A High-Speed Self-Contained Video Camera System for Optical Plume Velocimetry: OTIC Project Report

Timothy Crone
18 December 2009

Abstract

Hydrothermal flow within mid-ocean ridges strongly affects the transfer of heat and mass between the crust and the overlying ocean. Despite its importance, there are no long-term measurements of flow through high-temperature hydrothermal vents primarily because invasive-type flow measurements do not work in these environments. In this project we are developing a high-speed seafloor camera system for measuring flows in black smoker vents using image analysis. The development of this system and subsequent deployment in stand-alone configuration or as part of a cabled seafloor observatory will provide important new insights into the functioning of seafloor hydrothermal systems.

Present Status

During the first phase of this project engineer David Gassier and PI Timothy Crone completed the initial design and specification of the camera system in preparation for the construction phase. We were then offered a chance to deploy the instrument on a cruise led by Scott Nooner, but such a deployment would require additional funding. Using our progress to date and OTIC funding as leverage, we wrote an NSF proposal that was funded at $97,386. This proposal is attached to this document.

David was called off the project to concentrate on his duties in the OBS facility, and because we were unable to find the appropriate expertise at Lamont, we began working with engineer Carl Robinson of the BAS to complete the construction of the instrument. This work is now complete and we are currently at sea on the R/V Atlantis with DSV Alvin making the final preparations for a deployment in two day's time. Pictures of the completed instrument and the mounting tripod are below.

Benefits Realized

This OTIC project has been an enormous success. Even before the project was finished we were able to leverage NSF funding to expand the scope of work and build a better and more capable instrument. We have increased the visibility of LDEO as an instrument building institution, increased our capacity to build instruments, and obtained outside funding to supplement our efforts. I would highly recommend the continuation and expansion of this project.

Close up view of the OPV system light and camera bar sitting in the main lab of the R/V Atlantis on its way to the EPR for its maiden deployment.

OPV system and seafloor mounting tripod with the LED light illuminated. A light calibration target can be seen in the background.

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 08-1

NSF 08-1

FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.)

OCE - OCEAN TECH & INTERDISC COORDIN

FOR NSF USE ONLY

NSF PROPOSAL NUMBER

0917955

DATE RECEIVED	NUMBER OF COPIES	DIVISION ASSIGNED	FUND CODE	DUNS# (Data Universal Numbering System)	FILE LOCATION
12/31/2008	1	06040000 OCE	1680	049179401	01/05/2009 12:13pm S

EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN)

135598093

SHOW PREVIOUS AWARD NO. IF THIS IS
☐ A RENEWAL
☐ AN ACCOMPLISHMENT-BASED RENEWAL

IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES ☐ NO ☒ IF YES, LIST ACRONYM(S)

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE

Columbia University

AWARDEE ORGANIZATION CODE (IF KNOWN)

0027078000

ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE

Columbia University
2960 Broadway
NEW YORK, NY. 100276902

NAME OF PERFORMING ORGANIZATION, IF DIFFERENT FROM ABOVE

Columbia University Lamont Doherty Earth Observatory

PERFORMING ORGANIZATION CODE (IF KNOWN)

0027078040

ADDRESS OF PERFORMING ORGANIZATION, IF DIFFERENT, INCLUDING 9 DIGIT ZIP CODE

Columbia Lamont Earth Obs
Rt 9W
Palisades, NY 10964

IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions)
☐ SMALL BUSINESS ☐ MINORITY BUSINESS
☐ FOR-PROFIT ORGANIZATION ☐ WOMAN-OWNED BUSINESS

☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **A Seafloor Camera System for Flow Rate Measurements in Black Smoker Vents**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 97,386	12 months	02/01/09	

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

☐ BEGINNING INVESTIGATOR (GPG I.G.2)
☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C)
☒ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.D, II.C.1.d)
☐ HISTORIC PLACES (GPG II.C.2.j)
☒ SMALL GRANT FOR EXPLOR. RESEARCH (SGER) (GPG II.D.1)
☐ VERTEBRATE ANIMALS (GPG II.D.5) IACUC App. Date _____
PHS Animal Welfare Assurance Number _____
☐ HUMAN SUBJECTS (GPG II.D.6) Human Subjects Assurance Number _____
Exemption Subsection _____ or IRB App. Date _____
☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.j)
_____
☐ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.G.1)

PI/PD DEPARTMENT

Lamont-Doherty Earth Observatory

PI/PD FAX NUMBER

845-365-8156

PI/PD POSTAL ADDRESS

61 Route 9W

NEW YORK, NY 10964
United States

NAMES (TYPED)	High Degree	Yr of Degree	Telephone Number	Electronic Mail Address
PI/PD NAME **Timothy J Crone**	**PhD**	**2007**	**845-365-8687**	**crone@ldeo.columbia.edu**
CO-PI/PD				
CO-PI/PD				
CO-PI/PD				
CO-PI/PD				

Electronic Signature

Project Summary

Intellectual Merit

We request funds to develop and test a seafloor camera system that can measure fluid flow through black smoker hydrothermal vents using video image analysis. Fluid flow through black smoker vents plays a significant role in the exchange of heat and chemicals between the oceanic crust and the ocean. This flow delivers energy to a diverse subseafloor ecosystem and serves to link tectonic and magmatic processes to chemical and biological processes. Measurements of fluid flow in these systems are essential for measuring fluxes and understanding complex systematic linkages.

Despite the importance of measuring fluid flow rates, there is currently no instrument capable of obtaining long term flow measurements in black smoker vents. High temperatures, low pH, and mineral precipitation make invasive techniques infeasible. To address this problem, we propose to develop a non-invasive image-based instrument to obtain flow rates in black smoker vents. This camera system will employ a new technique for measuring black smoker flow, called Optical Plume Velocimetry (OPV), which has been developed in the laboratory and has been shown to work well on simulated black smoker flows. We will design and build the camera system including the OPV logic, which will be contained in a pressure housing provided by Deep Sea Power and Light. The system will include an LED array for efficient scene lighting and an adjustable tripod system for deployment from an ROV or HOV platform. We will test this instrument during a $\sim$1-week deployment at a black smoker vent on the East Pacific Rise (EPR) using ROV Jason in December of 2009. The opportunity to field test the camera system has been provided at no-cost by Dr. Scott Nooner, the chief scientist of the EPR cruise. This proposed project represents an excellent but time-critical opportunity to develop a new and potentially transformative instrument for studying mid-ocean ridge hydrothermal systems.

Broader Impacts

This study will develop an instrument that will increase our ability to understand the hydrology of marine hydrothermal systems and a variety of related processes, including the interactions between geomechanical processes (such as tectonic events) and other processes such as heat and chemical transport and biological productivity. With the advent of the Ocean Observatory Initiative, new instruments and techniques will be required to carry out long-term experiments and monitoring. The work proposed here will develop an instrument well-suited for deployment as part of a regional cabled observatory. The development and field test of this technology will open up a wide range of possible experiments at many vent fields on the mid-ocean ridge. This work will also support the work of a young scientist. Crone has a strong record of public outreach through the media, and communicating his results to scientific and general audiences.

A Seafloor Camera System for Flow Rate Measurements in Black Smoker Vents

Timothy J. Crone

1 Introduction

Hydrothermal flow within the mid-ocean ridge system is the primary mechanism by which new crust cools and it facilitates large chemical fluxes between the seafloor and the ocean (*Elderfield and Schultz*, 1996). These flows strongly influence the physical properties of the lithosphere, the chemistry of the ocean, and the geology of the crust. Hydrothermal flow also delivers the energy required to support large and diverse ecosystems living at and below the seafloor, and in this way serves as a critical link between the geophysical, chemical, and biological components of mid-ocean ridge systems (*Kelley et al.*, 2002).

The mid-ocean ridge scientific community has indicated a pressing need for information regarding heat and chemical fluxes in these systems, which will be critical for tuning numerical models, interpreting geochemical patterns, estimating biological productivity, and integrating our understanding of these systems across disciplines (*Fornari and Tolstoy*, 2008; *Wilcock*, 2008). Flow measurements in black smoker hydrothermal vents are essential for estimating fluxes, but historically these measurements have been difficult, and no long term measurements of this type have been collected. High temperatures, low pH, and mineral precipitation prevent the use of invasive flow measurement techniques for long term measurements in these flows.

We are very close to solving this problem through the development of a non-invasive flow measurement technique called Optical Plume Velocimetry (OPV), which is based on video image analysis. This method relies on the establishment of a time-averaged optical flow field which is computed from an image sequence showing the vent plume. The theory and practicality of this technique was developed in the laboratory and has been shown to work very well on simulated black smoker flows (*Crone et al.*, 2008). The next step is to implement the OPV technique within a stand-alone seafloor camera system that can collect vent imagery and process the video to obtain flow rates in real time.

The implementation of OPV in a stand-alone instrument will open up new avenues in vent systems research, as measurements of temperature and chemistry, which are common (e. g. *Butterfield et al.*, 1997, 2003; *Fornari et al.*, 1998; *Larson et al.*, 2007), can be converted into *fluxes*, which are the quantities of interest. This instrument will be capable of long-term monitoring which will allow investigations of the links between tectonic forces, magmatic processes, tidal loading, and the subseafloor biosphere. Further, this system will likely be a useful addition to seafloor cabled observatories which are currently under construction as part of the NSF Ocean Observatory Initiative (OOI).

In this proposal we briefly discuss the theory of OPV, then we describe the self-contained camera system we intend to build and the planned testing program using dive time made available at the East Pacific Rise. We conclude by discussing the need for SGER funding.

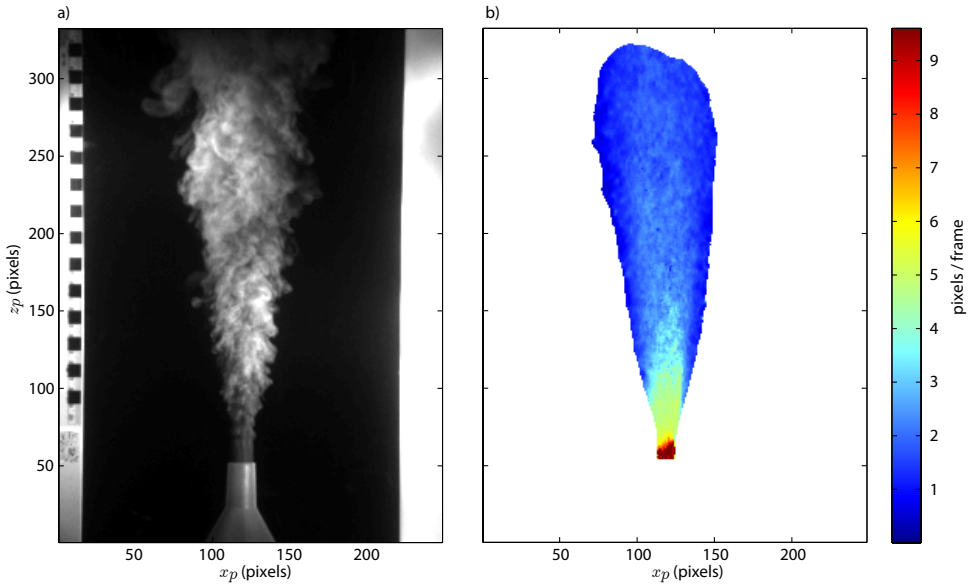

Figure 1: (a) Typical frame capture from a laboratory simulation, and (b) representative image-velocity field computed using OPV. A metric can be derived from the image-velocity field that is linearly related to the flow rate at the flow nozzle (see Figure 2).

2 Optical Plume Velocimetry

Optical Plume Velocimetry (OPV) is a new technique for obtaining black smoker hydrothermal vent flow rates using video image analysis. The technique was developed by *Crone et al.* (2008), using simulated black smoker flows with known flow rates and standard digital video camera image sequences. The technique is based on the establishment of the "image velocity field", which is a two-dimensional vector representation of the motion of the objects within an image sequence. Figure 1 shows a typical image frame from the simulated black smoker flow, and a typical image velocity field. The OPV technique utilizes a novel time-based cross-correlation scheme to establish the image velocity field based on the motions of large-scale flow structures.

A flow rate metric is then computed from the image velocity field which is a linear function of the black smoker flow rate. Figure 2 shows an example of the relationship between this flow rate metric and the true nozzle flow rate. *Crone et al.* (2008) show that the precision of flow rate measurements using OPV will be on the order of 2–3%, which is sufficient to capture the flow rate variability expected (*Crone and Wilcock*, 2005).

3 Proposed Work

An internal grant by the Lamont-Doherty Earth Observatory (LDEO) in the amount of $26,160 has been provided to begin the design of the OPV electronics system. This grant provides engineering support only, and funds were provided with the understanding that additional funding would be sought to develop and test a complete seafloor monitoring system. We hope to leverage this

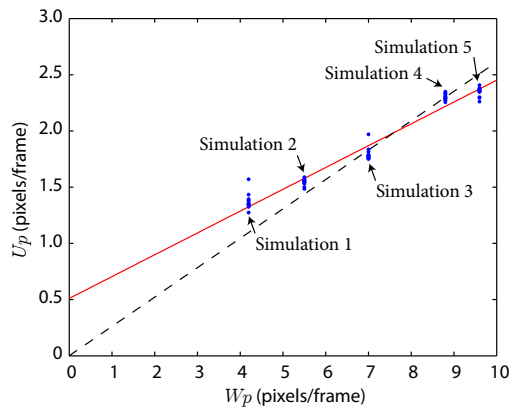

Figure 2: Data from five simulated flows showing the linear relationship of the OPV-derived flow rate metric, U_p, to the measured mean nozzle flow rate, W_p. Blue dots depict individual flow rate metric values calculated from 30 s video segments, of which there are 13 for each of five laboratory simulations.

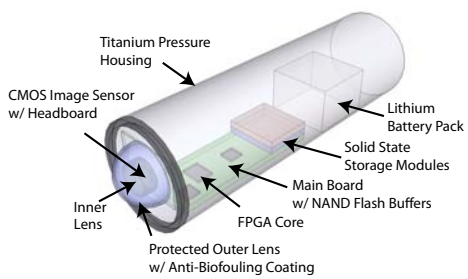

Figure 3: Schematic diagram of the proposed OPV camera showing the major system components. This camera system will be housed within the Super SeaCam 5000 pressure housing supplied by Deep Sea Power and Light. The system will also include an LED light array and a mounting system not shown in this schematic.

institutional seed funding with SGER funding.

Our preliminary work informs the following discussion in which we propose to complete the design and construction of an OPV camera system and conduct field testing at the East Pacific Rise using ship and ROV time made available to us by Dr. Scott Nooner, chief scientist of cruise 113595.

3.1 Camera System Design and Construction

A schematic diagram of the proposed system is shown in Figure 3. The exact system design will be established as part of this project through a collaboration between principal investigator Crone and LDEO engineer David Gassier. In general, the major components of the system are known, as are the required design specifications. This system will have a digital video imaging subsystem controlled by a field-programmable gate array (FPGA), and it will have a large memory module, a digital signal processor (DSP) to implement the OPV technique, and a data storage module to log computed data. The system will also include an LED light array with a separate battery pack and a mounting system for deployment and alignment using a manipulator arm. The camera will be contained within a titanium pressure housing with optical glass viewport supplied by Deep Sea Power and Light. This supplier builds pressure housings that are known and trusted by the WHOI Deep Submergence group.

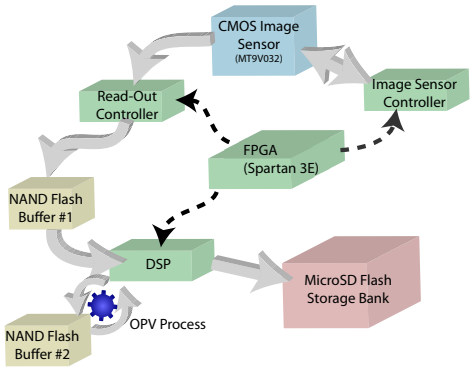

Figure 4: Conceptual diagram showing the logic chain for image capture, processing, and data storage. The camera system will be based on a CMOS imaging chip and will be controlled with a large field-programmable gate array (FPGA).

3.1.1 Imaging Subsystem and Field-Programmable Gate Array (FPGA)

For its image sensor, the OPV camera will use the Micron MT9V032 CMOS Image Sensor which can deliver 60 frames per second (fps) at VGA resolutions (640 by 480) in 10-bit monochrome. This chip has a global shutter for simultaneous integration and a high dynamic range for use in low-light conditions. The work of *Crone et al.* (2008) showed that imagery with higher temporal resolutions and relatively low spatial resolutions, as supported by this chip, is ideal for OPV.

An FPGA, which is a flash-configurable logic chip, will serve as the core of the camera's electronic system and will control the flow of data from the imaging chip to the memory module and from the memory module to the DSP. The FPGA will also control the flow of processed data from the DSP to the storage medium. We have chosen the Xilinx Spartan 3E chip to serve in this capacity, as it has the speed and gate count required. Figure 4 shows a conceptual flow chart indicating the relationship of subsystem components with the FPGA at framework center.

3.1.2 Digital Signal Processor (DSP) and Storage Medium

The OPV technique will be implemented within a dedicated DSP, built from a portion of the FPGA, which will accept a video sequence from the memory module and compute the image velocity field as described in *Crone et al.* (2008). The OPV algorithm will be written in the C programming language and compiled for the chosen DSP architecture. With an efficient algorithm the DSP should be able to compute image velocity fields in real time.

The OPV camera system will not store raw video data. Rather, it will store image velocity fields computed by the DSP. For this reason the data storage requirements of the system will be relatively modest. Compressed image velocity fields will be approximately 250 kB—thus one 16-GB compact flash card will be able to store about 64,000 velocity measurements. This number of measurements will be sufficient to monitor flow rates for several months. Longer deployments in subsequent generation devices will be accommodated with multiple storage modules.

3.1.3 Lighting Array

Scene lighting will be supplied by an application-specific compact LED light array with separate battery pack. The system will be based on the highly efficient Luxeon Rebel LED emitter centered

on 455 nm to maximize seawater transmission. This wavelength is also near the peak of sensor sensitivity. The array strobe and light output will be controlled by the camera and adjusted to supply optimal light levels for the camera's exposure settings. The light array will be positioned at an oblique angle to the fluid flow in order to properly illuminate turbulent flow structures, as described in *Crone et al.* (2008).

3.1.4 Mounting Base

We will design and construct a mounting base that will allow the camera system to be deployed and positioned using a remotely-operated manipulator arm. The base will be relatively heavy for solid support and will have a frictional ball mount for positioning.

3.2 Camera System Testing

We will have the opportunity to deploy and test the OPV camera system at the East Pacific Rise in December 2009. Using any free weather days, provided courtesy of Dr. Scott Nooner, chief scientist of the cruise, we will deploy the OPV camera system at a black smoker vent early in the cruise, and collect OPV data for approximately one week. We will recover the device near the end of the two-week expedition. This is an ideal length for a proof-of-concept field trial, as it will allow us to observe flow rate changes associated with tidal pumping that are predicted in these systems (*Crone and Wilcock*, 2005).

4 Need for SGER Funding

We are requesting SGER funding for two primary reasons. First, this is a relatively high-risk exploratory project that will have potentially transformative implications for the field of mid-ocean ridge hydrothermal research. While the OPV technique has been shown to work in the laboratory, it is unlikely that normal funding channels would be open to the idea of supporting OPV research until it is shown to work in the field. Once this instrument has been shown to work, it will likely become the standard method by which flow is measured in black smoker vents. High quality and long term flow rate information from seafloor vents will bring about significant advances in our understanding of these complex systems by constraining heat and chemical fluxes and elucidating connections between geomechanical processes and chemical, geological, and biological processes. Information that will be provided by this device has the potential to catalyze a range of integrative research across disciplines.

Second, we have an excellent but time-critical opportunity to test this instrument in a mid-ocean ridge setting by way of a no-cost piggy-back expedition. We will not be able to capitalize on this opportunity unless work begins in the early part of 2009 so the instrument can be ready for the December cruise. It is unlikely that normal funding channels would be able to provide support until mid-2009, which would preclude a no-cost field trial. Thus we request SGER funding to support this project.

References

Butterfield, D. A., W. E. Seyfried Jr., and M. D. Lilley (2003), Composition and evolution of hydrothermal fluids, in *Energy and Mass Transfer in Marine Hydrothermal Systems*, edited by P. E. Halbach, V. Tunnicliffe, and J. R. Hein, Dahlem Workshop Report 89, pp. 123–161, Dahlem, Berlin.

Butterfield, D. A., et al. (1997), Seafloor eruptions and evolution of hydrothermal fluid chemistry, *Phil. Trans. Roy. Soc. Lond. A*, *355*, 369–386.

Crone, T. J., and W. S. D. Wilcock (2005), Modeling the effects of tidal loading on mid-ocean ridge hydrothermal systems, *Geochem. Geophys. Geosyst.*, *6*, Q07001, doi:10.1029/2004GC000905.

Crone, T. J., R. E. McDuff, and W. S. D. Wilcock (2008), Optical plume velocimetry: A new flow measurement technique for use in seafloor hydrothermal systems, *Experiments in Fluids*, doi:10.1007/s00348-008-0508-2.

Elderfield, H., and A. Schultz (1996), Mid-ocean ridge hydrothermal fluxes and the chemical composition of the ocean, *Annu. Rev. Earth Planet. Sci.*, *24*, 191–224.

Fornari, D., and M. Tolstoy (Eds.) (2008), *Ridge 2000 East Pacific Rise 8°-11°N Integrated Studies Site Integration and Synthesis Workshop*, Hyannis, MA, Sept 26–28.

Fornari, D. J., et al. (1998), Time-series temperature measurements at high-temperature hydrothermal vents, East Pacific Rise 9°49'–51'N, *Earth Planet. Sci. Lett.*, *160*, 419–431.

Kelley, D. S., J. A. Baross, and J. R. Delaney (2002), Volcanoes, fluids, and life at mid-ocean ridge spreading centers, *Annu. Rev. Earth Planet. Sci.*, *30*, 385–491, doi: 10.1146/annurev.earth.30.091201.141331.

Larson, B. I., E. J. Olson, and M. D. Lilley (2007), In-situ measurement of dissolved chloride in high temperature hydrothermal fluids, *Geochim. Cosmochim. Acta*, *71*, 2510–2523, doi: 10.1016/j.gca.2007.02.013.

Wilcock, W. (Ed.) (2008), *Endeavour Integrated Studies Site Integration and Planning Workshop*, Seattle, WA, Sept 18–19.

LAMONT-DOHERTY EARTH OBSERVATORY OF COLUMBIA UNIVERSITY

26 November 2008

Kandace Binkley
Associate Program Director
Ocean Technology and Interdisciplinary Coordination
National Science Foundation

Dear Dr. Binkley,

As Chief Scientist of an upcoming cruise to the East Pacific Rise with *ROV Jason*, I am writing to confirm that we will have berthing available for Tim Crone to join our field campaign. This cruise is currently scheduled for December of 2009. Barring weather difficulties, we will also have the time available to allow Tim to deploy his proposed test instrumentation at a black smoker vent. If you have any questions about these potential arrangements, please do not hesitate to contact me.

Sincerely,

Scott Nooner, Ph.D.

Columbia University
Lamont–Doherty Earth Observatory
61 Route 9W
Palisades, NY 10964
Phone: 845-365-8944
Email: snooner@ldeo.columbia.edu