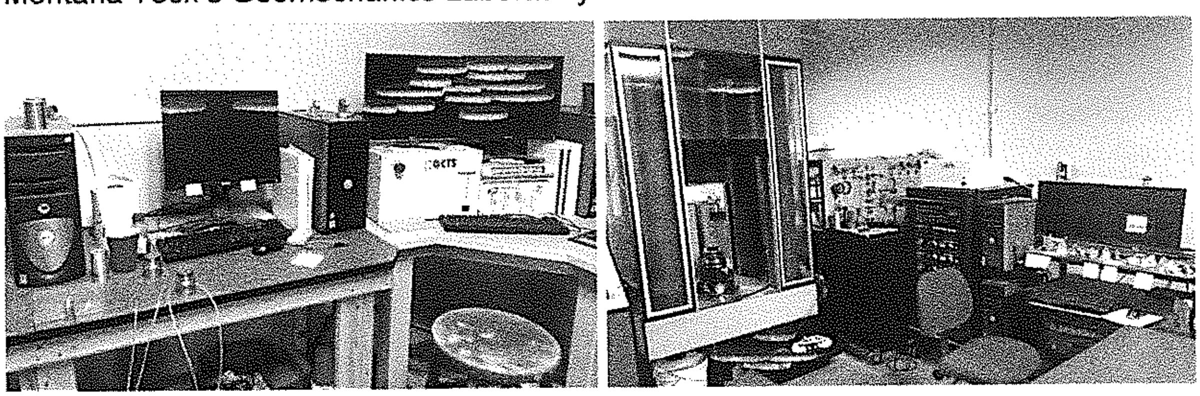
Introduction, Background, and Objectives

Laboratory testing of geological materials is critical because the engineering properties of natural materials (like rock and soil) are inherently more variable than human-made materials (like metal, concrete, and plastic). Historically, engineering properties (particularly strength) of materials have been determined using traditional laboratory testing procedures in which the test specimens are loaded to failure and consequently destroyed. More recently, nondestructive testing methods have been developed and are very attractive for a number of reasons. For instance, the specimens can be tested repeatedly to define behavior over time, or can be tested before and after being subjected to some condition of interest (mechanical load, hot or cold temperature, submergence in fluid, etc.).

One nondestructive technique used on rock cores is ultrasonic testing. This involves sending wave pulses through specimens to determine the velocities of the waves as they pass through the material, which in turn are used to calculate engineering properties. There is a standard procedure for performing ultrasonic tests on rock cores [1]. In 2012, the departments of geophysical and geological engineering at Montana Tech partnered to purchase ultrasonic testing equipment for use at Montana Tech, using capital equipment funds; since that time, the equipment has been used in laboratory activities for several courses, for several small research projects, and for a number of outreach activities. The equipment is shown in Figure 1a.

Unconfined compressive strength (UCS) is one critical engineering property that is NOT directly determined via the ultrasonic test, but studies have been conducted to identify correlation between wave velocities and UCS (for example [2],[3],[4],[5],[6],[7],[8],[9],[10]). While a number of different rock types have been investigated (mostly sedimentary rocks), the correlation does vary with rock type and no studies have been found that have focused on coarse-grained mafic igneous rocks. The basic objective of this proposed research is to determine the correlation between ultrasonic wave velocity and UCS for coarse-grained mafic igneous rocks obtained from the Stillwater Mine in Montana. UCS tests would be performed using the TerraTek load frame located in Montana Tech's Geomechanics Laboratory.



(a) (b)

Figure 1. Montana Tech's a) GCTS ULT-100 ultrasonic testing apparatus, and b) TerraTek load frame, both located in the Geomechanics Laboratory (MG 007).

Proposed RAMP Research

A pilot study conducted during summer 2016 in conjunction with several campus outreach activities yielded data with a very low correlation coefficient (< 0.10) as shown in Figure 2. The variability is attributed to a number of factors related to the fact that the primary goal was to provide a hands-on outreach activity rather than research-quality data: 1) the rock specimens were not uniform, 2) the rock specimens were not prepared to high quality standards, and 3) the UCS tests were performed by untrained high school students on a lower level testing device that was faster and cheaper to use than the TerraTek load frame. The RAMP project would provide the opportunity to do further investigation under more controlled conditions, yielding a higher quality dataset and, it is hoped, a stronger correlation.

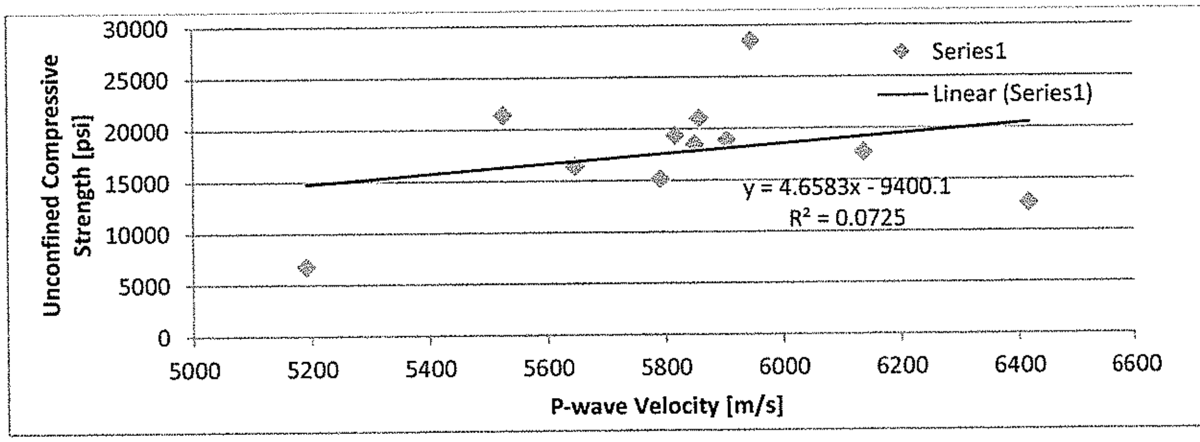


Figure 2. Preliminary data showing weak correlation between ultrasonic velocity and UCS.

If this project is selected for funding, a team of undergraduate students will prepare rock core specimens (approximately 10-20 per student) and subject them to ultrasonic tests (approximately 30 per student, as each student will test the entire population of specimens) and unconfined compression tests (10/student). This testing program will provide a rich dataset, with multiple determinations of wave velocity for each specimen that will allow evaluation of the variability introduced by individual interpretation of the data. After the ultrasonic and UCS test data are interpreted, the correlation between wave velocity and UCS will be determined. Regular group meetings will be held to discuss activities, progress, issues, results, and interpretation.

The students will be expected to work 2-3 hours per week, accomplishing the objectives according to the following anticipated schedule:

- January (4 weeks) – initiation and safety meetings, RCR training, specimen prep
- February (4 weeks) – ULT training, testing, data interpretation
- March (3 weeks) – UCS training, testing, data interpretation
- April (4 weeks) – ULT/UCS correlation, poster preparation, Techx-po

A unique and attractive aspect of the proposed work is that a parallel study (with separate funding) will be performed at the University of North Florida (UNF), with half of the specimens prepared at Montana Tech sent to UNF for testing using similar equipment. UNF participants will attend the group meetings via the internet.

Participants

Prof. Mary MacLaughlin has mentored 36 undergraduate researchers during her 20 years at Montana Tech, 16 of whom have published their work or presented at regional, national, or international conferences (including those held in Canada and Norway). She was a member of Montana Tech's Undergraduate Research Committee from 2005-2013, serving as Co-Chair and Chair from 2009-2013. Under her leadership, the Undergraduate Research Committee expanded its scope by initiating both the Research Assistant Mentorship Program (RAMP) and the Summer Undergraduate Research Fellowship (SURF) program. Based on her service to and success with undergraduate research and undergraduate researchers on the Montana Tech campus, Prof. MacLaughlin was recently honored by the U.S. Council on Undergraduate Research with the "2104 GeoCUR Undergraduate Research Mentor Award" acknowledging "leadership in transformative undergraduate research mentoring."

The proposed project provides the opportunity to reinitiate a very productive partnership with colleague Nick Hudyma, civil engineering professor at the University of North Florida (a primarily undergraduate institution), as well as incentive to pursue future collaboration with colleagues in Montana Tech's geophysical engineering department.

The undergraduate RAMP researchers will consist of Ms. Maranda Ratcliff and Ms. Alexandra Corlett (both geological engineering sophomore transfer students who have expressed interest in the geophysics minor), and a third student to be determined (several candidates have been identified, including a female geophysical engineering student). Additional funding will be pursued to facilitate the participation of the SURF student who did the pilot study (sophomore Brent Sordo), who would serve as team leader and perform advanced tests for additional comparison.

References Cited

[1] ASTM D2845-08, Standard Test Method for Laboratory Determination of Pulse Velocities and Ultrasonic Elastic Constants of Rock, ASTM International, 2008, www.astm.org.

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[10] Vishnu, C. S., Mamtani, M. A., & Basu, A. (2010). AMS, ultrasonic P-wave velocity and rock strength analysis in quartzites devoid of mesoscopic foliations–implications for rock mechanics studies. Tectonophysics, 494(3), 191-200.

APPENDICES

1. Requested Budget

In addition to the student stipends (3 students @ $300 each) and the mentor stipend of $300 that will be reinvested into lab fees, additional funding is requested to cover most of the UCS tests (30 tests @ $10 each, for a total of $300). Costs in excess of the budgetary limits will be paid from the mentor's IDC account or department funds.

2. NSF Bio Sketch

Mary M. MacLaughlin, Ph.D.
Professor, Department of Geological Engineering
Montana Tech of The University of Montana

Professional Preparation

Bachelor of Geo-Engineering, University of Minnesota – Minneapolis, 1988 (with distinction).

M.S., Civil (Geotechnical) Engineering, University of California at Berkeley, 1989.

Ph.D., Civil (Geotechnical) Engineering, University of California at Berkeley, 1997.

Appointments

Montana Tech of The University of Montana: Department of Geological Engineering, Professor, August 2004 to present; Dept Head, July 2009 to July 2013; Associate Professor, August 2000 to August 2004; Assistant Professor, August 1996 to August 2000

University of California at Berkeley: Department of Civil Engineering, Graduate Student Instructor and Research Assistant, August 1989 to August 1996

USDA Forest Service: Civil (Geotechnical) Engineer, May 1989 to August 1993 (summers)

5 Products Most Related to Proposed Project (superscript indicates student co-author)

Adams[MS], S., S. Smith[MS], M. MacLaughlin, J. Wartman, K.N. Applegate[PhD], M.D. Gibson[PhD], L. Arnold[PhD], and D.K. Keefer (2013). Experimental and Numerical Characterization of Synthetic and Natural Rock Properties in Support of the NEESROCK Project, Abstract S51B-2363, poster presented at 2013 Fall Meeting, AGU, San Francisco, CA, 9-13 Dec.

Medapati[MS], R.S., P.O. Kreidl, M.M. MacLaughlin, N. Hudyma, and A. Harris (2013). Quantifying surface roughness of weathered rock – examples from granite and limestone, *Geotechnical Special Publication No. 231 - Proceedings of the 2013 Geo-Congress* (C.L. Meehan, D. Pradel, M.A. Pando, J.F. Labuz, eds.), March 3-7, 2013, San Diego, CA, pp. 120-128.

Smith[MS], Shannon E. and Mary M. MacLaughlin (2012). Validation of Dynamic Modeling with UDEC: Block on an Inclined Plane, *Proceedings of the 44th Symposium on Engineering Geology & Geotechnical Engineering*, Reno, Nevada (10 pp).

Sarno[MS], A., Hudyma, N., Hiltunen, D.R., and MacLaughlin, M.M. (2009). Modal testing: an innovative approach to dynamic rock specimen characterization, *Proceedings of the 42nd Symposium on Engineering Geology & Geotechnical Engineering*, Pocatello, Idaho, pp. 61-74.

Sherman[UG], C., M. MacLaughlin, and N. Sitar (2009). Numerical Modeling of the Madison Canyon Rockslide (abstract), *Proceedings of the 42nd Symposium on Engineering Geology & Geotechnical Engineering*, Pocatello, Idaho, p. 37.

5 Other Related and/or Significant Products

Smith[MS], S.E., M.M. MacLaughlin, S.L. Adams[MS], J. Wartman, K. Applegate[PhD], M. Gibson[PhD], L. Arnold[PhD], and D. Keefer. Interface Properties of Synthetic Rock Specimens: Experimental and Numerical Investigation Manuscript GTJ-2013-0161 submitted to the *ASTM Geotechnical Testing Journal* 9/24/13 (in review).

Gage[PhD], J.R., D. Fratta, A.L. Turner, M.M. MacLaughlin, and H.F. Wang (2013). Validation and implementation of a new method for monitoring in situ strain and temperature in rock masses using fiber-optically instrumented rock strain and temperature strips, *International Journal of Rock Mechanics and Mining Sciences* 61 (July):244-255.

Jespersen[MS], C., MacLaughlin, M., and Hudyma, N. (2010). Strength, deformation modulus and failure modes of cubic analog specimens representing macroporous rock, *International Journal of Rock Mechanics and Mining Sciences* 47:1349-56.

MacLaughlin, M. M. and D. M. Doolin[PhD] (2006). Review of Validation of the Discontinuous Deformation Analysis (DDA) Method, *International Journal for Numerical and Analytical Methods in Geomechanics*, 30/4 (April 2006): pp 271-305.

Sitar, Nicholas, Mary M. MacLaughlin, and David M. Doolin[PhD] (2005). Influence of Kinematics on Landslide Mobility and Failure Mode, *ASCE Journal of Geotechnical and GeoEnvironmental Engineering,* 131/6 (June 2005): pp. 716-728.

Synergistic Activities

Developed completely new or significantly revised content for 10 undergraduate and graduate courses at Montana Tech, including a special topics course in earthquake engineering; added design projects to 5 courses, most integrating field, lab, analytical and numerical work; with combined support from grant funds and Montana Tech, able to acquire new lab equipment and incorporate associated lab experiments into existing courses

During the last 10 years, focused on building international research partnerships, by developing relationships with potential collaborators in other countries, hosting international visiting scholars (2 from Israel), finding international research/study abroad opportunities for grad students (2 in China, 2 in Austria), and teaching shortcourses (Scotland, China, and Austria)

Served as the Chair of the Montana Tech Undergraduate Research Committee from 2009-2013, developing two new undergraduate research initiatives and leading the program in its transition from NSF-EPSCoR funding to multiple smaller funding sources; mentored 36 undergraduate researchers since 1999

Collaborators & Other Affiliations

(i) ***Recent collaborators:*** C. Link, T. Moon, M. Pedulla, D. Reichardt, D. Smith, L. Smith (Montana Tech); S. Bang, L. Roberts, L. Stetler (SDSMT); Nick Hudyma, R.K. Bathini, A. Harris, K. Johnson, P.O. Kreidl, R.S. Medapati, A. Sarno (Univ of North Florida); D. Hiltunen (Univ of Florida); D. Fratta & H. Wang (Univ of Wisconsin – Madison); L. Murdoch (Clemson); J. Gage (Chevron); A. Turner (Micron Optics); T. Tokunaga (Univ of Tokyo); J. Wartman (Univ of Washington); D. Keefer (USGS scientist emeritus); R. Mokwa (MSU Bozeman)

(ii) ***Graduate Advisor:*** Nicholas Sitar, UC-Berkeley; Dissertation Committee: N. Sitar, R.E. Goodman, and N.G.W. Cook (all UC-Berkeley), Gen-hua Shi (consulting engineer)

(iii) ***Graduate Students (14 MS graduates):*** Sara. Adams, Elizabeth Berger, Katherine Berry, Kathryn Clapp, Bethany Erfourth, Phyllis Flack, Krista Hanson, Colleen Jespersen, Radford Langston, Lisa O'Connell, Barbara Pape, Shannon Smith, Zachary St. Jean, Cindy Wright; **5 current students:** D. Barrick, C. Kammerer, M. Petro, E. Russell, R. Turner