Review of " Development and Iterative Design of an educational game "Magma Pop" to teach undergraduate fractional crystallization concept" by Saha et al.

Review by F. Jourdan

It's the first time that I've been invited to review an education paper and therefore I'm more used to evaluating research papers, lots of them related to volcanology. That being said, I'm an educator myself teaching 1st year uni in geology and I truly enjoy the change of pace and topic here. This paper is well written and clear on its goal and its content. I'm therefore recommending publication with minor corrections. That being said, I have one main concern and a few comments after that.

Thank you very much for your thoughtful and constructive review. We're grateful for your recommendation for publication with minor corrections and for the helpful comments you provided.

Main concern: I've looked throughout the text, and sorry if I missed it, but I did not see any link for the code/game. I don't know the policy of this journal, but I would assume that if a paper is about a very cool and engaging game, then there should be a mean for the readers to access the game. Otherwise, I the purpose of sharing that with an audience is greatly diminish. A downloadable version should be provided, or a contact if someone want to access the game. If the authors want to sell it, this should be indicated as well, and I would still recommend an evaluation version to be provided.

We have added a statement on the game availability in the text At the time of writing, the public can play Magma Pop v.3 online using modern internet browsers (e.g., Google Chrome or any chromium browsers) at itch.io.

I have a few comments hereafter, at the discretion of the authors.

L67: a point to consider for an educator and I would suggest rephrasing a little: "reinforcing the learning by repetition" will work for the short term, but unlikely to have people remembering formulas. And why should they? Rather, knowing what elements goes into a given mineral is more useful. For example, Fe, Si and O in fayalite. Useful. The full formula? I don't even remember it exactly and I use this mineral all the time in my research! The difference might be subtle, but I would argue that the second approach is more likely to stick and not push people away. Who likes learning formula by heart after all? Why I'm saying that, simply because if this phase is too heavily gear toward forcing formulas into students' heads, that might be a big turn off for them even before the game truly begins. Something to keep in mind. However, in this case, I can see that the formula is provided (and even later in the text, it is provided at every level of the game), so it's not really to make them learn formula, but rather understand the concept of elements form minerals. Hence my suggestion to rephrase, so it's clear for the reader.

Rephrased to:

The first two levels of Magma Pop are designed to re-enforce the learning of mineral formulae by repetition

As a video gamer myself, things that are known to be addictive, are the visual effects and rewards associated with an action. So here, an anorthite crystal is collected a “pop” on the screen showing a small anorthite would be nice. A huge picture of anorthite when the players unlocked the full suite of 5 as well perhaps. In addition, this make sure that the student understand that the color of a mineral is a give away of its composition. E.g. darker mineral are more mafic and therefore include Fe and/or Mg. Good that characters have been added. What many gamers enjoyed (but not for everyone, so only as an option) is competition. So several well-seasoned teams could compete in completing the task (definitely not the first time going through it).

Thank you for this thoughtful feedback. These ideas align well with the direction we’d like to take the game, and we plan to incorporate them into future iterations- We also appreciate the note about optional competitive elements. Introducing team-based challenges for experienced players could add replay value without overwhelming newcomers, and this is something we will explore as we refine later versions of the game.

Level 2: Nice stuff. I would suggest adding a picture of a stratified magma chamber where the olivine end up at the bottom, followed by a mixture of olivine and pyroxene, etc … add the concept of mineral weight sinking at the bottom.

We will plan to incorporate this visual element in a later version of the game. Your feedback is much appreciated and will help improve the clarity and educational value of the experience.

Fig. 4: the answers are in reverse order from the questions listed above (even if the letters can be related). I would suggest changing the order either of the list, or the graph so it goes in the same order.

Done

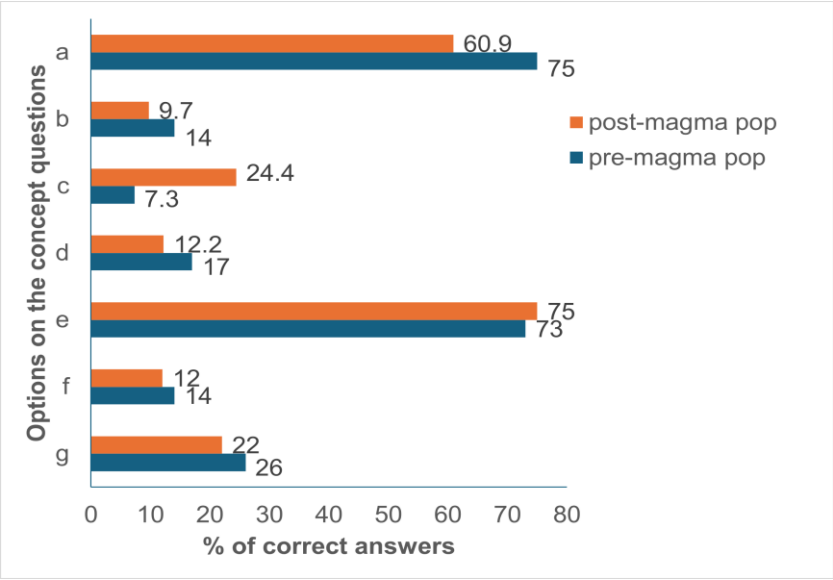

Fig. 4: I'm really surprised to see that this game did not change much there understanding – it's clearly a good one (except for question c, where still 75% of the student got it wrong). I assume the correct response is no. so they might be confused by seeing one big piece of gold (effectively 1 atom) and assume it's valuable. How to fix that misunderstanding though? It would be good to elaborate how that could be improved in the future.

We have addressed this in the text. We suspect that clarity in the instructions can alleviate this. Another factor that guides this outcome is the fact that students may have some prior knowledge of fractional crystallization processes from their geology course and the M&M factional crystallization lab.

L210: yes, the students should always have access to the formula, or as I was saying, what kind of atoms go into a mineral. Because, is the goal learning something by heart, or understanding a complex process? Obviously, the latter. I saw latter that it was implemented which was a very wise decision indeed.

Thanks for this encouragement. We also clarified in the text that the goal was to encourage an understanding of mineral formulae by repeated exposure.

L87: The pace of the game is described as rapid. In what sense? Is there a timer that force student to do it in a given time (A big no-no I would say), or something else? Could please the authors clarify this point.

We have now added the following (lines 99-100) to clarify this point, (i.e., an increasing number of minerals need to be crystallized). This leads to the increasingly rapid nature of the game play (as described by the students, see Section 4.2, Challenges with Pacing and Cognitive Load).

I think this game is great. I feel there is some untouched potential though. As for the next level of improvement, I would add a fourth level with two real-life scenarios (or that could be incorporated before in the previous levels). 1. Make a volcano explode. Once the melt is ultra-silicic and saturated with volatiles, it should just explode. I'm not a developer, but I don't think it's hard to do. "explode your own volcano". How cool would that be! 2. You were talking about valuable ore deposits. Too easy, concentrate the liquid and the gold, make it move to cracks at the end, and there you go. Ore deposits associated with volcanoes explained (in a very rudimentary way of course).

What I'm trying to say is that is all theoretical – unless the student will end up working directly with magmatic petrology, that is not going to be a game changer in their career. So it would be good to extend it to real life example (Pompei, etc…) that would connect the students with a real story and as I'm sure the authors know well, people remember stories even better. So there is more chance that this stick on the long term (again, gamer / teacher talking here).Thank you so much for the thoughtful feedback. Your ideas about adding a level where players can trigger a volcanic explosion or explore how ore deposits form are great suggestions, and they would definitely help connect the theory to real-life processes. We'll consider these suggestions for future iterations, subject to funding for the development of the game.

Comments from reviewer 2

This is an excellent attempt to improve the teaching and learning outcomes for a cognitively challenging geoscience topic, all too often presented as a memory task rather than an opportunity for a deeper understanding of the processes involved.

Gamification is a trend in education circles, frequently seen as a cure-all, that often fails to improve learning outcomes because the ultimate structure engages students in the gameplay far more than the desired learning. I am pleased to see the authors recognise this and have set out to create a “serious educational game” and have tried to find an appropriate balance between gameplay engagement and learning outcomes that is to be applauded.

The documentation of the iterative development of this game should be particularly informative and instructional for those who may seek to develop games for other equally challenging topics. However, I think this needs to be set out more explicitly as it is unclear just how different to v1 the v3 product is given the good descriptions of v1's structure. Perhaps this could be achieved through a more thorough tabular approach that Table 2 does not satisfy.

We’ve added details in Table 2 to the changes introduced in version 3.

Unfortunately, as the most senior geoscience courses, the student sample size available to the developers (especially v3) was probably sub-optimal but the quality of the feedback and resultant improvements seems to have made up for that lack of breadth. That said, I think an appendix of all feedback might be valuable and made available, rather than just the quotes selected for the text.

The findings from the evaluation of magma pop v1 have been reported elsewhere (Hoermann et al., 2022). The focus of this paper was on the process of game development; however we have provided a sample of feedback (from v.1) and evaluation transcript (v.3) to demonstrate what the process looked like.

Specific comments

(line 51) The authors state: Major elements usually exist as oxides in the magma and each major element …is represented by different coloured M&Ms. While it is geochemically convenient to express things as weight % oxides (with a large wet chemistry history behind it) that is not the same thing as “occurring as oxides” especially in a melt, even though stoichiometrically it might work. I wonder if that statement cannot be reworded a bit or the oxides bit left out entirely? After all, in Bowen’s reaction series we are talking about the crystallisation of silicates, not oxides.

Major elements in the magma are generally expressed as oxides and each major element (silicon (Si), titanium (Ti), aluminium (Al), iron (Fe), magnesium (Mg), calcium (Ca), sodium (Na) potassium (K)) is represented by different coloured M&M's®.

(line 75-81) Further to that point, we normally teach students that magma viscosity is related to $[SiO_4]^{4-}$ in the melt (albeit usually given as wt % SiO_2), implying all/most the Si cations and a good proportion of the O anions are already spoken for in the silica tetrahedra anions. I wonder if this does not create some cognitive dissonance amongst students who, on the one hand know the melt is cations and silicate anions and on the other the game starts with the melt just as cations and oxygen anions. While this overly simple model may help students discover and remember mineral formulae (eg: for forsterite is actually a silicate mineral composed of Mg cations and a silicate anion?

We have modified the text to: Although most rock-forming minerals are silicates—composed of elemental cations and the silicate anion $[SiO_4]^{4-}$—we simplify this in the magma "pop" model by representing the melt only as elemental cations and oxygen.

Further to the general comments above, it is unclear if this 'neophyte' approach survived into v3 or whether the silicate approach was adopted when the levels were labelled basic, intermediate and felsic. Perhaps these changes could be more fleshed out in the text to make it clear just what the final version looks like.

We have already explained this in the text (lines 269-275). Additionally, we have also added the following text to clarify the comment about the compositional aspect depicted in Figure 7.

The Magma Dealer level is replaced by Magma Crystallizer - where students explore how chemistry changes as magma cools and minerals crystallize i.e. exploring how the magma composition changes from basic, intermediate towards felsic (e.g. Fig 7).

(line 152) Table 1 caption. The multiple choice question is fine, but was it a "one answer only" question or were students told more than one option could be selected? While it may seem obvious (and you explain it in line 164), I think it needs to be clearly stated in the table caption (and maybe even the most appropriate answers identified) for total clarity.

Concept question which has six possible correct statements and one incorrect statement administered to students after completion of the M&M's® lab (before playing Magma Pop) and after they played Magma Pop.

Technical matters

We have fixed all the following technical matters highlighted by the reviewer

(line 20) Dohaney et al, 2012 does not appear in the references list

(line 21) Jolley et al 2023 does not appear in the references list

(line 21) Dohaney et al, 2023 does not appear in the references list

(line 25) Abdulmotaleb, 2014 does not appear in the references list

(line 35) McGowan et al, 2022 does not appear in the references list unless it is actually McGowan & Alcott (line 460) in the reference list which has no date

(line 38) Wirth, 2005 does not appear in the references list unless it is actually Wirth 2003 (line 495) in the reference list

(line 42 & line 50) Wirth, 2013 does not appear in the references list unless it is actually Wirth, 2003 (line 495) in the reference list

(line 64) Schonotz and Kurshur, 2007 does not appear in the references list unless it is actually Schnotz & Kürschner, 2007 (line 474) in the reference list

(line 149-151) This sentence maybe technically correct but would be better written another way

The concept question had six possible correct statements and one incorrect statement (Table 1).

Table 1: SiO2 should be SiO_2 and 1000-1050C should be 1000-1050 ^{o}C unless this is a faithful rendition of the MCQ text given to the students

There are many papers in the reference list that are not cited. I have only listed papers that are cited but not listed or apparently mis-listed.

I do not have the ability to ensure every paper cited or listed is appropriate but I encourage the authors to ensure the papers they do directly cite are correctly referenced re spellings, dates and titles. I also wonder if the many uncited papers listed are required for the paper even if they are relevant. If they have specific relevance should they not be cited?

Fixed

Feedback from focus group

- Magma Pop can be extremely useful for learning mineral formulae.
- Add opportunities for critical reflections through inclusion of characters or pop up messages.
- Survey was not useful.
- Magma Pop has the potential to cater different learning styles.
- Instructions can be clearer by addition of pop-up messages or animated tutorials.
- Magma Pop can be made more engaging through introduction of characters and stories.
- Additional/pop up messages and introduction of characters can make the game more reflective.

Sample transcript from evaluation- **Pre magma pop**

Speaker 1:Could you talk to me a little bit about your understanding of fractional crystallisation?

Speaker 2: So my understanding pretty much comes from [the Geology course]. So did you want me to talk about how the process?

Speaker 1: Yes

Speaker 2: Yeah, no, fractional crystallisation is basically where crystals form in the melt and as they get removed from the melt and as they crystallise and they get sink, you no longer count the portion of the melt that is, sorry, I'm getting all jumbled up. Basically, I think you have the crystals and the melt and as minerals crystallise from the melt, the melt composition changes. Although the absolute composition, it doesn't change. The relative amount changes. And so as crystals come out, they can become enriched in different, the melt becomes enriched with SiO_2 and other minerals because they are not taken out by the crystals that have crystallised.

Speaker 1: Do you feel confident about the order in which these minerals start to crystallise the according to the Bowen’s reaction series?

Speaker 2: I think I feel confident about Bowen's reaction series and I know that the order that Bowens goes in and I could tell you, oh yeah, I know that all of me crystallises first, but I am not too confident in being able to tell you the different minerals of olivine, how you have the different members… do you get my point? It's the different variants of say, Feldspar or which order that they come in that series.

Speaker 1: do you think that there's any concept around traction or crystallisation that you need a better understanding of or is still not clear?

Speaker 2: it's mainly that whole order of which variance I think is my biggest weakness. When there was that extra sheet in the lab from last week and it was talking about which would come first, and yeah, I could sort of try and piece things together based on my knowledge of Bowen's, but I was sort of struggling to think about which order they would come in and knowing which specific elements would it prefers. So, whether it prefers calcium or whether it prefers magnesium or which specific elements are preferred in the order of crystallisation.

Sample transcript from evaluation- Post magma pop

Speaker 1. Could you talk to me a little bit about how Magma Pop was helpful in clarifying fractional crystallization or what worked with Magma Pop? Anything that you liked about it?

Speaker 2:

I think I liked that you had to just work with the formula and actually have the repetition of putting the minerals together and that sort of help, I guess with remembering what formula it is. And then also that helps knowing the Bowen's reaction series. It helps to understand the fractional crystallisation, like, these elements going in first and these elements and this mineral. So it's sort of help making the connection, I guess.

Speaker 1:

Okay. Were you able to make the links between the changing composition and were its implications on what kind of eruption would it be?

Speaker 2 :Yeah, we could see that on the right hand corner, that field. It would be nice to have it a bit bigger, to be honest. I did look at it, but then I was like, oh, I've got to do these minerals and now I'm looking at that. So having it somewhere where it's a bit more in view, I guess

Speaker 1:Just wondering, did you try out the tutorial level first?

Speaker 2:Yeah, I had a look at the tutorial.

Speaker 1: Yeah. So in the second tutorial level, you have this part where you can actually zoom in both the concentrations, so maybe we need to do a better job telling that upfront

Speaker 2: Tutorials, no, you could look at the formulas, and you look at what to do. Zoom that and I didn't zoom the window at the right inside.

Speaker 1: Yeah. And any other thoughts on how we can make it better? Anything that caught your eye or you were stuck with at any point?

Speaker: No.