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Solid Earth Discussions

Interactive comment on "A review of analogue and numerical modelling in volcanology" *by* Janine L. Kavanagh et al.

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We thank the anonymous reviewer for their detailed and constructive review, and welcome the opportunity to improve our manuscript by reflecting upon and addressing the points that have been raised.

A. 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 two 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

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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.

- The scope of our paper was dictated by the aim of this Special Volume celebrating 200 years of modelling in Geosciences. We have worked hard to give an overview of each of the modelling approaches and how these have been applied in different volcanic processes. Our rationale for including both laboratory and numerical models is novel as it makes clear the disconnect that exists between the approaches and allows us to make the claim that this is something that should be remedied in future studies.
- We have expanded the discussion section to comment that the apparent disconnect between numerical and laboratory modelling is not universal in volcanology, and is perhaps dependent on the phenomenon of interest. For example, the application of volcanic plume models is reliant on those parameters defined in laboratory experiments, which is discussed in the paper.
- Our review paper also suggests that more specialist reviews on each volcanic process are needed that bring together the insights from laboratory models and numerical models in more detail, and so we have emphasised this point more strongly in the Discussion. We hope by combining a review of analogue and numerical modelling we provide a starting point for future discussions.

B. 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.

- We have addressed this particular example raised and have reviewed our manuscript in detail to edit down and tighten the text. An example includes the section on Intrusions that has been edited based on a point raised below which stated that it was too detailed.

C. Vagueness: in many places in the paper, the authors make statements that are overarching and vague. The language needs to be tightened up.

- Balancing providing an overview of such a broad topic with detailed but not overly detailed descriptions is challenging. We have worked hard to use language that is accessible to a broad audience and provide references where further specialist reading and reviews can be found. We have reviewed the manuscript comprehensively and made our best efforts to improve the balance of being too vague in places (addressing the point raised here) and too detailed in others (a point raised later).

D. 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.

- We thank the reviewer for this comment, and welcome the opportunity to address any bias that may have unconsciously entered our review. The Magma Chambers section and Magma Intrusions sections have been reviewed in detail reflecting on this point raised, with the Intrusions section on gelatine experiments being edited down and the Magma Chambers section expanded to broaden the scope of literature that is described.

E. 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).

- We have re-written and expanded the section on scaling to include a more detailed description of the scaling approach and strategy for laboratory and numerical modelling.
- The important scales for each process and the relevant non-dimensional numbers for each phenomenon are now more explicitly described in each section.

F. 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.

- Large scale experiments have been increasingly applied to understand surface eruption processes in recent years, and examples are highlighted in the plumes and flows sections.
- We have added some text to Section 3 which describes how the definitions of

analogue laboratory experimentation can be expanded to include natural materials and large-scale experiments.

Specific Comments:

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.*
   → We have deleted the references to the petrological experimental studies and have provided more details on Daubree's experiments, whose laboratory approach we view as laying the foundations of analogue experiments in volcanology.
2. *Lines 145-147: Should be rephrased to clarify what the experiments were measuring.*
   → Corrected.
3. *Lines 149-152: Were these experiments numerical? Analogue? Analytical? An important distinction in a paper such as this one.*
   → The models described are analytical and this has been clarified in the text.
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.*
   → We thank the reviewer for the suggestion and have relocated this text to Section 11 to expand our discussion.
5. *Line 180: "Density" – isn't density a "characteristic?*
   → In this case, density is used to refer to the erupted mixture of particles and gas while erupted products refers to the particulate matter alone. The sentence has been modified to clarify this.

6. *Line 194: Work by Anderson and Segall and Anderson and Poland are stochastic models*
   → We have rephrased to clarify that in general stochastic approaches are used in hazard assessments.

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.*
   → Significant efforts have been made to avoid the use of jargon throughout the manuscript due to our planned broad audience, so we thank the reviewer for indicating where this can be improved.
   → A brief description of the differences between 'deterministic' and 'stochastic' modelling is provided in lines 190 – 193. We have expanded this section to provide more details on these modelling approaches, and the application of statistical modelling approaches to deterministic models, such as Monte Carlo simulations.

8. *Lines 196-202: This paragraph reads awkward for some reason... Try rephrasing?*
   → The paragraph has been rewritten to ensure clarity.

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 com-*

monly 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...).
→ We have expanded our discussion of scaling as suggested by this reviewer and a previous reviewer, and there we explain more the challenges and approaches used to develop numerical models.

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.*
→ We have deleted this sentence for clarity and parity.

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)*
→ We agree this point was unnecessarily detailed and repetitive from Section 4, so have deleted it.

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*
→ Corrected.

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.*
→ We have added the reference to Optical Flow.

14. *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.*
→ This is an important point and we have added some text at the start of Section 3.2 on ‘Laboratory modelling’ to describe these benefits.

15. *Line 308: Magma can be modeled as a mufti-phase fluid" should say "Magma is a multiphase fluid"*
→ Corrected.

16. *Line 310: Should say: "Pure melts are considered Newtonian, with a linear relationship between stress and strain"*
→ Corrected.

17. *Line 313: Insert: "Magma, due to its multiphase nature, is considered non Newtonian. Several types of ..."*
→ Corrected.

18. *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.*
→ We thank the reviewer for pointing out this omission and we have added some text to describe the effect of particle load on magma viscosity.

19. *Section 4.2: Should explain how the capillary numbers enter the terms for the viscosity, otherwise these stay as just definition with low applicability.*
→ We have expanded the description of the capillary numbers, in particular by being more explicit about how these enter the terms of viscosity.

20. *Line 373: Express "Capillarity" using Ca and Cd, to tie the sections together*
    → Corrected.

21. *Lines 378-383: Perhaps switch the order of the phrases in this sentence, to emphasize that this understanding came from analog experiments.*
    → We have rephrased for clarity.

22. *Lines 410-418: Should explain what insights came from these experiments*
    → The analogue models of magma chambers

23. *Line 434-442: Important omission: work by Huber and Parmigiani, both numerical and analog*
    → We thank the reviewer for the suggestion and have included this paper when re-writing parts of the Magma Chambers section.

24. *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.*
    → We thank the reviewer for the suggestion and have included this paper when re-writing parts of the Magma Chambers section.

25. *Line 485: Never heard of the "Traffic jam" theory. Either explain it or remove this.*
    → This is a very interesting theory and so we have welcomed the opportunity to explain it a little further.

26. *Lines 480-491: Important omissions: Works by George Bergantz, Joe Dufek, Philipp Ruprecht on magma mixing.*
    → We thank the reviewer for the suggestion and have included this paper when re-writing parts of the Magma Chambers section.

27. *Lines 498-499: This statement is vague and overarching. There are definitely models that consider magma mixing and injection (e.g. Bergantz's)*

→ The sentence has been rephrased to reflect this point.

28. *Lines 524-529: Need to cite references*
→ The text has been reorganised so that the references that referred to the topics listed appear when they are first mentioned.

29. *Lines 532-536: Much too specific. Should also discuss what geologic observations this work helped explain.*
→ We have edited down the text in this section and pointed out more explicitly the geological observations it relates to.

30. *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.*
→ We have edited down the section on intrusions to better match the scope and length of other sections in the review.

31. *Line 596 – repeating what was said earlier. This is a specific imagine technique and is not important here. Only state the hypothesis and findings.*
→ We have rephrased and edited down the text accordingly.

32. *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.*
→ We have deleted the reference to the specific software and replaced with a general statement about SfM.
→ Galland et al. are the leading group using these materials to study analogue intrusions.

33. *Line 631 – do honey and syrup really solidify at lab conditions?*
→ We have rephrased for clarity.

34. *Line 632: There is no "Figure 7d", so either add the missing figure or remove this text.*
$\rightarrow$ Figure 7d was included in the manuscript, however the arrangement of the panels may mean it was overlooked. We have therefore relabelled these.

35. *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.*
$\rightarrow$ The experimental evidence explores both toughness and viscosity dominated dyke propagation as the natural data is ambiguous. This is an interesting point however would require substantial discussion about the field evidence which we feel is beyond the scope of this paper. However we have added a line of text to state that there is discussion about toughness vs viscosity propagation in nature based on field and geophysical evidence.

36. *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*
$\rightarrow$ We absolutely agree that conduit processes are an important topic in volcanology, however due to the breadth and already great length of our paper we have needed to make choices on which parts of the volcanic system to focus on. We have added a line to direct the reader to more specialist papers and reviews related to conduit processes, vent processes and calderas.

37. *Line 722: Should cite Patrick et al (2015, 2016) for Halemaumau*
$\rightarrow$ We thank the reviewer for the suggestion however we feel that the paper we already cited (Orr and Rea, 2012) covers this point, and we have added 'e.g' to show this is an example.

38. *Line 737: Actually, Beckett et al showed the importance of the viscosity ratio between the fluids. Huppert and Hallworth (JFM 2007) showed bidirectional flow*

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models earlier and should be cited.
→ We have amended the text accordingly.

39. *Section 7.1 should include the work by Molina on Erebus (JGR 2012)*
→ We have added the reference.

40. *Section 7.2 should include work by Blake 1990.*
→ We have added the reference.

41. *Line 788: Has –> Have*
→ Corrected.

42. *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. 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)*
→ It is correct that hazard models solve a set of typically simplified equations, and that choice of model would differ depending on whether it was being used prior to or in response to an eruption. This point has been highlighted in the text, with examples of the different situations in which the different models are used provided. Additional review papers have been cited.
→ There are several reviews and intercomparison papers within the numerical modelling community, for example volcanic flows and plumes. However the same is not the case for laboratory experiments in volcanology, and so we highlight this point in our review emphasising the need for increased benchmarking.

43. *Section 8.1.2 should provide a review of commonly used numerical techniques (finite difference, finite volume. shall-water approximation, SPH, cellular au-*

tomata...) 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
→ The section has been modified to provide a more extensive review of numerical techniques used in lava flow modelling.

44. *Lines 918-919 repetitive*
→ Sentence modified to remove repetition.

45. *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.*
→ Issues regarding scaling in numerical techniques have now been discussed earlier on in the paper, while details regarding the specific scaling issues have now been added where appropriate.

46. *Line 1043: "macro scale" is vague and could mean different things to different people. Be more specific.*
→ Macro scale has been used to describe those experiments typically referred to as large scale experiments in recent literature, and as such is used to refer to those experiments that are conducted on meters to 10's meters scale. This has been modified in the text.

47. *Line 1089-1090: this statement is vague*
→ The sentence has been rewritten to describe the use of complex 3D numerical models to investigate plume behaviour by changing parameters and environment to investigate the effect on model plume behaviour.

48. *Section 11.2 benchmarking: should add Cordonnier et al 2015 and Dietterich et al 2017 about benchmarking lava flow models.*
→ We have included these references.

49. *Section 11 (and probably other sections): inconsistency in section numbering format throughout the paper.*
→ We had chosen to use bold un-numbered headings for sub-divisions lower than third level, however we now realise this may not have been understood so have re-evaluated our headings structure.
→ In Section 11 there are no sub-section numbers, the listed points are meant to be read within Section 11.0. To improve communication of this, we have renamed the listed points A-D rather than 1-4.

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