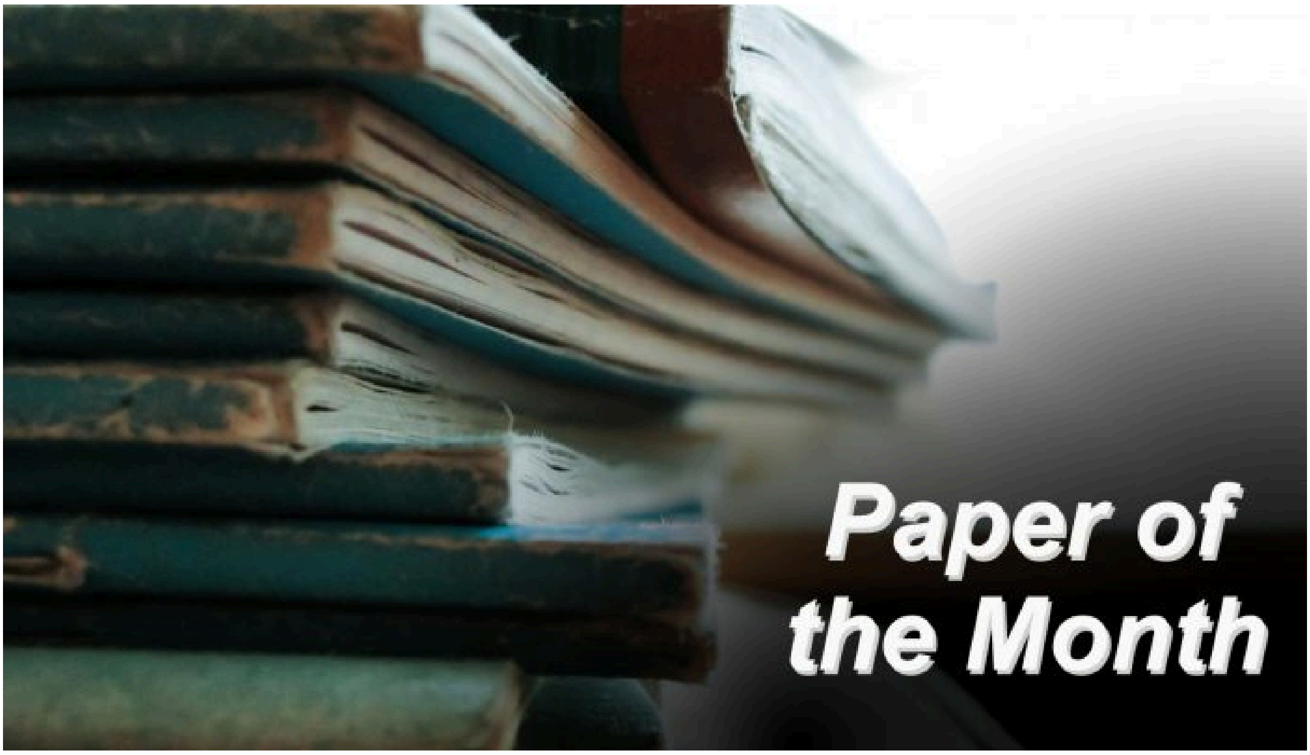
Paper of the Month – Self-healing slip pulses in earthquake rupture

Kathrin Spieker · July 15, 2016 · Paper of the Month · 2 Comments



The "Paper of the Month" (PoM) blog series, recently launched by the Early Careers Scientists (ECS) representatives of the Seismology Division at EGU, aims to present particularly interesting, important, or innovative research articles in all fields related to seismology. While peer-reviewed articles published in the last 12 months are the primary targets, also older "classical" papers can make it to this new blog format.

Engineering Division at KAUST. He joined KAUST in June 2009 as founding faculty member. Prior to his affiliation with KAUST, Prof. Mai worked as senior research scientist at ETH Zurich, Switzerland. In 2015, he was elected Division President of the Seismology Division of the European Geosciences Union (EGU). His research interests include the physics of earthquakes and the complexity of earthquake phenomena, focusing on earthquake-source imaging, dynamic rupture modeling, and earthquake mechanics.

Martin Mai's "Paper of the Month"
"Evidence for and implications of self-healing pulses of slip in earthquake ruptures"
by Thomas H. Heaton

For today's "PoM" blog, I chose a "classic" paper, a study that – in my opinion – influenced many seismologists and earthquake engineers in their thinking about earthquake rupture dynamics and its effects on near-source earthquake shaking. The paper is entitled *"Evidence for and implication of self-healing pulses of slip in earthquake ruptures"*, published in 1990 by Tom Heaton, professor of geophysics and civil engineering at Caltech. You will still find Tom at international meetings & workshops, engaged in lively discussions on earthquake physics, earthquake early warning, and earthquake engineering applications.

In this blog, I am not going to summarize all the details of this study, but rather provide a broad overview of the data analysis and scientific argumentation in this work, followed by a (personally biased) list of research topics that were triggered by this paper. In fact, "Evidence for and implication of self-healing pulses of slip in earthquake ruptures", is more of a discussion paper or conceptual study on fundamental aspects of earthquake ruptures, based on a number of key observations. This paper does not contain mathematical derivations or results of numerical simulations. Instead, Tom Heaton states in his Acknowledgements specifically that *'Because of the speculative nature of this study, I sought opinion of many of my colleagues'*. As such, it is a thought provoking study linking new seismological observations with known facts of earthquake physics to point out research directions to unravel the details of earthquake rupture dynamics.

In essence, the paper collects and presents key observations on how earthquake ruptures propagate over the fault (fracture) surface, showing that during an earthquake only a small portion of the entire rupture area moves at any given time. The so-called 'dislocation rise time' (also called slip duration) at each point on the fault is much shorter than the total rupture duration. This observation, based on a set of kinematic source inversions, is at odds with classical views in fracture mechanics on how cracks (fractures) propagate through a medium (rock volume). In classical linear-elastic fracture mechanics, a rupture grows as a crack until it receives information from its boundaries (through reflected waves) that it should heal (i.e., rupture stops). This gives rise to specific (elliptic, in the simplest cases) slip profiles, and dislocation rise times on the order of the total rupture duration. However, natural earthquakes seem to behave differently, showing something like "self-healing slip pulses" (for a while also called "Heaton-pulses"). Why is that?

> *What is happening in the Earth's crust that earthquakes don't behave as propagating cracks, but in fact display a distinctively different rupture behavior?*

After presenting the observational evidence for slip pulses and short rise times, Tom Heaton examines various hypotheses to explain these observations, for instances in the context of space-time dependent properties of stress in the Earth's crust. His careful argumentation shows that the healing of the rupture pulse requires additional physical mechanisms than commonly considered (at that time). He argues that 'barriers to ruptures' need to be introduced that may generate local rupture-healing fronts, stating that those barriers can be of frictional or geometrical nature, or may be due to stress heterogeneity. At the end, a combination of these mechanisms may act, at different space-

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mic moment release into a short slip pulse leads to large peak-slip rates on the fault that subsequently lead to strong near-fault shaking. Therefore, the small-scale details of the dynamic rupture process have an immediate bearing on earthquake-engineering related considerations. Tom Heaton discusses also these aspects of his observations, and then presents a qualitative model that produces the observed self-healing slip pulses, assuming that friction on the rupture surface is inversely related to the local slip velocity. In fact, this so-called slip-weakening behavior is now a commonly assumed feature in dynamic rupture simulations. His model further features high static rock strength, but low static stress drops and relatively low friction, thus accounting for observations of low seismicity and ambient stress on fault segments that have experienced large earthquakes.

To me, this paper is a landmark study because it combined new observations (based on kinematic finite-fault source inversions) with known theories to sketch a path for obtaining a much deeper general understanding of earthquake physics. Conjectures made in this paper some 25 years ago are testable only now with advanced HPC-enabled dynamic rupture simulations that include laboratory-based rock-friction models, rupture segmentation & small-scale fault roughness, or fractal stress heterogeneity. At the same time, finite-fault inversions have been further developed, providing much more detailed evidence for Heaton's early observations, while simultaneously realizing that rupture-imaging constitutes its own research topic with its own challenges & opportunities. As such, Tom Heaton's paper of 1990 not only inspired many researchers in earthquake source studies and earthquake engineering in the past, but it continues to do so as we analyze modern dense earthquake datasets and large-scale computer simulations of earthquake physics. Therefore, "Evidence for and implication of self-healing pulses of slip in earthquake ruptures", is my Paper of the Month. It's worth reading for students and researchers new in the domain of earthquake physics, as it is very well written, comprehensive in the covered material yet easy to follow due to its conceptual approach. It is also worth re-reading for the old geezers in this field to enjoy its depth of insight, intuition and inspiration.

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References

Heaton, T.H., 1990. Evidence for and implications of self-healing pulses of slip in earthquake ruptures, Physics of the Earth and Planetary Interiors, 64, 1, doi:10.1016/0031-9201(90)90002-F

Have you read Heaton (1990) and you want to share your opinion on this paper? Do you want to comment on the "Paper of the Month" blog post? If so, please have your say in the space below!

If you are an experienced seismologist and want to be the next author of our "Paper of the Month" series, get in touch with the ECS-reps (Early Career Scientist representatives) of the Seismology Division (ecs-sm[at]egu.eu)!

By EGU Guest blogger

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2 Comments

Tom Heaton · July 22, 2016, 7:00 pm

Thank you Prof. Mai for your kind comments about my 1990 slip-pulse paper. Many of the ideas in the paper evolved during the year that Prof. James Rice came to Caltech as a visiting Prof; he help me to better understand crack theory and I then realized that crack theory was incompatible with my work to describe the slip history of well-recorded earthquakes. I proposed an alternate view in the slip-pulse paper. This was a very controversial paper when I first wrote it. From my perspective, it presented a new perspective on rupture dynamics that was more compatible with observed recordings of earthquakes than was predicted from constant stress-drop crack models. I first submitted this paper to the Bulletin of the Seismological Society of America. Reviewers were not convinced that this paper helped to clarify rupture dynamics and after several rounds of trying to improve the paper, I withdrew it from the BSSA. The requirements of the editor would have changed the paper in a way that was unacceptable to me. As I look back on this decision, I am very happy that I did not bend to the requirement of the BSSA editor that I should remove the section of the paper that was "implications of" self-healing pulses of slip. Fortunately for me, Prof. Don Anderson (Caltech Geophysics and a close colleague) was the editor of Physics of the Earth and Planetary Interiors (PEPI). I made my case to Don that the ideas in the paper were worthy of discussion. After reviewing the comments of the BSSA reviewers, Prof. Anderson allowed publication of the paper with only minor edits.

Prof. Mai correctly points out that the 1990 paper was long on ideas, but it was short on precise equations, the solutions of which would support my speculation that earthquake ruptures are comprised of singular waves of slip. As it turns out, it has been extraordinarily difficult to solve rupture problems with strong rate weakening friction. Basically, this type of law removes natural length scales from the problem and even numerical simulations become problematic as solutions are very sensitive to initial conditions. Dr. Brad Aagaard (USGS, Menlo Park) and I tried hard to simulate recurring sequences of earthquakes using friction laws with strong rate weakening. We discovered that it is very difficult to achieve numerically stable simulations of sequences. After thinking about the situation, we speculated that we were dealing with a self-organizing chaotic system. Unfortunately, the computing resources necessary to explore the characteristics of this system in a 3-d grid are not currently available. see http://www.ecf.caltech.edu/~heaton/papers/Aagaard_Heaton_08_heterogeneity.pdf
In order to better understand how slip pulse systems self-organize, Ahmed Elbanna (Univ. of Illinois at Urbana/Champaign) and I decided to study the much simpler system of a 1-d spring-block-slider model. Although it is clear that the Earth's crust is distinctly different from a spring bock slider, we were able to show that strong rate weakening friction does produce pulse-like ruptures. We were further able to show that the system evolved into a kind of statistical equilibrium if we ran it through many cycles. These equilibrium states seem to have many attributes similar to real earthquakes (e.g., b-values, scale invariant stress drops). You can read about this in Prof. Elbanna's Caltech PhD thesis.
http://thesis.library.caltech.edu/6202/
Ultimately, Prof. Elbanna and I were able to derive the "slip-pulse energy balance equation" of 1-d spring block sliders. At long last, we had derived an equation that describes slip pulses. This equation is quite unlike any other equation used to understand dynamic ruptures and I personally consider the energy balance paper to be the zenith of my scientific career (at least so far). While I recognize that the Earth's crust has many important differences with a spring-block-slider, I feel comfortable in predicting that someday we will develop a pulse-energy equation for a 3-d continuum. Please read about it at
http://www.ecf.caltech.edu/~heaton/papers/Geophys.%20J.%20Int.-2012-Elbanna-1797-806%20(1).pdf

As a final comment, I must say that it's been an amazing journey. When I started as a grad student in 1972, things were much simpler (and clearer?); the Reid elastic rebound theory apparently explained

Reply

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