

## Earth History Sub-Committee Report

*Reconstructing past states of the Earth system and its components (including the atmosphere, hydrosphere, cryosphere, biosphere, and solid Earth).*

*Using these reconstructions to test, challenge, and advance scientific understanding of Earth system dynamics.*

### **Members:**

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Yair Rosenthal (DMCS/EPS)

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John Higgins (Princeton Univ.) - **External**

Jonathan Wilson (Haverford College) - **External**

### **Part I: Research**

**0. What are the most important questions in earth system history? What are the most likely breakthroughs in the coming decade? What are some of the testable hypotheses that EOAS is positioned to contribute (toward testing)? We should embrace important questions of all time periods in earth history, and we should keep in mind the potential implications to understanding the future trajectory of this planet (if we want to get funding).**

We see the co- evolution of life and Earth in the past present and future as the most important questions in Earth history (Fig. 1).

- How has the planet maintained habitability?
- How has biodiversity been generated and maintained throughout geologic time, and how have changes in biodiversity affected, and been affected by, planetary and environmental change?
- What were the causes of major extinction events, and how did the system recover?
- How have important transitions in biological history (e.g., evolution of oxygenic photosynthesis, terrestrialization of plants) affected the planet, and how have important planetary transitions (e.g., onset of plate tectonics) affected the biosphere?

- How does tectonics control ocean chemistry, and what are the links to ocean anoxic events, sea level, seafloor spreading rates, and hydrothermal output?
- What would a planet without tectonics be like?
- What was Archean tectonics like?
- How can we connect geologic evidence with geodynamic models?

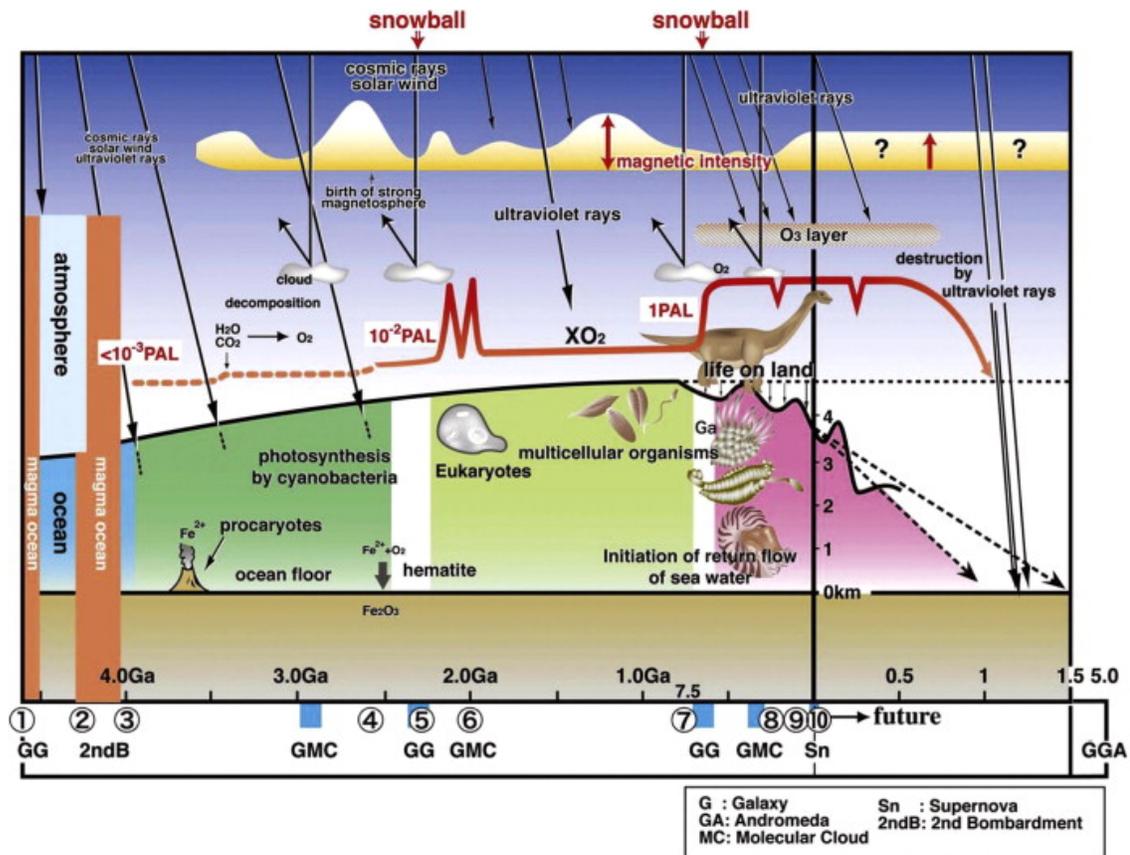


Figure 1: Co-evolution of life and abiotic Earth in past, present and future (from Maruyama et al 2013; Geoscience Frontiers)

The most interesting work in the last decade or two has been moving toward answers to these questions, either by reading directly from the Earth system record (e.g., isotopic analysis of rocks or samples) or looking from the present backward (e.g., in genomes, organisms, ecosystems, and environments today). Both views are complementary to one another, and EOAS is poised to be a location where people collaborate to answer these questions from perspectives across the geologic time scale.

A key question is how atmospheric gases, especially oxygen, nitrogen and carbon dioxide, are regulated and how they are coupled. Key geologically and biologically important gases exchange on timescales of minutes to millions of years with the major compartments of the Earth system, including the ocean, terrestrial biosphere, and the core and mantle. The multi-timescale dynamics provide one set of unifying themes that cross timescales and parts of the Earth system.

Earth system models (ESM) with various degrees of complexity can be used to project the ways human activity is changing the Earth system. Reconstructions of past states of the Earth system and the dynamics of life/environment interactions, over a variety of timescales, provide the only way outside the limited observational period of stress-testing our models. Models are therefore essential tools for predicting current and future Earth system dynamics that can inform policy makers. This is a key role that links EOAS's Earth system history theme to the Earth observations/forecasting and Earth system risks themes. For example, why do Earth system models have difficulty simultaneously reproducing paleo-reconstructions of global mean temperature change, pole-to-equator temperature gradients, and carbon dioxide concentrations from Cenozoic warm periods? And how does sea level, which ESMs do not fully represent, fit into this picture? Does this difficulty point to important feedbacks in the Earth system that are not currently captured by ESMs but could be relevant if fossil-fuel emissions continue at their current pace?

The DNA in living organisms provides an "unbroken document" of the Earth's history because, over all microbial and microbial phyla, it has recorded the sum of physical and biological interactions vis-à-vis the gene inventory and metabolic potential. Only 400 genes are responsible for basic metabolic processes (i.e, electron exchange). Remarkably,, although organism continue to evolve, the basic metabolism have stayed the same since the origins of life. Among these processes, the splitting of water is the most fundamental process, but it is not very well understood by the broader community. Integrating the genome of extant taxa with Earth history to provide a comprehensive explanation of the forces (e.g., Great Oxygenation Event, Snowball Earth) that have shaped our planet remains a key, and perhaps, the greatest challenge facing our field. This type of knowledge will prove critical in predicting how current changing conditions will impact both the biome and the physical environment.

**1. Given the big picture sketched above, what are the existing research strengths within EOAS that we should reinforce and grow, to make us uniquely positioned for competitive funding? This should include key existing faculty, established collaborations, and instrumentation/computation capabilities.**

Rutgers' strengths are in a diverse and abundant set of faculty with complementary areas of expertise and major equipment under one roof. There is a particular and notable strength in the marine realm and in analytical approaches to biology (genomics, for example) and geology. Another notable example are the three most recent hires in EPS (Jill van Tongeren, Juliane Gross, Sonia Tikoo), which have considerably strengthened our research in tectonics/volcanism/planetary sciences.

Evolutionary genomics and bioinformatics are particular strengths at Rutgers. We have the tools to uncover and translate the living document of time. The ability to interrogate multiple (100s to 1000s) of genomes simultaneously using sophisticated computational pipelines allows EOAS faculty to decipher at great detail the impact of environmental change on genomes and to reconstruct the evolutionary history of extant taxa through >3 billion years of Earth history.

The EOAS has access to a DNA sequencing and bioinformatics facility (*Genome Cooperative*; [http://dmlab.rutgers.edu/genome\\_cooperative/index.html](http://dmlab.rutgers.edu/genome_cooperative/index.html)) and a renowned protein structure database (*Protein Databank [PDB]*; <http://www.rcsb.org/pdb/home/home.do>) to empower genomic and protein analyses.

Another core strength are our analytical facilities for inorganic and isotope analysis of geological and biological samples. This includes a broad range in mass spectrometers, including a multiple collector inductively coupled mass spectrometer for the precise analysis of heavier elements, metal isotopes. The most recent addition was a laser ablation system that can be coupled to both the standard ICP-MS or the MC-ICP-MS for spatial analysis at high resolution. Efforts are also underway to update analytical facilities in Marine Sciences.

Sealevel reconstruction and prediction is currently well represented across EOAS, although this research thrust will be significantly weakened by the departure of Ben Horton.

**2. What are prominent gaps within EOAS? In particular, what modest steps can we take to fully capitalize on our existing strengths, and what drastic steps must we take to bring in new research components to fill in the missing parts and to connect the existing parts? What parts are we missing but essential for understanding system-level functioning?**

Despite the noted strength in bioinformatics, there is currently a lack of integration with geology and specifically paleo-reconstruction. One way to link bioinformatics with Earth sciences is through isotopes and geochemical data, and we have the facilities to accomplish this (Fig. 2).

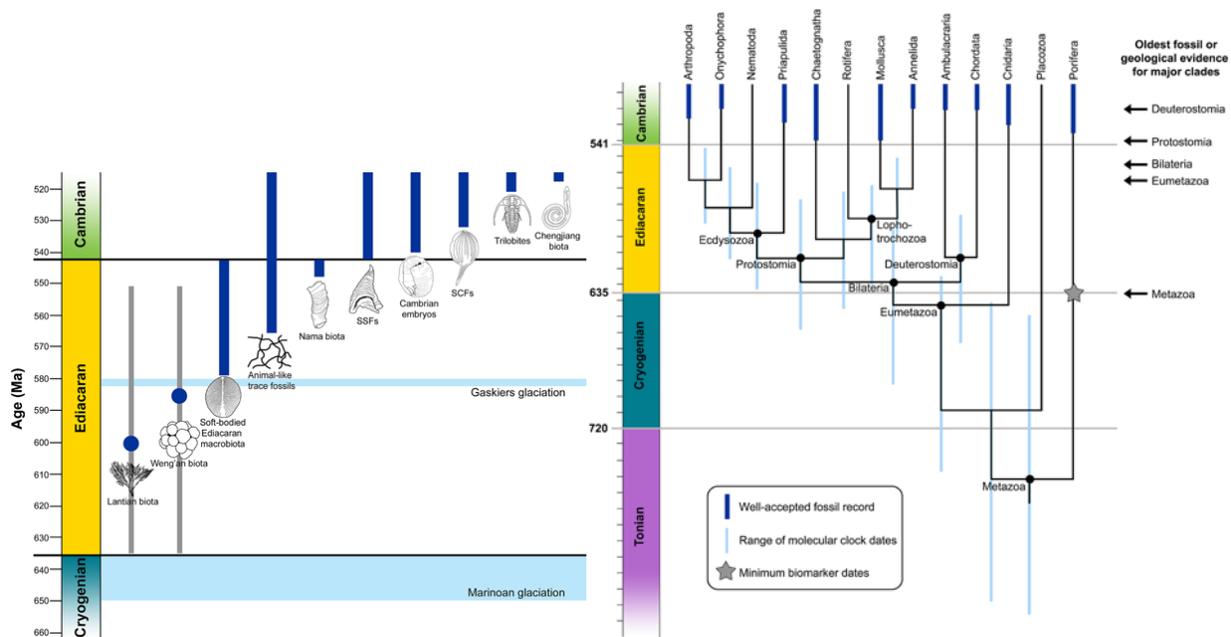


Figure 2: Integrating a molecular dated tree of life with fossil and geochemical data can be used to identify major transitions in Earth history (from Cunningham et al 2017; *BioEssays*)

The terrestrial realm, particularly interactions between the terrestrial biosphere and both terrestrial and marine environments is very poorly (if at all) represented within EOAS. This research thrust concerns questions of land plant evolution and colonization, and their effects on weathering, soil formation and biogeochemical cycles. An example of such a program outside Rutgers is the Critical Zone Observatories initiative, lead by Sue Brantley (Penn State) and Lou Derry (Cornell). Although members of EPS were involved in initiating the program there are currently no researchers at Rutgers involved in it.

Earth system modeling has been identified as a major gap within EOAS. This shortcoming may be somewhat alleviated by the recent hire of a theoretical ecologist (Juan Bonachela from Strathclyde University, UK), but strengthening our capabilities in modeling, especially lower order modeling of intermediate complexity, should remain a major focus of EOAS.

Another gap that was raised repeatedly is that of paleobiology (broadly construed) or someone who encounters and examines the fossil record directly (as opposed to a purely systematic or analytical paleontologist). There is a strong focus on microbiology within EOAS, but macrofauna is only poorly represented.

### **3. (moved to top as 0)**

#### **4. What are the top ~3 faculty hiring priorities? Please justify the proposed new hires in his/her role to fill in a critical gap and/or to connect the existing parts of EOAS.**

There would be great value in targeting hires to address at least two of the major gaps identified above with each hire. Identifying faculty members at various career stages who could be interfaces between the domains that are already represented would be a coup (biology and geology, marine and terrestrial, modern/comparative and historical, experimental and modeling). A terrestrial, historically-minded (but perhaps not exclusively paleobiological) scientist could catalyze interactions across EOAS. An additional faculty member trained and educated in both biology and geology, perhaps with a modeling perspective, could be identified, as well. Above all, three searches that are looking for colleagues to be mortar between the existing bricks of EOAS—identify unusual C.V.s and perhaps target specific scientists. Someone who can link past and future Earth system changes together would be valuable in tying together different threads of EOAS. The primary goal of any hiring strategy, however, is to find the best people.

#### **5. What potential new research collaborations could be formed within EOAS, elsewhere at Rutgers or elsewhere in the region? Not more seminars please, but focused activities for a day or 2?**

In addition to targeted hiring, efforts should focus on integrating research in bioinformatics with other ideas related to paleoreconstruction. The expertise and analytical facilities are largely in place, what is lacking are notable collaborations “across the river”. Similarly, EOAS is very well represented in the field of geobiology, but those efforts are currently poorly coordinated. Again, we have the expertise, but the research across campus is poorly integrated.

Geological time is important concept for many disciplines (e.g., ecology, atmospheric sciences), yet it is rarely taught outside Earth sciences. There should be efforts to integrate the teaching of geological time in disciplines outside Earth sciences, and also to foster collaborations.

Field trips would be essential activities to spark interactions among and between faculty members and graduate students. Building strong connections between faculty members through graduate student activities (co-advising, co-authorship, collaborative grants, etc.) could increase EOAS productivity and prominence.

**6. What research linkages could be strengthened between this theme and the other key EOAS themes (planetary habitability, Earth system history, Earth observations & forecasting, Earth system risks, and polar change)?**

At the townhall meeting, one suggestion is to have theme based EOAS symposiums. They can be one day long, with presentations given by Rutgers faculty/postdoc/students.

**7. If EOAS received an unrestricted gift of \$5 million to support research in this area, what would be the top ~3 priorities?**

- Nanoscale Secondary Ion Mass Spectrometry (NanoSIMS):
  - Quantitative chemical and isotopic imaging at high spatial resolution.
  - In situ intracellular imaging (50 nm) and flux measurements.
  - High spatial resolution U-Pb dating.
- Fourier Transform Infrared Spectroscopy (FTIR):
  - Microscopy and imaging at micron scale
  - Can be used to identify and study organic and inorganic compounds.
  - Broadband spectroscopy on materials in ultra-small quantities (single viruses and protein complexes)
- Collective negotiated service contract with Thermo for analytical instruments (especially mass specs for isotope analysis).
- Grad student support
- Field expeditions, bring the lab to the field.

**8. Suppose EOAS were to receive a small seed gift (roughly \$100K) to catalyze collaborative research over the next two years. What would be the top priorities for this gift? Please consider both (1) how these priorities will improve collaborative research and (2) how they will make Rutgers more attractive for larger grants and donations.**

A small seed gift targeted for early-stage research projects could be useful. (For example, a Pilot Projects Fund to support generating preliminary data for collaborative research from two or more faculty members.) The suggestion of dedicated workshops for training faculty, postdocs, and students on instrument construction or computational techniques is also a good one. (Perhaps a rotating series of “research boot camps” with a slightly different topic every year.)

**9. By what metrics and milestones could EOAS measure progress in promoting research in this theme over the next five years?**

The obvious ways to measure increased impact are good: publications, grants, student acceptance rates, recruiting success, etc. It is also important to keep track of where former students are being hired. An additional useful metric might be observing the number of students and postdocs who are working with more than one faculty member and doing collaborative work. For example, a student working with Paul Falkowski on calcification dynamics and partially advised by Debashish Bhattacharya for a chapter on genomic evolution of biomineralization capacity. As a department with numerous researchers who are investigating questions from many environments and time periods, this would be one way to measure if, or how, EOAS is training the next generation of interdisciplinary scholars.

**10. What are the funding opportunities for Earth system level projects?**

NASA - Exobiology (for individual PIs) and Astrobiology Institute (multi-PI collaborations)  
NSF - Geobiology and Low temperature Geochemistry, Integrated Earth Sciences  
Agouron Foundation - especially postdoc fellowships, meetings related to Geobiology  
Simmons Foundation  
Gordon & Betty Moore Foundation

**Part II: Teaching and Outreach**

**1. Suppose a student wanted to come to Rutgers to get an undergraduate degree within this theme. What pathways are currently available to the student? What career options would be available to the student? What potential new undergraduate teaching initiatives could be launched that would enhance revenue and/or our position of national and global leadership?**

If a student wishes to study Earth system history, it is not obvious which school and what major would offer the best path. Related courses are offered on multiple campuses and by multiple departments/majors. For a high school student, this can be very confusing. Possible solutions are:

- (a) Offer a new major, under the banner of EOAS, above the schools and departments, with an entirely new curriculum, requiring a broad-based education in physics, chemistry, biology and evolution (tier-1), geology, atmospheric science, oceanography (tier-2), etc. culminating in a set of integrated junior/senior courses on Earth system interactions.

However, creating a new major above several units may not be easy. The enrollment will likely be very small.

- (b) Building on existing programs, but making a few important changes: (b1) We must broaden the base of Earth science education by requiring more basic courses from related programs. For example, the Geological Sciences program should require students to take biology, just as they are required to take math, physics, and chemistry; Environmental Sciences, Meteorology and Ecology/Evolution programs should require students to take intro geology to be exposed to the concept of deep time and the co-evolution of the biotic-abiotic world; Ecology/Evolution program should require students to take a course in genetics. Such changes have been in discussion for decades, they are relatively easy to implement, and the benefit to students will be one of life-long time. (b2) On top of the broadened base education, we must create a set of integrative/synthesis courses at the junior/senior level, an example being History of the Earth System (01:460:476 x 11:628:476) taught by Paul Falkowski, and Major Events in Earth History (01:460:480) taught by a team of EPS/Columbia faculty led by Claude Herzberg. But we need to think through the gaps and emerging important topics and offer courses on these topics, examples being the history of the carbon cycle, life/rock co-evolution, etc. With the new faculty hires, EOAS is poised to create a core curriculum in Earth system history. (b3) With a broader base and a set of well-coordinated synthesis courses, we will be ready to create a new concentration called “Earth System History”, advertised on EOAS webpage, with detailed instructions on how a student can choose this concentration while having a major in existing programs in Geological Sciences, Marine and Coastal Sciences, Ecology and Evolution, Environmental Sciences etc. We can look into the successful programs of this kind at Harvard and UC Berkeley.

**2. Suppose a student wanted to come to Rutgers to get a Ph.D. within this theme. What pathways are currently available to the student? What potential new doctoral teaching initiatives could be launched that would enhance our position of national and global leadership?**

Although not fully integrated as a theme/program, there are sufficient faculty and courses that already exist across the campuses, allowing a PhD student to follow a thesis path in Earth system history. Students now can enter any of the graduate programs affiliated with their advisers. However, several important changes are needed to streamline the path.

- (a) New integrative programs need to be created. As an example, with current faculty and new hires, EOAS is ready to create a graduate concentration in Geobiology. Another future program to consider is Paleo-Ecology. Core faculty need to sit down and design the details of these new concentrations.
- (b) These new concentrations will create the platform for team advising of students, and team-teaching of core courses, critical for the success of these concentrations.
- (c) These new concentrations will need to be clearly advertised on the front page of EOAS, with instructions to applicants on what departmental graduate programs to apply, and what should be clearly indicated in their application statements.

- (d) The EOAS task force on integrating the graduate application pool will make the application and program options much more clear to the students.

**3. Suppose a student wanted to come to Rutgers to get a terminal masters' degree within this theme. What career options would be available to the student? What pathways are currently available to the student? What potential new teaching initiatives could be launched that would enhance revenue and/or our position of national and global leadership?**

Career options are:

- (1) Teaching high school science. Earth science education is dismal in K-12 curriculum, and a MS degree in Earth history, combined with courses required for teaching certification, would prepare these teachers with a much deeper knowledge and appreciation of the discipline. Perhaps EOAS can work with the education department on campus to create a certification path?  
Out-reach graduate fellowships, such as the Science (<http://sciencebus.rutgers.edu/rse>) program in the past, can fund these MS students, which not only provide funding for them, but also offer opportunities to work with schools and K-12 students, which can open doors for immediate employment after graduation. This would be a great service to the State and the nation, if we become known to the top producer of top-notch high school / middle school earth science teachers.
- (2) Lab managers/technicians in major research labs. We can even create a MS program that trains students to be familiar with key laboratory skills. This would be a great service to the nation/world if we can brand ourselves as the major producer of top notch earth science lab managers.

**4. What teaching linkages could be strengthened between this theme and the other key EOAS themes (planetary habitability, Earth system history, Earth observations & forecasting, Earth system risks, and polar change)?**

We passed this question due to time constraints.

**5. If EOAS received an unrestricted gift of \$5 million to support teaching in this area, what would be the top ~3 priorities?**

- (1) A state-of-science teaching lab, with adequate faculty and tech support, would be wonderful!
- (2) Low-cost, off-the-shelf, portable lab and field equipment can allow a larger number of students access to field/lab experience. These low-cost experience can get students thinking: what are we measuring, why are we measuring it, what does the number tell us?
- (3) The fund can also support summer courses in instrumentation.
- (4) The fund can support Graduate Fellowship for science education and outreach, such as operating the Science Bus, a successful but discontinued program that had supported graduate students and landed them jobs. Also see answer (1) under question-3 above.

**6. By what metrics and milestones could EOAS measure progress in promoting teaching in this theme over the next five years?**

More students with multiple advisors, more students taking courses across departments and river, more happy and intellectually free and creative students, more students period, and more students going on to great jobs.

Other exciting things we can do (not covered by Bob's questions)

Take incoming grad students to e.g. Godard Space Flight Center to see big-scale science in action, Brookhaven lab, PPPL Visit museum and see how to improve public education programs.

### Outreach and Policy Engagement

#### **7. What sort of public outreach activities is Rutgers currently undertaking related to this theme? What potential new outreach activities could be launched that would contribute to the broader impact of Rutgers research and teaching?**

The Geology Museum, RU Math and Science Learning Center are doing a great job currently.

We need to bring back the Science Bus! It funds graduate students, it does great public outreach service, and it lands them jobs.

We can work with curators of large museums, to create exhibitions on the co-evolution of life and the solid/liquid/gaseous earth. We can take our first year grad students and undergrad seniors to visit the top museums in the area, to find problems with the current programs, and to design a state-of-science exhibition to pitch to these museums.

#### **8. What sort of policy engagement activities (at local, state, national, and international levels) is Rutgers currently undertaking related to this theme? What potential new policy engagement activities could be launched that would contribute to the broader impact of Rutgers research and teaching?**

- We need to think about how to educate the policy makers and the public about the concept of geological time – how do we know the age of stuff?
- Need to coordinate with the Eagleton Institute to find opportunities
- We need to fully utilize spokesmen/women to communicate – we could support the experts on this (such as Lauren, Janice, Lisa, etc)

#### **9. What outreach and engagement linkages could be strengthened between this theme and the other key EOAS themes (planetary habitability, Earth system history, Earth observations & forecasting, Earth system risks, and polar change)?**

We can contribute the context of deep time – how we get here, how long does it take to make the fossil fuels, how fast we release it to the atmosphere, how long does it take to have the

biological diversity/heritage we see today, and how long does it take to solve our global problems, etc.

**10. If EOAS received an unrestricted gift of \$5 million to support outreach and policy engagement in this area, what would be the top ~3 priorities?**

- (1) Bring back the Science Bus
- (2) Support student design projects to overhaul museum programs on earth history
- (3) Support MS students to become middle/high school science teachers

**11. By what metrics and milestones could EOAS measure progress in promoting outreach and policy engagement in this theme over the next five years?**

General topics

**12. Other than those already discussed above, are there any additional obstacles that will need to be overcome or resources that will need to be acquired in order to advance the research, teaching, outreach and policy engagement vision identified?**

**13. Are there any additional roles EOAS should consider taking on to facilitate activities within this theme?**

**14. Suppose EOAS were to receive a small seed gift (roughly \$100K) to catalyze collaborative research, teaching and outreach over the next two years. What would be the top priorities for this gift? Please consider both (1) how these priorities will improve collaborative research, teaching and outreach, and (2) how they will make Rutgers more attractive for larger grants and donations.**

Fund graduate students through the Science Bus or similar outreach activities such as Geology Museum programs. It is a great use of the limited funds because it supports students in research and out-reach simultaneously.