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77 Massachusetts Avenue
NE18-901
Cambridge, MA 02139 -4307

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14. ABSTRACT

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Jay Perron
UU	UU	UU	UU		19b. TELEPHONE NUMBER 617-253-5735

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RPPR Final Report
as of 04-Sep-2018

Agency Code:

Proposal Number: 64940EV | **Agreement Number: W911NF-14-1-0037**

INVESTIGATOR(S):

Name: Jay Taylor Perron
Email: perron@mit.edu
Phone Number: 6172535735
Principal: Y

Organization: **Massachusetts Institute of Technology (MIT)**
Address: 77 Massachusetts Avenue, Cambridge, MA 021394307
Country: USA
DUNS Number: 001425594 EIN: 042103594
Report Date: 30-Apr-2018 Date Received: 16-May-2018
Final Report for Period Beginning 01-Feb-2014 and Ending 31-Jan-2018
Title: Probing the Effects of Topography on Bedrock Fracture in the Shallow Subsurface
Begin Performance Period: 01-Feb-2014 **End Performance Period:** 31-Jan-2018
Report Term: 0-Other
Submitted By: Jay Perron Email: perron@mit.edu
Phone: (617) 253-5735
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 1 **STEM Participants:** 2

Major Goals: The mechanical properties of rock are known to influence the erodibility of bedrock and the development of landforms, but the possibility that landforms in turn influence rock properties has received less attention. One way landform topography may influence bedrock is by perturbing the ambient stress field. A handful of studies have investigated this possibility theoretically and concluded that the resulting topographic stresses may be sufficiently large to fracture rock. This led to suggestions that there may be feedbacks between the evolution of landforms and the erodibility of the underlying rock. However, most of these studies were theoretical analyses of idealized landforms, and there had been few efforts to test their predictions by comparing modeled topographic stresses beneath real landscapes with rock fracture patterns observed in the field. The overall objective of this project was to test whether topographic stresses demonstrably influence rock fracture patterns in the shallow subsurface.

This project had 3 major goals:

Goal 1: Develop a modeling procedure for calculating the three-dimensional elastic stresses beneath an arbitrary topographic surface in the presence of an ambient tectonic stress field.

Goal 2: Use this stress model to study the predicted patterns of fracturing as a function of drainage basin topography and ambient tectonic stress.

Goal 3: Collect field observations of bedrock fracture and damage in the shallow subsurface and compare these observations with the spatial patterns predicted by the stress model.

Accomplishments: The implications and applications of topographic stress effects on bedrock fractures are numerous, and could include assessments of rock strength effects on infrastructure, predictions of shallow reservoir characteristics, slope stability modeling, and characterization of near-surface seismic response. Our study has provided: (1) some of the first observational evidence that topographic stresses alter bulk rock physical properties; (2) a theoretical framework for predicting bedrock fracture patterns as a function of surface topography; and (3) a computational framework for modeling these effects in three dimensions.

Accomplishments during the entire project period are described below, organized according to the major goals described in the previous section. All cited papers have been uploaded under the Products section of this report.

Goal 1: Develop a modeling procedure for calculating the three-dimensional elastic stresses beneath an arbitrary topographic surface in the presence of an ambient tectonic stress field.

We developed comprehensive 2-D and 3-D boundary element modeling procedures for calculating elastic stresses beneath arbitrary topography in the presence of gravity and ambient tectonic stress. These modeling procedures are described in detail in the journal articles cited under Goals 2 and 3 below.

In support of this effort, Collaborator and sub-awardee Steve Martel developed an analytical method for assessing the effects of small-amplitude topography on combined stresses due to gravity and tectonics (Martel, International Journal of Rock Mechanics and Mining Sciences, 2016).

Goal 2: Use this stress model to study the predicted patterns of fracturing as a function of drainage basin topography and ambient tectonic stress.

Using the procedures developed in fulfillment of Goal 1, we conducted an extensive numerical modeling study of predicted three-dimensional stress fields and fracture patterns as a function of drainage basin topography and ambient tectonic stress (Moon et al., Journal of Geophysical Research-Earth Surface, 2017). The main results presented in this paper are: (1) the stress field is most sensitive to topographic perturbations if the most compressive horizontal tectonic stress is oriented perpendicular to the long axis of elongated landforms such as ridges and valleys; (2) topographic stress perturbations are most pronounced beneath landforms with higher mean curvatures, such as channel junctions and ridge crests; and (3) the shape of a predicted fracture-rich zone in the subsurface depends mainly on the orientation of landforms relative to the most compressive horizontal tectonic stress direction and a dimensionless ratio that expresses the relative magnitudes of topographic stresses associated with tectonics and topographic relief.

Goal 3: Collect field observations of bedrock fracture and damage in the shallow subsurface and compare these observations with the spatial patterns predicted by the stress model.

Using the insights derived from the modeling study described above and the stress modeling procedures, we tested for evidence of topographic stress effects on bedrock damage by comparing 2-D and 3-D stress models with geological and geophysical field measurements of bedrock fracturing and weathering. First, we use the 2-D modeling procedure and measurements of regional tectonic stress fields to calculate stresses beneath a valley in the Susquehanna-Shale Hills Critical Zone Observatory in Pennsylvania, compared the modeled stresses with fractures observed in borehole image logs produced by Collaborator and sub-awardee Kamini Singha, and found that the vertical profile of fracture abundance beneath the valley floor is consistent with the modeled topographic stresses (Slim et al., Earth Surface Processes and Landforms, 2015). Second, we used the 3-D modeling procedure and measurements of regional tectonic stress fields to calculate stresses beneath ridges and valleys in three different sites in the United States with varying tectonic stresses. We compared the modeled stress fields with geophysical surveys (seismic velocities and electrical resistivity) and geological observations (fractures in borehole image logs and surface outcrops). The surprising result is that the interaction of tectonic stress and topography can create dramatic site-to-site differences in the thickness and shape of the layer of fractured, weathered rock immediately beneath Earth's surface (St. Clair, Moon et al., Science, 2015). Third, we constructed 3-D models of stresses within volcanic ocean islands and performed preliminary tests of the hypothesis that differences in eruptive style and volcano shape can lead to predictable differences in the location and extent of massive landslides, such as those that have occurred in the Hawaiian Islands and Canary Islands (Moon et al., Geological Society of America, 2017; American Geophysical Union, 2017).

As an additional outcome of our efforts to compile observational evidence of topographic stress effects, Collaborator and sub-awardee Steve Martel published a review of recent work on the causes and formation of surface-parallel fractures (also known as sheeting joints) in rock (Martel, Journal of Structural Geology, 2017).

Training Opportunities: Former MIT Masters student Mirna Slim, who received training in stress modeling and analysis of borehole data, now works for Schlumberger, Inc.

Former MIT postdoctoral researcher Seulgi Moon is now a tenure-track faculty member at UCLA. Our continued collaboration on the project has helped her start her independent research career and provided her with professional contacts and technical expertise that she intends to leverage in other projects.

The project has also provided training for MIT graduate student Maya Stokes in terrain analysis and stress modeling.

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Results Dissemination: Dissemination of our research results have taken several forms:

(1) Scientific journal articles (see Products for references and electronic reprints)

(2) Conference presentations (see Products for references and electronic abstracts)

(3) Lectures:

Perron, J. T. Topographic Stress, Bedrock Fractures and Landscape Evolution. Tech Talk (special school-wide seminar), Jackson School of Geosciences, UT Austin, 2015.

Perron, J.T. Cracking the Critical Zone. Department Seminar, Earth & Space Sciences, University of Washington, 2016.

Perron, J. T. (Untitled). Presentation at ARO workshop on Geomaterials, Chicago, IL, August 2016.

Perron, Moon and Martel each gave a presentation on different aspects of this project at a meeting with Swedish geologists and representatives of SKB, the public/private company responsible for managing Sweden's nuclear waste and developing Sweden's long-term nuclear waste repository site.

(4) News articles and multimedia:

https://youtu.be/5OlE41VOB94
http://news.mit.edu/2015/bedrock-weathering-based-on-topography-1029
https://www.sciencedaily.com/releases/2015/10/151030111111.htm
http://phys.org/news/2015-10-bedrock-weathering-based-topography.html
http://criticalzone.org/calhoun/news/story/new-study-suggests-bedrock-weathering-based-on-topography/
https://twitter.com/MITgeomorph/status/659922851735207936

Honors and Awards: J. Taylor Perron:

James B. Macelwane Medal, American Geophysical Union, 2014

Fellow, American Geophysical Union, 2014

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Taylor Perron
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Consultant
Participant: Stephen Martel
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:

National Academy Member: N
Other Collaborators:

Participant Type: Consultant
Participant: Kamini Singha
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Seulgi Moon
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Mirna Slim
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Maya Stokes
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
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International Travel:
National Academy Member: N
Other Collaborators:

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Journal of Geophysical Research: Earth Surface
Publication Identifier Type: DOI Publication Identifier: 10.1002/2016JF004155
Volume: 122 Issue: 4 First Page #: 823
Date Submitted: 10/17/17 12:00AM Date Published: 4/1/17 4:00AM
Publication Location:
Article Title: A model of three-dimensional topographic stresses with implications for bedrock fractures, surface processes, and landscape evolution
Authors: S. Moon, J. T. Perron, S. J. Martel, W. S. Holbrook, J. St. Clair
Keywords: Topography, stress, bedrock, fracture
Abstract: Bedrock fractures influence the rates of surface processes that drive landscape evolution and are in turn influenced by landforms that perturb ambient tectonic and gravitational stress fields. In this modeling study, we examine how three-dimensional topography and tectonic stress regimes influence elastic stress fields and bedrock fracture patterns beneath Earth's surface. We illustrate general effects of landform orientation and of tectonic stress magnitude and anisotropy using boundary element models of stresses beneath synthetic elongated ridges with different aspect ratios. We then examine the more detailed effects of landform shape using natural landscapes in Colorado and South Carolina. We show that the stress field is most sensitive to topographic perturbations if the most compressive horizontal tectonic stress is oriented perpendicular to the long axis of elongated landforms such as ridges and valleys and that topographic stress perturbations are most pronounced beneath landfor
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Journal of Structural Geology
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Volume: 94 Issue: First Page #: 68
Date Submitted: 10/17/17 12:00AM Date Published: 1/1/17 5:00AM
Publication Location:
Article Title: Progress in understanding sheeting joints over the past two centuries
Authors: Stephen J. Martel
Keywords: Fractures, joints, sheeting joints, review, stress, topography, water pressure
Abstract: Sheeting joints share many geometric, textural, and kinematic features with other joints, but differ in that they are (a) discernibly curved, and (b) open near to and subparallel to the topographic surface. Where sheeting joints are geologically young, the surface-parallel compressive stresses are large, typically several MPa or greater. Sheeting joints typically are best developed beneath domes, ridges, and saddles. They also are reported beneath valleys or bowls. A mechanism that accounts for these associations has been sought for more than a century: the commonly subscribed explanation of erosion of overburden, by itself, is inadequate. Principles of fracture mechanics, together with the mechanical effects of a curved topographic surface experiencing a surface-parallel compression, provide a framework that accounts for the cardinal characteristics of sheeting joints. A compressive stress parallel to a convex topographic surface induces a tension perpendicular to the surface at shall
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Volume: 89 Issue: First Page #: 1
Date Submitted: 10/17/17 12:00AM Date Published: 11/1/16 4:00AM
Publication Location:
Article Title: Effects of small-amplitude periodic topography on combined stresses due to gravity and tectonics
Authors: Stephen J. Martel
Keywords: Topography, stress, numerical modeling, approximate methods
Abstract: Topographic perturbations of gravitational body forces and horizontal tectonic stresses can be substantial, non-intuitive, and important in terms of subsurface engineering and rock fracture near the surface of the Earth. For (co)sinusoidal topography where the amplitude (A) is small relative to the wavelength (L), adjustments to published plane strain (two-dimensional) approximate elastic solutions for stresses in uniform, isotropic rock allow effects of gravity and a uniform regional horizontal stress (T) to be distinguished. These first-order solutions contain a characteristic stress and three geometric terms, one that varies linearly with elevation, one that decays exponentially with depth, and a (co)sinusoidal term; elastic moduli do not enter the solutions. The first-order solutions are useful approximations for A/L < 0.04. Both gravity and regional compression yield a compression parallel to the surface at ridge crests. Gravity, by itself, causes a localized horizontal tension be
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CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: American Geophysical Union Fall Meeting
Date Received: 30-Aug-2016 Conference Date: 15-Dec-2014 Date Published:
Conference Location: San Francisco
Paper Title: Modeling three-dimensional topographic stress and its effects on bedrock fractures
Authors: Moon, S.; St Clair, J. T.; Perron, J. T.; Martel, S. J.; Holbrook, W. S.; Singha, K.
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Americal Geophysical Union Fall Meeting
Date Received: 30-Aug-2016 Conference Date: 15-Dec-2014 Date Published:
Conference Location: San Francisco
Paper Title: Topographic Stress, Bedrock Fractures, and Landscape Evolution
Authors: Perron, J. T.; Moon, S.; St Clair, J. T.; Martel, S. J.; Holbrook, W. S.; Singha, K.; Hayes, J. L.
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: American Geophysical Union Fall Meeting
Date Received: 30-Aug-2016 Conference Date: 15-Dec-2014 Date Published:
Conference Location: San Francisco
Paper Title: Defining the base of the Critical Zone: Stress, Topography, Fracture Permeability
Authors: St Clair, J. T.; Moon, S.; Holbrook, W. S.; Perron, J. T.; Martel, S. J.; Singha, K
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: American Geophysical Union Fall Meeting
Date Received: 30-Aug-2016 Conference Date: 15-Dec-2015 Date Published:
Conference Location: San Francisco
Paper Title: Weathering, Fractures and Water in the deep Critical Zone: Geophysical investigations in the U.S. Critical Zone Observatories
Authors: Holbrook, W. S.; Carr, B.; Moon, S.; Perron, J. T.; Hayes, J. L.; Flinchum, B. A.; St Clair, J. T.; Riebe, C.
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: American Geophysical Union Fall Meeting
Date Received: 30-Aug-2016 Conference Date: 15-Dec-2015 Date Published: 31-Aug-2016
Conference Location: San Francisco
Paper Title: Three-dimensional topographic stress controls on bedrock fractures and landscape evolution
Authors: Moon, S.; Perron, J. T.; Martel, S. J.; Holbrook, W. S.; St Clair, J. T.; Singha, K.
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: American Geophysical Union Fall Meeting
Date Received: 17-Oct-2017 Conference Date: 12-Dec-2016 Date Published: 12-Dec-2016
Conference Location: San Francisco, CA
Paper Title: Interplay between tectonics and topography: Topographic stress controls on bedrock fractures and surface processes
Authors: Seulgi Moon, J. Taylor Perron, Stephen Martel, Steven Holbrook, James St. Clair, Kamini Singha
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: American Geophysical Union Fall Meeting
Date Received: 15-May-2018 Conference Date: 15-Dec-2017 Date Published:
Conference Location: New Orleans, Louisiana
Paper Title: Topographic stress and catastrophic collapse of volcanic islands
Authors: Seulgi Moon, Stephen J Martel, J Taylor Perron
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Geological Society of America Annual Meeting
Date Received: 15-May-2018 Conference Date: 24-Oct-2017 Date Published:
Conference Location: Seattle, Washington
Paper Title: Topographic stress and catastrophic collapse of volcanic islands
Authors: Seulgi Moon, J Taylor Perron, Stephen J Martel
Acknowledged Federal Support: **Y**

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution:
Date Received: 21-Sep-2015 Completion Date:
Title: Influence of topographic stress on rock fracture : a two-dimensional numerical model for arbitrary surface topography and comparisons with borehole observations
Authors:
Acknowledged Federal Support:

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as of 04-Sep-2018

Nothing to report in the uploaded PDF (see accomplishments).