UNDERSTANDING CLIMATE'S INFLUENCE ON HUMAN EVOLUTION

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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Committee on the Earth System Context
for Hominin Evolution

Board on Earth Sciences and Resources

Division on Earth and Life Studies

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OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

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International Standard Book Number-13: 978-0-309-14838-2 (Book)
International Standard Book Number-10: 0-309-14838-3 (Book)
International Standard Book Number-13: 978-0-309-14839-9 (PDF)
International Standard Book Number-10: 0-309-14839-1 (PDF)

Library of Congress Control Number: 2010921862

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet http://www.nap.edu

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Printed in the United States of America.

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Preface

Understanding the origins of humanity has long been one of our foremost intellectual pursuits, and one that greatly interests the general public as evidenced by museum attendance and by numerous media productions and general interest publications. Progress toward an improved understanding of our heritage is a continuing challenge for the scientific community, requiring advances in a range of disciplines that include archaeology, anthropology, geology, biology, oceanography, and genetics, and particularly research advances in areas where two or more of these fields intersect. One of the key questions in this interdisciplinary quest is how the environment, and specifically climate, shaped the evolution of our species and that of our close relatives.

Some of the most critical world issues today also bear on human evolution, in the sense that how we got here is relevant to where we are going as a species. For example, global warming, population growth with its attendant demands on limited resources, pandemic threats of virulent diseases, and availability of weapons that can cause massive damage and render parts of the globe uninhabitable, all demand more rational policy decisions that take into account the long evolutionary process that brought humanity to world dominance. Perhaps a greater appreciation of what the people of the world have in common, rather than their differences, might encourage more cooperation.

Although recent advances in knowledge of human evolution have been substantial, they really have only laid the groundwork for future achievements. New methodologies for establishing the ages of specimens and analyzing them with sophisticated instrumentation, and for acquiring information about past environments through drilling on land and in lakes and the ocean, set the stage for further discoveries. Accelerated research not only offers potential for highly significant advances, there is also an urgency in moving ahead due not only to the global and regional threats mentioned above, but also to the loss of potential specimen sites as a result of development and even vandalism.

Although research activity at the intersection of different scientific disciplines is inherently difficult, such research carries with it great potential for advances that can transform understanding. Although the usual issues of differing perspectives and different jargon were encountered during this study, the challenges of providing recommendations for new approaches that would guide research activity over the next decade or more provided the incentive to bridge the divisions. Our deliberations were particularly helped by the open community workshop hosted by the committee, with its focus on receiving a broad range of input from many experts whose disciplinary fields impinged upon the broad scope of the committee's charge. This input, and the presentations by other experts at committee meetings, provided a solid base for informing the committee's deliberations and recommendations.

Robert M. Hamilton

Chair

Acknowledgments

This report was greatly enhanced by those who made presentations to the committee at the public committee meetings and by the participants at the open workshop sponsored by the committee to gain community input—Leslie Aiello, Ray Bernor, René Bobe, Erik Brown, Frank Brown, Tony de Souza, Larry Edwards, Sarah Feakins, Mikael Fortelius, Don Grayson, Tim Herbert, Tim Jull, Rich Kay, Dennis Kent, Chris Kuzawa, Rich Lane, Peter Molnar, Curtis Marean, Kathleen Nicoll, Dolores Piperno, Todd Preuss, Christina Ravelo, Bill Ruddiman, Jim Russell, Jeff Schuffert, Eugenie Scott, Steven Stanley, Peter Ungar, Xiaoming Wang, Ken Weiss, Mark Weiss, Tim White, and John Yellen. The presentations and discussions at these meetings provided invaluable input and context for the committee's deliberations.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by P. Geoffrey Feiss, College of William and Mary, Williamsburg, Virginia, appointed by the Divison on Earth and Life Studies, who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Summary

The hominin[1] fossil record documents a history of critical evolutionary events that have ultimately shaped and defined what it means to be human, including the origins of bipedalism; the emergence of our genus *Homo*; the first use of stone tools; increases in brain size; and the emergence of *Homo sapiens*, tools, and culture. The geological record suggests that some of these evolutionary events were coincident with substantial changes in African and Eurasian climate, raising the intriguing possibility that key junctures in human evolution and behavioral development may have been affected or controlled by the environmental characteristics of the areas where hominins evolved. However, with both a sparse hominin fossil record and an incomplete understanding of past climates, the particular effect of the environment on hominin evolution remains speculative. This presents an opportunity for exciting and fundamental scientific research to improve our understanding of how climate may have helped to shape our species, and thereby to shed light on the evolutionary forces that made us distinctively human.

Employing a systematic research strategy and guided by recent discoveries, the discipline is poised to make major advances concerning possible causative linkages between human evolution and Earth's climate history. The intriguing possibilities regarding the role of climate in the evolutionary trajectories of our ancestral lineages can only be clarified—and causation established—with addi-

[1]The term hominin is used for any member of the evolutionary group of bipedal species most closely related to *Homo sapiens* that evolved following the split between humans and chimpanzees. The term hominid includes all great apes, encompassing chimpanzees, gorillas, orangutans, and humans.

tional evidence that will require more sophisticated tools. Significant progress into the question of whether past climate changes influenced human evolution will require a coordinated, focused, and cross-disciplinary research program designed specifically to address this problem.

Although we have a broad understanding of African and Eurasian climate history, this climate record generally lacks the temporal resolution and details of rainfall and temperature that potentially impacted how the hominins lived, and in particular does not adequately reflect differences in past climates between regions. Improved climate records for specific regions will be required before it is possible to evaluate how critical resources for hominins, especially water and vegetation, would have been distributed on the landscape during key intervals of hominin history.

The existing records of earth system history and hominin fossil history also contain substantial temporal gaps. A general understanding of the timing of major events in human evolution exists, but our ability to interpret what has driven these events remains limited by a paucity of fossil material, particularly over the most interesting periods of rapid evolutionary change. Major breakthroughs will almost certainly have to await discoveries of additional hominin fossils and associated archaeological materials. New hominin fossil discoveries should enable the more precise understanding of the ages of various events in the hominin evolutionary record that will be needed for robust correlation of climatic and evolutionary events. Similarly, a broad understanding of earth system history, and particularly past climate history, has been gleaned from other fossils found associated with hominin fossil discoveries and from analyses of lake and ocean sediment cores. This material provides a wealth of base information that can be used with the present generation of global climate models to understand paleoclimate characteristics and the factors that controlled past climates, particularly at continental and regional scales, but these are still limited for understanding the local climates that are so important for evaluating causative factors involved with hominin evolution.

This report proposes focused research initiatives that are designed, over a 10-20 year period, to dramatically improve our understanding of this research problem. These initiatives are presented in two major research themes.

Theme I: Determining the Impacts of Climate Change and Climate Variability on Human Evolution and Dispersal

Hypotheses linking climate change and hominin evolution are based on indications that large-scale shifts in climate or climate variability altered the landscape ecology which, in turn, presented specific adaptive or speciation pressures that led to genetic selection and innovation. However, efforts to test such hypotheses are fundamentally data-limited, constrained by gaps or poorly studied intervals in the fossil and archaeological record, coupled with the highly variable fossil density from different time periods and regions; the inconsistent collection of all components of available fossil assemblages (e.g., invertebrates, vascular plants and algae, as well as vertebrates), which have potential to offer critical tests of the climate evolution relationship; as well as by stratigraphic and geochronologic limitations. Concerted international efforts to substantially enhance the fossil hominin, archaeological, and other faunal records of evolution are necessary to establish with statistical reliability the precise first and last appearances of species, adaptations, and behaviors within particular geographic regions and strata. Precise determinations of the timing of evolutionary events are essential for more rigorous analyses of the climate-evouliton relationship.

At present there are few continuous quantitative paleoenvironmental records situated close to hominin fossil localities. By bringing the evidence of climate change and evolutionary events into close proximity, particularly by collecting high-resolution environmental records at or near the hominin fossil sites, it will be possible to test the extent to which those evolutionary events reflect responses to regional or local climate. In addition to the high-precision records of climate change that are required from long stratigraphic sequences located close to hominin sites, lake and ocean drilling records will be needed to integrate local climate records from hominin sedimentary basins with regional and global records.

Understanding past climates depends on a range of data that can be used to quantitatively reconstruct the range of climatic variables—temperature, precipitation, seasonality, vegetation and land cover, paleoaltitude, etc. It is important that new tools for quantitative reconstruction of past environmental conditions continue to be developed and applied to new and existing stratigraphic records. A key requirement for each of these elements will be formalized research funding to encourage scientific exchange and strategic analysis of climate evolution hypotheses by earth scientists, paleoanthropologists, and faunal researchers.

Theme II: Integrating Climate Modeling, Environmental Records, and Biotic Responses

This research theme describes research strategies to define the physical and biotic mechanisms whereby past environmental changes may have produced evolutionary (and behavioral) responses in fossil hominins. The approach will require developments in climate model and paleoecologic data integration. The aim of this effort is to use the new data collected under Theme I to constrain climate model simulations to explore the physical mechanisms and regionality of past climate changes. Existing environmental records are too sparse to draw firm conclusions about particular geographic patterns of climate in Africa and Eurasia and their variability, or about climate conditions along pathways to southern Eurasia, or temporal and spatial variability of Eurasian climates. In parallel with the efforts to collect additional environmental records proposed in Theme I, there is also a need for a program to integrate regionally resolved climate models with paleoecologic data. These would be developed for the specific regions and specific key time periods that bear on potential connections between environmental changes and hominin evolution and dispersal. Model-record experiments will be particularly important for developing predictions in data-sparse regions, as the basis for hypotheses that can be tested by the collection of new data. Because climate models simulate spatial and temporal patterns on a regular grid and at regular time intervals, they can provide a context for integrating or synthesizing environmental and fossil records that are discontinuous in space and time, or are otherwise incomplete.

The large-scale record of climate change over the past 8 million years (Ma) is reasonably well known, although much remains to be understood about the interactions and feedbacks among the various climate forcing factors. At issue are the relative influences on African and Eurasian climate from orbital monsoonal forcing, high-latitude ice volume changes, atmospheric carbon dioxide (CO_2) changes, Tibetan and East African uplift, and sea-level or ocean gateway changes, all of which changed over this time period. The focus of this new research initiative is to understand how changes in these boundary conditions affected climate in the specific regions where hominins lived. For example, the possibility of a dispersal of *H. erectus* or *H. heidelbergensis* from Africa to Eurasia at approximately the time of the climatic transition to large and long glacial/interglacial cycles (1.2-0.8 Ma) raises intriguing questions concerning the effects of these major climate swings on the environments inhabited by *Homo* in Africa and Eurasia. Moreover, the changing amplitude and duration of the orbitally forced changes in climate, other quasi-periodic changes of shorter duration, or relatively gradual changes in forcing, may have had different effects on ecosystems than the abrupt changes that are also a characteristic of the climate record. With improved density, accuracy, and dating of environmental records, there is a major opportunity to use climate models to ask more detailed questions and to obtain more detailed information about the climate, water resources, and vegetation comprising hominin habitats. In particular, the availability of accurate estimates of atmospheric CO_2 will permit simulation of the direct effects of greenhouse gases on climate, as well as the possible physiological effects on vegetation of changing levels of CO_2. These models can only be accurately tested by reference to actual paleoenvironmental data from Africa and Eurasia and the surrounding oceans. With the availability of greenhouse gas records and known orbitally controlled changes in solar radiation, along with known changes in orography, volcanism, coastlines, and ocean gateways, models have proven to be remarkably accurate in simulating past climates.

Implementation Strategies

Implementing this research vision will require community and organizational flexibility as it embraces a more collaborative and cross-disciplinary model, involving a transformative shift in how paleoanthropological research is conducted. Although the exploration of human origins is inherently an international activity, large field-based research projects have been mostly conducted and funded along national lines, and broader partnerships and funding efforts are still relatively rare. International collaboration and cooperation focused on understanding the extent to which the earth system was a factor in human evolution offers the potential for applying the intellectual, organizational, and funding resources of a much wider community to an important research problem.

We envision a new scientific program for international climate and human evolution studies that involves both essential and supporting components.Three elements should be carefully integrated to comprise the core program of research:

- A major exploration initiative to locate new fossil sites and to broaden the geographic and temporal sampling of the fossil and archaeological record. This would involve systematic exploration efforts with a remote sensing component to identify new potentially fossiliferous areas and sites, coupled with a substantially enhanced program of ground exploration.
- A comprehensive, integrated scientific drilling program in lakes, lake bed outcrops, and ocean basins surrounding the regions where hominins evolved. Drill cores containing the continuous, fine structure of the environmental record are needed to address questions about changes in the earth system at sufficiently high resolution to describe short-duration events and processes. Each component of such a program—including truck-mounted terrestrial drilling, barge-mounted lake drilling, and ocean drilling—would provide complementary elements that could be integrated to describe the paleoclimatic, paleohydrologic, and paleovegetation history of specific regions.
- A major investment in climate modeling experiments for the key time intervals and regions that are critical for understanding human evolution, focused on understanding the regional climate patterns and fundamental climate forcing mechanisms, and to model at a more local scale the interactions between climate, ecosystems, and species population dynamics. Simulations at high spatial resolution will be required to resolve the relatively fine-scale details of climate, vegetation, and hydrology that are recorded in environmental records in regions of complex local topography, such as the East African Rift System.

In addition, there are a number of components that will be required to complement the core research effort:

- A systematic analysis of existing fossil sites and collections, with application of new imaging and dating technologies, to better describe the nature and timing of species change and adaptive transitions in the hominin lineage.
- New techniques that should allow inexpensive sequencing of entire mam-

malian genomes, making it feasible to collect high-resolution, whole-genome sequences of a range of mammals. This technology could be used to sample *Homo sapiens* and other mammalian populations with varying ecologies from all parts of Africa, to enable comparisons of genetic changes with climate changes over the past 200,000 years. Climatic changes could also be contrasted with estimated population sizes of *H. sapiens* and other mammals, based on population genetics parameters, during this time period.

- Selected investigations of ecosystem dynamics through the collection of modern climate and calibration data will more accurately quantify the relationships between the environment and proxy records of the environment preserved in sediments and fossils. An important contribution to the understanding of evolutionary and environmental dynamics is the analysis of fauna and flora associated, geographically and temporally, with hominin fossils. An increased focus on adaptations in the faunal and floral assemblages associated with hominins—and by contrast, those that are not associated with hominins—will provide an invaluable resource for understanding the interaction between hominin evolution and past climates.
- Development of the informatics and data archiving tools needed to provide permanent storage for the wide array of information collected by the activities listed above, and to facilitate continued access to this information. An important corollary requirement will be speedy community access to samples and their derived data within all of the disciplinary areas encompassed by this initiative—the hominin fossils and their associated fauna and flora; as well as the ocean, lake, and terrestrial drilling samples and data.

The coordination and management of a major international scientific program for International Climate and Human Evolution Research would require a science advisory structure, with members representing the broader scientific community and with a broad vision of how these research components relate to each other, to foster communication among disciplinary groups, coordinate the implementation elements, and convey the science community's priorities to funding agencies. On the basis of community input, an advisory committee would establish and periodically update plans for exploration, drilling, and modeling, and prioritize regions to be investigated. This committee would require sufficient funding to sponsor a range of workshops and town meetings, spanning the full range of disciplines associated with this research enterprise, to obtain and distill community input.

Public Outreach Opportunities

The public is fascinated by media accounts and documentaries on human evolution and the long-term origin of our species. Additionally, climate change has become a focal point for public interest. The intersection of these two broad areas of scientific research thus offers powerful opportunities for public outreach aimed at communicating the process and value of science to the welfare of humans, all living things, and entire ecosystems. The subject matter itself, which deals with human survival and adaptation in the past, also offers avenues for inspiring the public's curiosity about scientific findings relevant to society's adaptation to climate change in the near and distant future.

A state-of-the-art program in public education and outreach creates opportunities for diverse audiences along several avenues, which include (1) development of dynamic and up-to-date public Internet sites; (2) dissemination of findings via the Internet or using print, radio, and television media; (3) organization of seminars, lectures, and dialogues in venues that are both visible and attractive to the public; (4) interaction with national science educators, who can translate scientific findings and data into the classroom; (5) development of museum-based and less formal exhibitions, which are attractions for family and school-group explorations of and learning about science; (6) engagement of adult learners in the excitement of research and discovery and encouragement of volunteerism (docents); and (7) provision of graduate, undergraduate, and high-school training and research experiences, which offer a means of building the future generations of scientists and educators. As the items in this list illustrate, an effective program of public education and outreach requires skillful approaches to formal and informal learning in which children and adults decide whether to pursue (and for how long) any particular topic that interests them.

No curriculum currently exists to inspire teachers and students to explore the relationship between past climate change, human evolution, and the long-term influence of environment on species survival, adaptation, and mitigation strategies. The following suggestions represent components of a broad effort to redress this deficiency:

- Develop opportunities that bring educators and scientists together, and that build new partnerships among research institutions, museums, science centers, and national scientific and education organizations, to contribute to the development of national and state science standards.
- Establish a National/International Educator Institute as a long-term effort that employs climate-evolution research to enhance professional educator development.
- Establish internships that connect students and teachers to the international scope and nature of scientific research on past climate change and human evolution.
- Engage adult learners who may be underserved and have ventured away from formal avenues of science education.
- Develop a concise and compelling education guide; curricula for teachers (available in print and online); and traveling exhibitions that introduce the

rationale, perspectives, and basic findings concerning the earth system context of human evolution.

As a package, these recommendations reflect a fundamental commitment to outreach and education, working in partnership with educators and scientists nationwide and worldwide.

The strategic integration of focused high-resolution modeling with new marine, lake, and terrestrial climate records proposed here will represent the most concerted research effort thus far to assess the precise influence of environmental dynamics (resolved on decadal to orbital timescales) on evolutionary history for any organism or time period in Earth's history. The research agenda described here—although presenting a bold vision that will require substantial resources to bring it to reality—offers an opportunity to make equally bold steps toward an understanding of the role played by past climates in the evolution of our ancestral lineage.

1

Introduction

The intersection of human evolution and Earth's environmental history brings together two areas of scientific study with exceptionally high public visibility and broad societal interest—human evolution and climate change. The origin of our species has long been a compelling focus of human curiosity, and the record of past climate change and its impacts on hominin evolution provide an ideal context for considering potential intersections between future climate change and the responses of our species to such environmental changes.

Of all the records of fossil organisms, the one offered by paleoanthropology is unique for its rich evidence of behavioral and ecological interactions derived from hominin (Box 1.1) and other fossil remains, as well as the unique aspect of hominin material culture in the later part of the record. This fossil record contains a history of critical evolutionary events that have ultimately shaped and defined what it means to be human, including the origins of bipedalism; the emergence of our genus *Homo*; the first use of stone tools; increases in brain size; and the emergence of *Homo sapiens*, more advanced tools, and culture. Some of these events appear to have coincided with major changes in African climate, raising the intriguing possibility that key junctures in human evolution and behavioral development may have been climatically mediated. This report recommends high-priority areas of scientific enquiry that should be pursued to investigate this possibility.

BOX 1.1

Hominins and Hominids

Throughout this report, the term hominin is used for any member of the evolutionary group of bipedal species most closely related to *Homo sapiens* that evolved following the split between humans and chimpanzees—it is a convenient way of referring to the evolutionary group that includes humans and our bipedal ancestors and evolutionary cousins. The term hominid includes all great apes, encompassing chimpanzees, gorillas, orangutans, and humans.

HUMAN INTERACTIONS WITH ECOSYSTEMS

All living things interact with the earth system—the combination of land, atmosphere, and oceans—that make up our environment. As the earth system changes over time, individual species respond to these changes. In some cases, species disperse to new locations that match their preferred habitats. They may also adapt to the environmental changes, which sometimes leads to the formation of new species. And in some cases, species become extinct. A simple example in today's world is the change in the range and population size of the polar bear. As Arctic climate has rapidly warmed over the past ~50 years it has become increasingly difficult for polar bears to feed, as their means of hunting—stalking seals from sea ice—has become more precarious as the Arctic ice pack retreats. Eventually, with a near total loss of summer ice cover in the Arctic Ocean, polar bears may become extinct. Through the processes of evolutionary change, dispersal, and extinction, organisms also modify the earth system, often in profound ways. On the largest scale, the evolution of oxygen-producing microorganisms permitted subsequent multicellular organisms to evolve. Or at a very local scale, large animals in Africa, such as elephants, substantially modify their physical environment by altering vegetation patterns and thereby affect the remainder of their ecological community. Study of the relationship between environment and evolution thus depends on understanding the basic interactions between biological and earth processes.

Humans are part of the global ecosystem and have an evolutionary history that has almost certainly been affected by—and in turn has affected—the earth system. The study of human evolution shows that, like other organisms, humans have evolved over a long period of time in the face of environmental challenges and opportunities. These challenges affected how early humans secured food, found shelter, escaped predators, and developed social interactions that favored survival. The capacity to make tools, share hunted-and-gathered food, control the use of fire, build shelters, and create complex societies based on symbolic communication set the stage for new ways in which humans interacted with their surroundings. More recently, humans have interacted with their surroundings through rapidly changing technologies, harvesting of foods, and the long-distance exchange of resources. The way of life afforded by the transition from hunting-and-gathering to the production of food proved so successful that *Homo sapiens* was able to spread worldwide and increase in population density. Particularly over the past several centuries, these developments have led to a dramatic expansion in the human influence on global ecosystems.

The dynamic interplay between environmental changes and hominin speciation, extinction, adaptive change, and population size change has been played out on many different spatial and timescales. Three examples—from progressively older parts of the evolutionary and earth records—illustrate the way in which hominins may have interacted with the earth system and illustrate some of the enduring scientific questions that remain to be explored:

The Mayan "Collapse" Between A.D. 750 and 1150, the Classic Mayan civilization of southern Mexico and Central America underwent a dramatic transformation involving complex changes in Mayan society and an apparent collapse of population size by 70 percent or more (Turner, 1990; Rice et al., 2004). Archaeologists have long argued about the root causes of this collapse, and many explanations have been proposed for this enigmatic story. Could an understanding of the earth system context help unravel the causes and effects involved in the population collapse and the major transformations that occurred in Mayan civilization during this time? Over the past 15 years, evidence has been accumulated from sediment cores taken from lakes in the region that may help illuminate this relationship (Hodell et al., 2005). These detailed sedimentary records show that the climate history over the period of collapse consisted of a series of protracted droughts, separated by intervening moister periods. The timing of these droughts coincides with indications from geological records of dry conditions elsewhere in the tropical Americas (Haug et al., 2003). Although many scientists have argued for a linkage between this history of drought and the archaeological record of declining Mayan population size, the connection remains controversial (e.g., Diamond, 2005).

Climate and the Evolutionary Histories of *Homo sapiens* and Neanderthals There are continuing questions concerning the possible effect of regional climate differences on the evolution of two separate hominin species—*Homo sapiens* and *Homo neanderthalensis*. The first appearance of *H. sapiens* occurs in Africa, at the beginning of glacial stage MIS-6 (White et al., 2003; McDougall et al., 2005). Neanderthals arose in Europe (Klein, 2009) under the extremely cold conditions of the middle Pleistocene (Hublin, 2009), and continued to exist there through rapidly changing glacial and interglacial climatic regimes. Each species has distinctive anatomical characteristics that can be inferred to be adaptations to climatic conditions—Neanderthals were shorter with more robust limb bones and shorter forearms, comparable with cold-adapted peoples of today (e.g., the Inuit), whereas the modern human skeleton possesses longer and slenderer limb bones indicating adaptations for warm environments (Trinkaus, 1981; Churchill, 2006). Eventually, *H. sapiens* expanded across the globe whereas Neanderthals became extinct at ~28 ka. Although the case for a climatic role in creating and/or regulating adaptive differences between these two species has received support (Finlayson, 2004, 2008), any causal relationships between climatic events and species anatomy remain to be determined.

Bipedality and Vegetation Changes There has been a long-standing assumption that hominins became bipedal as a consequence of the climatically controlled expansion of grasslands in Africa (e.g., Darwin, 1871). However, this assumption has been challenged as additional hominin fossils, recovered over the past 15 years, were found together with fauna that did not indicate grasslands (Reed, 1997; White et al., 2006). The expansion of grasslands in Africa over the past 3 Ma has been used to suggest causation for many events in human evolution, including not only the origin of bipedalism (and thus the earliest hominins), but also the development of megadont molars (Teaford and Ungar, 2000), the origin of *Homo erectus* (Stanley, 1992), and the origination of two separate hominin lineages (Vrba, 1988; Stanley, 1992). These latter authors suggested that vegetation became more open with fewer trees during the appearance of *Homo* and *Paranthropus*, induced by cooler and drier climatic regimes over Africa, and that these grassland habitats were factors in the further speciation events for both lineages. Grasslands expanded and contracted across Africa in the past 5 Ma (Cerling, 1992), and the extent to which these expansions and contractions impacted human evolution remains to be determined.

There is a common thread in these three examples of interactions between our human ancestors and the earth system—in each case, scientists face major limitations in resolving fascinating questions about our origins and history. A transformation in our understanding of the human story requires an improved understanding of the timing of critical evolutionary and climatic events, an improved sampling of the fossil and archaeological evidence for critical intervals in human prehistory, and—perhaps most importantly—a dramatic change in the way in which earth scientists, climate scientists, and anthropologists work together to interpret this story.

DEMONSTRATING CAUSALITY FOR HUMAN-ENVIRONMENTAL INTERACTIONS

Although scientists frequently seek to demonstrate temporal and causative correlations between environmental and evolutionary events, the processes that underlie the connections between the two are poorly known. These processes play out over extended periods of time, rather than in the "instant" of time often invoked in other scientific disciplines to demonstrate correlation. Nevertheless, a combination of the fossil record and the geological record of past climates can be used to convincingly demonstrate that organism interactions with the earth system have contributed to the evolution of life on Earth over the past several billion years. One dramatic example is the evolution of the earliest photosynthesizing unicellular organisms, which radically altered the early earth system by adding free oxygen to the atmosphere and thereby eventually providing the conditions for animals to survive and diversify.

The fossil record also demonstrates that the causative linkages and feedbacks do not always occur in simple or immediate ways—careful and creative investigations are usually required to demonstrate cause-and-effect relationships. A chemist can replicate an experiment many times to demonstrate a cause-and-effect relationship and can thereby reject a hypothesis when it is not supported by the replicated results. However, for historical sciences, our "experiment" has been run and it cannot be precisely replicated. In addition, there often are multiple causative factors as well as complicated feedbacks that controlled events recorded in the fossil and archaeological records. Accordingly, the task of historical scientists studying evolution is to test hypotheses through other means (e.g., Frodeman, 1995):

- By looking for robust correspondences of events in time and in the predicted cause-before-effect order. This requires an accurate and precise understanding of the ages of events.
- By testing whether the predicted cause-and-effect outcome took place multiple times, either under similar situations at different geologic times or, in the case of evolution and ecology, across multiple taxa (different organisms) for a given event. For example, multiple groups of animals with similar characteristics can be analyzed to determine whether their fossil records responded in similar ways to a proposed causative event (e.g., Vrba, 1988, 1992, 1995; Potts, 1996a, 1998).
- By "rerunning" this historical experiment multiple times with computer models, to test and understand the underlying dynamics of the possible cause-and-effect relationship as informed by a combination of hypothesized causal factors (climate forcing functions), initial environmental conditions, and findings from the fossil record.

An important consideration in any discussion of causality is the possibility that hominin evolution was largely unaffected by climate change—the evolution–environment "null hypothesis."

Ecological factors such as predation, competition, and disease among organisms operate in all environments, and these interactions have an important influence on their evolutionary history. Such interactions can be—but are not necessarily—strongly shaped by climatic conditions with their resultant habitat characteristics, and thus detailed climate studies can provide a critical context for understanding evolution. For example, animals preying upon other animals

BOX 1.2

Statement of Task

Earth scientists, paleoanthropologists, and archaeologists who study human evolution have long recognized the likelihood that environmental parameters, particularly paleoclimate, significantly impacted the evolution of our species. Nevertheless, many of the details of the paleoenvironmental context for the more than 7 million years of hominin evolution are poorly constrained, making inferences concerning the nature and extent of such impacts problematic. To address this shortcoming, an NRC committee will

- assess the present understanding of the earth system context for hominin evolution during the past 8 million years;
- describe high priority research directions for an enhanced understanding of the paleoenvironmental context for hominin evolution; and
- describe optimum strategies for achieving the priority research objectives, with particular emphasis on interdisciplinary initiatives.

In addition, the committee will suggest strategies for broad scientific dissemination of credible information concerning the earth system context for hominin evolution.

in grasslands have different capture techniques than predators inhabiting rain forests. Such ecological behaviors, which can be identified in the fossil record, serve as important ties that can help test the potential effects of climate on the evolution of organisms (Kappelman et al., 1997; DeGusta and Vrba, 2005).

Although genetic mutations operate independently of climate change, the spread of beneficial mutations is central to the process of evolution. These mutations become widespread because natural selection relies on the concept that environment plays the vital role in the difference between evolutionary success and extinction. An improved understanding of environmental change—that is, the earth system context as a dynamic force in evolutionary success and extinction—will substantially advance the scientific understanding of life on our planet, including human evolution.

COMMITTEE CHARGE AND SCOPE OF THIS STUDY

The National Science Foundation, with responsibility for supporting basic research activities in the United States, commissioned the National Research Council (NRC) to identify focused research initiatives that would, over a 10- to 20-year period, transform our understanding of the origin of human adaptations to environmental change. The study committee was also charged to present advice on research implementation and public outreach strategies (Box 1.2).

To address the charge, the NRC assembled a committee of 13 experts with disciplinary expertise spanning paleoanthropology, earth system science, climate modeling, and genomics. Committee biographic information is presented in Appendix A.

The committee held four meetings between September 2007 and October 2008, convening in Washington, DC; Irvine, California; Tucson, Arizona; and Woods Hole, Massachusetts (see Appendix B). The major focal point for community input to the committee was a 2-day open workshop held in February 2008, where concurrent breakout sessions interspersed with plenary addresses enabled the committee to gain a thorough understanding of community perspectives regarding research priorities. Additional briefings by sponsors and keynote addresses from other speakers were presented at the initial meeting of the committee.

This report is organized following the task statement—Chapter 2 contains a description of the existing scientific understanding of the approximately 8-million-year record of hominin evolution and climate change in the regions where hominins lived, as well as the interaction between other relevant organisms and climate. Chapter 3 contains a description of two overarching research themes, encompassing a range of individual research initiatives, which have the greatest potential to provide major advances in the understanding of potential interactions between the earth system and hominin evolution, and Chapter 4 describes the implementation strategies that will be needed to address these themes and initiatives. Recognizing deficiencies in the understanding of evolutionary principles and processes in the wider nonscientific community, Chapter 4 also contains the committee's response to the specific charge to suggest dissemination strategies. Chapter 5 briefly summarizes the conclusions and recommendations arising from the earlier chapters.

2

Existing Understanding of the Environmental Context for Hominin Evolution

Before presenting prioritized research initiatives designed to increase understanding of the interaction between human evolution and Earth's environmental history, it is important to assess what is known today about the fundamental steps in hominin evolution, the history of climate and other environmental parameters in areas where hominins evolved, the contribution of other biota recovered with hominins to understanding climatic impacts, and the history of human modifications of ecosystems. In each of these sections, the focus is on Africa from the time of the earliest hominins through to their first dispersal out of Africa at about 1.8 Ma. Descriptions of the youngest part of the record extend beyond Africa. These descriptions are necessarily brief and represent the committee's understanding of existing broad scientific consensus at the time of publication of this report. Although there is ongoing scientific research in each of these disciplinary areas to address the myriad scientific uncertainties and inconsistencies that will always exist in predominantly data-limited fields, the overview summaries presented here will not attempt to analyze or present the details of these uncertainties and inconsistencies.

MAJOR EVENTS IN HUMAN EVOLUTION

The pattern and process of human evolution can be described on the basis of a combination of comparative anatomy, the fossil record, and primate and human genetics (Kimbel and Martin, 1993). Comparative anatomy, even in Darwin's time, indicated a close relationship between humans and African apes (Huxley, 1863), and this has been confirmed by comparative genetic analyses. Although the branching order of the ape family tree—gibbons, orangutans, gorillas, chim-

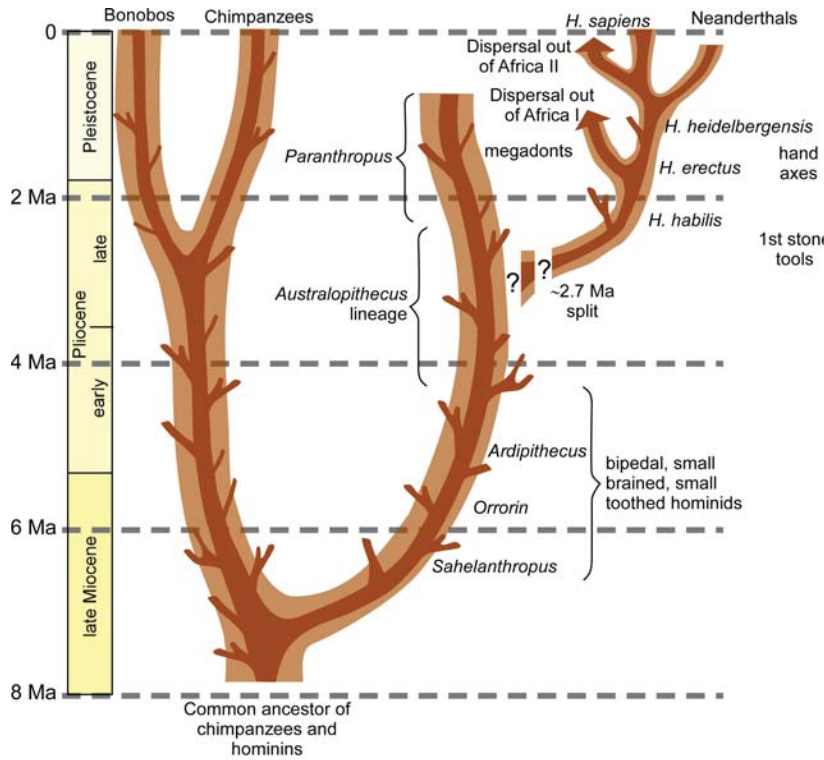

FIGURE 2.1 Highly simplified summary of hominin evolution over the past 8 Ma—the numerous terminating "twigs" schematically illustrate evolutionary "dead-ends."

panzees, humans—is firmly established, the dates of these branching splits are less certain (Kumar et al., 2005). The earliest fossils of the human lineage, after the split from the common ancestor of the chimpanzees (Figure 2.1), are fragmentary and the dates of some remain imprecise. A distorted cranium from Chad, *Sahelanthropus tchadensis*, has a reduced snout compared with apes, and skull characteristics that are sometimes taken to indicate bipedality (Brunet et al., 2002; Zollikofer et al., 2005). The site from which this specimen comes (Koro Toro on Figure 2.2) has recently been dated to between 6.8 and 7.2 Ma (Lebatard et al., 2008), and this estimate is consistent with the faunal evidence. Other early fossils from Kenya (O*rrorin tugenensis*; Senut et al., 2001) consist of fragmentary jaws and limb bones with dates of 5.7 to 6.0 Ma. Although there is debate about the exact relationship between *O. tugenensis* and later hominins, recent anatomical analyses of the skeleton (Richmond and Jungers, 2008) indicate that this species was habitually bipedal—a uniquely hominin trait. So by 6 Ma, our earliest

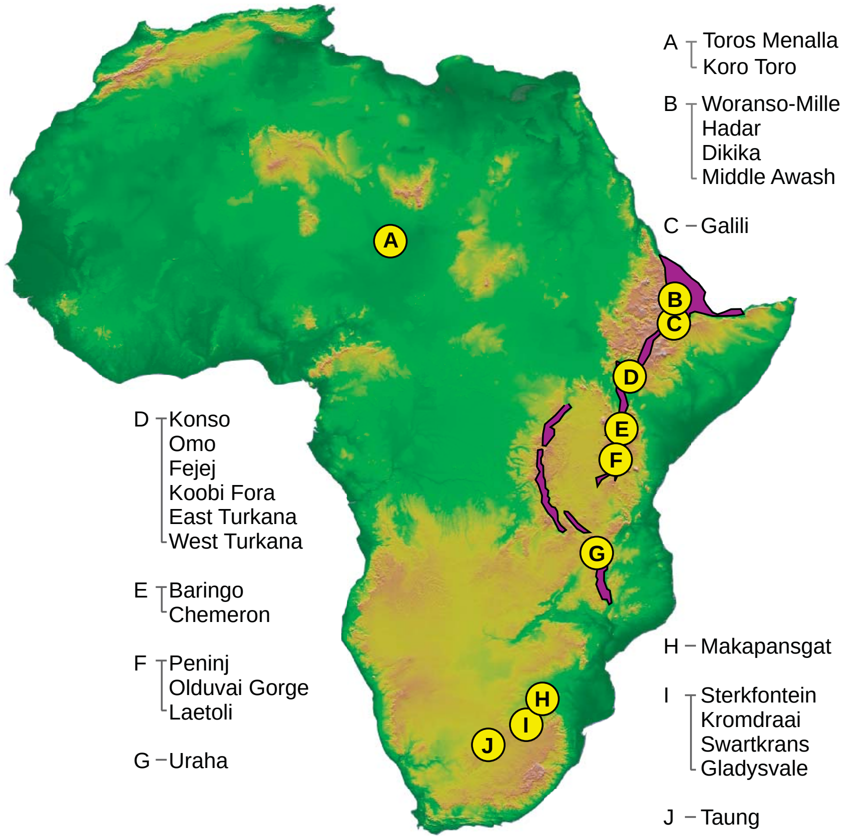

FIGURE 2.2 Geographic distribution of major exploration sites for hominins older than 1.8 Ma (i.e., prior to the first dispersal of *H. erectus* out of Africa). East Africa Rift System shown in purple. SOURCE: Digital elevation model image courtesy National Oceanic and Atmospheric Administration National Geophysical Data Center.

ancestors had split from the chimpanzee lineage and become adapted to bipedal locomotion, which is the major difference that separates us from great apes.

The fossil record of hominins between 6 and 3 Ma is patchy, but samples from Ethiopia, Kenya, Tanzania, and Chad record several bipedal hominins that have been placed in the genera *Ardipithecus* and *Australopithecus*. The early part of this hominin record (5.8 to 4.4 Ma) is represented by *Ardipithecus*, which had acquired some features seen in later *Australopithecus*, but which still exhibited primitive traits seen in African great apes (White et al., 1994, 1995, 2009 and associated articles).

The species in the genus *Australopithecus* all have larger molar and premolar teeth and thicker enamel than their predecessors (Ward et al., 1999, 2001;

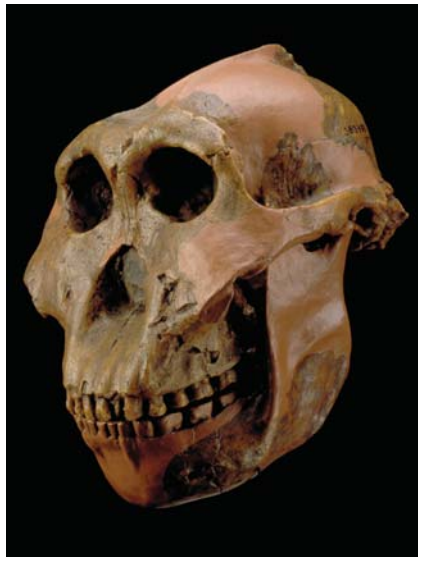

FIGURE 2.3 Replica of a 1.8-Ma *Paranthropus boisei* cranium found by Mary Leakey in 1959 at Olduvai Gorge, shown with a replica of a 1.2-Ma mandible of the same species from Peninj, Tanzania. SOURCE: Image courtesy Human Origins Program, Smithsonian Institution.

White et al., 2006), and gradual change from *A. anamensis* to *A. afarensis* has been documented (Kimbel et al., 2006). Although their food processing anatomy differed, this lineage of bipedal hominins had brain to body mass ratios that are about the same as those of extant great apes. Their limb proportions differed from those of both chimpanzees and humans, and their pelvic and hip structure suggests a somewhat different mode of bipedal locomotion from that of our own genus *Homo*. Confirmation of bipedal locomotion comes from fossilized footprints at Laetoli in Tanzania (Leakey and Hay, 1979). *Australopithecus* species exhibited differences in body size and canine dimensions between males and females (i.e., sexual dimorphism). *A. afarensis* is well known from cranial and postcranial parts and includes the famous partial skeleton "Lucy" from ~3.2 Ma. A related hominin—*A. africanus*—is well known but poorly dated from South African cave sites. One individual is of a nearly complete skeleton (Clarke, 1998; 2002), which promises to deliver much important information about this southern form. The youngest member of this genus, *A. garhi*, was recovered from 2.5-Ma deposits in Ethiopia (Asfaw et al., 1999), but little is known about it except that the trend throughout this lineage to larger jaws and teeth continued.

Extremely large-toothed hominins appear in the record around 2.7 Ma. These are sometimes placed in *Australopithecus* but are more commonly assigned to their own genus, *Paranthropus* (Figure 2.3). These "robust" creatures, so-called because of their massively sized jaws and teeth, may be direct lineal descendents of *A. afarensis*. The earliest species from East Africa is *P. aethiopicus*, known only from a single cranium and other isolated skeletal parts. This species evolved into *P. boisei*, and fossils of this younger species are relatively common in East Africa (Constantino and Wood, 2007). A similar species, *P. robustus*, is found in cave sites in South Africa; these fossils are also found with bone fragments that were used to dig both tubers and termites (Backwell and D'Errico, 2001; Pickering et al., 2004). Although we have only discovered limited numbers of skeletal bones of these robust-jawed hominins, they seem to have been very similar to the earlier *Australopithecus* in their postcranial adaptations (the skeletal features aside from the skull, jaw, and teeth). It is likely that the larger jaws and teeth were used for chewing very hard foodstuffs. *Paranthropus* appears to have become extinct at about 1.2 Ma or shortly after, at the same time that several other African mammal species became extinct. Although there are many characteristics and capabilities that remain unknown, one thing is clear; *Paranthropus* existed at the same time and in the same areas as the earliest members of our own genus, *Homo*. Their co-occurrence is the firmest evidence for different species of hominins existing together.

Behavioral evidence for the existence of our own genus, in the form of stone tools, predates any *Homo* fossils so far discovered, and although stone tools are commonly associated with the genus *Homo* throughout its existence it is not possible to be completely certain that *Paranthropus* did not make all or some of the earliest tools. Stone tools referred to as Oldowan technology,[1] as old as 2.6 Ma, have been found in Ethiopia (Semaw et al., 2003). The earliest definite *Homo* fossil is a 2.3-Ma maxilla (upper jaw) from an Oldowan archaeological site at Hadar, Ethiopia (Kimbel et al., 1996), which shows a steeper facial profile and a broader palate than *Australopithecus* species. By about 2.0 Ma, fossils of early *Homo* and sites with animal bones and stone tools are relatively common. However, it is important to emphasize that although these hominins have been assigned to the genus *Homo*, this does not imply that they were very much like modern humans in anatomy and behavior. Consequently, we should be wary of attributing any particular human behavior or physiology to early *Homo* without strong evidence. We do not know which particular *Australopithecus* species gave

[1]The oldest stone tool kit, called Oldowan (based on discoveries at Olduvai Gorge, Tanzania), consists of sharp flakes detached repeatedly from the edges of stone cores through percussive force by using hammerstones. Between 1.6 Ma and about 200 ka, this basic stone technology was complemented in Africa, portions of Asia, and Europe by the production of large tools, especially handaxes, which are roughly oval forms typically pointed at one end and rounded at the other. Large cutting tools typify the Acheulean technology (named on the basis of discoveries at St. Acheul, France). By 280-200 ka, Mousterian technology (originally discovered at Le Moustier, France) developed in Europe, and a suite of stone industries called the Middle Stone Age arose in Africa, both typified by smaller and more diverse tool forms. The Middle Stone Age is broadly associated with the origin of *Homo sapiens* in Africa, and the Mousterian with the presence of *Homo neanderthalensis* in Europe.

rise to *Homo*, although there have been suggestions that *A. garhi* was the precursor species (Asfaw et al., 1999).

The remains of *Homo habilis* are known from East Africa (Tobias, 1991; Wood, 1991), and possibly also from South Africa (Grine et al., 1993); this species is either very variable in cranial capacity and palate shape, or there are two species present. In general, this species has a mixture of primitive features as well as some that foreshadow those of the later *H. erectus*. Sexual dimorphism in body size was strong, like that of the preceding *Australopithecus* species.

The appearance of early *Homo erectus* at about 1.9 Ma is marked by changes in the limb skeleton that make it nearly indistinguishable from that of modern humans; these changes have been associated with the capacity for long-distance running (Bramble and Lieberman, 2004). This species is the first hominin to disperse out of Africa. Dispersal of *H. erectus* to present-day Georgia, where it is found at Dmanisi, apparently took place shortly after the first evidence for its existence in East Africa (Gabunia et al., 2001; Antón and Swisher, 2004), and evidence of the dispersal of *Homo* to East Asia by about 1.8 Ma is documented in China and Indonesia (Antón and Swisher, 2004; Zhu et al., 2004, 2008). This dispersal out of Africa is widely believed to have been facilitated by a major behavioral shift to increased hunting and meat consumption (Shipman and Walker, 1989). These hominins were quite variable in their cranial capacity (Spoor et al., 2007), probably due to sexual dimorphism. Studies of enamel formation show that their life history was like that of African apes rather than humans—they grew up quickly and died young (Dean et al., 2001). It is interesting to note that the Acheulean stone tool culture that is thought to typify *H. erectus*, which included the handaxe, had not been developed by the time their first fossils occurred. This species apparently used Oldowan technology until the Acheulean was invented at about 1.6 Ma; their dispersal to Eurasia, for example, took place without handaxes. The earliest strong evidence for the use of controlled fire occurs about 800 ka (Goren-Inbar et al., 2004).

Homo sapiens—in the form of skulls and skeletons that are practically indistinguishable, even in brain size, from those of modern people—appears first in Africa about 200 ka (McDougall et al., 2005). Before this event there are many fossils that are usually allocated to *H. heidelbergensis*, as well as other more arcane names. Some of these fossils from Europe appear to be the ancestors of the Neanderthals, a group of hominins that evolved in the glacial climates of Eurasia. Other fossils from Africa are most likely the ancestors of *Homo sapiens* (White et al., 2003), and others recovered in Asia may not have had any descendants.

Many behaviors that are usually attributed to modern people have left traces in the archaeological record of Africa from about 200 to 100 ka. These innovations appeared in the following order: (1) shellfishing; (2) fine stone blades, grindstones, and ochre use; (3) stone points; (4) long-distance exchange of material; (5) fishing, bone tools, barbed points, mining, and etched items to record information; (6) microlithic blades and bead ornaments; and (7) images (McBrearty and Brooks, 2000; Marean et al., 2007).

Modern humans emerged in Africa long before the Neanderthals became extinct in Europe. A dispersal of *H. sapiens* out of Africa occurred at about 60 ka, with modern humans reaching as far as Australia at that time. Humans arrived in the Americas only recently, at about 30-15 ka (Meltzer, 2003). The reasons for this late arrival are still unclear, but certainly during the most recent glacial maximum the climatic conditions were severe in eastern Siberia, the Bering Strait region, and the western portion of arctic North America.

In summary, the major evolutionary events in human evolution are:

1. The split from chimpanzees at 8-6 Ma.
2. The development of bipedal locomotion, probably occurring at the split.
3. The slow evolutionary change to bigger teeth, thicker enamel, and reduction of canines that characterize a 5-Ma-long lineage from *Sahelanthropus* and *Orrorin* (if those are not the same as *Ardipithecus*), through *Ardipithecus*, to *Australopithecus*, and finally to *Paranthropus*.
4. A splitting event between 3 and 2.5 Ma that produced *Homo* from an *Australopithecus* ancestor.
5. The development of stone tool technology at about 2.6 Ma.
6. The origin of a more carnivorous species, *Homo erectus*, at about 1.9 Ma.
7. The first dispersal by hominins out of Africa, by 1.8 Ma.
8. The development of the Acheulean stone tool culture at about 1.6 Ma.
9. An increase in cranial capacity in *H. heidelbergensis* at about 500 ka.
10. The origin of *Homo sapiens* at about 200 ka.
11. The origin of symbolic language.
12. The successive innovations in culture and lifestyle that led to the second dispersal event out of Africa at about 60 ka.
13. Expression of symbolic language in cave paintings and sculptures by about 60-30 ka.
14. The domestication of plants and animals within the last tens of thousands of years in different parts of the world.
15. The ever-accelerating spread and dominance of humans over global ecosystems in the last few thousand years.

There are, of course, many problems of interpretation and several major disagreements about human evolution that cannot be explored in this brief summary. One of these disagreements is that several researchers have followed the view of Stephen Jay Gould that human evolution must have produced a "bushy" evolutionary tree (Gould, 1994), whereas others prefer a simpler tree (White, 2003). Despite a large body of literature documenting extensive intraspecific variation in higher order primate morphology, there are still disagreements among researchers concerning the expected range of variation within fossil species.

MAJOR EVENTS IN EARTH SYSTEM HISTORY ASSOCIATED WITH HUMAN EVOLUTION

The environmental context for hominin evolution—the environmental characteristics that prevailed in the areas where hominins evolved—fundamentally reflects the interplay between Earth's orbital parameters, tectonism, and the biogeochemical processes that controlled greenhouse gas concentrations. The tectonic elements set the stage by delineating land and ocean, including oceanic gateways and land bridges, as well as controlling regional and local topography. Earth's orbital variations determined the amount of solar radiation any location on the Earth's surface received at a given time and season. Greenhouse gas concentrations controlled the very large scale characteristics of planetary temperature and regional moisture balance, and the state of the cryosphere. Together, these produced the interaction of atmospheric air masses with topographic and oceanic effects that controlled the specific regional climates that impinged on evolving hominins.

The history of East African tectonics and orography is dominated by the development of the East African Rift System (Tiercelin and Lezzar, 2002) (see Figure 2.2). Prior to inception of the East African Rift System, most of northeastern Africa was a low-lying landscape of deeply weathered terrain. Major eruptions of flood basalt and rhyolites created the Ethiopian Plateau around 30 Ma (Wolfenden et al., 2005), marking the onset of rifting along the East African Rift System. By 10 Ma, active rifting had propagated southward for 4,000 km, from the Gulf of Suez to the Mozambique Channel. Rifting in the Turkana basin, the Red Sea, and the Gulf of Aden were all coincident with the onset of Afar volcanism. The rift system has two distinct branches, an older and more volcanically active eastern branch, active since the Oligocene and occupied today by many small alkaline/saline lakes, and a younger (late Miocene) western branch, which has experienced much less extensive volcanic activity and is occupied by large and mostly freshwater lakes. Unlike the eastern branch of the Rift Valley, where southward propagation of rifting is well documented, the western branch appears to have developed along its entire length at about the same time between 8 and 12 Ma. Both rift branches are surrounded by major uplifted mountain ranges, which have acted since the late Miocene to intercept moisture and create rainshadows along their leeward (western) flanks (Sepulchre et al., 2006). This rift valley system and the flanking mountains regulated the extent of aridity in various parts of tropical Africa, as well as the occurrence of water resources upon which early hominins would have relied.

The development of the Nile River system was an additional significant element in the history of hominin evolution on the continent. There is no evidence for a Nile drainage system prior to the early Miocene, when major fluvial deposits began to accumulate south of the present Nile delta (Said, 1993). Today the Nile is fed by both the Blue Nile that drains the Ethiopian Highlands and the White

Nile that drains Lake Victoria and the lakes occupying the northern reaches of the western rift. The Ethiopian Highlands would have been the sole significant drainage area in the early stages of Nile development before rifting began in the western arm of the rift valley at around 15 Ma.

The other major element of African tectonic history for hominin evolution was the gradual and complex collision of Africa with Eurasia that began at about 15 Ma (Burke, 1996). This event had several critical implications for hominins. First, it generated land connections between Africa and Eurasia at various times that provided biogeographic corridors for terrestrial organisms, including hominins, to move between the two continents. And second, when coupled with variations in global sea level, this collision caused the episodic closure of the Straits of Gibraltar and isolation of the Mediterranean from the Atlantic during the late Miocene. This resulted in the evaporation of the Mediterranean Sea (the "Messinian salinity crisis" of about 7-5 Ma; see Rouchy et al., 2006), profound regional climatic changes, biogeographic corridors between Africa and Eurasia, and changing conditions for ecosystems in the region (e.g., van der Made et al., 2006). The sea-level history of the Mediterranean also strongly influenced the history of the Nile, a major biogeographic corridor between tropical Africa, the rift system, and Eurasia.

Regional and Global Controls on African Climate Change

An understanding of how African climate has varied through time and may have influenced human evolution requires a broad understanding of how the African climate system works today. The climate of tropical Africa is impacted primarily by three air masses—the northeasterly and southeasterly trade wind systems, which penetrate East Africa from the Indian Ocean and converge on the Intertropical Convergence Zone (ITCZ), and the Atlantic-derived westerly African monsoon, which extends into the African interior where it converges with the easterly trade winds along the Congo Air Boundary. This boundary is positioned along the western rift for much of the year, where orographic effects promote enhanced rainfall. The pattern of rainfall throughout East Africa is complex. In general the seasonal rain belt migrates north and south with the ITCZ, modified by regional orography, vegetation, and the energy exchange between extratropical and tropical regions (Leroux, 2001). Rainfall throughout most of the East African rift valley is derived from moisture off the Indian Ocean, and is strongly influenced by regional differences in sea surface temperatures (Hastenrath et al., 1993). South Africa is affected by the westerly wind belt as well as by tropical climate. The interannual variability of rainfall in South Africa is out of phase with that in tropical East Africa, and tends to be relatively dry in *El Niño* years (Goddard and Graham, 1999).

Climate variability during the Neogene is expressed on various timescales, each of which may have been important for hominin evolution. Over the longest timescales, climate trends over millions of years—the global cooling trend and the growth of polar ice sheets—set the stage for the overall evolution of hominins. On shorter timescales, Earth orbital (Milankovitch) processes were critical for controlling aridification cycles in Africa, which could have influenced hominin distribution, adaptation, and local water resource availability. And at millennial and shorter timescales, abrupt climate events could have influenced the demography of individual hominin populations, local extinctions, and population distribution around water resources. Each of these timescales is considered below.

Late Neogene Aridity Trends in Africa

Terrestrial and marine paleoclimate records have been interpreted to show that subtropical African climate has, over the past 2-3 Ma, progressively become more arid with an expansion of grasslands. This longer term aridity trend appears to have been superimposed on the higher frequency precessional wet-dry cycles, although the precise nature of this superposition remains unclear. Marine sediment records of African climate changes have provided several independent lines of evidence for this latest Neogene aridification trend. Depositional fluxes of eolian sediment off West and East Africa reveal increases coincident with the 2.8 Ma onset of Northern Hemisphere glaciation, and the dust cycles in these records exhibit changes in variability at 2.8 Ma, 1.7 Ma, and ~1 Ma coincident with similar changes in high-latitude ice volume variability (Tiedemann et al., 1994; deMenocal, 2004). A recent reanalysis of the timing and nature of these transitions suggests that there may be significant differences in the timing of these transitions between western and eastern North African sites (Trauth et al., 2009). Several studies have shown a close correspondence between the pacing of high-latitude glacial cycles and African climate using dust fluxes (Clemens et al., 1996; Tiedemann et al., 1994), dust grain size (Matthewson et al., 1995), pollen records (Dupont and Leroy, 1995), and biomarker tracers of tropical African rainfall (Tierney et al., 2008). Moreover, the pacing of the dust cycles is in phase and coherent with the oxygen isotopic record of glacial/interglacial climate changes, with three- to fivefold increases in dust fluxes during glacial maxima at sites off northeast and northwest Africa. Marine pollen records similarly document expansion of vegetation adapted to drier conditions during glacial maxima, and a general aridity trend after the mid-Pliocene (Dupont and Leroy, 1995).

Although terrestrial paleoclimate data have the potential to provide critical ground truth information on long-term climate trends near the fossil localities, continuous paleoclimate records are rare from East African terrestrial sequences because of active faulting, erosion, and nondeposition. The sparse existing records broadly support the view that East African climate changed from warmer, wetter conditions in the late Miocene and early Pliocene to a more seasonally-contrasted, cooler, and drier (and perhaps more variable) climate during the late Pliocene (after ~3 Ma). Pollen from fossil sites in northeastern Africa indicates shifts to cooler and drier vegetation types after ~2.5 Ma. Stable isotopic analyses of pedogenic carbonates from the Turkana and Olduvai basins indicate progressive replacement of closed forest woodland by open savannah grasslands between 3 and 2 Ma, with further increases after 1.8 Ma, 1.2 Ma, and 0.6 Ma (Cerling and Hay, 1988; Cerling, 1992; Levin et al., 2004; Wynn, 2004) (Figure 2.4). However, sufficient C4 grass biomass was present to support a diverse community of grazers from ~7 Ma to the present in many key hominin-bearing localities (Cerling et al., 1999, 2005; Levin et al., 2008).

A compelling new line of evidence for increasing African aridity is provided by stable isotopic analyses of plant wax biomarker compounds preserved in marine sediments off equatorial and northeast Africa. The Gulf of Aden is the closest marine basin to hominin fossil localities in northeast Africa, and low-resolution plant wax biomarker analysis from ocean cores recovered from the Gulf of Aden document a clear trend toward more open C4 vegetation, commencing between 3 and 2 Ma (Feakins et al., 2005) (Figure 2.4). Together, the terrestrial and marine records demonstrate that African savannah grasslands became an increasingly prominent component of the landscape after the mid-late Pliocene.

Orbital Precession Forcing of African Climate

The geological record provides abundant evidence of orbital precession (see Box 2.1) having been the persistent pacemaker of African climate changes. In the recent geological past, semiarid parts of North Africa have experienced periodic and dramatic changes in moisture availability due to regulation by orbital precession of African monsoonal circulation. During the early Holocene (North) African Humid Period, the modern Saharan Desert was nearly entirely vegetated (Jolly et al., 1998), and the landscape was dotted with numerous large and small permanent lakes supporting abundant large mammalian fauna (Roberts, 1998). Collectively, terrestrial and marine paleoclimate records present compelling evidence that African climate periodically alternated between wetter and drier conditions throughout the late Neogene.

The varying concentrations of eolian dust exported from regional North African source areas to offshore northwest and northeast Africa, noted above, have also recorded these precessional wet-dry cycles (Tiedemann et al., 1994; Clemens et al., 1996; Larrasoaña et al., 2003; deMenocal, 2004), and sedimentary records from East Africa lake deposits show extreme climatic variability with rapid shifts between wet and dry conditions (Trauth et al., 2007). Terrestrial paleolake deposits in Ethiopia, Kenya, and Tanzania contain a record of the precessional wet phases, but the preserved record of African humidity cycles is far less complete (Ashley, 2007; Kingston et al., 2007).

The climate history south of the equator in tropical East Africa also reflects a strong precessional cycle that is out of phase with North Africa. The Lake Malawi basin, at the southern end of the East African Rift Valley, was relatively

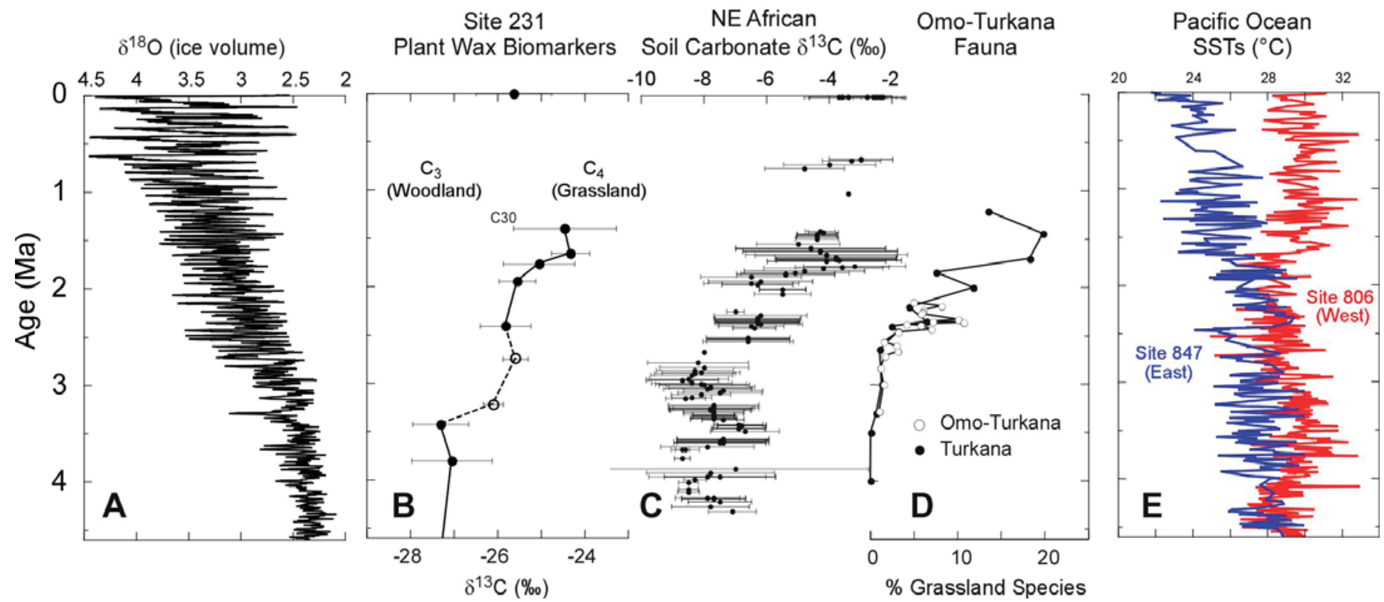

FIGURE 2.4 Long-term African climate trends (B-D) shown with oceanic temperature and ice volume records (A, E). (A) Marine $\delta^{18}O$ record showing the onset and amplification of high-latitude glacial cycles after 3 Ma (Lisiecki and Raymo, 2005); (B) Carbon isotopic composition of Deep Sea Drilling Program Site 231 terrestrial plant wax biomarkers (Feakins et al., 2005); (C) East African soil carbonate $\delta^{13}C$ data (Cerling, 1992; Cerling et al., 1994; Wynn, 2004); (D) Turkana Basin faunal shifts documenting C4 vegetation (grassland) expansion after the mid-Pliocene (Bobe and Behrensmeyer, 2004); and (E) Pliocene-Pleistocene evolution of equatorial Pacific Ocean sea surface temperature (SST) gradients documenting the absence of the modern-day east-west SST gradient during the middle and late Pliocene (Wara et al., 2005), an oceanographic boundary condition consistent with more humid conditions in East Africa (Cane and Molnar, 2001; Brierley et al., 2009).

BOX 2.1

Earth's Orbital Variation and Climate Variability—Milankovitch Climate Cycles and the Mediterranean Sapropel Record

In the early 20th century, Milutin Milanković, a Serbian scientist, demonstrated that the amount and distribution of solar energy reaching the Earth is predictably and cyclically related to variations in the Earth's orbit. Three types of orbit variation are particularly important for controlling the amount and seasonality of solar energy reaching different parts of the Earth—*precession cycles*, controlled by changes in the orientation of the earth's axis; *obliquity cycles*, reflecting the degree of tilt of the Earth's axis; and *eccentricity cycles,* the degree to which the Earth's orbit around the sun differs from a circle. For over 30 years, paleoclimatologists have recognized the importance of changes in—and interactions between—these various cycles as regulators of the Earth's climate. This is because the distribution of solar radiation reaching the Earth's surface not only controls how warm a given region will be at a given time of year, but also how atmospheric circulation redistributes moisture across the globe.

The Mediterranean sapropel record provides some of the most compelling evidence that North African climate has responded to orbital precession regulation of monsoonal climate since at least the late Miocene (Hilgen, 1991; Hilgen et al., 1995; Lourens et al., 1996; Kroon et al., 1998). When orbital precession invigorated monsoonal rainfall, the Nile drainage basin captured and directed runoff to the eastern Mediterranean where the excess supply of freshwater stratified Mediterranean surface waters (Sachs and Repeta, 1999). This stratification inhibited deep water convection and the deep Mediterranean became anoxic during African humid events, which are marked by intermittent (~5-ky duration) periods of organic-rich sediment accumulation in the deep basins of the central and eastern Mediterranean (Rossignol-Strick et al., 1982). The periodic regular-

dry during the early Holocene North African Humid Period (Finney and Johnson, 1991; Castaneda et al., 2007). Drill cores from Lake Malawi reveal a 150,000-year history of climate that differs considerably from that of the Congo Basin, with droughts occurring on a precessional frequency prior to 75 ka (Cohen et al., 2007; Scholz et al., 2007).

Millennial Scale and Shorter Climate Variability in Africa

African climate records show substantial variability on interannual to millennial timescales, and climate events on these scales may have had an important effect on hominin evolution by influencing water resources available to individual populations or through the occurrence of catastrophic events. During the Holocene period, when Greenland ice cores indicate a generally stable high-latitude climate, lakes located from the Afar region of Ethiopia to tropical West Africa experienced dramatic rises and falls in lake level, reflecting the recurrence of ity of these sapropel layers (Figure 2.5) reflect Earth's eccentricity and precession with remarkable fidelity throughout the late Neogene (Hilgen, 1991), and this periodicity, after correlation with rapidly-deposited beds containing hominin fossils, has been used as the basis for accurately dating the fossils (McDougall et al., 2008). Precession-paced changes in ocean salinity estimated from isotopic analyses of sediment cores near the mouths of major North African rivers (e.g., Nile, Niger, and Congo) have also been used to document the timing and duration of these African humid periods (Kroon et al., 1998; Rohling, 1999; Weijers et al., 2007; Weldeab et al., 2007).

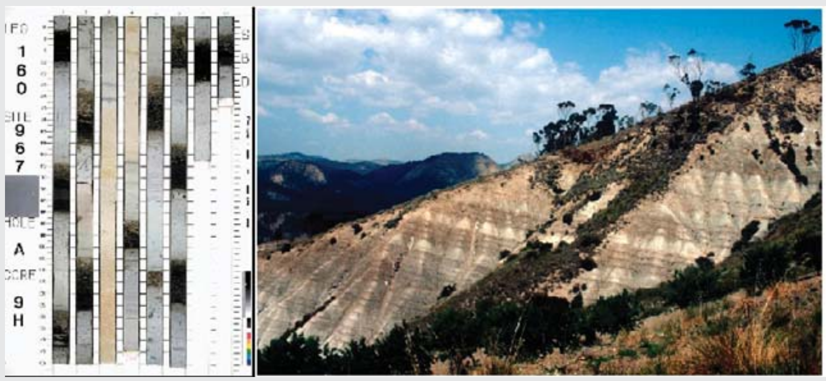

FIGURE 2.5 Left panel shows an Ocean Drilling Program core from Site 967 in the eastern Mediterranean Sea, dramatically illustrating cyclicity between sapropel layers (dark) interspersed with carbonate ooze (light). The right panel shows, on an outcrop scale, approximately 50 sapropel layers of late Miocene age (~9 Ma) from the Gibliscemi section in Sicily. SOURCE: Core photograph from Emeis, Robertson, and Richter et al. (1996). Outcrop photograph courtesy Dr. Frits Hilgen, University of Utrecht, Netherlands.

severe, persistent drought alternating with floods (Talbot and Delibrias, 1980; Street-Perrott and Perrott, 1990; Gasse, 2000).

Human population effects resulting from climate events on these timescales are well documented from the Holocene (e.g., Kropelin et al., 2008). Millennial-scale events have been little explored for older parts of the records, although a long core from Lake Tanganyika (Tierney et al., 2008) and a drill core from northern Lake Malawi (Brown et al., 2007) both provide evidence for abrupt and dramatic climatic shifts on this timescale during MIS-3.

PALEOBIOLOGICAL CONTEXT OF HUMAN EVOLUTION

An important contribution to understanding how human evolution might have been affected by climate and/or habitat change is provided by the other biota that existed both with hominins and apart from them. As climate altered vegetation habitats (determined by rainfall, evapotranspiration, soils, and other aspects of the earth system), this habitat modification applied selective pressures

BOX 2.2

Environmental Indicator Fauna Associated with Hominin Fossils

Paleoenvironmental interpretations of hominin habitats have become increasingly more sophisticated over time; whereas early paleoanthropologists typically inferred habitats based on one or two species, it is now more common to use fossil groups or lineages (e.g., Vrba, 1995) or the entire faunal assemblage (e.g., Bobe and Eck, 2001; Reed, 2008) recovered with hominins as the basis for habitat inference. The following mammal groups are often found at hominin localities; taken individually, they provide rather variable indications of the environmental attributes of their surroundings, but they become much more precise environmental indicators when considered in totality (e.g., see Figure 2.6).

Bovids, i.e., Antelopes, are probably one of the best indicators of habitat because of their particular adaptations to different kinds of savanna vegetation. Different bovid species are adapted to specific environments, and have been ubiquitous

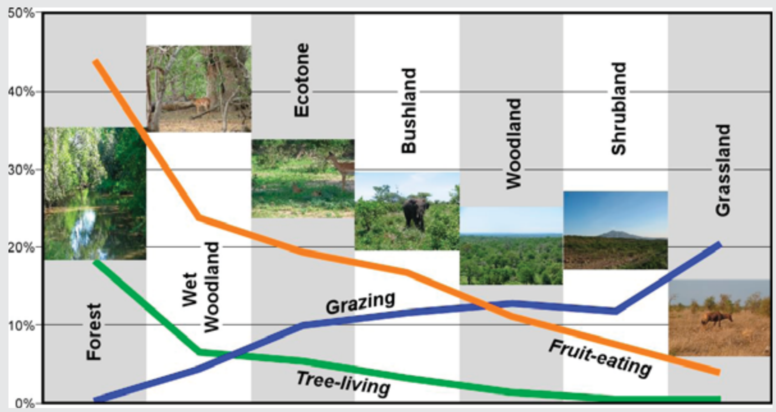

FIGURE 2.6 Variation in the ratio of adaptations (food types and habitats) in modern mammal communities for different ecosystems in game reserves and parks in Africa. SOURCE: Courtesy of Kaye E. Reed.

on the fauna that used these habitats, leading to new adaptations, speciation, or extinction. The adaptations that are evident in the faunal assemblages recovered with hominins provide a valuable line of evidence that can be used to reconstruct paleoenvironments and track environmental change.

One of the best ways to reconstruct the habitat and ecosystems in which hominins lived is to analyze the fossil flora associated with hominin sites—the pollen, leaf fossils, and other plant parts. However, this direct evidence of vegetation is typically better preserved only at younger paleoanthropological sites, but for older paleoanthropological localities—where fossil plants are less common—the fossil fauna often must be used to interpret habitat because faunal specimens are ubiquitous and nearly always associated with hominin fossils.

in Africa since the end of the Miocene. For example, the bovids that are related to modern wildebeests usually indicate open, seasonal, grassy environments.

Cervids are mammals, including deer, reindeer, and moose, where the males have antlers that are shed yearly and females usually have no headgear. These animals, found mostly in the Northern Hemisphere, are adapted to various habitats. Reindeer are usually inferred to indicate a tundra habitat.

Suids are the pigs of Africa, Europe, and Asia. Early animals in this group were omnivores, but they underwent an adaptive radiation during the middle Pliocene and many species became adapted to grazing. The teeth of the omnivores and grazing suids are distinctively different, allowing specific habitats to be inferred.

Giraffids are fairly common, usually long-necked browsing species that are typically associated with African savannas. Although there are only two non-overlapping species today, as many as four giraffid species coexisted in the same area in the Plio-Pleistocene. Different neck lengths of giraffids provide habitat information by indicating adaptations to different tree heights.

Hippopotamids are large, water-dwelling ungulates that indicate the presence of rivers and lakes in the tropical African Plio-Pleistocene. Occasionally they have been recovered from European sites (e.g., London) during warm interglacial periods, indicating that tropical conditions extended as far north as the British Isles.

Equids (horses) are mammals that possess a single toe today, but some past lineages had three toes. Equids originated in the Americas, but dispersed to Eurasia and Africa in the Miocene. Two groups are known from Africa—hipparions, which have been recovered from most Plio-Pleistocene hominin localities; and Equus, which migrated into Africa from Eurasia at about 2.5 Ma. The entire group of fossil species are grazers that existed in fairly open grasslands, but whether these represent wet or dry grasslands is debated.

Rhinocerotids are mammals with three toes and one or two nasal horns. Two rhino species are found at almost all African hominin localities, and Eurasian rhino species have been recovered with Neanderthals and modern humans in Europe and with modern humans in North Africa. Both African rhino species can be found in the same types of savanna habitats, although the Black Rhino generally prefers more bush and tree cover.

Floral Evidence Tree height and spatial distribution strongly affect animal species distributions and richness today, and it is reasonable to assume that they did so in the past. The spatial distribution spectrum ranges from closed habitats, with high tree densities, to open habitats with more dispersed trees. Variability of tree density is one of the terrestrial manifestations of climate change, and habitat change has been interpreted as an important selective force influencing many of the events in human evolution.

Faunal Evidence There are a number of ways to understand and interpret faunal information from the past. In some cases, individual fossil species can provide information on the habitat from which they were recovered through an understanding of how a skeleton moved, or by determining an animal's diet from morphological examination or isotope examination of the teeth. However, broader-based faunal community analyses using fossil fauna assemblages (see Box 2.2) can often provide a more reliable indication of the habitats of hominin fossil sites (Vrba, 1995; Reed, 1997, 1998, 2008), as well as an understanding of species turnover resulting from climate change (Behrensmeyer et al., 1997; Bobe and Eck, 2001; Alemseged, 2003).

Faunal assemblage changes—the shifts in species or faunal types through time or across space—indicate changes in vegetation structure. Species abundance or presence/absence data can also be used to understand faunal evolution associated with climate change; for example, the increased length of elephant teeth through time indicates development of more open, arid habitats with dust-coated leaves. The total assemblage of fossils, coupled with our understanding of adaptations in individual fossil species, can be used to interpret how habitats change through time (Reed, 1997, 2008). Finally, presence/absence patterns of fauna across the globe can provide evidence for dispersal patterns, and an understanding of when movement within and among continents was possible. This biogeographic information is a key element for understanding hominin movement within Africa and dispersal beyond Africa.

Vegetation and Faunal Changes Through Time in Africa

Savanna environments, where grasses are the dominant ground cover (White, 1983), can range from closed woodlands to open grasslands. Although temperature and rainfall are the major determinants of savanna occurrence elsewhere around the globe, African savannas and their vegetation types respond primarily to the amount and seasonal distribution of rainfall, with soil type as a less important influence. The seasonal distribution of rainfall is so important that seasons are described as either rainy or nonrainy, rather than the spring, fall, summer, and winter of higher latitudes. It is reasonable to infer that rainfall imposed a similar control on savanna distribution in the African past, leading to the conclusion that the forests from which middle Miocene apes have been recovered reflect high rainfall rates with the rainfall distributed evenly throughout the year. Cerling et al. (1997) and Brunet et al. (2002) suggested that the earliest hominins lived in a mixed grass and tree habitat or a more open lake margin setting. These reconstructions are based on soil isotopes and plant remains, as well as on the fauna recovered with the hominins. Mammalian and other fauna associated with *Orrorin* (Senut et al., 2001) and *Ardipithecus* (WoldeGabriel et al., 1994, 2001) fossils indicate that these hominins probably existed in predominantly closed woodlands, or even forests.

There were long-term changes in the seasonal distribution of rain in the later Miocene, with leaf analysis showing that the length of dry seasons increased by many months in the middle to late Miocene, and then shortened again near the Mio-Pliocene boundary (Jacobs and Deino, 1996; Jacobs et al., 1999). This climate change was mirrored by a change in faunal species compositions from a variety of sites in East Africa, with the extinction of many middle Miocene taxa and the appearance of modern lineages of mammalian taxa in the middle to late Miocene, at ~8.5–6.5 Ma (Hill, 1995). At the same time, plant isotopic records from the Tugen Hills, Kenya (6.8 Ma) indicate that some of the fauna, which were adapted to more open habitats, were consuming grasses that grow in a much cooler environment than is present in Africa today. Consequently, there appear to have been heterogeneous landscapes during the late Miocene of East Africa, including forests, woodlands, and grasslands. Fossil vertebrates show minor changes through time, from those adapted to living in forests to those adapted to more open country. For example, elephant and equid species changed from browsing (eating leaves and bushes) to grazing (eating grasses) during this time period.

Some of the earliest hominins from the Mio-Pliocene boundary period may have inhabited forests and/or closed woodlands (WoldeGabriel et al., 1994; Haile-Selassie, 2001; Senut et al., 2001), although *Sahelanthropus* at ~7 Ma was recovered with fauna that indicate a wooded grassland environment close to a lake (Brunet et al., 2002). Many fossil mammal assemblages in Africa show evidence of faunal interchange with Eurasia. The fauna associated with *Ardipithecus* at Adu-Asa, in the Middle Awash region of northern Ethiopia, are more closely associated with African, rather than Eurasian fauna, although there were some immigrant Eurasian taxa recovered. Interestingly, the other African site with fauna most similar to Adu-Asa is at Langebaanweg, on the west coast of South Africa. Langebaanweg also contains the Eurasian fauna and is approximately half a million years younger than Adu-Asa. Although no hominins have been recovered from Langebaanweg, the site is important for understanding climatic and biogeographic patterns during this important time period. This is one of the few periods in which there is evidence for Eurasian immigrant faunas and for shared mammals between eastern and southern Africa. Similarly, the fauna recovered from Chad with *Sahelanthropus* has African affinities, but seems to also have several endemic species, a trend that continued into the middle Pliocene.

Faunal evidence, based on large numbers of colobine monkeys, has been interpreted to indicate that *Ardipithecus ramidus* (4.4 Ma) from the Middle Awash region of Ethiopia lived in somewhat closed habitats (White et al., 2006), whereas isotopic evidence for this species (5.2-3.9 Ma) from the Gona region further to the north indicates a predominance of grass-eating animals (Levin et al., 2008). Together, the evidence may indicate that *A. ramidus* lived in environments that varied over time or favored areas that consistently contained both riparian forest and nearby open habitats. Soil isotope data indicate that *Australopithecus anamensis* lived in relatively open habitats in the Turkana Basin, Kenya (Wynn, 2000).

Faunal reconstructions of habitats of middle Pliocene localities bearing *A. afarensis*, *A. africanus*, *A. bahrelghazali*, and the fossils attributed to *Kenyanthropus platyops* (3.6 to ~2.8 Ma), indicate varied environments ranging from closed to open woodlands and bushlands, as well as wooded grasslands (Andrews, 1989; Harris, 1991; Reed, 1997; Leakey et al., 2001; Harris et al., 2003). Reconstructions show that *K. platyops* lived in wet and somewhat closed habitats (Leakey et al., 2001), and there are different habitats and faunal assemblages through time that are associated with the *A. afarensis* sites at Hadar in Ethiopia (Bonnefille et al., 2004; Reed, 2008) and Laetoli in Tanzania (Andrews and Bamford, 2008). The mammals from Hadar show a shift from dominantly browsers to mammals that lived in more arid environs and ate grasses and shrubs. In addition, gastropods from Hadar indicate that the length of the dry season increased across the latter part of *A. afarensis* existence (Hailemichael, 2000).

The australopithecine species from the Koro Toro site in Chad is associated with more open, lake-margin habitats, with fauna that have both East and North African affinities as well as endemic taxa (Geraads et al., 2001). Fauna recovered from the cave sites of Makapansgat and Sterkfontein in South Africa indicate two disparate habitats; Makapansgat, the older locality (~3.0 Ma), has fauna representing heterogeneous habitats that include floodplain, woodland, bushland, and forest. Sterkfontein, on the other hand, contains fauna that indicate very open grassland habitats, as well as plant species that indicate forest. Irrespective of the habitats associated with this southern hominin taxon, the faunal distribution during this time period suggest that habitat or climatic mechanisms contributed to the biogeographic isolation of South Africa from eastern Africa—the fauna from Makapansgat and Sterkfontein are more similar to each other, although separated by 500 ky, than to fauna recovered from sites of similar ages in East Africa.

Therefore, early to middle Pliocene habitats were heterogeneous, but with a tendency toward more open habitats broadly similar to modern African savannas. The adaptations evident in the fossil faunas show a great deal of variability with respect to habitat type, but there are more arboreal, and thus forest-associated, animals found in the late Miocene than the middle Pliocene. Through the early to middle Pliocene there is also evidence for environmental events that apparently caused species isolation not only in distant parts of the continent, but also between some of the East African sites.

In all sites for which there are data, the time period surrounding ~2.8 Ma shows some faunal turnover, but the rate and pattern of the faunal changes are different at each site (Bobe and Eck, 2001; Alemseged, 2003; Reed, 2008). There have been suggestions that these species turnovers were pan-African in nature, and caused by a global climate changes (Vrba, 1988, 1995), although the fossil-rich Turkana Basin exhibits a different pattern and timing of species turnover (Behrensmeyer et al., 1997) than would be expected with this hypothesis. By about 2.3 Ma, there was an almost complete replacement of mammalian taxa at many localities (e.g., Alemseged, 2003; Reed, 2008). New hominin species (e.g., earliest *Homo* species) also appeared at this time. However, the lack of continuity of faunal and floral records makes habitat interpretations more difficult and/or less reliable—there are fauna associated with each new hominin species recovered, but sites with continuous faunal records have discontinuous records of hominins. However, there was an overall trend in the fauna from ~2.8 to 1.8 Ma throughout Africa indicating a shift from more closed to more open habitats. At 1.8 Ma, not only were these faunas in Africa replaced by many grazing taxa, but also hominins had dispersed out of Africa for the first time. However, the stable isotope record of mammalian diets does not show a perceptible change in diets over this interval for most mammal groups (Cerling et al., 2005).

African fauna from 1.8 to ~1.0 Ma in hominin-bearing localities indicates fairly open, grassland habitats, and this interpretation is supported by paleosol isotope data (Cerling, 1992). In general, the percentages of grass and trees in African landscapes fluctuated during this time, but never reverted to closed conditions. South African cave sites from which *Paranthropus robustus* has been recovered indicate open woodland environments with some floodplains (Reed, 1997). There is some indication that the preservation of *P. robustus* fossils tended to occur only during relatively arid intervals, when sediments and bones more easily entered subterranean caves, and it has been proposed that southern Africa, in general, represented a more stable landscape than those associated with East African hominins (de Ruiter et al., 2009). *P. boisei* habitats in East Africa have been interpreted as wetter and more wooded (Shipman and Harris, 1988), and *Homo erectus* is associated with woodland and grassland habitats (Reed, 1997). Woodlands expanded to replace some of the grasslands at about 1.6 Ma, but there is another grassland peak at ~1.0 Ma (Cerling, 1992).

Vegetation Structure and Faunal Changes through Time Outside Africa (post-1.8 Ma)

After hominins dispersed from Africa towards the north, they interacted with different types of habitats and fauna. Some of these habitats were in more temperate climates with pronounced temperature seasonality, whereas other habitats, such as those in Southeast Asia, have completely different faunal assemblages compared with those in Africa, despite similarly tropical conditions.

There are few long continental records for Eurasia for this post-1.8-Ma period. Marine sediment records from the North Atlantic show the fundamental orbital-cycle pacing of glacial/interglacial cycles and long-period trends for this interval, as recorded in the marine oxygen isotope record (Raymo, 1994). By inference, this record provides a broad context for the timing of glacial advances and retreats in both Eurasia and North America. The most recent interglacial commenced around 125 ka, with the onset of glaciation at ~115 ka, glacial maximum at ~20 ka, and rapid initial retreat at ~15 ka. There are extensive land records for this period, and they provide a basis for inferring the large changes in climate—and related changes in flora and fauna—that influenced all of Eurasia during this period. Climate model simulations of global climates at glacial maxima and interglacial maxima also help bound the range of spatial and temporal climate variability over this vast area and time.

The earliest evidence for dispersal of hominins out of Africa is at ~1.8 Ma, when *Homo erectus* appears in the Caucasus Mountains of Georgia, and perhaps slightly later in mainland China and on Java, Indonesia. In western Asia, the *Homo erectus* site of Dmanisi has few African species, but many typical Eurasian species (Gabunia et al., 2000). The fauna from Dmanisi indicates an environment consisting of forested river margins with open steppe between rivers, and the lack of many African-derived species (Tappen et al., 2007) suggests the dispersal of *H. erectus* from Africa was unusual for the time. Although the Java site is wet tropical today, the fauna possibly indicate a drier woodland environment at 1.8 Ma (Storm, 2001). In general, orangutans and gibbons, characteristic of Southeast Asian rain forests, are not present in faunas from the *Homo erectus* sites of Trinil and Ngandong on Java. Fossil pollen and animal remains from the 1.7-million-year-old site of Yuanmou, South China, indicate that *Homo* was associated with a diverse habitat of open vegetation, bushland, and forest (Zhu et al., 2008), while Nihewan Basin archaeological sites dated at 1.66 to 1.32 Ma indicate an environment that varied between open grassland and more dense vegetation (Zhu et al, 2004). *Homo erectus* is known until at least 250 ka in China, and therefore must have adapted to the more extreme warm-cool climate variations in that area.

Little is known about the many habitats associated with *H. heidelbergensis*. *H. neanderthalensis* is associated with cold climates and cold-adapted faunas such as reindeer, bison, cave bears, and cave lions. Neanderthals dispersed into the Middle East at several times during their existence, and the associated fauna provides some interesting insights. First, the cold-adapted fauna are not found there, indicating that Neanderthals also dispersed without the other fauna. Second, the fauna recovered at the Neanderthal localities in the Middle East are the same as the fauna recovered with *Homo sapiens* from the same area, although there are indications that Neanderthals focused on exploiting fewer species, whereas *H. sapiens* used a broader range of animals as food (Reed and Fish, 2005). Early *H. sapiens* (~200-125 ka) in Africa were associated with fauna that indicate either open grassland (grazing bovids and equids) or fynbos[2]/Mediterranean habitats (small browsing bovids) (Rector and Reed, 2009). With the expansion of *Homo sapiens* out of Africa at ~60 ka, it is evident that they were no longer restricted or limited by any particular habitat or climate. Although modern faunas are essentially in place from about 200 ka in all parts of the globe, many large animals disappear during the late Pleistocene with their extinction representing some combination of habitat change and hunting.

[2]Fynbos are Mediterranean-like ecosystems typical of western coastlines of South Africa; they are characterized by winter rainfall, small scrubby bushes, and animals specialized to this habitat.

HUMAN MODIFICATION OF ECOSYSTEMS

The record of human modification of the environment spans at least 2.5 million years. During this period, changing climates would have resulted in changes and uncertainties in the availability of critical resources (e.g., food and water). Hominins that survived such uncertainty must have adapted to these challenges, with key evolutionary innovations altering the ways in which human ancestors interacted with their surroundings. New technologies variously involving the use of stone, the intensified hunting of animals and reaping of wild plants, and the potential to build shelters, to clear landscapes using fire, and to play a role in extinctions of other organisms, together with the developing ability to communicate and plan coordinated activity—all set the stage for a fundamental change in human ecology involving the transition from mobile hunting-gathering to food production and the emergence of human-dominated ecosystems. Framed in the context of late Pliocene and Pleistocene climate change, the capacity to make tools, exploit new foods, control fire, build durable shelters, and organize complex social activity reflect evolutionary responses that enabled human ancestors to survive and adapt to environmental risks and uncertainties (Potts, 1996b, 1998). The initially simple capacities to alter their immediate surroundings proved so successful that they enabled humans to spread over the planet and thus, ultimately, to induce environmental change on a global scale.

The most profound human modifications of ecosystems resulted from the transition from food foraging (e.g., hunting-and-gathering) to food production (e.g., farming, herding). This fundamental change in how humans acquired food involved a transition from dependence on wild food sources sought and found each day, involving much of the population, to dependence on food that could be grown and stored by a much smaller subset of the population (Flannery, 1986; Zeder, 2006). The investment in fields and food production meant that originally highly mobile groups became sedentary. Populations grew in size due to the existence of a more stable food supply, which also enabled some members of the population to become specialized craftsmen, artists, inventors, religious and political figures, along with the many other roles that people adopt in modern society (Diamond, 1997). The following is a summary of several distinct developments over the long course of human evolution that provided the antecedents to this critical transition.

Technology At present, the oldest documented stone tools attributable to hominins are dated to nearly 2.6 Ma (Semaw et al., 2003). Pliocene toolmaking involved the manufacture of sharp-edged stones (by using other stones as percussors) and the use of rocks for crushing and pounding. Even the simplest cutting and crushing activities enabled early hominin toolmakers to gain access to new higher-quality foods (e.g., animal fat and protein, or buried tubers and roots) (Potts, 1996b). From this simple technological beginning, a large array of food resources became available for exploitation by the relatively small-brained ancestors of living humans.

Similar stone toolmaking techniques were also practiced by the first populations of the genus *Homo* to disperse from Africa to Eurasia, by about 1.8 Ma (Rightmire et al., 2006; Zhu et al., 2008; Potts and Teague, in press). This basic technology persisted for hundreds of thousands of years, with few innovations. The innovation of striking large flakes and the emergence of Acheulean handaxes, by about 1.6 Ma, does not seem initially to have changed the way early hominins interacted with their surroundings, and the environmental factors that may have influenced the temporally and spatially patchy record of handaxe-focused technology are not well understood. Handaxes do, however, become very well crafted by at least 500 ka, and were useful in a wide range of tasks (Schick and Toth, 1993). The oldest known thrusting spears, made of wood, are from ~400 ka, indicating that human ancestors could reliably hunt animals by at least that time. Innovations in stone technology began to occur at a slightly faster rate after 300 ka, as smaller, more diverse, and easily transported tool kits began to replace handaxes and other large cutting tools that had dominated stone technology for the previous 1.3 million years. Early populations of *Homo sapiens* had developed the capacity to invent specialized tools (e.g., projectile points by at least 105 ka, and bone harpoon points by ~80 ka) that were useful in capturing dangerous and fast-moving prey.

Concentrations of Refuse and Intensification of Human Activities The human tendency to collect wastes is evident in the simple beginnings of the archaeological record. Early archaeological sites consist of concentrations of toolmaking refuse (stone chips) and food remains (typically butchered and broken animal bones). A mobile, foraging lifestyle meant that early toolmakers could follow resources as habitats changed seasonally in the short term, or more dramatically over longer time spans. This mobile existence also meant that hominins could move away from concentrations of wastes as they accumulated.

As modern humans began to develop new technologies, especially after 100 ka, some groups began to exploit and manage animal herds that were predictable in their behavior and to intensify their use of wild plants, particular cereal grains. Human populations were able to displace unwanted carnivores and other animals. In some places, this intensification of human activity entailed settling into an area where resources could be managed or cultivated; this less mobile way of life occurred thousands of years prior to the emergence of food production. Ultimately, the development of agriculture led to a certain degree of control over the food supply and an investment in the landscape that gradually led human populations to abandon hunter-gatherer mobility in favor of settlement. Building upon the human capacity to concentrate waste, these developments inevitably led to the buildup of wastes, pollutants, etc., that characterize human-modified ecosystems in the present.

Fire and Shelters The control of fire and the building of durable shelters were critical means by which mid-Pleistocene hunter-gatherers altered their immediate environment and this also occurred long before the emergence of agriculture. The oldest definitive hearths have been dated at approximately 790 ka (Goren-Inbar et al., 2004), and shelters that were sufficiently durable to be preserved in the archaeological record date from approximately 400 ka (deLumley, 1969; Schick and Toth, 1993). The construction of hearths and shelters enabled hominins to modify the temperature of their immediate surroundings, alter the digestive properties of cooked food, and to distance the group from harsh conditions beyond the shelter. These developments coincided with a period of heightened amplitude of glacial/interglacial oscillations, and thus may reflect the ways in which altering the immediate environment proved beneficial physiologically to individuals and socially to groups (Potts, 1996b). Ultimately, the use of fire also led humans, mainly after 100 ka, to modify entire landscapes as a means of hunting or land clearance to promote new plant growth (e.g., Lentz, 2000; Miller et al., 2005).

Sophisticated Symbolic and Cognitive Behavior The evolution of complex mental capabilities and language had a strong impact on how our species interacted with its surroundings. These developments provided an adaptive advantage in *Homo sapiens* by enabling social groups to trade resources over long distances and to cope with variations in food, water, and other critical resources in the face of climate change. These cognitive capabilities are indicated by early symbolic artifacts, such as pigments used for coloring, simple etching of objects, and the presence of decorative shell beads. These types of objects indicate an ability to code information symbolically—the essence of language. These artifacts first occur in the African archeological record between 285 ka and 70 ka, associated with the early evolution of *Homo sapiens* (Barham, 2002; Henshilwood et al., 2002; d'Errico et al., 2005). By approximately 130 ka, artifacts made from rocks from at least 300 km away suggest that human social networks were sufficiently complex to engage in long-distance exchange of high-quality stone and other resources (McBrearty and Brooks, 2000). By at least this date, therefore, our species manifested complex mental behavior and highly coordinated social activity. These developments laid an important part of the foundation for large-scale human impacts such as agriculture, trade, and cities, which have profoundly altered the relationship between humans and natural environments.

SUMMARY ENVIRONMENT-EVOLUTION CHRONOLOGY

The major features of human evolution and the major features of Earth's climatic evolution over the past 8 million years can be integrated to form a chronological summary, summarized in Table 2.1. This provides the context for the recommendations for the future research and outreach activities that are presented in subsequent chapters.

TABLE 2.1 Summary of Critical Intervals in Earth System and Hominin Evolutionary History for Africa During the Late Neogene.

Interval	Climate Events	Sea-Level Events	Tectonic Events	Hominin Evolutionary Events	Archaeological Record Events	Fossil Record Events (other than hominins)
8-4 Ma	• 7-4 Ma: Overall global cooling trend. • ~7-4 Ma formation of Greenland Ice Sheet and accompanying drop in global atmospheric CO_2 concentrations. • 8-5 Ma: Global expansion of C4 vegetation.	• ~7-5 Ma: Messinian salinity crisis; desiccation of Mediterranean.	• <8 Ma: Expansion of western rift, uplift of rift shoulders, regional rain shadows and aridification.	• ~7 Ma: Chimpanzee-hominin split; development of bipedal locomotion. • First *Australopithecus*.		• Plants and animals show length of the dry seasons increased by many months in the middle to late Miocene, and then shortened again near the Mio-Pliocene boundary. • ~8-7 Ma: Fauna indicates cooler conditions in Kenya/Ethiopia. • Heterogeneous landscapes but trending towards drier at Mio-Pliocene boundary. • Fauna indicates closed habitats at many hominin sites; biogeographic exchange across Mediterranean during Messinian drying.

4-2 Ma	• 4-3 Ma: Pliocene warming interval and higher CO_2 concentrations, humid conditions in East Africa, and weak zonal and meridional sea surface temperature (SST) gradients. • 3.6-3.4 Ma: Lake phase in NE Africa. • Onset of major Northern Hemisphere glaciation between 3.2-2.6 Ma and development of arid conditions in East Africa. • 3-2 Ma: Development of strong sea surface temperature gradients in equatorial Atlantic and Indian Oceans. • More seasonally-contrasted, cooler, and drier—and perhaps more variable—climate in North Africa. • ~2.8 Ma: Increase in eolian dust fluxes around North Africa. • After 2.8 Ma: Expanded amplitudes of North African wet-dry cycles. • 2.7-2.5 Ma: Deep lake phase in NE Africa. • By 1.8 ma: Disappearance of persistent El-Niño like conditions in tropical Pacific.	• 2.8 Ma: Growth of polar ice sheets and lowered sea-level, onset of glacial/interglacial cycles.		• Trend for *Australopithecus* to have larger and taller cheek teeth, reduction of canines, and to maintain a high level of sexual dimorphism. • ~ 3-2.4 Ma: Split between australopithecines and *Homo*. •~2.7 Ma: Evolution of *Paranthropus*. •~1.8 Ma: Evolution of more carnivorous *H. erectus*. • *Australopithecus* species disappeared from East African record.	• 2.58-2.52 Ma: Earliest stone tools. • After 2.3 Ma: Stone tools increasingly common.	• Australopithecines initially associated with fauna that indicates woodland with some grassland or more bushland habitats; first appearance of *Equus* in Africa and connections with Eurasia grassland expansion, which is coupled with increased body size in *Homo*.

Interval	Climate Events	Sea-Level Events	Tectonic Events	Hominin Evolutionary Events	Archaeological Record Events	Fossil Record Events (other than hominins)
2-0.5 Ma	• 1.9-1.7 Ma: Lake phase in NE Africa. •1.8-1.6 Ma: Development of modern tropical global SST gradients. • 1.8-1.6 Ma: Greatest expansion of C4 vegetation in East Africa.	• ~1 Ma: Enhanced amplitude glacial aridity cycles and shift to 100-ky cyclicity..		• *Paranthropus* widespread but goes extinct ~1.2 Ma. New species of *Homo* with smaller cheek teeth, larger brains, and more sophisticated tools, the extinction of others, and substantial improvements in technology. The first dispersal of *Homo* out of Africa into Eurasia..	• ~1.6 Ma: Acheulean stone tool technology. • 790 ka: Oldest definite evidence of controlled fire.	• 1.8 to ~1.0 Ma: African fauna indicate fairly open, grassland habitats
0.5-0.0 Ma	• Coldest glacial MIS-6 about time of first *H. sapiens.* • ~140-70 ka: Tropical/subtropical megadroughts.	• Very low sea level during MIS-6 and MIS-2.		• ~500 ka: First archaic *Homo* with substantially enlarged brain size. • *H. heidelbergensis* in Europe, Asia, and Africa beginning at about 400 ka. *H. erectus* expansion into northern latitude climates within	• Between 200-60 ka: Evolution of Middle Stone Age innovations. • ~400 ka: Oldest thrusting spears known.	

				glacial systems until ~250 ka. • ~200 ka: First modern *H. sapiens.* • South African, Ethiopian, and Maghreb *H. sapiens* in refugia during MIS-6. • ~60 ka: Dispersal of modern *H. sapiens* out of Africa. • ~10 ka: Origins of agriculture.		

3

The Research Vision–Priority Research Themes

The records of hominin evolution and dispersal outlined in the preceding chapter highlight important events in our past—the split between ancestors of chimpanzees and hominins at 8-6 Ma, the split that produced *Homo* from an *Australopithecus* ancestor around 3-2.5 Ma, the first dispersal of hominins (probably *H. erectus*) out of East Africa into North Africa and Asia about 1.8 Ma ago, the extinction of *Paranthropus* between ~1.4 and 1.2 Ma ago, and the more recent dispersals out of Africa about 0.9 Ma and after 0.1 Ma ago. Paralleling these records, we now have, and continue to acquire, more detailed records from marine and lacustrine sediments and polar ice cores of the environmental history of Africa, Eurasia, the Americas, and Australia. The dominant environmental signals over the past several million years have been the global cooling trend, the growth of polar ice sheets, the climate variability at orbital-variation timescales (20, 40, 100, and 400 ky) as reflected in glacial/interglacial and monsoon cycles, and the existence of millennial-scale variability and abrupt changes.

An overall global climate history based on oxygen isotope records obtained from benthic foraminifera in ocean sediments indicates that the gradual cooling of the planet, which began tens of millions of years ago, has continued, with only minor variations, during the past 8 Ma (Figure 3.1). Orbitally-paced glacial/interglacial variations of Northern Hemisphere ice sheets began around 2.7 Ma, and increased dramatically in amplitude and duration around 0.9 Ma. Additional records from land and ocean, from lake cores, and from ice cores, document changes in glacier extent, sea level, vegetation, lake levels and lake chemistry, river runoff, dust deposition, and atmospheric carbon dioxide (CO_2) concentrations. There is also evidence for changes in ocean circulation based in part on the opening or closing of oceanic gateways (e.g., the Isthmus of Panama, the

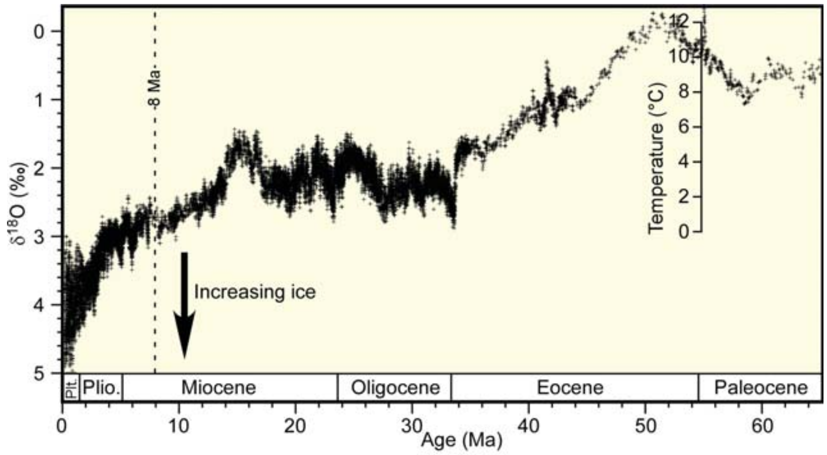

FIGURE 3.1 Synthesis of global deep-sea benthic foraminiferal oxygen isotope records, based on analyses of cores from Deep Sea Drilling Program and Ocean Drilling Program sites, updated with high-resolution records for the interval spanning the middle Eocene to the middle Miocene. Raw data were smoothed using a 5-point running mean. The conversion of oxygen isotope data to a temperature scale was computed for an ice-free ocean, and therefore only applies to the portion of the curve older than about 35 Ma. Note the strong cooling trend, with only minor perturbations, over the past 8 Ma. SOURCE: Modified from Zachos et al. (2008).

Straits of Gibraltar, and the Indonesia seaway). Despite this broad understanding of the history of global environmental change, there is limited understanding of the regional environments in which hominins evolved, and an incomplete understanding of the processes that have forced these global and regional climatic and environmental changes over the past 8 Ma.

Did climate change shape human evolution, and if so, how? As noted above, 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. This chapter defines a set of research activities that will develop the paleoclimatic, paleoanthropological, and archaeological observations needed to test hypotheses linking climatic and biotic change that encompass the major events in hominin evolution. A range of potential research topics and initiatives to clarify the relationships and interactions between these evolutionary and environmental histories were advanced by the wider community during the open workshop held as part of this study. The committee assessed these topics, and identified the following two high-priority research themes as having the greatest potential to transform our understanding of the origin of human adaptations to environmental change.

THEME I: DETERMINING THE IMPACTS OF CLIMATE CHANGE AND CLIMATE VARIABILITY ON HUMAN EVOLUTION AND DISPERSAL

This section articulates a vision for making substantive advances into the central question concerning the role of climate change in human origins. Simply put, how can we bridge the divide separating our current state of knowledge from what would be needed to address this question in a qualitatively improved way. Significant progress on this fundamental question of human origins cannot be attained without first recognizing that the problem is fundamentally data-limited. Data limitations include, but are not restricted to

- gaps or poorly-studied intervals in the fossil and archaeological record, coupled with the highly-variable fossil density from different time periods and regions;
- the inconsistent collection of all components of available fossil assemblages (e.g., invertebrates, vascular plants and algae, as well as vertebrates), which have potential to offer critical tests of the climate-evolution relationship;
- stratigraphic and geochronologic limitations;
- the rarity of quantitative paleoenvironmental records situated close to fossil localities; and
- the need for broad application of newly-emerging techniques for quantitatively and accurately reconstructing past climates.

The central goal of the research activities encompassed by this research theme is to make substantial progress in overcoming these limitations and to introduce novel analytical approaches that build upon the existing scientific foundation, thereby enabling rigorous tests of how human evolution and the adaptability of our own species have been shaped by climate change.

This research vision depends upon data collection and analysis that is strategically focused on a number of critical time windows in which pivotal evolutionary events occurred. This approach to data collection will stimulate, for example, an in-depth analysis of how the earliest origin of the human lineage, the broad trajectory of technological change, the increase in human brain size and cognitive complexity, and the origin of the social behaviors characteristic of humans today emerged in relation to the pace and patterning of climate change, and thus whether the core adaptations of human beings revolve around the ability to solve the challenges of climate change.

This research vision also depends on a new level of integration of disciplines and training of scholars in ways that motivate the growth of a richly collaborative enterprise. Furthermore, these vital activities of data integration and collaborative analysis need to be focused on advances in hypothesis testing in which evolutionary and climatic records are treated as sources of natural history "experiments."

This concept means that whereas the particulars of historical or evolutionary phenomena are not replicable in the sense of laboratory science, evolutionary and climate records do exhibit a surprising number of iterations—for example, the repeated emergence of certain food processing adaptations, recurrent geographic expansions, or the concurrent rise or loss of species diversity across diverse animal groups, all of which can be examined in relation to repeated periods of climate warming, cooling, heightened variability, or stability, along with the repetitive expansion and contraction of habitats. These iterations mean that there are numerous cases over time and space where the detailed relationships between climate and evolutionary response in humans can be defined, examined, and compared against the responses in the contemporaneous biota. Common patterns or regularities have the potential to yield new understandings of evolutionary processes and the influences of climate.

Overarching Research Strategy

Common to all hypotheses linking climate change and faunal evolution is the notion that large-scale shifts in climate or climate variability altered the landscape ecology, which, in turn, presented specific adaptive or speciation pressures leading to genetic selection and innovation. This view holds that the most significant evolutionary junctures—those evolutionary and behavioral transitions that were fundamental to shaping who and what we are today—were linked to some aspect of paleoenvironmental change. As noted earlier, the possibility that environmental change had negligible impact on evolutionary change also needs to be considered, because factors such as genetic mutation, resource competition, and social interaction were in effect under all environmental conditions and thus may have impinged on evolution independent of specific environmental transitions. Even if this were so, evolutionary success or extinction depends on the increase or reduction of a species and its particular way of life, which are inevitably influenced by large-scale or abrupt changes in environmental conditions. On the basis of well-tested ideas in evolutionary biology, therefore, environmental variables are critical in shaping the adaptations and geographic distributions of all organisms, and are expected to have made a difference in shaping the course of human evolution, the success and demise of earlier hominin species, and, ultimately, the existence and influence of our own lineage.

Hypotheses of how climate change affected evolution generally start by correlating patterns of evolution recorded in continental basins with marine or lake climate records that are located hundreds or thousands of kilometers away. Identification of such broad correlations has stimulated productive research, but these largely independent efforts have yielded fossil samples and climate records that are distant from one another, unable to be analyzed quantitatively, or are otherwise inadequate to address critical questions about evolutionary processes (see, e.g., Barnosky, 2001). Future progress depends on how well scientists move beyond general correlations to address the causal processes by which climate and evolutionary change have interacted. The following strategies of primary data collection and analysis will enable such progress:

- Improve the density of the evidence concerning the origin and spread of evolutionary innovations. Concerted international efforts to substantially enhance the fossil hominin, archaeological, and other faunal records of evolution are necessary in order to establish with statistical reliability the precise first and last appearances of species, adaptations, and behaviors within particular geographic regions and temporal sequences of strata. Precise determinations of the timing of evolutionary events will facilitate more rigorous analyses of the climate–evolution relationship.
- Close the geographic gap in the study of evolution and climate by obtaining high-precision climate records in close proximity to locations where the evolutionary events in question are recorded. Although progress has been made concerning certain hypothesized linkages between climate and evolution, many of the specific relationships and processes are largely unknown and/or untested, e.g., the relationship between global climate change and local environmental effects; the causal processes that relate climate and evolutionary change observed at specific sites; and the precise temporal expression of novel behaviors and ecological interactions in early humans as these may relate to climate. Bringing the evidence of climate change and evolutionary events into close proximity, particularly the development of high-resolution environmental records at the fossil sites, will substantially improve the ability to assess the extent to which those evolutionary events reflect responses to climate.
- Integrate the evidence of as many evolutionary events as possible, using the histories of other organisms to assess environmental effects on human evolution. This integrative aspect of the research is important in addressing which dimensions of human evolution (e.g., shifts in mobility, food processing, brain size, and population size, along with species formation and extinction) were coordinated with responses in other organisms or, alternatively, reflect uniquely human responses to climate change. In addition, by comparing adaptive change over time, scientists will be able to assess whether the variety of milestones in human evolutionary history tended to coincide with only specific types of climatic forcing or, alternatively, whether evolutionary events occurred under diverse environmental conditions that belie any generalized relationship between climate and evolution. A comparative approach that integrates findings across many taxa, time periods, and regions will necessarily provide numerous examples of both change and stasis, and thus offer the ability to test the diverse range of potential interactions between climatic and evolutionary change.
- Build collaborations across the physical, biological, and human sciences that are essential to dissect the array of geological, atmospheric, marine, biotic, and hominin factors that underlie the climate–evolution relationship. Undertak-

ing a program that successfully investigates this relationship will require high-level coordination among earth scientists, paleoanthropologists, and a network of professional researchers and students dedicated to understanding the detailed interplay between past climates and human evolution. The overall objective of this transdisciplinary vision is to develop a robust empirical foundation for understanding human interactions with their surroundings and for strengthening the interrelationships among disciplines in the natural sciences around one of the most profound scientific questions, the origin of our species.

Research Priorities

The following four research priorities are critical for bringing this visionary research theme to fruition.

The first priority is to develop an integrated, cross-disciplinary focus on crucial time windows of evolutionary change and stasis. Research on the climate-evolution relationship is now best conducted by strategic hypothesis testing and data collection focused around the four time intervals in which critical climatic or evolutionary events occurred (Table 2.1). Within the 4- to 2-Ma interval, the appearance of ice-rafted material in marine deposits in the North Atlantic around ~3.0-2.8 Ma along with the onset of moderate amplitude glacial/interglacial variations at periods around 41 ky is one example of a key climatic event for study. The origination of hominins at 8-6 Ma or of *Homo sapiens* around 200 ka offer examples of time windows defined from an evolutionary standpoint. Since important events are distributed throughout the past 6 to 8 million years, analysis of the entire period of human evolution can be framed in terms of intervals that are tightly focused in a way that stimulates the development of precise hypotheses, the improved recovery of evidence of biotic evolution, and the acquisition of high-resolution climate records.

The second—and related—priority is to develop high precision records of climate change from long stratigraphic sequences proximal to hominin sites and, simultaneously, to expand lake and ocean drilling efforts that will be essential to integrating the local climate records from hominin sedimentary basins with regional and global records. By bringing together environmental records at diverse geographic scales the climatic forcing factors that relate global, regional, and local climate can be investigated and better understood.

A third research priority is to develop and apply new environmental indicator records. All understanding of past climate depends on indicators of climatic variables, that is, proxy measurements that can be used to quantitatively reconstruct temperature, precipitation, seasonality, vegetation and land cover, paleoaltitude, among other variables. Climate records of unprecedented detail can be obtained by comparing across a wide range of such proxies. The integration of new and existing indicators will improve the evidence and resolution of environmental states, variability, and rates of change.

A fourth priority is to formalize research funding to encourage scientific exchange and strategic analysis of climate-evolution hypotheses by earth scientists, paleoanthropologists, and faunal researchers. High-precision analyses of climate and paleoecology should be integrated with the efforts of climate modelers. This overall approach, in which projects are unified by shared strategic goals, requires unprecedented collaboration across disciplines and encourages the development of innovative scientific tools and data exchange.

THEME II: INTEGRATING CLIMATE MODELING, ENVIRONMENTAL RECORDS, AND BIOTIC RESPONSES

The integration of physical and biotic records of past environmental change with regional climate modeling studies offers considerable potential for an improved understanding of the causes of the changes, as a basis for exploring specific questions concerning potential connections between environmental changes and hominin evolution and dispersal. Experiments using climate models can help us understand *why* climate changed (e.g., did greenhouse gas concentrations decrease sufficiently so that winter snows persisted through summer and created the conditions for glacial growth?), *what* happened (where and by how much did ice sheets grow?), and *how* events in one region influenced environments elsewhere through global and regional changes in atmospheric and oceanic circulation. A corresponding set of questions can be formulated for orbital-forcing of insolation changes, for ocean gateway changes, or for combinations of these factors. Moreover, climate models simulate spatial and temporal patterns on a regular grid and at regular time intervals that can provide a context for integrating or synthesizing environmental and fossil records that are discontinuous in space and time, or are otherwise incomplete. They can also provide the basis for predictions in data-sparse regions, to provide hypotheses that can be tested by the collection of new data.

In some cases, it will be highly desirable to simulate the climate (or climate change) at small spatial scales. This might be the case, for example, in regions with large topographic variability (see Box 3.1) such as within the East African Rift Valley or the East African highlands. In such regions, large differences in climate (or climate change) are found on scales of several 10s or 100s of kilometers. At present, there are two main approaches to simulating the climate at such high spatial resolution. The most straightforward approach is to run a global climate model at very high resolution, thereby avoiding the problem of spurious effects from lateral boundary conditions that occur when using a regional or limited-area model. With adequate computer resources, using a global model of high spatial resolution is the preferred approach. In some cases, however, lateral boundary conditions from a global model of intermediate spatial resolution may be useful to force a limited-area model (e.g., for the region of East Equatorial Africa). In that case, an awareness of the problems of lateral boundary conditions "contaminating" the climate solution in the interior of the domain is required, and considerable experimentation with a variety of domain sizes might be necessary. In either approach (global model or limited-area model), it will be necessary to have accurate estimates of the topographic (and other) boundary conditions for the particular times and places of interest, or alternatively, to run a series of experiments that span the range of uncertainties about past surface (and other) boundary conditions. These uncertainties must be assessed both inside the region of immediate interest as well as in the broader and ultimately global context. Both kinds of modeling have been applied in the past, and can form a starting point for future experimentation.

Major initiatives linking climate models and environmental records have contributed significantly to our understanding of the causes and patterns of climate at particular times, for example, during the mid-Holocene (6 ka) and the last glacial maximum (21 ka) (CLIMAP Members, 1976; Gates, 1976; Kutzbach and Guetter, 1986; COHMAP Members, 1988; Braconnot et al., 2007), the previous interglacial (125 ka) (Otto-Bliesner et al., 2006), and the mid Pliocene (about 3 Ma) (Chandler et al., 2008). These studies have demonstrated the value of evaluating environmental records in combination with the insights gained from climate model simulations. However, none of these pioneering studies has adequately explored the full range of climates of the past 8 Ma, or conducted systematic comparisons of the simulations with environmental records.

Four generalized time windows within the past 8 Ma illustrate the potential of a program of integrated data and modeling studies—the period prior to extensive continental glaciations of North America or Europe (8-4 Ma), the period within which glacial/interglacial cycles commenced (4-2 Ma), the period containing the transition to very large amplitude and long duration glacial/interglacial cycles (2-0.5 Ma), and the most recent period of continuing large glacial/interglacial cycles (0.5-0 Ma).

Time Window 1: Prior to Widespread Northern Hemisphere Glaciation (8-4 Ma)

Environmental records show important trends in global climate between 8 and 4 Ma. The global cooling trend that commenced around 15 Ma (Figure 3.1) led to growth of the West Antarctic ice sheet and the Greenland ice sheet between 7 and 4 Ma—a drop in CO_2 levels is a likely candidate for a proximate cause of this cooling. In support of this inference, carbon isotope records from plants show a shift from C3 to C4 vegetation in East Africa and Asia during approximately this same time interval (Cerling, 1992), a shift that indicates a likely lowering of the atmospheric concentration of CO_2 from values higher than 500 parts per million (ppm) to values below this threshold. However, analysis of marine sediments suggest that atmospheric CO_2 levels were relatively stable and closer to preindustrial levels (200-300 ppm) prior to and during this period (Pagani et al., 1999, 2005).

BOX 3.1

Potential of Regional Climate Models

Recent modeling experiments demonstrate the potential of regional models for improving our understanding of climate-evolution interactions in Africa at various timescales relevant to human evolution. Sepulchre et al. (2006) examined the probable climatic impact of the uplift of mountain ranges associated with the East African Rift System (EARS) during the late Neogene (Figure 3.2). Their experiments suggest that prior to this uplift, the absence of a topographic barrier to moisture allowed zonal circulation across equatorial Africa, which would

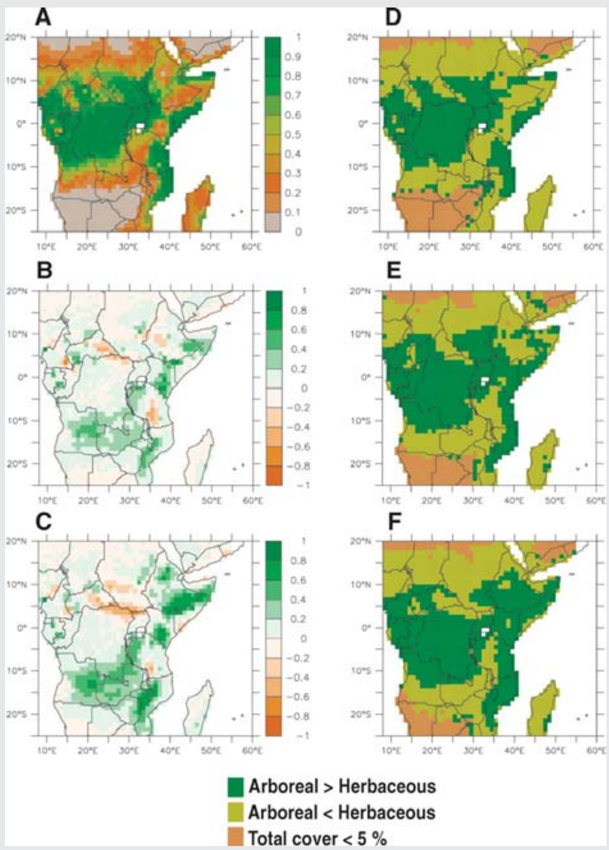

FIGURE 3.2 Simulated vegetation for three model runs showing biosphere responses to topographic changes linked to eastern and southern African uplifts. A-C depict the modeled differences between the present-day vegetation (A) and vegetation patterns for reduced (B) and low (C) topography situations. D-F show the distribution of arboreal-dominant, herbaceous-dominant, and desert-like fractions for the present day (D), reduced topography (E), and low topography (F). Note the massive spreading of arboreal fraction at the expense of herbaceous fraction over eastern Africa. SOURCE: Sepulchre et al. (2006).

have in turn maintained forests throughout the region. The modeling indicates that EARS uplift at ~8 Ma results in a dramatic reorganization of atmospheric circulation in the region, and subsequent aridification during the early phase of hominin evolution.

On a much shorter timescale, Cowling et al. (2008) simulated paleovegetation patterns for Africa during the Last Glacial Maximum (LGM) and preindustrial times (i.e., interglacial conditions unperturbed or little perturbed by anthropogenic CO_2 emissions) (Figure 3.3). Their experiments for the LGM suggest a tropical broadleaf forest reasonably similar in extent to that of the present, but with some reduction at the edges (especially in the north). However, the structure of these forests differed dramatically from modern ones, in terms of reduced leaf area, tree height, and carbon content. In contrast, their interglacial simulations suggest transcontinental broadleaf forests in Central Africa which could have acted as barriers to more open-habitat environment organisms, with possible implications for *Homo sapiens* distribution patterns. Similar experiments for earlier time periods might illuminate biogeographic and diversification/extinction events associated with earlier hominins.

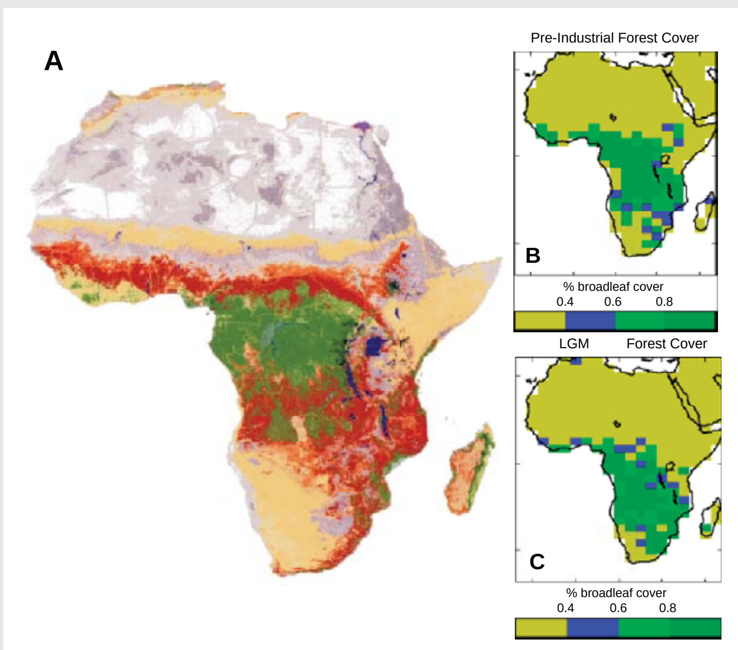

FIGURE 3.3 Model simulations for vegetation cover in (B) preindustrial and (C) Last Glacial Maximum time, compared with (A) modern-day vegetation distribution reconstructed from remotely sensed data. For the modern-day image, green colors represent forests and red colors represent woodlands and shrublands. SOURCE: Cowling et al. (2008).

By comparing modeled climate scenarios both to the polar glaciation records and to the terrestrial records of change from C3 to C4 vegetation, it may be possible to resolve this apparent difference in greenhouse gas levels and to place bounds on the likely climates associated with different greenhouse gas levels.

Changes in oceanic gateways may also have played a role in climate change during this period. A particularly dramatic example of a gateway change was the closing of the connection between the Atlantic and the Mediterranean around 7 Ma, which led to periodic episodes of drying of most or perhaps all of the huge inland sea (the Messinian salinity crisis) until about 5.3 Ma, when the gateway reopened (Rouchy et al., 2006). The effects of this drying in the core of the African-Eurasian land mass have not been studied in detail, but must have profoundly influenced regional climates both through changes in the heating of the African/Eurasian landmass and through circulation and other changes in adjacent oceans.

Although these largely marine-based environmental records of global and regional trends, along with sparse terrestrial records from Africa and Eurasia, indicate large changes in climate during this time window, the details are obscure. Climate models for the pre-Northern Hemisphere ice sheet expansion period (the 8- to 4-Ma interval) can be used to simulate the geographic patterns of African climate and vegetation, and to help constrain the causes and magnitudes of African climate and vegetation shifts in terms of the relative influences of possible ranges of atmospheric CO_2 concentrations, orbital forcing, and orographic and seaway changes, as well as to estimate ranges of uncertainty.

Time Window 2: The Onset of Glacial/Interglacial Cycles (4-2 Ma)

After 3 Ma, oxygen isotope records from marine sediment cores indicate continued cooling and development of continental ice sheets in the north. However, this general cooling trend was interrupted by a relatively brief warmer interval in the mid-Pliocene (~3 Ma), when there is evidence of increased warmth on global and regional scales, and perhaps somewhat elevated levels of greenhouse gases.

By 2.8 Ma, the general cooling trend continued, ice-rafted debris is found in North Atlantic Ocean sediments (an indication that icebergs were calving from polar ice sheets), and the marine-based oxygen isotope records show the onset of increased climatic variability. The waxing and waning of the developing northern continental ice sheets occurred at periods of known orbital cycles—the 41,000-year cycle in the tilt of Earth's rotational axis and the 23,000-year cycle of the precession of the rotational axis (see Box 2.1). Ocean sediment cores contain records of windborn (eolian) dust emanating from the African continent and show both a gradual increase in dust over time and cycles of more or less dust at 23,000-year and 41,000-year periods. The isotopic records from terrestrial and marine sediments show a continued shift from a more wooded to a more open grassland environment, particularly in East Africa.

Yet another huge change in Earth's climate between 3 and 2 Ma is recorded by equatorial ocean sediment cores. During this time, the equatorial ocean temperature in the Pacific, Atlantic and Indian Oceans changed from near east-west uniformity to the present-day pattern of strong east-west gradients. In modern terms, for example, the equatorial Pacific changed from being a "permanent *El Niño* pattern" to a dominant *La Niña* pattern (warm in the west, cold in the east), a change that had major effects on tropical continents worldwide (Wara et al., 2005; Fedorov et al., 2006).

These records of major climate shifts—both trends and changes in variability, and changes in climate forcing—occur within the span of important events in hominin evolution or dispersal, including the split between 3 and 2.5 Ma that produced *Homo* from an *Australopithecus* ancestor. A major new research initiative, focused on the 4- to 2-Ma time interval, would illuminate the extent to which changes in climate and/or biotic communities influenced the origin of *Homo*. New paleoclimate studies and faunal/vegetation analysis would also constrain the likely dispersal routes and corridors or examine the potential for long-term contact among populations of *Homo* across environmental boundaries (e.g., the Sahara). And, with more focused paleoecological studies, it should be possible to finally understand whether *Homo* first dispersed as part of an integrated faunal community, with other individual species, or on its own.

The environmental records alone are still too sparse to draw firm conclusions about geographic patterns of climate in Africa and Asia and their variability, or about climate conditions along pathways to southern Eurasia, or temporal and spatial variability of Eurasian climates. In our vision, targeted and more resolved climate simulations during the 4- to 2-Ma period, when global sea surface temperature gradients were rapidly changing and global ice volume was rapidly increasing, will play a critical interactive role with new data collection to test the likely climate system drivers underlying the new paleoenvironmental records. These will, in turn, allow us to link models of these rapidly changing earth system processes in the late Pliocene to studies of hominin history and evolution. This combination of blending current and new environmental records with new climate model experiments represents a great opportunity.

One aspect of this opportunity to provide a much improved knowledge of the environmental context in which hominin evolution occurred is that, although we understand the potential response of climate (and environment) to individual mechanisms, we have not studied combinations of these processes. For example, climate models have proven to be quite accurate in their ability to predict middle-latitude and tropical monsoonal responses to orbital forcing, the critical factors that might have triggered the onset of high-latitude glaciation, and the cause of the dramatic shift in equatorial ocean temperatures that may have had major consequences for tropical and subtropical climates. The great challenge will be to study the combination of these processes, including multiple experiments with different greenhouse gas levels to take into account uncertainties in CO_2 concentrations at this time, and uncertainties about the degree of ocean transport through the Panama and Indonesian seaways. It will also be important to investigate how likely scenarios of moisture transport would have impacted the vegetation and water resources on which early hominins depended. This combined use of models and environmental records should then provide, for the first time, the opportunity to compare our best estimates of spatial and temporal patterns of environmental change with the fossil record of hominins.

Time Window 3: Longer and Larger Glacial/Interglacial Cycles (2-0.5 Ma)

A major shift in the tempo of climate and its extremes began about 1.2 Ma, and was in full swing by 0.9 Ma. The dominant period of glacial/interglacial cycles switched dramatically to the 100,000-year eccentricity cycle, although the 23,000 and 41,000-year components remained present. Although details of the geographic extremes of these glacial boundaries are uncertain, we know from the most recent extremes (22 ka) that ice sheets probably extended from the European Arctic southward as far as western and central Europe, with belts of tundra reaching into middle latitudes and with dramatic drops in global sea level of well over 100 meters. In the tropics, the 23,000-year precession cycle influencing tropical wet/dry cycles remained strong, but with perhaps even more pronounced episodes of aridity in some parts of the tropics. During much of this period, starting at about 0.8 Ma, ice cores provide a key additional environmental variable—we know CO_2 and methane concentrations of the atmosphere through extraction and analysis of fossil air samples from the ice cores. Lowered CO_2 helped amplify the cold swings and higher levels of ρCO_2 occurred during the warmer interglacials. Both ice sheet changes and changes in CO_2 levels could also have influenced tropical and subtropical precipitation.

What we do not understand, and would be the focus of the new research initiative proposed here, is how these climatic changes and resulting vegetation and water resource changes were transmitted to the specific regions where hominins lived. Another dispersal of *Homo* from Africa to Eurasia happened around the time of the climatic transition to large and long glacial/interglacial cycles (1.2-0.8 Ma) and these major climate swings must have modified the environments inhabited by *Homo* in Africa and Eurasia. Moreover, the changing amplitude and duration of the orbitally forced changes in climate, other quasi-periodic changes of shorter duration, or relatively gradual changes in forcing, may have had different effects on ecosystems than the abrupt changes that are also a characteristic of the climate record. With improved density, accuracy, and dating of environmental records during this period, there is a major opportunity to use climate models to ask more detailed questions and to obtain more detailed information about both the climate and vegetation comprising hominin habitats. In particular, the availability of accurate estimates of atmospheric CO_2 will permit simulation of both the direct effects of greenhouse gases on climate (and vegetation) and the possible physiological effects on vegetation of changing levels of CO_2. These models can only be accurately tested by reference to actual paleoenvironmental data from Africa and Eurasia and the surrounding oceans. With the availability of greenhouse gas records and known orbitally controlled changes in solar radiation, along with known changes in orography, volcanism, coastlines, and ocean gateways, models have proven to be remarkably accurate in simulating past climates. However, challenges remain in accurately simulating the waxing and waning of ice sheets and the effects of glacial climates on tropical climates due to the complex interactions of several critical factors—the tropical forcing of monsoons by precession changes and forcing due to high-latitude climate changes, CO_2 changes, sea-level changes, and deep-ocean circulation changes.

Time Window 4: Continuing Large Glacial/Interglacial Cycles (0.5-0 Ma)

The last several glacial/interglacial cycles, and in particular the climate of the last 150,000 years, is relatively well documented worldwide, although details of the spatial and temporal variability of climate on the continents are scant except for the past 20,000 years. The previous interglacial, the period around 125 ka, has been the subject of detailed study, as has the subsequent onset of glaciation around 115 ka, the LGM around 22 ka, and the subsequent warming trends culminating in the mid-Holocene, around 9-6 ka. The changes in forcing are relatively well known—primarily the orbitally-forced changes in insolation and the changing levels of CO_2 and methane. This period then offers unique opportunities for detailed time-space simulation of climate, the comparison of the simulated climate with observations, and the subsequent analysis of potential linkages with hominin evolution and dispersal.

There are *H. erectus* fossils in China as recent as 250 ka and it should be possible to simulate the climate in Asia at this time and in particular the intensity of both summer and winter monsoons. Both *H. neanderthalensis* and *H. sapiens* appear in the period directly before or slightly into the penultimate glaciation (190-130 ka), and it should be possible to simulate the climate and vegetation of this period in considerable detail. There is evidence of megadroughts in tropical Africa between 135 ka and 90 ka, a period that preceded the dispersal of humans out of Africa around 60 ka and their widespread movements thereafter. It will be possible to use climate models, focusing primarily on the known orbital forcing and known glacial boundary condition forcing (ice sheets, sea level, CO_2 level) to simulate the period of the past 125 ka with considerable accuracy and make detailed comparisons with the observations, both spatial and temporal. Millennial-scale changes in climate are also well documented in both polar and tropical latitudes during much of this most recent period, and offer the unique opportunity to study the possible causes of these events and the possible effects on ecosystems and humans.

4

Implementing an International Scientific Program for Climate and Human Evolution Research

Although the exploration of human origins is inherently an international activity, the actual planning and execution of past and existing large research projects in the field have been largely conducted and funded along national lines. Although many projects involve a partnership between, for example, U.S. or European scientists and their counterparts in the African or Asian country where the field research occurs, broader partnerships and funding efforts are still relatively rare. This is an obvious impediment to future advances at the earth system/human origins research frontier, where truly international efforts have great potential to make significant progress.

Examples do exist at the earth system/human evolution research interface where successful collaborations have occurred, and the results of these research activities have been very exciting. A good example is the *Stage Three Project*[1] (Van Andel and Davies, 2004), a research consortium involving more than 30 scientists from 10 countries designed to investigate paleoclimates and ecosystem responses in Europe and surrounding regions during Oxygen Isotope Stage 3 (OIS-3). This period, from about 60 ka to 24 ka, immediately preceded the Last Glacial Maximum and encompasses the time when Neanderthals existed in Europe as the only hominin species, and then were joined by migrating populations of modern *Homo sapiens*, followed by the eventual extinction of Neanderthals. A major objective of the *Stage Three Project* is to understand the effects of changing climates on the conditions, resources, and demography of hominins in Europe during this period. This involves not only investigating paleoclimate, fossil hominin, and archaeological records, but also understanding

[1]See *http://www.esc.cam.ac.uk/research/research-groups/oistage3*

the fossil plant and animal records of the region, integrated with extensive climate modeling efforts to provide a dynamic understanding of the findings. This type of collaboration is a useful model for us to consider, but it lacks a critical element—the significant funding that will be required to undertake the types of projects proposed here.

We envision a new scientific program for international climate and human evolution studies that involves both essential and supporting components:

Essential Components Three elements must be carefully integrated to comprise the core program of research:

- A major exploration initiative to locate new fossil sites, and to broaden the geographic and temporal sampling of the fossil and archaeological record;
- A comprehensive, integrated scientific drilling program in lakes, lake bed outcrops, and ocean basins surrounding the regions where hominins evolved, to vastly improve our understanding of the climate and environmental history of these regions;
- A major investment in climate modeling experiments for the key time intervals and regions that are critical for understanding human evolution, focused on understanding the regional climate patterns and fundamental climate forcing mechanisms, and to model at a more local scale the interactions between climate, ecosystems, and species population dynamics.

Supporting Components In addition, there are a number of components that will be required to complement the core research effort:

- A systematic analysis of fossil sites and collections, with application of new imaging and dating technologies, to better describe the nature and timing of the hominin evolutionary lineage;
- An investigation of how population sizes have changed over the past 500,000 years, based on whole-genome samples of DNA from a number of species, including humans;
- Selected investigations of ecosystem dynamics through the collection of modern climate and calibration data to more accurately quantify relationships between the environment and the proxy records of environment preserved in sediments and fossils;
- Development of the informatics and data archiving tools needed to both provide permanent storage for the wide array of information collected by the activities listed above and to facilitate continued access to and the synthesis of this information.

Building an international community of scientists from such diverse fields as anthropology, climatology, Quaternary geology, paleolimnology, paleontology, paleoceanography, and archaeology will require a sustained effort. The primary goals of any such activity must include facilitating communication and making information easily accessible to participants. In this regard it is useful to consider possible models for an international consortium of climate, earth, and human evolution scientists. In addition to the Stage Three Project noted above, another highly successful and relevant model is the PAGES (Past Global Changes[2]) program, a core project of the International Geosphere-Biosphere Program (IGBP) dedicated to promoting past global change research. The PAGES program operates through a small secretariat and 23 national member contacts, with funding from the U.S. National Science Foundation, the Swiss National Science Foundation, and the National Oceanic and Atmospheric Administration. This program promotes research on past global climate change by identifying key research opportunities through a series of focal group meetings, through sponsored workshops, and with its publications. We envision a similar structure for an international climate and human evolution consortium.

INTERNATIONAL EXPLORATION INITIATIVE: ADDRESSING THE URGENT NEED FOR MORE FOSSILS

An urgent need exists for a major international initiative to recover significantly more hominin fossils, as well as the flora and fauna that are associated with these fossils. Exploration for new sites is required beyond the limited areas within continents that have been sampled so far. Such an initiative would greatly improve our understanding of

- the geographic distribution and variation of hominins;
- the phylogeny of the human lineage; and
- the first and last appearances of species, and of important archaeological or fossil evidence of human behavior.

This in turn will permit a vastly improved correlation of the significant events in human evolution with proxies for climate and other aspects of the earth system. At present, this is not possible at the level of resolution necessary if hypotheses that would relate changes in human evolution to extrinsic factors are to be meaningfully tested.

The discovery of fossil hominins, and the associated flora and fauna, has often been a random process resulting from chance occurrences, although there have been a few more deliberate and systematic exploration efforts. For example, remote sensing techniques were used in Ethiopia to predict new fossiliferous out-

[2]See *http://www.pages.unibe.ch/*

crops, to guide field logistics, and to formulate national research and conservation strategies (Asfaw et al., 1990). The ground surveys following this preparatory work led to the discovery of new sites and important new fossils.

There are a variety of satellite and aerial imagery techniques available that would aid in locating probable fossiliferous areas. These could be applied in a hierarchical sequence, with lower resolution but broader scale satellite analyses to identify promising areas (Figure 4.1A) being succeeded by progressively more focused and higher resolution satellite[3] and aerial imagery. Ultimately, we envision very high resolution multispectral imagery, perhaps collected by Unmanned Aerial Vehicles (UAVs) configured for civilian scientific research (Figure 4.1B). Enhancing discovery at the other end of the spectrum—actually finding hominin fossils—requires trained eyes to scan the surface of fossiliferous sediments for suitable fossils (Figure 4.1C). This component of the process can be optimized by an increase in the number of skilled observers, who would ideally be trained people from the particular country of research.

As a consequence of various human impacts (e.g., settlement), hominin fossils are a severely diminishing resource. Existing sites are being depleted, and are largely nonrenewable because of the long time periods needed for material to weather out from the subsurface (e.g., White, 2004). It is crucially important that an enhanced exploration program be carried out soon, before vital information about our deep past history and its relation to climatic change vanishes completely. This program of work cannot be deferred, or the results will diminish significantly.

This proposed venture will inject into the process of discovery a major multidisciplinary initiative to finance extensive remote sensing operations for the detection of new fossiliferous areas and sites, and to promote a substantially enhanced program of ground exploration. One outcome will be to redress the narrow focus that has resulted from relatively small, individual research groups tending to return to well-known areas and regions where the potential for success is thought to be highest. In Africa, for example, it will extend the range of exploration well beyond the confines of the Rift Valley. The initiative proposed here will greatly increase the potential for the discovery of new fossiliferous regions, new sites, and new information about human ancestry. Integrating these data with

[3]**MODIS** (Moderate Resolution Imaging Spectroradiometer) has a resolution of about 250 m to a pixel, or about 500 m in color, and such data are suitable for producing large-scale base maps. Elevation maps from the **SRTM** (Shuttle Radar Topography Mission) are resolvable to 90 m, and these data permit slopes and aspect to be calculated. **LANDSAT**, to be supplemented by the Landsat Data Continuity Mission (**LDCM**) from summer 2011, has provided great coverage since 1972 with a resolution of 20-30 m per pixel. These data are not only more finely resolved, but provide the advantage of enabling land cover classification. **ASTER** (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is still higher resolution (15 m, or 30 m in color). ASTER also permits the analysis of shortwave bands that are suitable for distinguishing different minerals, and hence provides potential to identify rock types. There are also higher resolution systems—**ALOS** (Advanced Land Observing Satellite) can resolve to 10 m in color; **IKONOS** can resolve from 3.2 m to 82 cm; and **QUICKBIRD** is advertised as achieving a pixel resolution of 61 cm in panchromatic bands.

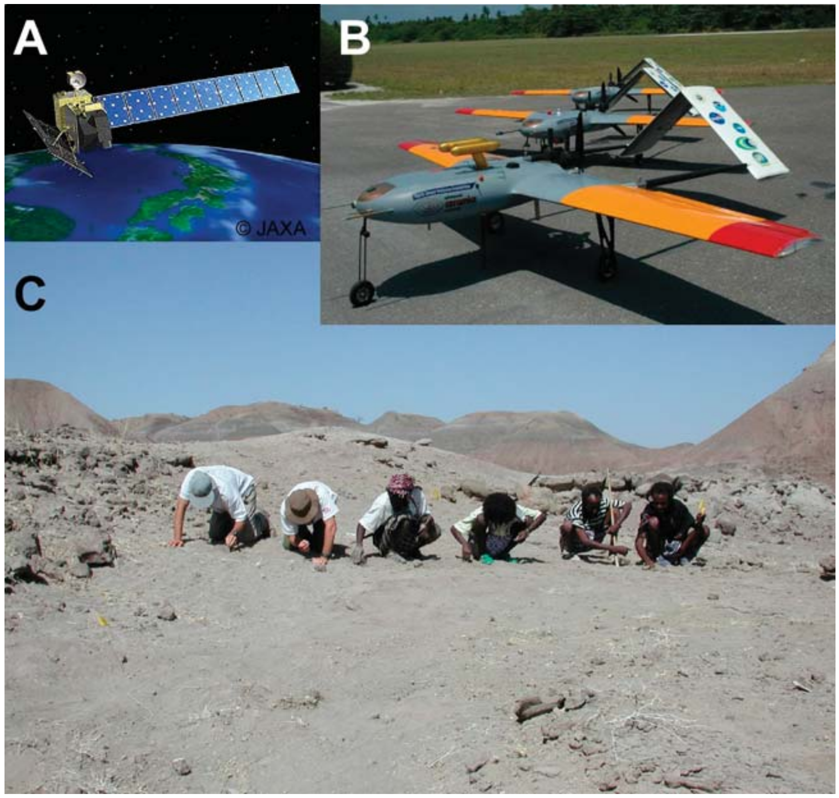

FIGURE 4.1 A vision for hominin fossil exploration in the future—initial reconnaissance and identification of potentially promising areas using (A) remote-sensing satellites and (B) Unmanned Aerial Vehicles (UAVs) with multispectral sensors, followed by (C) traditional detailed ground examination. SOURCES: (A) ALOS (Advanced Land Observation Satellite) image from JAXA (Japan Aerospace Exploration Agency); (B) UAVs shown are those that were used for the Cheju ABC Plume-Asian Monsoon Experiment (CAPMEX), courtesy of V. Ramanathan, http://www-ramanathan.ucsd.edu/capmex.html; (C) photograph from Afar Ledi Geraru, Ethiopia, courtesy of Kaye E. Reed.

high-resolution climatic information from linked drilling programs will result in a much more profound understanding of the forces that have contributed to the course of human evolution.

INTEGRATED MARINE, LAKE, AND TERRESTRIAL DRILLING PROGRAM

An integrated marine-lake-terrestrial scientific drilling program is an essential component of a research initiative to obtain a comprehensive paleoenvironmental history of human origins. Drill cores recover the continuous, fine structure of the environmental record needed to address questions about changes in the earth system at sufficiently high resolution to describe short-duration events and processes. Moreover, drill cores collected from below the Earth's surface are less affected by the surface alteration and weathering processes that affect and degrade outcrop samples.

Sediment cores from lakes and oceans can be analyzed for an extraordinary array of sedimentological, geochemical, and paleoecological data that are frequently complementary, providing independent cross checks for the interpretation of past environmental conditions. New analyses of aquatic and terrestrial organic components in distal marine fan and lacustrine environments have permitted more refined reconstructions of African vegetation, temperature, and hydrologic changes than had been possible from pollen analyses alone. Riverborne terrestrial organic matter contains a broad spectrum of biomarkers that can be used to decipher basin-scale changes in climate, vegetation, and hydrology. New biochemical proxies are being measured in sediment cores that provide promise for quantifying past conditions. One such proxy is TEX_{86}, an index that is based on compounds derived from prokaryotic Crenarchaeota that live among the picoplankton of lakes and oceans. The TEX_{86} index correlates well with surface water temperatures, and is well preserved in marine and lacustrine sediments up to millions of years in age (Schouten et al., 2003; Powers et al., 2005). Another highly promising method involves studies of clumped isotopes (isotopologues) in calcium carbonate minerals, which have also been shown to produce quantitative and accurate reconstructions of past temperature (Eiler and Schauble, 2004; Ghosh et al., 2006).

Marine Environments Among the most promising archives for reconstructing past changes in African climate are the sediment packages that accumulate on the upper slope near the mouths of rivers that drain large areas of continental Africa. Africa's largest drainage basins—the Nile, Niger, Zambezi, and Congo—each drain several millions of square kilometers and thus constitutes large areal integrators of regional climate characteristics. Smaller drainage basins, such as the Ganane and Rufiji, drain areas that contain known hominin fossil localities.

Proximal fan successions are commonly complicated by intermittent sedimentation and sedimentary gravity flows, whereas distal fan successions tend to be more continuous, with high accumulation rates of marine pelagic components (microfossils and marine organic carbon) as well as terrestrial lithogenic (riverine clays and silts) and organic (terrestrial organic matter and biomarkers) material. Oxygen isotopic analyses of marine foraminifera can be used to provide a high-resolution chronology at orbital (10^4 years) scale. The terrestrial organic fraction can be exploited to yield an impressive diversity of proxies that monitor the paleoclimatic, paleohydrological, and paleovegetational history of the specific drainage basin.

Recently published studies of sediment cores from deep-sea fans off Africa highlight the promise of these sediments for reconstructing African continental paleoenvironmental changes (e.g., Weijers et al., 2007; Weldeab et al., 2007). Most of these studies are based on short cores (Figure 4.2), but drill sites targeted near these core locations (as well as additional new sites) would permit extension of these results to include the Pliocene-Pleistocene timeframe that encompasses major events in early human evolution.

Offshore Environments Most of the longer, Pliocene-Pleistocene records of North African paleoclimate change have been derived from drill sites in open-ocean depositional environments. When properly sited to monitor past variations in the supply and composition of windborne eolian detritus transported from North African source areas, these open-ocean sites have provided robust, detailed, multiple proxy records of regional climate changes (e.g., Tiedemann et al., 1994; deMenocal, 2004; Feakins et al., 2005). For sites closest to East Africa, distinct volcanic tephra layers can be extracted and geochemically correlated to tephra horizons in terrestrial fossil-bearing sequences throughout the late Neogene, providing direct time-equivalent links between terrestrial and marine sediment archives (Sarna-Wojcicki et al., 1985; Feakins et al., 2007).

Most existing ocean drilling sites off the African continent have been sited off northwest Africa (Ocean Drilling Program [ODP] Leg 108), off southwest Africa (ODP Leg 174), in the Mediterranean (ODP Leg 160), or on the distal fans of large river systems. Very few sites have been drilled off northeast Africa near hominin fossil localities. In 1974, Deep Sea Drilling Program Leg 24 drilled several sites in the Gulf of Aden, and these remain the most proximal marine sediments to hominin fossil sites in Ethiopia, Kenya, and Tanzania. These cores have been intensively studied, and the results of these studies have been integrated into the description of our existing understanding presented in Chapter 2. However, further progress is severely limited by the discontinuous coring and rotary coring disturbance in these cores typical of early scientific ocean drilling. New high-quality sediment drill cores from the Gulf of Aden remains a top drilling priority. A proposal to drill six new sites in the Gulf of Aden was recently ranked by an international science panel of the Integrated Ocean Drilling Program (IODP) as the top priority for Indian Ocean drilling by the *JOIDES Resolution*—ultimately, however, regional security issues will determine whether these sites can actually be drilled in the near future.

Lake Basins Among the most promising sites for high-resolution paleoclimate records within Africa are the large modern and ancient lake basins. Although deposition patterns are often complex in large lakes (Johnson, 1996), sites can be identified where sedimentation is nearly continuous, with few disturbances by sedimentary gravity flows or erosional events, and where sedimentation rates are relatively constant and fast. Under ideal circumstances, sediment cores from

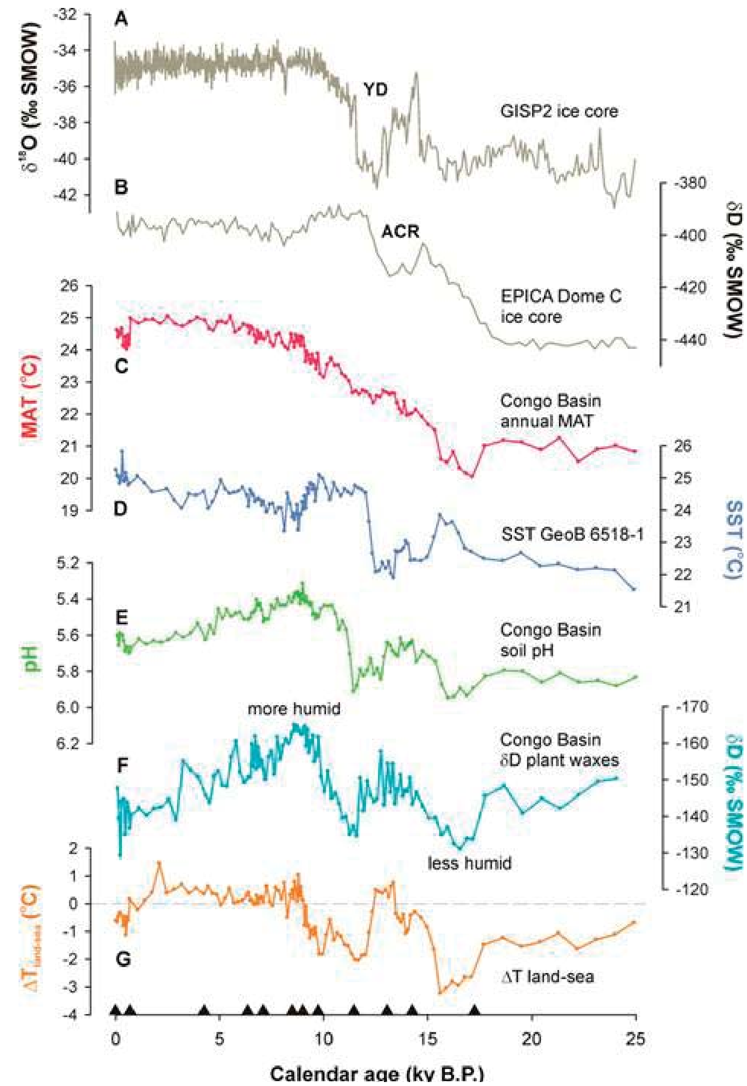

FIGURE 4.2 Results from a recent study of a sediment core off the Congo fan documented large changes in Congo Basin mean annual temperature over the past 25 ka, using terrestrial biomarkers that record soil temperatures (methylation index of branched tetraethers; MBT index; record C) as well as the δD composition of plant wax biomarker to document changes in regional humidity changes (record F) (from Weijers et al., 2007). Another related study from this same area used $\delta^{13}C$ analyses of plant wax biomarkers to document large glacial/interglacial changes in the relative proportion of C3-C4 vegetation in the Congo Basin (Schefuß et al., 2005). YD and ACR indicate the Younger Dryas and Antarctic Cold Reversal episodes.

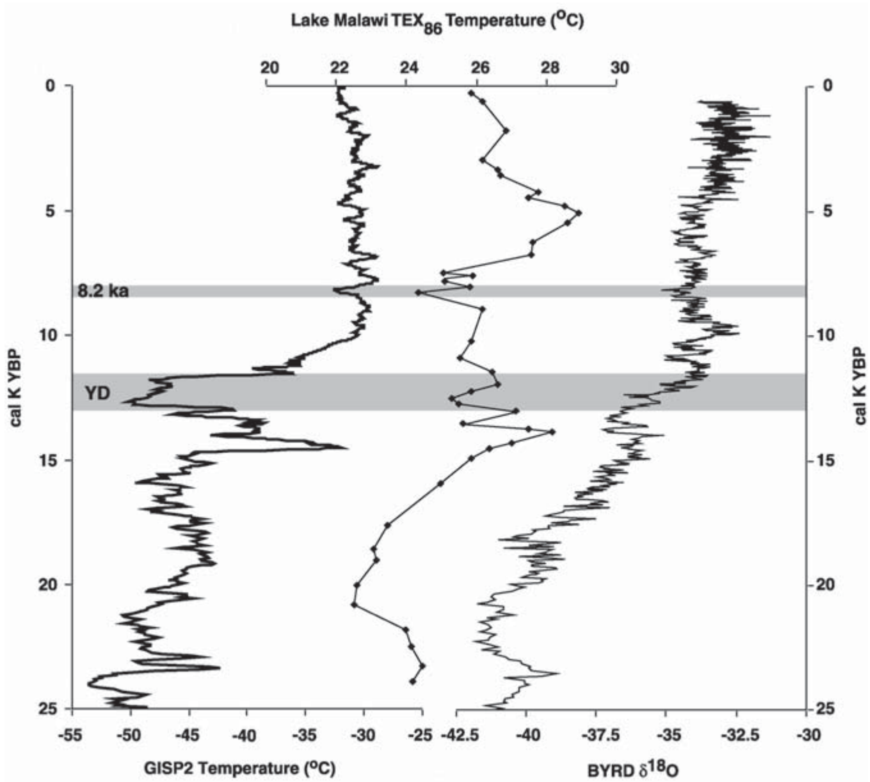

FIGURE 4.3 The first continuous temperature record from the African tropics extending back to the Last Glacial Maximum. Lake Malawi TEX_{86} temperature curve (center) plotted against the GISP2 temperature curve (left) and Byrd oxygen isotope record (right), on the GISP2 timescale. Two major events are highlighted, the Younger Dryas (YD), and the cooling at 8.2 ka. SOURCE: From Powers et al. (2005).

lakes can yield records with annual or even sub-annual resolution, as well as quantitative records of past temperature (Figure 4.3).

The recently completed Lake Malawi Scientific Drilling Project (Box 4.1) has demonstrated the exceptional potential of lake cores for generating new insights into African climate dynamics that are relevant to human origins. Cores collected by this project revealed the existence of a series of "megadroughts" during the early late Pleistocene (~135-70 ka), when lake levels dropped to an extraordinary degree as a result of extremely reduced precipitation (Scholz et al., 2007; Cohen et al., 2007) (Figure 4.5). The termination of these drought events closely corresponds with the timing proposed by molecular geneticists for the end of a previously unexplained "bottleneck" in *Homo sapiens* population size in Africa, and the time when modern humans appear to have expanded out of the African continent on a large scale.

Application of new core scanning X-ray fluorescence technology has allowed rapid analysis of cores at high resolution, providing for the first time clear evidence for abrupt climate change on a century-millennial timescale during the last glacial period, identical to the Dansgaard-Oeschger events noted in Greenland ice cores (Brown et al., 2007). Such dramatic, short-lived environmental changes undoubtedly affected the livelihood of our ancestors at that time.

Drilling Targets

Ocean Drilling A series of scientific ocean drilling expeditions are envisioned, dedicated to constraining African paleoenvironmental changes during the late Neogene. These expeditions would focus on recovering sedimentary records that would specifically address the timing and signatures of African climate change. An implicit objective of this drilling would be to coordinate with the lake drilling and terrestrial communities to provide the geographical and temporal coverage needed to address the fundamental issues of climate variability in the region and over the time period when key events in hominin evolution occurred.

Two drilling programs have the potential to fundamentally reshape our understanding of the timing and causes of African climate changes over the period of major African faunal evolutionary changes—drilling in the Gulf of Aden, and drilling the distal fan deposits from the Jubba, Rufiji, and Zambezi rivers. The Gulf of Aden represents the single best opportunity to recover sediments that have recorded past changes in northeast African climate proximal to hominin fossil localities in Ethiopia, Kenya, and Tanzania. An Integrated Ocean Drilling Program (IODP) proposal to drill six sites in the Gulf of Aden (Figure 4.6; see deMenocal et al., 2007) is highly ranked and awaiting potential scheduling. An objective of drilling the Jubba, Rufiji, and Zambezi distal fan deposits would be to use terrestrial biomarker compounds and other proxies to reconstruct the climate and vegetation history of each drainage basin as regional climate integrators. Significantly, the Zambezi drainage basin also includes Lake Malawi, so that lacustrine sequences drilled in the lake may be directly compared to the offshore drilled sequences of the Zambezi distal fan.

Lake Drilling Some of the large East African lakes are known to have long, nearly continuous records in their deep basins that extend several million years back in time, with annual to decadal resolution. These are first-order targets for assembling regional, high-resolution records of past climate dynamics. Rift lakes are the most promising targets, with potential for additional records coming from non-rift lakes Chad, Victoria, the central Botswana pans, and some crater lakes in Cameroon (Figure 4.7). Two phases of lake drilling are envisioned:

Phase I–Since 500 ka An initial phase of drilling would target the more

BOX 4.1

Lake Malawi Scientific Drilling Project

The Lake Malawi Scientific Drilling Project provides a model for modern lake drilling projects proposed in this report. In 2005, a transport barge on this tropical lake was reconfigured to serve as a drilling platform (Figure 4.4). A drill rig was constructed on the deck of the barge, with a "moonpool" through the deck allowing the drill string to be lowered to the lake floor (up to 600 meters be-

FIGURE 4.4 The drilling barge Viphya on Lake Malawi, East Africa in March 2005. Twenty-five scientists, drillers and mariners lived and worked aboard the vessel for 35 days, recovering long, continuous records from two sites in the lake–the longest a 385-m core from 600-m water depth (Scholz et al., 2006). SOURCE: Photograph courtesy of Jason Agnich.

recent geological past, a program that would require smaller, less-expensive drill rigs and barges. The rationale for drilling a large number of lakes containing middle and late Pleistocene records would be to obtain sufficient spatial coverage to accurately define paleoclimate variability across broad expanses of the African continent, and thereby to constrain climate models. Possible targets for Phase I drilling include a number of lakes located mostly in East Africa—these would need to be prioritized after discussion by the scientific community. Lake records typically provide paleoenvironmental information for a limited region, but when coupled with records from the river distal fans offshore, these should provide insights into the environmental history of much of the African continent. Potential lake targets would include Lakes Shala and Abhe in the Afar, and Lake Abaya in the Southern Ethiopian Rift, all of which would contribute substantially to understanding the more spatially and temporally integrated records that would be derived from the Jubba River distal fan off Somalia. Lake Tana on the Ethiolow the surface). Because of these substantial water depths, the barge's position was maintained through the use of a "dynamic positioning" system consisting of four large hydraulic thrusting engines (visible as blue outboard engines at each corner of the barge), which were controlled by a computer system with position and motion data inputs from satellite GPS and a lake-floor transponder.

Preliminary results show that the Last Glacial Maximum was relatively cool and dry, and that the lake basin experienced severe droughts at roughly precessional frequency prior to 60 ka (Figure 4.5).

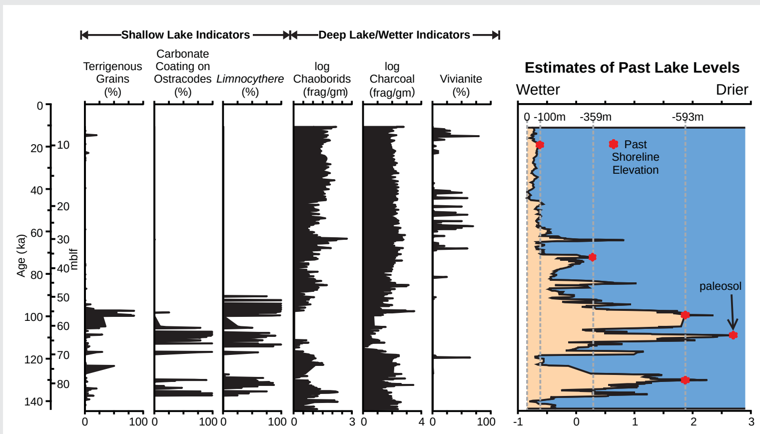

FIGURE 4.5 Preliminary results of Lake Malawi Drilling Project Site 1C, in 600-m water depth. Changes over the past 140+ ka in a range of variables provides a coherent history of paleoecological change, with the first axis (PC1) from a principal components analysis (plot on right) reflecting moisture availability and lake level. The probable paleosol at 108.5 ka indicates a minimum lake-level decline, and the lake may have dropped below the core site elevation. SOURCE: Modified after Cohen et al. (2007).

pian Plateau and Lake Turkana, which derives its water primarily from the Omo River draining the southwestern Ethiopian Plateau, would offer high-resolution sediment records to be compared to the Nile distal fan. Drilling Lakes Albert, Edward, and Kivu in the western Rift Valley would provide important contrasts to the records from the Congo distal fan, while records from Lakes Victoria, Challa, and Tanganyika should prove to be particularly relevant to the results from the Zambezi River distal fan. Lake Chad is likely to yield discontinuous records, but might be expected to provide higher resolution information during some time intervals.

Phase II—0.5–8 Ma A second phase of drilling would focus on obtaining a more limited number of "master" continental records in the longest-lived lake basins, where high-quality and long duration records are likely to be obtained. This phase would be restricted to the major ancient rift lakes, where the poten-

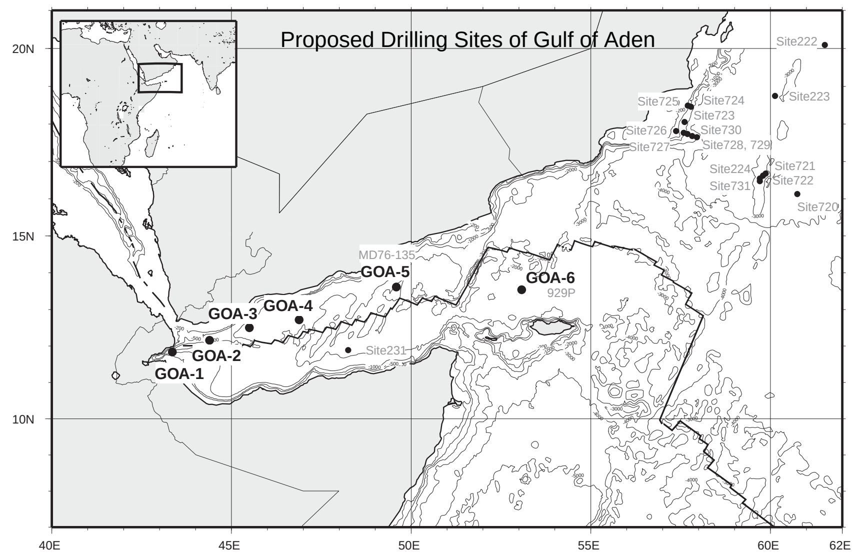

FIGURE 4.6 Sites (GOA-1 to GOA-6) proposed for Integrated Ocean Drilling Program (IODP) drilling in the Gulf of Aden. SOURCE: Unpublished IODP drilling proposal 724-FULL; deMenocal et al. (2007).

tial for obtaining such long records is highest. The primary targets for Phase II drilling would include Lakes Turkana, Edward, Albert, Tanganyika, and Malawi.

Terrestrial Drilling In parallel with efforts to drill the modern "extant" lakes, an effort should be made to obtain drill cores from paleolake deposits exposed on-land, located in key sedimentary basins where fossil hominins have been recovered. Many of these basins have been exposed through desiccation and/or uplift, and thus have the logistical advantage over lake drilling that they can be reached by truck-mounted drill rigs, avoiding many of the difficulties and substantial costs associated with lake drilling.

The objectives in targeting terrestrial sites would be to understand paleoclimate and paleoenvironmental conditions in close proximity to the fossils. Typically, these drill cores would record the dominantly organic-rich lacustrine deposits formed in or near the basin depocenters where sedimentation was most likely to be continuous and fast, providing a rich, high-resolution record of past environmental conditions. The targets of such studies could be of any age—there is no necessary requirement for drilling though the complete stratigraphic column of an extant lake to reach the target stratigraphic interval if the top of that interval currently lies at or near the surface. Possible targets and their ages for such drilling could include the Chad/Libyan basins (late Miocene), the Middle Ledi and Middle Awash in the Afar (mid-Pliocene), the Tugen Hills-Lake Baringo

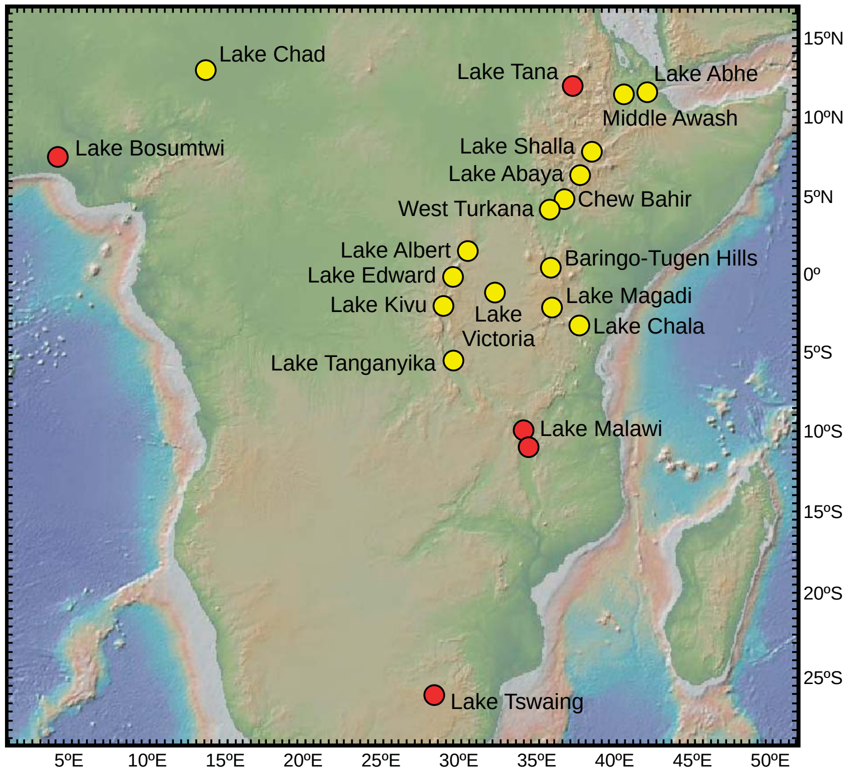

FIGURE 4.7 Map showing African lakes and paleolakes that have been drilled (red circles) or are the subject of drilling proposals or discussions (yellow circles).

area in Kenya (late Pliocene), the west Turkana area (early Pleistocene), and the Olorgesailie area (early to late Pleistocene).

INTEGRATED HIGH-RESOLUTION EARTH SYSTEM MODELING AND DETAILED ENVIRONMENTAL RECORDS

By combining analyses of observational data recording past environmental change with parallel earth system modeling studies at sufficiently high resolution, it will be possible to obtain a much more accurate and regionally based description of the evolution of paleoenvironments over the past 8 million years in Africa and Eurasia, as well as an improved understanding of the causes of the paleoenvironmental changes. Such an integrated approach would provide a tool for addressing specific questions regarding potential connections between environmental changes and hominin evolution and dispersal. Several key elements are required to realize this potential:

Climate Model Improvements At present, climate-focused models are transitioning to earth system models that include a broader range of parameters (Box 4.2; Figure 4.8). Some submodules have already been linked to climate models for studies of future and past climate (e.g., dynamic vegetation changes, fire ecology, ice sheet growth and decay, and hydrology of lakes and rivers). A focused effort is required to develop new submodels that are especially applicable to the kinds of past climate experimentation envisioned in this program. Examples would include simulating plant-animal interactions and community ecology; simulating isotope fractionation in evaporation/precipitation cycles; simulating the biogeochemistry of lakes and oceans, including sedimentation; and simulating the sources, transports, and sinks of dust. Simplified versions of such submodules are already being constructed and tested for some climate models, but much additional development, refinement, and testing are required. The addition of these new submodules will provide model output that would increasingly match the environmental signals recorded in sediments and other fossil records.

Computational Resources Requirements A major increase in computational resources will be required to simulate the range of specific time intervals over the past 8 Ma needed to address the relationship between paleoclimates and hominin evolution and dispersal. Multiple simulations will be required to test the sensitivity of the results to uncertainties in the forcing variables (e.g., CO_2 levels, topographic characteristics). Simulations at high spatial resolution will be required to resolve the relatively fine-scale details of climate, vegetation, and hydrology that are contained in environmental records in regions of complex local topography, such as the East African Rift System.

Support Requirements No new physical facility is necessarily required—computer resources can be located at existing facilities, and then be made available to the community via virtual networks. A small support staff of scientists and technicians would be required to facilitate the research activities of the scientists from many disciplines that would be involved in these coordinated interdisciplinary studies, and capabilities for archiving and retrieving model output and observations and graphical and statistical tools for efficient model/data comparison would also be needed. The model/data storage facilities and the small support staff could be located at an existing facility. Although increased computational resources are urgently needed for U.S. scientists working in this field, possibilities may also exist for shared computational facilities with the European Union and other nations or groups of nations. It will also be important to broaden electronic access to computational resources and data/model archives so that scientists from Africa and Eurasia can collaborate with U.S. scientists.

BOX 4.2

Earth System Climate Models

Earth system climate models represent the complex interacting set of components that includes the oceans, atmosphere, cryosphere, biosphere, and the Earth's surface. Model simulations show how the changing controls on climate from seasonal insolation, carbon dioxide concentrations, and ice sheet size may have affected regional and continental climate and environmental patterns.

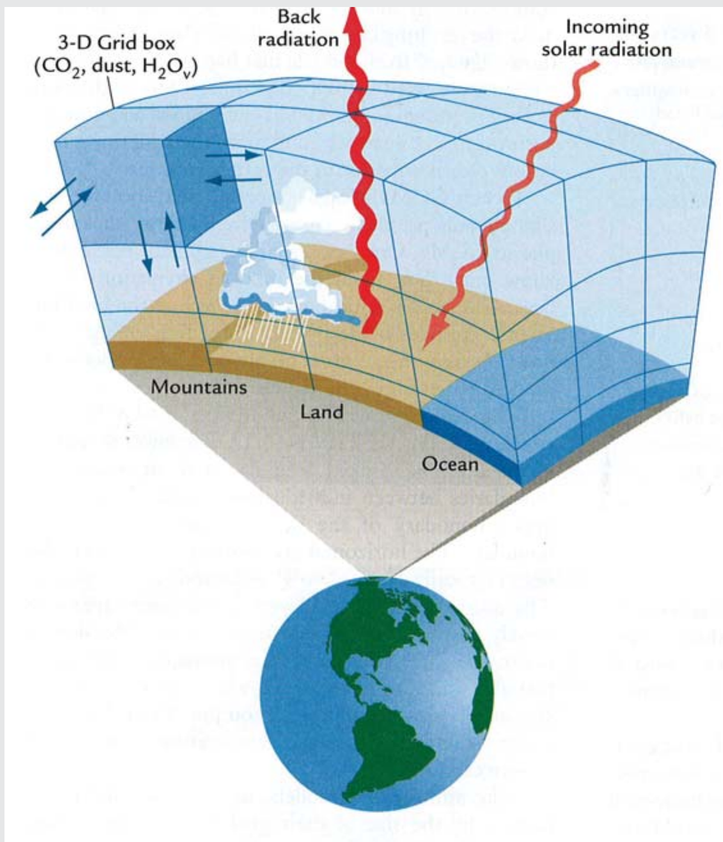

FIGURE 4.8 Schematic representation of a three-dimensional general circulation model for the earth system. Incoming solar radiation can be changed as a function of changing orbital parameters. The orography can be changed on the basis of evidence of mountain uplift or changes in ocean gateways. Changes in greenhouse gases are represented by changes within the atmosphere. Increasingly, ocean models include biogeochemistry, so that it will soon be possible to simulate components of the biogeochemical record that accumulates on the ocean floor. These records may then be compared to observational records. Similarly, land vegetation models simulate the evolution of plant communities making possible direct comparison with terrestrial records. SOURCE: Ruddiman (2008). © 2008 by W. H. Freeman and Company. Used with the permission of W. H. Freeman and Company.

PROGRAM SUPPORT COMPONENTS

In addition to the core research elements described in the preceding three sections, there are a several research activities that will complement the core elements:

Onsite High-Resolution Scanning

A program that places high-resolution microCT scanners, technicians, and computer systems in selected African museums would resolve many problems related to access to fossil data and provide the basis for a substantial improvement in analytical standards in this field. Specimens could be CT scanned at a resolution commensurate with their size and analytical needs, and slices stored for analysis. A pilot project has already been carried out at the National Museum of Kenya in Nairobi by the Max-Planck Institute for Evolutionary Anthropology in Leipzig, using a microCT scanner that was temporarily relocated to Nairobi in 2008, and which scanned hominids and a few other primates.

There are several major benefits from scanning as many fossils as possible in this way:

1. Technicians would no longer have to patiently remove matrix from fossils, they could be better employed scanning and curating specimens. African preparators would develop their skills from those of the 19^{th} to the 21^{st} century by learning scanning, computing, and analytical techniques.
2. Specimens would never be subjected to preparation damage, which is a relatively common occurrence. Note that there is usually no benefit in scanning after removing matrix. The fossils also would be protected by any overlying matrix so that no damage would be caused in the future by careless handling of fragile prepared specimens. A good example of this approach is provided by studies of Triassic archosaurs that have been scanned and analyzed rather than undergoing damaging preparation (Shipman, 2008).
3. The slice data, once stored, can be used by individual researchers both in the museum and overseas, obviating the need for expensive travel and giving the researcher time to study fossils at their home institution. Note that this saves airfares and hotel costs that are often a large part of the budget for an overseas museum trip.
4. Superb analytical programs already exist for extracting quantitative data from stacks of slices. Features such as enamel thickness, details of internal anatomy (e.g., tooth roots, semicircular canals, cochlea, brain case, nerve courses, turbinate bones) can be seen and measured with a mouse click (e.g., visualization and measurement of the cranial cavity of an Oligocene primate, see Simons et al., 2007).
5. Specimens that have suffered damage during fossilization may be recon-

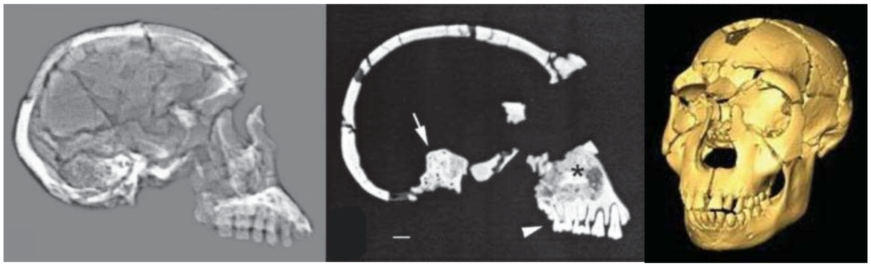

FIGURE 4.9 Images of the *Homo erectus* cranium KNM-WT 15000: lateral radiograph (left), parasagittal CT scan at the level of the right dental row and inner ear (middle), and 3D surface visualization extracted from a stack of CT scans (right). Unlike radiographs, CT scans have the ability to distinguish between fossil bone and the sedimentary matrix in the maxillary sinus (asterisk in center image), and to resolve details such as the root canals of the molars (arrowhead), and structures of the bony labyrinth (arrow). SOURCE: Left and middle images from Spoor et al. (2000); right image courtesy Fred Spoor, Department of Human Evolution, Max Planck Institute for Evolutionary Anthropology, Leipzig, Germany.

structed at or away from the museum site (e.g., Zollikofer et al., 2005). Note that sometimes it is not possible to assess distortion without x-raying a specimen.

6. In this way, vertebrate paleontologists, wherever they are on the globe, would have access to an ever-increasing sample of virtual specimens that were collected at remote field sites. They could also begin to analyze them quantitatively in ways never before possible (Figure 4.9).

7. Replicas with 600-dpi resolution can be made anywhere using such scans, at a fraction of the cost of a cast. In addition, they can be enlarged or scaled to nearly any size for comparison or exhibition.

This program would have to be augmented by similar scans taken on a large set of comparative vertebrates, so that researchers can study species variation. Several African museums have good comparative collections of modern animals that could form the basis of this dataset, but other modern datasets could be built up from European or North American osteological collections.

The time needed to scan a specimen depends on its size and the resolution required. Some large specimens can be scanned on medical CT scanners, and second-hand models of these should prove to be cost-effective because they are being replaced by newer versions all over the world, and the old versions still work well for this type of application. MicroCT and medical CT machines can run nearly 24 hours a day, depending on the local radiation regulations. Datasets of single specimens that are scanned on different machines at different resolutions can be merged relatively easily (e.g., Ryan et al., 2008).

New or Improved Geochronological Techniques

The development of new or more refined geochronological techniques is a critical requirement for an improved understanding of the climatic context of human evolution. Although the dating of terrestrial deposits has advanced enormously in the past two decades (e.g., cosmogenic isotopes are routinely used to date landscapes, with U-series dating of carbonates having a precision of less than 1 percent at 100 ka and $^{40}Ar/^{39}Ar$ dating having a precision of a few percent at 2 Ma) the improvements in accuracy and precision of dating that have occurred do not yet fully resolve the difficult questions related to determining time within a single locality, and in comparing ages between localities. An improved understanding of the relationship between geological events and the orbital cycles that provide the pacemaker for climate change over the past several million years requires that the precision and accuracy of dating be improved by an order of magnitude so that dates can be placed within individual orbital cycles (e.g., Deino et al., 2006).

Problems in chronology can be considered in two distinct and separate contexts; those concerning absolute chronology, where a high degree of accuracy and precision[4] is needed, and those that are associated with "floating chronologies," where the differential accuracy is high within a sequence but the absolute age is less important. Volcanic ash eruptions and other individual events require an absolute age, whereas the interpretation of repeating cycles (e.g., orbital, seasonal, and daily cycles) require a high differential accuracy.

Several important hurdles need to be overcome to establish improved absolute chronologies. Although analytical precision is high, deficiencies in absolute accuracy can cause acute problems when comparing chronologies that have been established using different methods—for example, the comparison of magnetic chronologies with orbitally-tuned chronologies led to revisions of the paleomagnetic timescale and the eventual recognition of an astronomically tuned polarity scale (Berggren et al., 1995). Perhaps some of the long-half-life isotope systems used for dating could be revised in a similar fashion—the current estimate of the age of the Fish Canyon Tuff is 28.20 Ma based on orbital tuning, whereas the age used in many dating studies is 28.02 Ma (Kuiper et al., 2008). A difference of ~0.5 percent is important when comparing volcanic ash dates from hominin-bearing terrestrial sequences with marine records of sapropel formation—a difference of 0.5 percent at 4 Ma equates to 20,000 years, and this corresponds to the periodicity of one of the major orbital cycles. Major improvements in the geomagnetic intensity timescale in recent years have been particularly exciting,

[4]The concepts of precision and accuracy are often confused. Precision refers to reproducibility, whereas the accuracy refers to the ability to get the correct answer. Thus, something can be highly precise (reproducible) but inaccurate (not the correct value).

because they promise to allow regional correlations between records to an accuracy of hundreds of years, extending back perhaps 2 Ma.

Although ^{14}C is the dating method that is most widely known, it is only useful for the past 50,000 years (~10 half-lives). Other cosmogenic nuclides used by geomorphologists include the radioisotopes ^{36}Cl, ^{26}Al, and ^{10}Be, with half-lives of 0.3, 0.7, and 1.4 Ma, respectively, and the stable nuclides ^{3}He and ^{21}Ne. These isotopes offer opportunities to date events of archaeological interest, and may be able to date time of burial if the initial concentrations of the isotope can be established and, in some cases, if the decay constant can be refined.

Capturing the long-term orbital climate signals in continuous terrestrial deposits, such as in lakes and in cave speleothems, will greatly aid our understanding of the nature of these cycles in the less continuous deposits in which the hominin fossils are discovered. In the past few decades, several superb long-term continuous sequences from cave deposits have been dated in China (Cheng et al., 2006) and the Middle East (Burns et al., 1998), and these document climatic changes associated with orbital cycles over the past several hundred thousand years. Speleothems have the potential to resolve long continuous annual precipitation records (Burns et al., 2002). Because each site records essentially local climatic conditions, a number of such continuous records are needed to understand climate patterns for any particular region. Comparable descriptions of regional climate characteristics for Africa would greatly improve our understanding of the important climate changes associated with long-term monsoon and *El Niño* histories. Well-dated, detailed, continuous climatic records from speleothems over the past million years would provide an excellent context against which to compare continuous lake records; both of these will provide a basis for understanding the noncontinuous records where hominin fossils are found. At present the accurate dating of lake records lags that of speleothems.

Against this background of highly precise and accurate chronologies, it is equally important to understand the relationships of "floating" chronologies—for example, understanding seasonal cycles does not require knowing the dates accurately. In many cases, biological or geological information is overprinted in such a way that the seasonality is blurred. Methods are needed to interpret signals so that the true nature of the input signal can be determined from the output signal. This is very much related to chronology because of the need to understand seasonality. For example, Ethiopia has a single annual rainy season, whereas Kenya has two. What are the amplitudes of the seasonality of rainfall or temperature? Much depends on getting the chronology correct.

Genetic Record of Ecosystem Dynamics

Genetic data provide a record of population history that stretches back hundreds of thousands of years. This record exists for two reasons—first, genealogical distances reflect population size. For example, two random women from

China (population 1,325,639,982) are less likely to be sisters than two from Callao, Utah (population 35). Second, genetic distances reflect genealogical ones and so it is reasonable to expect less genetic variation in Callao than China. By working backwards along this causal chain, genetics can be used to study the history of population size.

A great deal of genetic data is already available for human populations. For example, the International HapMap Project[5] is a database of over three million genetic polymorphisms typed in individuals from several human populations. The HapMap data will soon be supplemented by data from the 1000 Genomes Project,[6] which will provide much better information about allele frequencies throughout the world.

Both projects will be immensely useful in the scientific program for international climate and human evolution research proposed here, but neither is sufficient. Both will study DNA from the same individuals in three large African populations, but there are no plans to include small populations such as the San (or !Kung), the Hadza, or the various groups of Pygmy. These populations descend from much larger populations that once occupied much of Africa, and the little that is known about their genetics indicates that they are distantly related to the larger groups that are well represented in the samples of the HapMap and 1000 Genomes projects. By excluding these small groups, these projects exclude much of the genetic record of African history.

A different approach is proposed here. Within about 5 years, it should be possible to sequence an entire mammalian genome with high resolution for about $1,000. It will then become feasible to collect large samples of high-resolution whole-genome sequences. This technology can be used to sample human populations from all parts of Africa, including the small populations mentioned above, as well as populations from species with differing ecologies. This will make it possible for the first time to reconstruct the dynamics of entire ecosystems.

Any such effort will involve ethical concerns. Care must be taken that neither the individual human subject nor the population from which he or she comes is stigmatized in any way. Ethicists should be involved in the project from the outset. The International HapMap Project provides a successful model for dealing with these and other ethical concerns.

Calibrating the Proxy Records

Many of the indicator records that have been used to infer past climates in tropical Africa are not well calibrated against the purported forcing by the suspected key climate parameter. For example, diatom abundance in sediments in northern Lake Malawi has been interpreted as an indicator of upwelling intensity

[5]See *http://snp.cshl.org/*
[6]See *http://www.1000genomes.org/*

forced by northerly winds (Johnson et al., 2002). Although not an unreasonable conjecture, this relationship has not been demonstrated by actual measurements of wind velocity and lake circulation response, and the consequent diatom flux to the lake floor. As another example, the inference of regional aridity—based on relative abundance of C3 and C4 vegetation in a drainage area, derived from $\delta^{13}C$ analyses of long-chain n-alkanes in marine or lacustrine sediment (e.g., Feakins et al., 2005; Castaneda et al., 2007)—has not been calibrated against actual hydrological, vegetation, and river-born n-alkane data. An integral part of this initiative would be direct measurements of such phenomena coupled with high-quality regional weather data and climate reanalysis data (e.g., National Centers for Environmental Prediction), accomplished through emplacement or support for regional weather stations, stream monitoring programs, deployment of time-series sediment traps in the appropriate lakes and marine environments, vegetation inventories, and other selected modern process investigations. Because such activities can become overwhelming in scope and expense, it would be essential for the science community to act judiciously in determining the extent of this particular avenue of research, to ensure that limited resources are focused on approaches that are most relevant to understanding the earth history-human evolution connection.

Data Access, Databases, and an Informatics Infrastructure

As research at the interface of earth systems and hominid evolution is accomplished, a major effort is needed to ensure that all research results are made available in an integrated, accessible, and searchable manner. Scientific research supported by NSF is subject to an overarching data access policy that emphasizes open and timely access to research results, and some divisions have instituted data access policies that specify more precisely how this policy should be applied (e.g., guidelines published by the Division of Earth Sciences[7] or the *Data and Sample Policy* published by the Division of Ocean Sciences[8]). Despite NSF support for much paleoanthropology research, this disciplinary area has a history of contentious disputes regarding fossil access and the timeliness of publication (e.g., see Gibbons, 2002). The international scientific program for climate and human evolution research proposed here will need to establish data access protocols to ensure that research results—whether digital scans of hominin fossils, the fossils themselves, or climate proxy parameters from deep ocean cores—are provided to the broader scientific community in an open and timely manner. There are already examples where international consortia have established data access and availability protocols that adhere as closely as possible to NSF guidelines, but incorporate some degree of flexibility because of local or national

[7]See *http://www.nsf.gov/geo/ear/EAR_data_policy_204.pdf*
[8] See *http://www.nsf.gov/pubs/2004/nsf04004/nsf04004.pdf*

issues (e.g., International Continental Scientific Drilling Program [ICDP] and IODP), and some similar flexibility would be required for the research endeavor proposed here.

The application of modern informatics to the study of the potential link between human evolution and earth system parameters will require new information technology applications to solve research challenges across the disciplines of geology, paleoclimatology, paleoanthropology, and paleontology. Because a number of discrete disciplines contribute to this research endeavor, it is especially important that the acquired data from individual disciplines be integrated across time and space. The path from data collection and entry to information dissemination will require high-level computing and the use of visualization software. Geographic Information Systems (GIS) capabilities are a critical component, because most of the data associated with this research are place based and/or require three-dimensional imaging (e.g., see Conroy et al., 2008). A corollary requirement is the need to ensure—to the greatest extent possible—that the locations of specimens collected during earlier, pre-GPS/GIS activities at remote field sites are geolocated and integrated into a modern geoinformatics structure. This has become increasingly important with the pending retirements of senior paleoanthropologists whose work is recorded in notebooks or other nonelectronic media.

At present, existing online databases and data management systems mostly address the needs of specific research groups concerned with human and mammalian evolution or related earth science topics, for example, RHOI (Revealing Hominid Origins Initiative) for Mio-Pliocene faunal specimens, NOW (Neogene Mammals of the Old World), the Smithsonian's HOP (Human Origins Program Database), GEON (Geosciences Network), and the ICDP Data and Information Management System. The implementation and maintenance of relational databases for all published material in core disciplines has the potential to facilitate additional exciting research by encouraging cross-disciplinary collaboration. A data repository, either physical or virtual, is required to formalize the linkages between individual relational databases. The linked datasets should also be integrated with the mapping capabilities available in GIS systems to enable integrated visualization for particular localities, regions, or through time.

Coordination and Management

A Science Advisory Committee, composed of individuals representing the broader scientific community and with a broad vision of how these research components relate to each other, will be required to foster communication among disciplinary groups, coordinate the implementation elements, and convey the science community's priorities to funding agencies. On the basis of community input, this committee would establish and periodically update plans for exploration, drilling, and modeling, and prioritize regions to be investigated. The committee would oversee:

- a management team to deal with logistical issues associated with major initiatives, such as liaisons with foreign governments, permits, transport (including helicopter assistance to cover difficult terrain more efficiently during ground phases), and drilling operations;
- a geophysical and remote sensing analysis team;
- a database and data access management team; and
- an outreach and education team.

The committee would require sufficient funding to sponsor a range of workshops and town meetings to obtain and distill community input. It would be important for such workshops and town meetings to span the full range of disciplines associated with this research enterprise.

PUBLIC OUTREACH OPPORTUNITIES

Research focused on the earth system context of human evolution unites two scientific fields that are among the most publicly visible—climate change and human origins. The study of human evolution represents one of the most compelling subjects in the natural sciences in that it deals with the long-term origin of our species; and climate change has become a focal point in communicating the meaningfulness of science and its relationship to the welfare of humans, all living things, and entire ecosystems. The intersection of these two broad areas of scientific research thus offers powerful opportunities for public outreach aimed at communicating the process and value of science. The subject matter itself, which deals with human survival and adaptation in the past, also offers avenues for inspiring the public's curiosity about scientific findings relevant to society's adaptation to climate change in the near and distant future.

A state-of-the-art program in public education and outreach creates opportunities for diverse audiences along several avenues, which include (1) development of dynamic and up-to-date public Internet sites; (2) dissemination of findings via print, radio, and television media; (3) organization of seminars, lectures, and dialogues in venues that are both visible and attractive to the public; (4) interaction with national science educators, who can translate scientific findings and data into the classroom; (5) museum-based and less formal exhibitions, which are attractions for family and school-group explorations of and learning about science; (6) engagement of adult learners in the excitement of research and discovery and encouragement of volunteerism (docents); and (7) graduate, undergraduate, and high-school training and research experiences, which offer a means of building the future generations of scientists and educators. As the items in this list illustrate, an effective program of public education and outreach requires skillful approaches to both formal and informal learning in which children and adults decide whether to pursue (and for how long) any particular topic that interests them.

No curriculum currently exists to inspire teachers and students to explore the relationship between past climate change, human evolution, and the long-term influence of environment on species survival, adaptation, and mitigation strategies. The following recommendations represent components of a broad effort to redress this deficiency:

- **Develop opportunities that bring educators and scientists together, and that build new partnerships among research institutions, museums, science centers, and national scientific and education organizations, in order to further the development of national and state science standards.** There is a critical need to substantially improve the set of tools teachers and students have that promote science education and to create real opportunities for overcoming roadblocks to learning about evolution (NRC, 1998, 2008). The interplay between climate and human evolution can form a new, prominent cornerstone in efforts to prepare educators to teach, and students to learn, the basic concepts of evolution and the nature of science. Conferences and workshops would offer an initial step toward stimulating an open dialogue with K-12 educators and scientists. The Smithsonian Institution's National Museum of Natural History, for example, plans to convene a national conference of educators and scientists to discuss and define the issues that promote students' and the general public's understanding of science, focused especially on the processes of climate change and evolution. Such events would aim to create productive partnerships with education and scientific organizations such as the National Science Teachers Association (NSTA), the National Association of Biology Teachers (NABT), the American Institute for Biological Sciences (AIBS), the National Center for Science Education (NCSE), the National Science Education Leadership Association (NSELA), the National Academy of Sciences (NAS), and the American Association for the Advancement of Science (AAAS).
- **Establish a National/International Educator Institute as a long-term effort that employs climate–evolution research to enhance professional educator development.** This idea, initiated as part of the Smithsonian's Human Origins Initiative, is to offer a multiday institute for educators focused on human evolution and environmental change research and on strategies for improving the comprehension of science. The audience for this institute will include school-based educators, staff from informal science education institutions (e.g., museums, science centers), and outreach staff affiliated with science research organizations. The aim is for this institute to be a "trainer of trainers" model in which participants make a commitment to return to their institutions and communities to offer training, programs, and resources to their colleagues, local schools, and audiences.

- **Establish internships that connect students and teachers to the international scope and nature of scientific research on past climate change and human evolution.** Internships offer opportunities for students and teachers to experience research firsthand (discovery-based education) in order to learn what scientists do—how they find out about past climate change, human evolution, and the potential impact of environment on human adaptation, and why science depends on the public's understanding of the ways research is conducted and the meaning of new findings. Such internships would promote cross-national efforts in science education, and would allow students and teachers to participate in regular webcasts from field sites around the world that could be followed online by millions of people in formal and informal educational settings.
- **Engage adult learners who may be underserved and have ventured away from formal avenues of science education.** For example, young adults, typically from about 18 to 34 years of age, are often a lost generation for natural history museums, science centers, and other informal educational institutions. People often visit museums and science centers as children with their families and their schools and then return when they have their own children. This is the demographic that will be the next group of professionals and policy makers. Based on the Web habits of this group, this is a logical target demographic for national science outreach via YouTube, Flickr, and online social networking (e.g., Facebook, Twitter). In addition to building Internet destinations that seek out users based on Web habits, a key activity for reaching general public audiences is through mass media. Collaborating with television production and broadcast organizations (e.g., PBS NOVA, National Geographic, Discovery Channel) requires significant investment of effort and money, but reaches a large audience. Additional ways of engagement involve writing for popular publications (e.g., newspapers, magazines, books) and hosting online and face-to-face meetings that offer the public an opportunity to interact with scientists. All of these efforts would highlight the relevance of research on the interplay between climate change and evolution to society's overall scientific literacy.
- **Develop a concise and compelling education guide, curricula for teachers (available in print and online), and traveling exhibitions that introduce the rationale, perspectives, and basic findings concerning the earth system context of human evolution.** These outlets would provide activities and identify resources that teachers and students can use and that the general public finds engaging and useful in learning about our planet's climate, its deep past, and the emergence of human beings. Curriculum modules would aim for use in schools (grades 9-14, tailored to address specific state educational standards), informal science institutions, adult education classes, and other educational settings, and would serve as a resource for teacher training activities. The modules will promote active learning and inquiry, go well beyond the standard treatment of human evolution and climate change in textbooks, and will be disseminated and distributed for free through the Smithsonian and other science research/

education organizations. It will be important to link these efforts with partner organizations that have longstanding and successful experience in the development of science curricula, such as the NSRC (National Science Resource Center), TERC (Technical Education Research Centers), EDC (Education Development Center, Inc.), and BSCS (Biological Sciences Curriculum Study).

As a package, these recommendations reflect a fundamental commitment to outreach and education, working in partnership with educators and scientists nationwide and worldwide.

5

Conclusions and Recommendations

The hominin fossil record documents a history of critical evolutionary events that have ultimately shaped and defined what it means to be human, including the origins of bipedalism; the emergence of our genus *Homo*; the first use of stone tools; increases in brain size; and the emergence of *Homo sapiens*, tools, and culture. The geological record suggests that some of these evolutionary events were coincident with substantial changes in African climate, raising the intriguing possibility that key junctures in human evolution and behavioral development may have been affected or controlled by the environmental characteristics of the areas where hominins evolved. However, with both a sparse hominin fossil record and an incomplete understanding of past climates, the particular effect of the environment on hominin evolution remains speculative. This presents an opportunity for exciting and fundamental scientific research to improve our understanding of how climate may have helped to shape our species, and thereby to shed light on the evolutionary forces that made us distinctively human.

This report has identified research themes and initiatives designed to describe and understand possible causative linkages between human evolution and Earth climate history. Our recommendations depend on building a strong international network of scientific collaborators engaged in a systematic research strategy, and are designed to generate broad and significant impact in national science education and the engagement of diverse audiences in the excitement and understanding of science. The intriguing possibilities regarding the role of climate in the evolutionary trajectories of our ancestral lineages can only be clarified—and causation established—with additional evidence that will require more sophisticated tools. Significant progress into the question of whether past climate changes influenced human evolution will require a coordinated, focused, and cross-disciplinary research program designed specifically to address this problem.

Although we have a broad understanding of African and Eurasian climate history, this climate record generally lacks the temporal resolution and details of rainfall and temperature that potentially impacted how the hominins lived, and in particular does not adequately reflect differences in past climates between regions. Improved climate records for specific regions will be required before it is possible to evaluate how critical resources for hominins, especially water and vegetation, would have been distributed on the landscape during key intervals of hominin history. The existing records of earth system history and hominin fossil history also contain substantial temporal gaps. A general understanding of the timing of major events in human evolution exists, but our ability to interpret what has driven these events remains limited by a paucity of fossil material, particularly over the most interesting periods of rapid evolutionary change. Major breakthroughs will almost certainly have to await discoveries of additional hominin fossils and associated archaeological materials. New hominin fossil discoveries should enable the more precise understanding of the ages of various events in the hominin evolutionary record that will be needed for robust correlation of climatic and evolutionary events. Similarly, a broad understanding of Earth history, and particularly past climate history, has been gleaned from other fossils found associated with hominin fossil discoveries and from analyses of lake and ocean sediment cores. This material provides a wealth of base information that can be used with the present generation of global climate models to understand paleoclimate characteristics and the factors that controlled past climates, particularly at continental and regional scales, but these are still limited for understanding the local climates that are so important for evaluating causative factors involved with hominin evolution.

This report proposes focused research initiatives that are designed, over a 10- to 20-year period, to dramatically improve our understanding of this research problem. These initiatives are presented in two major research themes:

Research Themes

Theme I: Determining the Impacts of Climate Change and Climate Variability on Human Evolution and Dispersal Hypotheses linking climate change and hominin evolution are based on indications that large-scale shifts in climate or climate variability altered the landscape ecology which, in turn, presented specific adaptive or speciation pressures that lead to genetic selection and innovation. However, efforts to test such hypotheses are fundamentally data limited, constrained by gaps or poorly-studied intervals in the fossil and archaeological record, coupled with the highly variable fossil density from different time periods and regions; the inconsistent collection of all components of available fossil assemblages (e.g., invertebrates, vascular plants and algae, as well as vertebrates), which have potential to offer critical tests of the climate-evolution relationship; as well as by stratigraphic and geochronological limitations. Concerted international efforts to substantially enhance the fossil hominin, archaeological, and other faunal records of evolution are necessary to establish with statistical reliability the precise first and last appearances of species, adaptations, and behaviors within particular geographic regions and strata. Precise determinations of the timing of evolutionary events are essential for more rigorous analyses of the climate–evolution relationship.

At present there are few continuous quantitative paleoenvironmental records situated close to hominin fossil localities. By bringing the evidence of climate change and evolutionary events into close proximity, particularly by collecting high-resolution environmental records at or near the hominin fossil sites, it will be possible to test the extent to which those evolutionary events reflect responses to regional or local climate. As well as the high-precision records of climate change that are required from long stratigraphic sequences located close to hominin sites, lake and ocean drilling records will be needed to integrate local climate records from hominin sedimentary basins with regional and global records.

Understanding past climates depends on a range of data that can be used to quantitatively reconstruct the range of climatic variables—temperature, precipitation, seasonality, vegetation and land cover, paleo-altitude, etc. It is important that new tools for quantitative reconstruction of past environmental conditions continue to be developed and applied to new and existing stratigraphic records. A key requirement for each of these elements will be formalized research funding to encourage scientific exchange and strategic analysis of climate-evolution hypotheses by earth scientists, paleoanthropologists, and faunal researchers.

Theme II: Integrating Climate Modeling, Environmental Records, and Biotic Responses This research theme seeks to define the physical and biotic mechanisms whereby past environmental changes may have produced evolutionary (and behavioral) responses in fossil hominins. The research strategy will require developments in climate model and paleoecological data integration. The aim of this effort is to use the new data collected under Theme I to constrain climate model simulations in order to explore the physical mechanisms and regionality of past climate changes. Existing environmental records are too sparse to draw firm conclusions about particular geographic patterns of climate in Africa and Eurasia and their variability, to describe climate conditions along pathways to southern Eurasia, or to understand the temporal and spatial variability of Eurasian climates. In parallel with the efforts to collect additional environmental records proposed in Theme I, there is also a need for a program to integrate regionally resolved climate models with paleoecologic data. These would be developed for the specific regions and specific key time periods that bear on potential connections between environmental changes and hominin evolution and dispersal.

Model-record experiments will be particularly important for developing predictions in data-sparse regions, as the basis for hypotheses that can be tested by the collection of new data. Because climate models simulate spatial and temporal patterns on a regular grid and at regular time intervals, they can provide a context for integrating or synthesizing environmental and fossil records that are discontinuous in space and time, or are otherwise incomplete.

The large-scale record of climate change over the past 8 Ma is reasonably well known, although much remains to be understood about the interactions and feedbacks among the various climate forcing factors. At issue are the relative influences on African and Eurasian climate from orbital monsoonal forcing, high-latitude ice volume changes, atmospheric carbon dioxide (CO_2) changes, Tibetan and East African uplift, and sea-level or ocean gateway changes, all of which changed over this time period. With improved density, accuracy, and dating of environmental records, there is an opportunity to use climate models to ask more detailed questions and to obtain more detailed information about the climate, water resources, and vegetation comprising hominin habitats. In particular, the availability of accurate estimates of atmospheric CO_2 will permit simulation of both the direct effects of greenhouse gases on climate, as well as the possible physiological effects on vegetation of changing levels of CO_2. These models can only be accurately parameterized and their outputs tested by reference to actual paleoenvironmental data from the interior of Africa and its surrounding oceans. With the availability of greenhouse gas records and known orbitally caused changes in solar radiation, models have proven to be remarkably accurate in simulating past climates.

Implementation Strategies

Implementing this research vision will require community and organizational flexibility as it embraces a more collaborative and cross-disciplinary model, involving a transformative shift in how paleoanthropological research is conducted. Although the exploration of human origins is inherently an international activity, large field-based research projects have been largely conducted and funded along national lines, and broader partnerships and funding efforts are still relatively rare. International collaboration and cooperation focused on understanding the extent to which the earth system was a factor in human evolution offers the potential for applying the intellectual, organizational, and funding resources of a much wider community to an important research problem.

We envision a new scientific program for international climate and human evolution studies that involves both essential and supporting components:

Three elements must be carefully integrated to comprise the core program of research:

- A major exploration initiative to locate new fossil sites and to broaden the geographic and temporal sampling of the fossil and archaeological record. This would involve systematic exploration efforts with a remote sensing component to identify new potentially fossiliferous areas and sites, coupled with a substantially enhanced program of ground exploration.
- A comprehensive, integrated scientific drilling program in lakes, lake bed outcrops, and ocean basins surrounding the regions where hominins evolved. Drill cores containing the continuous, fine structure of the environmental record are needed to address questions about changes in the earth system at sufficiently high resolution to describe short-duration events and processes. Each component of such a program—including truck-mounted terrestrial drilling, barge-mounted lake drilling, and ocean drilling—would provide complementary elements that could be integrated to describe the paleoclimatic, paleohydrologic, and paleovegetation history of specific regions.
- A major investment in climate modeling experiments for the key time intervals and regions that are critical for understanding human evolution, to describe the regional climate patterns and fundamental climate forcing mechanisms, and to model at a more local scale the interactions between climate, ecosystems, and species population dynamics. Simulations at high spatial resolution will be required to resolve the relatively fine-scale details of climate, vegetation, and hydrology that can be found in environmental records in regions of complex local topography, such as the East African Rift System.

In addition, there are a number of components that will be required to complement the core research effort:

- Systematic analysis of existing fossil sites and collections, with application of new imaging and dating technologies, to better describe the nature and timing of species change and adaptive transitions in the hominin lineage.
- Collection of high-resolution, whole-genome sequences of a range of mammals by use of new techniques that should allow inexpensive sequencing of entire mammalian genomes. This technology could be used to sample *Homo sapiens* and other mammalian populations with varying ecologies from all parts of Africa, to enable comparisons of genetic changes with climate changes over the last 200,000 years. Climatic changes could also be contrasted with estimated population sizes of *H. sapiens* and other mammals, based on population genetics parameters, during this time period.
- Selected investigations of ecosystem dynamics through the collection of modern climate and calibration data to more accurately quantify relationships between the environment and the proxy records of the environment preserved in

sediments and fossils. An important contribution to the understanding of evolutionary and environmental dynamics is the analysis of fauna and flora associated, geographically and temporally, with hominin fossils. An increased focus on adaptations in the faunal and floral assemblages associated with hominins—and by contrast, those that are not associated with hominins—will provide an invaluable resource for understanding the interaction between hominin evolution and past climates.

- Development of the informatics and data archiving tools needed to provide permanent storage for the wide array of information collected by the activities listed above, and to facilitate continued access to this information. An important corollary requirement will be speedy community access to samples and their derived data within all of the disciplinary areas encompassed by this initiative—the hominin fossils and their associated fauna and flora; as well as the ocean, lake, and terrestrial drilling samples and data.

The coordination and management of a major international scientific program for International Climate and Human Evolution Research would require a small science advisory structure, with members representing the broader scientific community and with a broad vision of how these research components relate to each other, to foster communication among disciplinary groups, coordinate the implementation elements, and convey the science community's priorities to funding agencies. On the basis of community input, this advisory committee would establish and periodically update plans for exploration, drilling, and modeling, and prioritize regions to be investigated. The committee would require sufficient funding to sponsor a range of workshops and town meetings, spanning the full range of disciplines associated with this research enterprise, to obtain and distill community input.

Public Outreach Opportunities

The public is fascinated by media accounts and documentaries on human evolution and the long-term origin of our species. Additionally, climate change has become a focal point for public interest. The intersection of these two broad areas of scientific research thus offers powerful opportunities for public outreach aimed at communicating the process and value of science to the welfare of humans, all living things, and entire ecosystems. The subject matter itself, which deals with human survival and adaptation in the past, also offers avenues for inspiring the public's curiosity about scientific findings relevant to society's adaptation to climate change in the near and distant future.

A state-of-the-art program in public education and outreach creates opportunities for diverse audiences along several avenues, which include (1) development of dynamic and up-to-date public Internet sites; (2) dissemination of findings via the Internet or using print, radio, and television media; (3) organization of seminars, lectures, and dialogues in venues that are both visible and attractive to the public; (4) interaction with national science educators, who can potentially translate scientific findings and data into the classroom; (5) museum-based and less formal exhibitions, which are attractions for family and school-group explorations of and learning about science; (6) engagement of adult learners in the excitement of research and discovery and encouragement of volunteerism (docents); and (7) graduate, undergraduate, and high-school training and research experiences, which offer a means of building the future generations of scientists and educators. As the items in this list illustrate, an effective program of public education and outreach requires skillful approaches to formal and informal learning in which children and adults decide whether to pursue (and for how long) any particular topic that interests them.

No curriculum currently exists to inspire teachers and students to explore the relationship between past climate change, human evolution, and the long-term influence of environment on species survival, adaptation, and mitigation strategies. The following recommendations represent components of a broad effort to redress this deficiency:

- Develop opportunities that bring educators and scientists together, and that build new partnerships among research institutions, museums, science centers, and national scientific and education organizations, to contribute to the development of national and state science standards.
- Establish a National/International Educator Institute as a long-term effort that employs climate–evolution research to enhance professional educator development.
- Establish internships that connect students and teachers to the international scope and nature of scientific research on past climate change and human evolution.
- Engage adult learners who may be underserved and have ventured away from formal avenues of science education.
- Develop a concise and compelling education guide, curricula for teachers (available in print and online), and traveling exhibitions that introduce the rationale, perspectives, and basic findings concerning the earth system context of human evolution.

As a package, these recommendations reflect a fundamental commitment to outreach and education, working in partnership with educators and scientists nationwide and worldwide.

In summary, the strategic integration of focused high-resolution modeling with new marine, lake, and terrestrial climate records proposed here will represent the most concerted research effort thus far to assess

the precise influence of environmental dynamics (resolved on decadal to orbital timescales) on evolutionary history for any organism or time period in Earth's history. The research agenda described here, although presenting a bold vision that will require substantial resources to bring it to reality, offers an opportunity to make equally bold steps toward an understanding of the role played by past climates in the evolution of our ancestral lineage.

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Appendixes

A

Committee and Staff Biographies

Robert M. Hamilton retired as Deputy Executive Director of NRC's Division on Earth and Life Studies in 2004. He had previously served as Executive Director of NRC's Commission on Geosciences, Environment, and Resources, following 30 years as a geophysicist with the U.S. Geological Survey. He chaired the Committee on Disaster Reduction for the International Council for Science (ICSU), and chaired the Scientific and Technical Committee of the International Decade for Natural Disaster Reduction (IDNDR), a U.N. program for the 1990s. He also served for 2 years with the IDNDR Secretariat in Geneva, including a year as director. He has been a member of the Inter-agency Task Force for the International Strategy for Disaster Reduction, a follow-on U.N. program to the IDNDR. He also chaired the Subcommittee on Disaster Reduction of the National Science and Technology Council. Dr. Hamilton served as president of the Seismological Society of America, and president and secretary of the Seismology Section of the American Geophysical Union. He is a fellow of the Geological Society of America and the American Association for the Advancement of Science. Dr Hamilton has a geophysical engineering degree from Colorado School of Mines, and M.A. and Ph.D. degrees in geophysics from the University of California at Berkeley.

Berhane Asfaw (NAS) is a palaeoanthropologist who manages the Rift Valley Research Service. Dr. Asfaw has completed extensive survey work on the eastern and western sides of the Awash River in Ethiopia. He was instrumental in explorations that discovered fossils thought to be some of the earliest hominids (called Ardithecus ramidus, dated at about 4 million-plus years). Those same expeditions also led to the discovery of *Australopithecus garhi*, a 2.5-million-year-old hominid found in association with old bones with cut marks. Dr. Asfaw has held positions within the Ethiopian government, including director of National Museums and coordinator of the Paleoanthropology Laboratory of the National Museum of Ethiopia. He has a bachelor's degree in geology from Addis Ababa University and a Ph.D. from the University of California at Berkeley.

Gail M. Ashley is professor of geological sciences and director of the Quaternary Studies Graduate Program at Rutgers University, New Jersey. Her research interests include a comparison of terrestrial records of paleoclimate during the Quaternary in polar, temperate, and tropical regions, and reconstruction of the paleoenvironment of early hominids. She is currently president of the American Geological Institute and has served as president of the Geological Society of America, vice president of the International Association of Sedimentologists, editor-in-chief of the *Journal of Sedimentary Research*, and president of the Society for Sedimentary Geology. Dr. Ashley received B.S. and M.S. degrees in geology from the University of Massachusetts and a Ph.D. in geology from the University of British Columbia.

Thure E. Cerling (NAS) is Distinguished Professor of Geology and Geophysics and Distinguished Professor of Biology at the University of Utah. His research focuses on near-surface processes and the geological record of ecological change, particularly using geochemical proxies to understand the physiology and paleodiets of mammals, using soils as indicators of climatological and ecological change over geological timescales, and landscape evolution over the past several million years. Dr. Cerling has served on several NRC committees, including the Board on Earth Sciences and Resources (BESR), the U.S. Geodynamics Committee, and the U.S. National Committee for the International Union for Quaternary Research. He is a member of the U.S. Nuclear Waste Technical Review Board. Dr. Cerling is a fellow of the American Association for the Advancement of Science and the Geological Society of America. He received B.A. and M.S. degrees in geology from Iowa State University and his Ph.D. in geology from the University of California at Berkeley.

Andrew S. Cohen is a professor of geosciences and a professor of ecology and evolutionary biology at the University of Arizona. Dr. Cohen's research focuses on the depositional environments, paleoecology, and climate history of the African rift lakes and the arid climate lakes of the western United States. He has a major project investigating the history of human impacts from watershed deforestation around Lake Tanganyika on the lake's benthic ecosystem. He earned his Ph.D. from the University of California. Dr. Cohen is a member of the Board of Directors of DOSECC (Drilling, Observation and Sampling of the Earth's Continental Crust) the U.S. consortium for support of continental scientific drilling, and is also on the Scientific Advisory Board of the International Continental Scientific Drilling Program.

Peter B. deMenocal is a professor at Lamont-Doherty Earth Observatory of Columbia University. He uses proxies in marine sediments, primarily stable isotope and trace metal geochemistry, to reconstruct past changes in ocean circulation and terrestrial climate. Recent research projects include Holocene climate and ocean circulation variability, tropical to extratropical paleoclimate linkages, Pliocene-Pleistocene evolution of tropical climates, and human evolution and past African climates. Dr. deMenocal is recognized as one of the leaders of the scientific effort to understand Earth parameters during the time that hominins evolved. He has a B.S. in geology from St. Lawrence University, an M.S. in oceanography from the University of Rhode Island, Graduate School of Oceanography, and a Ph.D. in geology from Columbia University.

Andrew P. Hill is the J. Clayton Stephenson Professor of Anthropology at Yale University, and Curator of Anthropology in the Peabody Museum. Before coming to Yale in 1985, he held research positions at the National Museums of Kenya in Nairobi, and at Harvard. He is interested in the whole range of human evolution, particularly in the environmental and ecological context in which it occurred. Since 1968 he has carried out field work in eastern Africa, in Pakistan, and in the United Arab Emirates. For many years he has directed the Baringo Paleontological Research Project, a multidisciplinary research program operating in the Tugen Hills, Kenya. He teaches courses on different aspects of human evolution, faunal analysis, and taphonomy. Dr. Hill has a B.Sc. (Honouurs) from Reading University and a Ph.D. from the University of London.

Thomas C. Johnson is a Regents Professor of Geological Sciences at the Large Lakes Observatory and the Department of Geological Sciences at the University of Minnesota, Duluth. His research interests include paleoclimatology based on the analysis of lake sediment cores and sedimentological processes in large lakes, focusing mainly on those in the East African Rift Valley. Dr. Johnson was the founding director of the Large Lakes Observatory, and served as a member of the Great Lakes Research Managers Council of the International Joint Commission. He was the cofounder and served on the Steering Committee of the International Decade for East African Lakes (IDEAL) from 1995 to 2005. He is a member of the Board of Directors of the Drilling, Observation and Sampling of Earth's Continental Crust (DOSECC). He has a B.S. in oceanography from the University of Washington and a Ph.D. in oceanography from the University of California at San Diego.

John E. Kutzbach (NAS) is professor emeritus of atmospheric and oceanic sciences, and environmental sciences in the Gaylord Nelson Institute for Environmental Studies at the University of Wisconsin at Madison. Prior to retirement, he was associate director, senior scientist, and professor at the Center for Climatic Research. His research focuses on understanding the processes that control climate variablity, looking at decade/century-scale climate variability over recent millennia as well as linkages between vegetation changes and climate changes. Dr. Kutzbach is a fellow of the American Geophysical Union and the American Meteorological Society. Some of his awards include the Revelle Medal of the American Geophysical Union and the Milankovitch Medal of the European Geophysical Society. He has B.A., M.A., and Ph.D. degrees from the University of Wisconsin at Madison.

Richard Potts is a paleoanthropologist and director of the Human Origins Program and curator of anthropology at the National Museum of Natural History, Smithsonian Institution. His research focuses on the history of the interrelationships between human evolution and the ecosystem. Over the past decade, Dr. Potts has led excavations at early human sites in the East African rift valley, and currently directs a multidisciplinary research team at the handaxe site of Olorgesailie, Kenya. In addition to research articles and books, he has recently completed a book for a general audience titled *Humanity's Descent: The Consequences of Ecological Instability*. In addition, Dr. Potts was awarded a Certificate of Honor by the Academy of Television Arts and Sciences for the Emmy-winning *Tales of the Human Dawn* on PBS. He has a B.A. in anthropology from Temple University and a Ph.D. in biological anthropology from Harvard University.

Kaye E. Reed is associate director and associate professor in the School of Human Evolution and Social Change of the Institute of Human Origins at Arizona State University. Dr. Reed's main research focus is the ecological context of primate and hominin evolution, based on using the identification and analysis of mammalian faunas from Plio-Pleistocene hominin localities. Her current field research focuses on early hominin sites (*Australopithecus afarensis* and early *Homo*) in the Afar Region of Ethiopia and Neanderthal and modern human cave localities in Spain and Morocco. She earned her Ph.D. from the State University of New York at Stony Brook. Dr. Reed resigned from the committee in May 2009 to accept a secondment position at the National Science Foundation.

Alan R. Rogers is a professor of anthropology and adjunct professor of biology at the University of Utah. Dr. Rogers' research focuses on using genetic data to understand the history of human population size, based on developing new statistical methods to detect population size changes using sequence data. This largely focuses on understanding the huge population increase of early humans in the late Pleistocene. Additionally, his research interests include the adaptive evolution of such traits as menopause and human time preference. In 1991, the University of Utah recognized Dr. Rogers' work with their Superior Research Award. He was a former associate editor of *Molecular Biology and Evolution*. He received a B.A. in anthropology from the University of Texas at Austin and M.S. and Ph.D. degrees in anthropology from the University of New Mexico.

Alan C. Walker (NAS) is the Evan Pugh Professor of Anthropology and Biology at The Pennsylvania State University. Dr. Walker endeavors to extract ancient behaviors from the fossil and taphonomic record. Teeth record information about an individual's life history and semicircular canals are tuned to a species' rapidity of locomotion. Dr. Walker is now developing nondestructive methods for examining tooth enamel and measuring fossil labyrinths so that rare hominoid and hominid specimens can be used. He is a research associate of the National Museum of Kenya and has had many collaborative field programs with the museum, the latest being at Allia Bay, east Lake Turkana. He has a B.A. (Honours) in geology from Cambridge University and a Ph.D. in anatomy and paleontology from the University of London. He also has an honorary D.Sc. from the University of Chicago. Dr. Walker is a Fellow of the Royal Society.

National Research Council Staff

David A. Feary is a Senior Program Officer with the NRC's Board on Earth Sciences and Resources and staff director of BESR's Committee on Seismology and Geodynamics. Prior to joining the NRC, he spent 15 years as a research scientist with the marine program at the Australian Geological Survey Organisation (now Geoscience Australia). During this time, he participated in numerous national and international research cruises to better understand the role of climate as a primary control on carbonate reef formation and to improve understanding of cool-water carbonate depositional processes and controls. He is a member of the Science Planning Committee of the Integrated Ocean Drilling Program. Dr. Feary received B.Sc. and M.Sc. (Honours) degrees from the University of Auckland and his Ph.D. from the Australian National University.

B

Presentations to the Committee

Meeting 1 – September 27-29, 2007

NSF-SBE Perspective
Mark Weiss, Rich Kay, and Don Grayson, (Archeology/Anthropology) NSF-BCS
NSF-GEO Perspective
Rich Lane, Enriqueta Barrera, and Ray Bernor, (Earth Sciences) NSF-GEO
Personal Perspective on Committee's Task
Mikael Fortelius, Department of Geology, University of Helsinki
What They Hear vs What You Say—and Why it Matters
Eugenie Scott, National Center for Science Education, Oakland, CA
Thoughts on Human Evolution and Climatic Change
Steven Stanley, Department of Geology and Geophysics, University of Hawaii.
Thoughts on the Environmental Context of Human Evolution
Bill Ruddiman, University of Virginia.
(How) Do Genes Matter?
Ken Weiss, Pennsylvania State University

Meeting 2 – Workshop February 21-22, 2008

Tempo and Trends and Possible Causes of African Climate Change During the Pliocene-Pleistocene
Peter deMenocal, Lamont-Doherty Earth Observatory of Columbia University

The Tempo of Evolution
Rick Potts, Smithsonian Institution
Climate, Tectonics, and Hominin Evolution
Peter Molnar, University of Colorado
Early hominid skeletal biology, environmental context, and behavior–a view from Afar
Tim White, University of California at Berkeley
Tectonostratigraphic Context of Turkana Basin
Francis Brown, University of Utah
The Cape Floral Kingdom, Shellfish, and Modern Human Origins: Transdisciplinary Problems Require Transdisciplinary Projects
Curtis Marean, Arizona State University

WORKSHOP BREAKOUT QUESTIONS

Question 1: What was the history and variability of hominin paleoenvironments over the last 8 Ma?

Question 2: How do we improve geochronological control and temporal resolution?

Question 3: Can terrestrial, lacustrine, and marine paleoenvironmental record be reconciled in terms of known forcing mechanisms?

Question 4: How can biotic evolution and adaptation be quantified?

Question 5: How does the terrestrial biotic record relate to the paleoenvironmental changes indicated by terrestrial, lacustrine, and marine records?

Question 6: How do we improve our understanding of hominin interactions with their environment?

Question 7: What new archives, proxies, and methods are needed?

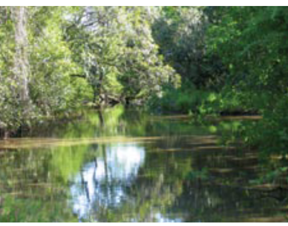
Question 8: How do we test the null hypothesis that human evolution was unaffected by environmental change?

C

Accronyms and Abbreviations

A.D.	Anno Domini (medieval latin–“in the year of the Lord”)
ALOS	Advanced Land Observing Satellite
ASTER	Advance Spacebourne Thermal Emission and Reflection Radiometer
C3	A plant that produces the 3-carbon compound phosphoglyceric acid as the first stage of photosynthesis
C4	A plant that produces the 4-carbon compound oxalocethanoic (oxaloacetic) acid as the first stage of photosynthesis
CO_2	carbon dioxide
DNA	deoxyribonucleic acid
dpi	dots per inch
DSDP	Deep Sea Drilling Program
GCM	Global Climate Model
GEON	Geosciences Network
GPS	Global Positioning System
HOP	Human Origins Program
ICDP	International Continental Scientific Drilling Program
IKONOS	Commercial earth observation satellite designed by Lockhead Martin Corporation and launched in 1999
IODP	Integrated Ocean Drilling Program
ITCZ	Intertropical Convergence Zone
JAXA	Japan Aerospace Exploration Agency
ka	thousands of years before present

ky	thousand years
Landsat	The Landsat Program is a series of Earth-observing satellite missions jointly managed by the National Aeronautics and Space Administration and the U.S. Geological Survey. Since 1972, Landsat satellites have collected information about Earth from space.
LDCM	LandSat Data Community Mission
LGM	Last Glacial Maximum
Ma	million of years ago
MBT	methylation index of branched tetraethers
MicroCT	Microscopic Computed Tomography
MIS	Marine Isotope Stage
MODIS	Moderate Resolution Imaging Spectroradiometer
NCEP	National Centers for Environmental Prediction
NOW	Neogene Mammals of the Old World
ODP	Ocean Drilling Program
OIS	Oxygen Isotope Stage
PAGES	Past Global Changes
ppm	parts per million
QUICKBIRD	a high-resolution commercial Earth observation satellite, owned by DigitalGlobe and launched in 2001
RHOI	Revealing Hominid Origins Initiative
SST	sea surface temperature
SRTM	Shuttle Radar Topogrpahy Mission
TEX_{86}	tetraether index of 86 carbon atoms; paleothermometer based on the composition of membrane lipids of marine picoplankton UAVUnmanned Aerial Vehicle
YD	Younger Dryas



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ISBN-13: 978-0-309-14838-2
ISBN-10: 0-309-14838-3