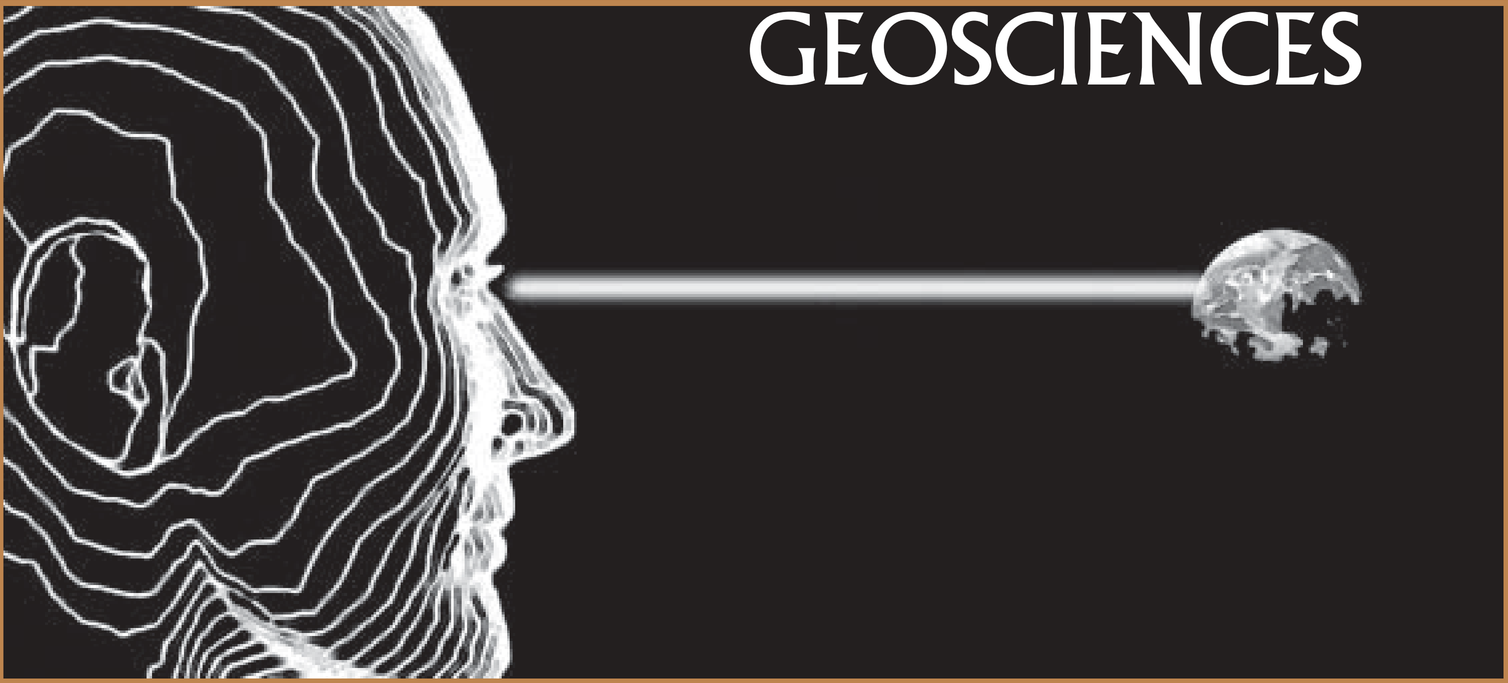
BRINGING Research ON Learning TO THE GEOSCIENCES



Cathy Manduca, David Mogk, and Neil Stillings

Report from a Workshop Sponsored
by the National Science Foundation
and the Johnson Foundation

THE JOHNSON FOUNDATION
Wingspread Conference Center

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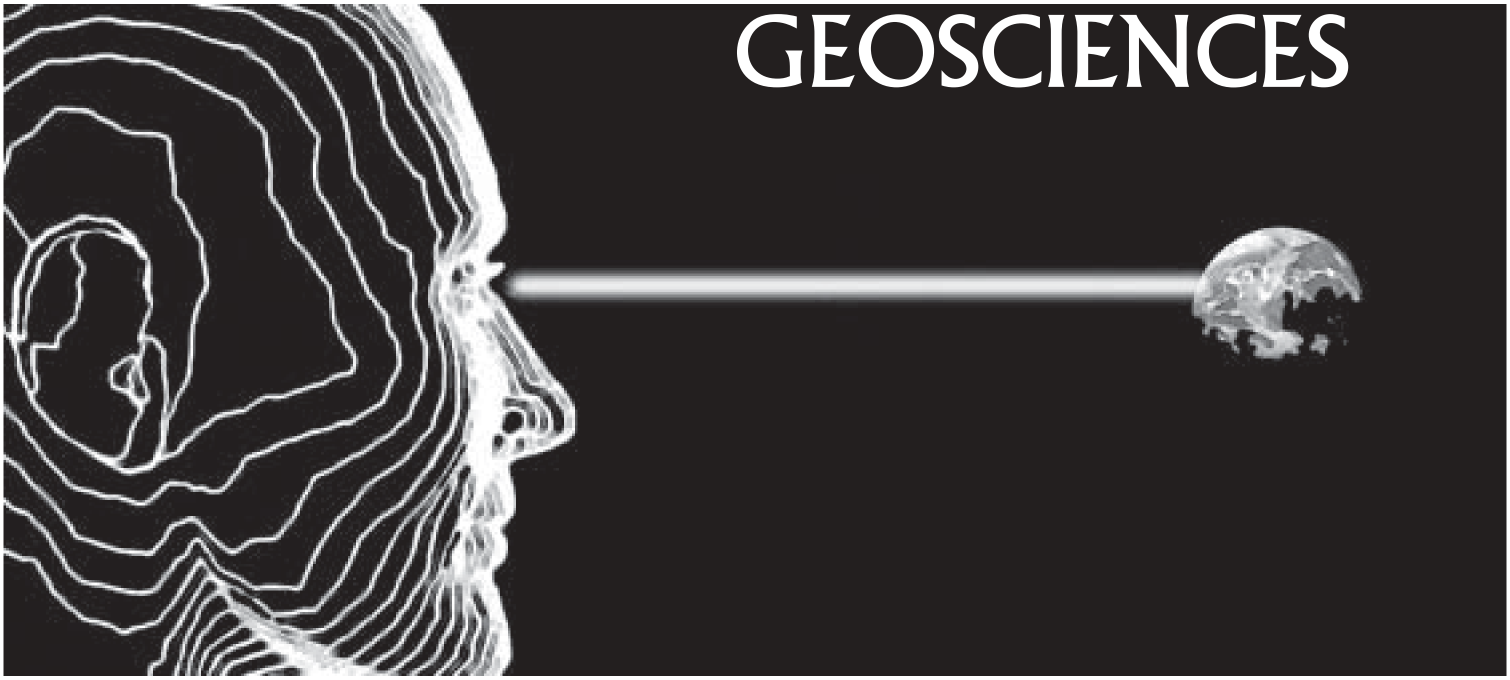

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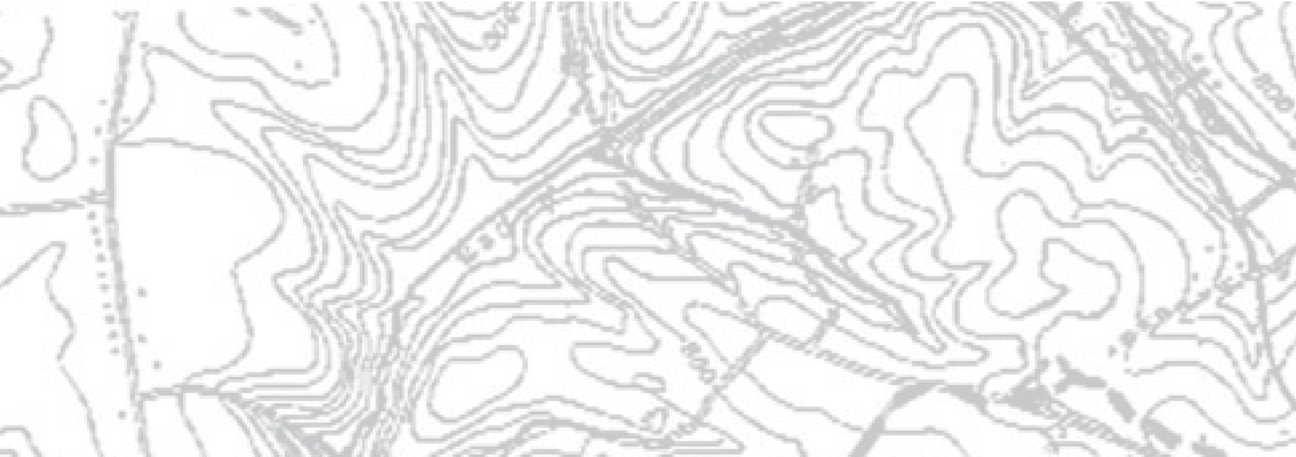

Research [on learning in the geosciences] and the tools developed for its implementation will allow students and faculty to understand what they are trying to learn and how it can be accomplished and to monitor the progress of learning. Toward this goal, it is recommended that a discipline-specific Center for Research on Learning in the Geosciences be established.

Credit, Background Image: Nancy J. Ashmore

EXECUTIVE SUMMARY (REC 021365)

One of the most exciting and influential changes underway in science education today is the increasing application of research on learning to education. This report summarizes discussions of how this research could be used to improve learning in the geosciences that were held in July 2002 at the Johnson Foundation's Wingspread Conference Center. Twenty geoscience educators, cognitive scientists, and scholars engaged in educational research in other scientific disciplines met for three days to develop an understanding of the current state of research on learning in the geosciences, to identify research questions of high interest to both geoscience faculty and learning scientists, and to develop a plan for fostering improved application of research on learning in geoscience instruction.

Three overarching themes emerged from the discussion:

- **Significant improvement in undergraduate geoscience instruction could be realized through a clear articulation of learning goals** describing what we want students to know and to be able to do and the use of these goals to design and implement new instructional practices and materials that are informed by learning science.
- **The geosciences provide unique challenges to learning that can be approached through cognitively oriented research.** This research should provide a foundation for instructional design of geoscience courses and curricula, as well as exciting new opportunities for fundamental research into how people think and learn.
- To effect change in undergraduate geoscience instruction, **discovery of what will improve education in the geosciences must be coupled with mechanisms to bring those findings into widespread practice.**

Making progress in these areas requires a partnership between geoscientists, education experts, and cognitive scientists. The time is ripe for such a partnership because:

- **Geoscience educators are receptive to research partnerships with the learning sciences.** Their interest stems, in part, from their awareness that there has been a lack of research on geoscience learning that would correspond to that done in chemistry, physics, and other sciences and, in part, from the growing reconceptualization in the geosciences in response to new scientific approaches and interdisciplinary connections.
- **From the standpoint of cognitive and learning scientists, the geosciences are an exceptionally rich cognitive domain that offers both interesting parallels to and differences from other scientific fields.** In addition, geoscience education reaches a very large and diverse student population with a curriculum that offers accessible opportunities for student inquiry that is enlivened by numerous policy issues.

Reflecting on the important opportunities that research on learning in the geosciences provides for improving geoscience and science education and furthering our understanding of how people think and learn, workshop participants recommend activities in three areas:

Research — New research that addresses areas of high interest to both geoscientists and learning scientists will have major benefits in both fields. A first-order goal for this research is understanding the nature of geoscience expertise:

- What characterizes the thinking of an expert geoscientist?
- What important geoscience concepts (e.g., geologic time, plate tectonics, global circulation) and skills are essential to practicing and applying geoscience?
- How do geoscientists understand the Earth system in the context of complex interactions in a heterogeneous, dynamic, uncertain, and often chaotic world (Ireton et al., 1997; NRC, 2001)?

Research results on the nature of geoscience expertise can then be translated into effective instructional practice. Towards this end:

- Learning goals and outcomes (in all contexts) should be informed by what we've learned about expertise in the geosciences.
- The stages of development of geoscience cognition should be investigated and related to more general issues in cognitive and intellectual development. Three areas were of particular interest to participating geoscientists and learning scientists alike: geologic time, complex systems, and visualizing the Earth.
- Research should be directed towards an understanding of how learning environments should be developed to effectively support students' achievement of geoscience expertise. Field experiences and experiences that engage students with geoscience datasets provide special, powerful opportunities for learning in the geosciences and should be a central part of these efforts.

Assessment tools are a critical aspect of this research to demonstrate when we are successful and the causes of this success. Excellent learning environments evolve over time, and assessment is essential to guide and measure evolutionary advances.

Dissemination — Currently, geoscientists are not fully aware of the advances in learning science that are relevant to their teaching. Materials need to be created and disseminated that present these results in a context that is accessible to geoscience faculty and makes a compelling case for adoption.

Professional development — Capacity needs to be developed for research on learning in the geosciences. Professional development opportunities that bring together geoscientists, educators, and learning scientists are a fundamental aspect of this capacity building, as are opportunities for faculty to develop their capacity to observe student learning and to design and evaluate their teaching practices.

In sum, we propose a coordinated effort among geoscience educators and learning scientists that works in a holistic fashion to articulate what is meant by geoscience expertise, the cognitive pathways to achieving this expertise, and the critical aspects of effective learning environments. This research and the tools developed for its implementation will allow students and faculty to understand what they are trying to learn and how it can most effectively be accomplished and to monitor the progress of learning. Toward this goal, it is recommended that a discipline-specific Center for Research on Learning in the Geosciences be established.

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INTRODUCTION: THE WORKSHOP

ONE OF THE MOST EXCITING AND INFLUENTIAL CHANGES UNDERWAY IN SCIENCE EDUCATION TODAY is the increasing application of research on learning to instruction. Not only is it clear from research that people learn by gradually building, modifying, and adapting their understanding on the basis of their experiences, but this fundamental aspect of learning is increasingly being incorporated into the design of learning activities (NRC, 1999). Similarly, studies of experts and expertise are informing the design of curricula, and research techniques are increasingly being applied to the evaluation of learning materials and instructional methods.

The geosciences are an important part of science education, focusing on the Earth system and its impacts on humans and on the ways in which humanity influences or changes the Earth in turn. To foster improved instruction and learning, a new community of scholars is needed to undertake research efforts that specifically address geoscience learning and expertise as well as the challenges of teaching in this field. Such disciplinary communities have played a critical role in the successful application of the principles of learning to science classrooms in other fields (e.g., chemistry, physics, mathematics).

This report presents the results of discussions held in Summer 2002 among 20 geoscience educators, cognitive scientists, and scholars engaging in educational research in other scientific disciplines. A three-day workshop was held July 8-10, 2002, at the Johnson Foundation's Wingspread Conference Center in Racine, Wisconsin. Prior to the workshop, participants posted essays on learning in the geosciences and participated in web-based discussions that helped to refine the agenda. The essays, a list of relevant resources, and other related information are available at the workshop website: *http://serc.carleton.edu/research_on_learning/workshop02/*. Our goals were to develop an understanding of the current state of research on learning in the geosciences, to identify research questions of high interest to both geoscience faculty and learning scientists, and to develop a plan for fostering improved application of research on learning in geoscience instruction.

From the discussion, three major themes emerged:

- **There is both a need and an opportunity for significant change in undergraduate geoscience instruction.** This can be realized through a clear articulation of what we want students to be able to do and the design and implementation of new instructional practices that are informed by learning science. Research into what it means to be a geoscience expert and how learning in geoscience is accomplished will illuminate these goals as well as the pathways to achieving them.

- **Several aspects of geoscience provide unique challenges to learning that can be approached through cognitively oriented research.** The study of these learning situations will provide a foundation for instructional design as well as opportunities for fundamental research into how people think and learn. Example areas include geologic time, spatial relationships, the Earth as a dynamic and evolving system, the use of visualization by geoscience experts and students, and making observations of natural, open, and complex systems to support reasoning about the connections between Earth and humanity.
- **Discovery of what will improve education in the geosciences must be coupled with mechanisms to bring those findings into widespread practice.** This will require basic research on cognition, research on effective educational practice, implementation projects, faculty professional development, and national dissemination.

Workshop participants affirmed that the geosciences present a favorable environment for systematic research in the learning sciences.

- **Geoscience educators are receptive to research partnerships with the learning sciences.** Their interest stems, in part, from their awareness that there has been a lack of research on geoscience learning that would correspond to that done in chemistry, physics, and other sciences and, in part, from the growing reconceptualization in the geosciences in response to new scientific approaches and interdisciplinary connections.
- **From the standpoint of cognitive and learning scientists, the geosciences are an exceptionally rich cognitive domain that offers both interesting parallels to and differences from other scientific fields.** In addition, geoscience education reaches a very large and diverse student population with a curriculum that offers accessible opportunities for student inquiry that is enlivened by numerous policy issues.

The workshop laid foundations for collaborations and partnerships between geoscientists and learning scientists, articulated below in four sections, which present

- Our common understanding of the **goals for geoscience education**;
- A conception of **expertise and learning in the geosciences** that will guide an anticipated program of research on cognition in geoscience as well as on the related basic issues in human cognition;
- A framework for the research and development required for **creating effective learning environments** in the geosciences; and
- **Recommendations for action**, including plans for national dissemination, professional development across the discipline, and research that will support improvements in geoscience education and make contributions to cognitive science.

“Thinking like a geoscientist,” in short, grows out of exposure to a continuum of scaffolded learning opportunities that start with the most basic of information and simplest of tasks and build gradually to a composite, integrated understanding of the Earth system.

Credit, Background Image: Captain Albert E. Theberge, NOAA Corps (ret.)

GOALS FOR GEOSCIENCE EDUCATION

AN OVERARCHING GOAL FOR GEOSCIENCE EDUCATION IS TO HELP EVERY STUDENT TO "THINK LIKE A GEOSCIENTIST." This includes the ability to understand the nature and processes of science and the roles of evidence and theory. A basic understanding of the Earth system, its composition, structure, and processes provides the knowledge base, methodologies, and global contexts that make science accessible, relevant, and meaningful for all students (Ireton et al., 1997). Our personal and communal health, security, and economic well-being are directly related to the connections between humanity and the Earth system, particularly in areas such as natural hazards, resource utilization, and environmental awareness.

For those who teach non-majors, helping them to "think like a geoscientist" translates into preparing them to make informed decisions as stewards of the Earth in their roles as voters, consumers, and contributing members of society.

For those who teach geoscience majors, and those who rely on geoscience expertise (e.g., journalists, policy makers), learning goals extend to a more sophisticated understanding of the Earth and mastery of related skills:

- The ability to observe nature and infer events in the past or processes beyond human perception;
- Understanding time, including rates, scales, and the relationship between the current state and the time-integrated history;
- Understanding geospatial relations and their representations;
- The ability to think simultaneously about temporal and spatial relations across many orders of magnitude;
- Creation and use of complex, multi-step models;
- Interpretation of incomplete data to derive rational conclusions;
- Integration of information across many subdisciplines of the geosciences and of related physical, life, and mathematical sciences; and
- The use of visualization to enhance understanding of complex systems.

"Thinking like a geoscientist," in short, grows out of exposure to a continuum of scaffolded learning opportunities that start with the most basic of information and simplest of tasks and build gradually to a composite, integrated understanding of the Earth system.

Having a firm grasp of what it means to "think like a geoscientist" is crucial to having productive discussions of both geoscience education and research on geoscience learning. Clearly articulated goals for geoscience learning provide instructors with guidance in developing courses and learning experiences. They clarify for students the aims of instruction in a course or major. They provide faculty with a framework in which to establish appropriate standards for student performance and outcomes. And — not least important in this context — they guide the development of research into what and how students are learning.

Goals for learning must be focused on students: what they should know, what they should be able to do, and how they can be encouraged to appreciate the value of science in their lives and in society. The geosciences can play at least four important roles in students' learning experiences:

- They can help students develop their understanding of the general nature of science;
- They can create an understanding of the geosciences in particular;
- They can provide an opportunity to integrate skills and learning from other sciences and mathematics in context; and
- They can provide an opportunity to apply scientific understanding to societal or personal decision-making.

In all of these roles, we identify goals for students that are related to

- **Content** — mastery of fundamental concepts and information that allows us to understand and function in the world around us;
- **Skills** — development of lifelong skills (e.g., reasoning, communication, quantification, graphical, collaborative) and technical skills (e.g., use of instruments);
- **Processes** — the ability to apply content and skills to a novel situation, to directly experience the methods and processes of inquiry and discovery, to formulate effective approaches to problem-solving, and to conceptualize, implement, and successfully complete a plan of action for an extended project; and
- **Attitudes** — understanding and valuing the processes and products of science and what it means to learn science and geoscience.

These goals can be summarized as the desire to help students develop in ways that lead toward becoming a geoscience "expert"— someone with the ability to think like a geoscientist and to apply geoscience knowledge to problems.

Expert geoscientists have many skills that are typical of scientists more generally (e.g., reasoning from evidence). However, in this report we focus specifically on goals, expertise, and learning that are either unique to the geosciences or particularly important in this field. Geoscience expertise includes both an understanding of important geoscience concepts (e.g., geologic time, plate tectonics, global circulation) and the skills that are essential to practicing and applying geoscience. Of increasing importance is the emphasis geoscience experts place on understanding the Earth system in the context of complex interactions in a heterogeneous, dynamic, uncertain, and often chaotic world (Ireton et al., 1997; NRC, 2001). How can we best help students learn to interpret data and draw conclusions about the Earth and Earth processes in ways that reflect the expertise and wisdom of the discipline?

The level or type of expertise we aim to develop will vary with setting and student. However, a strong grasp of what it means to have expertise in the geosciences can serve as a guide to the development of appropriate learning goals in all contexts. The workshop participants noted that the geosciences afford a number of special opportunities to broaden students' general scientific abilities. The geosciences are particularly well-suited to developing student understanding of the relevance of science and its application in daily life. In addition, since concepts from physics, chemistry, and biology play important roles in the geosciences, they can help students to transfer learning from other disciplines into a new context and to understand the linkages between disciplines and the value of bringing different tools and perspectives to complex scientific problems.

EXPERTISE AND LEARNING IN THE GEOSCIENCES

THE WORKSHOP, AS WELL AS PRE-MEETING ACTIVITIES, DEMONSTRATED THE IMMEDIATE FERTILITY AND POTENTIAL FOR COLLABORATION AMONG GEOSCIENTISTS, LEARNING SCIENTISTS, AND EDUCATIONAL RESEARCHERS from various perspectives who are willing to begin from first principles to build on each other's knowledge. Central to the group's discussion was a rich and systematic discussion of fundamental issues for the study of learning in the geosciences. The main results of the discussion are described in this section and provide the grounding for the anticipated research and development program which is addressed in later sections.

The discussion of fundamental issues begins with the consideration of the nature of expertise in the geosciences. Hypotheses about the nature of geoscience as a cognitive activity are developed in some detail. Because this report is oriented toward learning and instruction, these hypotheses are developed in psychological terms, but it should be pointed out that they entail assumptions about the logic of explanation and evidence in the geosciences. The workshop participants' provisional sketch of geoscience expertise frames the discussion, which follows, of a set of ideas about geoscience learning which emerged from the group's collective experience in the learning sciences, in research on learning in other disciplines (physics, chemistry, and biology), and in the study and practice of geoscience instruction.

Geoscience Expertise

At present, geoscience expertise is poorly understood. Determining its nature provides a major research opportunity for the future. Although research on geoscientific expertise will undoubtedly lead to considerable elaboration and revision of these remarks, discussions at the workshop established an initial conception of key cognitive dimensions of geoscientific knowledge:

- **Observation**. The pivotal role of evidential support in the creation, modification, and acceptance of explanations is a hallmark of science. Because evidence in the geosciences is largely observational and often ambiguous or incomplete, consequent causal models are often contingent and complex. Expert inference in the geosciences often involves gathering and weighing multiple, uncertain sources of data in the quest for convergent support. A model of scientific method and reasoning that emphasizes the systematic manipulation of variables and replicable laboratory control does not fit the research methods of this field well. We have much to learn about inferential reasoning with observational data, which is often uncertain, messy to some degree, and confounded or complicated by factors that cannot be experimentally eliminated. Although reductionism continues to have some value in geologic investigations, observations of complex natural systems increasingly require integrative or synthetic approaches to achieve more holistic understanding.

- **Confirmation**. A defining characteristic of expertise is the fluency of perception and action that arises from practice. This fluency often involves more than the tuning of peripheral sensory-motor mechanisms. To a surprising extent, arbitrarily abstract conceptual categories and the meanings associated with them can be integrated with perception. Thus, the fluent reader "sees" meaning, not black-and-white patterns, on the page. The physicist "sees" a situation in terms of a principle such as conservation of energy (Chi, Feltovich, and Glaser, 1981).

  These intuitions of the expert practitioners of a discipline reflect its core concepts and most fundamental meanings. An analysis of core concepts, of what it means to see the world as a geoscientist, is central to research on learning and teaching in the geosciences. One striking perceptual-cognitive skill discussed at the workshop is the ability of an expert to "read" the geological history of a field site in its physical features. This ability unites the visual, temporal, and conceptual aspects of the discipline in a heightened feel for physical place, augmenting a deeply rooted natural human tendency.

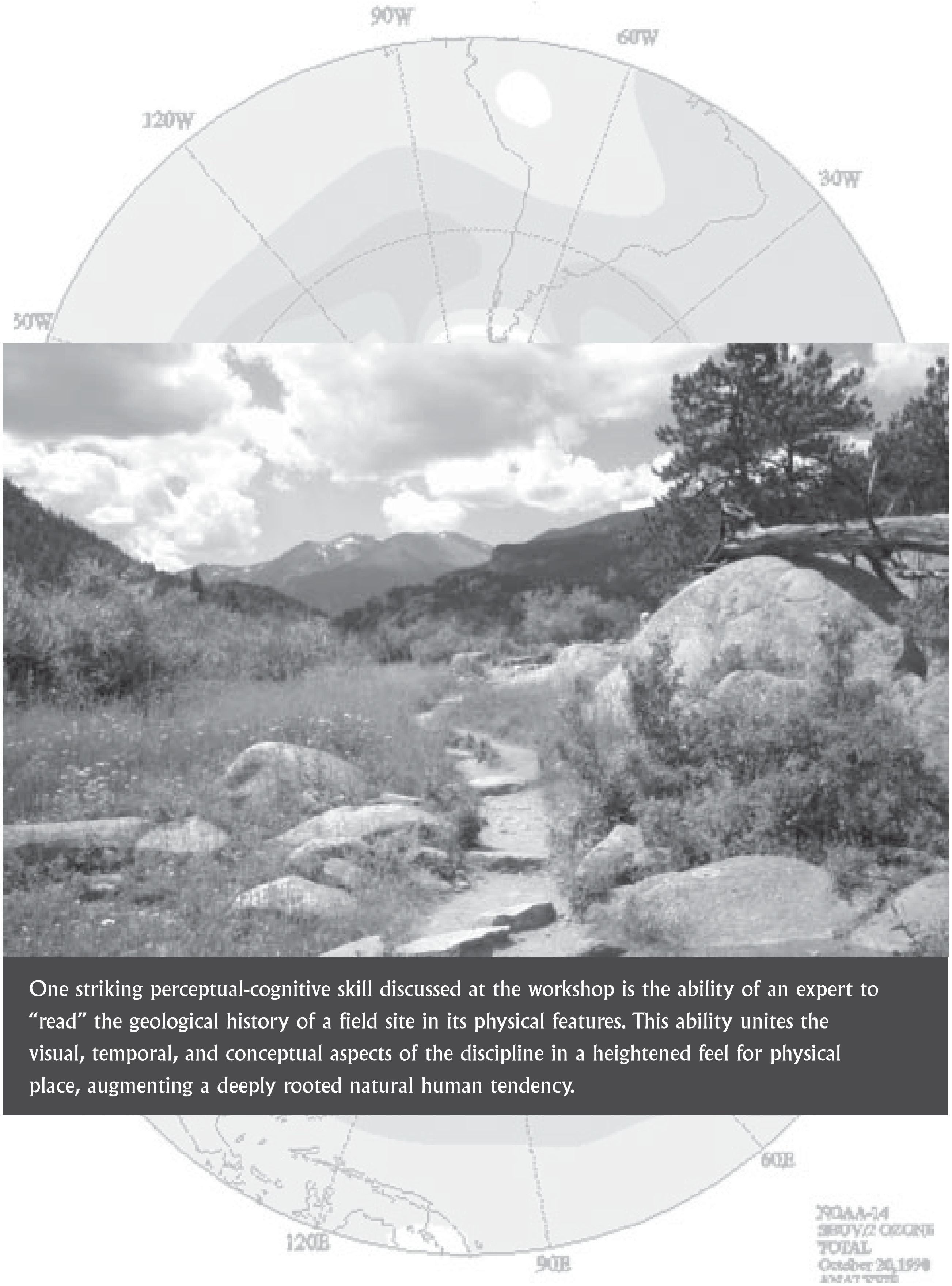
- **Explanation**. Explanation is an overarching goal of science; the theories and models of a field possess a special integrative role among its stock of concepts. Any analysis of core concepts in the geosciences, therefore, would necessarily feature major theories and models. A good deal of the discussion prior to and during the workshop abstracted away from the details of specific geoscientific theories. Rather, focus was directed on the complexity of explanatory models in the geosciences and on the hypothesis that a pervasive mode of explanation in the field involves models of complex systems with multiple interacting causal factors.

  The fact that geoscience is about a unique, exceedingly complex natural phenomenon, the Earth, affects the ability of the scientist to simplify, idealize, and set boundary conditions in constructing models. Geoscience appears to differ from physics and chemistry in this regard and, as a consequence, in its dependence on complex models. The complexity of explanation in geoscience is also affected by the fact that it is a higher-level science that draws on data and methodologies from physics, chemistry, and biology. (In its concern with complex phenomena and interaction, geoscience may resemble other higher-level sciences such as physiology or ecology. Workshop participants were not as familiar with the distinctive patterns of causal reasoning and model construction in such fields.)

- **Geological time**. Geoscience is a historical discipline in the sense that change in the Earth system over time is an intrinsic feature of many of its concepts. To a significant extent, to know geoscience is to understand a complex network of temporal relationships, and to think as a geoscientist is to think in terms of time. Working with this web of time-referenced concepts, which span many orders of temporal magnitude, requires cognitive, graphical, and quantitative representations of time that go well beyond those employed in everyday life.

- **Visualization**. The geosciences are rich in multidimensional visual representations. With some variation across subfields, experts clearly possess an impressive array of visualization skills and visually referenced concepts. These include the ability to interpret and to construct many different kinds of maps and the ability to relate a range of 3-D views of structure or patterns in the Earth, ocean, or atmosphere to processes that occur dynamically over time in three dimensions. It is of great interest that even for experts the forms and cognitive demands of these representations are changing rapidly with advances in digital imaging technologies.

What is most interesting about this initial sketch of cognition in the geosciences is the degree to which it is distinct from other sciences. As a result, geoscience



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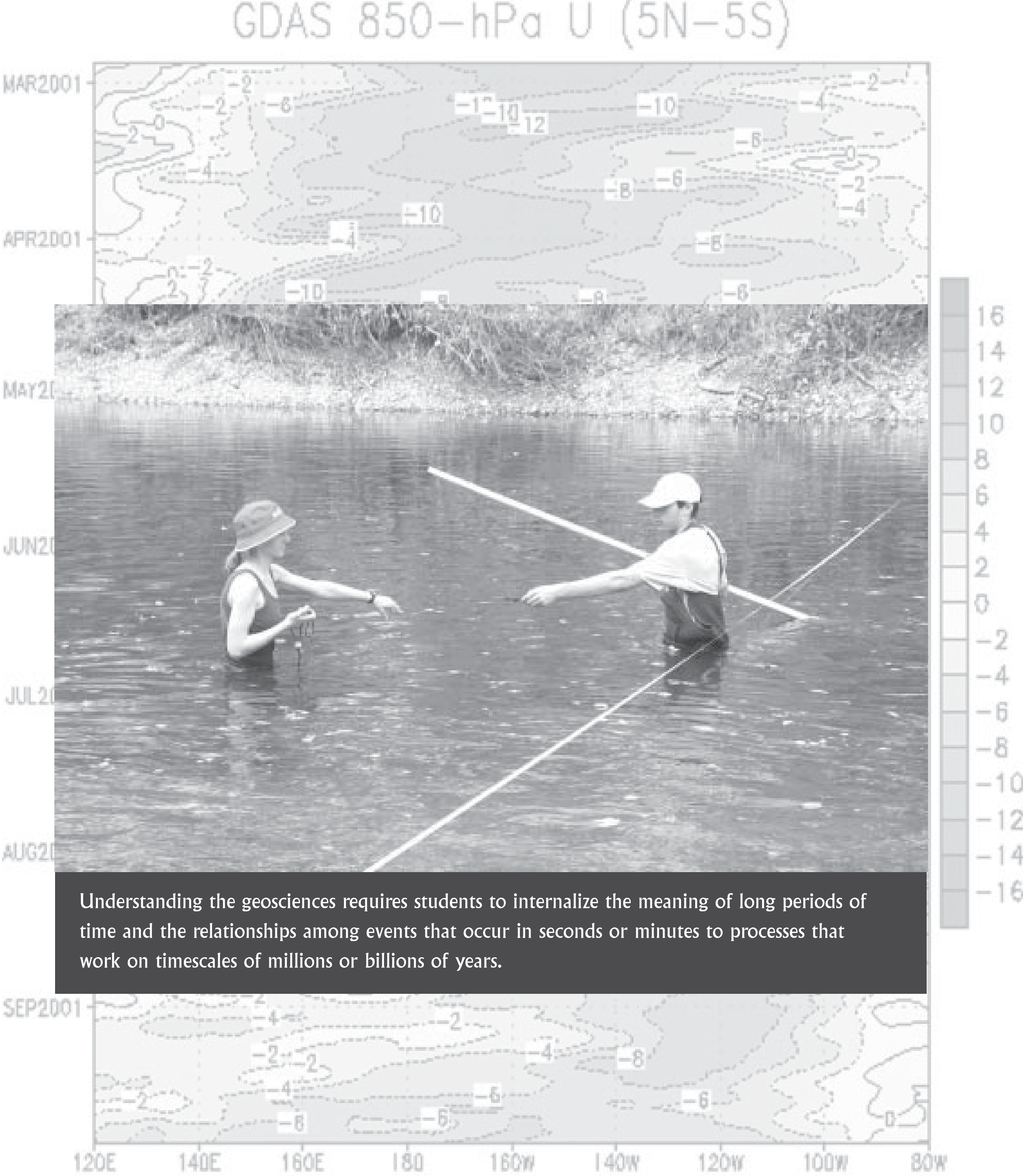
Credit, Background Image: NWS / National Centers for Environmental Prediction / Climate Prediction Center



Understanding the geosciences requires students to internalize the meaning of long periods of time and the relationships among events that occur in seconds or minutes to processes that work on timescales of millions or billions of years.

Credit, Background Image: NWS / National Centers for Environmental Prediction / Climate Prediction Center

offers new opportunities for research in cognitive science in addition to studies of the detailed expertise and learning needed to master specific key concepts in the field. It will also be necessary, of course, to study what it means to master and be able to reason with the central concepts of the discipline, such as the theory of plate tectonics, just as it has been important in research on physics learning to understand reasoning with Newton's laws (Hestenes, Wells, & Swackhamer 1992; Hake, 1998).

Geoscience Learning

Building on our initial sketch of geoscience expertise, we can ask how each aspect of geoscientific cognition is learned and how the learning process is related to more general issues in cognitive and intellectual development. Three areas were of particular interest to participating geoscientists and learning scientists alike: geologic time, complex systems, and visualizing the Earth.

Geologic Time

Learning about geologic time was singled out as a specific area of challenge by the geoscience educators at the workshop. Research on how a concept of geologic time develops out of everyday conceptions of time was of considerable interest to the cognitive scientists in the group.

Some researchers in cognitive science have suggested that the visual metaphor of the linear time line is a biologically natural representation for temporal reasoning (Lakoff and Johnson, 1980). The time line, however, is an inadequate representation for *geological* time. Understanding the geosciences requires students to internalize the meaning of long periods of time and the relationships among events that occur in seconds or minutes to processes that work on timescales of millions or billions of years. Such understanding requires a logarithmic representation and an ability to "zoom" mentally to different levels of temporal detail associated with different degrees of precision and accuracy. Quantitative representations of time involving powers of ten or rates of change are also challenging for many students. Finally, learners must coordinate the organization of geoscience concepts in terms of temporal representations with 2-D and 3-D spatial representations and with conceptions of underlying causal processes.

For example, mountain ranges are built over the course of millions of years by the cumulative effect of faulting and folding. However, the movement on faults occurs in discrete faulting events that take minutes or seconds. In addition, the understanding of time is often represented in the geologic record by spatial variation in deposits. The simplest example of this is a layered stratigraphy with oldest rocks at the bottom. More complex relationships are more typical, however. A river, for example, may simultaneously deposit gravel on its bed and silt on its banks. As the river migrates through space over time, layers of gravel and silt can be produced that contain deposits of different ages within a single layer. Thus, the student must work with complex spatial relationships and their correlations to changing processes acting through time.

This complex coordination of temporal and spatial evidence and causal process is critical, and it may be particularly difficult because understanding cannot be mediated by more direct access to events. Many geologic processes were never directly observed by anyone, and the conceptual leap from analogous processes that are observable to an understanding of the relevant geologic concept can be considerable. Consider, for example, what it takes to make the jump from observing convection of cream in a coffee cup (taking place on timescales of centimeters per second) to understanding convection operating in the Earth's interior (occurring with rates of millimeters per year). Since so much of our understanding of geologic time is based on concepts that we cannot experience directly, learning about geologic time may require different types of thinking than are applied in much of experimental-inquiry–based science.

Complex Systems

Learning about the Earth system is difficult. The Earth is a large, complex, non-linear system comprised of many sub-systems interacting through diverse chemical, physical, and biological processes over a range of spatial and temporal scales. These processes leave only a partial record of their history. Thus, critical challenges for geoscience students are developing a general understanding of how complex systems work, a specific understanding of the relationship of general concepts to specific aspects of the Earth, and strategies for observing and understanding complex natural systems through time.

Workshop participants identified several ways that complexity challenges students at a more basic level:

- Language about the Earth system is confusing or inadequate and is somewhat confounded by the creation of *ad hoc* names for objects and processes that are often rooted in historical or regional contexts, commingling of descriptive and genetic (or interpretive) terms, and general lack of consensus among diverse interests (e.g., in the recognition of major sub-systems.)
- Accessible representations of the system and its components are difficult to construct due to the complexity needed for accurate representation and due to incomplete understanding by the scientific community. Representations that *are* accessible to students are often unrealistic in their portrayals (and may be misleading or incorrect in their attempt to simplify), yet multidimensional representations of Earth phenomena defy attempts to succinctly convey information and their relations.
- A sequential model for learning, wherein one concept provides a starting point for the next, is not applicable. In the geosciences it is often necessary to understand two equally complex ideas at the same time. (For example, an understanding of plate tectonics requires an understanding of volcanic processes — and an understanding of volcanic processes requires an understanding of plate tectonics.) This is particularly evident in cyclical phenomena in the Earth system which have no clearly defined starting point and in which all parts of the cycle are integrally related to all other parts via dynamic processes and feedback mechanisms.
- There are often multiple possible causes for the same type of observable event. (For example, a change in average atmospheric temperature may reflect changes in solar radiation budget, changes in atmospheric composition, or changes in the Earth's albedo.)
- A satisfactory understanding, even at earlier levels of instruction, requires integration of many facets of Earth science and of fundamental scientific principles.

Expert geoscientists are facile at creating explanations based on complex conceptual models. They test these explanations with information derived from multiple, uncertain observational data sources. Their learning of new geoscientific concepts and skills is facilitated by a mature and active understanding of these strategies, but it is a safe assumption that most students enter college without this understanding. Even the best inquiry-oriented science instruction in their previous education probably emphasized controlled experimentation and relatively straightforward causal models. These students will have naïve or incomplete views of how geoscientific knowledge is structured and justified; this will affect their understanding of disciplinary particulars, which depend on the epistemological context. They face a bootstrapping process in which the challenge of learning more advanced science should spur their epistemological development, which in turn should facilitate their mastery of content. A crucial research objective, therefore, is coming to understand learning sequences not only in terms of the mastery of particular concepts or skills but also in terms of progress towards a more sophisticated and active grasp of the modes of explanation and empirical justification that are typical of the geosciences.

Visualizing the Earth

Research on visualization is a prominent strand of contemporary cognitive and learning science. Topics range from the basic neural capacity for visual imagination to students' mental processes while learning from 3-D molecular models in chemistry. The intrinsically spatial nature of many of their concepts and the extensive use of multi-dimensional visual representations make the geosciences an excellent site for research into spatial concept learning, visual imagery, and visualization. Maps of all kinds are intrinsic to geoscience investigations on many scales: topographic, geologic, and hydrologic maps derived from field observations; outcrop-scale maps that demonstrate mesoscopic relations; microscopic petrographic maps that identify minerals and their textures in thin section; X-ray elemental maps derived from electron beam analysis that demonstrate compositional differences in minerals on a micron scale. This extensive use of complex maps and of representations of 3-D transformations offers the visual cognition researcher a rich set of materials grounded in actual practice.

Geoscience investigations also commonly use multi-component datasets or integration of diverse datasets to describe and interpret the Earth (e.g., Manduca and Mogk, 2002a and 2002b). Diverse representations of these datasets are often used to demonstrate relationships which have specific meaning for "experts" but which are often impenetrable to "novices" (e.g., phase relations in the "basalt tetrahedron," mineralogical and structural stereonet projections, hydro-geochemical "Piper diagrams," seismic first motion "beach ball" diagrams).

New research is likely to yield insights both into visual cognition and into significant cognitive challenges for geoscience students at all levels, since teaching students to observe, to learn from and create visual representations, and to work with visual data are central aspects of geoscience education. The large and diverse undergraduate populations at introductory and more advanced levels offer opportunities for developmental studies and investigations of gender differences in spatial cognition. The increasing incorporation of computer-based visualization into professional practice and teaching also make the field a natural context for studies of the impact of digital technologies on visual learning.

CREATING EFFECTIVE LEARNING ENVIRONMENTS

WE ALL LIVE IN THE WORLD, DEPEND ON ITS RESOURCES, AND ARE IMPACTED BY ITS PROCESSES ON A DAILY BASIS. Yet, it is often a challenge to get students to observe the world around them and make these connections to their personal lives. In the previous section, we sketched a conception of what we want students to learn and of the cognitive challenges that often face them as they develop this understanding. This conception, particularly when fleshed out by further research, can provide a grounding for creating effective learning environments.

Workshop discussions highlighted the importance of creating learning environments that

- Foster students' ability to use and understand visualizations and other representations of data, understand complex causal models, gain an appreciation of geologic time, and apply geologic knowledge and approaches to public policy and decision-making;
- Motivate learning (Edelson, 2001);
- Recognize different learning styles at different life stages of an individual and for different people;
- Understand opportunities and challenges for learning in different physical spaces, including the field, lab (both for studying physical objects and computer-based objects), and classroom settings;
- Foster a transition from student initial thinking to thinking that is more like that of expert geoscientists;
- Implement an integrated framework for instruction across academic levels; and
- Improve attitudes toward science and develop an understanding of the role of science in society.

Students bring a wide variety of ideas about science, geoscience, and society to their learning. A fundamental lesson from research on learning is that our learning environments must help students themselves transform their existing understanding of a subject into one that reflects new knowledge (NRC, 1999). This requires that learning environments and activities take into account our students' current knowledge, misconceptions, and attitudes and provide opportunities and motivation for them to change and grow from this starting point.

Learning can be viewed as a process that begins by establishing what students know and what they want or need to know and proceeds by determining how to move them from where they are to where they want to be. (At this point, we know very little about the initial conceptions that students bring to the study of the geosciences at various levels of instruction. The research initiative we propose later in our recommendations for action must address this gap.) To help this process, students should have the opportunity to move beyond their personal experiences and into a variety of physically distinct learning spaces. In so doing, they can take advantage of, and integrate across, learning modalities that are optimized by making observations in the field, performing experiments in a lab, accessing computer-based technologies, and participating in a variety of classroom activities.

Much recent research on college and pre-college instruction supports the conclusion that traditional environments based on textbooks, lectures, and memory-based assessments do not optimally support the development of conceptual understanding, scientific inquiry skills, more sophisticated epistemologies, and an increased interest in science (NRC, 1999; Linn & Hsi, 2000; Schmidt, et al., 1997; Chi, et al., 1994; Bereiter & Scardamalia, 1989; Brown, 1997; Koedinger, et al., 1997). There is now a large arsenal of learning activities that are hypothesized to foster desirable learning outcomes, and in some disciplines there is considerable evidence to support the hypotheses (Redish, 1999; Hake,1998). The methods range from concept tests with small group discussion, peer-led team learning workshops, and model-based reasoning problems to extended inquiry projects, case-based learning, and extended critical writing assignments with structured peer or instructor feedback.

Geoscience educators at the workshop reported that many faculty feel that some of the largest barriers to learning geoscience are student attitudes and expectations. They commented on the difficulty of getting students to move beyond rote learning and multiple-choice tests to engage in the learning experience. Workshop participants are anxious to see learning environments develop that challenge students to change their attitude toward science and their expectations for geoscience learning, as well as enhancing their thinking skills, content understanding, and confidence in their ability to apply geoscience and science knowledge in their lives. The geosciences appear to be particularly well suited to strategies that use a social context to create such a learning environment, including the use of local issues or concerns, societal controversies, or historical events to motivate and organize learning.

Working with Geoscience Observations and Data

The tradition of including field experiences in undergraduate instruction is one of the strongest elements of current geoscience education, and it offers a platform and organizing strand for the design and refinement of learning activities and environments. Geological field experiences offer a number of advantages for inquiry-oriented science instruction:

- A field site typically offers a wealth of visible evidence;
- Particular field sites have specific histories that can pose unique scientific problems for students;
- The visible evidence at a site can be progressively deepened using other accessible measurement and collection techniques;
- Evidence from the site can be enriched with available GIS (geographic information system) information from the same geographical area or from similar sites elsewhere; and
- Explanatory hypotheses and their connections with evidence at a site are often accessible to beginning or intermediate students.

Traditionally, field methods are viewed as a fundamental technical skill and are taught to majors as part of their professional training. However, workshop participants believe that learning in the field may be playing other important and more fundamental roles in creating geoscience expertise. For example, learning in the field may be critical to the development of spatial reasoning, to the ability to create integrated mental visualizations of Earth processes, and to developing facility with analyzing the quality and certainty of observational data supporting geoscience theories. Much research is needed in this area both to determine the role of field study in geoscience expertise and to establish effective practices for field instruction at different levels of the curriculum.

Complementing learning in the field are learning experiences that engage students with geoscience datasets. These experiences are widely acknowledged as important to developing an understanding of scientific thinking and of geoscience expertise and as a critical aspect of science and geoscience education (Ireton et al., 1997; Manduca and Mogk, 2002a and 2002b). Geoscience datasets include global datasets, datasets that integrate multiple data sources or types, and results from models and simulations. Of particular interest to workshop participants was achieving a better understanding of principles for designing activities that allow students to learn how to interpret data and apply it to life decisions. A wide variety of research questions emerged including

- How to support students in learning to access, use, and interpret data;
- How to support students in learning to draw relationships between data representations and reality or alternative hypotheses;
- What characterizes activities with data or data representations that motivate learning; and
- What are effective design principles for data-rich learning activities for different purposes and audiences?

Activities that engage students with data are, more than any other aspect of geoscience education, intertwined with technological tools. Thus, much discussion was focused on the effective use of technology in developing data-rich learning environments. The fundamental question in this area was “Do students learn differently or better when working with different kinds of technological representations?” Areas to consider include

- Does the ability to manipulate a representation make it easier to interpret?
- Does familiarity with the 2- and 3-D visualizations used in video games impact the ability of students to interpret representations?
- How do technological representations allow us to guide students’ understanding of what is important or meaningful in a representation?
- How can technology scaffold student learning about data, representation, and Earth science?

A second major question regarded the role of technologically enhanced learning environments in replacing or supporting traditional teaching methods, including field observation, experiments, and physical models.

Working with Geologic Time and Complex Models

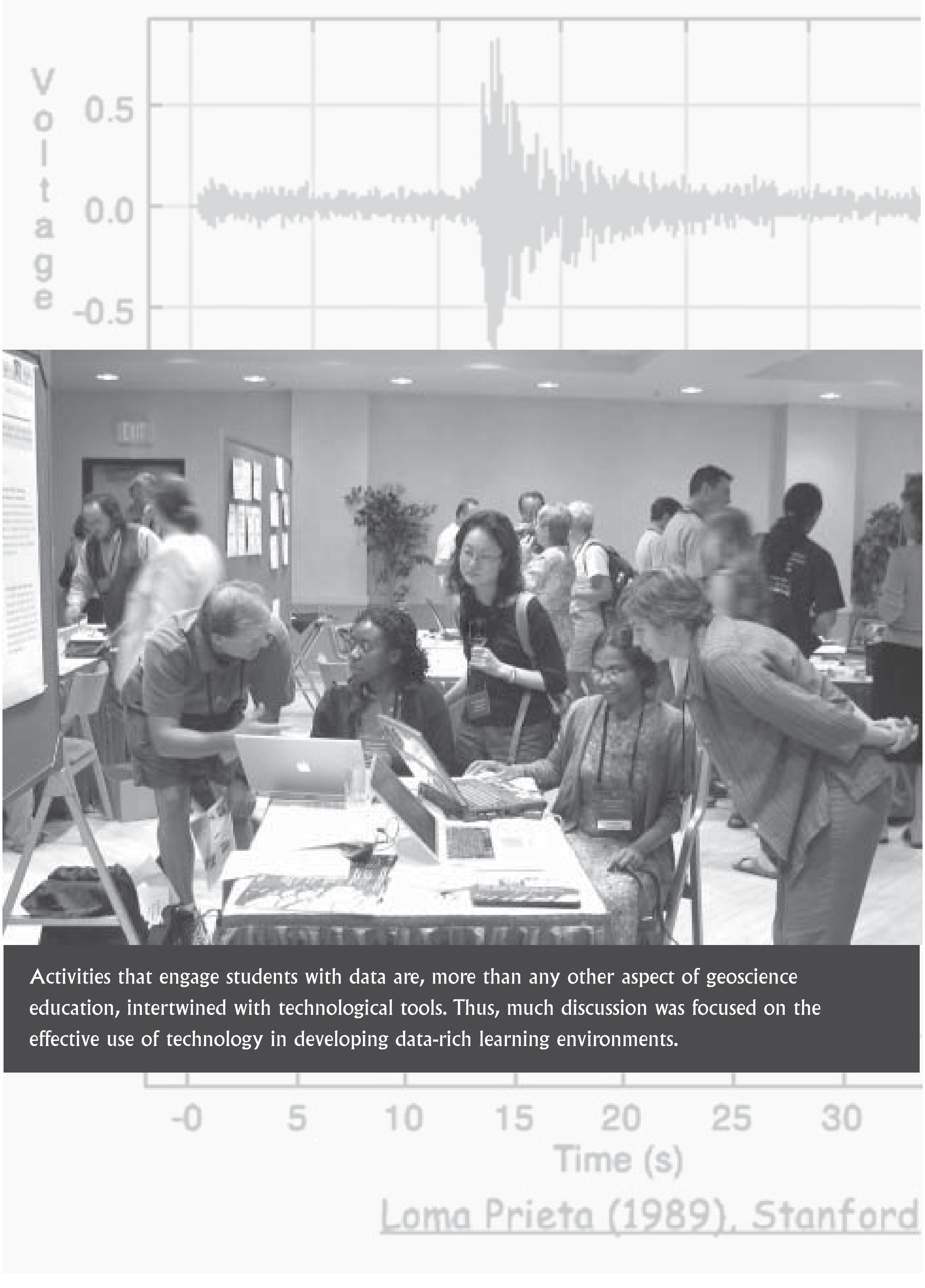
In teaching about geologic time, geoscience teachers have developed an array of techniques that can be categorized as featuring narrative, analogy, or representation.

Narrative is a familiar form for dealing with time. We often describe a geologic history in narrative form, telling the story of an area’s evolution.

Analogies are designed to help students grasp the relationships between scales, rates, and processes and to jump from familiar experiences to geologic ones. For example, we typically help students understand the slow rates at which rocks deform by providing an analogy to glass flowing in windowpanes, warming butter flowing on a dish, or silly putty being slowly stretched. The analogy between convecting coffee and convection in the mantle, atmosphere, or ocean provides a starting point for understanding the rates of movement in these very different environments.

Representations help us scale things appropriately. Most students and scientists begin their understanding of geologic time by creating a representation of geologic events on a time line which conveniently conveys the brevity of human habitation of the planet compared to all Earth history. Scaled computational or physical models that mimic geologic processes in seconds, minutes, days, or months are important tools for students and scientists alike in developing an understanding of the cumulative effect of slow processes operating over large timescales.

These teaching techniques constitute an existing test bed for educational research and for design experiments that would increase understanding of how to develop pivotal cases that expand students’ understanding of time to include geologic timescales, rates, and observations of pre-history. A set of examples could be developed to explore the use of narrative, current controversy, local motivation, hands-on activities, and analysis of data with a temporal component to develop understanding of geologic time and rates. A willingness to alter classroom organization offers the potential to expand the traditional techniques. For



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example, an interesting use of narrative to understand aspects of time is explored in the recent best seller *Longitude*, which uses a historical event to motivate understanding. The current, heated debate regarding evolution and creationism has tremendous potential for exploring all aspects of geologic time, including the development of skill with ordering events, determining rates, and placing events in intervals of absolute time.

Ideas about helping students learn to deal with complex models are perhaps less well developed in geoscience teaching, although workshop discussants felt strongly that learning at all levels will be strongly affected by the success with which students are introduced to the complexity of geoscience theory and data. There are opportunities for important new work in this area, addressing ideas as diverse as

- How do experts learn about complex systems? In particular, what are the relationships between their development of a conceptual model or theory and their observations and understanding of the natural system?
- What methods work in developing this type of thinking in students? What are the paradigmatic models at different levels of instruction?
- What sequencing works to help students learn both about pieces and the integrated system?

Learning Environments Based on Research

Excellent learning environments develop and evolve over time. To effectively guide this evolution, it is essential that we understand when we are successful and the causes of this success. Research is needed that addresses all aspects of the learning environment, including objectives, instruction, student assessment, and program assessment.

- **Learning objectives**. The definition of appropriate learning goals for different levels of instruction will be both a necessary point of departure for research on learning environments and a continuing result of the research. Desired outcomes should be articulated in terms of general principles of the learning sciences, the range of knowledge and skill in the entering students at various levels, and known or hypothesized learning sequences in the discipline.

  It should be pointed out here that, traditionally, the learning objectives for college science have not been articulated this way at all. Instead, they have been defined in terms of the formal structure of knowledge in the discipline, leading to discussions of coverage and prerequisite structure.

  At present, goals for geoscience learning are not well articulated. A common understanding of the characteristics of a geoscience expert is lacking, as is a firm understanding of what we want students to be able to do at the end of either an introduction to geoscience or the completion of a major. These goals will necessarily vary among the different parts of the geoscience community and from institution to institution. At present, however, we have few examples to draw from. Clearly, the content of a discipline matters. The program of learning research sketched above requires a detailed study of expert knowledge and pathways of acquisition.

- **Learning environments and methods of instruction**. Once the objectives of learning are clear, research is needed to determine the relationship between particular methods of instruction and the learning that is desired. The workshop demonstrated that geoscience educators are ready to undertake the program of research and development that is required to design, test, and optimize teaching techniques for use in the geosciences. As described above, learning in the field and learning with data (and the associated issues of technology) were of particular importance to workshop participants. The nationally coordinated effort developing out of the workshop is a unique initiative in the learning sciences, one which will allow comparative research at multiple sites on a range of instructional innovations addressing the issues in cognition and learning sketched above.

  For example, one difficulty with traditional undergraduate curricula is that entry-level courses have often been restricted to a relatively shallow introduction of a very wide range of concepts. The presentation of the material and the modes of assessment encourage students to adopt rote memorization as a primary learning strategy. The resulting memory structures are often poorly integrated (Bjork, 1999; Bereiter & Scardamalia, 1989). As a result, they lack persistence, are retrievable in only limited contexts, and provide very little support for reasoning or for more advanced learning. Instructors in mid- and upper-level courses often feel that they must re-teach the fundamental material, complaining that students seemed to have learned nothing in the introductory course.

To make progress in this area, we recommend that researchers use the results of prior and ongoing research to design target developmental sequences for geoscience learning and to relate them to current and potential organizations of the curriculum. For example, a goal for useful introductory instruction should be the acquisition of coherent conceptual structures that support scientific reasoning at beginning levels as well as the transition to more advanced learning. Sociological research can help faculty develop successful methods for negotiating new roles and responsibilities for students in their learning and developing transitions from old ways to learning environments that incorporate our best understanding of how people learn.

- **Student assessment**. Building instructional environments that are learner-centered as well as content-centered has profound consequences for student assessment that are only beginning to be explored in college science. Instruction that genuinely scaffolds conceptual development requires continuous formative assessments that provide feedback to both students and teachers about student learning. The relatively rigid separation between instruction and tests that characterizes much of college science teaching breaks down when assessments are used as learning experiences and when much of the instruction challenges students to use concepts actively.

  A key step in making progress will be to advance our knowledge of how formative assessment can be used to drive productive instruction in the geosciences, as well as in college science generally. The questions of what to assess and how to assess it must both be addressed. The development of learning objectives for various levels of geoscience instruction, based on learning research, will suggest concepts and forms of reasoning that must be assessed at key points to support successful learning. Classroom research will involve the design and evaluation of learning experiences that incorporate valid assessments. Summative student assessments, such as course grades, must also be carefully redesigned for learning-centered environments, and research must be conducted to determine whether the new assessments succeed in measuring significant learning.

- **Program assessment**. In the development of learning-oriented instructional environments, student assessment plays the dual roles of supporting individual student learning and of providing feedback to researchers and instructors on the success of their interventions. An advantage of the community-based initiative proposed here is that interventions in real instructional settings can be sustained long enough to ensure not only that the initial design is conceptually sound but that research-oriented student assessments can be used to refine or redesign the interventions. The sustained research-based curriculum development made possible by the initiative has the potential to build a cadre of learning researchers within the geoscience community.

An integrated research agenda that combines these four areas in a synergistic fashion can guide the development, assessment, and revision of geoscience programs that are capable of developing geoscience expertise in a wide range of students destined to work in a broad range of professions.

Geoscientists are not fully aware of the advances in learning science that are relevant to their teaching. Materials need to be created and disseminated that present these results in a context that is accessible to geoscience faculty and makes a compelling case for adoption.

Credit, Background Image: NESDIS / National Climatic Data Center

RECOMMENDATIONS FOR ACTION

A FUNDAMENTAL OUTCOME OF THE MEETING WAS THE RECOGNITION THAT BRINGING RESEARCH ON LEARNING TO THE GEOSCIENCES PROVIDES IMPORTANT OPPORTUNITIES FOR BOTH IMPROVING GEOSCIENCE AND SCIENCE EDUCATION and furthering our understanding of how people think and learn. A concerted effort will benefit geoscience research and education, science education more broadly, learning science, and educational research. Workshop participants recommend activities in three areas:

- **Research** — New research that addresses areas of high interest to both geoscientists and learning scientists will have major benefits in both fields, improving the ability of geoscientists to both pursue their own research and to instruct their students while providing new avenues to address important issues in understanding human cognition and learning.
- **Dissemination —** Currently, geoscientists are not fully aware of the advances in learning science that are relevant to their teaching. Materials need to be created and disseminated that present these results in a context that is accessible to geoscience faculty and makes a compelling case for adoption.
- **Professional development** — Capacity needs to be developed for research on learning in the geosciences. Professional development opportunities that bring together geoscientists, educators, and learning scientists are a fundamental aspect of this capacity building, as are opportunities for faculty to develop their capacity to observe student learning and design and evaluate their teaching practices.

Research Themes

New research plays a central role in bringing research on learning to the geosciences. Workshop participants recommend aggressive studies in three areas:

Cognitive Content

Studies must address the general cognitive character of geoscience and its relationship to other types of scientific expertise. In addition, studies that address the specific mastery of key concepts such as plate tectonics, geologic time, or the climate system will be needed.

Learning and Development

Studies of the learning pathways that lead to geoscience expertise provide an understanding of students' initial conceptions and the challenges of achieving stable conceptual change. Specific incomplete or faulty initial conceptions will have to be identified, as will intermediate states of knowledge in which novice and expert conceptions coexist uneasily or which rely too heavily on memorization or conceptually shallow algorithmic skills.

Learning Environments and Instruction

Studies are needed that determine the relationship between teaching and learning in the geosciences and place decision making about instructional methods on a scientific footing. These studies must include

- Defining appropriate learning goals that are articulated in terms of general principles of the learning sciences, skills and knowledge possessed by entering students, and learning sequences;
- Determining the relationship between particular methods of instruction and articulated learning outcomes;
- Developing continuous formative assessment methods for student learning; and
- Analyzing assessment results to design new experiments and improvements in learning environments.

We propose a coordinated effort among geoscience educators and learning scientists that works in a holistic fashion to articulate what is meant by geoscience expertise, the cognitive pathways to achieving this expertise, and the critical aspects of effective learning environments. This research and the tools developed for its implementation will allow students and faculty to understand what they are trying to learn and how it can most effectively be accomplished and to monitor the progress of learning.

Dissemination

Important information about the application of research on learning to education has been available for more than a decade, and excellent publications written specifically for faculty summarizing this research are now available (NRC, 1999; NRC, 2001). While there is much work that we can do to bring these resources to the attention of geoscience faculty, workshop participants emphasized that it will also be important to publish materials that place these research results in a geoscience context. Materials for the physics and medical communities that speak directly to the specific issues and examples faced in their classrooms provide an excellent example of the type of resources that are needed (Redish, 2003; Michael and Modell, 2003).

Similarly, it will be important to produce materials that summarize the compelling case developed in physics for improved learning gains related to active engagement of students (Hake, 1998) and that draw relationships to learning in the geosciences. Publications that target geoscience faculty and educators and relate to their experiences will be much more effective in capturing their interest and transforming their understanding of learning science. Once they have begun to understand the implications of research on learning for their teaching, they will be ready to read the existing literature.

Developing materials that will speak to geoscientists is the first step in bringing existing research to this community. This must then be coupled with a strong dissemination effort. Publication in newspapers and journals that reach the geoscience community can form a starting point for this dissemination. Professional societies (e.g., AGU/American Geophysical Union, GSA/Geological Society of America, AMS/American Meteorological Society, NAGT/National Association of Geoscience Teachers) provide important avenues for dissemination through their meetings, committees, and outreach programs. The first steps in this area have already taken place with workshop participants and other learning scientists involved in sessions at

- GSA (Pardee Session—Toward a Better Understanding of the Complicated Earth: Lessons from Geologic Research, Education and Cognitive Science), *http://serc.carleton.edu/research_education/talks.html*
- AGU 2002 Fall Meeting (Using Global Data in a Local Context, link to Fall 2002 meeting, Friday afternoon sessions), *http://www.agu.org/cgi-bin/sessionsf*
- On the Cutting Edge workshops sponsored by NAGT (Using Global Data Sets in Teaching

Earth Processes, Design Principles for Creating Effective Web-Based Learning Resources in the Geosciences), *http://serc. carleton.edu/ NAGTWorkshops/globaldata02/index.html* and *http://serc.carleton.edu/NAGTWorkshops/ webresources03/index.html*

- The 4th International Conference on Geoscience Education (Calgary 2003), *http:// www.geoscied.org/techprog.htm*

This dissemination process provides a unique opportunity to study how a disciplinary community comes to incorporate new information from an exterior source in its educational practice. Documentation of what works in the dissemination of research on learning to geoscientists provides the basis for an important contribution to the larger educational community.

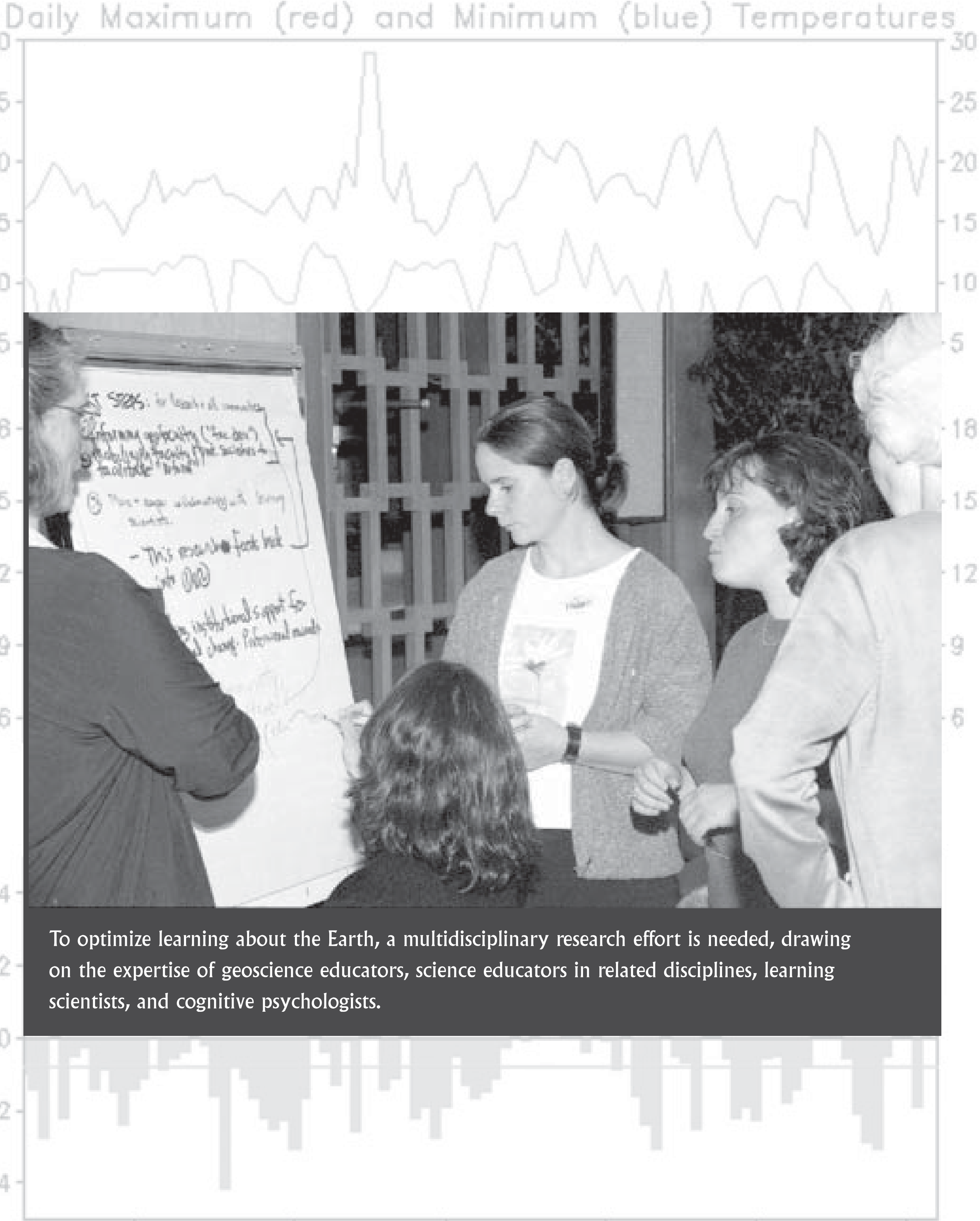
Professional Development

Fundamental to implementation of the research agenda put forward in this report is the creation of a new community of disciplinary science education researchers in geoscience. This community will form a bridge between the work taking place in cognitive science, education, and other scientific disciplines and faculty and educators in geoscience. The core of this new group includes the workshop participants and others including Ph.D. geoscientists who have shifted their focus to research on learning, learning scientists and educators with a special focus of the geosciences, faculty, curriculum developers, and teachers who are working to test the implementation of learning science theory in the classroom, and others who work on special projects that improve our collective ability to teach geoscience.

Workshop participants recognized the importance of nurturing this newly emerging community by fostering opportunities to learn from one another and to work together. Recommended activities include:

- Sessions at professional society meetings and publications in journals on research taking place in learning in the geosciences in all three contributing disciplines: cognitive science, education, and geoscience;
- Small grants to enable the establishment of collaborations and site visits;
- Joint projects and meetings that sustain and build collaboration;
- The establishment of a Science of Learning Center in the Geosciences;
- A special outreach effort to early-career researchers in geoscience, education, and cognitive science; and
- Collecting and disseminating examples of collaborative projects that exploit the synergies between learning science and geoscience (visualization appears to be a particularly fertile area for this).

Workshop participants felt that a second, equally important focus for professional development should be improving the ability of present and future faculty and teachers to reflect on their teaching practice and assess its effectiveness. An integral part of this ability is the skills needed to observe students engaging in learning, to evaluate student learning and its relationship to teaching, and to implement changes in instruction based on the results of observation and evaluation. While all faculty will benefit from increases in these skills, it is particularly important that faculty teaching future teachers model this behavior. Workshop participants recognized that a variety of approaches to faculty professional development, including publications and workshops, could be effective in this area. However, the development of action research projects that engage faculty in observations of their students appears to be a particularly promising approach. Work in the United Kingdom that is engaging faculty at a variety of institutions in research on the impact of field studies on learning (King, 1993; King, 1998) serves as a model for the type of program that might be undertaken. This program might begin by offering opportunities to interested faculty across the community.



To optimize learning about the Earth, a multidisciplinary research effort is needed, drawing on the expertise of geoscience educators, science educators in related disciplines, learning scientists, and cognitive psychologists.

Credit, Background Image: NWS/National Centers for Environmental Prediction / Climate Prediction Center

CONCLUSIONS

THE STUDY OF THE EARTH, ITS COMPOSITION, STRUCTURE, PROCESSES, HISTORY, AND EVOLUTION is an integral part of science, technology, engineering, and mathematics (STEM) education. Studies of the Earth system provide natural laboratories that are intrinsically interesting and accessible to students, that demonstrate applications of fundamental principles from sister physical and life sciences, and that demonstrate the integral connections between the Earth and our personal and communal lives (Ireton et al., 1997). Studies of the Earth system are increasingly multidisciplinary, emphasizing the connections, relations, and feedback mechanisms among and between different Earth system components.

At the same time, realizing the open, heterogeneous, dynamic, and complex nature of the Earth, there is growing recognition of the importance of teaching about the Earth using a systems approach. This presents many challenges and opportunities. To optimize learning about the Earth, a multidisciplinary research effort is needed, drawing on the expertise of geoscience educators, science educators in related disciplines, learning scientists, and cognitive psychologists. Workshop participants affirmed that:

- The geosciences offer scientific knowledge and methodologies that are of broad interest, with unique characteristics that complement research on learning in related disciplines. Special focus on time, spatial relations, complex systems, and the use of visualizations will extend current knowledge of how people learn in these domains.
- There is a need for discipline-wide professional development activities, including integration of research on learning in the geosciences into current instructional practice and training of geoscience faculty to contribute to research on learning through explorations of their own learning environments.
- There is a concomitant need for dissemination of the results of research on learning in the geosciences for broad application in curricular design and implementation.
- A coordinated, collaborative effort is needed to engage a discipline-wide research program on learning in the geosciences, to facilitate learning for ALL students, in diverse learning environments. Towards this goal, it is recommended that a discipline-specific Center for Research on Learning in the Geosciences be established.

This workshop provided the first steps towards forming a new scholarly community dedicated to understanding learning in the geosciences. The workshop participants strongly felt the need to increase the recognition of and reward for geoscientists who undertake research on learning.

- Geoscience education research should be pursued as a research field in many institutions. It should be recognized as both objective and experimental in nature.

- Geoscience education research should develop publication and dissemination mechanisms that promote peer review and reproducibility typical of any other research field.
- Geoscience education research can and should be subject to the same criteria for evaluation (papers published, grants, etc.) as research in other fields.
- The application of outcomes of this research should promote assessment and improvement of teaching and learning.

Geoscience education research should be championed as being as worthy of funding support from government agencies as are other areas of scientific research. All interested colleagues from the Earth sciences, sister disciplines, and learning sciences are invited and encouraged to participate.

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Lastly, Cathy Manduca and David Mogk would like to express special thanks to Neil Stillings, who bravely and cheerfully accepted an invitation to co-convene the workshop with people he had never met. His willingness to engage his colleagues in the cognitive science community made the workshop possible and his ongoing commitment to the project has made this a rewarding and productive collaboration.

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