Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality.

Decision letter and referee reports: first round

30th Apr 20

Dear Dr Shevchenko,

Your manuscript titled "The rebirth and evolution of Bezymianny volcano after the 1956 sector collapse" has now been seen by 3 reviewers, and I include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please note that both of the attached documents are from Reviewer#3

In addition, please ensure that the revised manuscript addresses the following editorial thresholds:

****Present a compelling documentation of the regrowth of Bezymianny volcano after 1956, and place this firmly in the context of existing relevant literature****

****Provide a clear and thorough explanation of the methodology involved in your numerical modelling****

****Fully justify your prediction of a new collapse event within 10-15 years, with reference to previous activity at Bezymianny, or re-evaluate this statement****

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter) and the completed checklist:

[link redacted]
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to receive your revised paper within three months; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we will close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

Please do not hesitate to contact me if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Joe Aslin

Associate Editor,
Communications Earth & Environment
https://www.nature.com/commsenv/
Twitter: @CommsEarth

EDITORIAL POLICIES AND FORMATTING

We ask that you ensure your manuscript complies with our editorial policies. Please ensure that the following formatting requirements are met, and any checklist relevant to your research is completed and uploaded as a Related Manuscript file type with the revised article.

Editorial Policy: Policy requirements

Furthermore, please align your manuscript with our format requirements, which are summarized on the following checklist:
Communications Earth & Environment formatting checklist

In the event that the manuscript is accepted we will be providing further guidance on formatting but please ensure that the manuscript generally complies with our house style at this stage. The main points are as follows:

* ABSTRACT: less than 150 words and accessible. It should include the background and context of the work, the phrase 'Here we' (present/show/suggest) to indicate where the description of your own work starts, and then the methods/data, main results and conclusions of the paper.

*The text must be split into:
- INTRODUCTION (<1000 words): includes the background and rationale for the work. The final paragraph should be a brief summary of the main results and conclusions. The results of the current study should only be discussed in this final paragraph.
- RESULTS: split into subheaded sections; ensure that the subheadings are no longer than 60 characters including spaces.
- DISCUSSION: without subheadings.
- METHODS: split into subheaded sections; ensure that the subheadings are no longer than 60 characters including spaces

* SUPPLEMENTARY INFORMATION should be organised logically, with all items labelled as one of the following item types, and cited in the main article:
- Supplementary Figures, labelled and referred to as i.e. Supplementary Figure 1 throughout both

the Supplementary Information and the main text
- Supplementary Tables, labelled as above
- Supplementary Notes, labelled as above
- Supplementary Discussion
- Supplementary Methods
- Supplementary References

Data: All Communications Earth & Environment manuscripts must include a section titled "Data Availability" at the end of the Methods section or main text (if no Methods). More information on this policy, and a list of examples, is available at http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf.
In addition, Communications Earth & Environment endorses the principles of the Enabling FAIR data project (http://www.copdess.org/enabling-fair-data-project/). We ask authors to make the data that support their conclusions available in permanent, publically accessible data repositories. (Please contact the editor if you are unable to make your data available).
In particular, the Data availability statement should include:
- Unique identifiers (such as DOIs and hyperlinks for datasets in public repositories)
- Accession codes where appropriate
- If applicable, a statement regarding data available with restrictions
- If a dataset has a Digital Object Identifier (DOI) as its unique identifier, we strongly encourage including this in the Reference list and citing the dataset in the Data Availability Statement.

DATA SOURCES: All new data associated with the paper should be placed in a persistent repository where they can be freely and enduringly accessed. We recommend submitting the data to discipline-specific, community-recognized repositories, where possible and a list of recommended repositories is provided at http://www.nature.com/sdata/policies/repositories.

If a community resource is unavailable, data can be submitted to generalist repositories such as figshare or Dryad Digital Repository. Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The manuscript by Schevckenko et al addresses an important and topical subject, concerning the response of volcanic activity to major structural collapse. There are relatively few such events in the historical record, and detailed study of all such examples can therefore provide important general insights into eruptive behaviour following collapse, and the influence of collapse and regrowth on subsurface magma systems. Although recent events such as the collapse of Anak Krakatau volcano put this type of volcanic process into focus, and detailed studies of Mount St

Helens also advanced understanding of volcano stability, the value of the record at Bezymianny is that it spans a longer timescale while also comprising relatively detailed field observations. The 7-decade perspective thus gives valuable insights into post-collapse volcano evolution.

Overall, the manuscript is well written, logically structured, and provides an interesting account. The dataset is novel, and it's fascinating to see the general development of the post-collapse units into a stratocone. The figures are also very well presented. I enjoyed reading the paper and think it will be of broad interest. My suggestions are generally minor, but there are several of them listed below. A few general comments would be that the citation could be improved in the opening sections, as noted below, and that the writing and detail could be more quantitative and specific in many places. I have indicated places throughout the manuscript where this could be improved. I also think that while the numerical modelling is a useful addition to help explain the vent migration and potential influences of regrowth on magma ascent, that this also needs developing further within the main manuscript to fully consider the caveats and simplifications involved in the modelling. It isn't especially clear from the modelling figure that focusing of the vents is demonstrated, and there are assumptions about changes in magma storage depths and bulk composition that might actually be a consequence of the regrowth (and that the modelling could provide further insights to), which aren't really explored in detail.

Comments:
It would be helpful to see a more specific description of processes in the abstract. The manuscript covers changes in eruption style, vent position and migration, and uses numerical modelling to understand these changes, but the way these are stated in the abstract could be more specific. Are there any constraints on eruption rates across this period (volume flux?); or any changes/acceleration/pauses etc.? From Lines 20-25, the authors describe vent focusing and migration – but in what direction, and which factors determine this, and over what distance or rate? This sort of quantitative and specific detail in the abstract would really help understand the changes observed in greater detail.
In the opening paragraph (L30-40), a recent review (Watt, The evolution of volcanic systems following sector collapse https://doi.org/10.1016/j.jvolgeores.2019.05.012) provides a summary of several other examples this type of evolution, and citation of this would place the study in the broader context of other studies in this field, many of which aren't cited in the opening paragraph – but which further support the inference of potential changes in erupted compositions, rates etc. At Line 39, Ritter Island provides a further historical example, and of course many prehistoric examples, such as Parinacota. At Line 41, it may be worth citing other examples as well, as there can be wide variations in collapse direction and dimension (e.g. Shea et al., Mombacho); and the collapse history of Shiveluch is also interesting in this regard.
At Line 48, I agree that detailed temporal observations of shifts in vent location don't exist, but I would expect a citation of some of the work on Stromboli that has shown this pattern (e.g. outlined in various papers by Tibaldi, but also in other geological reconstructions of Stromboli).
At Line 53, in general it does appear to be the case that post-collapse growth is in the centre of the scar; South Soufriere Hills may be a possible exception (e.g. papers by Cassidy et al. on Montserrat).
Line 58 – "6-decade long" is inconsistent with the 7-decades stated in the abstract (Line 16). It may be better to just state the start and end dates of the time series that has been analysed.
Line 61 – is it possible to justify the statement of Bezymianny being one of the most active andesitic volcanoes, by comparing the mean eruptive flux over the past few decades with other highly active volcanoes? It would be insightful to be able to compare the flux directly with an example of one or two other persistently active volcanoes.
Line 67 – can this be more specific on the dates of regrowth after collapse. Can you state if the volcano in a state of eruption at the time of the collapse; and specify the gap in time after this, before activity resumed. Similarly, at Line 61, can you state how many sector collapses are known, rather than just stating "repeated".
Fig 1c – is there any information on the age of the feature labelled "collapse scar". If not, probably good to clarify that this is an older collapse scar.

Line 93 – clarify that the width is 1300m, and the axial length (presumably?) 2700 m.
Line 94 – can you be more specific than "distributed". How did the vent location compare to the pre-collapse vent position? How many hundreds of metres away did these vents extend, and was there any pattern to this direction? [I see that this detail is given later on, at L196, but could it just be stated here?]
Line 95 – that's very interesting that there is an alignment, but you haven't stated the orientation of the collapse axis. Could you also provide that in the text, so that it's easy to compare the alignment of the two features.
Fig 2 – this is a very interesting dataset. I am slightly confused by your terminology. Lava dome growth could be either endogenous or exogenous (or some combination of both), but why is it of particular significance here (most of the dome growth in the 1967-68 images looks endogenous, but is labelled exogenous)? The distinction between extrusive and effusive is also unclear. Aren't all lavas, whether forming domes or flows, both extrusive and effusive? Would it be simpler to label these phases on the basis of the dominant styles of volcanism – dome-forming, onset of lava flows, mixed minor explosive-effusive activity (perhaps?, for the stratocone phase). Does the change to lava-flow generation in 1977 also coincide with a change in magma composition or other properties, as there is presumably a significant viscosity change?
Line 124 – what about the extrusion rate between 1956 and 1967? Table 1 suggests this was even higher? Just to also be clear, the 43,600 is just for the 1967-1968 period?
Table 1 – very interesting to see the volumes. What do these look like if plotted against time. Is there a clear long-term trend, or is the pattern much more episodic? Can you also clarify that the 56,600 rate is for 1956-1967 (i.e. just the post collapse period). If so, how did you estimate the immediately post-collapse morphology? It might be clearer to have a row for the collapse event itself, even if some parameters are unknown, so that the timing of the collapse is clear for the reader.
Line 135 – The change in aspect ratio of the extruded bodies is intriguing. Can you infer any viscosity changes from this information?
Line 177 – there is no mention at all of composition through here (or any comments on petrography, crystallinity etc.). I realise that this is not a petrographic paper, and perhaps no samples are available, but the change in lava morphology and gradual transition to more explosive activity does raise the obvious question of whether the magma composition changed across this period. The pattern appears to suggest a gradual shift to lower viscosities. Does this imply a gradual shift towards more mafic compositions? This might not be the direction that would be expected, so it warrants at least a brief comment based on any available compositional information.
[I see that you mention these at Line 259 – it would be helpful if you could point the reader to this earlier, so that it's clear that compositions will be covered later in the paper]
Line 188 – as noted in the Table 1 comment above – how was the baseline calculated for 1956 (to estimate the subsequent volume), and can it be listed as a row in the table.
Line 189 – so the long-term average is half the initial growth rate? Is there a long-term trend here?
Line 192 – This is certainly a notable result, and I don't know of a similar dataset that allows this regrowth projection to be calculated in this way. This could be stated in the abstract, alongside summary values of the post-collapse flux?
Fig 6 – although the vents gradually become closer together, they seem to be centred around a fairly stable point, SE of the pre-collapse vent. Is that correct? It could be slightly clearer in the previous paragraph.
In the longer term, because the edifice has achieved its pre-collapse dimensions, would we expect migration back towards the pre-collapse vent position. Or, because it has rebuilt slightly further east, would this imply a gradual long-term migration of the whole structure eastwards, governed by the collapse direction?
Fig 7 – The focusing of the red pathways in Fig b is not entirely clear – it looks like the red pathways are actually prevented from reaching the base of the volcano in this scenario, as they meet the 8 MPa stress field beneath the regrowing volcano? There are two pathways between the two regions of highest stress where it appears ascent is more feasible? Can the authors comment

on this? It isn't entirely clear from the schematic depiction of the red pathways in a and b that image b is more focussed (the width of the red pathways in Fig b is greater than that in image a? In general, I think the modelling needs a more detailed discussion to explain what the results indicate, and to consider assumptions about the driving pressure, lateral extent of the feeding system etc. (in the main text, not simply the methods section), to really provide a convincing case that they explain both the migration and the focusing. The way the figure is depicted is slightly misleading, because it implies that the actual topography has been modelled as the load, whereas the methods suggest that simplified geometrical forms have been modelled (triangular/trapezoidal) to represent regrowth. As this regrowth infills the scar, is 2D modelling valid throughout this scenario?
Lin 276 – Similar cycles have occurred before, but on a comparable timescale? Your results suggest an inter-collapse interval of as little as 75 years. Is there evidence in the geological record of such a high frequency of collapse events? This would be remarkably rapid, but perhaps not entirely unprecedented (could cite, for example, Beget and Kienle, Augustine volcano).
Line 303 onwards – this discussion suggests greater complexity in terms of both storage depths and magma viscosity through time, both of which are likely to be important parameters in the modelling that may also influence dyke ascent behaviour. Given this complexity, is the detail in the modelling sufficient to capture the processes involved? Or perhaps conversely, can the modelling also provide insights into why the volcano may be tapping deeper and lower-viscosity magmas through time, as it regrows?
Line 322 – as noted above, the regrowth rates do appear to be remarkably rapid; but counter examples could also be cited, such as Augustine, Stromboli, Parinacota, and arguably more recently, reconstruction at Anak Krakatau.

Sebastian Watt.

Reviewer #2 (Remarks to the Author):

Review on the paper by Shevchenko et al. "The rebirth and evolution of Bezymianny volcano after the 1956 sector collapse"

The paper presents a very interesting material on the evolution of the volcanic cone of the Bezymianny volcano after the 1956 sector collapse. The fact that it was growing so fast and almost reached the pre-collapse altitude is an interesting story, which might appear to be attractive for a broad audience. For the part of the analysis of the photogrammetric analysis and interpretation, I do not have any concern. All the findings are clearly described and supported by numerous figures and supplementary materials. The methods for the analysis of pictures are well established and previously tested in different sites.

For me it was unexpected to learn that at the initial stage of re-growth, the lava material outpoured from several vents widely spread in the caldera. However, while growing the cone, they became less and less dispersed; and, finally, concentrated in an only one vent located on the cone's summit. This is an interesting, but non-obvious observation that needs a physical explanation.

The authors provide a set of numerical models simulating the dome growth and the evolution of vents. I am not a specialist in numerical modeling and some argumentation provided by the authors appeared to me not sufficiently clear. I have a few questions that remained non-answered after careful reading of the manuscript. I apologize in advance if some of them will appear to be naïve. At the same time, if the article is oriented to the broad audience, these things should be explained very clearly. So my questions are following:

1. Is it a 2D or 3D modeling? In other words, do they model the dyke opening or isometrical

conduits (like a pipe)?

2. The authors propose that "magma pathways are governed by the background stresses". In my feeling, there are too many other factors that may have greater influence, such as inhomogeneities beneath the edifice including pre-existing geometry of previous conduits, gas and fluid distributions, plasticity/rigidity of the medium, pressure in the reservoir and many others. Can the authors estimate the role of these factors compared to the stress effect?

3. From the description, I do not understand how the conduits were modeled. There is a very short paragraph on this issue in L531-535 without any details. Was the crack opening simulated according to the hydrofracture mechanism? Or another simplified representation was used? This part needs more detailed description.

4. What are the criteria when the conduit was considered open or closed? I do not understand the process, when some conduits originate at depths, but did not reach the surface. I do not see any mechanism to close cracks at shallow depths, where the lithostatic pressure is lower. I would expect an opposite effect.

5. Why in the case of "Pre-Collapse", the topography load prevents reaching the conduits to the surface, whereas in another case of "Dome-Growth", the load by a dome intensifies the conduit forming compared to the no-loading "Post-Collapse" case? It appears to me not logic.

6. The presented models are intended to explain why just after forming the caldera, separate vents originate in a broad area, whereas after forming a large dome-cone there is only a single vent in the summit. However, from the presented description and figures, I did not understand the mechanism. It would possibly useful to illustrate this process with a conceptual cartoon and very simple words.

7. While modeling the conduits with propagation of viscous andesitic magma, do the authors consider any degassing? As far as I know, most of eruptions of Bezymianny occur as short-lived explosions with ejection of a large amount of gases from the magmatic system. Obviously, gas dynamics should play a very important role in forming the conduits.

The authors state in L272-276 that shortly after reaching the initial shape, Bezymianny may collapse again. This is not supported by records of previous catastrophic explosions of Bezymianny. Every known large collapses, including ones in 1956 and in 2100 yrs BP, were preceded by more than 1000 years of quiescence. It means that growing the cone up to a certain height blocks the conduits and ceases any eruption activity for very long time. It would be interesting if the authors could consider this scenario in their modeling.

Reviewer #3 (Remarks to the Author):

General comments:

The manuscript "The rebirth and evolution of Bezymianny volcano after the 1956 sector collapse" by Shevchenko et al. concerns the edifice regrowth and evolution of Bezymianny, after the 1956 eruption where the volcano experienced a sector collapse. This includes near-decadal mapping of the amphitheater including mapping the endogenous and extrusive dome growth and subsequent lava flow emplacement.
This analysis is based on a combination of photogrammetry based on aerial, satellite and drone data as well as numerical modeling examining the effect of unloading due to the collapse of the edifice and subsequent reloading associated with the regrowth of the stratocone. Overall the data and analysis is sound and well-presented.

This study reveal undoubtedly a very important time-series, that provides unique insight to the regrowth of a volcano as well as documentation for the hypothesis about vent migration caused by sector collapse put forward based on numerical unloading models by Maccaferri et al. (2017). By doing so the authors make an important contribution in order to understand and forecast how volcanic activity and vent location may change as volcanic activity resume after a sector collapse. Thus, this study clearly of interest for a wide volcanic community and deserves publication after a number of issues has been addressed:

1) The method description need improvement since some information is lacking. This includes:
• New section with description of morphological mapping, especially specification of how the authors distinguish between endogenous and exogeneous domes and lava flows. How is this done based on the aerial photographs and DEMs, or does this information stem from other sources ?
• Description of volume estimates. How were the added and removed volumes estimated. How do you constrain whether an area both have experienced removal and growth within an acquisition ? Or do you assume that areas that experience growth have not experienced removal and vice versa ? Such assumption should be mentioned here. What exactly is included in the dome/cone volume and area (include a schematic figure) ? How were the volumes from 1956-67 obtained when your base is the 1949 DEM (thus you both have sector collapse and activity from 1956-67 in your DDEM)?
o Could volume changes be categorized into dome growth (intrusive and exogenous), lava flow, pyroclastic deposition etc. based on the morphological mapping ?? Dividing the volume into dome, lava flows, pyroclastics etc, could be very relevant for hazard perspective (see e.g. Fink et al., 1990)
• The description on error estimation of the volume estimates is at places hard to follow and need a bit more explanations. Furthermore error should be included in table 1 as in suppl. Fig. 2-4.
• Modeling of magma path distribution: It is unclear to me if the effective volcanic loading used the volume estimates obtained from table 1 for (a) unloading due to sector collapse and for (b) loading by regrowth ? This should be clear if the volume estimates have been used for the modelling. Furthermore does the volume unloading fit Maccaferri et al., 2017 model of relocation ? It would also be appropriate to discuss if the pre-set boundary conditions make sense with respect to the suggested magma plumbing (2 magma chambers in 7 and 18 km depth)

2) Strengthening of the discussion. The authors have a unique opportunity to synthesize data sets in the discussion combining phases of activity, eruption volumes and extrusion rates, vent changes, geochemical data and plumbing system. This is eluded to in very general terms, but it seems like the full potential of their data and the existing ancillary information is not fully exploited.
• In the current discussion, it is argued that the eruption rates does not affect the activity and the reader has to consult table 1, look at individual numbers, combine it with fig. 8 and find the right time periods for the main stages. Similarly the reader themselves have to dig up the geochemical changes through the last 7 decades and try to plot them according to activity. This part of the discussion would be improved significantly by combining the model of the main stages of Bezymianny with cumulative volume graph, extrusion rates, vent changes and geochemistry.
o This can be done in a new figure 8 consisting of four panels: a) x, y graph (with 2 y-axis) displaying cumulative volume and extrusion rate as a function of time b) Illustration of regrowth from fig. 8 plotting according to the time periods; c) Vent concentration graph and d) geochemical data.

• The current discussion does compare to other cases of volcanic regrowth. However, there are no comparisons of degree of unloading, cumulative volume, extrusion rates, or vent shifts which could be very helpful parameters to broaden the discussion and make the Bezymianny-case more applicable to other sector collapses. It would be logical to compare to e.g. fig. 6a in Maccaferri et al., 2017 as well as discuss the case of Mt Helens where good volumetric and extrusion rates exists.

3) The text itself need it improvement;
• Precision and simplification of language would benefit the manuscript. The language is at places unclear, convoluted and/or unprecise due to different issues:
o Change from past to present tense (see detailed comments)
o Unnecessary redundancy: E.g. "conical shape, morphologically described by its circularity"
o Convoluted sentence such as E.g. "extension of exogenous growth is documented in 1968" which simply could be expressed as "the exogenous dome continue to grow in 1968" or "Decades-long repeat photogrammetric data acquisition" instead of "Repeated decadal acquisition of photogrammetric data"
o Overall it seemed that the authors were using American English over British English (e.g. using "color" and not "colour"), but there are example of British spelling such as "focussing" instead of focusing. Please be consistent either choosing American English or British English

• Ambiguous terminology/phrases:
o Authors refer to the length of the time series as: 7 decades, 6 decades and near-7 decades. Please be consistent.
o The terminology for volcanic products can be simplified, which will help the reader. Currently the following terms are used: endogenous (protrusive) dome growth, exogenous (extrusive) dome growth, which as far as I can see is used interchangeable with the term lava lobes and then finally effusive lava flows. The term effusive is a bit confusing since, dome growth also can be effusive, so what about simplifying and these terms and just call them endogenous dome, exogenous dome and lava flows ? That way you also avoid confusing using lava lobe, which also typically is used as the smallest unit of a lava flow.
o The terms dome/cone/stratocone is also used interchangeable (e.g. in table 1 and in the text). I understand that the activity changes from dome growth to a stratocone, but I think for table 1 it would be better to call dome/cone for volcanic edifice instead of dome/cone, and then use dome for the products in phases from 1956-2006 and stratocone for the last phase.

Minor comments:

• Merge suppl. Fig. 2-4 and error bars to the figures
• Add contours to Supp. Fig 5
• Provide data from 1949 that serves as a baseline,- it is not shown in the article nor in suppl. information

References
Fink, J.H., Malin, M.C., and Anderson, S.W., 1990, Intrusive and extrusive growth of the Mount St Helens lava dome: Nature, v. 348, p. 435–437, doi:10.1038/348435a0.
Maccaferri, F., Richter, N., and Walter, T.R., 2017, The effect of giant lateral collapses on magma pathways and the location of volcanism: Nature Communications, v. 8, p. 1–11, doi:10.1038/s41467-017-01256-2.

Detailed comments:
See annotated document

Dear Editor, please find a point-by point response to the reviewer comments below. Our replies **are marked in bold**.

Dear Dr Shevchenko,

Your manuscript titled "The rebirth and evolution of Bezymianny volcano after the 1956 sector collapse" has now been seen by 3 reviewers, and I include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

Reply: We appreciate these comments and carefully considered all the points raised by the 3 reviewers and by the editors. With this we could improve many aspects of the manuscript.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Reply: Below we provide the point-by-point reply, and highlight all changes made in the manuscript in color.

Please note that both of the attached documents are from Reviewer#3

Reply: We included the comments of the Reviewer#3 from the attached documents to this point-by-point response.

In addition, please ensure that the revised manuscript addresses the following editorial thresholds:

****Present a compelling documentation of the regrowth of Bezymianny volcano after 1956, and place this firmly in the context of existing relevant literature****

Reply: We appreciate this comment and made the documentation of the regrowth more compelling by rewriting and emphasizing our results and statements, which are now more carefully discussed in the context of the relevant literature. Specifically we largely rewrote the abstract and the introduction, and made a large number of improvements in the results, such as a much more detailed description of the morphological changes at Bezymianny. The reviewer comments and attached documents were all very helpful for this.

****Provide a clear and thorough explanation of the methodology involved in your numerical modelling****

Reply: We appreciate this comment and thoroughly rewrote the numerical modelling method explanations, addressing all comments raised by the reviewers. In the revised version we now have a much clearer description of the numerical models, including important information on the modelling approach, its constraints, assumptions, and limitations. We also improved the description of the results obtained with the numerical simulations, and their interpretation.

****Fully justify your prediction of a new collapse event within 10-15 years, with reference to previous activity at Bezymianny, or re-evaluate this statement****

Reply: We appreciate this comment and agree it was not entirely clear. The statement is based on literature descriptions stating that collapses are recurrent after regrowing edifices reach similar heights. This we now include by rephrasing and adding reference to previous activity at Bezymianny. We now improved the explanation as follows.

Old text:
The process of regrowth may be cyclic; when the new cone reaches a volume approaching the earlier pre-1956 cone, it may produce another partial or complete collapse in 10-15 years from today, so that the cycle will restart. Similar cycles have occurred at Bezymianny before, as indicated by remnants of scars and deposits that pre-date the current edifice(Braitseva et al, 1991).
New (improved text):
Since Bezymianny almost gained the pre-1956 collapse height, a new catastrophic collapse might be prone[21,26]. During the Holocene, Bezymianny repeatedly produced large-volume pyroclastic flows up to 0.3-0.4 km^3 [39] that may indicate the occurrence of large destructive events. However, each of those powerful eruptions were followed by a long period of effusive and moderate explosive activity that lasted from hundreds to thousands of years[39]. The last destructive episode before 1956, was associated with partial flank collapses that left behind two noticeable scars on the western and eastern flanks[34], yet their extent is not even close to that of the 1956 (Fig. 1c,e). Moreover, since the 1956 collapse was preceded by a long period of quietness[39] and was triggered by intrusion of a cryptodome (i.e. shallow magma body destabilizing the strength of the edifice)[32], we cannot say whether the next catastrophic edifice collapse will occur shortly after reaching the pre-collapse size. What we can say, is that if the current activity will go on (the latest two eruptions occurred in 2019), causing further steepening of the flanks, the volcano's upper slopes may eventually partially collapse, even in the near future. This clearly poses a hazard to the visitors of Bezymianny. Furthermore, the area of the potential hazard has increased since 2017, when the northern and southern sectors of the amphitheater rim were covered with pyroclastics, which led to an unhindered inflow of eruptive material towards the northern and southern feet of the volcano.

Reviewers comments:
Reviewer #1:
The manuscript by Schevckenko et al addresses an important and topical subject, concerning the response of volcanic activity to major structural collapse. There are relatively few such events in the historical record, and detailed study of all such examples can therefore provide important general insights into eruptive behaviour following collapse, and the influence of collapse and regrowth on subsurface magma systems. Although recent events such as the collapse of Anak Krakatau volcano put this type of volcanic process into focus, and detailed studies of Mount St Helens also advanced understanding of volcano stability, the value of the record at Bezymianny is that it spans a longer timescale while also comprising relatively detailed field observations. The 7-decade perspective thus gives valuable insights into post-collapse volcano evolution.

Reply: We appreciate this comment and agree that the 7-decades are unique.

Overall, the manuscript is well written, logically structured, and provides an interesting account. The dataset is novel, and it's fascinating to see the general development of the post-collapse units into a stratocone. The figures are also very well presented. I enjoyed reading the paper and think it will be of broad interest. My suggestions are generally minor, but there are several of them listed below.

Reply: We carefully considered all these suggestions, which helped us to make the work much clearer. Below we detail our replies and how we made these improvements.

A few general comments would be that the citation could be improved in the opening sections, as noted below, and that the writing and detail could be more quantitative and specific in many places. I have indicated places throughout the manuscript where this could be improved.

Reply: We appreciate this comment and now improved the referencing in the opening sections. We inserted important references related to other collapse events and case examples where knowledge exists on regrowth episodes. In this we also included all suggestions by the reviewers. The opening sections are now more quantitative and specific in places.

Specifically we now have added the following citations which help to significantly improve the opening sections: Froger et al., 2001; Voight et al., 1981; Walter et al., 2019; van Wyk de Vries et al., 2000; Calvari and Pinkerton, 2002; Masson et al., 2002; McGuire, 1996; Ryan et al., 2010; Watt, 2019; Dvigalo, 1988; Ventura et al, 1999; Hall et al., 1999.

I also think that while the numerical modelling is a useful addition to help explain the vent migration and potential influences of regrowth on magma ascent, that this also needs developing further within the main manuscript to fully consider the caveats and simplifications involved in the modelling.

Reply: We agree with the reviewer remark and we expanded the description of modelling assumptions within the main manuscript. Furthermore, we improved the description and interpretation of our modelling results, particularly with respect to the focusing due to the re-load applied within the collapse embayment. We also modified the modelling figure (Fig. 7).

New (improved text):
***Results section:* Based on studies analyzing the effects of loading and unloading at volcanoes and their magma pathways[14,47,48], we designed numerical models to investigate (i) how the 1956 sector collapse may explain the observed shift in vent location, and (ii) how regrowth of the central edifice relates to the focusing of the vents. We use a 2D boundary element model to simulate magma propagation paths. Our model refers to the cross-section of a mixed-mode magma-filled crack in plain-strain approximation. The most favorable direction for the magma pathway is computed iteratively, following the criterion of maximum energy release[14,47]. This approach is based on fracture mechanics principles, however, it neglects the dynamics of magma within the fracture so that it cannot account for magma viscosity[49]. Further detail on the modeling technique and assumptions are provided in the Method section.**
Discussion section:* However, our numerical models necessarily simplify a much more complex system: several aspects may affect the propagation paths of magma, and their likelihood to feed eruptions. Among others, the interaction with rock heterogeneities, as well as changes in magma density and viscosity (due to degassing, for instance), were not considered in our simulations. While it is known that changes in the volcanic edifice loading may affect magma composition and eruptive style[10], we still know very little about the effect of magma viscosity on the propagation paths of magmatic intrusions[50]. The effect of these processes should be investigated with different modeling approaches, in order to achieve better insights on their relevance for the observations considered here. Nevertheless, a shift of post-collapse vent-locations has been observed at several volcanoes, and Bezymianny fits well within the trend previously shown in[14] (Supplementary Fig. 7), suggesting a common mechanism – related to the amount of mass redistribution – which may be primarily due to the local stress state induced by large topographic changes.

Method section: ***Numerical simulations were performed following a previously published approach[14,47,48]. A short description of the main characteristics and assumptions of this approach are given here.***

Magma pathways are modeled as 2D boundary element mixed-mode cracks in plane strain approximation. The modeling plane is perpendicular to the crack plane, therefore the model refers to a cross-section of the intrusion. The crack opening depends on assigned normal and shear stress boundary conditions that are the magma overpressure and the shear component of the topographic stress, respectively. The overpressure along the crack is given by the difference between the magma pressure and the confining stress (superposition of the lithostatic pressure and the normal component of the topographic stress). Topographic stresses are computed using analytical formulas for loading and unloading forces at the surface of an elastic half-space[14,47,48]. Loading and unloading force distributions are used to model the loading of the pre-collapse volcanic edifice and the stress change induced by the flank collapse[14]. The model for the magmatic intrusion accounts for the magma buoyancy and compressibility, while it neglects magma viscosity. As a consequence, the magma overpressure profile within the crack is linear along the depth and proportional to the magma-rock density difference (hydrostatic overpressure profile). The trajectories within the crust are determined by testing the incremental elongation of the magma-filled crack in different directions. Our algorithm chooses the direction where the sum of elastic and gravitational energy release is maximal[47,48].

It isn’t especially clear from the modelling figure that focusing of the vents is demonstrated, and there are assumptions about changes in magma storage depths and bulk composition that might actually be a consequence of the regrowth (and that the modelling could provide further insights to), which aren’t really explored in detail.

Reply: We appreciate this comment and made the following changes to improve the modelling descriptions.

First, we thoroughly revised and improved the modelling figure (Fig. 7). We refer to the paths highlighted in red in the panel b: They get closer to each other, and show convergence towards the center of the loading distribution: this is what we interpret as an indication of vent focusing from the simulations.

Second, we made appropriate changes of the figure caption.

Third, we expanded the description of the modelling method and results in the main text and also the supplementary files.

We agree with the reviewer's comment that the assumptions made could be more discussed in the article. In the revised version we thus clarify that the models can not constrain the magma source depth. But we fully agree that the bulk composition of magma might be affected by the collapse and re-growth (Pinel and Jaupart 2005). We furthermore expect that changes in the magma composition would not drastically change the paths of dykes, however they might affect their likelihood to reach the surface (because of changes in buoyancy and viscosity). We add these considerations in the model discussion.

New (improved text and figure):

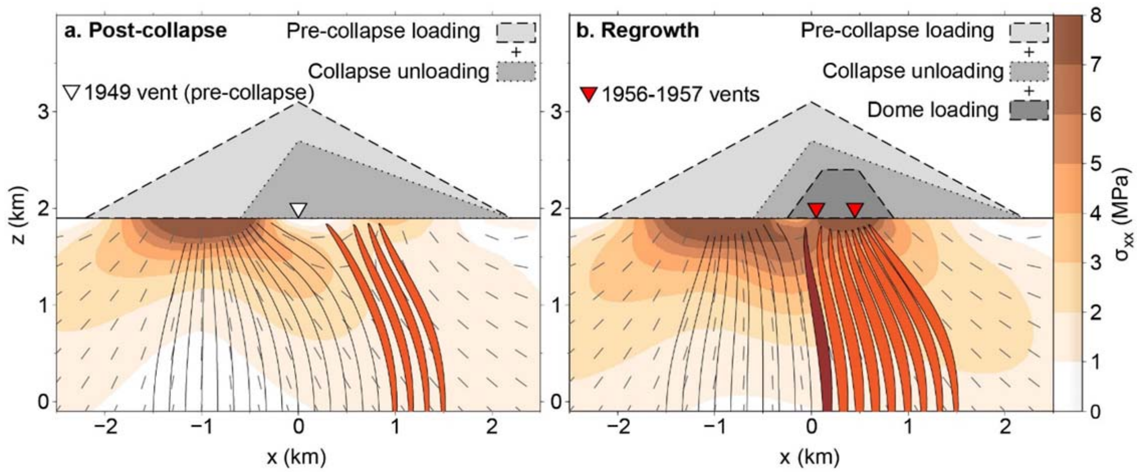


***Fig. 7** Stress scenarios and simulated magma pathways on a WNW-ESE vertical cross-section of Bezymianny. The colored contours represent the horizontal stress due to the unloading and reloading force distributions that simulate the effect of edifice collapse and re-growth, respectively (gray triangles and trapezoid shades, respectively). Gray dashes indicate the direction of maximum compression. The trajectories and the shape of magmatic intrusions are plotted in red when they are deflected towards the collapse embayment. Magma pathways that converge towards the rim of the collapse scarp are marked by solid black lines. a Post collapse scenario: the pre-collapse vent location (white reverse triangle), appears to be inhibited (paths diverge to both sides away from it). The most favorable position for post-collapse vents is within the collapse embayment (red trajectories), because of collapse unloading forces. New vents may be shifted up to several hundreds of meters towards the collapse direction. b Regrowth scenario: more paths are deflected towards the collapse embayment, and they tend to converge towards the center of the loading force distribution associated with the new dome (gray trapezoid). Even though the compressive stress below the collapse embayment is increased by the new dome, it is still lower than the horizontal compression underneath the rim. A region of relatively lower compressive stress (paths highlighted in dark red), may represent a more favorable location for magma paths to intrude within the new dome.*

***Result section:** We find that the unloading due to the 1956 sector collapse favors magma rising towards and beneath the collapse amphitheater, shifted eastward of the pre-collapse vent location by ~300 up to ~800 meters ($0.28<x<0.83$ km, Fig. 7a), in agreement with our photogrammetric observations at Bezymianny, and with previous results for the shift of vent location as a consequence of a flank collapse[14] (Supplementary Fig. 7). Our simulations for the post-collapse stress scenario results in magma paths that are rather scattered beneath the collapse embayment (highlighted in red in Fig. 7a). In contrast, the paths beneath the rim of the collapse scarp are more focused – pointing at the location of the rim – and get arrested beneath the rim, because of higher compressive horizontal stress due to the rim topography and the horizontalization of some paths, which reduce the effective buoyancy of the intrusion (black paths in Fig. 7a). Also, our photogrammetric observations at Bezymianny suggest that initial dome growth was spread out, causing the formation of two main coalescing domes elongated along the collapse amphitheater. When considering a stress scenario that accounts for the regrowth of the central cone (Fig. 7b), the number of magma pathways rising towards the collapse amphitheater increases, and paths focus, pointing at the location of the center of the new load (Fig. 7b). The distribution of magma pathways beneath the regrowing edifice resembles the distribution of paths below the scarp rim, however, the compressive stress beneath the growing cone is still lower (as in this simulation the new dome topography did not reach the height of the scarp, yet). In addition, a zone of lower compressive stress persists between the two lobes of maximum horizontal compression (in $0<x<0.3$ km). Such a "corridor" of lower compressive stress may further help magma rising within the new cone (dark red path in Fig. 7b). This is also in agreement with our observations, with vents progressively focusing towards the center of the new cone.*

Discussion section: ***The hypothesis of the activation of two different feeding sources, cannot be supported – neither is in contrast – with our magma path simulations: in fact, our model cannot account for viscosity changes. Also, accounting for the mechanical coupling with a magmatic reservoir (not considered here) may not add further constraints, since the unloading and loading force distributions affect magma pathways only at shallower depths (because of the relatively small collapse volume with respect to other cases previously studied with this approach[14] (Supplementary Fig. 7).***

Nevertheless, an effect of unloading and loading stress on the activation (or inhibition) of reservoirs at depth, may be possible[10]. At the moment it is not clear for how long the effect of topographic loading may last, but given the regrowing load of the new cone is approaching pre-collapse conditions, we conjecture that also the stress relationship at depth may become close to the condition as it was before the 1956 sector collapse.

It would be helpful to see a more specific description of processes in the abstract. The manuscript covers changes in eruption style, vent position and migration, and uses numerical modelling to understand these changes, but the way these are stated in the abstract could be more specific.

Reply: We appreciate this comment and have rewritten the abstract. The new abstract is much more detailed, and contains now quantitative information on eruption rate, dimension, and scales of migration, as well as modelling results that explain the observations. In return, we shortened the qualitative statements and focused on the most compelling results. Therefore, we hope that it has much improved.

Are there any constraints on eruption rates across this period (volume flux?); or any changes/acceleration/pauses etc.?

Reply: We appreciate this comment; and made appropriate improvements. We identified a decrease in the growth rate followed by its stabilizing since 1977 and now better explain how it could have affected the transitional changes. We added the description to the manuscript:

Old text:
However, the details of regrowth after a collapse may depend on a number of conditions other than stress changes. Eruption rates (Tab. 1), revealed to be near-constant since the 1970s. Therefore, we conjecture that eruption rates were not much affecting the observed changes very much.
New (improved text):
However, mechanisms of regrowth after a collapse likely depend also on factors other than stress changes, such as eruption rate variations (Tab. 1, Fig. 9). During Bezymianny's edifice reconstruction, the growth rate decreased noticeably from an initial ~56,000 m^3/day (1956-1967) to 33,000 m^3/day (1967-1977) and then to 15,500-17,000 m^3/day (1977-2017). The constant growth rates coincided with the occurrence of lava flow emplacements that successively covered the older dome complex. We conjecture that the lava flows may have acted as an armor preventing partial flank collapses and stabilizing the new edifice, which eventually facilitated the formation of a stable centralized vent through gradual load increase. Thick and unevenly distributed shear lobes, in turn, may contribute to slope instability leading to partial dome collapses, as was observed at Bezymianny in 1985[51] and frequently at Shiveluch[52].

From Lines 20-25, the authors describe vent focusing and migration – but in what direction, and which factors determine this, and over what distance or rate? This sort of quantitative and specific detail in the abstract would really help understand the changes observed in greater detail.

Reply: We agree that the abstract was not compelling enough and therefore we rewrote it, providing now more quantitative assessments and details on vent focusing and migration that the reader may find help to understand the changes.

Old text:

Volcanoes that experienced a sector collapse are commonly prone to regrowth of a central conical edifice. Due to the lack of long-term observations, the details of the regrowth process remain poorly understood, however. Here we present a unique, nearly 7-decade-long, photogrammetric time-series for Bezymianny volcano, Kamchatka, showing the sequential refill of the amphitheater after the 1956 sector collapse. Edifice regrowth started quickly with the formation of two endogenous lava domes originating at distinct eruption centers shifted to the east, followed by multiple lava lobe extrusions from migrating vents. After 2 decades, eruption style changed towards more effusive episodes, while the eruptive centers gradually focussed. After 5 decades, vent migration had ceased and the lava domes converted into a stratocone with a well-defined and localized summit crater. Numerical modeling suggests that the shifting and later focusing of the eruption vent locations can be expected after sector collapse at volcanoes. This is found to be associated with loading changes, affecting magma pathways at depth, and causing the gradual stabilization of the new central cone. Applied to Bezymianny, our results shed light on the complex edifice regrowth process following a sector collapse, with important implications for regrowing volcanoes elsewhere.

New (improved text):

Continued post-collapse volcanism can cause the rise of a new edifice. However, details of such edifice rebirth have not been documented yet. Here, we present 7-decade-long photogrammetric data for Bezymianny volcano, Kamchatka, showing its evolution after the 1956 sector collapse. Edifice rebirth started with two lava domes originating at distinct vents ~400 m apart. After 2 decades, activity became more effusive with vents migrating within ~200 m distance. After 5 decades, the activity focused on a single vent to develop a stratocone with a summit crater. We determine a long-term average growth rate of 26,400 m^3/day, allowing us to estimate the regain of the pre-collapse size within the next 15 years. Numerical modeling explains the gradual vents focusing to be associated with loading changes, affecting magma pathways at depth. This work thus sheds light on the complex regrowth process following a sector collapse, with implications for regrowing volcanoes elsewhere.

In the opening paragraph (L30-40), a recent review (Watt, The evolution of volcanic systems following sector collapse) provides a summary of several other examples this type of evolution, and citation of this would place the study in the broader context of other studies in this field, many of which aren't cited in the opening paragraph – but which further support the inference of potential changes in erupted compositions, rates etc.

Reply: We agree that the recent review (Watt, 2019) provides a good overview and other examples. Therefore, we have adopted a number of arguments and included also this reference and selected examples into our opening paragraph, which is now much broader. In specific we made the following changes:

Old text:

The consequences of sector collapses are often dramatic, both at depth and at the surface, associated with catastrophic pyroclastic flows and directed blasts, devastation over distances as far as tens of kilometers, and potential for triggering far-reaching secondary hazards such as lahars and tsunami. At depth, unloading forces cause changes in magma reservoir pressure (Pinel and Jaupart, 2005), location and geometry (Manconi et al., 2009), and are associated with compositional changes of the erupted products (Longpré et al., 2009). Numerical simulations of magma paths following a sector collapse suggest that they may deflect (Accocella, 2003) and bifurcate (Maccaferri et al., 2017), leading to a shift in the eruption site(s). At the surface, following a collapse the regrowth of a new volcanic cone was observed at Mount St. Helens (Lipman and Mullineaux, 1981), Soufriere Hills (Belousov et al. 2007), Shiveluch (Shevchenko et al. 2015), and Bezymianny (Gorshkov, 1959). The rebuilding of a new cone may continue until another sector collapse occurs, with similar direction, dimension, and effects (Walter and Schmincke, 2002).

New (improved text):

Active volcanoes are subject to flank instability that may cause large-scale sector collapses[1]. The collapses may occur slowly and creep-like[2] or fast and catastrophic[3], some with precursory activity[4] and others suddenly[5]. The volumes mobilized by sector collapses vary

considerably, from small scale[6] to large edifice collapses involving 10^8-10^11 m[3] [7], with the larger collapses being rarer[8]. The consequences of sector collapses are often dramatic and associated with catastrophic directed blasts and pyroclastic flows, devastation over distances as far as tens of kilometers, and potential for triggering far-reaching secondary hazards such as lahars and tsunamis, with an estimated 20,000 death toll caused by historic volcano flank collapses and associated hazards[9]. The mobilization of large rock masses at the surface is felt beneath the volcano: At depth, unloading forces cause changes in magma reservoir pressure[10], its location and geometry[11], and are associated with compositional changes of the erupted products[12]. Simulations of magma paths following a sector collapse suggest that they may deflect[13] and bifurcate[14], leading to a relocation of the eruption site(s). At the surface, following a collapse the regrowth of a new volcanic cone was observed at Mount St. Helens (USA)[15], Soufriere Hills (Montserrat)[16], Santa Maria (Guatemala)[17], Ritter Island (Papua New Guinea)[18], Shiveluch (Russia)[19], and Bezymianny (Russia)[20], and was geologically and experimentally reconstructed[21] for pre-historic collapse events such as evidenced at Socompa (Argentina and Chile)[22], Parinacota (Chile and Bolivia)[23], Vesuvius (Italy)[24], and Tungurahua (Ecuador)[25]. The Bezymianny case presented here, however, is providing the first detailed chronological evolution of a rebuilding cone morphology. The rebuilding of a new cone may continue until another sector collapse occurs, with similar direction, dimension, and effects[21,26].

At Line 39, Ritter Island provides a further historical example, and of course many prehistoric examples, such as Parinacota. At Line 41, it may be worth citing other examples as well, as there can be wide variations in collapse direction and dimension (e.g. Shea et al., Mombacho); and the collapse history of Shiveluch is also interesting in this regard.

Reply: We agree and made a number of changes to address the available literature. We added the Ritter Island example along with other examples. It now reads as follows:

Old text:

At the surface, following a collapse the regrowth of a new volcanic cone was observed at Mount St. Helens (Lipman and Mullineaux, 1981), Soufriere Hills (Belousov et al. 2007), Shiveluch (Shevchenko et al. 2015), and Bezymianny (Gorshkov, 1959). The rebuilding of a new cone may continue until another sector collapse occurs, with similar direction, dimension, and effects (Walter and Schmincke, 2002).

New (improved text):

At the surface, following a collapse the regrowth of a new volcanic cone was observed at Mount St. Helens (USA)[15], Soufriere Hills (Montserrat)[16], Santa Maria (Guatemala)[17], Ritter Island (Papua New Guinea)[18], Shiveluch (Russia)[19], and Bezymianny (Russia)[20], and was geologically and experimentally reconstructed[21] for pre-historic collapse events such as evidenced at Socompa (Argentina and Chile)[22], Parinacota (Chile and Bolivia)[23], Vesuvius (Italy)[24], and Tungurahua (Ecuador)[25]. The Bezymianny case presented here, however, is providing the first detailed chronological evolution of a rebuilding cone morphology. The rebuilding of a new cone may continue until another sector collapse occurs, with similar direction, dimension, and effects[21,26].

At Line 48, I agree that detailed temporal observations of shifts in vent location don't exist, but I would expect a citation of some of the work on Stromboli that has shown this pattern (e.g. outlined in various papers by Tibaldi, but also in other geological reconstructions of Stromboli).

Reply: We appreciate this comment and therefore have added the (Tibaldi, 2004) reference. It now reads as follows:

New (improved text):

The pathways of magma may adjust as a result of the stress field redistribution due to sudden topographic changes[13,14], causing a shift of the eruption locations and their pattern[28].

However, detailed observations of shifting and then gradually focusing vents at active volcanoes have not been documented, so far.

At Line 53, in general it does appear to be the case that post-collapse growth is in the centre of the scar; South Soufriere Hills may be a possible exception (e.g. papers by Cassidy et al. on Montserrat).

Reply: We agree and therefore made the following changes: The example of Soufriere Hills with the citation is now added into the sentence. It now reads as follows:

New (improved text):
After a sector collapse, the regrowth of the volcanic edifice may start immediately or with a delay and, with few[29] exceptions, commonly nucleates in the center of the newly exposed amphitheater. Regrowth may last days to years, as observed at Mount St. Helens in the 1980s[30] and 2000s[31].

Line 58 – "6-decade long" is inconsistent with the 7-decades stated in the abstract (Line 16). It may be better to just state the start and end dates of the time series that has been analysed.

Reply: We agree and corrected this inconsistency. In the revised version we now use the consistent formulation that the period of photogrammetric observation is 7-decades-long and lasted from 1949 to 2017.

Line 61 – is it possible to justify the statement of Bezymianny being one of the most active andesitic volcanoes, by comparing the mean eruptive flux over the past few decades with other highly active volcanoes? It would be insightful to be able to compare the flux directly with an example of one or two other persistently active volcanoes.

Reply: We appreciate this comment and added relevant references. As written in Manen et al (2010): Bezymianny is one of the most active volcanic regions in the world (with reference to Simkin and Siebert (1994) and in Gorbatov et al. (1997)).

New (improved text):
In this study, we investigate a 7-decade-long period of edifice regrowth after the 1956 sector collapse[32] at one of the most active andesitic volcanoes in the world[33] Bezymianny volcano (Fig. 1a,b).

Line 67 – can this be more specific on the dates of regrowth after collapse. Can you state if the volcano in a state of eruption at the time of the collapse; and specify the gap in time after this, before activity resumed. Similarly, at Line 61, can you state how many sector collapses are known, rather than just stating "repeated".

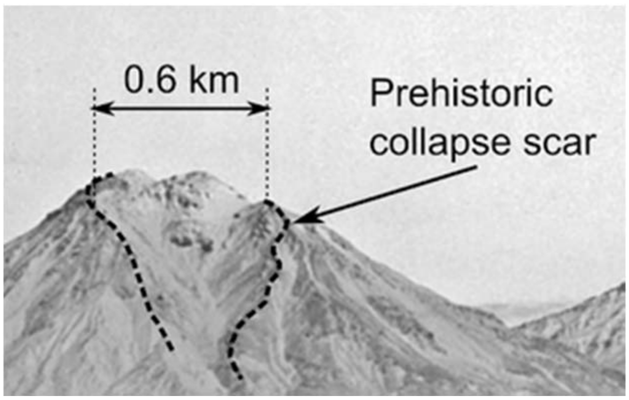
Reply: We agree and made appropriate changes. It was specified that the dome started to grow immediately after the collapse according to (Gorshkov and Bogoyavlenskaya, 1965). Braitseva et al. 1991 describe 3 powerful eruptions over the whole history of Bezymianny (2,400 B.P., 1350 B.P., and 1956). The prehistoric collapses are obvious because of the presence of two collapse scars in 1949, but their scales were smaller. As there is no certainty on how many collapses Bezymianny has experienced we decided to move this description into the Discussion part.

Old text (in Introduction):
During the last 1,400 years, Bezymianny experienced repeated sector collapses, each followed by intense periods of eruptions producing a new central cone with lava flows and pyroclastics (Braitseva, 1991).

New (improved text) (in Discussion):
During the Holocene, Bezymianny repeatedly produced large-volume pyroclastic flows up to 0.3-0.4 km^3 [39] that may indicate the occurrence of large destructive events. However, each of those powerful eruptions were followed by a long period of effusive and moderate explosive activity that lasted from hundreds to thousands of years[39]. The last destructive episode before 1956, was associated with partial flank collapses that left behind two noticeable scars on the western and eastern flanks[34], yet their extent is not even close to that of the 1956 (Fig. 1c,e).

Fig 1c – is there any information on the age of the feature labelled “collapse scar”. If not, probably good to clarify that this is an older collapse scar.

Reply: We thank for the comment and now have added the wording “prehistoric” to the figure, now it reads therefore “Prehistoric collapse scar”.



Line 93 – clarify that the width is 1300m, and the axial length (presumably?) 2700 m.

Reply: We agree and have corrected this as suggested.

New (improved text):
The processed data of the first post-collapse aerial survey from 1967 shows the presence of a steep headwall amphitheater (1,300 m in width, 2,700 m in axial length, and up to 400 m in visible depth) facing ESE.

Line 94 – can you be more specific than “distributed”. How did the vent location compare to the pre-collapse vent position? How many hundreds of metres away did these vents extend, and was there any pattern to this direction? [I see that this detail is given later on, at L196, but could it just be stated here?]

Reply: We acknowledge that this statement stimulates the interest for more details, and therefore better refer to the relevant section in the manuscript. A link to the “Vent migration and focussing” section was added.

Line 95 – that’s very interesting that there is an alignment, but you haven’t stated the orientation of the collapse axis. Could you also provide that in the text, so that it’s easy to compare the alignment of the two features.

Reply: Good point. In the revised version we have now added the direction of the collapse axis.

Old text:
The newly processed data of the first post-collapse aerial survey from 1967 shows the presence of a steep headwall (up to 400 m) amphitheater (1,300×2,700 m) open to the east-

southeast. Within the amphitheater, new volcanism was initially distributed and gave rise to a broad and elongated edifice that is separated by an N50°E striking linear depression up to 200 m wide, and 110 m deep.

New (improved text):

The processed data of the first post-collapse aerial survey from 1967 shows the presence of a steep headwall amphitheater (1,300 m in width, 2,700 m in axial length, and up to 400 m in visible depth) facing ESE. Within the amphitheater, scattered volcanic activity (see section "Vents migration and focusing") formed a broad NW-SE elongated edifice (azimuth 120°) that was formed between 1956 and 1967[35,40–42]. This new edifice is separated by a NE-SW linear depression (azimuth 50°), 200 m wide and 110 m deep, that delineates two consecutive endogenous[43] domes located in the southeast (1st) and northwest (2nd) of the amphitheater, and that coalesced through time (Fig. 2a, Fig. 3a,b) (see section "Morphological mapping" in Methods).

Fig 2 – this is a very interesting dataset. I am slightly confused by your terminology. Lava dome growth could be either endogenous or exogenous (or some combination of both), but why is it of particular significance here (most of the dome growth in the 1967-68 images looks endogenous, but is labelled exogenous)? The distinction between extrusive and effusive is also unclear. Aren't all lavas, whether forming domes or flows, both extrusive and effusive? Would it be simpler to label these phases on the basis of the dominant styles of volcanism – dome-forming, onset of lava flows, mixed minor explosive-effusive activity (perhaps?, for the stratocone phase). Does the change to lava-flow generation in 1977 also coincide with a change in magma composition or other properties, as there is presumably a significant viscosity change?

Reply: We thank the reviewer for the comment and now carefully checked the used terminologies and added references where necessary. Now we use the following terms according to the recent edition of Encyclopedia of volcanoes (Sigurdsson et al., 2015):

Endogenous growth - enlargement of a lava dome due to influx of magma into the dome interior.

Exogenous growth - enlargement of a lava dome due to discrete lobes of lava being emplaced at the surface or above each other.

Shear lobe - a large, often arcuate shaped, body of solid lava extruded through a vent or exogenously through the carapace of a dome.

Plug - a body of near-solid magma within the conduit, the upward movement of which is characterized by strain localized along or near the conduit margin.

Though the thick and viscous portions of lava that were extruded on top of the Bezymianny dome can be called "lava lobes" (lobes of exogenous dome), we decided to call them "shear lobes" to emphasize their obvious high viscosity (thickness from 60 m to 110 m, circular-symmetric shape) and to distinguish them from lava flows (thickness 15-20 m, length to width ratios from 1.8 to 2.1). Exogenous growth started at Bezymianny with the extrusion of separate lobes from the vents on top of the previously formed domes. Endogenous and exogenous growth separation is necessary in this study of Bezymianny, because only with the manifestation of exogenous growth there is a possibility of transition from a dome to a stratocone. The distinction between shear lobe extrusion and lava flow effusion is also necessary because lowering in viscosity and lava flow occurrence is one of the main factors for a stratocone formation. There is currently quite a long period of exogenous growth at Shiveluch with multiple shear lobes extrusion but not any sign yet for a stratocone formation. Though the terms "extrusive" and "effusive" are in most cases used as synonyms in international volcanological literature, these words are not synonyms in general. The term "extrusion" relates to emergence of highly viscous material by forcing or pushing it out through a small opening, and the term "effusion" relates to emission of liquid that can flow longer distances due to gravity. As it was quite a sharp and rapid change from the extrusion of shear lobes to the predominant effusion

of lava flows, and it played a significant role in the stratovolcano formation, we find it necessary to make this division in the current study. We changed the text to make our idea clearer:

New (improved text):
Result section: ***In 1977, a new, 180 m wide and 300 m long, portion of lava poured out onto the north-eastern flank of the dome complex (Fig. 2d and Fig. 4a,b). In contrast to previously observed shear lobes, it was much thinner (15 m), and flowed over a comparatively longer distance towards the foot of the dome complex. Therefore, we can consider it as a first post-collapse lava flow at Bezymianny, which is also in agreement with eyewitness accounts[36]. We link the different characteristics of shear lobes and lava flows with two distinct exogenous growth modes: Extrusion of higher viscous shear lobes and effusion of lower viscous lava flows. Hence, dome development between 1956 and 1976 was dominated by first endogenous and then extrusive growth, whereas from 1977 onwards dome growth was mainly marked by extrusive and effusive behavior. The change in growth style will eventually lead to a significantly different shape of Bezymianny's new edifice.***
Descussion section: ***Yet, the dome growth evolution of Mount St. Helens and Shiveluch does not show any trend towards the formation of a stratocone. This may be due to intermittent dome growth episodes (Mount St. Helens), the prevalence of destructive over constructive processes (Shiveluch), and/or because these volcanoes have not produced any lower viscosity lava flows that covered and thus stabilized the dome. For Bezymianny we argue that the transition from the extrusion of shear lobes to the effusion of lava flows in 1977-2006 may mirror a contemporaneous decrease of the viscosity of its eruptive products.***

Line 124 – what about the extrusion rate between 1956 and 1967? Table 1 suggests this was even higher? Just to also be clear, the 43,600 is just for the 1967-1968 period?

Reply: We appreciate this comment and need to clarify that the volume of the dome over the 1956-1967 period was calculated in previous research (Seleznev et al., 1984). This volume we added to the text, together with the reference (Seleznev et al., 1984). The extrusion rate between 1956 and 1967 was calculated on the base of this previously calculated volume, but with more precision as the exact date of the 1967 survey was not estimated before (see "Volumes and extrusion rates estimation" in the Methods section). Yes, the 43,600 is just for the 1967-1968 period.

Old text:
The area of the base of the whole dome complex was 1,975,000 m^2 with a maximum elevation of 2,801 m.
New (improved text):
The base of this dome complex covered an area of 1,975 km^2, the dome reached an elevation of 2,801 m and occupied a volume of 0.239 km^3 [34].

Table 1 – very interesting to see the volumes. What do these look like if plotted against time. Is there a clear long-term trend, or is the pattern much more episodic? Can you also clarify that the 56,600 rate is for 1956-1967 (i.e. just the post collapse period). If so, how did you estimate the immediately post-collapse morphology? It might be clearer to have a row for the collapse event itself, even if some parameters are unknown, so that the timing of the collapse is clear for the reader.

Reply: The graphs with the volumes and other parameters are in the supplementary part and it was also added to the main part (Fig. 9). There was a decrease in rates and stabilizing since 1977. The baseline (the post-collapse floor of the amphitheater) was calculated in previous research (Seleznev et al., 1984). To estimate the floor elevation and shape of the collapse amphitheater, which was the base surface for the volume calculation, the 1956 ground-based images (Fig. 1e) were used. They were taken in a few months after the emergence of the first dome when it occupied a small area of the amphitheater's bottom. The lowest elevation point of the bottom was estimated to be

at about 2,200 m, and the vertical sections of the amphitheater across the collapse direction are close to parabolic. The amphitheater inner walls in the 1967 elevation model were extrapolated according to the estimated parameters (Seleznev et al., 1984). Though the estimation of the baseline has been done before, we added this information to the Methods part with the citation of (Seleznev et al., 1984). We added the collapse date and parameters to the table.

Old text:

Date of survey (dd.mm.yyyy)	*Absolute height of the dome/cone (m)*	*Area of the dome/cone (m^2)*	*Added volume (m^3)*	*Removed volume (m^3)*	*Dome/cone volume (m^3)*	*Extrusion rate (m^3/day)*
1949	*3,113*	*-*	*-*	*-*	*738 million[21]*	
24.10.1967	*2,801*	*1,975,000*	*239 million*	*-*	*239 million*	*56,600*

New (improved text):

Date of survey, collapse (dd.mm.yyyy)	*Absolute height of the dome, amphitheater floor (m)*	*Area of the dome (km^2)*	*Added volume (km^3)*	*Removed volume (km^3)*	*Dome volume (km^3)*	*Volume error (%)*	*Growth rate (m^3/day)*	*Growth rate error (%)*
1949	*3,113*	*-*	*-*	*-*	*0.738 (Seleznev, 1984)*	*-*	*-*	*-*
30.03.1959	*2,200 (Seleznev, 1984)*	*-*	*-*	*0.738 (Seleznev, 1984)*	*-*	*-*	*-*	*-*
24.10.1967	*2,801*	*1.975*	*0.239*	*-*	*0.239 (Seleznev, 1984)*	*1.4*	*56,600*	*12.5*

Old text:

Aerial photography of the volcano was first performed in 1949 (before the 1956 collapse). Information about the morphology immediately after the 1956 sector collapse was derived from oblique ground-based images(Gorshkov, 1959; Kirsanov et al., 1971), and further by regularly realized aerial surveys starting from 1967.

New (improved text) in Data and Methods:

Aerial photography of the volcano was first performed in 1949 (before the 1956 collapse). The post-collapse topography was estimated in previous research[34] from the 1956 ground-based images, which were taken when the first dome occupied a small area of the amphitheater's floor (Fig. 1e). The base of the amphitheater was estimated to be ~2,200 m above sea level, and its vertical sections across the collapse direction appeared to be close to parabolic. The amphitheater inner walls in the 1967 elevation model were extrapolated according to the estimated parameters[34]. Information about the morphology immediately after the 1956 sector collapse was also derived from ground-based images[20,41], and further by aerial surveys, which were regularly realized since 1967.

Line 135 – The change in aspect ratio of the extruded bodies is intriguing. Can you infer any viscosity changes from this information?

Reply: We appreciate this comment but need to state that to calculate the viscosity two surveys during a single lava flow emplacement is needed. The Jeffreys equation (https://doi.org/10.1080/14786442508634662) might be applied for other datasets not considered in this manuscript, such as time lapse camera records, which is beyond the scope of the present manuscript. The emplacement of lava flows at Bezymianny is very fast (couple of days). Unfortunately, such a frequent aerial survey was not performed at Bezymianny.

Line 177 – there is no mention at all of composition through here (or any comments on petrography, crystallinity etc.). I realise that this is not a petrographic paper, and perhaps no samples are available, but the change in lava morphology and gradual transition to more explosive activity does raise the obvious question of whether the magma composition changed across this period. The pattern appears to suggest a gradual shift to lower viscosities. Does this imply a gradual shift towards more mafic compositions? This might not be the direction that would be expected, so it warrants at least a brief comment based on any available compositional information.
[I see that you mention these at Line 259 – it would be helpful if you could point the reader to this earlier, so that it's clear that compositions will be covered later in the paper]

Reply: We mentioned the trend in decreasing SiO_2 in composition which led to lover viscosity also in the introduction.

New (improved text):
The dome growth style was characterized as extrusive-explosive until 1977, when it changed to extrusive-explosive-effusive[36]. This transition was accompanied by a gradual change in rock chemistry. In fact, comprehensive petrographic analysis[37] showed that Bezymianny's eruptive products became continuously more mafic since 1956.

Line 188 – as noted in the Table 1 comment above – how was the baseline calculated for 1956 (to estimate the subsequent volume), and can it be listed as a row in the table.

Reply: We agree that this information is helpful and made appropriate changes in the table and in the text. Please, see also the reply to Table 1 few points above.

Line 189 – so the long-term average is half the initial growth rate? Is there a long-term trend here?

Reply: Exactly, the long-term average is half the early growth rate. The long-term trend was also estimated. In the new version, we identified a decrease in the growth rate followed by its stabilizing since 1977 and tried to explain how it could affect the transitional changes. We added the description to the manuscript.

Old text:
However, the details of regrowth after a collapse may depend on a number of conditions other than stress changes. Eruption rates (Tab. 1), revealed to be near-constant since the 1970s. Therefore, we conjecture that eruption rates were not much affecting the observed changes very much.
New (improved text):
However, mechanisms of regrowth after a collapse likely depend also on factors other than stress changes, such as eruption rate variations (Tab. 1, Fig. 9). During Bezymianny's edifice reconstruction, the growth rate decreased noticeably from an initial ~56,000 m^3/day (1956-1967) to 33,000 m^3/day (1967-1977) and then to 15,500-17,000 m^3/day (1977-2017). The constant growth rates coincided with the occurrence of lava flow emplacements that successively covered the older dome complex. We conjecture that the lava flows may have acted as an armor preventing partial flank collapses and stabilizing the new edifice, which eventually

facilitated the formation of a stable centralized vent through gradual load increase. Thick and unevenly distributed shear lobes, in turn, may contribute to slope instability leading to partial dome collapses, as was observed at Bezymianny in 1985[51] and frequently at Shiveluch[52].

Line 192 – This is certainly a notable result, and I don't know of a similar dataset that allows this regrowth projection to be calculated in this way. This could be stated in the abstract, alongside summary values of the post-collapse flux?

Reply: We thank the reviewer for the comment. We added this result to the abstract together with the post-collapse flux.

Fig 6 – although the vents gradually become closer together, they seem to be centred around a fairly stable point, SE of the pre-collapse vent. Is that correct? It could be slightly clearer in the previous paragraph. In the longer term, because the edifice has achieved its pre-collapse dimensions, would we expect migration back towards the pre-collapse vent position. Or, because it has rebuilt slightly further east, would this imply a gradual long-term migration of the whole structure eastwards, governed by the collapse direction?

Reply: We agree and made it clearer. Concerning the reviewers point, that a migration backwards is expected, a more differentiated picture is presented: The current vents position is located to the ESE from the pre-collapse vent position. We made it more clear in the text and also corrected the shift value, as previously it was given along the NW-SE axis (Fig. 6e), but not in map view (Supplementary Fig. 4), which would be more appropriate here. We think that as the vent location is stabilized it wouldn't migrate towards the pre-collapse position, neither migration towards the collapse direction is expected. To address the first part of the reviewers questions, we have improved the description as follows:

Old text:

After the 1956 collapse, the first endogenous dome (1956-1965) started to form at a position shifted about 420 m to the east with respect to the pre-collapse summit.

New (improved text):

After the 1956 collapse, the first endogenous dome (Fig. 2a) emerged from a vent with a location shifted ~500 m to the ESE of the pre-collapse summit (Fig. 6; Supplementary Fig. 4). The inferred vent of the second dome emerged 400 m north-westward from the vent of the first dome, and ~230 m north-eastward from the location of the pre-collapse vent.

Fig 7 – The focusing of the red pathways in Fig b is not entirely clear – it looks like the red pathways are actually prevented from reaching the base of the volcano in this scenario, as they meet the 8 MPa stress field beneath the regrowing volcano? There are two pathways between the two regions of highest stress where it appears ascent is more feasible? Can the authors comment on this? It isn't entirely clear from the schematic depiction of the red pathways in a and b that image b is more focussed (the width of the red pathways in Fig b is greater than that in image a?

Reply: The reviewer is correct, that the figure was not explained in full. Several paths become arrested in the proximity of the 8 MPa contour, at the base of the re-growing cone. In fact, the distribution of magma pathways beneath the re-growing cone looks similar to the distribution of paths below the scarp rim, however the compressive stress beneath the growing cone is lower than the one beneath the rim (in the simulation the new topography didn't reach the height of the scarp rim, consistently with a "re-growth" scenario). The paths that stop beneath the re-growing cone also converge – or point – towards the center of it. We interpret this as a possible explanation for the focusing of the activity: the intrusions would tend to accumulate beneath the new-cone, feeding eruptions from its summit, when/if they would build-up

the overpressure needed to propagate further (by magma accumulation). We acknowledge that our description of the numerical results, and our interpretation of them, was lacking in clarity and important details, which has been added in the revised version of the manuscript.

We also add a description of the area of lower compressive stress highlighted here by the reviewer. We thank the reviewer for pointing out this interesting observation that we missed to describe in the previous version of the manuscript.

New (improved text):
Results section: ***When considering a stress scenario that accounts for the regrowth of the central cone (Fig. 7b), the number of magma pathways rising towards the collapse amphitheater increases, and paths focus, pointing at the location of the center of the new load (Fig. 7b). The distribution of magma pathways beneath the regrowing edifice resembles the distribution of paths below the scarp rim, however, the compressive stress beneath the growing cone is still lower (as in this simulation the new dome topography did not reach the height of the scarp, yet). In addition, a zone of lower compressive stress persists between the two lobes of maximum horizontal compression (in 0<x<0.3 km). Such a "corridor" of lower compressive stress may further help magma rising within the new cone (dark red path in Fig. 7b).***
Figure 7b caption: ***Regrowth scenario: more paths are deflected towards the collapse embayment, and they tend to converge towards the center of the loading force distribution associated with the new dome (gray trapezoid). Even though the compressive stress below the collapse embayment is increased by the new dome, it is still lower than the horizontal compression underneath the rim. A region of relatively lower compressive stress (paths highlighted in dark red), may represent a more favorable location for magma paths to intrude within the new dome.***

In general, I think the modelling needs a more detailed discussion to explain what the results indicate, and to consider assumptions about the driving pressure, lateral extent of the feeding system etc. (in the main text, not simply the methods section), to really provide a convincing case that they explain both the migration and the focusing. The way the figure is depicted is slightly misleading, because it implies that the actual topography has been modelled as the load, whereas the methods suggest that simplified geometrical forms have been modelled (triangular/trapezoidal) to represent regrowth. As this regrowth infills the scar, is 2D modelling valid throughout this scenario?

Reply: We agree with the reviewer and we enriched the model description and discussion accordingly. We also changed Fig 7, showing the actual (simplified) loading geometry used for the simulations.

New (improved text):
Results section: ***We use a 2D boundary element model to simulate magma propagation paths. Our model refers to the cross-section of a mixed-mode magma-filled crack in plain-strain approximation. The most favorable direction for the magma pathway is computed iteratively, following the criterion of maximum energy release[14,47]. This approach is based on fracture mechanics principles, however, it neglects the dynamics of magma within the fracture so that it cannot account for magma viscosity[49]. Further detail on the modeling technique and assumptions are provided in the Method section.***
Our model domain is a vertical ~WNW-ESE cross-section of Bezymianny volcano (Fig. 6c) and extends from a depth (z) of -0.1 km up to 1.9 km above sea level, which is the approximate altitude of the post-collapse amphitheater's floor (dashed profile in Fig. 6c). We simulate the stress field due to topographic changes using loading and unloading force distributions applied at the top of the mode[14,47,48] (z=1.9 km). These force distributions have simplified shapes based on the profiles in Fig. 6c (triangles and trapezoids in Fig. 7). Magma paths start vertically, from the base of the model domain (z=-0.1 km), within a 3 km wide region centered below the summit of the pre-collapse edifice (-1.5<x<1.5 km). We choose the depth and extension of the region from where the intrusions start, in order to cover the whole area affected by the stress changes associated with the morphological changes we study. This area

should not be considered as the location of a magmatic reservoir (which should be deeper at Bezymianny, c.f. Discussion section). Rather, our assumption is that an intrusion would rise from deeper depths and enter vertically our model domain. These models, although being highly simplified in terms of topographic geometry and magma dynamics, are constrained by the Bezymianny morphologies as summarized in Fig. 6c, and the resulting magma paths can be compared with observations of post-collapse vent-shift and the final vent focusing. In fact, magma pathways are influenced by the local stress, whereby changes in the direction of principal stress affect the favorite direction of propagation (see Fig. 7; Supplementary Fig. 6).

<u>Discussion section:</u> The results from numerical modeling show that the stress change associated with edifice destruction and rebuilding causes the shift of new eruptive vents towards the collapse embayment, (as previously shown for other volcanoes[14]), and magma pathways pointing towards the center of the area where new topography has formed. These results are consistent with the observation of scattered endogenous dome growth after the collapse, and the successive dome-to-cone transition. However, our numerical models necessarily simplify a much more complex system: several aspects may affect the propagation paths of magma, and their likelihood to feed eruptions. Among others, the interaction with rock heterogeneities, as well as changes in magma density and viscosity (due to degassing, for instance), were not considered in our simulations. While it is known that changes in the volcanic edifice loading may affect magma composition and eruptive style[10], we still know very little about the effect of magma viscosity on the propagation paths of magmatic intrusions[50]. The effect of these processes should be investigated with different modeling approaches, in order to achieve better insights on their relevance for the observations considered here. Nevertheless, a shift of post-collapse vent-locations has been observed at several volcanoes, and Bezymianny fits well within the trend previously shown in[14] (Supplementary Fig. 7), suggesting a common mechanism – related to the amount of mass redistribution – which may be primarily due to the local stress state induced by large topographic changes.

Line 276 – Similar cycles have occurred before, but on a comparable timescale? Your results suggest an inter-collapse interval of as little as 75 years. Is there evidence in the geological record of such a high frequency of collapse events? This would be remarkably rapid, but perhaps not entirely unprecedented (could cite, for example, Beget and Kienle, Augustine volcano).

Reply: We appreciate this useful comment and have rewritten this part in accordance with the previous research at Bezymianny (Braitseva et al., 1991). But we think that Augustine volcano is not a case of a volcano that restored its conical shape before the collapses. It experienced multiple collapses at a dome growing stage and can be compared in this regard to Shiveluch, but not to Bezymianny.

<u>Old text:</u>

The process of regrowth may be cyclic; when the new cone reaches a volume approaching the earlier pre-1956 cone, it may produce another partial or complete collapse in 10-15 years from today, so that the cycle will restart. Similar cycles have occurred at Bezymianny before, as indicated by remnants of scars and deposits that pre-date the current edifice (Braitseva et al, 1991).

<u>New (improved text):</u>

Since Bezymianny almost gained the pre-1956 collapse height, a new catastrophic collapse might be prone[21,26]. During the Holocene, Bezymianny repeatedly produced large-volume pyroclastic flows up to 0.3-0.4 km^3 [39] that may indicate the occurrence of large destructive events. However, each of those powerful eruptions were followed by a long period of effusive and moderate explosive activity that lasted from hundreds to thousands of years[39]. The last destructive episode before 1956, was associated with partial flank collapses that left behind two noticeable scars on the western and eastern flanks[34], yet their extent is not even close to that of the 1956 (Fig. 1c,e). Moreover, since the 1956 collapse was preceded by a long period of quietness[39] and was triggered by intrusion of a cryptodome (i.e. shallow magma body destabilizing the strength of the edifice)[32], we cannot say whether the next catastrophic edifice

collapse will occur shortly after reaching the pre-collapse size. What we can say, is that if the current activity will go on (the latest two eruptions occurred in 2019), causing further steepening of the flanks, the volcano's upper slopes may eventually partially collapse, even in the near future. This clearly poses a hazard to the visitors of Bezymianny. Furthermore, the area of the potential hazard has increased since 2017, when the northern and southern sectors of the amphitheater rim were covered with pyroclastics, which led to an unhindered inflow of eruptive material towards the northern and southern feet of the volcano.

Line 303 onwards – this discussion suggests greater complexity in terms of both storage depths and magma viscosity through time, both of which are likely to be important parameters in the modelling that may also influence dyke ascent behaviour. Given this complexity, is the detail in the modelling sufficient to capture the processes involved? Or perhaps conversely, can the modelling also provide insights into why the volcano may be tapping deeper and lower-viscosity magmas through time, as it regrows?

Reply: We appreciate this comment and agree that modelling is always a (necessary) simplification of the complex nature. Nevertheless, the models help to understand a range of observations made in the photogrammetric dataset.

Concerning the question if the modelling allows further inferences on tapping deeper magmas, we would prefer to not focus more on such aspects, which are not the aim of the study and not identifiable by available data. An important limitation, in this perspective, is therefore due to the fact that changes in magma viscosity (due to the activation of different reservoirs, for instance), cannot be considered in our simulations. Therefore, the hypothesis of the activation of two different feeding sources, cannot be supported – neither is in contrast – with our paths simulations. Also, accounting for the mechanical coupling with magmatic reservoirs at different depths (which are not considered in our simulations) may not add further constraints, since the unloading and loading force distributions affects magma pathways only at shallower depths (because of the relatively small collapse with respect to other cases previously studied with this approach (Maccaferri et al., 2017), c.f. Fig. 7, supplementary). We added these considerations in the discussion.

New (improved text):

Discussion section: *The hypothesis of the activation of two different feeding sources, cannot be supported – neither is in contrast – with our magma path simulations: in fact, our model cannot account for viscosity changes. Also, accounting for the mechanical coupling with a magmatic reservoir (not considered here) may not add further constraints, since the unloading and loading force distributions affect magma pathways only at shallower depths (because of the relatively small collapse volume with respect to other cases previously studied with this approach[14] (Supplementary Fig. 7).*

Nevertheless, an effect of unloading and loading stress on the activation (or inhibition) of reservoirs at depth, may be possible[10]. At the moment it is not clear for how long the effect of topographic loading may last, but given the regrowing load of the new cone is approaching pre-collapse conditions, we conjecture that also the stress relationship at depth may become close to the condition as it was before the 1956 sector collapse.

Line 322 – as noted above, the regrowth rates do appear to be remarkably rapid; but counter examples could also be cited, such as Augustine, Stromboli, Parinacota, and arguably more recently, reconstruction at Anak Krakatau.

Reply: We agree and therefore significantly improved the comparison to other cases and expanded the number of cited references. Our work focuses on andesitic Bezymianny volcano, which experienced dome growth activity, and almost restored its pre-collapse conical shape. That is why, in our opinion, Augustine (see reply above) and Stromboli are not very suitable examples for the comparison. The examples of Anak Krakatau and Parinacota were added to the manuscript.

Old text:
The Santiaguito lava dome complex at Santa Maria volcano has been formed since 1922. Santa Maria also experienced the distribution of eruptive centers with subsequent centralization at the Caliente vent (Harris et al., 2003). During the early stages of Santiaguito volcanism, endogenous and exogenous lava domes formed, followed by extrusion of lava spines, gradually changing to lava flow dominated regime today. Another volcano, Soufriere Hills, which after only 2-decades regained its conical shape after the 1997 collapse (Belousov et al., 2007), but the scale of collapse and regrowth is much smaller than at Bezymianny. For the majority of other volcanic edifices, the regrowth after catastrophic collapses takes thousands of years. For example, cone regrowth after sector collapse at Avachinsky volcano took 4-5 thousands of years (Masurenkov et al., 1991); at Colima volcano 4 thousands of years (Luhr et al., 1988) and at Merapi volcano about 1,900 years (Newhall, 2000).
New (improved text):
The Santiaguito dome complex at Santa Maria volcano has been formed since 1922, thus started 2-decades after the volcano collapse in 1902. During the early stages of volcanism, endogenous and exogenous lava domes formed at Santiaguito, gradually changing to lava flow dominated regime today[53]. Santiaguito also experienced the distribution of eruptive centers with a D_{max} of about 1,300 m and subsequent centralization at the (currently most active) Caliente vent[17]. On Montserrat Island, Soufriere Hills volcano regained its conical shape in 2-decades after the 1997 collapse[58], but the scale of the collapse and regrowth is much smaller than at Bezymianny. On Anak Krakatau (Indonesia), a stratocone was rebuilding after the 1883 catastrophic eruption, and had repeated collapses to the SW, most recently in December 2018[4]. For the majority of other basaltic-andesite and andesitic volcanoes, the post-collapse regrowth takes thousands of years. For example, cone regrowth after sector collapse at Avachinsky volcano (Russia) took 4,000-5,000 years[59], at Colima volcano (Mexico) 4,000 years[60], at Merapi volcano (Indonesia) about 1,900 years[61], and at Parinacota volcano about 2,000 years[18].

Reviewer #2:
The paper presents a very interesting material on the evolution of the volcanic cone of the Bezymianny volcano after the 1956 sector collapse. The fact that it was growing so fast and almost reached the pre-collapse altitude is an interesting story, which might appear to be attractive for a broad audience. For the part of the analysis of the photogrammetric analysis and interpretation, I do not have any concern. All the findings are clearly described and supported by numerous figures and supplementary materials. The methods for the analysis of pictures are well established and previously tested in different sites.

For me it was unexpected to learn that at the initial stage of re-growth, the lava material outpoured from several vents widely spread in the caldera. However, while growing the cone, they became less and less dispersed; and, finally, concentrated in an only one vent located on the cone’s summit. This is an interesting, but non-obvious observation that needs a physical explanation.

The authors provide a set of numerical models simulating the dome growth and the evolution of vents. I am not a specialist in numerical modeling and some argumentation provided by the authors appeared to me not sufficiently clear. I have a few questions that remained non-answered after careful reading of the manuscript. I apologize in advance if some of them will appear to be naïve. At the same time, if the article is oriented to the broad audience, these things should be explained very clearly. So my questions are following:

Reply: We thank the reviewer for his/her questions, answering them helped us to further improve our work and to sharpen where our model description was lacking clarity. We carefully expanded the model description and discussion accordingly, added a much more detailed description into the main text, clarified the figure and explained aspects that were outlined too briefly before. This way we could improve the manuscript considerably.

1. Is it a 2D or 3D modeling? In other words, do they model the dyke opening or isometrical conduits (like a pipe)?

Reply: We appreciate this comment and made appropriate changes. The model is 2D, but in plane-strain configuration, meaning that a magma-filled crack extends infinitely in the out-of-plane direction. This is a common approximation in fracture mechanics because the opening of the crack (~m) is about 3 orders of magnitude smaller than the lateral (out-of-plane) extension (~km). This means that in our model the intrusions are laminar (dyke-like) intrusions, and we look at a vertical cross-section of them. We pointed it out in the revised manuscript (in the Results section and in the Methods: "Magma pathway simulations").

New (improved text):
Results section: ***We use a 2D boundary element model to simulate magma propagation paths. Our model refers to the cross-section of a mixed-mode magma-filled crack in plain-strain approximation.***
Methods section: ***Magma pathways are modeled as 2D boundary element mixed-mode cracks in plane strain approximation. The modeling plane is perpendicular to the crack plane, therefore the model refers to a cross-section of the intrusion. The crack opening depends on assigned normal and shear stress boundary conditions that are the magma overpressure and the shear component of the topographic stress, respectively. The overpressure along the crack is given by the difference between the magma pressure and the confining stress (superposition of the lithostatic pressure and the normal component of the topographic stress).***

2. The authors propose that "magma pathways are governed by the background stresses". In my feeling, there are too many other factors that may have greater influence, such as inhomogeneities beneath the edifice including pre-existing geometry of previous conduits, gas and fluid distributions, plasticity/rigidity of the medium, pressure in the reservoir and many others. Can the authors estimate the role of these factors compared to the stress effect?

Reply: It is true that several factors may contribute to the propagation paths of the intrusions, and our statement: "magma pathways are governed by the background stresses" was misleading. We changed it (c.f. Results section, below): "Magma pathways are influenced by the local stress". Several studies (among which Maccaferri et al., 2010 and 2011, that used the same modelling approach used here), showed the effect of rock heterogeneities on the propagation paths of magma-filled cracks. However, what we show here (and consistently in a previous study with similar application, Maccaferri et al., 2017) is that the effect of the stress change due to large morphological changes at volcanoes, are able to explain some observations in term of relocation of vents. Surely, the contribution of rocks heterogeneities may add variability to our results, which are difficult to quantify, but should be discussed. We added these considerations in the revised manuscript.

New (improved text):
Results section: [...] ***magma pathways are influenced by the local stress, whereby changes in the direction of principal stress affect the favorite direction of propagation (see Fig. 7; Supplementary Fig. 6).***
Discussion section: [...] ***our numerical models necessarily simplify a much more complex system: several aspects may affect the propagation paths of magma, and their likelihood to feed eruptions. Among others, the interaction with rock heterogeneities, as well as changes in magma density and viscosity (due to degassing, for instance), were not considered in our simulations. While it is known that changes in the volcanic edifice loading may affect magma composition and eruptive style[10], we still know very little about the effect of magma viscosity***

on the propagation paths of magmatic intrusions[50]. The effect of these processes should be investigated with different modeling approaches, in order to achieve better insights on their relevance for the observations considered here. Nevertheless, a shift of post-collapse vent-locations has been observed at several volcanoes, and Bezymianny fits well within the trend previously shown in[14] (Supplementary Fig. 7), suggesting a common mechanism – related to the amount of mass redistribution – which may be primarily due to the local stress state induced by large topographic changes.

3. From the description, I do not understand how the conduits were modeled. There is a very short paragraph on this issue in L531-535 without any details. Was the crack opening simulated according to the hydrofracture mechanism? Or another simplified representation was used? This part needs more detailed description.

Reply: We appreciate this comment and made appropriate changes. The reviewer is correct, the crack opening is computed according to a hydrofracture mechanism. We clarified this point in the manuscript.

New (improved text):
Results section:* *We use a 2D boundary element model to simulate magma propagation paths. Our model refers to the cross-section of a mixed-mode magma-filled crack in plain-strain approximation. The most favorable direction for the magma pathway is computed iteratively, following the criterion of maximum energy release[14,47]. This approach is based on fracture mechanics principles, however, it neglects the dynamics of magma within the fracture so that it cannot account for magma viscosity[49]. Further detail on the modeling technique and assumptions are provided in the Method section.
Methods section:* *[...] The crack opening depends on assigned normal and shear stress boundary conditions that are the magma overpressure and the shear component of the topographic stress, respectively. The overpressure along the crack is given by the difference between the magma pressure and the confining stress (superposition of the lithostatic pressure and the normal component of the topographic stress).

4. What are the criteria when the conduit was considered open or closed? I do not understand the process, when some conduits originate at depths, but did not reach the surface. I do not see any mechanism to close cracks at shallow depths, where the lithostatic pressure is lower. I would expect an opposite effect.

Reply: The criteria used for crack opening depend on the magma overpressure with respect to the confining stress (lithostatic + background stress). The overpressure is provided by the buoyancy of magma, therefore it depends on the balance between confining stress gradient vs magma pressure gradient. The arrest of the propagation may occur (it is the case here) when the intrusion approaches a region with confining stress gradient that does not favor upward propagation (i.e. is not decreasing fast enough, due to the background stress contribution). Another reason for the arrest of a magmatic intrusion may be its deflection towards horizontal: in this case the (effective) buoyancy may not provide enough overpressure to allow further rupture of rocks. The balance between overpressure and confining stress gradient is considered in our model through the "energy release" criterion used to compute the propagation condition (Dahm, 2000). We included a more detailed description of the modelling technique in the "Data and Method section".

New (improved text):
Results section:* *[...] get arrested beneath the rim, because of higher compressive horizontal stress due to the rim topography and the horizontalization of some paths, which reduce the effective buoyancy of the intrusion
Methods section:* *The crack opening depends on assigned normal and shear stress boundary conditions that are the magma overpressure and the shear component of the topographic

stress, respectively. The overpressure along the crack is given by the difference between the magma pressure and the confining stress (superposition of the lithostatic pressure and the normal component of the topographic stress). Topographic stresses are computed using analytical formulas for loading and unloading forces at the surface of an elastic half-space[14,47,48]. Loading and unloading force distributions are used to model the loading of the pre-collapse volcanic edifice and the stress change induced by the flank collapse[14]. The model for the magmatic intrusion accounts for the magma buoyancy and compressibility, while it neglects magma viscosity. As a consequence, the magma overpressure profile within the crack is linear along the depth and proportional to the magma-rock density difference (hydrostatic overpressure profile). The trajectories within the crust are determined by testing the incremental elongation of the magma-filled crack in different directions. Our algorithm chooses the direction where the sum of elastic and gravitational energy release is maximal[47,48].

5. Why in the case of "Pre-Collapse", the topography load prevents reaching the conduits to the surface, whereas in another case of "Dome-Growth", the load by a dome intensifies the conduit forming compared to the no-loading "Post-Collapse" case? It appears to me not logic.

Reply: Our results for the "Post-Collapse" stress-scenario suggest that in this case the stress conditions are the most favorable for feeding eruptions within the collapse embayment. In this scenario the intrusions propagate along pathways which are relatively sparse and do not point to a common location at surface (Fig. 7a), as it would be for the "Dome-Growth" (Fig. 7b) and "Pre-Collapse" scenarios (supplementary Fig. 6). The direction of propagation here is influenced by the orientation of the maximum compressional stress direction, and the paths tend to follow the direction of maximum compression. However they may (or may not) reach the surface, depending on the compressional stress gradient and buoyancy (the buoyancy is decreased by the horizontalization of the intrusion). We explained this in the revised manuscript.

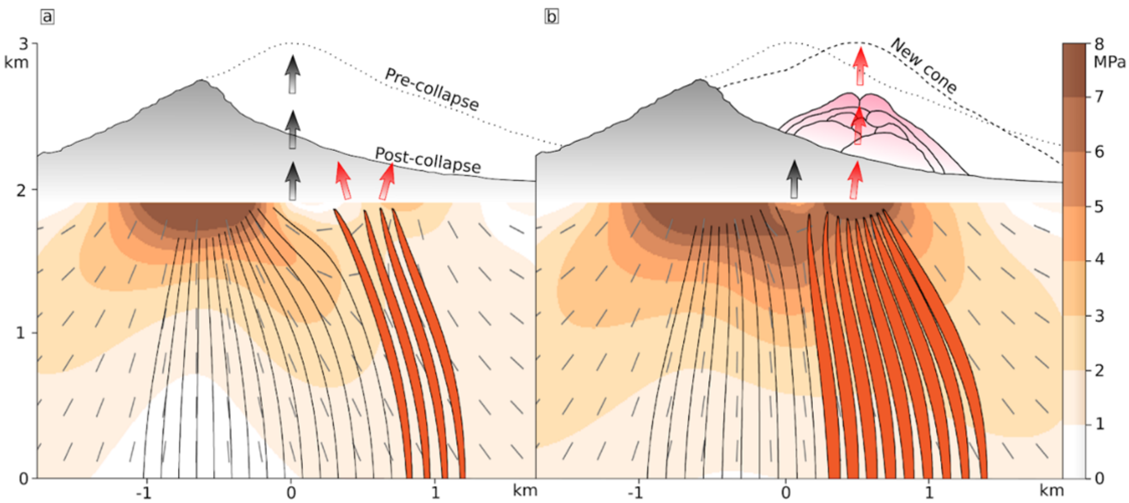
New (improved text):
***Figure 7 caption:* a Post collapse scenario: the pre-collapse vent location (white reverse triangle), appears to be inhibited (paths diverge to both sides away from it). The most favorable position for post-collapse vents is within the collapse embayment (red trajectories), because of collapse unloading forces. New vents may be shifted up to several hundreds of meters towards the collapse direction. b Regrowth scenario: more paths are deflected towards the collapse embayment, and they tend to converge towards the center of the loading force distribution associated with the new dome (gray trapezoid). Even though the compressive stress below the collapse embayment is increased by the new dome, it is still lower than the horizontal compression underneath the rim. A region of relatively lower compressive stress (paths highlighted in dark red), may represent a more favorable location for magma paths to intrude within the new dome.**
***Results section:* Our simulations for the post-collapse stress scenario results in magma paths that are rather scattered beneath the collapse embayment (highlighted in red in Fig. 7a). In contrast, the paths beneath the rim of the collapse scarp are more focused – pointing at the location of the rim – and get arrested beneath the rim, because of higher compressive horizontal stress due to the rim topography and the horizontalization of some paths, which reduce the effective buoyancy of the intrusion (black paths in Fig. 7a).**
[...] When considering a stress scenario that accounts for the regrowth of the central cone (Fig. 7b), the number of magma pathways rising towards the collapse amphitheater increases, and paths focus, pointing at the location of the center of the new load (Fig. 7b). The distribution of magma pathways beneath the regrowing edifice resembles the distribution of paths below the scarp rim, however, the compressive stress beneath the growing cone is still lower (as in this simulation the new dome topography did not reach the height of the scarp, yet). In addition, a zone of lower compressive stress persists between the two lobes of maximum horizontal compression (in $0<x<0.3$ km). Such a "corridor" of lower compressive stress may further help magma rising within the new cone (dark red path in Fig. 7b).

6. The presented models are intended to explain why just after forming the caldera, separate vents originate in a broad area, whereas after forming a large dome-cone there is only a single vent in the summit. However, from the presented description and figures, I did not understand the mechanism. It would possibly useful to illustrate this process with a conceptual cartoon and very simple words.

Reply: We agree that the previous Fig. 7 was lacking in clarity. We now changed Fig. 7 and Fig. 8 according to the reviewer comment including the representation of our simplified loading geometry (revised Fig. 7), and improving Fig. 8, consistently with the paths distributions obtained with our simulations. We also provided a summary of our simulation results and interpretation.

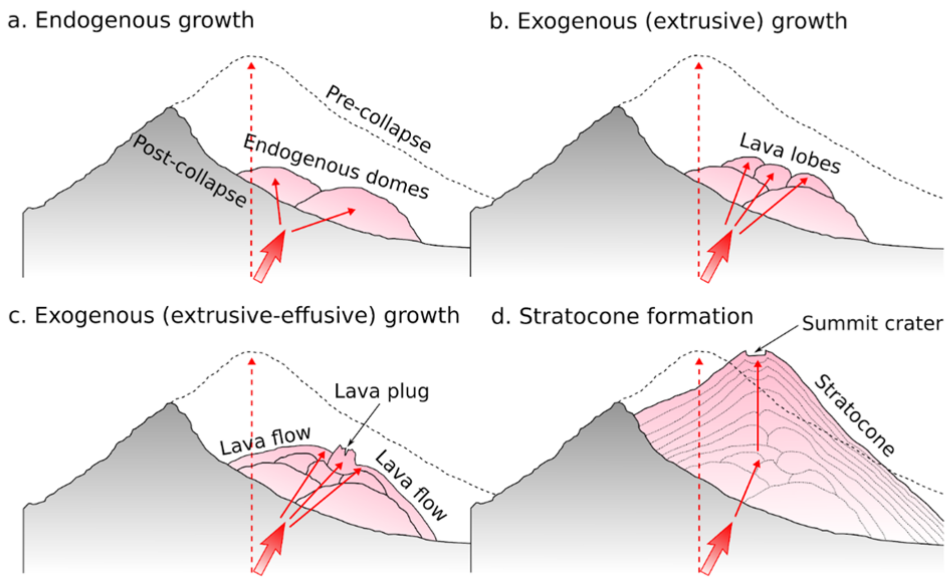
<u>Old Figure 6 and 8:</u>

Fig. 8: Modelling stress field changes and vent focusing during the Bezymianny volcano regrowth and modeled magma propagation pathways.



a, Topographic profile (direction WNW-ESE) of the post-collapse stage with new vent distribution. Lower figure indicates unloading stress (in MPa) and magma pathways, where red pathways represent those model solutions that can reach the upper boundary of the model (the base of the volcano). Note a shift of the new vents (red arrows) with respect to the vent location prior to the sector collapse (black arrows). b, Regrowing edifice shifted eastwardly further alters the loading. Red pathways represent those model solutions that can reach the upper boundary of the model (the base of the volcano). Note that the regrowth leads to convergence of pathways, and eventually focussing on the eruption vents to stabilize the growth of a stratocone.

Fig. 6: Main stages of Bezymianny regrowth.



a, 1956-1967 endogenous growth of two lava domes. b. 1967-1976 exogenous dome growth through the extrusion of lava lobes. c, 1977-2006 exogenous dome growth through lava lobes and lava plugs extrusion and lava flows emplacement. d, 2006 - present stratocone formation through interbedding deposition of lava flows and pyroclastic material.

New (improved Figure 7 and 8):

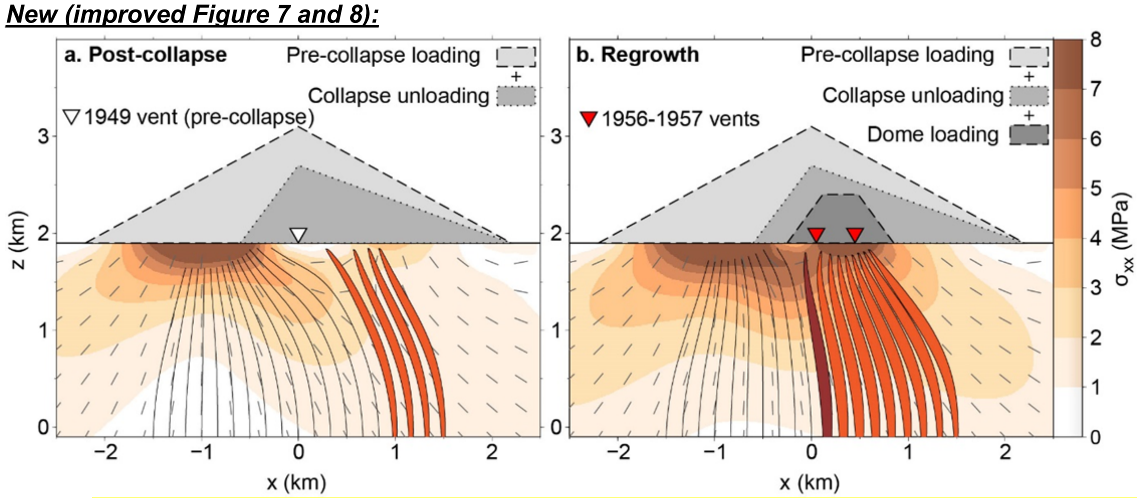


Fig. 7 Modeling stress field changes due to the Bezymianny collapse and regrowth, and associated magma pathways. Stress scenarios and simulated magma pathways on a WNW-ESE vertical cross-section of Bezymianny. The colored contours represent the horizontal stress due to the unloading and reloading force distributions that simulate the effect of edifice collapse and re-growth, respectively (gray triangles and trapezoid shades, respectively). Gray dashes indicate the direction of maximum compression. The trajectories and the shape of magmatic intrusions are plotted in red when they are deflected towards the collapse embayment. Magma pathways that converge towards the rim of the collapse scarp are marked by solid black lines. a Post collapse scenario: the pre-collapse vent location (white reverse triangle), appears to be inhibited (paths diverge to both sides away from it). The most favorable position for post-collapse vents is within the collapse embayment (red trajectories), because of collapse unloading forces. New vents may be shifted up to several hundreds of meters towards the collapse direction. b Regrowth scenario: more paths are deflected towards the collapse embayment, and they tend to converge towards the center of the loading force distribution associated with the new dome (gray trapezoid). Even though the compressive stress below the collapse embayment is increased by the new dome, it is still lower than the horizontal compression underneath the rim. A region of relatively lower compressive stress

(paths highlighted in dark red), may represent a more favorable location for magma paths to intrude within the new dome.

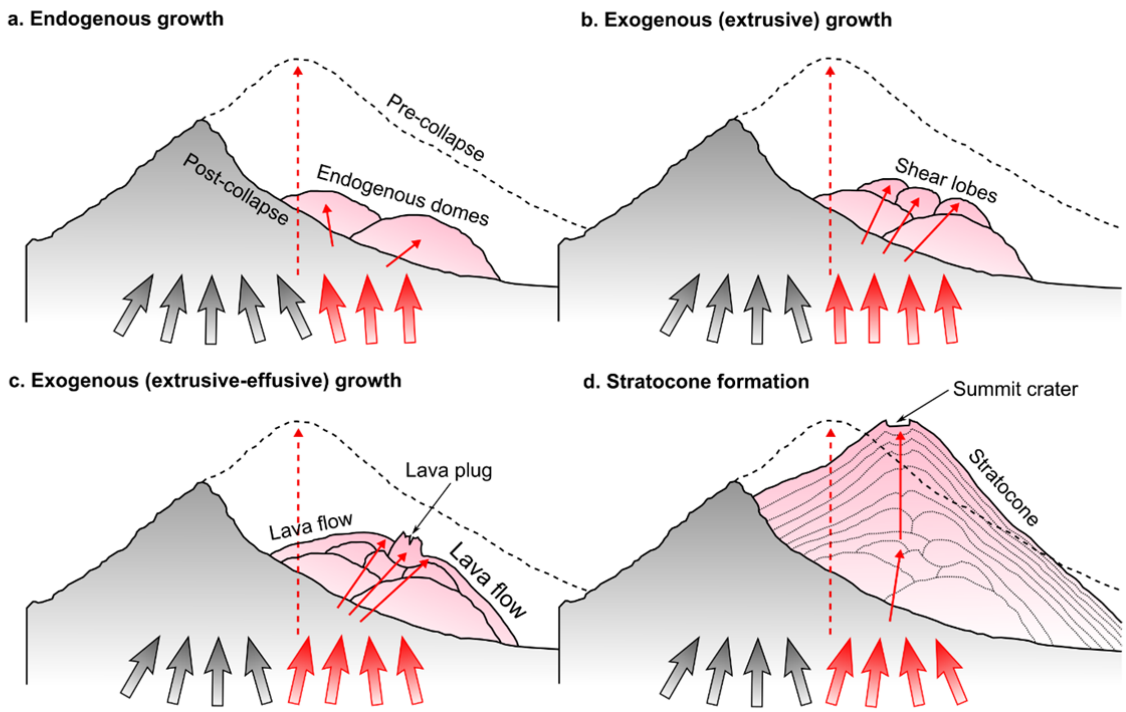


Fig. 8 Main stages of Bezymianny regrowth. a 1956-1967 endogenous growth of two lava domes. b 1967-1976 exogenous dome growth through the shear lobes extrusion. c 1977-2006 exogenous dome growth through shear lobes and lava plugs extrusion and lava flows effusion. d 2006 - present stratocone formation through interbedding deposition of lava flows and pyroclastic material.

New (improved text):
Results section: ***When considering a stress scenario that accounts for the regrowth of the central cone (Fig. 7b), the number of magma pathways rising towards the collapse amphitheater increases, and paths focus, pointing at the location of the center of the new load (Fig. 7b) [...] This is also in agreement with our observations, with vents progressively focusing towards the center of the new cone.***

7. While modeling the conduits with propagation of viscous andesitic magma, do the authors consider any degassing? As far as I know, most of eruptions of Bezymianny occur as short-lived explosions with ejection of a large amount of gases from the magmatic system. Obviously, gas dynamics should play a very important role in forming the conduits.

Reply: The reviewer is right, degassing processes would definitely play a major role within the conduit, particularly in the last hundreds of meters of magma rising, and would affect the likelihood and the style of an eruption. However, our modelling technique refer to the propagation path of deeper intrusions (the upper boundary for the simulation is the post-collapse embayment, that in the re-growth scenario correspond to 500 m below the summit of the new dome) and do not consider the magma propagation within the conduit that may feed an eruption. Nevertheless, degassing may be also important for our propagation paths, however our model cannot account for degassing (none of the models currently available for computing the trajectory of magmatic intrusions are able to consider the effect of degassing). We added this important point in the discussion.

New (improved text):
Discussion section:* [...] However, our numerical models necessarily simplify a much more complex system: several aspects may affect the propagation paths of magma, and their likelihood to feed eruptions. Among others, the interaction with rock heterogeneities, as well as changes in magma density and viscosity (due to degassing, for instance), were not considered in our simulations. While it is known that changes in the volcanic edifice loading may affect magma composition and eruptive style[10], we still know very little about the effect of magma viscosity on the propagation paths of magmatic intrusions[50]. The effect of these processes should be investigated with different modeling approaches, in order to achieve better insights on their relevance for the observations considered here. Nevertheless, a shift of post-collapse vent-locations has been observed at several volcanoes, and Bezymianny fits well within the trend previously shown in[14] (Supplementary Fig. 7), suggesting a common mechanism – related to the amount of mass redistribution – which may be primarily due to the local stress state induced by large topographic changes.

The authors state in L272-276 that shortly after reaching the initial shape, Bezymianny may collapse again. This is not supported by records of previous catastrophic explosions of Bezymianny. Every known large collapses, including ones in 1956 and in 2100 yrs BP, were preceded by more than 1000 years of quiescence. It means that growing the cone up to a certain height blocks the conduits and ceases any eruption activity for very long time. It would be interesting if the authors could consider this scenario in their modeling.

Reply: We thank the reviewer for this useful comment. The observation that volcano collapses re-occur into the same direction, with similar geometry and volcano loading, is based on observations of collapsed volcanoes elsewhere as well based on modelling. Therefore, a volcano can grow only to certain heights before it collapses again. Previous research describe the process of regrowth to be cyclic, where at many volcanoes the collapse of a sector has similar dimensions and occurs on similar sliding plane after the regrowing edifice is reaching similar heights (Siebert et al.,1995; Cantagrel et al., 1999; Urgeles et al., 1999; Tibaldi, 2001; Le Friant et al., 2003; Voight and Elsworth, 1997; Walter and Schmincke, 2002; Acocella, 2005). If such a scenario is valid for Bezymianny, the condition of reloading may be reached when the new cone reaches a volume approaching the earlier pre-1956 cone. Subject to debate is then what finally provides the final push for the collapse, whether new intrusions and/or earthquakes (as occurred at Mount St. Helens, 1980 or at Anak Krakatau, 2018). Therefore the next collapse of Bezymianny may depend on several other factors besides gravitational loading, and, of course, it is necessary to consider the eruptive history of the volcano. The prediction was rewritten in accordance with the previous tephrochronology research at Bezymianny (Braitseva et al., 1991).

Old text:
The process of regrowth may be cyclic; when the new cone reaches a volume approaching the earlier pre-1956 cone, it may produce another partial or complete collapse in 10-15 years from today, so that the cycle will restart. Similar cycles have occurred at Bezymianny before, as indicated by remnants of scars and deposits that pre-date the current edifice(Braitseva et al, 1991).
New (improved text):
Since Bezymianny almost gained the pre-1956 collapse height, a new catastrophic collapse might be prone[21,26]. During the Holocene, Bezymianny repeatedly produced large-volume pyroclastic flows up to 0.3-0.4 km[3 39] that may indicate the occurrence of large destructive events. However, each of those powerful eruptions were followed by a long period of effusive and moderate explosive activity that lasted from hundreds to thousands of years[39]. The last destructive episode before 1956, was associated with partial flank collapses that left behind two noticeable scars on the western and eastern flanks[34], yet their extent is not even close to that of the 1956 (Fig. 1c,e). Moreover, since the 1956 collapse was preceded by a long period of quietness[39] and was triggered by intrusion of a cryptodome (i.e. shallow magma body destabilizing the strength of the edifice)[32], we cannot say whether the next catastrophic edifice

collapse will occur shortly after reaching the pre-collapse size. What we can say, is that if the current activity will go on (the latest two eruptions occurred in 2019), causing further steepening of the flanks, the volcano's upper slopes may eventually partially collapse, even in the near future. This clearly poses a hazard to the visitors of Bezymianny. Furthermore, the area of the potential hazard has increased since 2017, when the northern and southern sectors of the amphitheater rim were covered with pyroclastics, which led to an unhindered inflow of eruptive material towards the northern and southern feet of the volcano.

Reviewer #3:
The manuscript "The rebirth and evolution of Bezymianny volcano after the 1956 sector collapse" by Shevchenko et al. concerns the edifice regrowth and evolution of Bezymianny, after the 1956 eruption where the volcano experienced a sector collapse. This includes near-decadal mapping of the amphitheater including mapping the endogenous and extrusive dome growth and subsequent lava flow emplacement.
This analysis is based on a combination of photogrammetry based on aerial, satellite and drone data as well as numerical modeling examining the effect of unloading due to the collapse of the edifice and subsequent reloading associated with the regrowth of the stratocone. Overall the data and analysis is sound and well-presented.
This study reveal undoubtedly a very important time-series, that provides unique insight to the regrowth of a volcano as well as documentation for the hypothesis about vent migration caused by sector collapse put forward based on numerical unloading models by Maccaferri et al. (2017). By doing so the authors make an important contribution in order to understand and forecast how volcanic activity and vent location may change as volcanic activity resume after a sector collapse. Thus, this study clearly of interest for a wide volcanic community and deserves publication after a number of issues has been addressed:

Reply: We thank the reviewer for the highly useful comments, which helped to improve the manuscript.

1) The method description need improvement since some information is lacking. This includes:
• New section with description of morphological mapping, especially specification of how the authors distinguish between endogenous and exogeneous domes and lava flows. How is this done based on the aerial photographs and DEMs, or does this information stem from other sources?

Reply: We appreciate this comment, and significantly improved the method description. Morphological mapping was performed by the visual interpretation of the high-resolution stereoscopic aerial images in anaglyph mode using Stereo Analyst module of Erdas Imagine. This method allows an operator, wearing anaglyph glasses, to see detailed morphology of the studied object in 3D and perform all measurements of the identified features. Each stereoscopic image was carefully compared to the next one to trace the same features and to understand their development or decay. The results of the interpretation of the dome's features are based on the own experience in the area of long-term observations of dome growths at andesitic volcanoes using commonly accepted classification of volcanic landforms and their elements (Sigurdsson et al., 2015; Williams, 1979; Fink et al., 1990; Schminke, 2004), which reveal the nature and sequence of their formation. The endogenous growth was distinguished from exogenous growth by a presence of separate shear lobe extrusions from the vents located on the top of the dome. The lava flows were distinguished by their low thicknesses (from 15 to 30 m), and length to width ratios (from 1.8 to 5.1 m) in comparison to the thick (from 60 to 110 m) and almost circle-symmetrical shear lobes. Morphologically lava flows differ from shear lobes having a drop shape; their vent parts are narrower than fronts. There are also differences in the directions of spreading: lava flows usually spread down the slope, and shear lobes at

Bezymianny spread in all directions from the vent. The lava plugs were identified as cylindrical bodies extruded at the vents part of the previously emplaced lava flows.

New (improved text):
Morphological mapping
To map the features of the Bezymianny new edifice we performed visual interpretation of the high-resolution stereoscopic aerial images in anaglyph mode using the Stereo Analyst module of Erdas Imagine. This method allows an operator, wearing anaglyph glasses, to see the detailed morphology of the studied object in 3D and perform all measurements of the identified features. Each stereoscopic image was carefully compared to the next one to trace the same features and to analyze their development or decay. The results of the interpretation of the dome's features are based on commonly accepted classification of volcanic landforms and their elements[43,70], which reveals the nature and sequence of their formation. The exogenous growth was distinguished from the former endogenous growth by a presence of separate shear lobes, which extruded from the vents or open craters at the different sectors of the dome. The lava flows were recognized by their low thicknesses (from 15 to 30 m), and length to width ratios (from 1.8 to 2.1) in comparison to the thick (from 60 to 110 m) and almost circle-symmetrical shear lobes. Morphologically lava flows differ from shear lobes having a drop shape; their near-vent parts are narrower and thinner than fronts, while shear lobes have the highest thickness at their top and near-vent parts. There are also differences in the directions of deposition: lava flows usually spread towards the foot of the dome, and shear lobes at Bezymianny usually accumulated at the place of extrusion. The lava plugs were identified as cylindrical bodies extruded at the vent areas of the previously emplaced lava flows. After the stereoscopic interpretation, the elements of the dome were easily identified on the hillshade visualizations of the DEMs and were outlined and shown with different colors (Fig. 3,4,5).

• Description of volume estimates. How were the added and removed volumes estimated. How do you constrain whether an area both have experienced removal and growth within an acquisition? Or do you assume that areas that experience growth have not experienced removal and vice versa? Such assumption should be mentioned here. What exactly is included in the dome/cone volume and area (include a schematic figure)? How were the volumes from 1956-67 obtained when your base is the 1949 DEM (thus you both have sector collapse and activity from 1956-67 in your DDEM)?

Reply: The CloudCompare software allowed automatic estimation of the added and removed volumes by comparing two surfaces (See height difference map in Supplementary Fig. 5). To avoid additional errors, we estimated volumes only within the areas of the dome (Tab. 1; Supplementary Fig. 4). CloudCompare provides the possibility to preselect an area for volumetric comparison. Each time comparing the consecutive DEMs, we outlined a clearly visible border between the dome's feet and the amphitheater's inner walls on both DEMs relatively to the later one.

The volume of the dome over the 1956-1967 period as well as the post-collapse base were calculated in previous research (Seleznev et al., 1984). To estimate the base elevation and shape of the collapse amphitheater, which was the base surface for the volume calculation, the 1956 ground-based images (Fig. 1e) were used, which were taken in a few months after the emergence of the first dome when it occupied a small area of the amphitheater's floor. The elevation of the base was estimated to be at about 2,200 m, and the vertical sections of the amphitheater across the collapse direction were close to parabolic. The amphitheater inner walls in the 1967 elevation model were extrapolated according to the estimated parameters (Seleznev et al., 1984).

This information was added to the Methods part.

Old text:
To quantify changes throughout the evolution of Bezymianny's new edifice, we calculated volumetric changes between consecutive DEMs with the 2.5D volume calculation tool in

CloudCompare. Since material may be added (e.g., intrusions, lava and tephra deposition) and/or removed (e.g., erosion, explosive excavation) during growth, volume differences may be represented by positive and negative changes that yield in a net volume change. The positive changes were then used to determine extrusion rates by dividing the volume by the time interval between the dates of the survey.

New (improved text):

The post-collapse topography was estimated in previous research[34] from the 1956 ground-based images, which were taken when the first dome occupied a small area of the amphitheater's floor (Fig. 1e). The base of the amphitheater was estimated to be ~2,200 m above sea level, and its vertical sections across the collapse direction appeared to be close to parabolic. The amphitheater inner walls in the 1967 elevation model were extrapolated according to the estimated parameters[34]...

... To quantify changes throughout the evolution of Bezymianny's new edifice, we calculated volumetric changes between consecutive DEMs with the 2.5D volume calculation tool in CloudCompare, which allowed us to automatically estimate the added and removed volumes by comparing two surfaces. Since material may be added (e.g., intrusions, lava, pyroclastics, and tephra deposition) and/or removed (e.g., erosion, explosive excavation, small flank collapses deposited outside the area of the dome) during growth, volume differences may be represented by positive and negative changes that yield in a net volume change. The positive changes were then used to determine growth rates by dividing the volume by the time interval between the dates of the survey.

The volume of the dome over the 1956-1967 period was calculated in previous research[34]. The 1967-2017 volumes were estimated only within the areas affected by the eruption (dome areas) (Tab. 1). CloudCompare provides a possibility to preselect an area for volumetric comparison. Each time comparing consecutive DEMs, we outlined a clearly visible border between the dome's feet and the amphitheater's inner walls on both DEMs relatively to the later one.

• Could volume changes be categorized into dome growth (intrusive and exogenous), lava flow, pyroclastic deposition etc. based on the morphological mapping? Dividing the volume into dome, lava flows, pyroclastics etc, could be very relevant for hazard perspective (see e.g. Fink et al., 1990).

Reply: We appreciate this comment, but the main goal of this work is to show the main successive stages of the new stratocone formation and the main morphological features of each stage. We tried to achieve this goal by processing materials from 8 aerial surveys and one satellite dataset. Currently, we have already begun to process data of at least another 50 aerial surveys that we have (shown in Fig. 1 in the Supplementary Information). These materials cover almost all volcanic eruptions that occurred in the period from 1967 until 2018. The photogrammetric processing will allow us to accurately restore in numbers and visualizations the details and consequences of almost all the eruptions, as it was done for Mount St. Helens in (Fink et al., 1990). In further research we will estimate the volumes and sizes of all shear lobes, collapse scars, lava flows, pyroclastic flows, deformations, which occurred in different parts of the dome, and perform a hazard assessment. But this work would take about several more years due to the lack of specialists in archive aerial images processing.

Currently, we can't perform volume calculation of the separate features of the dome as we don't have the underlying surfaces due to the low frequency of the processed datasets.

• The description on error estimation of the volume estimates is at places hard to follow and need a bit more explanations. Furthermore error should be included in table 1 as in suppl. Fig. 2-4.

Reply: The error estimation subsection was rewritten in more details. The 2017 volume error value in the text didn't match the table, because it consists of several

components including the alignment error component in the volume error. It was clarified in the text and added to Supplementary Tab. 1. The growth rate errors bars were added to the new Fig. 9, and to Supplementary Fig. 3. It is not possible to add error bars for volume calculations into the graphs, because they are not visible in this scale.

Old text:

The volume estimation errors (Supplementary Tab. 3) in this study mainly depend on the triangulation error (TRMSE), which we obtain from Erdas Imagine and Photomod triangulation reports. Possible sources of the TRMSE can be camera lens optical distortion, old analog films deformation, scanner distortion, manual GCPs assignment, and atmospheric conditions. Furthermore, the resolution of the extracted point clouds and manual points extraction also contribute to the volume error. Finally, the RMSE of the point clouds alignment (ARMSE) affects the volume estimation accuracy.

As Bezymianny's dome/cone is relatively round-symmetric, an XY shift of a DEM surface doesn't contribute to the volume error as much as the Z shift. Thus, we consider only Z triangulation errors and distribute them over the area affected by the eruption (dome area) at each date of the survey. Depending on triangulation errors, the volume uncertainty varies from 0.8 million to 3.2 million m3 (0.1 to 1.4%) of the total dome volume.

To estimate volume uncertainty caused by point clouds resolution and manual points extraction we used calculation according to(Lane et al., 2003). The precision of manual point picking in Photonmod is ~0.3 m. The amount of points within the area affected by eruption varies from 50,000 to 300,000 with the 2 to 5 m mean distances. In this case, the uncertainties in volumes are less than 10,000 m3 and might not be taken into account.

As the 2017 DEM was combined from the two point clouds (Pleiades and UAV) with the 0.8 m RMSE in alignment, we distributed this error over the area of the aligned UAV point cloud. The contribution of this ARMSE to the 2017 volume estimation is 360,000 m3 (0.06%).

To avoid the alignment errors, volumes for the aerial DEMs were derived from initial point clouds (unaligned to the 2017 Pleiades-drone point cloud). Only for the 2017 volume estimation, we used the base surface from 2013 aligned to the 2017 point cloud. The 2013-2017 ARMSE (1.3 m) extending to the area affected by eruption contributes 2,900,000 m3 (0.49%) to the volume error.

The extrusion rates were estimated by dividing the volumes by the time interval between the dates of the survey. The errors of the rates were determined on the basis of root sum squared volume errors for neighboring dates and the time interval between them. The smallest errors of the rates (2.1-4.3%) turned out to be for the periods between 1968-1976, 1982-1994, 1994-2006 measurements but this is only due to the length of these periods with a very high averaging of these values. The largest relative rates error (31.2%) occurs for the interval 1967-1968 due to the small increase in the volume, which is almost equal to the absolute values of the volume estimation error.

New (improved text):

The volume estimation errors (Supplementary Tab. 1) in this study mainly depend on the triangulation errors (TRMSE), which are calculated automatically in Erdas Imagine and presented in the triangulation reports. Possible sources of the TRMSE can be camera lens optical distortion, deformation of old analog films, scanner distortion, and manual GCPs assignment. Furthermore, the resolution of the extracted point clouds can also contribute to the volume error. Finally, the RMSE of the point clouds alignment (ARMSE) affects the volume estimation accuracy.

As Bezymianny's dome is relatively circular symmetric, a slight XY shift of a DEM doesn't contribute to the volume error as much as Z shift, since a volume adding at one side of the dome is compensated by the same amount of volume removed from the other side. Thus, we consider only Z triangulation errors. To determine the contribution of the triangulation errors in volume estimation, we distributed each TRMSE Z value over the respective area affected by eruption (dome area) (Tab. 1) similar to[31]. Depending on the TRMSEs, volume uncertainty varies from 0.5 million m^3 (in 2017) to 3.2 million m^3 (in 1967) that is 0.1 – 1.4 % of the dome volume.

To estimate volume uncertainty caused by point clouds resolution we used equation (14) from[68]. The base parameters for the calculation are the mean distance between points in each cloud, which varies from 2 m (in 2017) to 7 m (in 1977 and 2006), and the standard

deviation of the error in the spatially distributed points, which varies from 0.2 m (in 2017) to 0.5 m (in 1967 and 1968). The uncertainties in volume increase between two consecutive point clouds vary from 3,900 m^3 (in 2017) to 7,900 m^3 (in 1982) that is less than 0.001 % from the dome volume and might not be taken into account.

As the 2017 DEM was combined from the two point clouds (Pleiades and UAV) with the 0.8 m RMSE in alignment, we distributed this error over the area of the aligned UAV point cloud (430,000 m^3). The contribution of this ARMSE to the 2017 volume estimation is 344,000 m^3 (0.06%). The 2013-2017 point clouds alignment RMSE (1.3 m) distributed over the 2017 cone area contributes 2,900,000 m^3 (0.5%) to the volume error. Thus, the total ARMSE contribution in the 2017 cone volume is 0.6%, and the total 2017 volume error is 0.7 % (Supplementary Tab. 1).

The errors of the growth rates were calculated by dividing the root sum squared volume errors for neighboring dates by the time between them. This model of inaccuracy[69] was used because errors at different dates have an equal effect and are independent of each other. The smallest errors of the rates (2.1-4.3%) turned out to be for the periods between 1968-1976, 1982-1994, 1994-2006 because of their longer length and, thus, a high averaging of the values. The largest relative rate error (31.2%) occurs for the interval 1967-1968 due to the small increase in the volume, which is almost equal to the absolute values of the volume estimation error.

• Modeling of magma path distribution: It is unclear to me if the effective volcanic loading used the volume estimates obtained from table 1 for (a) unloading due to sector collapse and for (b) loading by regrowth? This should be clear if the volume estimates have been used for the modelling. Furthermore does the volume unloading fit Maccaferri et al., 2017 model of relocation? It would also be appropriate to discuss if the pre-set boundary conditions make sense with respect to the suggested magma plumbing (2 magma chambers in 7 and 18 km depth).

Reply: We thank the reviewer for the useful remark. The unloading and loading force distributions used to simulate the effect of the sector collapse and the dome re-growth are based on morphological observations. However, since the model is 2D we had to refer to the cross section of the topographic changes (profiles in Fig. 6), rather than the volumes. We clarify this point in the revised manuscript (please refer to the "new text" below).

The "collapsed-volume vs vent-shift" at Bezymianny fits with the observations collected in Maccaferri et al., 2017, we thank the reviewer for pointing this out. We commented this in the text, and we show it in a supplementary figure (supplementary Fig. 7).

We improved the description of our boundary conditions, and model domain, and discussed their implications within the discussion of magma reservoir depth (c.f. "new text" below).

New (improved text):

Results section:* *These force distributions have simplified shapes based on the profiles in Fig. 6c (triangles and trapezoids in Fig. 7). Magma paths start vertically, from the base of the model domain (z=-0.1 km), within a 3 km wide region centered below the summit of the pre-collapse edifice (-1.5 < x < 1.5 km). We choose the depth and extension of the region from where the intrusions start, in order to cover the whole area affected by the stress changes associated with the morphological changes we study. This area should not be considered as the location of a magmatic reservoir (which should be deeper at Bezymianny, c.f. Discussion section). Rather, our assumption is that an intrusion would rise from deeper depths and enter vertically our model domain. These models, although being highly simplified in terms of topographic geometry and magma dynamics, are constrained by the Bezymianny morphologies as summarized in in Fig. 6c, and the resulting magma paths can be compared with observations of post-collapse vent-shift and the final vent focusing.

Discussion section:* *The hypothesis of the activation of two different feeding sources, cannot be supported – neither is in contrast – with our magma path simulations: in fact, our model cannot account for viscosity changes. Also, accounting for the mechanical coupling with a

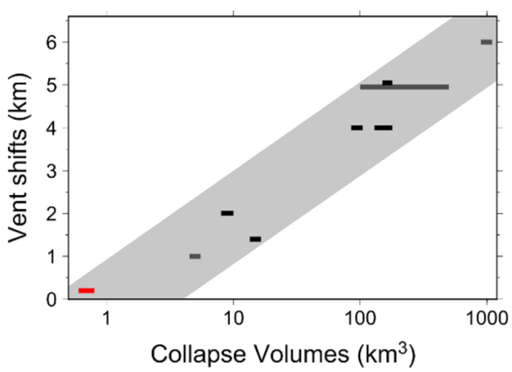
magmatic reservoir (not considered here) may not add further constraints, since the unloading and loading force distributions affect magma pathways only at shallower depths (because of the relatively small collapse volume with respect to other cases previously studied with this approach[14] (Supplementary Fig. 7).

<u>Methods section:</u> Pre-collapse scenario: We consider the loading due to the pre-collapse volcanic edifice based on the pre-collapse profile (black solid line) in Fig. 6c.

[...] We assume that during the emplacement of the pre-collapse edifice, non-elastic effects may have partially released elastic stress, this is accounted by testing different "Effective Volcanic Loading" (EVL)[14]. Conversely the flank collapse and the dome growth are very recent events, and therefore we consider them as "purely elastic"[14]. Different values of EVL were tested [0.5 – 0.6 – 0.7], meaning that 50%, 40%, and 30% of the elastic loading had been released at the time of the collapse[14]. We used the triangular difference approach to simulate the stress relaxation: "Trapezoidal Loading" in[14].

[...] Post-collapse scenario: We introduce the unloading force distribution simulating the flank collapse (superposed on the stress due to the pre-collapse edifice). Here we used a simple triangular profile to approximate the effect of the collapse. The maximum height of the unloading is Hpoc=0.8 km (in x=0), the base of the unloading is Wpoc=2.8 km, from x=-0.6 km to x=2.2 km. These geometrical constraints are based on the difference between the pre-collapse and post-collapse profiles in Fig. 6c (black solid and dashed lines, respectively).

[...] Regrowth scenario: The re-loading due to dome growth is introduced. We used a trapezoidal shape for the dome. Based on the 1956-1967 profile of Fig. 6c (first phase of dome growth), the trapezoid has a height Hdg=0.5 km, with a lower-base Wdg=1.1 km (from x=-0.25 km to x=0.85 km) and an upper-base Wdg=0.37 km.



Supplementary Fig. 7. Vent shifts vs. collapse volumes, modified from[14]. The vent shifts between the center of pre-collapse volcanism and the location of post-collapse volcanism is plotted as a function of the collapsed volumes. All shifts occurred towards the collapsed flank. Black segments refer to volcanoes with no evidence of shallow reservoirs, grey segments refer to volcanoes where shallow reservoirs exist, and the red segment refers to Bezymianny 1956 collapse.

2) Strengthening of the discussion. The authors have a unique opportunity to synthesize data sets in the discussion combining phases of activity, eruption volumes and extrusion rates, vent changes, geochemical data and plumbing system. This is eluded to in very general terms, but it seems like the full potential of their data and the existing ancillary information is not fully exploited.

Reply: We appreciate this comment and tried to strengthen the discussion according to it.

• In the current discussion, it is argued that the eruption rates does not affect the activity and the reader has to consult table 1, look at individual numbers, combine it with fig. 8 and find the right time periods for the main stages. Similarly the reader themselves have to dig up the geochemical changes through the last 7 decades and try to plot them according to activity. This part of the discussion would be improved significantly by combining the model of the

main stages of Bezymianny with cumulative volume graph, extrusion rates, vent changes and geochemistry.
This can be done in a new figure 8 consisting of four panels: a) x, y graph (with 2 y-axis) displaying cumulative volume and extrusion rate as a function of time b) Illustration of regrowth from fig. 8 plotting according to the time periods; c) Vent concentration graph and d) geochemical data.

Reply: We thank the reviewer, but it is difficult to combine the four graphs: dome volume, growth rate, SiO_2 content, and vents focussing with the conceptual model figure (Fig. 8). We decided to show the graphs in the separate figure (Fig. 9) marking the main stages of regrowth with different colours in the graphs.

New figure:

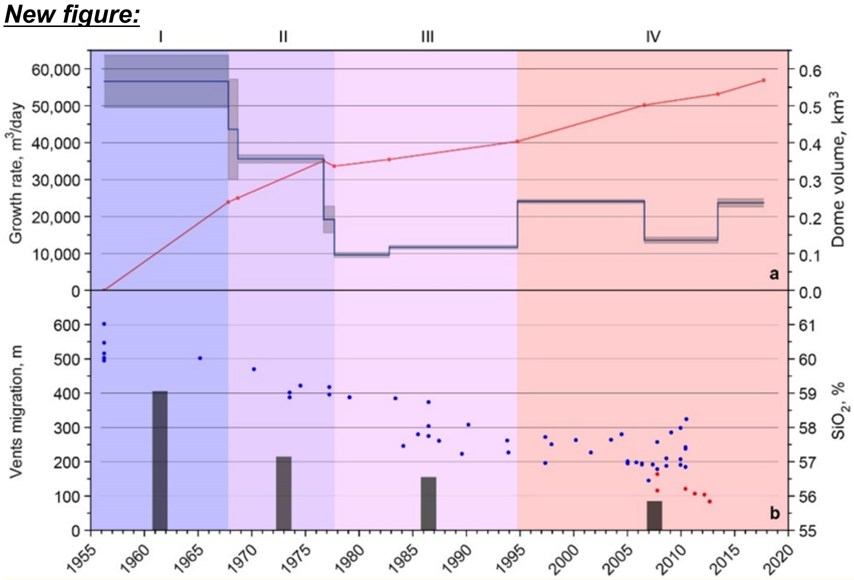


Fig. 9 Temporal evolution of the Bezymianny volcano characteristics in 1956-2017. a Dome volume (red line) and growth rate (blue line) changes. Gray transparent bars indicate ranges of the eruption rates uncertainties of 2.1-31.2 % related to inaccuracies in photogrammetric processing and DEMs alignment (see Tab. 1; Supplementary Tab. 1; and Error estimation section in Data and Methods). b Range of vents migration (black bars) at the different stages of regrowth and changes in SiO_2 content (blue dots from[37] and red dots from[56]). I - IV - stages of regrowth: I - endogenous, II - exogenous (extrusive), III - exogenous (extrusive-effusive), IV - stratocone formation.

• The current discussion does compare to other cases of volcanic regrowth. However, there are no comparisons of degree of unloading, cumulative volume, extrusion rates, or vent shifts which could be very helpful parameters to broaden the discussion and make the Bezymianny-case more applicable to other sector collapses. It would be logical to compare to e.g. fig. 6a in Maccaferri et al., 2017 as well as discuss the case of Mt Helens where good volumetric and extrusion rates exists.

Reply: We appreciate this comment and did comparison with Fig. 6a in Maccaferri et al., 2017 in Supplementary Fig. 7. We also compared our results on the growth rates to the available rates for Shiveluch, Santa Maria, and St. Helens volcanoes. The maximum distance between vents at Santa Maria was also added to the discussion part.

New (improved text):
During Bezymianny's edifice reconstruction, the growth rate decreased noticeably from an initial ~56,000 m^3/day (1956-1967) to 33,000 m^3/day (1967-1977) and then to 15,500-17,000

m^3/day (1977-2017). The constant growth rates coincided with the occurrence of lava flow emplacements that successively covered the older dome complex. We conjecture that the lava flows may have acted as an armor preventing partial flank collapses and stabilizing the new edifice, which eventually facilitated the formation of a stable centralized vent through gradual load increase. Thick and unevenly distributed shear lobes, in turn, may contribute to slope instability leading to partial dome collapses, as was observed at Bezymianny in 1985[51] and frequently at Shiveluch[52].

Similar to Bezymianny, the post-collapse dome growth at Shiveluch during the 1980-1981 extrusive period was characterized by an initially higher rate of 186,000 m^3/day that later decreased to ~60,000 m^3/day[19]. Over the 2001-2012 period of Shiveluch regrowth, the initial rate of resumed extrusive activity was 700,000 m^3/day that gradually decreased to 150,000 m^3/day[52]. After the collapse of Santa Maria volcano, regrowth of Santiaguito dome complex was characterized by multiple episodes[53], the highest rate 178,000 m^3/day was also observed during the first post-collapse episode in 1922-1925. Further the growth of each new dome began with a 3-5-year period of high rate (50,000-130,000 m^3/day), followed by a decrease to ≤16,000 m^3/day for up to 11 years[17]. During eruptive cycles at Mount St. Helens, decreasing of a higher initial rate was also observed. Over the 1980-1986 period, the average rate until 1983 was 370,000 m^3/day been then decreased to 78,000 m^3/day[54]. During the 2004-2008 period, the initial rates were in the range of 110,000-450,000 m^3/day until mid-2005, and then decreased to 26,000-78,000 m^3/day[55].

In general, the long-term average growth rate of Bezymianny's new edifice (26,400 m^3/day) is comparable to rates of Mount St. Helens during the 1980-1986 eruptive cycle (30,000 m^3/day)[54] and Santa Maria in 1922-2000 (38,000 m^3/day)[17] but notably lower than that of Mount St. Helens in 2004-2008 (173,000 m^3/day)[31] and Shiveluch in 2001-2012 (225,000 m^3/day)[52]. Yet, the dome growth evolution of Mount St. Helens and Shiveluch does not show any trend towards the formation of a stratocone. This may be due to intermittent dome growth episodes (Mount St. Helens), the prevalence of destructive over constructive processes (Shiveluch), and/or because these volcanoes have not produced any lower viscosity lava flows that covered and thus stabilized the dome. For Bezymianny we argue that the transition from the extrusion of shear lobes to the effusion of lava flows in 1977-2006 may mirror a contemporaneous decrease of the viscosity of its eruptive products…

…Santiaguito also experienced the distribution of eruptive centers with a D_{max} of about 1,300 m and subsequent centralization at the (currently most active) Caliente vent[17].

3) The text itself need it improvement:

• Precision and simplification of language would benefit the manuscript. The language is at places unclear, convoluted and/or unprecise due to different issues:

- Change from past to present tense (see detailed comments)

- Unnecessary redundancy: E.g. “conical shape, morphologically described by its circularity”

- Convoluted sentence such as E.g. “extension of exogenous growth is documented in 1968” which simply could be expressed as “the exogenous dome continue to grow in 1968” or “Decades-long repeat photogrammetric data acquisition” instead of “Repeated decadal acquisition of photogrammetric data”

- Overall it seemed that the authors were using American English over British English (e.g. using “color” and not “colour”), but there are example of British spelling such as “focussing” instead of focusing. Please be consistent either choosing American English or British English

Reply: We thank the reviewer for the comments and tried to improve the text writing by correcting the tenses, reducing repetitions, and using American English.

• Ambiguous terminology/phrases:

- Authors refer to the length of the time series as: 7 decades, 6 decades and near-7 decades. Please be consistent.

Reply: We appreciated this comment and changed the time interval to 7 decades of observations (1949-2017).

- The terminology for volcanic products can be simplified, which will help the reader. Currently the following terms are used: endogenous (protrusive) dome growth, exogenous (extrusive) dome growth, which as far as I can see is used interchangeable with the term lava lobes and then finally effusive lava flows. The term effusive is a bit confusing since, dome growth also can be effusive, so what about simplifying and these terms and just call them endogenous dome, exogenous dome and lava flows? That way you also avoid confusing using lava lobe, which also typically is used as the smallest unit of a lava flow.

Reply: We appreciate this comment, but we suggest that the terminology that we use in this work is the most suitable to describe the post-collapse evolution of Bezymianny. We changed the term "lava lobe" to more specific "shear lobe" to emphasize high viscosity of these dome elements (Sigurdsson et al., 2015). Other terms we also use in accordance with the recent edition of Encyclopedia of Volcanoes (Sigurdsson et al., 2015):

Endogenous growth - enlargement of a lava dome due to influx of magma into the dome interior.

Exogenous growth - enlargement of a lava dome due to discrete lobes of lava being emplaced at the surface or above each other.

Shear lobe - a large, often arcuate shaped, body of solid lava extruded through a vent or exogenously through the carapace of a dome.

Plug - a body of near-solid magma within the conduit, the upward movement of which is characterized by strain localized along or near the conduit margin.

The dome growth could be endogenous (protrusive or intrusive) and exogenous (extrusive and effusive). We see that Bezymianny has undergone clearly defined stages: classical endogenous growth, exogenous growth through thick shear lobes extrusion (thickness from 60 m to 110 m, circular-symmetric shape), and exogenous growth through thin and long lava flows effusion (thickness is 15-20 m; length to width ratio is from 1.8 to 2.1). The distinction between shear lobe extrusion and lava flow effusion is necessary because lowering in viscosity and lava flow occurrence is one of the main factors for a stratocone formation. There is currently quite a long period of exogenous growth at Shiveluch with multiple shear lobes extrusion but not any sign yet for a stratocone formation. Though the terms "extrusive" and "effusive" are in most cases used as synonyms in international volcanological literature, these words are not synonyms in general, and the term "extrusion" relates to emergence of highly viscous material by forcing or pushing it out through a small opening, and the term "effusion" relates to emission of liquid that can flow longer distances due to gravity. As it was quite a sharp and rapid change from the extrusion of shear lobes to the predominant effusion of lava flows, and it played a significant role in the stratovolcano formation, we find it necessary to make this division in the current study. We changed the text to make our idea more clear:

Old text:

A new lobe of ductile lava, up to 220 m in diameter, extruded from an eastward open crater on the top of the second dome. The area of the base of the whole dome complex was 1,975,000 m2 with a maximum elevation of 2,801 m…

...Our 1977 dataset reveals lava flows to become thinner while traveling over longer distances. The first detected lava flow, 300-m-long, poured out from the open crater and emplaced on the north-eastern flank of the dome (Fig. 2d; Fig. 4a,b).

New (improved text):

Result section:* *In 1977, a new, 180 m wide and 300 m long, portion of lava poured out onto the north-eastern flank of the dome complex (Fig. 2d and Fig. 4a,b). In contrast to previously

observed shear lobes, it was much thinner (15 m), and flowed over a comparatively longer distance towards the foot of the dome complex. Therefore, we can consider it as a first post-collapse lava flow at Bezymianny, which is also in agreement with eyewitness accounts[36]. We link the different characteristics of shear lobes and lava flows with two distinct exogenous growth modes: Extrusion of higher viscous shear lobes and effusion of lower viscous lava flows. Hence, dome development between 1956 and 1976 was dominated by first endogenous and then extrusive growth, whereas from 1977 onwards dome growth was mainly marked by extrusive and effusive behavior. The change in growth style will eventually lead to a significantly different shape of Bezymianny's new edifice.

Descussion section: ***Yet, the dome growth evolution of Mount St. Helens and Shiveluch does not show any trend towards the formation of a stratocone. This may be due to intermittent dome growth episodes (Mount St. Helens), the prevalence of destructive over constructive processes (Shiveluch), and/or because these volcanoes have not produced any lower viscosity lava flows that covered and thus stabilized the dome. For Bezymianny we argue that the transition from the extrusion of shear lobes to the effusion of lava flows in 1977-2006 may mirror a contemporaneous decrease of the viscosity of its eruptive products.***

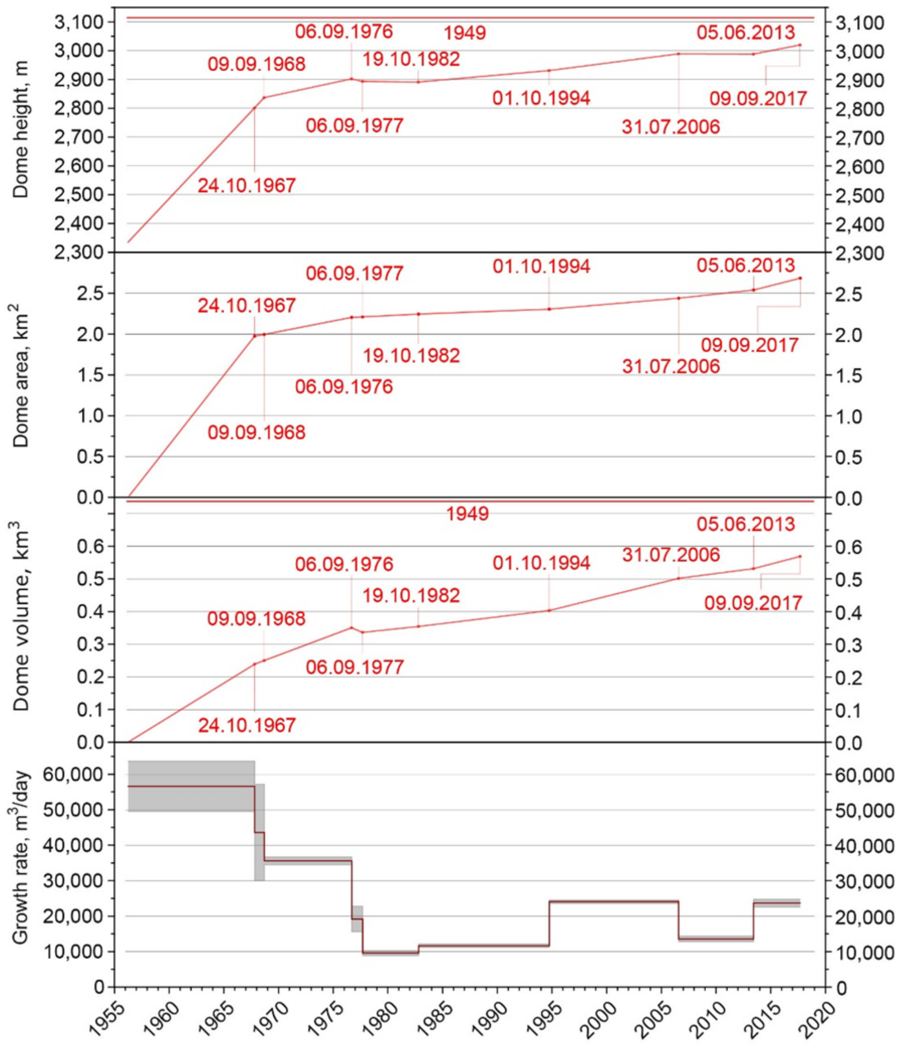
- The terms dome/cone/stratocone is also used interchangeable (e.g. in table 1 and in the text). I understand that the activity changes from dome growth to a stratocone, but I think for table 1 it would be better to call dome/cone for volcanic edifice instead of dome/cone, and then use dome for the products in phases from 1956-2006 and stratocone for the last phase.

Reply: We appreciate this comment but we can't change "dome" or "cone" to "volcanic edifice" here, because we don't refer to the whole edifice of Bezymianny, which includes the outer slopes not affected by the 1956 collapse, but only to the new edifice within the collapse-amphitheater. To simplify reading, we decided to leave only "dome" term in the tables and graphs, as for most of our observations the edifice within the amphitheater was a lava dome.

Minor comments:
• Merge suppl. Fig. 2-4 and error bars to the figures

Reply: We merged the figures in Supplement Fig. 3 and added the error bars for the growth rates, which is not possible for volumes due to the small scale of the graphs.

New (improved figure):

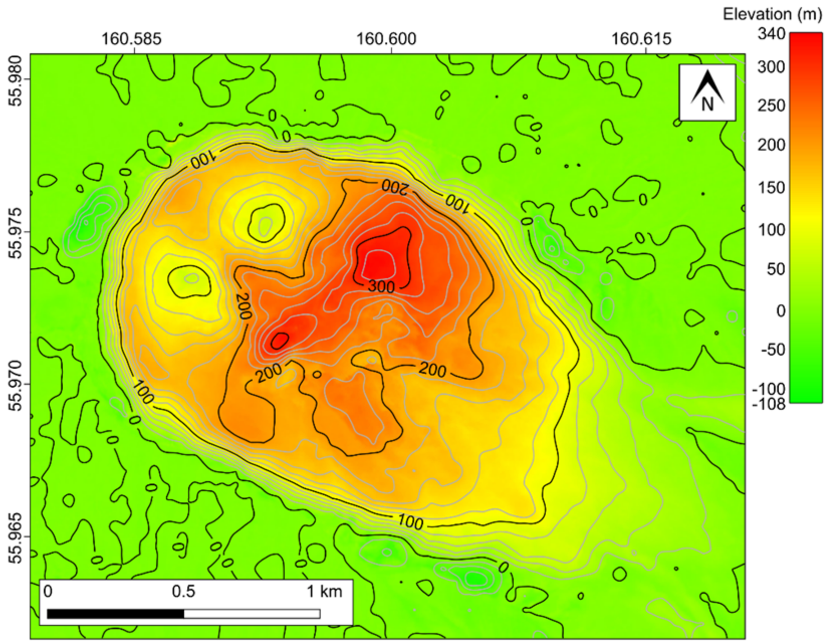


Supplementary Fig. 3. Temporal evolution of the height, area, volume, and growth rate of the dome and evolving cone. Gray transparent bars indicate ranges of the eruption rates uncertainties of 2.1-31.2 % related to inaccuracies in photogrammetric processing and DEMs alignment.

• Add contours to Supp. Fig 5

Reply: We appreciate this useful idea. We added the contour line to the figure.

New (improved figure):

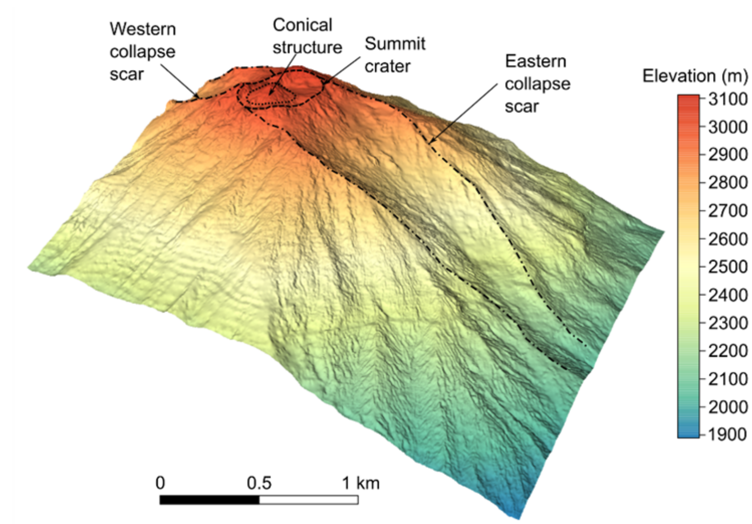


Supplementary Fig. 5. Height difference map of Bezymianny over the 1967-2017 period. The main areas of eruption material accumulation are observed in the central and north-eastern sectors of the dome. Isopachs are drawn with a 20 m interval.

• Provide data from 1949 that serves as a baseline, - it is not shown in the article nor in suppl. Information

Reply: We provided the data for the 1949 DEM construction. We are going to use this DEM for the further separate research of the pre-collapse state of Bezymianny. That is why we provide it here only as a supplementary figure.

New figure:



Supplementary Fig. 2. Oblique (from SSE) hillshade visualizations of the 1949 DEM of Bezymianny volcano. DEM was generated by photogrammetric processing of aerial images.

Reviewer#3 comments from attached documents

Reply: We appreciate the Reviewer#3 comments in the attached documents (manuscript and supplementary). We agreed with all the text corrections. Here we will reply to some of these comments, which were not listed above.

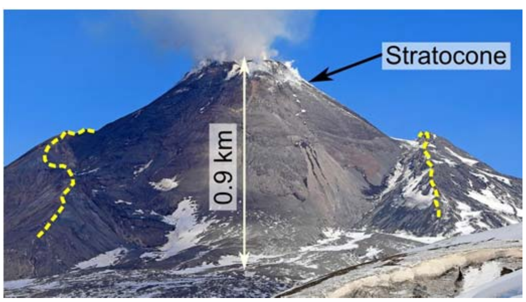
Manuscript
A11: Time and location

Reply: We added the exact time and location to the Fig. 1 caption.

Old text:
a, Location of Bezymianny volcano in the Kluchevskaya volcanic group; inset shows the location in the Kamchatka Peninsula. b, Shaded relief map of Bezymianny. c, State of Bezymianny in 1909. d, The 1956 eruption. e, Bezymianny soon after the 1956 collapse. f, Bezymianny in 2019. c, e, f, views from SE. Map data: a, 2018 ArcticDEM digital elevation model, b, 2017 Pleiades digital elevation model. Photos: c, by N.G. Kell, d, by I.V. Yerov, e, by G.S. Gorshkov, f, by Yu.V. Demyanchuk.
New (improved text):
Fig. 1 Bezymianny volcano and photo documentation of the edifice before, during, and after the 1956 sector collapse. a Location of Bezymianny volcano in the Kluchevskaya volcanic group; inset shows the location in the Kamchatka Peninsula. b Shaded relief map of Bezymianny. c State of Bezymianny in 1909 showing the scar of an earlier, albeit smaller collapse. d The 30.03.1956 eruption. e Bezymianny in August 1956. f Bezymianny on 13.04.2019. c, e, f views from the southeast. d view from the west. Map data: a 2018 ArcticDEM digital elevation model, b 2017 Pleiades digital elevation model. Photos: c by N. G. Kell, d by I. V. Yerov, e by G. S. Gorshkov, and f by Yu. V. Demyanchuk.

A13: Add yellow line

Reply: We added the yellow line to the 1956 collapse amphitheater.



A16: wouldn´t it be more appropriate to call this section "Regrowth and evolution after sector collapse" . You describe the entire growth sequence here, including two periods which you describe as dome growth, and only the latter period is described as establishment of the stratocone.

Reply: We called the section "Evolution after sector collapse"

A17: To help the reader getting an overview it would be appropriate to add one sentence mentioning that the regrowth has been divided into three phases. Mention the different type of dome growth endogenous (intrusive/protursive), exogenous (extrusive) and lava flows through effusive activity. In the following I suggest to use endogenous, exogenous and effusive instead of using the combination all the time. Please refer to the suppl. Table 1, on consider making it a table that can go into main text (not suppl.)

Reply: We appreciate this comment, but we discuss the division into separate stages in the Discussion part as it based mostly on our results. To make it more clear from the beginning we wrote additional text in the introduction part based on the previous research. Due to the limited number of figures and tables we couldn't move the table into the main text.

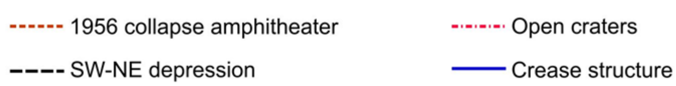
New (improved text):
The dome growth style was characterized as extrusive-explosive until 1977, when it changed to extrusive-explosive-effusive[36].

A19: It seems like there were many eruptions between 1956-67, so it would be appropriate to mention what is expected to have happened from 1956-67. Or maybe specify that the observations from the 1967 data reflect on the initial regrowth stage.

Reply: We thank the reviewer for this comment but since there were not aerial surveys over the 1949-1967 period, we can discuss in the results part only the state of Bezymianny visible in 1967 images that is in agreement with the eyewitnesses descriptions (Gorshkov and Bogoyavlenskaya, 1965; Dubik and Menyailov, 1969; Kirsanov, 1971, 1979), which we cite.

A22: It is very hard to see the difference between the red amphitheatre and red open crater lines. Same with crevasse structure and SW_NE depression

Reply: We thank the reviewer for this useful comment and showed the lines in clearly distinguishable way.



A33: Shouldn´t this be exogenous dome growth and lava flows

Reply: We suggest that as exogenous growth can occur through lava flows emplacement, we can't separate them as different types of activity. In the way suggested by the reviewer we could write: exogenous growth (shear lobes, lava plugs, and lava flows). But we decided to simplify it, and we wrote: exogenous growth (extrusive-effusive).

A34: Why are they called spherical ? they do not look like spheres more like crescents. In 1982 the "spherical lava lobe" looks like the lava plug in shape… what is the difference ?

Reply: We agree with the reviewer. We removed the word "spherical" and added the word "remnants". The remnants of shear lobes destroyed by eruptions look like crescents. Lava plug is a narrow cylindrical body that has the same diameter as a vent as it is a portion of lava remained in the vent since previous eruption and extruded after being solidified. We can distinguish a lava plug from a shear lobe by a diameter, and location at the vent part of the previously emplaced lava flow.

A39: weren´t there just two vent (Dome 1 & 2) ?? In that case pls you refer them as "those vents"

Reply: We agree with the reviewer and removed "D_{max}" from the description of the first two vents.

A40: wording is a few hundred meters large ?? Maybe more focus on the actual difference

Reply: We indicated the actual difference between the vents above in the same paragraph.

New (improved text):
After the 1956 collapse, the first endogenous dome (Fig. 2a) emerged from a vent with a location shifted ~500 m to the ESE of the pre-collapse summit (Fig. 6; Supplementary Fig. 4). The inferred vent of the second dome emerged 400 m north-westward from the vent of the first dome, and ~230 m north-eastward from the location of the pre-collapse vent.

A43: what is 0 on the y axis, aka what is the reference point ??

Reply: We thank the reviewer for the comment and indicated in the figure captions the reference point:

New (improved text):
Eruption centers migration along NE-SW and NW-SE directions, highlighting a shift/spread and then re-focusing of vents in the NW-SE profile. The reference is a central point between the two first domes.

A46: This model is unclear to me. How are the red dikes modeled, why do the model stall at depth (2 km) ?Why are the red dikes at b thicker than at a ?

Reply: We improved the model description and the description of simulation results according to this and other comments (c.f. "new text" below). Please also note that the thickness of the intrusions may vary due to i) different stress gradients, ii) different orientations (dip angles), and iii) slightly different "volumes" (actually, 2D cross sectional area A, c.f. "Method section": A=[9×10^{-4} – 4×10^{-4}] km^2).

New (improved text)
Results section: ***We use a 2D boundary element model to simulate magma propagation paths. Our model refers to the cross-section of a mixed-mode magma-filled crack in plain-strain approximation. The most favorable direction for the magma pathway is computed iteratively, following the criterion of maximum energy release[14,47]. This approach is based on fracture mechanics principles, however, it neglects the dynamics of magma within the fracture so that it cannot account for magma viscosity[49]. Further detail on the modeling technique and assumptions are provided in the Method section.***
[...] In contrast, the paths beneath the rim of the collapse scarp are more focused – pointing at the location of the rim – and get arrested beneath the rim, because of higher compressive horizontal stress due to the rim topography and the horizontalization of some paths, which reduce the effective buoyancy of the intrusion (black paths in Fig. 7a).
Figure 7 caption: ***Modeling stress field changes due to the Bezymianny collapse and regrowth, and associated magma pathways. Stress scenarios and simulated magma pathways on a WNW-ESE vertical cross-section of Bezymianny. The colored contours represent the horizontal stress due to the unloading and reloading force distributions that simulate the effect of edifice collapse and re-growth, respectively (gray triangles and trapezoid shades, respectively). Gray dashes indicate the direction of maximum compression. The trajectories and the shape of magmatic intrusions are plotted in red when they are deflected towards the collapse embayment. Magma pathways that converge towards the rim of the collapse scarp are marked by solid black lines. a Post collapse scenario: the pre-collapse vent location (white reverse triangle), appears to be inhibited (paths diverge to both sides away from it). The most favorable position for post-collapse vents is within the collapse embayment (red trajectories), because of collapse unloading forces. New vents may be shifted up to several hundreds of meters towards the collapse direction. b Regrowth scenario: more paths are deflected towards the collapse embayment, and they tend to converge towards the center of the loading force***

distribution associated with the new dome (gray trapezoid). Even though the compressive stress below the collapse embayment is increased by the new dome, it is still lower than the horizontal compression underneath the rim. A region of relatively lower compressive stress (paths highlighted in dark red), may represent a more favorable location for magma paths to intrude within the new dome.
Methods section: ***Magma pathways are modeled as 2D boundary element mixed-mode cracks in plane strain approximation. The modeling plane is perpendicular to the crack plane, therefore the model refers to a cross-section of the intrusion. The crack opening depends on assigned normal and shear stress boundary conditions that are the magma overpressure and the shear component of the topographic stress, respectively. The overpressure along the crack is given by the difference between the magma pressure and the confining stress (superposition of the lithostatic pressure and the normal component of the topographic stress).***

A51: This seems like a postulate, pls provide a reference, or an argument

Reply: We appreciate this comment and write this idea in more details:

New (improved text):
The constant growth rates coincided with the occurrence of lava flow emplacements that successively covered the older dome complex. We conjecture that the lava flows may have acted as an armor preventing partial flank collapses and stabilizing the new edifice, which eventually facilitated the formation of a stable centralized vent through gradual load increase. Thick and unevenly distributed shear lobes, in turn, may contribute to slope instability leading to partial dome collapses, as was observed at Bezymianny in 1985[51] and frequently at Shiveluch[52].

A53: , Guatemala

Reply: We added country names to all the volcanoes in the Introduction part.

A54: Why not include volumetric comparisons ? What about mt. st Helens, weird not to mention results from e.g. Fink et al. 1990

We appreciate this comment and added eruption rates comparison to the Discussion part. Unfortunately, we can't compare eruption rates results to the results of Fink et al. 1990, because to make a similar division of volume contribution to endogenous and exogenous growth regimes, we need more frequent data. We are planning this study for the future after processing all archive aerial data for Bezymianny.

New (improved text):
During Bezymianny's edifice reconstruction, the growth rate decreased noticeably from an initial ~56,000 m^3/day (1956-1967) to 33,000 m^3/day (1967-1977) and then to 15,500-17,000 m^3/day (1977-2017)…

… Similar to Bezymianny, the post-collapse dome growth at Shiveluch during the 1980-1981 extrusive period was characterized by an initially higher rate of 186,000 m^3/day that later decreased to ~60,000 m^3/day[19]. Over the 2001-2012 period of Shiveluch regrowth, the initial rate of resumed extrusive activity was 700,000 m^3/day that gradually decreased to 150,000 m^3/day[52]. After the collapse of Santa Maria volcano, regrowth of Santiaguito dome complex was characterized by multiple episodes[53], the highest rate 178,000 m^3/day was also observed during the first post-collapse episode in 1922-1925. Further the growth of each new dome began with a 3-5-year period of high rate (50,000-130,000 m^3/day), followed by a decrease to ≤16,000 m^3/day for up to 11 years[17]. During eruptive cycles at Mount St. Helens, decreasing of a higher initial rate was also observed. Over the 1980-1986 period, the average rate until 1983 was 370,000 m^3/day been then decreased to 78,000 m^3/day[54]. During the 2004-2008 period, the initial rates were in the range of 110,000-450,000 m^3/day until mid-2005, and then decreased to 26,000-78,000 m^3/day[55].

In general, the long-term average growth rate of Bezymianny's new edifice (26,400 m^3/day) is comparable to rates of Mount St. Helens during the 1980-1986 eruptive cycle (30,000 m^3/day)[54] and Santa Maria in 1922-2000 (38,000 m^3/day)[17] but notably lower than that of Mount St. Helens in 2004-2008 (173,000 m^3/day)[31] and Shiveluch in 2001-2012 (225,000 m^3/day)[52].

A56: how many GCPs

Reply: We added the number of GCPs to the text:

New (improved text):
The coordinates of 12 ground control points (GCPs) were derived from a Theo 010B theodolite dataset collected at geodetic benchmarks during a 1977 fieldwork.

A57: what is the theodolite measurements compared to ?

Reply: Theodolite measurements are geodetic measurements with an optical instrument - theodolite, which allows to perform ground based triangulation similar to present-day tacheometers, with the exception that the tacheometers can measure angles and distances between points, and theodolite can measure only angles.

A58: How many ?

Reply: We added the number of GCPs to the text:

New (improved text):
Those benchmarks covered by volcanic deposits made it necessary to extract new coordinates similar to(Schilling et al., 2008) of 6 clearly distinguishable and stable (not affected by eruptions) topographic prominences in the vicinity of Bezymianny (peaks or large rocks).

A59: Date? Important to know since you are filling out the gaps with the drone aquisition

Reply: We added the date to the text:

New (improved text):
To complement the temporal coverage of our aerial time-series, we additionally tasked tri-stereo high-resolution Pléiades satellite imagery acquired on 09.09.2017.

A61: Coregistration ?

Reply: This operation can be called "coregistration", but regarding point clouds processing it is usually called "alignment".

A62: Please provide (unclear what is meant ? Resolution ? extent ?)

Reply: We specified it exactly:

New (improved text):
The investigated aerial, satellite and drone data have the same spatial scale but shifted in geo-position, depending on the coordinate system (USSR State Geodetic Network for the aerial data and WGS84 for the merged Pleiades-UAV data) and precision.

A63: Number of points ? your RMSE depend on number of points so pls provide

Reply: We provided the numbers of points:

New (improved text):
In order to allow quantitative comparison and analysis of the differently located data, we aligned the aerial point clouds relatively to the merged Pléiades-UAV point cloud with 8 distinct points on the 1956 crater's rim using the CloudCompare software.

A68: Please explain in more detail,- this is hard to follow. Are you talking about special areas ?

Reply: We explained it in more detail:

New (improved text):
To determine the contribution of the triangulation errors in volume estimation, we distributed each TRMSE Z value over the respective area affected by eruption (dome area) (Tab. 1) similar to[31].

A72: Again, quite vague

Reply: We tried to explain our idea in more details:

New (improved text):
For the exogenous (extrusive) growth period (1967-1976), we identify a vent location based on the thickest part of shear lobes as they become thinner at their margins due to crumbling of solidified material.

A73: Only elastic or also viscous response included ? What assumptions have been made ?

Reply: The collapse unloading and re-growth loading are purely elastic (assuming non-elastic effects are not relevant for such recent events). The pre-collapse effective loading (EVL) accounts for non-elastic effects that may have partially released elastic stress.

New (improved text):
Method section: ***We assume that during the emplacement of the pre-collapse edifice, non-elastic effects may have partially released elastic stress, this is accounted by testing different "Effective Volcanic Loading" (EVL)[14]. Conversely the flank collapse and the dome growth are very recent events, and therefore we consider them as "purely elastic"[14]. Different values of EVL were tested [0.5 – 0.6 – 0.7], meaning that 50%, 40%, and 30% of the elastic loading had been released at the time of the collapse[14]. We used the triangular difference approach to simulate the stress relaxation: "Trapezoidal Loading" in[14].***

A74: Argument for choosing this depth ?? why 1900
A75: Does this fit the unloading calculated based on volume?
A77: How were these numbers obtained
A78: Does this fit the loading obtained from the volume calculations ??

Reply: We constrain the loading and unloading force distributions according to the profiles in Fig. 6b. This is because the model is 2D therefore we have to use cross-sections rather than volumes. We clarify this in the revised manuscript.

New (improved text):
Method section: ***Pre-collapse scenario: We consider the loading due to the pre-collapse volcanic edifice based on the pre-collapse profile (black solid line) in Fig. 6c. The effect of topography on the crust beneath is modeled by vertical forces applied on a reference horizontal surface at 1,900 m on the sea level (which is the approximate altitude of the post collapse embayment, dashed profile in Fig. 6c). [...]***

Post-collapse scenario: ***We introduce the unloading force distribution simulating the flank collapse (superposed on the stress due to the pre-collapse edifice). Here we used a simple triangular profile to approximate the effect of the collapse. The maximum height of the unloading is Hpoc=0.8 km (in x=0), the base of the unloading is Wpoc=2.8 km, from x=-0.6 km to x=2.2 km. These geometrical constraints are based on the difference between the pre-collapse and post-collapse profiles in Fig. 6c (black solid and dashed lines, respectively). Similar to the pre-collapse scenario, the magnitude of the unloading force is proportional to the density of shallow rocks, but with opposite sign. We do not consider any stress relaxation effect for the unloading forces[48] since the collapse event is sudden and recent.***
Regrowth scenario: The re-loading due to dome growth is introduced. We used a trapezoidal shape for the dome. Based on the 1956-1967 profile of Fig. 6c (first phase of dome growth), the trapezoid has a height Hdg=0.5 km, with a lower-base Wdg=1.1 km (from x=-0.25 km to x=0.85 km) and an upper-base Wdg=0.37 km. Again, forces are proportional to the shallow-rock density, and they are superposed to the post-collapse scenario.

A79: Only the first phase or all phases ??

Reply: Only the first phase, we clarified it in the manuscript.

New (improved text):
Methods section: ***Regrowth scenario: The re-loading due to dome growth is introduced. We used a trapezoidal shape for the dome. Based on the 1956-1967 profile of Fig. 6c (first phase of dome growth), the trapezoid has a height H_{dg}=0.5 km, with a lower-base W_{dg}=1.1 km (from x=-0.25 km to x=0.85 km) and an upper-base W_{dg}=0.37 km.***

A80: Why at this depth ? And how does these models fit the suggested 2 magma model

Reply: We clarify the motivation for this choice (model domain) in the revised manuscript, and discuss why the magma-paths model do not really have implications for the hypothesis of the "2 magma model".

New (improved text):
Results section: ***Our model domain is a vertical ~WNW-ESE cross-section of Bezymianny volcano (Fig. 6c), and extends from a depth (z) of -0.1 km up to 1.9 km above sea level, which is the approximate altitude of the post-collapse amphitheater's floor (dashed profile in Fig. 6c). We simulate the stress field due to topographic changes using loading and unloading force distributions applied at the top of the model[14, 47, 48] (z=1.9 km). These force distributions have simplified shapes based on the profiles in Fig. 6c (triangles and trapezoids in Fig. 7). Magma paths start vertically, from the base of the model domain (z=-0.1 km), within a 3 km wide region centered below the summit of the pre-collapse edifice (-1.5 < x < 1.5 km). We choose the depth and extension of the region from where the intrusions start, in order to cover the whole area affected by the stress changes associated with the morphological changes we study. This area should not be considered as the location of a magmatic reservoir (which should be deeper at Bezymianny, c.f. Discussion section). Rather, our assumption is that an intrusion would rise from deeper depths and enter vertically our model domain.***
Discussion section: ***The hypothesis of the activation of two different feeding sources, cannot be supported – neither is in contrast – with our magma path simulations: in fact, our model cannot account for viscosity changes. Also, accounting for the mechanical coupling with a magmatic reservoir (not considered here) may not add further constraints, since the unloading and loading force distributions affect magma pathways only at shallower depths (because of the relatively small collapse volume with respect to other cases previously studied with this approach[14] (Supplementary Fig. 6).***

Nevertheless, an effect of unloading and loading stress on the activation (or inhibition) of reservoirs at depth, may be possible[10]. At the moment it is not clear for how long the effect of topographic loading may last, but given the regrowing load of the new cone is approaching pre-collapse conditions, we conjecture that also the stress relationship at depth may become close to the condition as it was before the 1956 sector collapse.

A81: Right DOI ?

Reply: We included the right DOI:

New (improved text):
The photogrammetrically processed dataset and metadata will be freely available through the GFZ Data Publishing Service at DOI:10.5880/GFZ.2.1.2020.002

Supplementary
A5: Why do they vary in thickness ?? what does that imply ? E.g. between e and f
Similarly as in Fig. 7a and b, also here

Reply: the thickness of the intrusions may vary due to i) different stress gradients, ii) different orientations (dip angles), and iii) slightly different "volumes" (actually, 2D cross sectional area A, c.f. "Method section": A=[9×10^{-4} – 4×10^{-4}] km^2).

A6: So why aren´t both triangles plotted on b, e, h. If they are related to initial vent opening the loading at this point should have been minor ? Adding both triangles would help constraining best scenario (e.g. is it e or h ?)

Reply: The first active vent location should be the one further to the east (therefore it is the most relevant for the post collapse scenario), while the other location, closer to the pre-collapse center, it should have become active later on, and all vent locations after it have opened between these two (therefore both are relevant in the dome-growth scenario). We better clarified this point in the figure caption.

New (improved text):
Supplementary Fig. 6. ***Magma paths ways change and stress distribution. a,d,g, Pre-collapse stresses simulation. b,e,h, Post-collapse stresses simulation. c,f,i, Regrowth stresses simulation. The color contours and the gray dashes represent the magnitude of horizontal stress and the direction of maximum compression induced by the topography, respectively. Dashed and dotted lines represent the simple geometrical shapes chosen for the force distributions that simulate the effect of topography (dashed lines represent the distribution which is actually considered in that figure panel, while the dotted lines represent the topographic feature that will develop at a later stage). Solid black lines represent the paths of magmatic intrusions that are converging towards the rim of the collapse amphitheater. We highlight in red the trajectories and shapes of magmatic intrusions which are expected to feed vents within the collapse scarp. The red reversed triangles represent vent locations within the collapse scarp (c.f. Fig 6b, 1956-1967 profile): the first vent that opened within the collapse embayment is the one further towards the east (and its location is plotted in the panels relative to the post-collapse scenarios) later vents opened at locations between the 1957-1967 vents (therefore their location is plotted in the panels relative to the dome-growth scenarios).***

The Stress scenario with EVL=0.6 seems to explain better the location of the first vent and the focusing of vents at the dome location, after the first dome growth. Smaller EVL would cause larger deflections, however, if intrusions would start even at shallower levels also EVL=0.5 may give a good fit with the vent locations. EVL=0.7 seems to be already too large, the loading dominates over unloading, and the first dome growth seems to compensate already for the collapse.

Another interesting observation is that looking at stress contours – which represents the horizontal stress induced by topography – for the post-collapse scenarios, we always get a region with lower horizontal compression, exactly beneath the location where the dome will develop. This region tends to move towards the left with the establishment of the first dome topography (regrowth scenarios).

Decision letter and referee reports: second round

9th Jul 20

Dear Dr Shevchenko,

Your manuscript titled "The rebirth and evolution of Bezymianny volcano after the 1956 sector collapse" has now been seen by our reviewers, whose comments appear below. In light of their advice I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

EDITORIAL REQUESTS:

Please review our specific editorial comments and requests regarding your manuscript in the attached "CommsEarth Final revisions information checklist". Please outline your response to each request in the right hand column.

SUBMISSION INFORMATION:

In order to accept your paper, we require the files outlined in the attached "CommsEarth Final submission file checklist.pdf"

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Joe Aslin

Associate Editor,
Communications Earth & Environment
https://www.nature.com/commsenv/
Twitter: @CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The manuscript by Schevchenko et al. presents an interesting and important dataset and interpretation of regrowth processes at Bezymianny volcano, following the destructive 1956 sector collapse. I stand by my previous review comments that this unusual dataset provides important insights into the medium-term eruptive response following sector collapse, and thus warrants publication. I am also very pleased to see how thoroughly the reviewers have taken on board and responded to all the reviewers' comments. They have addressed these comments clearly and comprehensively, and the manuscript is much improved. The modelling is now more clearly explained and better integrated into the paper as a whole. I found the results well presented and the arguments balanced and supported by drawing on other relevant examples from the literature.

I have just provided a few further minor comments and suggestions below.

The abstract and opening paragraphs are now very clear and give comprehensive citation and context to the study. A few very minor suggested text edits:
L15 – Perhaps expand the very first line of the abstract to introduce the process of sector collapse and what you mean by "continued" volcanism.
L30 – "precursory eruptive activity"?; and "without any apparent change in behaviour" instead of "suddenly"?
L40 – perhaps "… and bifurcate from their pre-collapse course".

Results:
L109 (and L220) – can you clarify how you know that the SE dome is older (in the figure, listed as first and second dome).
L112 – Can you state the basal depth of the dome (or at least the base of the flanks/its overall height). I realise the information on this may be limited, but the elevation of 2801m isn't meaningful without an estimate of the initial depth of the collapse scar, to judge the overall height of the dome.

Discussion:
Line 343 (and L217 and figure 6) – It's interesting to note that although the edifice is now close to reaching the pre-collapse volume, the position of the vent is clearly different, and appears to have persistently shifted to the SE. Can you speculate on why this might be? It implies a long-term influence of the collapse on the vent position. With repeated collapses (assuming they were always SE), would you expect the edifice to gradually shift further in this direction, thus influencing the overall volcano morphology. The evidence of the pre-1956 cone morphology doesn't particularly seem to suggest this effect from previous collapses? Are you able to comment on this any further?

Other points are well covered in the discussion, and Fig 9 is very interesting.
A L451, you seem to suggest that the current, rapid rate of regrowth is a significant departure from long-term Holocene patterns of activity at Bezymianny, which were characterised by much longer periods of quiescence. Can you speculate on whether anything has fundamentally changed in the magmatic system to drive this departure (changes in erupted composition or style perhaps?), or if perhaps the pattern of past activity isn't well enough constrained to make this comparison.

Sebastian Watt

Reviewer #2 (Remarks to the Author):

The authors did exellent job to address all the reviewers' comments. I am impressed by the detailed responses to all issues and by the amount of reworking the text and figures. For my comments, I am completely satisfied by the responses. In my opinion, the article is ready for publication without any delay.

Reviewer #3 (Remarks to the Author):

I ran over the manuscript and response to my review and think the authors have done a great job implementing the comments. The method section has been significantly improved (both the morphological mapping, volume estimation and modeling) and the discussion has been strengthened, both by providing the new figure 9, but also doing a better job discussing Benzymianny in the context of other observations of volcano regrowth. Language has also improved. There are none of my reviewer comments that they haven´t addressed/misunderstood.

Dear Editor, please find a point-by point response to the reviewer comments below. Our replies are marked in bold.

____

Dear Dr Shevchenko,

Your manuscript titled "The rebirth and evolution of Bezymianny volcano after the 1956 sector collapse" has now been seen by our reviewers, whose comments appear below. In light of their advice I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

Reply: We thank the editors for the decision to publish our manuscript and considered all reviewer's comments below in the point-by-point response. Also, we edited the manuscript in accordance to the format requirements.

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Reply: We thank the reviewer very much for his remarks and comments.

I have just provided a few further minor comments and suggestions below.

The abstract and opening paragraphs are now very clear and give comprehensive citation and context to the study. A few very minor suggested text edits:

L15 – Perhaps expand the very first line of the abstract to introduce the process of sector collapse and what you mean by "continued" volcanism.

Reply: We appreciate this comment but as the abstract is limited by 150 words, it is not possible to extend it. To make our idea clearer we changed "volcanism" to "volcanic

activity". Thus, we show that the new edifice can start to form in the case when a volcano continues to erupt after a sector collapse.

L30 – "precursory eruptive activity"?; and "without any apparent change in behaviour" instead of "suddenly"?

Reply: We thank the reviewer for this comment and made changes according to it.

L40 – perhaps "… and bifurcate from their pre-collapse course".

Reply: We appreciate this comment and made changes according to it.

Results:

L109 (and L220) – can you clarify how you know that the SE dome is older (in the figure, listed as first and second dome).

Reply: The sequence of the dome development was described by eyewitnesses (Gorshkov & Bogoyavlenskaya, 1965; Kirsanov & Studenikin, 1971). The authors indicated that the south-eastern sector of the dome developed first, and then the north-western part was formed. We added the citations to these works after the description of the sequence.

L112 – Can you state the basal depth of the dome (or at least the base of the flanks/its overall height). I realise the information on this may be limited, but the elevation of 2801m isn't meaningful without an estimate of the initial depth of the collapse scar, to judge the overall height of the dome.

Reply: We appreciate this comment and added the suggested information. The initial elevation of the collapse amphitheater bottom (2,200 m) was estimated in (Seleznev et. al, 1984). We showed this value with the citation to (Seleznev et. al., 1984) in Table 1. Thus, we can estimate the dome's relative height in 1967 to be about 601 m and in 2017 – about 820 m. We include this information in the text. Now it is read as follows:

The base of this dome complex covered an area of 1,975 km^2, the dome reached an elevation of 2,801 m (~600 m in relative height) and occupied a volume of 0.239 km^3 [34]…

…Moreover, the height of the cone reached 3,020 m (~820 m in relative height), which is about 90 m lower than the pre-collapse height in 1949.

Discussion:

Line 343 (and L217 and figure 6) – It's interesting to note that although the edifice is now close to reaching the pre-collapse volume, the position of the vent is clearly different, and appears to have persistently shifted to the SE. Can you speculate on why this might be? It implies a long-term influence of the collapse on the vent position. With repeated collapses (assuming they were always SE), would you expect the edifice to gradually shift further in this direction, thus influencing the overall volcano morphology. The evidence of the pre-1956 cone morphology doesn't particularly seem to suggest this effect from previous collapses? Are you able to comment on this any further?

Reply: We thank the reviewer for such an interesting comment. The shift in the position of the post-collapse vent can be explained by the effect of unloading on the magma pathways propagation. Such effect was studied in (Maccaferri et al., 2017) for other volcanoes, and for Bezymianny, in the current work:

In fact, magma pathways are influenced by the local stress, whereby changes in the direction of principal stress affect the favorite direction of propagation (see Fig. 7; Supplementary Fig. 6). We find that the unloading due to the 1956 sector collapse favors magma rising towards and beneath the collapse amphitheater, shifted eastward of the pre-collapse vent location by ~300 up to ~800 meters (0.28<x<0.83 km, Fig. 7a), in agreement with our photogrammetric observations at Bezymianny, and with previous results for the shift of vent location as a consequence of a flank collapse[14].

We don't expect a further shift of the vent position towards SE in near future, because the edifice of the new stratocone with the central conduit has been stabilized. The further shift of the vent is expected after the next edifice collapse. We can assume that the SE shift of the main vent had occurred before 1956; we can see the evidence of it in the 1949 profile (Fig. 6c). If we extrapolate the line of the slope not affected by this pre-historic collapse, we will see that the summit of the pre-collapse edifice should have been in about 200 m towards NW from the 1949 summit. In our next research, we are going to investigate the morphology of Bezymianny in 1949 in more detail, and we would like to develop this idea further in a separate study.

Other points are well covered in the discussion, and Fig 9 is very interesting.

Reply: We thank the reviewer for this comment.

A L451, you seem to suggest that the current, rapid rate of regrowth is a significant departure from long-term Holocene patterns of activity at Bezymianny, which were characterised by much longer periods of quiescence. Can you speculate on whether anything has fundamentally changed in the magmatic system to drive this departure (changes in erupted composition or style perhaps?), or if perhaps the pattern of past activity isn't well enough constrained to make this comparison.

Reply: We appreciate this comment. According to (Braitseva et al., 1991) the previous Holocene activity of Bezymianny was characterized by several powerful eruptions with intermediate periods of moderate effusive and explosive activity, and periods of quiescence. We suppose that Bezymianny can be currently at such a moderate effusive-explosive activity period, and since the new stratocone with a stabilized conduit has been formed, it can further function as a classical stratovolcano over a long period of time, which is in agreement with the (Braitseva et al., 1991) results. Indeed, the current post-collapse rates at Bezymianny are higher than the pre-historic eruption rates calculated in (Braitseva et al., 1991), but it would be difficult to speculate on changes at the magmatic system in comparison with prehistoric activity in current study because it requires separate petrological research.

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Reply: We thank the reviewer very much for his/her remarks and very useful previous comments.

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Reply: We thank the reviewer for his/her remarks and for the previous comments that helped to significantly improve the paper.