Geological Society of America Special Papers

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Geological Society of America Special Papers 2012;486;131-163
doi: 10.1130/2012.2486(24)

The Geological Society of America
Special Paper 486
2012

Learning in the field: Synthesis of research on thinking and learning in the geosciences

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ABSTRACT

Learning in the field has traditionally been one of the fundamental components of the geoscience curriculum. In light of the historical value that has been ascribed to field instruction, there is a surprising paucity of scholarly studies that provide the direct evidence to support these claims. The preponderance of literature is descriptive and anecdotal, but in aggregate, these reports reveal a communal experience, which we recognize as "practitioners' wisdom," that places a high value on field instruction in the training of geoscientists. We initially review the attributes of learning in the field environment, instructional goals for field instruction, the place of field instruction in the modern geoscience curriculum, and the value that has been ascribed to learning in the field in terms of cognitive and metacognitive gains, aspects of the affective domain, impacts on learning through immersion in nature, and the role of field instruction in providing the foundation for development of skills and expertise in the geosciences. The theory and practice of the cognitive, learning, and social sciences provide further insights into thinking and learning in the field setting in three important domains: (1) embodiment, how body and mind are integrated through interactions within the natural and social environments in which geoscientists work; (2) creation and use of inscriptions (i.e., constructed representations of natural phenomena such as maps, sketches, and diagrams) to explain, confirm, rationalize, and externalize our understanding of Earth; and (3) initiation into the community of practice that has established accepted norms and practices related to language and discourse, selection and use of tools, ethics and values, and a common understanding of the assumptions, limitations, and uncertainties inherent in the discipline. These insights on how people learn in the field have important implications for what and how we teach in the geoscience curriculum, and they provide a framework to guide future research. Our initial findings indicate that learning in the field results in cognitive and metacognitive gains for students; produces affective responses that have a positive impact on student learning; affords types of learning that cannot be easily achieved in other, more controlled environments; facilitates creation and use of representations of nature (inscriptions) in learning; helps initiate novices into the community of geoscience practice; and provides a solid foundation for development of geoscience expertise.

Mogk, D.W., and Goodwin, C., 2012, Learning in the field: Synthesis of research on thinking and learning in the geosciences, *in* Kastens, K.A., and Manduca, C.A., eds., Earth and Mind II: A Synthesis of Research on Thinking and Learning in the Geosciences: Geological Society of America Special Paper 486, p. 131–163, doi:10.1130/2012.2486(24). For permission to copy, contact editing@geosociety.org.

Come forth into the light of things,
Let Nature be your teacher.
—William Wordsworth, *The Tables Turned* (1798)

AN ILLUSTRATIVE VIGNETTE

The following vignette is a stylized account of the types of activities and interactions observed over the course of numerous days in a geology field camp. This scenario is a "historical fiction" that projects from actual observed events the key components of learning in the field that we explore in this paper. For a description of the geologic setting, see Renik et al. (2008). As you accompany the vignette participants through their field day, notice how (1) questioning and understanding are organized through systematic work practice within the community of students in the field setting who are (2) working under the direction of their instructor (a master geoscientist), (3) who guides their observations, (4) directs their mastery of the skills, methods, and tools required to become a competent earth scientist, (5) monitors their questioning and facilitates discussion to help focus, prioritize, and critically evaluate their observations of the field relations they are investigating, and notice how (6) understanding and interpretation are revealed through many types of portable and permanent representations of natural phenomena (e.g., maps, sketches, graphs, plots of data) that can be shared with the group, (7) within the context of contemporary theory and practice, and (8) that ultimately inform the arguments and discourse that animate current debates in the scientific discipline. In the field, a geoscientist's journey to find meaning in the raw nature of Earth from observation to explanation is accompanied by a parallel intellectual journey of discovery in the professional development of geoscientists themselves that reveals not only what, but also how, we know about Earth.

As breakfast ends at the field camp, a senior professor shows the students a recent journal article that uses as its primary evidence descriptions of one of the outcrops they will visit that day. The articles states that clasts found there, which clearly came from a source area more than 100 km away, were originally deposited in an alluvial fan. This led the authors to interpret extreme crustal extension based on mapping the distribution of these surficial deposits, which seemed to indicate a tectonic cause for the large magnitude of spatial separation from source to the current location of these sediments. The professor asks the students to examine the outcrop to determine whether or not this claim is true.

At the outcrop, the students, all on their first field trip, crawl on their knees with hand lenses to try and figure out what processes might have produced the layers in the rock they are observing. Under the guidance of the professor, they document successive minute changes in the size, shape, and distribution of the sedimentary particles that make up a slightly curved layer, a process that repeats in the next layer. Each student draws in their notebook a cross section of what they see. Then, the students meet as a group with their sketches to try and figure out what these layers might have looked like as three-dimensional objects. Eventually, they decide that what they are looking at are two-dimensional traces on the outcrop of layers of sand that are oriented at a small angle to the main bedding surface, and that are locally truncated by successive layers in the sedimentary sequence. A consensus is reached that these sedimentary structures can be interpreted as cross beds. Some of the students also note the occurrence of asymmetric ripple structures, and other students report on the presence of distinctly rounded clasts of pebbles and cobbles in discrete layers. By minutely examining the patterns left by sediments that were initially deposited in events lasting only a few moments in real-time, they develop a picture of a landscape as it existed in the middle Miocene (~13.4–11.6 m.y. ago).

The students then move through space to a different part of the outcrop and, by using both hand lenses and careful scrutiny of larger distributions of sediment and rock, locate a much larger pattern that undulates along a slope on the outcrop for many meters, becoming sequentially thicker and thinner. They then gather together as a group, and the professor asks several students to walk the boundaries of this new shape while others sketch the geometry of the patterns defined by these rocks in the outcrop. He then asks them to figure out what could have caused such a lens-shaped formation that is composed of sands and gravels. By discussing what that shape might have looked like as a three-dimensional object, they eventually recognize that they have found a channel left by an ancient river. One of the students exclaims in excitement, "Oh, now I can see it!" experiencing the thrill of discovery as she looks from her sketch map to the landscape. Her ability to recognize a structure in the messy, complex visual field provided by the outcrop emerges (1) from her work to separate relevant from irrelevant observations in order to make a representative sketch map, and (2) through discussions with other students about what they might be seeing.

The intellectual and physical work required of geoscientists to see Earth in a disciplined way so as to solve puzzles posed by the landscape has led her not just to mastery of knowledge, but also to a powerful affective experience. Moving from the ancient physical landscape in front of them to the landscape of ideas articulated in text, graphical representations, and discourse, the students see a new possibility: The clasts that the journal article had used as evidence for dismemberment of alluvial fans in an extensional tectonic environment could rather have been transported a great distance by fluvial processes. The article authors' claims about extension are not supported by what the students themselves have seen. More precisely, the structures that have been made visible and mapped by using accepted and relevant geologic tools and practices to examine the outcrop, and then form and evaluate hypotheses under the probing guidance of a senior, skilled geologist, have created a new knowledge base for the students to interpret the processes, structure, and geologic history of this landscape. Through this same process, they start on the road toward competent membership in the geoscience community by systematically probing and evaluating the analytic claims made in their readings.

In the afternoon, the students learn how to use a Brunton compass to make strike and dip measurements of bedding of sedimentary rocks that crop out in different places in the landscape. After each measurement is plotted on a map, they move to a new location and repeat the process. As the group moves through space, these representations of the vast landscape in front of them propagate on the graphic space of their map, gradually revealing a kilometer-scale set of open folds. The students could not have recognized this geologic structure from any single position, or without the representations made on the map. The representation of the orientation of rock strata in their natural setting onto a geologic map was made possible by collection of data with a particular tool, the Brunton compass, and the representation of multiple selective but relevant images on a developing map. At the end of the day, back at camp, students reflect on the day's experiences and report a sense of achievement in undertaking a significant research question, through which they have gained self-confidence in their ability to make revealing observations and interpret the geologic setting in a new way, and have valued their interactions with peers and instructors as they worked through the day's challenges.

Through all of this interrogation of the landscape by using the tools of field geology, such as lenses, maps, and compasses, the students begin to gain an understanding of the transformations that occurred in deep time that produced the landscape through which they are now walking. Simultaneously, they find themselves transformed as individuals, on a scale of hours and days, from rank novices into developing geoscientists (Fig. 1).

INTRODUCTION

From the earliest days of geology, great advances and insights have derived from keen observations of Earth: James Hutton's recognition of the vast expanse of geologic time through his studies of the unconformity at Siccar Point; Louis Agassiz's study of Alpine glaciers in Switzerland and similar glacial deposits in Scotland and North America, which led to the proposition that Earth was once gripped by a massive Ice Age; Alfred Wegener's development of the theory of continental drift based on correlation of rock types, structures, and faunal distribution, followed by the integration of oceanographic, geophysical, and geological observations that led to J. Tuzo Wilson's formulation of the theory of plate tectonics. Butler (2008) asserted that the four key paradigms of the earth sciences (Quality Assurance Agency for Higher Education in the UK, 2007)—uniformitarianism, the extent of geological time, evolution and the history of life, and plate tectonics—all derive from field observations and related interpretational skills. In reflecting on Hutton's cognitive breakthrough regarding geologic time, Gould (1987, p. 5) noted, "Hutton broke through those biblical structures because he was

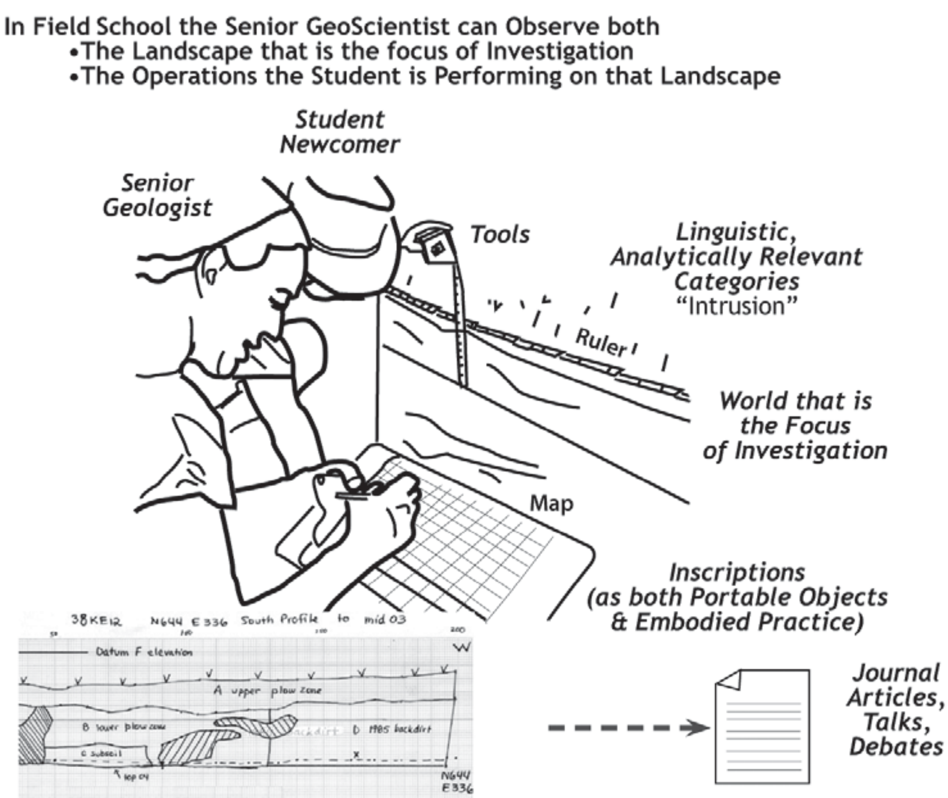

Figure 1. Learning in the field: where geoscientists are transformed from novices to practicing geoscientists through the intertwining of apprenticeship, guided discovery, mastery of tools, theory, and embodied practice.

willing to place field observation before preconception—speak to the earth and it shall teach thee."

The early practices of fieldwork (mapping, sampling, and in situ measurement of natural features) have more recently been extended to include long-term monitoring of natural phenomena and events, remote sensing of features on Earth's surface, and "indirect" observations of the hidden Earth using a variety of geophysical and geochemical techniques. Field studies have provided the conceptual framework and inspired research questions that have subsequently been investigated using modern high-resolution analytical methods, experiments, physical and computational modeling, and the formulation and application of theory. In turn, direct study of Earth in field settings has been greatly enriched through application of the results of these modern approaches (e.g., Ernst, 2006). There is an iterative, positive feedback mechanism in understanding Earth and its processes that derives from the flow of information between research that is grounded in nature and laboratory-based studies.

Geoscience education also has a long tradition of teaching and learning through direct experience from nature and from each other in the field setting among a community of geoscientists. One of the earliest accounts of field instruction concerns John Wesley Powell, who was an instructor at Illinois Wesleyan University after the Civil War:

> Powell led his students on frequent field trips, a then innovative approach to science education. "We all recall how textbooks went to the winds with Major Powell," recalled student J. B. Taylor. "He made us feel that we had conquered the commonplace, broken our way through the accepted, and come into the heritage of free thinkers, and there was no shame in it anywhere." (Steinflacher-Kemp, 2010)

Studying geology in the field has also contributed to the social structures that have served to train generations of geoscientists. The practice of field instruction of students has included formal class instruction, one-on-one master-apprentice relations, communal events (e.g., field trips and conferences), and independent field-based research by undergraduate and graduate students. The field setting is one of the important crucibles where science and scientists codevelop: Learning in the field has always been about creation of new knowledge by direct observation of Earth while providing an important foundation in the training and professional development of the next generation of geoscientists. The maxim, "The best geologist is the one who has seen the most rocks" (H.H. Read, 1939 address, published in 1957), has been embedded in geoscience education for generations.

Based on this heritage of contributions of field studies to the development of geoscience and geoscientists, there appears to be a tacit assertion among many geoscientists that field instruction is an important, and even critical, component of geoscience education (e.g., Macdonald et al., 2005; Drummond and Markin, 2008), but what is the evidence? Are there clear learning gains that are uniquely, or optimally, achieved in a field setting? How does learning in the field complement or supplement learning outcomes achieved in other learning environments (Elkins and Elkins, 2007)? How can we best use these insights to inform course and curriculum design and development?

In light of the historical value that has been ascribed to field instruction, there is a surprising paucity of scholarly studies that provide direct evidence to support these claims with regard to the geosciences (Maskall and Stokes, 2008). However, interest in field instruction in the geosciences appears to be enjoying a renaissance of interest (Whitmeyer and Mogk, 2009). A recent triad of articles from the UK (Boyle et al., 2007; Butler, 2008; Maskall and Stokes, 2008); a special issue of the *Journal of Geoscience Education* on teaching in the field (Manduca and Carpenter [eds.], March 2006); and Geological Society of America Special Paper 461, *Field Geology Education: Historical Perspectives and Modern Approaches* (Whitmeyer et al., 2009), have begun to address these questions in a comprehensive way. Supporting evidence can be found in other disciplines that also have a strong heritage of field instruction (e.g., geography—Kent et al., 1997; Gerber and Chuan, 2000; Fuller et al., 2006; ecology—Gibson et al., 1999; Manzanal et al., 1999; Baldwin, 2001; archaeology—Bender and Smith, 2000). New insights into the processes and benefits of learning in the field can also be found from research on learning that derives from emerging collaborations among cognitive, social, and geoscientists (Manduca et al., 2004).

The purpose of this contribution is to explore the cognitive (knowledge, concepts), affective (motivations, emotions, values), metacognitive (awareness of learning strategies), and social (community practices, norms, and standards) ways of knowing that are developed by geoscientists through learning in the field (Kastens and Manduca, this volume). Our primary focus is on instruction in field geology, although we do report on supporting studies from the ocean, atmospheric, and environmental sciences. We focus on undergraduate education, because this level represents the nexus of connections among future and current geoscientists, in-service and preservice teachers (Huntoon et al., 2001; O'Neal, 2003; Mattox and Babb, 2004; Hemler and Repine, 2006; Thomson et al., 2006; Tretinjak and Riggs, 2008; Schwimmer and Hester, 2008; Bishop et al., 2009; Lee et al., 2009; St. John et al., 2009; Kitts et al., 2009; Marcum-Dietrich et al., 2011; Almquist et al., 2011), decision makers, and citizens-at-large (e.g., Louv, 2006, and references therein). In the following sections, we first describe distinctive aspects of the field learning environment and the learning goals and pedagogical practices of field-based instructors. We then acknowledge that field learning has undergone recent scrutiny, and assemble the range of arguments that have been advanced in support of the cognitive, metacognitive, affective, and professional-preparation values of learning in the field. We put these forward as "practitioners' wisdom," a standard of evidence based on experience well above anecdote but well below research on learning. We then look at field learning through three lenses or frameworks from social sciences: embodiment (i.e., the idea that psychological processes, including ideas, thoughts, concepts, and categories, are influenced by the body's morphology, sensory systems, and motor systems as they interact with the natural and social environments where learning occurs), inscriptions (i.e., constructed representations of natural phenomena such as maps, sketches, and diagrams), and induction into the community of practice as represented by the appropriate selection and use of tools, engagement in scientific discourse, and the social structures that inform professional practice in the geosciences. Finally, we make recommendations for instruction and for future research.

DISTINCTIVE ATTRIBUTES OF FIELD LEARNING ENVIRONMENTS

We use "learning in the field" to literally mean physically going out into the natural environment; making observations; taking samples and making measurements of objects, structures, processes, and phenomena; and using the human senses and remote instrumental sensors to interact with Earth (e.g., Lonergan and Andresen, 1988). The features of interest may include rock outcrops, soils, landforms, bodies of water, weather, plants, animals, the interrelations among these, and the processes by which they change through time or vary across space, either naturally or due to anthropogenic influences. We are looking at the raw materials of nature, not synthetic materials, selected or "representative" samples, models, or derivative or distilled representations.

Field studies provide the opportunity to study phenomena in open, unconstrained, dynamic, and complex systems (Stillings, this volume). The Earth system is inherently complex, dynamic, heterogeneous, and often chaotic, and it presents many challenges to geoscience education (Ireton et al., 1996). As a historical and interpretive science (Frodeman, 1995), field-based geoscience often relies on methodical observation of natural variation within or between field sites and along gradients where hypothesized forcing factors are thought or known to vary (Kastens and Rivet, 2008). The geologic record is often incomplete or ambiguous, and, consequently, the nature of geoscience expertise requires the development of cognitive strategies that allow geoscientists to work effectively in a world in which the available evidence is both complex and uncertain. In the field setting, students come into direct experiential contact with the raw materials of nature in their full, primal, and complex contexts. In the laboratory, on the other hand, sample collections are displayed out of the full context of their natural setting, and the rationale for collecting particular samples (e.g., to show representative minerals, rock types, textures, structures) may not be obvious to novice learners.

These aspects of field instruction are particularly important for K–12 teachers, who must be confident in their ability to both understand and teach science. Field experiences should be an important component of training for present and future teachers, particularly as a means of encouraging inquiry and discovery about the world around us (Huntoon et al., 2001; O'Neal, 2003; Mattox and Babb, 2004; Hemler and Repine, 2006; Thomson et al., 2006; Tretinjak et al., 2008; Bishop et al., 2009; Lee et al., 2009; St. John et al., 2009; Kitts et al., 2009; Marcum-Dietrich et al., 2011).

In the field setting, the scale of the study is typically large relative to the observer, on the scale of meters to kilometers, as contrasted with the micron- to centimeter-scale objects studied in the laboratory (Fig. 2). Thus, the features under study are perceived from an internal spatial viewpoint (i.e., the observer is immersed within the object of study, an important component of embodiment; Bryant et al., 1992) rather than the external spatial viewpoint from which one views small objects. In addition, physical movement in an environment is sensed through vision, audition, and proprioception (i.e., sense of the orientation of one's body in space) to produce knowledge of spatial relations that are stored in memory and are available for retrieval for later use (e.g., Wilson, 2001, 2002; Montello et al., 2004). By physically moving through the natural environment, students gain a unique perspective of the world around them that cannot be reproduced in artificial (laboratory) or virtual (computer-based) environments. Strong sensory inputs associated with immersion in a physical field setting are typically ascribed to impacts on the affective domain, which in turn, are strongly coupled with cognitive and memory functions (Gray, 2004; Storbeck and Clore, 2007; Pessoa, 2008).

The field setting allows students to make their own informed decisions about what to observe, for what purpose, how to represent these observations, and how to interpret and ascribe meaning to their work. In contrast, when students learn from derivative representations or preselected sample collections, someone else has already done the critical work of deciding what is important. Thus, the student does not experience the full cascade of representations of nature from the simplest and most direct types (e.g., pictures, sketches) derived from the most local, concrete, and material examples to the more abstract and mathematized representations (Latour, 1987; Lynch, 1990; Roth, 1996). In a school laboratory, most objects on the laboratory table are

Figure 2. In the field setting, the scale of the study is typically large relative to the observer, on the scale of meters to kilometers, as contrasted with the micron- to centimeter-scale objects studied in the laboratory. Photo credit: David Mogk.

relevant to the inquiry at hand, whereas for field-based inquiry, most objects in view are not relevant, and it is not obvious to the novice which features are important and which are not (Goodwin, 1994; Reynolds et al., 2006). The act of creating representations (inscriptions) of nature (such as sketches, field notes, maps, and diagrams) of selective phenomena in the field (while ignoring or obscuring other aspects of the environment being investigated) can reveal the degree of mastery attained, and cognitive processes utilized, by learners. These representations of nature can then be transported out of the field site and shared with the larger community. This aspect of learning in the field has strong metacognitive (Weinstein et al., 2000; Lovett, 2008; Wirth and Perkins, 2008; Petcovic et al., 2009) impacts, as students must be self-aware of their approach to a given field task, self-monitor their progress, and self-regulate their actions as they confront emerging problems, unexpected findings, or inconsistencies.

The "affective domain" refers to factors such as attitudes, values, beliefs, opinions, interests, and motivation. Students working in the field often experience a sense of awe and wonder about natural phenomena and are consequently motivated to learn more about the natural environment (Gagné and White, 1978; Hendrix and Suttner, 1978; MacKenzie and White, 1982). Like the students of J. Wesley Powell quoted earlier herein, they gain an increased sense of self-confidence and self-reliance. Social aspects of learning in the field include heightened interpersonal interactions, lifelong memories and friendships, reduced social barriers (Crompton and Sellar, 1981; Kern and Carpenter, 1984; Kempa and Orion, 1996; Tal, 2001; Fuller et al., 2003, 2006), and the intrinsically social process of gaining knowledge and skill in the geosciences through apprenticeship. The evocative sensual experiences imparted by the experience of being situated in a field setting cannot easily be replicated in other more controlled environments (e.g., Millar and Millar, 1996).

Because the field setting provides such distinct learning contexts, a whole arsenal of investigative skills and tools that are distinct from the laboratory sciences is required. In the natural world, it is often difficult or impossible to conduct controlled experiments. Frodeman (1995) suggested that the hegemony of the physical sciences should be supplanted by the more holistic view afforded through field-based geoscience. Young scientists beginning careers in field-based science may be frustrated that "the scientific method" that they have been taught from an experimental point of view does not describe the type of research that is being done in natural settings. However, direct observation of Earth and its processes opens entirely new lines of inquiry and pathways to discovery that lead to theory and consequential work such as follow-on analysis or modeling (e.g., Ernst, 2006). The theory of evolution emerged from intense immersion in the field, observing Earth in its full complexity, by both Darwin and Wallace. Initiates to field-based sciences, with an emphasis on historical and interpretive approaches (Wilson, 1994; Frodeman, 1995), must be introduced to new sets of questions that can appropriately be asked in this setting, strategies and approaches to successfully find answers, utilization of tools, modes of representation and discourse, and social fabrics that have evolved to enable inquiry and discovery in the field. Increasingly, field-based research projects are being incorporated into the geoscience curriculum, in part to emphasize the importance of direct observation of nature, that are subsequently integrated with experimental, modeling, and other analytical approaches (e.g., Anderson et al., 1999; Carlson, 1999, Huntoon et al., 2001; Hemler and Repine, 2006; Connor, 2009; de Wet et al., 2009; Eppes, 2009; Gonzales and Semken, 2006, 2009; May et al., 2009; St. John et al., 2009; Swanson and Bampton, 2009; Whitmeyer et al., 2009).

INSTRUCTIONAL GOALS AND PRACTICES IN FIELD SETTINGS

Field-based instructional programs vary widely in scope, format, venue, learning goals, and instructional approaches. For K–12 students and the general public, field experiences may include short trips to local sites, more extended field trips to a site of specific interest, or participation in informal educational activities hosted by civic organizations, parks, museums and aquariums, and citizen-scientist programs. For prospective geoscientists, learning in the field ranges in scale from a single outdoor class activity with a duration of an hour or two, to sustained individual or group projects with a duration of a semester or longer. "Capstone" field camps at the undergraduate level, and extended group or individual field projects at the undergraduate or graduate level can bring students all the way to the point of producing original research results (Anderson et al., 1999; Aitchison and Ali, 2007; Butler, 2008; Gonzales and Semken, 2006, 2009; Whitmeyer et al., 2009).

Field instructional programs may be planned as focused studies at a single site or as a regional reconnaissance to investigate large-scale relations in a region. They may be local or international (e.g., Ham and Flood, 2009; Marshall et al., 2009). The focus may be to deploy and use specialized instrumentation on the ground or aboard ships or planes (e.g., Francis et al., 1999; Smith, 1995; Reynolds, 2004; McClennen and Meyer, 2002; Gawal and Greengrove, 2005; Schwimmer and Hester, 2008; St. John et al., 2009). The disciplinary focus need not be geology: other foci include geophysics (e.g., May and Gibbons, 2004), hydrology (e.g., McKay and Kammer, 1999; Fryar et al., 2010; Rathburn and Weinberg, 2011), paleontology (Clary and Wandersee, 2008), petroleum geology and engineering (Anderson and Miskimins, 2006; Puckette and Suneson, 2009), soil geomorphology (Eppes, 2009), environmental studies (LaSage et al., 2006; Elkins et al., 2008), hydrogeochemistry (Carlson, 1999), and watershed science (Pearce et al., 2010).

Learning goals also vary widely. At the pragmatic level, learning goals include reinforcement of content and concepts learned in the classroom, and development of practical skills such as observation, note-taking, sketching, sampling, measurement taking, and mapping. Learning in the field also provides the opportunity for students to develop higher-order thinking skills (comprehension, application, analysis, synthesis, and evaluation; Bloom, 1965) that lead to "deep understanding" via experiential learning (Kolb, 1984; Bransford et al., 1999). Lessons learned in the field provide a rich resource of contexts (of natural phenomena, their scale, and relations), knowledge, and skills that students can then apply to other scholarly pursuits in related disciplines in the geosciences and elsewhere. A survey of instructors in the UK revealed that the main objectives for fieldwork are to put theory into context and to teach students subject-specific skills, whereas learning of transferable skills was more important to students than their instructors (Scott et al., 2006). Bluth and Huntoon (2001, p. 13) stated, "Field-based courses force students and instructors to consider geologic features in their full environmental context." Field activities readily integrate interdisciplinary concepts. Learning goals that can be realized in the field include a full range of cognitive skills that will prepare students to be keen observers, critical thinkers, and problem solvers in addressing the complex questions of the science of Earth.

Finally, a wide range of instructional practices is used to meet these learning goals. The pedagogical rationale behind the choice of instructional practice is often the practitioner's experience of "what works" (see numerous articles in Whitmeyer et al., 2009). Other approaches are grounded in literature on experiential learning (Kolb, 1984; Johnson et al., 1991; Millar and Millar, 1996), including inquiry and discovery (Field, 2003; Apedoe et al., 2006; Anderson, 2007), constructivism (Orion, 1993), problem-based learning (e.g., Bradbeer, 1996), and collaborative and cooperative learning (Johnson et al., 1991; Kempa and Orion, 1996; Srogi and Baloche, 1997; Slavin et al., 2003; Mooney, 2006). Use of information technology to prepare for the field (e.g., Warburton and Higgitt, 1997; Schlische and Ackermann, 1998; Cantwell, 2004; Neumann and Kutis, 2006; Kelly and Riggs, 2006) and use of information technologies while working in the field (e.g., Walker and Black, 2000; McCaffrey et al., 2005; Knoop and van der Pluijm, 2006; Guertin, 2006; Menking and Stewart, 2007; Swanson and Bampton, 2009; Whitmeyer et al., 2009; Elkins, 2009; Pavlis et al., 2010) have grown in importance in recent years.

WHAT PLACE DOES LEARNING IN THE FIELD HAVE IN THE MODERN GEOSCIENCE CURRICULUM?

The role of field instruction in undergraduate geoscience curriculum has recently come under intense scrutiny. Traditionally, field experiences were a regular component of geoscience courses at all levels (e.g., AGI, 2001; Knapp et al., 2006; see numerous articles in Whitmeyer et al., 2009), and a "capstone" immersive field course was required as a final rite of passage into graduate school and the ranks of professional geoscientists. Drummond and Markin (2008) reported that a field camp is required of 99% of 278 surveyed undergraduate geology degree programs in the United States (although, increasingly, many departments are now consolidating or outsourcing this course; Drummond, 2001). In the United States, the scope and breadth of such field courses are largely left up to the discretion of the home institution. In contrast, the UK and Ireland adhere to a more standardized approach to field studies required by accreditation bodies (Boyle et al., 2009). Field trips have also been an important component of K–12 instruction, and they are often highly anticipated and memorable experiences for students (Orion, 1993; Kempa and Orion, 1996; Orion et al., 1997b). Notwithstanding the central role field instruction has traditionally played in the geoscience curriculum, significant questions have recently been raised about the importance of field learning experiences for current and future students. Factors that come into play include the changing emphasis in earth science curricula (e.g., toward environmental issues, emerging disciplines such as geomicrobiology); increased use of technology in the classroom (virtual learning spaces; e.g., Kelly and Riggs, 2006; Reynolds et al., 2006); funding patterns that support research that is unrelated to field geology; research practices that are increasingly focused on modeling, theory, and analysis; logistical issues regarding lost access to traditional field sites (Mogk, 2004); and increased concerns about demands on time, costs, safety, and liability (e.g., Boyle et al., 2007; Butler, 2008). The critique is not so much that fieldwork has necessarily outlived its usefulness, but rather, it has been somewhat eclipsed by other competing research initiatives. In light of these concerns, what is the justification of a continued emphasis of field-based learning in the geoscience curriculum (Drummond, 2001)? Is field training a quaint throwback to another era, or are there demonstrable benefits derived by training young scientists (and the public) through field instruction (Kirchner, 1997)? This is a question that has vexed geoscientists for generations:

> It is stated, as a scandalous sign of the times, that in certain departments geologic mapping is considered to be, not research, but a routine operation—something like surveying from the point of view of an engineer—and therefore not suitable as a basis for the doctoral thesis. (J. Hoover Mackin, 1963, p. 135)

It would appear that discipline-wide reflection on the nature of fieldwork, its contribution to the development of geoscience and geoscientists, and its appropriate role in the geoscience curriculum is warranted in light of the changing nature of geoscience research, geoscience education, and the learning environment in which we apply our trade.

THE VALUE OF LEARNING IN THE FIELD: PRACTITIONERS' WISDOM

The heritage of a century and a half of field instruction in the geosciences has produced a wealth of observations, experience, and practice that have placed a high value on learning in the field. There is a large body of literature that defends these assertions (Table 1). The level of evidence rises above anecdotal but falls short of a rigorous body of research on learning. We present these claims as a summary of hard-earned practitioners' wisdom or pedagogical content knowledge, and as a rich source of hypotheses for future research. To frame the argument, Maskall and Stokes (2008) offer the following assertions:

1. Fieldwork provides an "unparalleled opportunity" to study the real world.
2. Student perceptions of fieldwork tend to be overwhelmingly positive.
3. Fieldwork provides the opportunity to reinforce classroom-based learning.
4. Fieldwork increases students' knowledge, skills, and subject understanding.

Similarly, an international review published in the UK on the effectiveness of geography fieldwork in learning identified common themes, which include: providing firsthand experience of the real world; skills development (transferable and technical); and social benefits (Fuller et al., 2006).

We consider five general areas where claims are made about the value of field instruction in the geosciences: (1) cognitive gains; (2) metacognitive gains; (3) affective aspects of field instruction; (4) benefits of immersion in nature; and (5) foundations of geoscience expertise.

Cognitive Gains from Learning in the Field

The cognitive domain encompasses both acquisition of knowledge, and the more sophisticated cognitive tasks of comprehension, application, analysis, synthesis, and evaluation. These higher-order thinking skills can be well aligned with field instruction throughout a student's career (AGI, 2001). This is particularly the case if a field learning curriculum is designed to include a continuum of instructional experiences that emphasize inquiry and discovery, and increasingly require critical-thinking and problem-solving skills (AGI, 2001; Anderson, 2007; Fig. 3). Higher-order thinking skills attributed to learning in the field include the ability to synthesize a broad range of theoretical knowledge, evaluate uncertainties, and distinguish between observation and inference, communicate results, and generally develop "scientific habits of the mind" (AAAS, 1989; Niemitz and Potter, 1991; Carlson, 1999; Rowland, 2000), and to have students engage in the scientific method (observe, create a hypothesis, make a prediction based upon that hypothesis, make a plan of action and test the hypothesis, and modify the hypothesis as needed; e.g., Butler, 2008). Because of the fragmentary nature of the rock record, field studies also help students develop the ability to make reasonable interpretations of complex Earth phenomena from data that are incomplete, ambiguous, and uncertain (e.g., Ault, 1998; Raab and Frodeman, 2002).

Learning in the field is integrative, requiring holistic thinking that applies the skills, learning outcomes, and results of multiple investigative approaches (theoretical, analytical, experimental, and modeling) to interpret, explain, predict, or confirm explanations about natural phenomena. Learning in the field is also iterative, as field observations suggest new lines of inquiry in these related approaches, and laboratory-based results inform (and often require) reinterpretation of field observation (Trop, 2000; Noll, 2003; Ernst, 2006; Fig. 4) and then perhaps another round of field observation and sampling. The positive feedback

TABLE 1. GEOLOGISTS' CLAIMS ABOUT THE VALUE OF FIELDWORK IN THE GEOSCIENCES

In the field setting, students have the opportunity to learn FROM nature and ABOUT science as a social enterprise (Frodeman, 2003).
Field-based inquiry brings learners into direct experiential contact with the raw materials of nature, and provides the fundamental platform on which hypotheses about Earth are formulated and tested.
Fieldwork has led to the development of an epistemology that is heavily focused on observation and interpretation of natural phenomena and historical relations (Frodeman, 1995). This provides a strong complement to methodologies used in the experimental sciences, and it greatly enriches the ways in which we understand the universe around us.
Field studies require integration of content knowledge, observation and interpretation, analysis, experiment and theory, and all their representations (e.g., Ernst, 2006). All lines of evidence need to come together to form a coherent, internally consistent interpretation.
Practices that are emphasized in field instruction, such as question asking, observation, representation, and communication (e.g., Niemitz and Potter, 1991; Carlson, 1999; Rowland, 2000), are important to the formative training of all geoscientists.
Exploration of three- and four-dimensional relations in nature (Liben and Titus, this volume; Frodeman and Cervato, this volume) provides a sense of scale (spatial and temporal) of Earth phenomena and processes that provides an important context for the creation of interpretive models.
Field studies can be an effective mechanism to recruit and retain students in the geosciences (e.g., Kern and Carpenter, 1984; Manner, 1995; Karabinos et al., 1992) and to introduce nontraditional students to the geosciences (e.g., Gawel and Greengrove, 2005; Semken, 2005; Elkins et al., 2008). Alumni report strong support for field geology learning experiences (Kirchner, 1994; Plymate et al., 2005), and many departments showcase their field programs (e.g., brochures, Web pages) to recruit new majors (e.g., Butler, 2008).
Field studies provide a holistic view of Earth that reveals the interconnections among the many components of the Earth system (Ireton et al., 1997); the field setting provides the ability to see relationships among parts, and not just parts. In the laboratory, it is very hard to learn how things are embedded in larger contexts.
Field studies allow students to see relationships that demonstrate or validate theory, and to critically evaluate the adequacy of model output in comparison with the complexities of nature (Stillings, this volume).
Field studies provide students with the opportunity to engage in "authentic" activities done by professionals as first steps towards their development as geoscientists.
In the field, students make their own observations, order their experiences, make decisions, and set their own priorities as to what to focus on and what to ignore (Isen, 2000), becoming autonomous, self-directed learners.

between first-order observations of nature and other knowledge acquired through experiment, theory, or modeling can help students develop higher-order thinking skills such as analysis, integration, and synthesis. Using geologic mapping as one example of learning in the field, Ernst (2006, p. 13) writes:

Figure 3. Learning in the field provides a continuum of instructional experiences that emphasizes inquiry and discovery, requires application of knowledge and skills from across the geoscience curriculum, and provides opportunities for students to develop critical-thinking and problem-solving skills. In this setting, students are applying knowledge learned in the classroom to characterize and measure preserved sedimentary structures that can lead to an interpretation of the environment of deposition. Their physical position in the outcrop allows them to explore the spatial relations of the outcrop while simultaneously directing the attention of their peers to features of interest on the outcrop. Photo credit: David Mogk.

Figure 4. Students at a field camp compiling data collected in the field. Structural data plotted on a stereonet and maps of geochemical sample locations were used to inform future field mapping and sampling activities. Photo credit: David Mogk.

> A geologic map represents the melding of field observations with various types of analytical data and earth science concepts. … Some would claim that in the mapping process, theory meets reality. However, a map is a more subjective product based on the sum of the geologist's prior training, aggregate field experience, and the stage of development of scientific concepts, the complexity of the mapped units, the extent and quality of exposures, the wealth of constraining ancillary data, and the time and thought expended in the mapping.

Metacognitive Gains

Metacognition involves thinking about one's own cognitive processes, i.e., being aware of thinking, learning, reasoning, and problem-solving strategies (Israel, 2007; Lovett, 2008). Metacognition is essential for effective learning in complex situations (Lovett, 2008) such as the field setting (Petcovic et al., 2009), and it provides a foundation for students to develop higher-order thinking skills (Bloom, 1965) and critical thinking skills (King and Kitchener, 1994; Paul and Elder, 2004; Bissell and Lemons, 2006) and to become lifelong learners (Wirth and Perkins, 2008). Key components of metacognition are self-monitoring and self-regulation (Flavell, 1979; Weinstein et al., 2000). Thinking can then be translated into action. Conation refers to the connection between knowledge and affect (personal will, motivation) and intentional, goal-oriented personal actions or behaviors (e.g., the desire to go out and learn more, engage in proactive activities), and it provides critical evidence of self-direction and regulation (Snow, 1989; Hilgard, 1980). Self-aware learners have the ability to engage in planning and goal setting for an assigned task, monitor their own progress, and adapt to changing conditions as needed (Lovett, 2008).

This excerpt from Shubin (2009, p. 5–6) is illustrative:

> We make all kinds of plans to get us to promising fossil sites. Once we're there, the entire field plan may be thrown out the window. Facts on the ground can change our best-laid plans. … Paleontologists still need to look at rock—literally to crawl over it—and the fossils within must often be removed by hand. So many decisions need to be made when prospecting for and removing fossil bone that these processes are difficult to automate.

In the field setting, all of the preparatory knowledge and skills available to a geoscientist are brought to bear. Each field day requires articulation of goals for the day, and a general work plan. These must be modified on the fly to respond to contingencies such as terrain, weather, unexpected observations, and other logistical influences. An entire field day must necessarily be accompanied by a cascade of self-monitoring and self-regulatory questions: Is this what I expected? Is this consistent with what I know from other contexts? Where should I go next, and how will I get there? Should I take a sample or measurement, and for what purpose? Are there additional tests/tools I should use? Am I sure of the nature of that contact? Should I go back and take another look? Research on metacognitive strategies of geoscience experts and students is now in its formative stage (e.g., Manduca et al., 2004; Petcovic and Libarkin, 2007; Manduca and Kastens, this volume). Recent pioneering studies on metacognition in field settings have begun to document differences in expert-novice cognitive and behavioral processes in situated map making (Petcovic et al., 2009) and problem solving and decision making by students in field mapping exercises as tracked by global positioning system (GPS) instruments (e.g., Riggs et al., 2009a, 2009b).

Affective Aspects of Field Instruction

The affective domain includes factors such as student motivation, attitudes, perceptions, and values (Krathwohl et al., 1973). There is a growing body of evidence that indicates that cognition and affect are intimately linked (e.g., Schumann, 1994; Ashby et al., 1999; Gray, 2004; Storbeck and Clore, 2007; Pessoa, 2008), and that one's ability to learn is strongly impacted by affective aspects, both positive (e.g., curiosity, interest, self-motivation) and negative (e.g., fear, insecurity, cultural or social barriers). It is in the affective domain that students' motivation to learn is initiated and reinforced (e.g., Glynn and Koballa, 2006; Koballa and Glynn, 2007). Positive outcomes in the affective domain can be viewed as an important antecedent to success in the cognitive domain (Eiss and Harbeck, 1969; Iozzi, 1989; Boyle et al., 2007; Stokes and Boyle, 2009; Rathburn and Weinberg, 2011).

The relationship between affect and cognition is further realized in the concept of "novelty space" (Orion and Hofstein, 1994; Rudmann, 1994; Hurd, 1997; Mogk, 1997). With respect to learning in the field, novelty space concerns students' uncertainty about three important dimensions: where am I geographically, what is the geologic context and what am I supposed to be doing in this setting, and what is my personal comfort and safety level (is it too hot/cold, are there rattlesnakes here, will I be back in town in time to pick up my children from day care)? No significant learning can occur when students are unsure about where they are, what they are supposed to do, what the expectations are for learning outcomes, or if they have concerns about their personal comfort and safety. The extent to which novelty space can be decreased, by preparing students for field experiences by using activities such as pre-activity assignments, slide shows, virtual environments and field trips (Hesthammer et al., 2002; Kelly and Riggs, 2006), road logs, demonstrations on how to use equipment, examples of learning products, or simulated experiences (Benson, 2010), can have positive effects on students' learning outcomes (Falk et al., 1978; Orion and Hofstein, 1994; Mogk, 1997). Once novelty space is decreased, students can be more open to exploring and enjoying the wonders of the world around them.

The field environment is particularly rich in learning experiences that inspire curiosity (this is just so cool I have to learn more!) and need (I need to learn more about this phenomenon because it has the potential of impacting my personal or communal safety and well-being). Learning is enhanced in a field environment that is simultaneously intellectually challenging, rich in social interactions, and presents the opportunity to observe awe-inspiring natural phenomena. These experiences tend to build self-confidence through increased competence gained by overcoming physical, intellectual, and emotional challenges. The joy of discovery in the field is frequently described as a transformative experience. One of the most important roles of field trips in the learning process is in the "direct experience with concrete phenomena and materials" (Orion, 1993), following the advice of the American Association for the Advancement of Science (AAAS, 1989; Chapter 13, Effective Teaching and Learning): "Start with questions about nature," and "progression in learning is usually from the concrete to the abstract."

The field setting provides an important interactive social learning environment, and the strong emotions that are engendered by field experiences deliver cognitive responses that are unique with respect to other learning environments (Kempa and Orion, 1996; Alsop and Watts, 2000, 2003; Marques et al., 2003; Fuller et al., 2006; Fig. 5). Shared experiences in the field form the basis for strong social and professional networks that may last a lifetime. These networks may be between student and mentor or peer to peer. Mentoring by master geoscientists plays many roles: stimulating interest and motivation to learn through their enthusiasm and knowledge base about the assigned tasks; assisting students in their own professional development by presenting

Figure 5. The field setting induces strong affective responses. These include creation of an interactive social learning environment that can develop social and professional networks that may last a lifetime. Unique or unusual experiences in the field can commit information to long-term memory that can be retrieved for future use. Photo credit: David Mogk.

guiding questions (e.g., about observations and interpretations); and teaching by example (e.g., acting as co-learners in field settings, allowing students to see their own field notes and maps as examples of what is expected; see Hoskins and Price, 2001). The field camp setting may set up strong affiliative (building strong ties) and competitive interactions in student peer groups (Boyle et al., 2007; Butler, 2008). Numerous collaborative learning strategies that apply equally as well to learning in the field as in the laboratory or classroom have been described by Johnson et al. (1991), Munn et al. (1995), Srogi and Baloche (1997), and Slavin et al. (2003). However, as a caution, many field exercises are done in small groups for safety reasons, but many students report misgivings about group work, particularly with respect to assigned grades (Boyle et al., 2007). In a survey of undergraduate students in the UK, Boyle et al. (2007) reported that most students enjoyed the social aspects of doing fieldwork. Students generally report that they have a positive view about fieldwork, and concerns about learning methods in the field (especially group work) can be mitigated by designing positive field learning experiences (Kempa and Orion, 1996; Boyle et al., 2007; Stokes and Boyle, 2009). A unique opportunity to assess students' attitudes about fieldwork occurred in 2001 when field instruction was prohibited in the UK due to an outbreak of foot-and-mouth disease. Responses from 300 students from five institutions reported overwhelmingly positive perceptions of fieldwork, particularly as related to the experience of geographical reality, developing subject knowledge, acquiring technical, transferable, and holistic skills, and working with peers and lecturers (Fuller et al., 2003).

Many field scientists assert that well-designed field experiences are an effective means to recruit students to the earth science majors (Kern and Carpenter, 1984, 1986; Karabinos et al., 1992; Manner, 1995; McKenzie et al., 1986; Salter, 2001), and to introduce nontraditional students to the geosciences (e.g., Gawel and Greengrove, 2005; Semken, 2005; Elkins et al., 2008). Alumni of field camps generally report that they personally and professionally valued their experience (Kirchner, 1994; Plymate et al., 2005), and many departments showcase their field programs (e.g., brochures, Web pages) to recruit new majors (e.g., Butler, 2008). However, the converse may be equally true: Poorly designed activities where students are bored or threatened (e.g., "boot camp" mentality on field trips) may drive students away from the discipline.

Immersion in Nature

The field is where the truth resides; it is the essential core of geology. Models are essential figments of the imagination which must be tested by observation. Those who do no field work and do not gather data will never understand geology.

—John Dewey (quoted in Butler, 2008, p. 6)

Field-based inquiry brings learners into direct experiential contact with the raw materials of nature, and it provides the fundamental platform on which hypotheses about Earth are formulated and tested. Fieldwork has led to the development of an epistemology that is heavily focused toward observation and interpretation of natural phenomena and historical relations (Frodeman, 1995). By studying natural phenomena in situ, we see the results of natural experiments that have been in progress for eons, and gain a sense of scale (both spatial and temporal) of natural phenomena. For example, field-based sequence stratigraphy studies provide context for interpreting seismic-reflection profiles used to define the size and geometry of potential oil or gas deposits.

In nature, the observer is confronted with the full range of natural variability. Nature reveals what is possible: Observations in the field allow us to interpret and explain what has happened in the past (postdiction) in order to show us what is possible regarding present and future Earth phenomena (prediction). Field studies also may be used for correlation or comparison of one geologic site with another as a way of confirming or verifying a process or history. The field setting, with all its natural variation and complexity, plays an essential role in helping students understand sources of error and limits of certainty. The survey of field instructors in the UK during the 2001 foot-and-mouth epidemic reported that alternative activities such as slide shows, virtual field trips, and data-intensive problem solving activities did not adequately replace fieldwork, although such activities could be used in support of fieldwork (Scott et al., 2006). No amount of computer modeling firepower can adequately simulate the natural variability produced by the long-term operation of the Earth system (notwithstanding *Hitchhiker's Guide to the Galaxy*; Adams, 1979).

Immersion in the environment activates all five senses (Millar and Millar, 1996) and results in a strong affective response. The observer is necessarily within and part of the environment, not external to it. Field trips that are designed to immerse students in the environment evoke strong sensory experiences that include interactions with nature, particularly those that result in strong emotions. Having to physically move from place to place in the environment requires students to slow down their engagement with the subject of interest, take time to talk with mentors and peers about observations as they emerge, and have time to reflect on their work to gain deeper understanding (e.g., Locke, 1989). This point has been emphasized by Ingold (2007), whose anthropological studies define the concept of "wayfaring" as applied to those who move through an environment inspecting everything around them, as opposed to "transportation," where the trip itself is irrelevant and is simply the means for getting from point A to point B. A memory of spatial relations is enhanced through sensing the environment through vision, audition, and proprioception (e.g., Frodeman, 1996; Montello et al., 2004). In many cases, a particularly poignant event (e.g., witnessing a beautiful landscape; summiting a mountain peak after a hard climb; experiencing a violent thunderstorm) may evoke strong memories that also contribute to learning (MacKenzie and White, 1982). For the general public, immersion in nature has many benefits. Louv (2006) and others have argued that spending time in close contact with nature is important for children's physical, psychological, social, and spiritual development. Modern children are spending less time outdoors because of urbanization, parental fears, and competition from electronic entertainments. Field-based science and environmental education can help to counteract this trend. Louv makes the case that early and frequent exposure to nature fosters increased motivation to learn, willingness to engage in creative activities, a heightened curiosity and sense of wonder, and a calming influence that helps focus attention on learning and mitigates behavioral problems; these attributes carry over into improved academic performance in other subject areas.

Foundations of Geoscience Skills and Expertise

With respect to the professional development of students for careers in geology, learning in the field has been cited as valuable or essential to: reinforce fundamental geological concepts, apply geologic content and skills, develop note-taking skills (clear and objective), sketching (to demonstrate key relationships based on focused observations), describe rocks and structures, select and appropriately use tools (e.g., Brunton compass, Jacob's staff), create geologic maps and cross sections, develop the ability to interpret three-dimensional geological structures, and see process and history in geological features (e.g., AGI, 2001). Practices that are emphasized in field instruction, such as question asking, problem solving, observation, representation, and communication (e.g., Niemitz and Potter, 1991; Carlson, 1999; Rowland, 2000), help to acculturate the novice into the common set of perspectives, approaches, and values (Manduca and Kastens, this volume) that characterize the community of geoscientists. Learning in the field requires development of higher-order cognitive strategies (e.g., data acquisition, analysis, synthesis) required to master and retain abstract concepts (e.g., MacKenzie and White, 1982; Orion, 1993). Field experiences, often under difficult conditions, help students to develop efficient work habits, stimulate independent thinking, engage in decision-making strategies (Isen, 2000), develop personal work ethics (e.g., perseverance, integrity), and promote interpersonal collaboration and communication skills (Kent et al., 1997; Berg, 1986; AGI, 2001; Heath, 2003; Gray, 2006; Butler, 2008; Maskall and Stokes, 2008).

Field instruction also leads to the development of important personal and professional social networks through shared experiences at field camps and field conferences. Field experiences can help students gain confidence in their ability to contribute to group work (Fuller et al., 2006; Boyle et al., 2007). Conversely, many geoscientists work alone in the field, and the professional expectation is that work will be completed in stressful environments that are intellectually and physically demanding, and in the face of natural adversity (e.g., weather, terrain, potential physical dangers). This dichotomy requires that geoscientists must have self-confidence in their ability to work independently to achieve results, but these results must then be presented to and validated by peers and mentors (e.g., Vygotsky, 1978; Bandura, 1986). On a personal level, the field environment affords students the opportunity to explore personal interests, and to readily identify peers with common interests (Thompson, 1982). In an immersive field environment, knowledge, abilities, and personality traits are readily revealed that can engender a sense of trust and confidence between participants that carry over into other aspects of professional life. Fieldwork can help break down teacher-student barriers through shared field experiences (often under stressful conditions; Fuller et al., 2006; Boyle et al., 2007). As important as group work is in the field, this learning environment can also contribute to self-confidence and self-reliance among students who are faced with challenging intellectual and physical tasks in the field (e.g., Hendrix and Suttner, 1978; Marques et al., 2003). Field experiences empower students to learn how to learn in an open, unconstrained environment.

Perhaps the most important indicator of expertise in the geosciences is the ability to ask appropriate questions about Earth in contexts that are realistic and meaningful. Field studies are done on many scales and for many purposes. So, it is essential for a novice geoscientist working in the field to be able to articulate the purpose of the fieldwork: reconnaissance (just seeing what's out there, to determine if there's any questions that may emerge that are viable for further study), mapping (on what scale, for what purpose—bedrock? structural? hydrologic? soils?), sampling (for geochemical or paleontological purposes?), and novice geoscientists learn to employ the strategies, methods, and tools required to solve the problem. In the conduct of field studies, the geoscientist must have the ability to cope with the unexpected, to make new meaningful and consequential observations, to have a nimble and "fertile mind" that is well prepared to understand the significance of new discoveries, to be able to integrate this new information with extant knowledge, and to formulate new hypotheses and tests.

An important corollary is the ability to make meaningful (and realistic) interpretations from data and to analyze the quality and certainty of observational data supporting geoscience theories (Manduca et al., 2004). The geoscientist must be able to engage in analogous reasoning and make inferences when the available data are missing, incomplete, or ambiguous (Ault, 1998; Raab and Frodeman, 2002). At times, it is necessary to make correlations from one field area to another and to integrate fragmentary information of different types from different localities (Turner, 2000); to apply the methods of multiple working hypotheses (Gilbert, 1886; Chamberlain, 1890) and integrate numerous lines of evidence into internally consistent arguments; to develop healthy skepticism about the nature of observations and evidence; to make meaningful interpretations and representations; and to understand the relationship between the representations and the real world. In confronting the complex Earth system, geoscientists must develop the ability to establish causality when often competing factors lead to singular features we see in the field today. The geoscientist must unravel multiple types of evidence, which then leads to interpretation of history, process, physical and chemical conditions, biological or anthropogenic influences, and ultimate sources (e.g., Stillings, this volume).

Geologic expertise is broadly concerned with the architecture and history of Earth; thus, spatial and temporal reasoning skills are highly valued (Orion et al., 1997a; Reynolds et al., 2006; Butler, 2008; Liben and Titus, this volume; Frodeman and Cervato, this volume; Manduca and Kastens, this volume). Perhaps the most important spatial skill is the ability to see structures in three dimensions, and to be able to infer these structures where they are buried below the surface or removed via erosion (Reynolds et al., 2006). Expert geologists appear to have advanced pattern recognition skills, and they have a cultivated ability to know what to look for, and what to exclude in complex natural settings (a process known as disembedding; Goodwin, 1994; Reynolds et al., 2006). Geologists also have the ability to "zoom" across many spatial scales with little cognitive dissonance, and to integrate observations on scales that range from microns to mountains. Another important indicator of geospatial expertise is the development of spatial memory, i.e., the ability to find places again, navigate in the environment, and communicate about spatial locations and relations. This ability is developed directly through perceptual-motor interactions while moving through an environment (Montello et al., 2004), and Frodeman (2003) asserted that to understand three-dimensional space, one must move through it. Related skills in terrain analysis include self-location, "seeing" three dimensions from topographic maps, predicting where natural phenomena will occur, and planning traverses to be in a position to make appropriate field observations (e.g., Riggs et al., 2009a, 2009b). Similarly, master geoscientists are called upon to make observations and integrate evidence across many temporal scales (Cervato and Frodeman, this volume). Geoscience expertise requires the ability to visualize the evolution of natural systems and changes through time through analysis of geological phenomena and the ability to see process/history in objects or landscapes that appear to be static (Dodick and Orion, 2003; Frodeman and Cervato, this volume). Fundamental observations in the field can contribute to an overall understanding of geologic time (Thomas, 2001).

INSIGHTS FROM THE COGNITIVE AND SOCIAL SCIENCES

The empirical approaches to field instruction that geoscientists have evolved over the years through intuition, experience, and observation of students can be analyzed and interpreted through the principles and research results from the cognitive and social sciences. In the following sections, we provide the theoretical foundations that explain three important components of learning in the field: embodiment, inscriptions, and the community of practice.

Embodiment

Embodiment is a fundamental attribute of cognition that facilitates and enhances organization of knowledge by geoscientists. To avoid having this term appear opaque, we here provide a brief discussion of the reasons why some contemporary research in cognitive science focuses on the role played by the body in the organization of knowledge, and more crucially why this is important to the education of geoscientists. The case we make is that learning in the field affords the acquisition of embodied skills in both natural and social settings, knowledge and ways of seeing and acting that sit at the base of geoscience practice, and that instructors can leverage understanding of embodiment to improve geoscience instruction.

Early work in cognitive science treated thinking, and cognitive activity in general, as the manipulation of abstract symbols, such as digital 0's and 1's. In theory, such symbols could be manipulated by not only living beings but also machines such as computers. The body, or machine, which housed the calculator was irrelevant to the logic of its operations. Cognition was analyzed as a process that was formal, abstract, and disembodied (Cunningham, 2007).

This view has been strongly challenged by important work from several different disciplines, which together demonstrate the central importance of the body in human (and animal) cognition. Within philosophy, phenomenologists including Husserl (1960), Heidegger (1962), and Merleau-Ponty (1962) have argued that the ability of the living body to act in the world, for example, by grasping objects or moving around them to reveal multiple perspectives, creates the conditions within which consciousness and knowledge become possible. The phenomenological perspective is evident in contemporary geoscience as described in the work of Frodeman (2003) and Foltz and Frodeman (2004). Thus, he argues that being able to see the relevant details in an outcrop "has little to do with native intelligence, or following a set of logical procedures. Rather it depends upon *knowing your way around* the topic, being oriented in conceptual space—or in the case of field science, in an actual geographic and geologic space" (Frodeman, 2003, p. 127).

Within contemporary cognitive science, embodiment is now recognized as an important component of human cognition (Nairn, 1999; Gibbs, 2005), a position that is summarized succinctly in the title of Clark's (1997) *Being There: Putting Brain, Body, and the World Together Again*. Within neuroscience, the body, and not just the brain in isolation, is recognized as central to the organization of cognition. Damasio (1994, 1999) showed how the brain uses the body's interactions with the world to build models of both that world and the body's possibilities for action within it. Moreover, the body uses emotions to code, remember, and mark as salient those features that are important in these encounters. Affect is thus linked to cognition (Gray, 2004; Storbeck and Clore, 2007; Pessoa, 2008). From a different perspective, Proffitt (2006) demonstrated that physiological and psychological states, especially when tied to anticipated courses of action, can alter an actor's perception of the environment, as when hills are judged to be steeper when one is wearing a heavy knapsack.

Within cognitive linguistics, great attention has been paid to the way in which the experience of our bodies structures the metaphors that shape our understandings of many crucial phenomena (Lakoff and Johnson, 1980, 1999). Language does not occur within a vacuum but emerges within embodied participation frameworks, what Goffman (1972) called "ecological huddles" organized through the mutual orientation of the participants' bodies toward each other and the environment that is the focus of their scrutiny. These facing formations (Kendon, 1990) create a public organization of attention that enables participants to recognize what each other is about to do—something that is central to the organization of multiparty collaborative action—and to attend together to relevant phenomena in the environment, such as landscapes, maps, and the relevant actions of others (Nairn, 1999; see Fig. 3). These arrangements make it possible for a senior geoscientist to observe both the landscape and the operations being performed on that terrain by a student. They are central to the process through which the skills and knowledge of a young geoscientist are organized as public practice (Lave and Wenger, 1991; Wenger, 1998; Goodwin, 2010). Such arrangements create environments within which other kinds of sign exchange processes, such as talk and gesture, can flourish. Figure 6 demonstrates typical mentor-student interactions on an outcrop, demonstrating the use of gesture to represent orientation of structures in an outcrop and use of a folded field notebook to model orientation of a plunging fold.

Gesture displays our embodied knowledge of both concepts being expressed and the world within which the hands are acting (McNeill, 1992; Duncan et al., 2007; Goodwin, 2003; Kendon, 2004; Streeck, 2009). Research has shown that when learning new concepts, students frequently display understanding through gesture before they can do so in speech (Goldin-Meadow, 2003; Goldin-Meadow and Singer, 2003; Alibali et al., 2000; Alibali, 2005). This has been found to occur in the learning of plate tectonics in a sixth-grade geoscience class (Singer et al., 2008) and among undergraduates trying to explain the shape of a geological structure (Kastens et al., 2008). Moreover, the spatial nature of gesture allows students to collaboratively negotiate and explore in complex three-dimensional space the meaning of concepts such as rift zones. In one study, a student moved another's hands apart and then placed her own between them to represent the intrusion of magma. "The external nature of gesture meant that students could manipulate each other's representations; copy another student's gesture; and add to, correct, and revise a concept through gesture" (Singer et al., 2008, p. 380).

Figure 6 provides a number of examples of gesturing hands, combined with materials such as notebooks and pieces of paper that can model planes and folds. The gestures and materials are being used to represent for students critical geological structures that are present within the dense landscape being scrutinized, but that are difficult for an untrained eye to selectively see. Students' bodies, positioned in the midst of the field setting, take into account simultaneously both the complex Earth that they are trying to study, and the transient representations artfully constructed through the embodied activities of their professor that selectively highlight consequential structure. Through this process, the students are guided to develop the professional vision required to be a competent geoscientist. As will be discussed in more detail later herein, the practices required to construct and work with maps

Figure 6. Embodied representations of natural phenomena, using gestures, notebooks, and folded paper to demonstrate physical features in the outcrop to students. Photo credit: Chuck Goodwin and David Mogk.

and representations of the world being studied are crucial to the organization of knowledge and practice in the geosciences. These practices are intimately tied to gesture. Both maps and features in the landscape being mapped are among the principal phenomena being pointed at, and articulated in ways relevant to the social and cognitive projects at hand, by environmentally coupled gestures (Goodwin, 2007). It is through use of embodied practices such as pointing that the process of selecting the limited phenomena in a rich landscape that are to be transferred to a map is organized as public practice. Field education is crucial for the acquisition of these embodied skills.

Not all bodies are the same, and this has particular importance for education in the geosciences. In an extended line of research, Liben (2008) and Liben and Titus (this volume) have demonstrated great variability in students' abilities to perform spatial tasks and work with spatial concepts. Rather than treating students as a homogeneous population, educators can now design instruction to take such variation into account.

Exploring and Explaining Earth through Inscriptions

The field setting is where geoscientists initially translate nature into culture, i.e., where we begin to create representations based on communally tested and accepted practices (e.g., maps, graphs, visualizations) that explain, confirm, rationalize, and externalize our understanding of Earth. Working with these stylized and derivative materials, students learn how to construct and "read" the story of Earth, and the corollary, to "tell its story" through professional discourse that uses these materials to interpret and explain. The awesome nature of Earth and its history can present a very heavy, overwhelming cognitive load indeed. Thus, it is often necessary to create representations that focus attention on details that enlighten a particular concept or key piece of evidence. It is in the field where crucial selections lead to first inscriptions, such as maps that translate observations and information from the raw essence of nature into representations that are constructed to enhance meaning or utility. The field learning environment provides rich opportunities for students to make discerning observations about complex nature, to distill these observations and critically evaluate what is important to report and what to neglect, and then to make representations that demonstrate understanding of natural phenomena and communicate results to peers, mentors, and broader audiences.

Scholars investigating scientific practice, in a continuing line of research extending from work such as Latour and Woolgar (1979), have demonstrated that the documents through which scientific knowledge is codified and disseminated, such as journal articles and conference presentations, are systematically produced through a process that involves skilled work with tools that transform the subject being investigated by a particular scientific discipline into appropriate, tractable graphic representations. The different kinds of graphic representations used by scientists are sometimes glossed as "inscriptions," a term meant to encompass representations as diverse as preliminary maps, graphs of numerical data, images from microscopes and other scientific instruments, the overheads used in talks, the enhanced graphic displays used as figures in journal articles, animations, 3-D visualizations, etc. (Fig. 7). Inscriptions are necessarily simplified representations of the real world; they "… do not simply 'reveal' facts about the world, but rather simultaneously obscure many aspects of

Figure 7. Inscriptions of natural phenomena transform observations of nature into permanent, portable records. Inscriptions represent distilled nature, and purposefully emphasize specific observations while excluding other information. The first inscription is the most crucial, because this is where informed decisions are made about what is important to record, and what is not. Photo credit: Chuck Goodwin and David Mogk.

the represented world while making others visible" (Radinsky, 2008, p. 147). A crucial property of inscriptions is that, unlike the raw nature being investigated (an outcrop, tissues in a rat's brain, microorganisms living in the extreme conditions of a Yellowstone hot spring, etc.), they are *portable* representations that can be contained on sheets of paper or computer files and moved fluidly to the diverse environments where subsequent analysis, presentation, and debate are done. In the case of geologic studies, the creation of inscriptions means that information is no longer bound to the physical presence of the natural phenomena under study, and it provides a primary way to disseminate essential information to wider audiences who cannot physically be present in the natural environment. Thus, inscriptions create public and permanent records that facilitate transfer of facets of personal understanding to the corpus of knowledge that can readily be shared with the larger community.

Specific to geology, the creation of geologic maps assumes an important role in the development of geoscientists. Geologic maps are one of the primary means of conveying information in the geosciences, and they contribute to further interpretive work in the preparation of cross sections and interpretations of geologic history. They require informed decision making on the part of the mapper, e.g., scale of observation, classification of rocks or units, decisions about the particular features to map (bedrock, surficial geology) and data to include (e.g., Ernst, 2006). Harrison (1963, p. 225) noted, "The geologic map, although in part objective and a record of actual facts, is also to a very large degree subjective, because it also presents the geologist's interpretation of these facts and his observations. …" Sturkell et al. (2008) developed a student mapping exercise that demonstrates that geologic maps are "… most often made from sparsely and spatially non-uniformly distributed data implying that the final products depend both on sampling strategies and interpretation. The pedagogic, take-home lesson from our exercise is that no map is better than the input data, and no map represents the absolute truth." Geologic maps typically reflect the theory of the day (Harrison, 1963), but also, the act of mapping will test new hypotheses and inform the creation of new theories (Ernst, 2006). Geologic maps are not static or timeless, and they necessarily will be revised to portray evolving understanding. The information represented on a geologic map based on field studies is often revised when additional data are collected (e.g., petrographic analysis, geochronology). Typically, the field geologist collects more data than can be shown on a map, so decisions must be made about what is most significant to represent on the map. Also, field geologists can never be complete in their observations, so they must be reconciled to working with ambiguous or missing data (e.g., Ault, 1998; Raab and Frodeman, 2002). More than one interpretation can be made of the information presented on the map; another geologist may make interpretations quite different from those of the author and may even see more than the original author realized was there (Harrison, 1963).

Lynch (1990) argued that the work done by scientists to organize nature into clear graphic representations provides them with radically new ways of seeing the world they are investigating, what he calls an "externalized retina," and that scientific work proceeds by successively modifying and enhancing these graphic representations, producing a "chain of inscriptions." An example of this flow of information from observations in the field to more refined representations can be found in the way in which a Brunton compass is used to collect the data in the field, which are then represented on a map as a series of strike and dip measurements. These data create an image of a structure in the landscape that could not readily be seen from any single vantage point. Subsequent plotting of the data on a stereonet then quantifies the style and orientation of structural elements that occur in nature. The field site occupies an especially important place in this process since (1) it is the place where the first inscriptions, the ones that all subsequent transformations build from, are produced (Fig. 7); and (2) at the field site, it is possible to examine in detail not only the graphic inscription, but also the tools, situated seeing, and work practices required to make the inscriptions that define both work and knowledge within a particular scientific community. Field schools are thus especially relevant sites for scientific education because they are the beginning of two crucial transformative processes: (1) the transformation of nature into data, knowledge, and new understanding; and (2) the transformation of novices into geoscientists, through a rich process of apprenticeship that socially organizes the work with tools required to build and analyze the crucial graphic objects that make possible the scientific knowledge of the processes that shape Earth (Hoskins and Price, 2001).

Given the complexity of Earth processes and history, and the iterative and integrative nature of geoscience investigations, we modify Lynch's (1990) concept of a "chain of inscriptions" (as a simple, linear series of representations) to be better represented as a "braided stream of inscriptions" (to use a geologic metaphor, Fig. 8). We envision that a spring of information emanates from the existing literature (maps, journal articles), which informs the formulation of the research question and selection of field site. Then, anastomosing channels of information draw from many lines of inquiry (field observation, field notes, photos, measurement, sampling) and branch out and recombine as the field project moves ahead, taking ideas (eroding) from some areas and accumulating (depositing) information in new combinations in others (e.g., new inscriptions such as maps, stereonets, chemical variation diagrams). The flow gains competence and capacity through subsequent analysis and testing, responding to a dynamic flow regime where eddies force information to cycle around and sometimes encounter turbulent flow (that can muddy the water) in this ever-changing landscape of understanding. The many strands of information ultimately coalesce into a coherent channel of information, presented as scholarly reports or presentations. In this sense, any single node in this process is not a separate self-contained point but a "knot tied from multiple and interlaced strands of movement and growth" (Ingold, 2007, p. 75). Like peripatetic walking, the recursive movement of geoscientists through physical and conceptual landscapes constituted by

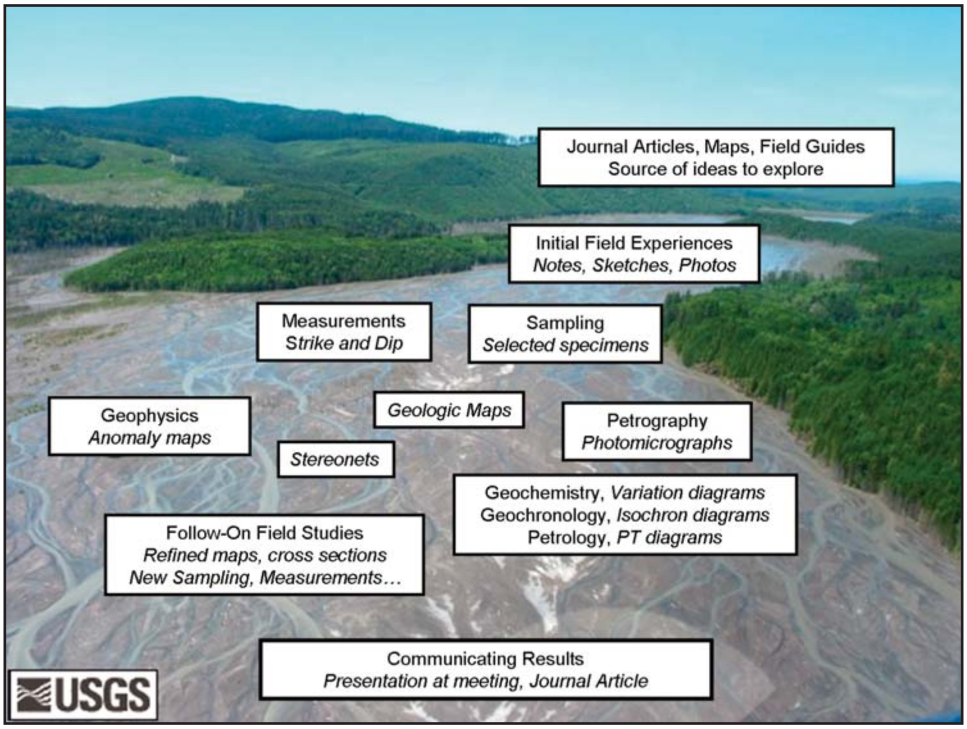

Figure 8. A representation of the "braided stream of inscriptions" that would represent a typical field study. From the spring of information emanating from the existing literature and maps, initial field studies lead to anastomosing channels of information that include field observations and measurements, sampling and mapping, and a wide variety of follow-on analytical work (as appropriate to the research question at hand), and these multiple lines of evidence ultimately coalesce into a coherent channel of information that leads to scholarly presentations or journal articles. Italicized items are examples of the types of inscriptions that are produced at various stages in the project.

both the actual Earth they are interrogating, and the inscriptions that enable them to know and understand that Earth in relevant ways, is "like the spiral of a harmonic progression, [that] allows us to return to, and regenerate, the places that give us sustenance" (Olwig, 2002, p. 23).

The maps and categorizations of rocks, structures, and physiographic features produced by geoscientists are not murky, inadequate images of something that can be far more richly seen, known, and experienced by actually being there. Rather, they are enhanced representations that actually give a clearer analytical picture of the landscape being investigated, because the geoscientist has made informed decisions about the type and quality of the evidence required to answer a specific question and has actively selected the information to be included on the map.

For educators, the ready availability of such rich, analytically relevant inscriptions has the paradoxical effect of suggesting that actually going to the field is unnecessary. Not only is fieldwork expensive, and it can include physical danger and potential liability claims, but pedagogically, it might be argued that the students are actually able to see the phenomena they are studying more clearly with analytically organized inscriptions than they could in the rich but confusing environment of the actual landscape itself. Learning by moving through a world of idealized representations, in textbooks and on the computer (including virtual environments), is not only easier and clearer (since so much of the relevant analytic work has already been done by those who made the inscriptions), but also cheaper and safer. However, much is lost if this work with inscriptions is not grounded in actual experience of the complex worlds they vividly but incompletely render: the challenge to make discerning observations in a complex environment, the quandary of deciding what to report and what to leave out, and the power of transforming the raw material of nature into a human-made artifact. In fact, what is missing if one merely looks at end-product inscriptions is the important role of embodiment in learning, and in the next section, we turn our attention to the connections between inscription and embodiment.

Linking Inscriptions to Embodiment

Inscriptions, which can easily move unchanged from setting to setting on bits of paper (thus, Latour [1987] famously called them immutable mobiles) and endure in books long after the individuals who made them are deceased, might seem to be a very different kind of phenomenon from embodiment, which occurs within a specific environment, with a distinct cohort of participants at a particular moment, and which consists of postures and movements, such as gestures, that rapidly disappear without leaving any physical traces. However, the "first inscription," the initial map or image where the raw material provided by a landscape is transformed into a geological representation, is something done by actors through embodied activities. This is true even when, as with sonar images, the inscription is produced mechanically. Human selection and judgment are required for the production and interpretation of the representation, for example, in determining where to deploy the instruments, judging the

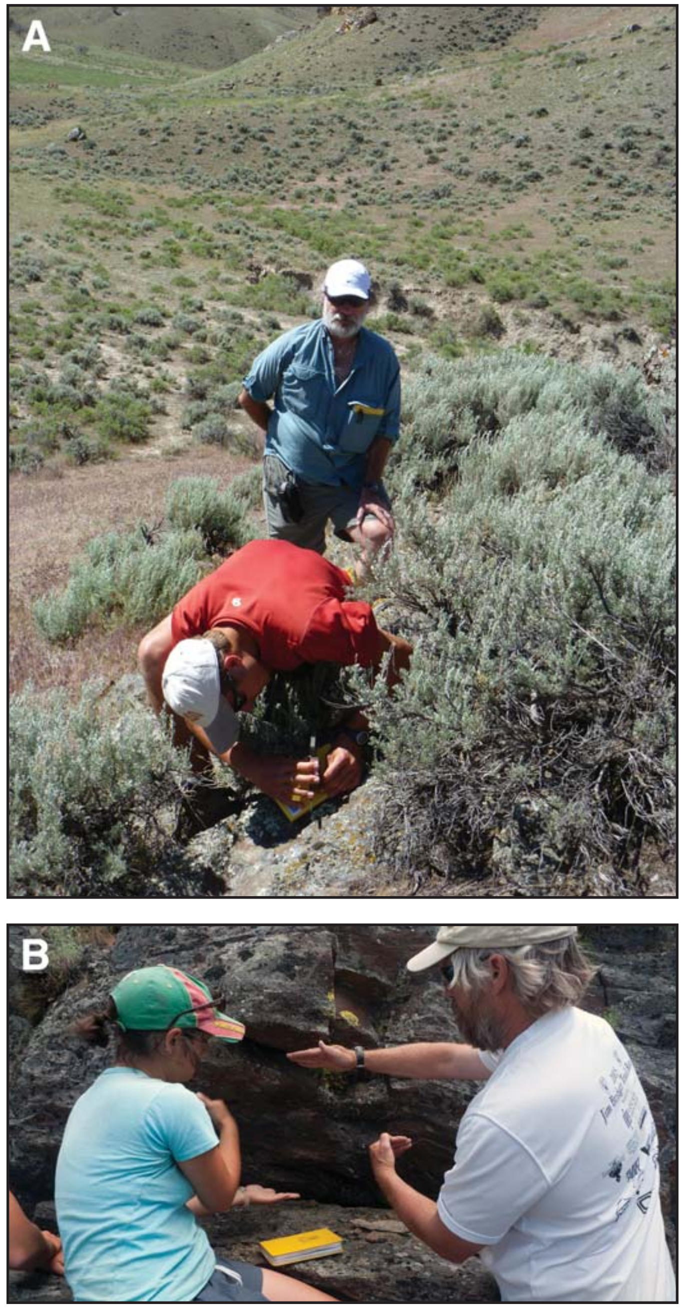

Figure 9. (A) Embodied practice demonstrated as a student collects structural data under the guidance of a senior geologist. The instructor simultaneously is interacting with the student, monitoring the activity, and interacting with the natural environment that he is observing. Photo credit: David Mogk. (B) The use of gesture by a senor geologist to draw attention to structures on the outcrop, and through movement, to demonstrate deformational processes. Photo credit: Chuck Goodwin.

import of what can be seen in the images produced, annotating or highlighting key features for emphasis, and selecting the images to be published and thus enter into a larger discourse.

Consider Figure 9A, where a senior geologist is monitoring the work of a student collecting structural data on an outcrop; the senior geologist is simultaneously interacting with the student and the natural environment. In Figure 9B, the senior geologist uses gesture to focus the attention of the student on particular features in the outcrop, and to impart information about the deformational processes that developed these structures. Through phenomena such as the linked gestures and movements made by each hand, the rich, sometimes chaotic visual materials provided by the complex actual landscape are selectively reduced to crucial structural features visible to a skilled geologist in the intricate patterns. The judgments and consequent activities through which the original landscape is seen selectively are crucial to the production of the map or image. The first inscription is thus embedded within the embodied actions of actors attempting to see significant structure in order to transduce the materials provided by the landscape into geologically relevant representations.

The way in which a senior geologist shapes and guides the seeing of a newcomer through such embodied practice is central to the public, replicable organization of knowledge within a community. It was noted previously herein that cognitive science is now trying to put the brain, the body, and the world together again. However, the crucial factor for scientific knowledge (and indeed all forms of communal knowledge) is not the individual brain or body, but multiple bodies, and brains, working together to see, understand, and represent the world in just the ways that are appropriate to the distinctive work of their community. The gestural work of representing structure so that it can be mapped in Figure 9B is one concrete place where the ability to see the world and think as a geoscientist is organized as public knowledge across generations.

The importance of the embodied cognitive activities that occur in the field before an inscription is even produced points toward a crucial time dimension in field learning that requires much more systematic investigation. In the field, students do not simply make maps, or carry out a traverse, but constantly circle back, for example, repetitively looking at the landscape, drawing a representation, looking back at the landscape to check what they've drawn, making revisions to the drawing, moving to a different position to get a different view, etc. (For examples of the traces of student navigation in field mapping exercises as recorded by GPS, see Riggs et al., 2009a, 2009b.) Such embodied looking, gesturing, and moving through space is central to not only producing maps and other inscriptions, but also to knowing how to understand the inscriptions produced by others. In our opinion, an important future research agenda for understanding field learning is videotaping actual processes of making inscriptions and related field activities, so that the crucial embodied, and linguistic, events that occur on this moment-by-moment time scale, and that seem central to the formation of both competence and knowledge in the earth sciences, can be adequately understood (for analysis of such processes in archaeological field schools, see Goodwin, 2010).

This process of going back to look again at a landscape occurs on longer time scales as well, as older geologists revisit sites they mapped years earlier (e.g., see Ernst, 2006), frequently now seeing something different, and as members of the profession use the opportunity provided by a professional meeting to include field trips so that they can look together at significant landscapes. Inscriptions come into existence and become relevant through the embodied work of cognitively active geoscientists. The recursive process of constructing and working with inscriptions: (1) renews and sometimes changes existing inscriptions such as maps; (2) changes the conceptual models that are applied toward interpreting a particular landscape; (3) transforms earth scientists themselves, as their understanding of nature matures; (4) is informed by subsequent analysis of Earth materials, and other observational data obtained by techniques such as remote sensing or "indirect" observations such as geophysical measurements; (5) enables comparison and correlation based on insights about relations recorded at other similar field locations; and (6) exposes the strategies and methods of the discipline itself as part of a public, communal cognitive enterprise.

Debates in other disciplines shed light on the importance of visceral hands-on experience in the shaping of new practitioners. In a process that has direct analogies to field experience in the earth sciences, dissecting an actual human body has traditionally been a crucial, early component of medical education. However, like field experience, actual cadavers are expensive and messy. Bodies generated by computer programs are not only cheaper but are also able to visually display relevant structure with much greater clarity. Arguing strongly against the movement to eliminate cadavers, Christine Montross (2009, p. A29) noted that "the dissection of cadavers … gives young doctors an appreciation for the wonders of the body in a way that no virtual image can match. It is awe-inspiring to hold a human heart in one's hands, to appreciate its fragility, intricacy, and strength." Such a combination of embodied cognitive knowledge—of learning through practice precisely how to see relevant structure in the world that will be the focus of one's life's work—tied to strong affect is characteristic of geoscience field schools and is reported by many to have been pivotal in their decision to become an earth scientist (Kern and Carpenter, 1984, 1986; Boyle et al., 2007).

Community of Practice

Like many highly skilled activities, such as being a surgeon or a hunter in a traditional society, proficiency in field science requires a long apprenticeship, initially under the tutelage of experienced master scientists and subsequently through peer-to-peer interactions. In the field setting, students have the opportunity to learn *from* nature and *about* science as a social enterprise (Frodeman, 2003). In this section, we emphasize four commonalities that derive from learning in the field that enrich and enhance students' initiation into the geoscience community of practice: language translated into practice; tools used to acquire, organize, and advance community knowledge; shared ethics and values; and collective understanding of limits and uncertainties.

First, as Wittgenstein (1958, p. 242) argued, "if language is to be a means of communication there must be agreements not only in definitions but also (queer as this may sound) in judgments." If we stretch the term "language" to include map symbols and other analytical inscriptions used to communicate ideas, then Wittgenstein's assertion describes an important challenge in science learning. Being able to recognize a relevant structure on a map, or the definition of a category such as "fault" or "fossil," does not in any way guarantee that one can then locate proper instances of this category in/on actual Earth. The development of such "agreement in … judgments" happens during apprenticeship in the settings where geoscientists encounter the actual phenomena that are the focus of scrutiny. A master geoscientist can express professional judgment based on a lifetime of experience to help focus attention on salient features, to draw analogies with other similar natural occurrences, and to bring to bear external knowledge from experiment, models, and theory. In a field school, an experienced competent geologist can observe both the landscape being studied and the operations being performed on that landscape by a newcomer to the profession (Figs. 9A and 9B). Thus, the maps that a student draws and the labels he applies can be juxtaposed to the actual phenomena being recorded, and the fit between the two can be evaluated through the skilled eyes of the senior geologist. Problems associated with the appropriate parsing of the landscape and the proper use of the tools required to record it become visible and public through the student's actions and words, and the student's practices can be critiqued and corrected in situ by the professor (Goodwin, 2010). The field school thus creates an environment where what Wittgenstein referred to as "judgment" can be organized as systematic practice within the actual work life of a scientific profession. In brief, there is always a gap between idealized descriptions and the real-world phenomena being studied, interrogated, and probed through analytic categories. Guided building of inscriptions bridges this gap through situated practice while producing a new generation of competent geoscientists. An example of situated learning as part of the apprenticeship required to learn how to "see" Earth and apply systematic practice can be found in Shubin (2009, p. 63–67):

> My baptism in field paleontology came from walking out in the Arizona desert. … At first, the whole enterprise seemed utterly random … I'd set off looking for fossils, systematically inspecting every rock I saw for a scrap of bone at the surface. At the end of each day we would come home to show off the goodies we found. Chuck would have a bag of bones. … And I had nothing, my empty bag a sad reminder of how much I had to learn. After a few weeks of this, I decided it would be a good idea to walk with Chuck. He seemed to have the fullest bags each day, so why not take some cues from an expert? Chuck did not look at every rock, and when he chose one to look at, for the life of me I couldn't figure out why … Chuck and I would look at the same patch of ground. I saw nothing but rock–barren desert floor. Chuck saw fossil teeth, jaws and even chunks of skull … I wanted him to describe exactly how to find bones. Over and over he told me to look for "something different". … Finally, one day, I saw my first piece of tooth glistening in the desert sun. The enamel had a sheen that no other rock had. … The difference was this time I finally saw it, saw the distinction between rock and bone. All of a sudden, the desert floor exploded with bone; where once I had seen only rock, now I was seeing little bits and pieces

of fossil everywhere, as if I were wearing a special new pair of glasses. … Now that I could finally see bones for myself, what once seemed a haphazard group effort started to look decidedly ordered. Over time, I began to learn the visual cues for other kinds of bones. … Once you see these things you never lose the ability to find them … a fossil finder uses a catalogue of search images that make fossils seem to jump out from the rocks. The power of those moments was something I'll never forget. Here, cracking rocks in the dirt, I was discovering objects that could change the way people think. That juxtaposition between the most child-like, even humbling, activities and one of the great human intellectual aspirations has never been lost on me.

Second, a most crucial aspect of human cognitive and social life, one that distinguishes us from almost all other animals, is the ability to create cognitive structures, such as maps, category systems, tools, and indeed language itself, in a public environment where these visible artifacts can organize the cognitive and social actions of others (Goodwin, 2010; Hutchins, 1995). Skillful use of tools can be one of the most important ways that community knowledge is acquired, organized, and applied. For example, communities of archaeologists and geoscientists, who are faced with the task of systematically describing the color of the soil or sediment, use a tool that provides a solution to this task: the Munsell color chart and its accompanying category system. This simple physical object encapsulates the outcome of a long history of scientific analysis of color by providing grids of color samples of closely related colors on pages in a portable notebook that can be carried into the field. Next to each color patch is a small hole. The scientists wanting to classify the color of a soil sample can put it on a trowel and move it from hole to hole until the best match is found. A replicable description of the color can then be written down as both grid coordinates and a standard name in the local language (Goodwin 2000, 2010). Communities of geologists faced with the task of systematically describing the orientation of rock strata have developed the Brunton compass and the convention of the T-shaped strike and dip symbol. By using these tools and their associated representations, the eyes of individual workers are transformed into practices and products of public perception that can be shared within a community. Tools such as the Munsell chart or the Brunton compass provide public architectures for perception that can organize in quite fine detail the work and cognitive activity of those using these tools to do the mundane but central classification work of a scientific community attempting to describe and then understand some part of the natural world. The ability to competently use such crucial tools is best acquired in field settings where young geoscientists encounter the genuine complexity of the phenomena they must selectively describe, map, or measure (Figs. 10 and 11).

Actual tool use is subordinate to the analytic decision-making process that leads, for example, the field worker to choose to make a map of this but not that (and related decisions about map scale, choices of rock units, style of mapping), to measure the strike and dip of a particular rock because it will provide relevant information that may not be evident in other nearby rocks, or selection of samples for future analysis. The hands using the tools are tied to a mind that is learning to see and think as a geologist through the actual work of deciding what parts of the landscape to describe, measure, or sample and thus to return from the field with analytically relevant representations of what they saw there (Fig. 11).

Figure 10. Students acquire the ability to appropriately use tools in the field setting as they encounter the genuine complexity of the environments they must selectively measure. Photo credit: David Mogk.

Figure 11. Use of tools in the field (e.g., Brunton compass) requires knowledge of how to use the instrument itself, and knowing where to make measurements, why this measurement should be made, and how it will be applied. Photo credit: Chuck Goodwin.

The pervasive use of such tools to do science has a range of important consequences for students developing understanding of the unique properties of graphic representations and the use of tools by scientists to organize their perception of nature. Consider not only the cognitive and embodied skills required to take strike and dip measurements with a Brunton compass (including, most crucially, where in the landscape to take such measurements; Fig. 11), but also the ability to extract meaning from the esoteric character of the strike and dip symbol used as an inscription to represent the rich complexity of the environment. By participating in the process of acquiring structural data in the field and plotting the results on a map, the newcomer acquires not only the skills required to perform the measurement, but also deep recognition of the partial, situated nature of the relevant inscriptions. Rather than constituting a simple picture of the landscape, the graphic representation provides a selective and focused tool for probing and systematically describing a crucial aspect of its structure (Liben and Titus, this volume; Kastens and Ishikawa, 2006; Liben, 1999). By experiencing data collection in the field, including selection of a sampling site amid natural variation and complexity, physically obtaining an accurate and representative measurement, and committing the data record to field book and map, the scientist gains a more complete appreciation of the aggregate cognitive and physical work that is required to produce these simplified representations. She also gains an understanding of the inherent assumptions, limitations, and uncertainties associated with data collection and a profession's representations. Use of tools in specific settings can lead to a deep appreciation for selective, relevant transformation by inscription, and opens the possibility of serendipitous discovery and growth in practice that would otherwise be difficult to achieve in a teaching environment composed entirely of already-constructed inscriptions.

More generally, the ability to work with different kinds of graphic representations seems absolutely essential to the development of competence, or even literacy, in science (e.g., Piburn et al., 2005; Liben et al., 2008). The extensive, complex embodied, socially organized work with inscriptions in a field experience provides one crucial place where these skills can be developed, though certainly not the only place. Ultimately, through practiced experience, a skilled practitioner can readily see inconsistencies or physical impossibilities that are revealed in graphical representations, may be able to determine the source of these anomalies (e.g., natural variation, instrumental or operator error), and may find meaning or cause for future investigations in identified outliers in data sets.

Third, the process of constructing representations in the field has an ethical dimension. Students are held accountable for the difficult, hard, systematic work required to produce appropriate inscriptions in the field, sometimes while cold, hungry, and wet (e.g., Lawson et al., 1999; Roth and Bowen, 2001). It is only through this process of guided apprenticeship that newcomers as part of their developing identity as practitioners of science acquire both the embodied practice and the ethical standards demanded by their profession. By actually working in the field in concert with experienced seniors, students learn what counts as appropriate rigorous practice, and the importance of adhering to the standards that define work in their profession. They do this under the observation of a senior scientist with genuine concern for the validity of the representations they construct. Their work in the field simultaneously incorporates affective, ethical, and cognitive dimensions. Eventually some current students will leave the nest provided by the field experience and work alone as new geoscientists. They may then produce inscriptions while working alone, in a situation where no one else can compare the map they draw with the actual landscape. They will have to make internal value judgments such as the decisions related to the distribution and density of data points or samples to collect—Will they finish a traverse under adverse conditions? Have they fully completed any required tasks at a field site knowing that they will probably not have the opportunity to return to that location? The representations they produce can and will be trusted by others within variable limits. This is not, however, because of another's absolute knowledge of the fit between landscape and representation. Instead, such trust emerges from the ways in which students are initiated into their profession through a process of field experience that encompasses (1) the construction of maps and other inscriptions in a consequential environment; (2) scrutiny by a senior geoscientist who is holding them accountable to the professional and ethical standards of the discipline and its work; and (3) ultimately by peer review, measured against norms of community knowledge and practice. The validity of the graphic representations they construct and share is warranted by the ethics and craftsmanship acquired through field experience.

Fourth, through doing their own fieldwork, students begin to develop an appreciation for the systematic but contingent validity of the inscriptions they are producing, which are necessarily simplifications constrained by available tools, available time, budget, logistical considerations, and the state of prior knowledge (e.g., Harrison, 1963; Ernst, 2006). Senior geoscientists understand that science is a process. Based on rich experience, they will note how interpretations, maps, and other representations can change dramatically as theoretical understanding of the processes forming Earth structures changes (Ernst, 2006), or as a landscape is revisited by an investigator whose ability to see Earth structure has been informed by a changing theoretical framework (Harrison, 1963). By actually making maps of structures observed in situ, the student begins to see that rather than providing a literal, absolutely truthful record of the landscape, any inscription constitutes the best effort of a researcher with specific skills, contexts, purpose, and theoretical interests (Sturkell et al., 2008). This recognition, that the maps and other inscriptions found in journal articles are not disembodied truths, but the competent products of the systematic craftwork of situated actors who have completed the work for a specific purpose and in self-determined contexts, seeds the ground for later discussion by geoscientists who advance the theoretical discourse of their field by questioning the descriptions published by others. The way in which the students at the field school in our opening illustrative example found evidence that did not support a journal article's claim for the presence of a dissected and transported alluvial fan provides one example of the way in which this critical reading of inscriptions is acquired through systematic practice that includes field experience.

It might be argued that exposure to the values, approaches, and perspectives of the geoscience community is only relevant to that small subset of students who will themselves become geoscientists. However, even if one does not become a scientist (or a geoscientist who works in the field in their professional duties), having a firm grounding in the actual practices of science, and not simply the reports through which scientific findings are made known to the public, is valuable for proper citizenship in a world where decisions about science are becoming increasingly crucial for our survival. Such a critical consumer of science is less likely to be misled by specious arguments about the limitations of science as nothing but unproven theories and inscriptions as merely being fanciful "cartoons." Similarly, it is clearly not being argued here that all geoscience must occur in the field, but rather that it is only with a firm grounding in field experiences that one can begin to comprehend the enormity, complexity, and uncertainty of the Earth system, and comprehend the discursive artifacts, such as maps and other representations like stereonets and stratigraphic columns, through which such knowledge is consolidated, dispersed through the community, and challenged or accepted. It is then possible for scientists and citizens to appropriately engage in scientific instruction and discourse, cognizant of the limits to our knowledge of the natural world, and to use the genuine power of inscriptions to make a range of extraordinary scientific worlds visible within books, classrooms, and computer screens.

In summary, we find that field experience is a crucial site for the initiation of students as skilled, cognitively rich actors into the community of practice of the geosciences. The field activities of the students sit at the intersection of:

1. Natural Earth systems, which initially present themselves to the students as a visual and material field of almost overwhelming complexity;
2. Interactions with master geoscientists who are skilled both in interpreting Earth, and guiding students to higher levels of understanding;
3. The academic debates that structure geology as a science seeking to describe and explain the natural processes that formed specific Earth phenomena;
4. The maps and other inscriptions that are constructed to both selectively filter the complexity of phenomena present at the site, and to begin to order what can be seen there into relevant analytic objects;
5. The tools created or appropriated by their predecessors to solve the systematic problems posed in fieldwork, such as hammers, acids, Brunton compasses, and geologic maps, which the students must learn to use in appropriate ways that are necessary to do earth science; and
6. The skilled practices that must be mastered by new students to make relevant analytic objects so that they can participate in geological questioning and debate.

It is in the field setting where nature is transformed into science, and students begin to develop as scientists. In *Gulliver's Travels*, Gulliver met two groups of scientists, one that carried around immense sacks full of things that they required in order to adequately ground their discourse empirically, and another that lived on islands that floated in the sky and never touched Earth. Field experience provides the means for mediating between these extremes and building actors capable of participating in consequential, relevant scientific discourse in both realms.

IMPLICATIONS FOR GEOSCIENCE EDUCATION

What constitutes an excellent field learning experience? Based on the insights and claims presented herein, and informed by earlier reviews by Butler (2008) and Maskall and Stokes (2008), several principles emerge:

Field Instruction Must Be Student Centered

In addition to a focus on content and skills mastery (including technical and interpersonal skills), there is a concomitant need to attend to students' needs, motivations, prior experience, scholarly preparation, and learning styles. While field experiences are justifiably intellectually, physically, and emotionally challenging, they must also be appropriate and realistic in terms of expectations for the participating students (Butler, 2008), particularly to help students improve their interests, attitudes, motivation, self-confidence, and belief in their own abilities (i.e., self-efficacy; Thompson, 1982; Kern and Carpenter, 1984, 1986; Boyle et al., 2007). Learning activities should be created that require a certain amount of risk-taking and stretch students beyond their own perceived limits—but not too far (e.g., Vygotsky's zone of proximal development, 1978).

Field Experiences Must Be Purposeful and Well Integrated with the Rest of the Geoscience Curriculum

In addition to residential field camps (Douglas et al., 2009; Sisson et al., 2009; De Paor and Whitmeyer, 2009), some courses have been focused on introductory field experiences (Geissman and Meyer, 2009), traditional courses for geology majors have been realigned to emphasize field-based research studies (Gonzales and Semken, 2009; May et al., 2009; Potter et al., 2009; Connor, 2009; de Wet et al., 2009), and some departments have organized their entire undergraduate curriculum with a strong field emphasis (Kelso and Brown, 2009; Thomas and Roberts, 2009). Purposes for field activities may include observation (at a particular location to see a specific phenomenon), a regional overview or synthesis of relations, focus on sample collection, instruction in the use of instrumentation (Whitmeyer et al., 2009; Swanson and Bampton, 2009; Bauer et al., 2009; Vance et al., 2009), mapping on many scales, or problem-based or research-intensive field programs (Fuller et al., 2006; Butler, 2008; Maskall and Stokes, 2008).

Learning Goals for Field Instruction Must Be Clearly Articulated

For citizens, the learning goal could be to instill an appreciation of nature, or of the systematic scientific thinking that has led to understanding of Earth processes. For students (K–12 and nonmajor undergraduates), a field experience may be used to invoke curiosity and inspire a sense of awe and wonder about the world around us. The learning goals for geoscience majors could include an introduction or description of a location or specific phenomenon; an opportunity to develop skills (note taking, structural measurements); independent projects, research, or other in-depth experiences; a disciplinary focus (e.g., paleontology, hydrology, geophysics); addressing affective aspects (social networking, motivation); or addressing issues of societal importance (e.g., Ort et al., 2006; Tedesco and Salazar, 2006). Fuller et al. (2006) suggested that in the early stages of geoscience education, staff-centered field activities of a descriptive or explanatory nature are most effective, whereas in later stages, student-centered, investigative studies of an analytical or predictive nature work best. A scaffolded curriculum can be designed in which there is a progression of skills from rudimentary note taking and sketching at the beginning to more sophisticated mapping or integration of multiple lines of evidence at latter stages (Kent et al., 1997; Butler, 2008). It is also important to note that most novices do not see the importance or relevance of field activities compared with upper-division earth science majors, so different types of experiences may be necessary to engage students at different stages of their professional development (Boyle et al., 2007). The instructor should purposefully select from among these many possibilities, and articulate the choice—and reasons for the choice—to the students.

Assessment Is Critical and Must Be Aligned Well with Learning Goals (Pellegrino et al., 2001)

The field setting (and time spent back at camp) provides continual opportunities for formative and informal assessments of students via observations, interviews, Socratic questioning, and professional dialogue throughout the day. The use of formative assessments to provide immediate feedback (through real-time discussions or end-of-day reviews of field notes and maps), authentic assessments (e.g., to ascertain mastery of field skills), peer assessments of group work, and reflective journaling has been recommended by Hughes and Boyle (2005). Geissman and Meyer (2009) used "postage stamp" mapping exercises of small but revealing field areas and scoring rubrics to provide rapid and detailed instructor feedback and reinforcement of students' developing field skills. More formal assessments of field programs are also warranted in the form of rubrics and other standardized review criteria (Gold, 1991; Orion et al., 1997b; Pyle, 2009). Traditional measures of student learning outcomes (e.g., geologic maps, cross sections, stratigraphic sections, field notes, reports) based on technical criteria (e.g., map accuracy, adhering to standard practices in map preparation) are fairly well established. We also need new metrics to be able to assess the cognitive and affective gains related to student fieldwork in areas such as students' ability to formulate new questions, to integrate multiple lines of evidence collected in the field with knowledge from other sources, and the ability to apply a concept to a new situation that does not directly match the initial instruction, as in transfer to a new field locality.

Careful Planning by Instructors Is Essential to a Good Field Experience

This includes a range of considerations, including the choice of a field site, mode of instruction (day trip, multiday, residential), size of the class, level of specialization required of the students, preparatory work and training, use of information technology (to prepare for the field or in the field), and the specific learning activities and expected outcomes. Logistical details (e.g., access, weather, personal comfort and safety) can obviously make or break a field experience. Special attention may have to be paid to issues of gender, nontraditional students (e.g., underrepresented groups, students over the traditional age), and students with disabilities (Hall et al., 2004). A poorly planned field trip may be as memorable as a well-planned field trip for all the wrong reasons (Lonergan and Andresen, 1988).

Finally, going out into the field does not necessarily mean that students will learn (Maskall and Stokes, 2008), but with careful planning, and attention to ways in which students learn in the field, a series of field experiences can be of tremendous benefit to the personal and professional development of young geoscientists, and for the general public, in terms of what they know and how they relate to Earth.

RECOMMENDATIONS FOR FUTURE RESEARCH

There is a great need for geoscientists to document their intuitions and assertions about the value of fieldwork for student learning outcomes and pre-professional training. It is important to ask what we actually know about the ways in which people learn in the field and the benefits that are accrued through learning in the field by students at all levels and in the professional development of geoscientists (e.g., Healey and Blumhof, 2001). Solid evidence is needed to convince skeptical colleagues (and administrators) that field instruction should remain an integral part of the geoscience curriculum. With help from the cognitive, learning, and social sciences, there is now an emerging theoretical foundation with allied analytical tools that can be directed to undertake a major research initiative on learning in the field. In the same way that geoscience research was initially of a descriptive nature and subsequently has evolved to more quantitative, experimental, analytical, theoretical, and modeling approaches, research on learning in the field to date has largely been anecdotal and descriptive based on the "practitioners' wisdom" described earlier. We are now poised to undertake quantitative, hypothesis-driven, testable studies based on controlled experiments and theory (Pellegrino et al., 2001; Shavelson and Towne, 2002) to demonstrate learning gains afforded to students in this unique instructional setting. Such a paradigm shift can be enabled through collaborative work with cognitive scientists who provide insights into how people learn in the field, learning scientists who can provide sound advice on pedagogic and assessment strategies, and geoscientists who bring exciting new approaches to field-based Earth research. A robust research agenda could be organized around the following topics:

Characterization and Development of Geoscience Expertise

The ability to learn directly from nature is a distinctive component of geoscience expertise (e.g., Manduca et al., 2004; Petcovic and Libarkin, 2007; Manduca and Kastens, this volume). There is a first-order need to articulate the ways in which master geoscientists think, and to demonstrate what they do, in the field. What cognitive strategies are used in the field by "master" geoscientists to inform their decision making (e.g., what traverse to follow, what samples to collect, where to draw the contacts between map units; Brodaric et al., 2004; Riggs et al., 2009a, 2009b)? Amid the visual complexity of nature, how do they pick out the signs, patterns, and contrasts that have causal significance (Frodeman, 1996)? By what processes of observation, integration, and interpretation is new knowledge constructed and represented based on field studies (e.g., Ernst, 2006)?

Professional Development of Geoscientists

Given that many twenty-first-century geoscientists do not do fieldwork professionally, in what ways do field studies inform subsequent studies of Earth using the methods of analysis, experiment, modeling, and theory? To what extent does learning in the field help develop cognate scientific investigative and higher-order thinking skills? In what ways does field training enable, enhance, and inform other approaches used to interrogate Earth?

Initiation into the Community of Practice of Geoscientists

What types of mentor-student and peer-to-peer interactions are best used to inculcate accepted approaches and behaviors, introduce and practice the selection and use of appropriate tools, provide opportunities to make inscriptions that impart meaning to natural phenomena, and engage in the scholarly discourse of the discipline? What are the longitudinal impacts of field studies on students' decisions to pursue careers in the geosciences, and how well did the field experiences prepare students for future work in graduate school (Mogk, 1993) and in professional careers?

Student Learning in the Field

What can be done to best prepare students to learn in the field? What content or concepts are necessary for students to be successful in a field learning experience? What is the proper sequencing of field learning experiences? How can we best integrate learning experiences in the field, laboratory, classroom, and independent study to provide a holistic learning experience for students (e.g., Orion et al., 2000; Noll, 2003; Gonzales and Semken, 2006; Maskall and Stokes, 2008)?

Motivation and Barriers

How do students' prior life experiences influence field-based learning (e.g., Boyle et al., 2007; Stokes and Boyle, 2009)? What kinds of field-based learning activities are most effective for urban students with limited experience in nature (e.g., Hoskin, 2000; Birnbaum, 2004; O'Connell et al., 2004; Tedesco and Salazar, 2006), based on gender (e.g., Maguire, 1998), or from underrepresented groups (Semken, 2005; Riggs et al., 2007; Sedlock and Metzger, 2007; Miller et al., 2007)? Can essential aspects of field-based learning be made accessible to students with limited mobility (e.g., Hall et al., 2004)?

Instructional Practice and Assessments

What makes an excellent field learning experience? What skills and/or understandings need to be in place in order for students to be able to transfer their prior learning from book or classroom to the field setting? How can we assess the impacts of field experiences on student learning (e.g., concepts, content, skills, and attitudes) about science (e.g., Stanesco, 1991; Orion et al., 1997b; Hughes and Boyle, 2005; Pyle, 2009)? In assessing student learning in the field, to what extent should we assess the process of working in the open and unconstrained field setting in addition to assessing the products of field exercises? Can we determine that students are better able to see the "big picture," and to be able to transfer knowledge and skills to new applications? Instructors in the earth sciences should have access to the assessment tools required to undertake an action research plan (e.g., models of pre- and post-tests, concept maps, scoring rubrics, observational and interview protocols, learning logs and confidence surveys, journals, self-assessments; Pyle, 2009).

Instructional Technology

What is the added value of using computer-aided learning in preparatory or reflective activities to assist learning in the field (Hesthammer et al., 2002; Cantwell, 2004; Kelly and Riggs, 2006; Fletcher et al., 2007) or of bringing technology into the field, such as ruggedized computers with global positioning system (GPS) and geographic information system (GIS) capabilities or portable audio/visual instruments (e.g., Walker and Black, 2000; McCaffrey et al., 2005; Elkins and Elkins, 2006; Guertin, 2006; Knoop and van der Pluijm, 2006; Swanson and Bampton, 2009; Whitmeyer et al., 2009; Elkins, 2009; Pavlis et al., 2010)? Studies that directly compare learning outcomes in the field and in the laboratory (including computer-based) are few (e.g., Spicer and Stratford, 2001), but there is a growing literature that demonstrates that learning in the field can be enhanced by laboratory or computer work (e.g., Noll, 2003; Kelly and Riggs, 2006). More detailed studies are needed that utilize GPS technology to document students' decision-making strategies while solving authentic field problems (e.g., Riggs et al., 2009a, 2009b) (Fig. 12).

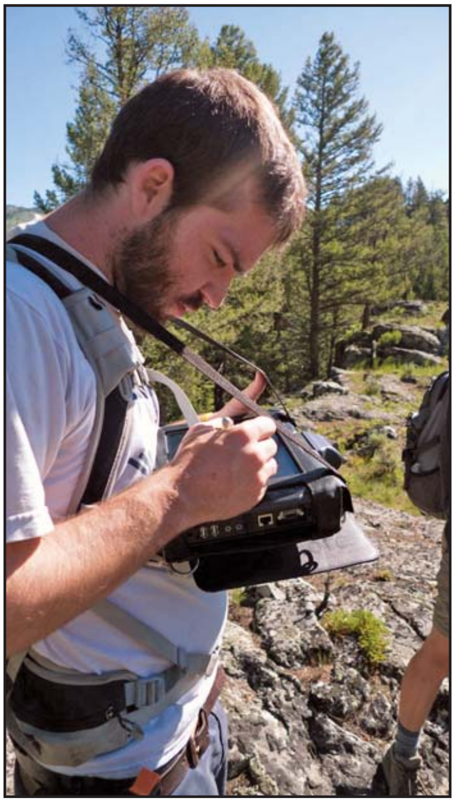

Figure 12. An example of using information technologies in the field. Will this be the new professional standard for fieldwork? How does this technology impact learning in the field? Photo credit: Chuck Goodwin.

Understanding Human Cognition

Themes addressed in this volume, including spatial and temporal reasoning and understanding complex systems (Liben and Titus, this volume; Cervato and Frodeman, this volume; Stillings, this volume), hold great interest among cognitive and learning scientists. How is spatial memory best developed, and how do direct experiences in the field interact with indirect representations (e.g., maps, virtual environments) to develop spatial skills (Liben, 1999; Montello et al., 2004; Kastens and Ishikawa, 2006; Liben and Titus, this volume)? Given that humans have difficulty grasping long expanses of time (Cervato and Frodeman, this volume), does embodied personal experience with the products of long-duration, slow Earth processes (e.g., mountains, canyons) facilitate development of a mental model of deep time? Given that humans have difficulty developing intuition about complex systems (Stillings, this volume), does embodied experience with the observably complex field environment help students recognize connections and feedbacks in the Earth system and break loose from their expectation of simple, unidirectional, causal relationships? Cognitive research shows that "masters" in a field (e.g., Chase and Simon, 1973; Petcovic and Libarkin, 2007) are capable of amassing large "chunks" of information that can be readily drawn upon for application to new situations. How can we help students amass and organize "chunks" of information to expand their own cognitive capabilities in the earth sciences?

Ethnographic and Linguistic Studies

What can be learned about the ways in which geoscientists communicate, interact, learn to use the tools of the trade, and report observations and results as we pursue our craft in the field (e.g., Latour, 1987; Goodwin, 1994, 1995)? Analysis of videotapes and audio logs of situated interactions among students, peers, and professors in the field can elucidate the way in which science progresses, and the way in which scientists develop, in the field setting (e.g., Goodwin, 1994, 1995; Singer et al., 2008; Radinsky, 2008; Petcovic et al., 2009). A recent example of an ethnographic study of undergraduate geoscience students working in a field setting was conducted by Feig (2010) to observe and document the lived experiences of students in their use of technology in the field and the way in which it informs students' understanding of scientific reality. Similarly, sociological studies of student populations, particularly from underrepresented groups, are needed to evaluate the success of recruitment and retention programs to the geoscience "pipeline" as a result of critical incidents and interventions such as field experiences that influence career choices (Levine et al., 2007).

Reflections: Emerging Insights from This Synthesis Project

This Synthesis project has provided a unique opportunity to explore how people think and learn in the natural field environment by integrating two disparate traditions of scholarship: study of the physical world through the geosciences, and studies of how the human mind works to comprehend Earth through the cognitive, learning, and social sciences. We have come to realize that there is a remarkable congruence between the empirical evidence accumulated over more than a century of field instruction by geoscientists, and analysis of how geoscientists work and think as explained by the theory and practice of the cognitive, learning, and social sciences. The physical and social environments of learning in the field are intricately interconnected. We simultaneously learn about Earth and from each other. This interplay between physical and social structures creates a rich learning environment in which inquiry, discovery, exploration, discernment, skepticism, judgment, and discourse are valued and emphasized (e.g., Frodeman, 2003; Field, 2003). Nature, self, and community are connected through learning in the field.

By articulating a conceptual framework that explains how geoscientists learn in the field, we hope to (1) help geoscientists reflect on their own ways of knowing about the complicated Earth and thus enhance the conduct of their science; and (2) provide a foundation to more effectively train the next generation of geoscientists. Emerging insights about the value and benefits of learning in the field are summarized here.

Learning in the Field Results in Cognitive and Metacognitive Gains

Learning in the field engages the cognitive, affective, and psychomotor skills, which all contribute to learning (Bloom, 1965; Krathwohl et al., 1973; Simpson, 1972). Bloom's taxonomy of cognitive skills (knowledge, comprehension, application, analysis, synthesis, evaluation) can be fully engaged through increasingly demanding field exercises. Learning in the field is a particularly rich environment to embrace the tenets of how people learn (Bransford et al., 1999; Donovan et al., 1999): (1) preconceptions about how the world works are directly encountered in the field environment; (2) learners must have a deep foundation of factual knowledge, must understand facts and ideas in the context of a conceptual framework, and must be able to organize knowledge in ways that facilitate retrieval and application while working in the field; and (3) a "metacognitive" approach to instruction, learning to think as a geoscientist to solve problems, can help students learn to take control of their own learning by defining learning goals and monitoring their progress as they work. Learning occurs as experience (in the field) is transformed into knowledge (Kolb, 1984).

Learning in the Field Produces Strong Affective Responses

The natural world can inspire a sense of curiosity, awe, and wonder that motivates students to learn. All the senses are engaged in field studies, and this contributes to memorable experiences that become available for future recall and application (Millar and Millar, 1996). There is also a strong social component between students and masters or peers working in the field that has a strong affective impact (e.g., Boyle et al., 2007). Affect and cognition are closely linked (e.g., Ashby et al., 1999; Gray, 2004; Storbeck and Clore, 2007; Pessoa, 2008), and positive affective aspects are important to motivate (e.g., Glynn and Koballa, 2006; Koballa and Glynn, 2007) and prepare (Eiss and Harbeck, 1969; Iozzi, 1989; Boyle et al., 2007; Stokes and Boyle, 2009) students to learn.

Immersion in a Field Environment Affords Types of Learning That Cannot Be Achieved as Easily or At All in Other More Controlled Environments

Immersion in a field setting imparts a different kind of knowledge about the natural world than does learning from representations (e.g., Goodwin, 1994, 2010). In the field, the learner observes the environment from an internal viewpoint (i.e., the student is immersed in the larger object of study), and must make decisions about what is important to observe in the complex context of raw nature. Situated learning in the natural setting contributes to a deep understanding of concepts and relations such as the scale of geological phenomena, as well as spatial and temporal relations (e.g., Liben, 2008), that cannot otherwise be duplicated in the laboratory or virtual learning environments. Because the geologic record is often incomplete or ambiguous, geoscientists must learn to reason by analogy and inference to be able to work effectively in a world in which the available evidence is both complex and uncertain.

Embodiment is an important component of human cognition. Because the human body plays an essential role in cognition, a case can be made that learning in the field affords the acquisition of embodied skills that are developed in both natural and social contexts. Embodied practices in nature involve ways of knowing about how to interact with and move through the natural environment, whereas embodied practice of scientists working together in the field include the interactions (such as gesture) that serve to organize, prioritize, and communicate knowledge that leads to communal, collaborative understanding and action.

Representations of Nature (Inscriptions) Facilitate Learning

Geologic investigations rely heavily on the use of maps, graphics, and other representations to communicate ideas and promote understanding. These portable artifacts are immutable in the sense that they retrain crucial structure when they are moved to new settings. However, they are simultaneously a locus for structured elaboration and change. As they participate in braided streams of inscriptions, they can be (1) transformed by subsequent operations (for example, annotations on a map) and (2) linked to other representations and embedded within new theoretical arguments. Such portable, immutable artifacts that can act as a substratum for further systematic work are used to develop new ideas and translate them to distant audiences. First inscriptions occupy a crucial place in this process. This step is where raw nature is transformed into the representations that permit an organized and structured understanding of Earth and how it works. These first inscriptions are of primary importance because this is where human selection, judgment, and decisions, based on whether the material in question is interesting, important, or useful, are made that sort the complex world into categories to be represented. All other derivative inscriptions, the "chain of inscriptions" of Latour (1987), become increasingly refined and sanitized (while being embedded in new contexts that add rich, crucial structure of their own). Although such subsequent transformations showcase a central idea with increasing clarity, details and contexts of the original state are systematically lost. Learning about nature as interpreted from inscriptions (maps, figures, text in books) is decidedly not the same as learning directly from nature (a lesson also learned from Plato's "myth of the cave").

Field Instruction Is an Important Initiation into the Community of Geoscience Practice

The field setting provides a rich environment in which the community of practice is developed and demonstrated to novices. Situated practice in the social environment of field instruction embodies the professional practices that define the discipline. This includes the testing and vetting of methods, appropriate selection and use of tools, creation and use of inscriptions that confer meaning about the world around us, norms and models for social interactions, personal and professional work ethics (e.g., perseverance, integrity), and communication through gesture, representations, and words that animate the profession (Goodwin, 1994, 1995, 2007).

The Field Environment Provides a Solid Foundation for Development of Geoscience Expertise

A long apprenticeship is needed, under the tutelage of master geoscientists, to earn mastery of geoscience expertise (Goodwin, 1994; Hutchins, 1995; Ingold, 2000). The breadth of geologic "ways of knowing" (e.g., spatial and temporal reasoning), skill development (cognitive, technical, social), attitudes and values, and communal practices described throughout this contribution all have direct connections and applications to learning in the field. As young geoscientists gain experience in the field, they are systematically adding to their reservoir of information that can then be accessed in memory ("chunked"; Chase and Simon, 1973) as references with which to compare and correlate new information. Learners become increasingly capable of transferring lessons learned from one experience to new situations. This apprenticeship can include sustained opportunities to practice their trade (Hoskins and Price, 2001). As young geoscientists learn how to transform information about Earth into knowledge, they themselves are transformed as individuals into the ranks of geoscientists. Geologic epistemology is built on its tradition as an interpretive and historical science (Frodeman, 1995), and this tradition derives largely from field studies.

Finally, an understanding of Earth in its natural state is important to both the development of future geoscientists, and for the enjoyment, health, and well-being of the general public, if we are to make informed decisions about how to live sustainably and responsibly on this planet. So, the message is clear: Get out into nature early and often. …

The Earth never tires,
The Earth is rude, silent incomprehensible at first,
Nature is rude and incomprehensible at first,
Be not discourag'd, keep on, there are divine things well envelop'd,
I swear to you there are divine things more beautiful
than words can tell.

—Walt Whitman, "Song of the Open Road," *Leaves of Grass* (1855)

ACKNOWLEDGMENTS

We would like to thank Kim Kastens and Cathy Manduca for leading this synthesis project, and our collaborators on this project for insightful discussions throughout: Cinzia Cervato, Robert Frodeman, Lynn Liben, Tim Spangler, Neil Stillings, and Sarah Titus. Rick Duschl, Stephanie Pfirman, Tim Shipley, and Mike Tabor provided useful feedback during early stages of the project. We are deeply indebted to Nicholas Christie-Blick of the Lamont-Doherty Earth Observatory of Columbia University for allowing one of us (Goodwin) to spend time at his Earth Science field school to observe firsthand geologists and students at work in the field. Reviews by Nicholas Christie-Blick, Eric Riggs, Kim Kastens, and an anonymous reviewer helped to improve the final version of this contribution. The ideas presented herein remain the responsibility of the authors. This project was supported by National Science Foundation grant DRL 07-22268. Images of students at work in the field were from the 2010 Research Experiences for Undergraduates project on The Evolution of Archean Rocks in Yellowstone National Park (grant EAR 08-52025). Any opinions, findings, conclusions, or recommendations expressed in this article are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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Manuscript Accepted by the Society 7 November 2011

Printed in the USA