Computed Tomography Facility (UTCT). There the cores were scanned on the high-energy subsystem of the North Star Imaging scanner. This subsystem employs a 450 kV GE Titan X-ray source and a Perkin Elmer flat-panel detector. These data were acquired at 355 kV and 1.5 mA, and four brass X-ray prefilters were employed. The detectors were binned 2×2, resulting in a voxel size of 0.1825 mm. Depending on the length of the core segments, the scanning protocol used helical or cone-beam acquisition or a combination of the two; most core segments required the latter, with resulting volumes digitally stitched together. The core segments were scanned in groups of three, with an aluminum rod placed between them to reduce CT artifacts and provide a greyscale calibration standard (Fig. 8). All cores were labeled with aluminum tags stamped with the core identifiers, and affixed to indicate coring orientation. The final data volume comprises 394 CT data sets ranging from 299 to 4330 16 bit TIFF slices.

After CT scanning the cores were shipped to the LacCore facility at the University of Minnesota for Initial Core Description (ICD). Facility staff passed the cores through a Geotek MSCL-S multisensor core logger, for standard parameters: magnetic susceptibility, gamma density, P-wave velocity, electrical resistivity, and natural gamma radiation. Cores were subsequently split in half lengthwise with a rock saw plumbed for continuous deionized water flush (no recirculation) and cleaned. One-half of each core was photographed with a Geotek MSCL-CIS optical linescan camera at 50 micron resolution, and then logged on a Geotek MSCL-XYZ split-core multisensor logger for high-resolution magnetic susceptibility and color reflectance spectrophotometry. Visual lithologic core descriptions were generated by project staff using PSICAT software and modified FGDC standard vocabularies for lithologies, with petrographic smear slide analysis, SEM-EDS, and XRD analyses as needed for component identification. A subset of core archive halves (Petrified Forest and upper Sonsela members) were scanned using an ITRAX XRF Core Scanner for elemental distributions. Scanning of the rest of the cores is anticipated during 2018. The cores remain the property of the US Federal Government (with PEFO (PFNP) catalog numbers: core 1A is PEFO 39602; core 2A is PEFO 39603; core 2B is PEFO 39604); the cores are on long-term loan with all archive halves permanently curated at the LacCore/CSDCO core repository and working halves curated at the Rutgers University Core Repository for subsampling, and additional detailed descriptions.

The LacCore/CSDCO facility coordinates access to core archive halves and fundamental data; Rutgers University coordinates access to core work halves for subsampling. Fundamental datasets include core metadata, multisensor logger data, core photographs, lithologic core descriptions, XRF elemental scans, and derived products such as color profiles and stratigraphic columns. Depth scales were standardized by LacCore/CSDCO, using scaled meters below surface (applying a linear compression/scaling where recovery is above 100 %), equivalent to the CSF-B depth scale used in IODP.

The initial sampling party for core 1A was held on 17–20 April 2015 at the Rutgers Core Repository with samples being taken for paleomagnetic analysis, U-Pb geochronology, carbon isotope stratigraphy and soil carbonate CO_2 proxy, palynology and organic geochemistry (compound-specific C isotopes, $\delta^{13}C_{wax}$), by the lead National Science Foundation PIs and their coworkers along with several additional scientists. Individual teams have sampled and will continue to sample core 1A as needed. Sampling parties for cores 2A and 2B, recently processed by at UTCT and LacCore (funded by a supplement from NSF), took place during spring 2018.

5 Initial results

A basic result evident from the stratigraphy of core PFNP13-1A is that the major discrepancies between the stratigraphy and thickness estimates of Chinle Formation sections in Petrified Forest National Park, as reported by various workers due to the large geographic distances between outcrops where superposition cannot be demonstrated, can now be resolved. The stratigraphy and thicknesses of the major members in core 1A (Fig. 6) closely approximate those of Martz and Parker (2010), Ramezani et al. (2011), and Atchley et al. (2013) and are dramatically different from those depicted by Billingsley (1985), Murry (1990), Steiner and Lucas (2000), and Heckert and Lucas (2002). It can thus serve as a standard lithostratigraphic reference for most of the Late Triassic age continental rocks of the Colorado Plateau. In terms of depositional environments, the Chinle strata in the cores are almost entirely comprised of muddy fluvial paleosols and coarser fluvial channel deposits (Fig. 9).

Overall, there is perhaps a surprising degree of agreement in the lateral consistency of facies between the 1A and 2B cores as evident in the geophysical logs, especially natural gamma (Fig. 6). There is variability between the alternations of mudstone and sandstone in the Sonsela Member, but nonetheless, details of log character persist across the ~ 31 km separating the cores. There are also negligible thickness differences between the lower Chinle strata in the cores, despite the change in facies in the basal-most part of the formation. Supposedly, the conglomeritic facies of the basal Chinle Formation, traditionally referred to as the Shinarump Member, occupies incised valleys in the underlying Moenkopi, but that is not at all evident in core 2B, which contains that conglomerate (clasts up to medium cobble size), and 1A, which does not and the Shinarump is simply replaced by finer-grained facies of the Mesa Redondo Member lying directly on top of the Moenkopi Formation (Fig. 9). The Moenkopi Formation itself is nearly exactly the same thickness in core 1A and 2B, and also shows a strong similar consistency in the log properties of the members of the formation, most notably in the Moqui Member (Fig. 5).

However, there is a major consequential difference between the outcrops in the park and what is seen in the cores. There is a complete absence of facies resembling the Newspaper Rock Sandstone and attendant low-energy well-bedded mudstones and siltstones in all the cores. These strata comprise large, sandstone, meandering channel complexes up to 10 m thick with large-scale greenish lateral accretion sets making up scroll bars (ridge-and-swale topography) visible in satellite images. The lateral accretion sandstones have basal lags with abundant fossil wood and plant impressions, and there are associated lacustrine deposits (Trendell et al., 2013) that yield a diverse aquatic fauna and macro- and micro-flora (Daugherty, 1941; Miller and Ash, 1988; Ash, 1989, 2005; Murry and Long, 1989; Demko, 1995; Heckert, 2004; Parker, 2006; Parker et al., 2006a). Very similar facies have been described at various areas of outcrop of the Chinle Formation and have been collectively termed the “Monitor Butte facies”, ascribed to incised valleys (Demko et al., 1998). These facies only outcrop locally even in the park and in most areas it they are represented by a laterally continuous red band of pedogenically modified strata about 1 m thick. However, in several areas outside the park such “incised valleys” appear related to underlying halokinesis of Paleozoic salt (Matthews et al., 2007; P. E. Olsen et al., 2016). Such strata are often characterized by extraordinarily fast accumulation rates as evidenced by the burial of in situ plants, including trees (Parker et al., 2006b; Trendell et al., 2013) implying rates of several meters in a few years (Fig. 10), which would be highly problematic for interpreting paleomagnetic polarity sequences, had this facies occurred in the cores. The southern part of the PFNP in fact lies directly on the center of the thick evaporites of the Holbrook Basin (Rauzi, 2000), making halokinesis a plausible cause of localized development of the Monitor Butte-Newspaper Rock facies.

Outcrops of the Chinle Formation at Petrified Forest National Park have provided much of the basis for our understanding of the palynostratigraphy of the American Southwest Late Triassic (Gottesfeld, 1972; Scott, 1982; Fisher and Dunay, 1984; Litwin et al., 1991; Reichgelt, et al., 2013; Whiteside et al., 2015; Lindström et al., 2016). In total, 258 samples were collected from core CPCP-PFNP13-1A for palynological, bulk C-isotope, and $\delta^{13}C_{wax}$. Of these about thirty samples were processed at the University of Oslo and all were barren of recognizable sporomorphs, although very dark, degraded woody or cuticle-like plant fragments are present, consistent with recalcitrant soil organic matter in paleosols (Fig. 11). The prevalence of red and purple paleosols and the lack of “Newspaper Rock-Monitor Butte facies” are at least partially responsible for the near lack of organically preserved plant macrofossils and sporomorphs from the core. Samples were processed for organic geochemistry at Utrecht University (NL) following the methods outlined in Miller et al. (2017). Results indicate very low concentrations of *n*-alkanes which did not have the odd-over-even carbon prefer-

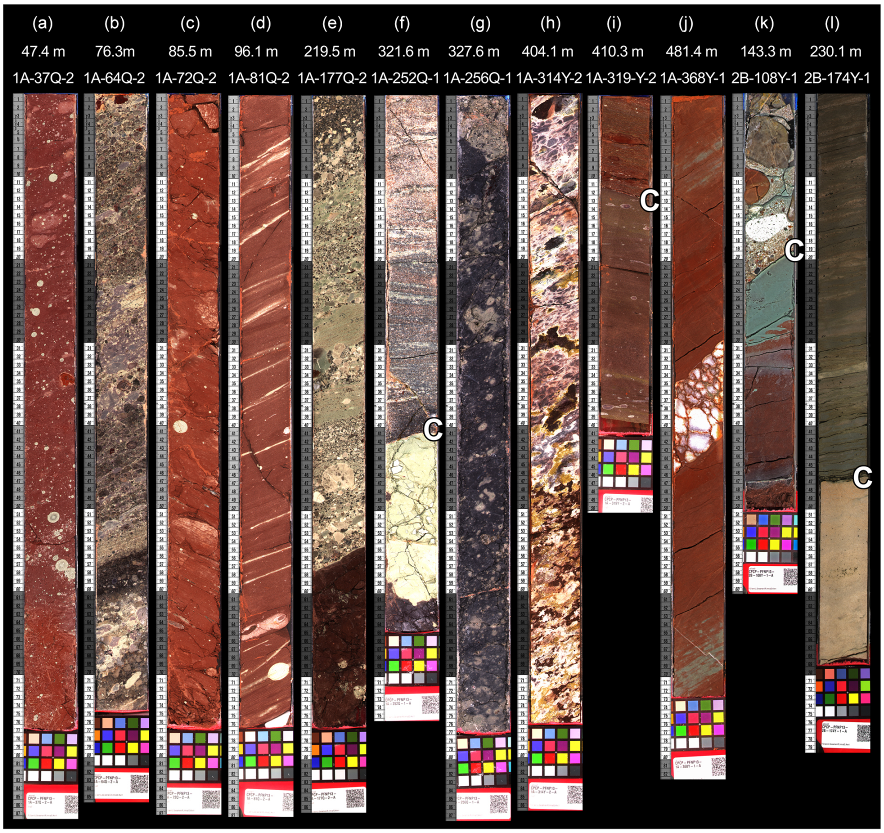

Figure 9. Representative facies in core segments from cores CPCP-PFNP-13-1A **(a–j)** and CPCP-PFNP-13-2B **(k–l)** with bedding dipping down towards left except as noted (see Fig. 5): **(a)** pedogenic mudstone of lower Owl Rock Member of the Chinle Formation in which bedding is obscure but indicated by long axes of elliptical spots ("reduction spots or haloes"); **(b)** lower Black Forest Bed of the Petrified Forest Member of the Chinle Formation with abundant intraformational carbonate clasts and volcaniclastic material; **(c)** pedogenic mudstone of the Petrified Forest Member of the Chinle Formation with long axis of elliptical spots inclined downward to the right indicating a misoriented core segment; **(d)** pedogenic ripple-bedded fine sandstone and siltstone of the Petrified Forest Member of the Chinle Formation with long axes of elliptical spots clearly aligned with bedding; **(e)** sandstone and conglomerate overlying pedogenic mudstone within the upper Sonsela Member of the Chinle Formation; **(f)** Contact C between coarse sandstone of the overlying Sonsela Member of the Chinle Formation and the underlying Blue Mesa Member of the Chinle Formation; **(g)** pedogenic mudstone of the Blue Mesa Member of the Chinle Formation; **(h)** four-color mottled pedogenic mudstone of the Mesa Redondo Member of the Chinle Formation; **(i)** Contact C between sandstone of the overlying Mesa Redondo Member of the Chinle Formation and sandstone and siltstone of the underlying Holbrook Member of the Moenkopi Formation (core segment appears misoriented); **(j)** chicken-wire gypsum bed in siltstone of the Moqui Member of the Moenkopi Formation; **(k)** Contact C between cobble conglomerate of the overlying Shinarump Member of the Chinle Formation and sandstone and siltstone of the underlying Holbrook Member of the Moenkopi Formation; **(l)** Contact C between sandstone of the overlying Wupatki Member of the Moenkopi Formation and sandstone of the underlying Coconino Sandstone of Early Permian age.

ence typical of waxes derived from vascular plants as can be seen in rocks of comparable age elsewhere (Fig. 12) (Whiteside et al., 2010). These results are unsurprising in as much as the samples also lacked sporomorphs and well-preserved cuticles. The extracted n-alkanes may be indigenous, sourced from pedogenic bacteria or fungi, or the result of biomass burning (e.g., Kuhn et al., 2010; Eckmeier and Wiesenberg, 2009). They could also be natural migrated hydrocarbons. Hydrocarbon shows have been reported in drill holes in the region around PFNP, presumably derived from marginally mature, marine sources rocks in the underlying Paleozoic age Holbrook Basin (Heylmun, 1997; Rauzi, 2000; Schwab et al., 2017). Furthermore, there is also a remote possibility of an n-alkane contribution from drilling fluid additives, although their effect should be minimal because of standard sample preparation protocols. The lack of n-alkanes derived from higher plants and the very low concentrations of indigenous organic matter within the samples meant that further organic geochemical, bulk C isotope and sporomorph, studies were not pursued by WMK, CM, and VB. Nevertheless, additional work on the organic petrology and geochemistry is planned by others.

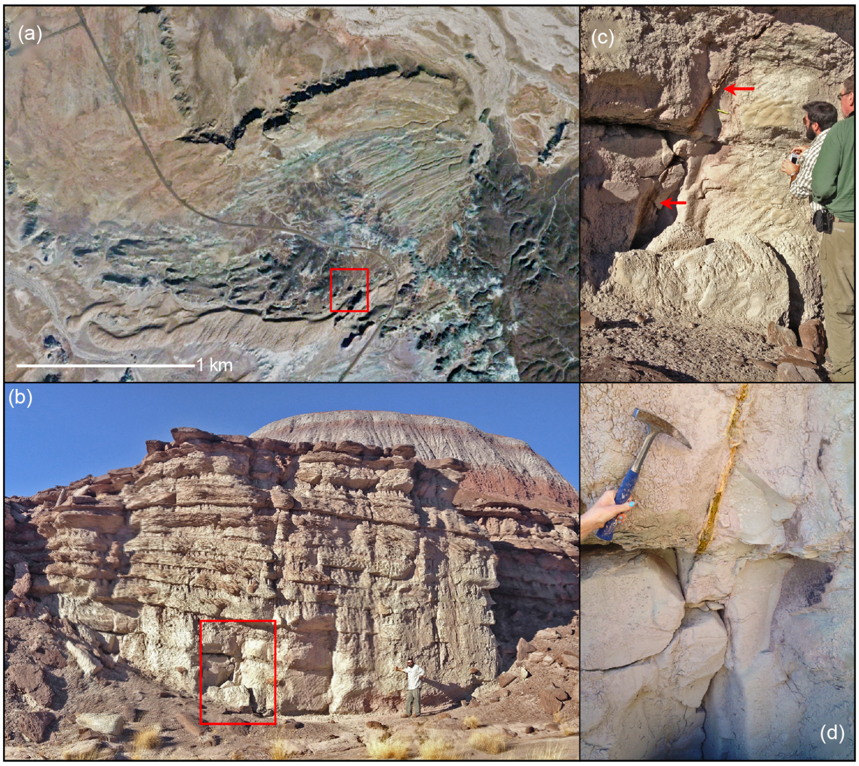

Figure 10. Details of Newspaper Rock facies which is absent in cores: **(a)** GoogleEarth image of scrollbars (best developed in middle of image), red box is location of photo in **(b)**; **(b)** tilted beds of greenish ripple-crosslaminated sandstone and siltstones looking north at scrollbar (point bar) at 34.949°, −109.776° with +2 m upright, plant stem (?*Equisetities*) in growth position in red box enlarged in **(c)** indicative of extremely fast accumulation (∼ +1 m/season) – Morgan Schaller for scale; **(c)** plant stem (?*Equisetities*) in growth position (portion between arrows) is enlarged in **(d)** – beds dip from right (west) to left (east) with faint left-inclined streaks being aligned lee faces of climbing ripples; **(d)** close up of stem in growth position, hammer is 28 cm long – yellow color is due to weathered pyrite.

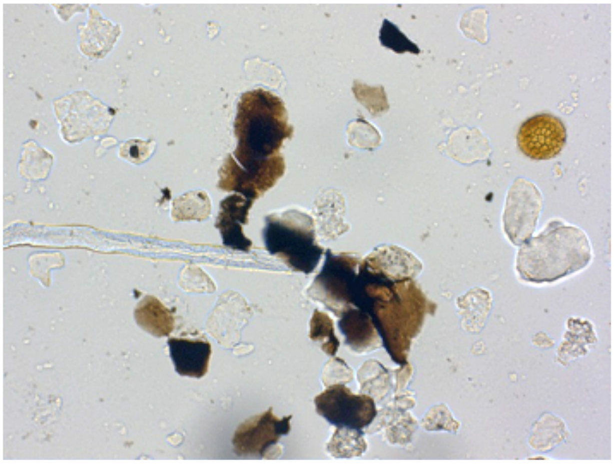

Figure 11. Photograph showing organic residue with degraded cuticle, charcoal, and wood fragments. Identifiable sporomorphs are modern *Lycopodium* spores added to calibrate abundances during palynological preparation.

As planned, the CPCP cores provide a venue for answering the major questions posed at the start of the project. Although work on these cores is still in its early stages, we can report some results and work in progress that address the questions set out during the project's origin as follows.

1. Is the Newark-Hartford Astrochronostratigraphic-calibrated magnetic Polarity Time-Scale (APTS) for the Late Triassic consistent with independent radioisotopic dates and magnetic polarity stratigraphy from the Chinle Formation? Thus far, we have been able to recover magnetostratigraphic polarity sequences from the full middle Sonsela through the entire Petrified Forest members of the Late Triassic-age Chinle Formation (40–240 msd) (Kent et al., 2018). Young euhedral detrital zircons apparently largely representative of the depositional age were identified in 29 out of 41 levels in core 1A surveyed using the LA-ICP-MS US NSF Facility at the University of Arizona, with about 100 to >300 crystals being dated in most samples. Of these, the youngest populations of the same zircons of 10 samples were selected thus far for CA-ID-TIMS dating

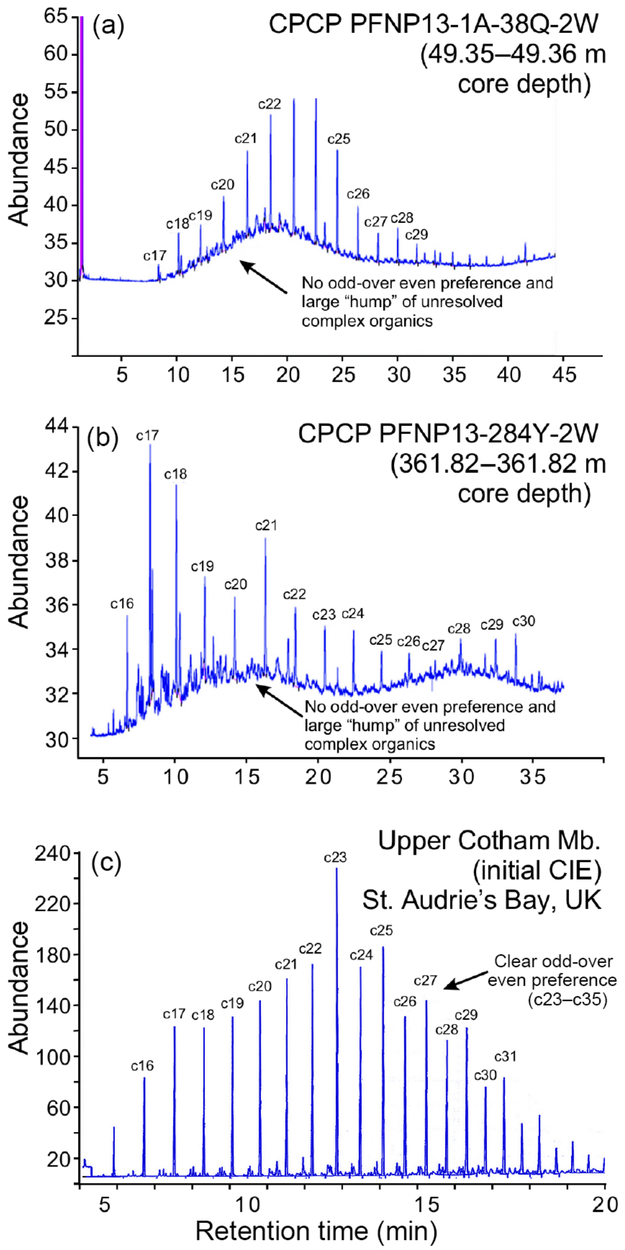

Figure 12. GC chromatogram traces for n-alkanes of the saturate fractions of the extracts from PNFP core samples. **(a)** Trace of CPCP PFNP13-1A-38Q-2W 47–48 cm in the Petrified Forest Member (= 49.35–49.36 m core depth) from detector 1, showing no odd-over-even preference of n-alkanes and a large hump of unresolved organic compounds, possibly due to organic degradation during pedogenesis or because the samples were too thermally mature. **(b)** Trace of CPCP PFNP13-1A-38Q-2A-284Y-1W 65–70 cm in the Blue Mesa Member (= 361.82–361.82 m core depth) from detector 1, showing low abundance of organics, and mostly short chain n-alkanes characteristic of migrated, mature hydrocarbons. **(c)** Trace of the latest Rhaetian age upper Cotham Member, St. Audrie's Bay, Somerset, UK, with the δ^{13}C initial excursion of Hesselbo et al. (2002) from Whiteside et al. (2010).

at the Berkeley Geochronology Center yielding maximum depositional ages in stratigraphic order, within error four of which are published (Figs. 13 and 16). For the Chinle Formation these ages are consistent with published CA-ID-TIMS ages from outcrops in PFNP (Ramezani et al., 2011, 2014; Atchley et al., 2013). Of the new CA-ID-TIMS ages, four are registered to the Chinle magnetic polarity sequence from core 1A. The zircon-calibrated Petrified Forest and upper Sonsela member magnetostratigraphy fully validates the Newark-Hartford APTS, and answers the first major question addressed by the CPCP (Fig. 13) (Kent et al., 2018). It is important to note that correlation of the Newark-Hartford APTS with marine Tethyan strata resulted in a major revision to the duration of the divisions of Late Triassic, with the duration of the Norian Age increasing from 11–14 Myr (Gradstein et al., 1994; Ogg, 2004, 2012; Lucas, 2018) to 21 Myr (Kent et al., 2017a), making it the longest age (stage) of the Phanerozoic. It also had the consequence of showing that the lower half of the Chinle Formation (of Adamanian Age) that was formerly regarded as Carnian (e.g., Lucas et al., 1993, 1998, 2010) is in fact Norian in age (Olsen et al., 2011). Based on these results we can show that a globally exportable timescale can be developed from cores of these types of continental strata. In addition, paleomagnetic and magnetic anisotropy data have been developed for all of the Moenkopi Formation in PFNP13-1A (Buhedma et al., 2016; Buhedma, 2017; McIntosh et al., 2017) (Figs. 14 and 15), and this CA-ID-TIMS zircon calibration of this sequence will provide an independent assessment of how faunal assemblages from this formation fit into the global recovery from the Permo-Triassic mass extinction. We anticipate working out the rest of the magnetostratigraphy in cores PFNP13-1A and in -2A and -2B, during 2018.

2. Were marine (Onoeue et al., 2016) and continental biotic turnover events in the Triassic synchronous? Specifically, was the apparent largest magnitude faunal turnover event on land during the Late Triassic (Mid-Norian, Adamanian–Revueltian boundary; Parker and Martz, 2011) synchronous with the giant Manicouagan bolide impact (Ramezani et al., 2013; Olsen et al., 2011), independent of it, or an artefact of a condensed section or hiatus, and does it correlate with the marine turnover? No certain representation of the "persistent red silcrete" that acts as a local stratigraphic marker of the Adamanian–Revueltian boundary in the southern part of the park was identified in the core 1A. This is not surprising because the "persistent red silcrete" occurs only in a very limited area in the northern area of the park and its possible equivalent, Billingsley's (1985) "brown sandstone" (Parker and Martz, 2011) has not

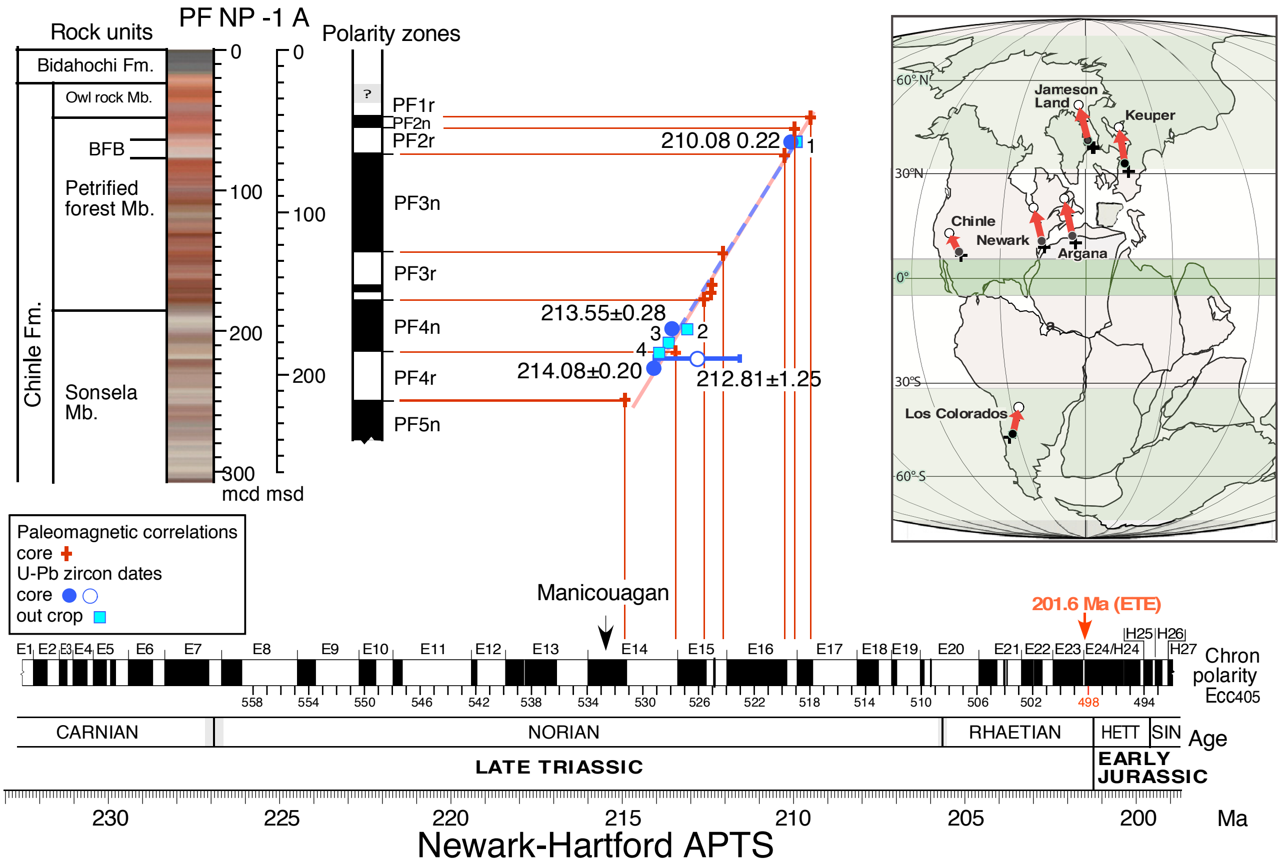

Figure 13. Depth versus age plot for core CPCP PFNP13-1A based on correlation of magnetostratigraphy with the Newark–Hartford APTS (from Kent et al., 2018). Stratigraphic units, graduated depths, and color log of CPCP PFNP13-1A. Red crosses are magnetozone boundaries in CPCP PFNP13-1A; correlated with the NH-APTS solid red line is a linear regression for base magnetozone PF1r to base magnetozone PF4r to their correlative chronological ages. Blue circles are U-Pb CA-ID-TIMS detrital zircon dates from CPCP PFNP13-1A; light blue squares are published U-Pb CA-TIMS detrital zircon dates from outcrop (from Ramezani et al., 2011; Atchley et al., 2013): 1, 209.93 ± 0.07 Ma; 2, 213.12 ± 0.07 Ma; 3, 213.63 ± 0.13 Ma; 4, 213.87 ± 0.08 Ma. Linear regression on U-Pb ID-CA-TIMS dates (blue dashed line) based on sample data from core CPCP PFNP13-1A (excluding sample 177Q1); and light red line is regression of polarity boundaries in CPCP PFNP13-1A and Newark-Hartford APTS. U-Pb zircon date for Manicouagan crater impact melt rocks (Ramizani et al., 2005), which are characterized by normal polarity (Larochelle and Currie, 1967), is shown for reference. Inset shows a paleocontinental reconstruction of Pangea (from Kent et al., 2018) positioned according to a 220 Ma mean composite paleopole (Kent et al., 2014) with some key continental localities indicated by filled circles connected by arrows to their relative positions at 200 Ma by open circles.

yet been positively identified in the core either. There is also no reason to suspect these markers are related to the cause of the Adamanian–Revueltian boundary or the Manicouagan impact. Hence, additional fieldwork is needed to recover an unambiguous polarity stratigraphy to register the biotic transition with the core magnetic stratigraphy. We do know that at least broadly speaking the marine turnover is close in time to the Adamanian–Revueltian boundary. However, additional work will be needed, presumably by others, to place the marine biotic changes in a magnetostratigraphic context that is thus far lacking except for a very few sections (e.g., Muttoni et al., 2004, 2014).

3. Is the apparent pattern of latitudinal biotic provinciality seen in the Late Triassic supported by high-resolution, independent (i.e., non-biostratigraphic) correlations and does that change with climate-related environmental proxies? The match of the magnetic polarity stratigraphy and zircon U-Pb dates from core 1A to the Newark-Hartford APTS (Kent et al., 2018) and a rather obvious correlation with magnetic polarity stratigraphy records through North and South America shows that the apparent pattern of latitudinal biotic provinciality seen in the Late Triassic is supported by high-resolution independent (i.e., non-biostratigraphic) correlations (Fig. 16). This means that the strong biotic provinciality of Triassic Pangea, and the 30 million-year delay in the rise of dinosaurian ecological dominance in the tropics (White-

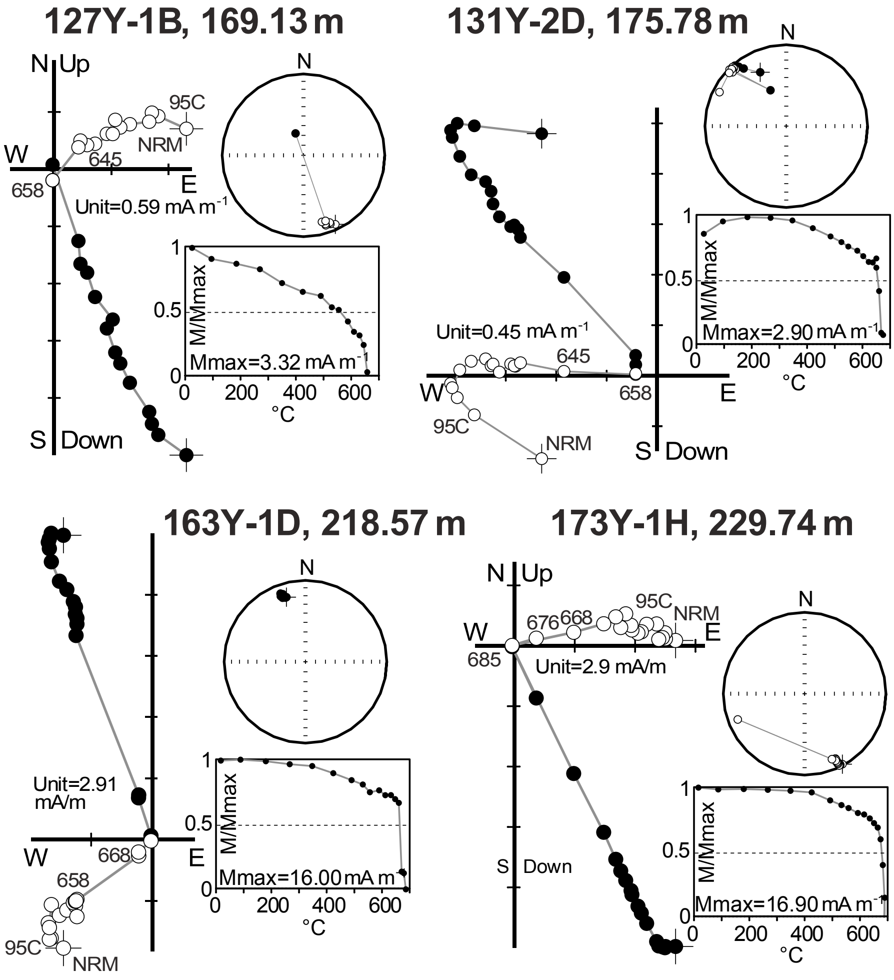

Figure 14. Examples of orthogonal progressive demagnetization diagrams for the Moenkopi Formation showing the end point of the magnetization vector plotted onto the horizontal (filled symbols) and vertical (open symbols) planes (NS-EW, EW-Up/Dn) for individual specimens from core segments of Moenkopi Formation rocks intersected in CPCP Phase 1 Core 2B that have been subjected to progressive thermal demagnetization. Demagnetization steps, in temperatures (°C) are given alongside selected vertical projection data points. NRM is the natural remanent magnetization. Also shown are normalized intensity decay plots showing response to progressive thermal treatment (abscissa is temperature, °C) and equal area stereographic projections of the magnetization vector measured at each step. Note that the coordinate axes for each and every diagram are identical in orientation and the diagrams are in geographic coordinates, assuming that each core segment is properly oriented.

side et al., 2011, 2015) indicated by previous correlations using the Newark-Hartford APTS, is not an artefact of biostratigraphic miscorrelation as asserted by some (e.g., Lucas, 2018), but a real feature of that world which can now be quantified both in time and space (Kent et al., 2018).

4. Is the orbitally paced (Milankovitch) cyclical climate change recorded in the Newark basin lacustrine deposits reflected in the largely fluvial Chinle and Moenkopi formations? Based on work still underway, a perhaps surprising preliminary result from the Petrified Forest and upper Sonsela members is that the 405 kyr cycle is in fact reflected in the Chinle Formation, as seen in the redox-sensitive magnetic susceptibility logs (Olsen et al., 2017) (Fig. 5). A lower-frequency cycle around 1.8 Myr is present as well and is also seen in the Newark record (Olsen et al., 1999). Higher-frequency orbital cycles have yet to be identified with certainty, although there is a hint of some ∼ 100 ky cyclicity in the magnetic susceptibility logs. Additional work with other environmental proxies, including the CT scans of paleosol fabrics (Fig. 8), and analysis of the rest of the section and cores should provide a deeper knowledge of how the cycles are expressed in the fluvial environments.

5. Do $p\mathrm{CO}_2$ proxies in the western US track those from the eastern US, and how do they relate to the records

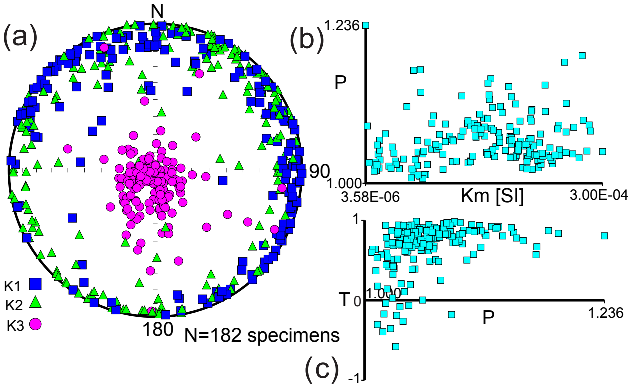

Figure 15. Preliminary anisotropy of magnetic susceptibility (AMS) data from Moenkopi Formation rocks intersected in CPCP Phase 1 Core 2B. **(a)** The stereographic projection shows the principal susceptibility axes ($K_1, K_2, K_3 = K_{\mathrm{max}}, K_{\mathrm{int}}, K_{\mathrm{min}}$) for each specimen measured (lower hemisphere projections). **(b)** The anisotropy parameter P, where $P = K_{\mathrm{max}}/K_{\mathrm{min}}$, is plotted vs. bulk susceptibility for each specimen measured. **(c)** The anisotropy parameter T, where T, the shape parameter ($= ([2\ln K_{\mathrm{int}} - \ln K_{\mathrm{max}} - \ln K_{\mathrm{min}}]/[\ln K_{\mathrm{max}} - \ln K_{\mathrm{min}}])$ is plotted vs. P. T values close to 1.0 are associated with strong oblate fabrics. In **(a)** the data from most Moenkopi rocks show a fabric that is typical of very fine-grained detrital sedimentary rocks, with the minimum susceptibility axis essentially vertical and overall well grouped. The principal susceptibility axes are plotted assuming that all sampled core segments are properly oriented; as discussed in the text this assumption is likely not always valid and thus improper core orientation may be a source of some of the observed dispersion in the data. An additional source of dispersion is that some Moenkopi facies may have preserved a well-defined sedimentary imbrication fabric, where the minimum susceptibility axis is canted from the vertical.

of environmental change seen in the cores, and other areas? Preliminary results from parts of core 1A show that the carbonate paleosol $p\mathrm{CO}_2$ proxy does yield comprehensible results consistent with those from the eastern US (Schaller et al., 2015; Whiteside et al., 2015). At least one major fluctuation falls in the age range of the CPCP-PFNP13-1A core with a $p\mathrm{CO}^2$ local minimum at about 211–212 Ma (Knobbe and Schaller, 2018), associated with a Norian temperature low (Trotter et al., 2016). There are also encouraging results that atmospheric O_2 concentrations are obtainable from the same soil carbonates from the CPCP cores and eastern North America (Schaller et al., 2017). Other fluctuations in $p\mathrm{CO}_2$, such as the Rhaetian drop and the Hettangian rise associated with the emplacement of the Central Atlantic Magmatic Province (CAMP) as well as the supposed Carnian “Pluvial” (Ruffell et al., 2016), do not fall within the age range of these cores.

6 Outreach and broader impacts

Petrified Forest National Park is a major tourist destination with some 600 000 visitors per year from around the world who are predisposed to be receptive to a geologic narrative. To highlight the CPCP and its potential for public education and outreach, the National Park Service posted a link devoted to the project (https://www.nps.gov/pefo/learn/nature/coring.htm, last access: September 2018), and produced a flyer that was distributed while we were on-site. During drilling we hosted several tours for local residents and tourists. There was significant international to local publicity associated with the project, including Nature (http://www.nature.com/news/geologists-take-drill-to-triassic-park-1.13866, last access: September 2018), PLos Blogs (http://blogs.plos.org/paleo/2013/11/21/the-colorado-plateau-coring-project-getting-dates-in-the-triassic/, last access: September 2018), Arizona Geology (http://arizonageology.blogspot.com/2013/11/scientific-core-drilling-at-petrified.html, last access: September 2018), Discover Magazine (http://discovermagazine.com/2015/may/18-sands-of-time, last access: September 2018), National Geographic (http://phenomena.nationalgeographic.com/2013/11/19/getting-to-the-core-of-the-triassic/, last access: September 2018), WNYC (https://www.wnyc.org/story/shutdown-stymies-scientific-research/, last access: September 2018), and the Arizona Daily Sun (http://azdailysun.com/news/local/petrified-forest-a-fossil-every-inches/article_ee70579c-4906-11e3-9324-001a4bcf887a.html, last access: September 2018). A time-lapse video by Max Schnurrenberger of rig set up and coring set to music is posted as well (https://www.youtube.com/watch?v=0cbWuKnmVKk and linked to the CPCP site http://www.ldeo.columbia.edu/$∼$polsen/cpcp/PFCP_13_main.html, last access: September 2018) and the LacCore group developed and maintains a Facebook page for the project (https://www.facebook.com/Colorado-Plateau-Coring-Project-1436554049899932/, last access: September 2018), with news updates throughout drilling, and coordinated workforce development training in drilling and core workflows for five people, which developed over 300 likes and nearly as many followers during the coring period. The ultimate goal of Petrified Forest National Park is to provide a million-year (at least) resolution time line of the 20 million-year history of the area during the Triassic and then tying this through to the modern era. The data from the cores will be a big part of generating this story as exhibits develop. A permanent website for the project was developed and is maintained by PEO (http://www.ldeo.columbia.edu/~polsen/cpcp/CPCP_home_page_general.html, last access: September 2018). The latter has seen over 12 000 visitors.

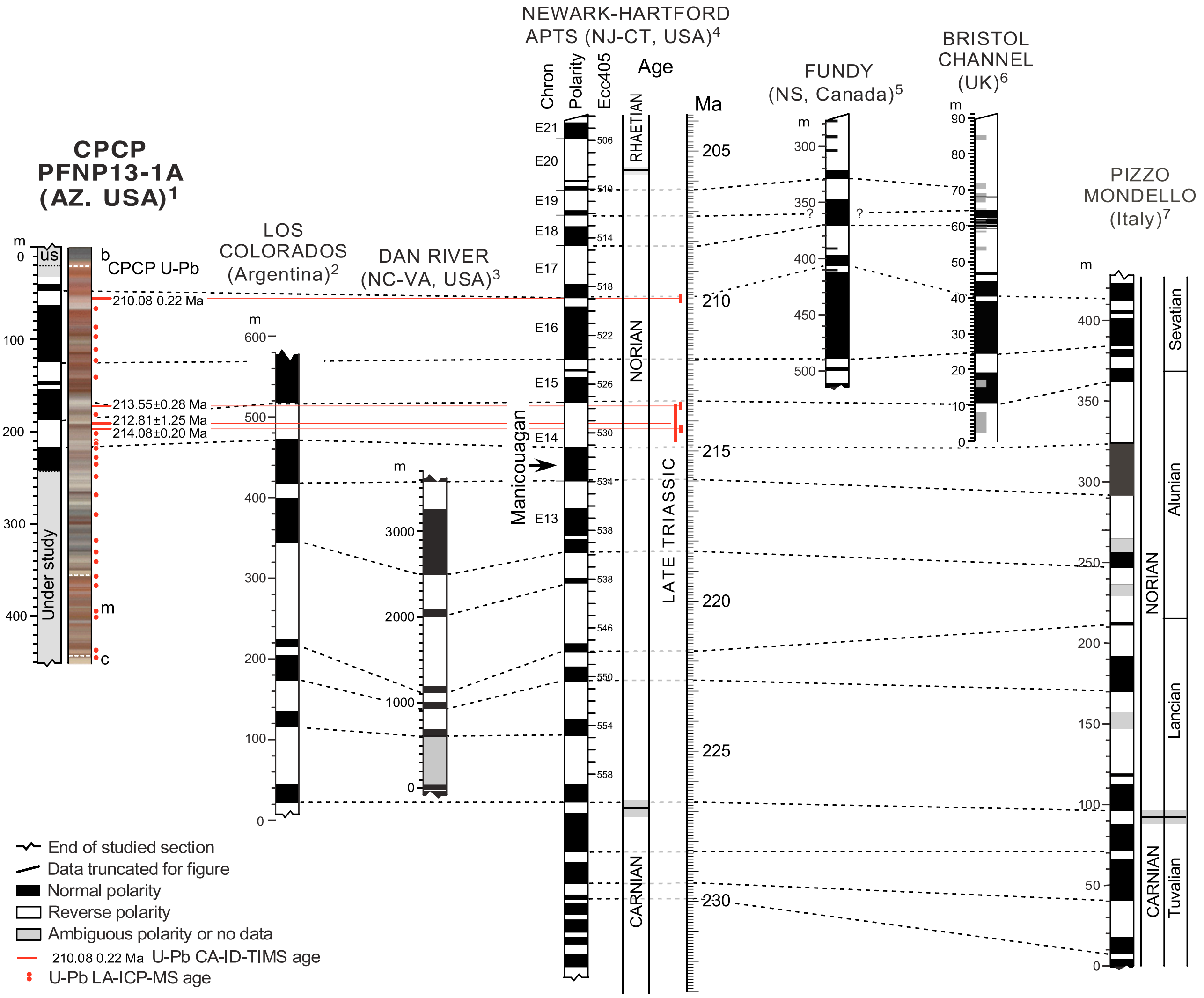

Figure 16. Paleomagnetic polarity stratigraphy of the upper part of the Chinle Formation in CPCP PFNP-13-1A correlated with the Newark-Hartford APTS and sections in Argentina, eastern North America (Dan River and Fundy basins), the UK, and Italy. Dotted white lines in the CPCP section are formation boundaries. Note that no correlation is implied for the Chinle Formation below 245 m stratigraphic depth. Sections are shown in stratigraphic (thickness) coordinates, except the APTS, which is in time, pinned to zircon U-Pb dates from the Central Atlantic Magmatic Province (CAMP) (Blackburn et al., 2013) and tuned to the 405 kyr orbital cycle. CPCP zircon U-Pb ages are correlated (horizontal red lines) with the Newark-Hartford APTS by paleomagnetic polarity stratigraphy and a linear age–depth model (Kent et al., 2018) (with the analytical error shown by the vertical red bars). Each paleomagnetic polarity stratigraphy is independently correlated in this diagram with the Newark-Hartford APTS via the first and last polarity boundaries according to the original author (not shown for the sections truncated here). Additional abbreviations are Ecc405, the Jupiter–Venus eccentricity cycle of a 405 kyr period; us, unsampled; b, Neogene Bidahochi Formation; m, Early to nominally Middle Triassic Moenkopi Formation; and c, Early Permian Coconino Sandstone. Sources are [1] Kent et al. (2018); [2] Kent et al. (2014); [3] Kent and Olsen (1999) and Olsen et al. (2015); [4] Kent et al. (2017); [5] Kent and Olsen (2000); [6] Hounslow et al. (2004) and Briden and Daniels (1999); and [7] Muttoni et al. (2004) and Kent et al. (2017).

The CPCP has included and will continue to include significant career training and mentoring. Thus far, this has included post-doctoral fellow Charlotte Miller (University of Oslo); PhD graduate fellows Cornelia Rasmussen (University of Utah), Sean Kinney (Columbia University), and Viktória Baranyi (University of Oslo); MSc graduate students Dominique Geisler (University of Arizona) and Hesham Buhedma (University of Texas at Dallas); and undergraduate honors student Julia McIntosh (University of Texas at Dallas).

7 Continuing science and plans

The Petrified Forest National Park part of the CPCP is in the post-drilling science phase. Preliminary results were presented at the AGU national meetings in 2013, 2014, 2016 (P. E. Olsen et al., 2013, 2014; Geissman et al., 2014; Buhedma et al., 2016), the Geological Society of America national meeting (Irmis et al., 2014), the Society of Vertebrate Paleontology Meeting in Berlin (P. Olsen et al., 2014a), the International Paleontological Congress in Mendoza Argentina (P. Olsen et al., 2014b), the International Geological Congress in Cape Town, SA (P. Olsen et al., 2016; P. E. Olsen et al., 2016; Geissman et al., 2016), and an AGU national meeting special session in 2017 entitled, “Chronostratigraphic Advances Integrating Paleomagnetism, Tephra, Climate Correlation, and Other Stratigraphic and Proxy Methods to Solve Earth System Processes and Events” (Irmis et al., 2017; Kent et al., 2017b; McIntosh et al., 2017; Olsen et al., 2017; Rasmussen et al., 2017; Schaller et al., 2017). Peer-reviewed publications have begun appearing this year (e.g., Kent et al., 2018). It is not an overstatement to conclude that the results from the CPCP project have transformed one of the poorest calibrated intervals of the Phanerozoic to one of the best. Our success at providing an independent and globally exportable zircon U-Pb-calibrated, paleomagnetic polarity stratigraphy, and atmospheric gas constraints from these kinds of continental sequences and their applicability to regional and global problems, has already resulted in a fundamental advance (Kent et al., 2018) and will spur future efforts in other parts of the geologic column. Plans for CPCP Phase 2 are underway with an international workshop that will coordinate efforts at building on Phase I of the CPCP, extending the core record though the rest of the Late Triassic, the Triassic–Jurassic transition, and nearly the complete Early Jurassic. The CPCP Phase 2 project will be coordinated with the ongoing JET project (https://www.facebook.com/JETMochras/, last access: September 2018) in the cyclical Early Jurassic marine epicontinental Jurassic of the UK. Ideally it will be paired with coring a high-latitude site, together resulting in an unprecedented synoptic view of Triassic to Jurassic $p\mathrm{CO}_2$, climate evolution and orbital pacing, and biotic transitions, including two mass extinctions and the rise to ecological dominance of the dinosaurs. A ICDP-funded workshop on these possible coring projects is planned for May 2019.

Team list. G. Bachman, V. Baranyi, R. Blakey, K. Brady Shannon, H. Buhedma, M. Colbert, D. Edey, G. Gehrels, J. Geissman, D. Giesler, Z. Haque, R. Irmis, D. Kent, S. Kinney, W. Kürschner, C. Lepre, J. MacIntosh, J. Maisano, C. Miller, R. Molina-Garza, R. Mundil, A. Noren, R. O’Grady, P. Olsen, W. Parker, C. Rasmussen, M. Schaller, D. Schnurrenberger, J. Sha, J. Whiteside, N. Zakharova. The CPCP teams include all of the authors plus R. Blakey, Z. Haque, and J. MacIntosh.

Data availability. The underlying data for this paper, not already presented in previous papers, are freely available from https://osf.io/5vd8u/ at this persistent DOI: https://doi.org/10.17605/OSF.IO/5VD8U (Stone et al., 2016). The archive split of the CPCP cores are stored at the LacCore, National Lacustrine Core Repository (http://lrc.geo.umn.edu/laccore/repository.html, last access: September 2018) and the working split is at the Rutgers University Core Repository where available (https://eps.rutgers.edu/centers-institutes/rutgers-core-repository, last access: September 2018).

Author contributions. PEO, JWG, DVK, GEG, RM, RBI, WGP, WMK, RMG, GHB, RMG, JHW, GHB, RCB, and JS designed research. PEO, JWG, DVK, GEG, RM, RBI, CL, CR, DG, WGP, NZ, WMK, CM, VB, HB, MFS, JHW, DS, AN, KBS, RO’G, MWC, JM, DE, STK, RMG, GHB, RCB, and JS designed research. PEO, JWG, DVK, GEG, RM, RBI, CL, CR, DG, WGP, NZ, WMK, CM, VB, HB, MFS, DS, AN, KBS, RO’G, MWC, JM, DE, STK, RMG, JMI, ZH, performed research. PEO, JWG, DVK, GEG, RM, RBI, CL, CR, DG, NZ, WMK, CM, VB, HB, MFS, JHW, and STK analyzed data. PEO, JWG, DVK, GEG, RM, RBI, WGP, WMK, CM, JHW, and STK wrote the paper.

Competing interests. The authors declare that they have no conflict of interest.

Disclaimer. Any opinions, findings, or conclusions of this study represent the views of the authors and not those of the U.S. Federal Government.

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