Sedimentary Geology and the Future of Paleoclimate Studies

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ABSTRACT

Recent community efforts have highlighted the importance of deep-time paleoclimatology to the understanding of Earth processes as a way of expanding our understanding of the vast range of states possible in the Earth System. Advances in our collective understanding of these "alternative-Earth" states shed light on forcings and feedbacks of the climate system, as well as responses of the biosphere, ultimately bringing more rigor and predictability to the study of current and future global change. Sedimentary geology and paleontology are squarely in the middle of these efforts. Geoscientists from both subdisciplines have posed the major questions that must be answered and have implemented an action plan to answer those questions. Furthermore, increasing resolution of time and parameters (climatic and biotic) enabled by technological advances are bringing new rigor to paleoclimate studies, extending our collective reach to strata dating to ever-deeper reaches of geologic time. New advances will require, increasingly, the actions and coordination of large multidisciplinary teams galvanized around critical science questions, and armed with the latest proxies and geochronologic tools.

INTRODUCTION

In the March issue of The Sedimentary Record, Montañez and Isaacson (2013) outlined recent developments in which the sedimentary geology and paleontology communities have "loudly and clearly through various venues articulated a research agenda for the future" (Montañez and Isaacson, 2013, p. 8). These venues include NRC reports (National Research Council, 2011, 2012); a new, community-driven initiative, TRANSITIONS (Parrish et al., 2012); and a new NSF funding initiative, Earth-Life Transitions (NSF Program 12-608), which was based on TRANSITIONS and on recommendations in the National Research Council (2012) report that examined research opportunities in the Earth sciences. In this article, we would like to focus on the community's research agenda for paleoclimate studies, and give a glimpse into the critical role of this research.

CHALLENGES AND QUESTIONS

The TRANSITIONS team (Parrish et al., 2012) reviewed more than 10 years of white papers and initiatives, which collectively illustrate that all parts of our very large and diverse community are and have been for many years united around a singular intellectual challenge: "Understanding the full range of Earth-life process behaviors through all of Earth history, including deep time, is vital for addressing urgent societal issues, and these processes must be addressed in a systematic and interdisciplinary fashion" (Parrish et al., 2012). The importance of paleoclimate studies is demonstrated by the four overarching questions identified in TRANSITIONS that must be answered in order to meet this challenge:

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

Deep time (before 2 Ma) records contain information about climate that must be understood in order to confidently model and predict future climates. The TRANSITIONS initiative specifically delineated **deep-time climate** as one of the key directions this research will take; others include landscapes, and biology and environments. Specifically with respect to the deep-time research direction, TRANSITIONS emphasized the following questions:

1. What is the full range of potential climate states and transitions on Earth?
2. What are the thresholds and feedbacks in Earth's climate system?
3. What is the biotic response and resilience to changes in climate states?

Answering these questions falls directly under the purview of sedimentary geology and paleontology communities. The deep-time sedimentary record is the repository of nearly all evidence of climate and environmental change, including, for example, previous abrupt climate-

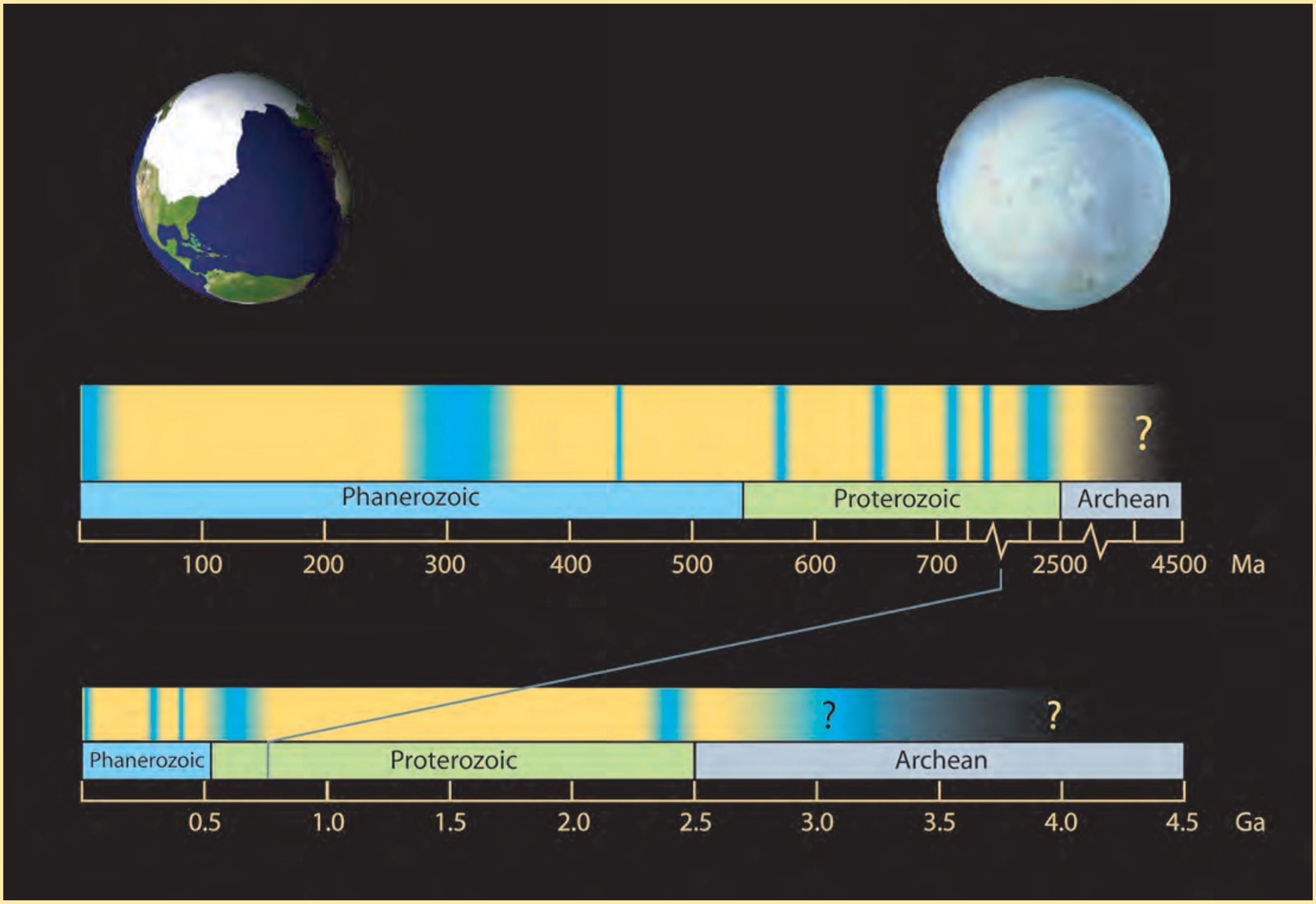

Figure 1: Schematic representation of icehouse-greenhouse intervals through Earth history. Lower bar illustrates all of Earth history, whereas upper bar focuses primarily on the Phanerozoic-Neoproterozoic. Icehouse times are inferred from published records of well-accepted glacial deposits recording the former presence of land-based ice sheets. Thus, greenhouse times are inferred on negative evidence of such deposits. The globes illustrate schematically the shift in icehouse modes--from the so-called "snowball" states of the Neoproterozoic (right) to reconstructed Last Glacial Maximum ice of the Pleistocene. Figure from G.S. Soreghan.

change events, changes in Earth's hydrological cycle, oscillatory states (Fig. 1), past ice-sheet controls and effects, and dramatically different sea level conditions that included flooded continental seaways. The current warming is changing Earth's climate state to one characterized by pCO_2 levels higher than any time since at least the Pliocene (~5 Ma; Seki et al., 2010), meaning that the current and future temperature regimes are ones that were last recorded in deep time (Figs. 2, 3). As atmospheric CO_2 concentrations increase, they reflect conditions on Earth further back in time. For example, as pointed out in TRANSITIONS (Parrish et al., 2012), the Intergovernmental Panel on Climate Change's A2 scenario (IPCC, 2007) projects CO_2 levels by 2100 that will be comparable to the Eocene, at least 35 million years ago. Even climate states beyond a doubling of CO_2 by 2100 may be possible, which will require examination of even deeper time to study analogous conditions and related impacts. This illustrates the need to understand the full range of climates that have occurred in deep time. We do not know what previous states may be duplicated in the future, so it behooves us to understand the full range of states experienced in the past. Even more importantly, should anthropogenic or natural climate changes push the Earth into a previously unrealized state, our ability to predict the consequences is enhanced by a fuller understanding of how climate has changed in the past and how the Earth has recovered from abrupt, extreme changes.

Evidence is strong in the geological record that the Earth rapidly transitioned between climate modalities, most notably in the Eocene-Oligocene greenhouse/icehouse transition (e.g., Jovane et al., 2009), and in the period leading up to the Paleocene-Eocene Thermal Maximum (PETM) and marking the transition into the Eocene Climatic Optimum (Zachos et al., 2008; McInerney and Wing, 2011; see Fig. 3). In both cases the change in CO_2 appears to have been slow relative to modern rates, but the response of the climate system appears to have been dramatically non-linear, abrupt, and unpredictable. For example, the rate of carbon emissions to the atmosphere today exceed by more than a factor of five that estimated (albeit over a much longer time) for the PETM (Kump, 2011), implying an urgent need to understand responses of Earth's climate system to such perturbations. Further concerns are that the transitions into prior greenhouse states involved substantial "overshoots" and consequent biotic effects. Warming linked to atmospheric carbon release during the PETM triggered significant biotic changes, for example, shifts in geographic range as well as some extinctions, and "recovery" of the atmosphere to pre-perturbation levels of

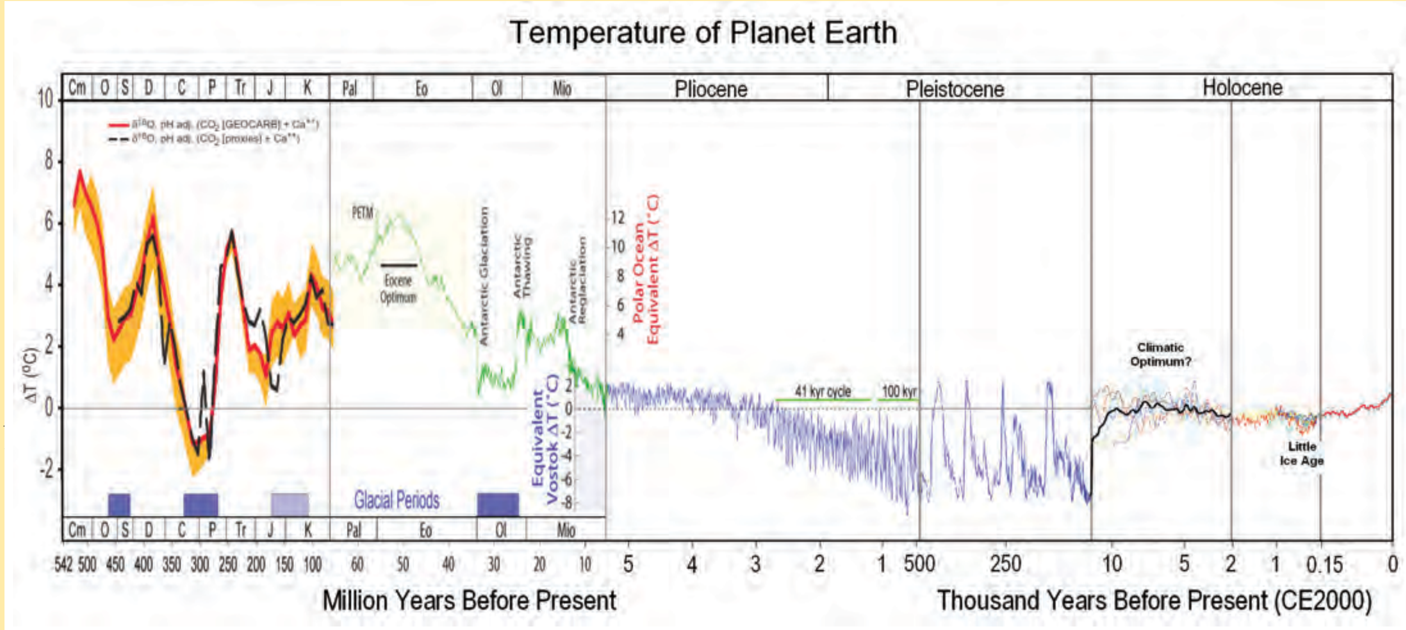

Figure 2: Schematic of paleotemperatures for the Phanerozoic. http://en.wikipedia.org/wiki/File:All_palaeotemps.png, accessed 21 May 2013. Compiled from multiple sources (information on website). As the methods used to determine temperature are not identical, the variations should be taken as relative and not absolute. However, the figure represents current thinking about relative temperature changes.

carbon required more than 80 ky (McInerney and Wing, 2011). Our current warming could require drastic lowering of pCO_2 to pre-industrial levels in order to restore our current icehouse climatic state (Hansen et al., 2008). The prospective unpredictability of these abrupt changes and possible hysteresis (lag in response followed by an abrupt shift to a new state) is the result of an incomplete understanding of thresholds and feedbacks. Deeper, more detailed study of abrupt events, occurrences of similar starting conditions that failed to lead to dramatic warming, and a thorough understanding of times of relative climate stability is required to be able to anticipate the response of climate to anthropogenic forcing. It is increasingly clear that, although pCO_2 is a primary control on temperature (Alley, 2011), how climate change plays out in the face of pCO_2 change is highly complex and non-linear, and the better we understand the complexities, the better prepared we will be as a society to address future changes.

Although atmospheric carbon emissions garner the bulk of attention, oceanic uptake of carbon poses increasing concerns owing to the resultant ocean acidification. Acidification is a well-verified consequence of rising atmospheric CO_2 (Fig. 4) and results in reduced pH and lower $CaCO_3$ saturation in surface waters (Doney et al., 2012); mean surface pH of the oceans since preindustrial times has dropped by ~0.1 units (The Royal Society, 2005). Ocean acidification has recently been proposed as directly linked to the end-Permian mass extinction (Hinojosa et al., 2012)-- yet another example of the past shedding light on potential futures.

Earth's archives contain untold numbers of climate states and transitions--a virtual laboratory book of completed experiments with results waiting to be tapped. Deciphering these results can shed light on potential geoengineering applications increasingly being considered as a means to control future warming (The Royal Society, 2009). Such schemes are fraught with ethical and political issues, and may ring of science fiction. Yet, scenarios such as ocean fertilization are already being seriously considered (Wallace et al., 2010), and even (illegally?) implemented (Service, 2012). Similarly debated are thoughts of reducing incoming shortwave radiation via injection of reflective particles into the atmosphere, mimicking volcano-induced cooling, but the risks remain largely unknown (Hegerl and Soloman, 2009). As society begins to grapple with the prospect of geoengineering our climate future, sedimentary geologists and paleobiologists can shed light on both causes and consequences of such tinkering, drawing upon Earth's past.

Finally, understanding biotic response to climate change is critical, not only to enhance our ability to anticipate the impact of anthropogenic warming on the biota but because of biotic feedbacks to climate itself. Some large, abrupt changes in climate appear to have had global, widespread impacts on biota, whereas other, apparently equally large and abrupt changes appear to have had much smaller impacts (Barnosky et al., 2012). Clearly, identifying the factors in these disparate responses is critical for informing our response to warming.

AN ACTION PLAN

The previous paragraphs highlight some "big" questions for deep-time paleoclimatology going forward. Inherent in this agenda is the ability to identify critical and revealing sedimentary sections and study them in great detail, taking advantage of new and evolving approaches to both geochronology (e.g., EARTHTIME, 2012), and to proxy development. These studies will require team-based, multi-disciplinary approaches, as called for in the new NSF program (12-608), "Earth-Life Transitions," involving, in each study, not only sedimentary geologists and/or paleontologists, but stratigraphers, geochronologists, modelers, geochemists, and so on, as appropriate, to fully unlock the climate information. Sedimentary geologists and paleobiologists have a long and

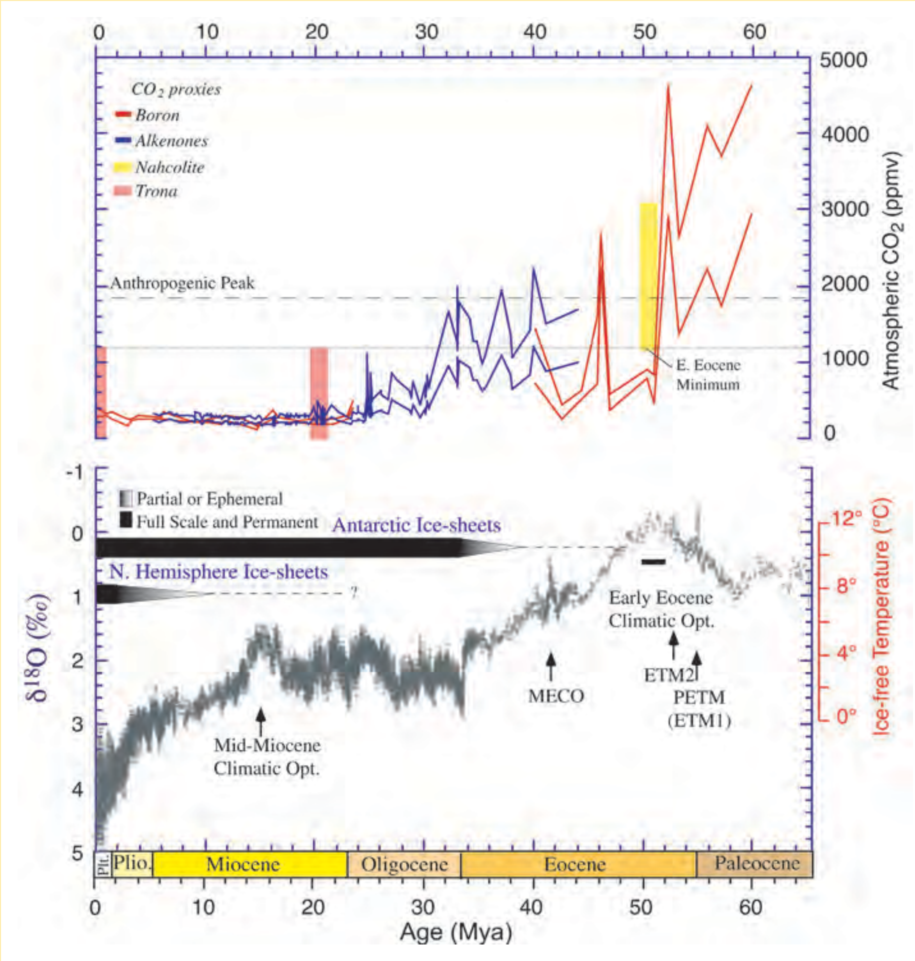

Figure 3: Record of changes in atmospheric pCO_2 and temperature during the Cenozoic (from Zachos et al, 2008). Top: CO_2 determined from marine and lacustrine proxy records. The dashed horizontal line indicates the maximum pCO_2 for the Neogene and minimum for the early Eocene. Bottom: $\delta^{18}O$ from foraminifera and interpreted ice-free ocean temperature; horizontal bars indicate development of polar ice sheets. For more information, see Zachos et al. (2008).

fruitful tradition in independent research that could be conducted by individuals armed with tools as simple as a hammer, compass, and Jacob's Staff. Perhaps our biggest challenge as the sedimentary geology community moves forward is to envision and embrace a much broader approach to our science, conducted in large teams, to address large questions. A full understanding of climate behavior requires simultaneous integration of all of our individual, detailed talents for clues to similarities and differences in climate behavior at different times and in different geographic settings. Doing so also requires careful coordination with climate modelers, and iterative integration of climate models with data. Only by integrating this information can we begin to understand true causes, effects, and feedbacks. Increasingly, the records we will need in order to conduct such integrated science will require drilling to obtain long, continuous, unweathered sections, on which to apply the new generation of climate proxy analyses. The near-time paleoclimate community has long embraced this approach (Cohen, 2011), to great success (e.g., Scholz et al., 2011; Melles et al., 2012), and such efforts are beginning to gain ground for deep-time studies (e.g., Clyde et al., 2012) .

Sedimentary geologists and paleontologists, together with low-temperature and isotope geochemists have led the way in the development of paleoclimate proxies so key to accumulating the high-resolution data sets needed to fully document changes in the rate of climate change and different climate states. Many examples of the new energy in the development and integration of paleoclimate proxies exist. For example, paleotemperature proxies can be combined with paleo-CO_2 proxies to better constrain CO_2-temperature sensitivity for projections of future climate change (Royer et al., 2007). Analysis of triple oxygen isotope compositions of sulfate from ancient evaporites enables assessment of pCO_2 in the Precambrian (Bao et al., 2008). We now have proxies for climate parameters that previously were resistant to quantification, including mean annual precipitation based on paleosol chemical composition (Sheldon et al., 2002; Nordt and Driese, 2010) and leaf 13C composition (Diefendorf et al., 2010). A variety of biomarker proxies, e.g. the tetraether index of lipids with 86 carbon atoms (TEX86), provide insights

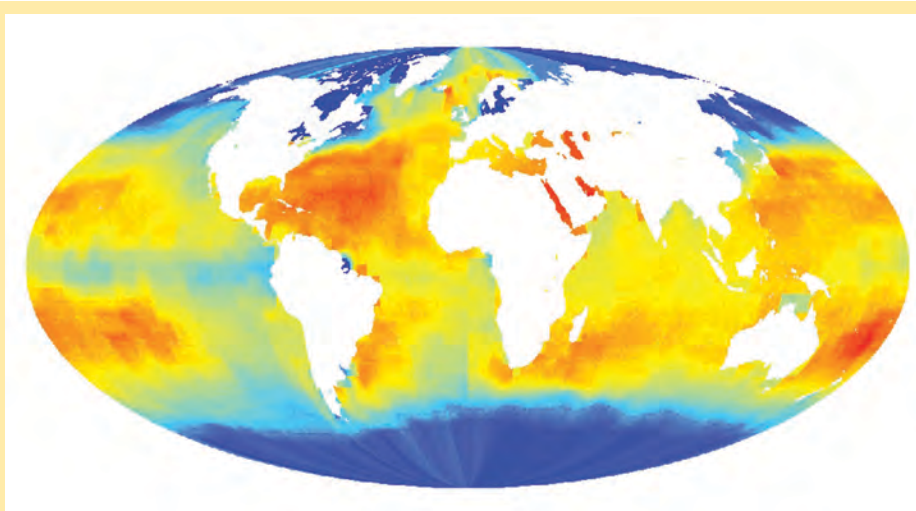

Figure 4: Acidification of the modern oceans. Acidification is at least partly attributable to increases in atmospheric CO_2, and it is likely that ocean acidification was a significant factor in deep time during times of high pCO_2 levels. From Halpern et al. (2008, supplement).

Figure 5: Graduate students (from the University of Oklahoma) conducting water and sediment sampling in Taylor Valley, Antarctica, to assess weathering signals in this extreme end-member climate. Some of these weathering signals might be preservable and thus useful for assessing climate signals in deep time. Antarctica's Matterhorn appears in the background. Photo by Lynn Soreghan.

into paleotemperature (Eglington and Eglington, 2008), and can extend to deep time (Mesozoic). Stable isotope geochemistry has provided insights to paleoceanography for half a century, but the field has now expanded to transition metals to track seawater chemistry and oxygenation, extending to the Precambrian (e.g., Anbar and Rouxel, 2007; Lyons et al., 2009; Pufajl and Hiatt, 2011). Refinements in instrumentation now enable rapid U-Pb analyses of even silt-sized detrital zircons, increasingly useful as a means to assess atmospheric circulation by tracking provenance of loess deposits (Soreghan et al., 2008; Xiao et al., 2012). Remarkably, evaporite fluid inclusions yield measurements of temperature down to the diurnal (paleoweather) scale (Zambito and Benison, 2013), and document extremes in Permian continental temperatures previously unimagined. Other climate parameters important for understanding climate change and feedbacks—including seasonal precipitation and temperature changes, weathering rates, cold-month mean temperatures, and evapotranspiration rates—remain more poorly constrained, but on-going research on various fronts strives to fill our knowledge gaps (Fig. 5). Nevertheless, the gap between capabilities of near-time and deep-time proxies is narrowing.

These proxies will also be the information against which new paleoclimate model results can be tested, leading in turn to refinement of climate models that can simulate the full range of climate states. The data sets may challenge current climate models and require substantial modification of them, and this is why it is so critical for sedimentary geologists and paleontologists to work with Earth-system modelers. The latest climate models, which have been used extensively to study climatic variability in the glacial-interglacial mode of the last million years, are of unknown applicability to the greenhouse or hothouse climate state that the Earth may be heading to--and clearly was in--at various times in the geologic past. Through Cenozoic and Mesozoic time, and perhaps throughout the entire Phanerozoic, the Earth was operating in a greenhouse state much more of the time than it was in an icehouse state. Therefore, to discover what controls the climatic behavior of the Earth when it is in a greenhouse state, and how those controls might differ from those associated with an icehouse state, we must examine and document the wide variety of environmental and ecosystem information archived in key sedimentary deposits of greenhouse periods—and this is work only the sedimentary geology and paleontology community can do. Similarly, we need to understand behavior of Earth's climate system during transitions between icehouse and greenhouse states, especially as Earth edges toward such a possible transition. Moreover, we need to push models to incorporate parameters that are currently ignored for deep-time modeling, and to do that, we must continue to produce new and refined paleoclimate proxies. Despite wide recognition of the importance of aerosols on Earth's radiative balance, these effects are typically ignored for deep time modeling (Heavens et al., 2012), even though geologic data exist to constrain aerosol loading (e.g., Sur et al., 2010).

LOOKING TO THE FUTURE

Sedimentary geology and paleontology are key disciplines in a push toward Earth-system modeling, including, perhaps human social and economic processes (Slingo et al., 2009). The ability to study the full range of Earth system behaviors, including those in deep time, will come about because of two developments: (1) vastly improved geochronology, permitting examination of Earth-surface processes on human or near-human time scales for all climate states reaching arguably to the last half-billion years (Parrish et al., 2012); and (2) the development and application of Earth-system models, which are outgrowths of climate models and include fully coupled ice, ocean, and vegetation models along with other land-surface and deep-ocean feedbacks. This work, much of which must be carried about by sedimentary geologists and paleontologists in collaboration with climate modelers, geochronologists, and others, will permit full integration of the climate processes revealed in studies of Quaternary climates with those revealed in deep-time climate studies, so that a continuous record of climate change and dynamics can be produced. Integrating the deep-time and Quaternary records has been, until now, at best imperfect owing to the 1) higher resolution of pre-Quaternary geologic records, 2) difficulties of acquiring quantitative proxy data in deep time, and 3) traditional approaches to sedimentary geology research, which have long thrived on successes of individual and small-group researchers in field-based studies. New developments, coupled with integration of Earth-system models with human-system (economics and social) models, could lead to a new paradigm in our understanding of humanity's place on Earth. In many respects, sedimentary geologists and paleontologists have always been on the forefront of such thinking because of our commitment to understanding the geology of resources (minerals, fossil fuels, water) not just as geological problems but as human problems as well. Thus, our community is well positioned to provide leadership in defining the new paradigm.

ACKNOWLEDGMENTS

We thank editors I. Montanez and P. Isaacson for inviting this review, and M. Elrick and an anonymous reviewer for constructive comments. Many thanks to N. A. Anbar, H. Brumsack, and N. Heavens for discussions. Funding for fieldwork shown in Fig. 1 was provided by NSF grant ANT-0842639, to Soreghan and collaborator Megan Elwood Madden.

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Accepted June 2013

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