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Integrating hydrology and geophysics into a traditional geology field course: The use of advanced project options

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ABSTRACT

The incorporation of increasingly multidisciplinary aspects of geoscience curricula into a traditional geology field camp requires compromises. Among these, decisions about projects to reduce or eliminate and course prerequisites are two of the most challenging. Over the past 10 yr, the University of Missouri's geology field camp has completed a two-stage plan to expand our projects in hydrology and geophysics while maintaining traditional aspects of our course and our standard prerequisites. The first stage added projects in surface and groundwater hydrology, seismic refraction, and surficial mapping during the fifth week of our six-week course, replacing an existing mapping project. The second stage added advanced project options that students can select to complete during the last week of the course. Advanced projects in hydrology and geophysics were added as alternatives to the existing hard-rock structural analysis project that had been the sixth-week project for all students. This staged addition has allowed us to: (1) integrate these projects into a curriculum that maintains a strong emphasis on historical bedrock geology, geologic mapping, and three-dimensional visualization; and (2) accommodate differences in the coursework that students have completed prior to beginning the field camp. Rather than requiring students to have prerequisite courses in hydrogeology or geophysics in order to select these advanced project options, we include sufficient instruction during the fifth and sixth weeks that builds upon previous projects to provide the required background.

To set up the context for our expanded hydrology and geophysics projects, this paper briefly describes our traditional field projects and our instructional philosophies. We describe the expanded projects that have been implemented during the fifth and sixth weeks of our course, project objectives, and the ways that these projects

reinforce lessons learned during traditional field projects. We present the results of student surveys that have been used to evaluate the success of these efforts, and we discuss the personnel and equipment expenses required.

INTRODUCTION

Geology summer field camps give upper-division undergraduate geoscience students intensive instruction and field experience and integrate standard coursework into a field setting. Historically, this integration has involved geologic mapping and three-dimensional subsurface interpretations in a wide range of geologic terrains. However, today's geoscience curricula are more multidisciplinary, and many programs commonly incorporate hydrology, aqueous geochemistry, and geophysics. Although the majority of geology field camps continue to place strong emphasis on traditional field mapping, increasing numbers of field programs now offer projects in hydrology, geophysics, and environmental geology (e.g., McKay and Kammer, 1999; Baker, 2006), and some programs integrate various new technologies into these projects or the field mapping process (e.g., Knoop et al., 2007; Swanson and Bampton, this volume; Whitmeyer et al., this volume). Two of the principal challenges when adding such components are: (1) to achieve a balanced curriculum that provides sufficiently broad field instruction while integrating new topics and techniques, and (2) to accommodate differences in the coursework that students have completed prior to beginning the field camp. Some field camps accommodate the second challenge by specializing in hydrology, geophysics, or environmental geology—avoiding any pretense of a broad field curriculum—and requiring that students have the prerequisite courses in the specialty subject. However, we asked: how and to what degree can both of these challenges be met?

Over the past 10 yr, the University of Missouri has introduced a series of hydrology, aqueous geochemistry, and geophysics exercises into our six-week course in an effort to broaden our curriculum and overcome *both* of these challenges. Our course continues to emphasize traditional aspects of field geology and regional geology during the first four weeks. However, we have also developed instructional modules for the last two weeks that serve the interests and abilities of students that have little or no previous course work in hydrology and geophysics, as well as students who have previous background courses in these subjects and/or who have advanced interests in hydrology or geophysics.

The fifth week of the course includes instruction and projects in surface and groundwater hydrology, seismic refraction, stream terrace mapping, and hard-rock structural analysis. Although structural geology is a course prerequisite, courses in hydrogeology, geophysics, and geomorphology are not required. As a result, the instruction during the fifth week provides considerable fundamental background for the projects. During the sixth week of the course, we offer a series of advanced options: students have the choice of completing advanced projects in hard-rock structural analysis, seismic reflection, refraction, and

tomography studies, or groundwater and surface water hydrology. This paper describes our fifth and sixth week projects with emphasis on the hydrology and geophysics projects. To provide a course context for the addition of this new material, we describe our instructional philosophy, our basic course curriculum, and the ways in which we have integrated geophysics and hydrology into a traditional geology field course.

As a basis for general comparison with other field courses, our course operates from a permanent residential base camp that includes a laboratory where students complete their project reports, and computer facilities that include satellite broadband access. We accept a maximum of 40 students for our six-week course, which has prerequisites of structural geology, historical geology, sedimentology, and mineralogy. Typically, less than one third of the students are from our department, and the remainder of participants come from other departments across the country and the state of Missouri. All students pay the same fees. The students work 6 d per week. Faculty members generally rotate into the course for two-week periods to teach projects in their research specialties. Most field projects are completed at sites within a 45 min drive from the camp, but the curriculum also includes a 4 d instructional trip through Teton and Yellowstone National Parks, and adjacent areas of the Snake River Plain and Beartooth Mountains.

FIELD SETTING FOR OUR PROJECTS

The Branson Field Station is located in Sinks Canyon in the foothills of the Wind River Mountains near Lander, Wyoming, ~200 km southeast of Yellowstone National Park (Fig. 1). The immediate field areas provide a wide variety of rock units and deformation features that form the basis for our field instruction and projects. The rock section includes exposures ranging from Precambrian granite-greenstone belts through most of the Paleozoic (not including Silurian), Mesozoic, and Tertiary stratigraphic sections (Fig. 2).

The Wind River Mountains were deformed by basement-involved uplift during the Laramide orogeny (ca. 75–51 Ma in Wyoming), which exposed the Precambrian core of the range and tilted the overlying Paleozoic and Mesozoic strata to the northeast, dipping into the adjacent Wind River basin (e.g., Keefer, 1970). Our field station is located near the Precambrian-Paleozoic contact within the steep-walled Pleistocene glacial valley containing the Middle Fork of the Popo Agie River. Several doubly plunging, en echelon anticlines, which formed during the Laramide uplift of the range, occur along the southwestern margin of the Wind River basin within ~25 km of our camp. These anticlines fold Paleozoic and Mesozoic strata and trend subparallel to the northwest-southeast trend of the Wind River Mountains

Figure 1. (A) Geologic index map of the state of Wyoming showing the outline of the area containing the Wind River Mountains (after Roberts, 1989). (B) Geologic map of the Wind River Mountains and adjacent areas of the Wind River basin. (C) Map overlay of B showing the location of the major features discussed in the text.

Figure 2. Stratigraphic section exposed in the Wind River Mountains and adjacent parts of the Wind River basin. M—units that are included in major mapping projects; P—units that are studied during major sedimentation and stratigraphy projects; S—units that are examined in the field for their stratigraphic and regional historical significance. Pleistocene units not shown in the section were also included in a mapping exercise.

(e.g., Willis and Groshong, 1993). The folds range from 8 to 15 km long and contain numerous normal and reverse faults produced during the Laramide folding. Two of these folds, Dallas dome and Derby dome (Fig. 1C), have well-exposed faulted and folded Mesozoic sections, and serve as field sites for several of our stratigraphy, sedimentation, geologic mapping, and advanced geophysics projects. Exposures of deformed and metamorphosed rocks of the South Pass greenstone belt (cf. Figs. 1B and 1C) occur in the uplifted Precambrian core of the range, and these exposures provide field sites for our hard-rock projects in structural analysis and mapping of igneous and metamorphic rocks.

By the end of the Tertiary, the Wind River basin was filled with Tertiary sediment eroded from the adjacent uplifted mountain ranges and with interlayers of volcanic ash from the Eocene Absaroka volcanic field to the north-northwest of the basin (Fig. 1). The result was a landscape of relatively low relief (e.g., Mears, 1993). Subsequently, late Cenozoic regional uplift or regional climate change (cf. Epis and Chapin, 1975; Gregory and Chase, 1994; Riihimäki et al., 2007) resulted in exhumation of much of the Wind River basin by the Wind River and its tributary streams. This process produced the current relief between the basins and adjacent ranges and also exposed numerous angular unconformities between the relatively flat-lying Tertiary strata and the underlying Paleozoic and Mesozoic strata dipping off of the uplifted core of the Wind River Mountains. Our instruction and projects in sedimentology, stream terrace mapping, hydrology, and geophysics take advantage of these exposed relationships and/or the associated stream systems.

Although our project settings are primarily geologic, we also take advantage of our location near the towns of Lander and Riverton, Wyoming, and nearby mining operations in Fremont County to help our students appreciate the societal implications of field geology. For instance, our groundwater and geophysics projects have examined the relationship of municipal water quality and waste disposal to the local geology. Students also learn how field geologists working for the Wyoming Department of Environmental Quality in Lander oversee mine reclamation in abandoned iron and gold mines in the area.

INSTRUCTIONAL PHILOSOPHY

Geoscience students have a fairly broad spectrum of geology field courses from which to choose. These range from courses that concentrate primarily on traditional field mapping, to specialty courses in hydrology, geophysics, or environmental geology, and courses that broadly integrate field computers and geographic information system (GIS) technologies into the mapping process. Our basic course philosophy has been to give students a broad diversity of field problem-solving experiences while still providing thorough training in field geologic mapping. We have continued this philosophy with the addition of our advanced course options by working to integrate mapping and subsurface interpretation techniques into the more instrumented data gathering and analysis that are associated with the advanced projects.

Beyond this general philosophy, we have developed our own philosophies about field and laboratory instruction, field mapping, and technology integration.

Field and Laboratory Instruction

Our primary instructional goal is to teach field-oriented problem solving that reinforces critical work skills. We emphasize five-dimensional problem solving—understanding the three physical dimensions of geological features, the way these features have developed with time, and the processes responsible for the observed features over time. We emphasize this approach in all of our projects, and students are asked to address each dimension in their project reports. The general work skills that we promote include cooperative group work, effective time management, report writing skills, and dealing with uncertainty by considering interpretations with incomplete data.

All of our projects are conducted in groups that usually include three students. Groups change with each project to allow students to work with other students of varying interests, expertise, and abilities. This approach promotes cooperative learning among the students, provides for field safety, and allows us to group students with different academic and physical strengths. As in any work situation, group dynamics and abilities will vary, but we do find that collaborative learning increases students' involvement in the learning process. When students share and discuss their ideas, their thinking about the projects is enhanced and their understanding deepens. Group projects make up 50% of the students grade, and three individual exams make up the remaining 50%. The diversity of students within a group may lead to uneven work efforts (reflecting a real-world work environment), but the grading system rewards those who are the active learners.

Most of our projects include full field days (6 d/wk) combined with evening data analysis or report writing in a laboratory setting using group laptop computers for project completion. Longer projects may include an entire day in the laboratory preparing reports. Strict time constraints for project completion require that the groups develop effective group time management.

Geologists, probably more than other scientists and engineers, are commonly called upon to make interpretations based on incomplete data. This is particularly true in the development of structural cross sections and three-dimensional (3-D) interpretations of the subsurface from geologic maps (e.g., Groshong, 2006), but it is also common in hydrologic and geophysical interpretations. We discuss techniques for making subsurface interpretations and cross sections from geologic maps, and instructors work individually with student groups to help them understand the process of making reasoned interpretations when faced with limited data.

Part of our instructional philosophy includes hiring instructors to teach projects in their areas of specialization. For the 40 students that we instruct during our course, we typically hire a cadre of eight to ten faculty members and three teaching assistants. Faculty members and teaching assistants come from a

variety of institutions; generally less than half of the instructors are from the University of Missouri faculty. Most of the faculty members teach over two-week periods. Generally, at least five instructors (faculty and teaching assistants) are in the field with student groups during the projects. The project areas are well-exposed exemplary areas for the problems addressed, and they are well-known to the instructors. We promote instructor-student interactions in the field and prompt feedback to students upon completion of the projects. Lectures to set up and provide background for the projects are presented in our laboratory just prior to the projects. Lecture materials are made available to students as handouts that can be stored in their course binders, and they are also available for review on the desktop computers in our field camp laboratory.

Field Mapping

Traditional field geologic mapping continues to be a prominent component of our field course. Our students use paper topographic maps and registered paper orthophotos as base maps. The mapped areas are well exposed and allow students to draw map-unit contacts on the topographic maps as contacts are viewed either from a distance or along traverses. Each project group also has a handheld global positioning system (GPS) receiver to record UTM coordinates of specific station locations or to reinforce location decisions, but we strongly emphasize the reading of topographic maps, the use of the Brunton compass, and the integration of orthophotos as the primary mapping tools. We believe that this is the best approach to help students develop the three-dimensional perspective that is so critical to geologists, geophysicists, and hydrogeologists. We emphasize that the geologic map is an interpretation of field data and observations, and it serves as the basis for subsurface interpretations and “five-dimensional” hypothesis testing.

Integrating Technology

We have embraced the use of various technologies to enhance our data collection, analysis, and report writing for various projects. Each project group has a notebook computer available for compilation and analysis of field data in the laboratory. Programs available on these computers and several desktop computers in our laboratory include commonly available software such as spreadsheet, word-processing, and photo editor programs. We have satellite broadband access and a local wireless network that allows students to download remote data sets and print to networked printers. We also use project-specific equipment and several specialty programs in our advanced geophysics, hydrology, and structural analysis projects.

Nevertheless, we have not attempted to integrate technologies for recording general project notes or data in the field (e.g., using tablet or handheld computers), or for the field mapping or the map preparation process. The principal factor that influenced this decision is the time required to instruct students in

the effective use of these technologies and associated software. Although most students are already familiar with laptop computers and the commonly available software noted here, at this point, few students come to field camp already familiar with GIS or map preparation software, or with the hardware and software used for real-time computer-assisted field mapping. Relative to our general objective of exposing students to as many different types of relevant *field* experiences as possible, we have decided that taking time to instruct students in the use of such rapidly evolving technologies is not a priority at this point. Students who consider exposure to these technologies as an educational priority have several field camp options that provide this experience (e.g., Knoop et al., 2007; Swanson and Bampton, this volume; Whitmeyer et al., this volume).

TRADITIONAL COURSE CURRICULUM— WEEKS ONE THROUGH FOUR

The first four weeks of our course (Table 1) include a series of instructional sessions and field projects that: (1) review basic field methods and introduce students to the Mesozoic and Paleozoic sections, (2) provide projects that help students understand the sedimentation histories and processes that produced the sedimentary sections, (3) teach students how to map folded and faulted sedimentary rocks, and (4) include field mapping projects in the deformed Mesozoic section (Fig. 2). Following the mapping projects, the students receive a day of field review and feedback in the area of the last mapping project, and, finally, all students complete an individual 1 d field mapping exam.

All of our projects are discussed in a regional geologic context. To set up this context, faculty members present a series of evening lectures on: the regional geology and geologic history of Wyoming, deformation styles during the Laramide and Sevier orogenies, the geologic history of northwestern Wyoming, tectonic history of the Snake River Plain and Yellowstone hotspot, and the Pleistocene glacial history of northwestern Wyoming. The culmination of the lecture series is a 4 d instructional tour of the geology of Teton and Yellowstone National Parks and adjacent areas of the Snake River Plain and Beartooth Mountains, which follows shortly after the field mapping exam.

WEEK FIVE INSTRUCTIONS AND PROJECTS

Philosophy and Logistics

Our fifth week of instruction begins shortly after students return from their 4 d trip through northwestern Wyoming and adjacent areas. The general objective during this week is to instruct the students in a broad range of projects in areas that are not covered by our basic prerequisite courses. During this week, we place particular emphasis on hydrology and geophysics to help the students understand water-related environmental problems and their relationship to the surface and subsurface geology of the area (Table 2). We emphasize the five-dimensional

TABLE 1. SUMMARY OF THE TRADITIONAL FIELD CAMP PROJECTS AND INSTRUCTION INCLUDED DURING THE FIRST FOUR WEEKS OF THE COURSE

	Projects	Objectives	Units/features/location
Week 1	Pace and compass methods	Become familiar with field methods	All Paleozoic and Mesozoic units
	Section reconnaissance	Learn stratigraphic sections	
	Sedimentary structures	Recognize/interpret structures	Mesa Verde Formation
	Sedimentary facies	Interpret sedimentary facies	Mesa Verde Formation
Week 2	Tertiary unconformity	Observe Tertiary sedimentary facies and their tectonic implications	Tertiary units and unconformity
	Section measurement	Learn to measure and describe sedimentary units, draw section	Sundance & Gypsum Springs
	Paleocurrent analysis	Learn paleocurrent techniques	Derby and Dallas domes
	Mapping folded and faulted sedimentary rocks	Mapping instruction/techniques	Nugget Sandstone
	Map evaluation		Dallas Dome–Mesozoic units
		Individual group evaluations	Camp laboratory
Week 3	Mapping folded and faulted sedimentary rocks	Learn from the mapping experience, produce maps and cross sections	Derby Dome–Mesozoic units
	Review of the map area	Participate in half-day field review of the area just mapped	Derby Dome–Mesozoic units
Week 4	Field exam	Individual test of mapping skills	Previously unseen area
	Mine reclamation tour	Learn how geologists oversee the mine reclamation process	Atlantic City Mine
	Wyoming geotour (4 d)	Show and discuss features of the geologic history of northwestern Wyoming and adjacent areas	Teton, Yellowstone Parks, Snake River Plain, Beartooth Mtns, Absaroka Mtns

approach that we used during the previous course projects and that continues to provide students with a mental framework to relate hydrologic and geophysical interpretations to surface and subsurface geological environments (Siegel, 2002). We strive to underscore the association between subsurface geometries and 3-D hydrologic systems through field exercises that are organized around the core concept of 3-D visualization the students learn from field mapping.

The projects during the fifth week each include a day in the field studying: surface water hydrology, groundwater hydrology, seismic refraction, stream terrace mapping, and structural analysis in igneous and metamorphic rocks. The first four projects are completed over a 4 d field period on property owned by The Nature Conservancy in the picturesque Red Canyon (RC) area (Fig. 3, located on Figs. 1C and 4). The setting lies along the Paleozoic-Mesozoic boundary between the upper Phosphoria Formation (Permian) and the lower Red Peak Formation of the Chugwater Group (Triassic). The location includes the confluence of two streams, Red Canyon Creek and Cherry Creek (Fig. 4), and includes a series of Pleistocene glaciofluvial terraces. Each of the Red Canyon area projects is run by a faculty member, and all of the projects are conducted on each of the four field days. The student groups (of three students each) are combined into four “supergroups” made up of three or four of the student groups. Each supergroup is assigned to one of the four Red Canyon projects on a given day, and each supergroup receives a morning lecture and instruction prior to traveling to the field site to collect data and make observations for the projects. The hydrology and geophysics project reports are due by 10:00 p.m. on the day of their assignment. All groups have a full day at the

end of the 4 d project period in which to prepare their maps and reports for the terrace mapping project. The structural analysis project is completed by all of the student groups on the last day of the project week at a location in the Precambrian South Pass greenstone belt (Fig. 1C) and is due by 10:00 p.m. on the day of the assignment.

The hydrology, geophysics, and surficial mapping projects that are now covered during the fifth week replaced an extensive mapping project in the Paleozoic section and a more extensive hard-rock mapping and structural analysis project than we now include during week five (Table 2). Since the new materials developed for this week are primarily associated with the hydrology and geophysics projects, the following sections concentrate on these subjects.

Hydrology Projects

The hydrology exercises emphasize fundamental field and instrumental skills, data collection, and data interpretation that are common to a wide range of hydrologic and geochemical studies in a 3-D setting (Siegel, 2008). Red Canyon creek flows through a spectacular valley along the contact between a thick sequence of Paleozoic and Mesozoic sedimentary rocks that dip off of the uplifted core of the Wind River Mountains (Figs. 3 and 4). The climate is semiarid, which is typical of western Wyoming. Most precipitation occurs during the winter, and snow-melt provides most of the water to rivers in the region. The field site is located on The Nature Conservancy property where Red Canyon Creek meanders through a series of stepped dams that are separated by narrow downcut channels. The water from the

TABLE 2. SUMMARY OF THE NEW FIFTH AND SIXTH WEEK PROJECTS AND THE PROJECTS THAT THEY REPLACED

	Projects (old vs. new)	Objectives	Units/features/location
Week 5 (old)	Mapping folded and faulted sedimentary rocks	Provide more mapping experience Exposure to mapping different rock units and different fault and fold geometries	Paleozoic section that includes different faulting and folding mechanisms than the previous map areas—Sheep Mountain
	Analysis of deformation fabrics in igneous and metamorphic rocks	Learn to map igneous and metamorphic rocks, record and analyze deformation fabrics	Folded Precambrian gneiss and schist with variable deformation fabrics—Sheep Mountain
Week 5 (new)	Surface-water hydrology Groundwater hydrology	Expose students to a broad range of surface-water and groundwater monitoring techniques to illustrate surface-groundwater interactions	Floodplain of Red Canyon Creek reworking the lower part of the Triassic Chugwater Group
	Shallow seismic refraction	Introduce shallow seismic techniques and their relationship to local stratigraphy and groundwater	(Same location as above)
	Stream terrace mapping	Introduce surficial mapping techniques	Red Canyon glaciofluvial terraces
	Analysis of deformation fabrics in igneous and metamorphic rocks	Learn to record and analyze deformation fabrics produced during folding and boudinage	Folded schist and boudinaged granitic layers in the roof area of a granite pluton—South Pass greenstone belt
Week 6 (old)	Mapping and structural analysis of folded and faulted schist intruded by granite and mafic dikes	Learn to map igneous and metamorphic rocks and large-scale folding without stratigraphy. Record and analyze deformation fabrics as an aid to regional deformation geometries and deformation–metamorphism history	South Pass greenstone belt Precambrian amphibolite-facies schist intruded by two igneous units and mafic dikes
Week 6 (new)	Option 1. Same as the old sixth week project	Same as the old sixth week project	Same as the old sixth week project
	Option 2. Advanced hydrology	Expose students to a variety of “real-world” hydrology problems (examples described in the text)	Varies depending on opportunities in a given year (example locations described in the text)
	Option 3. Advanced geophysics	Expose students to a variety of “real-world” seismic problems (examples described in the text)	Varies depending on opportunities in a given year (example locations described in the text)

creek mixes with groundwater, leading to biogeochemical reactions and mixing relationships down the hydraulic gradient either in the creek or in the subsurface adjacent to the creek. Different segments of the creek both receive and lose water to the water table (Lautz and Siegel, 2006). The Nature Conservancy is interested in determining whether complex hydraulics associated with meanders and dams effectively add moisture to the unsaturated soils of the prairie and thereby increase biodiversity. Our field projects focus on this local interface between surface water and groundwater, the hyporheic zone, allowing us to easily expose our students to both surface and groundwater techniques. In a broader sense, the hyporheic zone is widely considered to be the richest and most accessible hydrogeologic setting for multidisciplinary 3-D field investigations (Triska et al., 1993; Winter et al., 1998; Jones et al., 2000).

We began our integrated hydrologic and geophysical studies in 1999 (Bauer et al., 2003). Subsequently, we have incrementally installed 35 shallow wells using a Geoprobe® and have added other small amounts of instrumentation, including several in-stream mini-piezometers and a Parshall flume, to progres-

sively expand our project area (Fig. 4). The projects that we have developed are designed to give students a broad understanding of surface water–groundwater interactions in arid mountain environments, and they are often linked to large-scale research projects (Lautz et al., 2006; Lautz and Siegel, 2006; Lautz and Siegel, 2007; Fanelli and Lautz, 2008; Lautz and Fanelli, 2008). The three days of surface water, groundwater, and geophysics projects include: water-table mapping, water-quality sampling, shallow seismic-refraction imaging, single-aquifer testing techniques and data analysis, stream gauging, and tracer tests. We are able to logistically compress these experiences within a short time frame because the diversity of stream-groundwater interaction at our site occurs over a relatively restricted area.

Students measure water level elevations in the 35 monitoring wells and mini-piezometers installed in an ~2-acre meadow adjacent to a meander of Red Canyon Creek. From these water levels, students construct a water-table map, focusing on the way that contours change as they cross the creek under different groundwater–surface-water settings, which change from year to year. Students use water-height differences between the stream and

Figure 3. Red Canyon viewed to the northwest from Wyoming Highway 28 overlook showing the location of the Red Canyon project areas in the distance and Red Canyon creek in the foreground. The rock units shown are dipping to northeast (to the right) into the Wind River basin off of the uplifted Precambrian core of the range. The flat-lying mesa above the project area is capped by Tertiary sediment, illustrating the angular unconformity described in the text. The distance from the location of the photographer to the study area is ~9 km.

Figure 4. (A) Bedrock geologic map of the Red Canyon area showing the location of the Red Canyon project site near the intersection of Red Canyon Creek and Cherry Creek. The "X" on the southeast side of the bedrock map is the location from which Figure 3 was photographed, facing northwest. This point is located at 42°36'13"N, 108°35'52"W. (B) Map of the Red Canyon field site showing the distribution of wells and instrumentation on The Nature Conservancy (TNC) property. Fm—Formation; Ls—Limestone; SS—Sandstone.

inside the mini-piezometers in the streambed (i.e., the hydraulic gradient) to identify segments of gain and loss along the creek.

Students measure discharge along Red Canyon Creek using multiple methods, including stage-discharge relationships around flow-control structures, velocity-area methods of varying complexity, and dilution gauging. By using multiple methods, students learn several techniques commonly used in professional settings, get exposure to a variety of field equipment, and engage in discussion of precision and accuracy of various methods. In 2005, we installed a Parshall flume at the site to measure water height and stream discharge year-round (Fig. 5). Flumes and other similar structures, including weirs, have prescribed rating curves that describe the relationship between water height and discharge. Using these rating curves, student measurements of water height are easily converted to stream discharge in a manner similar to that used by the U.S. Geological Survey (USGS) at gauging sites across the country. Students then compare the stream flow rate derived from the flume to values derived from current meter measurements and dilution gauging. For the current meter measurements, we use a Marsh-McBirney Flo-Mate 2000, which is a top-of-the-line meter that relies on

electromagnetics for velocity measurements. For dilution gauging, we purchased an Opti-Sciences GFL-1 Flow-through Field Fluorometer to continuously measure the concentration of Rhodamine WT, a fluorescent surface-water tracer, in the stream during tracer tests. The students are exposed to cutting-edge technology and get experience programming, using, and extracting data from these instruments.

Students measure hydraulic conductivity from slug tests in the wells, and they use their results, along with hydraulic gradients they measure from their water-table maps, to calculate groundwater discharge (Q) and velocity (v) using Darcy's law, both horizontally across the stream and vertically up or down through the streambed (from the mini-piezometer data). We address the water-chemistry aspects in both groundwater and surface water by using chemical analysis ampoule kits (Chemetrics). The students measure dissolved oxygen and iron in the field and alkalinity and total and calcium hardness in the laboratory later. They also measure field pH and specific conductance in the field using WTW 340i multiparameter probes.

All of these chemical parameters are then used to determine major water-rock interactions through bivariate plots (e.g., based on mass action equation stoichiometry), coupled with reasonable assumptions about the remaining solutes in the waters. The systems we investigate have low concentrations of Na and Cl, for example, and these can either be neglected as a first approximation for much of the analysis, or they can be calculated by charge balance difference from the concentrations of cations and anions we measure. We particularly focus on the way in which organic matter in streambeds and/or groundwater changes the oxidation-reduction potential of water and how this changes water chemistry (Siegel, 2008). We use bivariate plots to distinguish gypsum dissolution from calcite dissolution.

Geophysics Project

Students complete their shallow seismic-refraction exercise on the floodplain of Red Canyon Creek adjacent to the hydrology project areas. The broader instructional objective of this exercise is to give all of the students, especially to those who have not had a geophysics course, a basic background in seismic waves and how they can be used to image Earth's interior (even the shallow subsurface). The local objective is to determine whether seismic-refraction techniques can be used to image the shallow floodplain strata or the groundwater table.

The seismic data are collected using a 32-channel Geode Seismic Data Acquisitions system with a sledgehammer as the source. The students are required to design their own seismic profile that will be able to image relatively shallow seismic boundaries (1.5–2 m deep) beneath the floodplain. The students deploy 32 geophones and collect the data entirely themselves. After collecting the data, the students determine the number of layers that the data support using an interactive computer program on laptop computers to determine the traveltime of the first arriving P waves. The students then calculate the velocities

Figure 5. Students measuring stream discharge using the float method (one type of velocity-area measurement), just downstream of Parshall flume.

and layer thicknesses for each of the layers in their model using simple ray theory calculations. This technique is presented during the project's introductory lecture, and the students make this determination without the use of computer software, allowing them to develop a better understanding of principles of seismic wave propagation.

After formulating a simple one-dimensional seismic velocity model that best fits the data, the students are required to interpret their velocity model. Because the students are conducting their seismic experiment at the same field site as the ongoing hydrology projects, they can use their measurements of groundwater depth to interpret their seismic velocity models. The water table generally causes the largest velocity change at this site, so the students are typically able to see how the shallow geophysical measurements can be integrated with the hydrology projects that they are also completing.

Terrace Mapping

The glaciofluvial terraces in Red Canyon, adjacent to the hydrology and geophysics project sites, provide the setting for a surficial mapping project that introduces students to basic aspects of stream geomorphology, to concepts of stream equilibrium and terrace formation, and to concepts of relative age determination in surficial deposits. The project is set up in a consultant-client context in which The Nature Conservancy (the property owner) needs information about the relationship of the local alluvial history to glacial episodes in the alpine headwaters to the west of their Red Canyon Ranch. In order to expand their irrigation system, The Nature Conservancy is particularly interested in identifying and correlating stream terrace deposits across the area. To address these needs, each student field group: (1) identifies and maps the Pleistocene and Holocene stream terraces and modern floodplains associated with the local streams (Cherry Creek, Red Canyon Creek, and Barrett Creek; Fig. 4), (2) describes the lithologies of the terraces, and (3) gathers data on the relative ages of the terraces. The final report, which is completed during a day in the laboratory, includes a map of the terraces, lithologic descriptions, a cross section across the mapped area, and a report discussing a series of questions about the terrace formation history and processes responsible for the terrace development.

Structural Analysis Projects

The Archean rocks of the South Pass greenstone belt were the site of a gold rush near South Pass City beginning in 1867, and gold was mined intermittently at the Carissa Mine into the late 1940s. The day-long structural analysis study involves two projects in lower-amphibolite-facies metamorphic country rocks and local plutonic igneous rocks that are located near the abandoned Carissa Mine. The students are asked to determine fold geometries and finite elongation orientations that may have locally concentrated gold-bearing veins in the area. The two projects are designed to instruct the students in field data gather-

ing and plotting techniques to evaluate: (1) fold geometries, and (2) principal strain orientations using small-scale deformation features and rock fabrics. The project area includes highly folded metagraywacke in the roof area of a peraluminous granite pluton. Data collected for the fold geometry project include the orientations of folded bedding, fold hinge lines, axial plane foliations, and lineations that are all plotted manually on stereographic projections to determine the 3-D fold geometries. Data collected for the principal strain project include the orientations of boudin necks in peraluminous granite veins and a strong foliation that both occur parallel to the pluton-country-rock contact in the roof area. Student groups plot the data manually on stereographic projections using techniques described during a general lecture for the project the evening prior to the field study. The completed projects are due the evening of the field day.

The projects reinforce the 3-D perspectives that we emphasize throughout the course and also prepare the students who elect to complete the hard-rock mapping and structural analysis project during the sixth project week.

WEEK SIX ADVANCED PROJECTS

Philosophy and Logistics

We began offering advanced project options during the sixth week of our course during the summer of 2005. This change in our curriculum was made possible through a National Science Foundation grant that allowed us to purchase the equipment required for our advanced projects in hydrology and geophysics. Prior to 2005, the entire sixth week was dedicated to studying deformed igneous and metamorphic rocks (Table 2) and included a simpler version of the hard-rock structural analysis and mapping project that has now become one of our sixth week project options.

With the completion of our fifth-week projects, students have received sufficient instruction and experience in hydrology, geophysics, and structural analysis in metamorphic and plutonic igneous rocks to select and complete advanced projects in any one of these three areas. The principal objective of the sixth-week projects is to allow students to pursue advanced topics in areas that they find most interesting and/or are most consistent with their employment objectives. Many of our students come to our course because of our advanced projects and are already prepared with previous courses in hydrogeology or geophysics or have advanced interests in structural geology. However, some students are not certain which advanced project area they will choose until after completion of the fifth week's projects, at which point, all students are required to select an advanced project. Over the 4 yr period that we have offered our advanced projects option (2005 through 2008), 25% of the students have chosen the geophysics option, 30% have chosen the structural analysis option, and 45% have chosen the hydrology option. This relative division of the students among the three project options has worked well, but we are somewhat constrained logistically by our transportation capacity. We use 15-passenger vans with a maximum of

10 occupants per van, and each of the advanced project groups must have independent transportation to their various project sites. Field instrumentation and laboratory computing capacity for completion of the projects have not been an issue, and to date, we have been able to honor all students' project preferences.

Faculty members in charge provide both laboratory and initial field instruction for each of the advanced projects to make sure that all students have the basic background required to complete the project. In addition to advanced subject matter, these projects also have a greater integration of technology. This is particularly true for the geophysics and hydrology projects, which require instrumentation for data acquisition and computer programs for data reduction and analysis, but the students completing the structural analysis project also use laptop computers and fabric analysis software for their data reduction, plotting, and analyses.

Upon completion of the sixth-week projects, all students complete an individual final field exam over the material covered during their final project week. These exams make up 16.6% (one-sixth) of the student's grade (equal to the first field exam and a regional geology exam).

Advanced Hydrology Projects

The sixth-week hydrologic projects vary from year to year depending on circumstances and opportunities that avail themselves. The general objective of these projects is to give our students "real world" problems, often with insufficient data to clearly answer the questions asked. Many of the projects can only be solved by approximation, which is the case in many hydrologic settings in practice. In some cases, the geophysics and hydrology portions of the camp have addressed common problems, but again, we vary each year's experience somewhat. Despite project and/or site changes from year to year, the same pedagogical and scientific approaches that we use during our more traditional stratigraphic, lithologic, and structural mapping exercises (e.g., our five-dimensional geology approach), are readily integrated into the critical thinking and learning experiences provided by our advanced projects.

We have developed several hydrology projects for the sixth week that: (1) teach both data collection and problem-solving skills, and (2) create ongoing discovery by building upon data sets collected during previous camp sessions. Most of the projects involve dynamic geologic systems that allow students to learn from the changes in the systems from year to year in addition to their own data collection and analysis. During the past 4 yr, the students have completed the following projects, several of which are described briefly here: (1) characterizing source waters for Dry Lake, (2) determining the viability of the Lander landfill, (3) siting a landfill near Riverton, Wyoming—the Sand Draw case study, (4) tracing water in the karst system of the Popo Agie River, (5) evaluating the hydrogeology of the Branson Field Camp site, (6) evaluating the hydrology of Cherry Creek meadow, and (7) evaluating variations in the surface-water quality in the Popo Agie River watershed.

The pedagogical format for these projects involves faculty presenting the problem in ~30 min at the beginning of each day, and then the students work in the field in small teams until mid-afternoon, after which they complete their analysis and written reports by 10 p.m. of the same day. We have students prepare reports in different formats including: two-page letter reports to clients, abstracts in Geological Society of American (GSA) format, and small engineering-style reports. We insist that all reports be typed and prepared professionally and the students usually rise to the challenge. We have also had noncamp lay personnel review reports. For example, the Waste Management Supervisor for Fremont County recently reviewed student reports for clarity from a lay person's standpoint. Having nonfaculty reviewing reports adds a real-world dimension to the work that captures the students' attention. We have also had students submit their GSA abstracts for the annual meeting and attend the conference for presentation of that abstract (e.g., Baum et al., 2006).

Dry Lake Project

Dry Lake (Fig. 6) is located just south of the southern tip of Dallas dome (Fig. 1C) in a valley with sparse surface water other than irrigation drainage ditches. Areas immediately adjacent to the lake include wetlands that attract numerous waterfowl. The lake reportedly creates "quicksand" mud boils on its bottom, which may be discharge zones that sustain the lake, even during drought. A syncline along the southwestern margin of Dallas dome passes through Dry Lake and has a very steep NE limb and a shallowly dipping SW limb that parallels the dip slope coming off of the Wind River Mountains (Fig. 6). The hinge area of the fold is likely to be highly fractured, so it has been hypothesized that the lake receives groundwater flow through this fracture system that is recharged up the rock dip slope to the southwest, where the regional groundwater flow system is replenished. To test this hypothesis, the students prepare a water balance for the lake, based on map data on evaporation and precipitation coupled to measurements of water loss from agricultural ditches that border the lake and to measurements of specific conductance of water in the lake. What they find is that the lake is completely supported by irrigation water, and that ground water is a negligible part of the water budget.

Lander Landfill

The Lander landfill, located just east of Lander, is a source of local controversy. Landfills are ubiquitous sources of potential groundwater and surface-water contamination, but do they all leak? If so, how significant is the leakage with respect to public health, safety, and welfare? For this project, we have students divide into groups and prepare brief summary reports to the Wyoming Department of Environmental Quality on behalf of either: Fremont County, the landfill owner, or "Citizens for an Improved Environment," an advocacy group that wishes to have the landfill closed.

In this report, the students give their professional opinion whether leachate contaminates a small stream adjacent to the landfill in a meaningful way. The county would like to see the

Figure 6. Map of the Dry Lake area along the southern margin of Dallas dome. Topography in the western part of the map is due to the Mesozoic dip slope dipping to the northeast into the Wind River basin. The syncline axial trace through Dry Lake marks the change from this dip slope to the steep southwest limb of Dallas dome. Irrigation ditches flow along the margin of the dip slope into the valley containing Dry Lake.

landfill used for another 30 yr. The citizens want it shut down. The point of this exercise is to understand how the same hydrogeologic and geochemical data can be used to argue toward different aims. Students must stick to *plausible* science, and be careful not to stretch their interpretations too far. The project can be easily related to projects that the students completed during the first part of the course (weeks 2 and 3) because the landfill was placed, unlined, in the exhumed axis of a dome (Fig. 7), similar to Dallas and Derby domes. The students map the Mesozoic rock units that are deformed by the dome, and they are given water-level elevations and water chemistry from monitoring wells installed at the landfill. They prepare a hydrogeologic cross section oriented normal to the axial trace of the dome and through the landfill cells; the section must include their mapped rock units, equipotential lines, and a few flow lines to document the direction of groundwater flow. These lines are prepared based on the water-table map that the students construct from monitoring well data and their interpretation of the vertical directions of groundwater flow with respect to their mapped rock units. These data and interpretations are the basis for their conclusions in the environmental risk report that they complete.

Popo Agie River Dye Tracing Test

The Branson Field Camp is located less than 2 km from Sinks Canyon State Park, next to the raging Middle Fork of the

Figure 7. Air photo of the Lander landfill area showing the axial trace of the breached anticline, the location of monitoring wells (white dots), and the landfill. The center of the landfill is located at 42°50'43"N, 108°41'4.5"W.

Popo Agie River. This steep, alpine river flows at a discharge rate of up to 500 cfs (cubic feet per second) during spring snow-melt over large boulders and glacial erratics that cover the valley floor. Within the state park, the river goes underground into a cave system at the “Sinks.” The cave system is a dissolution feature in the Madison Limestone, and ~400 m downstream from the Sinks, the river resurfaces through a series of springs at the “Rise” (Wilson and Rankl, 1996). There is a long-term U.S. Geological Survey (USGS) gauging station about a kilometer downstream from the Rise.

In August 1983, the USGS completed a dye test through the Sinks Canyon cave system using a fluorescent dye, Rhodamine WT, to establish the hydrologic connection between the Sinks and the Rise (Wilson and Rankl, 1996). They found that the fluorescent dye did appear at the Rise, but it took 2 h for the leading edge of the dye pulse to appear at the Rise and over 6 h for the complete dye pulse to pass through the system. The long traveltimes indicate a complex system of tortuous flow paths through the cave and/or a series of large pools in the system that temporarily store water, increasing residence time (Wilson and Rankl, 1996). The USGS also observed an increase in water temperature and flow rate through the cave, suggesting additional sources of water.

For this project, the students repeat the USGS dye tracing test, in conjunction with stream flow measurements up and downstream of the cave and a synoptic sampling of the longitudinal geochemical gradient through the Popo Agie River valley. Details on the first dye tracing experiment at the camp can be found in Lautz et al. (2007). Students inject ~100 g of Rhodamine WT dye (depending on streamflow conditions) into the Popo River just upstream from the Sinks. They monitor the dye concentrations in real-time using the GFL-1 Flow-through Field Fluorometer (Opti-Sciences) (Fig. 8) that they learned to use during the previous week of instruction (fifth-week project). The collected data are

downloaded to a spreadsheet program for analysis. During the dye test, students measure the flow rate upstream of the Sinks using a the Marsh-McBirney Flo-Mate 2000 current meter and measure the stream flow rate downstream of the Rise from the gauging station, which is available online via our internet link. Based on the streamflow rates and the residence time of the test, the students derive the storage volume of the cave. Differences in the discharge rates up and downstream of the cave are used to determine if there is additional water coming out at the Rise. Finally, the students generate a longitudinal profile of specific conductance and the temperature of the river water throughout the canyon to assess the impact of the cave system and the additional sources of water (if any) on the geochemistry of Popo Agie River.

The final product of this project is an abstract prepared by each student group for the annual GSA meeting, with supporting materials. GSA abstracts include an introduction to the project, the methods used, the results, and a discussion of the conclusions of the study (similar to a full-length journal article). The students are asked to address unanswered questions about the system, which include: (1) the residence time and storage capacity of the cave under the current flow conditions (early July), (2) whether additional sources of water contribute to the outflow at the Rise, and (3) given the characteristics of the cave system, the way in which water flow through the cave impacts the geochemistry of the Popo Agie River. The abstract is limited to 300 words and must include one supporting figure. The students actually submitted a composite abstract to GSA for the 2006 annual meeting and presented a poster on their work.

Advanced Geophysics Projects

In order to give the students the broadest possible experience in active source seismology, we arrange the week-long advanced geophysics experiments into two separate projects, one project designed for refraction processing (i.e., time term analysis and refraction tomography) and the other designed for reflection data processing (muting, filtering, and normal move-out corrections). During both of our projects, students learn how to design an appropriate data acquisition schema for a particular target depth, and how to determine whether refraction or reflection data analysis is most appropriate for a given problem. For each project, the students work in two-person groups, and individuals from each group are assigned jobs as part of the seismic acquisition crew. Each project involves one day in the field collecting data and a corresponding day in the laboratory processing the data. From year to year, specific project locations and objectives vary depending on circumstances and opportunities that are available to us.

To help the students understand the application of seismic techniques to real field problems, we focus on areas or settings that the students have studied during the earlier part of the course (weeks 2 and 3). We explain how various techniques can be applied to specific problems and how the interpretation of the data collected helps to address problems that are familiar to the students from their previous mapping projects. In the process,

Figure 8. Two students learning to program the field fluorometer during the Popo Agie dye tracing experiment.

students learn both basic data analysis and seismic survey design methods as well as the basic theory underlying the data processing and analysis that they complete in the laboratory. In 2008, the objectives of both of our refraction and reflection seismic experiments (Dallas dome–Dry Lake and the Riverton landfill, respectively) overlapped with advanced hydrology projects being conducted in the same areas. As a result, the interpretation of the seismic data included both the seismic images processed by the geophysics students and the results of well data and hydrologic models used for the hydrology projects.

Data for both the refraction and reflection projects are acquired using a 32-channel Geometrics Geode data acquisition system, using 10 Hz geophones and both a hammer and a Betsy gun (blank shotgun rounds) for the source (Fig. 9). A total station is used to survey and locate all sources and geophones. During some phases of the experiments, students are able to use the total station data to apply elevation corrections in their reflection and refraction analysis. The general field and data reduction procedures used for our projects are described in Burger (1992) and Underwood (2007).

Refraction Data Collection and Processing—The Dallas Dome Site

The seismic-refraction projects over the past several years have given students the opportunity to learn how to apply seismic imaging to structural problems of faulting and folding near Dallas and Derby domes. The project for 2008 imaged the bedding in the forelimb of Dallas dome beneath Dry Lake (discussed in the hydrology section and shown in Fig. 6). The students found evidence of the small syncline in the subsurface directly below the lake (Fig. 6). The students also image the water table beneath Dry Lake, which was observed to dip away from the lake, indicating that the lake was losing water to groundwater.

The Time-Term Method Used to Estimate Refractor Depth.

This method only requires layer assignments for each of the first break arrivals. It assumes discrete constant velocity layers as well as a horizontal refractor, which are valid assumptions in our case. The students divide the refraction arrivals into a three-layer model by identifying the changes in slopes of the traveltimes plots. We use the software package Plotrefa[®] to calculate the velocities for an n -layer model. The students must decide, based upon the observed traveltimes, how many layers the data will support. Next, they use a time-term inversion scheme to improve the data fit beyond a simple one-dimensional (flat-layer) velocity model. The results of the inversion calculations show a top layer that has a relatively constant layer thickness of ~2 m (Fig. 10). The second layer has a maximum thickness of ~18 m that pinches out toward both ends of the cross section. This pinching out is most likely an artifact of our acquisition geometry (pinching out at the ends due to less coverage) and is not a reliable feature of the model. The boundary between the first and second layers is probably the top of the water table, while the third layer is probably a distinct lithologic unit (e.g., Frontier Sandstone). The shape of the model is consistent with a synclinal structure. If reliable, these results may

Figure 9. Setting off the Betsy gun for a seismic-reflection experiment.

Figure 10. Time-term inversion for traveltime data collected along the northern shore of Dry Lake. The thickening of sediments is consistent with the existence of a synclinal feature underlying the lake.

affect how we understand folding and faulting in the basin-margin folds adjacent to the Wind River Mountains (Fig. 1). Since the students have already become very familiar with this geologic setting from their mapping projects on Dallas and Derby domes (weeks 2 and 3 in Table 1), they can use this background to form a sound interpretation of the resulting velocity model.

Tomographic Analysis Used to Model Traveltime Data.

Students run several different tomographic models with different

numbers of iterations and with different smoothing parameters. This exercise illustrates the trade-off in model smoothness and the root mean square error for their velocity models. Students also use the density of raypaths to determine which parts of the model are reliable and which are not. They find that the thickening of sediments in the center of the spread, once again, suggests the existence of a synclinal feature underlying the lake (Fig. 11).

When comparing the different models generated in Plotrefa[®] using the different parameters described here, we do not see a large difference between any of the models. This leads us to think that the features identified in the upper two layers between 18 and 78 m horizontally (both velocities and boundaries) are reliable. However, we have slightly less confidence in the third layer (due to variations between tomographic models and the lack of raypath penetration).

Reflection Acquisition and Processing—The Riverton Landfill Project

The seismic-reflection project in 2008 was conducted in the Riverton landfill area. There are important questions concerning the depth of groundwater in the landfill and the possible existence of a perched aquifer. Students collected a seismic-reflection line in order to try and image this perched aquifer and possibly the deeper regional water table.

During the project, the students learn the basics of seismic-reflection experimental design, data acquisition, and data processing. Seismic-reflection data allow geophysicists to image boundaries where there are changes in the properties of the rocks, such as rigidity, density, and even water content. Students collect data using two different types of shooting geometries—a fixed spread and a rolling spread—so they are able to learn the advantages and disadvantages of different types of experiment design. Students learn basic seismic processing using Seismic Unix (SU) and how to filter, mute, and eliminate any bad or dead traces. They then input the acquisition geometry and sort the data into

common depth point (CDP) gathers. They experiment with different velocity models by applying the normal move-out corrections before stacking the data. Finally, they learn how to convert their data from two-way traveltimes into depth.

After processing the data, the students must interpret the seismic section using their knowledge of the local geology and any available well control to try and image the potential perched water table ~100 ft (~30.5 m) below the surface. An important aspect of this interpretation is an understanding of the ambiguity inherent in their data. For instance, deep well control is not available; the shallowest reflection is just under 100 ft (~30.5 m) deep, but the deepest well only penetrates to a depth of ~55 ft (~17 m). The interpretation is also hampered by our limited knowledge of the local seismic velocity structure. As a result, the students are expected to discuss both their possible interpretations and the limits of their interpretations based on the quality and limits of their data sets.

Despite these limitations, we did obtain a spectacular subsurface image of the Wind River Formation (Fig. 12). The image suggests a remarkably laterally heterogeneous rock unit, which is consistent with Wind River Formation exposures that the students examined during the second week of the course (Table 1, Tertiary unconformity). The reflection profile includes evidence of inter-layered sandstone and siltstone lenses and possibly river channels produced during the unroofing of the Wind River Mountains. We also observe several major discontinuities at 200, 300, and even 700 ft (~61, 91, and 213 m). These boundaries could represent significant changes in lithology, such as transitions from sandstone to claystone, or perhaps even the presence of water. Recognition of the alternative hypotheses and their relationship to earlier field observations or to regional tectonic processes that the students have learned about during previous project is an important part of the general learning experience. It helps us reinforce the importance of the “five dimensional” thinking that we promote as part of our course.

Evolution of the Advanced Geophysics Projects

Each year our students conduct new seismic experiments in a region where we only have a vague idea of the subsurface structure. In areas that are proximal to previous year’s studies, the students are given the prior years results as background, but they are expected to independently formulate their own interpretations from the data that they collect. We have used several different software packages to process the seismic data. Currently, we are using the Plotrefa[®] suite of programs for the refraction component and Seismic Unix (SU) for the reflection component. We expect to eventually process both the reflection and refraction data using SU.

Structural Analysis and Mapping of Metamorphic and Plutonic Rocks

The advanced hard-rock mapping and structural analysis project is completed on well-exposed outcrops in the South Pass

Figure 11. An example tomographic model using the same traveltimes data used in Figure 10. Students contrast and compare this approach to modeling their data versus the time-term approach. The different colored raypaths correspond to different shot points and give the students a good idea which part of their model is reliable.

Figure 12. Common depth point (CDP) stacks using a single stacking velocity with static corrections. The profile was taken along the western edge of the Riverton landfill (Fig. 1). The landfill is located within the Eocene Wind River Formation, which consists primarily of fluvial and terrestrial sediments from the Laramide uplift of the Wind River Mountains. The spacing between each CPD trace shown here is 0.5 m, and the total spread length is 93 m. The R16 location along the profile indicates the location and depth of penetration of the only water well in the area.

greenstone belt, and it builds upon the one-day set of structural analysis projects that all students complete during week five. It is designed to appeal to students who want more extensive mapping experiences as well as students with advanced interests in structural geology or metamorphic and igneous petrology. Most students who select this option have already completed an introductory course in igneous and metamorphic petrology in addition to our prerequisite of structural geology. To make sure that students have sufficient background for the project, we provide further instruction on the origin and crystallization of peraluminous granites, the use of small-scale folds and fabric to map large-scale fold features, and the use of porphyroblast-fabric relations to evaluate thermal-deformation histories in such terranes.

The project area includes a thick sequence of folded and faulted Archean metagraywacke intruded by a granodiorite batholith, peraluminous granite/pegmatite, and by a series of mafic dikes. The metasedimentary rocks and some of the intrusive units are deformed by a single large-scale folding event that has associated small-scale folds and well-developed deformation fabrics, including an axial plane foliation and lineations that are subparallel to the associated fold hinge lines. The metagraywacke

contains metamorphic porphyroblasts and mineral assemblages consistent with middle-amphibolite-facies metamorphism, but it still preserves easily recognized bedding planes.

The students work in groups of two or three to map the distribution of rock units, bedding orientations, and deformation fabrics and features across a map area of approximately three square miles (eight square kilometers). The mapping is completed at a scale of 1:12,000 on paper topographic base maps with registered orthophoto coverage. Lacking a stratigraphic succession to define fold geometries or relative ages, students must rely on the orientation and geometries of small-scale features and detailed field observations to determine the deformation geometry and geologic history of the area. They collect orientations of bedding, minor fold hinges, axial plane foliation, and both intersection and mineral lineations. Representative field data and minor fold asymmetries are plotted on field maps to assist in defining axial traces of large-scale folds. All orientation data are plotted on stereographic projections to determine the dominant fold axial plane and hinge line orientations. Rather than plotting the data by hand (the method used during the “basic” week five structural exercise), students compile their data in a spreadsheet during the

evenings and import it into a fabric analysis program for plotting and orientation analysis.

The final group project report, completed during a day in the laboratory, includes a completed geologic map, a cross section, a table of all data collected, stereonet plots of the data, and a written report describing the geologic history of the map area. In addition to showing the distribution of all of the rock units and faults, the map contains plotted representative orientation data that constrain the location of fold axial traces. Appropriate axial trace symbols plotted on the map are guided by the orientation data on the map, the symmetry of minor folds, bedding-foliation relationships, and by the concentrations of orientation data on the stereographic projections. The geologic history report includes a description of the 3-D fold geometries in the area, the relative timing of all of the rock units, metamorphism, and deformation affecting the area, and a brief paragraph on processes that may have produced the deduced history of the area. Students are encouraged to support their interpretations with as many as three field photos in their report, which may be submitted digitally or as printed hardcopy.

Unlike the advanced hydrology and geophysics projects, which include multiple projects that may vary from year to year, this advanced project relies on a single area with appropriate exposures and level of complexity (e.g., does not involve multiple periods of deformation or metamorphism that confuse the analysis). Such ideal areas are not common, so this project is repeated in subsequent years. Although the project covers some relatively advanced aspects of structural analysis, it is fundamentally part of a traditional field camp program that emphasizes mapping, 3-D interpretations, and geologic history.

DISCUSSION

The changes to our curriculum during the fifth week of our course were instituted over a 10 yr period (1999–2008), while changes during our sixth week have only been in effect for the past 4 yr (2005–2008). During this implementation period, we have been particularly concerned with: (1) maintaining our philosophy of providing a broad field camp experience that continues to have a strong field mapping component, (2) preparing students for projects that require background beyond our prerequisite courses, (3) student opinions on the value of the advanced projects to their field camp learning experience, and (4) the ways in which our course changes affect how we spend our course resources.

To help evaluate the first three issues, we ask the students to complete a very extensive course evaluation toward the end of the sixth week of the course. We have administered versions of this evaluation since 1993, but the responses noted here are only from the 4 yr period that includes our advanced projects. The survey is set up to allow the students to provide a quick evaluation of each of our projects in terms of duration, preparation they received, their interest in the project, the value of the project, and the format and logistics for the project. Students can also add detailed comments about any specific project. To help evaluate student

satisfaction with the breadth of our curriculum, we ask if there are areas of field instruction that they would like to see added/expanded or deleted/reduced. To further evaluate student satisfaction with our fifth- and sixth-week projects (beyond the project evaluations noted here), we ask the students how important their advanced project was to their overall field camp learning experience (very important, important, somewhat important, not important), and how important the availability of environmental geology/hydrology projects was in selecting a field camp (with the same choices).

In general, students are satisfied with our curriculum. The most common suggestion for changing the curriculum is to add another hard-rock project at the expense of one of the sedimentary rock projects. Recall that our sixth-week advance projects replaced a week of structural analysis in metamorphic and igneous rocks, which is now only one of our advanced project options. The evaluation of the preparation that we provide students for our fifth- and sixth-week projects rates high; most rate greater than 3.5 on an ABC grade point scale ($A = 4$, $B = 3$, $C = 2$) and none ranks lower than 3.0. In response to the question about the importance of the advanced projects, the percent of students responding in each category was: 61% very important, 28% important, 9% somewhat important, and 2% not important. The student responses were nearly the same from students participating in each of the three advanced projects. However, the student response to the question about the importance of environmental/hydrology to their field camp choice varied considerably depending on the advanced project they selected. Overall, the percentage of students responding in each category was: 26% very important, 24% important, 11% somewhat important, and 39% not important. As might be expected, a greater percentage of students choosing the hydrology advanced project felt that the availability of environmental/hydrology projects was very important or important to their field camp choice. Nevertheless, 22% of these students felt that such availability was not important to their field camp selection. The way in which this question is asked could be biased by our (University of Missouri) students, who are generally required to attend our field course.

The student opinion results indicate that most students recognize the importance of some exposure to environmental/hydrology projects as part of their field camp experience. However, it is clear that the ability to choose advanced projects as part of their field camp experience is important or very important to nearly all of the students (89%). This importance is quite clear in the student's enthusiastic participation in the advanced projects. Most students are anxiously anticipating the end of field camp by the sixth week of a six-week course, but the chance to participate in a week of projects that are more likely to be interesting for the students clearly helps to sustain their interest in learning and not just finishing the course.

Although we feel that our fifth- and sixth-week projects are providing successful student learning experiences, they are expensive experiences to provide in terms of both personnel and equipment. During the last two weeks of our course, four faculty

members and three teaching assistants are in the field and/or in the laboratory with the students every day (and most evenings), providing a student-instructor ratio of less than six to one. The average of the fifth- and sixth-week faculty salary expenses is nearly twice that of the average for the first four weeks. Most of the expensive equipment that we use for these projects (seismic equipment, total station, fluorometer, pH-conductivity meters, flow meters, pumps, and chemical kits) was purchased with grant funds from the National Science Foundation or with funds available from a field camp endowment made possible by alumni contributions. Our computer equipment is subsidized by the University of Missouri, which provides our laptop computers and standard site licensed software based on a computing fee paid by the students in addition to their tuition. Although our course's room, board, and transportation costs are operated on a break-even basis, the university and our endowment provide a significant subsidy for our instructional costs. Our expanded curriculum would not have been possible without these grants and subsidies.

CONCLUSIONS

The two-stage expansion of hydrology and geophysics projects for our field course has allowed us to progressively develop projects that are built on the foundation of our four weeks of bedrock geology, geologic mapping projects, and regional geology. Our careful site selection and emphasis on shallow groundwater-surface-water interactions has also allowed us to integrate our hydrology and geophysics projects and accommodate logistical aspects of our fifth- and sixth-week projects. We have taken advantage of our fifth-week projects to provide fundamental instruction and background that allows students to successfully complete hydrology and geophysics exercises during both the fifth- and sixth-week projects without requiring students to have prerequisite courses in these subjects. Although students who have previously completed introductory hydrogeology or geophysics course may already be prepared with fundamental background for our fifth-week projects, such students are still challenged and gain valuable practical experience during our advanced projects in hydrology and geophysics. Our advanced option in hard-rock structural analysis provides an advanced mapping and bedrock geology field experience for students who are more interested in honing their geology skills than expanding their background in hydrology or geophysics. Although we continue to make adjustments to our curriculum, we feel that we are successfully maintaining our program breadth and providing fundamental instruction and experience in geologic mapping even as we provide all students with basic exposure to field aspects of hydrology and geophysics.

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