Results from Prior NSF Support

Not applicable.

Project Setting

Keene State College (KSC) is a public four-year liberal arts and science college with a tradition and strength in teacher preparation. As part of its mission, KSC promotes strong relationships among students and faculty that emphasize creative and critical thinking, scholarship and research, and a passion for learning, with a commitment to service. One of our responsibilities is to provide access and educational opportunity to a broad spectrum of students. We have approximately 3800 full and part-time matriculated undergraduates from across New England, as well as about 90 graduate students (in Education) and about 700 non-matriculated students. Approximately 40% of each entering class are first-generation college students.

The Geology Department offers major and minor programs in Geology (including a Teacher Certification option), provides significant contributions to interdisciplinary major and minor programs in Environmental Studies (ENST), and serves a large number of non-science major students, including prospective K-12 teachers, through the college's General Education program. The Department includes 3 full-time faculty (Peter Nielsen, Steven Bill, and Timothy Allen, who has a 1/4-time appointment in ENST), several adjunct instructors, and graduates about 3 Geology majors each year, as well as a similar number of ENST students specializing in Geology. Over the past ten years, the Department increased its full-time faculty complement from two to three to accommodate significant growth in total enrollment. For the Fall 1999 semester, total enrollment in Geology courses was an average of 112 students per full-time faculty member.

Within the Geology curriculum, we have emphasized the integration of detailed field observations (albeit mostly qualitative in nature) with “big picture” tectonic and earth-system syntheses. Most (but not all!) of our courses incorporate a laboratory component, sometimes organized around integrated lecture-laboratory sessions. Recent evolutionary reforms have included the addition of new field-based laboratories to courses in Environmental Geology (Allen, 1997a) and Hydrogeology (Allen, 1998). In the Geology Department, and across KSC in general, we are really only just beginning to develop a tradition of independent research involvement among our students. In 1996, KSC's President established a fund to award modest grants to students in support of their independent research and creative projects. Some efforts by Geology and ENST students have resulted in undergraduate student authorship or co-authorship on posters or presentations at regional scientific meetings (Drobat & Nielsen, 1995; Howe et al., 1995; O'Rourke et al., 1998). As the tradition of independent research continues to develop, students (and faculty) learn from the projects and students that have gone before. The new laboratory component of the Hydrogeology course is a direct by-product of such student-faculty cooperative research (O'Rourke et al., 1998; Allen, 1998).

Goals and Objectives

While field-based observation remains fundamental to the science of Geology, a more complete understanding of the earth system and its processes requires a multi-disciplinary approach including the collection, interpretation, and application of quantitative geochemical data. In adapting exemplary models from several other institutions (see below), we seek to integrate modern quantitative geochemical analysis into our program. The goals of this integration are to (1) increase the involvement of our students (including non-science majors and prospective K-12 teachers in introductory courses) in the process of modern scientific investigation, consistent with national trends in science education towards student-centered, inquiry-based, active participatory learning (e.g. Culotta, 1994; Markovics, 1990) and the involvement of undergraduates in authentic scientific process (e.g. Goodwin & Hoagland, 1999; McConnaughay et al., 1999; McGinn & Roth, 1999), with progressive course-based research experiences preparing students for independent research; and (2) enhance student understanding of fundamental relationships between chemical composition, mineralogy, rock-type, tectonic setting, and global biogeochemical cycling. An automated Wavelength Dispersive (WD) X–Ray Fluorescence Spectrometer (XRFS) with element mapping and spot analysis capabilities, along with associated sample preparation equipment, will enable Geology and ENST students to undertake major and trace element analyses of, and explore compositional relationships in, solid rock, mineral, sediment and soil samples. We currently do not have any such analytical capability in Geology, and only very limited elemental analysis capability in Chemistry. The XRFS will be used in courses across the Geology curriculum, including *Physical Geology, Mineralogy, Petrology, Environmental Geology, Geochemistry,* and *Independent/Directed Study* (i.e., student-faculty cooperative research), as well as a Chemistry course in *Chemical Analysis of the Environment,* and in the ENST *Senior Seminar*. Students in other Geology courses (e.g. Stratigraphy & Sedimentation), other Chemistry courses (e.g. Instrumental Analysis), and in the Technology, Design and Safety program (e.g. Materials of Manufacturing) might make additional use of the XRFS.

Our specific objectives include: (1) enhancing introductory *Physical Geology* laboratories by exposing students to chemical analyses obtained from the very rocks and minerals they are studying in hand-sample, and facilitating student investigative projects; (2) re-designing the course in *Geochemistry* to include a new analytical geochemistry laboratory component integrating research projects; (3) adding inquiry-based laboratory exercises involving geochemical analysis of solids to courses in *Mineralogy, Petrology, Environmental Geology,* and *Chemical Analysis of the Environment;* and (4) supporting *Independent/Directed Study* student-faculty cooperative research projects, and projects by students in the ENST *Senior Seminar,* requiring geochemical analysis of solids.

Detailed Project Plan

In developing this proposal, we have looked to exemplary models at several other institutions, each of which (as it happens) has previously received support from NSF towards similar reforms, principally Albion College (NSF ILI Award #9751006; see letter from Tim Lincoln, Appendix II), and Dickinson College (NSF ILI Award #9850549; see letter from Jeff Niemitz, Appendix II), as well as Furman University (NSF ILI Award #9651368) and Middle Tennessee State University (NSF CCLI-A&I Award #9950820). These institutions have each acquired an XRFS for use by students to obtain whole-rock chemical analyses for course-based and independent research projects. These projects are facilitating student involvement in scientific investigation and enhancing student understanding of geochemical relationships in tectonic and earth system processes, in ways unique to each program. We draw from aspects of each of these models in integrating modern quantitative geochemical analysis into our own curriculum:

GEOL 201 Physical Geology

Multiple sections of this introductory laboratory course is offered every semester, typically enrolling a total of about 50 students per semester. Most of these students are non-science majors seeking to fulfill physical science general education requirements—many of them are prospective K-12 teachers. The identification of mineral and rock hand samples are important exercises in these courses, but fail to fully convey to students fundamental relationships between chemical composition, mineralogy, rock-type, and tectonic setting. Further, while these identification exercises do represent an application of scientific method, often students rely on the expert opinion of the instructor to test their hypothesized identification—verification discovered independently by the students would, of course, be preferable. To address these issues, as students reach closure in their identifications we will share with them chemical composition data for the samples they have been studying (as at Dickinson College and Furman University). So that these data do not appear to have come out of thin air, or from a "black box", we will give the students a tour of our new sample preparation and analytical facilities (as at Furman University) and have them participate in an analysis of already-prepared samples of the same rocks they are identifying, using a pre-programmed rapid qualitative analytical procedure (as at Middle Tennessee State University and Albion College). Because XRF is a non-destructive technique, we will be able to accumulate a library of prepared samples that can be analyzed anew with each new cohort of students.

To explore the mineralogic composition of rocks beyond macroscopic observations (as at Dickinson College), we will also introduce students to petrographic microscopy, and use the spot analysis capability of the XRFS to qualitatively confirm mineral identifications.

Students will be able to discover that basalt and gabbro, for example, have similar mineralogy consistent with their similar chemical compositions. Thus they may better appreciate the textural difference and its relation to tectonic setting (as at Dickinson College). The compositional differences between basalt and granite, for example, will also illustrate the differentiation of the earth, reinforcing the chemical and physical distinctions between mantle, oceanic crust, and continental crust. Students may also finally be able to grasp that obsidian, even though it is dark-colored, is typically felsic in composition!, with implications for discussion of eruptive styles related to magma composition.

Furthermore, the compositional data will provide students with additional information they can use to verify their hypothesized identifications independently of the instructor's expert opinion, enhancing their experience with scientific methodology. To reinforce this, in lieu of submitting the traditional identification worksheet, students will be required to prepare a scientific research style report documenting their investigations and discoveries (e.g. Niemitz & Potter, 1991).

GEOL 412 Geochemistry

This upper level course meets elective requirements in Geology and ENST and is offered every other spring semester by Allen. Typical enrollment is 8 Geology and ENST students. The course has not previously had a laboratory component, consisting solely of lecture/discussion, problem sets, and literature-based research projects. To better provide a participatory learning environment, Allen is undertaking a complete re-design of the course to incorporate a new laboratory component in analytical geochemistry (Gill, 1997a). Analytical techniques employed will include stable isotope ratio analysis of water, carbonate, and graphite samples using our new modular multi-purpose vacuum preparation line (isotopic ratios of prepared gases will be determined using mass spectrometers at another institution; Kirchner et al., 2000), as well as major and trace element analysis of rocks, sediment and soil using the XRFS.

Exercises will involve group collaborations (Beiersdorfer & Beiersdorfer, 1995) applying these techniques to problem-based questions (as at Albion College; Smith et al., 1995) such as:

What is the average chemical composition of the Earth's crust? (analyze samples of major rock types and identify groups of elements with similar distributions, as at Albion College). How are trace elements re-distributed when crustal rocks begin to melt? (analyze migmatites and anatectic granites). What happens to such rocks when they are exposed to the weather? (analyze unweathered rocks, weathered rocks, soils and sediments, compare with compositions of rain, ground and river water, as at Albion College; Drever, 1997; Railsback, 1993). Can we track the movements of fluids (both within the crust and at the Earth's surface) that may have interacted with these rocks? (trace element analyses of vein materials and altered rocks, stable isotope analyses of waters and minerals). While much is already known about the basic answers to these questions, as detailed in any geochemistry text, the students don't know these answers (yet) and there is still much that is not known. Since the students will be collecting and analyzing their own samples, unexpected results may occur, providing opportunities for discussion of uncertainties (as at Albion College) and the nature of scientific research (McConnaughay et al., 1999; McGinn & Roth, 1999).

The course will culminate with a multi-week group research project (as at Dickinson College) entailing problem definition, field work, sample preparation and analysis, data processing, interpretation, and presentation. These projects could be continued investigation of the problem based questions addressed earlier, such as relating the stable isotope composition of soil moisture and ground water to that of precipitation, investigating the nature and origin of carbonate fracture fillings in local rocks using trace elements and stable isotopes, or applying the element-mapping and spot analysis capabilities of the XRFS to trace element distribution in migmatites. Other candidate projects include developing and testing methods to extend our existing analytical capabilities, such as using the XRFS to analyze the trace element composition of natural waters by evaporative pre-concentration (http://www.moxtek.com/ppt/pagetwo.htm).

Throughout, the emphasis will be on scientific process, critical, creative, and analytical thinking, problem-solving, quantitative reasoning, and communication skills (e.g., discourse and visual representation, McGinn & Roth, 1999).

GEOL 301 Mineralogy

Required of Geology majors, this course is offered every other fall semester by Nielsen, typically enrolling 10 students. The course is taught in integrated lecture-laboratory sessions of three hours duration meeting twice per week. Adapting some of the best practices in the teaching of mineralogy (Brady et al., 1997), the XRFS will be used by students to obtain chemical compositions of unknown minerals, from which they can determine mineral formulae; to investigate relationships between compositional variation or impurities and variation in physical properties (e.g. coloration); and to study compositional zoning (using the element mapping and spot analysis capabilities of the XRFS) in large porphyroblasts. Students will collect their own samples on class field trips, and then prepare and analyze them. The diverse geology of New England provides the opportunity for students to collect and identify nearly all of the eighty to ninety minerals normally required in most undergraduate mineralogy courses (Brady et al., 1997).

GEOL 302 Petrology

Required of Geology majors, this course is offered every other spring semester, following Mineralogy in the fall, by Nielsen. The typical enrollment is 10 students. Like Mineralogy, Petrology is taught in integrated lecture-laboratory sessions of three hours duration meeting twice per week. Several field trips are required for this course, and these trips provide an opportunity for students to collect samples for later laboratory work. These include two suites of rocks from a Vermont field trip (both mafic and pelitic bulk compositions, ranging from lowermost greenschist to upper amphibolite facies). Students often have difficulty in recognizing the protolith for medium to high grade metamorphic rocks—bulk rock XRFS data will help students to correlate mineralogy, metamorphic grade and protolith composition. Additional suites of samples from Dutchess County, NY, the Pallisades Sill, and the Stillwater Complex (from our teaching collections) will serve as a means of introducing chemical characteristics of important rock associations and the products of igneous differentiation. The element mapping and spot analysis capabilities of the XRFS will be of particular value in examining chemical zoning of large garnet porphyroblasts in metamorphic rocks, as well as large phenocrysts from differentiated igneous bodies.

GEOL 315 Environmental Geology

This intermediate-level (*Physical Geology* is a prerequisite) course meets elective requirements in Geology and ENST and is offered annually in the fall semester by Allen. It typically enrolls 12-15 Geology and ENST students. The course uses geological, geophysical, and hydrological techniques to gather information about the geologic environment necessary in engineering and planning contexts, for resource exploration, and for understanding and evaluating geologic hazards (Allen, 1997a, 1998). The XRFS will be used to obtain chemical composition data of soils to complement existing field-based laboratory exercises investigating the physical properties (e.g. seismic velocity, grain size distribution, porosity, compaction and strength, moisture content) of these deposits. Students will address such questions as: Are there any relationships between variations in chemical and physical properties? How do mature soils differ chemically from less mature deposits? What does this tell us about soil formation processes, or about the suitabilities of different environments for development? Students will also analyze the sediments of the Ashuelot River (which runs through the KSC campus) for possible heavy metal contamination, above and below industrialized reaches of the river, and together with hydrologic measurements consider the transport and fate of these materials.

CHEM 351/355 Chemical Analysis of the Environment and Lab

This course, an important component of the ENST program, is offered annually in the spring semester by Stepenuck, typically enrolling 10 students. The course emphasizes understanding the rationale for an environmental chemical analysis (such as the regulatory context) and then, in a 5-hour laboratory, students devise sampling strategies, prepare calibration standards, collect environmental samples in the field and analyze them, all the while maintaining quality control and quality assurance procedures (Stepenuck, 1999, 1975). Existing exercises involve primarily liquid and gas chromatography, techniques not applicable to elemental analysis of solid environmental samples. An Atomic Absorption Spectrophotometer (AAS) is used for elemental analyses of waters, but is limited to one element at a time and is capable of analyzing only a limited number of elements. The XRFS, therefore, will facilitate new exercises investigating trace element or heavy metal (e.g. Pb) contamination of soils (as at Albion College; Crain et al, 1992); the mobilization of metals in soils as a result of acid deposition; the analysis of metal content in sewage sludge slated for composting or land application (as at Albion College); and elemental analysis of airborne particulate matter collected on filters with a high volume air sampler.

GEOL 498 Independent/Directed Study and **ENST 495 Senior Seminar**

Involvement of undergraduate students in real scientific research through student-faculty cooperative research projects is held out as an ideal approach to teaching science (e.g. Goodwin & Hoagland, 1999). Student involvement in research outside of course-based projects is not currently a required component of the Geology curriculum. Students may, however, apply credits earned in Independent/Directed Study towards elective requirements in the major. Whether or not a student chooses to pursue this option depends on their own motivation as well as the willingness of a faculty member to supervise their project.

Among other projects (Appendix I), Allen has worked with a number of students over several years in a variety of field projects exploring the dynamics of the sub-surface hydrologic cycle (O'Rourke et al., 1998). A few of these projects could have benefitted from access to analytical instrumentation such as an XRFS, such as an attempt to relate ground water geochemistry to the composition of the aquifer matrix. Continuing work in hydrologic dynamics will also take advantage of our new stable isotope laboratory.

Another student undertook a petrographic and geochemical characterization of rocks collected in Mexico as part of her participation in an NSF-sponsored Research Experience for Undergraduates program. Her samples were sent to a commercial laboratory for XRF analysis.

Allen is currently also working with students in undertaking detailed geologic and structural mapping of plutonic and metamorphic rocks in the vicinity of Lake Sunapee in west-central New Hampshire (Allen, 1997b). The project is investigating relationships between structural development, magmatism and metamorphism during the Acadian Orogeny. One student is now finishing a petrographic analysis of an initial suite of samples from the area; another will be supported by the US Geological Survey EDMAP program to map on a full-time basis over the summer (see Current and Pending Support attachment). The XRFS will be used extensively by students in this on-going project to help better characterize the map units and investigate petrologic relationships between them.

Nielsen has worked with undergraduate students in investigating the nature of brittle fracturing and associated hydrothermal fluid flow responsible for deposits of gem-quality fluorite in southwestern New Hampshire (Nielsen & Drobat, 1995; Howe et al., 1995). Published results have focussed on structural controls of mineralization, as well as fluid inclusion and stable isotope constraints on the fluid source and composition. The XRFS will enable students to obtain chemical analyses of vein material and altered host rocks in order to better understand these deposits.

Similar projects are also undertaken in the ENST Senior Seminar, where students are expected to work in interdisciplinary teams on research-based projects resulting in products useful to the community (i.e., service learning). Stepenuck has in the past worked with students in the Seminar on the leaching of metals from soils by acid precipitation using AAS, one element at a time. Continuation of this work will be greatly enhanced by the availability of the XRFS. Examples of more recent projects in this course that could also have benefitted from the XRFS include a survey of salt contamination (measured as conductivity of soil solution extract) adjacent to roadways as a function of road classification and maintenance jurisdiction, and an assessment of the levels of airborne particulate matter on campus. With assistance from the PIs, the XRFS will be available to student teams in the ENST Senior Seminar who might require geochemical analysis of environmental solids as part of their project. All of these students will have previously taken one or more of the Geology or Chemistry courses described above, and so will already have some familiarity with the instrument.

Many students may continue to choose field-based research projects that involve only qualitative observations and simple measurements, but multi-disciplinary approaches that involve quantitative chemical and isotopic analyses are increasingly being employed to address problems across the earth and environmental sciences. We currently do not have any capability to perform multi-element chemical analyses; the XRFS will allow our Geology and ENST students to pursue some of these modern approaches in their own research.

Equipment Request

We seek to acquire a Rigaku ZSX 100e sequential wavelength dispersive X-ray fluorescence spectrometer with element mapping and spot analysis capabilities, and associated sample preparation equipment including jaw crusher, Shatterbox and grinding container, hydraulic press and pellet die set, platinum crucibles and molds, and a muffle furnace.

We considered several alternative approaches to obtaining elemental analysis of geological and environmental solids, including AAS, Inductively Coupled Plasma (ICP) Optical Emission Spectrophotometry (OES) and ICP Mass Spectrometry (MS), as well as XRFS. While well suited for the analysis of natural waters, AAS, ICP-OES and ICP-MS would all require problematic digestions of solid samples. AAS is additionally limited to one element at a time. Studies of water chemistry are important and could be applied to good effect in many of our courses and research projects, but much of the science of geology is still fundamentally concerned with solid earth materials. XRFS has the advantages of a wide analytical range (% to ppm concentrations) and of being non-destructive, allowing us to accumulate a library of prepared samples that can be analyzed anew with each new cohort of students. WD–XRFS is the perhaps the most widely used technique for "whole-rock" major and trace element geochemical analyses (Fitton, 1997; Gill, 1997b); the institutions whose models we are adapting all acquired XRFS's with WD capabilities. The Rigaku ZSX 100e is desirable because it can be configured to mask the incident X-ray beam down to a 0.5 mm spot, which in combination with a movable sample stage allows elemental mapping of heterogeneous samples and (with a CCD sample observation system) spot analysis of individual mineral crystals within a rock.

Existing equipment to be used in this project includes diamond slab and trim saws, thin section saw and grinder, hydraulic rock splitter, lapping tables for polished rock slabs, disc mill pulverizer, drying oven, sieves and shaker, sample splitter, research petrographic microscope with video display, student petrographic microscopes, stable isotope vacuum preparation line and peripherals, analytical balance, and various field equipment, as well as the AAS, liquid and gas chromatographs, and other instrumentation in the Chemistry Department (see Facilities and Equipment attachment).

Implementation and Maintenance

The XRFS will be housed in space available to the Geology Department, adjacent to the stable isotope laboratory, displacing an an existing use by students in introductory laboratories as an out-of-class study area. The room is already appropriately plumbed and wired having previously housed a now-defunct powder X-ray diffractometer belonging to the Chemistry Department. KSC will make other renovations as necessary (see letter of support from the Dean of Sciences, Appendix II). Much of the sample preparation equipment will be housed in our existing "rock room," together with the saws and thin-sectioning equipment.

The instrument will be ordered in winter 2001 and installed in summer 2001 (delivery time 4-5 months). While awaiting delivery, Allen will travel to the model institutions to observe the geochemistry laboratory facilities and their integration into the curriculum. Over summer 2001, the faculty (supported by small stipends) will train on the instrument, work on calibration and standardization, develop analytical methods, and prepare to incorporate use of the instrument into their courses as proposed above. We will also hire a part-time technician to help prepare thin sections, powder pellets, and fused disks from samples in our teaching collections for use in introductory labs. In fall 2001, the XRFS will see its first use in *Physical Geology, Mineralogy,* and *Environmental Geology,* as well as by research students. Before the end of the semester, we will entertain a visit from a team of external evaluators (see below), to help provide a formative evaluation of the project. In spring 2002, the XRFS will be used in *Physical Geology, Petrology,* *Geochemistry* and *Chemical Analysis of the Environment,* and by research students. The external evaluators will return to meet with students in these courses and continue assisting us in evaluating the project. In fall 2002, the instrument will again be used in *Physical Geology, Environmental Geology,* and by research students. We will compile summative evaluation information and disseminate project results, perhaps at the 2002 meeting of the Geological Society of America (GSA).

Students will be thoroughly supervised by their instructor as they learn how to prepare samples and operate the XRFS in a safe manner. Once certified as competent to do so, students in upper-level courses and those undertaking research will be allowed to use the XRFS with minimal supervision (as at Dickinson College).

The principle maintenance issue for the instrument is the lifetime and replacement of the X-ray tube. Rigaku states that the expected life of the X-ray tube is 3 to 5 years, although they also note that some users have obtained as many as 10 years of service from their tubes. While we will take all steps to extend the life of our tube for as long as possible, KSC is committed to replacing the tube when the need arises (see letter of support from the Dean of Sciences, Appendix II). The modular design of the Rigaku facilitates on-site maintenance and upgrades, and diagnostic troubleshooting of the instrument can be performed by service engineers via internet connection. Consumables will be accommodated within the Geology department budget.

Experience and Capability of the Principal Investigators

Both Allen and Nielsen have training and experience in quantitative and qualitative x-ray analysis in electron microprobes, and have prepared rock powders for XRF analyses and used whole-rock major and trace element data in their work. Allen has additional experience in Stable Isotope Ratio Mass Spectrometry. Stepenuck has extensive experience in both organic and inorganic analytical chemistry, particularly of environmental samples, and had experience using an XRFS in testing garden soils and house dusts for Pb contamination while on a sabbatical at the United States Environmental Protection Agency Laboratory. Nielsen has also been active in curriculum reform, having served on the KSC General Education Task Force (1995-98) and participated in several Project Kaleidoscope and other workshops on science education. One outcome of this was an experimental introductory interdisciplinary integrated science course, team-developed with colleagues in the Biology Department (Nielsen et al., 1998a, 1998b).

Evaluation Plan

Questions to be addressed in evaluation of this project include: (1) Are students increasingly involved in the process of scientific investigation in their learning, at all levels from introductory laboratories to Independent/Directed Study? and (2) Has student understanding of fundamental relationships between chemical composition, mineralogy, rock-type, tectonic setting, and global biogeochemical cycling been enhanced?

To address these questions we will: (a) administer "knowledge surveys" (Nuhfer, 1995) in introductory courses (beginning in Fall 2000 prior to implementation of the proposed reforms); and (b) entertain two site-visits (Fall 2001 and Spring 2002 as described above) from a team of two external evaluators, who will review relevant course materials and examples of student work, observe our operations, and meet with students and faculty, in order to provide independent progress (formative) evaluations on both questions. Jeffrey Niemitz from Dickinson College (see letter of support, Appendix II) has agreed to serve on the evaluation team; a second evaluator will be selected through the consultancy service provided by the Council for Undergraduate Research (CUR; see http://www.cur.org/consulting.html). Professor Niemitz has long experience in curriculum reform at Dickinson College (Niemitz, 1995; Niemitz and Potter, 1991) and has successfully used XRFS to enhance integration of geochemistry into the geology curriculum (NSF ILI Award #9850549). He is currently President of, and a Distinguished Speaker for, the National Association of Geoscience Teachers (NAGT), in which capacity he has consulted with geoscience departments across the nation.

Information to be considered in summative evaluation of this project will include results of and responses to formative evaluations, and before-and-after comparisons of standard student course evaluation responses, results of “knowledge surveys,” student performance on exams, quality of other student course-work, enrollments in impacted courses, numbers of Geology and ENST majors, numbers of Geology and ENST students participating in research projects, numbers of published or presented student projects, and placements of graduates. It should be noted, however, that some of these impacts may not be fully realized within the project’s funding duration.

We must also ask, are our students obtaining major and trace element compositional data from their samples that is of good quality? In addition to careful calibration of the instrument with appropriate standards, we will both analyze other certified reference materials to estimate bias, and submit some duplicate samples to other laboratories for independent and alternative analyses, and practice other quality control/assurance procedures as appropriate.

Dissemination of Results

We will, of course, create a web site for the XRF laboratory, targeted at current and prospective students. The site will include information about our facilities and capabilities, methods of analysis, and results (for example, see the existing web site for our Stable Isotope Laboratory, http://kilburn.keene.edu/ENST/isotopes/). Students will be encouraged to present results from their research projects at regional scientific meetings (e.g. GSA Northeastern Section, state geological societies, New England Intercollegiate Geological Conference) as appropriate. Projects by ENST students in the Senior Seminar will be shared with the communities the projects serve. The PIs will share their experience with the curricular reforms in presentations at meetings of GSA, NAGT, CUR, or the New England Association of Chemistry Teachers and/or by publications in appropriate journals (e.g. *Journal of Geoscience Education, Journal of Chemical Education, CUR Quarterly*).

References Cited

Allen, T., 1998, "Field Laboratories in Hydrogeology and Environmental Geology," *Geological Society of America Abstracts with Programs,* v. 30, n. 7, p. A306

Allen, T., 1997a, "Geophysics in an Environmental Geology Context," *Geological Society of America Abstracts with Programs,* v. 29, n. 6, p. A368.

Allen, T., 1997b, "Nappes, Gneiss Domes and Intrusive Sheets of West-Central New Hampshire," in *Guidebook to Field Trips in Vermont and Adjacent New Hampshire and New York,* Grover, T.W., Mango, H.N., and Hasenohr, E.J. (editors), New England Intercollegiate Geologic Conference 89th Annual Meeting. pp. A2.1–A2.19.

Beiersdorfer, R.E., and Beiersdorfer, S.L., 1995, "Collaborative Learning in an Advanced Environmental-Geology Course," *Journal of Geological Education,* v. 43, p. 346-351.

Brady, J.B., Mogk, D.W., and Perkins III, D.(editors), 1997, *Teaching Mineralogy,* Washington, DC, Mineralogical Society of America, 406 pp.

Crain, J., Hansel, J., and Troxel, J.E., 1992, "Determining Regulated Metals in Soil: A Comparison of EPA Methods with Laser Ablation ICP-MS and XRF Spectroscopy," *Spectroscopy,* v. 7, pp. 40-46.

Culotta, E., 1994, "New models for making scientists," *Science,* v. 266, p. 875-888.

Drever, J.I., 1997, *The Geochemistry of Natural Waters: Surface and Groundwater Environments*, 3rd edition, Upper Saddle River, New Jersey: Prentice-Hall. 436 pp.

*Drobat, P.A. and Nielsen, P.A. 1995, "Structural Controls on Fluorite Mineralization at the Wise Mine, Westmoreland, New Hampshire," *Geological Society of America Abstracts with Programs* 27(1): 41.

Fitton, G., 1997, "X-ray fluorescence spectrometry," in Gill, R. (editor), *Modern Analytical Geochemistry: An Introduction to Quantitative Chemical Analysis for Earth, Environmental and Materials Scientists*. Harlow, England: Addison Wesley Longman Ltd. pp. 87-115.

Gill, R. (editor), 1997a, *Modern Analytical Geochemistry: An Introduction to Quantitative Chemical Analysis for Earth, Environmental and Materials Scientists*. Harlow, England: Addison Wesley Longman Ltd. 329 pp.

Gill, R., 1997b, "Which Method Should I Use?" in Gill, R. (editor), *Modern Analytical Geochemistry: An Introduction to Quantitative Chemical Analysis for Earth, Environmental and Materials Scientists*. Harlow, England: Addison Wesley Longman Ltd. pp. 207-214.

Goodwin, T., and Hoagland, K.E., 1999, *How to Get Started in Research,* Washington DC: Council on Undergraduate Research, 37 pp.

Howe, S.S., Arehart, G.B., Nielsen, P.A., and *Perkowski, R., 1995, Rift-Related Fluorite-Quartz-Barite-Base-Metal Deposits in Southwestern New Hampshire, *Geological Society of America Abstracts with Programs* 27(1): 55.

Kirchner, D, Encarnacion, J., and Agosta, F., 2000, "Incorporating Stable-Isotope Geochemistry in Undergraduate Laboratory Courses," *Journal of Geoscience Education,* v. 48, p. 209-215.

Markovics, G., 1990, "The 'Involvement' Component in Teaching Earth Science," *Journal of Geological Education,* v. 38, p. 456-457.

McConnaughy, K., Welsford, I., Stabenau, E., 1999, "Inquiry, Investigation, and Integration in Undergraduate Science Curricula," *CUR Quaterly,* v. 20, p. 14-18.

McGinn, M. K., and Roth, W.-M., 1999, "Preparing Students for Competent Scientific Practice: Implications of Recent Research in Science and Technology Studies," *Educational Researcher,* v. 28, pp. 14-24.

Nielsen, P.A., *Leger, C.A., Welsford, I.G., and Whittemore, S.L., 1998a, "An Integrated Laboratory and Field Experience for Non-science Majors: 500 Mllion Years of Earth History at Turners Falls, Massachusetts," Poster Presentation at the Project Kaleidoscope Workshop *What Works: Alternatives to Lecture-Based Learning in Math and Science,* Wheaton College, 4 June, 1998

Nielsen, P.A., *Leger, C.A., Welsford, I.G., and Whittemore, S.L., 1998b, "A Hands-on Group Laboratory Activity: Introduction to the Rock Cycle and Classification of Rocks," Demonstration at the Project Kaleidoscope Workshop *What Works: Alternatives to Lecture-Based Learning in Math and Science,* Wheaton College, 4 June, 1998

Niemitz, J., 1995, "Preparing geology majors for their future by assessing what works for students and faculty," *Journal of Geoscience Education,* v. 44, p. 401-407.

Niemitz, J. and Potter Jr., N., 1991, "The Scientific Method and writing in introductory landscape-development laboratories," *Journal of Geological Education,* v. 39, p. 190-195.

Nuhfer, E., 1995, "The Place of Formative Evaluations in Assessment and Ways to Reap Their Benefits," *Journal of Geoscience Education,* v. 44, p. 385-394.

*O'Rourke, J.; *Ravella, M.; *Lance, D.; *Smith, M.; *Grunauer, A.; *Stiles, T.; *Martin, J.; Allen, T. T.; *Villanova, J.; and *Drobat, P., 1998, "Field Studies of Sub-Surface Hydrologic Dynamics," *Geological Society of America Abstracts with Programs,* v. 30, n. 1, p. 64.

Railsback, L.B., 1993, "A geochemical view of weathering and the origin of sedimentary rocks and natural waters," Journal of Geological Education, v. 41, p. 401-411.

Smith, D.L., Hoersch, A.L., and Gordon, P.R., 1995, "Problem-Based Learning in the Undergraduate Geology Classroom," *Journal of Geological Education,* v. 43, p. 385-390.

Stepenuck, S.J., 1999, "Chemical Analysis of the Environment," invited paper in the session "Teaching with Problem Solving and Case Histories;" *American Chemical Society, North East Regional Meeting,* Clarkson University, June, 1999.

Stepenuck, S.J., 1975, "Chemical Analysis of the Environment—A Course for Non-Chemistry Majors," *Journal of Chemical Education,* December, 1975.

* indicates undergraduate co-authors