The Geological Society of America
Special Paper 461
2009

A comparative study of field inquiry in an undergraduate petrology course

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ABSTRACT

Since 2003, the standard igneous and metamorphic petrology class at Fort Lewis College has been taught as a field-based, inquiry-driven course focused on topics in three different field areas (Ship Rock, Western Needle Mountains, San Juan volcanic field). This format allows undergraduate students to investigate advanced topics in petrology through field research while developing skills for continuing education and scientific careers. These courses serve the needs of the students by promoting critical analysis and inquiry, and building on content taught in previous courses to solve actual geologic problems. Many of the students also find enthusiasm for continued research and make further contributions to the geologic community.

A research-focused field course at the undergraduate level allows students to engage in all facets of research in the context of natural geologic complexity. In addition, these students can collaborate with professional geoscientists to network and find opportunities that are not readily available to their peers outside the course. Engaging undergraduate geoscience students in authentic research projects is a benefit to their education and career development.

INTRODUCTION

Petrology at the undergraduate level is a core element of geology curriculum. This course plays an important role in the education of students, helping them to develop skills in inquiry, observation, and analysis. In the past 20 years, the undergraduate igneous and metamorphic petrology course at many colleges and universities has undergone a major transformation. The traditional format of this course often involved laborious, time-intensive petrographic and hand-specimen studies of rocks and memorization of abstruse terminology. At many institutions, the course has been dropped under an assumption that it is not essential to the career needs of students. At other schools, igneous-metamorphic petrology is melded into a more general "Earth materials" course (e.g., Goodell, 2001; Mogk et al., 2003) to reflect the focus of modern petrologic research on rock-forming processes in the context of material reservoirs and cycles (e.g., Dutrow, 2004; Best, 2003). This shift in curriculum has reduced student engagement with advanced topics in petrology except at large, well-funded research institutions equipped with modern instrumentation and technologies for materials analysis.

For colleges and universities with limited research infrastructure, field studies offer an alternative means of introducing

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Gonzales, D., and Semken, S., 2009, A comparative study of field inquiry in an undergraduate petrology course, *in* Whitmeyer, S.J., Mogk, D.W., and Pyle, E.J., eds., Field Geology Education: Historical Perspectives and Modern Approaches: Geological Society of America Special Paper 461, p. 205–221, doi: 10.1130/2009.2461(18). For permission to copy, contact editing@geosociety.org.

authentic research in petrology to enhance the undergraduate experience. In this paper, we discuss a one-semester, inquiry-driven upper-division undergraduate course in igneous and metamorphic petrology with research conducted exclusively in the field after a brief period of preparation. This course was designed to complement and reinforce existing curriculum while sustaining student engagement with rocks and petrologic processes, as well as bolster meaningful student-faculty research opportunities.

Our field-research course is taught in the Southern Rocky Mountains and Colorado Plateau, and it is focused on petrologic studies relevant to current faculty research on igneous-metamorphic systems. This experiential format is suited to programs sited anywhere where rocks are exposed and accessible. The pilot offering of the class was described in Gonzales and Semken (2006), and it has since been taught twice more in different localities and focused on different petrologic problems. Here, we present formative and summative assessment data to compare the effectiveness and outcomes of different learning strategies used, and we report on the way that the field-research course has influenced subsequent academic (and later career) paths of the students.

INQUIRY IN EDUCATION

Inquiry has become an important if not yet ubiquitous component of science education, and the merits and methods of inquiry are disseminated in the *National Science Education Standards* (NSES; National Research Council, 1996). The positive impact on student learning of inquiry via authentic, scientific research and similar experiential activities is documented (e.g., Project 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; Seymour et al., 2004; Apedoe et al., 2006; Apedoe, 2007; Hunter et al., 2007). The overall implication is that students can benefit greatly when they have the opportunity to design a research project, collect and interpret their own data, and communicate their findings in field settings. However, MacDonald et al. (2005) reported that only 1% of a sampling of geoscience faculty in the United States used research as a component in their curriculum.

Anderson (2007) defined *inquiry learning* as an active, student-centered process that mirrors scientific inquiry and is characterized by: (1) active, personal construction, rather than absorption, of meaning; (2) reliance on prior conceptions that are held by each learner, and that may be changed in the learning process; (3) dependence upon the contexts in which learning takes place (the more diverse the contexts, the richer the knowledge constructed); and (4) enhancement by engagement of ideas in concert with other learners. These four characteristics of inquiry learning (or constructivist learning) constitute a metric for assessing the authenticity and effectiveness of courses such as our field-research petrology course, and we will return to them later herein.

FIELD-BASED STUDIES IN EDUCATION

Most undergraduate geoscience students have some component of field-based inquiry in their education and training. In the past 20 years, numerous studies have provided evidence that field activities have a positive effect on geoscientific knowledge and higher-order learning skills (Kern and Carpenter, 1984, 1986; Orion and Hofstein, 1994; Garvey, 2002; Ambers, 2005; Guertin, 2005; Boyle et al., 2007; Elkins and Elkins, 2007); sense of place (Rossbacher, 2002; Semken, 2005); student confidence in the classroom (Bluth and Huntoon, 2001); and enhancement of curriculum in modern liberal arts programs and preparation for diverse workplace challenges (Kirchner, 1994; Schwab, 2001; DiConti, 2004; Plymate et al., 2005). Field studies can also benefit faculty mentoring of students (Hoskins and Price, 2001) and enhance expertise of in-service science teachers (Mattox and Babb, 2004). Frodeman (2003) contended that field research is the most authentic model for scientific inquiry, developing intuitive knowledge and skills for education and professional development. In spite of all this, a poll of geoscience faculty in the United States in 2005 indicated that fewer than 10% included field studies as a routine part of the curriculum (MacDonald et al., 2005).

COURSE CONTEXT

The host institution for the field-research petrology course is a four-year, public liberal arts college in southwestern Colorado that serves ~4000 undergraduate students per year and is governed by the state university system. The geoscience department sustains 60–80 total majors, including traditional and nontraditional (e.g., returning, second-career) students.

In 2002, the department changed its traditional igneous and metamorphic petrology course from a degree requirement to an elective for geology majors. We saw this as an opportunity to recast the class with a research and field focus. The redesigned course retained an additional petrology option in the curriculum and offered undergraduates a richer opportunity to learn and practice field and research skills. Several other courses in the program integrated small one- to two-week research projects, but there was no regular opportunity for students to investigate an authentic, complex geological problem over an extended period. The field-research course supplements other courses in the program that develop knowledge of scientific ideas and methods, but in a more authentic context than a verification laboratory course.

Our field-research petrology courses were taught in three different localities (Fig. 1), each of which offered a unique context for research. Enrollments in the class ranged from 14 to 4. The small class sizes are attributed to the fact that the course is no longer required for graduation, and it mostly attracts students interested in igneous and metamorphic petrology. This makes for better faculty-student interaction but hinders robust quantitative assessment of the course outcomes.

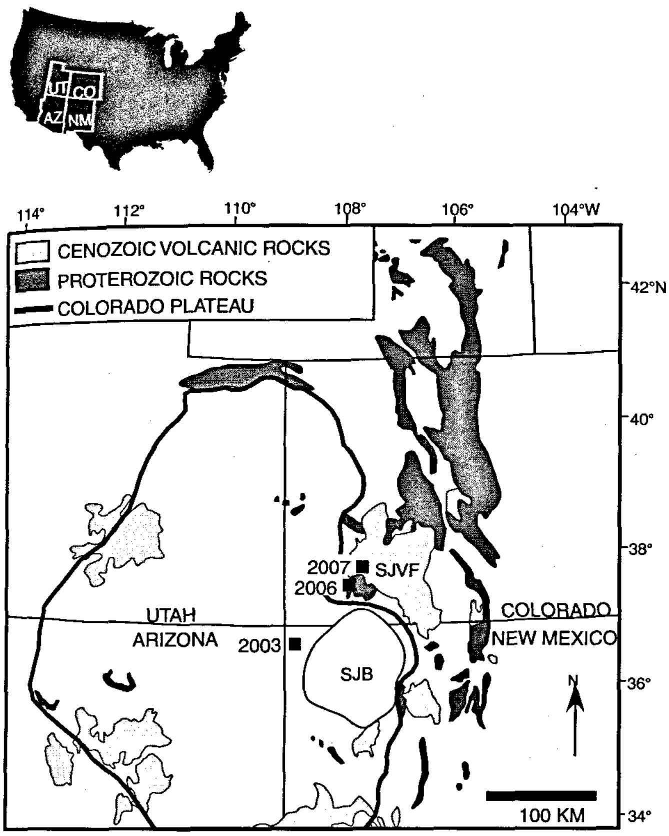

Figure 1. Locations of the field-research petrology courses taught from 2003 to 2007. SJVF—San Juan volcanic field; SJB—San Juan basin.

COURSE LEARNING OBJECTIVES

Syllabi for the field-research petrology courses have varied slightly (Table 1), reflecting different settings and logistics, but the learning objectives for the course remain essentially unchanged (Table 2).

The primary pedagogical strategy of the field-research petrology course is to blend field studies with inquiry to promote authentic, student-driven research. Students apply and test their prior knowledge and use observational and interpretative skills to investigate major regional rock bodies and geologic histories, as opposed to completing a set of activities with predefined outcomes. Students choose and pursue projects in a specific geologic setting (e.g., Ship Rock in 2003) or collaborate in ongoing projects led by an extramural researcher (e.g., a U.S. Geological Survey [USGS] geologist in the San Juan volcanic field in 2007). The field-research course promotes critical and creative thinking through struggles with "messy" real rocks that defy neat textbook-classification schemes, in a natural environment that poses physical and intellectual challenges. Students collaborate in research teams and are required to communicate and defend their findings before their peers and instructors. This provides a true sense of student ownership in the learning process and typifies inquiry learning as defined by Anderson (2007). Learning objectives of the course were conceived to provide preparation for any kind of scientific career (Carver, 1996; DiConti, 2004).

COURSE DESIGN AND CONTENT

Although the different settings and topics in each offering of the course necessitate some logistical variation, the mechanics for each course are similar (Fig. 2; Table 1). On-campus activities are mostly concentrated toward the start of the trimester and involve 10 to 30 min interactive presentations by the instructor interleaved with inquiry exercises and student-led presentations. Literature searches on pertinent geologic topics and a review of scientific citation formats are an integral part of each course.

A persistent thread of the course is reflection on scientific inquiry and research methods. Discussion topics and class activities focus on practical and logistical aspects of project design, formulation and testing of hypotheses, and the collection and analysis of data. For example, students are asked to respond to the questions posed by Kurdziel and Libarkin (2002) in their study of scientific methodology, and then read the article. The students also engage in lessons designed to develop skills in posing causal questions, constructing and testing hypotheses, critiquing scientific interpretations, and considering tools and methods to solve geologic problems. These lessons are developed from published material (e.g., Carey, 1998), class discussions on geologic problems familiar to students, and geologic phenomena encountered on field trips (Table 1).

Each offering of the course includes a review of solid-earth structure and plate-tectonic systems, and a thorough overview of major regional geologic events (Fig. 2; Table 1). Students read and discuss a set of journal articles on Proterozoic to Neogene evolution of the Colorado Plateau and Southern Rocky Mountains (e.g., Bally et al., 1989; Oldow et al., 1989; Burchfiel et al., 1992; Miller et al., 1992; Christiansen et al., 1992). For the 2003 course at Ship Rock, students also received preparation in Navajo knowledge relating to the landform, cultural awareness, and the tribal regulations on fieldwork there.

Some laboratory sessions focus on examination of igneous and metamorphic rocks in hand specimens and thin sections, with emphasis on textural and compositional descriptions (Fig. 2; Table 1). Other laboratory activities apply petrologic data to petrogenetic problems related to magma generation and emplacement, volcanic processes, rock deformation, and metamorphic processes. Most of the students come with some prior, mostly textbook-based, knowledge of these subjects from the introductory Earth materials course.

After the first few weeks, laboratory sessions shift toward discussion of field research methods, including data collection and analysis. Field sessions are scheduled on Friday afternoons to minimize time conflicts with other courses. This also allows

TABLE 1. A COMPARISON OF TOPICS AND STUDENT TASKS

Course calendar	2003: Ship Rock	2006: Western Needle Mountains	2007: San Juan volcanic field
Precourse	Fall of 2002: reconnaissance field work. Discussed potential research problems, and did literature review.	Not applicable	Not applicable
Week 1	Discussed process of research; conducted exercises and discussions on scientific inquiry.	Overview of regional geologic history and geology of the study area. **Field trip** to explore research topics.	Discussed process of research; conducted exercises and discussions on scientific inquiry. Reviewed reference styles, and compiled bibliography of existing published work for portfolio.
Week 2	Reviewed igneous rock types and textures, and physical properties of magma.	Discussed process of research; conducted exercises and discussions on scientific inquiry. Participated in 2 day field conference focused on topics near research area.	Overview of regional geologic history, and San Juan volcanic field. Four-day **trip** to conduct field research.
Week 3	Reviewed International Union of Geological Sciences (IUGS) classification of igneous rocks. Studied rock specimens from Navajo volcanic field and other local igneous masses.	Group reviewed and presented on reference styles. Submitted outline of field research for approval, and presented it to class. **Started field research.**	Reviewed earth structure and tectonic settings. Constructed an illustrated summary of igneous-tectonic systems for portfolio.
Week 4	Reviewed earth structure and igneous systems in tectonic settings. Constructed an illustrated summary of igneous-tectonic systems.	Reviewed earth structure and tectonic settings. **Continued field research.**	Reviewed origin and evolution of magmas: conducted exercises, class activities, and homework on partial melting and fractional crystallization.
Week 5	Discussed petrogenesis of mafic magmas. Submitted outline of field-research for approval, and presented it to class.	Reviewed common igneous rock types and textures. Classified igneous rocks in study area using IUGS scheme. **Continued field research.**	Reviewed volcanic landforms and systems. Summarized dominant tectonic-magmatic models for San Juan volcanic field for portfolio.
Week 6	Overview of regional Cenozoic magmatism and Navajo volcanic field.	Reviewed common metamorphic rocks. Studied metamorphic rocks from study area. **Continued field research.**	Reviewed caldera systems and deposits. Students gave presentations on different calderas systems of western San Juan volcanic field.
Week 7	Overview of geology and Navajo ethnogeologic knowledge of the study area. Planned research strategy with faculty.	Reviewed plutonic igneous environments. Constructed an illustrated summary of igneous suites and processes in tectonic systems. **Continued field research.**	Reviewed classification/nomenclature of igneous rocks; applied information to name samples from field trip.
Week 8	**Started field research.**	Reviewed regional metamorphic environments. Constructed an illustrated summary of metamorphic suites and processes in tectonic systems. **Continued field research.**	Discussed volcanic rock textures and structures; applied information to describe samples from field trip. Compiled a summary on chronology of events in western San Juan volcanic field for portfolio. **Field trip** to gold deposit near Cripple Creek.
Week 9	**Continued field research.**	Discussed how to interpret and analyze geologic structures in field area. **Continued field research.**	Reviewed plutonic rock textures and structures; applied information to describe samples from field trip.
Week 10	**Continued field research.**	Compiled, analyzed, and interpreted data.	Summarized major units of the San Juan–Silverton calderas for portfolio.
Week 11	**Continued field research.**	Compiled, analyzed, and interpreted data.	Studied rock samples in thin section.
Week 12	**Continued field research.**	Compiled, analyzed, and interpreted data.	Discussed ore systems of the San Juan volcanic field. Students worked with Dr. Yager on acid-neutralizing capacity (ANC) titration analyses in Denver.
Week 13	Compiled data and worked on research report and presentation.	Worked on research report and presentation.	Students presented on common ore mineral & associations for the San Juan–Silverton calderas. Submitted overview of deposits for portfolio.
Week 14	Completed research report and presented results of research.	Finished research report and presented results of research.	Completed research portfolio and presented results of research.

TABLE 2. SUMMARY AND COMPARISON OF PROJECTS, PRODUCTS, AND CONTINUED OUTCOMES FOR FIELD-RESEARCH COURSES

Project goal	Types of data collected	New hypotheses	Class products and new contributions	Thesis projects	Professional contributions
2003					
A detailed study of diatreme, plugs, and dikes. Focused on the different geologic units and rock structures to gain more insight into the eruptive history.	Maps of composition, distribution, and general orientation of rock units and features. Hand-sample and thin-section descriptions of rocks and textures. Geochemical data from dikes. Structural measurements of diatreme bedding, and dike fabrics and structures. Described soil horizons and their geochemical signatures. Studied types and abundances of xenoliths.	Diatreme has layered-conical geometry with two different eruptive phases cut by minette dikes and late-stage tuff dikes. Subsurface magma tubes and "pillow" formed in segments of dikes enriched in volatiles. Little or no effects on the mineralogy and chemistry of dike rocks from wall-rock contamination. Foliation developed in outer margins of dike segments containing tubes; interpreted as magma-shear fabric.	Class research papers/presentations Geologic maps Continued faculty research New geochemical and petrologic data Digital database	Three students from course and two in 2005 who did not take the class	Burgess and Gonzales (2005) Gonzales et al. (2006) Turner and Gonzales (2006)
2006					
Studied metamorphic assemblages and fabrics in Proterozoic rock units. Conducted detailed petrologic and structural studies of ca. 1.7 Ga granitic dikes. Conducted petrochemical and field studies on Tertiary intrusive rocks to assess magma genesis and emplacement histories.	Petrographic descriptions of metamorphic mineral assemblages and fabrics. Documented relationship between metamorphism and deformation. Geologic map of ca. 1.7 Ga dikes and trends. Outcrop and thin-section descriptions of dike rocks. Documented structural fabrics and deformational history of dikes, and constrained relationships of dike emplacement to deformation. Petrologic descriptions and geochemical data for different Tertiary intrusive rock units.	Multiple stages of metamorphic mineral growth during ductile deformation of ca. 1.78 Ga rocks under upper-amphibolite-facies conditions. The grade of metamorphism, and timing relative to deformation, in ca. 1.7 Ga pelitic rocks were inconsistent with previous published results. Proterozoic dikes were syn- to postdeformational, and emplaced during N-S compression at ca. 1.7 Ga. Tertiary intrusive rocks had similar petrogenesis and emplacement histories.	Class research paper/presentation Continued research by faculty and student New pressure and temperature constraints from metamorphic mineral assemblages New geochemical, petrologic, and structural data for ca. 1.7 Ga dike rocks and Tertiary intrusive rocks	Five	Herb and Gonzales (2008) Martin and Gonzales (2008) Marsters and Hannula (2008) Shumway and Gonzales (2008)
2007					
Collaborative study with U.S. Geological Survey to investigate the acid-neutralizing capacity (ANC) of altered igneous rocks in the western San Juan volcanic field.	Hand-sample and thin-section descriptions of altered and unaltered rock samples from different units exposed in the caldera systems of the western San Juan volcanic field. Measured pH, conductivity, temperature and dissolved oxygen of mine drainage. Set up a map grid to collect unaltered and altered rocks to use in ANC-titration tests and scanning electron microscope (SEM) analyses at U.S. Geological Survey facilities; measured field magnetic susceptibility of rocks.	Further data on mineral associations and ANC capacities to assess remediation potential of acid-mine drainage.	Class research paper/presentation Continued research by Dr. Yager and one student Involvement of Fort Lewis College field geology class in related projects in summer of 2008 Results contributed to the ongoing U.S. Geological Survey research	One student in 2008 who did not take the class	None

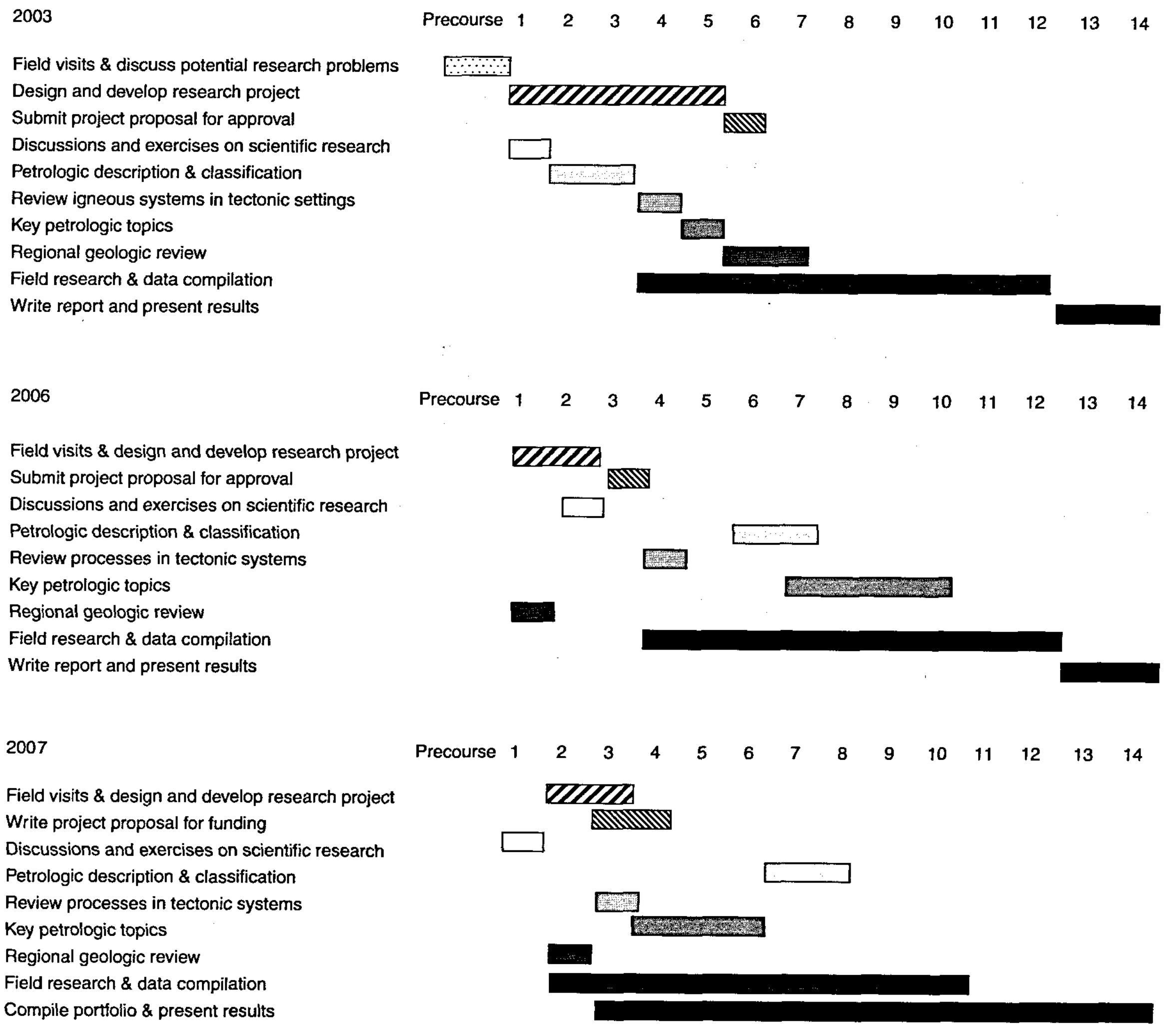

Figure 2. Comparison of the time line of topics covered in the 2003, 2006, and 2007 field-research petrology courses.

students to stay in the field longer without pressing conflicts with other classes. The course was first offered in the winter trimester (January to April), which limited significant fieldwork until weather allowed, around the eighth week. We moved the subsequent offerings to the fall trimester, allowing students to go into the field right away, and hence develop their projects sooner.

Logistical issues (e.g., travel arrangements, procurement of field supplies and tools, scheduling) are dealt with as a group, and duties are shared by faculty and students. In the field, instructors and collaborating scientists help student teams to learn and practice proper field techniques, such as structural measurements, rock description and interpretation, field mapping techniques, and sampling methods for geochemical analyses. This is critical to develop confidence in the skills of students. Instructors keep apprised of teams' progress, both to offer timely guidance and to help students to remain focused on tasks. Our intent is to establish a learning community: a key element of effective experiential learning (Carver, 1996).

Students spend from 6 to 16 full days in the field, depending on the logistical demands of particular projects. They are responsible for identifying and justifying any data needed to complete their projects. All of the students work together to analyze and interpret the data collected. Faculty provide guidance in the process, but students are responsible for their own hypotheses, tests, and conclusions. Throughout the course, the students are encouraged to discuss their findings and problems with each other, and again during lecture periods or outside of class, to facilitate sharing of data that might contribute to other projects.

Research papers and presentations were the capstone deliverables for the course in 2003 and 2006. In 2007, students were required to compile a portfolio on a set of assigned topics related directly to the project (Table 1). Various sections of the portfolio had to be submitted every several weeks. Each section of the research portfolio focused on different topics, and students used published information and any new data from their research to build a detailed compilation for each topic. For example, for one section of the portfolio, students built a chronology of volcanic events for the western San Juan Mountains. The portfolio enabled the instructors to monitor the progress of the students more closely. Unlike a research paper, the portfolio was a compilation of information that included a summary report, but that also provided a more comprehensive resource the students could use in future research or coursework. Students in the 2007 class were still required to present the results of their research at the end of the course, but they were also assessed on the content and quality of their portfolios (Table 1).

COURSE SETTINGS

The areas selected for the 2003, 2006, and 2007 field-research courses (Fig. 1; Table 2) reflected the interests of the instructors and students. Selections were influenced by logistical concerns such as proximity to campus and prevailing weather conditions. Each of the field areas chosen was characterized by a range of interesting petrologic problems sufficient to serve the class. This enabled students to identify and pursue projects that were most interesting to them, while also learning from complementary projects pursued by their peers.

We selected the diatreme-dike complex at Ship Rock, Navajo Nation, New Mexico, for the first course offering in 2003 mostly because of our own research interests, and because many aspects of the petrology and structure of Ship Rock had not been studied in detail to that point. Although all of the students in the course participated in group exploration and interpretation of the diatreme and dikes, each student pursued individual projects that specifically interested them (e.g., soil geochemistry). This permitted the group to work independently on topics but allowed collaboration on a common geologic feature. These projects contributed to class discussions of the geologic history of Ship Rock in the context of the evolution of the Colorado Plateau and the cultural significance of the locality (Semken and Morgan, 1997; Semken, 2003), making this an authentically place-based course (Semken, 2005).

In 2006, students studied the petrology and structure of Paleoproterozoic basement and mid-Tertiary plutonic rocks in the Western Needle Mountains, ~30 mi (~ 50 km) north of campus (Fig. 1). The study area was closer to campus and offered a greater diversity of potential projects than were available at Ship Rock (Table 2). As a consequence, students pursued regionally based projects that were not tied to a specific rock unit or feature. A few students developed projects around a common problem, allowing for productive interaction, but others worked on problems that were scientifically and logistically independent. This had the unanticipated effect of diminishing interaction and collaboration among student groups.

The 2007 course took a different tactic: it was organized to complement the ongoing regional research of a USGS professional, Dr. Doug Yager. The overarching theme (Table 2) was Oligocene volcanism in the San Juan Mountains, particularly the volcanic succession of the San Juan caldera complex (Fig. 1). Students developed specific projects to characterize the acid-neutralizing capacity (ANC) of igneous rocks in the vicinity of the historic mining town of Silverton, Colorado, in support of an environmental program managed by the USGS and the U.S. Bureau of Land Management. This provided a unique opportunity for students to apply igneous petrology in the context of a significant regional problem dealing with acid-mine drainage. The students were able to contribute to an authentic federal research project and to interact with research scientists outside of academia. To facilitate this work, the students applied for and received a grant from the college's Dean of Sciences, gaining skills in proposal writing.

The logistics of the 2007 class were considerably different from those of the prior offerings (Table 1). Most fieldwork was condensed into an intensive four-day course during which students worked alongside Dr. Yager and two instructors. The students characterized and sampled volcanic rocks over a 100 mi (161 km) traverse, studied ANC-related mineralogical and chemical characteristics of fresh and altered rocks in situ, and mapped a sequence of Oligocene volcanic rocks near Silverton. They learned geochemical sampling techniques (including chain-of-custody procedures), statistical grid-cell sampling, field magnetic susceptibility measurement, and the "field-pace" method of mapping (Barnes, 1981). They also collected baseline data for water quality (pH, dissolved oxygen, conductivity, and temperature), and improved their skills in the use and interpretation of geologic maps.

The main four-day field excursion in 2007 was followed by two supplemental day-long field trips in the San Juan Mountains to study other volcanic rock exposures. Later in the trimester, students learned to do ANC titration and scanning electron microscope (SEM) analyses of their samples at the USGS laboratory in Denver.

CONTENT EVALUATION

The student learning objectives for the course, and the characteristics of inquiry learning identified by Anderson (2007), form the basis for evaluation of our field-based, inquiry-driven approach to teaching petrology. Table 3 matches the learning objectives to their corresponding means of evaluation, some of which are quantitative and some qualitative. Data included instructor observations of student behaviors and performance, representative examples of student work, summative course evaluations, and postcourse tracking of students' academic success and career paths. Because of the small number of student participants, however, we cannot demonstrate statistical significance for the quantitative results, and they are discussed only as general indicators.

Summative Student Evaluations

Overall Student Rating

Students in the geosciences program anonymously rate each course they complete on a five-point scale, with five signifying

TABLE 3. STUDENT LEARNING OBJECTIVES AND CORRESPONDING MEANS OF EVALUATION

Student learning objectives	Summative student evaluations	Instructor observations	Continued postcourse research	Instructor-rated quality of research products	Professional contributions to geologic community
Enhance interest in geology and petrology through focused study of rock masses or landforms.	Applied	Not applied	Applied	Not applied	Not applied
Enhance familiarity with the region.	Applied	Not applied	Not applied	Not applied	Not applied
Conduct authentic research project from planning to interpretation and dissemination of results. Enhance skills in scientific inquiry and critical thinking.	Applied	Applied	Not applied	Applied	Not applied
Apply petrologic and other geologic knowledge and skills in a field setting.	Applied	Applied	Not applied	Not applied	Not applied
Develop abilities to work productively as part of a research team.	Not applied	Applied	Not applied	Not applied	Not applied
Further develop skills in oral and written communication.	Not applied	Not applied	Not applied	Applied	Not applied
Advance knowledge of the petrology and geology of the field area.	Not applied	Not applied	Not applied	Not applied	Applied

the top score. The field-research igneous and metamorphic petrology course received higher overall ratings in 2003 (4.82 ± 0.4, $N = 12$) and 2007 (5.0 ± 0.0, $N = 4$) than the average rating for two sections of the previous laboratory-based course (4.53 ± 0.7, $N = 20$). However, the 2006 class was rated much lower (3.9 ± 1.5, $N = 8$). As noted already, the 2006 course differed in that the students' inquiry learning was far more open and unguided; projects that year did not address a common problem nor were they situated in close proximity to each other. Although several of the students in the 2006 course gave the class a comparatively low overall rating, five of the eight who completed it continued to pursue their individual projects for senior theses (Table 2).

Student Surveys

At the end of each offering of the course, students anonymously completed a quantitative 16-item survey developed specifically to address student attitudes and learning (Table 4). Students agreed most strongly that a research-based course is more professionally useful than one without a research component (3 yr average = 4.9), that the course increased their interest in doing research (4.8), and that it improved their knowledge of regional geology and geologic history (4.8). They also expressed strong agreement with other statements affirming the personal value of doing research and fieldwork (4.6–4.7). They were less affirmative that they fully understood how to complete their projects (4.2), gained understanding of local culture in the study area (4.0), were able to accomplish all required tasks (3.9), and that they met their project objectives (3.9). Their only disagreement, which was expected, was with the statement that they were familiar with their study site before taking the class (2.9). It is interesting that this survey shows that the students in 2006, who did not give a high rating for the course overall, were very positive about its research components and its impact on their interest.

Following the 2006 and 2007 courses, we administered a qualitative summative survey with 21 short-answer questions (Table 5). The items asked students to elaborate on their positive and negative impressions of the course, and on its impact on their knowledge, interests, and professional preparation. Students often provided more than one response to a given item. These data were analyzed using a naturalistic approach (Miles and Huberman, 1994) to identify themes in the student responses rather than matching them against prior classifications.

Similar and affirmative themes emerged from our analyses of the quantitative and qualitative parts of the summative-student surveys. Scheduling and lack of prior research experience posed minor challenges, but students generally found their projects attainable, enjoyable, and worthwhile. The opportunity to practice skills in the field was particularly valued, and most students thought that the course provided the best preparation for senior theses and professional careers of any they took.

Pre–Post Survey

In 2006 and 2007, we also administered a quantitative survey to assess students' own perceptions of how their interests and skills had changed from the start to the end of the class (Table 6). The difference in the values is reported as normalized gain (Hake, 1998). It is evident that in most instances, students felt that their interest and geologic knowledge increased.

Quality of Student Final Papers and Presentations

As a capstone exercise, all students were required to present their findings individually or in their project teams of two or three (Table 1). Each student wrote a Geological Society of America (GSA)–style research paper, which in 2007 was part of the summary portfolio. These were graded for scientific content and style using the set of rubrics in Table 7. Greater weight was given to the "science" of the paper.

Oral presentations, the first for some students, were given with digital slides in 15 min GSA format. They were judged by the lead instructor (first author) using content rubrics given in Table 8. Emphasis was placed on scientific merit, quality of data and methods, validity of interpretations and supporting evidence, organization, and presentation style. Nearly all of the

TABLE 4. MEAN STUDENT RESPONSES TO THE SURVEY ITEMS IN THE SUMMATIVE COURSE EVALUATION, BY YEAR (1—STRONG DISAGREEMENT, 2—DISAGREEMENT, 3—NEUTRALITY, 4—AGREEMENT, 5—STRONG AGREEMENT)

Learning objective	Relevant item(s) from summative evaluation	2003 means (N = 12)	2006 means (N = 7)	2007 means (N = 4)
Enhance interest in geology and petrology through focused study of a significant local crystalline-rock body or landform.	My interest in geosciences increased as a result of taking this class.	4.6 ± 0.6	4.6 ± 0.52	5.0 ± 0.0
	My interest in igneous petrology increased as a result of taking this class.	4.2 ± 1.3	4.5 ± 0.53	5.0 ± 0.0
	My interest in doing scientific research increased as a result of taking this class.	4.6 ± 0.6	4.9 ± 0.35	5.0 ± 0.0
Enhance familiarity with the region.	My knowledge of regional geology and geologic history improved as a result of taking this class.	4.9 ± 0.5	4.5 ± 0.76	5.0 ± 0.0
	Prior to taking this class, I was familiar with the geologic feature where I did my research work.	3.3 ± 1.5	2.4 ± 1.06	2.8 ± 0.96
	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	3.1 ± 0.64	3.8 ± 1.50
	I gained understanding and appreciation of the local culture in my study area as a result of taking this course.	3.9 ± 0.9	3.9 ± 0.90	4.5 ± 0.58
Conduct an authentic research project from initial planning to interpretation and dissemination of results.	I understood the objectives of my research project.	4.2 ± 0.8	4.1 ± 0.64	5.0 ± 0.0
	I understood what I needed to do in order to complete my research project.	3.8 ± 0.8	4.4 ± 0.52	4.8 ± 0.50
	I was able to accomplish all of the tasks needed to complete my research project.	3.9 ± 0.8	3.8 ± 0.71	4.3 ± 0.50
	I feel that my work and results met the objectives of my research project.	3.8 ± 1.1	3.5 ± 0.93	4.8 ± 0.50
	A course with a research component is more interesting than one without a research component.	4.6 ± 0.8	4.5 ± 0.53	5.0 ± 0.0
	A course with a research component is more useful professionally than one without a research component.	4.8 ± 0.6	4.9 ± 0.35	5.0 ± 0.0
	If possible, I would choose to take other geoscience courses that enable me to do scientific research.	4.9 ± 0.5	4.4 ± 0.52	5.0 ± 0.0
Enhance skills in scientific inquiry and critical thinking.	I better understand how scientific research is done as a result of taking this class.	4.7 ± 0.6	4.6 ± 0.53	4.8 ± 0.50
Apply petrologic and other geologic knowledge and skills in a field setting.	My interest in doing field work increased as a result of taking this class.	4.6 ± 0.6	4.6 ± 0.52	5.0 ± 0.0

presentations were found to be good to excellent and impressed the instructor more than did the written reports, many of which had numerous stylistic errors in spite of the specifications and guidance provided by the instructor. The oral presentations also helped students prepare for similar mandatory senior thesis talks presented later to the entire department.

Continued Student-Faculty Research and Contributions

Table 2 summarizes the 24 research projects completed by the students from 2003 to 2007, and it also indicates the projects that were developed further as senior theses or professional contributions. Nine students continued their research for senior theses. Another student became interested in the evolution of a diatreme complex in the less-studied northeastern Navajo volcanic field near Mesa Verde National Park, Colorado. This new project also included two geology majors who had not taken the field-research petrology course. Two of the 2007 students also worked on Navajo diatremes after completing their course research in the San Juan volcanic field. In addition, at least five students who did not take the course have pursued research projects spun off from it. Although we have not yet assessed its full impact, there appears to be a trickle-down effect from the interest and passion for field research demonstrated by many of the participants in the course.

Research experiences in the field-research petrology course gave some students a jump start on senior thesis projects that were subsequently presented at professional meetings to a broader geologic community (Table 2). Student findings from the course have already led to new models of diatreme emplacement (Burgess and Gonzales, 2005; Gonzales et al., 2006; Turner and Gonzales, 2006), insight into pressure and temperature histories of metamorphosed basement rocks (Martin and Gonzales, 2008; Marsters and Hannula, 2008), and mechanisms of magma generation and emplacement related to crustal evolution at ca. 1.7 Ga (Herb and Gonzales, 2008;

TABLE 5. ANALYSIS OF STUDENT RESPONSES TO A 21 ITEM QUALITATIVE SURVEY ADMINISTERED AFTER THE 2006 ($n = 7$) AND 2007 ($n = 4$) COURSES*

Question	Responses
Why did you take this elective course?	Learn more about igneous and metamorphic petrology: 5 Learn more about research: 4 Gain more field experience: 4 Interest in local geology and petrology: 1 For career potential: 1
What were your career interests when you took the course?	Some aspect of geology: 3 Environmental geology: 2 Igneous petrology: 1 Petroleum geology: 1 Undecided: 7
What are your current career interests?	Hydrogeology/environmental geology: 4 Economic (including petroleum) geology: 4 Petrology: 1 Structural geology: 1 Field geology: 1 Some aspect of geology: 1
Did the course have an influence on your career interests?	Yes: 7; No: 4
What was your overall impression of the research-based focus of the field-research petrology course that you took?	Effective in teaching how research is done: 6 Application to real-world situation: 1 Imparted a better understanding of igneous systems: 1 Learned by doing: 1 Project a little weak and rushed: 1 Did not improve technical writing skills as wished: 1
In what general ways did the course effect (impact) your education and learning?	Enhanced research interest and/or skills: 4 Increased interest in field work: 2 Taught by application: 1 Enhanced confidence: 2 Increased independence as a learner and researcher: 1 Provided a professional contact for future collaboration: 1
What were two things that you experienced or learned in the course that you felt were the most useful to you, or most successful in the way it was taught?	Problem solving: 4 Field methods: 4 Data collection and analysis: 5 Better understanding of scientific method: 2 Observational skills: 2 Presentation skills: 1 Better understanding of regional geology: 1 Use of technology: 1
What were two things that you experienced or learned in the course that you didn't think were successful or something you might want added, or you thought could be better?	Needed more time to complete project: 3 Needed more in-depth understanding of geologic concepts: 4 Needed more opportunity to develop communication skills: 2 Wanted more collaboration with peers: 1 Wanted more time with instructor: 1 No negative experiences at all: 1 No response: 6
Do you feel you had a good understanding of how to conduct scientific research when you took the course?	No real understanding: 4 Some understanding: 5 Understood how, but had never really practiced it: 2
Do you feel that your understanding of how to conduct scientific research improved after you took the course?	Yes, greatly: 9 Yes, somewhat: 2
How did your interests in field studies change after you completed the course?	More interested in field studies after the course: 10 No change in interest: 1
How did your interests in petrology change after you completed the course?	More interested in petrology after the course: 8 Slightly more interested in petrology: 3
If you had a choice, would you prefer to have research integrated in other courses? Why?	Yes: 11; No: 0 Students learn better using inquiry: 3 Research links classroom to real world: 3 Good preparation for professional career: 2 Students have more direct involvement in learning: 1 Field-based research is integral to geology: 1 Good preparation for senior thesis & careers: 2
Have you taken another research-based course? Explain.	Have done some research in other courses: 5 No other authentic research courses: 6
What was the most important feature or characteristic of this course to you?	Working in the field: 6 The research process: 4 Literature review: 1 Hands-on learning: 2

(Continued)

TABLE 5. ANALYSIS OF STUDENT RESPONSES TO A 21 ITEM QUALITATIVE SURVEY ADMINISTERED AFTER THE 2006 ($n = 7$) AND 2007 ($n = 4$) COURSES (*Continued*)

Question	Responses
Did the course have an impact on your professional development? Explain.	Yes: 10; No: 1 Initiated collaboration with professional geologists: 2 Good preparation for professional presentation: 2 Solidified geological knowledge: 2 Increased appreciation of research in geology: 1 Enhanced field skills: 1 Provided preparation for senior thesis: 1 Too academic; did not enhance skills: 1
Have you continued the research topic that you started in the course? If you have, explain how.	Yes: 10; No: 1 As a senior thesis: 4 Through continued collaboration with professional geologist: 2 In other courses: 1 Through employment: 1 In community outreach activities: 1
Are you considering any topic in the field of petrology for graduate studies? Did this course influence your decision? Explain.	Yes: 4; Maybe: 4; No: 3
Is there anything else you would like to write about this course?	Recommend this course as good preparation for senior thesis: 2 Recommend more research-based courses like this for professional preparation: 3 This course would benefit any geology student: 2 It was fun: 1 It was a great experience: 2 When will the next one be offered? 1 Helped to show me that geology is not just lectures and labs: 1 Helped me learn proper citation form for future communication: 1 No response: 3

*Students typically included more than one explanation or reason in their responses.

Shumway and Gonzales, 2008). One of these student authors is now pursuing graduate research on maar-diatreme volcanism at Arizona State University (ASU). We attribute these diverse and positive outcomes in part to the longevity of the research projects initiated in the field-research petrology course, and the collaborative skills the course fostered.

Students involved in the field-research petrology course had opportunities to collaborate with professional geologists at various levels. One of the students joined faculty and graduate students from ASU to study Navajo diatremes in the Chuska Mountains, New Mexico, and later helped lead a field trip for the Four Corners Geological Society in 2005. In 2006, several students conducted microprobe analysis with the help of research scientists at New Mexico Tech and ASU. As noted previously, students in the 2007 class conducted geochemical analyses at USGS laboratories in Denver. These collaborations enabled students to confer with experts and use analytical instruments that were not otherwise available.

We have found that geoscience research in the field is a feasible way to allow undergraduate students to study and learn from authentic problems at a level more typical of graduate students or professional geoscientists. Although laboratory-based research opportunities at small undergraduate institutions can be limited by infrastructure and funding, most institutions have access to field areas where research can be conducted, and extramural professional collaboration may also be possible.

Students who completed the field-research petrology course, and who have taken positions in industry or pursued graduate studies, have noted that their experience in the course had a significant impact on their success. One student commented: "The research aspect of the class was the most valuable part. Learning how to go about a scientific investigation that includes actual field work prepared me for my senior seminar research."

Postcourse Evaluation of Students by Colleagues

To track the academic progress and success of the 24 student participants in the field-research petrology course, we polled faculty colleagues who encountered these students in subsequent courses or as advisees on thesis projects. In 2003, two of the faculty who taught most of the students in following semesters noted an increased enthusiasm and motivation for geology and research (J. Collier and G. Gianniny, 2004, personal commun.). It was also noted that the research experiences that students had in the course was critical to their intellectual development, and, as a result, a research component was implemented into an existing sedimentology course (G. Gianniny, 2004, personal commun.).

In 2008, we administered a survey to all departmental faculty ($N = 5$) to determine their impressions of the impact of the course on students in the context of the entire undergraduate program (Table 9). All of the students in the 2003 and 2006 courses had graduated, and two of the students from the 2007 course had begun senior thesis projects by the start of the 2008–2009 academic year. We asked faculty to judge how well the course met its principal learning objectives based on their subsequent interactions with students. These data are presented in

TABLE 6. COMPARISONS OF STUDENT RESPONSES (2006 AND 2007) TO THEIR PERCEIVED GAIN IN KNOWLEDGE AND SKILLS FOR THE TOPICS LISTED

	Interest in petrology	Interest in research	Interest in field studies	Understanding of topics in petrology	Field skills	Research skills	Knowledge of scientific citation	Professional development	Communication skills	Research opportunities
Responses	7, 9, 0.67	7, 10, 1.0	7, 10, 1.0	6, 8.5, 0.63	5, 8, 0.6	5.5, 8.5, 0.67	4, 8, 0.67	6, 8.5, 0.63	7.5, 9, 0.6	7, 9, 0.67
	7, 9, 0.67	5, 10, 1.0	5, 10, 1.0	6, 9, 0.75	5, 8, 0.6	5, 8, 0.6	5, 8, 0.6	7, 9, 0.67	8, 9, 0.5	7, 9, 0.67
	10, 10, 0	10, 10, 0	5, 8, 0.6	5, 8, 0.75	4, 8, 0.67	4, 8, 0.67	2, 9, 0.88	5, 8, 0.6	5, 7, 0.4	5, 10, 1.0
	5, 9, 0.8	5, 9, 0.8	6, 10, 1.0	5, 10, 1.0	6, 9, 0.75	2, 8, 0.75	2, 10, 1.0	5, 10, 1.0	5, 10, 1.0	0, 10, 1.0
	2, 6, 0.5	5, 9, 0.8	4, 8, 0.67	1, 8, 0.78	3, 10, 1.0	4, 10, 1.0	2, 9, 0.88	5, 9, 0.8	1, 8, 0.78	2, 8, 0.75
	8, 10, 1.0	10, 10, 0	8, 10, 1.0	6, 9, 0.75	6, 10, 1.0	8, 10, 1.0	5, 10, 1.0	10, 10, 0	7, 9, 0.67	8, 10, 1.0
	8, 10, 1.0	10, 10, 0	10, 10, 0	2, 6, 0.5	2, 6, 0.5	2, 6, 0.5	4, 8, 0.67	4, 6, 0.33	4, 4, 1.0	4, 8, 0.67
	7, 9, 0.67	8, 9, 0.5	8, 10, 1.0	6, 7, 0.25	5, 6, 0.2	3, 9, 0.86	1, 9, 0.89	3, 7, 0.57	4, 8, 0.67	3, 8, 0.71
	5, 7, 0.4	7, 9, 0.67	9, 9, 0.5	5, 8, 0.6	5, 8, 0.6	3, 7, 0.57	2, 6, 0.5	4, 6, 0.33	4, 8, 0.67	5, 8, 0.75
	3, 7, 0.57	6, 9, 0.75	6, 9, 0.75	4, 8, 0.67	5, 7, 0.4	5, 7, 0.4	3, 6, 0.43	3, 7, 0.57	2, 5, 0.38	4, 8, 0.67
	6, 9, 0.75	8, 10, 1.0	8, 10, 1.0	5, 8, 0.6	3, 7, 0.8	3, 7, 0.8	7, 8, 0.33	5, 9, 0.8	6, 9, 0.75	5, 10, 1.0
Mean change	0.64	0.59	0.77	0.66	0.56	0.71	0.71	0.57	0.67	0.81

Note: The first and second numbers in each set indicate the ranking before and after the class, respectively (10—highest). The third number is the weighted gain (difference/potential difference).

Table 9, embellished with additional comments on positive and negative impacts of the course. The responses were analyzed and coded by a constant-comparative method (Merriam, 1998), in which the data were categorized to correspond to the nine student outcomes.

Several themes emerged from this survey. Faculty respondents felt that the greatest impact of the field-research petrology course was on student enthusiasm for geology and field research, even for middling students who may not be comparably engaged by conventional courses. Respondents thought the course had a positive impact on students' field skills, research skills, and preparation for professional careers, but not on communication skills. Respondents suggested that substitution of research depth for topical breadth may not serve all students equally well in subsequent geoscience courses.

COURSE CHALLENGES AND INSTRUCTOR OBSERVATIONS

Engaging students in field-based and inquiry-driven learning is rewarding but met with challenges such as the expense and difficulty of scheduling field trips, safety and liability concerns, instructor or student unfamiliarity or discomfort with fieldwork, lack of good teaching resources, and even a view that the field is not an effective learning environment (Orion, 1993; Orion and Hofstein, 1994; Jarrett and Burnley, 2003; O'Neal, 2003; Elkins and Elkins, 2007). However, these challenges had little impact on our courses.

A research course allows for less subject-matter "coverage" than a conventional course, as considerable class time must be devoted to skills development and then the student research projects. The more latitude students are given to pursue diverse topics, the more difficult it becomes for the instructor to define the set of concepts needed to prepare the students for their research and also meet course objectives. There is also more of a demand on faculty time to assist student research teams with specific issues. These time constraints were particularly acute during the 2006 course, in which the teams were the most topically and geographically independent of each other.

We typically spent a total of about two full field days with each student or student team. In most cases, this was long enough to render the teams self-sufficient, but with a few students, more time was required, and they wanted more direct guidance from the instructors. Some students, however, expressed frustration with the amount of time that faculty were able to spend with them in the field.

Overall, the instructor of a field-research course must expect to serve as a teacher, motivator, 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. These activities involved communication with other scientists involved in projects, scheduling vehicles and field trips, finding and disseminating reading

TABLE 7. GRADING RUBRIC USED TO ASSESS PORTFOLIOS IN 2007 (A FRACTIONAL POINT VALUE WAS GIVEN WHEN REQUIRED)

Grade	Assessment criteria
5	A superior product that goes beyond the basic requirements. An excellent compilation of information and supporting resources that is complete, organized, and presented in a professional manner. This is a compilation that is a useful tool in a job or research project.
4	Meets requirements for assignment. Summaries are complete, thorough, and supported with additional information. Summary is a good resource.
3	An average, solid job. Summary provides basic information that has been discussed or covered in textbook; does not add further insight into the issue.
2	Coverage of the discussion is cursory and does not meet minimum requirements (i.e., incomplete, too general, or many inaccuracies). Summary is not well organized or developed.
1	Summary is inadequate, and there are major flaws in explanations and organization. The information does not serve as a useful resource.
0	No summary is turned in on the deadline date.

TABLE 8. GRADING RUBRIC USED TO ASSESS CAPSTONE ORAL PRESENTATIONS

Grade	Assessment criteria
6	Superior presentation of research and results.
5	Goes beyond an adequate job. Presentation is excellent and well developed. Insightful and innovative information is presented. Presentation is highly effective in helping people understand the project and conclusions.
4	Meets requirements for assignment noted for grade 3. Presentation is innovative and effective and gives the audience a clear understanding of the research topic. The presentation is well organized and easy to follow, and it is well supported with figures or other visual aids.
3	An average, solid presentation. The subject material is presented, but does not go into much depth. Information is correct and informative. Main points are clear and instructive. The presentation is clearly developed and information is easily followed. There is a progressive development of the research project. Presentation attracts and engages the listener. All sources of data and supporting information that are not created by the student are clearly noted in the presentation or at the end of the presentation.
2	Presentation is poorly developed and does not guide audience to an understanding of the topic. Has limited effectiveness. No written summary is turned in.
1	Presentation is poorly developed and ineffective.
0	Did not create a presentation or was not in attendance on day presentation was to be given. If there is any evidence of plagiarism or gross disregard for the sources of information, grade of zero is assigned.

materials, and conducting field surveys and checks with students on weekends. Reviews and critiques of student research proposals were critical to ensure that students remained on track, but these activities also demanded a major commitment of faculty time and energy, especially in larger classes.

A field-research course can also be time consuming for the students. Instead of simply attending a fixed weekly laboratory session of about three hours, students must obtain and analyze whatever data are needed to answer their research questions. Some students became so interested in their projects that they spent as many as ten days in the field beyond those scheduled for the course. This sometimes caused conflict with other courses and job commitments. Travel to a field site can also take considerable time. For instance, Ship Rock is located 95 mi (154 km) from the campus, a three-hour roundtrip. Yet we received no negative comments from the students about too much work or too-long days. This may have been because students interested in fieldwork were preferentially attracted to this course.

Difficulty in thinking critically and problem solving were issues common to students in all of the offerings of the course. DiConti (2004) noted that undergraduate liberal arts institutions have generally not promoted experiential inquiry-based experiences in the curriculum. The general education requirements for undergraduate degrees at many institutions hold that basic scientific knowledge should be transferred to the students, but not necessarily by application. It should not be assumed that students entering a field-research class understand anything about scientific inquiry. Particularly during the initial stages of their projects, many of our students required considerable coaching to overcome an expectation of finding straightforward and concise answers typical of textbooks and verification laboratory exercises. However, such problems typically waned by the end of each course. Over time and through immersion in complex field settings, students became confident and comfortable with a continuous process of formulating, testing, and revising their hypotheses on the basis of data they collected. They had to engage in critical thinking and inquiry to have a successful project. On a postcourse evaluation, one student noted that this course gave "confidence to ask questions, write papers, and compile information." Another noted that conducting research in this course "gave me a guideline to follow, which makes research easier." Over time, students' questions about the quality of their data and the significance of their findings became more thoughtful and professional.

Open communication and sharing of ideas in peer-led collaborative activities can be complicated by personality conflicts, desire of students to work alone and not as a team member, lack of engagement in class discussions, failure of some team members to complete their fair share of the work, and a perception by high-achieving students that they are "carrying" their teammates (Shea, 1995; Apedoe, 2007). It is important for faculty to actively

TABLE 9. RESPONSES OF DEPARTMENTAL FACULTY TO A SURVEY OF IMPACTS OF THE FIELD-RESEARCH PETROLOGY COURSE ON STUDENT LEARNING, BEHAVIORS, AND ATTITUDES (INDIVIDUAL NUMERICAL FACULTY RATINGS ARE LISTED, AS WELL AS OVERALL MEANS AND RESULTS)

Overall objectives and criteria	Numerical ratings*					Mean ratings	Overall results	Additional responses
Enhance interest in geology and petrology								
Impact on enthusiasm for geology and petrology	5	5	5	3	4	4.4 ± 0.9	Somewhat better	Most of the students who take this elective class are motivated, but some of our better students have not been a part. The class has been successful in taking middle-of-the-road students and developing their excitement for geologic research. [Field-research course] students are much more enthused and excited by the notion of problem solving and research in geology. Students who completed field-research course acquired a passion and enthusiasm for their project that carried over into further research projects. Students were interested and excited about doing "research" in geology.
Preparation to conduct an authentic research project								
(1) Impact on professional development	5	5	4	3	NA	4.3 ± 1.0	Somewhat better	Improves the students' basic research skills by exposing them to journal articles, historical background, and data collection. I...think the field-based sessions will leave students with a more cohesive set of associations to retain knowledge that they will be able to apply to new problems. Most of the students who completed the courses were better prepared to tackle the complexities and challenges of research. More...research experience is generally a good thing. The greatest impact seems to be on students who are already strong, and who are ready to make the most of a research experience. Some students just don't have the background with their minimal petrology exposure to successfully work in this type of individual research environment. Some students struggled with the concept of research and did not develop the skills needed to tackle more complicated problems to the fullest extent. The students who took [field-research course] did not seem to gain much theoretical understanding of the subject. Students working on igneous rocks wrote research proposals that showed a lack of understanding of igneous geochemistry. Because students take [field-research course] early (junior or sophomore year), many have put off required math classes. Some students felt that the only significant research being done was related to field-research course. Some important advanced topics in petrology might not be covered in field-research course; mix some advanced petrology topics with research project. It might be good to alternate research-intensive [field-research course] with other upper-level courses in sedimentology, advanced structural geology, etc. As is typically the case, [field-research course students] will probably not have been exposed to the breadth they would have in a traditional approach.
(2) Impact on quality and success of senior theses	4	4	4	3	4	3.8 ± 0.4	Somewhat better	Continued work on a single topic during [field-research course] and then as a senior thesis topic strengthens their understanding...some students broaden their research through time. For some, the field-research course gave them a jump start on their senior thesis. Other students recognized that senior thesis projects were also an actual contribution to...geology.

(Continued)

TABLE 9. RESPONSES OF DEPARTMENTAL FACULTY TO A SURVEY OF IMPACTS OF THE FIELD-RESEARCH PETROLOGY COURSE ON STUDENT LEARNING, BEHAVIORS, AND ATTITUDES (INDIVIDUAL NUMERICAL FACULTY RATINGS ARE LISTED, AS WELL AS OVERALL MEANS AND RESULTS) *(Continued)*

Overall objectives and criteria	Numerical ratings*					Mean ratings	Overall results	Additional responses
(3) Impact on research opportunities beyond this college	3	5	4	3	NA	3.8 ± 1.0	Somewhat better	Interaction with professionals outside of the department [was beneficial]. Some students had an opportunity...to collaborate with other students and professional scientists.
<u>Enhance skills in scientific inquiry and critical thinking</u>								
(1) Impact on scientific research skills	4	4	4	3	4	3.8 ± 0.4	Somewhat better	Some students had an opportunity to learn new skills that otherwise they would not have.
(2) Impact on critical-thinking skills	4	4	4	3	4	3.8 ± 0.4	Somewhat better	*None*
<u>Apply petrologic and other geologic knowledge and skills in a field setting</u>								
(1) Impact on field skills	5	4	4	3	4	4.0 ± 0.7	Somewhat better	Field work always seems to bring out the best in students; i.e., they have a better understanding of geologic processes after observing field relationships. Also improves their performance in field camp; they start with strong field skills (map reading, compass skills, field notes, etc.). More field...experience is generally a good thing.
(2) Impact on interest in field studies and research	5	5	5	3	5	4.6 ± 0.9	Somewhat to much better	*None*
<u>Further development of skills in oral and written communication</u>								
Impact on communications skills	3	4	4	3	NA	3.5 ± 0.6	Little or no improvement	The majority of students had a better idea of how to write a report, cite resources, and present their results. The oral and written products, however, were not significantly advanced over students who did not take the course. The written and oral presentations were not of equal quality, with oral presentations tending to be better.... The change to a portfolio seemed to cure some of this problem, but better writing skills need to be expected or developed in a research class. From what I've observed, the writing skills and research preparation haven't been significantly different between the students who did and did not take the field-research course.

*1—much worse in most students; 2—somewhat worse in most students; 3—no improvement in any student; 4—somewhat better in most students; 5—much better in most students.

promote communication within and among student research teams in order to foster the teamwork skills that are required for most modern scientific research. Overall, in our course, the students worked well together in teams and developed a strong sense of community. Information sharing was typically full and prompt. On occasion, some students avoided communications or encounters with other students because of personality clashes. These problems were solved with instructor intervention.

Other challenges included weather, a major issue each year as with most field courses. At Ship Rock in winter 2003, wind-blown dust made it difficult to work on some days. In 2006, our field studies were interrupted by a major snowstorm in late September that left outcrops covered for several weeks. Students continued their field studies as best they could, but cold temperatures and lack of outcrop access posed a formidable challenge.

In 2007, weather was less of an issue since students did most of their field studies and sample collection over a four-day field trip. For this, however, we had to rent four-wheel drive vehicles rather than use college vans to get to the study areas. Students also had to spend exceptionally long (10–14 h) days in the field. However, as noted above, they did not complain and instead accepted the conditions as a learning experience.

Finally, class size is always a concern at a small institution. Research courses with small enrollments benefit from greater student-faculty interaction with faculty, but they may not be allowed by administrators. The 2007 research course was considered for cancellation because of its low enrollment. Lower enrollments also make it difficult to compile enough information for full and authentic assessment.

In order to develop meaningful models and interpretations for projects, the students had to integrate what they had learned from the interactive lectures and laboratory sessions held early in the course. For instance, students involved in mapping of rock units not only used class discussions as a starting point for unit designations and divisions, but 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. The use of a portfolio with staged deadlines for different sections in 2007 made it easier for faculty to formatively monitor student progress and provide advice on the structure and content as the project developed.

It was our perception that in all of the field-research petrology courses, the students evolved from a group of individuals into a team of collaborative learners and teachers. Although it is not possible to quantitatively assess which of the course formats was the most robust, we think that research projects linked by a well-defined theme (as at Ship Rock in 2003 and in the San Juan volcanic field in 2007) are the most effective for undergraduates. This format allows for greater communication amongst faculty and students, more time available for faculty to assist students, and a reduction in logistical issues.

CONCLUSIONS

The three different field-based, inquiry-driven formats described in this paper illustrate the flexibility and dynamics that this type of course and their impacts on undergraduate education. We illustrate an alternative that emphasizes direct engagement and student responsibility for learning: traits valuable in transforming undergraduates into experienced and competent professionals.

Field-inquiry courses imparted valuable scientific research skills, incited interest and enthusiasm for research in general, and petrology and regional geology specifically, promoted interest in certain topics in student peers beyond the course, and enhanced students' sense of place. The student-faculty research initiated in these courses continues to seed undergraduate interest in field research on geosciences topics and is making contributions to the broader scientific community. These courses are not without pitfalls, however, and they can be taxing for both faculty and students.

The most significant outcome of a research-based petrologic course is the opportunity afforded geoscience students to design, conduct, and present authentic research as a complement to their classroom learning. Such a course serves both academic and pre-professional purposes. After most conventional undergraduate courses, students are not compelled to reengage with learning outcomes until graduate studies or employment. The field-research petrology course encouraged students to continue to integrate scientific inquiry and field studies directly into their undergraduate studies. The field-intensive course that we designed and implemented fits the blueprint for undergraduate liberal arts education recommended by DiConti (2004), where course work is supplemented by intensive activities outside the class. This combination has the benefits of providing the required knowledge base of topics need for educational advancement, while at the same time providing opportunities to gain experience and insight into activities that are essential to career development and professional outreach (Carver, 1996).

ACKNOWLEDGMENTS

Fieldwork at Ship Rock was conducted with the permission of the Navajo Nation Minerals Department. We thank the faculty in the Department of Geosciences and the administration at Fort Lewis College for supporting our efforts. We also wish to express our deep appreciation to Dr. Doug Yager of the U.S. Geological Survey in Denver, Colorado, for the time, energy, and resources that he provided to the 2007 class. All of the Fort Lewis College geosciences students who participated in the three courses are recognized for their enthusiasm and contributions. Finally, we appreciate the insightful reviews of Allen Glazner and Chris Condit.

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Manuscript Accepted by the Society 5 May 2009

Printed in the USA