Review of "A review of analogue and numerical modelling in volcanology". by Kavanaugh, Engwell and Martin
Solid Earth Discussions

Summary: The paper presents a review of analogue and numerical models in volcanology by covering first the basic principles of numerical and analogue modeling (parameterization, scaling, materials, imaging techniques), followed by short discussion of magma rheology (with emphasis on multi-phase), and then systematically reviewing analogue and numerical modeling work done per each of the main components of the magmatic system: magma chambers, magma intrusions, lava lakes and domes, volcanic flows, plumes and ash dispersal.

Recommendation: I found the paper to be an interesting and thoughtful review, that will likely be a useful reference for people new to the field of analogue modeling in volcanology. For example, I can see this paper (or, more likely, individual segments of it) being assigned as reading to new students in an experimental or numerical volcanology lab. That said, there is room for improvement in the structure, writing and content. I recommend this paper for publication upon a moderate revision in response to the specific comments I list below.

General Comments

1. The paper attempts an enormous task of reviewing an extremely wide subject. It is my opinion that the paper has achieved medium success in this goal. The main issue is that it is covering essentially to topics -- numerical modeling and analogue laboratory experiments, and the connection between them is not achieved. Except for the call for using laboratory experiments to benchmark and inform numerical models, the two topics are covered pretty much independently. Thus, unless a much stronger connection is made, for instance by comparing insights from experiments and numerical models and identifying agreements and contradictions, it might have been better to simply keep these as two separate papers.
2. Conciseness: I found the paper unnecessarily long and repetitive, with many segments that say the same thing multiple times. This is particularly a problem in sections 1-4, which can be condensed and cleaned up. Examples: lines 78-86 repeat the motivation for studying volcanoes already discussed in the Introduction;
3. Vagueness: in many places in the paper, the authors make statements that are overarching and vague. The language needs to be tightened up.
4. Unbalanced emphasis on work by specific groups while ignoring many important works done elsewhere: The manuscript reports in great detail works by the authors themselves (e.g., intrusions into gelatin) and by e.g. Annen, while complementary works are either not mentioned or are mentioned very briefly. For instance, it seems that a paper of such span is not complete without mentioning major works by George Berganz, Chris Huber, Joe Dufek, Andrew Harris, Michele Dragoni, Ciro del Negro, Einat Lev, Helge Gonnerman, and others.

5. Scaling is a critical subject, and while it is discussed both in general in the introduction and in some application-specific segments, the authors do not in fact explain what "scaling laws" and scaling challenges are facing laboratory experimentalists. I suggest that there will be a more careful explanation of how scaling is actually done (through non-dimensional numbers that express the relative magnitude of forces, velocities, and times in the natural and laboratory system). A paper about analogue experiments without a single mention of any non-dimensional numbers is actually quite puzzling. It will also be useful to explain per each application (sections 5-10) what are the important scales at play: grain size distribution for ash, cooling versus flow speed for lava (e.g. definitions by Gregg and Fink 1995).
6. Future directions: The manuscript correctly identifies benchmarking efforts and a stronger collaboration between laboratory and numerical modelers as essential future steps. Another exciting development in recent years has been the possibility to conduct large scale experiments using natural materials such as lava and ash. For example, see experimental facilities at Syracuse University and SUNY-Buffalo. Example references are Lev et al., 2009 and Edwards et al., 2011.

<u>Specific Comments</u>:

1. Lines 104-118: A mix of analogue and traditional petrology experiments. This paper shouldn't cover petrology experiments, and instead provide more details for the analogue experiments described in this paragraph.
2. Lines 145-147: Should be rephrased to clarify what the experiments were measuring.
3. Lines 149-152: Were these experiments numerical? Analogue? Analytical? An important distinction in a paper such as this one.
4. Lines 164-175: I agree completely with the point raised here, but I think this belongs in the discussion. It feels out of place right here.
5. Line 180: "Density" -- isn't density a "characteristic?
6. Line 194: Work by Anderson and Segall and Anderson and Poland are stochastic models
7. Lines 188-195: A paper like this one, which is likely to be read by newcomers, should make an effort to avoid jargon. In this case, should define "deterministic" vs "stochastic", and also acknowledge that fast deterministic models can be run as part of stochastic investigation for instance using Monte Carlo approaches
8. Lines 196-202: This paragraph reads awkward for some reason... Try rephrasing?
9. Section 3.1, Numerical Modeling: I found this segment to be much less thought through compared with the sections dealing with analogue experiments. As mentioned above, I believe the paper would have been stronger if it was reviewing only analogue work and not numerical works. Specifically, there is very little discussion of numerical challenges that are typical to volcanology, such as free surfaces, sharp transitions in material properties, multiple phases and phase changes, variable timescales. Just as techniques are discussed for analogue experiments, the paper should include an overview of the numerical models commonly used in volcanology, and the advantages and disadvantages of each to a particular application (e.g., finite volume models more easily handling free surface and fit advancing lava flows;

finite difference models are fast; finite elements are good at dealing with heterogeneity, transitions and complex geometries; SPH is meshless and good for strong deformation...).

10. Line 226: This line is not the most important point about analogue experiments. Also, dimensionality was not discussed for numerical models (despite being extremely important), so there is no parallel.
11. Lines 253-261: The point here of selecting the best fitting materials to each application is an important one. However, this paragraph is not well written. It delves into specifics such as defining greek symbols, and how rheology is measured, which doesn't't matter really as long as it is well characterized. For instance, in my opinion it will be better to define the symbols at the beginning of the section about rheology (section 4.0)
12. Lines 268-273: Shouldn't list a specific software, but stay with describing the overall method of structure-from-motion (SfM). There are multiple tools for this method, e.g., Agisoft Photoscan and Pix4D are among the more popular ones
13. Lines 285-286: can also mention Optical Flow (e.g., Lev et al., 2009), which is similar to DIC and works well for fluid flows.
14.
15. Lines 291-294: It is indeed true that the ability to examine both the inside and the surface of an analog model are a hug advantage, but also a real power of analog experiments is the ability to span a large set of parameter values and establish trends, influences and correlations and provide physical intuition and insight into processes.
16. Line 308: Magma can be modeled as a mufti-phase fluid" should say "Magma is a multi-phase fluid"
17. Line 310: Should say: "Pure melts are considered Newtonian, with a linear relationship between stress and strain"
18. Line 313: Insert: "Magma, due to its multiphase nature, is considered non Newtonian. Several types of ..."
19. Section 4.1: Focused on particles in dilute suspensions such as plumes. Should also mention the impact of particle load on viscosity of viscous mixtures, giving orders of magnitude, e.g. the Einstein-Roscoe equation.
20. Section 4.2: Should explain how the capillary numbers enter the terms for the viscosity, otherwise these stay as just definition with low applicability.
21. Line 373: Express "Capillarity" using Ca and Cd, to tie the sections together
22. Lines 378-383: Perhaps switch the order of the phrases in this sentence, to emphasize that this understanding came from analog experiments.
23. Lines 410-418: Should explain what insights came from these experiments
24. Line 434-442: Important omission: work by Huber and Parmigiani, both numerical and analog
25. Section 5.2: Should include recent work by Karakas and Dufek, e.g. 2015 EPSL or 2017 Nature Geoscience papers. These are more recent than the works by Annen.
26. Line 485: Never heard of the "Traffic jam" theory. Either explain it or remove this.
27. Lines 480-491: Important omissions: Works by George Bergantz, Joe Dufek, Philipp Ruprecht on magma mixing.

28. Lines 498-499: This statement is vague and overarching. There are definitely models that consider magma mixing and injection (e.g. Bergantz's)
29. Lines 524-529: Need to cite references
30. Lines 532-536: Much too specific. Should also discuss what geologic observations this work helped explain.
31. Lines 579-585: Too much detail. This is a review paper with a huge scope, and can't afford to spend half a page on one paper.
32. Line 596 -- repeating what was said earlier. This is a specific imagine technique and is not important here. Only state the hypothesis and findings.
33. Lines 617-624: Is Galland et al the only ones doing such experiments on intrusions? Seems unlikely but I didn't check. Again, the specific software used is not important.
34. Line 631 -- do honey and syrup really solidify at lab conditions?
35. Line 632: There is no "Figure 7d", so either add the missing figure or remove this text.
36. Lines 694-705: Should tell the reader what the hypothesis is regarding natural dikes: is it toughness or viscosity? Will help put the experiments in context.
37. Huge omission -- models and experiments looking at conduit processes! The jump from magma intrusions to lava domes was very surprising, given how much work there has been on conduit dynamics, both numerically and in the analog lab
38. Line 722: Should cite Patrick et al (2015, 2016) for Halemaumau
39. Line 737: Actually, Beckett et al showed the importance of the viscosity ratio between the fluids. Huppert and Hallworth (JFM 2007) showed bidirectional flow models earlier and should be cited.
40. Section 7.1 should include the work by Molina on Erebus (JGR 2012)
41. Section 7.2 should include work by Blake 1990.
42. Line 788: Has --> Have
43. Line 815-816: Hazard assessment models are not necessarily more computationally efficient. They simply solve completely different sets of equations. Also, hazard assessment models used before a crisis, e.g. to produce a hazard map, don't necessarily need to be fast, but rather to be complete and up to date.
44. Should cite review papers such as Costa and Macedonio 2005, Cordonnier et al (Geological Society special publication, 2015) Dietterich et al (Jour of Applied Volcanology 2017)
45. Section 8.1.2 should provide a review of commonly used numerical techniques (finite difference, finite volume. shall-water approximation, SPH, cellular automata...) and available software (LavaSIM, FLOWGO, MAGFLOW, SPH-based code...) There is a whole world beyond cellular automata! The special publication on effusive eruptions published in 2016 by the Geological Society of London and edited by Andrew Harris provides a thorough review of the state of the art on modeling lava flows, and I suggest the authors consult with it
46. Lines 918-919 repetitive
47. Lines 1041-1048: The paragraph mentioned "scaling issues" but doesn't't actually say what the scaling issues are (and stratification is not a scaling issue, it is a model detail issue). And macro-scale experiments are still going to have scaling issues, as long as they are not at the exact same length, time, and force scales as the natural system.

48. Line 1043: "macro scale" is vague and could mean different things to different people. Be more specific.
49. Line 1089-1090: this statement is vague
50. 11.2 benchmarking: should add Cordonnier et al 2015 and Dietterich et al 2017 about benchmarking lava flow models.
51. Section 11 (and probably other sections): inconsistency in section numbering format throughout the paper

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