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White Paper
On
China-US Collaboration On Critical Transitions In History of Life
- Recent Progress, Opportunities and Future Strategies

US-China Workshops On Geology and Paleontology

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Complementary Scientific Strengths of China and the US - Over the past decade many important discoveries and advances in understanding Earth's great evolutionary transitions have come from China and the United States, two countries with remarkable scientific resources and complementary strengths in geological and paleontological research. By virtue of their size and geological history, both China and the US have extremely rich fossil records; but Chinese and American scientists developed different, but complementary, research strengths in paleontology and geology. These research activities included collaborative efforts focused on critical intervals and events that impacted the earth and its diverse forms of life. These critical transitions include the origins and early evolution of animal phyla during the Neoproterozoic and Cambrian, the great biotic extinction and subsequent recovery through the Permo-Triassic transition, the Mesozoic origins of flower plants and mammals, the rise of birds from dinosaurs, and the radiation of mammals in the early Cenozoic that eventually led to the evolution of man.

For historical reasons, the formal science of paleontology began in China the 1920s and thus the fossil record of China wasn't studied and exploited to the same extent as that of North America and Europe, which have been studied for more than 300 years. However, over the past two decades, major programs of focused research and exploration of the vast geological record in China yielded a spectacular array of new fossil discoveries. The most important examples are: Neoproetrozoic fossils that preserve soft tissue features, the famous Cambrian Chengjiang biota that is comparable to the Burgess shale, and the Cretaceous Jehol biota with spectacular feathered dinosaurs. In addition, the rocks of China yielded significant new information for nearly every segment of the fossil record from the Neoproterozoic through the Pleistocene.

The recent blossoming of paleontological research in China allowed many of the discoveries to be integrated into the relatively new fields of evolutionary and developmental biology and thus their significance is much more widely appreciated. For example: the discoveries of fossilized animal embryos in the Neoproterozoic and fossil embryos and juveniles of extant vertebrate lineages began to illuminate the evolutionary development of these groups; and discoveries of the earliest-known fossils angiosperm plants and the extant mammalian lineages helped to test hypotheses about their origin and phylogenetic relationships based on recent molecular phylogenetic studies.

Progress in describing the patterns and processes associated with these critical transitions were aided by breakthroughs and progress in related fields of high-precision geochronology, paleobiological studies using large-scale databases, and the integrative analyses of both fossil and molecular datasets in phylogenetics. A critical issue in understanding these transitions is the relative importance of ecological processes and response to changes in physical environment. High-precision geochronology now provides an unprecedented high-resolution temporal framework for the environmental and biological events. Stable isotope and organic chemistry, phylogenetic analysis of evolutionary relationships and quantitative methods in paleoecology and taphonomy allow old questions to be addressed in a more rigorous fashion, and are opening new avenues of research. In recent years, US geologists and paleontologists made significant progress in integrative and multi-disciplinary approaches to studies of paleobiology and earth history. The US scientific community as a whole is innovative in developing the laboratory, cyber- and database infrastructures for such integrative research.

Advantage of the China-US Collaboration in Paleontology –US-China collaborative research has had a disproportionate international impact in paleontological research because of the complementary strengths of the two research communities and their resources. New discoveries from China have gained broad international recognition because collaborative research on these discoveries (often in association with US scientists) helped to place these discoveries in a broader context and facilitate more rapid dissemination. Chinese scientists are gaining increasing influence on overall progress in the geological and paleontological sciences, while the world scientific community has benefited from the fresh insight and stimulation provided by new discoveries and approaches from China.

Joint Workshop of Chinese and American Scientists – The extensive and successful collaboration by Chinese and US paleontologists is being invigorated through two joint Chinese-American workshops (November 2005 in USA and June 2006 in China) supported by the National Science Foundation (USA) and the National Natural Science Foundation of China respectively. These workshops focus on several ***Critical Transitions In History of Life*** under active collaborative research by Chinese and US scientists, including:

(1) ***Biotic and environmental evolution of Neoproterozoic and Cambrian;***
(2) ***Permo-Triassic extinction and recovery;***
(3) ***Origin of modern terrestrial biotas in the Mesozoic;***
(4) ***Cenozoic mammalian faunal and biogeographic evolution;***
(5) ***Pleistocene human cultural evolution and climate changes;***
(6) ***Cyber and database infrastructures for studying critical transitions.***

Participants in the workshops included many active Chinese and American scientists with strong research agendas addressing these transitions. These experts reviewed recent progress and major accomplishments on each of these transitions. They also identified future opportunities and challenges for Chinese and US research. They also developed recommendations on strategies to facilitate research and suggestions for the National Natural Science Foundation of China and the National Science Foundation of USA. Here we discuss opportunities and provide recommendations for research on each critical transition:

Critical Transition I: Neoproterozoic and Early Cambrian

Contributors: Shuhai Xiao (Coordinator), Samuel A. Bowring, Derek Briggs, Douglas Erwin, Roger Summons, Chongyu Yin, Xingliang Zhang, Maoyan Zhu.

Synopsis: The Neoproterozoic and Cambrian are a major focus of recent Earth system research, because these geological periods are characterized by non-actualistic climate change and major evolutionary events. Some argue that the multiple global glaciations—known as "Snowball Earth" events (Hoffman et al., 1998)—in the early to middle Neoproterozoic (760 to 580 million years ago [Ma]) may be causally linked to the radiation of multicellular organisms, which cascaded into the diversification of macroscopic Ediacara organisms and finally the Cambrian radiation of macrobilaterian animals (Hoffman and Schrag, 2000; Xiao, 2004; Condon et al., 2005). Others have proposed that glaciations may have a side effect of the development of land biotas such as fungi, lichens, and plants (Heckman et al., 2001). In any case, it is clear that the interactions among the different components of the Earth system (i.e., biosphere, atmosphere, hydrosphere, and geosphere) have left tangible evidence in the Neoproterozoic-Cambrian sedimentary record. The challenge is to understand the nature of these interactions.

Accomplishments: American and Chinese geologists have recently made a number of landmark contributions to untangling Neoproterozoic-Cambrian Earth systems, especially through their collaborative research on the Neoproterozoic Doushantuo Formation and the Early Cambrian Chengjiang biota.

Collaborative research on the Neoproterozoic Doushantuo Formation: The Doushantuo Formation plays a key role in understanding the biotic recovery from the 635 Ma Marinoan glaciation, the early evolution of animals, and the correlation of late Neoproterozoic rocks. Doushantuo phosphorites contain exquisitely preserved animal embryos and florideophyte red algae (Xiao et al., 1998; Xiao et al., 2004), as well as abundant and diverse acritarchs (Zhang et al., 1998; Yin et al., 2004), possible marine lichenoids (Yuan et al., 2005), and putative cnidarian larvae and bilaterian animals (Chen et al., 2000; Chen et al., 2002; Chen et al., 2004).

Significant progress in Neoproterozoic geochronology has resulted from recent collaboration between Chinese and American geologists (Barfod et al., 2002; Condon et al., 2005; Yin et al., 2005; Zhang et al., 2005). Most significantly, precise U-Pb geochronometry of Doushantuo ash beds constrains the age of the Doushantuo Formation to between 635.2±0.6 Ma and 551.1±0.7 Ma, providing a basic foundation for global correlation of upper Neoproterozoic successions.

Collaborative research on the Early Cambrian Chengjiang biota: The Cambrian radiation of macrobilaterian animals is a unique evolutionary event. Much of the paleontological evidence for the Cambrian radiation comes from small shelly fossils and Burgess Shale-type macrofossils. Small shelly fossils from the Meishucunian Stage and Burgess Shale-type fossils from the Chengjiang and Kaili biotas of South China have featured prominently in the study of the Cambrian radiation. A variety of macrofossils, representing more than 10 animal phyla and including a number of primitive deuterostomes, chordates, and vertebrates (Shu et al., 2003a; Shu et al., 2003b; Shu et al., 2004), have been recovered from the Chengjiang biota (Hou et al., 2004; Chen, 2005). Comparative studies of Burgess and Chengjiang fossils (e.g. Zhu et al, submitted) are helping to further elucidate these assemblages.

Opportunities:

Cryogenian Earth history and climate change: The Cryogenian Period is characterized by multiple global glaciations that may have had significant impact on the Neoproterozoic biosphere. Currently one of the major obstacles toward a fuller understanding of Cryogenian glaciations is a lack of precise radiometric age constraints. As a result, we are uncertain of the exact number, duration, and extent of these glaciations. Neoproterozoic successions in deep-water slope facies of the South China Block contain 2-3 glacial intervals and multiple datable horizons. Initial analysis has yielded several preliminary radiometric dates (Yin et al., 2003; Zhou et al., 2004), but a more systematic investigation of these datable horizons using high-precision geochronologic techniques will pave the way for Cryogenian correlation and help to establish a global stratotype section and point for the Cryogenian Period. The Bowring lab at MIT is a world leader in high-precision geochronometry, has already been engaged in collaborative projects with Chinese colleagues (Drs. Yugan Jin and Maoyan Zhu of Chinese Academy of Sciences), and is positioned to play a key role in unraveling the Cryogenian geochronometry of South China.

High-resolution biostratigraphy, sedimentology, chemostratigraphy, and geochronometry of the Ediacaran System: Since the official ratification of the Ediacaran Period (the first new geologic period in over a century), the next task is establishing the subdivisions of this system and identifying criteria for the global correlation. A number of lithological criteria, including glacial deposits and bolide impact ejecta layers, may be useful, but the most valuable chronostratigraphic markers are probably such fossils as acritarchs, Ediacara macrofossils, and biomineralized tubular fossils. All these fossils are found in the Doushantuo and Dengying Formations occur in the Yangtze Gorges area of South China, providing a rare opportunity to establish the sequence of fossil occurrences. The Xiao lab at Virginia Tech has established long-term collaboration relationship with colleagues from the Chinese Academy of Sciences (Drs. Xunlai Yuan and Chuanming Zhou) and Chinese Academy of Geological Sciences (Dr. Chongyu Yin). Plans have been charted to carry out a high-resolution, bed-by-bed sampling of acritarch fossils and detailed microfacies analysis of the Doushantuo and Dengying formations in the Yangtze Gorges area. Ganqing Jiang at University of Nevada at Las Vegas has accumulated a large number of carbon isotope data and Xuelei Chu of Chinese Academy of Sciences has published a first-order trace sulfate isotope curve of the Doushantuo and Dengying formations. However, high-resolution C, S, Sr, and Fe isotope analyses have not been attempted. These potential geochemical tracers, when integrated with geochronometric, sedimentological, and biostratigraphic data, will provide important constraints on the redox condition of the Ediacaran ocean.

Organic biogeochemistry of Ediacaran and Cambrian successions: Molecular fossils have become an indispensable tool to understand the evolution, ecology, and biogeochemical impact of the ancient biosphere (Briggs, 1999; Brocks et al., 1999; Summons et al., 1999; Briggs et al., 2000; Brocks et al., 2005; Grice et al., 2005). The Summons lab at MIT and Briggs lab at Yale are specialized in the analysis of ancient biomolecules produced by microbes, animals, and plants. Recent biomarker analysis of Neoproterozoic successions (Logan et al., 1995; Olcott et al., 2005) points to a promising future of biomarker study of the Chinese Ediacaran and Cambrian successions, which offers a unique opportunity to tie the biomarker evidence to paleontological and geochronological data.

Paleoecology, biocomplexity, biogeochemistry, taphonomy, and diversity research on the Cambrian radiation: South China has excellent paleontological resources in its Cambrian successions. Well-known examples include Early Cambrian small shelly microfossils, Early Cambrian animal embryos, the Early Cambrian Chengjiang biota, and the Middle Cambrian Kaili biota. Previous study of these fossils has focused primarily on the phylogenetic interpretation of individual taxa. Little attention has been paid to the ecological interactions, biogeochemical impacts, preservation mechanisms, and macroevolutionary patterns of these fossils. The Briggs lab at Yale and Erwin lab at NMNH have abundant experience investigating Cambrian Lagerstätten and macroevolutionary patterns. Collaborative work with their Chinese colleagues (e.g., Maoyan Zhu and Yue Wang of Chinese Academy of Sciences, Xingliang Zhang at Northwest University) to assemble a comprehensive database of Cambrian fossils of South China will be an important contribution to the Paleobiology Database Project. More importantly, integrating this data with that from North America (e.g., Burgess Shale, Spence Wheeler, and Marjum Formations), will allow us to address issues of the taphonomic bias of small shelly fossil and Burgess Shale-type preservation, to reconstruct the paleoecological interactions in the Cambrian marine ecosystem, and ultimately to understand the evolutionary patterns and processes behind the Cambrian radiation.

Challenges and prospects:
To take full advantage of the collaborative opportunities, we have to overcome a number of funding and infrastructure challenges. We believe that the following strategies will greatly further the collaboration between American and Chinese geoscientists working on the Neoproterozoic and Cambrians Earth systems.

1. Development of interdisciplinary teams: The scientific questions outlined above are interdisciplinary in nature, and their solutions require truly interdisciplinary collaboration. The confidence and trust required for interdisciplinary collaboration has already been consolidated through decades of collaboration between Chinese and American Neoproterozoic-Cambrian workers. What is lacking is a funding mechanism that allows this long-established cooperation to generate scientific results. A NSF-supported interdisciplinary collaborative team is particularly appropriate at present, because our Chinese colleagues are currently enjoying an enviable funding climate, which means NSF-funded collaboration will be cost-effective.

2. To drill several cores that penetrate the Neoproterozoic-Cambrian successions in South China: Several potential research opportunities identified above, particularly biomarker analysis, require core sampling to avoid possible modern contamination. Complete core recovery is also critical for continuous micropaleontological and chemostratigraphic sampling as well as the discovery of thin ash-layers. Two key areas for core drilling are the Yangtze Gorges area (Ediacaran successions) and eastern Yunnan Province (for Cambrian successions).

3. To assemble databases of Chinese Neoproterozoic-Cambrian fossils and geochemical data: This is a key to integrate the paleontological data and to calibrate geochronometric data. The infrastructure for such databases is available (e.g., Paleobiology Database Project, GeoTimes, GeoChronos?? Is this different from CHRONOS?), and both the Chinese and American geological communities are committed to partnership in assembling such databases. We believe that such databases will benefit to the broader geological community.

4. To enhance the exchange of students and to train the next generation of Neoproterozoic-Cambrian geobiologists: Neoproterozoic-Cambrian geobiologists of the next generation will have to be interdisciplinary thinkers who can communicate in sedimentological, paleontological, biological, and geochemical languages. The geochemistry labs at MIT and the Nanjing Institute of Geology and Paleontology have had a number of cross-disciplinary exchanges of students and post-doctoral researchers.

This forges long-term collaborative relationships and allows mutual access to paleontological resources and research facilities. In this respect, it is encouraging that the Nanjing Institute of Geology and Paleontology has been advised by its international advisory committee to host international students and post-doctoral fellows, in paleontology and other interdisciplinary fields. US universities, including Yale, are willing to host Chinese scientists on similar programs, given appropriate funding.

Critical Transition II:
Permian-Triassic Extinction and Recovery

Contributions: Shuzhong Shen (Coordinator), Douglas H. Erwin, Samuel A. Bowring, Yugan Jin and Jinnan Tong

Synopsis: Chinese and US geoscientists have had a long-standing cooperative relationship aimed at understanding the P-T critical transition. Over the past decade, the United States has been the principal partner in China's quest to develop a few collaboration programs. Those include the end-Permian mass extinction (Jin et al., 2000; Erwin et al., 2002), a high-resolution conodont biostratigraphy of the Permian System in South China (Wardlaw and Mei, 1998; Mei et al., 1998a, b; Mei and Henderson, 2001; Mei et al., 2002a, b, 2004; Wang et al., 2004), the Lopingian-base and Changhsingian-base GSSPs (Jin et al., in press a, b), a series of radiometric dates across the Permian-Triassic boundary at the Meishan, Heshan and Tieqiao sections in South China (Bowring et al., 1998), high-resolution carbon isotope geochemistry, biomarkers and their paleoenvironmental interpretation at the Meishan sections (Cao et al., 1998, 2002; Grice et al., 2005). The main collaborators in the US include Doug Erwin (Smithsonian Institution), Sam Bowring and Roger Summons (MIT), Bruce Wardlaw (USGS), Frank Kyte (Univ. California) and others, and the Late Paleozoic Research Group in Nanjing Institute of Geology and Palaeontology in Nanjing and Yin Hongfu and Tong Jinnan at China University of Geosciences. In 2004, two wells were drilled at a quarry about 550 m from the P-T GSSP section in Changxing, Zhejiang Province, SE China. A total thickness about 340 m was collected. In addition, the Late Paleozoic Research Group in Nanjing has headed an intensive effort to obtain large quantities of very fresh samples by blasting fresh quarry faces at Meishan. These samples are curated in Nanjing.

On October 9th and 10th, 2004, an international workshop on the Meishan-cores Project was held in Nanjing Institute of Geology and Palaeontology (NIGPAS). Participants include Luann Becker (UC Santa Barbara), Samuel A. Bowring, Douglas Erwin, Charles Henderson (University of Calgary, Calgary), Frank Kyte, Richard Lane (NSF, USA), Roger Summons (MIT), Yao Yupeng (NSF China), Shang Qinghua (IVPP, CAS), Jin Yugan, Shen Shuzhong, Wang Yue, Cao Changqun, Wang Xiangdong, Liu Lujun, Wang Jun, Wang Wei, and Yang Qun from NIGPAS. A consensus between the Chinese and US geoscientists has emerged that it is time that the relationship evolves more deeply.

Opportunities: Many questions about the patterns of extinction and survival during the Permo-Triassic mass extinction remain unanswered, and we are only beginning to understand the earlier mass extinction at the end of the Middle Permian. Through a discussion over the past year, studies on the following aspects are suggested:

*1) Timing of PT events***:** The Meishan Permian-Triassic sections contain volcanic ash and carbonized tuff at over twenty different levels. U-Pb zircon geochronology of the ash-beds from Meishan and other sections has resulted in a number of published dates. The difficulty in obtaining precise ages from these volcanic horizons has made Meishan a crucible for technique development and interlaboratory comparisons. At present, the best estimate for the age of the boundary at Meishan and Shangsi is around 252 Ma although more work remains. Using the latest techniques it should be possible to determine the age of ashes to ±< 200,000 years and perhaps less than 100,000 years. This level of precision will allow the development of one of the most highly resolved records of a major extinction anywhere on the planet.

Eliminating interlaboratory bias is a major effort of the EARTHTIME initiative and with help from NASA and NSF Bowring has made zircons from two ash beds available to any lab in the world that would like to analyze them and compare results. Preliminary results from MIT and the University of Toronto (formerly the ROM) indicate excellent agreement. With new samples and improved interlaboraory calibration these differences can be resolved, providing a firm temporal framework for the PT extinction. Similar efforts are needed to establish the date and rate of the earlier, end-Guadalupian mass extinction.

2) A blind test for the suggested extraterrestrial event: Evidence for an extraterrestrial impact at the P/T boundary is controversial. Evidence cited for and against an impact trigger for the extinction include the analysis of iridium and other siderophile elements (Sun et al., 1984; Chai et al., 1986; Clark et al., 1986; Orth, 1989), the presence of fullerenes (Becker et al., 2001; Farley et al., 2001; Li et al., 2005), interpretations of anomalous sulfur isotope signatures (Kaiho et al., 2001; Basu et al., 2003) and the presence of micro-spherules (He, 1985) from the boundary clay. In order to determine whether there is credible geochemical evidence to support arguments of an asteroid impact or other extraterrestrial event, studies on Iridium, fullerenes and ^{3}He, platinum group elements, microspherules and other micro-objects, and sulfur, iron and osmium isotope must be undertaken.

3) The organic geochemistry evidence: Analyses of carbon isotopes (carbonate or/and organic) have been done by Zhou and Kyte (1988), Xu et al. (1993), Li (1998), Cao et al. (2002) and Nan and Liu (2004). A dramatic depletion of 6 ppm within Bed 27 was reported by Xu et al. (1993) but has not been subsequently reproduced (see Jin et al 2000). Further studies on the nature of organic molecules are being undertaken but the value of existing samples is limited by the highly weathered nature of surface outcrops. New sample obtained from drill cores are required for new studies.

4) An integrated succession for the Lopingian Series: As a consequence of intensive studies of various aspects of stratigraphy, Section D at Meishan, Changxing was ratified by IUGS as the GSSP for the Permian-Triassic boundary (Yin et al., 2001), and the Wuchiapingian-Changhsingian boundary (Jin et al., in press b). Establishment of the GSSPs for the top and bottom boundaries of the Changhsingian Stage gives us a unique opportunity to establish a unit stratotype for a stage. The core provides a precise and uniform stratigraphical succession to integrate the results from parallel investigations of paleontology, geochemistry and sedimentology, and thus might lead to better understanding the relation between various lines of evidence. In addition, the Lopingian-base GSSP has been settled at the Penglaitan section in Laibin, Guangxi Province. Thus, a unique opportunity to develop a Lopingian high-resolution biostratigraphical, geochemical and geochronological timescale emerged.

5) A comparative study between the Ediacaran-Cambrian and Permian-Triassic transitions. The association of large carbon-isotopic excursions, continental glaciation and stratigraphically anomalous carbonate precipitation during the late Neoproterozoic Era may provides a framework for interpreting the reprise of these conditions in the Late Permian (Knoll et al., 1996). A comparative study of the paleoenvironmental and paleoecological backgrounds of these two transitions may be particularly informative for interpreting the unusual states of ecosystems during these time intervals. In addition to the Meishan P-T Cores, Precambrian-Cambrian boundary sections are also well exposed and a core from the Kunming area, Yunnan Province is available. A new project for drillings across the Ediacaran-Cambrian boundary interval is planned. Radiometric dating of important bio- and geological events from the Precambrian-Cambrian transitional interval has been partly carried out between the US and Chinese geoscientists.

6) Co-evolution in P-T terrestrial and marine ecosystems. Modern tropical rainforests are a haven for millions of plants and animals. The terrestrial alluvial and transitional sea marsh-littoral Permian-Triassic boundary sequences in Southwest China record a rapid climatic drought and deforestation of the tropical *Gigantopteris* megaflora. However, it has been little known whether the extinction pattern of the terrestrial megaflora is synchronous with that of marine organisms or not and the P-T boundary in the terrestrial sequences is poorly defined until now. The eruption of the Emeishan basalt on the Kangdian Continent in the late Middle Permian may have triggered the formation of a large coal-bearing depositional system during the Late Permian along the eastern margin of this volcanic plateau and accommodation of terrestrial alluvial and transitional sea marsh-littoral deposits in their peripheral areas. Collaboration on the studies including geochemical, physical, and sedimentological and biostratigraphical aspects will be very important to unravel the end-Permian mass extinction in both the terrestrial and marine ecosystems.

Proposed Joint Projects On P-T Transition:

1) Paleontology: foraminifers, palynology, conodonts, ostrocods, radiolarians, calcareous algae and other microbes.

2) Sedimentology and mineralogy: Microfacies, diagenesis, mineralogy of tuff, ash clay and other special beds, and heavy minerals.
3) Paleobiology database sharing (PaleoStrata).
4) Paleomagnetic susceptibility, electric log, and depositional and astronomical cyclicity.
5) Isotope chemistry: Isotopic oxygen, carbon, strontium, sulfur etc.
6) Geochronology of different sections from Early Permian to Triassic.
7) Elemental geochemistry: Rare earth elements, Iridium and other trace elements
8) Organic geochemistry: Isotope carbon of organic matter and biomarkers.
9) Micro- and nano-sphaerules, Fullerene etc.
10) Comparison of extinction patterns and isotopic profiles among different facies from extremely shallow to deep water.
11) Comparison between P-T transition and Precambrian-Cambrian, and recent changes.
12) Early Triassic recovery models of delayed biotic rebound and environment.
13) Correlation between marine and terrestrial ecosystems.
14) End-Guadalupian mass extinction.

Critical Transition III: Origins of Modern Lineages and Rise of Modern Terrestrial Ecosystems and Biotas in Mesozoic

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Synopsis: Mesozoic fossil beds in China offer some of the best record of the origin of modern terrestrial biotas and their ecosystems. During the Jurassic and the Early Cretaceous, key events profoundly altered the history of the Earth's terrestrial biotas and major groups of terrestrial animals and plants first appeared. Modern amphibians were firmly established in the Early Jurassic (Jenkins and Walsh 1993; Shubin and Jenkins 1995) and major diapsid groups, such as crocodylomorphs and sphenodontians, became important faunal components by the Early Jurassic (Fraser and Sues 1994). By the Middle Jurassic, the first modern salamander lineages had appeared (Gao and Shubin 2001, 2003). In the Late Jurassic, birds had evolved from non-avian theropod dinosaurs; and the anatomically modern birds (Neornithes) diversified in the Cretaceous (Chiappe and Witmer 2003). All three modern mammalian clades (monotremes, marsupials, and placentals) had appeared by the late Early Cretaceous (Ji et al. 2002; Luo et al. 2001, 2002, 2003; Rich et al. 1999, 2005; Kielan-Jaworowska et al. 2004). The Early Cretaceous also saw the rise of angiosperm plants (Sun et al. 1998; 2001; 2002; Dilcher 2000) and the terrestrial invertebrates that co-evolved with the angiosperms (Ren 1998; Moreau et al. 2006). Today's terrestrial biotas and ecosystems are dominated by the major clades of organisms that arose in the Jurassic and Early Cretaceous.

In the last 10 years, our understanding of these crucial evolutionary events and their causes has improved greatly. Infusion of new discoveries from China has significantly influenced synthetic evolutionary analyses and reshaped paleobiological studies. The unprecedented pace of discoveries and rapid dissemination of research results in China in the last 10 years were greatly accelerated by fruitful collaborations of Chinese and US scientists. The most notable accomplishments in collaborative research on Mesozoic biotas include the following.

Accomplishments:
Discoveries of significant new fossil evidence from the crucial transitions of major vertebrate and plant clades. The exceptional fossils of the Cretaceous Jehol lagerstätte in Northeastern China greatly elucidated the earliest evolution of several major vertebrate and plant clades (Gee 2001): discoveries of a diverse feathered dinosaurs that corroborated the hypothesis that birds evolved from the non-avian theropods (Chen et al., 1998; Ji et al. 1998; Xu et al. 1999, 2000, 2003); discoveries of new plant fossils documenting the earliest evolution of angiosperm plants (Sun et al. 1998; 2002; Friis et al. 2003; Leng and Friis 2003); discoveries of basal eutherian (placental) and metatherian (marsupial) mammals with new data on ancestral morphology and the timing of the early evolution of major mammalian groups (Ji et al. 2002; Luo et al. 2003); discoveries of fossils with soft-tissue features from the Jehol lagerstätte and other sites, such as embryos of birds and pterosaurs (Zhou and Zhang 2004; Wang and Zhou 2004; Ji et al. 2004), feathers on the hindlimbs of non-avian theropods and basal birds (Xu et al., 2003; Xu and Zhang 2004; Zhang and Zhou 2004), dental replacement pattern in mammaliaforms (Luo et al. 2001, 2004), and fur in primitive mammaliaforms (Ji et al., 2006). The rare preservation of soft-tissue has led to new insights into the evolution of integument structures and related endothermic physiology of birds and

mammals, and their growth and development; the new fossils also shed light on the origins of the powered avian flight.

Integration of morphological and genomic datasets into large-scale evolutionary analyses of extant groups with Mesozoic fossil records. The vast improvement of the fossil record now makes it feasible to map the "deep time" divergences of the modern groups that are also being investigated by molecular evolutionists. With the rapid growth of DNA datasets of many extant plant and vertebrate groups, molecular studies have become an increasingly powerful tool for inferring ancient evolutionary history. Improved analytical methods, enlarged datasets, and better taxonomic sampling have all helped to improve molecular phylogenies of major plant and vertebrate groups and for estimating the timing of key evolutionary events (reviewed by Edwards et al. 2005 for birds; Bremer et al. 2004 for angiosperms; van Rheede et al. 2006 for all mammals; Moreau et al. 2006 for ants). Because studies of molecular evolution require calibration by independent geochronological and fossil evidence, there is a great research opportunity in developing independent and credible tests of hypotheses based on molecular data using the fossil record, and vice versa. This integrative approach, as demonstrated by a series of NSF-sponsored projects on "Assembling the Tree of Life" (current underway for theropods – birds, squamates, amphibians, green plants, and proposed for mammals), has made it feasible for US and Chinese scientists to resolve evolutionary patterns at a much deeper level but with more refined temporal calibration. The capacity to achieve much greater sampling of extant and fossil biodiversity and easy access to much larger and more informative datasets have painted a much richer picture of evolution than was conceivable just 10 years ago.

New insight into the earliest ecomorphological diversification of major groups. Patterns of the earliest ecomorphological diversification of modern animal and plant clades have been greatly improved by the new fossils discovered in the Mesozoic in the last 10 years. It is now possible to correlate the earliest diversification of pollinating flies with the earliest diversification of the flowering plants (Ren 1998; Labandeira 1998). The earliest-known angiosperms have turned out to be herbaceous and aquatic (Sun et al. 2002; Friis et al. 2002; Leng and Friis 2003), shedding light on the niche in which the earliest-known angiosperms diversified. Conflicting the traditional misconception that Mesozoic mammals were generalized and small terrestrial insectivores, recent discoveries revealed that some Mesozoic mammals developed diverse locomotory adaptations in climbing, burrow, and swimming, and diverse feeding adaptations, such as carnivory and piscivory by large-sized mammals (Hu et al., 2005; Ji et al. 2006) and highly specialized feeding on colonial insects (Luo and Wible, 2005).

Precise geochronology of Mesozoic biotic evolution. The fossiliferous Mesozoic formations of northeastern China are well dated using recently improved geochronologic methods. Sampling was extensive and the majority of the radiometric dates are in good agreement with the field stratigraphical sequence (notwithstanding disagreement in interpreting some local geological outcrops). In northeastern China and neighboring Japan, the terrestrial fossil assemblages can also be reliably correlated with the marine stratigraphic sequences (Matsuoka 2000; Sha et al. 2003). These have provided one of the best-dated terrestrial stratigraphical sequences for global calibration of faunal and floral evolution from the Jurassic to the Cretaceous (Swisher et al. 1999; 2003; Chang et al. 2004; Ji et al. 2004).

Opportunities:
Recent collaborations of Chinese and US scientists have made significant advances in understanding Mesozoic biotas and ecosystems, and have also opened further opportunities for paleobiological and geological studies, including joint field exploration:

(1) *Fieldwork*: Long-term and sustainable exploration of the major lagerstätten in the Mesozoic of China continues to hold out great promise for further discoveries. The collaborative fieldwork in Xinjiang (Xu et al. 2006) by George Washington University (GWU) with the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP) and in Northern China by the Carnegie Museum with Chinese Academy of Geological Sciences (CAGS) (Ji et al. 2006) should continue. Recent joint fieldwork by US and Chinese geologists and paleontologists have been highly successful and should be expanded. The funding required to sustain extensive field exploration will be a major challenge for both the research community, and for funding agencies.

(2) Integration of fossils in multi-disciplinary studies of evolutionary biology: Mesozoic fossils provide an independent test of molecular hypotheses on evolution of major clades of extant organisms. There is a great potential for better integration of new morphological data from newly discovered fossils from China into the global systematic databases, for combined genomic and morphological analyses of phylogeny and the timing estimates of key evolutionary events of modern plants (gnetales and angiosperms), major clades of insects and modern bird and mammal lineages. But projects of this magnitude require multi-institutional teams with diverse expertise, and will require longer time, stable funding and greater scope of collaboration than traditional projects by individual investigators.

Major transitional fossils of non-avian dinosaurs and basal birds discovered in the US and China have been incorporated into a series of systematics datasets shared by an international community of paleontologists and systematists, through the collaborative studies by Institute of Vertebrate Paleontology and Paleoanthropology (IVPP: Xu) and Chinese Academy of Geological Sciences (CAGS: Ji and Ji) with American institutions (Norell of AMNH and Clark of GWU), by IVPP (Z. -H. Zhou and F.-C. Zhang), CAGS (S.-N. Ji and Q. Ji) and the Los Angeles County Museum (Chiappe). The merger of these datasets in combined molecular and morphological systematic studies is now under way in the NSF-supported "Assembling the Tree Of Life" project on non-avian theropods and birds, squamates and amphibians.

Excellent Mesozoic fossil mammals discovered in China and the US have been integrated into the datasets for reconstructing mammalian phylogenies (Hu et al. 1997, 2005; Ji et al. 1999, 2002, 2006; Luo et al. 2001a, 2002, 2003; Luo and Wible 2005). The morphological datasets will be incorporated into the combined genomic and morphological approach to build a comprehensive mammalian family tree. This project is being developed by a multi-institutional team of US scientists, with participation from IVPP and CAGS colleagues.

The Mesozoic of northern China has produced abundant early salamander fossils (Gao and Shubin, 2003), currently under the study by Ke-qin Gao of Peking University and collaborators. Thanks to their superb preservation, some of these fossils can be assigned unambiguously to the modern salamander families. This presents the opportunity to integrate the earliest fossil records of major urodele lineages into the combined analysis of molecular and morphological datasets. This work has the potential to shed light on the evolutionary development and morphogenesis of vertebrates, as well as the paleobiogeographic pattern of all of salamander groups.

(3) Studies on Origins of Modern Terrestrial Ecosystems: China now has the best documented Early Cretaceous assemblages of insects and angiosperms (Ren 1998; Labandeira 1998), and produced the earliest evidence of the co-evolution of pollinating flies and angiosperms. There is also now an emergent consensus that some of the earliest-known angiosperm plants are herbaceous and aquatic. Newly discovered skeletal fossils of Middle Jurassic and Early Cretaceous mammals show that the stem clades of mammals developed major locomotory and dietary specializations for diverse niches. There is now evidence of dietary preferences and habitat diversity among Mesozoic bird groups (Zhang and Zhou 2004). These all indicate a much greater ecological diversification within the Mesozoic ecosystems than previously thought. Ecomorphological studies to infer the ecological parameters of mammalian and avian taxa are now become, as are studies of the ecological parameters for insects and plants. When these ecomorphological data are placed in the context of taphonomy and paleo-environment (as reviewed by Zhou et al. 2004), it will be feasible to trace the emergence of extant ecosystems.

Challenges and Prospects:

1) Improvement of funding for field exploration: Recent fossil discoveries in the Mesozoic of China and US have had a major impact on our understanding of the origin of major modern clades and modern ecosystems. The scientific success, driven by field exploration and discoveries, has not been supported by sufficient funding. The funding climate for paleontological fieldwork is less than ideal, even by comparison to other paleobiological research. While the National Geographic Society (Committee of Research and Exploration) has funded many projects for paleontological exploration, funding for US scientists by NSF and other sources for field projects has been very low. Support for fieldwork from the National Natural Science Foundation of China for Chinese scientists is better than NSF funding for US scientists, but it is also difficult for researchers to obtain NSF-China grants. To address these funding problems, the Mesozoic subcommittee in US-China Paleontology Workshop appeal to both NSF-US and NSF-China to make support of collaborative Mesozoic field projects a funding priority.

2) Need for studies in paleoecology and ecosystem evolution: Currently, studies of paleoecology and taphonomy have lagged behind the pace of descriptive studies of major fossil assemblages. Because the basic descriptive and taxonomic data from the major Mesozoic fossil assemblages are accumulating at a rapid pace, now is the time to utilize the newly available datasets for ecomorphological and paleoenvironmental studies (Zhou et al. 2004). A conspicuous void in the current scientific research on Chinese Mesozoic fossil assemblages is the lack of comprehensive and quantitative ecomorphological and paleoecological studies. The paleobiogeographic studies are also limited in geographic scope. The major fossil assemblages in the regional stratigraphical section have yet to be placed in the context of global climactic evolutionary events. To address this imbalance, US and Chinese scientists must jointly develop collaborative research on paleoecology and taphonomy of the major fossil assemblages in China and in the US, to achieve the understanding of ecosystem evolution and evolutionary biogeography at a global scale.

3) Inter-laboratory calibration for geochronology: There have been more than a dozen studies on radiometric dating published in recent years about the major Mesozoic fossiliferous horizons in Northern China, by separate laboratories or field teams. Different dating methods have yielded different dates of the same sites (Lo et al. 2000; Swisher et al. 2002). There is also disagreement about the geological relationship of the dated rocks and the fossil horizons at several important outcrops (He et al. 2004; Chen et al. 2004; Liu et al. 2005). Chinese and US research communities need to develop inter-laboratory calibrations, and achieve the consensus about the age of these field sites. On a global scale, there is a great need to calibrate the datings by different laboratories, as promoted by the EARTHTIME Initiative (www.earth-time.org). Inter-laboratory calibration and consensus on field geology of major sites will lead to a better temporal framework of the precision key events in the Mesozoic biotic evolution from both the North American and Chinese fossil records.

4) Involvement of more students and junior scientists in the international research: The integration of molecular datasets from extant groups of organisms and morphological datasets from extant and fossil taxa can easily involve junior scientists and students. Field exploration is also a good platform for training students We advocate that major collaborative teams of senior Chinese and US scientists should also include graduate students and postdoctoral researchers.

Critical Transition 4: Biotic Responses to Global Climate Changes during the Cenozoic

Contributors: K. Christopher Beard (Coordinator), Scott L. Wing, Paul Koch, Xi-Jun Ni, Meng Jin, Richard Potts, Hai Cheng, Gerilyn Soreghan

Synopsis: Increased collaboration between Chinese and American scientists has greatly advanced our understanding of how major perturbations of Earth's physical environment affect the geographic distribution and evolutionary history of terrestrial organisms and ecosystems (Dickens et al., 1997; Bowen et al., 2002; Beard, 2002). Important tectonic and climatic events are now recognized as having shaped the course of evolution, notably including the history of humans and other primates. Students of human evolution have long attributed the acquisition of bipedalism in our distant ancestors to increasing worldwide aridity and the spread of grasslands during the late Miocene. Now, it is becoming increasingly apparent that the initial dispersal of the earliest primates around the globe was mediated by a dramatic shift in global climate at the Paleocene-Eocene boundary, roughly 55 million years ago (Beard and Wang, 1995; Beard, 1998a; Beard and Dawson, 1999; Ni et al., 2004). Likewise, an episode of global warming during the early Pleistocene apparently facilitated the rapid expansion of hominids out of Africa and into northern China (Zhu et al., 2004).

Understanding the complex interactions among tectonic and climatic changes, on the one hand, and evolutionary responses among organisms and ecosystems, on the other, requires interdisciplinary cooperation among an international community of scientists. This type of cooperation is particularly important in advancing our knowledge of the Chinese fossil record, because of its exceptionally high quality and the pivotal role of Asia in reconstructing early primate and human evolution. Perhaps the greatest advance in our knowledge of primate evolution during the 20th Century was the discovery, during the 1990s, that Asia was the cradle of numerous modern primate lineages, including the anthropoid or "higher" primates whose living members include monkeys, apes, and humans (Beard et al., 1994, 1996; Gebo et al., 2000; Beard and Wang, 2004; Rossie et al., 2006). Primates are particularly susceptible to climatic and environmental changes, because primates are among the most thermophilic of all living mammals, typically being restricted to tropical and subtropical habitats that are reasonably wet and forested. Within Asia, the uplift of the Tibetan Plateau during the Neogene profoundly affected regional climate and rainfall patterns, which in turn impacted Asian ecosystems and key organisms (Qi and Beard, 1998; Dawson et al., 2006).

Accomplishments:

Advances in our understanding of the critical role of Asia, and China in particular, in reconstructing primate and human evolution

Prior to 1994, the fossil record of Paleogene primate evolution in Asia was meager, largely restricted to a few fragmentary specimens from China, Mongolia, and Myanmar. This picture changed dramatically in the mid-1990s, as a result of collaborative research by paleontologists from the Institute of Vertebrate Paleontology & Paleoanthropology (IVPP, Chinese Academy of Sciences, Beijing) and the Carnegie Museum of Natural History (CMNH, Pittsburgh, USA). Investigations of middle Eocene fissure-fillings in southern Jiangsu Province produced the first evidence that China supported a taxonomically diverse primate fauna at this early date, including the world's oldest anthropoid and tarsiid primates (Beard et al., 1994; Gebo et al., 2000; Rossie et al., 2006). Subsequently, further collaboration by the same researchers in the Yuanqu Basin, a small graben in central China, amplified and extended these results (Beard et al., 1996; Beard, 1998b; Beard and Wang, 2004). These discoveries of middle Eocene primates in China hinted that even older fossils of primates and their close relatives would be found there. To date, this prediction has been partly borne out. The first Asian "archaic primates" or plesiadapiforms were discovered in early Eocene coal beds in Shandong Province (Beard and Wang, 1995). More recently, Ni et al. (2004) described the first undisputed early Eocene primate from Asia, a beautifully preserved skull from Hunan Province. Taken together, the new evidence bearing on Asian primate evolution unearthed over the course of the past decade improves the fossil record of Asian primates by at least an order of magnitude. The scientific community is only now beginning to appreciate the significance of this exciting addition to the Asian fossil record of primate and human evolution.

Assessing the role of Asia in the dramatic biological and geological events that transpired near the Paleocene-Eocene boundary

Paleontologists have known for more than a century that there was a dramatic modernization of mammalian faunas across the Paleocene-Eocene boundary (Rose, 1981; Gingerich, 1989; Beard and Dawson, 1999). In North America and Europe, the onset of the Eocene is marked by the synchronous first appearance of several taxa of modern mammals, including primates, artiodactyls (even-toed ungulates such as deer, cattle, pigs, and camels), and perissodactyls (odd-toed ungulates such as horses, tapirs, and rhinoceroses). Phylogenetic and biostratigraphic evidence suggest that most, if not all, of these mammalian taxa likely originated in Asia (Beard, 1998a; Beard and Dawson, 1999). In the early 1990s isotope geochemists noted that the Paleocene-Eocene boundary correlates with a dramatic shift in carbon isotopes, which has now been found in multiple stratigraphic sections around the globe (Kennett and Stott, 1991; Koch et al., 1992). This carbon isotope excursion was generated by a massive dissociation of oceanic methane hydrates, which caused a brief but intense episode of global warming at the Paleocene-Eocene boundary (Dickens et al., 1997). Ameliorating climate across the Paleocene-Eocene boundary would have facilitated intercontinental dispersal of modern mammals, including primates, across the high latitude Beringian land bridge connecting northeastern Asia and northwestern North America (Beard and Dawson, 1999).

Interdisciplinary studies on the Paleocene-Eocene boundary in Asia remain in their infancy. Meng et al. (1998) described a Paleocene hyaenodontid creodont and a possible Paleocene perissodactyl from the Bayan Ulan region of Inner Mongolia, thus corroborating the hypothesis that these mammalian taxa originated in Asia. Bowen et al. (2002) demonstrated that mammalian faunas in Hunan Province containing primates and perissodactyls are at least as old as the earliest Eocene faunas known from North America and Europe. Preliminary paleomagnetic results from Paleocene-Eocene strata in the Erlian Basin of Inner Mongolia promise to refine our understanding of biotic turnover in Asia near the Paleocene-Eocene boundary in the near future (Bowen et al., 2005). This subject, currently the focus of ongoing collaboration by Chinese and American scientists from IVPP, CMNH, and the American Museum of Natural History (New York, USA), offers outstanding potential for advancing our understanding of this critical transition in Earth history.

Integrating phylogenetic and biostratigraphic data into large-scale attempts to reconstruct paleobiogeography during the Cenozoic

Theoretical approaches to biogeography suggest that large landmasses should support greater biodiversity than smaller landmasses, and that such biologically diverse faunas and floras should dominate their more depauperate counterparts whenever they come into contact. The history of mammalian dispersal during the Cenozoic offers several excellent examples of this phenomenon. These include: (1) the “Grande Coupure” near the Eocene-Oligocene boundary in western Europe, when endemic European mammals were devastated by the immigration of new taxa from Asia; and (2) the “Great American Interchange” during the late Pliocene, when Laurasian mammals invaded South America across the newly formed isthmus of Panama, resulting in high levels of extinction among South American endemics. Beard (1998a) hypothesized that Asia has served as a potential cradle for higher-level mammal taxa throughout the Cenozoic. This model, the “East of Eden” biogeographic pattern, is consistent with an Asian origin for mammalian taxa that appear at the beginning of the Eocene (see above).

Recent work by American and Chinese paleontologists allows the East of Eden biogeographic pattern to be extended across a much broader temporal spectrum. For example, Meng Jin and his collaborators have shown that basal Glires (modern rodents and lagomorphs) are restricted to Asia during the early and middle Paleocene (Meng et al., 1994, 2005). Wallace and Wang (2004) have recently documented the surprising occurrence of a fossil relative of the lesser panda, an Asian endemic carnivore, in early Pliocene lacustrine strata in Tennessee, USA.

Understanding the effects of the Tibetan uplift on Asian climates and Asian ecosystems

It is widely acknowledged that the uplift of the Tibetan Plateau exerted a profound effect on Asian climates and ecosystems. Much current research focuses on constraining the timing of this uplift, and how this tectonic event impacted regional climate and ecosystems (An et al., 2001; Wang et al., 2006).

Opportunities:

Despite the notable advances made by collaborating teams of Chinese and American scientists in recent years, significant research opportunities present themselves.

1) Fieldwork: Many of the most exciting interdisciplinary endeavors that lie within the realm of this "critical transition" can only be achieved through joint field expeditions, ideally conducted by Chinese and American scientists working together. This is certainly the case with respect to learning more about the fossil record of early primate evolution in Asia, where ongoing collaboration between scientists from the IVPP (Wang Yuanqing and Ni Xijun) and their American counterparts at the Carnegie Museum of Natural History (K. Christopher Beard) and the American Museum of Natural History (Meng Jin) is virtually guaranteed to yield outstanding results in the near future. This collaborative project currently focuses on Paleocene-Eocene strata in the Erlian Basin of Inner Mongolia, where the first fossil primates from that region have only recently been unearthed. Similar collaborative efforts between Rick Potts (National Museum of Natural History) and his Chinese colleagues will further illuminate early human evolution in China.

2*) Interdisciplinary approaches to critical transitions in Earth history, especially the Paleocene-Eocene boundary*: Only through collaboration among paleomagnetic stratigraphers, sedimentologists, isotope geochemists, vertebrate paleontologists, and paleobotanists will we be able to fully understand the complex interactions among geological and biological aspects of "critical transitions" such as the one that occurred across the Paleocene-Eocene boundary. Chinese and American teams have already been assembled to address this problem, and their research should be fully funded as a result. American members include Paul Koch (University of California at Santa Cruz), Gabriel Bowen (University of Utah), Will Clyde (University of New Hampshire), K. Christopher Beard (Carnegie Museum of Natural History), and Meng Jin (American Museum of Natural History). Chinese members include Wang Yuanqing, Li Chuankui, and Ni Xijun (IVPP).

3) *The paleobiological ramifications of Tibetan uplift*: Ongoing collaboration between Chinese and American geologists and paleontologists promises to shed a great deal of additional light on this important topic. Leading researchers in this area include Wang Xiaoming (Los Angeles County Museum of Natural History), Qiu Zhuding and Deng Tao (IVPP), Brian Horton (UCLA).

Challenges and Prospects:

1) Improvement in funding for field exploration: Most of the recent progress that has been made in elucidating interactions among tectonics, climate change, and biological evolution has resulted directly from fieldwork. Many of the most important advances have been made by collaborative teams of Chinese and American scientists, working together. However, the present funding climate, especially at US NSF, significantly constrains the scope of fieldwork that can be undertaken. Participants of the Cenozoic subcommittee of the US-China Paleontology Workshop suggest that both NSF-US and NSF-China should increase funding for basic fieldwork aimed at illuminating interactions between the physical environment and biological evolution during the Cenozoic.

2) Targeted support for interdisciplinary approaches to "critical transitions": Scientific advances on "critical transitions" such as the Paleocene-Eocene boundary hinge on creation and sustenance of international teams of scientists with multiple areas of expertise. Once these teams are established, maintaining them through longstanding financial support is critical. A great deal of cross-fertilization of interdisciplinary projects can occur, but such consortia are inherently unstable due to their interdisciplinary nature and international group composition. To address this problem, US NSF and NSF-China should consider launching a new program specifically aimed at providing long-term funding for interdisciplinary research by consortia of Chinese and American scientists. Given its multifaceted nature, the Paleocene-Eocene boundary would be an excellent target for such a program.

3) Involvement of more students and junior scientists in international research: Enhanced collaboration between Chinese and American scientists can best be addressed by involving students from both sides in interdisciplinary research as part of their graduate training. Long-term relationships between Chinese and American scientists can thus be established at an early career stage, building an excellent platform for even deeper collaboration in the future.

Critical Area 5:
Promotion of China-US collaboration in research on critical transitions: the role of databases, cyberinfrastructure, and web-hosted analytical tools

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Research on critical transitions must, of necessity, be highly collaborative. Proposed working groups will synergize data from multiple disciplines, including paleobiology, geochemistry, stratigraphy, and geochronology. In this respect, centrally-available databases, and the cyberinfrastructure that links them together, must play central roles.

Databases provide dynamic, web-hosted tools for data entry, download, visualization, and quantitative analyses. By their very nature, these tools will help to spur collaborative research, permitting researchers to evaluate their data in novel ways that they might never have considered previously. Furthermore, with the establishment of a workable cyberinfrastructure, the data produced by working groups will ultimately become available to the broader research community, where they are likely to be of value for purposes that far transcend the objectives of the core research on critical transitions. For all these reasons, we believe that a joint Chinese-American effort to establish an infrastructure for the collection and analysis of data should be an essential element of any effort to conduct multidisciplinary research on critical transitions.

In the investigation of critical transitions, two themes have become clear: 1) data collected at localities in China have proven essential to the emerging understanding of several important intervals in the history of life; 2) the dissection of the physical and biological changes that mark any critical transition requires a careful piecing together of data from around the world, with particular attention devoted to understanding, at high resolution, the relative timing of important events in different parts of the world (e.g., see Beard 2002 for a perspective on the Paleocene/Eocene transition). Therefore, a workable cyberinfrastructure should enable both the synthesis and analysis of the global-scale data required for this research to be successful. With this in mind, a successful collaboration between Chinese and US scientists in the development of this cyberinfrastructure should be viewed as a first step in establishing a fully global-scale linkage among databases The proposed collaboration could therefore serve as an important exemplar to scientists worldwide who are interested in developing a truly global infrastructure.

Against this backdrop, we recommend the establishment of a working group consisting of Chinese and American scientists with expertise in the large-scale assembly and analysis of paleobiological data whose main goals would be to establish the groundwork for a workable joint cyberinfrastructure, and to secure the participation of a large array of scientists in both countries. From a practical standpoint, there are several issues that the working group will have to confront:

1) *Researchers focused on particular topics or regions are understandably reluctant to share data openly with a broader community of researchers, many of whom will not be known to them.* While this was once a problem in the development of web-hosted databases such as *The Paleobiology Database*, it has become less of a problem as researchers have come to recognize that there are many advantages to participating in database projects, including the availability of sophisticated, intuitive means for data storage, retrieval, and analysis. Nevertheless, when considering the development of cooperative ventures among researchers from different countries whose participants have had little previous contact with one another, this reluctance is likely to persist. Therefore, we suggest that, once a workable infrastructure is developed, data should be

housed separately in the two host countries, on cyber-platforms that would be virtually identical. These data should, however, be retrievable seamlessly by researchers interested in analyzing data housed in either or both countries. From an operational standpoint, it should make little difference where in cyberspace the data actually reside.

2) *Choices must be made concerning what kinds of data to assemble, as well as the platforms through which to house and analyze them.* Given the progress of the past decade in database and cyberinfrastructure development in the geosciences, several successful models are available in both countries, all of which contain unique elements that should be of value in designing a workable infrastructure. These include, but are not limited to:

a) *The Paleobiology Database* (PBDB; http://paleodb.org/), an international, distributed databasing effort that seeks to cover every taxonomic group, geographic region, and time interval. The PBDB incorporates a variety of data types, including taxonomy, geological and lithological contexts of fossil collections, and taxonomic lists. Participants directly enter and analyze their data using web-based tools. Thus far, the PBDB has helped to spur more than 40 official publications, many of which focus on the dissection and analysis of diversification in the context of paleogeographic and paleoenvironmental variables (e.g., Miller and Connolly 2001, Patzkowsky and Holland 2003, Kiessling and Baron-Szabo 2004, Foote *in press*, Tomasovych, *in press*), something that was not possible with the previous generation of global-scale compendia (e.g., Sepkoski 2002).

b) The Palaeontological and Stratigraphic Database of China (http://www.paleontology.csdb.cn/index.asp), an online compendium of data a about key stratigraphic intervals throughout China. A variety of information is available at the website, including stratigraphic columns for key intervals. Notably, the site is copiously illustrated and provides an array of primary information, including taxonomic occurrences, for localities included in the database.

c) The Miocene Mammal Mapping Project (MIOMAP; http://www.ucmp.berkeley.edu/miomap/), which integrates a Geographic Information System (GIS) with a detailed relational database of late Oligocene through Miocene mammal occurrences to provide comprehensive spatial and temporal analysis of paleomammalian taxa, localities, and associated data for the western United States. The database includes all published mammalian fossil localities 30 and 5 million years old from the western United States and incorporates geographic, taxonomic, stratigraphic, and paleoenvironmental information for each taxonomic occurrence. Several publications have now resulted from the use of MIOMAP (e.g., Barnosky and Carrasco 2002, Davis 2005, and Barnosky et al. 2005).

e) The Digital Morphology Library (DIGIMORPH;http://digimorph.org/index.phtml), a dynamic archive of images and information on morphology, based on high-resolution X-ray computed tomography of biological and paleobiological specimens. The library and methods used for the imaging of specimens are providing unprecedented looks a morphological information beneath specimen surfaces that had previously been unavailable to paleontologists. In several cases, this has resulted in reconsideration and reinterpretation of the phylogenetic and functional attributes of imaged taxa (e.g., Rowe et al. 2005, Clarke et al. 2005, Rossie 2006, Maisano et al. 2006).

f) CHRONOS (http://www.chronos.org/) , a team of geoscientists and IT specialists working to develop a cyberinfrastructure that aims to seamlessly link together a global federation of Earth history databases, tools, and services, including the aforementioned databases. Importantly, CHRONOS seeks to make available to researchers cutting-edge tools for the analysis of paleontological and other data in a stratigraphic/temporal context, such as Peter Sadler's CONOP9 correlation tool (http://portal.chronos.org/gridsphere/gridsphere?cid=lbl_cnp9) . CONOP9 and related, computer-assisted correlation techniques are transforming the way in which events are correlated across regions, as well as the way in which timescales and diversity curves are constructed, through the development of "interval-free" interpretations of event sequences (see Sadler and Cooper 2003, Sadler et al. 2003, Sadler 2004). These methods should be particularly useful in piecing coming to grips with the relative timing of important events in different regions during critical intervals.

3) *A truly seamless means of communication must be developed among existing database structures and analytical processes.* This is a central goal of CHRONOS, which has made considerable progress in this area, but there is still have a long way to go. In this respect, the proposed development of a Chinese-US cyberinfrastructure will require an unprecedented level of direct discussion and collaboration among participants representing different databases, several of which provide unique tools for the assembly and analysis of data that are important to research on critical transitions. Based on our discussions at the NSF-sponsored November 2005 workshop in Washington DC, we are optimistic that this level of cooperation is feasible. In addition, the possible use of the Global Ring Network for Advanced Applications Development (GLORIAD) should be explored, since it appears to be highly appropriate for the goals of the proposed initiative.

4) *The educational value of this effort should be recognized from the outset, and steps should be taken to provide opportunities for students to take advantage of the unique opportunities that will be available through the development of international, interdisciplinary partnerships.* It would be particularly appropriate to seek funding from NSF's Integrative Graduate Education and Research Traineeship (IGERT)

program for this purpose. In addition, as several of the projects highlighted earlier have discovered, there will be significant opportunities to engage the public in the activities and products of this partnership, and plans to do so should be part of the initial discussions of the working group.

5) *The activities proposed here will be costly, particularly at a time of retrenchment on at some potential funding agencies.* That said, the diversity of activities that would be conducted under the umbrella of this initiative would provide opportunities from an equally diverse set of funding opportunities. An important part of the initial deliberations of the working group would be the development of a plan to secure funding from these sources, and we would urge that funding be procured from a consortium of sources, thereby lessening the danger of the project being undercut in the future if some of the funding sources are no longer viable.

In summary, as research on critical transitions moves forward, we believe that cooperative efforts aimed at the construction of appropriate databases and cyberinfrastructure should play central roles. In this respect, the timing of this initiative is fortunate, given the successful development in the past decade of multifaceted approaches to the web-hosted assembly and analysis of paleontological data. These provide models and tools that, if carefully extended into this new venture, significantly enhance its chances for success.

Summary of Recommendations

(These are just some quick ideas from Luo, and please change anyway you like in any case it needs to be refined)

The following general recommendations and suggestions from the US-China workshops in paleontology will be broadly applicable to all research on the critical transitions in the history of life, therefore necessitate the priority for funding from the National Science Foundation (USA) and the National Natural Science Foundation of China:

(1) There is still an enormous potential in the exploration and discovery-driven field research for future discoveries and breakthroughs, especially in China. Promotion and support for joint field exploration and research will be indispensable for sustaining current successes in the US-China collaboration in paleontology.
(2) A key strategy to synergize the complementary strengths of China and the US is to promote the timely integration of the new fossil and fresh stratigraphic data into large-scale databases developed by the international communities of scientists for paleobiological research and for combined molecular and morphological databases for studying phylogeny.
(3) High-precision geochronology and detailed stratigraphic work is the key to integrated and multidisciplinary studies of the critical transition in history of life,

especially the ecological response of organisms to the associated environmental changes. The EARTHTIME Initiative and inter-laboratory calibration of datings are of primary importance for placing the biotic extinction and recovery in the context of global environmental change.

(4) Development of an effective cyberinfrastructure will be a critical first step in establishing a fully global-scale linkage among databases of the US and China for paleobiological research. Such a cyberinfrastructure is required for web-hosted assembly and analysis of paleontological, stratigraphic, and geochronological databases that are the foundation of successful research on critical transitions.

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