Integrating Undergraduate Education and Scientific Discovery Through Field Research in Igneous Petrology

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ABSTRACT

We recast a standard igneous petrology course at Fort Lewis College into a field-based, inquiry-driven research course focused on a specific field area, in this case the Tertiary volcanic complex at Ship Rock, Navajo Nation, New Mexico. The main goal was to allow undergraduate students an opportunity to use field work to investigate advanced topics in igneous petrology while engaging in scientific research and developing important skills that are needed for all careers in science. Constructing research projects around this class enabled students to learn science by doing it, and to carry enthusiasm for research into further studies. This also better served the needs of the Geoscience program at Fort Lewis College by further developing skills for critical analysis and inquiry, and building on content taught in the introductory petrology course.

INTRODUCTION

Crystalline silicate rocks make up about 68% of Earth by mass (Newsom, 1995) and hold fundamental clues to understanding dynamic Earth and planetary processes and history. Igneous petrology at the undergraduate level has historically played an important role in the education of geoscience students, serving as a link to other key courses (e.g., mineralogy, structural geology, geochemistry), and offering students opportunities to develop skills in inquiry, observation, and analysis. Meaningful engagement with a course that focuses on igneous processes can benefit all geoscience students (Mogk et al., 2003a), because of connections to many relevant scientific and societal topics, such as atmospheric and environmental studies (e.g., Halmer et al., 2002; Gran and Montgomery, 2005), mineral resource exploration and development (e.g., Sillitoe and Bonham, 1984; Goff et al., 1994), and assessment of natural hazards (e.g., Schmincke, 2004). Igneous petrology also remains a dynamic area of research on Earth and elsewhere in the solar system (e.g., Hawkins and Wiebe, 2004; McSween et al., 2004; Marsh, 2004; Tatsumi, 2005).

The traditional, upper-division undergraduate igneous or igneous-metamorphic petrology course often emphasized the study of extensive specimen suites from unfamiliar localities, daunting webs of terminology for rock types and structures, and laboratory-based exploration with thin sections and related information. Over the last decade, many programs have dropped such courses or have blended them with mineralogy and petrography (Mogk et al., 2003b) into more general "Earth materials" courses (e.g., Goodell, 2001), under an assumption that such courses no longer meet the career needs of geoscience students. An advantage of an Earth materials approach is the opportunity to present rock-forming and other geochemical processes together in an Earth systems or whole-Earth context (e.g., Dutrow, 2004). A potential disadvantage is reduction of student engagement with igneous rocks in the laboratory or the field due to time constraints. Earth materials curricula can be supported at major universities and colleges that actively conduct petrologic or materials-science research because students have access to state-of-the-art equipment to engage in a wider range of research topics. This option was not available at Fort Lewis College, a smaller liberal-arts college with a viable geoscience-degree program but with limited sources of funding and equipment.

In this paper we discuss a field-based and inquiry-driven igneous petrology course that is suited to programs sited in regions where assemblages of igneous rocks are exposed and accessible. At Fort Lewis College, a three-credit lecture-based petrology course (Geology 210) covers all rock systems, whereas the igneous petrology class (Geology 364), formerly a separate three-credit course required for the major, is now an elective course taught only when demand warrants, typically once every several years. An unanticipated benefit of this change from core course to elective was more freedom to experiment with the syllabus. Consequently, we redesigned igneous petrology as an experimental three-credit course, Geology 390, to be conducted exclusively in the field after the first several weeks. Our intent was to complement the general petrology course, sustain student engagement with rocks and rock-forming processes, and to add opportunities for student-faculty research to the curriculum.

LEARNING THROUGH FIELD RESEARCH

Authentic inquiry-based science learning means active participation in the exploration of natural phenomena and the testing of hypotheses. The *National Science Education Standards* (National Research Council, 1996) promote exploration and inquiry as a means to enhanced scientific literacy in grades K through 12 (Siebert and McIntosh, 2001). But students who are exposed to innovative high-school science courses may still encounter stagnation at the undergraduate level, typified by coverage-driven or even outdated curricula (Project Kaleidoscope, 1991). A stronger effort to develop scientific habits of mind in undergraduate students is necessary, whether the outcome is a successful scientific career or simply enthusiasm and aptitude for life-long learning. Undergraduate students must be challenged to apply knowledge and skills gained in the classroom to an engaging problem without a predefined outcome, in a context that emphasizes discovery, creative development and testing of ideas, critical thinking, and a sense of ownership in the scientific process. Students can benefit greatly when they can design a research project, collect and interpret their own data, and communicate their findings in a professional setting.

A number of studies have, to varying degrees, demonstrated the effectiveness of authentic research experiences for undergraduate students (e.g., Project

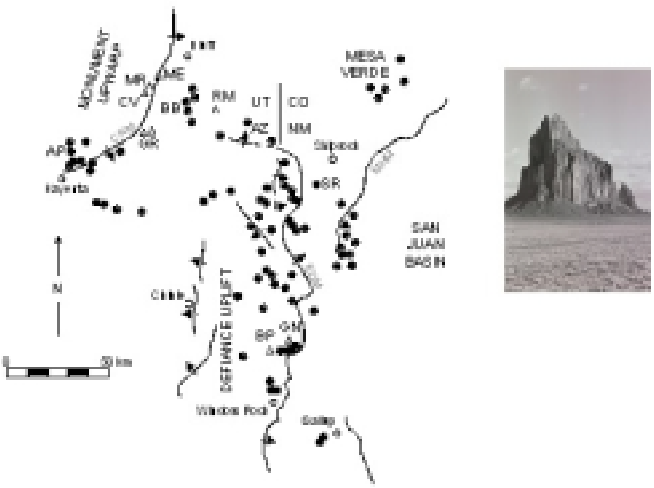

Figure 1. Location map of the central Navajo volcanic field, after Smith and Levy (1976) and McGetchin *et al.* (1977). Dark circles indicate minettes; open triangles represent SUMs (serpentinized ultramafic microbreccia). Monoclines are indicated by heavy lines. Abbreviations: AP, Agathla Peak; AZ, Arizona; BB, Boundary Butte; BP, Buell Park; CO, Colorado; CRM, Comb Ridge Monocline; CV, Cane Valley; EDM, East Defiance Monocline; GN, Green Knobs; GR, Garnet Ridge; ME, Mule Ear; MHM, Mesaverde Hogback Monocline, MR, Moses Rock; NM, New Mexico; RM, Red Mesa; SR, Ship Rock; UT, Utah. Major communities are also shown. Photograph of Ship Rock taken by Steven Semken.

Kaleidoscope, 1991; Tobias, 1992; Haury, 1993, National Academy of Sciences, 1997; Huntoon et al., 2001; Harnik and Ross, 2003; Jarrett and Burnley, 2003; O'Neal, 2003). Difficulties encountered in such inquiry-driven approaches are generally attributed to logistical problems such as scheduling and faculty availability, rather than pedagogical shortcomings (e.g., Jarrett and Burnley, 2003; O'Neal, 2003).

The rock record is the ultimate source of time-integrated data on the Earth system, and as many other geoscientists do, we prefer that our students meet it in the field, in all of its authentic complexity. From an epistemological perspective, Frodeman (2003) argues that field research is the most authentic model for scientific inquiry, because it imparts not only teachable skills, but the intuitive knowledge characteristic of experts. Field research requires that students and instructors consider geologic features in their full environmental context, to integrate data from different sources, and to apply concepts from many if not most of their prior courses. What is learned in the field can be applied fruitfully elsewhere: Bluth and Huntoon (2001) observed that students who successfully completed their field course performed more confidently in classroom settings afterward, and Hoskins and Price (2001) showed how field experiences can serve as effective tools for mentoring students. Schwab (2001) noted that knowledge of field methodology and skills such as observation and recording of data, sketching, and mapping remain relevant to geoscientific education, and that some companies have sought to hire geologists from outside the United States because of a lack of graduates with field experience here.

Our goal was to offer a course that would enable students to learn important observational and interpretative skills while doing science in the field, rather than by completing a set of class activities developed around suites of unfamiliar specimens and predetermined outcomes. Such goals require a trade-off: fewer topics can be presented and discussed, so that students are allowed enough time for comprehensive and reflective work on their own field projects. Research abilities and intuitive knowledge thus imparted are arguably far more valuable than declarative knowledge offered out of context, and it has been duly noted that "one doesn't need…to be exposed to everything in order to be equipped to work in the discipline" (Project Kaleidoscope, 1991, p. 51).

The entire project extended across the fall 2002 and winter 2003 trimesters at Fort Lewis (late September to early May), and was focused on the igneous complex at Ship Rock, Navajo Nation, New Mexico (Figure 1), a regular venue for more conventional expository field trips led for many years by both authors. Ship Rock is located approximately 95 road miles (mostly on multi-lane U.S. highways) from the Fort Lewis College campus. This is a drive of two hours or less each way, which makes for long days but is not atypical for field trips in the Four Corners area.

PROJECT LOCATION

The Ship Rock monolith, known to the indigenous Navajo as Tsé bit'a'í ("Rock with wings") is an exhumed tuff-breccia diatreme flanked by a complex of large and small minette (potassic mica lamprophyre) dikes and necks. It is the largest and most prominent landform in the mid-Tertiary Navajo volcanic field (NVF) on the Colorado Plateau (Semken, 2003), with a dramatic appearance that has earned it wide exposure in geology textbooks (e.g., Press et al., 2004, p. 122), Southwestern photography and graphic arts (e.g., http://www.rockymesa.com/shiprock.htm), and numerous forms of local iconography including newspaper mastheads (http://www.daily-times.com). But even though Ship Rock is familiar both locally and globally, many aspects of its lithology and structure had not been studied in detail. It was mapped only in a regional context at very small scales (Williams, 1936; Beaumont, 1955; O'Sullivan and Beikman, 1963; Cooley et al., 1969; Akers et al., 1971; Ward, 1990). Only one detailed field study of Ship Rock has been published (Delaney and Pollard, 1981), focusing on intrusive processes at one of the three major radial dikes. Two more general publications (Delaney, 1987; Semken, 2003) summarize interpretations of its origin.

Ship Rock is a deeply-exhumed, well-exposed, potassic mafic intrusion, situated between two Laramide monoclines, surrounded by a low-relief semi-arid steppe formed on Cretaceous Western Interior marine shale, on the homeland of the largest Native American nation. It is thus a locality where a number of interesting geoscience-related problems can be pursued (e.g., landscape evolution, soil formation, geologic controls on flora), not only those specific to igneous petrology. We selected it as the setting for the experimental course for these reasons as well as our own research interests. Although all of the students in the course participated in group exploration and interpretation of the diatreme and dikes, they were also able to pursue individual projects that specifically interested them. These projects, discussed below, contributed to class discussions of the

Student Learning Objective	Means of Evaluation
1. Enhance interest in geology and petrology through focused study of a meaningful local igneous landform.	• Summative student evaluations of personal interest, relevance, and value of the course. • Continued pursuit of research by means of a senior thesis project or internship.
2. Conduct an authentic research project from initial planning to interpretation and dissemination of results.	• Instructor observation of teams at work in the field and laboratory. • Scientific quality of final paper and oral presentation of research results.
3. Enhance skills in scientific inquiry and critical thinking.	
4. Apply petrologic and other geologic knowledge and skills in a field setting.	• Instructor observation of teams at work in the field and laboratory. • Comments drawn from summative student evaluations.
5. Develop abilities to work productively as part of a research team.	
6. Further develop skills in oral and written communication.	• Style and clarity of final paper and oral presentation of research results.
7. Advance knowledge of the petrology and geology of Ship Rock and of the Navajo volcanic field.	• Conference presentations by students, and publication of conference abstracts and refereed papers as a direct outcome of the research conducted during the course.

Table 1. Student learning objectives and means of evaluation as initially planned for the experimental Geology 390 course in 2002-2003.

Fall Trimester 2002: Pre-course Activities		
Field Trip		Post-trip Activities
Geologic reconnaissance of Ship Rock and surrounding region. Exploration of potential research problems.		Group discussions and selection of research topics for the course, and initial literature searches.
Winter Trimester 2003: Geology 390 Course		
Week 1	Introduction Exploring Science and the "Art" of Research	Complete inquiry exercises.
Week 2	Defining Igneous Rocks Physical Properties of Magma Textural Classification of Igneous Rocks	Review common igneous rock textures.
Week 3	IUGS classification of igneous rocks	Identify a suite of hand specimens of NVF and other local igneous rocks.
Week 4	Review Earth Structure and Plate Tectonics Magmas and Tectonic Environments Igneous Structures and Field Relationships Plate Tectonics and the Origin of Magmas	Construct an illustrated summary of global igneous-tectonic systems.
Week 5	Origin of Magmas Ways that Magmas Change Composition Petrogenesis of Mafic Magmas	Submit outline of proposed field research project.
Week 6	Overview of the Cenozoic Magmatism in the SW Introduction to the Navajo Volcanic Field Geologic Setting and History of Ship Rock	Receive project approval. Present and discuss research idea with entire class.
Week 7	Geology and Navajo Ethnogeologic Knowledge of the Navajo Volcanic Field	Plan field research strategy with faculty input.
Field work began in week 8		
Week 8	Geology of the Ship Rock Complex	Field work at Ship Rock on Friday afternoons.
Week 9	Student-faculty consultation on progress of research projects.	
Week 10		
Week 11		
Week 12		
Week 13	Preparation of research manuscripts and presentations.	Compile data and work on research report and presentation.
Week 14	Student research symposium	Complete research report and make presentation.

Table 2. An abridged syllabus for the Geology 390 course.

Figure 2. Steve Semken discussing strategies in the field with students at Ship Rock.

geologic history of Ship Rock in the context of the evolution of the Colorado Plateau and the cultural significance of the locality, making this an authentically place-based course (Semken, 2005).

COURSE DESIGN AND IMPLEMENTATION

Learning objectives for the course, matched with planned methods of assessing student accomplishment of each, are presented in Table 1. The course was advertised to students in the fall of 2002, and those interested were asked to participate in several non-credit meetings and a field excursion to Ship Rock, so that they could become acquainted with the locality and investigate potential research topics. A decision was made to accept freshmen to seniors, without any specific prerequisites, so that students with different levels of knowledge and experience could work together in teams and learn from each other. Twelve Fort Lewis geoscience majors (10 junior-senior, 1 sophomore, 1 freshman) participated in the pre-course meetings, and all enrolled in the Geology 390 field course for the fourteen-week winter 2003 trimester.

Prior to the start of the field course, students were directed to select a topic and begin literature reviews. Within the first four weeks of the course (Table 2), students submitted research proposals to the instructors, in which they outlined the goals of their projects. These proposals also listed the data and other information they deemed necessary to conduct their research. Instructor approval was required before the students could begin their projects. Students were allowed to conduct research individually or in teams of two, but all were required to report their progress and findings to the entire class on a weekly basis.

The pre-existing igneous petrology course (Geology 364) was presented almost exclusively in the lecture-laboratory format, with lab sessions emphasizing verification over inquiry (see Lawson et al., 1999, for an exploration of the perils of such an approach). Seven weeks of this course were dedicated to a review of igneous processes. Students explored related topics in the laboratory sessions primarily with hand specimens and thin sections from different compositional suites of igneous rocks. The last seven weeks were similar in format but focused on metamorphic petrology. No more than two three-hour field trips were offered, and these were expository in nature.

The revised course also began indoors, in part because weather conditions on the Colorado Plateau are not dependably conducive to field work until March. However, the class format was quite different. Geology 390 began with a set of interactive lectures, in which ten- to fifteen-minute presentations were interleaved with inquiry exercises involving textural and compositional interpretation of regional rock specimens. This part of the course was intended to present concepts in igneous petrology (weeks 1-5) and regional geology (weeks 6-8) that were prerequisite to the planned research (Table 2). These sessions also included explorations of the nature and methods of geologic inquiry. For example, students were asked to respond to the questions posed by Kurdziel and Libarkin (2002) in their study of scientific methodology, and then were given the article to read. The students then engaged in a sequence of lessons (after Carey, 1998) to develop skills in posing causal questions, developing and testing hypotheses, and critiquing scientific models.

An overview of the regional geologic history and tectonic setting of the study area was also presented, with an emphasis on Late Cretaceous to Tertiary magmatism on the Colorado Plateau and Southern Rocky Mountain provinces (e.g., Akers et al., 1971; Nelson et al., 1992; Laughlin et al., 1993; Semken, 2003). Students were required to read a series of related papers (Christiansen and Lipman, 1972; Lipman et al., 1972; Dickinson, 1979; Roden et al., 1979; Roden, 1981; Bally et al., 1989; Lipman, 1989; Oldow et al., 1989; Ulrich et al., 1989; Burchfiel et al., 1992; Christiansen et al., 1992; Miller et al., 1992) as part of this discussion. Because Ship Rock is located on the Navajo Nation and figures prominently in Navajo culture, students also received preparation in indigenous knowledge relating to the landform, cultural sensitivity, and the tribal regulations that constrain field work there (Semken and Morgan, 1997; Semken, 2003, 2005).

Field sessions, which began in the eighth week, were scheduled on Friday afternoons to minimize time conflicts with other courses. Logistical issues (e.g., travel arrangements, procurement of field supplies and tools, scheduling) were discussed as a group and duties were shared by faculty and students. In the field, both instructors worked with the student research teams to ensure that correct field techniques were applied (e.g., strike and dip measurements, sampling for soil and rock geochemistry, xenolith point counts, criteria for differentiating rock units, mapping techniques, use of GPS), so that students would have full confidence in their data. The instructors worked (Figure 2) with the teams to keep apprised of their progress, offer suggestions, and occasionally to prod students to remain focused on their tasks. On several occasions, undergraduate science students and instructional staff from Diné College, the Navajo tribal college located a short distance from Ship Rock, joined the teams in the field to learn about the geological observations and to share cultural knowledge and experiences.

Students spent between six and fifteen 8 to 10-hour days in the field, depending on the requirements of each project and the difficulty of the methods they employed. They were also responsible for collecting, justifying, and

Project Description & Goals	Types of Data Collected	Contributions	Products
Compilation of detailed geologic map of the Ship Rock diatreme and related plugs. Focused on the geologic units and structures of the diatreme in order to gain more insight into the eruptive history of this volcanic feature.	• Petrologic descriptions of map units. • Structural measurements on bedding and dikes. • Mapping of rock units. • Documentation of relationship between units.	Established that the diatreme has a layered-conical geometry composed of two different eruptive-breccia phases cut by minette dikes and late-stage tuff dikes. The mapping also provided insight into the relationship into the composition and character of minette plugs around the diatreme, and the distribution and disruption of sedimentary country rocks.	• Class Research Paper • Class Research Presentation • Geologic Map • Continued as Senior Thesis Project • Provided basis for further studies on diatremes near Mesa Verde National Park. This work served as a senior-thesis project for a student from this class who published the results (Burgess & Gonzales, 2005).
An investigation of "folding" in the south and west dikes.	Careful field observations and studies were applied to document the geometry, composition, distribution, and general orientation of these features.	This research led to a working hypothesis that the structures are subsurface magma tubes that developed in segments of the dikes that possibly were enriched in water and volatiles.	• Class Research Paper • Class Research Presentation • Continued as Senior Thesis Project • Continued research by faculty.
Geochemical assessment of the contribution of volcanic material to soils adjacent to Ship Rock.	• Outcrop descriptions of soil horizons at selected intervals. • Soil samples collected and submitted for major & trace element geochemistry. • Collaborated with research team doing geochemical analyses on dikes.	Project revealed that the geochemical signatures of the soils did have distinct contributions from the mafic rocks, but contributions were not systematic and predictable.	• Class Research Paper • Class Research Presentation • New geochemical data. • Continued as Senior Thesis Project
Petrochemical investigation of the contamination effects of country rock along the south dike.	• Outcrop & thin section descriptions of dike rocks texture and mineralogy. • Examination of possible contamination affects in dikes. • Samples collected and submitted for major & trace element geochemistry.	Data were used to demonstrate that there were little or no effects on the mineralogy and chemistry of the dike rocks from wall-rock contamination.	• Class Research Paper • Class Research Presentation • New geochemical data.
A study of xenoliths in the south dike to assess types, abundance, and distribution. The goal of this project was to gain insight into the contribution of crustal and mantle xenoliths, and possibly into magma sources.	• Outcrop point counts to document xenolith abundances. • Outcrop and thin section descriptions of different xenoliths.	No distinct patterns were established, but several new varieties of crustal and mantle xenoliths were identified and described.	• Class Research Paper • Class Research Presentation • New Petrographic Data
Testing ideas on the origin of "pillow-like" structures in the dikes.	Careful field observations and studies were applied to document the distribution, shapes, geometry, and characteristics of these features.	Research established that the south dike only contained these features in where "folds" were present. Other segments of the dikes contained distinct columnar joints at right angles to the margins of the dikes, but none of the other features were present. In addition, accretion balls were also described in certain zones where xenoliths were encapsulated with magma forming spherical to ellipsoidal structures. Data from this research suggested that there might be "pillow" structures in zones of the dikes that were water rich, but no definitive conclusions were drawn.	• Class Research Paper • Class Research Presentation
Photographic documentation of the geologic phenomena at Ship Rock for educational purposes.	• Digital documentation of all geologic features. • Collaboration with other students to develop an overview of project. • Field descriptions of geology and research projects.	A descriptive overview of the entire research project and features documented during the field studies. A layperson's summary of the geology was developed.	• Class Research Paper • Class Research Presentation • Digital documentation.
Study of mica-rich margins in certain dike segments to understand the origin and development of shear foliation in these zones.	Careful field observations and studies were applied to document the distribution and mineralogy of mica-rich zones, as well as structural fabrics. Petrographic studies were conducted to assess microstructures and fabrics.	Research established that zones were confined to the outer margins of dikes that contained tubes. Foliation was developed parallel to dike margins and was interpreted as shear foliation.	• Class Research Paper • Class Research Presentation • New Petrographic Data

Table 3. A summary of field projects and outcomes.

Question	Mean	SD
My interest in geosciences increased as a result of taking this class.	4.6	0.6
My interest in igneous petrology increased as a result of taking this class.	4.2	1.3
My interest in doing scientific research increased as a result of taking this class.	4.6	0.6
I better understand how scientific research is done as a result of taking this class.	4.7	0.6
My interest in doing field work increased as a result of taking this class.	4.6	0.6
My knowledge of regional geology and geologic history improved as a result of taking this class.	4.9	0.5
I understood the objectives of my research project.	4.2	0.8
I understood what I needed to do in order to complete my research project.	3.8	0.8
I was able to accomplish all of the tasks needed to complete my research project.	3.9	0.8
I feel that my work and results met the objectives of my research project.	3.8	1.1
Prior to taking this class, I was familiar with the geologic feature where I did my research work.	3.3	1.5
It was more interesting to study a geologic feature I was familiar with, rather than one I was not familiar with.	3.8	1.4
I gained understanding and appreciation of the local culture in my study area as a result of taking this course.	3.9	0.9
A course with a research component is more interesting than one without a research component.	4.6	0.8
A course with a research component is more useful professionally than one without a research component.	4.8	0.6
If possible, I would choose to take other geoscience courses that enabled me to do scientific research.	4.9	0.5

Table 4. Student responses to the summative course evaluation (N = 12; 1 represents strong disagreement and 5 strong agreement); SD is standard deviation.

submitting samples for geochemical and petrographic studies, and any other data that were necessary to complete their projects. All of the students worked collectively to analyze and interpret their data. Faculty provided guidance during this process, but students were responsible for their own hypotheses, tests, and conclusions. At the end of each field session and before returning to Fort Lewis College, teams discussed their findings with each other in the field, and again during lecture periods, to facilitate sharing of data that might contribute to other projects.

FORMATIVE OUTCOMES

Table 3 summarizes the research projects conducted by the students, which yielded far more insight into the structural and lithologic features of the diatreme-dike complex (Gonzales et al., geologic map in prep). Several new discoveries and models were developed from our work including an intriguing new hypothesis for the emplacement of the prominent 10-km south dike (Semken et al., 2003; Gonzales and Semken, 2005; Gonzales and Semken, in prep). Owing to the diversity of research activities they pursued, the students were able to enhance their overall knowledge of field petrology and Ship Rock, and their sense of place, by sharing information and working in collaborative teams. This would not have been possible if students had simply engaged in individual senior-thesis-type projects.

One student team, which was dubbed "National Geographic," documented landform features, place knowledge, and the progress of the research teams in photographs and text. This work linked all other aspects of the project and yielded graphic and literature-derived content that all teams could incorporate into their reports and presentations. The other teams focused on specific geologic problems and used their time in the field to collect data intended to test competing hypotheses (Table 3).

Throughout the course, a strong emphasis was placed on the process of scientific inquiry rather than definitive answers to problems. Many students began with expectations of specific findings, but as the field work progressed, they became increasingly comfortable with a continuous process of formulating, testing, and revising their hypotheses. Immersed in a complex field setting, they were continually challenged to solve problems on the basis of data they themselves were able to collect.

EVALUATION

Student learning objectives identified at the start of the course (Table 1) form the basis for our evaluation of the effectiveness of this field-based, inquiry-driven approach to teaching igneous petrology.

Instructor Observations - Shea (1995) discussed several potential problems with peer-led collaborative activities, such as dominance by a few overbearing or aggressive team members, failure of some team members to complete their share of the work, and a perception by high-achieving students that they are "carrying" their teammates. We did not experience any of these problems. In fact, over the course of this project students maintained a positive outlook and worked well together as a team, and developed a strong sense of community. They shared information and ideas, and when teams found information that would benefit another team that information was promptly shared with the group. It was our perception that the class evolved from a group of individuals into a team of collaborative learners and teachers. One aspect that stands out was the attitudes of the students towards the project. At no point did the instructors experience any negative feedback about the project, or having to work long days in the field. This may be attributable to the fact that the course was an elective and preferentially attracted students interested in field research.

In order to develop meaningful models and interpretations for their projects, the students had to integrate information from prior lectures and laboratory sessions into their projects. For instance, students involved in mapping of rock units not only used our class discussions as a starting point for unit designations and divisions, but then as the project developed, they expanded and revised the criteria and provided new information into the types of rocks in the area and their relationships. When necessary, the instructors would review key concepts and information in the field with students to ensure an accurate level of understanding.

Because the students were faced with open-ended problems that for the most part had not been addressed by the instructors or previous researchers, they had to engage in critical thinking and inquiry to have a successful project. We did not assess the level of the critical thinking, but we did feel that students not only developed a higher order of thinking in the project, but over time they also started to consider more meaningful questions about the significance and validity of their data and results. On the course evaluation one student noted that this course gave them "confidence to ask questions, write papers, and compile information" in the context of scientific research. In the post-course evaluation another student noted that conducting research in this course "gave me a guideline to follow, which makes research easier."

Summative Student Evaluations - A five-point Likert-scale evaluation was conducted after the course was completed; the results are presented in Table 4. Statistical significance could not be demonstrated with only 12 students, but the revised course received a higher overall rating than did the prior versions of the course: 4.82 ± 0.4 (N = 12) versus an average (N = 20) of 4.53 ± 0.7 from the two most recent offerings of the pre-existing Geology 364. Students responded most affirmatively when asked if they had improved their knowledge of regional geology (4.9 ± 0.6), whether they would select another research-based course (4.9 ± 1.3), whether they found the research-based format of the course professionally useful (4.8 ± 0.6), and if they better understood how scientific research is conducted (4.7 ± 0.6). They were only slightly less confident that they had fully completed their projects (3.9 ± 1.5).

Quality of Student Final Papers and Presentations - As a capstone to this class, all of the students were required to present their results as individuals or as a small team, and write a summary research report. The presentations were in PowerPoint format and 15-minute GSA style. This was the first digital presentation for several of the students. For those students who were also developing their mandatory senior thesis projects, this presentation was useful preparation for a similar talk to be given before the entire department. The student presentations and reports were judged by the lead instructor (Gonzales) for scientific merit, quality of data and methods, validity of interpretations and supporting evidence, organization, and style. The presentations overall were good to excellent with the presentations ranking higher overall than the written reports, mostly due to problems in grammar and writing structure in the written products.

Continued Student-Faculty Research and Contributions - At the start of this research course, only one student had committed to conducting senior-thesis research at Ship Rock. After this class, three other students decided to develop projects based on the research they had conducted in the class. The Geology 390 field experience provided them with a jump start and more focus.

Another student became interested in the formation and evolution of a hydrovolcanic feature in the less-studied northeast flank of the NVF near Mesa Verde National Park. This research has now expanded, involving two other Fort Lewis undergraduates who are working on similar volcanic centers in the Ute Mountain Ute Nation near the Park. Collectively, this work suggests an alternative method of diatreme emplacement, strongly dependent on depth and overlying stratigraphy (Burgess and Gonzales, 2005). The students currently involved in this research are also preparing to lead a field trip for professionals and amateurs to the area.

Students from the Geology 364 course and those currently doing research have had several opportunities to accompany other geologists working in different parts of the NVF. For example, one of the students working near Mesa Verde joined faculty and graduate students from Arizona State University to examine NVF centers in the Chuska Mountains.

Student Performance Following the Course - To track the academic progress and success of the twelve student participants in the Geology 364 petrology course, we polled faculty colleagues at Fort Lewis College who encountered the students in subsequent courses or as advisees. Eight of the twelve had begun their required senior-thesis projects by the start of the 2004-05 academic year. The current department head, who is instructor of record for these projects, reported that five of the students showed increased enthusiasm for geology and research, whereas three did not (Collier, J., personal communication).

Another faculty member provided this statement:

> The Ship Rock research experience class run two years ago…was a very positive, motivating turning point for most of the students enrolled. At least half of the students were literally transformed from moderately interested geoscience majors to students that took pride in geologic problem solving and independent research. What was an even more positive outcome was the fact that this experience reached several students [who were] otherwise not engaged or living up to their full potential prior to this class. In my opinion some of these students might not have finished science degrees without this positive experience that taught science by doing scientific research. It convinced me of the pivotal and critically important role of undergraduate research imbedded in the geology curriculum… I have now integrated a four week group research project as a regular part of my Stratigraphy and Sedimentology class…I believe that this type of education is engaging a wider range of students and invigorating our

undergraduate program. (Gianniny, G., personal communication).

Two of the Geology 390 students who are currently employed as geologists noted that their experiences in this class contributed significantly to their careers and perspectives. We believe that these qualitative data establish that the Geology 390 experiment contributed to the long-term development of undergraduate research projects at Fort Lewis College, which in turn have contributed meaningfully to the professional preparation, network-building, and the careers of the students involved.

CHALLENGES

Although engaging students in field-based, inquiry-driven coursework is an approach that has many rewards, it clearly presents challenges not experienced in the classroom. The primary challenge was the time commitment required to read the student research proposals and give critical feedback on their project plans. Although some of the students were already conducting senior-thesis studies elsewhere and had an understanding of how to undertake research, some of the students required considerable guidance and assistance. The two instructors had many different roles: teacher, mentor, administrator, reviewer, and peer researcher. A minimum of 15 hours per week over the entire trimester were spent by the faculty (who were already teaching multiple classes) on logistical and advisory activities outside of the classroom and field. Overall, a much greater commitment of time is required for the field-research approach.

As discussed above, the time required for students to conduct their research meant that fewer general topics in igneous petrology were presented in class. The instructors deliberately focused on key topics and laboratory exercises most relevant to the student projects. For example, students mostly used igneous rocks from the NVF and outlying parts of the Colorado Plateau to practice general interpretation of texture and mineralogy in hand specimens and thin sections.

The greatest challenge to the students in the course appeared to be the open-ended inquiry format, which required them to define and obtain reasonable answers to their own problems, rather than work through verification exercises. Most students were initially frustrated at their inability to obtain concise textbook-style answers to problems of lithology and structure encountered in the field, but this frustration waned noticeably by the end of the course.

CONCLUSIONS

A field-based, inquiry-driven approach to teaching igneous petrology is an alternative that emphasizes direct engagement and student responsibility for learning: traits valuable in transforming undergraduates into experienced and competent professionals. It was apparent that the students who participated in this course were excited to do field research, and carried that enthusiasm into their subsequent studies. Work in a local but globally-known field area enhanced their sense of place.

Subsequent to the experimental course, additional senior-thesis and faculty research continues, involving other Fort Lewis undergraduates in NVF research (Table 3). Current and planned research focuses on the emplacement histories and mechanics of different structural types of diatremes and associated dikes, and the mineralogical and textural properties of signatures of hypabyssal NVF rocks. The student-faculty research initiated in Geology 390 in 2003 thus continues to seed undergraduate interest in field geoscience research, and is making contributions to understanding of Tertiary hydrovolcanism on the Colorado Plateau.

After most conventional undergraduate courses, students are not compelled to re-engage with learning outcomes until graduate studies or employment. Geology 390 at Fort Lewis College challenged students to integrate scientific inquiry and field studies directly into their undergraduate education.

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