TRANSITIONS

The Changing Earth-Life System—Critical Information for Society from the Deep Past
FOREWORD

Over more than a decade, the sedimentary geology and paleontology communities have held workshops and provided input to numerous National Research Council reports. These workshops and reports have addressed research opportunities in paleoclimate, paleoenvironmental studies, evolution, and more, with an increasing emphasis on integrated, global studies, and the efforts have become increasingly interdisciplinary and collaborative. In addition, the community has continued to develop research with a direct bearing on human impacts on the globe.

In March and October, 2011, the sedimentary geology and paleontology communities held workshops that laid the groundwork for the initiative proposed here: TRANSITIONS: The Changing Earth-Life System—Critical Information for Society from the Deep Past. The workshops and the following report represent a coalition of numerous individual groups within the community.

In December, 2011, the National Research Council released the report, “New Research Opportunities in the Earth Sciences” (NROES; NRC, 2011a), with recommendations for research emphases over the next ten years. Many of these recommendations reflect research opportunities identified by the sedimentary geology and paleontology science communities over the past ten years, especially in this initiative. The convergence of these efforts indicates the urgent necessity for Earth scientists, in collaboration with biologic, oceanographic, and atmospheric scientists, to address issues critical to humankind. Crossing the natural divide between those who study the modern Earth and those who study the long history of Earth is fundamentally important to society because we cannot predict the future without understanding the past.
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EXECUTIVE SUMMARY

TRANSITIONS is a collaboration among several funded and unfunded initiatives originating in—but not limited to—the sedimentary geology and paleontology science communities. These communities are united around a singular intellectual challenge:

*Understanding the full range of Earth-life process behaviors through all of Earth history, including deep time, is vital for addressing urgent societal issues, and these processes must be addressed in a systematic and interdisciplinary fashion.*

TRANSITIONS has identified four overarching questions that must be answered in order to meet this challenge:

- What is the full range of potential climate system states and transitions experienced on Earth?
- What are the thresholds, feedbacks, and tipping points in the climate system, and how do they vary among different climate states?
- What are the ranges of ecosystem response, modes of vulnerability, and resilience to change in different Earth-system states?
- How have climate, the oceans, the Earth’s sedimentary crust, carbon sinks and soils, and life itself evolved together, and what does this tell us about the future trajectory of the integrated Earth-life system?
These questions are central to several of the research opportunities in the Earth sciences identified by the National Research Council in the 2011 report, “New Research Opportunities in the Earth Sciences” (NROES; NRC, 2011a) as being the most fruitful directions for funding in the next ten years.

TRANSITIONS tackles these questions from three directions to take advantage of recent advances and promising future research opportunities: Deep-Time Climate, Landscapes, and Biology and Environments.

Deep-Time Climate addresses the climate system directly, including the development of paleoclimate models, paleoclimate and paleoenvironment proxies, and data-model integration. The principal questions are:

- What is the full range of potential climate states and transitions on Earth?
- What are the thresholds and feedbacks in Earth’s climate system?
- What is the biotic response and resilience to changes in climate states?

Landscapes addresses specifically the interface between the solid Earth and the hydrosphere and atmosphere, especially on the continents; this interface is called the Deep-Time Critical Zone (DTCZ). Landscapes plays a critical role in the development of paleoclimate and paleoenvironment proxies, and the understanding of the interactions of life and the solid Earth. The principal questions are:

- What is the full range of climate states and behavior of the Critical Zone during the 4-billion-year record of “natural experiments” that have already occurred on Earth?
- How did the Critical Zone respond to perturbations like abrupt climate change, extreme events, or climate states very different than exist today (e.g., Snowball Earth, Hothouse Earth)?
- Can Deep Time Critical Zone (DTCZ) records from Earth states significantly different from today help predict future change?

Biology and Environments focuses more directly on life on Earth, including evolutionary responses to change, extinctions, and biodiversity. The principal questions are the grand challenges identified in the DETELON (2011) initiative, namely:

- How do physical and geochemical conditions change for biological systems during and after the transition to a greenhouse world?
- How do greenhouse worlds accommodate biodiversity?
- How resilient are ecosystems to the forces of ongoing and predicted environmental change?
- How do biota react when confronted by new physical, biological and climatic conditions?

As can be seen from the questions above, TRANSITIONS takes advantage of convergent lines of intellectual inquiry from the entire sedimentary geology and paleobiology community and beyond. The initiative represents an opportunity for integration of all necessary lines of inquiry that are required to address some of society’s most pressing concerns.
INTRODUCTION

Advances in modeling in the past 30 years have provided important insights into the future of the Earth’s climate and environment, but the current models have been unable to track the pace of current environmental change. Most research has, instead, focused on the climate state of the Earth for the very recent past—younger than 2 million years, when the northern hemisphere ice cap was present. The waning of the ice caps and the rise of atmospheric CO₂ concentrations are rapidly taking the Earth into conditions not experienced for more than 30 million years. Hence the models on which we rely to predict future change are unlikely to be fully developed for radically different Earth-system states. We may now be entering such a radically different state, raising the concern that such models may be deficient for the uses to which they are being put (e.g., see NRC, 2011b).

Throughout its history, the Earth system has experienced many environmental states very different from today’s, as well as large and abrupt climatic, biologic, and environmental perturbations. To date, climate models remain only partially successful in simulating even present conditions, much less these past, non-modern-analog system states (NRC, 2011b). The geological community—especially sedimentary geologists and paleobiologists—has long recog-
nized the necessity of studying the complete diversity of these past Earth system states in detail (Parrish et al., 2011), but progress has been slow for a variety of reasons, including the difficulty of accurately positioning the numerous, high-resolution environmental records in time.

Despite the slow progress, the community has increasingly coalesced around a singular intellectual challenge:

*Understanding the full range of Earth-life process behaviors through all of Earth history, including deep time, is vital for addressing urgent societal issues, and these processes must be addressed in a systematic and interdisciplinary fashion.*

The community is poised to launch a major coordinated research initiative to address fundamental questions about global change that we must answer for society to move forward on this vital issue. This challenge can only be answered in the deep-time geological record (NRC, 2011b).

The most recent strategic plan for the Geosciences Directorate at the National Science Foundation, Geovision (2009) and the recent National Research Council report, “New Research Opportunities in the Earth Sciences” (NRC, 2011a), both strongly emphasize the importance of deep-time studies (see Box 1).

Understanding the full range of Earth-life process behaviors cannot be achieved solely by studies of the last 2 million years. Most of the wide variety of Earth-system states are not represented in that time interval; indeed, Earth-system behavior has operated within a very narrow range during that time (NRC, 2011b). Therefore, there is an urgent need to mobilize the resources of all the geosciences—with sedimentary geology and paleobiology at the center—to answer the challenge in an organized, interdisciplinary, and coordinated fashion by examining high-resolution records from all parts of Earth history. Only then can we integrate what we have learned from the younger record (the last 2 million years) and the present-day conditions to more confidently predict what is likely to occur in the future.

Moreover, climate and environmental change are not the only concern. Shifts in the global economy and politics are again bringing resource sustainability and quality and quantity of resource reserves to the forefront. As the repository

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**BOX 1**

Recently, the recognition of the importance of deep-time studies has gone beyond the sedimentary geology and paleontology science community:

**Geovision,** the latest (2009) strategic plan for the Geosciences Directorate at the National Foundation, states: “To comprehend the full range of physical, biological, and chemical processes of Earth’s dynamic system, scientists must study deep-time records of these processes archived in the Earth’s sedimentary carapace (crust) at all spatial and temporal scales. These records are fingerprints of the processes that produced them—processes that continue to shape the Earth. A deep-time perspective (spanning the billions of years of Earth history) is critical for predicting potential climate, energy, water, and other boundaries for human life on the planet. Without this deep-time backdrop, the ability to make accurate predictions becomes severely limited.”

**New Research Opportunities for the Earth Sciences,** the recent (late 2011) National Research Council report recommending future funding trends for the National Science Foundation, states “The deep-time geological record has provided a compelling narrative of changes in Earth’s climate, environment, and evolving life, many of which provide analogs, insight, and context for understanding human’s place in the Earth system and current anthropogenic change.”
of many, if not most, of those reserves, the sedimentary record must be subjected to new methods of analysis to enable society to take advantage of Earth-based resources, including not just fossil fuels, but soils and water, and even geothermal resources. Sedimentary basin studies are essential to utilizing these resources, and understanding the dynamics of basins requires study of the Earth’s sedimentary carapace.

To answer the challenge, the leaders of several active research initiatives and National Research Council reports\(^1\)—representing the full range of geosciences required to address these fundamental questions—have proposed a major initiative to accomplish this important work. A preliminary workshop was held in March 2011 (Parrish et al., 2011), and a workshop to draft this science plan was held October 24-25, 2011, in Washington, DC. Participants included leaders and at-large members of the geological community as well as NSF staff members; input was also sought from the community at large via a website. The initiatives represented are:

Community Surface Dynamics Modeling System (CSDMS; ongoing)
EarthChem (ongoing)
EARTHTIME (ongoing)
Paleobiology Database (ongoing)
Community Sedimentary Model for Carbonate Systems (2011)
Continental Drilling (2011)
Conservation Paleobiology (2011)
Deep Time Earth-Life Observatory Network (DETELON; 2011)
New Research in Paleopedology (2011)
GeoSystems (2005)
Geological Record of Ecological Dynamics (2005)
Paleoclimate and Human Evolution (2005) and Understanding Earth’s Influence on Human Evolution (2010)

In addition, other members of the broad community that have not yet proposed formal initiatives, such as low-temperature geochemistry and geobiology (Freeman and Goldhaber, 2011), have expressed interest in being part of this coalition. Finally, we also draw from the NRC report, “Landscapes on the Edge” (2010a)\(^2\), and numerous older reports documented by Parrish et al. (2011) were consulted (Appendix I).

Fundamental questions that can be answered only by studying Earth processes in deep time will necessarily be addressed primarily by the sedimentary geology, stratigraphy, geochronology, and paleobiology communities, but the ability to take advantage of emerging information will also rely on the collaborative efforts of biologists, mathematical modelers and computer scientists, social and behavioral scientists, and engineers. Therefore, we propose an NSF-wide

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1 National Research Council (NRC) reports are intended to be reports on the state of a science, but many of them also serve as foundations for research initiatives. This is the case with most of the NRC reports cited in this report, so they are treated as initiatives herein.

2 At the time of initial organization, we could not identify specific personnel to represent this effort at the workshop.
initiative to engage and focus the science community and address the challenge to deepen and sharpen our understanding of the dynamics of the Earth-life system.

The TRANSITIONS collaboration will bring the full resources of the community to bear on critical societal issues, such as global change, and on human environmental concerns, such as soils, global biodiversity, and conservation. As stated by the authors of “Conservation Paleobiology”, “The ‘near-time’ past, approximately the last 2 Ma, provides valuable perspectives on what has been lost and the interactions of human societies and ecosystems, and fossil records of all ages can provide insights into how species and ecosystems respond to environmental change”.

STRUCTURE OF THIS REPORT

This report is in two parts. Part I provides background for TRANSITIONS and outlines the problem. This is drawn largely from the preliminary workshop report (Parrish et al., 2011). Part II is the science plan for the proposed initiative, which resulted from the October 2011 workshop. The science plan is developed in three themes: Deep-Time Climate, Landscapes, and Biology and Environments.
Part I— Current Status and Statement of the Problem

INTRODUCTION

Over more than a decade, the sedimentary geology and paleobiology (SGP) science community foresaw and has continued to focus on a key issue identified by the 2009 Geovision report: “…the challenge posed by the current scope and pace of human-induced change cannot be fully understood by only studying and modeling processes in the current environment. Indeed, to reach a greater understanding of future conditions one must study and model a wide range of proxy sources of Earth’s history.” Like ice and sedimentary core records of the last few millennia, deep-time geologic records provide key evidence of past physical, chemical, and biological states of Earth’s surface environments, but the deep-time records possess two key advantages. One is the broader perspective that deep-time records provide on possible states, rates of change, and system variability. Such data are the essential raw material for understanding the dynamics and underlying mechanisms of change in environmental conditions (including climate, biodiversity, paleo-ecology, and material cycling) and for evaluating stability and steady states (e.g., are equilibrium states ever attained for long periods of time, what levels of turnover exist within stable states, what feedbacks are most critical at regional and global scales?).

The second critical advantage of deep-time records is the window they provide into fully natural, pre-Anthropocene conditions. During the past 10-20 years, scientific studies by the geosciences community have established that human activities have significantly modified many fundamental aspects of diverse terrestrial and marine environments, both regionally and, in some instances, globally. These human impacts range from altered rates of detrital sediment runoff from land (e.g., by agricultural clearing, damming) and increased nutrient input (e.g., by atmospheric deposition of fertilizers, waste from agriculture and urban areas) to widespread alteration of soil and seabed structure and elemental cycling (e.g., by plowing and bottom trawling, paving and coastal armoring), and reduced biodiversity and ecosystem
functions (e.g., by over-harvesting, introduction of non-native species, loss of key habitat-forming species, habitat fragmentation), as well as the highly publicized human influences on climate. Some of these impacts date back to the first stages of human culture, and many are still accelerating: it is clear that the Anthropocene is here to stay.

As recognized by the Geovision report itself, the deep-time geologic record thus provides unique access to baseline data on pre-Anthropocene conditions on Earth’s surface, the better to (1) achieve truly general models of surface systems and (2) assess environmental perturbations associated with climate variation, human land-use practices, resource extraction, and marine harvesting.

A consistent and urgent call for understanding the full range of Earth process scales and system states has been put forth by all segments of the community. Recently, the NRC panel on deep-time climate change (NRC, 2011b) argued forcefully that our current understanding of climate processes, based on the study of climate processes that have operated during the recent past (2 million years), is inadequate for understanding the substantial global climate change projected by the Intergovernmental Panel on Climate Change (IPCC). In particular, climate processes and thresholds that operated in a warm world may be radically different from those that can be studied in the more recent (< 2 million years) geologic record. The NRC panel argued that we cannot understand climate without understanding how it functioned in vastly different states. The same is true for biological and geological processes, ranging from the response of ecosystems under different climatic regimes, to soil processes, sedimentation, and so on. If we are to predict future human impacts and Earth-system changes, we must incorporate in our investigations and models all the states and behaviors that the system has already experienced.

Climate has not been the sole focus of SGP community’s proposed initiatives to take full advantage of the deep-time record. For example, the 2005 NRC report “The Geologic Record of Ecological Dynamics recommended focused studies on (1) the environmental and ecological legacies of human activities; (2) using deep-time biotic records as natural laboratories to understand ecological and evolutionary processes under a range of past environmental conditions, and to develop truly general models of life-environment interactions at multiple scales (DETELON elaborates on these opportunities); and (3) using the geologic record to better predict the response of biotic and ecological systems to climate change. Analysis of geologic records permits tests in key past intervals of time—e.g., before the Industrial Revolution, or before Ice Age culling of diversity, or when past pCO2 levels were similar to those we anticipate in the future. These records also permit sampling over the lengths of time necessary to consider many generations, even of long-lived species, and of multiple examples of a single kind of perturbation (e.g., multiple warming events, multiple anoxic events of decadal duration). The 2010 NRC report “Landscapes on the Edge” identified similar key questions that focused on terrestrial environments—for example, what does our planet’s past tell us about its future? How do the biota, ecosystems, and landscapes co-evolve? What controls landscape resilience to change? Although these are basic scientific challenges, they all reveal an underlying commitment for science to contribute toward a sustainable Earth surface, and all require a deep-time, as well as historical, approach.

Finally, these same themes of deep-time research were also identified in the 2011 initiative, “The Future of Continental Scientific Drilling”, even though this report’s main focus was on the potential of a single particular modality of SGP science. The key motivating intellectual challenges were understanding: (1) aspects of the history of Earth, climate,
and life, broadly grouped as global environmental and ecological change; (2) the Earth as an operating system, loosely geodynamics; (3) the geo-biosphere of the present day (continental drilling efforts penetrate geologically young records en route to deep time); and (4) the interaction of humanity and the Earth through understanding natural resource systems and related environmental concerns.

**STATEMENT OF THE PROBLEM**

In order to meet the challenge of understanding the full range of Earth-life process behaviors through all of Earth history, the community must develop paleoclimate and paleoenvironment proxies and models. As emphasized by the NROES report (NRC, 2011a), “Proxy development and calibration studies need to be matched by complementary efforts to build more spatially and temporally resolved multiproxy paleoclimate and paleoecological time series with high precision and chronological constraints. There is an associated need for improved dynamic models and expanded data-model comparisons.”

**Development of Paleoclimate and Paleoenvironment Proxies**

Great strides have been made in the development of climate proxy indicators, but the studies leading to these advances have been scattered and unsystematic because of the lack of funding for broader integrative research efforts. Thus, a coherent program focused on the development of new climate proxies, particularly in response to newly discovered processes, is a concern that is foremost in the deliberations of the SGP science community. Inherent in this research is the need to further test modern analogs. Because of human alteration of the Earth, it may not be possible to find complete modern controls for proxy interpretation and consequently such baselines will have to be found in the pre-human geologic record. In some cases, advances in basic sedimentology, paleontology, stratigraphy, and biogeochemistry, including field work, are required to accomplish this research. Addressing the relative importance of biological, chemical, and physical processes on sedimentology and stratigraphy will result in major breakthroughs in understanding feedbacks and the expression of climate proxy indicators in the geologic record. In addition to providing pre-human baseline information, the study of deep time also provides the opportunity to understand the effects of large-scale change. “Only the geologic, geochemical and paleontological records of Earth history can provide examples of change that rival the scale of the human-induced changes in land, biota, and climate that we are experiencing today. Thus, understanding past biosphere-geosphere behavior is a powerful approach to anticipating how life-chemistry relationships may be impacted by human activity in the coming decades” (Freeman and Goldhaber, 2011).

The SGP community as a whole recognizes that climate change is an inherently integrating focus, and that other challenges will be addressed naturally in the pursuit of understanding climate change. For example, understanding the tem-
pos and modes of evolution, extinction, and changes in biodiversity, including ecosystem as well as climate thresholds, is critical to understanding the history and future of life; in addition, by studying them, important information is also revealed about climate as well as other drivers.

**Development of Paleoclimate and Paleoenvironment Models**

Studies that integrate both paleoclimate models and observational data have been critical in expanding our understanding of climate processes, but few apply to deep time. Funding priority has been concentrated on studies of the Quaternary and younger record, that is, the last 2 million years. There are a number of reasons for this, including paleogeography similar to the modern geography, extant biotic paleoclimatic indicators, and the high-resolution of proxy records. However, as discussed by many of the reports, the pre-Quaternary SGP science community also addresses these issues, and is poised to take full advantage of collaborative research with paleoclimate modelers. Current funding limits access to paleoclimate models and modeling expertise to a few people, and thus restricts the ability to investigate the integration of the processes revealed by SGP research into those models. The SGP science community strongly recognizes the value of integrated modeling and observational studies in deep time.

The ultimate vision for the community constitutes fully coupled Earth-system models that include vegetation, landscape, biogeochemistry, and sedimentary systems as well as the atmospheric component. These models will be capable of simulating the full range of climate and environmental states for the last 540 million years and older (Box 2). The paleoclimate modeling community has already taken some small steps toward integrating paleoclimate predictions with paleobotanical studies, for example, but models with paleovegetation and paleosol feedbacks await exploration. Likewise, there are sedimentary system-climate feedbacks that remain to be explored, even though such feedbacks potentially have a large effect on certain climate states. Some integral parts of such models are already discussed or in place, including basin and sedimentary models, but these need to be integrated with other types of modeling. The SGP science community has also explicitly proposed research emphases on key processes integral to climate change that are also important targets for research. These include the carbon cycle, hydrology, and paleogeographic change. The clear intent of the community is to integrate these processes.

**Critical Tools**

A majority of the SGP science community shares the view that three critical tools are required to meet the challenge of understanding the full range of Earth-life system processes. These are (1) continental drilling, 2) access to high-quality geochronologic information, and (3) access to, quality of, and maintenance of community data through collections and cyberinfrastructure. Although there have been some notable successes in the establishment of community databases, funding for these three needs remains inadequate to further research on the intellectual challenge outlined in the previous section.

In general, the need most directly addressed by continental drilling, field work, and geochronology is the nearly universal recognition by the SGP science community of the need for high-resolution, continuous stratigraphic records. While continental drilling must be supplemented by outcrop studies, such records are vital for examining processes that decrease the faithfulness of the stratigraphic record, such as preservational bias; for acquisition of unaltered biogeochemical records; and for establishing quantitative stratigraphic models, as well as for establishing an accurate record.
The Early Earth

The profound biological, environmental, and climatic TRANSITIONS to a habitable planet with oxygenated oceans and atmosphere capable of sustaining animal life are preserved in Earth’s Precambrian sedimentary shell. While these ancient archives are often fragmented by tectonics and are poorly calibrated by Phanerozoic standards, they harbor fossils of the earliest life on the planet in the form of stromatolites and microfossils, as well as geochemical clues to the origin of photosynthesis and other key microbial metabolisms that ultimately created the hospitable world we now occupy.

Recent high-resolution empirical records of lithological, magnetic, and geochemical variations in Precambrian sedimentary successions have resulted in startling discoveries that challenge Phanerozoic paradigms of global change. Time-series studies track the initial buildup of oxygen in surface environments, which enhanced continental weathering and stimulated novel microbial systems. Across the Archean-Proterozoic transition, the sustained and irreversible rise of atmospheric oxygen (aka The Great Oxidation Event) led to the development of the protective ozone layer—our global sunscreen—to a series of potentially global Paleoproterozoic ice ages associated with the modulation of greenhouse gas abundances, and speculatively, to the diversification of eukaryotes, which require set levels of oxygen for sterol. Precambrian environmental change also came with a high cost to existing biological communities, pushing the diversification of some and the mass extinction of others. While oxygen was on the rise, geochemical and biomarker evidence from Mesoproterozoic successions suggests that for hundreds of millions of years—during which the climate may have been relatively stable—the deep oceans oscillated between anoxic and sulfidic (aka Canfield Ocean) states, much like the present-day Black Sea.

Environmental TRANSITIONS into the Neoproterozoic Era heralded the big bang of eukaryotic evolution—consistent with molecular clock studies—and profound reorganization of the exogenic carbon and sulfur cycles associated with a series of widespread ice ages that test the limits of extreme climate change (aka Snowball Earth). The evolution and diversification of higher life forms, including the famed Ediacaran biota, appeared as the last of the global ice ages melted away in the midst of Pan-African orogenesis, and yet another step up in the oxidation of surface environments. These earliest experiments in multi-cellularity and the animals that arrived with a bang in the succeeding Cambrian Explosion were the result of ecological opportunities and genetic possibilities that may have also appeared in the aftermath of Phanerozoic mass extinctions.

Taken as a whole, the lessons learned from the Precambrian sedimentary record—albeit lacking the temporal constraints that aim to pin Phanerozoic studies to human timescales—provide tangible examples of Earth’s pre- and early-biotic state, demonstrating that extreme and prolonged environmental change fostered the evolution of higher life forms.
Continental drilling

Although drilling in lakes and oceans is important to the understanding of the Earth system, there is widespread agreement that the sampling of continental basins by drilling is particularly crucial for the advancement of deep-time science. The report, “The Future of Continental Scientific Drilling”, while not exclusively focused on SGP science, nevertheless includes three (of four) themes that are SGP science, deep-time emphases. Continental drilling recovers rocks in which the effects of modern weathering are minimized, which is particularly valuable for many geochemical, biogeochemical, and geochronologic studies. Cores can also provide uninterrupted, very high-resolution records from thick, basin-center rock sections, where stratigraphic completeness is greater than along the basin margins, from which outcrop data are usually derived. As temporal resolution of the deep-time record improves, these high-resolution, stratigraphically continuous records can provide and be placed in a precise numerical time scale, and can also contribute to more precise temporal placement of outcrop sections. The entire history of the planet is recorded in strata deposited on the continents; indeed, rocks incorporated in the continental crust are the only source of pre-Jurassic stratigraphic and historical records of the Earth, the biosphere, the oceans, and the atmosphere. The NRC panel on deep-time climates argued that drilling should be done in transects, as is sometimes done in ocean drilling, and linked with outcrops. The SGP science community recognizes that continental drilling is expensive, but observes that it is no more so than deploying oceanic drill ships or atmosphere- and space-observing aircraft. Continental drilling projects commonly have multiple objectives, only some of which are historic records, which significantly lowers their cost-benefit ratio. The extreme importance of continental records to all aspects of SGP science, including science not directed specifically toward the deep-time processes challenge, is the reason the community is solidly and enthusiastically behind increased commitment to continental drilling programs. Moreover, the NROES panel stated that “Sampling at appropriate spatial and temporal scales will require new continental coring and continued ocean drilling. This is a limiting factor in fully developing the deep-time archive of past
climates and the co-evolution mechanisms operating through time. Drilling availability is limiting progress”.

Currently, continental drilling projects are funded and implemented on a one-off basis, with only some using capabilities provided by the DOSECC drilling facility. A significant program of investigating deep-time will require a systematic program and standardized procedures, preferably overseen or even managed by a central facility. The continental scientific drilling community has proposed a baseline-drilling program with funds for planning and community maintenance as well as for drilling operations. A substantial effort in SGP and success of TRANSITIONS would require a substantial increment to that baseline funding.

**Geochronology**

The importance of high-resolution records and stratigraphy cannot be overemphasized, and indeed, “the pressing need to enhance the community’s capacity to produce high-quality dates” constituted a separate, major finding of the NROES panel. The strength of the Quaternary Earth systems record lies in large part with its temporal resolution, and the perceived lack of a similar resolution is a common criticism leveled at proposals to extract climate proxies in deep-time sedimentary archives. Yet the decadal-to-millennial resolution of Quaternary climate records is not exclusive; rather it is a circumstance deriving from a combination of an availability of high-fidelity, relatively continuous depositional systems (ice sheets, lake bottoms, and the deep sea), the easier linkage of these records to boundary conditions of the present, and sustained funding efforts to sample and study these records over the past four decades. By comparison, a similar resolution and fidelity exists in deep-time sedimentary archives (this is a function of depositional environment and preservation, not absolute age), if the fragmental records preserved in the older ocean basins and the continents can be spliced into a framework of absolute time (Box 3).

A combination of sidereal, radioisotopic, and astrochronologic (orbital cyclicity) methods contribute to the construction of age models capable of calibrating proxy records whether they are thousands or hundreds of millions of years old. Dating of Quaternary records has unique challenges, but such deposits can tolerate comparatively larger relative errors in age and still retain their utility; by contrast, a Cretaceous deposit must be dated 100 times more precisely to achieve the same temporal resolution. Remarkable innovations in radioisotopic dating over the past decade are now achieving orbital-cycle age resolution (~0.03% error) throughout the Phanerozoic Era (i.e., the last 540 million years). These innovations have been achieved in an exciting environment of community cooperation and collaboration fostered by the EARTHTIME Initiative in both North America and Europe. The power of these new radiometric ages is captured by their incorporation into astrochronologic and quantitative biochronologic composite records. When bootstrapped together, these complementary data sets can produce continuous deep-time age models with Milankovitch-band resolution accurately framed in absolute time; a case in point is the fully astronomically tuned Neogene timescale, which will soon be extended back to the Cretaceous-Paleogene boundary.

The frenzy of radioisotopic technique development of the past decade leaves the geochronological community poised to deliver on its collaborative potential. EARTHTIME has successfully promoted calibration and quality control on geochronologic methods, but access is still a critical issue. Geochronology labs are used by much of the geoscience community, and the needs of the SGP community alone far exceed the current capacity of those labs; mechanisms to reduce the cost and increase the throughput of geochronological data are required. A network of high-quality, deep-time geochronology labs must be supported and expanded, and new interdisciplinary geochronologists must be trained and funded, in order to advance SGP science and TRANSITIONS (as well as other Earth sciences).
The DETELon (2011) initiative outlines the capabilities well: “Geologists’ measurement of absolute and relative chronologies has simultaneously and radically improved. Once burdened with uncertainties of several Myr, radiometric methods now routinely return absolute ages with uncertainties of ±0.05% (i.e., ≤~15 kyr for Oligocene rocks; ≤~50 kyr for Cretaceous rocks, etc.). Such high-resolution chronologies have, for example, allowed recovery of the details of Milankovich cycles even in the Paleozoic. Accretionary structures can additionally record environmental conditions with annual, seasonal, and sometimes nearly daily resolution, and include such features as varves, tree rings, and sequentially or progressively grown shells and teeth that are preserved for large portions of the Phanerozoic. These data provide windows into ecological and climatic conditions with relative temporal resolutions that closely approach modern measurements.”
**Community databases (geoinformatics) and sample archives**

The importance of high-quality, interlinked, and accessible community databases is another almost-universally recognized need in the SGP science community. With initiatives such as CHRONOS, Paleobiology Database, MacroStrat, GeoStrat, EARTHTIME and EarthChem, GEON, etc., the SGP science community has made substantial progress. For example, there have been several efforts to establish or explain the need for database standards. However, long-term funding and consistent and continuous management of the databases are persistent problems because of a lack of commitment on the part of NSF to post-development maintenance efforts. Related to this is the lack of preservation of so-called legacy data, data that might not meet current quality standards but that are nevertheless still useful and were sometimes collected at great expense.

Management of community data, such as samples and cores, is likewise a vital but unglamorous need that requires long-term commitment. Although museums and a few universities have the ability to provide much-needed, long-term data archives, the cataloging, storing, and long-term management of samples remain great problems and are a major concern across most segments of the SGP science community. Just as there have been attempts to establish standards for databases, several segments of the SGP science community have called for standards in collection density and methods. New approaches and methods will also require new field studies, and integration and management of collected samples will be vital for TRANSITIONS.

In the findings on co-evolution of life, environment, and climate, the NROES panel also acknowledged the critical role community databases play: “Integrated efforts on the development of digital databases to store proxy and genomic data and to facilitate data integration and comparison across all spatial and temporal scales are also necessary to support advances. Such an effort might incorporate a strategy to integrate databases where relevant and with paleoclimate model archives so as to make them fully interactive.”
Part II—The TRANSITIONS Initiative Science Plan

TRANSITIONS will be successful because it brings the resources of the entire sedimentary geology and paleobiology community—and beyond—to bear on four overarching questions:

- What is the full range of potential climate system states and transitions experienced on Earth?
- What are the thresholds, feedbacks, and tipping points in the climate system, and how do they vary among different climate states?
- What are the ranges of ecosystem response, modes of vulnerability, and resilience to change in different Earth-system states?
- How have climate, the oceans, the Earth’s sedimentary crust, carbon sinks and soils, and life itself evolved together, and what does this tell us about the future trajectory of the integrated Earth-life system?

These might be summarized in the following question: Is the assumption that the current Earth system state is representative for all past and possible future states valid? If not, how does the geologic record of past Earth states and changes/transitions inform understanding of possible states of the current Earth system and its future (Box 4)?

Although all activities within the community have at least an indirect bearing on all the others, we have divided the science plan into three themes: Deep-Time Climate, Landscapes, and Biology and Environments. In the following sections, we outline the science plan and illustrate that the initiatives are already collaborating and how the links are being made.

DEEP-TIME CLIMATE

There is an increasing likelihood that our world is moving toward a greenhouse state due to increases in anthropogenic carbon dioxide in the atmosphere (IPCC, 2007). This change provides a powerful motivation for understanding the dynamics of Earth’s past “greenhouse” climates. As noted in the recent NRC report, “Understanding Earth’s Deep Past: Lessons for Our Climate Future” (NRC, 2011b), those climate states cannot be understood through the lens of human or even recent geologic history, and instead require an understanding of the deep-time geological record. The deep-time record has already revealed critical feedback mechanisms that are unique to warmer worlds and that are beyond the reach of more recent paleoclimate archives, such as ice cores or tree-ring records. The potential for amplification of both positive and negative climatic feedbacks in a warmer world relative to pre-industrial conditions underscores the need to study climate thresholds and tipping points in the deep-time record. The deep-time record provides evidence...
of previous abrupt climate-change events, substantial differences in the Earth’s hydrological cycle relative to today, evidence of past ice-sheet collapses, and dramatically different sea level conditions that include flooded continental seaways.

The need to understand fully Earth’s past climate as a template to understand future climate change is the source for the overarching questions that will be addressed by the TRANSITIONS Deep-Time Climate research:

• What is the full range of potential climate system states and transitions experienced on Earth?
• What are the thresholds, feedbacks, and tipping points in the climate system, and how do they vary among different climate states?

The 2011 NRC report entitled “Understanding Earth’s Deep Past: Lessons for Our Future Climate” (NRC, 2011b) summarizes recent advances in our understanding of the Earth’s past climate and establishes six critical challenges uniquely accessible through study of Earth’s deep-time geologic record. Those critical challenges provide a framework for future investigations that will enable an understanding of:

• How sensitive climates are to increased atmospheric CO₂
• How heat is transported around the globe and the controls on pole-to-equator thermal gradient
• Sea level and ice sheet stability in a warm world
• How water cycles will operate in a warm world
• Abrupt transitions across tipping points into a warmer world
• Ecosystem thresholds and resilience in a warming world.

The first critical challenge is to understand the sensitivity of Earth’s climate to increases in atmospheric CO₂. It is “very highly likely” that Earth’s climate is changing as a result of anthropogenic carbon emissions (IPCC, 2007), which equates to a >90% likelihood that the observed climatic changes are due to human activities. However, regardless of whether human activities are the sole driver or a partial driver, it is nonetheless clear that the Earth’s climate is transitioning to a new, warmer state. Both the IPCC (2007) and National Research Council (2011b) consider as unequivocal the evidence that Earth’s climate is warming. Viewed in the perspective of Earth history, this new climate state has not been realized on Earth since at least the Miocene (23 million years ago), meaning that our current and future state is one that was last recorded in deep time. As atmospheric CO₂ levels increase, the Earth shifts further back in time. For example, the IPCC’s A2 scenario projects CO₂ levels by 2100 that will be comparable to the Eocene, at least 35 million years ago. If anthropogenic emissions continue to accelerate, climate states beyond a doubling of CO₂ by 2100 may be possible, which will require examination of even deeper time to study analogous conditions and related impacts.
The science plan for this theme of the TRANSITIONS initiative is organized around three topics: 1) understanding Earth’s climate states, thresholds, and transitions; 2) critical challenges to our understanding of Earth’s climate; and 3) societal relevance of understanding deep-time paleoclimate, followed by brief summaries of previously proposed research programs that address these topics, a discussion of the strategies and infrastructure needed to address these topics, and a summary of the deliverable scientific returns from TRANSITIONS for understanding Earth’s climate.

**Understanding Earth’s Climate States, Thresholds, and Transitions**

Based on past climate change and modeling, Earth’s climate system does not respond linearly to CO$_2$ forcing. Instead, incremental changes in boundary conditions such as atmospheric pCO$_2$, if certain but still poorly known thresholds are passed, appear to cause it to transition between icehouse (characterized by continental-based ice sheets at high latitudes, as in the present) and greenhouse mean states, suggesting the triggering of strong positive feedbacks in the climate system. Our current icehouse climate state has been subject to rapid changes in atmospheric pCO$_2$ and related boundary conditions, but not nearly the magnitude of our current excursion which is more comparable to the pCO$_2$ of former greenhouse times, generating concerns that critical thresholds will soon be passed, leading to large, unanticipated shifts in Earth’s environments and ecosystems.

Even though we do not at present fully understand these thresholds or the complex feedback dynamics that control them, there is strong evidence in the geological record that the Earth rapidly transitioned between climate modalities, most notably in the Eocene-Oligocene greenhouse/icehouse transition, and the period leading up to the Paleocene-Eocene Thermal Maximum marking the transition into the Eocene Climatic Optimum. In both cases the change in CO$_2$ appears to have been gradual, but the response of the climate system appears dramatically non-linear, abrupt, and from a prospective position, unpredictable (Box 5).

Further concerns are that the transitions into prior greenhouse states were not only rapid, but involved substantial overshoots and relatively long, protracted periods of recovery, including a hysteresis characteristic that could require drastic lowering of CO$_2$ to pre-industrial levels in order to restore our current icehouse climatic state.

One of the most challenging issues facing climate change research is that the sophisticated modeling efforts to date have been parameterized by using much of the variability in our present atmospheric and icehouse climatic state. Thus the latest GCMs, which have been used to probe climatic variability in the glacial-interglacial mode that the Earth has been in for the last million years, are of unknown applicability to the greenhouse or hothouse climate state that the Earth may be heading to, and clearly was in at various times in the geologic past. In fact, through Cenozoic and Mesozoic time, the Earth was operating in a greenhouse state much more of the time than it was in an icehouse one. Therefore, to discover what controls the climatic behavior of the Earth when it is in a greenhouse state, and how those controls might differ from those associated with an icehouse state, we must examine and document the wide variety of environmental and ecosystem information that is archived in key sedimentary deposits of greenhouse periods. This information includes multiple CO$_2$ proxies (especially for the same time intervals), temperature proxies, and biomarkers.

In addition to the major changes in the mean climate system, the geologic record documents abrupt changes in CO$_2$, which appear to have been forced by extraordinary events external to the climate-life system and are related to mass-extinction. These include the famous K-Pg boundary involving two huge events (the Chicxulub impact and eruption of the Deccan Traps) and the end-Triassic and end-Permian mass extinctions, associated with the emplacement of
Stratigraphic context and faunal change across the Paleocene-Eocene Thermal Maximum (PETM) in western North America. Note the rapid transient 120-thousand-year excursion at 55.7 million years before present (red line) flooding the carbon isotope record with light carbon-12 (solid circles in red box). Early Artiodactyla (ancestors of cows, sheep, deer, etc.), Perissodactyla (ancestors of horses, etc.), and Primates (ancestors of monkeys, apes, etc.) that dominate faunas today first appeared early in the PETM (Gingerrich, 2010).

Around-the-clock coring to recover a continuous continental record of sedimentation and chemical change through the Paleocene-Eocene Thermal Maximum at Polecat Bench in northwestern Wyoming.
the Central Atlantic Magmatic Province (CAMP) and the Siberian Traps, respectively. Of these, only the CAMP is unequivocally related by superposition and temporal sequence to the igneous events (see Box 6) and known from two different proxies, the soil carbonate and stomatal proxies. Of considerable importance is that while the initial conditions were quite different from today, with very high background CO₂ (+1000 ppmv in the case of the CAMP), doublings of CO₂ likely occurred on timescales comparable to anthropogenic change over hundreds to thousands of years. Relevance to predicting future climate change is fairly obvious.

An enormous challenge for the future is understanding the thresholds in the feedback systems. These thresholds result in a non-linear sensitivity of climate to CO₂ forcing, and are at least in part responsible for changing climate states. The nature of the underlying feedback mechanisms also need to be understood as these cannot be read directly from geological archives. Rather, they need to be developed through more comprehensive data-model efforts, all the while keeping an awareness that unexpected phenomena might reveal the presence of additional processes that need to be incorporated into the models or modeled separately.

Critical Challenges to Understanding Earth’s Climate

Interactions between the biosphere and the Earth’s climate are complex and involve a number of linked cycles that involve everything from nutrients, to water, to atmospheric gases such as CO₂ and CH₄ that impact annual and seasonal temperatures, to O₂ levels that impact basic survivability (Fig. 1). As an example, plants use CO₂ to perform photosynthesis, and as a result, O₂ is released to the atmosphere, which impacts both evolution and survivability among vertebrate and invertebrate animals. To facilitate respiration, plants must draw nutrients from their environment, so by both physical means (e.g., roots splitting bedrock) and chemical means (mycorrhizal fungi breaking down the rocks), nutrients are extracted via weathering. This process draws down CO₂ from the atmosphere, and if the soils that the plants formed are weathered, may transfer sediments and dissolved nutrients to lakes, rivers, and oceans where further productivity (e.g., by algae) may take place, which impacts both the atmosphere (e.g., further CO₂ drawdown) and biosphere (e.g., development of a foodweb). While it is possible to measure the rates of many of these processes directly using the modern systems, it is not clear that the relative importance and magnitude of each of these processes would be the same for Earth in a different climate state, or that the thresholds that control whether some of these processes and feedbacks would be the same, for example, in a warmer, wetter world.

Understanding how these types of processes might operate in the future thus requires a robust understanding of how they have varied in the past during both warmer and colder climate states. Because it is not possible to make direct measurements of, for example, atmospheric CO₂ levels in the Eocene, proxy relationships have been derived for many environmental variables (Fig. 2). By combining independent proxies for different variables that span a climatic transition, it is possible to constrain the sensitivity of one variable to changes in another. For example, when paleotemperature proxies are combined with paleo-CO₂ proxies, it is possible to better constrain CO₂-temperature sensitivity for projections of future climate change (Royer et al., 2007). Given that CO₂-temperature sensitivity is one of the primary remaining uncertainties in future projections (IPCC, 2007), this is a critical piece of information that can only be constrained from the deep-time record. However, while CO₂-temperature sensitivity to a doubling or even larger increase in CO₂ is perhaps the most critical outstanding variable for future climate predictions, it is just one of many inputs into models of future climatic and environmental change that are not fully understood (Fig. 2). For example, while proxies exist for mean annual precipitation based on paleosol (fossil soil) chemical composition (Sheldon et al., 2002;
Emplacement of the huge Central Atlantic Magmatic Province (CAMP) is associated directly by superposition with doublings of CO$_2$ (Schaller et al., 2011). Within the outcropping belt of the CAMP lavas in eastern North America and Morocco, there are three main intervals of basaltic flows, all of which are represented in the Newark basin of New York, New Jersey, and Pennsylvania. Each of these multiple flow events is directly succeeded by paleosols indicating a doubling of CO$_2$ from background levels based on a soil carbonate CO$_2$ proxy that relies on measuring the isotopic composition of carbonate and co-occurring organic carbon (Cerling et al., 1992). This proxy indicates that pre-CAMP CO$_2$ hovered around 2000 ppmv during the last few million years of the Triassic, jumping to more than 4000 ppmv in paleosols directly above each of the three lava flow sequences, beginning in the very latest Triassic.

Overall, time control for this sequence is provided by an astronomically calibrated time scale derived from these very continental strata (Kent and Olsen, 1999; Whiteside et al., 2007; Olsen et al., 2011) as well as very high precision CA-TIMS U-Pb ages from zircons from CAMP flows and intrusions (Blackburn et al., 2009; Schoene et al., 2010). This constrains the duration of the time it took CO$_2$ to double to 200 ky or less for each event. However, paleo-secular variation data (Kent et al., 2009, 2012) from the flows indicates much less time was involved, with the actual extrusive events at submillenial time scales. Providing the eruptions were the source of the CO$_2$, they occurred over intervals of time comparable to the anthropogenic rise. The recovery back to near background levels from each major event, however, evidently took hundreds of thousands of years.

The oldest of the CAMP lavas (a Moroccan continuation of the lowest flow sequence in the Newark basin) coincides with the initiation of the end-Triassic extinction (ETE; Marzoli et al., 2004; Deenen et al., 2010). Based on U-Pb of the oldest flows in North America, the ETE as seen in these continental strata is coincident with the marine ETE as well (Schoene et al., 2010). Leaf stomatal data from Greenland and the UK show a similar doubling of CO$_2$ in strata correlative with the CAMP, although the absolute magnitude of the values is a factor of two lower (McElwain et al., 1999; Steinthorsdottir et al., 2011).

These data confront us with at least two major questions. First, is the association of the mass extinction with the large igneous province a result, directly or indirectly, of the doubling of CO$_2$ and climatic sequelae, an associated phenomenon (methane release, sulfur aerosols), or a result of the much higher background levels of CO$_2$? Second, how do we reconcile the different absolute values of CO$_2$ of each proxy (soil carbonate vs. stomata)? These are challenges that face not only our understanding of the role of CAMP in the ETE, and other mass extinction associated with large igneous provinces (e.g., end-Permian and K-Pg), but also predictions of the consequences of the anthropogenic doubling of CO$_2$ to Paleogene levels.
Nordt and Driese, 2010), leaf δ¹³C composition (Diefendorf et al., 2010), or for mean annual temperature based on fossil leaf morphology (Uhl et al., 2007), seasonal precipitation and temperature changes are much more poorly constrained (Fig. 2). Similarly, while a broad ensemble of climate models predict increases in global average temperature and precipitation, the regional expressions of temperature and precipitation can be dramatically different (e.g., IPCC, 2007). For example, in the US, while the northern Great Plains are projected to experience an increase in mean annual precipitation between now and 2060, the southwestern part of the US is projected to experience increasingly arid conditions (IPCC, 2007). Thus, in terms of the impacts on society of climate change, the seasonal range of climate and the regional (rather than global) expressions of a changing climate will be much more important for mitigation planning than understanding the mean global or annual state. As a result, while the deep-time paleoclimate record can currently provide critical constraints on future climate change, there is ample scope both to improve existing proxies for climatic and environmental variables, and potentially, to provide constraints on a variety of other important climatic and environmental factors (Table 1). For example, by modeling past warm climate states or transitions to warmer climate states using constraints provided by proxies for past environmental conditions, it will be possible to understand better things like how storm frequency and magnitude might change in a warming world.
Societal Relevance of Deep-Time Paleoclimate Research

The answers to the overarching research questions posed by the TRANSITIONS initiative are relevant not only for answering fundamental research questions about how the Earth’s climate system works and what the impacts of a warming climate on the biosphere may be, but also have critical implications for addressing human-needs questions including:

**Sustainability**

A major current overarching theme at the National Science Foundation is the Science, Engineering and Education for Sustainability (SEES) initiative. The mission statement of SEES is as follows: To advance science, engineering, and education to inform the societal actions needed for environmental and economic sustainability and sustainable human well-being.

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**Table 1. Examples of Environmental Information for Which No Proxy Currently Exists**

*Weather Phenomena*
- Cloud cover and albedo
- Storminess and monsoonality
- Mesoscale climatic phenomena (e.g., atmospheric eddies, storm tracks)

*Climatic Factors that Influence the Biosphere*
- Distribution of precipitation throughout the year
- Seasonal distribution of freezing temperatures; seasonal distribution of hot days leading to high mortality
- Soil moisture and degradation
- Emission rates and composition from volcanic sources
- Intensity of hydrological cycle processes (e.g., rate of moisture transport)

*Environmental Factors that Influence the Biosphere*
- Ocean mixing and redox
- Paleo-pH
- Ocean and lake acidification

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**Figure 2. Summary of paleoclimatic proxies available in deep-time that bear on attempts to model future climate change.**

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A critical part of that initiative is to provide a forum for integration of information about both society and the natural world with a goal of informing future policy decisions based on a sustainable future. Without a much deeper understanding of the variability of Earth’s climate that incorporates both past records of warmer times and accurate, precise models of the likely outcomes of continued anthropogenic carbon emissions, realizing the goals of SEES will be impossible. The social and economic dimensions of sustainability require a detailed understanding of the Earth’s climatic and environmental conditions through time. Furthermore, the geologic record archives multiple examples of large-scale sustainability crises within the natural environment, including records of the precursor and aftermath states. Because these are the areas that can be informed by the TRANSITIONS initiative to study deep-time paleo-climate records, TRANSITIONS forms a crucial and complementary program for the success of the SEES initiative.

**Impact of climate change on resources**

One of the primary limitations on economic growth and development is distribution and scarcity of mineral, fuel, food, and water resources. Some resources, like fossil fuels or rare Earth element metals, have a fixed distribution and are non-renewable on human time scales. Others, like water or food resources, do not have a fixed distribution and may or may not be renewable and sustainable on human time scales. For example, three specific questions about renewable resources that are critical to answer as we face the challenges of a warming world are:

1. **What are the potential impacts on arable land and water resources due to rapid climate change?** Arable crops require either sufficient natural precipitation or irrigation to produce both food and biofuels. Changing amounts, distribution, and timing of precipitation would substantially impact crop productivity. Similarly, warmer temperatures and changing seasonal temperature ranges will impact crop productivity. In addition, although much of the Earth’s freshwater is currently frozen in polar ice caps, the rest is actively involved in the Earth’s hydrological cycle. Changes in the amount, distribution, and timing of precipitation are already having significant impacts on the western US (Rosenzweig et al., 2008; EPA 2010). Future climate changes will exacerbate these problems.

2. **What are the potential impacts of a changing climate state on future energy production and consumption?** Although the majority of US energy production comes from the burning of fossils fuels (coal and natural gas), in many regions of the country alternative energy sources based on climate patterns are either currently of great importance or projected to be of great importance in the future. The impact of a changing climate on such alternative energy sources is currently poorly understood. For example, many western states rely on hydropower. Changes in the amount, distribution, and timing of precipitation would have significant impacts on the availability and feasibility of hydropower. Similarly, many states rely on wind power for a significant part of their electricity generation, and most states are currently rapidly expanding the use of wind power. Thus, changes in wind speeds, duration of sustained winds, and seasonal variability would have significant impacts on the availability and feasibility of wind power (IPCC, 2011).
3. How different will regional climatic responses be from the global climatic response? Changes to the Earth’s average climate state are only one means of projecting future climatic changes. The observed post-industrial global temperature rise of about ~1°C is greater or smaller in certain regions, and is greater on land than in the global oceans (IPCC, 2007). For example, South America and Australia have experienced less warming than North America, Europe, Africa, and Asia, and the Arctic is experiencing especially marked warming. These regional differences are critical, both because the rates of change may be different in the future, but also because the magnitude of climate change may also be different from one region to the next.

Deep-Time Climate Deliverables in Transitions

The following is a preliminary list of deliverables from the TRANSITIONS initiative resulting from the work on deep-time climate:

- Calibrated model-data comparisons of paleoclimatic reconstructions
- Synoptic reconstruction of climate change during critical transitions and new understanding of the impact of climatic change on the biosphere
- Reconstruction of the Earth’s surface in climate states vastly different from any time in the last 2 million years to provide better understanding of future climatic and environmental changes
- Potential impacts on arable land and water resources due to rapid climate change (e.g., regional vs. global changes in precipitation, temperature, seasonality) and impacts of a changing climate state on future energy production and consumption (hydropower, wind power).
LANDSCAPES

As noted in the NROES report, the Critical Zone initiative at NSF has been a highly successful program for research into the land-water-climate interface. The initiative has shown, among other things, that the zone is highly sensitive to changes at the Earth’s surface, and that it is also a highly sensitive recorder of climatic and environmental change. The Landscapes theme is focused largely, although not exclusively, on the Critical Zone in deep time, and on the TRANSITIONS overarching question:

• How have climate, the oceans, the Earth’s sedimentary crust, carbon sinks and soils, and life itself evolved together, and what does this tell us about the future trajectory of the integrated Earth-life system?

The archive of Earth history records a far richer range of states and behaviors of the landscape and environment than we can observe directly in the tiny slice of time we occupy today. If we are to understand the full range of Earth-surface processes, we must understand not just how the Critical Zone operates today, but how it has responded in deep time to very different climatic and biotic states, and the range of information is recorded in the Deep-Time Critical Zone. Critical questions to be addressed by this theme in TRANSITIONS are:

• What is the full range of climate states and behavior of the Critical Zone during the 4-billion-year record of “natural experiments” that have already occurred on Earth?
• How did the Critical Zone respond to perturbations like abrupt climate change, extreme events, or climate states very different than exist today (e.g., Snowball Earth, Hothouse Earth)?
• Can Deep Time Critical Zone (DTCZ) records from Earth states significantly different from today help predict future change?

In the following sections, we discuss the Critical Zone as it is understood now, the evolution of the Critical Zone in deep time, how the Critical Zone Observatory concept can be extended into deep time, and the potential deliverables of such research.

The Critical Zone

Earth’s Critical Zone represents the interface between the fluid and solid Earth; it is “the environment.” The Critical Zone is the “heterogeneous, near-surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources” (NRC, 2001). The Critical Zone (CZ) is the non-lithified outer skin of the Earth’s surface recording the collective impacts of atmosphere, cryosphere, hydrosphere, and biosphere on the lithosphere, producing the pedosphere through weathering (Amundson et al., 2007; Brantley et al., 2007; Fig. 3). Most Critical Zones begin at the top of the plant canopy and extend down through the vadose zone into the groundwater, where biogeochemical mediation of biotic and abiotic reactions occurs across various chemical gradients, exchanging matter and energy with the Earth systems through space and time (Brantley et al., 2011). Spatial scales range from nanoscale to landscape, and temporal scales from the microsecond to thousands of years. Processes acting in the Critical Zone are affected by the internal dynamics of a system with many operating parts that is also subject to anthropogenic, climatic, and tectonic forcing.
The surface environment we see today is a small subset of the configurations and conditions that the surface has experienced in the past. Fortunately, the Earth-surface system is remarkably effective at preserving records of its own evolution. The stratigraphic record—a time sequence of surfaces and affiliated deposits—provides a window to the long view of the Earth surface system. The Earth’s record-keeping preserves a detailed picture of the evolution of the atmosphere, oceans, tectonics, life, and the surface system itself. In other words, the Earth’s sedimentary carapace contains a four-billion-year history of the Earth recorded in paleo-Critical Zones. These deep-time records have the potential to preserve vestiges of ancient atmospheres, hydrospheres and biospheres as isotopic and geochemical signatures. The time-slice records, when viewed globally, can provide insights into the impacts of global climate change on both terrestrial and marine environments. “Only in the long record of Earth history can we measure the variability, and thus the predictability, of the planetary surface system” (NSF, 2004).

Transferring the CZ concept to deep time slices, i.e., a Deep Time Critical Zone (DTCZ), provides an opportunity to study the interface of Earth systems on ancient landscapes mediated by biotic and abiotic processes in response to forcing mechanisms. DTCZ Observatories might include a series of boreholes within a targeted sedimentary basin calibrated to seismic data or rock outcrops, and accompanied by morphological description and sample collection and analysis. Whereas, in theory, DTCZs represent time slices across numerous, laterally extensive and contiguous environments of deposition and associated facies, they can also be studied collectively through critical time intervals to better characterize and interpret the response of DTCZs—and their evolving landscapes—to changing environmental condi-
tions that may more appropriately forecast the future of the Earth state. The spatial extent of a studied DTCZ is set by the purpose of the investigation or the available resources. Figure 4 illustrates a hypothetical, vertically extensive outcrop exposure of a surface CZ and four buried DTCZs within a large alluvial basin some 2 kilometers wide. Sedimentary records can provide critical information about how the landscape and the greater environment could change in the future.

It should not be of any surprise that theoretical models for predicting the evolution of the Critical Zone are only in their early stages given the complexity of the interconnected and highly nonlinear physical, geochemical, and biotic systems that form the surface environment. Scientific field experiments designed to better understand aspects of this system are common but necessarily involve short length and time scales. We can add substantially to this knowledge by making better use of the roughly 4-billion-year record of natural experiments that have already occurred on Earth. This record of natural experiments includes extreme events such as meteor impacts and rapid climate changes, as well as different Earth states—for example, an Earth that is nearly ice-free—that are quite different from the modern. A crucial next step is to accelerate the process of learning to read these often fragmentary sedimentary records quantitatively, so that we can understand long-term dynamics, reconstruct extreme events and variability, and present these results in a form that

Figure 4. Modern surface Critical Zone, and four discrete Deep Time Critical Zones (DTCZ) illustrated within a thick stratigraphic succession across a landscape (~ 2 km wide). Interpreted features include soil structures, tree stumps, various lithologies denoted by patterns, and the location of three core holes that might constitute a DTCZ observatory. Interpreted changes (with depth) of paleo-atmospheric CO₂ concentration is drawn alongside (unpublished, L. Nordt).
can be used by decision makers. As humans become a predominant geologic agent, understanding the full range of planetary behavior has become crucial.

The sedimentary record preserves the response of Earth’s surface environment to external drivers such as climate change, tectonics, and volcanism, as well as to the internal dynamics of erosion and deposition acting over long periods of time. Properties of the Critical Zone generally fluctuate within some predictable range in response to variation in external drivers and internal dynamics, as long as the altering processes remain below some level of intensity. When conditions change with sufficient magnitude and duration, the Critical Zone may become altered beyond the range within which it can recover, exceeding its resilience to change. The geologic record provides plenty of evidence for surface-system thresholds, or tipping points, beyond which rapid changes can occur without any additional forcing. The changes in state across such tipping points are typically abrupt or accelerated relative to the apparent rate of forcing.

Today, the question of how close Earth is to a tipping point, when it could shift abruptly into a new climate state, is of critical importance to the Critical Zone as well as to other Earth systems discussed in this report. For example, deposits preserving the record of the late Paleozoic ice age may provide crucial information necessary for accurately answering this question because these sediments provide the only record of Earth with a complex biota transitioning from icehouse to greenhouse conditions (Gastaldo et al., 1996). Two long-term glacial cycles have been identified in Permian-Carboniferous time. The waxing and waning of ice during the height of each glacial cycle resulted in the spatial displacement of vegetation, and also in minor perturbations of tropical climate (Berner, 1990). Ecological responses included major changes in plant assemblages, including extinctions, changes in spatial distribution of plants in the topics and temperate zone, and nearly synchronous changes in the structure of vegetation throughout the globe. It appears that probably more than 10% but less than 50% of common species of trees and shrubs went extinct. Although the plants of the late Paleozoic and the geography of that time differed entirely from those of today, the rates, geographic distribution and nature of vegetation changes can serve as examples of similar patterns in the transition to a modern greenhouse world.

How Does the Critical Zone Evolve on a Changing Planet?

How rapidly physical and biological systems can adjust to abrupt environmental change is a fundamental question accompanying present-day global warming. An important tool to address this question is to describe and understand the outcome of equivalent “natural experiments” in the deep-time geologic record where the behavior of the surface system has been played out and recorded countless times. Only in the long record of Earth history can we measure the variability, and thus the predictability, of the planetary surface system. But existing stratigraphic data sets, collected piecemeal under programs of limited scope, will not be sufficient to test full-scale Critical Zone models. Rather, model testing will require data collected under field programs conceived from the outset to be as comprehensive, spatially complete, and analytical as the predictive models themselves.

Developing a system of DTCZ Observatories is thus necessary for TRANSITIONS to reconstruct Earth’s surface evolution from short-term to geologic time scales using quantitative methods to identify thresholds and abrupt changes and to study the interplay of tectonics, climate, biota, and surface processes. The reconstructed evolution of the Earth’s surface will be used (1) to test and develop predictive models for the Critical Zone that couple tectonics, climate, biota,
lithology, and landscape evolution; (2) to constrain Critical Zone resilience and the tolerable limits of stochastic variability before tipping points and abrupt changes occur; (3) to constrain the frequencies and causes of rare but important surface events; and (4) to provide baseline information on pre-human landscapes and their response to change as a guide for restoration and management (NRC, 2010a).

The theory of complex systems shows us that systems with strong nonlinearity and many interacting parts—both hallmarks of the Critical Zone—can behave in unexpected ways that make theoretical modeling futile unless paired with comprehensive, analytical observation. Each DTCZ Observatory must therefore foster broad-based collaborations of observation-based scientists and modelers. We envision these collaborations producing team-based studies of important paleoclimate time-slices. In the section below we focus on seven important scientific attributes of DTCZ Observatories that, when successfully addressed can lead to precise and accurate, quantitative reconstructions of past Critical Zone states through the study of Earth’s sedimentary cover.

Attributes of a Successful DTCZ Observatory

*Greatest Possible Temporal Resolution of the Sedimentary Record*

As discussed elsewhere in this report, recent developments in geochronology and in stratigraphic correlation indicate that for the first time it will be possible to calibrate the entire geologic timescale to better than 0.1% back at least to the beginning of the Phanerozoic, 542 million years ago (Box 3). This will allow us to pose a new level of increasingly sophisticated questions related to the evolution of the Earth and its Critical Zone, and a successful DTCZ observatory requires a high level of temporal resolution.

*Quantitative Assessment of the Stratigraphic Filter*

The stratigraphic record filters information about Earth-surface conditions, and our ability to image past states of the Earth depends upon our ability to quantify these filters in terms of both their deterministic and statistical components (NSF white paper, 2004). Decoding the stratigraphic record involves segregating multiple, simultaneously acting, internally and externally driven processes from one another as cleanly as possible—a challenging kind of nonlinear deconvolution. For example, stratigraphic sequences control patterns of species’ first and last occurrences, affecting the reliability of biostratigraphic correlations, evolutionary interpretations, and paleoecological reconstruction. These same processes that control time-averaging and stratigraphic architecture also modify geochemical and other proxy data for ecological, climate, and other environmental analyses. Fortunately, an effort is underway to develop the quantitative tools necessary for assessing the resolution, biasing, and filter properties of the stratigraphic record (Schumer et al., 2011), and a successful DTCZ observatory will take advantage of these developments.
Proxies of Paleoenvironmental Conditions

The geosciences community must continue to carry out targeted efforts to refine existing proxies and develop new proxies, particularly where the level of precision and accuracy—and thus the degree of uncertainty in inferred Critical Zone parameter estimates—can be significantly reduced (NRC, 2011b). These proxies include, but are not limited to the development of additional and improved quantitative estimates of paleoprecipitation, paleowind, paleoseasonality, paleoaridity, and paleo-soil conditions (including paleo-productivity). Geochemical analysis at each DTCZ observatory would require bulk sediment sampling to determine elemental concentrations and sampling of special features for isotopic analysis. From stable C and O isotopes, an array of environmental factors can be quantified, such as mean annual precipitation, mean annual temperature, \( p\text{CO}_2 \), and biomass contributions from C3 and C4 plants. Based on these environmental parameters, as well as paleobiological evidence, paleosol data, and quantitative reconstructions of the sediment-depositing fluids, the climate state is interpretable. DTCZ observatories will contribute significantly to the proxy development critical to TRANSITIONS as a whole.

DTCZ Observatories as 3-D Volumes of Environmental Data

Sites selected as DTCZ Observatories should always link outcrops to their affiliated deposits in the subsurface via a drilling program for collecting core and a geophysics program that continually pushes to improve the technologies for imaging DTCZ sedimentary deposits in three dimensions. In order to collect the necessary core, a deep-time drilling program must be designed to identify, prioritize, drill, and sample key paleoclimate targets—involving a substantially expanded continental drilling program and additional support for the existing scientific ocean drilling program—to deliver high-resolution, multi-proxy archives for the key paleoclimate targets across terrestrial-paralic-marine transects and latitudinal or longitudinal transects (NRC, 2011b). Such a drilling strategy will permit direct comparison of the marine and terrestrial proxy records, contrasting local and regional effects on continents against relatively homogenized oceanic signals. An expanded continental drilling program could reverse a chronic under-sampling of terrestrial (paleosol) records, which can be more sensitive to geographical and latitudinal variations in climate.

Tectonic Analyses

The deep-time record of landscape evolution provided by DTCZ Observatories will require the development of models including realistic crust and mantle rheologies in order to quantify the connections between the Earth’s interior and its surface boundary. Successful reconstruction of the tectonic forcing tied to the sedimentary deposits at these sites will require the application of geohistory analyses and numerical models that define patterns of net subsidence based on the long-term behavior of the Earth’s convecting interior and its moving tectonic plates.

Numerical Modeling of Deep-Time Critical Zones

If the Earth’s surface were simple enough, we could test models for the Critical Zone in the modern world over short time scales and then just extend them to long times to reproduce Earth history. But the Critical Zone is a complex, nonlinear system and models built to predict its evolution do not lend themselves to this style of analysis and testing. Instead system-scale models of the Critical Zone must be tested on the time and space scales over which whole-system behavior is played out, and any reliable general model must reproduce the behavior of ancient Earth states, as well as the modern Critical Zone (NRC, 2010a). Building fully coupled, climate-tectonic, geochemical, ecological-surface
process models will require coordinated development by the geoscience, biology, and atmospheric disciplines and must engage existing numerical modeling initiatives. We envision a suite of models being produced that define a matrix where on one axis is the level of model complexity, on the other axis is the optimal distance/time. Reduced complexity (RC) models, while not suitable for detailed predictive simulation, will be valuable because they are smaller, faster, easier to run than large models, and often more efficient for testing specific hypotheses. Because RC models are typically focused on large-scale interactions, they also offer the opportunity to explore aspects of system dynamics that may be harder to pick out of the details of a high-resolution model. At the 3D and simulation end of the spectrum we must develop components to build Critical Zone model that includes at least an ecoregosphodynamic flow and sediment-transport module, a low-temperature geochemistry module, and a climate-tectonics module. These linked components, as well as the RC models for the ancient Critical Zones, will be built within the Community Surface Dynamics Modeling System (CSMDS) framework. All themes in TRANSITIONS will contribute to the development of these models.

**Landscapes Deliverables in TRANSITIONS**

In order to ensure that DTCZ Observatories generate the deep-time environmental records necessary to yield unique scientific understanding of the Critical Zone response to climate forcing the following set of preliminary deliverables are proposed:

- Develop precise chronologies for existing and new geologic archives of paleoclimate interest that approach the temporal resolutions than are possible in the Pleistocene and Holocene
- Demonstrate that the preservation filter can be precisely quantified by passing DTCZ stratigraphic data backward through the filter to generate accurate statistics of surface kinematics tied to the formative depositional environments
- Obtain proxies for a broad range of surface and atmospheric conditions that are of higher precision and accuracy than currently available through some combination of proxy refinement, proxy development, and multi-proxy studies
- Demonstrate the growth of essential intellectual collaborations between researchers with knowledge of deep-time and modern Earth processes, as well as between DTCZ researchers focused on collection of analytical data and construction of numerical models.
Global change affects biodiversity, agriculture, disease vectors, and thus the ability of humans to adapt. Studies of Recent species and ecosystems are insufficient to address the full range of processes that act to shape biological evolution and ecosystem functioning, and their linkages to climate processes. Modern ecosystems, even when considered globally, fail to sample the environmental and climatic conditions the Earth will experience in the coming decades. Anticipating the physical, chemical, and biological consequences of these ongoing environmental and climatic changes requires intensive study and modeling of past responses to similar challenges in deep time. Only these records provide examples of the ecosystem-environment interactions involving rapid shifts in environmental forcing parameters similar to those predicted for the next 100 years. And only deep time witnesses the biological response to these changes.

Two of the overarching question of TRANSITIONS particularly focus on biological systems:

- What are the ranges of ecosystem response, modes of vulnerability, and resilience to change in different climate states?
- How have climate, the oceans, the Earth’s sedimentary crust, carbon sinks and soils, and life itself evolved together, and what does this tell us about the future trajectory of the integrated Earth system?

These are also primary questions raised by NROES in the research opportunity “Co-Evolution of Life, Environment, and Climate.”

The Deep-Time Record of Climate and Life

The Intergovernmental Panel on Climate Change report (IPCC, 2007) projected that by the year 2100—only two generations into the future—environments on Earth could resemble those of the Eocene, more than 35 million years ago. An increase in global mean temperatures and the acidification of the ocean have the potential to profoundly affect life and ecosystem functions everywhere on the planet. How will the ecosystems that sustain us respond to the coming changes?

The deep-time history of the Earth contains an archive of plant and animal species, communities, and ecosystems that lived under a much wider variety of conditions than can be studied in the present or recent (<2 million years) past, including those expected in the coming centuries. The last greenhouse-icehouse transition occurred more than 30 million years ago, and there were many such transitions earlier in Earth’s geologic history. Therefore, only the deep-time
history of the Earth contains a record of real ecosystems functioning under conditions analogous to those expected in the coming future, a record of natural experiments in deep geological time. Anticipating the physical, chemical, and biological consequences of these ongoing environmental changes requires intensive study and modeling of past responses to similar challenges. Only deep time can provide examples of ecosystem-environment interactions involving rapid shifts in environmental forcing parameters similar to those predicted for the next 100 years.

The deep-time record allows, even requires, multiple scales of investigation of pre-human conditions. "The profound effect of human activities on natural environments and ecosystems is clearly evident, but the consequences are less well understood. In effect, an unintentional global experiment is already in progress. However, the initial conditions of this far-reaching experiment are largely unknown because the onset of human interactions with natural systems—both intentional and unintentional—predates scientific monitoring efforts... There is also no 'control' in this experiment; completely natural habitats are no longer available either locally or globally to use as a benchmark for comparison with habitats that have been modified. The geohistorical record is thus the only source of information on (1) the natural range of environmental variability and ecosystem function before human impact; (2) how ecosystems functioned in the absence of human influence; (3) how ecosystems have responded to progressive human impacts; and (4) which aspects of present day environmental variability and ecosystems are legacies of past societal activity" (NRC, 2005).

The environmental perturbations that can be traced in deep time range from cycles of sea-level rise and fall driven by Milankovitch orbital cycles, to singular catastrophic events such as bolide impacts, to directional changes such as the Proterozoic oxygenation event that drove permanent ecosystem shifts (Box 2). Studies of recent ecosystems alone cannot provide this information. *Deep time contains the results of multiple natural experiments recording perturbation of communities and ecosystems of different diversity levels.*

DETELON (2011)—one of the collaborating initiatives in TRANSITIONS—has provided a roadmap for the study of biological systems that we follow here, with input from other initiatives. DETELON (2011) identified four grand challenges that are parallel to and expand on the TRANSITIONS overarching questions: 1) how do physical and geochemical conditions change for biological systems during and after the transition to a greenhouse world; 2) how do greenhouse worlds accommodate biodiversity; 3) how resilient are ecosystems to the forces of ongoing and predicted environmental change; and 4) how do biota react when confronted by new physical, biological and climatic conditions?

*How do physical and geochemical conditions change for biological systems during the transition to and from a greenhouse world?*

Biological systems must operate within physical and geochemical conditions that change through time. Greenhouse worlds are of particular interest because of the possibility that Earth is entering a greenhouse state owing to human activity. By studying only the modern transitional state (which is not yet a full greenhouse state), we implicitly assume
that the current physical and geochemical conditions are those faced by all biological systems that have entered such states in the past. But this is almost certainly not the case. Thus, in order to understand what might be happening today, we must have much fuller knowledge of the range of conditions under which greenhouse climates were initiated and terminated.

While large, relatively short-term perturbations such as the Paleocene-Eocene Thermal Maximum and the end-Cretaceous bolide impact have garnered much attention as possible models for abrupt change, the complex dynamics of climate suggest that abrupt change may also occur as a threshold or tipping point event, wherein an incremental change on a trend may suddenly change the state of the climate. Understanding such events requires deconvolving the relationships among variables with different response times—we must study the evolution of the Earth-life system prior to state changes, but must compare these results with similar intervals where abrupt events did not occur. Over the past several decades, considerable research effort has focused on specific events, yielding a wealth of information in planning for global change. This information is a critical foundation for a more comparative approach, including the development of formal models. But we have gained great understanding of the processes within these large perturbations at the expense of understanding processes of change during seemingly more static times. We cannot truly predict the future until we understand Earth-life system dynamics in both states.

There are three key issues that must be addressed in order for us to better understand—and predict—what the future might hold:

1. Do greenhouse worlds experience more extreme climate states than are found in an icehouse world?
2. How do improved proxy data alter predictions from the climate models? What effects do extreme climate changes have on the biosphere?
3. What is the proxy record of climatic seasonality as archived in the stratigraphic record?

**How do greenhouse worlds accommodate biodiversity? What are the feedback processes between the climate and the biota?**

Greenhouse worlds have a mixed record for biodiversity. Biodiversity was high during some greenhouse states (e.g., the Cretaceous and Eocene) but low in others (e.g., the Triassic). Clearly, we need to understand what the relationship between greenhouse climates and biodiversity is, how it evolves, and why it is different at different times in Earth history. Put differently, what kind of greenhouse state are we likely to face in the future and how will it affect life on Earth? The key issues are:

1. What regions will become uninhabitable for humanity? What regions will become uninhabitable for economically important animals and plants?
2. How stable will our new greenhouse world be to contingent events (e.g., large-scale unpredictable events)?
3. How will species and ecosystems respond and change?
4. How will a physical world that differs in latitudinal, elevational, and seasonal climatic gradients affect standing diversity, the rate of diversification, behavioral or functional links among organisms, and the geographic distribution of ecosystems?
5. Are greenhouse ecosystems (both terrestrial and marine) more or less productive than modern icehouse ecosystems, and why?
6. Which biophysical feedbacks impact the fluxes of greenhouse gases (e.g., CO₂, methane) or cloud-condensation nuclei beyond those understood in the cool world of the present?

7. Were there feedbacks that generate oceanic anoxia or euxinia under greenhouse conditions that do not operate in the modern world?

8. Based on the responses of organisms to previous severe climate changes, will absolute physiological thresholds limit the habitability of certain regions? Will environmental changes predicted in the greenhouse world surpass the physiological tolerances of certain groups of organisms (e.g., will there be regions in deep oceans where metazoans can no longer live; will there be tropical regions that mammals can no longer inhabit; will oceans be so acidic that no coral reefs can persist)?

**How resilient are ecosystems to the forces of ongoing and predicted environmental change?**

Future ecosystem stability and resilience is an important issue for society. Environmental changes almost certainly influenced human evolution (NRC, 2010b) as well as the evolution of other organisms (DETELON, 2011), but how ecosystems respond to change is not well understood. What advantages, if any, does diversity convey for stability? Ecologists have argued that diverse ecosystems are more stable because the web of biotic interactions resists the negative effects of environmental change. However, from their significantly longer-term perspectives, paleoecologists commonly find that communities are more diverse where stable environments permit subdivision of niches and specialization of biotic interactions—stability permits diversity, not vice versa—and that even the most diverse biotas such as reefs and the deep-sea are destabilized by environmental change (Benton, 2009; Yasuhara et al., 2008).

This cause-versus-effect dichotomy is important: If high biodiversity enhances ecosystem stability, then conserving biodiversity becomes the priority. If, on the other hand, environmental variability is the first-order control on biodiversity, then the preservation of particular settings and environmental remediation (such as de-fragmentation of habitat) become the priorities. This simple dichotomy is of course an oversimplification of complex relationships between ecosystem stability, environmental variability, and biodiversity. Ecosystem stability might, for example, depend on biodiversity in some ecosystems and on environmental stability in others. And differences in scale are almost certainly critical: the stabilizing effects of biodiversity can dominate on the spatially small and temporally short scales of manipulative experiments, and yet be overwhelmed by the destabilizing effects of natural and/or human environmental changes operating on larger scales. Any one-size-fits-all solution by policy makers, or exclusive reliance on observational data having a narrow temporal scope, would thus likely yield mixed results, detrimental in some instances and beneficial in others. Using the geologic record to explore biotic response under a range of past conditions, and thereby revealing basic principles of biologic response and behavior, is the only way to sort out these conflicting influences. The key issues here are:

1. How do responses to major perturbations at the level of species, communities and ecosystems differ and interact?
2. Are there hierarchal differences in the way that species, communities, and ecosystems respond to perturbation?
3. Do the different hierarchal levels influence one another?
4. What is the role of biodiversity in maintaining ecosystem resistance, resilience and persistence?
5. What are the critical biotic and environmental feedbacks that maintain ecosystem stability?
6. What are the critical biotic and environmental thresholds that trigger regime shifts?
7. What is the role of multiple stressors in overcoming resistance and triggering regime shifts?
How do biota react when confronted by new physical, biological, and climatic conditions?

Co-evolution of life and climate is a strong theme in many of the collaborating initiatives. Understanding Climate’s Influence on Human Evolution (2010b) posed the question, “Did climate change shape human evolution, and if so, how? … there is now evidence that several major junctures in human evolution and behavior were coincident with fundamental changes in global and regional climate. As intriguing as these temporal coincidences are, demonstrating a causal linkage between them is a much more challenging and intensive task.”

The key issues here are:

1. How do species, communities, biomes and ecosystems exploit environments, such as newly ice-free regions, hypoxic oceans, or epicontinental seas that are not continuously present on Earth?
2. How do biotic communities assemble and disassemble after major perturbations in the physical environment?
3. How do biotic communities assemble and disassemble after major perturbations to trophic structure?
4. What are the consequences of changes in community composition and organization on ecosystem services, such as organic productivity and recycling efficiency?
5. Do the processes of community assembly and disassembly documented for Quaternary ecosystems differ from those that governed recovery from biotic crises in the deep past?
6. How does environmental change provide opportunities for adoption of innovations by succeeding species and biotic communities?
7. What are the characteristics of species, clades, or functional groups most likely to persist in the face of expected environmental changes?
8. What are the functional traits and biogeographic attributes of lineages that diversify following environmental perturbations or crashes in diversity?
Biology and Environments Deliverables in TRANSITIONS

Following DETELON and other collaborating initiatives, TRANSITIONS will produce critical information needed to answer the overarching questions:

For the physical environment:

- Measure and aggregate proxy data (temperature, moisture, pH, \( p\text{CO}_2 \), and other environmental variables) from the geohistorical record for key greenhouse time periods
- Obtain data for critical regions as specified by models
- Perform climate and biogeochemical simulations, with higher spatial resolution for areas of high density of proxy data
- Perform rigorous model-data comparisons to evaluate agreement and discrepancies
- Conduct simulations with and without feedback processes to evaluate their effects on greenhouse states
- Develop new proxies for climatic and environmental variables that are currently difficult to measure quantitatively (e.g., seasonality, productivity, redox state, continental weathering (erosion, mass flux), carbon burial, and ocean circulation)

For biodiversity:

- Develop plans for data integration that are spatially and temporally explicit, for data quality via standard collection and archiving protocols, and for data accessibility via physical (collection-based) and digital data archives
- Integrate biodiversity data (taxonomic counts, evenness, ecological structure and interactions) for well-documented groups over large spatial scales in both marine and terrestrial records to monitor the biogeographic gradients of greenhouse worlds
- Use evolutionary processes and ecological niche modeling to analyze processes generating greenhouse ecological gradients
- Conduct Earth-system simulations with and without feedback processes and compare results to spatially and temporally explicit records of biophysical state from proxy data for temperature, \( p\text{CO}_2 \), productivity, redox conditions, bioturbation, continental weathering, carbon burial, and ocean circulation
- Collaborate with physiologists to study climatic tolerances of critical groups and to conduct physiologically constrained niche modeling. Compare model results to spatially and temporally explicit data on biogeography in greenhouse worlds

For ecosystem resilience:

- Acquire integrated paleobiological and paleoenvironmental proxy data at high stratigraphic resolution across critical state changes in order to understand the response of ecosystems to environmental forcing
- Investigate and model ecosystem dynamics before, during, and after perturbations to develop and test early-warning indicators of regime collapses and shifts
- Evaluate environmental and ecosystem change at a variety of spatial, temporal, and taxonomic scales using physical data and ecosystem modeling in order to understand hierarchical behavior of complex natural systems
• Build and integrate a database network to link multiple geohistorical data streams in order to test linkages, feedbacks, and thresholds in deep-time ecosystems
• Link physical data (cores, samples, specimens) to the database network and make them available to the geoscience community to reveal new connections
• Increase coordination among paleontologists, ecological modelers, geochemists, stratigraphers, and others studying feedbacks between ecosystems and environmental forcing

*For co-evolution of environment and life:*

• Generate quantitative models of community assembly and disassembly over evolutionary timescales
• Identify the characteristics of groups likely to persist under predicted future environmental conditions
• Identify the temporal origin of innovations versus when they are adopted in the context of biological system change
• Integrate biogeochemical data in order to understand environmental influences, responses, and feedbacks on patterns of ecosystem assembly
• Develop tools to integrate and synthesize archival/museum geochemical, paleontological, and sedimentological data with newly acquired information from field, laboratory, modeling and analytical efforts.
CONCLUSION

TRANSITIONS is a multi-disciplinary, innovative, and integrative initiative that takes full advantage of the broad intellectual strength of the sedimentary geology and paleobiology communities because it constitutes a coalition of well-developed initiatives that represent more than a decade of effort by these communities. It weaves together new science in widely disparate fields to better inform decision makers and society as a whole about climate and environmental change in all its extremes and variations in rate. TRANSITIONS addresses the Earth system as an integrated whole, rather than the sum of various parts, which has been the goal of Earth scientists for decades. The need for this approach is more urgent than ever as humankind faces unprecedented changes in climate, water availability, land use, and resource utilization.

TRANSITIONS will address a number of the research opportunities identified by the recent NROES report (Box 7). A decade-long effort directed toward providing funding for the initiatives in the coalition and bridge funding to allow full integration of parts of the community not currently represented by recent initiatives will answer a long-standing need for sufficient funding to address issues critical to society and of the NROES report for taking advantage of current research opportunities.

IMPLEMENTATION

Many elements of the coalition (DETELON, Conservation Paleobiology, EARTHTIME, Community Sedimentary Model for Carbonate Systems, CSDMS, Continental Drilling, EarthChem, PaleoDB, and New Research in Paleopedology) are either ongoing or brand-new. Among them, they represent most of the skill set that is required to address the overarching questions of TRANSITIONS. Furthermore, initiatives are arising from the more-recent NRC reports cited here. Targeting funding toward those initiatives, with supplemental funding to fill in the gaps, will allow the National Science Foundation to address research opportunities identified by the NROES report, especially “Co-Evolution of Life, Environment, and Climate.” In addition, TRANSITIONS anticipated and fully supports the NROES recommendation for improving quality and access to geochronology laboratories.

Both DETELON and the Landscapes theme recommend approaching implementation of the science in the form of deep-time observatories. This approach has worked well for the Critical Zone initiative. In DETELON’s conception, “each observatory would involve integrated teams of 10-20 paleontologists, sedimentologists, geochemists, stratigraphers, geochronologists, paleoclimatologists, modelers and other geoscientists focusing on questions of significant aspects of the [research]. Each observatory would last for 5-10 years (an initial 5 year grant followed by a possible renewal). Projects would need to integrate existing data sets, develop quantitative, process-based models, as well as plan coordinated field work and analyses. DETELON projects would provide significant opportunities for junior faculty and post-doctoral scholars and include joint training of graduate students.

“Such projects present significant opportunities for education and outreach. The public is fascinated with fossils and the history of life on Earth. DETELON provides a structure to tease out the details of past landscapes, ecosystems, and the abrupt events that have shaped the evolution of life on our planet. The ‘observatory’ component of DETELON can be amplified by scientists working in natural field laboratories, providing an excellent opportunity to engage the public in observing scientists at work and to participate in the process of science and the excitement of discovery.”
This concept would work well for TRANSITIONS as whole, and thus we propose TRANSITIONS deep-time observatories that address the overarching questions through the three themes. However, as recommended by several groups, and by the NROES report, there should be room in the funding for smaller teams of researchers to pursue particularly pertinent intervals and/or areas.

Communication within such a large and diverse community as the practitioners of SGP science has been a challenge. There is currently underway a proposal by the Geological Society of America and the Society for Sedimentary Geology for an office of deep-time studies ("STEPPE") that will greatly facilitate this communication, along the lines of PAGES and DOSECC, which publish e-newsletters and maintain links to resources. If this office is funded and staffed properly, it will go a long way toward achieving some of the goals of “interoperability” in the broadest sense of the word within SGP science. Indeed, this office could play a key role in helping the community meet the research opportunities identified by the NROES panel.

**Beyond Sedimentary Geology and Paleobiology**

The collaboration described in this initiative must be broad, with sedimentary geology and paleobiology at the core. Atmospheric, oceanic, and biologic sciences must clearly be major players in this effort as well. Computer scientists, statisticians, and mathematicians will be needed to help optimized modeling, model integration, and database utilization. Social and behavioral scientists will be required to help analyze impacts on decision-making and analysis of societal response to human evolution and environmental change, and engineers will be required to implement practical applications that may arise from analysis of trajectories of environmental change.

Many of the initiatives have recognized the efficacy of establishing deep-time observatories. Linkages with current observatory networks, such as the NSF Critical Zone Observatory (CZO) and Long Term Ecological Research (LTER) programs, those identified within the Critical Zone Exploration Network (CZEN), and those proposed through the National Ecological Observatory Network (NEON), are natural. Creating a seamless continuum of knowledge about Earth processes from deep-time to the present is inherent in this exercise and critical for understanding Earth process behaviors. The underutilized deep-time portion of this continuum is critical for this transformational way of looking at the Earth.

Thus, this initiative may be expanded as an NSF-wide initiative to explicitly enhance collaboration in the broader scientific community.
Together, the science stressed in the three TRANSITIONS themes address all the research opportunities indicated in the NROES report in “Co-Evolution of Life, Environment, and Climate”, including the modalities in which the research can be best carried out. The NROES report states that “The deep-time geological record has provided a compelling narrative of changes in Earth’s climate, environment, and evolving life, many of which provide analogs, insight, and context for understanding human’s place in the Earth system and current anthropogenic change” and “Real or virtual paleoclimate/deep-time initiatives can be pursued that draw together a broad community of researchers asking critical questions about key intervals in time or key processes through time that could be evaluated using cutting edge environmental proxies, paleobiological methods, and numerical models”. The NROES report goes on to recommend that “EAR should develop a mechanism to enable team-based interdisciplinary science-driven projects involving stratigraphy, sedimentology, paleontology, proxy development, calibration, application, geochronology, and climate modeling at highly resolved scales of time and space to understand the major linked events of environmental, climate and biotic change at a mechanistic level. Such projects could be expected to be cross program and cross directorate.” This is the core of the TRANSITIONS initiative. Every Finding by NROES in this research opportunity was already addressed in TRANSITIONS: Drilling, proxy development, high-precision geochronology, biotic response to change, and paleoclimate modeling.

Deep-Time Climate and Landscapes also address some of the research opportunities identified by the NROES report in “Interactions Among Climate, Surface Processes, Tectonics, and Deep Earth Processes”. The NROES report states that “Understanding the interplay among climatic, geomorphic, and geological/tectonic processes in governing Earth surface processes and landscape evolution requires integrating processes across a wide range of temporal and spatial domains. Addressing the most compelling problems and Grand Challenges under this theme will involve studies of the evolution and dynamics of particular physiographic regions over orogenic timescales and studies to address how to scale up mechanistic, process-based understanding of short-term processes to quantitatively characterize and constrain system behavior and interactions over longer timescales” and that “Developing geomorphic transport laws that account for climate and the role of biota to describe and quantify river and glacial incision, landslides, and the production, transport, and deposition of sediment are needed to address how to integrate the effects of event-based processes into long-term system behavior. Measuring and modeling landscape evolution under diverse and varying climatic conditions, with an emphasis on identification of physiographic signatures of climate and climate variability, will allow for the identification of thresholds of landscape response and the limits of landscape resilience.”

The Landscapes and Biology and Environment themes also address research opportunities in “Coupled Hydrogeomorphic-Ecosystem Response to Natural and Anthropogenic Change”. The NROES report noted that “The ways in which ecosystems and landscapes have co-evolved through time and the nature of their coupled response to human activity and climate change present tremendous opportunities for advancing our understanding of Earth surface processes.” TRANSITIONS brings the deep-time perspective to this problem by broadening the range of landscape-ecosystem interactions that can be studied. NROES further noted that “Critical zone research contributes understanding essential to addressing larger-scale questions concerning co-evolution of landscapes and ecosystems and landscape response to disturbances (natural or anthropogenic).” Again, TRANSITIONS brings the deep-time perspective to this problem by broadening the range of landscape-ecosystem interactions that can be studied.

Finally, all three science themes of TRANSITIONS contribute to the NROES research opportunity, “Biogeochemical and Water Cycles in Terrestrial Environments and Impacts of Global Change”. The NROES report stated, “Among the key research opportunities is development of a theoretical framework for the interactions among hydrological, geochemical, geomorphic, and biogeochemical processes in the critical zone, including the roles of climate and geological setting that have heretofore been only loosely constrained.” TRANSITIONS provides the deep-time perspective on this, expanding the range of possible states that can be studied and incorporated into models.
Broader impacts

The initiatives that are involved in TRANSITIONS have all addressed the broader impacts of the research extensively. TRANSITIONS fully supports and intends to participate in the education of undergraduate and graduate students; outreach to schools, communities, and policy makers; and participation in workforce development. The expectation is that proposals submitted under TRANSITIONS would address these issues, and TRANSITIONS itself will result in a body of work that can be synthesized for greater public and policy maker understanding of global climate and environmental change.


## APPENDIX I


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<thead>
<tr>
<th>Title</th>
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<td><strong>CHRONOS Strategic Plan; CHRONOS— Integration of Chronostratigraphic Databases for the 21st Century</strong></td>
<td>Cervato; Ogg, Sikora</td>
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<td><strong>Community Sedimentary Model Science Plan for Sedimentology and Stratigraphy; Sedimentary Systems in Space and Time (these became CSDMS, <a href="http://csdms.colorado.edu/wiki/Main_Page">http://csdms.colorado.edu/wiki/Main_Page</a>)</strong></td>
<td>Syvitski, Paola, Slingerland; Nummedal et al.</td>
<td>1999; ongoing</td>
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<td><strong>Paleobiology Database (PaleoDB, formerly known as PBDB; <a href="http://www.paleodb.org/cgi-bin/bridge.pl">http://www.paleodb.org/cgi-bin/bridge.pl</a>)</strong></td>
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<td><strong>EARTHTIME—Calibration of the Geological Timescale (<a href="http://www.earth-time.org/">http://www.earth-time.org/</a>)</strong></td>
<td>Erwin et al.</td>
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<td><strong>New Research Opportunities in Paleopedology</strong></td>
<td>Driese</td>
<td>2011*</td>
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<td><strong>DETELON; Future Research Directions in Paleontology</strong> (<a href="http://detelon.org/">http://detelon.org/</a>)</td>
<td>Erwin, Bottjer; Bottjer</td>
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<td><strong>Understanding Earth’s Deep Past—Lessons for Our Climate Future</strong></td>
<td>NRC report, Montanez et al.</td>
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<td><strong>Grand Challenges in Sedimentary Geology, Geochemistry and Paleobiology</strong></td>
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<td><strong>Landscaes on the Edge: New Horizons for Research on Earth’s Surface</strong></td>
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<td><strong>GeoSystems: Probing Earth’s Deep-Time Climate &amp; Linked Systems</strong></td>
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<td>Maples et al. (developed from an NRC study and recommendations)</td>
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<td>unknown</td>
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†Different versions of the same efforts are separated by semicolons, as are their authors and years of appearance, if known. The newest versions are listed first.
APPENDIX II

It is important to emphasize that the SGP community has worked toward TRANSITIONS for many years, and that this science plan represents a coalition of the efforts of individuals and subsets of this broader community. In fact, the need for deep-time records was argued as early as 1994 in the report, “Applications of Sedimentary Geology and Paleontology into the 21st Century” (Clifton and Ashley, 1994). The community is very large and very diverse. Thus, for logistical reasons, the community has forwarded several smaller initiatives, representing a tremendous amount of thought and discussion. As indicated in Part I and in Parrish et al. (2011), the striking feature of all these initiatives is the unanimity of purpose—to understand the full range of Earth processes—and identification of needed tools: continental drilling, geochronology, and community databases and archives.

Each theme of TRANSITIONS—Deep-Time Climate, Landscapes, and Biology and Environments—requires collaboration among these efforts. Below, we briefly describe each collaborating initiative and indicate where each plays a primary role in TRANSITIONS4. Much of the material in the following is taken from the original reports. The full reports for each initiative, except the NRC reports, are available at http://www.uidaho.edu/sci/geology/sgp-workshop. NRC reports can be accessed through the National Academies Press website: http://www.nap.edu/.

GeoSystems: Probing Earth’s Deep-Time Climate and Linked Systems

Contributor to all three themes.

GeoSystems arose from NSF-sponsored workshops in 2003 and 2004, and a joint NSF-DOSECC drilling workshop in 2005 that focused on the importance of the deep-time perspective for understanding the complexities of Earth’s atmosphere, hydrosphere, biosphere and surficial lithosphere using climate as the nexus. These community-based workshops brought together geoscientists from various subdisciplines (notably sedimentary geology and geochemistry, paleobiology, and climate modeling) to emphasize that Earth’s climate operates on a continuum of temporal, spatial and parametric scales, as a fundamental mediator of change. The deep-time geologic record preserves numerous proxies of past climate states and transitions, many of which are far more extreme than those archived in instrumental, historical, or Quaternary records. The GeoSystems workshops were motivated strongly by the realization that aspects of our modern climate are returning to a state last known from deep time. Hence understanding the ranges, rates, and processes responsible for past extremes in global systems is urgently needed for predicting potential impacts of future changes. Processes such as extinction and evolution of species, orogenic and volcanic events, sea-level change, and the like operate over a variety of time scales and are complexly entwined with climatic trends, many of which also operate over a variety of time scales and must be viewed within the context of the deep-time perspective to achieve a holistic understanding of Earth’s climate and related systems.

Funding for the 2003-2004 workshops was provided by grants (EAR-0323841, EAR-0427093) from the National Science Foundation through the Geology and Paleontology Program (Earth Sciences Division), Paleoclimate Program (Atmospheric Sciences Division), and the Division of Polar Programs, with major contributions from DOSECC for the 2005 drilling workshop.

4 It is important to emphasize here that the initiatives discussed are the most recent, still-active initiatives of those reviewed by Parrish et al. (2011). In fact, the unanimity of purpose within the community extends back 10 years, although some of the older initiatives are no longer active.
This initiative will play a major role in understanding the mechanisms and feedbacks in climate and linked systems, climate and ecosystem function in Earth modes that are not analogous to the modern or recent past (e.g., greenhouse), terrestrial-marine climate linkages by recovering new records from continental drilling (and outcrops), and applying high-resolution geochronology and quantitative climate proxies coupled with new global climate models. All of these components directly address the key questions outlined above, and therefore an NSF-funded Geosystems program would significantly advance our understanding of the Earth-life system in deep time.

DETELON (Deep Time Earth-Life Observatory Network)

*Contributor to all three themes.*

Earth’s 4.5-billion-year history provides natural observatories in which to explore critical questions about the processes that impact the biota, the global environment, and climate. Studies in deep time provide a unique perspective on the processes driving the Earth-life system that cannot be studied in the present or in recent history. The Earth is predicted to transition from an icehouse to a greenhouse climate state by 2100. Only through studies of the Earth-life system in deep time will society gain an understanding of the effects of the climate of 2100 on life and how life will transition to these conditions.

In response to the need for these societally critical deep-time analyses, the Paleontological Society, in conjunction with other paleontological organizations, organized two recent workshops to develop the concept of a Deep Time Earth-Life Observatory Network (DETELON), a program designed to address these problems in a coordinated fashion. Building off the success of the Long-Term Ecological Research Network, and similar efforts, the Deep Time Earth-Life Observatory Network is proposed as a program that would allow focused efforts by teams of scientists to increase the pace towards solution of highly significant problems for society within a systems framework. A science plan for this program was produced as the result of the second DETELON Workshop on February 2-4, 2011, which was sponsored by the National Science Foundation.

DETELON seeks to understand climate-ecosystem linkages in deep time, particularly in a warming world, through the application of intensive multidisciplinary studies to areas and/or geologic time intervals that record critical transitions in Earth-systems processes, such as transitions to and from greenhouse worlds. DETELON funding would provide a cohesive multidisciplinary approach to answering the key questions of deep time studies, with direct relevance for understanding near-future climate change, as well as helping to train the next generation of the geoscience workforce.
Continental Drilling

*Contributor to all three themes as an essential tool.*

Many fundamental and exciting scientific problems can only be solved by drilling. Problems for which drilling is essential encompass a wide range of *themes*: global environmental and ecological change; geodynamics, including related earthquake and volcano hazards; the geobiosphere; and natural resources and related environmental concerns. Intellectually coherent *topics* lie within these themes or cross theme boundaries. Themes include geologic records of coupled climate, sea level, and environmental change; history of the magnetosphere; melting processes of mantle plumes and their interaction with continental crust; fault and earthquake source mechanics; evolution of volcanic systems; extraterrestrial impact structures and processes; subsurface ecosystems; ground water; hydrothermal processes, geothermal energy and ore deposition; and CO$_2$ sequestration, to mention a few. Drilling is necessary to access, for example, key structures, rock bodies, and active processes that are not exposed, but lie within range of the drill bit; time series where surface outcrops are unavailable or not usable; or fluids and microbes at depth.

The future of scientific drilling was considered at a workshop in Denver, Colorado, on June 4 and 5, 2009. The workshop emphasized the future of drilling under US auspices, although it had international participation. The goal of the workshop was to identify key scientific issues that could be addressed by drilling and to foster new scientific drilling projects within the US-based community, in cooperation with the International Continental Scientific Drilling Program (ICDP).

Drilling into continental sediments and rocks complements drilling in ocean basins. The continental record potentially extends our knowledge of deep time to the Archean, while ocean drilling generally provides information only back to the age of the oldest oceanic crust. Continental drilling can elucidate uniquely continental processes and structures, as well as provide alternate but complementary views to observations made in the oceans. However, many problems require drilling in both the continental and oceanic realms, so cooperation and coordination between the continental and marine drilling community is critical.

A serious continental drilling campaign is necessary to recover records for the studies that will be carried out in TRANSITIONS. Current funding lines within NSF are not appropriate for the scale of resources to undertake continental drilling projects, and we are already behind Europe and China in this respect. Funding a specific continental drilling program would allow the development of critical deep-time records necessary for studies proposed by Geosystems, DETELON, and other initiatives.
EARTHTIME and EarthChem

Contributors to all three themes in providing temporal control for events and records.

These are both critical ongoing initiatives. EARTHTIME has sought to bring together all interested members of the geochronology, paleontology, and stratigraphic communities to seek means of expediting the high-precision calibration of Earth history and its associated processes and products via inter-disciplinary collaboration and intra-disciplinary cooperation. EARTHTIME takes advantage of recent developments in geochronology and in stratigraphic correlation and proposes that, for the first time, it will be possible to calibrate the entire geologic timescale to better than 0.1% back at least to the beginning of the Phanerozoic, 542 million years ago. This effort will require about a decade of focused work; unprecedented cooperation between different geochronological laboratories to resolve inter-laboratory calibration, sample handling and data-analysis issues; and community-wide involvement of stratigraphers, geochronologists, geochemists, magnetostratigraphers, and paleontologists.

The effort will require allocation of new funding to new and existing labs so that dedicated personnel and equipment can be brought to bear on the project. The payoff of this effort is enormous, for when combined with CHRONOS and other new initiatives, it will provide a new temporal stratigraphic framework for geoscience research. This will allow us to pose a new level of increasingly sophisticated questions related to the evolution of the Earth. Naturally, this effort will require the training of a new generation of students and researchers that can interact with all sub-disciplines and be equally comfortable dealing with geochronological and stratigraphic data.

The EARTHTIME workshop at the National Museum of Natural History was held 3-4 October, 2003, to gauge community support for such a coordinated effort, identify the opportunities and challenges in producing a highly calibrated geologic timescale, and to discuss the community needs to deliver on this ambitious project. In preparing for the workshop, the conveners developed a name and a webpage for this initiative, dubbed EARTHTIME (see www.eaps.mit/earthtime/).

EarthChem is a community-driven project to facilitate the compilation and dissemination of geochemical data of all types. Among other goals, the initiative strives to standardize databases to maximize their usefulness to the geologic community at large. The project is active at building a home for future data contributions by working with authors, societies, and publishers as well as government organization. In addition, the EarthChem project responds to community needs to facilitate compiling and serving data.

A recently identified community need is in the area of geochronology. At the GeoEarthScope town hall meeting held in association with the 2006 GSA Annual Meeting in Philadelphia, attendees discussed the necessity of a home for geochronology data collected by that project. Consensus opinion of attendees and organizers was that EarthChem should be the group to provide data management for data collected in association with GeoEarthScope, storing and serving geochronological data submitted by participating facilities. Such a management system would be useful to other workers in geochronology. EARTHTIME, for example, strongly endorses EarthChem’s leadership in this regard and will work to encourage members to contribute data. This emphasis was endorsed by the EarthChem advisory board at its 2006 annual meeting.
Current EARTHTIME funding has necessarily focused on increasing analytical precision of geochronologic methods, cross-calibrating different methods, and providing improved inter-laboratory standards and calibration. These improvements have been absolutely critical, but do not replace funding for developing empirical geochronologic records from key times of Earth history. Funding of a successor initiative to EARTHTIME specifically tailored to the NROES and TRANSITIONS goals would allow the development of high-resolution geochronologic records that are a necessary precursor to studying paleoclimatic and paleoecological changes in deep time. If these future analyses focus on stratigraphic sections that contain these important paleoclimatic and paleontologic records, they will directly help answer the key questions posed in this report.

**New Research in Paleopedology**

*Contributor to all three themes.*

The “deep-time” (i.e., pre-Quaternary) pedology community, which is engaged in the study of fossil soils (paleosols), is currently poised to make significant new contributions to reconstructions of environmental conditions interpreted from paleosols preserved in terrestrial stratigraphic successions, providing valuable insights on past climate, landscapes, vegetation, and atmospheric chemistry. The paleopedology community, as part of the broader sedimentary geology and paleobiology scholarly community, shows potential for significant new growth in several areas: (1) refinement and calibration of existing paleoclimate proxies, as well as development of new proxies from surface (modern) soil systems useful for interpreting changes in environmental conditions recorded in paleosols, including precipitation amounts and seasonality, as well as temperature, biogeochemistry, and reconstructed colloidal soil properties, (2) development and refinement of geochemical proxies useful for estimating changes in paleoatmospheric chemistry, especially $pCO_2$ and $pO_2$, (3) interpretations of changes in terrestrial biotic productivity and in floral and faunal compositions, (4) understanding linkages between paleosols forming within fluvio-lacustrine depositional systems and their climatic, tectonic, eustatic and autocyclic forcing mechanisms, and 5) using paleosols to test veracity of new climate and energy-balance models.

An assembled group numbering 42 registrants (27 Ph.D. professionals and 15 students), plus 2 National Park Service geologists, convened in a workshop held at Petrified Forest National Park near Holbrook, in northeastern Arizona, from September 22-25, 2010. The workshop focused on specific paleopedology subjects related to identifying: a) the current state of knowledge, and b) future research opportunities.

An SEPM Special Publication (SP) volume, “*New Frontiers in Paleopedology and Terrestrial Paleoclimatology*”, is in press.
Paleoclimate and Human Evolution

Contributor to all three themes

This initiative can contribute to and benefit from TRANSITIONS by helping to bridge the deep versus “shallow” time gap. The NSF Workshop in 2005, “Paleoclimate and Human Evolution” made a strong call for the necessity of understanding the full range of Earth system behaviors, which is the focus of TRANSITIONS. The paleontological record (including humans) and geological records are indispensable for understanding how ecosystem function on various timescales and how biodiversity and habitats are assembled perturbed and rebuilt. The workshop was followed by “Understanding Climate’s Influence on Human Evolution” (NRC, 2010b). The report called for (1) a major investment in climate modeling experiments for the key time intervals and regions that are critical for understanding human evolution and (2) for a comprehensive, integrated scientific drilling program in lakes, lake bed outcrops, and ocean basins surrounding the regions where hominins evolved.

A Joint Program Planning Group composed of ICDP (International Continental Scientific Drilling Program and IODP (Integrated Ocean Drilling Program) was then established charged to plan an integrated onshore, lake, and ocean drilling program that would dramatically enhance scientific understanding of how past climates may have influenced the early stages of human evolution. The joint drilling program recognizes the high scientific value and widespread societal interest in understanding how, or whether, climate influenced the early stages of human evolution on the African continent. Four drilling sites have been approved in East Africa. The collaboration with this paleoclimate and human evolution initiative would directly address questions about ecosystem-climate linkages in the geologic past. Only deep time provides analogous climate events that are fast enough and of high-enough magnitude to compare with modern and near future climatic events.

Paleobiology Database (PaleoDB), MacroStrat, and GeoStrat

Contributors to Biology and Environments and Landscapes, respectively

One of the critical tools identified by the SGP community for progress on the overarching questions (Parrish et al., 2011) is the maintenance, access to, and integration of community databases. The importance of such databases, however, is highlighted by the major push by NSF to construct a global integrated database, called EarthCube. This is not an easy problem because of the complexity and diversity of the data required to understand Earth processes in deep time (and this complexity and diversity will be orders of magnitude larger in EarthCube), and numerous attempts have been made over the years to construct such databases, with varying success (GEON, CHRONOS, etc.). One of the most successful such efforts is the Paleobiology Database (PaleoDB, formerly known as PBDB). New efforts toward stratigraphic databases are MacroStrat, which takes a relatively low-resolution, quantative approach to macrostratigraphy, which includes records of igneous rocks and other events. GeoStrat provides high-resolution stratigraphic records more suitable for detailed, high-resolution studies of the kind that will be needed to compare deep-time climatic events to those in more recent times.
The Paleobiology Database (PaleoDB; http://paleodb.org/cgi-bin/bridge.pl) is a public resource for the global scientific community. It has been organized and operated by a multi-disciplinary, multi-institutional, international group of paleobiological researchers. Its purpose is to provide global, collection-based occurrence and taxonomic data for marine and terrestrial animals and plants of any geological age, as well as web-based software for statistical analysis of the data. The project’s wider, long-term goal is to encourage collaborative efforts to answer large-scale paleobiological questions by developing a useful database infrastructure and bringing together large data sets.

Macrostrat Beta 0.3 (http://macrostrat.org/about.php) is the initial public, graphical interface for a comprehensive relational database currently containing 31625 stratigraphic units and more than 90,000 attributes (radioisotopic ages, lithologies, economic uses, etc.). Macrostrat is intended to become a community-driven platform for macrostratigraphy, which facilitates the rigorous testing of hypotheses related to the spatial and temporal distribution of sedimentary, igneous, and metamorphic rocks and proxy data extracted from them. It is also meant to facilitate teaching in the Earth sciences.

GeoStrat targets the next generation of data management for field- and laboratory-based science. All data associated with all research can be accessed in their most granular, discrete form while maintaining the attribution of each bit of data to its original author. These data will be openly accessible after a publication moratorium period. GeoStrat will have seamless links from the structured databases to publications. This will allow future users to easily move from the published paper to the data and metadata behind the publication and just as easily utilize these data in their ongoing research. GeoStrat will take a thesaurus approach to terminology; this increases the technological challenges, but better supports the integrity of the knowledge behind the data. For example, some geologic maps may be “edge-matched” with units, their ages and descriptions uniform across all maps - but only at the regional to global scales. At the quadrangle scale or larger, it is the differences among maps that carry the meaning as these differences reflect the interpretations of the authors. In short, the system will not overly impose its design restrictions on the scientist.

**Community Surface Dynamics Modeling System (CSDMS) and Community Sedimentary Model for Carbonate Systems (CSMCS)**

**Contributors to all three themes**

The Community Surface Dynamics Modeling System (CSDMS) is ongoing and should be continued. CSDMS provides the cyber-infrastructure for the development, distribution, archiving, and importantly the integration of the suite of numerical models that define the Earth’s surface—the ever-changing, dynamic interface between lithosphere, hydrosphere, cryosphere, and atmosphere. CSDMS is also the virtual home for a diverse community of experts who foster and promote the modeling of earth surface processes, with emphasis on the transport and sequestration of water, sediment and solutes, across landscapes and sedimentary basins.

Community Sedimentary Model for Carbonate Systems is intended to be a complement to CSDMS for carbonate systems. Developing predictive models of carbonate systems has important implications for monitoring and managing global climate change affecting societies around the world. Carbonate sediments and rocks form an important part of the global carbon cycle. More than 80% of Earth’s carbon is locked up in carbonate rocks. Almost all of the remainder is in the form of organic carbon in sediments. About 0.05% of Earth’s carbon is present in the ocean in the form of the carbonate and bicarbonate ions and dissolved organic compounds, whereas 0.0008% is tied up in living organ-
isms, and about 0.002% is in the form of CO$_2$ in the atmosphere. Carbonate rock is the primary ultimate sink for CO$_2$ introduced into the atmosphere.

Throughout most of Earth history, precipitation of mineral carbonate has been closely linked to the metabolism and activities of living organisms. An important but often neglected part of understanding the carbon cycle requires that we understand how mineral carbonate is produced, how it accumulates into sedimentary deposits, how it is altered after burial, and how it is recycled back into mobile chemical species.

Although we have learned a lot about carbonate fixation, deposition, and dissolution in open ocean deep-sea environments, our knowledge of the rates of formation of mineral carbonate in shallow waters remains rudimentary. Knowledge of the changes of rates of deposition and dissolution with rises and falls in sea level associated with climate change is largely speculative and becomes increasingly uncertain for the more distant geologic past. A better understanding of these processes is essential to progress in understanding the effects of alterations of the carbon cycle resulting from the introduction of fossil fuel CO$_2$ into the atmosphere.

Reefs and carbonate platforms, in general, are sensitive climatic indicators, are “global sinks of carbon”, and contain important records of past climate change. They are reservoirs of biodiversity, and provide critical fisheries habitat. Changes in global climate dramatically affect carbonate systems and the peoples that live amongst them. Rising sea level heightens erosion of islands, reduces shoreline stability, causes marine flooding of coastal freshwater aquifers, and displaces indigenous people (e.g., South Pacific). Increased global CO$_2$ causes ocean acidification, which in turn affects the ability of many modern carbonate-producing organisms and processes to function optimally.

Ancient carbonate platforms and systems play a significant role in the global economy. They are the raw material for construction, both as building stone and as the parent material required for manufacture of cement. Through their high permeabilities and porosities, carbonate rocks serve as important aquifers and as petroleum reservoirs. They are major freshwater aquifers critical to the health of urban and rural areas (e.g., Edwards Aquifer, central Texas, USA), and in many island nations, the primary source of fresh water. Likewise, carbonate rock reservoirs host more than half of the world’s petroleum. Finally, carbonate systems that fringe island nations across the planet form the basis of tourism and food for island peoples.

In response to the needs discussed above, an NSF-sponsored workshop on carbonate systems and numerical systems modeling was held in late February, 2008, at the Colorado School of Mines. The purposes of the workshop were to identify grand challenges for fundamental research on ancient and recent carbonate systems, and to identify promising areas for advancing the next generation of numerical process models to enhance our ability to meaningfully and accurately model carbonate systems.
Earth’s environment is in constant flux. Driven by physical processes, biological processes (now including the effects of human activity), and their interactions, incessant changes occur at virtually all temporal and spatial scales. Recent research has greatly increased scientific understanding of the nature and pace of current and past physical environmental changes, and is now also yielding information on the complex ways biological systems contribute to and react to environmental change. Given the diverse roles played by biota in Earth’s environmental system, as well as the direct importance of wild and managed biological resources to human welfare, a deeper understanding of the ecological dynamics of environmental change constitutes a critical scientific priority.

Longer-term historical perspectives are essential for answering a host of questions about the ecological dynamics of present day environmental systems and about feedbacks between biotic systems and environmental change, including climate change. The geologic record—the organic remains, biogeochemical signals, and associated sediments of the geological record—provides unique access to environmental and ecological history in regions lacking monitoring data and for periods predating human impacts. It also provides information about a broader range of global environmental conditions than exist today, as well as insights into biological processes and consequences that are expressed only over longer time intervals and the opportunity to discover general principles of ecological organization. Understanding how ecological processes scale up from short-term to evolutionary time frames is critical to a full understanding of the biotic response to environmental change, and thus to developing sound policies to guide future management. Advances during the past 10-20 years have transformed the ability of Earth scientists to extract critical biological and environmental information from the geologic record. These advances at the interface of earth and biological sciences—combined with a greatly improved capacity for accurate dating of past events, the development of high-resolution timescales, and new techniques for correlation—set the stage for this assessment of research priorities in geohistorical analysis of biotic systems.

The committee sees three directions as most promising for significant advances and identifies these as initiatives with the highest scientific and policy value: (1) using the geologic record as a natural laboratory to explore biotic response under a range of past conditions and thereby revealing basic principles of biological organization and behavior; (2) using the record to enhance our ability to predict the response of biological systems to climate change in particular; and (3) exploiting the relatively young geologic record to evaluate the effects of anthropogenic and non-anthropogenic factors in the variability of biotic systems.
Conservation Paleobiology

*Contributor to Biology and Environments and Deep-Time Climate.*

Although the Conservation Paleobiology report stresses using relatively young records to acquire long-term perspectives on present-day species and ecosystems, beyond the timeframe of direct human observations, it contributes to and benefits from TRANSITIONS by helping bridge the deep versus “shallow” time gap. Conservation Paleobiology makes a strong call for understanding the full range of Earth system behaviors in order to develop truly general models of biological vulnerability and resilience, which is a key focus of TRANSITIONS.

Climate change is one of the major stressors on ecosystems today, along with habitat alteration and fragmentation, species loss through exploitation and other removal, the spread of non-native species, and the alteration of biogeochemical cycles, for example via cultural eutrophication. The paleontological and geological records are indispensable for building a general understanding of how ecosystems function across a range of timescales and how biodiversity and communities are assembled, perturbed, and rebuilt. Only geohistorical records have sufficient reach in time to determine past trajectories of change in biological diversity, and to determine—via correlation, comparative analysis, and modeling—the drivers of those trajectories. The rates and magnitude of that change can inform managers and policy makers and steer efforts more effectively given limited time and resources.

Collaborations and cross-training of students between the earth sciences and biological sciences will be critical to developing the theory, methods, and human capital needed to “use the past to manage for the future”. Support for the discipline of Conservation Paleobiology also provides research opportunities in Earth Sciences that are consonant with those of TRANSITIONS, including model validation, the analysis of physical-biological coupling among the atmosphere, hydrosphere and biosphere, and methodological challenges such as scaling issues when merging instrumental or neobiological and paleobiological data, methods of inter-correlation and age-calibration of data, the transformation of information associated with burial and fossilization, and proxy development for environmental and biotic conditions.
TRANSITIONS

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Conservation Paleobiology, Geological Record of Ecological Dynamics, and Landscapes on the Edge: Susan Kidwell, University of Chicago
Continental Drilling: Anthony Walton, University of Kansas
DETELON: David Bottjer, University of Southern California; Douglas Erwin, National Museum of Natural History; Philip Gingerich, University of Michigan
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PaleoDB and MacroStrat: Shanan Peters, University of Wisconsin-Madison (participation via Skype)
Geosystems: Gerilyn Soreghan, University of Oklahoma
New Research in Paleopedology: Lee Nordt, Baylor University; Paul McCarthy, University of Alaska
Paleoclimate and Human Evolution: Gail Ashley, Rutgers University
(Paleobiology Database was not represented specifically)

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David Feary, Arizona State University
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Lindsey Henry, University of Wisconsin-Milwaukee*
Jack Hess, Geological Society of America (discussing the proposed deep-time studies office)
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Alan J. Kaufman, University of Maryland
Isabel Montanez, University of California, Davis
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Funding for the TRANSITIONS workshops and associated activities was provided by grants from the National Science Foundation. These grants (EAR-1129111 and EAR-1157282) were administered through the Sedimentary Geology and Paleobiology Program in the Earth Sciences Division.

Photo descriptions and credits

p. 4 Coal bed overlain by epsilon crossbeds, Nanushuk Formation (Cretaceous) North Slope, AK.  
*Photo by Judy Parrish*

p. 6 Section near Moab, UT, from bottom to top: Cutler Formation (Permian), Moenkopi Formation (Triassic), Chinle Formation (Triassic), Wingate Sandstone (Triassic-Jurassic).  
*Photo by Judy Parrish*

p. 9 Triassic section in Ischigualasto Basin, Argentina, from bottom to top: upper part of the Los Rastros Formation, Ischigualasto Formation, Los Colorados Formation.  
*Photo by Judy Parrish*

p. 10 Flooding in Iowa, 2009.  
*Photo by Judy Parrish*

p. 12 Fossil leaves from the Nanushuk Formation (Cretaceous), North Slope, AK.  
*Photo by Robert A. Spicer*

Box 2 Strelly Pool Chert (Early Archaean), Pilbara Craton, Western Australia; Mt. Roe Basalt (Late Archaean), Western Australia; Ramsay Lake diamictite of the Huronian Supergroup (Paleoproterozoic), southern Canada; tri-lobed Ernietta fossils (Ediacaran), Aar Farm, southern Namibia.  
*Photos by Alan Jay Kaufman*

Box 3 Big Basin Member of the John Day Formation (Eocene-Oligocene), Painted Hills, OR.  
*Photo by Mark Schmitz*

p. 17 Core of the Shublik Formation (Triassic), North Slope, AK.  
*Photo by Judy Parrish*

p. 18 Thin section of fossil wood from the Nanushuk Formation (Cretaceous) North Slope, AK.  
*Photo by Judy Parrish*

p. 20 Cretaceous section at Book Cliffs, UT, Mancos Shale at the bottom overlain by the Blackhawk Formation.  
*Photo by Judy Parrish*

Box 5  
*Photo by Philip D. Gingerich*

p. 28 Alaska Highway, SW Yukon Territory.  
*Photo by Judy Parrish*

p. 29 The Teepees, Chinle Formation (Triassic), Petrified Forest National Park, AZ.  
*Photo by Judy Parrish*

p. 33 Gleyed paleosol, Chinle Formation (Triassic), Petrified Forest National Park, AZ.  
*Photo by Judy Parrish*

p. 36 Permian coral, southern China.  
*Photo by Judy Parrish*

p. 37 Bridge Creek Limestone (Cretaceous) near Pueblo, CO.  
*Photo by Judy Parrish*

p. 40 Cluster of *Buchia* shells, Naknek Formation (Jurassic), Katmai National Park, AK.  
*Photo by Judy Parrish*

p. 46 University of Idaho and Washington State University field camp students, near Dillon, MT.  
*Photo by Judy Parrish*