Progressive Failure of Brittle Rocks (PRF2022)

20–24 June 2022 | Flat Rock, North Carolina, USA

CONVENERS

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OVERVIEW

At PRF2022, a wealth of research and energetic discussion by a diverse group of attendees explored and supported the idea that rates of crack growth in rock in the natural and built environment are typically non-linear, manifest as slow, progressive ("subcritical") deformations that can accelerate without obvious warning toward rapid and hazardous macroscale critical rock failure—i.e., Progressive Rock Failure, or PRF. The full conference program with extended abstracts is online at **https://gsa.confex.com/gsa/2022PR/meetingapp.cgi/Home/0.**

A common theme throughout the conference was that there has been a fundamental lack of recognition and/or misunderstanding of how PRF applies to earth-surface processes. In parallel, many noted that engineers have long recognized that PRF-driving molecular bond-breaking is strongly linked to crack-tip environment, and fracture can proceed at stresses much lower than a rock's critical strength. PRF2022 served to join these two frameworks that have been, in the past, constrained by traditional disciplinary divides.

The research presented at PRF2022 made clear the value of surface-process problems for field-validation of rock mechanics experiments and theory, and vice versa. Geomorphology has of late turned its eye more directly to the key roles fractures play in a myriad of earth-surface systems, and a range of hypotheses were presented that cannot be fully tested without rock physics experiments and theory. Similarly, PRF2022 allowed rock physicists and other fracture-focused scientists (such as seismologists and structural geologists) to more fully recognize opportunities to embrace potential applications—and critique—of their work in the cognate geoscience subdiscipline of earth and planetary surface processes.

At the end of PRF2022, all participants agreed that the catchall *progressive rock failure science* should be used to help communicate and unify fracture-focused research across traditional disciplines, just as previous terms such as *ecohydrology*, *hydrometeorology*, and *critical zone science* have been coined in the past to drive forward transdisciplinary approaches. We argue that PRF science is not just limited to the shallow subsurface, which is what most of the conference focused on, but rather on all water-catalyzed and time-dependent deformation in the brittle lithosphere on Earth and beyond.

CONFERENCE DETAILS

The conference took place at the lovely and relaxing Highland Inn Lake and Resort, Flat Rock, North Carolina, USA, from 20–25 June 2022, and hosted 85 attendees from 12 countries.

Financial support from the Geological Society of America and the National Science Foundation, plus generous sponsorship from Durham University, Psylotech Inc., and the University of North Carolina at Charlotte (Colleges of Arts + Architecture and Liberal Arts & Sciences, and the Office of Research and Economic Development) allowed for us to ensure that financial need was not a barrier to attendees traditionally underrepresented in the geosciences, including women, those with disabilities, and LGBTQ+, minority ethnic, early-career, and first-generation researchers. We provided 24 conference scholarships that directly served to boost representation from key groups. While there is much work still to do on diversity, equity, and inclusion in the geosciences generally, we are pleased to report the following (based on information provided by conference attendees):

- 46% of attendees identified as female (only 36% of initial applicants were female);
- 21% of attendees were from minority groups, including ethnic, LGBTQ+, and persons with disabilities;
- 52% of attendees described themselves as early career (research students; postdoctoral researchers; and those <5 years since their first permanent position); and
- 11% of attendees took non-traditional academic paths and/or were first-generation scholars.

The conference began with an icebreaker event that focused on early-career researchers, providing mentoring and advice on both integrating with more senior colleagues during the conference and broader goals, including career development and networking.

During three days of technical sessions, our invited keynote speakers discussed PRF from the perspective of their own subdisciplines of engineering geology, rock physics, rock mechanics, critical zone science, reservoir geology, geomorphology, and rock weathering. The key themes identified in these talks were further explored, exemplified, and/or critiqued in 41 oral and 29 poster presentations. These presentations added perspective from field, laboratory, and/or modeling studies that considered the spatial spectrum from microscale to the macroscale. They also considered a wide range of environmental settings that varied in temperature, moisture, and pressure conditions. The scientific sessions ended with a clear commitment to the development of PRF as a collaborative and multidisciplinary research discipline over the next five years, as evidenced by pledges to develop and run a PRF mailing list (email us to be added), social media sites, and scientific sessions at key geoscience conferences, culminating in the next PRF conference in 2027.

A one-day field trip to Hickory Nut Gorge provided insight into how fractures in the geological record can be generated over multiple spatial and temporal scales and how isolating the cause and mechanisms of fracture growth (particularly whether subcritical or critical) is a difficult, time-consuming but fundamental endeavor in both pure and applied geology.

The excellent contributions by all presenters were recognized in a conference award ceremony, with winners voted for by attendees in a broad range of categories; unique prizes were hand-crafted

Group photo of conference attendees (drone image taken by Dylan Ward).

and donated by our vibrant early-career attendees. The conference ended with a performance by the PRF2022 artist-in-residence, dancer and choreographer Melissa Riker (of the Kinesis Project Dance Theater), who expressed the key concepts discussed at the conference in a new, entertaining way, bridging the gap between our science and wider public engagement. Melissa also participated throughout the conference via some insightful and thought-provoking discussions and through live and collective interpretations of rock cracking and failure.

EMERGENT THEMES

PRF2022 highlighted a potential paradigm shift in how surface-process researchers consider rock fracture and in how those from rock mechanics, structural geology, and rock physics disciplines view their prior assumptions regarding the origins and evolution of fractures in outcrops and near-surface environments. The breadth of perspectives for considering very similar questions during the conference was both striking and encouraging, allowing (and, in some cases, forcing) attendees to take stock of their own disciplinary biases and to extend their thinking beyond conventional research boundaries. By the end of the conference, the following of cross-cutting research themes and opportunities emerged:

1. **Universality.** The ubiquitous and dominant nature of PRF processes and effects was emphasized throughout the conference, with examples including fatigue-related failure of asteroids, large-scale fracture features described on planetary surfaces, tree-root controls on near-surface fracture, and fracture generation in reservoirs and hazardous rock slopes. There was conference-wide consensus that fractures progressively grow in response to relatively small stresses long after rocks are exhumed from the deep subsurface.
2. **Moisture dependence.** Barring, possibly, the extraterrestrial, every example of time-dependent rock failure emphasized the importance of access to water in driving fracture. PRF2022 served to bring more general attention to the vital importance of water on driving fracture rates, and thus increasing permeability, reactive surface area, rates of sediment cycling, and more. Another key consensus of the conference was that water feedbacks and effects must be considered to fully understand the architecture and behavior of the lithosphere from the earth surface down, perhaps even to the Mohorovičić Discontinuity.
3. **Time dependence.** Another key theme repeated in talks was that subcritical cracking in surface environments likely varies in rate over time and could be considered "critical" (driven by critical stresses or stress-intensities) on some spatial scale and for some duration. Based on the broad range of examples and settings presented, there is a clear continuum in cracking rates over time from an incremental and continuous process to one that is highly episodic. Where the growth of any particular crack sits on that continuum is a function of a myriad of factors; this has profound implications for our understanding of rates of earth-surface change.

CHALLENGES AND LOOKING FORWARD

1. **Terminology.** There was considerable discussion of terminology to ensure that all attendees were on the same page with respect to the meaning of many terms—including "fracture" itself! These disciplinary differences will not disappear, and, therefore, a key component of all future PRF work must be in clearly defining all fracture-related terminology in every publication.
2. **Rethinking 4D observations.** Some laboratory-scale process studies of chemical weathering have been transferred successfully to the field (in critical zone science, for example). In contrast, broader mechanical linkages between process and form has been lacking, particularly over time and across space. Furthermore, how do chemo-physical state-and-rate effects and feedbacks operate as fractures grow? We have likely been treating a dynamic problem too statically as it relates to both chemical and physical processes. A range of multiscale studies must address this key knowledge gap, with important future roles for novel remote-sensing approaches that can help to link across scales.
3. **Spreading the word.** Publishing, and obtaining funding for, fundamental multidisciplinary PRF work can be difficult, as confirmed by several attendee anecdotes of manuscript and grant reviews. Peer-review comments often suggest that not all scientists across the disciplinary spectrum have accepted and adopted a full understanding of PRF in the context of surface processes and/or fracture mechanics problems, and a range of deep-seated misconceptions and misunderstandings are evident in peer reviews. To continue to develop PRF as a key explanatory component of geoscience, PRF2022 attendees noted the need to continue to communicate and exemplify PRF as widely as possible. We assert that the only way to fully disentangle PRF, and the factors that contribute to it, will be to continue along this tortuous, but exciting, multidisciplinary path paved with a wide range of perspectives, spatial and temporal scales, and methods.

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Attendees

Italic text indicates keynote speaker: Rodrigo Alcaino-Olivares, Jennifer Aldred, Alison Anders, Alex Arzoumanidis, Jennifer

Bauer, Mariam Ben Hammouda, Matan Ben-Asher, Erin Bessette-Kirton, Eric Bilderback, Andy Bobyarchick, Matt Brain, Kristin Chilton, Danilo D'Angiò, Maxwell Dahlquist, Marco Delbo, Vrinda Desai, William Dietrich, *Erik Eberhardt*, Peter Eichhubl, Terry Engelder, Martha Cary (Missy) Eppes, Riley Finnegan, Henry Gage, José Gámez, Benjamin Gilbert, Bradley Goodfellow, Guglielmo Grechi, Xin Gu, Brian Gulick, William Hefner, Mengsu Hu, Mong-han Huang, Marius Huber, Berit Hudson-Rasmussen, Ignacio Ibarra, Michelle Ives, Samuel Johnstone, Russell Keanini, Sophie Kenmare, Eric Kirby, Jennifer Lamp, Jackie Langille, Jeffrey Larimer, *Stephen Laubach*, Thomas Lees, Karin Lehnigk, Kerry Leith, Gian Marco Marmoni, *Jill Marshall*, Salvatore Martino, Justin Mattheis, Nicholas McCarroll, Mauri McSaveney, *Philip Meredith*, *Seulgi Moon*, Faye Moser, Amit Mushkin, Mariel Nelson, Nicolas Oestreicher, Marisa Palucis, Lyman Persico, Nathan Peters, Elizabeth Petrie, Regina Pläsken, *Laura Pyrak-Nolte*, Monica Rasmussen, Miles Reed, Melissa Riker, Alex Rinehart, Estefania Roland Nicolau, Shahrzad Roshankhah, Maryn Sanders, Ira Sasowsky, Behnoush Honarvar Sedighian, Uri Shaanan, Sophie Silver, Carl Steefel, Matthew Struve, Lisa Tranel, Priya Tripathi, Apostolos Vasileiou, *Heather Viles*, Anne Voightlaender, Liang Wang, Dylan Ward, Cheryl Waters-Tormey, Chenxi Zhao, Martin Ziegler, Jesse Zondervan.

Field Trip Leaders

Rick Wooten, North Carolina Geological Survey; Burt Cattanach, North Carolina Geological Survey; David Korte, North Carolina Geological Survey; Jennifer Bauer, Appalachian Landslide Consultants; Philip Prince, Appalachian Landslide Consultants; Cheryl Waters-Tormey, Western Carolina University; Karl Wegmann, North Carolina State University.