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[154], Jessie Maisano[12], David Edey[12], Sean T. Kinney[1], and the CPCP 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, Tucsan, 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, Mich. 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

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

Abstract. Phase 1 of the Colorado Plateau Coring Project (CPCP-I) recovered a total of over 850 m of overlapping core from two sites and 3 coreholes 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 high graded for CA-ID-TIMS U-Pb ages), which together with their magnetic polarity stratigraphy demonstrate that a globally exportable timescale can be produced from these continental sequences and in the process filling a prominent gap in the calibrated Phanerozoic record. The portion of the core completed thus far spans from ~215–209 Ma of the Late Triassic age part of core CPCP-PFNP13-1A, and validates the longer Newark-Hartford Astrochronostratigraphic-calibrated magnetic Polarity Time-Scale (APTS) based importantly on cores recovered in the 1990s during the Newark Basin Coring Project (NBCP).

Core recovery was ~100% in all holes (Tab. 1). The coreholes were inclined ~60°-75° approximately to the south to ensure azimuthal orientation by 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 all cores were split and processed at the CSDCO/LacCore Facility, in Minneapolis, MN where they were scanned for physical properties logs and imaging. While remaining the property of the Federal Government the archive half of each core is curated at the 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 and more anticipated for the future. 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. 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 placed in confident context with important events such as the giant Manicouagan impact at ~215.5 Ma and long wave-length 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. 2014), and the longest recovered continuous records of orbitally-paced climate change (Olsen and Kent, 1996; Ikeda and Tada, 2014; Kent et al., 2017a, b) - 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. In the oceans, during this time, calcareous nanoplankton made their appearance, modern reef-forming corals evolved, and archaic forms such as conodonts declined.

But despite the pivotal role of the Triassic, the period is characterized by very poor chronological 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-1990's served as the basis of a high-resolution time-scale, has been broadly accepted (e.g., Walker et al., 2013; IUGS/ISC, 2017), but 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 (Gallet et al., 2003; Kozur and Weems, 2005; Tanner et al., 2004).

Progress in past Earth System Science fundamentally depends 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 History. To address this cross-cutting issue for the Triassic, we launched the Colorado Plateau Coring Project (CPCP) an interdisciplinary multiphase coring experiment in a geological setting where there was sufficient information to know there would be abundant U-Pb datable deposits and a recoverable paleomagnetic polarity record that together would allow for a meaningful, globally exportable time-scale. 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) that recognized "Western Equatorial Pangea (Colorado Plateau)" as a key coring target. Subsequently CPCP workshops were held in 2007 and 2009 (funded by 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), where strata of ?Early-Middle Triassic age Moenkopi Formation and Late Triassic Chinle Formation are well represented and have been comparatively very well-studied in previous projects, where some demonstrated that U-Pb geochronologic information (Riggs et al., 2003) and a paleomagnetic polarity stratigraphy (Steiner and Lucas, 2000) could be recovered. Furthermore, long-term study (Parker and Martz, 2011) of the superb outcrops of Petrified Forest National Park (PFNP) had resulted by that time in a well-characterized physical stratigraphy (Woody, 2006; Martz and Parker, 2010), into which rich assemblages of vertebrates (Long and Murry, 1995; Parker and Irmis, 2005) and plants (Ash, 1972, 1988; 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 scientific coring experiment 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).

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, and while 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.

1.2 Tectonic environment

The overall tectonic context of early Mesozoic strata in the American Soutwest is uncertain, because, compared to 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 Pacific, eastwardly-directed oceanic-crust subduction of Pacific lithospheric elements beneath North America with a magmatic (Cordilleran) arc over the subducting slab and west of the backarc or foreland retroarc basins in which the Triassic-Jurassic deposits accumulated (Burchfiel and Davis, 1972; Gehrels et al., 2000; Barth and Wooden, 2006; Sigloch and Mihalynuk, 2017). An alternative and controversial model based on geological and geophysical (tomographic) data postulates that western North America was a passive continental margin from the Paleozoic until the Cretaceous with westward-dipping subduction (Hildebrand, 2009). 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 orogeny, toward the Cordilleran margin (Riggs et al., 1996). The sources of the fluvial and eolian transport systems during Triassic-Jurassic time has been documented using detrital zircons by Dickinson and Gehrels (2008a, b). In both models there must be a southwestern source of silicic volcanic debris generally identified with the postulated Cordilleran arc. Although the active margin, back arc – retroarc models have basin depocenters and syndepositional deformation localized by proximal active compressive and flexural forces of the approaching arc, there is ample evidence that much local deformation and localized subsidence was controlled by early Mesozoic halokenesis (Shoemaker et al., 1958; Hazel, 1994; Banham and Mountney, 2014) that might, in fact, prove more important than either basement-involved tectonics or eustasy in structuring much of the stratigraphy (Olsen et al., 2016). An additional, normally 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 & Gurnis (2010). The Plateau is characterized by relatively undeformed crust and is almost entirely surrounded by strongly compressed and subsequently highly extended regions. Apparently, 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 streams and rivers deeply incised parts of the Plateau, resulting in the more modern version of the Grand Canyon of the Colorado River and associated erosional features. The combined effects of the compression 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 and Lucas, 2000; 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 remains 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. 3). Apart from the Moenkopi Formation, which remains anomalous in being so “arid-looking” despite being 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 time (Fig. 2).

The oldest Triassic age strata in the PFNP area are part of the nominally Early to Middle Triassic age Moenkopi Formation, but in reality, as there are no fossils known from very low in the formation and correlation of the formation has been based on marine fossils found in distant areas to the west and tetrapod biostratigraphy (Morales, 1987; Lucas and Schoch, 2002). The base could conceivably be as old as Late Permian or considerably younger and the top could be as young as early Late Triassic (Carnian) based on admittedly sparse available geochronology (Dickinson and Gehrels, 2009) and could 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 geochronological 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 principle 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:

1) Is the Newark Basin astrochronostratigraphic polarity time-scale (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) Is the apparent pattern of latitudinal biotic provinciality that is seen in the Late Triassic supported by high-resolution independent (i.e., non-biostratigraphic) correlations, and does that change with climate-related environmental proxies?
4) Is the orbitally paced (Milankovitch) cyclical climate change recorded in the Newark basin lacustrine 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. 4 and 5; Tab. 1). Less than two weeks into the coring of the Chinde Point hole, at a depth of over 400 meters, 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. 4 and 5; Tab. 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 November 26, 2013 (Fig. 4), with the planned total depth of core 1A (bottoming in Early Permian age Coconino Sandstone) having been reached on November 24, 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

December 2 and total depth was reached on December 7, 2013 (again bottoming in Early Permian age Coconino Sandstone) (Tab. 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 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 heavy weight 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). This allows bedding, or some physical proxy of bedding, to serve for core orientation (Fig. 6). This of course 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. 7), 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 also provide a wealth of three-dimensional sedimentological details otherwise not visible (Fig. 7). 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 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 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. 4; Tab 1), was selected as the main site (for CPCP-PFNP13-1A) because the U-Pb dated Black Forest Bed 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 (Mio-Pliocene) lacustrine pale red mudrock, which locally overlies the Triassic age section. The knowledge that there is remnant of a possible vent (Ouimette, 1992) on the northwest 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 that 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., 2017b), 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. 5: Tab 3) (in stratigraphic thickness all rounded to the nearest m). The recovered core represents the first time both the lower and upper parts of the Chinle Formation, as it 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, the opportunistically advanced 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 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 minimising 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 ~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 meters 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 its 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 the lower two-thirds of the section recovered at Chinde Point (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 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 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 2X2, 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 last, 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 grayscale calibration standard (Fig. 7). 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 16bit 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, 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) catalogue 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 April 17–20, 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. A sampling party for cores 2A and 2B, just recently processed by at the UTCT and at LacCore (funded by a supplement from NSF), will take place in early 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 the 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 closely approximate those of Martz and Parker (2010), Ramezani et al (2011), and Atchley et al. (2013) and are dramatically different than depicted by Billingsley (1985), Murry (1990), Steiner and Lucas (2000), and Heckert and Lucas (2002). It can thus serve 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. **8**).

Overall, there is perhaps a surprising degree of agreement in the lateral consistency of facies between cores as evident in the geophysical logs, especially natural gamma (Fig 5). 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 that 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 Moenkopi Formation (Fig. 8). 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). 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 is represented by a laterally continuous red band of pedogenically modified strata about 1 meter thick. However, in several areas outside the park such "incised valleys" appear related to underlying halokinesis of Paleozoic salt (Matthews et al., 2007; Olsen et al., 2016). Such strata are often characterised by extraordinarily fast accumulation rates as evidenced from the burial of in situ plants, including trees (Parker, 2006; Trendell et al., 2013) implying rates of several meters in a few years (Fig. 9), 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 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. 10). 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 preference typical of waxes derived from vascular plants (Fig. 11). 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, derived presumably, 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 *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 the organic petrology and geochemistry and is planned by others.

As planned, the CPCP cores provide a venue for answering the major questions posed at the start of the project. While 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 <u>Astrochronostratigraphic</u>-calibrated magnetic <u>P</u>olarity <u>T</u>ime-<u>S</u>cale (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 (Kent et al., 2017b, 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, in core 1A with about 100 to >300 crystals being dated in most samples. Of these, the youngest population of the same zircons of 10 samples were selected thus far for CA-ID-TIMS dating at the Berkeley Geochronology Center yielding maximum depositional ages in stratigraphic order, within error. 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 and one from the uppermost Moenkopi strata. 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. It is important to note that correlation of the Newark-Hartford APTS to 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 Phaneozoic. 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). We are thus able to produce a globally exportable time-scale that can be developed from cores of these types of continental strata. In addition, paleomagnetic polarity stratigraphy has been developed for all of the Moenkopi Formation in PFNP13-1A (Buhedma et al, 2016; Buhedma, 2017; McIntosh et al., 2017), and this CA-ID-TIMS zircon-calibrated 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 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) 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? No certain representation of the "persistent red silcrete" that accompanies the Adamanian-Revueltian boundary in the south part of the park was identified in the core 1A. This is not surprizing because even though Billingsley (1985) identified a bed that might be equivalent to this unusual feature and called it the "Brown Sandstone" in the north area of the park, in fact its identity is not certain, and furthermore the "Brown Sandstone" has not yet

been positively identified in the core either. 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 U-Pb dates from core 1A to the Newark-Hartford APTS (Kent et al., 2017, 2018) and a rather obvious correlation to magnetic polarity stratigraphy records in Greenland 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. 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 (Whiteside 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 reflected in the largely fluvial Chinle and Moenkopi formations? A perhaps surprising result from the Petrified Forest and the upper Sonsela members is that the 405 kyr cycle is in fact reflected in Chinle Formation as seen in the redox-sensitive magnetic susceptibility logs (Olsen et al., 2017). 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. Additional work with other environmental proxies, including the CT-scans of paleosol fabrics (Fig. 7), 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 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? Very preliminary results from parts of core 1A show that the carbonate paleosol CO_2 proxy does yield comprehensible results (Schaller et al., 2017) consistent with those from the eastern US (Schaller et al. 2014; Whiteside et al., 2015). That said, there are 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).

6 Outreach and broader impacts

Petrified Forest National Park is a major tourist destination with some 600,000 visitors from around the world a year who are predisposed to be receptive to a geological 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), 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), PLos Blogs (http://blogs.plos.org/paleo/2013/11/21/the-colorado-plateau-coring-project-getting-dates-in-the-triassic/), Arizona Geology (http://arizonageology.blogspot.com/2013/11/scientific-core-drilling-at-petrified.html), Discover Magazine (http://discovermagazine.com/2015/may/18-sands-of-time), National Geographic (http://phenomena.nationalgeographic.com/2013/11/19/getting-to-the-core-of-the-triassic/), WNYC (https://www.wnyc.org/story/shutdown-stymies-scientific-research/), and The Arizona Daily Sun (http://azdailysun.com/news/local/petrified-forest-a-fossil-every-inches/article_ee70579c-4906-11e3-9324-001a4bcf887a.html). 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) and the LacCore group developed and maintains Facebook page for the project (https://www.facebook.com/Colorado-Plateau-Coring-Project-1436554049899932/). 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.

LacCore Staff produced an on-site Facebook page (https://www.facebook.com/Colorado-Plateau-Coring-Project-1436554049899932/) with news updates throughout drilling, and coordinated workforce development training in drilling and core workflows for 5 people. 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). The later has seen over 12,000 visitors).

The CPCP has 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 (Olsen et al., 2013, 2014a; 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 (Olsen et al., 2014b), the International Paleontological Congress in Mendoza Argentina (Olsen at al., 2014c), the International Geological Congress in Cape Town, SA (Olsen et al., 2016a, b), 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). We anticipate that peer reviewed publications will begin appearing this year, with one presently in submitted in January, 2018 (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 independent and globally exportable U-Pb geochronologic, paleomagnetic polarity, 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 portions of the geological column.

The CPCP Team

Authors, plus G. Bachmann, R. Blakey, H. Buhedma, J. MacIntosh, R. Molina-Garza, J. Riedel, J. Sha,. This includes all the NSF and ICDP Principal Investigators, as well as staff of LacCore/CSDCO and the University of Texas, Austin's CT-Scanning facility, additional researchers, students and postdocs.

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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Tables

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

Figures

Figure 1: Context for the CPCP cores. A, Late Triassic-Early Jurassic Pangea showing position 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 (gray 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.

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, Petrified Forest National Park; 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".

Figure 3: Position of North America (modified 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/), change in precipitation for 2100 (from https://www.gfdl.noaa.gov/will-the-wet-get-wetter-and-the-dry-drier/), 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).

Figure 4: CPCP Coring sites: A, Chinde Point (GoogleEarth image) looking south with CPCP-PFNP13-1A coring site in 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 Headquaters 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 distance are Hopi Buttes Bidahochi Formation mares and buildings in foreground, left are partsof the Rainbow Forest Museum; D, CPCP-PFNP13-2B site at "West Bone Yard" during coring, looking west.

Figure 5: **Lithological logs, line-scan images, natural gamma, 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 core or hole with msd = 0.866 • mcd in 1A.**

Figure 6: The nearly horizontal bedding in PFNP was used for orientation by inclining the corehole 60°-75° in a southerly direction. A, Earth's magnetic field line (normal polarity) with Earth with Triassic Pangea and location of Colorado Plateau (red dot) – note field lines near horizontal near equator. B, Diagram of inclined core hole at 60° with normal and reverse field lines near horizontal due to low latitude position of the Colorado Plateau during the Triassic – field lines are directed slightly up-core for normal polarity and slightly down down-core for reverse polarity and because the core was intended to be split down the plane of this cross-section bedding is seen to dip 30° relative to the long axis of the core (compare with Fig. 8).

Figure 7: CT scans of CPCP-PFNP13-1A core: A, 3 core segments bundled with aluminium 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); 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 sloping to left (cores are approximately 0.7 m long) (see https://www.youtube.com/watch?v=ynM-H8_Qu7A&feature=youtu.be).

Figure 8: **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 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 Petrified Forest Member of the Chinle Formation with abundant intraformational carbonate clasts and volcaniclastic material; C, pedogenic mudstone of Petrified Forest Member of the Chinle Formation with long axis of elliptical spots dipping 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 upper Sonsela Member of Chinle Formation; F, Contact (c) between coarse sandstone of overlying Sonsela Member of the Chinle Formation and underlying Blue Mesa Member of Chinle Formation; G, pedogenic mudstonme of the Blue Mesa Member of the Chinle Formation; H. 4-color mottled pedogenic mudstone of the Mesa Redondo Member of the Chinle Formation; I, Contact (c) between sandstone of overlying Mesa Redondo Member of the Chinle Formation and sandstone and siltstone of underlying Holbrook Member of Moenkopi Formation; J, chicken-wire gypsum bed in siltstone of Moqui Member of Moenkopi Formation; K, Contact (c) between cobble conglomerate of overlying Shinarump Member of the Chinle Formation and sandstone and siltstone of underlying Holbrook Member of Moenkopi Formation; L, , Contact (c) between sandstone siltstone of overlying Wupatki Member of the** Moenkopi **Formation and sandstone and sandstone of underlying Coconino Sandstone of Early Permian age.**

Figure 9: 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 scroll-bar (point bar) at 34.949°, -109.776° with +2m upright, plant stem (?Equisetities) in growth position in red box enlarged in C indicative of extremely fast accumulation (~+1m / season) – Morgan Schaller for scale; C, plant stem (?Equisetities) in growth position (portion between arrows) is enlarged in D – beds tilt from right (west) to left (east) with faint left-tilted 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 10: Photograph showing organic residue with degraded cuticle, charcoal, and wood fragments. Identifiable sporomorphs are modern *Lycopodium* spores added to calibrate abundances during palynological preparation.

Figure 11: 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) cm 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..

Figure 1

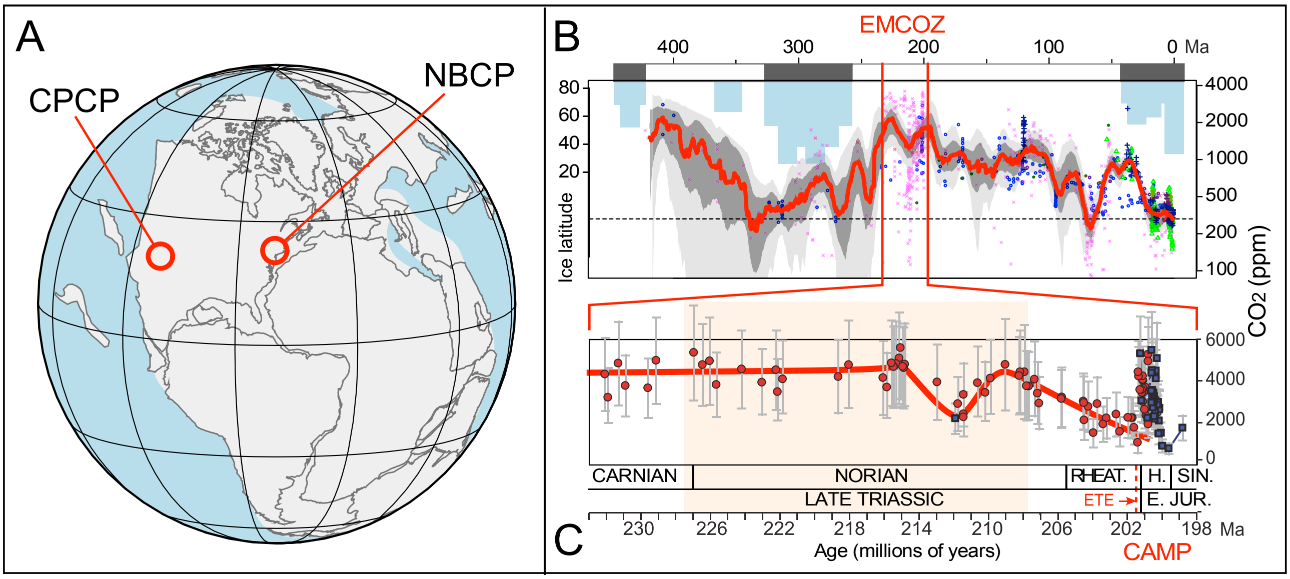
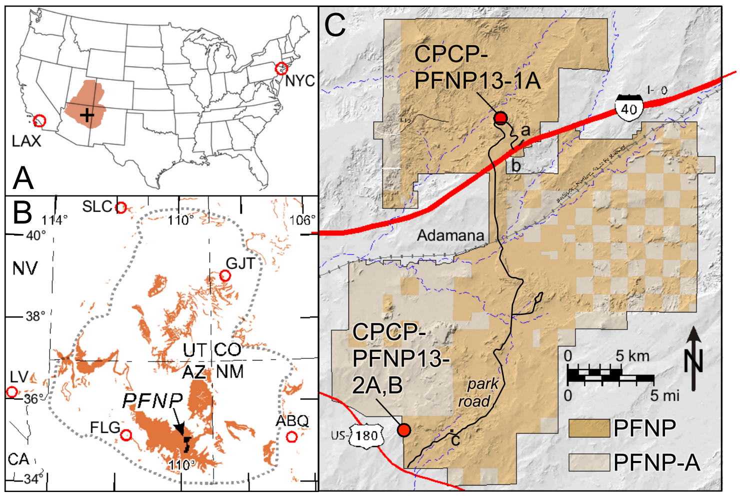
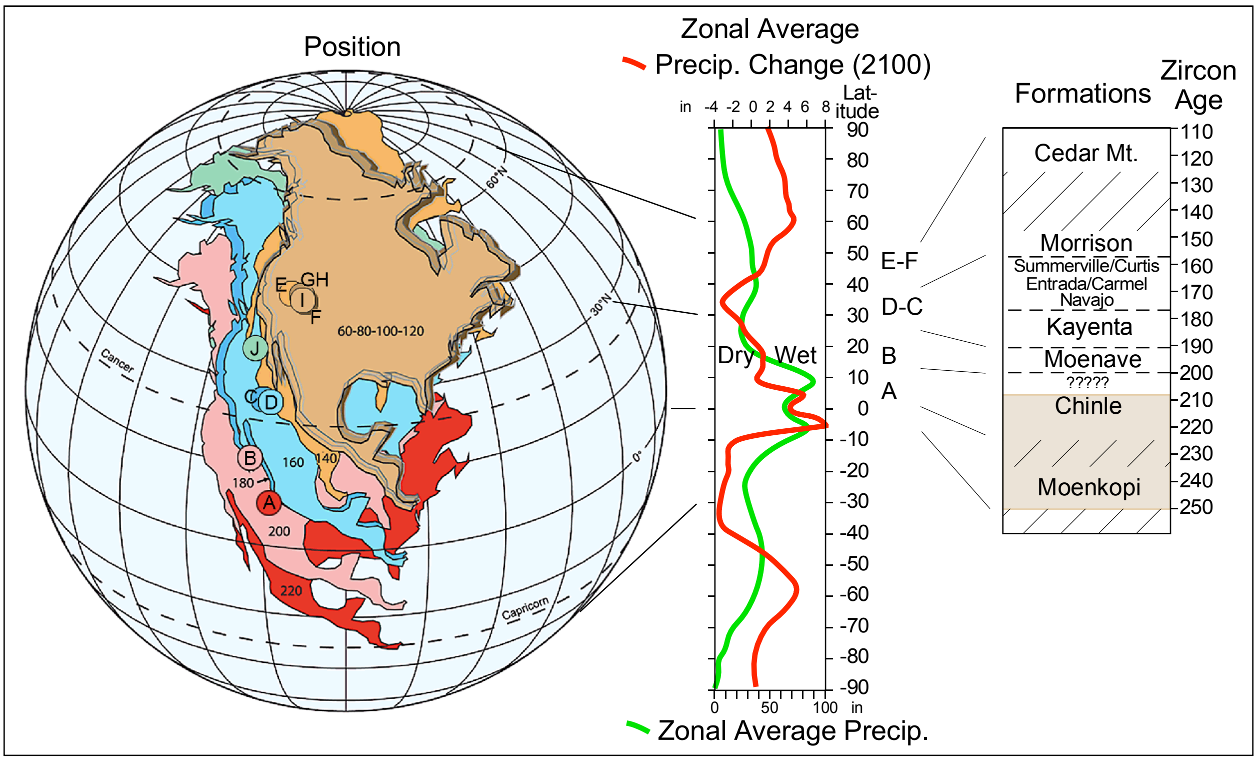

A
CPCP
NBCP
B
EMCOZ
400
300
200
100
0 Ma
80
60
40
20
Ice latitude
4000
2000
1000
500
200
100
CO2 (ppm)
6000
4000
2000
0
CARNIAN
NORIAN
RHEAT.
H.
SIN.
LATE TRIASSIC
ETE
E. JUR.
C
230
226
222
218
214
210
206
202
198 Ma
Age (millions of years)
CAMP

Figure 2



A
NYC
LAX
B
SLC
114°
110°
106°
40°
NV
GJT
38°
UT
CO
AZ
NM
LV
36°
PFNP
FLG
ABQ
CA
110°
34°
C
CPCP-PFNP13-1A
I-40
a
b
Adamana
CPCP-PFNP13-2A,B
park road
US-180
c
0
5 km
0
5 mi
N
PFNP
PFNP-A

Figure 3



Position
Zonal Average
Precip. Change (2100)
in -4 -2 0 2 4 6 8
Lat-
itude
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
0 50 100 in
Zonal Average Precip.
Dry
Wet
E-F
D-C
B
A
Formations
Zircon Age
Cedar Mt.
Morrison
Summerville/Curtis
Entrada/Carmel
Navajo
Kayenta
Moenave
?????
Chinle
Moenkopi
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
60°N
30°N
0°
Cancer
Capricorn
60-80-100-120
140
160
180
200
220
E
GH
I
F
J
C
D
B
A

Figure 4

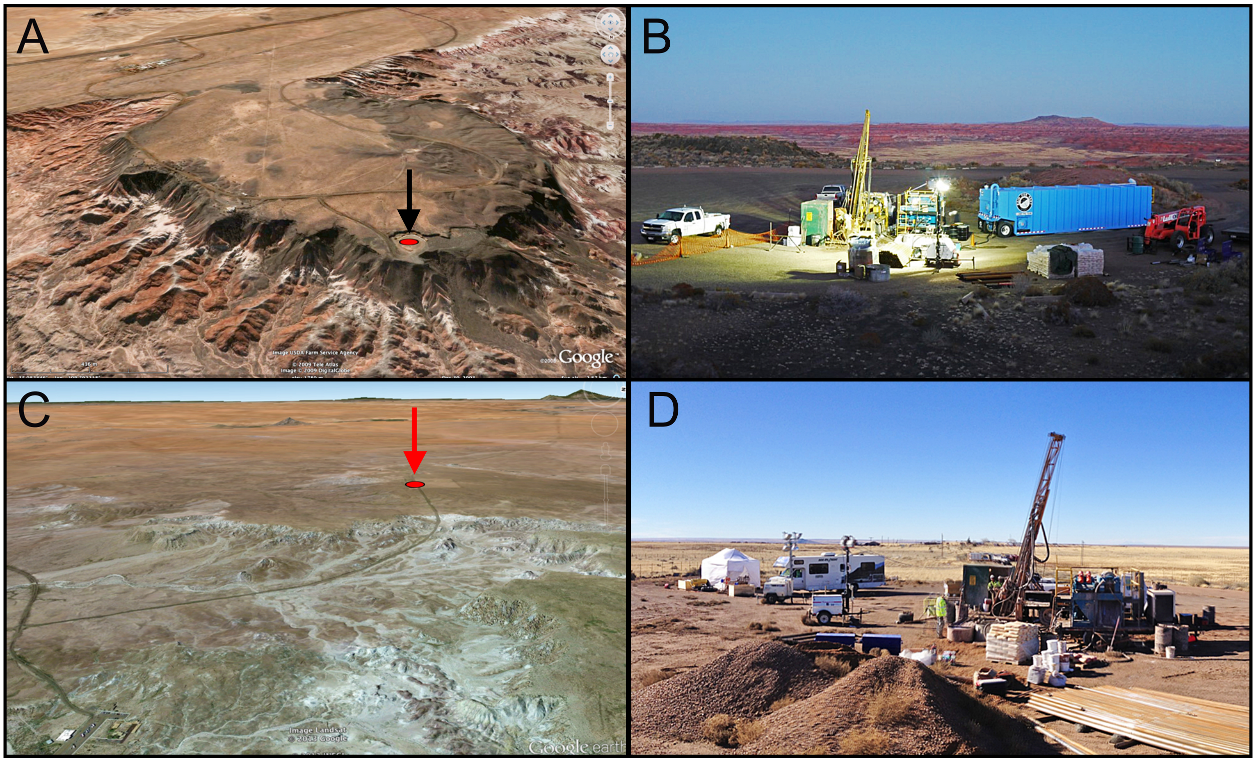


Figure 6

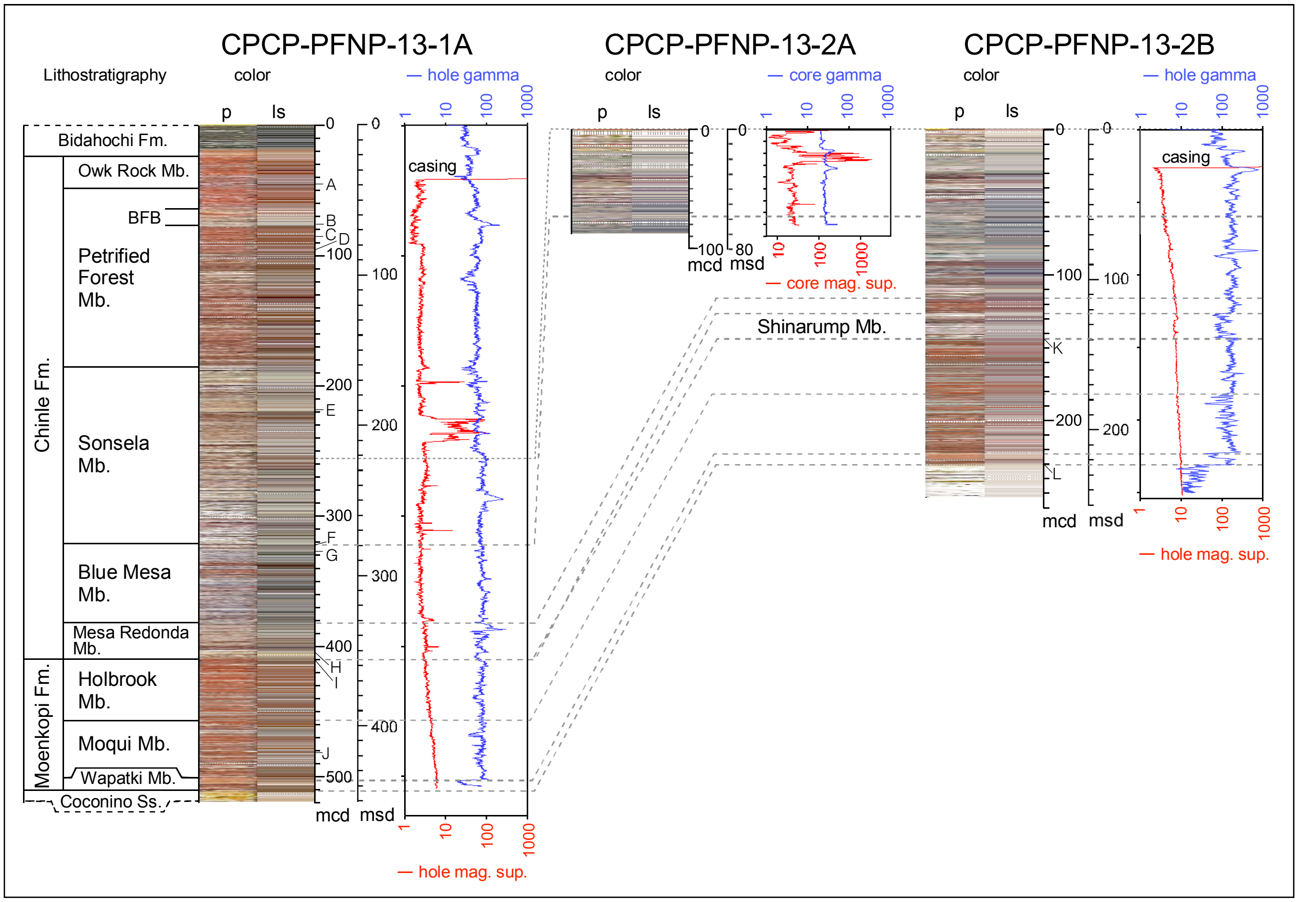
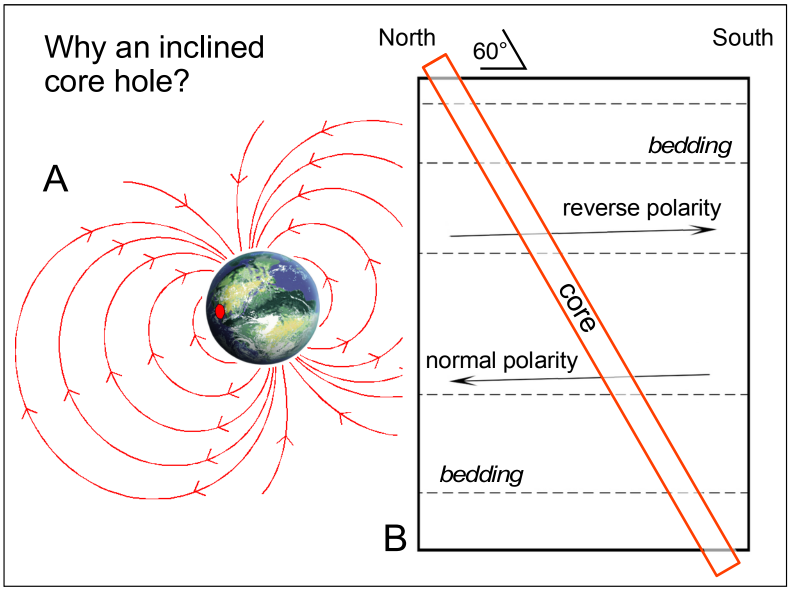

CPCP-PFNP-13-1A
CPCP-PFNP-13-2A
CPCP-PFNP-13-2B
Lithostratigraphy
color
hole gamma
core gamma
p
ls
Bidahochi Fm.
Owk Rock Mb.
BFB
Petrified Forest Mb.
Chinle Fm.
Sonsela Mb.
Blue Mesa Mb.
Mesa Redonda Mb.
Moenkopi Fm.
Holbrook Mb.
Moqui Mb.
Wapatki Mb.
Coconino Ss.
casing
Shinarump Mb.
mcd
msd
hole mag. sup.
core mag. sup.

Figure 6



Why an inclined
core hole?
A
North
60°
South
bedding
reverse polarity
core
normal polarity
bedding
B

Figure 7

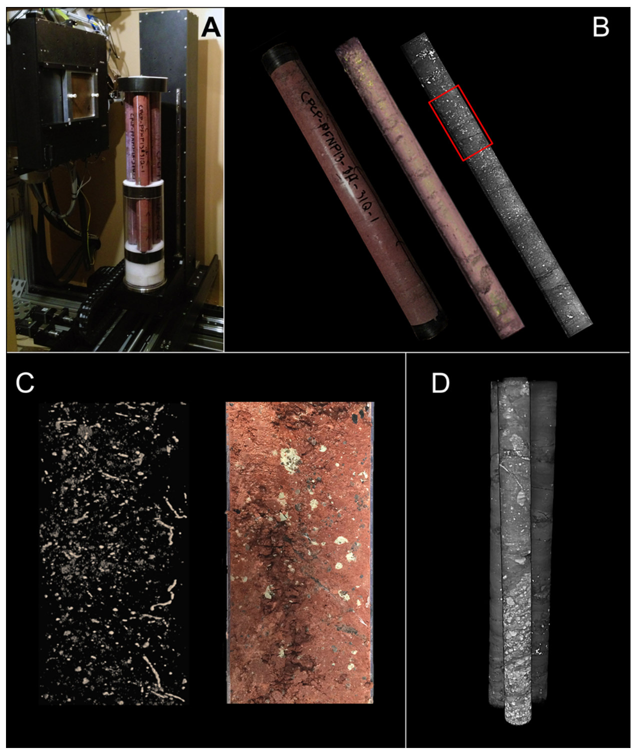
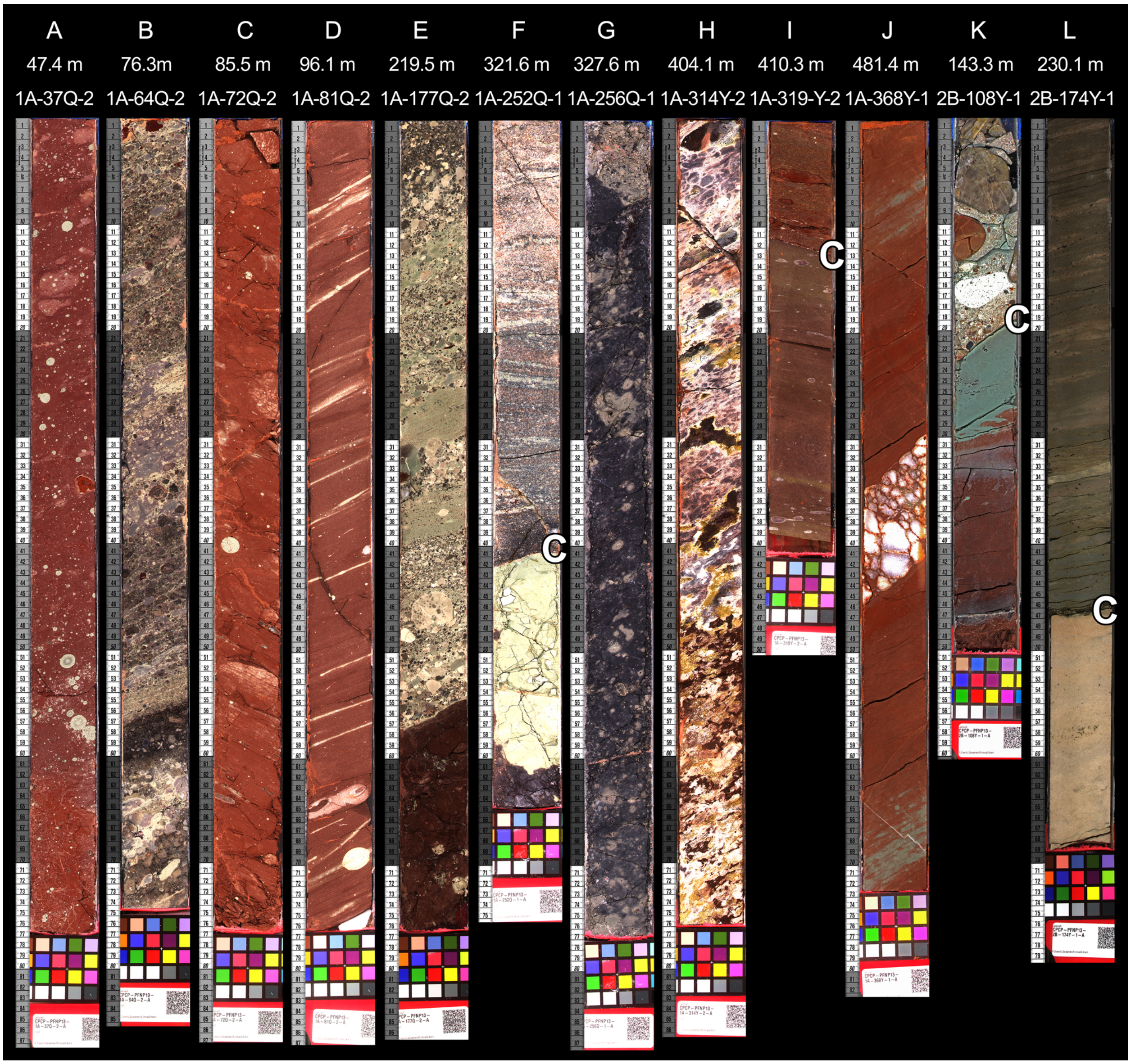


Figure 8



A
47.4 m
1A-37Q-2
B
76.3m
1A-64Q-2
C
85.5 m
1A-72Q-2
D
96.1 m
1A-81Q-2
E
219.5 m
1A-177Q-2
F
321.6 m
1A-252Q-1
G
327.6 m
1A-256Q-1
H
404.1 m
1A-314Y-2
I
410.3 m
1A-319-Y-2
J
481.4 m
1A-368Y-1
K
143.3 m
2B-108Y-1
L
230.1 m
2B-174Y-1
C
C
C
C

Figure 9

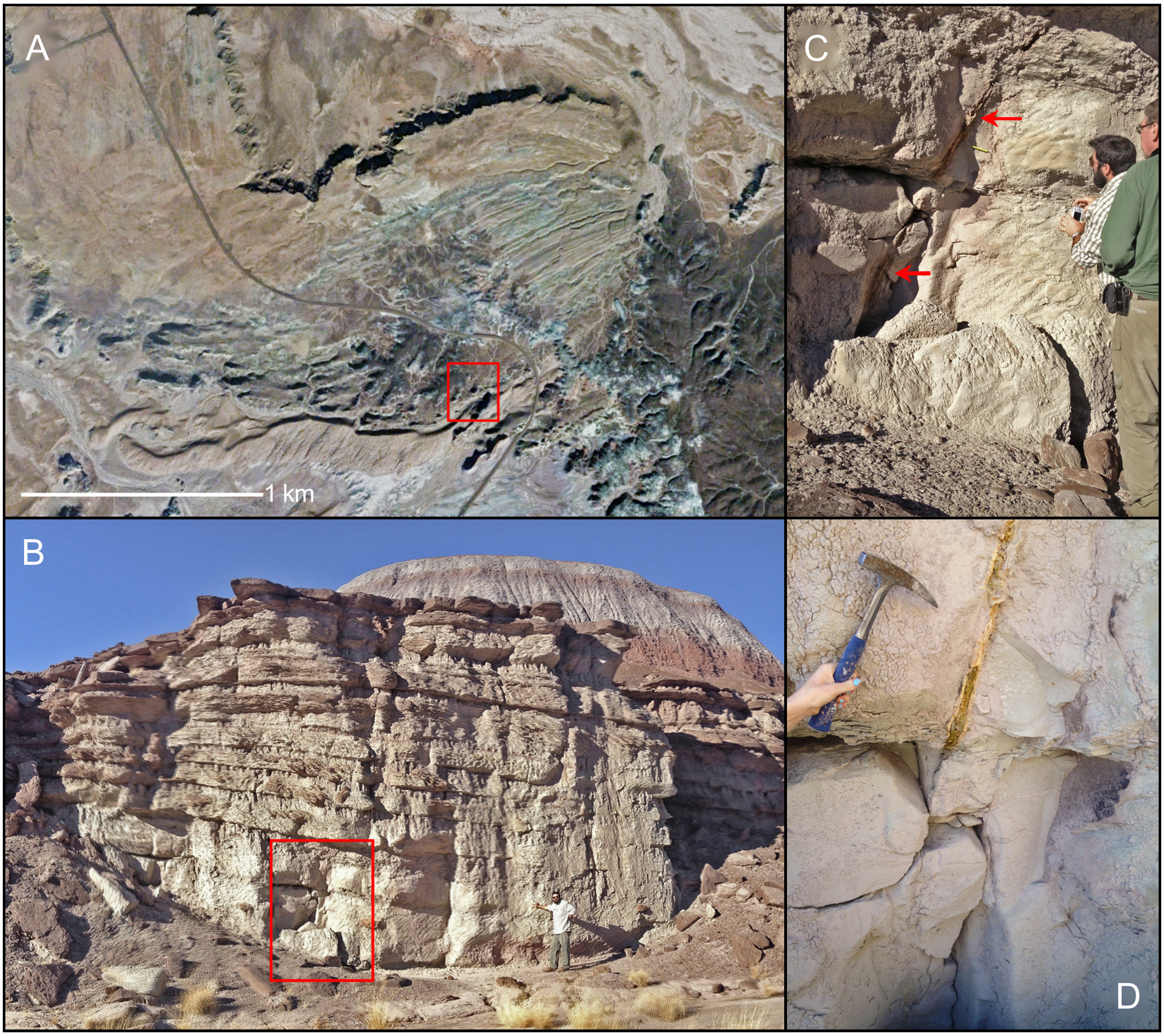


Figure 10

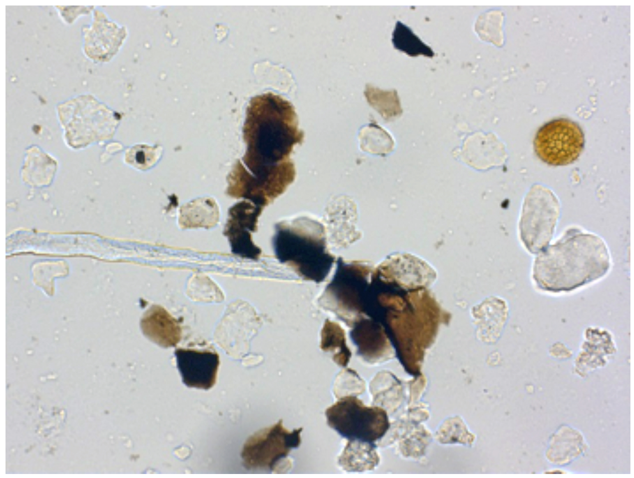
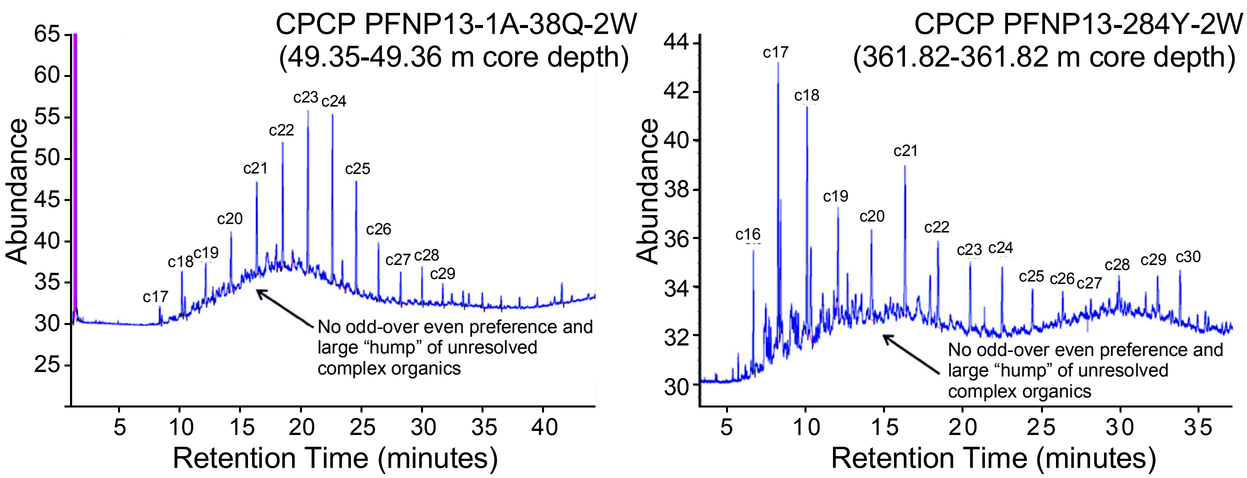


Figure 11



CPCP PFNP13-1A-38Q-2W
(49.35-49.36 m core depth)
Abundance
Retention Time (minutes)
c17
c18
c19
c20
c21
c22
c23
c24
c25
c26
c27
c28
c29
No odd-over even preference and large "hump" of unresolved complex organics
CPCP PFNP13-284Y-2W
(361.82-361.82 m core depth)
c16
c30

Table 1

Table 1: Summary Data for CPCP Drilling Sites and cores

Site	Drill Hole	Dates Cored	Lat (N)	Lon (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