Nicholas Deardorff
Department of Geosciences
Indiana University of Pennsylvania

REQUIRED FORMAT FOR TITLE PAGE OF PROPOSAL

University Proposal # FOR PASSHE OFFICE USE ONLY: FPDC proposal #

Project Title: **LiDAR and Field Investigation of Lava Flow Textures in Central Oregon**

RFP Category: 1-A Total Grant Amount Requested from FPDC: $9,975

Discipline: Geoscience Sub-Discipline: Volcanology

Project Director (name, position, department, university, telephone number, and e-mail address):
Nicholas Deardorff, Assistant Professor, Geosciences, IUP, 724-357-2611, n.deardorff@iup.edu

Faculty Status (see definitions below):
☐Tenured ☒Probationary ☐Non-Tenure Track

Other Participants (names, departments, e-mail addresses):

IRB/IACUC Status: ☐ Approved (IRB # ) ☐ Pending ☐ N/A

ABSTRACT (one paragraph of approximately 150 words in non-technical language):

Few intermediate to high silica composition lava flows have been observed during emplacement limiting our understanding of their emplacement conditions, such as eruption rate, duration, and rheology (particularly viscosity). Alternatively, using measurements of surface features of solidified lava flows, researchers have developed a method to estimate lava flow emplacement rates and duration. The advent of high resolution digital topography allows researchers to *remotely* extract accurate measurements of flow morphologies and surface textures; however, determining viscosity still requires direct sampling. In this study, I intend to develop a method of remotely determining lava flow viscosity by relating the dominant wavelengths of lava surface folds to silica content and apparent viscosity. This proposal seeks funding for the acquisition of existing Lidar (Light Detection And Ranging) data sets, as well as support for field work, sample preparation, and geochemical analyses. The proposed funding would initiate my research program and create numerous undergraduate projects.

Endorsement:________________________________________
Chair, University Faculty Professional Development Committee Date

Endorsement: ________________________________________
University President Date

## 1.0 Background and Significance

Lava flows are a common form of volcanic activity, resurfacing the landscape and potentially triggering secondary hazards such as fires or flooding. For this reason, predictive modeling of lava flow emplacement has been a focus of investigation in volcanically active areas (e.g., Crisci et al., 2008). Important input parameters for flow models include lava flux (mass eruption rate), flow duration, and viscosity, which, in turn, control both the rate of lava flow advance and the final flow length (e.g., Walker, 1973; Kauahikaua et al., 2003). These flow parameters are well constrained for basaltic (low silica) lava flows from Hawaii and Italy, where eruptions are both frequent and carefully documented. Less well constrained are emplacement conditions relevant for flows of intermediate and high silica compositions, which are both less frequent and more difficult to monitor. Very few intermediate to high silica lava flows have been observed during emplacement (i.e. while erupting and flowing into place; exceptions include Naranjo et al., 1992; Borgia et al., 1983; Cigolini et al., 1984; Borgia and Linneman, 1990), resulting in limited direct observations of emplacement conditions.

An alternative to making direct measurements on active flows is to develop methods to infer emplacement conditions and rheology from the morphologies of solidified flows. Published field measurements of high silica flow features are limited, primarily because of the difficulties inherent in collecting accurate data on flows that are both rough and spatially extensive; intermediate and high silica lava flows can be 10s of meters thick and 10s of kilometers long. However, recent advances in airborne and satellite remote sensing techniques allow the production of 3D high resolution (<1m) digital topographic data, revolutionizing geomorphic analyses. In particular, the development and increasing availability of airborne Light Detection And Ranging (Lidar), is changing the way that we view volcanic landscapes. Three dimensional Digital Terrain Models (DTM) derived from Lidar data can be used to extract accurate morphologic measurements from emplaced lava flows. Recently, a method was presented for determining effusion rates and emplacement times of a prehistoric intermediate composition lava flow in central Oregon using numerical modeling and morphologic measurements extracted from Lidar-derived DTMs (Deardorff et al., 2012). One large assumption in the methods of Deardorff et al. (2012) is that of lava flow viscosity. For this study, I intend to develop a method to remotely determine viscosity using quantitative analyses of lava surface textures from Lidar data. Viscosity measured in this way would greatly improve the accuracy of flow emplacement models by eliminating assumptions on rheology.

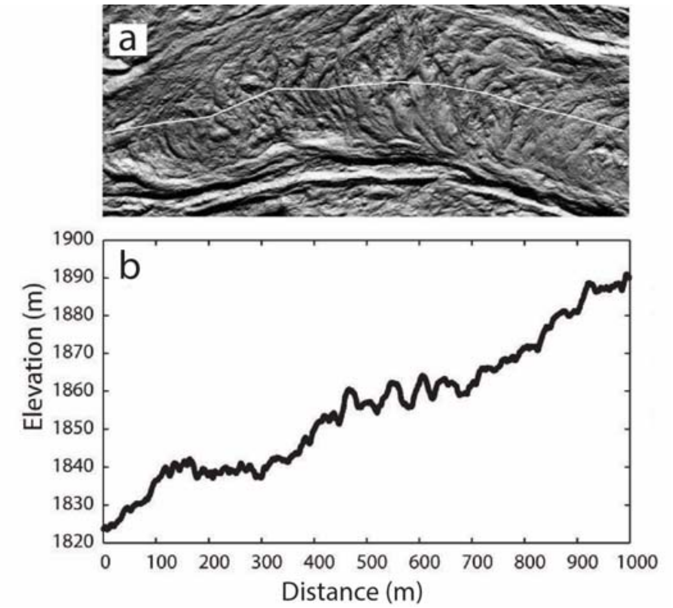

**Fig. 1** (a) Lidar DTM of lava flow channel with 1000m transect line (white). Surface ridges present within the channel, are easily observed in profile (b), showing multiple sizes and wavelengths.

### 1.1 Lava Surface Ridges

The crust of lava flows is commonly folded into arcuate ridges, bent such that the convex ridges point down flow (Fig. 1a). Surface folding is common in lava flows of all compositions, from basalt (<52wt% $SiO_2$) to rhyolite flows (>69wt% $SiO_2$). Surface folds are believed to be due to changes in viscosity and flow velocity between the cooling crust and the more fluid flow interior. In theory, the geometry of flow surface folds can be used to constrain the thickness and viscosity of the folding layer (from the fold wavelength) and the compressional stress (from the fold amplitude; e.g., Fink and Fletcher, 1978; Gregg et al., 1998). Crustal thickness is controlled primarily by lava composition and extent of cooling - lavas of more evolved compositions (higher silica content) advance more slowly and have thicker crusts, which should generate surface folds with larger wavelengths. A detailed comparison of lava flow viscosity with surface fold wavelengths and amplitudes has not been accomplished. In fact, very few surface fold wavelengths of lava flows have been reported in the literature. The wavelengths of surface folds should scale with crustal thickness and flow viscosity, which depend on effusion rate and lava composition. Therefore, increases in surface fold wavelengths should correlate with more evolved (higher viscosity) lava compositions.

## 2. Goals and Objectives

I am a new tenure-track faculty at IUP in the Geosciences department, working on getting a research program started that will produce undergraduate research projects as well as advance my own research, publications, and general scholarship. This project would serve my long-term goal of exploring the uses of high resolution digital topography to analyze volcanic terrains, as well as increasing my computational analytical abilities and skills in guiding undergraduate research projects. I believe this project has the potential for numerous undergraduate research opportunities over the next few years.

This project will collect accurate measurements of surface fold morphologies over a range of lava compositions and focus on correlating the flow surface textures with changes in rheology, specifically viscosity. The specific goals of this project are as follows:

1) Collect and analyze field samples of targeted lava flows in central Oregon to calculate lava viscosities over a range of lava flow compositions.
2) Remotely analyze lava flow surface morphologies to determine dominant wavelengths and amplitudes of surface folds. Analyses will be completed using high resolution 3D Lidar DTMs in Geographical Information Systems (GIS).
3) Correlate lava rheology with measured dominant surface features and produce a numeric model for remote application, allowing researchers to determine lava viscosity without visiting the flow.
4) This project will provide valuable field experience to at least one student working on lava flows and multiple students will complete individual research projects and gain experience using increasingly popular modern technologies (GIS, Lidar) and commonly used analytical techniques (scanning electron microscope, image processing, petrographic microscope).

## 3. Description of Project- Work Plan

My analyses will focus on lavas with compositions ranging from andesite to rhyolite (i.e. lavas >52wt% $SiO_2$) as basaltic lava (<52wt% $SiO_2$) surface textures and rheologies are well constrained due to numerous observations during emplacement. My hypothesis is simply that increased surface fold wavelengths will correlate with more evolved lava compositions; i.e. surface fold wavelengths will increase with increased $SiO_2$ content and increased crystallinity.

This project will include analysis of Lidar datasets using GIS, to compile surface fold measurements, and detailed field work collecting samples to determine compositional data from several lava flows over a range of compositions. Surface fold measurements of wavelength and amplitude will be extracted from high resolution (<1m) Lidar data sets in the central Oregon Cascades. The Oregon Cascades are an ideal locality due to the high frequency of lava flows over the range of compositions required and because of the accessibility of Lidar data. The Oregon Lidar Consortium is currently collecting Lidar over the entire state and making the datasets available for purchase to the public. Additionally, the intended lava flows are accessible by vehicle and/or by trail and are relatively unvegetated, making observation and sampling more accessible.

### 3.1 Field Work

Field measurements of lava surface textures will serve as ground truthing for analyses of digital topography (Lidar data). The lava flows must be thoroughly mapped and sampled to determine each flow's geochemical variability.

To determine lava viscosity remotely, I must be able to correlate measured surface fold wavelengths with calculated viscosities from the solidified flows. In an active flow viscosity can be calculated using the Jeffrey's equation:

$$\eta_a = \frac{g\rho a d^2}{3v_c}, \qquad (1)$$

where $\eta_a$ is apparent viscosity, g is the acceleration due to gravity, $\rho$ is magma density, d is the mean depth of the lava flow, and $v_c$ is the mean velocity of the advancing lava front. Flow velocity can be determined during emplacement and lava density requires in situ sampling. Unfortunately, using the Jeffrey's equation is not possible for previously emplaced lava flows. However, apparent viscosity can be calculated from solidified flows using the method of Pinkerton and Stevenson (1992):

$$\ln \eta_a = \left\{ \frac{\alpha D_m}{\left[ \left( \frac{\phi max}{\phi} \right)^{\frac{1}{3}} - 1 \right]} \right\} - k \qquad (2)$$

where $\alpha=0.011$, $D_m$ is the mean crystal diameter in microns, $\phi$ is the particle (crystal) concentration, $\phi_{max}$ is the maximum particle concentration (assumed to be 1), and k=0.15. Hand samples from a solidified lava flow can be cut, polished, and imaged using a scanning electron microscope (SEM). SEM images will be processed using a freely available image analysis software (ImageJ) to quantitatively determine the mean crystal diameter ($D_m$) and volume percent of crystals ($\phi$). Samples will also be analyzed for bulk geochemical composition through x-ray fluorescence (Washington State University GeoAnalytical Lab).

### 3.2 GIS/Matlab analyses

The primary goal of this project is to accurately measure surface fold waveforms on lava flows with a range of rheologies and compositions. Lidar DTMs allow accurate measurement of both wavelength and amplitude through the application of Discrete Fourier transform (DFT) analysis on along-flow transects. DFT allows unbiased analysis, extracting periodicities within lava flow surface profiles that may be missed by manual measurements.

In a previous study, I characterized the surface folds of the Collier Cone lava flow field in Central Oregon (using the techniques presented in this proposal) as a test study to determine the feasibility of using DFT analyses on lava surfaces to extract dominant wavelengths. To determine the characteristic scale of prominent surface folds, I selected representative 1000m segments of a transect running along the center of the lava channel (e.g. Fig. 1) to cover a range in channel widths, surface fold expression (i.e. larger vs smaller folds), and distance from the vent. I measured the wavelengths and amplitudes for each representative segment by DFT analysis (using the software program Matlab). My DFT analysis measured the power spectral density (in units of amplitude squared) of the input profile (elevation with distance-Fig. 1b). The DFT periodograms produce 1D arrays of spectral density over a range of spatial frequencies, which describe the amplitude and spatial scale (wavelength) of lava surface topography (Fig.2a). Dominant wavelengths are visualized in detrended profiles (Fig. 2b), commonly occurring at 10m, 20m, and 40m along the Collier Cone flows. The DFT analysis presented here extracts the dominant wavelengths of lava surface folds more accurately than manual measurements, which commonly ignored wavelengths of ≤10m, and should work well with lava flows of all compositions.

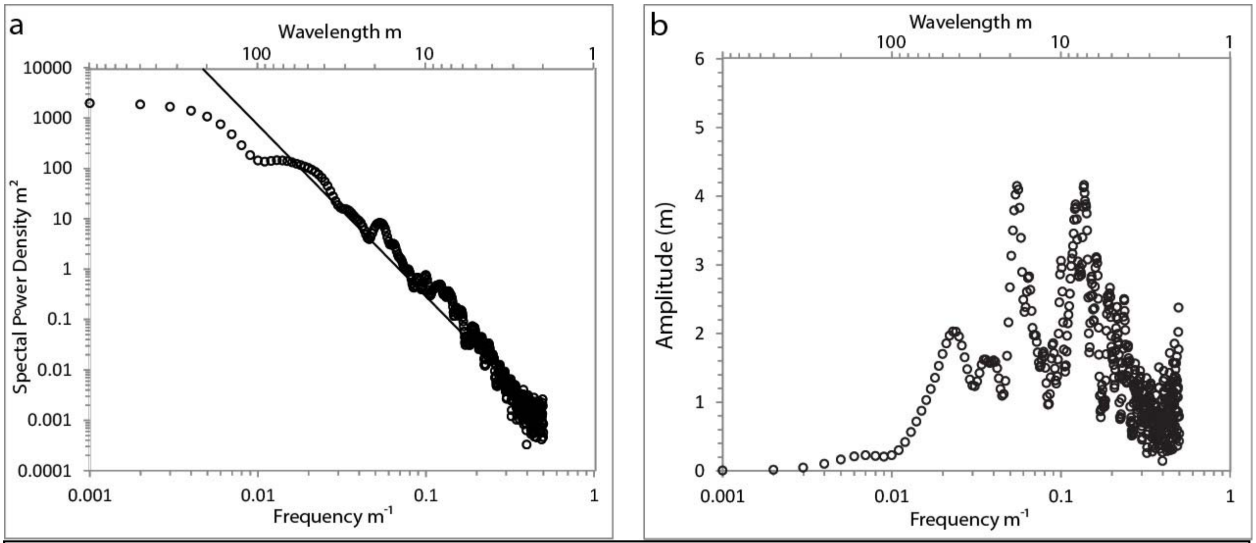

**Fig. 2**- Discrete Fourier Transform periodograms of 1000m profiles. Significant topographic signals (i.e. surface folds) are represented by vertical deviations from the powerlaw trendline. The frequencies at which these deviations occur provide dominant wavelengths of surface folding. Dominant wavelengths are more easily observed in normalized periodograms (b). Profile (a) has pronounced folding with dominant wavelengths at 40-50m, 20m and 5-10m (a,b).

### 4. Expected Outcomes

If successful, our efforts will produce a GIS-based analysis that allows researchers to estimate lava flow viscosity and composition remotely, significantly improving our ability to predictively model lava emplacement for intermediate to high silica lava flows. Many lava flows are nearly or completely inaccessible due to location, rough terrain, heavy vegetation, or political unrest. Remote sensing techniques and analyses allow high quality quantitative research on volcanic landscapes that would otherwise be impossible. This project also has implications for research on extraterrestrial volcanoes; e.g. we could remotely determine the lava compositions on Venus, Mars and other planets and moons.

This project should require 1.5 years for completion. Field work will be accomplished in July-August 2014 and/or 2015, with the help of at least one undergraduate student (possibly Troy Berkey), who will assist with sample collection, mapping and data collection in the field. Once the Lidar datasets are in hand, other computer savvy students will be included for the GIS and Matlab analyses back at IUP. All undergraduates involved will use a portion of this research for personal research projects, which they will be encouraged to present at academic conferences. The Geoscience department at IUP believes strongly that research experiences, such as this, are instrumental in developing undergraduates into scientists and, therefore, require every major to complete a research project before graduation. This project will help multiple students fulfill their research requirement and introduce them to geologic research, as well as modern techniques and technologies.

This project is expected to greatly improve my professional skills in project management (planning and implementation), computer skills using Matlab and GIS, and in advising undergraduate research projects (this will be my first time guiding student projects). Additionally, the results of this project will increase my own, and the volcanologic community's, understanding of lava flow emplacement. Receiving this faculty professional development grant would allow me to collect preliminary data, which in turn, will be used to secure external (e.g. National Science Foundation) funding for a larger, more broadly defined analysis of lava flows with greater compositional range around the world and on extraterrestrial bodies.

**REQUIRED FORMAT FOR BUDGET SUMMARY**

| **Project Budget** | **Proposed Grant** | **University Contribution** | **Other Revenue Sources** | **Totals** |
|---|---|---|---|---|
| Salaries/Stipends | $2000 | | | $2000 |
| Student Wages | 0 | | | |
| Benefits | **XXXXXX** | $380 | | $380 |
| Supplies | | | | |
| Equipment | $200 | | | $100 |
| Operating Expenses | $3325 | | | $3325 |
| Travel | $2850 | | | $2850 |
| Other (Lidar) | $1600 | | | $1600 |
| **TOTALS** | **$9975*** | | | **$10355** |

**Budget Notes** –

Salary: To help fund undergraduate research the Geoscience Dept. at IUP allows each student to request up to $500/yr for research assistance. Therefore, no student salaries are requested in this proposal. To remove the need to teach a summer course, I am requesting $2000 (plus $380 in benefits, covered by the IUP graduate school) to cover 1 month of personal salary.

Equipment, Supplies, and Software: Equipment funds needed for this project will be for shovels, canvas sample bags, and field maps ($100). I will provide all other field equipment including digital cameras, tripod, hammers, compasses, etc. The software packages, ArcGIS and Matlab, are absolutely essential for this project to succeed, as they will be used to analyze the lava flow Lidar data. ArcGIS is freely available to students and faculty on the IUP campus. I will require a student Matlab license for two years ($50/year) for a student work computer. (Total: $200)

Operating Explenses: Analysis of lava flow samples is crucial in determining the bulk composition and crystallinities. Therefore, I am requesting funding for the creation of thin sections (~25ts at $25each), bulk geochemical analysis, through x-ray fluorescence, at Washington State University GeoAnalytical Lab ($35/sample for 20 samples), and 50hrs on the Scanning Election Microscope (SEM- est. $40/hr, location to be determined). Imaging of thin sections using the SEM will allow quantitative analysis of sample crystallinities, which are needed to determine the lava viscosity. (total: $3325)

Travel funds: Travel to and from the field site will include the cost of airline tickets for myself and one student (est. ~$800ea) as well as a rental vehicle (~$1000) and fuel ($250) for two weeks of field work. I will cover lodging expenses (camping fees) with the help of the IUP Geosciences department.

Other: Lidar datasets are currently available through the Oregon Lidar Consortium for $200 per USGS quadrangle. I am requesting funding for 8 quadrangles, totaling $1,600 worth of processed digital topography, which will allow me and my students to analyze at least 12 lava flows over the necessary range of compositions. (total: $1600)

## References

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Cigolini, C., Borgia, A., Casertano, L. (1984) Inter crater activity, aa blocklava, viscosity and flow dynamics: Arenal volcano, Costa Rica. J Volcanol Geotherm Res. 20:155–176.

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Deardorff, N., Cashman, K., (2012). Emplacement conditions of the c.1600 year-BP Collier Cone lava flow, Oregon: a LIDAR investigation. Bull. Volcan. Vol. 74: 9, p. 2051-206 DOI: 10.1007/s00445-012-0650-9

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Gregg, T. K. P., Fink, J. H., Griffiths, R. W. (1998) Formation of multiple fold generations on lava flow surfaces: Influence of strain rate, cooling rate, and lava composition. J. Volcanol. Geotherm. Res. 80: 281-292.

Kauahikaua, J., Sherrod, D. R., Cashman, K. V., Heliker, C., Hon, K., Mattox, T. N., Johnson, J. A. (2003) Hawaiian lava-flow dynamics during the Pu’u’O’o-Kupaianaha eruption: A tale of two decades. U.S. Geological Survey Professional Paper. 1676: 63-88.

Naranjo JA, Sparks RSJ, Stasiuk MV, Moreno MV, Ablay GJ (1992) Morphological, structural and textural variations in the 1988-1990 andesite lava of Lonquimay Volcano, Chile. Geol. Mag. 129(6): 657-678.

Pinkerton, H., Stevenson, R. J. (1992) Methods of determining the theological properties of magmas at sub-liquidus temperatures. J. Volcanol. Geotherm. Res. 53: 47-66.

Walker, G. P. L. (1973) Lengths of lava flows. Philosophical Transactions of the Royal Society, ser. A, 274: 107-118.

## *Curriculum Vitae*

### Education

| | |
|---|---|
| 2011 | Doctor of Philosophy - Geology, University of Oregon, Eugene, OR.<br>Dissertation: "Eruptive Processes of Mafic Arc Volcanoes- Subaerial and Submarine Perspectives" (advisor: Kathy Cashman) |
| 2003 | Bachelor of Science - Marine Science and Geology (with Honors in Geology), University of Miami, Coral Gables, FL. Honors Thesis: "Volatiles in Indian Ocean Mid-Ocean Ridge Basaltic Glasses: Contamination of the Indian Ocean Mantle by Hydrated or Dehydrated Crustal Components." (advisor: Jackie Dixon) |

### Appointments

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| 2013-present | Assistant Professor, Indiana University of Pennsylvania |
| 2012-2013 | Assistant Professor, University of Minnesota, Duluth, MN |
| 2011-2012 | Assistant Professor, University of Minnesota, Morris, MN |
| 2005-2011 | Graduate Teaching Fellow, University of Oregon, Eugene, OR |

### Publications

*Published*

Cashman KV, Soule SA, Mackey BH, Deligne NI, Deardorff ND, Dietterich HR, 2013. How Lava Flows: New Insights from Applications of Lidar Technologies to Lava Flow Studies. Geosphere. Vol. 9: 6.
Deardorff, N., Cashman, K., 2012. Emplacement conditions of the c.1600 year-BP Collier Cone lava flow, Oregon: a LIDAR investigation. Bull. Volcan. Vol. 74: 9, p. 2051-206 DOI: 10.1007/s00445-012-0650-9

Deardorff, N., Cashman, K., Chadwick, W., 2011. Observations of eruptive plume and pyroclastic deposits from submarine explosive eruptions at NW Rota-1, Mariana Arc, J. Volcanol. Geotherm. Res. Vol. 202, p. 47-59. doi:10.1016/j.jvolgeores.2011.01.003

Chadwick, Jr., W. W., Cashman, K. V., Embley, R. W., Matsumoto, H., Dziak, R. P., de Ronde, C. E. J., Lau, T. K., Deardorff, N. D., Merle, S. G., 2008. Direct video and hydrophone observations of submarine explosive eruptions at NW Rota-1 volcano, Mariana arc, J. Geophys. Res., 113, B08S10, doi:10.1029/2007JB005215.

*Most Relevant Published Abstracts*

Deardorff, N., Cashman, K., 2012 Recycling and reheating of pyroclasts as possible mechanism for increased groundmass crystallization in basaltic tephra. Abstract V51E-05 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 7 Dec.

Deardorff, N., Cashman, K., 2010 Post-eruptive magma mixing: recycling in volcanic vents. Abstract V43C-2391 presented at AGU Fall Meeting, San Francisco, Calif. 16 Dec., 2010.

Deardorff, N., Cashman, K., Chadwick, W., 2009 Anomalous Chlorine Concentrations Indicate Recycling of Submarine Pyroclasts at NW Rota-1, Mariana Arc. Eos, AGU Vol. 90, No. 52, Fall Meet. Suppl., Abstract V44B-04.

Deardorff, N., Cashman, K., 2009 Morphologic Measurements on an Intermediate Composition Blocky Lava Flow Field in Central Oregon Using High Resolution (~1m) Lidar DEMs- a Technical Approach, Geological Society of America *Abstracts with Programs*, Vol. 41, No. 7, p. 432.

## Research Cruise Experience

| | |
|---|---|
| 2010 | Return to NW Rota-1 (southern Mariana Arc), expedition to observe changes in eruption dynamics, biological and hydrothermal activity, and sample rocks and vent fluids from the active vent with Jason II ROV. |
| 2009 | Return to NW Rota-1 (southern Mariana Arc), observations of eruption dynamics, biological and hydrothermal activity and sampling with Jason II ROV. |
| 2006 | Submarine Ring of Fire 2006, NOAA- expedition exploring nine submarine volcanoes along the Mariana Arc for hydrothermal, volcanic and biological activity. Collected direct video and hydrophone recordings, and hand samples from explosive eruptions at NW Rota-1, with Jason II ROV. |
| 2003 | Exploration and mapping of Endeavor Deep, located on the Nazca/Juan Fernandez plate boundary. Assisted in collection and sampling of rocks retrieved and video recording by Jason II ROV. |

## Field Experience

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| 2006-2010 | Field mapping and rock sampling of Holocene Collier Cone lava flow field, Oregon High Cascades |
| 2007 | IAVCEI workshop in Nevada, Utah, California, entitled *Surtseyan volcanism: shallow subaqueous explosive eruptions*, lead by James White. |
| 2007 | GPS, Total Station and Ground-based Lidar mapping and scanning of cinder cone and lava flow morphologies at Four Craters Volcanic Field, Central Oregon |
| 2007 | International consortium EHaz field trip, focused on natural hazards: Volcano edifice failure in Cascades and Western Canada |
| 2006 | Ground-based Lidar scanning of lava flows in the Oregon High Cascades |

## Analytical/Field Equipment and Software Experience

Microprobe, Scanning Electron Microscope, Fourier Transform Infrared Spectroscopy, X-ray Diffractometry, Trimble GPS, Total Station, Optech Ilris 3D Ground-based Lidar system, ArcGIS, Matlab