Project Summary: The Colorado Plateau Coring Project (CPCP)

The CPCP is an interdisciplinary, multi-institutional coring project designed to decipher the biotic, climatic, and tectonic evolution of the first 100 million years of the Mesozoic Earth System (Triassic and Jurassic, ~250 – 145 Ma) as expressed in the epicontinental basins of the Colorado Plateau and its environs. This community-driven science and coring project derives from an international workshop (November, 2007) involving broad segments of the Earth science community. Motivating the CPCP is the need to understand the links between major events in the history of life, climate change, and Earth System crises during the Early Mesozoic, particularly the two major and two subsidiary mass extinction events, the ascent of the dinosaurs, and the origin of the modern biota. While Colorado Plateau outcrops comprises a unique field laboratory with a long history of research, a scientific coring program is essential because the most continuous sections in outcrop are either inaccessible in vertical cliffs or are intensely weathered and geochemically altered, making geological observations and sampling at the appropriate level of detail practically impossible. Furthermore, the shallow bedding attitudes, lateral facies changes, and covered intervals compromise unambiguous superposition in surface sections over long geographic traverses that so far have inhibited the assembly of a comprehensive chronostratigraphic scheme.

The CPCP coring strategy from the 2007 workshop involves five cores in three phases designed to recover the full expression of the critical early Mesozoic transitions in clear superposition and with sufficient stratigraphic overlap to optimize stratigraphic completeness. In total, the cores would span from the top of the Morrison Fm. through the base of the Moenkopi Fm. with enough overlap between cores to firmly tie the sections together and to provide information on lateral facies and thickness changes. Phase 1 consists of two cores spanning the Triassic, the Triassic-Jurassic transition, and most of the Early Jurassic age: a ~400 m core in Petrified Forest, National Park, AZ, and a ~800 m core in the Ward Terrace/Moenkopi Plateau area, AZ. These will capture the thickest known development of the Late Triassic Chinle Gp. and a thick and finest-grained facies of the Early Jurassic Kayenta Fm. adjacent to the richest faunal localities. Phase 2 also consists of two cores designed to examine the Triassic and Early Jurassic part of the record: a ~1100 m core near St. George, UT, and a ~600 m core in the Rock Point/Lisbon Valley area in AZ-UT. These cores will capture a thickened sequence of Early to Middle Triassic Moenkopi and a thick and fine-grained part of the Jurassic Glen Canyon Group adjacent to the faunally richest Triassic-Jurassic boundary sections. Phase 3 is comprised of a ~1400 m core in the San Rafael Swell area, UT that will recover the entire Jurassic Morrison Fm., San Rafael Gp., and Glen Canyon Gp. This core will sample strata documenting the return to more humid conditions, as well as the interval producing arguably the richest Late Jurassic continental biota in the world, exemplifying the culmination of dinosaur dominance. Each phase builds on our previous coring and research, hence a vision and a program, but each phase could stand-alone. Depending on funding rates, each could be accomplished in around 18 months.

The initial CPCP management team consists of Olsen and 3 PIs: John W. Geissman (Univ. of New Mexico), Dennis V. Kent (Rutgers Univ.), and Roland Mundil (Berkeley Geochronology Center). The multidisciplinary approach using magnetostratigraphy, geochronology, biostratigraphy, chemostratigraphy and cyclostratigraphy will require about a half dozen additional national and international PIs, undergraduate and graduate students (in all the research) and postdocs, plus the expected services of DOSECC, ICDP, CoreWall, a professional educational and outreach specialist, and intramural sampling-archiving, geoinformatics, and education/outreach committees. We already have expressions of support from the Interior Department to drill in Petrified Forest National Park (Phase 1) and the Utah state survey to serve as potential core repository. Estimated budget for drilling, borehole and core logging and processing, and science is ~$4.4M, roughly divided between drilling and science costs. An ICDP workshop will take place in May, 2009, and coring could begin as soon as practicable (e.g., Fall 2009).

The Colorado Plateau Coring Project (CPCP): Preliminary Proposal

INTRODUCTION

Lasting over 100 million years, the early Mesozoic (252 to 145 Ma) is punctuated by two of the five major mass extinctions of the Phanerozoic (Permo-Triassic and Triassic-Jurassic) plus several smaller extinction events. It witnessed the evolutionary appearance of the modern terrestrial biota including frogs, salamanders, turtles, lizards, crocodilians, dinosaurs, birds, and mammals, and spans a time of dramatic climate changes on the continents. What is arguably the richest record of these events lies in the vast (~2.5 million km^2) complex of epicontinental basins in the western part of Pangea, now largely preserved on the Colorado Plateau (Fig. 1). Since the mid-19th century, classic studies of these basins, their strata, and their fossils have made this succession instrumental in framing our context of the early Mesozoic Earth system as reflected in the international literature. Despite this long and distinguished history of study of the Colorado Plateau region, striking ambiguities in temporal resolution, major uncertainties in global correlations, and significant doubts about paleolatitudinal position hamper incorporation of the huge amount of information from the region into tests of major competing climatic, biotic, and tectonic hypotheses and a fundamental understanding of Earth system processes.

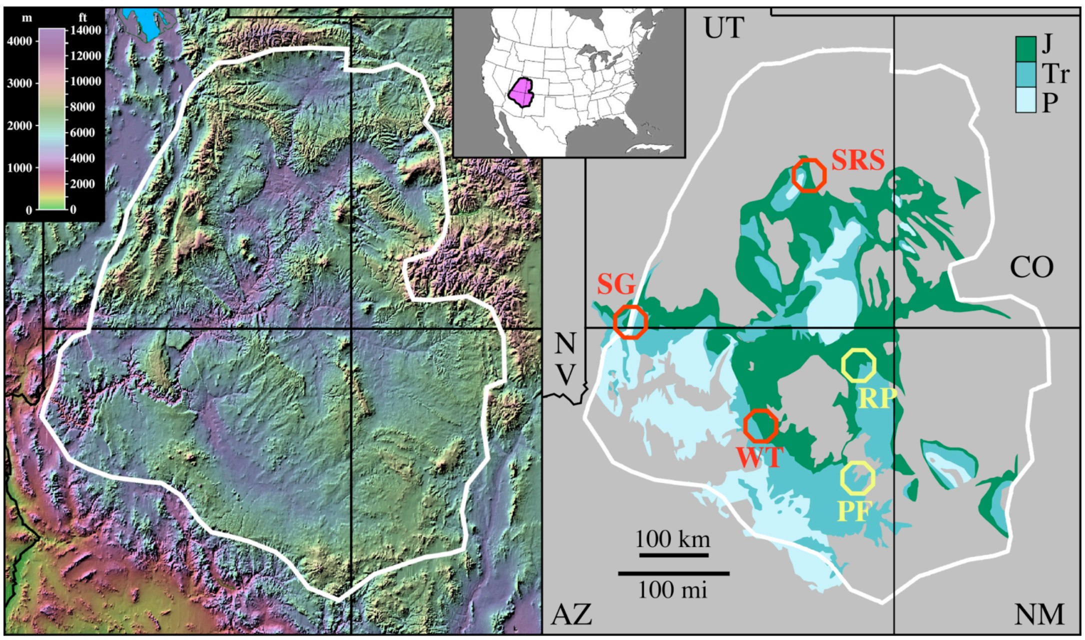


Figure 1. Map of the Colorado Plateau (white line) and adjacent areas: left, shaded digital elevation map; right, generalized geological map showing Permian and Triassic and Jurassic strata (from ref.3). Tentative drilling target areas are: PF, Petrified Forest, Arizona; RP, Rock Point, Utah; SG, St. George, Utah; WT, Ward Terrace, Arizona; SRS, San Rafael Swell, Utah.

A basic question posed by the exceptionally rich paleobiological record of the Plateau and adjacent areas is, what is the nature of the links between major events in the history of early Mesozoic life, climate change, and Earth System crises, particularly the mass extinction events, the ascent of the dinosaurs, and the origin of modern biota. In order to elucidate these connections we propose a phased interdisciplinary, multi-institutional coring project – the Colorado Plateau Coring Project or CPCP (Fig. 1). As described below, the overall coring strategy for the entire project involves 5 cores: three long (~1000 m) cores and two shorter (300-600 m) cores intended to recover the full expression of the critical early Mesozoic transitions in clear superposition and with sufficient stratigraphic overlap to minimize gaps. The array of cores would span from the base of the Moenkopi to the top of the Morrison Formation (representing the Triassic and Jurassic) with sufficient overlap between cores to splice the sections into a composite and to provide information on lateral facies and thickness changes and stratigraphic completeness. As planned, the CPCP will result in a major improvement in our ability to address outstanding issues of global importance, involving chronology, paleogeography, paleoclimate, and biotic evolution in this sector of the Pangea supercontinent. This project can begin virtually immediately with the initial phase, which is the sampling of the Triassic-Early Jurassic interval in Arizona.

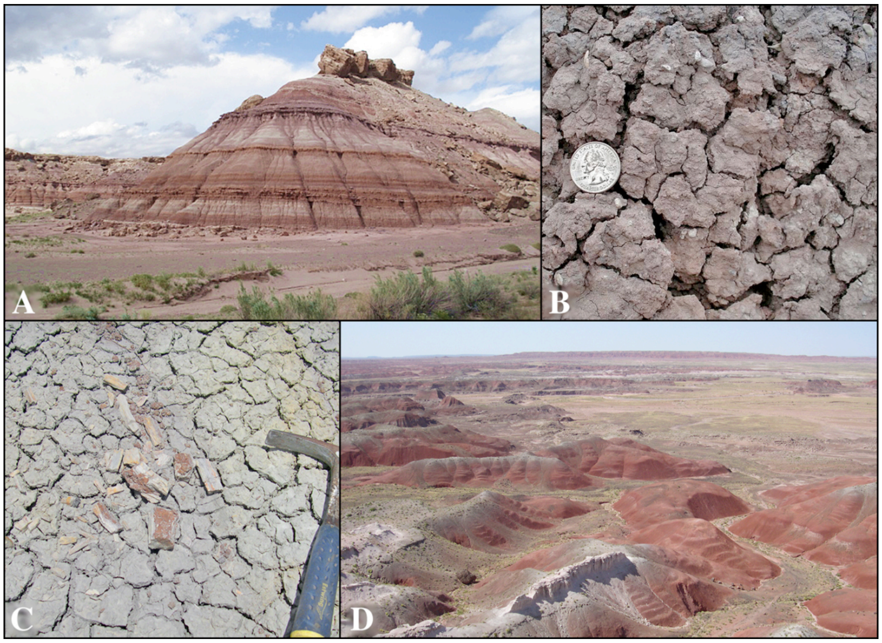


Figure 2. Opportunities and challenges in the bentonitic facies of the Colorado Plateau with near 100% outcrop. Mudstones have a partial volcanic source, meaning there are datable ashes, but also that the outcrops present very significant sampling problems where freshness and competency are at premium as for geochemistry or paleomagnetism. **A**, Morrison Fm. west of Green River, UT. **B**, typical "popcorn" surface of bentonitic mudstone of the Morrison Fm. (near A). **C**, "popcorn" surface of the Chinle Gr. in Petrified Forest National Park (PFP), with fragmentary weathered amphibian bones. **D**, outcrops Chinle Gr. in PFP with the white U-Pb dated Black Forest Bed foreground (ref. 54).

Origin of Project

The CPCP developed from the recommendations of a 1999 NSF-ICDP funded workshop on early Mesozoic Pangea (1). The concept was more fully developed in a 2007 NSF and DOSECC-funded workshop that provided a broad-based, community-driven science and coring plan for the CPCP. Reports of this workshop have been published in *EOS* (2), *Scientific Drilling* (3), and on the web (http://www.ldeo.columbia.edu/~polsen/cpcp/CPCP_home_page_general.html). An ICDP-funded international workshop will be held in May 2009, in Albuquerque, NM, to refine the specific CPCP site plans and proposals. We have also benefited from feedback from the NSF Continental Dynamics program to a previous preproposal that has been incorporated here.

Need for Drilling

A scientific coring program is essential in this seemingly strikingly well-exposed and well-studied region because, by modern standards and the requirements of the scientific questions posed, outcrops simply do not permit investigation of the physical, magnetic polarity, or chemical stratigraphy of the Plateau and environs at the appropriate levels of resolution or confidence. The most continuous sections in outcrop are either inaccessible in vertical cliffs or are intensely weathered and geochemically altered (e.g., 4), making high resolution and high fidelity geological observations and sampling practically impossible. Furthermore, the shallow bedding attitudes, lateral facies changes, and covered intervals compromise unambiguous superposition in surface sections over long geographic traverses. These problems are not unique to the CPCP but generally characterize other proposed coring projects in similarly well-exposed well-studied arid regions where the goal is to tie the changes in abundant fossil remains to environmental changes, including the *Bighorn Basin Coring Project* in the western United States (http://earth.unh.edu/clyde/BBCP.html) and the *Hominid Sites and Paleolakes Drilling Project* in East Africa (http://www.icdp-online.org/contenido/icdp/front_content.php?idcat=1225).

SCIENCE QUESTIONS

The CPCP is stimulated by four compelling and intertwined, hypothesis-driven questions to address outstanding issues of Pangean biotic evolution, chronology, paleogeography, paleoclimate, and basin evolution.

1, How is the major biotic transition from the Paleozoic to essentially modern terrestrial ecosystems, including biotic events such as mass extinctions, linked to climatic and tectonic events, and what are the rates and magnitudes of these changes?
2, What are the trends in global or regional climate vs. those resulting simply from paleolatitudinal drift in "hot house" Pangea and Laurasia?
3, How did the largely fluvial systems and their biological communities respond to the climate changes?
4, How does the stratigraphy of the basin sections reflect the interplay between dynamic growth in accommodation space, uplift, and eustatic fluctuations in an intracontinental setting?

None of these questions can be addressed with the available data or, practically speaking, with the existing outcrops, and in fact virtually nothing remotely secure is known about these issues. Cases in point are illustrated in two recent papers: Rowe et al. (5) and Lucas et al. (6).

Rowe and others argue that the Early Jurassic age Navajo Sandstone, the product of the largest sand sea in Earth History, was deposited virtually at the equator based on comparison with a numerical climate model rather than in the subtropics as determined from apparent polar wander paths. One of the authors is the preeminent paleomagnetist Rob Van der Voo, who concurs that the Plateau's paleogeography and temporal context are so poorly understood and determined that this is possible. If this model is correct, then the North American plate was virtually stationary over the entire Triassic through the Early Jurassic and the climate change expressed in the stratigraphic and paleontological records was due to true regional if not global climate change. Alternatively, North America drifted 25° northward during this time and thus the climate model is incorrect. Either way, the results are fairly shocking, but we will not know which hypothesis is more correct unless the needed temporal and stratigraphic contexts are much better developed.

Lucas and others (e.g., 7,8,9), using data from the Colorado Plateau, argue against the idea that the Triassic-Jurassic boundary marks a mass-extinction that literature compilations (e.g., 10) show that the Triassic-Jurassic extinction event is larger than the K-T boundary event and, by some metrics, even larger than the end-Permian event. The argument proffered by Lucas and others - that there is virtually no extinction event at this boundary - can be made solely because of the extremely poor constraints not only on the relative ages of the rich faunas relative to other parts of the world, but, even more importantly, relative to each other within and adjacent to the Colorado Plateau. This is because the geographically dispersed localities lack the criterion of superposition and are correlated to each other by lithostratigraphy and biostratigraphy, the same biostratigraphy that fails first-order quantitative correlation tests as witnessed by a 10 Ma change in the age strata inferred to be Carnian age to Norian age based on new U-Pb zircon ages (e.g., 11) outlined below. This is most unfortunate, given that the Colorado Plateau has the richest Triassic-Jurassic vertebrate assemblages in the world. These types of issues that permeate the entire early Mesozoic section will not be resolved until a proper temporal context is available, as we propose to develop in the CPCP.

These are just two examples of urgent issues on which a great deal of additional science hinges. If the largest erg on Earth did lie at the equator in the Early Jurassic, then basic ideas of climate processes clearly require revision. If there is no Triassic-Jurassic mass extinction, what is the point of looking for its cause in large igneous provinces or impacts? Herein lies our point - a rigorous chronostratigraphy and paleogeographic framework, both key scientific goals of the CPCP, are essential to be able to move forward.

We expect the CPCP to stimulate an entirely new generation of field studies tying their results to the cores. Some of the signature outcomes of the CPCP are expected to include: 1, a high resolution magnetic polarity stratigraphy in combination with high-resolution radio-isotopic ages for the Triassic and Jurassic epicontinental sediments which is essential for regional and especially global chronostratigraphic correlations to other continental (e.g., Newark, Central European, or Chinese basins) as well as marine (e.g., Tethyan) sections; 2, tight constraints on the paleogeography, particularly changes in paleolatitude, of western Pangea during the Triassic and Jurassic and the relationship to the expression of paleoclimate in the sedimentary record, particularly the apparent aridification in the Triassic and Early Jurassic; 3, a well-calibrated paleoclimate record for comparison to other parts of Pangea for tests of climate models; 4, a thorough reassessment of lithostratigraphic and biostratigraphic correlations, including pinpointing the ages and extents of proposed regional unconformities and their possible relationship to eustatic fluctuations; 5, development of a chemostratigraphic reference section for the American Southwest for the early Mesozoic; 6, development of a sufficiently detailed stratigraphic framework to establish teleconnections between the Colorado Plateau sedimentary record and rifting of Pangea, the emplacement of the Central Atlantic Magmatic Province, and the opening of the Atlantic Ocean, as well as the eruption other large igneous provinces, notably the Karoo-Ferrar, Siberian, and Paraná-Etendeka basalts; and 7, development of a quantitative tectonostratigraphic database that will allow the development and testing of models of dynamic basin evolution.

The success of CPCP will have major implications for understanding early Mesozoic global climate change, the evolution of the modern terrestrial biota, and possible linkages with the breakup of the Pangean supercontinent and the eruption of some of the world's most extensive large igneous provinces. For example, several results of this project having considerable societal relevance and these include direct tests of the ability of current climate models to address different boundary conditions, such as high-CO_2. Presently, there are apparent inconsistencies between predictions of climate models and paleogeography for the Colorado Plateau in the Permian to Jurassic (5). These inconsistencies cannot be resolved with the existing data but are among the scientific issues that the CPCP is designed to address.

A useful model for the success of the CPCP is the NSF-funded Newark Basin Coring Project (NBCP: 1990-1994)[1], which transformed Late Triassic chronostratigraphy by providing an astronomically calibrated geomagnetic polarity time scale for an interval of time as long and arguable at the same level of resolution as the entire Neogene. It is this magnetic polarity time scale that will serve as the template for correlation with the older part of the CPCP record, while the Late Jurassic marine magnetic anomaly record will serve a similar purpose in the younger part of the CPCP record. Since the publication of the main set of NBCP papers in 1995 – 1999 (e.g., 12-16), virtually every significant paper on chronology and correlation of the Triassic including GTS2004 and the Geological Society of America GTS2009 refers to the time scale from the NBCP. As the longest continuous, high-resolution record of cyclical climate forcing on the planet it has been cited in arguments as far ranging as calibrating Solar System chaos (17), human evolution (18), the Paleocene-Eocene boundary (19), and thermohaline circulation controls on modern climate (20). Results of the NBCP have been described in 88 papers and 130 abstracts, the subject of 11 theses, and cited in 19 papers a year on average (Web of Science). The NBCP resolved the durations of Late Triassic stages, the role of precession-related Milankovitch forcing in the Pangean tropics, correlation of the Triassic-Jurassic of Eastern North American, Morocco, and Greenland, the duration of the largest igneous event in Earth History (CAMP), and constrained the chaotic Earth-Mars gravitational system for the Triassic and more down to earth, the qualitative pattern of rift basin growth. These points have withstood every quantitative challenge (e.g., 21-24). We think that the approach to chronostratigraphy

[1] Included here based on a suggestion by the NSF panel summary to our previous preproposal.

exemplified by the NBCP has been at least mildly transformational, and we think the CPCP will be more so.

CPCP OBJECTIVES AND TECHNIQUES

Chronostratigraphy

A basic foundation for all aspects of the CPCP will be the greatly increased reliability of early Mesozoic chrono-stratigraphy developed from the cores. Three suites of chronostratigraphic tools will form this foundation: magnetostratigraphy; radio-isotopic age determination; and cyclostratigraphy. These will be registered with other observables including biostratigraphic range data, climate-sensitive lithofacies, and chemostratigraphies. The need for considerable refinements to the chronostratigraphy is illustrated by the following points:

1. Except in a nominal sense (at formation boundaries or unconformities), the stratigraphic position of the system boundaries (Permo-Triassic, Triassic-Jurassic, or Jurassic-Cretaceous) is unknown. In fact the system boundaries could be within formations (e.g., Moenave for the Triassic-Jurassic and Morrison for the Jurassic-Cretaceous).
2. Ages, both relative and absolute at a stage level are practically unknown or based on uncritical and untested correlation schemes. A prime recent example is the previously mentioned inferred age of strata in the lower Chinle Group that was long assumed to be Carnian (ca. >230 Ma) even in the recently-published geologic time scales (GTS2004 and GTS2009), but turns out, on the basis of a high precision U-Pb zircon age (11), is 10 million years too old. Many more reliable age determinations are required to establish a robust chronostratigraphic framework; this example, however, forcefully underscores the urgent need for high-precision geochronological data using multiple state-of-the-art methods.
3. Even within a given formation, it is not yet possible to place biotic assemblages from different localities in a testable temporal sequence even though most of our "knowledge" of North American vertebrate biochronology for the early Mesozoic is based on observations from strata on or adjacent to the Colorado Plateau. Thus, the fact remains that the stratigraphic understanding is pretty much still in the 19th century and incapable of being applied to useful and exciting evolutionary, climatic, or geodynamical models that have relevance not just in a regional but also in a global context. This is not for lack of effort on the part of researchers, rather it is a direct consequence of the physical limitations of the outcrop itself. There is thus an urgent need for new information that the CPCP will be designed to provide.

The Colorado Plateau region has been a classic source of early Mesozoic paleomagnetic data for North America, including some of the earliest magnetostratigraphic records for the Triassic and Jurassic (e.g., 25-37). To date, the longest Colorado Plateau polarity sequence is derived from outcrops of middle Chinle Group strata in the Petrified Forest National Park (38) that allowed a correlation to the only Late Triassic polarity timescale with independent time control - the NBCP astronomically-calibrated geomagnetic polarity timescale (39-43).

The recent U-Pb single-zircon ages from the Chinle Group in the Petrified Forest (44) and Six Mile Canyon, near Fort Wingate, NM (11) suggest that the magnetostratigraphic correlation proposed by Steiner and Lucas (38) is essentially correct. The implication is that a meaningful polarity sequence can be recovered from the Chinle Group in general, despite the low implied accumulation rate (150 m/10 Ma.=0.015 m/1 ka) and largely fluvial facies. For the Chinle to be sampled at Newarkian temporal levels (~20 ka) to avoid aliasing, the sampling should be done at the 0.3 m level, which would be hardly feasible in the crumbly outcrops of the bentonitic Chinle Group (e.g., Fig. 2), as driven home by the experience of PI Geissman with the Chinle (45). In addition, although the new U-Pb-zircon ages provide a more encouraging framework than had previously existed, the Six Mile Canyon date is from a tuff located over 140 km east of Petrified Forest to which it has been correlated lithostratigraphically, a correlation that needs to be confirmed. Both of these objectives are further motivation for coring and obtaining the appropriate level of sampling resolution.

We expect to find additional layers that are suitable for radio-isotopic dating. In this context it is important to recognize the need for the application of multiple dating methods (where feasible) to resolve any complications resulting from systematic and random bias. The core material is particularly suited to detect primary (or redeposited) volcanic material containing datable minerals, and recent studies have demonstrated that even minute samples recovered from cores, containing very small numbers of datable crystals (on the order of 10s) are perfectly adequate for high-precision age determinations (e.g. 46). Radio-isotopic age data from different isotopic systems, of variable vintage and quality, are available from early Mesozoic age strata on the Colorado Plateau, but a recent focus on acquiring single-crystal U-Pb zircon ages using the CA-TIMS technique (47) has begun to yield meaningful and precise preliminary results. However for these to be of utmost utility and maximally parsimonious they should be from the same place as other complementary data, which is typically and practically possible only in core. The cores themselves (in combination with samples from outcrops) will provide three kinds of age information: 1) depositional ages of ashes or tuffaceous sandstones providing penecontemporaneous ages (tephrochronology); 2) zircon data from redeposited volcanic layers providing maximum ages; and 3) correlation by magnetic polarity zone boundaries to age information acquired elsewhere. In addition, the cores should provide a continuous record of detrital minerals, including zircons that will be a valuable asset to provenance studies (e.g., 48,49,50). We plan to use a combination of "reconnaissance" techniques (e.g. LA-ICP mass spectrometry, in order to screen the age spectrum of zircon populations within tuffaceous deposits: 44), followed by "high-resolution" techniques including CA-TIMS applied to zircons and $^{40}Ar/^{39}Ar$ applied to K-bearing volcanic minerals.

The largely fluvial to paralic or eolian nature of most of the Colorado Plateau section, lacking independent assessments of accumulation rates, has profoundly hindered cyclostratigraphic interpretations. Available data suggest relatively low accumulations rates, so that it is unlikely that the higher frequency orbital cycles will have a faithful record. However, the eccentricity cycles, especially the 405 ky and longer eccentricity cycles (16), should leave a decipherable record of environmental change in the style of the fluvial systems, the distribution of eolianites, and in the biota from the cores (pollen, invertebrates) and outcrop (vertebrates: e.g., 51) that can be tied to the cores by magnetic polarity stratigraphy. Correlation to the astronomically-calibrated Newark record will provide a check on the local environmental response to known cyclicity. We expect that the resulting chronostratigraphic framework will be closely tied to sedimentary archives from terrestrial and marine environments elsewhere.

Biotic History and Events

CPCP cores will provide a framework for a detailed chronology of faunal and floral change for the early Mesozoic of western North America by linking the rich reservoir of surface information to the core chronostratigraphy. This will allow the recognition of the positions of major biotic events, such as the end Triassic, Toarcian, and possibly the Jurassic-Cretaceous transitions. In addition the pace of faunal and floral change can be quantified once there is a chronostratigraphy developed by the CPCP and tied to outcrop.

Crucial in this vein are correlations to continental and marine sequences from elsewhere. There are, for example, major differences in the first-order composition of continental vertebrate assemblages from different areas of the globe, despite the fact that during the Triassic and Early Jurassic the existence of Pangea meant that terrestrial vertebrate could in principle walk from nearly the south pole to the north pole. Differences amongst these faunas have been attributed to differences in ages following a paradigm outlined nearly 40 years ago by Alfred Sherwood Romer (52). However, this purely biostratigraphic argument masks the first-order pattern of real biogeographic provinciallity as illustrated by the realization that Norian age assemblages from mid-paleolatitudes from both hemispheres are very distinct from tropical assemblages from the Colorado Plateau just now recognized as of contemporaneous Norian age on the basis of new U-Pb single-zircon ages (53). Similarly, continental vs. marine correlations are in limbo. The distinctive genera-level faunal turnover at the Sonsela Member of the Chinle Group of the

Colorado Plateau was thought to be correlative with the marine Carnian-Norian boundary extinction event, but instead is mid-Norian in age. Such obfuscation makes it impossible to even recognize what the major biological patterns are, let alone test existing hypothesis of biotic change and their origin. These actual patterns of biotic change can only be revealed if an accurate and precise chronostratigraphy is in place, such as will result form the CPCP.

Environmental History

Key to the CPCP will be a continuous record of environmental change in the cores. Environmental changes are largely recorded via sedimentary, pedogenic, and biotic processes, sensitive to climatic and drainage basin (e.g., tectonic) changes. The CPCP cores will be an unprecedented archive of these processes spanning 100 million years. Key environmental observations derived from the cores will include the detailed record of depositional conditions, a pedostratigraphy (soil types), stable isotope carbonate and molecular-level biomarker chemostratigraphies (pedogenic C and organic C, O, H, etc.), and palynologies (pollen, spores, dinoflagellates). Core and downhole logs will be able to provide cross-bedding orientation for wind and current direction.

Tectonostratigraphy and Tectonic History

The position of sequence boundaries identified in outcrop can be tied to the CPCP cores, the chronostratigraphy of which will allow an assessment of the duration of associated hiatuses and proposed sequence boundaries and hence tests of their regional significance. The CPCP chronostratigraphy coupled with the temporal overlap between cores will allow quantification of accumulation rates, backstripping, and elucidation of the geographically and temporally evolving subsidence history. Coupled with the detrital provenance records this will allow a synoptic view of the dynamic evolution of epicontinental basins in this huge region.

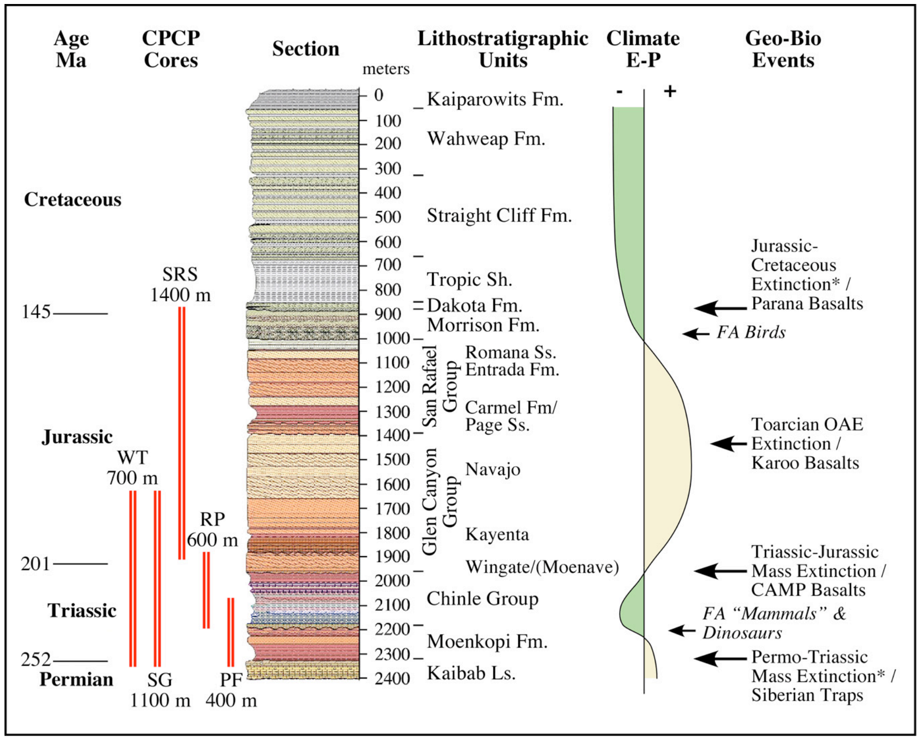
CORING TARGETS FOR *CPCP* INTERDISCIPLINARY RESEARCH

The overall coring plan, as defined at the St. George workshop in 2007, involves three long (~1 km) cores and two shorter cores intended to recover the full expression of the critical early Mesozoic transitions in clear superposition (Fig. 3). Five major stratigraphic packages were identified as key coring targets. From oldest to youngest, these are: Early to Middle Triassic Moenkopi Formation, Late Triassic Chinle Group, latest Triassic to (?) Middle Jurassic Glen Canyon Group, Middle to (?) Late Jurassic San Rafael Group, and the Late Jurassic Morrison Formation. Specific areas (but not yet sites) were selected for coring (Fig. 3: note scale)

Two cores, Ward Terrace, Arizona (**WT**) and St. George, Utah (**SG**), would span the Glen Canyon Group through the Chinle to the base of the Moenkopi Formation; a third core, from the San Rafael Swell, Utah (**SRS**), would span the top of the Morrison Formation through the San Rafael Group. These three cores embrace the overall stratigraphic goals of the project and were selected based on the identification of a succession of stratal packages variously representing sequence boundaries and/or key lithologic transitions or horizons.

Two shorter coring intervals in the Rock Point, Arizona to Lisbon Valley, Utah (**RP**) and at Petrified Forest, Arizona (**PF**: Fig. 3), are critical to tie key outcrop areas to the principal cored intervals. In the case of **RP**, the key intervals are the upper Chinle Group and the Wingate Sandstone of the Glen Canyon Group, outcrops of which have yielded paleontologic and magnetostratigraphic evidence of a potentially complete Triassic-Jurassic boundary, unknown from elsewhere in western North America. In the case of **PF**, the Chinle Group in the Petrified Forest and other areas has produced extremely rich paleontological assemblages and datable tuffs (11,54), as well as a clear magnetic polarity stratigraphy (38). These prospective core sites satisfy one of the key strategies for the CPCP, which is to intersect key horizons and packages multiple times, thus enhancing prospects of understanding their respective importance and testing the relative completeness of the sections.

Figure 3. Generalized Colorado Plateau section (Glen Canyon/ Kaiparowits Plateau, with the tentative sections proposed for coring, as discussed by the St. George workshop participants and a very generalized evaporation – precipitation (E-P) curve loosely based on climate sensitive facies. See caption to Fig. 1 for core area abbreviations. Note that the relative thicknesses of tentative drilling intervals through stratigraphic units are <u>in general different</u> than what is shown in the color section and not the same among different coring target areas.



CPCP PHASED CORING PLAN

We propose the CPCP cores be acquired in three phases, roughly in stratigraphic order that includes the initial description and scientific results of the coring consistent with IODP practice. Each phase builds on the others, hence a vision and a program, but each phase actually has stand-alone science. Depending on funding rates, each phase could be accomplished in around 18 months.

Phase 1: This inaugural phase, which could begin as soon as funding were available (Fall 2009), will obtain two cores spanning the Triassic, the Triassic-Jurassic boundary interval, and most of the Early Jurassic age strata of the Plateau.

<u>Core 1</u> - Petrified Forest, Arizona (**PF**: Figs. 1, 3), will be a roughly 400 m-long core in Petrified Forest National Park, Arizona. This core will span the Late Triassic uppermost Petrified Forest Formation and the underlying rest of the Chinle Group, and the local expression of the Early to Middle Triassic age Moenkopi Formation, bottoming in the Permian Kaibab Limestone. Working in conjunction with Petrified Forest park officials, we have already identified a suitable coring site that is located on the north edge of the park. This core would tie directly to critical extremely rich paleontological assemblages, a well-developed local lithostratigraphy and an existing (38) and developing (45) paleomagnetic polarity stratigraphy. Acquisition of this core, although modest in scope but high in profile, is selected as the first phase of this project because it will: 1) allow assessment of coring conditions in the bentonitic Chinle Group, conditions that will be experienced at often appreciably greater depths at other core sites; 2) test the lateral continuity of specific lithologically distinctive stratal intervals and magnetic polarity zones; and 3) serve as an example of an environmentally responsible coring process for other phases of the project.

<u>Core 2</u> - Ward Terrace/Moenkopi Plateau, Arizona (**WT**: Figs. 1, 3), will be a 700-800 m-long core in the Ward Terrace/Moenkopi Plateau area in the Navajo Reservation in Arizona. This core will capture the thickest known development of the Late Triassic Chinle Group as well as a significant part of the overlying Jurassic Glen Canyon Group (Moenave and Kayenta formations at Ward Terrace/Moenkopi. This area has produced the bulk of the Early Jurassic faunal remains in the Western Hemisphere. The lower part of Core 2 nominally overlaps completely

with Core 1, but will be separated by roughly ~160 km and will test the lateral continuity of the physical and magnetic stratigraphy where the Chile Formation is best developed.

Phase 2: Two complementary cores, one long, one short are designed to examine the Latest Triassic and Early Jurassic part of the record.

<u>Core 3</u> - St. George, Utah (**SG**: Figs. 1, 3), will be a ~1100 m core that will recover the basal Early Jurassic Navajo Formation of the Glen Canyon Group through the base of the Moenkopi Formation. This core complements cores 1 and 2 of Phase 1, but differs in having an erosionally truncated Chinle Group and yet a greatly expanded section of Moenkopi, Moenave, and Kayenta strata. Both the Moenkopi and Moenave appear strikingly cyclical in these areas.

<u>Core 4</u> - Rock Point/Lisbon Valley area in Arizona/Utah (**RP**: Figs. 1, 3), will be a 600 m-long core that will capture the thickest known development of the Late Triassic Chinle Group as well as a significant part of the overlying Jurassic Glen Canyon Group (Wingate formation). This core would be adjacent to the faunally richest putative Triassic-Jurassic boundary sections.

Phase 3: Core 5 - San Rafael Swell area, Utah (SR: Figs. 1, 3), will capture the entire Jurassic Morrison Formation, San Rafael Group, and Glen Canyon Group in a ~1400 m. This core will sample strata documenting the return to more humid conditions in the Colorado Plateau area, as well as the interval producing arguably the richest Late Jurassic continental biota in the world, exemplifying the culmination of dinosaur dominance.

CPCP LOGGING AND CORE-HOLE REGISTRY

A standard suite of slimhole logs will be acquired, including natural gamma, dipmeter and resistivity, along with a standard suite of pass-through core logs, including natural gamma, magnetic susceptibility, and continuous digital color images. These will allow precise depth registry of cores in the section. Of particular importance will be digital core-hole registry for azimuthal core orientation, which will be accomplished by matching features in images of the cores to those of the hole. Images may be optical for the cores and either acoustic televiewer or microscanner for the holes. The use of these and additional borehole measurements and logs will be discussed at the May meeting in Albuquerque in conjunction with ICDP Schlumberger personnel.

PERSONNEL

The initial CPCP management team consists of Olsen and 3 other PIs: John W Geissman (University of New Mexico, jgeiss@unm.edu), Dennis V Kent (Rutgers University, dvk@rci.rutgers.edu), and Roland Mundil (Berkeley Geochronology Center, rmundil@bgc.org). The scale of the project and the large span of disciplines it encompasses require PIs from other institutions and other disciplines. As shown in Table 1, the individuals involved in this project and the associated proposed ICDP project are international in scope and span a significant cross-section of the Earth Science community.

There are to be, in addition, the expected subcontracted services of DOSECC, ICDP and

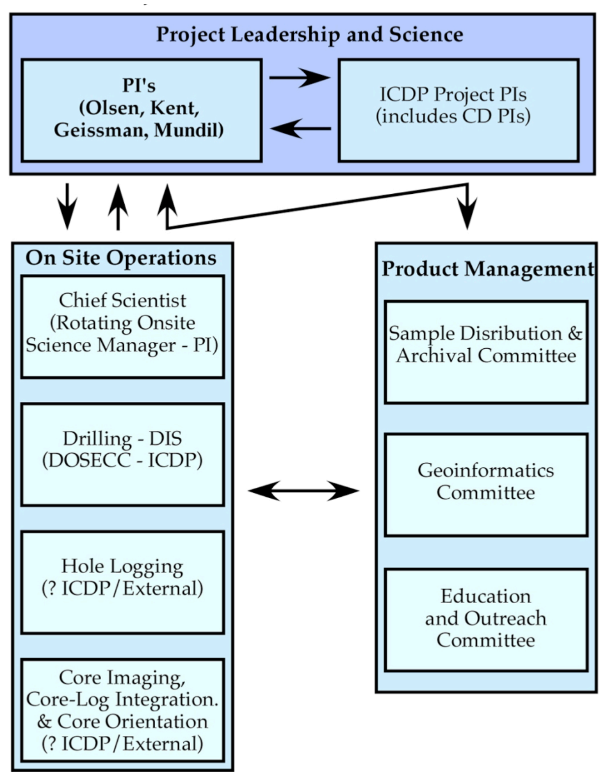


Figure 4. CPCP Project Management Structure.

CoreWall, plus a professional educational and outreach specialist. We have already obtained expressions of support from the Interior Department (encouragement to drill in the Phase 1 PF core in the Petrified Forest National Park) and Utah state survey as a potential repository for the cores. An estimated budget for all the phases of drilling, downhole logging, core logging and processing, and science support is ~$4.4M, roughly evenly divided between drilling logistics costs and science costs, or about $1.5M per phase.

CPCP MANAGEMENT

CPCP management will be led by the PIs of the NSF-funded component of the project in conjunction with the overlapping PIs of the ICDP component (Table 1), the umbrella management structure of which is shown in Fig. 4. Management of the drilling will be contracted to DOSECC, who will be engaged to conduct or subcontract drilling services. Logging will be contracted to ICDP or a local logging contractor, as appropriate. Core processing will be contracted to ICDP. Core-hole log integration will be done as part of the science effort and displayed through CoreWall. The PIs and their institutions will assume fiduciary responsibilities for permitting and subcontracting.

Other downstream tasks will be assisted by advisory and management oversight committees, including Geoinformatics (Fig. 5), Sample Distribution and Physical Archiving, and Education and Outreach (Fig. 4).

Table 1

PI[1]	Institution	Disciplines[2]	NSF (PAs)[2].
Olsen, P.E.	LDEO, Columbia University	3 6 8 9	A C G
Kent, D.V.	Rutgers University	4 8	A D E
Geissman, J.W.	University of New Mexico	4 8 10	A D F
Mundil, R.	Berkeley Geochronology Center	5	A E F
Bachmann, G.H.	Martin-Luther-Universität Halle-Wittenberg	8 10	A F
Blakey, R.C.	Northern Arizona University	8	A
Kürschner, W.M.	Universiteit Utrecht	2 3 7	A B C G
Sha, Jingeng	Nanjing Institute of Geology and Paleo.	1 8	A C G

[1] PIs for this proposal shown in bold.
[2] Key to Disciplines and NSF Program areas (PAs): 1, invertebrate paleontology; 2, paleobotany; 3, paleoclimatology; 4, geophysics; 5, radioisotope geochronology; 6, sedimentology; 7, stable isotope chemostratigraphy; 8, stratigraphy; 9, vertebrate paleontology; 10, tectonics; A, EAR-Sedimentary Geology and Paleobiology; B, EAR-Geobiology and Low-Temperature Geochemistry; C, ATM/EAR-Paleo Perspectives on Climate Change; D, EAR – Geophysics; E, EAR-Petrology and Geochemistry/SGP; F, EAR-Tectonics; G, DEB-Systematic Biology

Involvement of Students and Post-doctoral Researchers

The CPCP project will include several postdoctoral researchers and students at the undergraduate and graduate levels from different institutions, who will acquire both field related and laboratory skills, as well as experience with integrated scientific teamwork and thus enhance their training as research scientists.

CPCP CORE ARCHIVING

Cores and derivative samples will ultimately be archived in an appropriate facility. Both LDEO and Rutgers have core storage facilities and personnel. We have also been exploring the Utah Geological Survey core storage facility and have opened discussions with James Kirkland of the survey, who will be attending the May meeting in Albuquerque. Another option is the Houston Research Center of the Bureau of Economic Geology of the University of Texas at Austin (http://www.beg.utexas.edu/crc/houston.htm). The ultimate repository of the cores will be determined by the CPCP Sample Distribution & Archival Committee overseen by the PIs and in conjunction with NSF.

CPCP EDUCATION AND OUTREACH

Given the spectacular venue and the deep public interest in climate and Mesozoic evolution the educational and outreach potential of the CPCP is enormous. To be serious about leveraging this potential, and to produce novel products useful for the education community, it will be necessary to hire a professional educational and outreach specialist who will be responsible for the planning and production of these products, and who will chair the Education and Outreach Committee (Fig. 4), overseen by the PIs. This specialist will coordinate and leverage education and outreach activities related to the project, *as mandated by NSF*. There are a very large number of National Parks and Monuments located in the general area that our CPCP is ultimately intended to cover, and thus emphasizing the tremendous opportunities for education and outreach to a very large number of individuals.

LONG TERM USES OF HOLES

Although the primary objectives of the CPCP can be accomplished by coring, logging and then plugging the holes as soon as possible, there may be other science that can conceivably be carried out that requires open holes, for example, installation of long-term observatories, hydrological experiments, etc. The CPCP project leaders are receptive to additional uses of the holes, which would have to be dealt with on a case-by-case basis and be consistent with land permitting and other restrictions and regulations.

INTEGRATING AVAILABLE SURFACE DATA AND CORES

A major goal of the CPCP is to provide the impetus for integrating the vast amount of existing information and resources into what we anticipate will be a reliable and high-resolution framework.

Searches of available core databases (e.g., http://ugs.utah.gov/emp/ucrc/index.html) have not revealed the existence of a series of cores that remotely approach even one of the cores proposed here. However, some relatively short cores do exist that may complement our proposed cores, by being very close to important sources of surface data. The full proposal will provide more complete discussion of these cores and any existing studies on them. Although these cores will be a valuable assets to the overarching goals of the project they cannot be used as a substitute for CPCP coring because they were not acquired in optimal locations (e.g., Petrified Forest, Ward Terrace on native lands) and most importantly lack the critical core orientation information needed for paleomagnetic and paleocurrent analysis. In fact, the value of existing short cores and downhole logs may only be fully realized within the regional framework ultimately provided by the proposed CPCP coring.

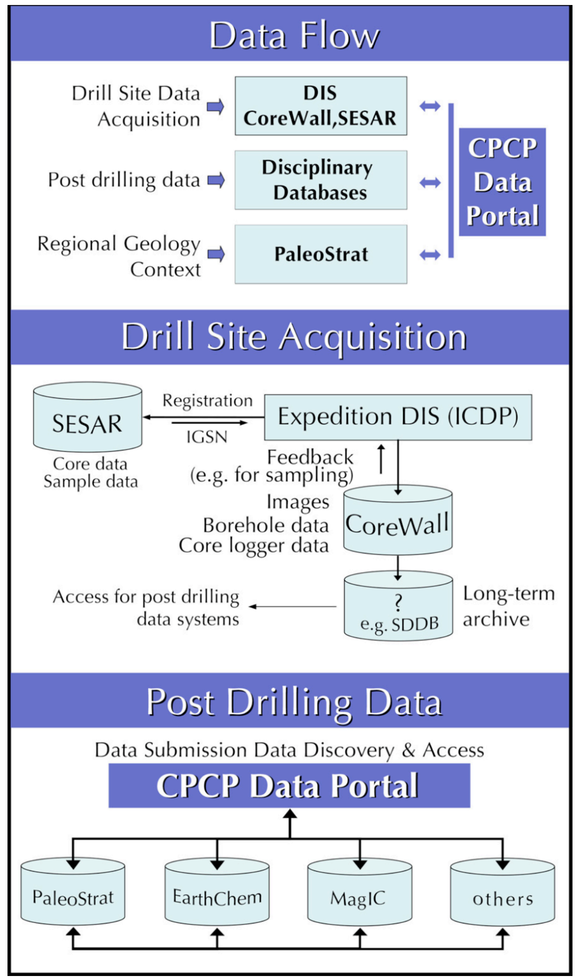


Figure 5. CPCP Geoinformatics (from ref 3).

BUDGET OUTLINE

We have obtained preliminary estimates for coring and logging at the five proposed CPCP sites from DOSECC and ICDP. We envision the CPCP as consisting of the three drilling phases, the actual time-scale of which is contingent on funding exigencies, rather than drilling technology logistics or hole location. We further assume that core logging will be of comparable cost to downhole logging, and that science costs (including travel and accommodation at drill sites, geoinformatics, education and outreach, transportation of cores to repository) distributed over some 10 PIs and collaborators (the need for which arises from both the scale of the project as well as NSF and ICDP guidance) will be comparable to first-order drilling plus hole and core logging and processing costs. These assumptions provide the following phased estimated project costs[1]:

Phase:	Cores	Drilling	Logging[2]	Core Logging & Processing[3]	Science[4]
Phase1:	Petrified Forest	$232,000	$32,000	$32,000	$296,000
	Ward Terrace	$331,000	$32,000	$32,000	$395,000
Phase 2:	Saint George	$427,000	$32,000	$32,000	$491,000
	Rock Point	$303,000	$32,000	$32,000	$367,000
Phase 3:	San Rafael Swell	$577,000	$32,000	$32,000	$641,000
Subtotals		**$1,870,000**	**$160,000**	**$160,000**	**$2,190,000**
Total: $4,380,000					

[1]A significant fraction of these estimates may be born by an ICDP funded project, but the mix of funding sources is difficult to estimate at this time.

[2]Assumes ICDP equipment transportation costs to and from Potsdam for each phase.

[3]Core logging and processing includes imaging and physical property data and core hole integration.

[4]Science includes the supervision and participation on site as well as oversight of data collection including initial sampling for paleomagnetism and fossils, responsibility for initial core description following the format of the initial reports of IODP. The final year is to produce the "scientific results" publications for the project. As we have framed it here "Science" does NOT include support for graduate students and post-docs, and educational-outreach specialist support which will be added in the budgets for the full proposal. Obviously this will be presented in much more detail in a full proposal.

[5]Publication costs of the initial reports and scientific results we outline above, should be covered by DOSECC and ICDP and are not included. Other costs such as possible core-hole software development are difficult to assess at this time, but will be included in full proposals.

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