Acquisition of an Electron Backscatter Diffraction System

PI: Rachel Beane, Bowdoin College

Funded by: NSF, 2003

Directorate: Geosciences
Division(s): Earth Sciences
Program(s): Major Research Instrumentation (MRI)

Project Summary

This grant facilitates the acquisition of Electron Back Scatter Diffraction (EBSD) and Forward Scatter Detector hardware and software. The instruments will be installed on an existing modern scanning electron microscope (SEM) equipped with energy-dispersive spectrometery (EDS) in the Department of Geology at Bowdoin College. The instruments will expand the scope of research and research training at three institutions of higher learning: Bowdoin College, Middlebury College, and the University of Maine at Orono. Prof. Rachel Beane of Bowdoin College, who has experience with EBSD techniques and analysis, is the Principle Investigator and responsible for the operation and use of the EBSD system.

In geology, EBSD systems are becoming increasingly powerful tools for the observation and analysis of microstructures and for phase identification. The EBSD system uses backscattered electrons (BSE) emitted from a specimen in a SEM to form a diffraction pattern that is imaged on a phosphor screen. Analysis of the diffraction pattern allows identification of the phase and its crystal lattice orientation. The scanning and mapping capabilities of the system permit rapid acquisition of data, from polished rock thin sections, at sub-micron resolutions. Among other uses, these data may be applied to evaluate crystallographic preferred orientations (CPO) of mineral fabrics, and to examine misorientation axes and angles that may signify processes such as subgrain development and dislocation creep.

The relatively new capabilities of EBSD systems are allowing geologists to test existing nucleation, growth, and deformation models for minerals and rocks, and to develop new ones. Researchers at Bowdoin College, Middlebury College, and the University of Maine will use the EBSD system to model grain-scale processes such as dislocation creep, coalescence of multiple-nucleation centers, recrystallization, and rotation of garnets; to examine the accommodation of strain in rapidly growing plutons; to evaluate controls on the orientation of micas in metapelites; and to interpret microscale processes associated with strain development across fault zones. These types of research projects are not possible with the current instrumentation at these institutions, or elsewhere in the area.

The instrument will serve as a vehicle to educate student and faculty researchers about EBSD technology and its potential. Students will use this cutting-edge technology in their courses and for research projects. Then, when they move on to advanced degree programs or careers in the sciences they will be able to use the experience and knowledge to better advance research in their discipline. Because the EBSD system is well suited for application towards a range of problems and for analysis of various samples, the installation of the instrument is expected to catalyze new approaches to research for scientists in the area, and to encourage collaborative research.

3a) Results from Prior NSF Support for Instrumentation

NSF 99-51390 *$100,000, July 1, 1999 - Jun 30, 2002. "Improving undergraduate learning through use of a low-vacuum scanning electron microscope (LV-SEM) with an energy dispersive x-ray spectrometer (EDS)."*

A LEO 1450 VP-SEM and an EDAX-EDS were installed at Bowdoin College in November 1999. *(Note: VP = variable pressure, and is another term for LV = low vacuum.)* In January 2000, twelve faculty members from geology, biology, chemistry, anthropology, and arctic studies participated in a three-day on-campus training course offered by LEO. In June 2000, I took a one-week microanalysis course at EDAX.

Undergraduate student use of the instrument, both in and out of class (curiosity driven use), has been enthusiastic. From Fall 1999 – Spring 2002, the VP-SEM/EDS was used in several undergraduate courses: Geo 100 (comparison of marine sediments), Geo 101 (exploration of crystal form and mineral chemistry; investigation of sand sampled during beach study, investigation of mineral compositions from igneous dikes), Geo 103 (comparison of diatoms between two ponds), Geo 202 (3 labs on mineral chemistry), Geo 219 (identification of conodont specimens), Geo 241 (examination of microstructures), Geo 262 (use SEM for petrologic study), Bio 216 (characterizing nematode morphological differences), Chem 210 (material analysis), Chem 310 (advanced material analysis), and Classics 302 (multiple sessions for ancient coin analysis).

In addition to its classroom uses, the availability of the instrument has provided other benefits. I have used the instrument for x-ray maps and mineral analyses for my research. Twelve geology students have used the instrument for independent study or senior honors thesis research. Many of these projects have been presented at regional meetings, and several are being prepared for publication. Two biology students have used the instrument for honors thesis research, and one of the student's work is in review for publication. The excitement of the new instrument, and its location in the center of the science building, have contributed to drawing students and faculty to the VP-SEM/EDS laboratory.

Publications resulting from NSF 99-51390: **denotes undergraduate student author*

Van Vleck, H.* and Beane, R., 2002. Geochemical Comparison of Mafic and Ultramafic rocks in the Hurricane Mountain Melange and in the Boil Mountain Ophiolite Complex, west-central Maine. *Atlantic Geology*, v. 37, p.

Beane, R. J., 2002. Using EBSD analysis to interpret garnet microstructures. *Geological Society of America, Abstracts with Programs*, v. 34, no. 1.

Szramek, L.* and Beane, R. J., 2002. Correlation and stratigraphy of exotic blocks in the Vinalhaven Pluton, Maine to the Seal Cove Formation. *Geological Society of America, Abstracts with Programs*, v. 34, no. 1.

Beane, R. J., 2001. Using the scanning electron microscope for discovery based learning in undergraduate courses. *Geological Society of America, Abstracts with Programs*, v. 33, no. 6.

Lawrence, K. E.* and Beane, R. J., 2001. Geochemistry of the metamorphosed Spring Point and Cushing Formations. *Abstracts with Programs, Geological Society of America,* v. 33.

Meyer, E. E.* and Beane, R. J., 2001. A petrographic study of the Spring Point Formation, Casco Bay, Maine. *Abstracts with Programs, Geological Society of America,* v. 33.

Taylor*, P. B. and Shapiro, R. S., 2000. Petrographic and S.E.M. Examination of Lacustrine Stromatolites of the Upper Carboniferous (Westphalian D) Morien Group, Sydney Coal Fields, Cape Breton Island, Nova Scotia, Canada. *Abstracts with Programs, Geological Society of America* v.32, p. 77-78 .

Thomas*, D. W. and Beane, R. J., 2000. Deformation of the Hurricane Mountain Formation Mélange along Tomhegan and Cold Streams, west-central Maine. *Abstracts with Programs, Geological Society of America* v.32, p.78.

Note: Two additional journal manuscripts have been submitted for publication, and three more are in preparation for submission in the next two months.

3b) Research Activities

Background

Electron Backscatter Diffraction and Orientation Imaging Microscopy (EBSD/OIM) are powerful petrologic tools with great potential to revolutionize our understanding of the microscale processes involved in the nucleation, growth, and deformation of minerals. An EBSD/OIM system is attached to a scanning electron microscope (SEM) to allow in-situ determinations of crystal lattice structures and orientations. The EBSD/OIM system uses backscattered electrons (BSE) emitted from a specimen to form a diffraction pattern that is imaged on a phosphor screen. The system, among other features, measures crystallographic preferred orientation (CPO) of minerals as small as 1um, maps orientations of grains in a specimen, plots the orientations on pole figures, and calculates misorientation axes and angles between any two points.

Geologists are increasingly publishing research applying EBSD techniques to problems such as "the effects of microstructures on intragrain argon isotope ages” (Reddy et al., 1999), the "development of garnet porphyroblasts by multiple nucleation" (Spiess et al., 2001) and "plastic deformation of metamorphic pyrite" (Boyle et al., 1998). During her sabbatical last year, Prof. Beane was a Research Fellow at the University of Liverpool working in D. Prior's EBSD laboratory. During her visit, she collected data for a couple projects (Beane and Prior, 2002; Beane and Prior, in review), and recognized the advantages and potential of EBSD research.

An EBSD/OIM system has several advantages over other petrologic tools, for example: 1) it allows crystallographic preferred orientation (CPO) measurements of minerals too small for measurement on a U-stage, and obtains the CPO measurements more rapidly; 2) it allows insight into the micro-structures of isotropic minerals such as garnet, 3) it determines crystallographic lattices of minerals in thin section - without powdering for traditional X-ray diffraction methods; and 4) it permits crystal lattice data to be collected and mapped at the same time as mineral chemistry data for phase identification and for interpretation of variations. These enhanced capabilities are allowing researchers to test existing nucleation, growth, and deformation models, and to develop new ones (c.f. Daniel et al., 1999; Prior et al., 1999; Lee et al., 2002).

Participants

The electron backscatter diffraction laboratory will be used by a collection of scientists and students from three regional institutions: Bowdoin College, University of Maine at Orono, and Middlebury College. The EBSD/OIM system will be attached to the new SEM at Bowdoin College. Currently there is no college or university in Maine that has an EBSD/OIM system. The EBSD/OIM system will greatly enhance our research capabilities, complement the new electron microprobe facilities at the University of Maine (NSF #0116235), and introduce students to a new method of exploring crystallography. Below is a compilation of the research interests of the scientists who will use the facility, and a description of how the EBSD/OIM system will be used in their work.

Name	**Institution**	**Research Area**	**Application**
1 Rachel Beane	Bowdoin	Metamorphic Petrology	Interpretation of garnet microstructures
2 Scott Johnson	U. Maine	Petrology/Structure	Strain partitioning in rapid growth granitoids
3 Charles Guidotti	U. Maine	Mineralogy	Controls on mica orientation
4 Rachel Beane	Bowdoin	Structural Geology	Strain development across fault zones
5 David West	Middlebury	Structural Geology	Strain development across fault zones

1. Interpretation of Garnet Microstructures in Amphibolite- and Eclogite- facies Metamorphic Rocks: Rachel Beane, Assistant Professor of Geology, Bowdoin College.

Prof. Beane is a metamorphic petrologist who has involved eight undergraduates in research over the past four years. During a junior faculty leave (2001), she used an EBSD system in collaboration with D. Prior and J. Wheeler at the University of Liverpool to begin investigations of garnet microstructures. Garnet is used, routinely, to interpret the pressure-temperature-time paths of amphibolite, eclogite and other metamorphic rocks. The assumption generally applied in these interpretations is that garnet grains grow from core to rim, and a core to rim traverse of a garnet grain and its inclusions will represent successive time slices in its growth history. Recent studies seem to bring this assumption into question for some metamorphic rocks, and integrated EBSD/EDS research may provide needed insight into mineral nucleation, growth, recrystallization, and diffusion mechanisms that affect garnets.

Several researchers (c.f. Daniel et al., 1999; Prior et al., 2001; Spiess et al., 2001) have used EBSD data to approach microstructural questions in garnet. At the University of Liverpool, Beane began her investigation with atoll garnets, from eclogite, where faceted rings of garnet surround a "lagoon" of other phases and subhedral "islands" of garnet. The EBSD data showed that the islands of garnet have exactly the same orientation as the atoll ring that surrounds them. In order to have identical orientations, and to be consistent with other textural observations, the garnet ring and islands likely shared a single nucleation point. Then, the garnet and inclusions were redistributed by diffusion to form the atoll shape, resulting in decreased surface to volume ratio, and lowered interfacial energy (Beane and Prior, in review). Beane's next project examined elongated garnets, from amphibolite in Casco Bay, Maine, with a 4:1 length to width ratio. EBSD analyses revealed a dispersion of lattice orientations about a <100> axis, with almost no subgrain boundary development. The data were interpreted to suggest the garnet may have underwent crystal plastic deformation at relatively low temperatures (c. 550 deg C) (Beane and Prior, 2002). The results of the previous studies by Beane and other researchers, combined with the variety of garnet microstructures observed in nature, suggest much more data is needed to fully understand the processes that affect garnets, and the crystallographic responses of garnets to various temperature and stress conditions.

The acquisition of an EBSD system will substantially impact the research activities of Prof. Beane and her students. Initially, it will allow Beane to continue her studies of garnet microstructures and to pursue questions regarding strain development across a fault zone in Maine (see "4"). Through field research in Russia, Greece and Maine, Beane has collected eclogites and amphibolites hosting garnets with various textures (atoll, sector, stretched, spiral, inclusion-free and inclusion-prominent…) that will provide a good foundation for the investigations. Beane and her students will use the integrated EBSD/EDS system to address the following basic questions: Are there variations in mineral chemistry or crystal lattice orientation that accompany the observed garnet microstructures? And, if so, what does this suggest about the mechanism of formation and, in some cases, deformation?. More specifically, the EBSD system will allow crystallographic observations, through collection and analysis of orientation maps, such as the development of subgrain boundaries, dispersion of lattice orientations around specific axes, boundary and interface misorientations, and any preferential orientation of garnet within a sample; and, the EDS system will allow observations regarding chemical zoning or other variations in crystal chemistry. These combined observations will then be used to model grain-scale processes such as dislocation creep, coalescence of multiple-nucleation centers, recrystallization, and rotation.

2. Accommodation of Strain in Rapidly Growing Plutons: Scott Johnson, Associate Professor of Geology, University of Maine at Orono.

Prof. Johnson is a structural geologist who is currently advising five graduate students; his research integrates aspects of petrology and structural geology, and he frequently conducts microstructural studies. He is currently conducting microstructural analyses on a tonalite pluton that has a carapace of solid-state deformation around its margin. Careful structural mapping and SHRIMP U-Pb work on zircon suggest that the tonalite is "post tectonic" (Johnson et al., in press). This is significant, because it indicates that the solid-state carapace was formed during emplacement, as opposed to being formed in a later, regional deformation overprint.

The pluton carapace preserves a beautiful progression of completely undeformed tonalite to mylonitic tonalite. The mylonitic foliation begins as discrete microshear zones that coalesce to form the foliation. These microshear zones are lined by fine-grained biotite, feldspar and quartz derived from the coarse-grained original minerals. Johnson will use the EBSD system to evaluate the accommodation of strain in these microshear zones at different stages in their development. Much recent work indicates that the growth of plutons occurs at very rapid rates (c.f. Johnson et al., 2001). Thus, the carapace around the tonalite pluton MAY have been deformed at rates as high as 10^{-7} s^{-1}, six orders of magnitude faster than regional tectonic rates. The problem is, if these fast rates really do occur, how do we recognize the microstructural evidence for them? The proposed EBSD studies will provide essential information about the deformation mechanisms operating in the microshear zones, that will help to explain how very high strain rates may be accommodated in naturally deformed rocks.

In the microshear zone showing solid-state fabrics, forescatter, orientation contrast and color orientation contrast images could be used to identify the smallest, crystallographically coherent sub-domains in quartz and feldspar regions. Orientation image mapping will be used to measure the crystallographic orientation of the sub-domains and to locate the misorientation boundaries between them. By comparing crystallographic preferred orientations to the shape fabrics and macrostructural symmetry, Johnson and his students will assess whether dislocation creep was the dominant deformation mechanism. By comparing correlated, uncorrelated and random misorientation angle distributions they will assess processes that modify grain boundary misorientations, including recovery, subgrain rotation, grain-boundary migration and granular flow. Modeling of microstructural pathways will allow isolation of misorientation and grain-boundary hiearchy signals associated with each of these processes. In samples where evidence for dislocation creep is identified, the boundary misorientation axis distributions and orientation dispersions will be used to constrain applicable slip systems.

3. Controls on the Orientation of Layer Silicates in Metapelites: Charles Guidotti, Professor of Geology, University of Maine at Orono.

Porf. Guidotti is a mineralogist, who advises PhD students, and whose recent research includes examining Maine's metamorphic minerals, and the effect of temperature and pressure changes on micas (c.f. Guidotti et al., 2000). Metapelites in Maine are typically subjected to multiple metamorphic events. Guidotti initially will use the EBSD system to test the extent to which the micas in the metapelites have been reoriented crystallographically as a function of the number of polymetamorphic events, and as a function of the metamorphic grade of the last event.

Next, Guidotti will use the integrated EBSD/EDS system to test the possibility of a significant control by layer silicate crystal chemistry with regard to the ease with which layer silicates become oriented during formation of slates. This is a project on which Guidotti is currently working with European colleagues. There are features in the case of some slates that suggest that within the foliation planes, the b-crystal axes might show a preferred directional orientation relative to the a-axes (roughly at 90 degrees to each other). Pole figure and misorientation data will be used to ascertain any systematically different orientations of the a- and b-axes of these slates. If systematically different orientations are found for the two axes, it would provide strong support for a model suggesting a significant impact by crystallochemical controls on the ease with which layer silicates become oriented during formation of slates.

4&5. Microstructural evidence for strain development across the Norumbega Fault Zone, Maine: Rachel Beane, Assistant Professor of Geology, Bowdoin College and David P. West, Jr., Assistant Professor of Geology, Middlebury College.

Prof. Beane is the PI; Prof. West is a structural geologist who involves 2-3 undergraduates in his research every year. The Norumbega Fault Zone, well-exposed in Maine, is one of the most extensive and longest-lived structures in the Appalachians. West has continued investigating the timing of displacement along the Norumbega Fault Zone and the resulting deformation since his graduate work at University of Maine at Orono (c.f. West, 1999; West and Hubbard, 1997). He conducts summer field research in Maine with his students every year. Beane, West and their students will conduct sampling traverses across the Norumbega Fault Zone, where significant strain gradients are observed across the fault zone. The EBSD system then will be applied to provide much needed quantitative crystallographic preferred orientation (CPO) data, and to provide insight into how deformational mechanisms vary as a function of the strain gradient.

As an example of how this project will proceed, Beane currently is supervising an undergraduate's independent study to investigate progressively strained samples of Deblois Granite from the Kellyland Fault in the northern portion of the Norumbega Fault Zone. Strain indicators observed under a petrographic microscope have been recorded, and collection of EBSD data is underway. Given time constraints, this student's project likely will conclude with the presentation of CPO data for quartz, feldspar, hornblende and mica in the sample. Additional data analysis then will be needed to interpret the mechanisms of deformation, such as: Is there evidence for dislocation creep? Do misorientation angles suggest the development of subgrains? Is there evidence for unstrained mineral lattices that might indicate that strain in the rock was accommodated by recrystallization? These are the types of questions that we will continue to address as this project proceeds.

West also will pursue a related project in which he has had a long-standing interest. He will investigate the deformational mechanisms that prevail in what appear to be “low temperature mylonites” along the Norumbega fault system. Several years ago these anomalously low temperature (< 250°C) mylonites were identified through a combination of $^{40}Ar/^{39}Ar$ thermochronology and microstructural analysis – however, an accurate characterization of the rocks could not be completed due to their fine-grained and polymineralogic nature. The EBSD system is ideally suited for examining the fine grains, and the results will provide important constraints on the temperatures at which various deformational mechanisms are operative.

Research Training Activities

The principle use of the EBSD system will be in faculty-directed research, which includes the active participation by undergraduate and graduate students. Undergraduates at Bowdoin College and Middlebury College, and graduate students at University of Maine-Orono will use the instrument in connection with the research projects described above. (Currently the PI is advising a student in a project using the EBSD system that is on loan; the ease with which the student is learning to operate the instrument and analysis software suggests the EBSD system is well suited to student use.) In addition, Bowdoin College undergraduates in mineralogy, igneous and metamorphic petrology, and structural geology courses will use the SEM/EDS/EBSD system to pursue mini-research projects in their courses. The integration of research into these courses is already being established and supported through the PI’s ongoing NSF-CCLI grant (#0126234). Students in the sciences at Bowdoin College present research from their independent-study projects and course work at interdisciplinary poster sessions once a semester. Students in the Geology Department also routinely present their research at the regional Geological Society of America meetings and the Geological Society of Maine meetings.

3c) Research Instrumentation and Needs

The instrument that will best serve the research needs described above is the TSL/EDAX OIM and Delphi Combined System (PV1300/00). This is a complete system for Orientation Imaging Microscopy and Phase Identification using EBSD. This system will integrate with the EDAX

EDS system that is currently attached to Bowdoin College's SEM to form what the company calls the Pegasus system. The simultaneous collection of EBSD and EDS data improves the speed and accuracy of processing the multiple phases present in most rocks. It also allows for comparison of changes in crystal chemistry and orientation for research, as described in some of the projects above. A further advantage of the TSL/EDAX Pegasus system is that there is a single user interface for the EDS and EBSD systems; this simplifies use and reduces the training required for the multiple users in the laboratory.

The PI has used two of the leading companies', TSL/EDAX and HKL, EBSD systems in her research. Both systems collected and indexed EBSD patterns well. One advantage of the TSL/EDAX system is the integration of EDS and EBSD data collection and processing with the Pegasus system. The other advantage is that TSL/EDAX has the OIM/EBSD system (integrated with the existing EDS system to form Pegasus) on loan to Bowdoin College for six months. The PI and the department's laboratory instructor, Ms. Catherine Field, as well as some undergraduates already will be familiar with this instrument and software by the time the grant begins. This familiarity will eliminate the start-up time that typically accompanies the installation of a new instruments to get them operational so that research projects can be initiated.

The TSL/EDAX Orientation Imaging Microscopy (OIM) and Delphi combined system will be purchased with a Forward Scatter Detector System, with a DigiView1612 CCD Camera and interface, with OIM Data Collection and Analysis software, with Delphi Electron Diffraction Phase Identification Software, and with the American Mineralogical Database. With the high specimen tilt (70°) required for EBSD pattern detection, the backscatter-electron (BSE) detector is not functional, and navigation around a rock thin section becomes near impossible; the Forward Scatter Detector System allows for ready navigation, and it provides orientation contrast imaging that can be used on its own or to guide the selection of points and map areas for pattern collection. The DigiView camera and phosphor coating provide quality patterns suitable for indexing. The OIM Data Collection software allows for automatic or interactive indexing of EBSD patterns, based on Hough transforms, for single points or mapped regions. The OIM Analysis software allows the creation of maps, charts and plots required to analyze the collected data for the described research projects, including the following: pole figures, inverse pole figures, Euler maps, phase maps, Taylor and Schmid factor maps, and misorientation boundary maps and charts. The Delphi Electron Diffraction Phase Identification Software uses the EBSD pattern, EDS data (if collected), TSL database and American Mineralogical Database to identify phases in all seven crystal systems. The range of options included with the OIM/Delphi EBSD system will permit it to be versatile enough to meet the needs of multiple researchers.

3d) Impact of infrastructure projects

Science at Bowdoin College

Bowdoin College is a highly selective four-year liberal arts and sciences college with approximately 1600 undergraduates and 140 faculty. It is consistently ranked in the top ten of national liberal arts colleges by *U.S. News and World Report.* Science faculty at Bowdoin College have a three course per year teaching load, and have active research programs that encourage and depend upon undergraduate student activity in their laboratories.

Bowdoin College has excelled at preparing undergraduate students in the sciences, going back to the College's first science curricula, designed in the 1800s by Professor Parker Cleaveland, a noted mineralogist. Currently, Bowdoin College produces science graduates at a rate almost twice the national average. Each year, approximately thirty percent of our graduates major in the natural sciences and mathematics, and more than 50 percent go on to graduate and professional school. Eighty percent of our science students undertake a faculty-guided research project, and approximately half of the publications by science faculty are co-authored by undergraduates. Bowdoin College ranks in the upper ten percent of small colleges and universities in terms of the number of graduates who go on to receive Ph.D.s in science. More specifically, Bowdoin ranks 34th in the number of Ph.D.s (157) produced in the sciences, a disproportionately large number given our rather small student body.

The college is committed to faculty and student research activities. In 1997, Bowdoin College completed a new science facility (funded in part by NSF grant STI #9313422) that is well-suited for modern analytical equipment, and houses the departments of chemistry, biology, and geology. Furthermore, the college has shown its support by the three-course teaching load for laboratory science faculty, by the hiring of laboratory instructors and instrument support personnel in the sciences, and by supporting the maintenance of high-end instrumentation.

Impact on Research and Education

The proposed EBSD system will have a significant impact upon the PI and her ability to pursue quantitative microstructural studies. Indeed, the research of each of the senior personnel will benefit from this cutting-edge instrumentation, and the published results of their research potentially will impact the geologic community at large. One of the challenges of carrying out research at a small, undergraduate institution is the more limited opportunity to gain access to instrumentation that is at the cutting-edge of gaining recognition as a widely applicable analytical tool. The EBSD system will give both faculty and students experience with an advanced analytical technique, and allow them to approach microstructural problems and test models in ways they would otherwise be unable to pursue. Housing the EBSD at Bowdoin College also will foster collaborations between researchers there and those at other institutions who come to use the instrument.

Furthermore, the purchase of the EBSD system addresses one of NSF's goals: to integrate current technology and research with education. As described previously under "Research Training," undergraduates at Bowdoin College and Middlebury College, and graduate students at University of Maine-Orono will use the instrument in connection with the research projects and course laboratories. Recent pedagogical studies and reports (c.f. Holliday, 1996; Mogk, 1993; NSF, 1996; NSF 1997) recommend that undergraduate courses create opportunities for students to "do" science by engaging in research activities that provide them with life-long learning skills in problem-solving, quantitative reasoning, and communication. In essence, science and the skills learned by "doing" science are integral to everyone's life, regardless of background or (future) occupation. Integration of EBSD techniques and research into the undergraduate courses should provide ample opportunity for students to make discoveries and "do" science. In addition to integrating research projects into the mineralogy, petrology, and structural geology courses, this spring Prof. Beane is beginning to develop exercises and laboratories using the EBSD system to teach crystallography in the mineralogy course. The application of EBSD techniques and imaging has the potential to be a new and valuable method of teaching crystallography in mineralogy courses that will be right in line with the current pedagogical emphasis on "hand's on" and "exploration" learning. She plans to refine the exercises over the next couple years and submit the results for dissemination through DLESE (Digital Library for Earth System Education) and the Journal of Geological Education.

3e) Project and management plans

Instrument Maintenance and Support

Bowdoin College is committed to the acquisition and maintenance of advanced research instrumentation in the sciences. During the two years of the grant, a yearly maintenance contract is budgeted in the proposal. After that, the college will budget to support expenses, including the yearly maintenance contract. The EBSD system will be installed in the climate-controlled SEM laboratory in the new Science Center at Bowdoin College. This room is located on the main floor of the Science Center, and is easily accessible to students and faculty.

The PI will be responsible for overseeing the operation, maintenance and training for the new instrument. Prof. Beane has been responsible for the SEM for the past four years. Ms. Catherine Field, a Department of Geology Laboratory Instructor, has assisted in the operation, maintenance and training for the SEM for the past two years, and will continue in this role for the EBSD system.

Instrument Use Policy and Schedule

Use of the SEM is currently scheduled on Meetingmaker and by posting calendar sheets on the laboratory door. At present, time preference is given to course laboratories, and there has been ample time for individual researchers to use the instrument. Instrument use is anticipated to increase with the addition of the EBSD. Before each semester and summer, the PI will ask all users – including those from other institutions – of their intended use of the instrument, and preferred schedule. These "prior commitments" will receive preference, with additional use scheduled around these commitments. In case of potential scheduling conflicts, decisions will be made to ensure equitable time allocation among interested users, to achieve a mix of independent users with users that require more assistance from the PI and Ms. Field, and to encourage projects that involve students in research collaborations.

User Training

Prof. Beane has previously taken an EBSD short-course taught by D. Prior at the University of Liverpool, and has used EBSD systems in her research. Further training by TSL is provided in the cost of the instrument. Through TSL materials, including information on their website and a CD with tutorials, Beane will train Field, and other primary users, in the operation of the instrument and analysis software. (Because TSL currently is loaning Bowdoin College an EBSD system, much of this training will be completed prior to the start of the grant.) Training will include the principles of operation, sample preparation, instrument use, and data analysis. Users, both senior personnel and students, will be required to be certified for competence by Beane and Field before they use the SEM/EBSD system. This approach has worked well for the SEM to date. Beane and Field are committed to work more closely with researchers who will use the instrument less frequently. Beane and Field also plan to establish a Bowdoin College web site where protocols, methods, and links are available. This web site will display results from users to foster communication, and to stimulate ideas for further research applications of the instrument.

Beane, R. J. and Prior, D. J., in review. Crystallographic orientation evidence for the formation of atoll garnet in eclogite. Geology.

Beane, R. J. and Prior, D. J., 2002. Using EBSD analysis to interpret garnet microstructures. Geological Society of America, Abstracts with Programs, v. 34, no. 1.

Boyle, A. P., Prior, D. J., Banham, M. H. and Timms, N. E., 1998 Plastic deformation of metamorphic pyrite; new evidence from electron-backscatter diffraction and forescatter orientation-contrast imaging. Mineralium Deposita, v.34, p. 71-81.

Daniel, C. G., Prior, D., Spear, F. S., Hirsch, D. and Carlson, W., 1999. Testing the model of multiple nucleation sites for complexly zoned garnet: an application of electron backscatter diffraction and orientation contrast imaging. Geological Society of America, Abstracts with Programs, v. 31, p. 168-169.

Guidotti C.V., Sassi F.P., Comodi P., Zanazzi P.F., and Blencoe J.G., 2000. The contrasting responses of muscovite and paragonite to increasing pressure: petrologic implications. Canadian Mineral 38, 707-712.

Holliday, W.G., McMahon, M.M., and Ridky, R. W., 1996. Straight talk about research to geoscience teachers. Journal of Geoscience Eduction, v. 44, p.54-56.

Johnson, S.E., Fletcher, J.M., Fanning, C.M., Vernon, R.H., Paterson, S.R. and Tate, M.C., in press, Structure and emplacement of the San José tonalite pluton, Peninsular Ranges batholith, Baja California, México. Journal of Structural Geology.

Johnson, S.E., Albertz, M. and Paterson, S.R., 2001. Growth rates of dike-fed plutons: are they compatible with observations in the middle and upper crust? Geology, v. 29, p. 727-730.

Lee, Kyung-Ho; Jiang, Zhenting; Karato, Shun-ichiro , 2002. A scanning electron microscope study of the effects of dynamic recrystallization on lattice preferred orientation in olivine. Tectonophysics, vol.351, p.331-341.

Mogk, D.W., 1993. Undergraduate research experiences as preparation for graduate study in geology. Journal of Geological Education, v. 41, p. 126-128.

NSF, Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology (NSF 96-139), Arlington, VA, 1996.

NSF, Directorate for Geosciences. Geoscience Education: A recommended Strategy (NSF 97-171).

Prior, D. J., Boyle, A., Brenker, F., Cheadle, M., Day, A., Lopez, G., Peruzzo, L., Potts, G., Reddy, S., Spiess, R., Timms, N., Trimby, P., Wheeler, J., and Zetterstrom, L., 1999. The application of electron backscatter diffraction and orientation contrast imaging in the SEM to textural problems in rocksAmerican Mineralogist, v. 84, p. 1741-1759.

Prior, D. J., Wheeler, J., Peruzzo, L., Spiess, R., and Storey, C., 2001. Some garnet microstructures: an illustration of the potential of orientation maps and misorientation analysis in microstructural studies. Journal of Structural Geology, v. 24, p. 999-1011.

Reddy, S. M., Potts, G. J., Kelley, S.P., and Arnaud, N., 1999. The effects of deformation-induced microstructures on intragrain argon isotope ages in feldspars. Geology, v. 27, p. 363-366.

Spiess, R., Peruzzo, L., Prior, D. J., and Wheeler, J., 2001 Development of garnet porphyroblasts by multiple nucleation, coalescence and boundary misorientation driven rotations. Journal of Metamorphic Geology, vol.19, no.3, pp.269-290, May 2001

West, D.P., Jr., 1999. The timing of displacements along the Norumbega fault system, south-central and south-coastal Maine: in Ludman, A. and West, D.P., Jr., eds., The Norumbega Fault System of the Northern Appalachians: Geological Society of America Special Paper 331, p. 167-178.

West, D.P., Jr., and Hubbard, M.S., 1997. Progressive localization of deformation during exhumation of a major strike-slip shear zone: Norumbega fault zone, Maine: Tectonophysics, vol. 273, p. 185-201.