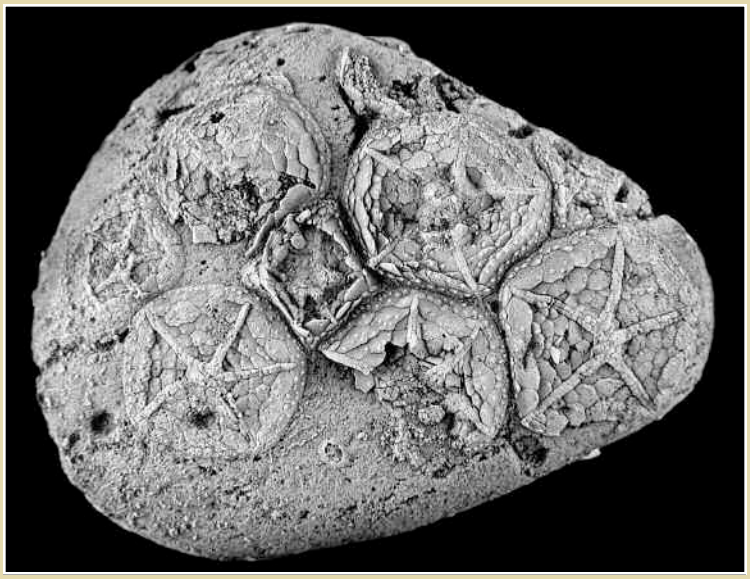
To contact The Paleontological Society
http://www.paleosoc.org

To contact the Society of Vertebrate Paleontology
http://www.vertpaleo.org

Future Research Directions in PALEONTOLOGY



Report of a Workshop Held April 8-9, 2006

Sponsored by the National Science Foundation

Hosted by the Department of Paleobiology, National Museum of Natural History, Smithsonian Institution

Organized by the Paleontological Society

In Cooperation With the Society of Vertebrate Paleontology

Executive Summary

Five initiatives are proposed that will allow paleontologists to fully take advantage of the extraordinary opportunities which currently exist for paleontological research. These include proposals for the development of two new paleontological research programs, as well as initiatives aimed at improving the support and management of paleoinformatics and museum resources, increasing involvement of professional societies in the promotion of paleontology to other scientists and the public, and provision of necessary opportunities for the next generation of paleontologists.

Deep Time Earth Life Observatories (DETELOs)

Studies of deep time provide a unique perspective on the processes driving the Earth-Life system that cannot be studied in the present or in recent history. Typically research on deep time has proceeded within the framework of the single investigator. Deep Time Earth Life Observatories are proposed as a program that would allow focused efforts by teams of scientists to increase the pace towards solution of highly significant problems within a systems framework.

These DETELOs would involve integrated teams of perhaps 10-20 paleontologists, geochemists, stratigraphers, geochronologists, paleoclimatologists, modelers and other geoscientists focusing on questions of sufficient interest as to justify such an effort. Each observatory would last for 5-10 years (an initial 5 year grant followed by a possible renewal). Projects would need to integrate existing data sets, develop quantitative, process-based models, as well as plan coordinated field work and analyses. DETELOs would provide significant opportunities for junior faculty and postdoctoral scholars and include joint training of graduate students.

Given the variety of problems of sufficient scope to require such attention, we suggest that allocation of $4 million per year (2007 dollars) by the National Science Foundation (NSF) would be sufficient to fund three such observatories at approximately $1 million per year with an additional $1 million per year devoted to supporting the associated infrastructure costs.

Paleontological Probes (PALPROBEs)

Anthropogenic influences are adversely affecting biodiversity and ecosystems in ways that might be irreversible. Present-day environmental and biological monitoring of these systems is insufficient for understanding anthropogenic effects because they

lack a critical, deep-time perspective. A program of Paleontological Probes (PALPROBEs) is proposed to generate studies that will provide unique information on species response to rapidly changing environmental conditions. PALPROBE grants would be smaller than those for DETELOs, involving several PIs, but would be larger than the typical NSF individual investigator grants. As for DETELOs, PALPROBE grants would emphasize providing support for junior faculty, postdoctoral scholars, and training of graduate students.

For the PALPROBE program to obtain a sufficient start we envision this would entail $1 million per year for 5 years which would fund 5 projects running in any given year. Thus grants for the PALPROBE program would be significantly smaller than those envisioned for DETELOs.

Database and Museum Collection Development and Integration

Paleoinformatics is proving to be of increasing importance to both biology and to geology. Increasingly, research couples both databases and collections in order to answer broad evolutionary and/or deep time questions. Databases and museums undergird integrative multiuser research initiatives as well as individual projects. Being able to combine different datasets provides opportunities to ask new and more widely ranging questions in deep time studies. Development and integration of museum collections and comprehensive databases such as the Paleobiological Database (PBDB) and CHRONOS requires long-term support and stability from funding agencies.

Increasing the Role of Professional Paleontological Societies

The professional societies have a major role to play in fostering and sustaining future research directions in paleontology, including the growth of new community-wide research programs. It is generally agreed that the societies would benefit from more frequent interactions and improved coordination. Benefits could include establishment of circumstances to foster innovative research, development of a more unified vision of research goals and opportunities, and creation of opportunities to educate the public on subjects of general relevance.

Increased Funding Opportunities for Graduate Students and Postdoctoral Scholars

Intellectual interest in paleobiology is growing among a range of disciplines. However there is a lack of funds for graduate student research as well as postdoctoral positions available for paleobiologists. Several solutions are apparent. These include adjusting funding allocations within NSF so as to allow routine funding of postdoctoral positions through paleobiology grants, as well as reconstitution of NSF Division of Earth Sciences (EAR) funded postdoctoral positions for paleobiology. To improve funding for graduate students it is recommended that NSF EAR establish a Doctoral Dissertation Improvement Grant program. Special attention for inclusion of funds for graduate student training and postdoctoral support should also be a high priority in the DETELO and PALPROBE programs.

Future Research Directions in Paleontology (FRDP)

Never before has the study of past life been as exciting and as urgent. Technical advances present unprecedented opportunities for dissecting causal relationships between patterns of organic and environmental change chronicled in the sedimentary record of deep time. Elevated rates of global change give such studies pressing societal significance. New understanding of the relationships between genetics and organismal form offer a wider perspective on the evolutionary history of life, with paleobiology serving as an empirical arbitrator in debates that span a vast array of biological disciplines. For example, the use of fossils has become a critical part of calibrating the molecular clock and establishing the divergence times of lineages.

At the same time, funding levels to support paleontological research have proven increasingly inadequate, both for the development of new and promising research directions and for the growth and maintenance of critical intellectual and physical infrastructure. Paleobiological research currently receives about $3 million per year through NSF's EAR budget. This accounts for approximately 2.5 % of the EAR budget and 0.5% of NSF's overall Geosciences budget. Thus we have reached a critical juncture: although the intellectual prospects of paleobiology have never been brighter, funding opportunities are lagging well behind needs.

Consequently, it has become increasingly clear that the paleontological community needs to articulate a coherent and prioritized set of scientific goals that will guide its research activities over the next decade. These research goals will establish the context for specific projects that will be devoted to reaching them and will define what resources will be required to accomplish them.

These goals will need to be addressed not just by paleontologists, but by teams of scientists representing a broad variety of expertise. This contrasts with the traditional academic approach of the science, which emphasized the role of individual investigators in pursuit of their own research agendas.

As a major step towards developing these goals, the Paleontological Society (PS), in conjunction with the Society of Vertebrate Paleontology (SVP), has launched a community based effort on Future Research Directions in Paleontology (FRDP). This effort has focused on:

> Recognizing large-scale collaborative projects that will attract substantial new funding.

> Emphasizing the crucial insights that paleontological research can return to society in efforts to understand and manage environmental change caused by anthropogenic influence.

> Developing mechanisms to enhance paleontological infrastructure, particularly in the form of additional support for museum collections and databases.

> Improving funding for graduate students and postdoctoral scholars.

> Increasing the role of professional societies in enhancing and disseminating paleontological research, as well as acting as advocates for the profession.

With a community-based aproach, this effort has emphasized outreach to the paleontological community to generate ideas on avenues of research and professional development that the broad spectrum of paleontologists views as of great significance.

The centerpiece of this effort was the FRDP Workshop held on April 8-9, 2006 at the Department of Paleobiology, National Museum of Natural History (NMNH), Smithsonian Institution, Washington, D.C. The demographically diverse group of 38 participants (see Contributors, p.24) reflected the wide variety of research outlook among paleontologists today. The workshop was preceded by a research forum at the North American Paleontological Convention (NAPC) (June 19-25, 2005) in Halifax, Nova Scotia that was open to all NAPC participants, which included an information and brain-storming session, as well as a similar research forum at the Geological Society of America (GSA) Annual Meeting (October 14-19, 2005), held in conjunction with the PS Annual Meeting, in Salt Lake City. Following the workshop a forum was held at the GSA Annual Meeting in Philadelphia (October 22-25, 2006) to present the results from the workshop for broader discussion by members of the paleontological community.

With a community-based aproach, this effort has emphasized outreach to the paleontological community to generate ideas on avenues of research and professional development that the broad spectrum of paleontologists views as of great significance. It should be emphasized that this is an ongoing endeavor - the ideas contained in this report are intended to lay out general concepts, to spark continued discussion and refinement, and, most importantly, to lead to specific plans for implementation.

The current products of this effort are reflected in the following report. It should be emphasized that this is an ongoing endeavor - the ideas contained in this report are intended to lay out general concepts, to spark continued discussion and refinement, and, most importantly, to lead to specific plans for implementation.

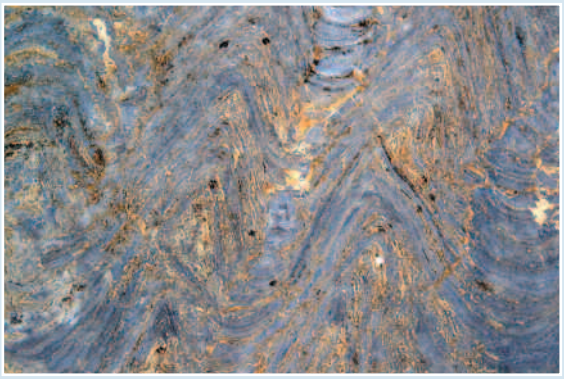
This document consists of five sections and is meant for wide distribution to paleontologists and our colleagues in the broader scientific community. It will also be shared with decision-makers in government and private funding agencies.

1

A Proposal for Deep Time Earth Life Observatories (DETELOs)

Introduction

Major advances in understanding critical transitions in the history of life require integration of paleontological, geochemical, biological, stratigraphic and other information into a temporal and spatial framework. Only within such a framework can we understand the processes that have driven such transitions in the biosphere, whether they are mass extinctions, the spread of novel groups such as angiosperms or new types of phytoplankton, or more regional events such as the changing reef architecture in response to sea-level change in the Permian Basin of west Texas. In the past, the development of these integrated datasets and associated analyses have occurred in an uncoordinated and often haphazard fashion. As a result many critical questions remain unresolved. For example, we still do not know, in detail, the pattern of selectivity of extinction during the end-Permian mass extinction, nor the biogeographic patterns of extinction and survival for the Cretaceous-Tertiary mass extinction. Even more importantly, we have little knowledge of the underlying process of biotic diversification or diversity loss, in part because of a lack of quantitative models with testable predictions for changes in biodiversity.



Studies of deep time provide a unique perspective on the processes driving the biodiversity of complex organisms. How have plants and animals changed the planet, and by what processes has the planet itself been altered by their presence. The geological record contains perturbations of the Earth-Life system that cannot be studied in the present or in recent history, and studying these events reveals how the processes of the system work. The uniformitarian perspective that undergirds modern geology provides little help in understanding the climate dynamics of the Paleocene-Eocene Thermal Maximum, the dynamics of extra-terrestrial impact, or the developmental and ecological driving forces associated with the Cambrian diversification of animals. It can truly be said that: "The Holocene is just a hypothesis about how the Earth works." In addition, many Earth system processes operate too slowly to be observed in the present or in the recent past, and the only way to observe them is through the record they leave behind in deep time.

What is a Deep-Time Earth Life Observatory (DETELO)?

These observatories would involve integrated teams of perhaps 10-20 paleontologists, geochemists, stratigraphers, geochronologists, paleoclimatologists, modelers and other geoscientists focusing on a particular question in deep time. The question to be pursued would have to be of sufficient scope and interest as to justify such an effort. As we discuss in greater detail below, we anticipate that such coordinated efforts would last for 5-10 years (an initial 5 year

grant followed by a possible renewal). Projects would need to integrate existing data sets, develop quantitative, process-based models, as well as plan coordinated field work (including probably drilling) and analyses. DETELOs would provide significant opportunities for junior faculty and postdoctoral scholars and include joint training of graduate students.

We anticipate that the research would require acquisition of new fossil collections with associated stratigraphic, sedimentological and geochemical data. The systematics and paleobiology of appropriate groups would be buttressed through new studies (perhaps in coordination with Tree of Life groups). Cores would be subject to paleontological, sedimentological, geochemical and other studies. High-resolution geochronology and allied chronostratigraphic techniques would be applied to develop an appropriate temporal framework. Existing museum collections of fossils of target intervals would receive special attention, including updating and entry into databases. Tectonic and stratigraphic studies might be needed to understand paleogeography. All data would be accessioned into appropriate, publicly available databases.

Examples

Such observatories could take a number of forms, depending on the questions of interest. All of them will share a concern with the processes, not simply the patterns, underlying major events in Earth history, but some will have a global scope while others will be focused more tightly on a specific region. All will focus on complex life and its interactions with geochemical cycles and most will involve connections between the oceans and continents. From a broad variety of possibilities we suggest two examples of the kind of project that could be considered for a DETELO. The first would focus on the events within a single time-slice at the Cretaceous-Tertiary Boundary, while the second would address the major changes in ocean life and geochemical cycles associated with changes in marine plankton during the late Neoprotoerozoic-Ordovician and the Mesozoic.

What Processes Might DETELOs Study?

Such observatories are ultimately concerned with understanding processes in a systems framework. Thus, a crucial component of such research is understanding the interactions between different components of the Earth's biota and the physical environment and the appropriate positive and negative feedbacks. At the largest scope, the questions to be addressed through such observatories would include:

> How has complex life controlled redox chemistry and how is it controlled by same?

> How does complex life influence surface processes (e.g., erosion, deposition) and how is it controlled by same?

> How are ecological communities assembled, and how has this changed over time and in different environmental settings?

> What are the reciprocal interactions between life and the carbon cycle?

> How does complex life control climate and how is it controlled by same?

> How do perturbations in the Earth's environments affect the diversity (taxonomic, morphologic, ecologic) of life and its ability to modulate processes like the carbon cycle, atmospheric composition and erosion?

> How does the environment affect interactions among organisms?

> What are the processes through which complex organisms control ocean chemistry, and how is it controlled by same?

> How has life engineered habitats (local physical and chemical conditions) over time?

Types of Data Necessary for DETELOs

Resolving these process-based questions will require a range of paleontological data, including well-developed phylogenies and systematics, paleoecological data based on standardized sampling of abundances, stable isotope geochemistry and the generation of a high-resolution temporal framework (essential for any study of rates) based on radiometric dating, chemo-, bio-, magneto- and orbital stratigraphy. In many cases quantitative studies of morphometrics will be needed.

Such observatories could take a number of forms, depending on the questions of interest. All of them will share a concern with the processes, not simply the patterns, underlying major events in Earth history, but some will have a global scope while others will be focused more tightly on a specific region. All will focus on complex life and its interactions with geochemical cycles and most will involve connections between the oceans and continents.

Criteria for Evaluating DETELO Proposals

We do not feel it is appropriate to identify target time slices or questions for specific observatories, but we do offer a number of criteria for the evaluation of proposals.

Observatories will clearly require a diversity of expertise, including appropriate systematic paleontologists, paleoecologists and paleobiologists, as well as geochemists, geochronologists, stratigraphers and sedimentologists. We believe it is impossible to understand the processes underlying paleontological patterns without explicit models, ideally quantitative models. We therefore believe that an important component of all such observatories should be a real integration of modeling and data approaches with explicit predictions from process models being used as a basis for designing field work and sampling design. Further, early field work should be used as a basis for iterative testing and refinement of the models.

Data collection and modeling should be at the appropriate temporal resolution and spatial scale to study the phenomenon of interest, with due consideration for sedimentary and taphonomic biases that affect data interpretation. Although these deep-time observatories must begin with the identification, updating and integration of existing data and collections, much existing data is unlikely to be at appropriate scale or nature. Thus, such observatories must be designed around the acquisition of new data, and its appropriate integration with existing data and collections. In addition, such new data sets should be collected in an integrated fashion (i.e. with geochemists and paleontologists sampling the same sections, not two different sections 10 kilometers apart). Such sample sharing and multiple proxy study of sections should be standard practice. There should also be specified in each proposal how analysis of disparate data types and model results will be synthesized.

Finally, proposals must present an adequate plan to archive the data in existing community databases and an adequate plan to archive specimens and samples and cores in existing community museums. Plans for education and outreach should also be presented with each proposal.

Supporting Infrastructure

There are several core infrastructure needs that are beyond the scope of individual observatories but which provide expertise that is required for their success and for research across the broader paleontological community. We therefore budget for support of these community infrastructure needs.

A Ongoing support for existing community databases, including the Paleobiology Database, CHRONOS, GeoSystems and others. These databases are a vital resource as an archive of information and, more importantly, as a tool for broader analytical studies.

B The development of continental drilling equipment and capability, including the use of non-organic solvents needed for isolation and recovery of organic biomarkers.

C Support for a network of laboratories doing high-resolution geochronology (U/Pb and Ar-Ar and new techniques as they become available). Existing facilities are far less than the demand. Support must also be provided so that geochronologists can continue to resolve issues of inter-laboratory calibration and laboratory standards. Isolation and identification of organic biomarkers is also a highly specialized area at present and support is needed for the capacity to process the additional samples expected from these observatories. Geochronologists and organic geochemists should be incorporated in observatory teams as full partners in the research (and not viewed as service providers).

D Support is required for long-term, stable repositories of specimens, samples and cores.

E Modest support is required for development of a field-to-lab-to-museum sample tracking system. Biologists have developed such systems to track specimens from the field through all analyses and collections. They greatly reduce the backlog of cataloging specimens in museums and repositories, and properly designed can ensure the easy integration of disparate data sets.

Cost Estimates

Given the variety of problems of sufficient scope to require such attention, we suggest that allocation of $4 million per year (2007 dollars) by NSF would be sufficient to fund three such observatories at approximately $1 million per year with an additional $1 million per year devoted to supporting the associated infrastructure costs.

2

A Proposal for Paleontological Probes (PALPROBEs) to Determine the Effects of Human-Induced Environmental Change

Introduction

There is growing concern that anthropogenic influences are adversely affecting biodiversity and ecosystems in ways that might be irreversible. That said, present-day environmental and biological monitoring of these systems is insufficient for understanding anthropogenic effects because they lack a critical, deep-time perspective. This has been demonstrated clearly in a variety of studies that illustrate the influence of humans on ecosystems on millennial timescales in ways that would have been overlooked entirely if not for the analyses of longer term, historical records dating back to the first measurable human exploitation of these systems.

With this in mind, paleontological principles and methods should play central roles in the investigation of present-day stresses to ecosystems in two important respects that are not mutually exclusive:

A Paleontological tools should be employed to better understand biological responses to **present-day, anthropogenic environmental change,** and to predict the effects of continuing anthropogenic change in the future. The accumulating record of sediments and skeletal material (the subfossil record) provides important, but largely unexploited data on both natural and human-induced transitions to ecosystems, particularly in critical settings, such as coastal environments along the eastern seaboard of the United States. A concerted effort should be undertaken to develop a repository of data from these settings, both to assess the post-Pleistocene record of environmental change at individual localities, as well as to correlate regional transitions and perturbations that transcend particular localities.

B Biotic response to rapid global change in deep time should be investigated at high spatio-temporal resolution, using the fossil record as a source of ground truth, against which predicted effects of anthropogenic modification of the environment can be tested. Dovetailing on the call for the establishment of Deep Time Earth Life Observatories (DETELOs), the fossil record provides important opportunities to investigate the local, regional, and global effects of physical perturbations that closely approximate those caused by humans in the present

day. Investigations of the Paleocene-Eocene transition, for example, are currently providing an opportunity to investigate in detail the biotic response to a significant pulse of global warming. In conjunction with the establishment of DETELOs, there should be some focus on intervals that appear based on geochemical analyses to provide a protracted window through which to investigate the biotic impacts of physical transitions, such as global warming, dysoxia/anoxia, and eutrophication.

The proposed program of PALPROBEs should be designed to generate a variety of studies that bear on species response to rapidly changing environmental conditions. PALPROBE grants would be smaller than those for DETELOs, involving several PIs, but would be larger than the typical NSF individual investigator grants. They would overlap with DETELOs in that many would focus on deep time settings, but a significant number would focus on more Recent time frames.

It goes almost without saying that efforts in both of these arenas should integrate paleobiological, geochemical, and sedimentological data at the finest scales of stratigraphic resolution attainable. A large spectrum of investigations in the marine and terrestrial fossil and subfossil records has demonstrated clearly that fine-scale analyses are likely to provide meaningful data at high temporal resolution that, in many cases, will not be compromised unduly by time averaging or postmortem transport.

What are PALPROBEs?

In general, the proposed program of PALPROBEs should be designed to generate a variety of studies that bear on species response to rapidly changing environmental conditions. PALPROBE grants would be smaller than those for DETELOs, involving several PIs, but would be larger than the typical NSF individual investigator grants. They would overlap with DETELOs in that many would focus on deep time settings on the order of hundreds of millions of years old, but a significant number would focus on more Recent time frames. PALPROBE grants would emphasize providing support for junior faculty, postdoctoral scholars, and training of graduate students. Some examples of research to be pursued under such a program are as follows:

Present-day, anthropogenic environmental change:

A Evaluation of changes in species distribution and survivorship in response to rapid shifts in Holocene and Late Pleistocene climates, based on systematic coring of coastal and estuarine wetlands.

B Assessment of the timing and magnitude of effects of diverting river water for human purposes on productivity of estuaries along the arid Pacific Coast of North America. Can a nick point be recognized in the transition from natural conditions to human influence, in this and other studies?

C Assessment of changes in the transfer of nutrients among terrestrial, shallow shelf marine and open ocean environments, and the impact of these transfers in each setting. How does the magnitude of human influence on these transfers compare with perturbations recorded in the fossil record?

D Application of new geospatial technologies to test hypotheses relating changes in geographic distribution and rates of speciation and extinction in clades and communities to environmental perturbations.

E Evaluation of the impact of major evolutionary innovations, especially those that affect access to food or energy resources and the ability to process them rapidly, on the innovators and on their environments

F Assessment of the impact of fishing boats' drag nets on shallow benthic marine communities in comparison with activities of 'biological bulldozers' today and in the geologic past. What sorts of species have the greatest capacity to recover from such disruptions and which are likely to be devastated?

Biotic response to rapid global change in deep time

A Impact of rapid changes in climate, oxygenation, nutrient input, sea level, composition of surface ocean water, disruption of habitats and vegetation cover on species distributions, ecological diversity and extinction rates during transitional intervals in the geologic past.

B Biotic response to the Permian transition from icehouse to greenhouse climatic conditions.

C Comparison of species responses to the short-lived Late Ordovician glaciation and the later glaciation spanning much of Pennsylvanian-Permian time.

D Impacts of rapid shifts in Cenozoic climate, including the recurrence of warm intervals after the onset of glacial conditions in the mid-Miocene.

E Comparative analysis of invaders and survivors among species affected by temperature decline in several Neogene basins (multiple events in both temperate and tropical basins).

F Response of reef-building corals and planktonic microorganisms living at shallow depths to rapid shifts in atmospheric CO2.

G Comparison of responses of species living in coastal wetland and inshore marine environments to rapid versus more gradual rates of transgression.

H Biotic effects of the rapid proliferation of species introduced into environments where they were previously absent.

I Evaluation of direct and indirect effects of rapid shifts in vegetation cover on plant and animal species distributions and feedback to climate, not only in the Quaternary, but also earlier in the geologic record.

J Studies of ecosystem structure and productivity: how has ecosystem structure evolved over time? Can the productivity of ancient terrestrial, shelf and open ocean ecosystems be determined? Have ecosystems become more or less resistant to major environmental perturbations, or resilient in response to them, over time? What implications do these shifts have for the likely impact of anthropogenic disturbance?

Necessary Infrastructure

Broadly speaking, the research agenda proposed here is heavily dependent on maintenance and further development of basic infrastructure. Individual projects may require support for field studies at key sites, coring of coastal and wetland sediments, or even continental drilling in some cases (see also the previous section on DETELOs). Funding of this research program should include direct support for facilities that are essential to many of the projects envisaged here, including:

> Enhanced development of the Paleobiology Database and integration of other relevant databases with it.

> Establishment of laboratories to provide analyses of key geo-biochemical markers.

> Curation of museum collections, with updating and standardization of taxonomic and other databases.

> Maintenance of drill core archives.

Paleontological data have been under utilized in documenting the historical context and dynamics of present-day ecosystems, let alone to predict the outcomes of future change. The proposed program is designed to take advantage of an obvious but relatively neglected avenue of investigation.

Cost Estimates

For the envisioned PALPROBE program we propose a decadal commitment from NSF, for basic research, training of students, and development of collaborative efforts between biologists and geologists (2005 National Research Council Report). For this program to get a sufficient start this would entail $1 million per year for 5 years which would fund 5 projects running in any given year. Size of such grants is based on the need for coring and other fieldwork, geochemistry support, and for two Principal Investigators with several RAs and/or a postdoc. Thus grants for the PALPROBE program would be significantly smaller than those envisioned for DETELOs.

Concluding Remarks: Links to Other Scientific Enterprises

Paleontologists routinely use knowledge of living organisms and communities to interpret the skeletal remains and other traces of past life that are preserved in the fossil record. As suggested earlier, however, paleontological data have been under utilized in documenting the historical context and dynamics of present-day ecosystems, let alone to predict the outcomes of future change. The proposed program is designed to take advantage of an obvious but relatively neglected avenue of investigation.

Research under this program will complement work that is being conducted under two other major programs. Research funded through the Tree of Life initiative is significantly improving our understanding of human origins and evolutionary relationships among living organisms. Evidence from the fossil record is used extensively to test inferences drawn from molecular data generated by this project. This work bears most directly on where *Homo sapiens* and other living species have come from, historically, and on how we got here.

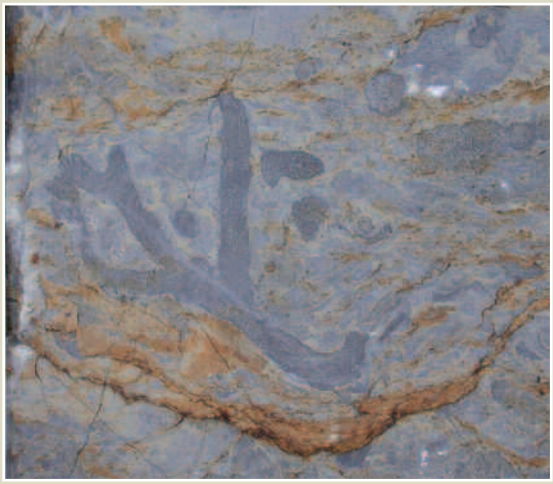
The Human Genome Project is also yielding information that bears on evolutionary relationships. However, its main focus is on elucidating the genetic basis of developmental processes. In the future, it would be desirable to couple genetic data directly with the kinds of analyses proposed here to produce more highly integrated analyses of the evolution of *Homo sapiens* and other species in a paleoecological context.

3

Database and Museum Collection Development and Integration

Introduction

Museum collections, databases and informatics are an integral part of the infrastructure of paleontology at present, and will continue to be so into the future. In order to be dynamic and useful resources, both require long-term support. Further, these two infrastructural resources are quite naturally complementary and interlinked, but this aspect can be developed more as suggested in later sections.



Paleoinformatics is as relevant to biology as to geology. Increasingly, research couples neo- and paleo-data, most often using both databases and collections in order to answer broad evolutionary and/or deep time questions. Databases and museums undergird integrative multiuser research initiatives as well as individual projects. Being able to combine different datasets provides opportunities to ask new and more widely ranging questions in deep time studies (such as are outlined in other parts of this document). Thus, both require long-term support and stability.

Informatics initiatives should minimize redundancy and maximize interoperability and accessibility. While informatics needs to database or make accessible museum collections may differ from other database needs or goals, interfaces/ontologies that allow interaction, or even simultaneous development, would maximize time investment, since both require oversight by specialists.

Recommendations

A Support distributed teams to develop data sets and/or information technology for a variety of question-oriented research projects, including the Deep Time Earth Life Observatories.

A series of "Paleo SWAT Teams" will focus on answering major questions that target specific times, places, or groups. A team may use a combination of methods to obtain data. For example, teams may: **1** collect and describe new specimens; **2** revise and capture museum data; **3** capture literature data; and/or **4** integrate diverse types of data. Data would be reposited into existing databases to guarantee long-term access and avoid replication of data and software development. An example of such a currently active "team" involving a group of specialists entering and/or providing data is the Neogene Marine Biota of Tropical America (NMiTA) database, which focuses on Neogene marine neotropical organisms.

B Support a repository, which will be the paleontology equivalent to GenBank, which is the National Institutes of Health (NIH) genetic sequence database. Such a repository will require long-term funding. Funding will be targeted for both software development and database management, so that the database will be current and interactive. Such a repository will house both data newly reposited by individual teams and data currently stored in databases that are no longer being developed. Archival data sets exist as both electronic databases [e.g., the Palynological Literature Information Collection (Palynodata)] and card catalogs, so extra funding for digitization will be needed. A major feature of the repository is that it will be interoperable, and thus will employ cutting edge standards and protocols to provide web services. Interoperability with biological databases will be accomplished using internationally agreed-upon biological protocols like Darwin Core 2 and ABCD, which already are being employed by the Paleobiology Database to provide data to the Global Biodiversity Information Facility (GBIF). Equally important, the repository database(s) will be interoperable with museums (see next).

> Paleoinformatics is as relevant to biology as to geology. Increasingly, research couples neo- and paleo-data, most often using both databases and collections in order to answer broad evolutionary and/or deep time questions. Databases and museums undergird integrative multiuser research initiatives as well as individual projects. Being able to combine different datasets provides opportunities to ask new and more widely ranging questions in deep time studies.

C Support existing databases which have already demonstrated a great utility for paleontology. Two existing databases involving cooperative efforts of many individuals are the **Paleobiology Database** (PBDB) and **CHRONOS**.

The community-governed PBDB includes not just occurrences, which are the focus of most paleontology databases, but taxonomic classifications, synonymies, measurements, ecological and taphonomic categorizations of taxa, digital images, stratigraphic sections, and numerous separate time scales. Its system is extensively normalized and dynamically updates its integration of taxonomy, occurrences, and time scale data sets upon entry of new data records. It has been built by more than 180 contributors from 22 countries and has seven years of experience with creating web-based data entry and editing software. It has uploaded many existing data files provided by individual contributors, as well as entire stand-alone databases such as Sepkoski's Compendium, the Paleogeographic Atlas Project Databases (PGAP), the Evolution of Terrestrial Ecosystems (ETE) Program, and the Bibliography and Index of Paleozoic Crinoids. It also exchanges data with CHRONOS, GBIF, the Geosciences Network (GEON), and NMITA.

Unlike the PBDB, CHRONOS is designed to function as an Earth history portal spanning not just paleontology but cognate parts of the Earth sciences, such as geochronology and stratigraphy. CHRONOS currently is the home of some fossil taxonomic dictionaries or atlases (Mesozoic Planktonic Foraminifera Dictionary, Atlas of Paleocene Planktonic Foraminifera, Foraminifera Guide) and has linked or federated such paleontology databases as the PBDB, the late Quaternary mammal distribution database FAUNMAP, the Miocene Mammal

Mapping Project (MIOMAP), and the Integrated Ocean Drilling Program database Janus.

Databases can link to CHRONOS and PBDB, be housed by CHRONOS, or be uploaded by the PBDB. Both house "data-streams" of newly generated, as well as literature-based, data, but each possesses unique attributes. These organizations can be supported and further developed as the main paleontological data repositories, if the community so desires. The PBDB and CHRONOS are in a position to provide leadership in promoting common standards and protocols within the paleontological community, and to also lead the way in developing necessary technologies for interoperability.

CHRONOS and the PBDB were previously funded by NSF, but have recently not received additional funding. EAR program officers have stated that NSF does not intend to provide long-term funding for such efforts. However, other sources of support are not evident: no program within NSF's Directorate for Biological Sciences will fund paleontological databasing for its own sake, NASA's Astrobiology program has significantly reduced support for paleontology, the National Oceanic and Atmospheric Administration (NOAA) does not fund deep time research, and no major private foundations support Earth sciences databases. Nonetheless, precedent for long-term support does exist: NOAA has funded the North American Pollen Database since 1990, NIH has funded the National Center for Biotechnology (NCBI) (which runs GenBank) since 1988, and NSF has funded the Long Term Ecological Research (LTER) network since 1980.

Comprehensive databases are a prerequisite for future studies of paleontology. It is recommended that these databases be considered core disciplinary infrastructure instead of short-term research projects, and thus eligible for truly long-term funding by NSF. Although efforts must be made to find other funding streams for discipline-wide databases, EAR remains the only government program with a defined mission that includes large-scale paleontological research. The current mechanism of having these organizations compete for funding within small programs like the NSF EAR Sedimentary Geology and Paleobiology program, that are intended to handle narrow research proposals, is not viable, and it is recommended that EAR set aside funding for informatics and explicitly make it available for long-term growth and maintenance of paleontological databases, not just their initial development.

D To implement and facilitate the above initiatives, and to minimize redundancy, various tools must be developed. At the interdisciplinary scale, a portal such as CHRONOS needs to develop tools that enable simultaneously analyzing different data types from different parts of the Earth sciences, such as geochemistry, geochronology, and lithostratigraphy. At the disciplinary scale, analytical tools specific to paleontology already exist within such databases as the Paleobiology Database that handle common and readily exchanged data types (e.g., maps and diversity curves based on occurrences, ecological statistics based on abundances, confidence intervals based on stratigraphic ranges). Tools for systematic work to be performed by specialist teams also already exist within, for example, CHRONOS' foraminiferal databases, NMITA, the phylogenetic web-application MorphoBank, and the PBDB, including fossil identification keys and methods for storing and displaying measurements, diagnoses, character descriptions, and digital images. However, tools for exchanging these data, as opposed to occurrences, have yet to be developed. Other types of tools that will need to be developed include those specific to each team's research project. Again, communication within the paleontological community, and also between it and both the geological and biological community, is critical so that redundant efforts are not made.

4

Development of the Role of Professional Paleontological Societies to Promote Paleontology and Paleontological Research

Introduction

The professional societies have a major role to play in fostering and sustaining future research directions in paleontology, including the growth of new community-wide research programs. Most professional paleontologists belong to one or more professional societies with paleobiology as their focus. The societies publish scholarly journals, sponsor annual meetings, and provide venues for regular communication with their members. Historically, the professional societies have not worked closely together, although members from different societies have organized joint symposia, Geological Society of America (GSA) Penrose conferences, and short courses from time to time. In addition, the societies have not functioned as advocates for our science with the larger scientific community and the public, nor have they spoken with one voice on areas of common interest. It is generally agreed that the societies would benefit from more frequent interactions and improved coordination. Benefits could include establishment of circumstances to foster innovative research, development of a more unified vision of research goals and opportunities, and creation of opportunities to educate the public on subjects of general relevance.

Increased Role of Professional Societies

There are three major areas in which the professional societies could enhance the field of paleontology. The first area concerns activities within and among the societies to enhance research and funding prospects. The second aspect involves promoting paleontology to other scientists. The third area involves promoting paleontology to the public at large. Although the themes are interrelated, each theme has its own goals and audience.

Increased Activity Within and Between Professional Societies

Several mechanisms within and among the professional societies should be pursued in order to enhance future paleontological research, including shaping its future directions and increasing the funding for them. The audiences for these activities are paleontologists actively involved in scholarly research (at universities, museums, and other organizations) and funding agencies, including the NSF. In order to create the circumstances in which synthetic, community-wide research initiatives would arise, more communication and interaction among the societies are needed. To address these needs, the

following recommendations are made for increased interactions among paleontological societies:

> Within each society, appoint a member of the executive committee/council with the specific responsibility to be a liaison with other societies and funding agencies.

> Arrange for the Paleontological Society and the Society of Vertebrate Paleontology (SVP) to meet in the same city on overlapping dates every few years (e.g., every 5 years). This overlap would enhance opportunities for jointly sponsored events and interaction in a broader paleontological group.

> Co-sponsor symposia with one or more of the other paleontological societies at the annual meetings. Co-sponsor conferences (e.g., Penrose, Gordon) or working groups involving paleontologists from two or more societies.

> Jointly apply (PS and SVP) to NSF for funding for workshops or fieldwork.

> Ensure that several paleontological societies [e.g., PS, SVP, the Paleobotanical Section of the American Botanical Society, American Association of Stratigraphic Palynologists, American Quaternary Association, Cushman Society, Society for Sedimentary Geology (SEPM)] contribute substantially to the organization of the North American Paleontological Conventions (next in Cincinnati in 2009). Investigate the possibility of reviving the functions of the Association of North American Paleontological Societies (ANAPS).

In addition, opportunities exist within each paleontological society to broaden the discussion of community-wide research initiatives.

> Each society can regularly schedule a town-hall meeting at its annual meeting to discuss new research frontiers so that all members in attendance can participate in developing goals and strategies.

> Include amateur members of the societies in these discussions to maintain involvement and communication with this part of the paleontological community.

> Improve communications about research initiatives and funding opportunities via digital methods (e.g., society website, wikis, etc.).

> Arrange for a representative from each professional society to visit NSF on a regular basis. This activity could also be coordinated among the societies (and combined with visits to Congress as described below).

> Urge paleontologists to apply for rotating and permanent positions at NSF in order for the interests of the paleontological community to have better representation in the NSF leadership.

A final recommendation appears in all three areas of activity because the core concept has implications for all three audiences. We propose that the paleontological societies organize and co-sponsor a cross-cutting Darwin Conference every other year. This conference would have activities for professional paleontologists, other scientists, and the public. This two-day conference would occur in Washington, DC, and would feature a high-profile lecture for the general public, specialized sessions on a research theme for professional paleontologists and other interested scientists, and pre-arranged visits to NSF and members of Congress. The Darwin Conference would have a different theme each time and would produce a paper for publication in a journal for a general scientific audience (e.g., American Scientist, Bioscience).

Promoting Paleontology to Other Scientists

Promoting paleontology to other scientists is critical to the future of paleontology. It should demonstrate the relevance of paleontology to many fields of biology, Earth history, and education, among others. It should enhance the knowledge and regard that scientists in other fields have for paleontological research. And it may retard the loss of academic positions in paleontology at many U.S. universities, colleges, and museums. The audience includes academic colleagues at our home institutions, scientists at funding agencies, and the professional scientific readership. The following activities are recommended:

> Two or more professional paleontological societies co-sponsor a symposium at the annual meeting of the American Association for the Advancement of Science (AAAS). This meeting is attended by a broad range of scientists, policy makers, and media representatives. High-profile subjects can receive good media coverage.

> Co-sponsor a paleobiological symposium at the annual meeting of a related scientific society that typically has relatively little paleontological representation (e.g., Ecological Society of America, American Geophysical Union).

> Encourage the writing of synthetic review papers for journals read by a wide range of scientists (e.g., Bioscience, Trends in Ecology & Evolution, Science, PNAS). Such papers can convey the interdisciplinary nature and broad relevance of paleontological research.

> Co-sponsor a National Evolutionary Synthesis Center (NESCent) working group with scientists from other disciplines. This suggestion builds upon the National Center for Ecological Analysis and Synthesis (NCEAS) model in which working groups have sometimes been quite interdisciplinary and brought together scientists who would not otherwise cross each other's paths.

> The biannual Darwin Conference should have a theme of broad significance to other scientists so that some attend the public lecture or are invited to participate in the technical sessions. A person from another field could be invited to give the public lecture.

> Create a booklet about evolution and the fossil record for a general scientific audience.

> Sponsor an evolution theme semester/year at your home institution with links to a wide range of courses and events.

> The professional societies should consider the benefits of joining the Council of Scientific Society Presidents (CSSP). It meets twice a year in Washington, provides regular opportunities to interact with heads of other scientific societies and with leaders in government agencies, and also arranges meetings on Capitol Hill.

Promoting Paleontology to the Public, Including Elected Representatives

Promoting paleontology to the public, including elected representatives, is the final area in which the professional societies can take a more active role. At a time when the teaching of evolution is under attack in many state and local school boards, paleontologists can ill afford to be complacent about communicating the nature of their subject to the

public. Rather a series of ongoing efforts is needed to educate the public about evolution and the fossil record and the value of the deep-time perspective. The audience includes teachers, students, law-makers, and the public at large. Included in our recommendations are the following.

> The paleontological societies should consider jointly sponsoring a Congressional Fellow. Sponsorship would be more feasible as a joint effort than for any society alone. It would provide paleontologists with a voice in Congress. A related suggestion is to use the American Institute of Biological Sciences (AIBS) office to set up Congressional visits and possibly to co-sponsor their Congressional Fellow.

> Professional (and amateur) paleontologists should schedule visits with their representatives in Congress to discuss funding for basic science, teaching of evolution in public schools, protection of fossils on public lands, and other relevant issues. We need more visibility in Congress.

> The paleontological societies should continue to sponsor teacher-training workshops at their annual meetings and at NAPC. The PS and SVP have been doing this for some time and these workshops are very popular.

> Have a cadre of professional paleontologists attend the annual national and state meetings of the National Science Teachers Association to talk about evolution and fossils to K-12 teachers.

> Develop a paleontological speakers bureau for talks to the public and amateur groups.

> The Darwin Conference should provide a stimulating public lecture on a subject relevant to paleontology and Earth history and give the attendees an opportunity to talk with professional paleontologists.

> The societies should hire a media specialist either to give workshops in presenting information to the media or to prepare regular releases for broadcast or print.

These recommended activities will require a committed effort from members of the professional societies over many years to become more outward looking—to other paleontologists, other sciences, and the public. We cannot afford to do otherwise if the public is to understand the basic principles of evolution and the fossil record and if universities are to continue hiring paleontologists and supporting research collections. Many of these activities should create circumstances for fostering community-wide initiatives that will also stimulate creative basic science.

This is an ambitious agenda, especially given the volunteer organization of the societies. Copies of this document will be submitted to the council and executive committees of the societies for discussion at their meetings. Additional copies will be sent to the leaders of the other member societies of ANAPS. The goal will be to produce a prioritized list of actions for the societies to carry out and plan for their accomplishment.

5

Increase in Federal Research Funding Opportunities for Graduate Students and Postdoctoral Scholars

Introduction

Never before has the study of past life been as exciting and as urgent. Technical advances present unprecedented opportunities for dissecting causal relationships between patterns of organic and environmental change chronicled in the sedimentary record of deep time. Elevated rates of global change give such studies pressing societal significance. New understanding of the relationships between genetics and organismal form offer a wider perspective on the evolutionary history of life, with paleobiology serving as an empirical arbitrator in debates that span a vast array of biological disciplines. Accordingly, young scientists need to master a broad and integrated set of geological and biological skills. This requires extensive cross-disciplinary training.

The current level of paleobiological funding in NSF's EAR budget virtually precludes PI's from hiring postdocs through grants funded by the NSF Sedimentary Geology and Paleobiology program because the average award levels are much lower than in other geological disciplines. Concomitantly, the recent funding window offered through NASA's Astrobiology and Exobiology programs, which provided significant postdoctoral support for some leading younger paleobiologists, now has an uncertain future. Thus we have reached a critical juncture: although the prospect of paleobiology has never been brighter and the training for our students has become increasingly demanding, funding opportunities for such training are lagging well behind needs.

The Critical Lack of Postdoctoral Positions in Paleobiology

Intellectual interest in paleobiology is growing among a range of disciplines, ranging from paleoclimatology, geochronology and tectonics, to developmental genetics. Advertisements for academic positions in the environmental and biological sciences increasingly list paleobiology as a potential area of research interest. This encouraging trend reflects paleobiology's pivotal position as a cross-disciplinary science. Yet the number of paleobiologists hired in such positions is small. One explanation is the lack of postdoctoral positions available for paleobiologists, which limits the competitiveness of our students. Scientists from other disciplines routinely benefit from a number of years of postdoctoral experience, often undertaken in several different labs. Such positions enhance academic maturity and provide opportunities for exploring other fields and for acquiring new technical skills. The lack of similar opportunities for paleobiologists leaves our students at risk of being seen as

uncompetitive. Those who do successfully obtain positions commonly have a more limited range of experience than colleagues in other fields.

Two solutions are apparent. The first is to adjust funding allocations within NSF so as to bring paleobiology funding in line with that of sister disciplines in geosciences. Current funding levels reflect traditional low-cost approaches to paleobiology. As the discipline expands into new areas and employs new approaches, funding levels need adjustment to reflect these changes, with particular attention paid to training needs. This will necessitate documenting how increased funding for paleobiology will materially enhance the discipline in a cost-effective manner. The second solution, which is specifically related to NSF funding of postdoctoral positions in paleobiology, is a targeted request that can serve as a pilot approach for the first goal.

Reconstitution of NSF EAR Postdoctoral Program

NSF traditionally has supported independent postdoctoral positions, and still does so in the Mathematics and Biology directorates. Current staff changes in the EAR education directorate (which has an annual budget comparable to that of paleobiology funding) present an opportunity for reconsidering support of postdoctoral positions, constituted along the lines of those supported by other directorates, but tailored to specific disciplinary needs.

Implementation

The establishment of EAR funded postdocs will require a coordinated approach among EAR-funded disciplines. Officers of the Paleontological Society and Society of Vertebrate Paleontology would approach other professional societies within the EAR remit to discuss a coordinated approach to NSF. Representatives of these societies would then approach the NSF EAR education director collectively.

The specific purpose of such postdocs should be to foster interdisciplinary training. This focus requires that the program have the following characteristics:

A Monies should be linked to individuals, rather than specific lab groups (to encourage PIs to accept postdocs coming into their labs from different backgrounds).

B There should be operational resources in addition to salary (to prevent burdening Principal Investigators).

C The duration should be long enough to permit comprehensive training (minimum 3 years).

Other possible sources of postdoctoral support

In addition to reconstituting the EAR postdoctoral program, we see two additional possibilities for increasing postdoctoral training opportunities specifically within paleobiology. These would both be linked to new initiatives that draw additional funding into the SGP program.

A Positions associated with the DETELO and PALPROBE initiatives should be built into those proposals.

B A specific training program along the lines of that proposed in the report of the Molecular Paleobiology Workshop should be developed. That document argued that young workers in paleontology must be trained to understand both the genomic and geological records with equal ease, and to integrate both types of historical information to address questions about the history of life on Earth, especially in today's climate of "post-genomics". Traditionally, students in paleontology receive little or no training in molecular biology during their graduate years, especially since historically paleontology is often taught within geology departments. Funds for postdoctoral training in the molecular sciences are essential for young paleontologists, because their postdoc is usually the only time that they can become exposed to the

techniques and methodologies routine in molecular studies. In addition, funding for these postdoctoral positions must be tailored to the specific needs of this integrative field. Specifically, the cross-disciplinary nature of this area is necessary to provide an initial period of training at the start of postdoctoral appointments to permit researchers to become familiar with approaches they have not employed previously (how many paleontologists have sequenced a gene or determined the expression pattern of a gene?).

Graduate student support

Paleobiologists have enjoyed recent success in the NSF Graduate Research Fellowship competition, which provides three years of tuition and stipend for predoctoral students. Such appointments are valuable both in allowing students to focus on their own research rather than teaching commitments and also as a demonstration of ability to secure NSF support. However, paleobiology students have a disadvantage relative to many disciplines in that many paleobiologists are not eligible for Doctoral Dissertation Improvement Grants (DDIGs).

Doctoral Dissertation Improvement Grants are currently available for students in anthropology, animal behavior, environmental biology, systematic biology, and a handful of other fields. These grants, typically $10,000 or less, can be applied toward any aspect of a student's work, particularly that which cannot be accomplished with the resources available. For instance, a DDIG could fund fieldwork, museum travel, sample analysis, or equipment. This is particularly critical for paleobiology students, given that many work quite independently of their academic advisors. Although some students from the paleobiology community—particularly those studying paleoanthropology or systematics—are eligible for DDIGs, the majority are not. Most importantly, no DDIG program exists in SGP, nor in any part of EAR.

A DDIG demonstrates to potential employers that a candidate can apply for and win NSF funding—a major advantage for anyone entering academia. Additionally, DDIGs improve the quality of dissertation research. Finally, DDIGs are an excellent value for the money, given the number and quality of publications that typically result from doctoral work. Even ten $10,000 grants could have an immeasurable impact on the field. However, as a DDIG program would draw from SGP general funds, the community needs to evaluate whether to fund this from existing resources.

In addition, because most paleontologists are trained within the context of geology departments, we recommend developing an expanded range of short courses aimed at graduate training in the sub-disciplines related to evolutionary developmental biology and adequate funding to permit this. Ideas include:

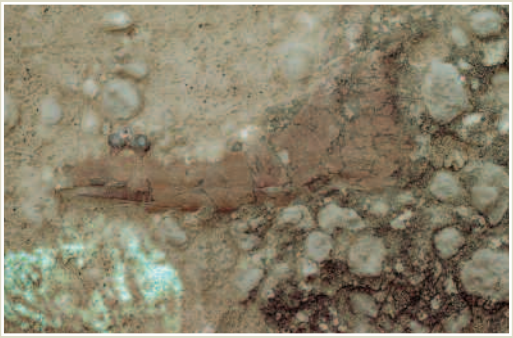
A Establishment of weeklong workshops, offered annually, aimed at encouraging extremely strong undergraduates to enter the field at graduate school. Entry would be competitive and open nationally.

B Monies for students to attend established short courses currently available to graduate students at the Woods Hole Marine Biological Laboratories and University of Washington Friday Harbor Laboratories, the University of Southern California Wrigley Geobiology Course, and the National Center for Ecological Analysis and Synthesis Paleobiology Course.

Arrangements to promote enhanced student mobility among labs through the establishment of a formalized scheme for funding and facilitating lab rotations between paleontology labs and molecular labs in order to foster cross-disciplinary training are also recommended. The ability to provide extended lab visits (a month or months in duration) is key to providing the range of experience necessary to further this area.

Conclusions

With the growth of science over the past few decades, many of the most important problems can only be solved with interdisciplinary teams of scientists using the best available technology. Those engaged in paleontological research would agree that many challenges towards our understanding of how life has evolved and survived on Earth would be best approached in a collaborative, integrative fashion. The FRDP Workshop and associated research forums have provided a community-based platform where several of these most important research problems have been addressed through development of research initiatives in the form of DETELOs and PALPROBEs. Such activities will provide numerous opportunities for research training and experience in forefront areas of science, particularly the growing number of women and other under-represented groups which are currently entering the Earth sciences. Additional funding is also necessary for maintenance and development of databases and museum collections, which play a crucial role in the future development of paleontology. The professional infrastructure of paleontology, our professional societies, also must play an increasing role in the development and promotion of paleontology to other scientists and the public. Perhaps most importantly, mechanisms for provision of increased resources for graduate students and postdoctoral scholars are necessary to ensure the best possible training for the next generation of paleontologists.



It is with the strongest recommendation of the FRDP Workshop that over the next ten years these recommendations be implemented. The potentially easiest program to be implemented is that for postdoctoral and graduate student funding, which we place as the highest priority and in need of immediate action. Devising a funding support system for the variety of growing paleontological databases, such as the Paleobiology Database and CHRONOS, is also a critical need, and warrants immediate solution. DETELOs and PALPROBEs are both key initiatives for paleontology and we propose that these programs be founded and in place over the next two to five years. Our longest-term goal, an increase in the scope and interaction of the major paleontological societies, is recommended to steadily grow over the next ten years to the levels envisioned herein.

A key agenda of contemporary science is the impact of global climate change with biodiversity change. Paleontology is the only discipline that can provide a foundational perspective to which modern-day changes can be calibrated. This is an essential component of this research agenda, but present funding levels prevent a full contribution by paleontologists.

Future Research Directions in Paleontology (FRDP) Contributors

Steering Committee

David J. Bottjer, *Chair,* University of Southern California

Warren D. Allmon, Paleontological Research Institution

Arnold I. Miller, University of Cincinnati

Steven M. Stanley, University of Hawaii at Manoa

Scott Wing, Smithsonian Institution

FRDP Workshop Attendees, April 8-9, 2006

David Bottjer, University of Southern California

Roger Thomas, Franklin and Marshall College

Derek Briggs, Yale University

Bill Ausich, Ohio State University

Mark Patzkowsky, Penn State University

Scott Wing, Smithsonian Instititon

Catherine Badgley, University of Michigan

Pat Gensel, University of North Carolina at Chapel Hill

Arnie Miller, University of Cincinnati

Tricia Kelley, University of North Carolina Wilmington

John Alroy, University of California, Santa Barbara

Dick Bambach, Smithsonian Institution

Rowan Lockwood, College of William and Mary

Doug Erwin, Smithsonian Institution

Peg Yacobucci, Bowling Green State University

Susan Kidwell, University of Chicago

Jocelyn Sessa, Penn State University

Mark Wilson, The College of Wooster

Kevin Peterson, Dartmouth College

Nigel Hughes, University of California, Riverside

Shuhai Xiao, Virginia Tech

Anne Raymond, Texas A&M University

David Jablonski, University of Chicago

Roy Plotnick, University of Illinois at Chicago

Greg Retallack, University of Oregon

Lisa Park, University of Akron

Johnny Waters, Appalachian State University

Elizabeth Heise, University of Texas at Brownsville

Lisa Amati, SUNY Potsdam

Rich Lane, National Science Foundation

Mary Droser, University of California, Riverside

Nancy Budd, University of Iowa

Brian Huber, Smithsonian Institution

Gene Hunt, Smithsonian Institution

Andrew Farke, SUNY Stony Brook

Jason Head, University of Toronto

Jaelyn Eberle, University of Colorado

Colin Sumrall, University of Tennessee

Final Report

Editor

David J. Bottjer

Section Preparation

1 Douglas Erwin

2 Roger Thomas, Arnold Miller

3 Pat Gensel, John Alroy

4 Catherine Badgley

5 Nigel Hughes

Cover **Bored limestone clast with Pennsylvanian edrioasteroids**, courtesy of Colin Sumrall.

Page 5 ***Conophyton*** **from the Mesoproterozoic Belt/Purcell Supergroup**, courtesy of Frank Corsetti.

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Page 23 **Oncolites and tragulid (Artiodactyla) dentary from Miocene conglomerate in Pakistan**, courtesy of Catherine Badgley.