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Scientific Drilling
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Scientific drilling and the evolution of the earth system: climate, biota, biogeochemistry and extreme systems

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Abstract. A US National Science Foundation-funded workshop occurred 17–19 May 2013 at the University of Oklahoma to stimulate research using continental scientific drilling to explore earth's sedimentary, paleobiological and biogeochemical record. Participants submitted 3-page "pre-proposals" to highlight projects that envisioned using drill-core studies to address scientific issues in paleobiology, paleoclimatology, stratigraphy and biogeochemistry, and to identify locations where key questions can best be addressed. The workshop was also intended to encourage US scientists to take advantage of the exceptional capacity of unweathered, continuous core records to answer important questions in the history of earth's sedimentary, biogeochemical and paleobiologic systems. Introductory talks on drilling and coring methods, plus best practices in core handling and curation, opened the workshop to enable all to understand the opportunities and challenges presented by scientific drilling. Participants worked in thematic breakout sessions to consider questions to be addressed using drill cores related to glacial–interglacial and icehouse–greenhouse transitions, records of evolutionary events and extinctions, records of major biogeochemical events in the oceans, reorganization of earth's atmosphere, *Lagerstätte* and exceptional fossil biota, records of vegetation–landscape change, and special sampling requirements, contamination, and coring tool concerns for paleobiology, geochemistry, geochronology, and stratigraphy–sedimentology studies. Closing discussions at the workshop focused on the role drilling can play in studying overarching science questions about the evolution of the earth system. The key theme, holding the most impact in terms of societal relevance, is understanding how climate transitions have driven biotic change, and the role of pristine, stratigraphically continuous cores in advancing our understanding of this linkage. Scientific drilling, and particularly drilling applied to continental targets, provides unique opportunities to obtain continuous and unaltered material for increasingly sophisticated analyses, tapping the entire geologic record (extending through the Archean), and probing the full dynamic range of climate change and its impact on biotic history.

1 Scientific rationale

Over the past decade, numerous workshops and study groups within sedimentary geology, paleoclimatology, and paleobiology have repeatedly highlighted the importance of continental scientific drilling to address important science questions in climate and linked earth systems (e.g., the US National Science Foundation (NSF)-supported GeoSystems, DETELON, and Transitions workshops, and the US National Research Council (NRC) reports on Deep-Time Climate and Climate and Human Evolution, Soreghan et al., 2003, 2005; Montanez and Soreghan, 2006; Bottjer and Erwin, 2010; NRC, 2010, 2011; Parrish, 2012). In recognition of this sustained surge of interest, a workshop was held on 17–19 May 2013 at the University of Oklahoma to identify high-priority targets for scientific drilling aimed at assessing critical questions related to paleoclimate, paleobiology, and extreme events in earth's history. The objectives of the workshop were to (1) develop a community of researchers interested in using scientific drilling for stratigraphic targets to answer questions about earth system evolution, (2) identify topics and drilling targets of broad scientific interest, and

(3) offer researchers direction on how to develop compelling drilling proposals, how to evaluate and plan logistical issues related to drilling, and how to develop a funding plan for drilling strategically. The ultimate intent is to galvanize research teams to move forward with future proposals involving continental drilling.

2 Workshop format and proceedings

All interested researchers were invited to submit a brief pre-proposal identifying a viable continental scientific drilling target to examine questions of scientific importance in the areas of paleoclimate, earth history, stratigraphy, paleoecology and/or paleobiology from any interval of earth history. The 41 participants submitted 30 pre-proposals that articulated scientific themes in earth, and evolutionary and ecological history spanning geologic time. Participants discussed the role of drill core studies in earth/life history and identified locations where critical questions can best be approached.

The workshop included plenary sessions in which invited speakers addressed topics of overarching interest in scientific drilling. Additionally, principal investigators for each submitted pre-proposal presented a 5 min talk outlining the science drivers, significance, and rationale to enable all participants to grasp the vast breadth of proposed projects, which span the geological record from the oldest sedimentary rocks to modern lakes, and range geographically from pole to pole (Fig. 1 and Appendix Table A1).

Through the rest of the 2.5-day workshop, breakout groups identified critical science questions in earth history that can be assessed with drill core data, and evaluated discipline-specific drilling problems. Themes were chosen to explore earth history processes across timescales, and to consider how drilling can inform our understanding of those events.

3 Glacial–interglacial and icehouse–greenhouse transitions and biotic consequences

Earth's atmosphere reached a historic threshold in May 2013, when sustained atmospheric CO_2 levels exceeded 400 ppmv for the first time in human history, and the first time in approximately 3 My (Beerling and Royer, 2011). Passing this threshold offers the opportunity to engage the public in climate transitions in earth history, and the earth system linkages accompanying these transitions, such as changes in biodiversity and ecosystems during glacial–interglacial transitions. To this end, much research has focused on, in particular, the transition from the Last Glacial Maximum (LGM) to our current interglacial, as well as other transitions within the Pleistocene (e.g., Fawcett et al., 2011; Ivory et al., 2011; Brigham-Grette et al., 2013). These studies provide important insights into earth's climate behavior at a very high-resolution (millennial to annual) scale that are critical for grasping earth's recent climate behavior and informing deep-time studies of glacial–interglacial transitions. It is equally important, however, to understand the potential diversity of glacial–interglacial behavior throughout earth's record. What insights can we gain into climate behavior by examining Paleozoic and Neoproterozoic glacial–interglacial and – at a broader scale – so-called "icehouse–greenhouse" transitions (e.g., Bao et al., 2008; Fike et al., 2006; Kennedy et al., 2008; Mills et al., 2011; Barham et al., 2012)? Research over the past decade has highlighted the occurrence of major biological turnovers in earth history accompanied by changes in greenhouse forcing, ocean acidification and climate change (e.g., Jiang et al., 2009; Johnston et al., 2012; Katz et al., 2008). Continental drilling can provide high-resolution records of these climate and life transitions. Looking back into the period of the Cenozoic when atmospheric CO_2 levels differed from today provides estimates of future climate change and ecological response. The deep past also highlights abrupt change, the information necessary to test how well climate models will predict abrupt changes in the coming centuries (Valdes, 2011). The Paleozoic and Neoproterozoic icehouse–greenhouse transitions provide particularly extreme examples that, albeit poorly constrained, span evolutionary events such as the origin of animals and terrestrial ecosystems central to our existence.

4 Records of long-term evolution events and extinctions

Developing reliable records of evolution and extinction requires access to high-resolution geochronological control, and also unambiguous superposition, which is a great benefit of drill core over purely outcrop studies. Furthermore, both micro- and macrofossil records are critical for assessments of life transitions, so linked outcrop and coring studies are critical for questions targeting these issues. In addition, a core provides access to unweathered material critical for geochemical analyses, including organic (e.g., biomarker) and potentially fossil DNA studies, which can shed light on ecological (including catastrophic) events and evolutionary history (e.g., Clyde et al., 2013). Effective strategies for obtaining sufficient sampling across critical intervals include planning for multiple shallow cores across a series of dipping strata, or targeted coring of key intervals defined by nearby outcrop studies. Drill cores eliminate the human bias of outcrop-based studies by taking an essentially random sample of local sedimentary facies through time and providing a continuous (albeit not necessarily complete) stratigraphic record across biotic transitions.

5 Records of major biogeochemical events in the oceans

The first oxygenation of the atmosphere and ocean is a critical biogeochemical event in earth history. This transition

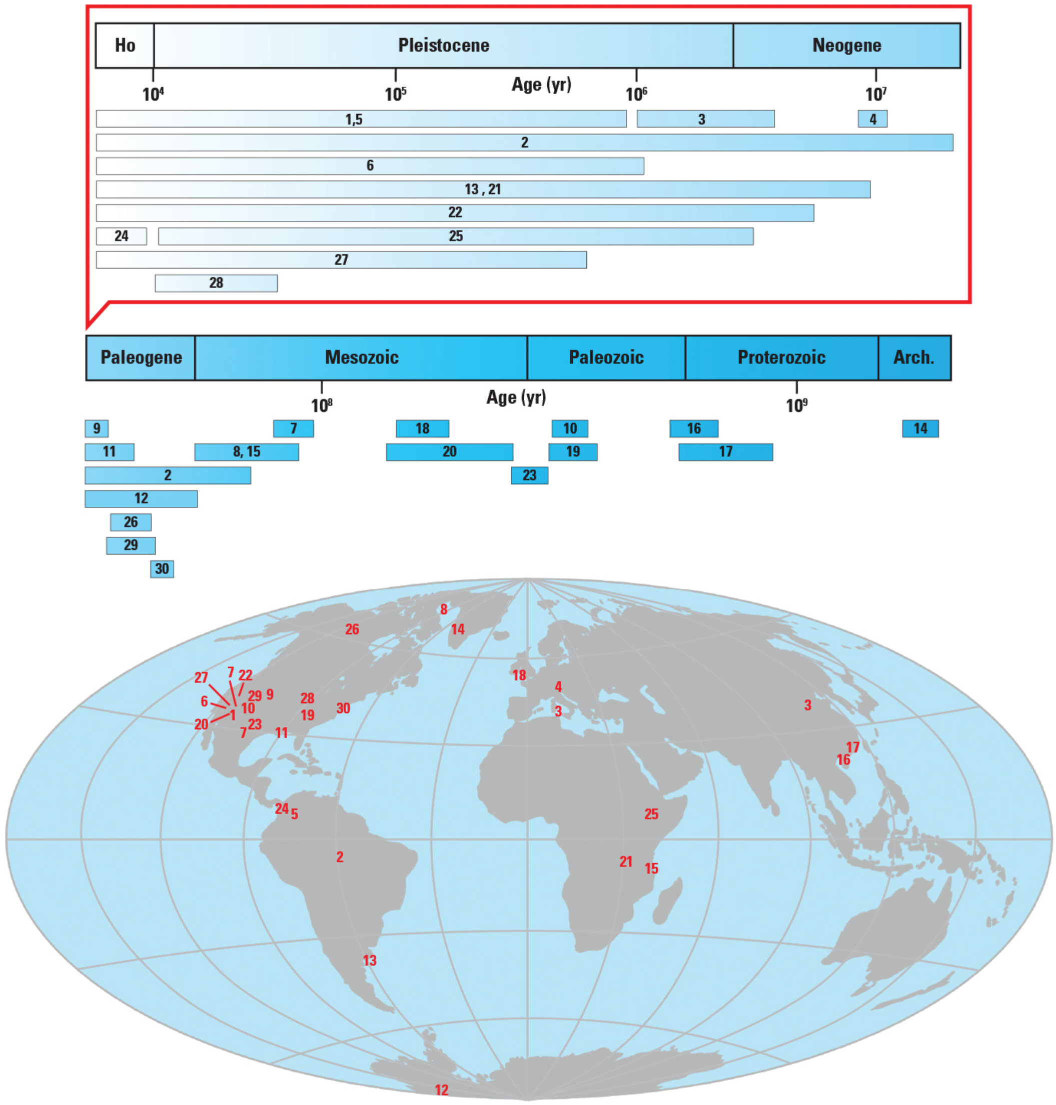

Figure 1. Geologic timescale (above) and global map (below) listing the (enumerated) 30 drilling project pre-proposals submitted to this workshop. The gray to black bars show the various timescales of the projects proposed. Note that the upper timescale is an enlarged version of the Holocene through Neogene interval, to portray projects proposed for this "near-time" slice. See Appendix Table A1 for the titles of the proposed projects (key to the numbers in the bars in this figure).

was a prerequisite to the appearance of eukaryotic organisms and ultimately to emergence of animals and their major radiation – the Cambrian explosion. Many evolution and extinction events, especially those in earth's Precambrian record, are tied either directly or indirectly to oxygen availability. Research on Precambrian earth systems has experienced a resurgence of interest as new geochemical tools have come online to assess these events – especially various redox-sensitive metal tracers and their isotope systematics (Buick, 2007; Scott et al., 2008; Partin et al., 2013; Reinhard et al., 2013) and basin-scale reconstructions of redox state (Sperling et al., 2013a, b) that enable tracking of oceanic oxygen levels.

Collectively, this work demonstrates that the view of a single large oxygenation event yields to a model of dynamic rises and falls in oxygen levels. This requires that the precision of our proxies increase and/or expand to meet the constraints placed by physiology (microbial and metazoan) in order to understand earth's major biological transitions (Sperling et al., 2013). Improved understanding of Precambrian oxygenation events also informs views of the global ocean redox landscape during Phanerozoic anoxic events (Lyons et al., 2009). Drill-core records provide a unique and fundamental opportunity to assess timing, duration, and possible drivers of these events, owing to their capacity to provide both continuous and, critically, unweathered (unoxidized) material. Beyond the ocean, coring of paleosols sheds light on the spread of oxygenation to continental systems and a direct measure of atmospheric oxygen. Further, refined data on ancient oxygen conditions inform our view of ocean deoxygenation scenarios under recent human influences, such as lower oxygen solubility in warmer surface waters and elevated riverine nutrient delivery (e.g., Falkowski et al., 2011).

Although atmospheric and oceanic oxygenation are tied directly or indirectly to many of the most fundamental biogeochemical events in earth history, other events best accessible through continuous and unweathered cores include ocean-acidification events (e.g., the Permian–Triassic and Paleocene–Eocene Thermal Maximum, as potential analogs for earth's near-term future, e.g., Zachos et al., 2005), the C_3–C_4 vegetation transition, and the effect on global carbon cycling linked to the radiation of diatoms and calcareous nannoplankton more recently (Katz et al., 2005). Drill cores can also provide links between oceanic and continental records to assess the role of continental processes such as nutrient recycling during times of oceanic anoxia, for example, and to evaluate the "buffering" capacity of the oceans at times of high $p\mathrm{CO}_2$.

6 Core records of reorganization of earth's atmosphere

Earth's atmosphere has evolved and reorganized through time as reflected by changes in (1) chemical composition, such as the presence and proportions of O_2, CO_2, and SO_2, (e.g., Kump, 2008; (2) aerosol composition, including the presence and proportions of mineral dust and black carbon, and – speculatively – dimethylsulfide and O_3 (Wolff et al., 2010; Diessel, 2010; Bisiaux et al., 2012); and (3) circulation, such as the position of the Intertropical Convergence Zone (ITCZ), presence and strength of monsoons, and storm intensity (e.g., Ito et al., 2001; Frappier et al., 2007). Key events in atmospheric reorganization include both Precambrian and Phanerozoic shifts in (1) O_2 in response to evolutionary radiations of photosynthesizers (Canfield et al., 2007); (2) CO_2 in response to biological, tectonic, and weathering drivers (Bergman et al., 2004; Berner, 2006); and (3) atmospheric circulation (e.g., shifts from zonal to monsoonal circulations associated with continental positions and mountain elevations) (e.g., Parrish, 1993; Clift et al., 2008). Proxies and indicators useful to reconstructing atmospheric composition include various approaches to measuring, for example, atmospheric CO_2 such as paleosol carbonate isotopes, leaf stomatal densities, and bryophyte photosynthetic fractionation (e.g., Royer et al., 2001; Fletcher et al., 2008). Proxies and indicators exist for temperature, moisture, and transport, such as various isotopes, biomarkers, and eolian provenance indicators (e.g., Soreghan et al., 2002; Eglinton and Eglinton, 2008; Severman and Anbar, 2009; Pullen et al., 2011; Woltering et al., 2011; Zambito IV and Benison, 2013), all of which benefit from pristine material offered by drill cores. Target records include loess deposits, paleosols, lacustrine and epeiric marine strata, and facies conducive to preservation of leaf waxes and associated biomarkers (e.g., Brigham-Grette et al., 2013). Drilling of continental records is particularly needed to assess the range of responses on the continents to global change. The integration of proxy results to constrain climate models offers the potential to refine predictions for future sea level and agricultural productivity under higher levels of greenhouse gases.

7 *Lagerstätte* and exceptional fossil biota in cores

Some continental cores preserve fossil *Lagerstätten* (exceptionally preserved fossil biota) of microfossils or very small macrofossils (Pearson et al., 2006; Wendler et al., 2011; Wolfe et al., 2006). Microfossil *Lagerstätten* in cores are especially useful for yielding estimates of true diversity (Jiménez Berrocoso et al., 2010). Cores can also provide critical sedimentary and geochemical context for *Lagerstätten* of larger fossils or extraordinarily preserved sedimentary deposits (e.g., varves or tidalites) that give detailed records of environmental conditions. Access to such deposits via core recovery facilitates high-resolution geochronological correlation and provides well-preserved samples with no weathering overprint. Analyses of *Lagerstätten* in the context of continuous core can reveal biotic sensitivities to environmental change and shed light on kill mechanisms during extinction events. As such, cores containing fossil *Lagerstätten* or exceptional sedimentary deposits offer key insights on the evolution of earth's system states over time.

8 Drill core records of vegetation and landscape change through time

Landscapes reflect the combined effects of physical, biological, and (since humans evolved) anthropogenic influences occurring on earth's surface over time, and thus preserve a 4-D record of processes affecting a sedimentary basin (Driese and Nordt, 2013). Vegetation and landscape changes are identified through composition of and changes in, for example, fossil flora (e.g., leaves, wood, seeds, flowers, root traces, phytoliths, palynomorphs, charcoal, etc.), trace fossils, paleosols, thermochronological signatures, and various isotopic records. The geologic record of landscapes is best addressed by an approach that combines outcrop studies (where feasible) with drilling – the former to access records such as megaflora, and the latter to enable geochemical analyses of pristine material (e.g., Retallack and Dilcher, 2011).

Outstanding issues in landscape analysis that could benefit from systematic inclusion of drill core records include (1) linking sediment sources to sinks, (2) characterizing extinct soil types and ecosystems, (3) determining spatial variability in fossil landscapes, and (4) determining uplift histories (potentially rates and reliefs and even paleoelevation through time now accessible by detrital thermochronology). Ultimately, core analyses could enable systematic analysis of the evolution of earth's critical zone through time. With regard to landscape analysis, even the surfaces encountered in cores – the hiatal events – provide key data for landscape reconstruction (e.g., Nordt et al., 2013; Sauer et al., 2013). Beyond the deep-time geological record of landscape change, the recent anthropogenic record offers insights into landscape changes wrought by pre-industrial human transformations, especially the commonly recognized but poorly characterized history of anthropogenic deforestation and fire use (Ruddiman, 2013). Cores may allow us to distinguish the onset timing and magnitude of human-induced fire, for example in the fire-adapted ecosystems of the African miombo or Australian woodlands.

9 Paleobiology

Recovery of adequate macrofossil assemblages and fragile or flat biota in cores is possible, and could be maximized in novel ways not available to paleobiologists relying on a single core. For example, multiple cores taken along a transect, or through recovery of long lateral sections via horizontal drilling of fossiliferous units, and inclusion of outcrop studies can best account for assemblage characteristics. The usefulness of paleobiologic records, especially if biogeochemical analyses are envisioned, can be compromised by potential contamination, so logistical issues are critical, including choice of lubricants, drilling fluids, and core recovery techniques (e.g., use of liners, etc.), as well as post-drilling core handling and curation (cutting, sieving). A processing technique should be planned so as to avoid inadvertent destruction of macro-remains. Use of analytical methods such as X-rays and CT scans can be extremely helpful for imaging macrofossils as well as traces in 3-D and in situ, to reveal the occurrence of thin or small specimens that might be enigmatic in 2-D slab cuts. Much as yet unexplored potential exists in the integration of paleobiology with genomics/molecular genetics/protenomics in unweathered drill core samples (Cohen, 2011).

10 Stratigraphy/sedimentology

All stratigraphic/sedimentary studies benefit from recovery of pristine, continuous records, uniquely offered by drilling. In addition, a core provides critical tie points that link outcrop with seismic imaging data sets. This is essential for building robust, basin-wide chronostratigraphic frameworks that ensure reproducible correlations. The spatial perspective, coupled with linkages to paleoecological research in complex terrestrial environments, suggests that multiple drill cores or core transects may be required to address interdisciplinary research objectives in some basins. Key subject areas for science questions that can be addressed in the realm of stratigraphy and sedimentology include large-scale basin geodynamics and source-to-sink issues (e.g., sediment budgets, long-term erosion rates, subsidence analysis, fault evolution), including biogeomorphological feedbacks, such as source–sink systems at major earth/life and climatic transitions. For example, fluvial records show a fundamental shift in stratigraphic architecture associated with major phytogeographic changes (Ward et al., 2000; Davies and Gibling, 2009) – an important set of transitions in the Phanerozoic earth system (atmosphere–biosphere). At finer timescales, cyclostratigraphy applied to continental drill core holds promise for casting new light on the dynamics of earth's orbit (e.g., Olsen and Kent, 1999). Cyclostratigraphic insights span timescales beyond the well-known application to Milankovitch periodicities, including diurnal records that reveal profound changes in earth's speed of revolution and interactions among the Earth–Sun–Moon system. Drill core stratigraphic records likewise hold strong potential for preserving sedimentary evidence of catastrophic "events" important to the evolution of the earth system, including ancient storms, earthquakes, and volcanoes. Drill core studies applied to such issues can be greatly augmented through the collection of ancillary geophysical logs for color spectra, neutron, formation imaging and geochemical element logging.

11 Geochemistry/geochronology

Best practices for maximizing recovery of geochemical and geochronological information from drill cores include (1) obtaining core orientation for paleomagnetic and fabric studies, (2) minimizing variation in core description by involving a minimal number of observers, (3) routine XRF and UV scanning (highlighting occurrences of, for example, tephras), and measurement of downhole temperatures (which can shed light on incipient diagenesis, and augment auxiliary databases relating to, for example, trends in climate warming and heat flow).

The importance of special handling to maximize recovery of geochemical and geochronological data merits creation of a study committee to create a best-practices document to detail contingency preparation (long-term core sample storage for analyses using future technologies), and how to strategize recovery of information with cost-effectiveness. From the initial drilling to core handling and curation, care should be taken to record all "metadata" associated with core capture and subsequent treatment – any action that could potentially impact future analyses, such as (1) characterization of all drill site fluids and lubricants used, (2) sampling of pore fluids, and (3) subsequent storage conditions of the core (e.g., dry at ambient temperature, dry at 4 °C, frozen, or stored in an N_2 (anoxic) atmosphere). Such "best practices" are applicable to many data sets beyond geochemistry and geochronology.

Potential geochronological approaches useful for sedimentary core material include U–Pb (tephras, detrital zircons), Ar–Ar (feldspars from tephra), Re–Os (organic-rich shales), Lu–Hf (phosphorites), Pb–Pb (carbonates, primary and secondary), and Sr isotopes. Other useful methods include low to moderate temperature thermochronology using U–Th–He, and Ar–Ar, and thermochronology/geochronology (e.g., C-14, U-series disequilibrium, thermo-luminescence, cosmogenic nuclides, etc.). Exciting novel geochemical proxies include redox metal and isotopic approaches to assess productivity, methods to assess paleo-redox conditions, temperature, pH and $p\mathrm{CO_2}$, weathering and hydrothermal fluxes (e.g., Anbar and Rouxel, 2007; Severmann and Anbar, 2009; Frank, 2011; Pufahl and Hiatt, 2012). Many of these techniques depend on the acquisition of pristine materials best obtained from core samples.

12 Science drivers

Closing discussions at the workshop focused on the overarching science drivers for which drill core can make a difference in our understanding of the evolution of the earth system. The key theme, holding the most impact in terms of societal relevance, is that of climate change and biotic evolution. More specifically, how do transitions in climate drive biotic change, and what role can unweathered, stratigraphically continuous scientific drill cores play in advancing our understanding of this linkage, and the relevant processes (e.g., Jaramillo et al., 2010)? In the face of growing concerns over the current pace and possible future impacts of climate change, we must understand how climate changes archived in earth's past have affected life (i.e., to assess the biotic tolerances of environmental changes) at all timescales. This is best done by focusing on times in the geologic past that capture transitions in climate states (e.g., Parrish et al., 2012). Tied to this theme, albeit at longer timescales, is research on climatic–tectonic feedbacks, to understand the full range of how climate has varied on earth.

Other areas that could be addressed by drilling include research on the function and history of the "geodynamo", and long-term solar-system dynamics – topics that arose from consideration of the centrality of geochronology to all other endeavors relating to scientific drilling of stratigraphic targets. Pursuit of these areas could ultimately lead to a fully calibrated astrochronology through the Paleozoic.

13 The unique role for continental drilling

Scientific drilling, and particularly drilling applied to continental targets, provides truly unique opportunities in earth science research. Perhaps the key opportunities are the abilities to (1) obtain pristine material suitable for geochemical and (potentially) paleogenomic analyses; (2) obtain a continuous stratigraphic record with minimal sampling gaps, especially in depocenters poorly exposed in outcrops; (3) tap earth's entire geologic record (extending through the Archean); and (4) tap the full depth of the dynamic range of climate change (see below).

Outcrop-based studies are and will continue to be fundamental for research on earth-system evolution. However, as our abilities to extract climatic and biotic data from the past have grown, most notably from an abundance of novel geochemical approaches, the need for pristine sedimentary samples has become paramount. Indeed, the very "shelf life" of cores may be more limited than previously recognized, owing to the emergence and growth of analyses utilizing organic biomarkers, redox-sensitive transition metals, and DNA analyses, all of which rely on availability of fresh, unoxidized material. The potential utility of core for such analyses becomes compromised the moment the core is exposed to the atmosphere. Addressing this issue, and especially the possibility of archiving material for use in perpetuity, may require future workshops on novel approaches to core archival. These could include the storage of sample splits in anoxic conditions. In addition to providing pristine sample material, drill cores have long been recognized as the primary means to obtain a continuously sampled section, and – where the drilling site is chosen to maximize it – to obtain a stratigraphically continuous section. The latter is particularly critical in the case of basin depocenters in tectonically stable regions lacking outcrop. The value of such archives only increases as new tools for continuous core analysis become routine, including, e.g., whole-core CT scans, XRF scans, etc.

The rich potential offered by drilling the continental record remains vastly underutilized. Ocean drilling has provided paradigm-shifting insights into our understanding of the earth system (e.g., deMenocal, 1995; Haug et al., 2001; Zachos et al., 2005; Sluijs et al., 2006), but is limited by subduction to (primarily) the Cretaceous and younger record. Continental drilling lays open earth's archive extending to the far depths of deep time preserved on the planet – the Archean. Vast stores of undeformed sedimentary sections dating from throughout the Phanerozoic and into the Precambrian lay preserved across the stable cratons of the world.

Perhaps most critically, albeit a great treasure of climatic data, the ocean record exhibits a limited dynamic range of response to climate change in that the effects are buffered by the vastness of the ocean system. In contrast, the continental record exhibits an extremely broad range of environmental and climate states, capturing local, regional, and global conditions tied to the history of life on land, in freshwater, and in marginal seas: the full dynamic range of climate change. In light of the land-based existence of our species, documenting the regional and even local responses to global changes in continental (and epeiric sea) regions is critical to documenting the biotic responses to climate change.

Table A1. Key to proposed drill sites map (see Fig. 1).

1	Stoneman Lake, Arizona Paleoenvironments Drilling Project (proponents: R. S. Anderson, P. Fawcett, E. Brown, J. Werne, D. Kaufman, G. Jiménez-Moreno, J. Geissman, M. Ort)
2	Trans-Amazon Drilling Project: History of the Neotropical Rain Forest (proponents: P. Baker, S. Fritz, D. Battisti, B. Horton)
3	African Late Pleistocene Biotic and Environmental Revolution (ALBER) (proponents: R. Bernor, M. Fortelius, L. Rook, X. Wang, G. Woldegabriel)
4	Drilling the Late Miocene Höwenegg *Lagerstätte*, Hegau, southern Germany (proponents: R. Bernor and A. Kaufman)
5	The Lago de Tota Drilling Project (proponents: B. Bird, J. Escobar, P. Pollisar, M. Velez)
6	Kings River Alluvial Fan Terrestrial Drilling (KRAFTD) (proponents: M. Brady, C. Johnson, P. Van de Water, B. Weinman)
7	Drilling to Elucidate Causes of Extinction During the Oceanic Anoxic Event at the Cenomanian/Turonian Boundary (proponents: T. Bralower, M Arthus, M. Fantle, L. Kump, M. Follows, J. Sepulveda, R. Leckie, B. Sageman)
8	The Arctic in a Greenhouse World: Drilling within a Cretaceous Deep Time Observatory (proponents: K. Chin, D. Harwood, R. DeConto, M. Pagani, and S. Warny)
9	The Terrestrial Greenhouse to Icehouse Transition (Eocene–Oligocene) of the Northern Great Plains (proponent: D. Terry)
10	Pennsylvanian Cyclothems of the Paradox Basin (proponents: B. Dyer and A. Maloof)
11	Project EOCore (proponents: R. Fluegman, J. Grigsby, K. Miller, J. Wright, M. Katz, B. Wade)
12	ANDRILL Coulman High Project: CO_2, Thresholds of Past and Future Ice Sheet Behavior (proponents: D. Harwood, R. Levy, B. Luyendyk, F. Rack, A. Shevenell, ANDRILL Science Committee)
13	Argentina Loess Sequences (proponent: C. Heil)
14	Eoarchaean Tidal Signatures in the > 3.7 Ga Isua Greenstone Belt, Greenland (proponents: L. Hinnov and N. Nofffke)
15	Cretaceous Microfossil *Lagerstätte* from Coastal Sections in Tanzania (proponents: B. Huber and K. MacLeod)
16	Drilling the Ediacaran–Cambrian Transition in South China (proponents: A. Kaufman and S. Xiao)
17	ONSET: Observing the Neoproterozoic Snowball Earth Transition (proponents: F. Macdonald, M. Schmitz, C. Dehler, T. Bosak, P. Cohen, S. Pruss, D. Johnson, A. Brandon, R. Simmons, K. Karlstrom, D. Condon, G. Halverson, A. Prave, and M. Zhu)
18	US Participation in the “Return to Mochras: A New Global Standard for Early Jurassic Earth History” (proponents: K. Miller, J. Browning, L. Hinnov, and K. Williford)
19	“Blue Sky” Geology-Core Drilling in the Unstudied Grove Center Late Paleozoic Outlier in Western Kentucky (proponents: S. Elrick and W. J. Nelson)
20	Colorado Plateau Coring Project (proponents: P. Olsen, D. Kent, J. Geissman, R. Mundil, G. Bachman, R. Blakey, W. Kürschner, and J. Sha)
21	Environments of Tropical East Africa since the Late Miocene: Continental Drilling in Lake Tanganyika (proponents: M. McGlue, J. Russell, E. T. Brown, I. Castañeda, A. Cohen, C. Ebinger, S. Ivory, T. Johnson, C. Scholz and members of the 2012 PAGES/NSF East African Drilling Workshop)
22	Recovering a 3 to 5 Million Year Paleolimnological Record from Butte Valley, California (proponents: A. Smith, E. Ito, J. Werne, J. Feinberg, C. Whitlock, and D. Adam)
23	Documenting Tropical Climate During Earth’s Last Icehouse Collapse: The Permian of Western Equatorial Pangaea (proponents: G. Soreghan, K. Bennison, W. DiMichele, T. Rasbury, N. Tabor, and N. Heavens)
24	Drilling Through Holocene Fossil Reefs on the Caribbean Coasts of Panama and Columbia to Document Geochronology, Pristine Reef Paleobiology and Paleo-sea-level (Geophysical) Significance in an Unstudied Subequatorial Region (proponents: M. Toscano, J. González, A. O’Dea, J. Lundberg, I. Correa, and H. Mora)
26	Potentially Extensive Plio-Pleistocene Earth System Records at Yardi Lake (proponents: G. Woldegabriel, S. Ambrose, B. Asfaw, A. Asrat, R. Bernor, J.-R., Boissieri, T. Endale, H. Gilbert, W. Hart, H. Lamb, P. Renne, F. Schäbitz, M. Trauth, and T. White)
26	Post-eruptive Maar Sediments from the Giraffe Kimberlite: Potential for a World-Class Continental Record of Middle Eocene Paleoclimate from Northern Canada (proponents: A. Wolfe, and P. Siver)
27	Building a High-Resolution History of Mono Lake from yesterday to 760 kyr BP (and beyond?) (proponents: S. Zimmerman, S. Hemming, A. Deino and Team Mono)
28	Records of Glacial Advance, Retreat, and Large-Scale Deglacial Flooding in Central North America (proponent: B. Curry)
29	The Early Eocene Lacustrine Green River Formation (proponents: M. Machlus, S. Hemming and S. Bowring)
30	Outpacing the Anthropocene: The case for a rapid release of carbon at the Paleocene–Eocene Thermal Maximum (proponents: M. Schaller and J. Wright)

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