Interactive comment on "Analogue earthquakes and seismic cycles: Experimental modelling across timescales" by Matthias Rosenau et al.

M. Cooke (referee)
cooke@geo.umass.edu

General Comments:

This discussion paper summarizes research on analog modeling of earthquakes and seismic cycles and provides a comprehensive resource for workers in this field. The paper nicely classifies and describes various experimental approaches, materials used and observational methods. In addition to covering a wide range of experimental results, the paper provides useful reviews of the fundamentals of scaling, rheology, fault friction, and earthquake statistics in order to provide context for the analog studies. I learned much from reading the paper and appreciate the authors' vast and deep knowledge of the subject. This paper serves as an excellent reference for experimentalists interested in earthquake and seismic cycle processes. I offer suggestions for the authors to take opportunity to improve the paper's utility.

Specific Comments:

A. The third classification of experiments as 'scale' models might more accurately called scaled crustal models. Some fault block models are scaled and so the term scale models doesn't fully describe the models of this classification. I recommend replacing with the term 'scaled crustal models'.

B. Page 2, line 3; Why not consider all earthquakes? While the scaled crustal models primarily pertain to tectonic earthquakes, the spring slider and fault block model certainly can be applied to any earthquake, regardless of setting. The mechanisms presented in the paper are broad enough to consider all earthquakes.

C. The paper misses an opportunity to promote the benefit of experimental results over numerical simulations. The discussion mentions that numerical simulations can be used to understand the experimental results and a reader could be left with the impression that one could dispense with experiments entirely and go right to numerical models. Should we not bother with the challenge of scaling the crustal experiments to both short and long term processes and just develop numerical models?

D. The review is comprehensive but its utility could be improved by additional presentation of particular configurations, rheology etc that would be adept at capturing particular processes. For example, in the scaling discussion, the appropriate scaling to use in the model depends on the questions of interest. If you are more interested in the directivity and details of rupture evolution you will

probably scale the experiment differently then if you are interested in the statistics of thousands of rupture events. Examples of this could be very helpful.

E. The implementation of equation (4) is based on the assumption that the Coulomb failure dominates within the brittle regime. Since it is the creation of new faults and not the sliding along existing faults that is the process of interest, the scaled parameter should be inherent shear strength rather than cohesion, which describes the strength of existing faults. For dry sand, this distinction is blurry because sand has many surface, grain boundaries, along which to slide and there is no explicit material failure. For this reason, many people have used the term cohesion for scaling of experiments but since this discussion paper goes beyond dry sand, the formulation should be clear that the assumption is failure strength of the material. This also applies to section 4.2.1 on Mohr-Coulomb plasticity. The parameter of interest there should also be inherent shear strength, So, which for dry sand happens to be the same as cohesion.

F. Please explain why the characteristic length scale for the quasi-static model should be peak slip. The peak slip may a consequence of dynamic processes in the model. If the dynamics aren't properly scaled then the peak slip might not scale regardless of whether the quasi-static regime is properly scaled. For some models the more appropriate length scale for the quasi-static regime would be thickness of the brittle material, which should scale to locking depth of the crustal system.

G. For the dynamic regime, the scaling of Dc, slip-weakening distance, should be discussed. If the Dc of the material is artificially high, this can change the nature of dynamic rupture. This parameter is challenging to scale within numerical models and should be addressed within the scaling of the dynamic regime. Dc is mentioned in equation 18 but its scaling is not discussed.

H. The discussion of the incompatibility of scaling the Froude and Reynold's numbers is very interesting and relates to the issue that the most important aspect of scaling is to ensure that you scale the processes important for the questions asked. Some scaled models may aim to capture all of the processes acting within the crust but many very useful models will investigate a subset of processes. For most models it will be critical to scale some but maybe not all of the crustal processes. The scaling section of this paper should make note of the importance of matching your scaling to the processes of investigation.

I. The text on rate and state friction within section 4.2.1 overly relies on the textbook of Scholz. As a review paper, this manuscript should cite additional resource. Even Marone, 1998, which is cited in the figure caption, does not appear in the text.

J. The end of section 5.2 .2 mentions that numerical models can deepen our understanding of the experimental strain fields. This doesn't really belong in the image correlation techniques section. Numerical simulations of experiments have

great potential and could warrant a separate sub section within the techniques or applications sections.

K. The paper misses an opportunity in the discussion of seismic versus aseismic faulting to highlight the simple block slider experiments that are used in teaching classrooms. These simple brick on sandpaper (or variations) demonstrations very effectively convey the concepts of stick slip to students and the public. Some apparati include accelerometers, acoustic emissions, force data etc for students to analyze various earthquake properties.

L. There is a rich literature of stick slip experiments with glass beads that is not included in this review (e.g. Savage and Marone 2007 JGR). Since glass beads are analogs for rock they should probably be considered within this review paper.

M. Section 6.4 may need a different title or become more broad in scope. For many researchers, site effects include the very local effect of the geotechnical layer on ground shaking. For example, some civil engineers care only about the attenuation and amplification within the geotechnical layer.

Technical Corrections:

- Page 1 line 11 kept developing -> developed
- Several occurrences of 'which' should be 'that'. Page 1, line 14; Page 6 line 12; Page 7 line 23; Page 8 Line 1; Page 11, Line 23;
- When using 'which', it should always be part of a phrase that is bracketed by commas. First comma before 'which' and second comma at the end of the phrase (unless the phrase ends the sentence).
- Page 1 line 23 The San Francisco earthquake was in 1906 (revise throughout paper)
- Page 1 Line 28: flouring -> flourishing (probably there is a better word to us)
- Page 1 Line 30: Add 'e.g.' before reference
- Page 2 Line 3: anthropogenic pumping can also produce earthquakes
- Page 2 Line 11: if -> while
- Page 2 Line 19-20: …mainly utilizes analytical and numerical modeling methods in order to constrain complementary…
- Page 3 Line 28-29: awkward sentence needs rewriting
- Page 4 Line 20-28: Since the Reber system is a deformable slider-spring, maybe it should be presented after the paragraph that starts at line 23 about the rigidity of the classic spring-slider system.
- Page 5 Line 19: …strain monitoring, such as digital image correlation (e.g. Adam et al., 2005), it became…
- Page 5 Line 25: awkward sentence needs rewriting
- Page 5 Line 28: add comma after models,

- Page 7 Line 16-17: sentence has awkward structure.. maybe -> challenge to conduct.. and to record deformation..
- Page 7 Line 17: Either -> If
- Page 7 Line 21: Do not start a sentence with 'however'. This is a linking word to be used after a semi colon
- Page 7 Line 21: comma after view,
- Page 7 Line 24: comma after regime,
- Page 7 Line 25: comma after Consequently,
- Page 7 Line 29: comma after system,
- Page 7 Line 29: add 'that' after suggest
- Page 7 Line 29: comma after velocity,
- Page 8 Line 3: Remove 'In the following'
- Equation 3. The Ramberg number doesn't seem to be utilized in this paper. Please explain its utility.
- Page 8 Line 12: remove '
- Page 8 Line 13: comma after),
- Page 8 Line 24: comma after model,
- Superscripts are not formatted correctly: Page 8, lines 2 and 3
- Page 9 Line 22: does play no -> plays limited
- Page 9 Line 23: remove 'in'
- Page 9, Line 24, commas before which and after deformation,
- Page 9 Line 25: comma after above,
- Page 9 Line 25: the rate and state parameter Dc has dimension and should be scaled.
- Page 10 Line 9: what is s.s?
- Page 10 Line 9: I may have missed something but I didn't see where Mo* was defined.
- Page 10 Line 23: inherent -> exhibit
- Half-space should be hyphenated Page 11 lines 20 24, 30and elsewhere
- End of section 4.1.1. You could point out that in the case where DL equals Ds the sum of the interseismic deformation and the coseismic deformation produce a set function of the tectonic velocity.
- Page 12 Line 13: Photoelasticity
- Page 12 Line 14: remove 'accordingly'
- Page 12 Line 24: constraint -> constrained
- Page 12 Line 31: add undesired before reflection
- Page 13 Line 7-9: Awkward sentences
- Page 13 Line 14: pressures is plural in one instance and singular in the other
- Page 13 Line 15: remove first 'deformation'
- Page 13 Line 17 commas after is, and case, (to bracket the phrase)
- Page 14 Line 1: Researchers are still using both static and dynamic friction as well as the a-b values for rate and state friction. It really isn't a matter of one or the other, both sets of parameters are involved in the empirical formulations, which is evident in equations 19-21.

- Page 14 Line 27-28 Consequently, earthquakes nucleate only in the unstable regime but can propagate…
- Page 15 Line 22: The latter -> This apparatus
- Page 15 Line 23: 'Accordingly' doesn't seem right here
- Page 15 Line 29: add comma after strain rate,
- Page 16 Line 6 and 7: add e.g. before citations
- Page 17 Line 1: Please explain why the Maxwell model is considered more relevant than the Kelvin-Voigt model.
- Page 17 Line 10: add 'has' after It
- Page 17 Line 13: add e.g. before citation
- Page 18 Line 15: Helst -> Elst
- Page 19 Line 8: in-line hydraulic pressure gauge needs a citation
- Page 19 Line 23: Can Tchalenko, 1970 GSA Bull, v 81 pm 162501640. A very cool paper that like Niewland et al. (2000) shows the pressure changes associated with faulting.
- Page 19 Line 27: Paul Young has also done a lot with AE for precursory failure.
- Page 20 Lines 3-6: What are the drawbacks and benefits of laser techqniues?
- Page 20 Line 10: Karen Daniels has some very nice granular experiments using photoelastic materials that should be included.
- Page 20 Line 14: awkward sentence
- Page 21 Line 13: PIVLAB is another used by some groups
- Page 21 Line 5: This mentioned of stresses from constitutive laws is out of place as it is an application rather than an experimental technique.
- Page 21 Line 26: Add references to stick slip experiments of Reber et al 2014 GRL and Reber et al 2015.
- Page 22 Line 1: iconographic -> iconic
- Page 22 Line 7: different spelling of Burridge Burrdige
- Page 22 Line 7-8: remove 'as well'
- Page 22 Line 25: unclear sentence
- Page 22 Line 26: Numerical earthquake simulators often show stress transfer between patches (see Tullis et al 2012 SRL).
- Page 23 Line 10: … distribution of slip events in…
- Page 23 Line 18: in -> is
- Page 23 Line 23: The danger of faults
- Page 24 Line 16: Add Rosakis references here.
- Page 27 Line 19-20: Can add citation to Kaj Johnson 2013 JGR
- Page 27 Line 29: constituted -> consists of
- Page 28 Line 18: experiment
- Page 28 Line 18: remove semi colon
- Page 28 Line 27: thereby -> therefor