**Final Report: Probing the Effects of Topography on Bedrock Fracture in the Shallow Subsurface**

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrived as an official Department of the Army position, policy or decision, unless so designated by other documentation.

**ABSTRACT**

**SUBJECT TERMS**

**SECURITY CLASSIFICATION OF:**

- **REPORT:** UU
- **ABSTRACT:** UU
- **THIS PAGE:** UU
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
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.
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, 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
   - https://www.sciencedaily.com/releases/2015/10/151030111111.htm
   - 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:
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:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

ARTICLES:
**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 landforms.

**Distribution Statement:** 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

---

**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:** Sheet joint 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 sheet joint are geologically young, the surface-parallel compressive stresses are large, typically several MPa or greater. Sheet 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.

**Distribution Statement:** 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y
Effects of small-amplitude periodic topography on combined stresses due to gravity and tectonics

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
Publication Type: Conference Paper or Presentation  
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: 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  
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  
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  
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  
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:
Nothing to report in the uploaded PDF (see accomplishments).