

A 'Sedimentary Record' of Opportunities

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EDITORS' MISSION

Several recent National Academy of Sciences publications (NRC 2005, 2010a, 2010b, 2011, 2012) and a subsequent community driven initiative report (*Transitions* 2012) provide the earth surface scientific community a framework of high-priority research targets for the next decade or so. Many of the research opportunities identified by these reports were defined through the efforts of the SEPM community, coordinated by workshops and initiatives (e.g., GeoSystems, Paleopedology, DETELON, and EARTHTIME), to articulate the most enduring scientific issues and associated challenges for the future. As the scientific research agenda has evolved so have the disciplinary boundaries of the scientific community, which now includes geochronologists, geochemists, geomorphologists, ecologists, microbiologists, atmospheric scientists, oceanographers, soil scientists, mathematicians and computer scientists.

A singular intellectual challenge, echoed throughout the aforementioned publications, further unifies the broad array of interests and efforts of this diverse scientific community: A better understanding of how earth system processes respond, interact,

and evolve over a range of climate states and conditions is pivotal to informing society on critical future issues including climate change, energy and water resources, landscape evolution and management, and ecosystem health and conservation under dynamic environmental conditions (*Transitions* 2012). The importance of broad-based and cross-disciplinary collaborations involving observation-based scientists and numerical modelers is now fully recognized as a means of realizing the potential of the sedimentary archive of dynamic earth system processes.

As the new editors of the *Sedimentary Record*, we consider this publication forum as an opportunity to articulate the vision and recent discoveries behind this community momentum. We propose a series of articles over the next three years that highlight exciting research directions and that delineate the cultural and technological infrastructure that will be required to fully develop such opportunities and overcome their associated challenges. This article provides an introduction to the proposed journal series; your participation and feedback as to how the 'Sedimentary Record of opportunities' might evolve is strongly encouraged.

A COMMUNITY BASED RESEARCH AGENDA

The following discussion highlights just a few of the growing and emerging research opportunities identified by various community based activities and assimilated in the aforementioned publications. This discussion is not comprehensive and unquestionably fails to identify all of the exciting research directions in which members of the SEPM community are involved. Our goal is that this prospectus and the papers to follow will stimulate discussion about emerging research opportunities and help to coordinate the building research momentum shared by many SEPM members.

CO-EVOLUTION OF LIFE AND CLIMATE

Environmental and climate conditions on Earth may well be changing faster than any time in the past 4.6 billion years of the planet's history. Two decades of research into past warm worlds and turnovers in climate

state have revealed that even the most abrupt periods of global warming (e.g., the early Cenozoic hyperthermals) occurred at minimally two orders of magnitude slower rates than is predicted for our near future (Kump 2011). Many of these past warmings were brought on by release of greenhouse gases of magnitude comparable to, or possibly larger, than that anticipated if we burn through most of our fossil fuel resources, but with release rates minimally an order of magnitude slower than present-day (NRC 2011). Despite the apparent 'sluggish pace' of these abrupt events, they impacted conditions widely in the oceans and on land. In this context, it is increasingly becoming clear that we lack a true analogue for the 'Great Geophysical Experiment' (Revelle & Suess 1957) currently being carried out on Earth.

If atmospheric CO₂ concentration, currently at 398.5 ppmv (Feb. 2013), continues to increase at its current rate and with no increase in



Figure 1: An enigma in the Late Devonian. While several argue that late Paleozoic glaciation began in the latest Devonian (Isaacson et al., 2008), the presence of 10^4 to 10^5 ky stratigraphic cycles in older Devonian successions, such as seen here at Devils Gate, Nevada, suggest the initiation of glaciation and glacioeustasy much earlier in the Devonian (Sandberg et al., 1988).

carbon sequestration efforts, the Earth could soon surpass CO_2 levels last experienced prior to the onset of our current glacial state 34 million years ago (NRC 2011). If observations of historic changes in climate and ecosystems under rising, but generally low atmospheric CO_2 levels are any indication, a future high CO_2 world will be drastically different than today. How different is the critical question. Without a clear analogue for our future, we proceed with great uncertainty with regards to how surface conditions and ecological processes will evolve with continued forcing (Hansen et al. 2008).

The deep-time geologic record provides a unique resource for better understanding how processes in the Earth system will function in the evolving and high CO_2 environment predicted for our future. Presently, this vast archive is largely underdeveloped thus offering the potential for significant scientific

discovery and for transformation of our scientific understanding of the dynamics of surface system processes. Well constrained reconstructions of how earth system processes have operated and responded to external forcing in the past not only provide natural baselines against which to assess change in the warming Anthropocene, but capture the sensitivity of processes to perturbation beyond that captured in records of the more recent past (Fig. 1). Moreover, only the deep-time record offers the temporal continuity and captures the full spectrum of environmental conditions needed to assess the signs of imminent climate and ecological thresholds (Barnosky et al. 2012) and to evaluate ecological response and resilience to perturbation.

The scientific community is embarking on multi- and inter-disciplinary team-based studies focused on mining this deep-time sedimentary and paleobiologic archive, fueled in part by new initiatives at the National Science Foundation

(*Earth-Life Transitions* and the STEPPE consortium (www.STEPPE.org)). Ongoing and future efforts will involve the development and calibration of new and existing proxies and systematic efforts to develop empirical datasets of temporal and spatial resolution of the scope produced for the post-Jurassic by the deep-sea and continental drilling communities. Such datasets have permitted refined understanding of the forcings and feedbacks involved in past equilibrium warm states (e.g., Pagani et al. 2013), abrupt climate change (reviewed in McNerney & Wing 2011), and greenhouse-icehouse transitions (e.g., Tripati et al. 2005, Katz et al. 2008). Observation-based datasets of such scope will provide the framework and benchmarks for modeling of past climates, and deeper insight into the still yet poorly understood fundamental processes behind data-model mismatches. Modeling efforts by the community extend well beyond climate models

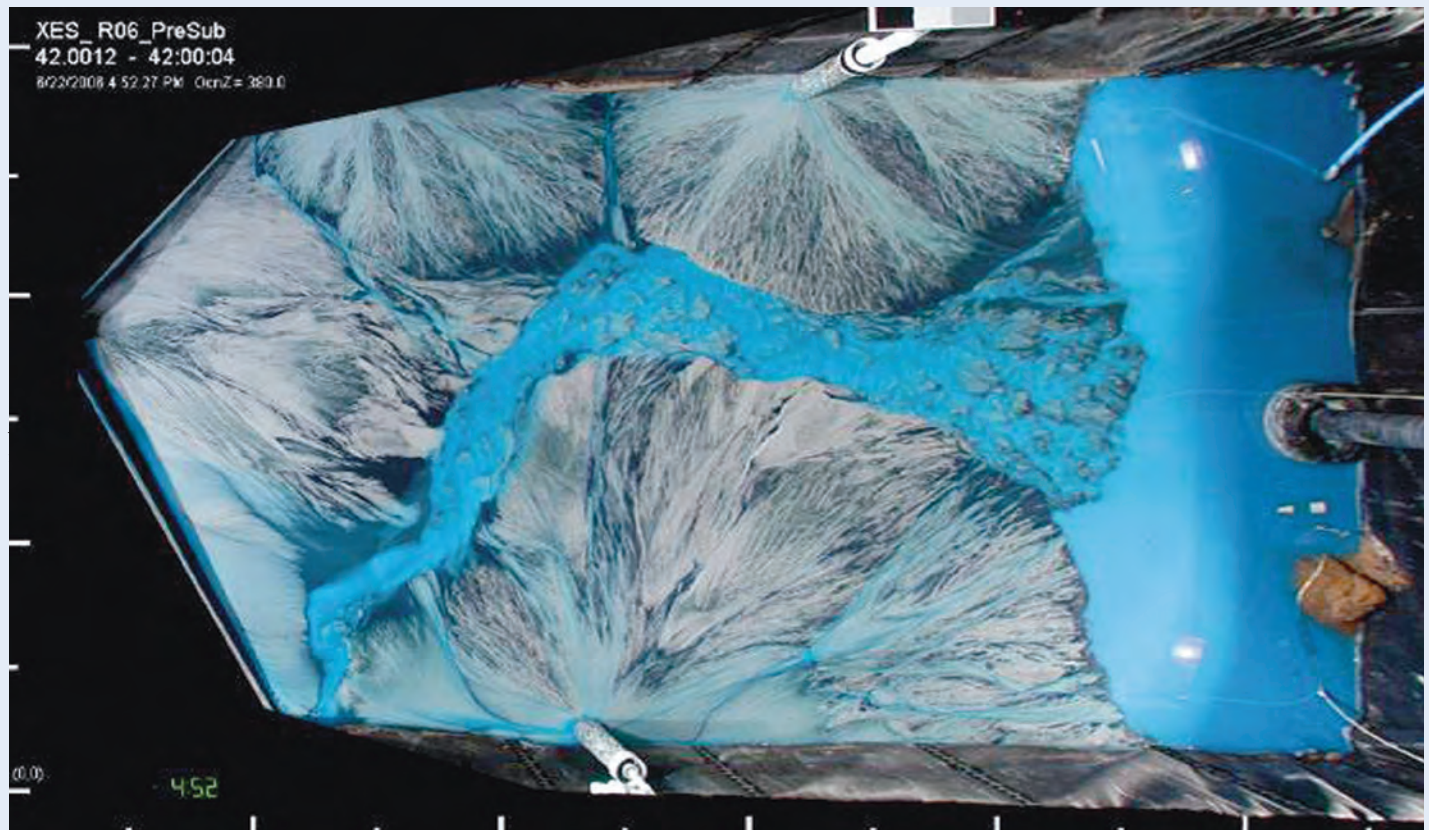


Figure 2: Interacting alluvial fans and channels generated from four point sources of sediment and water around the perimeter of the Experimental EarthScape (XES) basin at St Anthony Falls Laboratory, University of Minnesota, Minneapolis. For details, see Connell et al. 2012a, 2012b. Courtesy of C. Paola.

and integrate novel datasets obtained through new research approaches such as genomic and proteomic methods (NRC 2012).

THE EVOLVING EARTH SURFACE

The Earth's surface is the dynamic interface between the various components of the Earth system and is thus the locus of all environmental change. Within this dynamic interface, physical, chemical, biologic, and human processes interact across a realm of spatial and temporal scales to define and reshape it. Over the past two decades, studies in geomorphology, sedimentology, and neotectonics have greatly advanced our understanding of the mechanistic nature of feedbacks between landforms, topography, water and biogeochemical cycling, climate, ecosystems, deformation and sedimentation while providing insight into how the landscape has evolved under climate-, tectonic- and anthropogenic-forcing. Notably, the sedimentary record captures a unique aspect of the dynamics of the Earth's continental surface – i.e., how the system operates under climate states that differ from today and during abrupt

perturbation, including periods involving critical climate and ecological thresholds. Unraveling the intricacies of what governs change or maintains stability in continental surface environments is the only means to a complete picture of the resilience of this complex interface and how it may evolve in the future (NRC 2010a). The SEPM community plays a pivotal role in developing this critical 4th dimensional component of landscape evolution.

Coupling of experimental and modeling studies with natural experiments captured in the sedimentary record is rapidly changing our view of how physical and biotic processes of sedimentation have worked to shape the landscape and fill depositional basins. Laboratory-scale experiments (Fig. 2), such as those utilizing the Experimental EarthScape system at St. Anthony Falls laboratory, Univ. of Minnesota, permit 'real-time' study of hydrodynamic and sedimentation processes that typically evolve over much longer time-scales. Such experimental studies are capable of defining the full range of stochastic variability in notoriously dynamic systems such as fluvial and delta systems (e.g., Paola et al. 2009,

2011). Experimental representations of small-scale and short-term mechanics of fluid flow and sediment transport designed to reproduce aspects of natural landscapes have been shown to successfully scale up to reveal new insight regarding system-scale dynamics (Paola et al. 2009). On the theoretical side, open-source community tools for earth surface prediction such as the Community Surface Dynamics Modeling System (CSDMS, <http://csdms.colorado.edu>) provide testable models of complex environments. Efforts by the community to merge these tools is permitting rigorous analysis of how surface systems process and record information and the development of predictive models of how they evolve with time. Such insight is important not only for interpreting the natural sedimentary record but can be applied to the management of water resources, delta restoration, and ecosystem conservation and restoration.

An intricate component of the Earth's surface is the 'critical zone' – the interface between the earth's mineral surface (rock, soil) and the atmosphere, hydrosphere and terrestrial ecosystems (introduced in NRC 2001). Study of the critical zone has intensified over

the past decade given the realization of its unique role as a highly sensitive dipstick of environmental change. This complex 'system', responds to internal processes that determine its natural habitat and availability of life-sustaining resources (Brantley et al. 2011), and is further modified by climatic, tectonic and anthropogenic forcing. With the advent of paleopedology as a sub-discipline has come a growing appreciation for how paleo-critical zones, which developed on ancient landscapes, archive the response of this complex 'interface system' to different climate states and major transitions. The SEPM community is uniquely poised to mine this record of the interface between Earth system components through studies of paleosols and their geochemistry, associated terrestrial ecosystems, and modeling of the system dynamics. A core component of this community effort could be deep-time critical zone observatories —field- or virtually based (*Transitions* 2012).

SEPM'S PRESENCE IN THE DEVELOPING GREEN REVOLUTION

We are in the infancy of a second green revolution – one centered on a transition from a fossil-fuel powered world to one that incorporates alternative energy sources. The first green revolution, propelled by the development of fertilizers in the first half of the last century, permitted the exponential growth of the world population to seven billion people (Erisman et al. 2008). Resource sustainability and development of new energy sources is at the forefront of this second green revolution. A century of study of the fundamental processes that control the filling of sedimentary basins and the architecture of its deposits has been central to the development of subsurface reservoirs and the extraction of vast amounts of fossil fuels. These sedimentary basins host yet another large-scale energy source – heat energy (Tester et al. 2007). Deeply buried deposits in sedimentary basins offer the spatial continuity and petrophysical properties to yield geothermal resources of up to an order of magnitude greater scope than those generated presently by hydrothermal systems. Such resources could potentially replace a notable portion of fossil-fuel consumption in the US. Efforts to explore the nation's potential for geothermal energy in sedimentary basins, coordinated by members of the

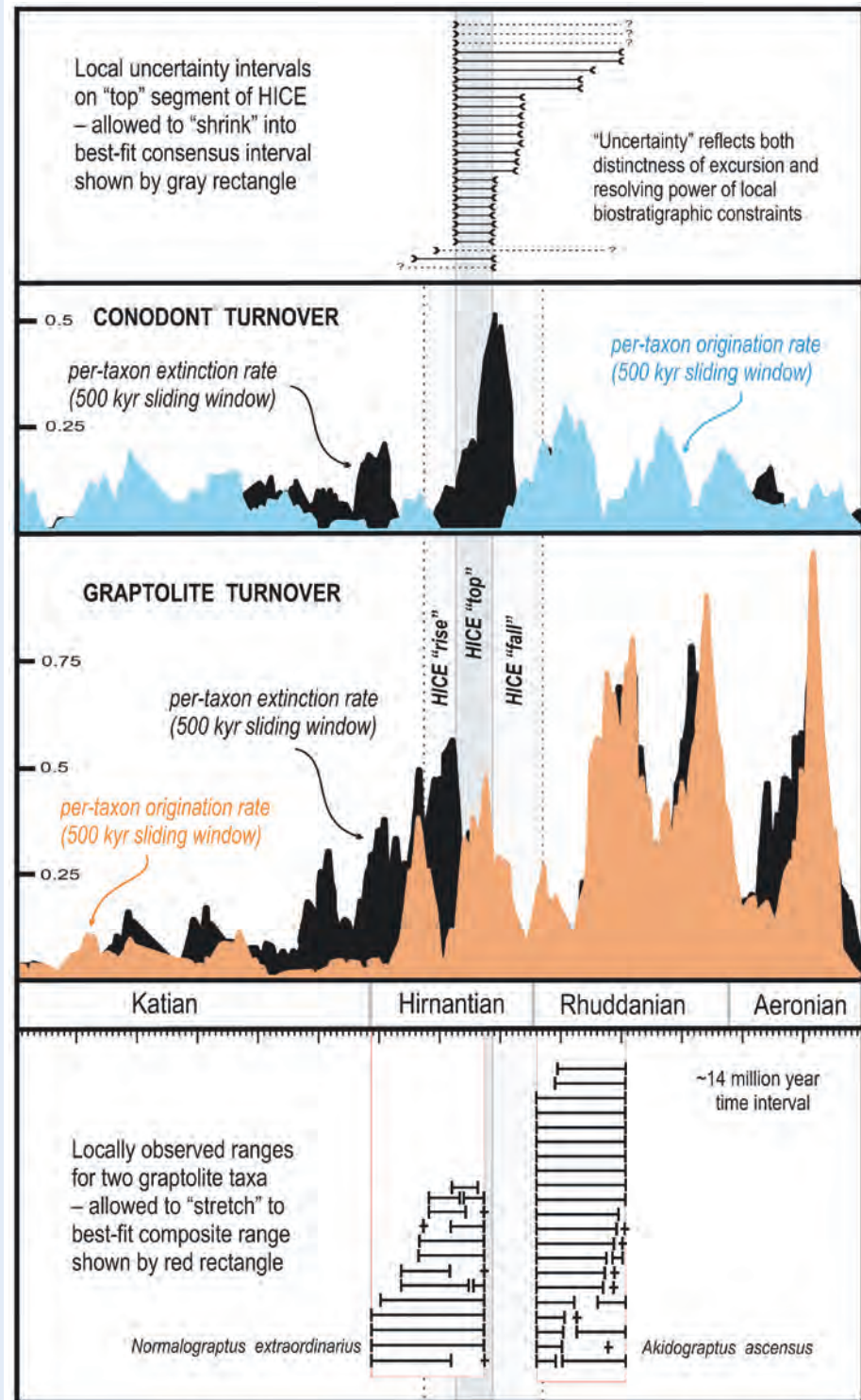


Figure 3: Macroevolutionary dynamics of the end-Ordovician (Hirnantian) extinction, extracted from a numerically-optimized, fully-resolved, calibrated, Sandbian through Telychian time-line of events. The underlying global data set includes first- and last-appearances of 1000 taxa (graptolites, conodonts, chitinozoa and acritarchs, noted in at least 3 of 401 published sections) plus 146 other time stratigraphic events (e.g. dated ash falls and segments of stable isotope excursions). Uppermost panel: optimal placement of HICE "top" segment by overlap of all local uncertainty intervals. Second and third panels: conodont and graptolite extinction and origination rates, expressed as fractions of taxon richness, and calculated at every event horizon. Origination graphs placed as masks in front of extinction rate time series to highlight the 2-phase extinction that straddles the isotope excursion; in the first phase, graptolites undergo 3 increasing extinction pulses, possibly on a ~400 kyr cycle; the single conodont extinction pulse marks the second phase. Lowermost panel: optimized composite ranges and all local ranges for two index taxa, possibly indicating diachronism. Courtesy of P. Sadler and students of GEO 206B.

sedimentary geology community, suggest “sedimentary basins have the potential to move geothermal toward a meaningful portion of our energy needs, and to do so with minimal environmental impact, negligible impact on global climate change, and without concerns of long-term depletion” (Holbrook et al. 2011). Sedimentary basins and the stratigraphic architecture of their deposits have an equally important role in efforts to develop subsurface carbon sequestration.

EVOLVING INFRASTRUCTURE & RESEARCH TOOLS

The community, endorsed by the National Research Council (NRC 2011, 2012), has identified the need for investments in new infrastructure that includes amongst other things continental drilling, improved chronostratigraphy, and data management sources capable of integrating diverse datasets through time and space. Here we briefly present three areas of developments driven in part by the SEPM community and which we plan to highlight in the *Sedimentary Record* series.

Continental Scientific Drilling: Efforts are underway to galvanize researchers interested in questions of Earth System evolution (see accompanying article by Soreghan & Cohen) that have been raised in the aforementioned NRC reports, workshop reports such as *Transitions* (2012), and defined by individuals in our community as part of their research efforts. The community has repeatedly reasoned, via these reports and publications, the need for recovery of high-quality continental core through drilling. This reflects the requisite preservational quality and sampling resolution needed to build the multiproxy archives of temporal and spatial resolution dictated by the scientific questions being asked by the community (NRC 2011). Continental drilling opens up opportunities to critically evaluate marine-terrestrial linkages and to directly compare their fundamentally different climate responses to the same forcings. Moreover, such data sets are likely the primary means of high-resolution calibration of critical climate transitions and thresholds. Soreghan and Cohen (this issue) define a path forward for scientific groups who share mutual research interests, which they aspire to be brought to ‘drilling fruition’.

Chronostratigraphy Revolutionized: The common thread in many components of earth surface research is the increasing reliance on geochronology in order to quantitatively constrain ages, the rates of change in components of the earth system and their phasing, and the synchrony and causality between processes during major biological or climatic events. The past decade has seen major advances in analytical methods and calibrations of several dating methods as well as the introduction of novel numerical chronostratigraphic approaches. In radiometric dating, synergistic efforts by geochronologists, sedimentary geologists, and paleobiologists as part of the EARTHTIME initiative (<http://www.earth-time.org/>) now permits, through high-precision ID-TIMS U-Pb analysis, temporal resolution of (sub)orbital-scale (at times less than 0.05% precision) throughout the Phanerozoic. Novel computational approaches that integrate biostratigraphic and chemostratigraphic records with radiometric ages promise deep-time age models of unprecedented resolution and continuity. For example, applying unbinned global compilations of first and last appearances of taxa with chemostratigraphic data and radiometric ages to a trial-and-error optimization algorithm reveals previously unrecognized macroevolutionary dynamics across major faunal events in the early Paleozoic (Fig. 3). Variations in per-taxon extinction and origination rates, resolved at a sub-10⁶ yr scale by a multi-dimensional graphic correlation, provide unprecedented constraints on the nature of and possible forcings driving major climatic perturbation during the Late Ordovician Hirnantian glaciation (Fig. 3, Sadler, personal comm. 2013).

Cyberinfrastructure: A high priority associated with the development of large and diverse datasets, which are anticipated to result from the aforementioned research endeavors, is a pressing need for digital databases to store and facilitate the integration and sharing of data. There are several community-based efforts in this arena (e.g., Paleobiology Database, Macrostrat, summarized in NRC 2011, 2012, *Transitions* 2012), and most recently a coordinated effort to engage the sedimentary geology and paleobiology community in the EarthCube initiative (<http://earthcube.ning.com/groups>). A workshop for the sedimentary geology community in late March, coordinated

by Marjorie Chan (Univ. of Utah) and David Budd (University of Colorado Boulder), aims to define, for our community, (1) the nature, challenges and impediments of sharing data, (2) evaluate how access to digital data of the scale proposed by EarthCube could transform our ability to explore the complex interactions of the Earth system, and (3) establish the types of repositories, software and tools that would foster community-based “big-science” collaborations within our community. Stay tuned for further developments!

CONCLUDING REMARKS

The SEPM community has loudly and clearly through various venues articulated a research agenda for the future — one that is collaborative and inter- and multi-disciplinary and requires new resources and changing cultural and technical infrastructure. The advent of the new research track, *Earth-Life Transitions*, in the Sedimentary Geology and Paleobiology program at NSF and the STEPPE consortium office is a large, yet initial, step forward for the community. In an effort to contribute to the community’s building momentum, we solicit papers that present exciting research directions, articulate existing challenges and the resources needed to overcome them, and which highlight evolving research opportunities. We further hope that the *Sedimentary Record* will be a forum to evaluate and hone the vision of the community and promote multidisciplinary research.

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