Research on Learning in the Geosciences: Contexts, Goals and Opportunities

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Some Contexts

What are the geosciences? Broadly defined, the geosciences encompass disciplines that study the solid earth (e.g. rocks and their structures), surficial deposits (e.g. soils, surface waters), the atmosphere, and the oceans; related disciplines are also included such as near-space physics, planetology, paleontology and physical geography. In detail, each sub-discipline in the geosciences has developed its own knowledge base, methodologies, philosophies and approaches to problem solving, and cultural attributes that inform the conduct of science in these varied domains, and by extension, educational practice in these subjects. At the same time, in the study of our planet we often apply "first principles" of science shared with sister disciplines in biology, chemistry, physics, engineering, and mathematics to understand the natural world around us—so our work is often inter- or multidisciplinary in its scope.

In recent years there has been a growing movement towards research and education using an Earth system approach (AGU 1997). Connections between different components of the Earth system are being emphasized, interesting research results are being realized at the interfaces between diverse sub-disciplines, and new hybrid disciplines are emerging, e.g. geomicrobiology. Earth system studies increasingly focus on the processes that connect the components of the Earth system: e.g. the transfer of mass and energy through complicated pathways and reservoirs, feedback mechanisms, the physical and biological evolution of systems. Time is an essential component of understanding the Earth system—the concepts of "deep geological time", rates, and fluxes. There is also an increasing awareness of the importance of understanding the linkages between the physical world and the life forms it nurtures (e.g. coupled biogechemical cycling) and with humanity (e.g. dynamics of coupled natural and human systems).

The Earth system is dynamic, heterogeneous, complex and often chaotic. And this presents a number of challenges to learning about a system that is naturally ambiguous, uncertain, and largely unpredictable. The Earth system operates on spatial scales ranging from atomic to planetary, and over time scales that may be considered instantaneous and catastrophic to inexorable over the eons. Earth system processes typically operate beyond every-day human experience, and we consequently rely on other ways of observing the Earth such as remote sensing (e.g. via satellite imaging) or by making inference based on indirect observations of things we can't see directly (e.g. seismic records and tomography). The geologic record is incomplete, and we are left with a detective's mystery trying to fill in the missing pieces. It is very difficult for geoscientists to conduct controlled experiments: we don't have a separate world that can be used as a control for comparison, and given the complexity of natural systems it is difficult to construct comprehensive physical or computational models. Nonetheless, we do find it useful to use simulations or visualizations to model, represent and interpret these complex systems.

The geosciences obviously encompass a wide variety of fields of study, and there are consequently many factors that influence what we teach, how we teach, and whether or not students can or will learn. Here are some observations for context:

> The geosciences have somewhat an identity problem. In some cases, departments self-identify as Geology (or Geological Science), Oceanography, Atmospheric Sciences along strict disciplinary lines. Other departmental names become more inclusive: Geosciences, Earth Sciences, Earth and Planetary Sciences, Geology and Geography…There's important meaning behind these names which reveals philosophy and structures for organizing information, inclusion or coverage of content and consequent curricular design, approaches to education, etc.
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> There is not a curricular "canon" in the geosciences. Most departments continue to offer courses along disciplinary lines (geology, oceanography, meteorology…). Traditionally these topics have been taught as stand-alone courses with little reference to each other. Across the geoscience disciplines, or even within a given discipline, it is very difficult to find "core content" that would be common to similar courses offered by different instructors/departments. This appears to be the case for introductory courses as well as upper division courses. Even a topic as broad as plate tectonics leaves ample room for instructors to pick and choose among topics to be covered. When we convened the workshop that led to "Shaping the Future of Undergraduate Earth Science Education, Innovation and Change Using an Earth System Approach" (AGU, 1997), it quickly became apparent that participants were strongly resistant to the creation of a uniform, centralized (and prescriptive) curriculum. Consensus showed that most geoscience educators wanted to retain autonomy in their choices of *what to teach*, and insisted on the need to optimize opportunities afforded by their local geographic setting, institutional resources, and to meet the specific needs of their student clientele. This is in sharp contrast with our friends in physics and chemistry (personal communications) wherein a standard introductory course in these fields covers essentially the same material no matter where it is taught or by whom. The question of *what to teach* has been settled (at the introductory level) a century ago in these disciplines. The geoscience educator must make choices about what to teach, as well as how to teach it.
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> At the Shaping the Future workshop we did encourage participants to look for commonalities among the geoscience disciplines. Since that report, the Earth system approach is increasingly being adopted within the context of traditional classes (i.e. some connections across the Earth system are being articulated), and dedicated Earth system classes are coming on-line.
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> Fundamental concepts underlie our approach to understanding the world. For example, in geology the principles that "the present is the key to the past" and the "principle of uniformitarianism" are applicable throughout the Earth system and

geologic time (or are they?). Given the complex and incomplete geologic record, we often apply the tenets of "multiple working hypotheses" to help winnow out erroneous explanations as new evidence is acquired. This presages a very Popperian approach to our science in that we can rarely hope to "prove" our hypotheses, but rather, must often settle for interpretations that are internally consistent at best.

Field work is at the heart of our science, although this is done in different contexts in the different disciplines: the classic field geologist with brunton compass and pick in hand hiking over hill and dale; a change in emphasis from mapping to sampling; shipboard activities on extended deep ocean cruises involving drilling, dredging, and submersible dives; airborne data collection using sophisticated instrumentation; and an increasing dependence on technology, e.g. global positioning systems, remote sensing instruments with data relayed by telemetry (i.e. you don't actually need to be in the field to collect field data), and robotics (in the deep sea, in volcanoes and on other planets).

Geoscience education relies heavily on geospatial and temporal referencing—we need to know where we are in the Earth system, and what the physical, chemical, and biological contexts are;—when did an event occur, over what time scale, and at what rate? We must continually iterate between global principles and local examples. Concepts of relative and absolute time are essential, as well as the ability to represent "deep time" i.e. geological time over millions or billions of years. In virtually al of the geosciences it is important to understand Earth processes in three and four dimensions.

We place a strong emphasis on use of data, real-time or archived, to interpret the world, although the range of information that is considered "data", the tools to manipulate and represent "data", and how we use data in the classroom can be quite varied (see the results of the recent "Using Data in the Classroom" workshop at dlesecommunity.Carleton.edu).

At times a reductionist approach is required —selecting representative sub-systems to more precisely understand a given phenomenon at increasingly smaller scales of observation; at other times it is necessary to integrate or synthesize across many lines of evidence.

To fully understand any part of the Earth system, we typically integrate a) over many scales of observation—processes that occur on the atomic scale, in aggregate, contribute to planetary scale processes; b) across disciplines—utilizing the principles, concepts, and methodologies from physics, chemistry, biology, mathematics, computer science, and engineering; c) using numerous, disparate types of data (e.g., physical and chemical measurements, imagery of many types, biological surveys, human census data…); and d) using a variety of approaches including observation (sometimes aided by technology), analysis, modeling, experiment, and theory.

Representations of the Earth have become increasingly important to demonstrate natural processes. Models of all types, numerical, physical, visualizations, simulations, and projections are typically used to make complex systems more accessible to understanding.

Goals for Learning in the Geosciences

Goals for learning must be established in the context of the diverse attributes of the geosciences as outlined above, and in the knowledge that we must reach diverse audiences for different purposes. There are some broad domains where learning goals can be established, appropriate to each subject or audience. The challenge is to translate these broad goals into specific practice across the many interests in geoscience education.

An overarching goal from NSF (NSF Geosciences Beyond 2000): *To benefit the nation by advancing the scientific understanding of the integrated Earth systems through supporting high quality research, improving geoscience education and strengthening scientific capacity.*

Mastery of content knowledge: a minimum understanding of basic taxonomies, formulae, etc., is required for communication and understanding. (e.*g.* National Science Education Standards, NRC, 1996)

Mastery of fundamental "first principles" and concepts: including the ability to apply a concept appropriately to a new situation.

Making connections: "*Science is knowledge not of things, but of their relationships*" (Lucien Poincaré, Science and Hypothesis)

"Inculcating scientific habits of the mind"*: Project 2061 Science for All Americans*, AAAS, 1989.

Skill development: many skills are of a technical nature—the ability to operate an instrument or use a software package; other skills relate to personal growth—communication, quantitative, and interpersonal skills.

Attitudes about science, values, ethics: in many cases, in our instructional practice it may be appropriate to demonstrate the personal and societal value of the scientific process and its products, and to address ethical issues that impact the conduct of science.

Recruitment, retention, diversity: what practices can help to make the geosciences an attractive career option—for those who aspire to become a professional scientist, and those who need to use science in their daily activities (e.g. policy planners, journalists, …)? The geosciences have made important strides in recruiting women, but we are greatly in arrears with respect to recruitment from underrepresented groups. We need to identify barriers and incentives to make the geosciences more accessible and attractive to all people.

Training the "Workforce for the 21st Century": adapting curricula content and methods to meet the changing needs of the future job market.

A scientifically literate, scientifically capable public: our personal and communal health, safety and economic well-being are directly impacted by natural hazards and resources; everyone should be able to read a weather map, be aware of local natural hazards, understand their connections to global systems.

An Invitation to Collaborate

The Earth is a wonderful natural laboratory, and geoscience classes provide great laboratories for research on learning. During the past decade the NSF has sponsored a series of workshops that have helped to build a vibrant community of geoscience educators. The professional societies (e.g. American Geophysical Union, Geological Society of America, National Association of Geoscience Teachers, American Meteorological Society, American Geological Institute) have contributed in many ways to support geoscience education through theme sessions, committee work, and publications. The Earth and Planetary Sciences are recognized as an important component of the K-12 National Science Education Standards (NRC, 1996), and geoscience courses are among the most popular on college campuses.

We recognize the significant advances that have been made in cognitive psychology (e.g. *How People Learn: Brain, Mind, Experience and School*, NRC, 1999) and in research on learning in our sister STEM disciplines. There are ample opportunities to adapt or adopt these lessons to the geosciences. At the same time, the geosciences have special interests and needs related to research on learning that are intrinsic to their subject matter, methodologies and audiences. Important outcomes of this workshop will be:

- Development of collaborations among all partners interested in pursuing future work on research on learning in the geosciences; establishing a common understanding of the contributions that can be made from other disciplines as applied to the special needs of the geosciences.
- Engaging the geoscience education community to contribute to research on learning projects. Collaborative projects are needed to design and implement research experiments that meet high scholarly standards in the fields of human cognition, education, and the geosciences.
- Providing a research environment in geoscience educational settings that will help to contribute to the larger arena of understanding human learning (e.g. with respect to 3 and 4-dimensional representations; optimizing learning in field settings; measuring the value of simulations and visualizations in instructional practice; understanding complex, dynamic, and chaotic systems).
- Translating the results of this research on learning into effective instructional practice in the geosciences—covering all geoscience disciplines, instructional settings, and for all audiences.

We anticipate that the proceedings of this workshop will be the first step towards long and productive collaborations with all interested contributors.

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