MRI: Acquisition of a Scanning Electron Microscope (SEM) with EDS, EBSD and CL detectors to advance research and undergraduate research training

PIs: Emily Peterman (Principal Investigator) and Rachel Beane (Co-Principal Investigator)

Funded by NSF EAR

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PROJECT SUMMARY

Overview:

This proposal seeks funding for a modern scanning electron microscope (SEM) equipped with a backscattered electron (BSE) detector, cathodoluminescence (CL) detector, energy dispersive spectrometer (EDS), and a fully integrated electron backscatter diffraction (EBSD) system. Equipped with these detectors, the SEM will serve as a primary data acquisition instrument for the PIs and their collaborators. Example applications include: 1) characterization of accessory minerals that record pressure-temperature-time constraints, 2) crystal orientation measurements via EBSD to infer the mechanics of plutonic-volcanic, deformation, and crystal growth processes, 3) determination of compositional zoning and/or domains in rock-forming minerals to track changes in pressure, temperature, deformation, and composition, 4) characterization of deformation microstructures, 5) measurement of the impact of freshwater flow on the carbonate chemistry of estuarine environments, 6) identification of growth bands in deep sea corals, 7) determination of the origin of artefacts in the Artic, and 7) evaluation of metallurgy and the circulation routes of ancient coins. In addition to acquiring data with the SEM to address research question, the PIs will also provide research training for undergraduates using the SEM at Bowdoin College, a primarily undergraduate institution. Research projects will train students in the application of modern analytical techniques to original research questions in Earth Science and enhance the infrastructure for research across disciplines at the College.

Intellectual Merit :

The proposed research activities will leverage the high spatial resolution of the SEM and the ability to simultaneously acquire multiple datasets (i.e. geochemistry and crystal orientation) to investigate a variety of mineralogic, petrologic, and tectonic questions. Selected research questions include: what controls the preservation of ultrahigh-pressure mineral assemblages? What do quartz and feldspar textures indicate about silicic magma reservoirs? What is the link between plutonic and volcanic processes? What is the timing and tempo of strain localization along strike-slip faults? Exciting new insights into the mechanics of these large-scale processes may be gained by examining minerals and rocks at the micrometer-scale. The new capabilities of the instrument will also address critical questions in carbonate chemistry (e.g. the impact of freshwater on clamshell strength and the development of growth bands in deep sea corals) and archaeology in both the Arctic and the Greco-Roman world.

Broader Impacts :

Acquisition of the SEM will enhance the infrastructure for research and teaching at Bowdoin College, broaden the participation of traditionally underrepresented groups and develop scientific literacy and training of undergraduates. Specifically, the SEM will provide research training for students who will benefit from multiple analytical sessions using the SEM. Access to the enhanced SEM on campus will strengthen the research programs of five faculty members, including two early career female faculty and contribute to incorporating SEM-based student research in courses, independent studies and honors projects. The PIs will specifically focus on broadening the participation of underrepresented groups by partnering with the Bowdoin Science Experience (BSE) Program. This pre-matriculation outreach program targets underrepresented undergraduate students through a 3-day science immersion program. In association with the new instrumentation, PIs Peterman and Beane will offer a research project that is SEM-based. For example, in association with Peterman’s proposed research, BSE students will measure the compositions of the rock-forming minerals in thin section using EDS and collect images of targeted geochronologic minerals (e.g. monazite, zircon and rutile) with the CL and BSE detectors. Students will be offered the opportunity to continue working with their samples as a work-study project. Having access to a SEM with EDS, EBSD and CL capabilities will afford geoscience, chemistry and archaeology undergraduate students the kind of research opportunities normally conducted by graduate students. Based on the numbers in our courses, we expect 75-100 undergraduates to use the instrument each year. Transferable geoscience exercises developed using EDS, BSE, EBSD, or CL data will be submitted to the On the Cutting Edge on-line activity collection (http://serc.carleton.edu/NAGTWorkshops/exemplary.html.

Project Description

a. Information about the Proposal

a1: Instrument location: 108 Druckenmiller Hall, Bowdoin College, Brunswick, ME
a2: Instrument Code: MRI-21

b. Research Activities to be Enabled

This proposal seeks funding for the acquisition of a modern scanning electron microscope (SEM) equipped with a cathodoluminescence (CL) detector, backscattered electron (BSE) detector, energy dispersive spectrometer (EDS) and electron backscatter diffraction (EBSD) system. Microbeam techniques such as these allow geoscientists to obtain detailed observations and measurements to link processes at the micrometer scale to the thin section, hand sample, outcrop, region and plate tectonic scale (e.g. Foster et al., 2002; Kohn and Malloy, 2004; Kohn et al., 2005; Cottle et al., 2009; Janots et al., 2009; Peterman and Grove, 2010a; Ague et al., 2013; Kruckenberg et al., 2013). Such research is enabled by modern instrumentation that combines high spatial resolution with fast throughput and the ability to integrate multiple microanalytical datasets (e.g. EDS, BSE, CL and EBSD).

The proposed instrumentation will 1) advance the research of 3 female faculty members in the Earth and Oceanographic Science (EOS) department at Bowdoin College: early career PI Emily Peterman, co-PI Rachel Beane, and early career faculty Michèle LaVigne, 2) facilitate undergraduate research training through courses and independent projects, 3) enhance research by faculty in the Arctic Studies, Archaeology, and Chemistry departments (see *Letters of Collaboration*), and 4) foster external research collaborations (see *Letters of Collaboration*). As described below, projects #1 – 4 feature some of the geoscience research that will be advanced by this instrumentation, projects 5 & 6 highlight oceanographic research, and projects 7 & 8 describe archaeological research.

Project #1: *Measuring the P-T-t path of metamorphic tectonites from the Northern Appalachians*: *the first UHP locality in North America?* PI Emily Peterman (Bowdoin) & Michael Williams (UMass)
A suite of complexly folded and boudinaged garnet-kyanite schists, garnet amphibolites, garnet-gedrite-tourmaline schists, and K-feldspar augen gneisses crop out along the western margin of the Goshen Dome, located in western Massachusetts. The diverse compositions of these rocks, their close proximity, and the presence of consistent top-to-the-North shear sense indicators among all lithologies indicate that they were structurally juxtaposed, the timing of which has not yet been measured. The garnet-kyanite schists contain restitic garnet megacrysts (3 to 5 cm in diameter) with phosphatic cores (>0.18 wt. %), crystallographically controlled rutile, and abundant zircon inclusions with radiating fracture patterns (Peterman et al., 2013). These unique features found exclusively in the relict garnet megacrysts have been interpreted to represented ultrahigh-pressure (UHP) metamorphism (Snoeyenbos et al., 2011); the timing and precise determinations of pressure-temperature (*P-T*) conditions of metamorphism are primary targets of Peterman's research. The relict garnet megacrysts are included in a reconstituted matrix of biotite, cordierite, plagioclase, quartz, muscovite, chlorite, and multiple generations of kyanite, which suggests re-equilibration at mid-crustal conditions. Importantly, monazite, rutile and zircon exist in a variety of petrographic contexts (i.e. as inclusions in garnet and kyanite, within the matrix) in *all* of these lithologies, thus providing an opportunity to link each of these metamorphic processes with time to yield an integrated pressure-temperature-time (*P-T-t*) history of these rocks.

Intellectual Merit: This research addresses two fundamental questions. **(1)** What controls the preservation of UHP assemblages? Many UHP assemblage rocks appear volumetrically scarce because they are overprinted during exhumation (e.g. Walsh et al., 2007; Gilotti et al., 2013), but the schists in this field area preserve evidence of metamorphism at multiple *P-T* conditions. This research capitalizes on this rich preserved history and will examine what controls the preservation vs. overprinting of UHP assemblages. **(2)** Can UHP terranes exhume through the subduction channel? Numerical models suggest that this is possible, but no reported UHP terrane "shows the degree of mixing of metamorphic pressures that might be considered diagnostic of formation and exhumation within a channel" (Hacker and Gerya, 2013). The range of metamorphic pressures recorded by this locality provides an excellent opportunity to evaluate the exhumation path of this terrane. Furthermore, because the rocks analyzed by this research preserve both prograde ***and*** retrograde assemblages, their *P-T-t* paths can be directly measured. Addressing these research questions requires combining detailed textural analysis of thin sections on the SEM with *in situ* geochemistry and geochronology of both accessory and rock-forming minerals.

How Instrumentation Advances Research: The research will rely upon all capabilities of the proposed instrument: BSE mapping, BSE/EDS analysis, CL imaging, and EBSD crystal orientation. First, full thin section scans will be generated using BSE (e.g. **Fig. 1**); the integrated BSE/EDS system will then be used to locate minerals suitable for geochronology, geochemistry, and thermobarometry (i.e. monazite, zircon, rutile, quartz). Because full thin section scans locate *all* grains, regardless of size, this approach eliminates the inherent bias in manual scanning. BSE imaging and EDS analysis will be used to map compositional domains within monazite grains; these maps will be used to guide the placement of spot locations for laser ablation ICP-MS analysis. The CL

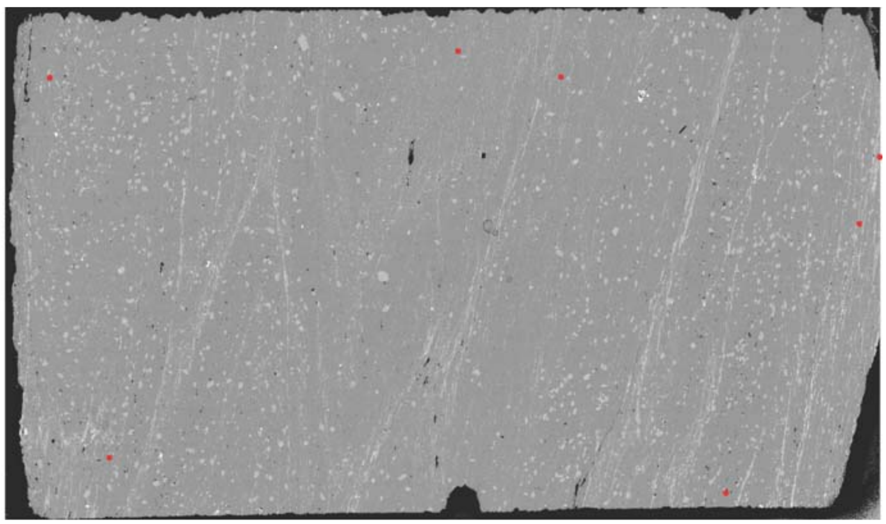

Fig. 1 *Full thin section BSE scan of a mica-rich quartzite (sample 3130B) from the base of a thrust fault in Massachusetts. Red dots (n = 7) mark the locations of monazite grains that will be analyzed via laser ablation ICP-MS.*

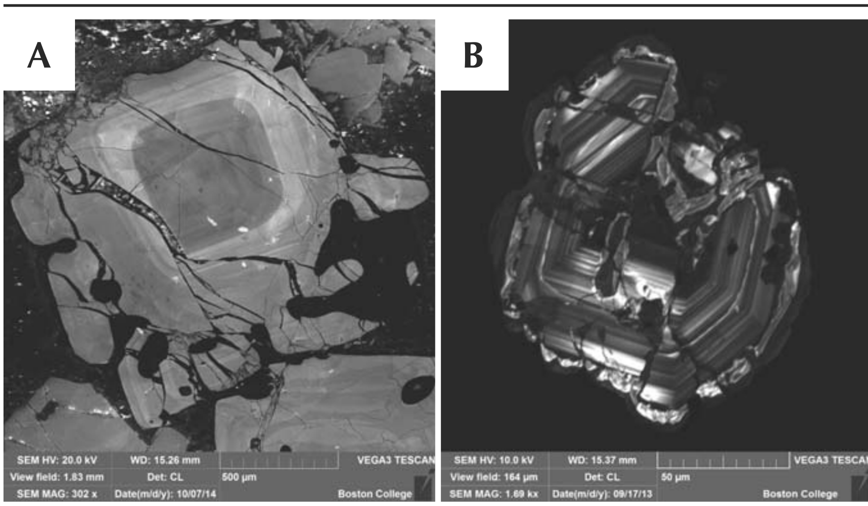

Fig. 2 *CL images.* ***A)*** *CL zoning in quartz. Image acquired by R. Haynes (Bowdoin) for her undergraduate honors thesis with PI Beane—see Project #3.* ***B)*** *Magmatic CL zoning in a zircon core rimmed by complex CL zoning. Peterman et al., (2013) used CL images to guide laser ablation analyses. Peterman acquired this CL image during the SEM evaluation process.*

detector will be used to image zoning patterns in quartz (**Fig. 2A)** and zircon (**Fig. 2B**). In quartz, the intensity of cathodoluminescence (CL) is used as a proxy for Ti concentration, which is interpreted as a function of crystallization temperature (e.g. Wark and Watson, 2006; Peterman and Grove, 2010a; Thomas et al., 2010; Spear et al., 2012). In zircon, CL zoning commonly preserves evidence of multiple thermal pulses and phases of igneous and/or metamorphic growth (e.g. Gebauer et al., 1988; Corfu et al., 2003; Hoskin and Schaltegger, 2003). For example, magmatic zircon is characterized by oscillatory zoning that reflects minor changes in the trace element composition during crystallization (core of grain in **Fig. 2B**). Complex CL zoning usually indicates multiple phases of igneous and/or metamorphic growth (**Fig. 2B**). In this research, CL zoning patterns in both quartz and zircon will be used to guide locations for *in situ* analyses: Ti-in-quartz for thermometry and laser ablation ICP-MS of zircon for geochronology and geochemistry. These data will be used to quantify components of the *P-T-t* path of these anomalous rocks, as recorded by these minerals.

The electron backscatter diffraction (EBSD) system will be used to determine crystal orientations of garnet, kyanite and quartz within these samples. Because lattice planes within minerals diffract electrons in predictable patterns, acquired diffraction patterns (Kikuchi bands) are compared to patterns modeled from known lattice parameters using a kinematic electron diffraction model to index the acquired patterns (Schmidt and Olesen, 1989, Prior et al., 1999). These indices are used to identify minerals and to determine their 3D orientations. The orientation relations between and within grains, as well as the lattice preferred orientations of grains within rocks, yield interpretable information for a variety of processes (Prior et al., 1999; Prior et al., 2009). Because these rocks in this research project preserve multiple generations of garnet and kyanite that exhibit distinct morphologies and petrographic contexts (Peterman et al., 2014a), EBSD analysis will be a critical tool for unraveling the metamorphic and deformation history. Following the methods of Robyr et al. (2009), Peterman and her students will integrate compositional EDS maps of garnet with EBSD misorientation maps to interpret garnet growth and deformation histories. Peterman will use EBSD to investigate garnet microstructures that commonly yield

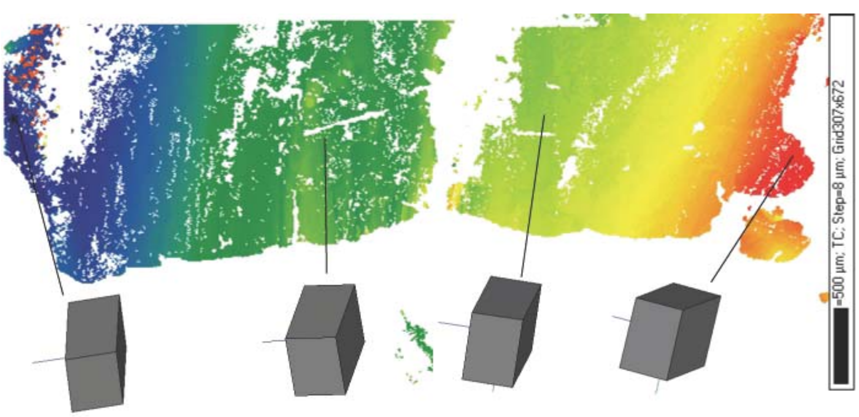

Fig. 3 *Orientation map of undulatory kyanite with misorientation scaled from 0° (dark blue) to 50° (red) relative to the orientation of the leftmost side of the grain. The 3D crystals show orientations as viewed looking down on the thin section. Data acquired and map processed by Beane using Channel 5 software (Figure is Fig. 4 from Beane and Field, 2007).*

insight about the mineral reaction and deformation processes that accompany metamorphism (Spiess et al., 2001; Terry and Heidelbach, 2004; Storey and Prior, 2005; Whitney et al., 2008). Peterman will also measure the crystallographic orientations within kyanite (**Fig. 3**) to investigate the strain conditions that accompanied kyanite growth and deformation following the methods of Beane and Field (2007). Lastly, Peterman will explore the effect of misorientations within zircon on geochemical variation observed in initial data collected from these samples. Previous EBSD studies have revealed dislocations in zircon that act as fast diffusion pathways (Reddy et al., 2006; Timms and Reddy, 2009), thus explaining some variation; this research will test whether this phenomenon is observed in these samples.

Funding for Above Project: A Bowdoin College Faculty Research Fellowship provides initial support; a collaborative proposal with Williams is pending to NSF EAR Petrology & Geochemistry.

Project #2: *Integrating EBSD/SEM/LASS analyses of garnet-staurolite schists to quantify the timing and rates of deformation: Appleton Ridge, Maine*, PI Emily Peterman (Bowdoin)
Recent advances in the understanding of how strike-slip faults accommodate deformation at the surface and at depth has resulted in detailed studies of fault zones at various depths, lengths, and timescales (e.g. Cole et al., 2007; Gomez-Rivas et al., 2007; Druguet et al., 2009). The Norumbega Fault Zone (NFZ) presents an ideal setting to investigate the mechanics of fault zones because (1) differential exhumation provides a range of structural depths for analysis (e.g. Hubbard et al., 1995), (2) the NFZ extends 350 kilometers, thereby allowing investigators to examine changes in structural style along strike (e.g. Ludman and West, 1999), and (3) low-temperature thermochronology establishes that the NFZ was active from ~280 to 180 Ma (e.g. West et al., 1993).

Intellectual Merit: The Appleton Ridge section of the NFZ, located in central Maine, provides exposures of high-strain rocks that contain cm-scale staurolite grains that record multiple deformation events (Frieman et al., 2013). Monazite grains with multiple growth domains are texturally associated with the staurolite porphyroblasts, thus affording an opportunity to constrain the timing of each of these events. Dating monazite domains associated with each stage of deformation will provide a coherent picture of the timing and tempo of high-strain deformation along the NFZ, which may illuminate processes occurring in modern high-strain zones.

How Instrumentation Advances Research: Peterman will use the new SEM to acquire BSE images and EDS maps of compositional variability in monazite that is hosted by staurolite to identify grains for geochronology. As with Project 1, the BSE maps and EDS data will guide laser ablation ICP-MS analyses. Geochronology data collected from each textural association will enable dating the timing of deformation of staurolite porphyroblasts. Peterman will then collect lattice preferred orientation (LPO) data from quartz to evaluate the conditions of deformation (cf. Toy et al., 2008; Mehl and Hirth, 2008; Skemer et al., 2010; Kruckenberg et al., 2013). Collectively, these data will provide insight into the partitioning of deformation among phases, the timing of deformation and the *P-T* conditions of strain localization. These questions are of critical importance to the structural geology and tectonics community and are cited as grand challenges in the field.

Funding for Above Project: Bowdoin College Faculty Research Fellowship awarded to Peterman.

Project #3: *Interpretation of Plutonic-Volcanic Processes through Mineral Crystal Analysis;* co-PI Rachel Beane (Bowdoin) & Chad Deering (Michigan Tech University; see letter of collaboration)
What do quartz and feldspar textures record with regards to the dynamic processes in silicic magma reservoirs? How can our knowledge of these further our understanding of plutonic-volcanic connections? Beane and Wiebe (2012) used a novel EBSD-CL approach to evaluate a cumulate origin of quartz crystals from the Vinalhaven, Maine granite and porphyry. Crystal accumulation coupled with wall-rock assimilation is thought to be a key factor in the generation of andesitic to rhyolitic magmas.

Intellectual Merit: This research tests the hypothesis that crystals come into contact with each other in many orientations during accumulation; once the mush is remobilized due to magma recharge, however, only crystals with prominent faces attached remain as clusters; other clusters separate during remobilization (Beane and Wiebe, 2012). Some suggest that cumulates are rare to non-existent in silicic plutonic rocks (c.f. Glazner et al., 2004; Reubi and Blundy, 2009); others offer compelling evidence that large volumes *do* exist (c.f. Miller and Miller, 2002; Vernon and Paterson, 2006; Walker et al., 2007). If the cumulates exist, then they record valuable information about volcanic systems that is otherwise inaccessible. Beane's current research uses EBSD-CL methods to evaluate the evidence for cumulates in rocks from the Turkey Creek Caldera, Arizona, the Lake City Caldera, Colorado, and the Searchlight Pluton, Nevada. This spring, while on sabbatical, she will extend this research to the Taupo Volcanic Zone and Halfmoon pluton, New Zealand.

How Instrumentation Advances Research: For these projects, EBSD methods will be used to determine the 3-D crystallographic orientation of minerals to test whether quartz and feldspar mineral clusters from the sampled volcanic and plutonic rocks formed together as cumulate crystals with prominent faces aligned. CL images of quartz (**Fig. 2A**) are used to test whether quartz crystals came together after their initial crystallization by imaging the growth zones (as correlates with Ti concentrations and temperature of crystallization) to look for truncations that indicate a period of resorption (methods of Muller et al., 2010; Wark and Watson, 2006 and Wiebe et al., 2007). Similarly, EDS maps of feldspars help to reveal their growth histories. With the new SEM, CL images, EBSD orientations, and EDS maps all will be acquired at Bowdoin College. As with Projects 1 &2, simultaneous acquisition and full thin section mapping afforded by the proposed instrumentation will enhance the scope, depth, and progress of this research.

Funding for Above Project: NSF Research Grant #1250259 to C. Deering and R. Beane (July 2013-June 2016), Bowdoin College Research Grant and Sabbatical Fellowship to R. Beane.

Project #4: *Deformation in high-strain zones*; co-PI Rachel Beane (Bowdoin), PI Emily Peterman (Bowdoin) and collaborator Walter Sullivan (Colby College)

Over the past six years, Beane's research has included collaborative studies of quartz crystallographic preferred orientations in high strain zones with EBSD data acquired at Bowdoin. These collaborative studies have included modeling strain in shear zones through a study of the Norumbega fault zone, Maine (Johnson et al., 2009); testing numerical simulations of crystal fabric patterns through a study of the Pigeon Point high-strain zone in the Klamath Mountains, California (Sullivan and Beane, 2010); distinguishing deformation modes in the Aetopetra shear zone, Greece (Xypolias et al., 2013); and testing a transpression hypothesis for high-strain zones of the Cheyenne belt, Wyoming (Sullivan et al., 2011; Sullivan and Beane, 2013). Beane's on-going research will now include exploratory work on the crystal preferred orientation of feldspars (in addition to quartz) and collaborative projects with Peterman, Sullivan and Colby College undergraduates (typically 1-2 per year).

Intellectual merit: The goals of this collaborative research are to assess: (1) deformation partitioning and formation of shear zones from the brittle-ductile transition to the lower continental crust, (2) the spatial and temporal operation of different deformation mechanisms and their control on crustal strength, and (3) the formation of microstructures and crystallographic fabrics.

How Instrumentation Advances Research: (1) Beane and Sullivan will use the integrated EBSD and EDS systems to collect crystallographic-orientation datasets from high-strain rocks from the Norumbega Fault Zone, located in Maine. Importantly, the design of this instrumentation permits accurate crystallographic mapping of very fine-grained polyphase aggregates, which is only possible via integrated EBSD and EDS. Although polyphase aggregates are common in mylonitic rocks, we still do not understand how and why they form, the role they play in weakening the rock, and what they may reveal about the operation of different deformation mechanisms that govern rock strength. **(2)** Peterman will use the BSE and CL detectors to generate full-thin section maps (e.g. **Fig. 1**) to locate and image monazite and zircon grains that have been deformed along with the polyphase aggregates (question 1 of this project). The BSE and CL images will be used to evaluate which domains within monazite and zircon can be linked to the deformation regime to guide laser ablation ICP-MS geochronology to determine the timing of activation of different deformation mechanisms. This project will build upon Peterman's active Appleton Ridge Formation research (Project #2). **(3)** Because color CL imaging can reveal otherwise undetectable compositional variations in quartz, the PIs will use the instrument to evaluate the role of pressure-solution and dissolution-precipitation creep in crustal shear zones. Understanding the role of these mechanisms is critically important for testing the long-standing assumption that dislocation creep is the dominant deformation mechanism governing the rheology of shear zones that ultimately control plate-scale processes.

Funding for Above Project: Bowdoin and Colby Faculty Research Awards

Project #5 *Decadal climate, carbon and nutrient variability: New insights from deep-sea bamboo coral records on the California margin.* Michèle LaVigne (Bowdoin)

Bamboo corals (family *Isididae*, order *Alcyonacea*) are gorgonian octocorals named for their jointed structure of alternating cm-long calcite internodes and protenaceous gorgonin nodes. As bamboo corals grow, the calcitic internodes and organic nodes are precipitated simultaneously forming ~annual radial bands (resembling tree rings) (Roark et al., 2005; Tracey et al., 2007; Thresher et al., 2009; Hill et al., 2011). Corals currently available to this project provide a depth transect across the eastern Pacific oxygen minimum zone, one of the world's strongest (Paulmier and Ruiz-Pino, 2009), which resides below the California Current System, a major upwelling region. This research uses trace elemental bamboo coral proxy records to address the following overarching question: How are deep-sea nutrient biogeochemistry and carbon cycling in the California Current System affected by climate change?

Intellectual Merit: This research will provide crucial information on how ocean productivity, nutrient and carbon cycling are impacted by rapid climate variability, and fill gaps in knowledge for predicting future consequences of climate change. Paleoceanographic reconstructions of intermediate water nutrient concentration will provide the first continuous high-resolution (inter-annual-decadal scale) records of intermediate water biogeochemistry that would extend modern instrumental records (e.g. CalCOFI). One of the major challenges in generating reliable proxy record timeseries is the development of robust chronologies. The identification of mineral growth bands has been proposed as a possible sclerochronological technique for dating bamboo coral proxy timeseries. Mineral growth bands present in calcitic internodes caused by changes in crystal orientation have been suggested to occur annually, and could serve as chronological markers.

How Instrumentation Advances Research: Bamboo coral thin sections contain banding patterns that are difficult to identify under light microscopy. Selected well-dated coral thin sections will be analyzed using the proposed SEM-EBSD capabilities to locate mineral bands and characterize band mineralogy. Banding frequency and structure will be examined in coral specimens using high-resolution (1μm) SEM/EBSD mapping to identify three types of bands: (1) mineralogical growth bands caused by changes in fibrous crystal bundle orientation (Noe and Dullo, 2006, Noe et al., 2008), (2) organic seams connecting organic nodes to calcitic internodes, and (3) major interruptions in lateral accretion. This technique will help determine whether these types of bands influence trace element incorporation. Identification of the growth bands of precisely dated coral thin sections will determine banding frequency and test the validity of using sclerochronology in bamboo corals.

Funding for Above Project: NSF-OCE-Research Initiation Grant #1420984 to M. LaVigne (2014-2016).

Project #6 *Evaluating the Impact of Freshwater Flow on Estuarine Environments: A Case Study in the Kennebec River Estuary.* Michèle LaVigne (Bowdoin)

Rising levels of atmospheric CO_2 increase global temperatures and ocean acidity. Calcium carbonate shells of marine organisms (e.g. clams, mussels, corals, etc.) dissolve more readily in acidic seawater. The natural variability of Maine's coastal and estuarine chemistry offers a unique environmental mosaic and natural analogs for future conditions. Maine's estuaries are home to important shellfish habitats (such as clam flats), which naturally experience daily to seasonal variations in acidity driven by tides, freshwater flow, and biological productivity. The proposed study addresses the question of how freshwater flow influences the carbonate chemistry of estuarine environments and thus, clamshell integrity**.**

Intellectual Merit: This project will 1) collect baseline data to understand how freshwater flow influences carbonate chemistry in three distinct clam flats along the Kennebec Estuary, and 2) investigate how differences in carbonate chemistry among these sites influences clam shell integrity and composition. The seawater chemistry and clam mineralogy data from the most acidic sites studied could serve as analogs for future ocean conditions. Recent research has documented negative impacts of acidification on the calcification and shell integrity of estuarine bivalves (e.g. Clements and Hunt, 2014; Green et al., 2013; Green et al., 2009; Talmage and Gobler, 2010; Waldbusser et al., 2010a; Waldbusser et al., 2011; Waldbusser et al., 2010b).

How Instrumentation Advances Research: This project takes advantage of the proposed SEM-EDS instrument to inspect the clam shell specimens from each site for evidence of dissolution (e.g. pitting of surface) and changes in elemental composition (Mg/Ca ratio) that could impact susceptibility to future acidification. These results will serve as seed data for future larger-scale field and laboratory-based culturing projects utilizing Bowdoin's newly renovated Coastal Studies Center.

Funding for Above Project: Bowdoin College Faculty Research Grant.

Project #7 *Distinguishing smelted from meteoric iron in archaeological samples from Greenland*: Genevieve LeMoine, Arctic Studies (Bowdoin)

A central objective of archaeological studies is to determine the sources of artefacts to establish trade routes and travels within a region. Archaeological research led by G. LeMoine (NSF Arctic Social Science 0732620) has had success using the EDS capabilities of the existing LEO SEM at Bowdoin, including using it to distinguish smelted from meteoric iron in samples excavated in northern Greenland. The next phase of this research project will expand the sample set of metal artefacts for analysis using the EDS and advance the research by using CL imaging to identify the sources of cherts and quartzites used to manufacture tools (c.f. methods of Augustsson & Reker, 2012; Hunt, 2013).

Project #8 *SEM analysis of the Bowdoin numismatic collection to evaluate the metallurgy and circulation routes of ancient coins:* Jim Higginbotham, Classics Department and Curator of the Ancient Collection at the Bowdoin College Museum of Art (Bowdoin)

With over 2000 coins, the Bowdoin College Museum of Art numismatic collection contains examples from the Near East, Egypt, and the Greco-Roman world spanning over one thousand years of history. Using the SEM is non-invasive and does not harm the artifact, rendering it the ideal tool for analyzing these archaeological specimens. The high-resolution images of entire coins produced by the photostitching software on the SEM will permit the study of minting technique and the craftsmanship employed in the original design of the master die. Examination of the coin surface by the SEM can help identify the origin and date of the artifact as well as suggest to what degree the coin was circulated. Because ancient coins were minted in a variety of metallic alloys, insight regarding metallurgic techniques employed by ancient coiners can be evaluated by measuring compositional variation using the EDS and by imaging the coins using CL detection (c.f. Reif et al., 2001; Pingitore et al., 2008; Buccolieri et al., 2014). Higginbotham's research will lead to the publication of an online catalogue of Bowdoin's numismatic collection.

Results from Prior NSF Support

The PIs have not participated in NSF-MRI awards in the past five years. This section summarizes information on the PIs most relevant current NSF research awards.

NSF EAR-PF 0948158 Tracking rocks from depth to the surface: Coupled (U-Th)/(Pb-He) dating of monazite to Emily Peterman ($170,000: 05/01/2010-09/30/2013).

Intellectual merit: Peterman successfully developed new analytical techniques for monazite (U-Th)/He thermochronology. She evaluated monazite thermochronology results against traditionally used thermochronometers from the same rock to demonstrate the effectiveness of this new tool (publications listed below). Her work with collaborators at UCSB and Stanford has improved the accuracy and precision of monazite (U-Th)/Pb and (U-Th)/He geochronology to 1-2% and 5%, respectively.

Broader impacts: Peterman developed an upper division course at Stanford on thermochronology that integrates the newly developed analytical techniques with teaching. Her courses at Bowdoin now integrate these lesson plans and pedagogical techniques (relevant exercises have been posted to *On the Cutting Edge).* Significant professional development for an early career female geoscientist included: teaching upper division courses, research training using a range of analytical equipment (SEM, SHRIMP-RG, Nu Noblesse, JEOL electron microprobe), mentoring postdocs, graduate, undergraduate and high school students (see asterisk below), and accepting a tenure-track position at Bowdoin College.

Products: (full references in bibliography) **2** manuscripts were published (Peterman et al., 2012, Peterman et al., 2014b), and **2** manuscripts are in preparation for submission, and **6** abstracts were presented (Peterman et al., 2010a; Peterman et al., 2010b; Peterman and Grove, 2010b; Day et al., 2010*; Peterman et al., 2011; Peterman and Hourigan, 2012) * denotes high school mentee.

NSF 1250259 Collaborative research: RUI: Probing Caldera Forming Magmatism: Crystal Accumulation in Large, Upper Crustal Silicic Magma Chambers to Chad Deering and Rachel Beane ($46,678: 07/01/2013-06/30/2016).

Intellectual merit: A multi-analytical approach to sub-volcanic intrusions and overlying silicic volcanic units is being applied to establish the genetic relationship between large, zoned ignimbrites and their plutonic roots. This research tests the hypothesis that the plutonic porphyries in the Lake City Caldera (Colorado) and the Turkey Creek Caldera (Arizona) are the quenched magma reservoirs remaining in the crust following caldera collapse. If true, then these porphyries provide a snapshot of the evolution mushy rootzone associated with super-eruptions. The methods being applied are: 1) detailed field sampling of the plutonic porphyries and the volcanic units, 2) geochemical characterization of all units, 3) quantitative investigation of crystal clusters using electron microprobe analysis, LA-ICP-MS, EBSD and CL, and 4) high resolution U-Pb dating and trace element analysis of zircons (CA-TIMS-TEA). Halfway through the project, field sampling Turkey Creek is complete; EBSD analysis monomineralic clusters is complete for Turkey Creek; CL images and geochemical characterization are underway.

Broader impacts: The project has supported undergraduate research training (to date: 3 undergrad summer projects, 2 independent studies, and 1 mineral science course project with 16 students).

c. Description of the Research Instrument and Needs

Based upon the research objectives of the PIs and an SEM evaluation process by Peterman, this proposal seeks funding for the acquisition of a Tescan Vega3 scanning electron microscope (SEM) with a tungsten filament equipped with a color cathodoluminescence (CL) detector, backscattered electron (BSE) detector, energy dispersive spectrometer (EDS) and a fully integrated electron backscatter diffraction (EBSD) system from Oxford Instruments.

The Tescan Vega3 SEM is ideal for several reasons. First, the SEM yields higher spatial resolution than what is possible on the LEO SEM. Second, as configured for this model, each filament lasts 300+ hours and users report 500 to 1000h per filament (S. Kruckenberg (Boston College), pers. comm. Oct. 2014; J. Weaver (Harvard Wyss), December 2014). For comparison, filaments on the LEO SEM typically last 50 to 150h. Third, the configuration of detectors permitted by the Tescan Vega3 design permits simultaneous acquisition of EDS data with any of the other detectors (EBSD, BSE and CL) *and* BSE with EBSD; simultaneous acquisition of BSE and CL are also possible with a few changes to the detector arrangement. The ability to simultaneously collect data on multiple detectors will significantly impact the speed of data acquisition routines and increase the level of sophistication of research questions that can be directly addressed. Fourth, because the LEO SEM does not have a CL detector, maps of zoning within grains are currently acquired through collaborative arrangements off-campus. For example, the CL maps in **Fig. 2** were collected at Boston College. The latest color CL detectors have shown remarkable improvements in caliber and provide the ability to acquire both panchromatic and color CL data. Color CL is particularly useful for imaging fine-scale zoning in minerals (e.g. Ti-in-Quartz zoning). Fifth, the detector configuration on the Tescan Vega3 permits collection of full thin section maps via EDS, BSE, CL and EBSD—an example full thin section BSE map is shown in **Fig. 1**. These maps form an integral component of the PIs research and are used across all research projects. Sixth, the Tescan Vega3 can be operated in variable pressure mode. This analytical mode minimizes sample preparation time, thereby enhancing analytical throughput. Faster throughput is particularly important when training students to conduct research because it affords *all students* an opportunity to use the instrument.

The Oxford EBSD system was selected for the following reasons. First, co-PI Beane has successfully used the software for multiple research projects (see examples in **Projects 1, 3 and 4**). Second, a large network of colleagues use Oxford Instruments and can provide assistance with troubleshooting, sharing match files and optimizing analytical conditions. Third, the Tescan + Oxford combination permits simultaneous EDS/EBSD analysis; this configuration uses the EDS to assist EBSD measurement for phase detection, thus improving the quality of EBSD results. Fourth, although the current acquisition software is not being updated, the new acquisition software is improved and faster. Fifth, the EOS department currently has 5 copies of post-processing software. Because of the high analytical throughput of the Tescan Vega3, researchers will rapidly acquire data and process it using these 5 computers, which will improve overall productivity. In support of the EBSD system currently in place, The EOS department maintains a colloidal silica polisher on campus to prepare samples for EBSD. The EOS department also maintains a carbon coater to prepare samples for analysis in high vacuum mode. Both have been used successfully for the past decade and still work well.

Why a new SEM?
The EOS department currently maintains a LEO 1450VP SEM that was funded in 1999 through equal contributions from the NSF Course, Curriculum and Laboratory Improvement (CCLI) program and Bowdoin College. When purchased, the primary purpose of this SEM was for use in undergraduate courses. Its use has increased substantially over the past few years to be a major analytical tool for faculty in the department to expand the scope of research and to initiate new research directions. The LEO SEM is equipped with BSE, EDS and EBSD detectors and affiliated software. The EBSD system was purchased through an NSF MRI award in 2003. The LEO SEM is 15 years old and, over the last two years, has 30% downtime. Increased downtime as the instrument has aged is compounded by an increase in use as the EOS department's faculty has doubled from 3 to 6 full time faculty members and the number of student majors has *quadrupled* in the last 5 years (~5-7 per year to 28-30 students per year).

Furthermore, the EOS department has been informed that the Zeiss (for SEM) and EDAX (for EDS) vendors will no longer extend offers for service contracts after 2016 and that needed repair parts may no longer be available. EOS faculty members—primarily Co-PI Beane—have covered general maintenance of the instrument and Bowdoin College has funded service contracts for both the SEM and the EBSD system (see Letter in Supplemental Documents).

Because the EOS department incorporate research at all levels of the curriculum, the number of students who use the SEM per year has significant increased. Each year, over 65-85 students use the SEM in course-related research projects, approximately 5-8 independent research projects (including honors projects) use the SEM as a primary tool in their research, and 3 EOS faculty members routinely use the SEM in their research. A new instrument will facilitate research that will allow the PIs and colleagues in the department to continue successful research track records that would otherwise be in jeopardy due to an aging instrument with increasing downtime, relatively slow EBSD acquisition, and lack of cathodoluminescence (CL) detection. Faster acquisition times and the ability to simultaneously collect data on multiple detectors also will allow more efficient use of the SEM during class and lab periods.

d. Impact on Research and Training Infrastructure

Broader Impacts of the Proposed Work

Use of the proposed instrument will: **(1)** enhance the infrastructure for research and teaching, **(2)** broaden the participation of underrepresented groups, and **(3)** develop scientific literacy and training of undergraduates.

(1) Enhance infrastructure for research and teaching:

New faculty research (see **section B**) requires acquisition of high-resolution BSE, EDS, CL and EBSD data, including full-thin section scans that cannot be achieved with the current instrumentation. The closest SEM laboratories equipped to acquire *all* of these types of data are the University of New Hampshire, University of Maine (Orono) and Boston College, (MA). These locations are approximately 2h from Bowdoin and subject to lab time availability. Although the PIs have been fortunate to have access to instruments at Boston College and UMaine-Orono, in-house use at these institutions has increased such that scheduling time for outside users can be difficult. Furthermore, use for student research training or in course-related research is not possible.

This project establishes new instrumentation for research and teaching at an undergraduate institution in Maine, an EPSCoR state. As detailed in the previous sections, the instrumentation will enhance the infrastructure for research and teaching through use by students and faculty in the Earth and

Oceanographic Science, Arctic Studies, Archaeology and Chemistry departments, and foster use through collaborations with external researchers. Scientific research will be published in academic journals, and the numismatic research will be published in a museum catalogue. Transferable geoscience laboratories and exercises developed using EDS, BSE, EBSD, or CL data will be submitted to the *On the Cutting Edge* on-line activity collection hosted by SERC at Carleton College. In addition, the proposed research activities will provide research training for students, whose training will benefit from multiple analytical sessions using the SEM—this simply cannot occur if travel to other facilities is required. Access to the enhanced SEM on campus will greatly strengthen the research programs of five faculty members – including two early career faculty – and contribute to incorporating SEM-based student research in courses, independent studies and honors projects.

(2) Broaden participation of underrepresented groups

Undergraduate students: Bowdoin College is a highly selective liberal arts institution currently consisting of 1792 undergraduates and 190 faculty members. U.S. News & World Report consistently ranks Bowdoin among the top ten liberal arts colleges. In recent years, a key priority of Bowdoin College has been broadening the diversity of its student body. To accomplish this, Bowdoin maintains a policy of need-blind admissions, backed by financial aid resources. As a result, the percentage of students supported by Bowdoin financial aid has increased from 35% to nearly 44% for the Class of 2017. The percentage of students of color on campus increased from 12% in the 90s to 31% in the 2010s.

As part of these efforts to increase diversity, Bowdoin established the Bowdoin Science Experience (BSE) in which 30 incoming first-year students arrive on campus a week before the start of college. The goal of this pre-matriculation program is to promote the recruitment and retention of first-generation college students, students of color and women interested in the physical sciences. The BSE program successfully attracts a range of students and retention is typically high—54% of BSE "alums" have declared a science major. Through the BSE program, four students work with a faculty mentor on a 2-day research project. PIs Peterman and Beane both have participated as faculty mentors in the past. In association with the new instrumentation, the PIs will offer a research project that is SEM-based. For example, in association with Peterman's proposed research, BSE students will measure the compositions of the rock-forming minerals in thin section using EDS and collect images of targeted geochronologic minerals (e.g. monazite, zircon and rutile) with the CL and BSE detectors. Students will be offered the opportunity to continue working with their samples as a work-study project.

Female faculty: Instrumentation acquired through this proposal will advance and accelerate the research of two early-career female tenure-track professors —PI Peterman and Prof. LaVigne, and one senior female faculty member—Co-PI Beane. Bowdoin emphasizes a balance in teaching and research in its faculty; tenure is based equally on both components of a faculty's work. In the Earth and Oceanographic Science Department, each faculty member teaches three courses a year, thus allowing time for research and for mentoring students in research.

(3) Develop scientific literacy and training of undergraduates

Having access to an SEM with EDS, EBSD and CL capabilities will afford geoscience, chemistry, Arctic Studies and archaeology undergraduate students the kinds of research opportunities normally conducted by graduate students. Based on the numbers in EOS courses, an expected **75-100 undergraduates** will use the instrument **each year**. Pedagogical studies and reports have long recommended that undergraduate courses create opportunities for students to "do" science (c.f. Eaton, 1995; Holliday et al., 1996; NSF97-171, PCAST 2012). The integration of research and learning has been shown to "provide students with a greater understanding of the scientific investigation, increase their scientific literacy, and promote free thinking and creative approaches to problem solving" (Ireton et al., 1996). In particular, the Earth and Oceanographic Science department provides students with authentic research experiences that integrate research and teaching at all levels of the curriculum (Beane et al., 2013). This approach engages undergraduates in scientific research, develops their scientific literacy, and trains them as future researchers. Many of these students will gain expertise in research training by using the SEM as they progress through the curriculum, as follows.

Introductory courses: The PCAST (2012) *Engage to Excel* report states: "research experiences in the first two years increase retention of students in STEM majors and improve students' attitudes toward STEM fields." One example of how the SEM will support research experiences in the introductory course is a mineral research project. Students will begin studying minerals by identifying the physical properties of an "unknown" mineral. From these observations, students will construct multiple working hypotheses for what their mineral is and state how they will use the SEM to distinguish among their hypotheses. During laboratory sections, each of the 36 students will acquire an EDS spectrum using the SEM to support or refute their hypotheses. They will present their results in a class wide poster session. The SEM will also be used in subsequent research projects that build upon the types of data collected during the mineral research project.

Intermediate courses: The SEM will be used in the petrology, structural geology, and volcanology courses (typically 18 students per course). Example in-class research questions include acquiring EDS data to evaluate using major element zoning in garnet and determine *P-T* paths, acquiring CL images of monazite and quartz to interpret growth and alteration histories, and acquiring EBSD crystallographic orientation data to assess deformation mechanisms. Research will typically be conducted by pairs or small groups of students, and will culminate with student presentations of their research to the class.

Senior research experience level: The SEM will be the main analytical instrument used in the 3000-level research-project courses (typically 25 students per year) and in many student independent study, honors, and summer research projects (typically 15-20 students per year). In the required 3000-level research-project courses, students propose, conduct, trouble-shoot, and present research projects. Mogk (1993) attributes research activities in geoscience courses for helping to prepare students for graduate school. As a result of participating in research projects at all levels of the department's curriculum, students will gain increasing sophistication with SEM techniques and be well-prepared to use it for senior-level research, some of which are expected to lead to publications co-authored by undergraduates (e.g. Graeter et al., *in review*).

Increasing undergraduate and public scientific literacy: Images collected with the new instrumentation will be used to increase public scientific literacy through displays and web pages. An annual undergraduate exhibition of SE/BSE/CL/EBSD images with explanations will be given in the atrium of the science building with the public invited. This event will also provide an opportunity for students to practice communicating science to the general public. The annual event will build upon the success of PI Peterman's exhibit at the Bowdoin Museum of Art in Spring 2013—*Sense of Scale; Measure by Color* that showcased 12 petrographic microscope images and vibrant mineral specimens.

e. Management Plan

This section describes the space in which the instrument will be housed, how and by whom the instrument will be operated and maintained, the technical expertise available in support of the instrument, the anticipated costs to maintain and operate the instrument, a description of the process for allocating user time, and a plan to attract new users and develop new collaborations. The management plan builds upon the collective laboratory management experience of the PIs and establishes a long-term vision for how the SEM will be operated and maintained.

The Space:

The Tescan Vega3 SEM will be located in Druckenmiller 108. This space is proximal to both Peterman and Beane's research laboratories and central to the EOS and Chemistry department laboratories. The Bowdoin Facilities Department has ensured that the room has proper ventilation, power supply, lighting (e.g. dimmer switches), and temperature control for the instrument (see the Supplementary Letter from Bowdoin College). In addition, a computer workstation, sample prep space, and sample storage areas have been designated within the lab space to optimize workflow.

Operation and Maintenance of the Instrument:

The Tescan SEM will be primarily operated and maintained by the PIs (Peterman and Beane). PI Peterman will be the director of the new SEM laboratory; Beane will provide assistance as needed and will assume directorship when Peterman is on sabbatical. The SEM Lab Director will supervise the installation of the instrument, write standard operating procedures, compile a quick-reference user guide, create the SEM laboratory website, and run the annual student show of SEM images (see Broader Impacts section). The EOS Department technician (Celeste Morin Renaud) will provide support for the instrument by coordinating service and maintenance visits, tuning and calibrating the instrument, recording daily parameters in a log book, updating the SEM laboratory website, running the annual training refresher course (see below), and providing additional support for undergraduate research training (e.g. sample preparation (colloidal silica polishing, carbon coating), data acquisition, data analysis and basic troubleshooting). Tescan will provide training for Peterman, Beane and Renaud; it is included in the purchase of the instrument (see Budget).

Long-term maintenance support and annual service visits for the instrument will be provided through service contracts funded by Bowdoin College (see Letter from the College in Supplemental Documents).

Technical expertise:

PI: Emily Peterman

Peterman brings 10 years of analytical experience on a variety of SEM, LA-ICPMS, SIMS and TIMS instruments. As a postdoc, she managed the Thermo Neptune MC-ICPMS, VG Sector 54 TIMS and Class 1000 Clean Lab Facility at UC Santa Cruz, which had a user group of ~40 people, both internal and external. She will be the director of the new SEM laboratory at Bowdoin College. Her research specializes in developing geochronometers and linking geochronology and thermobarometry with metamorphic and deformation processes (e.g. Peterman et al., 2009; Peterman and Grove, 2010a; Peterman et al., 2012; Peterman et al., 2013; Peterman et al., 2014a). She has trained students at Bowdoin College in research techniques that they have applied to honors projects (e.g. McDonough, 2014), conference abstracts (Peterman et al., 2014a), and forthcoming publications.

Co-PI: Rachel Beane

Beane brings 15 years of experience managing the SEM laboratory at Bowdoin College; she will assist Peterman with the management of the new SEM laboratory. Beane specializes in using microstructures to interpret crustal processes. She has over 10 years of EBSD experience (c.f. Beane and Field, 2007; Sullivan and Beane, 2011; Beane and Wiebe, 2012), and has trained and supervised undergraduate students, graduate students and faculty in EBSD methods. She routinely incorporates SEM-based research projects into undergraduate courses (c.f. Beane, 2004; Beane and Urquhart, 2009). She is co-PI on a Probing Caldera-Forming Magmatism project for which she is applying EBSD and CL methods to test crystal accumulation models (NSF 1250259).

EOS Department technician: Celeste Morin Renaud
Renaud has 7 years of experience assisting with maintenance of the LEO SEM. She has completed SEM training at Zeiss and currently changes filaments, calibrates the instrument for EDS analysis, chills the EDS detector, and coordinates service visits with both Oxford (EBSD detector) and Zeiss (the SEM vendor). Renaud also has 7 years of experience managing the ICP-OES lab in the Chemistry Department at Bowdoin and maintaining/repairing analytical instruments and equipment. Her position provides 10 hours per week to support the SEM.

Costs

Based upon the PIs collective experience, the annual costs of operating and maintaining the SEM are primarily consumables and service visits. Most consumables (i.e. kimwipes, ethanol, carbon tape, colloidal silica polish for EBSD) are nominal in cost and typically total less than $500 per year. The largest annual cost – apart from service visits – is replacing filaments. Given expected use of ~2000 hours of analytical time, the PIs anticipate requiring 7 filaments per year (~2000 hours of analytical time per year, conservative estimate of 300 hours per filament). Filaments from Tescan can be purchased in bulk for $850 for 10 filaments.

Consumables will be funded by recharge of $100/week. Given the expected 40+ weeks of use per year, revenue from internal usage alone should be more than sufficient to cover these costs. Additional support for consumables has been and will continue to be sought through research grants.

All service visits—including annual maintenance—will be covered by service contracts with Tescan and Oxford purchased by Bowdoin College (see Letter from the College provided in the Supplemental Documents). Service contracts from Tescan guarantee 95% uptime, which will meet the anticipated need of ~2000 hours per year.

Allocating instrument time

User access
Because of the differing needs of users, the SEM laboratory will implement a two-tiered user training system. *Tier 1* users are classified as long-term, independent researchers (including the PIs, professors, researchers, collaborators, and students who intend to use the SEM independently). *Tier 2* users will only use the instrument in course-related research—for example, measuring mineral compositions for research projects in introductory geology (EOS 1105). This two-tier system will train *Tier 1* users to operate the instrument, troubleshoot common problems and apply the collected data to their research questions and allow students in class (*Tier* 2 users) to focus on ***how*** the data they are collecting can be used to inform their research projects.

Tier 1: Long-term researchers will be required to attend a three-hour course in laboratory safety. This program was created in 2013 at Bowdoin College and is led by the Science Center Lab Manager. Attendees are trained in general lab safety protocols and are evaluated on their ability to respond to hypothetical laboratory problems. Training is offered every semester and annual refreshers are offered online. Certificates for completion of this training are posted on all relevant laboratory doors and archived by the Science Center Lab Manager. In addition to general lab safety training, *Tier 1* users will attend a two-hour training seminar co-led by the SEM Lab Director and EOS Department technician. In this training session, *Tier 1* users will learn standard protocols, common errors and how to troubleshoot problems specific to the SEM. Before they can be certified as *Tier 1* users, researchers must demonstrate proficiency in tasks such as: loading and unloading samples, calibrating the instrument, inserting and retracting detectors. Certificates for *Tier 1* users will be cataloged in a binder stored by the entrance to the laboratory. *Tier 1* users will be granted key-card access to the laboratory that will be renewed on an annual basis following successful completion of the refresher SEM training course led by Renaud, the EOS Department technician.

Tier 2: Students who use the SEM during class research projects (i.e. research in mineral science, chemistry, and archaeometry) will be trained by Renaud during class on how to operate the instrument to accomplish the specific goals of the research project. Renaud will calibrate the instrument, load/unload samples, and remain in the room during sample analysis to answer questions and ensure successful use of the instrument.

User scheduling procedures
At the start of each semester and the start of summer, the SEM Lab Director will meet with users to determine the expected instrument usage—i.e. detectors used and length of time anticipated for each project—for research, research training, and use in courses. The SEM Lab Director will use this information to create a user schedule that balances the research needs of the PIs and collaborators with the objectives of broadening participation of underrepresented groups and developing scientific literacy and training of undergraduates. The user schedule will be posted online—visible to the public—and requests for instrument time will be handed via online requests. Priority will be given to NSF-funded research projects—including time allocated for research training. To coincide with Bowdoin class scheduling, course related research will be accommodated during the afternoon laboratory sessions. To attract new users and provide consistently available time to explore new research directions, two Fridays per month will be designated as open days (i.e. recharge free) for method development and exploratory work. These days will be advertised on the calendar and shared with colleagues at the College, with researchers at the Maine Geological Survey, with community partners (e.g. Mussel Flat Research Consortium), and with local schools to attract new users and to facilitate the development of new research collaborations. User scheduling on the LEO SEM has successfully accommodated research needs, research training, and use in courses.

The long-term vision of the SEM at Bowdoin

The proposed instrument will enable the PIs to conduct exciting, innovative research that meaningfully involves professors, collaborators, students and community partners. The PIs research programs will flourish because of the new capabilities and faster throughput enabled by the instrumentation. More students will benefit from using the instrumentation to address original research questions in independent research and class projects, thereby providing more technical research training to undergraduates at a small liberal arts college. Lastly, the PIs will apply the broad range of new capabilities (CL, full thin section mapping, etc.) to current and future scientific questions that expand the scope of research and the breadth of scientific inquiry at Bowdoin and beyond.

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