

## Radar-Based Observation of a Lava Tube on Venus

Corresponding Author: Professor Lorenzo Bruzzone

**This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.**

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This manuscript details the very exciting confirmation of a lava tube entrance on Venus. Over the last few decades, orbital data has strongly suggested (or even confirmed) the existence and nature of lava tubes on the moon and Mars, and this new confirmation for Venus just goes to show that these are ubiquitous features of planetary surfaces with histories of basaltic volcanism. It uses an approach developed and previously applied by the authors for characterizing lunar lava tube entrances using radar, and includes a comparison of radar data for a terrestrial analog lava tube, and the manuscript convincingly rules out other potential features. As such it is worthy of publication.

However, there is definitely room for improvement. My main criticism of this manuscript is its repeated exaggeration- of the novelty of this work (e.g. there being no confirmed Martian detections) and its importance (e.g. relevance to future robotic missions, access to layered deposits), however this could be remedied by more measured language, better referencing, and more realistic (but still important!) implications. The core of the manuscript is strong enough to support publication without the hyperbole.

Here are some specific recommendations:

The manuscript misses out on some early studies of crater chains (and prospective lava tubes) from the early post-Magellan mission days. Citations of those works would help show how long this question has been out there, and that this work is using a novel SAR interpretation approach (and new analog comparisons) to answer a question where only speculation existed before.

This one is only a thesis but has extensive coverage of the topic:

Melville, Graeme P (1994). Lava tubes and channels of the Earth, Venus, Moon and Mars. University of Wollongong. Thesis. <https://hdl.handle.net/10779/uow.27649461.v1>

This one is shorter but mentions Venus lava tubes (co-authored by the author of the thesis listed above):

Publications of the Astronomical Society of Australia, Volume 10, Issue 3, 1993, pp. 200 – 202. DOI: <https://doi.org/10.1017/S1323358000025662>

The introduction says that "...from optical images (e.g., by photoclinometry) it is very difficult to assess whether a subterranean cave extends from the skylight." I will agree that this is true, but it also undersells some of the quality work that has been done trying to do just that- e.g. in Haruyama et al. (2009), a paper you're already citing elsewhere. You make the stronger case for your work in the next sentence (e.g. you couldn't use imagery for Venus anyways).

A sentence later in the Intro, you say that "Magellan is a spaceborne side-looking SAR..." Do you mean that Magellan HAD a spaceborne side-looking SAR? Or more precisely that it had a radar system (the RDRS) that could operate in a SAR mode?

Page 7, last sentence of the first paragraph states "These deposits tend to increase the radar backscattering uniformly around the feature" in reference to impact craters. The reference cited relates to radar imaging of craters on the Moon- could you cite a Venus-specific source? Venus craters have much different ejecta patterns than lunar ones, often involving more impact melt, and not as "rough" in radar as lunar craters (and can even be brighter than their surroundings in radar images).

See <https://www.hou.usra.edu/meetings/lpsc2023/pdf/1052.pdf> and other refs regarding Venus ejecta.

Page 7, second paragraph, second sentence: "Given that there are no confirmed detections of intact lava tubes for the Martian case..." Are you sure you want to say this? Do you mean confirmed using the SAR method? I'm sure there are members of the HiRISE team (MRO) who would contend that their lava tube entrances on Alba and Arsia Mons are "confirmed." Sauro et al. (2020), which you are already citing, discusses this. With no other discussion in this manuscript about what you mean by "confirmed," this statement is unsupported.

Same paragraph, in reference to the critical factors influencing lava tube stability- the reference cited is great but makes no mention of Venus. You should make it clearer that this reference does not mention Venus (or Venus-specific conditions). I don't know but I'd be curious if factors such as high atmospheric pressure, or prolonged cooling times (given high surface temperatures) could affect their stability, or the tensional strength of the lava material. As you've just stated ahead of this sentence, there is currently no info about the structural stability of lava tubes on Venus. While it is clearly beyond the scope of this paper to model this, it might be good to acknowledge that Venus surface conditions could potentially influence this (and perhaps that further work is needed to assess whether the general conditions for lava tube stability developed in the paper cited can be applied to Venus).

Final paragraph, page 8. Some of the applications seem wildly fanciful to me and should be scaled back. That this skylight "could also be of great interest as targets for a possible lander robotic mission" with a citation to a DAVINCI mission paper is way off- that is not a robotic mission and will at best only return data for minutes if it as a soft landing, and it already has a target area. The next sentence talks about "preserved layers within the conduit walls could serve as a detailed record of the planet's volcanic history, enabling the reconstruction of geological timelines." I've spent many weeks in lava tubes on multiple continents (and islands) and I have never seen layered deposits, except for maybe one flow covering another flow or two (but likely separated in time by years at most). It's just not the kind of environment that preserves a long record.

I've made multiple minor corrections and suggestions for more concise language, for example replacing "in the proximity of" with "near" throughout. I'm attaching an annotated PDF with my suggestions.

Good luck!

## Reviewer #2

### (Remarks to the Author)

The authors present an argument that a geologic feature on the western flank of Nyx Mons, Venus, is a lava tube. This would be a new identification of a lava tube on Venus. Lava tubes have been discussed briefly in the Venus volcanology literature but little to no evidence has been presented identifying one. The primary evidence that the feature is a lava tube is the unique radar return pattern and a qualitative comparison to a terrestrial example at Lanzarote, Spain. The authors do an excellent job using radar remote sensing to present an argument that the feature on Venus is a lava tube. However, the manuscript is lacking in several essential areas that I explain below. Identifying a lava tube on Venus is an exciting possibility, however as this manuscript is currently written I cannot recommend it be published. The majority of my comments can be addressed with text edits. I recommend major revisions and look forward to seeing the revised manuscript. -Ian T.W. Flynn

### Major Comments:

- A general major comment is that the authors rely on the planetary cave literature rather than the planetary volcanology literature. This by itself would not be an issue, but the authors do not include accurate information about lava tube formation and similar volcanology processes. I make several line edits and other major comments related to this issue. As the manuscript focuses on the identification of a lava tube, a volcanic feature, I encourage the authors to revisit some of their citations to make sure they are appropriate.
- The authors do not cover the full spectrum of volcanology processes that could form a lava tube. I made a note of this in the introduction (see the attached PDF) and below are some references that could be used to help the authors expand the introduction. Only a few additional sentences would be needed to explain the other lava tube formation processes in the introduction. As written, the authors give the impression lava tubes can only form under one mechanism, and this is not correct.
  - o Peterson, D. W., Holcomb, R. T., Tilling, R. I., & Christiansen, R. L. (1994). Development of lava tubes in the light of observations at Mauna Ulu, Kilauea Volcano, Hawaii. *Bulletin of Volcanology*, 56, 343-360.
  - o Valerio, A., Tallarico, A., & Dragoni, M. (2008). Mechanisms of formation of lava tubes. *Journal of Geophysical Research: Solid Earth*, 113(B8).
  - o Calvari, S., & Pinkerton, H. (1999). Lava tube morphology on Etna and evidence for lava flow emplacement mechanisms. *Journal of Volcanology and Geothermal Research*, 90(3-4), 263-280.
- Similar to the above comments, the authors should add some discussion either in the introduction or discussion as to if the formation of lava tubes on Venus is expected. Given the extreme environmental conditions on Venus, it is unclear on how lava tubes will form on the planet. Head and Wilson, (1988) briefly describe that lava tube formation on Venus should be more common than on Earth. Flynn et al., (2023) discusses how the reduced gravity on Venus should promote the increased formation of crust cover, which could promote the formation of lava tubes. There needs to be some discussion in the manuscript about whether the formation of lava tubes is expected or could occur on Venus.

o Head III, J. W., & Wilson, L. (1986). Volcanic processes and landforms on Venus: Theory, predictions, and observations. *Journal of Geophysical Research: Solid Earth*, 91(B9), 9407-9446.

o Flynn, I. T., Chevrel, M. O., & Ramsey, M. S. (2023). Adaptation of a thermorheological lava flow model for Venus conditions. *Journal of Geophysical Research: Planets*, 128(7), e2022JE007710.

- Page 5 last paragraph: The authors do an adequate job comparing their results to those on the Moons and Mars. However, there are two issues with the comparison. (1) There should be a comparison to an equivalent Earth lava tube included. This is necessary to contextualize the results between the other planetary bodies. (2) The Mars reference is for pit craters and not all pit craters are formed via lava tube collapse (Wyrick et al., 2004). The authors need to be consistent and make sure they are comparing the correct volcanic features to each other. Furthermore, we do not have good spatial constraints (lengths, widths, volumes) on the reported extents of planetary lava tubes. As this text is currently written it makes it sound like these values are 100% accurate and does not provide the necessary context.

o Wyrick, D., Ferrill, D. A., Morris, A. P., Colton, S. L., & Sims, D. W. (2004). Distribution, morphology, and origins of Martian pit crater chains. *Journal of Geophysical Research: Planets*, 109(6). <https://doi.org/10.1029/2004JE002240>

- The main text of the manuscript mentions the “unique radar backscatter” associated with lava tube skylights. This is the primary result used in the manuscript to indicate the Venusian feature is a lava tube. However, the specific radar return pattern is not described in quantitative detail in the main text. There is a minor description of the unique radar return pattern in a figure caption, but the supposed diagnostic radar return pattern for a lava tube is not described in the main text. The “unique radar backscatter” used to identify a Venusian lava tube needs to be described in the main text in detail so that readers can evaluate the identification criteria. At present this description lacks significant detail and needs to be greatly expanded.

#### Minor Comments:

- All my line edits are made within the PDF. I made comments over specific locations where sentences needed revisions. Text with lines through it indicate it should be removed or substantially rephrased.

- Line numbers in a manuscript are standard formatting practice for Nature articles and most journals. It was frustrating to not have them and made making specific comments more difficult. Please make sure to include line numbers in the future.

- A rille is not a lava tube. A rille is believed to form through a primarily deconstructive process (thermos- or mechanical-erosion of the substrate during a high-volume effusive eruption). Lava tubes are primarily a constructive process. Please update this detail throughout the manuscript.

- I agree with the authors that the feature may be a lava tube. Simila features are observed at Api Mons, Uti Hiata Mons, and Kali Mons. It would be useful in the discussion section or a conclusion paragraph to highlight the possibility of identifying lava tubes elsewhere on Venus.

- The manuscript switches between refereeing to the feature as a cave and skylight. This is confusing at times, as caves can have different formation processes and geologic implications. Please use consistent terminology throughout the manuscript. Since you are focused on volcanic features I suggest using volcanology terms.

#### Reviewer #3

##### (Remarks to the Author)

Review by Ernst of Carrer et al. “Radar-Based Observation of a Large Subsurface Lava Tube on Venus”

The absence of line numbers makes reviewing this paper more difficult!

The authors make the interesting proposal that a pit (labelled A in Fig.1) in the area of Nyx Mons, Bell Regio, Venus could be an example of a “skylight” on the top of a lava tube.

I like their idea that such pits could be “skylights”, and think that their geometric analysis is thoughtful and comprehensive

However, for multiple reasons detailed below, I think this example of this pit (labelled A in Fig. 1) and other pits visible in Fig. 1 represent collapse features located above laterally propagating subsurface dykes—particularly given that pit chains are widespread on Venus and that everywhere I have looked (in at least 40 different regions in connection with the detailed mapping by our student members of our International Venus Research Group), the pit chains tend to be parallel to sets of grabens, which are typically interpreted to be underlain by mafic dyke swarms.

And for these reasons (elaborated upon below), I must suggestion rejection of this manuscript.

1) First of all the particular feature that they have chosen, labelled A in figure 1 is not particularly unique and is clearly aligned with other pits along a NW-SE trend---- and another line of smaller pits about 15 km to the NE (by the way, Figure 1 needs a scale bar). There is also another NW-SE trend of small pits near their white arrow.

In Davey et al. (2013 *Can. J. Earth Sci*) and in Patterson et al. (2016, LPSC, extended abstr. #2097) it is proposed that pit chains are typically aligned with sets of grabens, and also underlain by dyke swarms---- since there is now abundant literature to suggest that graben-fissure fracture systems (with linear, radiating and circumferential patterns) on Venus are typically underlain by mafic dyke swarms (e.g. Grosfils and Head, 1994 EMP; Grosfils and Head, 1994 GRL; Ernst et al. 2001 *Ann Rev Eand Planetary Rev*; Buchan and Ernst, 2021 *Gondwan. Res.*; El Bilali et al. 2023 *Comm. E and Environ*; El Bilali and Ernst, 2024 *Nat. Comm.*; Ben Marzoug et al. 2024 *Icarus*; Hannour et al. 2024 *Icarus*; Tessier et al. 2024 *Icarus*).

In fact Riaz et al. (2023; LPSC, extended abstract #1510) did detailed mapping of graben fissure systems and pit chains in the Bell Regio region and have interpreted a number of distinct dyke swarms. So I think that your pit chains (including the one labelled A) are likely part of one of her dyke swarms (haven't had a chance to double check)

I should also point out that Davey et al. (2013) in particular suggest that whether dykes produce overlying grabens or pit chains, depends on the surface material—specifically that less cohesive surface units (e.g. poorly welded volcanoclastic material) would be more likely to produce pits, while more massive mechanically competent flows have surface failure in graben mode.

It also true that the pit chains on Mars are generally linked to subsurface dykes: e.g. Mege and Masson (1996 Planet. Space Sci.), and the recent El Yazidi et al (2024 Icarus). Although I should note that the recent paper of Wyrick and Buczowski (2002, JGR Planets) is less favouring of the dyke swarm interpretation)

2) A second concern of the skylight interpretation is the following: that “skylight A to belong to a winding (sinuous) collapse chain originating NW and progressively descending SE (see Supplementary Fig. 2).” But if this is the path of lava tube, then the downhill topography direction should be to the SE. Therefore available Magellan topography data needs to be discussed to reveal whether the downhill direction is to the SE (unfortunately, this may be difficult to do with the large uncertainty footprint of the Magellan altimetry data).

3) A third concern is that while their geometric analysis of SAR data seems rigorous, I think represents an overinterpretation based on the poor resolution of the available Magellan data. There are large uncertainties in their analysis given the 75 m/pixel resolution and potentially additional uncertainties such as a “layover effect” in SAR image interpretation --- I think the uncertainties in their analysis are large in comparison with the values they determined “a roof thickness of at least 150 m and an empty void height of no less than 375 m. The conduit extends in the subsurface for at least 300 meters from the skylight.”

I suspect if they included uncertainties and error propagation in their analysis that the uncertainties would be of the scale of their preferred values.

I should point out that their analysis approach may be useful for higher resolution data from future missions to Venus

Another comment on this text--- near the end of manuscript “The preserved layers within the conduit walls could serve as a detailed record of the planet's volcanic history, enabling the reconstruction of geological timelines and aiding in the understanding of geological processes on Venus and other celestial bodies.” But the lava tube represents a single flow--- and ledges on the walls of the tube will simply reveal changes partial crystallization of the flow at different stages of the flow history of this particular flow--- NOT anything more grand about the “detailed record of the planet's volcanic history”

Figure 1: needs a scale bar

Version 2:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

I was very happy to read this revised manuscript and the response to reviewers, and was impressed with how thoroughly they addressed my concerns and recommendations. The new references provide a stronger basis for their interpretations and better integrate this study into the existing body of work on planetary lava flows (and orbital detections of potential lava tubes on other planets), and introduced me to a few great new papers. The more over-the-top and less substantiated, generalized claims from the last version are gone, and we are left with a focused, well-supported, but still very exciting application of a novel radar processing method on Magellan data, yielding the first (to my knowledge) confirmed detection of a lava tube on Venus.

I have made minor comments in a tracked-changes PDF- mostly grammar but with a few suggestions in the margins.

I did notice that the main text is specifically calling out details in a figure that is currently in the supplement (supplemental Figure 2). If this is important enough to be discussed in this level in the main text, perhaps this figure should be moved to the main text? This is the one place in the paper where you are showing that the radar backscattering pattern for other Venus pits you examined is distinct from your Pit A (the one with the lava tube), so if you have the space, it might be worth promoting it to the main text.

Nice work!

Reviewer #2

(Remarks to the Author)

The authors of the manuscript "Radar-Based Observations of a Large Subsurface Lava Tube on Venus" have addressed the majority of comments I brought up during the initial review. Specifically, I want to acknowledge the authors have done an excellent job expanding the description of the radar signature they observe on Venus (lines 103-119). After reviewing the updated manuscript, my remaining comments are minor and primarily meant to improve the clarity and accuracy of the text. These text edits are relatively minor but are important to ensure readers correctly understand the authors and for consistent terminology in the literature. -Ian T.W. Flynn

Minor Comments:

1. I recommend a minor title change by removing the words "large" and "subsurface". The new title would be "Radar-Based Observations of a Lava Tube on Venus". My logic behind this is that we don't have constraints on how large Venusian lava tubes are. This one is large when compared to Earth lava tubes, but we don't know how it compares to other Venusian lava tubes, thus having "large" in the title may be misleading. As for "subsurface", lava tubes, by definition, are a structure that is below the surface. Saying a "subsurface lava tube" is redundant. Please consider this title change.
2. There are basic volcanology terms that are consistent throughout the peer-reviewed published literature. I have made note of these issues in my line edits. Please use established terms for describing volcanic features and processes.

Line Edits:

1. Line 15: remove "very", an adverb is not required to describe this feature. As I mentioned above, you have a sample size of one for lava tube sizes.
2. Line 33: Levee does not need the "é".
3. Line 33: Channelized lava flow, not "channeled lava stream".
4. Line 35: Mobile pieces of crust, not plates.
5. Line 58: "...thick CO<sub>2</sub> atmosphere". The composition is important to mention due to the atmospheric windows blocked by CO<sub>2</sub>. If the atmosphere was thick but composed of oxygen and nitrogen, visible images would be possible.
6. Line 75-76: It should say "receding lava chamber" or something similar. Just stating "lava chamber" is unspecific.
7. Line 85: Remove "very" in the sentence. The adverb is not needed.
8. Line 96-97: The diameter of the volcano is 362 km (Ivanov & Head, 2025). I recommend updating the value and adding this reference to the sentence.
  - a. Ivanov, M. A., & Head, J. W. (2025). Large volcanoes on Venus: Morphology, morphometry, and stratigraphy. *Icarus*, 429, 116404. <https://doi.org/10.1016/j.icarus.2024.116404>
9. Line 145-146: "It is worth noting that the Magellan data altimetric vertical uncertainty and low horizontal spatial resolution limits our ability to resolve small topographic variations."
10. Line 245-247: Usually peer-reviewed publications are preferable references over a dissertation thesis. Below is an example reference that may be more appropriate.
  - a. Komatsu, G., & Baker, V. R. (1996). Channels in the solar system. *Planetary and Space Science*, 44(8), 801-815.
11. Line 251-252: Similar to my above comment, the references below may be more appropriate.
  - a. Gregg, T. K. P., & Greeley, R. (1993). Formation of Venusian canali: Considerations of lava types and their thermal behaviors. *Journal of Geophysical Research*, 98(E6), 873-882. <https://doi.org/10.1029/93je00692>
  - b. Head, J. W., & Wilson, L. (1986). Volcanic processes and landforms on Venus: Theory, predictions, and observations. *Journal of Geophysical Research*, 91(B9), 9407. <https://doi.org/10.1029/jb091ib09p09407>
12. Line 253: "Indeed, Venus has a lower gravity....." Venus has a lower gravity, it doesn't show this.
13. Line 253-255: The Flynn et al., (2023) reference you cite in this sentence is not appropriate. We do state in the paper that due to the lower gravity of Venus, a 0.1% increase in crust would occur. We do not state this crust would be thick or form rapidly. Please either update the sentence to accurately reflect the results of the study or remove the reference from the sentence.
14. Figure 1: Is this the left-look or right-look mosaic? Please specify in the figure caption.
15. Figure 3: In my initial review I made several comments related to Figure 3. None of them have been made. I'll restate the necessary changes again. Figure 3a needs a scale bar. The figure caption description of Figure 3b needs to include more specific information than @Bing Maps Platform. This is unhelpful information for a future reader. Please state the satellite instrument that acquired the image and its spatial resolution.
16. Line 594-595: For the code availability statement, the Nature Portfolio of journals consider it best practice to release custom computer code in a way that allows readers to repeat the published results. I recommend the authors make any relevant code available via an open-source platform (e.g., GitHub or Zenodo).

Reviewer #3

(Remarks to the Author)

The authors have improved the manuscript to address my comments and those of the other two reviewers. But I still have concerns and cannot recommend acceptance.

On the positive side; they have shown that the topography is OK (downhill) for the interpreted path of the lava tube-- In the Supplementary File, Figure 1.

Regarding the uncertainties: they have calculated the uncertainties given a SAR pixel size of 75 m. But actually the SAR uncertainty is 100-200 m, which larger than the pixel size--- I am not sure of the specific SAR uncertainty for the Nyx Mons area.

Also in their modelling they infer that they are seeing into the interior of a lava tube >300 m deep. So the I think the "layover

effect" (where variations in elevation may cause lateral offsets in the positioning of the returned radar signal) may be relevant and should be discussed.

The link between figure 1 and Figure 2 (with their model) is illustrated in Supplementary Figure 6. However, how do we know that the radar bright material on the east side (labelled Delta R g2 and Delta R g3) is the interior of a lava tube and not some rough surface lava flow material. Also the supposed rock pile (Delta R g1) is radar dark which would seem to indicate that it is smooth material--- That would NOT be consistent with representing collapse material from the top of the lava tube.

When I look at the Figure 1, is it clear that their chosen pit /skylight is part of trend of at least 5 pits, and so if their chose pit (A) is a skylight then the 5 other pits should also be. So you should comment on the characteristics of these other pits and any evidence for or against them as skylights

But we know lines of pits associated with underlying dykes are common on Venus only; but the present text is focussed on the lava tube Skylight story. It still seems that the authors are pushing the skylight interpretation too hard, and should more fully address the underlying dyke swarm---in the revised manuscript, the dyke swarm interpretation is only addressed at the end of the paper.

I am sorry that I cannot be more positive. From reading the revised manuscript, I still think that this represents a significant overinterpretation of the available SAR data, but does represent a technique that can be used for Venus once we have higher resolution SAR and altimetry data.

[By the way Figure 1 needs a scale bar for the main part of the feature].

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# **Radar-Based Observation of a Large Subsurface Lava Tube on Venus**

*Leonardo Carrer, Elena Diana & Lorenzo Bruzzone*

We would like to thank the Editor and the Reviewers for their valuable suggestions. We performed the following major modifications to the paper:

- Added early Venus lava tube studies and planetary volcanology references; expanded discussion on lava tube formation processes and expected occurrence on Venus under extreme environmental conditions.
- Corrected Magellan radar description, clarified limitations of optical imagery, updated Venus specific references for radar backscatter, and refined terminology for consistency.
- Expanded description of radar backscatter signatures, added terrestrial and Venusian pit comparisons, included uncertainty analysis for geometric estimates from Magellan data, improved the radar signatures description of the various terrestrial analogues in the Discussion section.
- Added morphometric comparison with planetary and terrestrial lava tubes; discussed alternative interpretations of Pit A (dyke-related collapse) while highlighting the distinctive radar signature supporting the skylight and horizontal conduit hypothesis; confirmed downhill orientation using topographic data, removed speculative claims regarding preserved layered deposits.
- Reformulated exaggerated claims, integrated minor stylistic edits, added Figure 1 scale bar, and included line numbers per journal standards.
- Implemented editorial suggestions provided by the Reviewers in the pdf file.

In the following pages the point-by-point answers to the Reviewers comments are provided.

## Reviewer 1

*This manuscript details the very exciting confirmation of a lava tube entrance on Venus. Over the last few decades, orbital data has strongly suggested (or even confirmed) the existence and nature of lava tubes on the moon and Mars, and this new confirmation for Venus just goes to show that these are ubiquitous features of planetary surfaces with histories of basaltic volcanism. It uses an approach developed and previously applied by the authors for characterizing lunar lava tube entrances using radar, and includes a comparison of radar data for a terrestrial analog lava tube, and the manuscript convincingly rules out other potential features. As such it is worthy of publication.*

*However, there is definitely room for improvement. My main criticism of this manuscript is its repeated exaggeration- of the novelty of this work (e.g. there being no confirmed Martian detections) and its importance (e.g. relevance to future robotic missions, access to layered deposits), however this could be remedied by more measured language, better referencing, and more realistic (but still important!) implications. The core of the manuscript is strong enough to support publication without the hyperbole.*

*Here are some specific recommendations:*

*[RC-1-1]The manuscript misses out on some early studies of crater chains (and prospective lava tubes) from the early post-Magellan mission days. Citations of those works would help show how long this question has been out there, and that this work is using a novel SAR interpretation approach (and new analog comparisons) to answer a question where only speculation existed before. This one is only a thesis but has extensive coverage of the topic: Melville, Graeme P (1994). Lava tubes and channels of the Earth, Venus, Moon and Mars. University of Wollongong. Thesis. <https://hdl.handle.net/10779/uow.27649461.v1> This one is shorter but mentions Venus lava tubes (co-authored by the author of the thesis listed above): Publications of the Astronomical Society of Australia, Volume 10, Issue 3, 1993, pp. 200 – 202. DOI: <https://doi.org/10.1017/S1323358000025662>*

**Author Reply:** Thank you for the useful suggestion. We have included the citation to the proposed thesis work with relation to the hypothesis of lava tubes on Venus.

*[RC-1-2]The introduction says that "...from optical images (e.g., by photoclino-metry) it is very difficult to assess whether a subterranean cave extends from the skylight." I will agree that this is true, but it also undersells some of the quality work that has been done trying to do just that- e.g. in Haruyama et al. (2009), a paper you're already citing elsewhere. You make the stronger case for your work in the next sentence (e.g. you couldn't use imagery for Venus anyways).*

**Author Reply:** We agree. We reformulated it by stating that optical images are of great aid in locating and analyzing skylights, but the use of satellite optical remote sensing instruments is precluded on Venus because of its thick atmosphere.

*[RC-1-3] A sentence later in the Intro, you say that “Magellan is a spaceborne side-looking SAR...” Do you mean that Magellan HAD a spaceborne side-looking SAR? Or more precisely that it had a radar system (the RDRS) that could operate in a SAR mode?*

**Author Reply:** Thank you for pointing out the misleading sentence. Magellan is actually the name of the mission and spacecraft. Its primary instrument was a radar system capable of operating in three different acquisition modes, (a SAR mode, an altimeter mode and a radiometer mode). We have corrected the mentioned sentence accordingly.

*[RC-1-4] Page 7, last sentence of the first paragraph states “These deposits tend to increase the radar backscattering uniformly around the feature” in reference to impact craters. The reference cited relates to radar imaging of craters on the Moon- could you cite a Venus-specific source? Venus craters have much different ejecta patterns than lunar ones, often involving more impact melt, and not as “rough” in radar as lunar craters (and can even be brighter than their surroundings in radar images). See <https://www.hou.usra.edu/meetings/lpsc2023/pdf/1052.pdf> and other refs regarding Venus ejecta.*

**Author Reply:** Thank you for your suggestion. We have added citations to the following papers:

- The unusual surface texture of Venusian impact ejecta (Neish et al. 2023), as suggested
- Geology and Distribution of Impact Craters on Venus: what are they telling us? (Schaber et al., 1992)

From the two papers it is possible to observe that, despite the peculiar aspect of some impact craters, (e.g., due to outflow deposits), bright areas related to ejecta surround in a relatively uniform manner the central crater rather than concentrating exclusively on a single direction. Moreover, according to Schaber et al., it appears that extensive bright outflows are generally related to bigger impact craters.

*[RC-1-5] Page 7, second paragraph, second sentence: “Given that there are no confirmed detections of intact lava tubes for the Martian case...” Are you sure you want to say this? Do you mean confirmed using the SAR method? I’m sure there are members of the HiRISE team (MRO) who would contend that their lava tube entrances on Alba and Arsia Mons are “confirmed.” Sauro et al. (2020), which you are already citing, discusses this. With no other discussion in this manuscript about what you mean by “confirmed,” this statement is unsupported.*

**Author Reply:** We thank the reviewer for this helpful clarification. We have removed the sentence to avoid ambiguity. In our original wording, by “confirmed” we intended to refer specifically to skylights that demonstrably provide access to an open, laterally extensive subsurface conduit (“an intact lava tube”), rather than simply the surface expression of a collapse feature.

*[RC-1-6] Same paragraph, in reference to the critical factors influencing lava tube stability- the reference cited is great but makes no mention of Venus. You should make it clearer that this reference does not mention Venus (or Venus-specific conditions). I don't know but I'd be curious if factors such as high atmospheric pressure, or prolonged cooling times (given high surface temperatures) could affect their stability, or the tensional strength of the lava material. As you've just stated ahead of this sentence, there is currently no info about the structural stability of lava tubes on Venus. While it is clearly beyond the scope of this paper to model this, it might be good to acknowledge that Venus surface conditions could potentially influence this (and perhaps that further work is needed to assess whether the general conditions for lava tube stability developed in the paper cited can be applied to Venus).*

**Author Reply:** Agreed. We modified this sentence in the manuscript: "The critical factors influencing their stability are the thickness of the tube's ceiling, the lava tube cross section and the tensile strength of the lava material" → "The critical factors influencing their stability are the thickness of the tube's ceiling, the lava tube cross section and the tensile strength of the lava material. The surface of Venus experiences significantly higher temperatures and pressures than Mars or the Moon. These extreme conditions may influence the morphology and stability of the lava tube."

*[RC-1-7] Final paragraph, page 8. Some of the applications seem wildly fanciful to me and should be scaled back. That this skylight "could also be of great interest as targets for a possible lander robotic mission" with a citation to a DAVINCI mission paper is way off- that is not a robotic mission and will at best only return data for minutes if it as a soft landing, and it already has a target area. The next sentence talks about "preserved layers within the conduit walls could serve as a detailed record of the planet's volcanic history, enabling the reconstruction of geological timelines." I've spent many weeks in lava tubes on multiple continents (and islands) and I have never seen layered deposits, except for maybe one flow covering another flow or two (but likely separated in time by years at most). It's just not the kind of environment that preserves a long record.*

**Author Reply:** Thank you for the suggestion. We decided to remove the paragraph.

*[RC-1-8] I've made multiple minor corrections and suggestions for more concise language, for example replacing "in the proximity of" with "near" throughout. I'm attaching an annotated PDF with my suggestions.*

**Author Reply:** Thank you. The corrections have been integrated in the revised paper.

## Reviewer 2

*The authors present an argument that a geologic feature on the western flank of Nyx Mons, Venus, is a lava tube. This would be a new identification of a lava tube on Venus. Lava tubes have been discussed briefly in the Venus volcanology literature but little to no evidence has been presented identifying one. The primary evidence that the feature is a lava tube is the unique radar return pattern and a qualitative comparison to a terrestrial example at Lanzarote, Spain. The authors do an excellent job using radar remote sensing to present an argument that the feature on Venus is a lava tube. However, the manuscript is lacking in several essential areas that I explain below. Identifying a lava tube on Venus is an exciting possibility, however as this manuscript is currently written I cannot recommend it be published. The majority of my comments can be addressed with text edits. I recommend major revisions and look forward to seeing the revised manuscript.*

### *Major Comments:*

*[RC-2-1] A general major comment is that the authors rely on the planetary cave literature rather than the planetary volcanology literature. This by itself would not be an issue, but the authors do not include accurate information about lava tube formation and similar volcanology processes. I make several line edits and other major comments related to this issue. As the manuscript focuses on the identification of a lava tube, a volcanic feature, I encourage the authors to revisit some of their citations to make sure they are appropriate.*

**Author Reply:** Thank you. We greatly revised the paper by including planetary volcanology literature to complement the one on planetary caves.

*[RC-2-2] The authors do not cover the full spectrum of volcanology processes that could form a lava tube. I made a note of this in the introduction (see the attached PDF) and below are some references that could be used to help the authors expand the introduction. Only a few additional sentences would be needed to explain the other lava tube formation processes in the introduction. As written, the authors give the impression lava tubes can only form under one mechanism, and this is not correct.*

- o Peterson, D. W., Holcomb, R. T., Tilling, R. I., & Christiansen, R. L. (1994). Development of lava tubes in the light of observations at Mauna Ulu, Kilauea Volcano, Hawaii. *Bulletin of Volcanology*, 56, 343-360.*
- o Valerio, A., Tallarico, A., & Dragoni, M. (2008). Mechanisms of formation of lava tubes. *Journal of Geophysical Research: Solid Earth*, 113(B8).*
- o Calvari, S., & Pinkerton, H. (1999). Lava tube morphology on Etna and evidence for lava flow emplacement mechanisms. *Journal of Volcanology and Geothermal Research*, 90(3-4), 263-280.*

**Author Reply:** Thank you for pointing out the confusion that can arise from the limited explanation about lava tube formation. As suggested, we have extended the introduction to include a more detailed explanation.

*[RC-2-3] Similar to the above comments, the authors should add some discussion either in the introduction or discussion as to if the formation of lava tubes on Venus is expected. Given the extreme environmental conditions on Venus, it is unclear on how lava tubes will form on the planet. Head and Wilson, (1988) briefly describe that lava tube formation on Venus should be more common than on Earth. Flynn et al., (2023) discusses how the reduced gravity on Venus should promote the increased formation of crust cover, which could promote the formation of lava tubes. There needs to be some discussion in the manuscript about whether the formation of lava tubes is expected or could occur on Venus.*

*o Head III, J. W., & Wilson, L. (1986). Volcanic processes and landforms on Venus: Theory, predictions, and observations. Journal of Geophysical Research: Solid Earth, 91(B9), 9407-9446.*

*o Flynn, I. T., Chevrel, M. O., & Ramsey, M. S. (2023). Adaptation of a thermorheological lava flow model for Venus conditions. Journal of Geophysical Research: Planets, 128(7), e2022JE007710.*

**Author Reply:** Thank you for the suggestion. In the Discussion section, we have added a discussion about why lava tubes are expected to form also on Venus, including reference to the suggested papers.

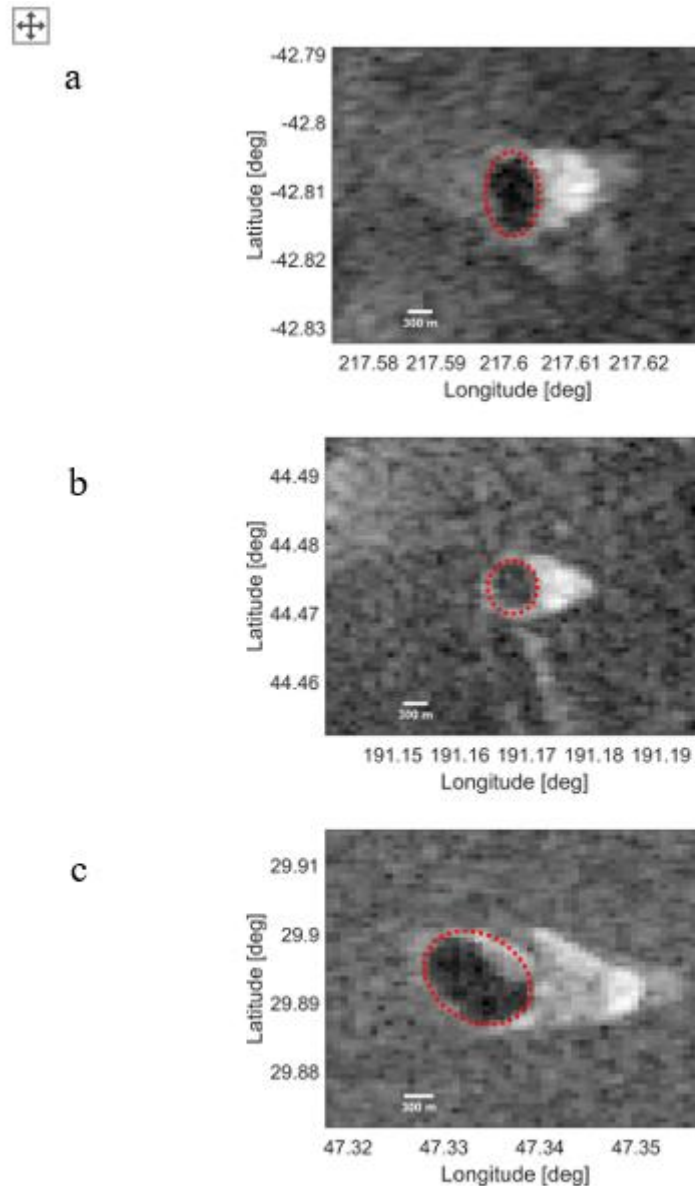
*[RC-2-4] Page 5 last paragraph: The authors do an adequate job comparing their results to those on the Moons and Mars. However, there are two issues with the comparison. (1) There should be a comparison to an equivalent Earth lava tube included. This is necessary to contextualize the results between the other planetary bodies. (2) The Mars reference is for pit craters and not all pit craters are formed via lava tube collapse (Wyrick et al., 2004). The authors need to be consistent and make sure they are comparing the correct volcanic features to each other. Furthermore, we do not have good spatial constraints (lengths, widths, volumes) on the reported extents of planetary lava tubes. As this text is currently written it makes it sound like these values are 100% accurate and does not provide the necessary context.*

*o Wyrick, D., Ferrill, D. A., Morris, A. P., Colton, S. L., & Sims, D. W. (2004). Distribution, morphology, and origins of Martian pit crater chains. Journal of Geophysical Research: Planets, 109(6). <https://doi.org/10.1029/2004JE002240>*

**Author Reply:** We agree with the comment. We have decided to expand the discussion, by adding a new subsection in the Results section to better address the morphometric comparison of planetary lava tube collapses. Now, we explicitly cite the paper from which we extracted the measures for martian, lunar and terrestrial lava tube collapse candidates (Sauro et al. 2020). Finally, we have included a brief size comparison between the hypothesized lava tube on Venus and the Corona lava tube.

*[RC-2-5] The main text of the manuscript mentions the “unique radar backscatter” associated with lava tube skylights. This is the primary result used in the manuscript to indicate the Venusian feature is a lava tube. However, the specific radar return pattern is not described in quantitative detail in the main text. There is a minor description of the unique radar return pattern in a figure caption, but the supposed diagnostic radar return pattern for a lava tube is not described in the main text. The “unique radar backscatter” used to identify a Venusian lava tube needs to be described in the main text in detail so that readers can evaluate the identification criteria. At present this description lacks significant detail and needs to be greatly expanded.*

**Author Reply:** We thank the reviewer for this important comment. We have revised and expanded the main text (see revised *Study Area and Magellan Radar Image Analyses* section) to provide a more detailed description of the radar backscatter pattern that we associate with lava tube skylights. Furthermore, we have added additional radar images to the discussion (see Supplementary Fig.2), illustrating more clearly the contrasts between the Magellan backscattering response of a skylight connected to a lateral subsurface conduit and that of other types of pits (e.g., vertical collapse pits).



25 **Supplementary Figure 2. Comparison of Magellan SAR radar responses from different pits.**  
 26 **a**, a pit near Idunn Mons. **b** a pit in Ganiki Planitia and **c**, the candidate skylight denoted as pit A  
 27 near Nyx Mons shown in Fig. 1.

Minor Comments:

- *All my line edits are made within the PDF. I made comments over specific locations where sentences needed revisions. Text with lines through it indicate it should be removed or substantially rephrased.*

**Author Reply:** Thank you. We have revised the paper according to the comments within the PDF.

- *Line numbers in a manuscript are standard formatting practice for Nature articles and most journals. It was frustrating to not have them and made making specific comments more difficult. Please make sure to include line numbers in the future.*

**Author Reply:** We included the line numbers. We apologize for having forgotten them. Thank you for the detailed suggestions.

- *A rille is not a lava tube. A rille is believed to form through a primarily deconstructive process (thermos- or mechanical-erosion of the substrate during a high-volume effusive eruption). Lava tubes are primarily a constructive process. Please update this detail throughout the manuscript.*

**Author Reply:** Thank you for pointing out this. We have fixed this in the paper.

- *I agree with the authors that the feature may be a lava tube. Simila features are observed at Api Mons, Uti Hiata Mons, and Kali Mons. It would be useful in the discussion section or a conclusion paragraph to highlight the possibility of identifying lava tubes elsewhere on Venus.*

**Author Reply:** The possibility of detecting similar feature across other regions on Venus has been included in the conclusions section.

- *The manuscript switches between refereeing to the feature as a cave and skylight. This is confusing at times, as caves can have different formation processes and geologic implications. Please use consistent terminology throughout the manuscript. Since you are focused on volcanic features I suggest using volcanology terms.*

**Author Reply:** This has been fixed in the revised paper.

### Reviewer 3

*The authors make the interesting proposal that a pit (labelled A in Fig. 1) in the area of Nyx Mons, Bell Regio, Venus could be an example of a “skylight” on the top of a lava tube.*

*I like their idea that such pits could be “skylights”, and think that their geometric analysis is thoughtful and comprehensive.*

*However, for multiple reasons detailed below, I think this example of this pit (labelled A in Fig. 1) and other pits visible in Fig. 1 represent collapse features located above laterally propagating subsurface dykes—particularly given that pit chains are widespread on Venus and that everywhere I have looked (in at least 40 different regions in connection with the detailed mapping by our student members of our International Venus Research Group), the pit chains tend to be parallel to sets of grabens, which are typically interpreted to be underlain by mafic dyke swarms.*

*And for these reasons (elaborated upon below), I must suggest rejection of this manuscript.*

*[RC-3-1] First of all the particular feature that they have chosen, labelled A in figure 1 is not particularly unique and is clearly aligned with other pits along a NW-SE trend---- and another line of smaller pits about 15 km to the NE (by the way, Figure 1 needs a scale bar). There is also another NW-SE trend of small pits near their white arrow.*

*In Davey et al. (2013 Can. J. Earth Sci) and in Patterson et al. (2016, LPSC, extended abstr. #2097) it is proposed that pit chains are typically aligned with sets of grabens, and also underlain by dyke swarms---- since there is now abundant literature to suggest that graben-fissure fracture systems (with linear, radiating and circumferential patterns) on Venus are typically underlain by mafic dyke swarms (e.g. Grosfils and Head, 1994 EMP; Grosfils and Head, 1994 GRL; Ernst et al. 2001 Ann Rev Eand Planetary Rev; Buchan and Ernst, 2021 Gondwan. Res.; El Bilali et al. 2023 Comm. E and Environ; El Bilali and Ernst, 2024 Nat. Comm.; Ben Marzoug et al. 2024 Icarus; Hannour et al. 2024 Icarus; Tessier et al. 2024 Icarus).*

*In fact Riaz et al. (2023; LPSC, extended abstract #1510) did detailed mapping of graben fissure systems and pit chains in the Bell Regio region and have interpreted a number of distinct dyke swarms. So I think that your pit chains (including the one labelled A) are likely part of one of her dyke swarms (haven't had a chance to double check)*

*I should also point out that Davey et al. (2013) in particular suggest that whether dykes produce overlying grabens or pit chains, depends on the surface material— specifically that less cohesive surface units (e.g. poorly welded volcanoclastic material) would be more likely to produce pits, while more massive mechanically competent flows have surface failure in graben mode.*

*It also true that the pit chains on Mars are generally linked to subsurface dykes: e.g. Mege and Masson (1996 Planet. Space Sci.), and the recent El Yazidi et al (2024 Icarus). Although I should note that the recent paper of Wyrick and Buczkowski (2002, JGR Planets) is less favouring of the dyke swarm interpretation)*

**Author Reply:** We acknowledge that apart from lava tube collapses, Venusian's pits may have originated from different geologic processes, such as tectonic or volcanic activity such as dyke intrusion (Davey et al., 2013, Sawford et al. 2015, Wyrick and D. L. Buczkowski 2022). In fact, we included a discussion on this in our previous paper (Carrer et al., 2024) where we assess the morphometry of pit craters on Venus from SAR data. In that paper, we have not identified any discernible differences in the analyzed pit's morphometric radar-derived parameters that would suggest variations in the underlying genetic processes. In this context, it is worth highlighting recent research suggesting that the shape and dimensions of pit craters may not provide substantial insights into the specific processes responsible for their formation or the characteristics of the surrounding materials (Magee et al., 2022).

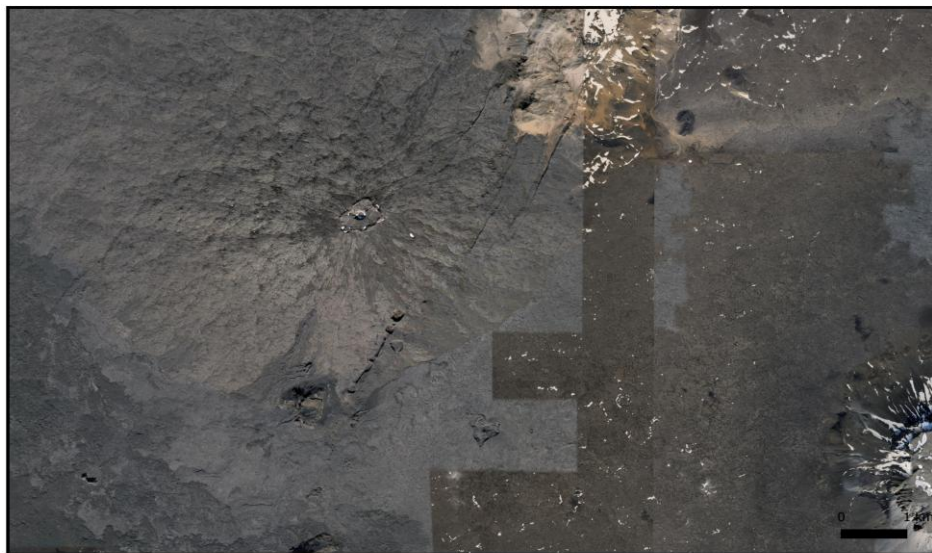
However, the pit analyzed in this study exhibits a distinctive radar signature that sets it apart from all other Venusian pits we examined in Carrer et al. (2024). Its radar response closely resembles that of a lava tube skylight, consistent with the terrestrial analogs presented in Carrer et al. (2022), which we also reference in this paper (see also the additional analysis we added in the new Supplementary Fig. 2). Taking into account the comment of the reviewer, we decided to add another example of SAR of collapse pits, produced by dyke swarms in Iceland.

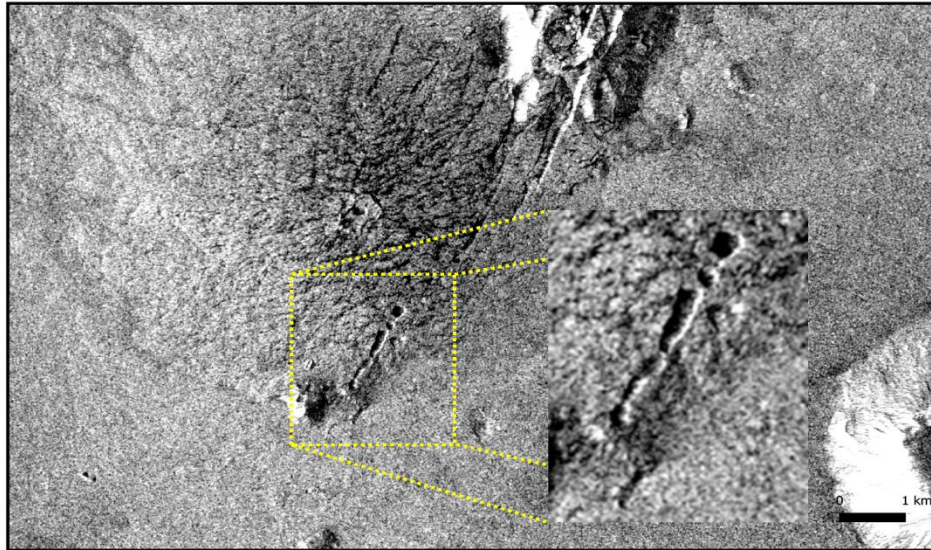
The pits belong to a 1.7 km long chain located in the Kollóttadyngja lava shield, in the Northern Volcanic Zone of Iceland, and is considered to be part of the Askja fissure swarm (Hjartardóttir 2008). The chain includes five pits crater, with a maximum width of about 150 m and a maximum depth of about 50 m. Besides, two shallower pits can be observed east to the main chain. Analyses have been conducted that associate the pit chain with the intrusion of one or more dikes under the Kollóttadyngja lava shield. In particular, Hjartardóttir (2008) suggests that the chain results from the collapse of a subsurface pipe, originated by an horizontal component of a dike under the mountain.

The radar response of the dyke induced pit resemble the response of a typical Venusian pit with no horizontal continuation. Thus based on the radar signature the most plausible explanation is that pit A is a surface collapse into an open void. We acknowledge the dyke swarm hypothesis and the revisioned paper explicitly discuss both these possibilities. We also added text noting that pit chains on Venus are often interpreted as dyke-swarm collapse features, and we cite relevant literature (Davey et al., Riaz et al., etc.) for completeness. We also state in the paper that dike intrusion accompanied by roof collapse remains a possible alternative. Laterally propagating magmatic dikes can separate overlying strata and create void spaces, and if the overlying material is sufficiently thin, localized collapse may occur, forming a pit that connects to a horizontal magmatic pathway.

**Text added to the manuscript:**

Another relevant hypothesis is the one of pit chains produced in association with dyke swarms, as these chains on Venus are frequently interpreted in this latter context <sup>35,36</sup>. A relevant terrestrial analogue example is from the Kollóttadyngja lava shield in the Northern Volcanic Zone of Iceland, where a 1.7 km-long chain of collapse pits, up to about 150 m wide and about 50 m deep, has been linked to the Askja fissure swarm<sup>37</sup>. The chain is interpreted as having formed by collapse into a subsurface pipe generated by the horizontal component of a dyke intrusion beneath the shield. The radar response of these dyke-induced pits resembles that of typical Venusian pits with no horizontal continuation (Supplementary Fig. 5). Therefore, the observed radar signature is most consistent with the interpretation that pit A represents a lava tube roof collapse into an underlying void with horizontal continuation. In general, laterally propagating magmatic dykes can separate overlying strata and create void spaces. If the overlying material is sufficiently thin, localized collapse may occur, forming a pit that connects to an horizontal magmatic pathway. The analysed terrestrial SAR data favours the lava tube hypothesis but we cannot completely rule out the possibility that pit A formed through dyke intrusion.





*Example of pits presumably generated by a dyke swarm in Iceland. These figures are reported in Supplementary Fig. 4 in the paper.*

#### References for this answer

Carrer, L., Diana, E., & Bruzzone, L. (2024). Assessing the Morphometry of Pit Craters on Venus from Orbital Synthetic Aperture Radar Data. *IEEE Transactions on Geoscience and Remote Sensing*.

Carrer, L., Castelletti, D., Pozzobon, R., Sauro, F., & Bruzzone, L. (2022). A novel method for hidden natural caves characterization and accessibility assessment from spaceborne VHR SAR images. *IEEE Transactions on Geoscience and Remote Sensing*, 61, 1-11.

Magee, C., Kling, C., Byrne, P., & A-L Jackson, C. (2022). Seismic reflection data reveal the 3D subsurface structure of pit craters. *Journal of Geophysical Research: Planets*, 127(8), e2021JE007155.

S. C. Davey, R. E. Ernst, C. Samson, and E. B. Grosfils, "Hierarchical clustering of pit Crater chains on Venus," *Can. J. Earth Sci.*, vol. 50, no. 1, pp. 109–126, Jan. 2013.

W. Sawford, R. Ernst, C. Samson, and S. Davey, "Pit Crater chains in the NYX mons region, Venus," in *Proc. 46th Lunar Planet. Sci. Conf.*, 2015, pp. 1–2.

D. Y. Wyrick and D. L. Buczkowski, "Pit Crater chains across the solar system: Evidence for subterranean tectonic caves, porosity and permeability pathways on planetary bodies," *J. Geophys. Res. Planets*, vol. 127, no. 12, Dec. 2022, Art. no. e2022JE007281.

Hjartardóttir Á.R., "The fissure swarm of the Askja central volcano", M.Sc thesis. University of Iceland, Reykjavík, 2008, pp 1-113.

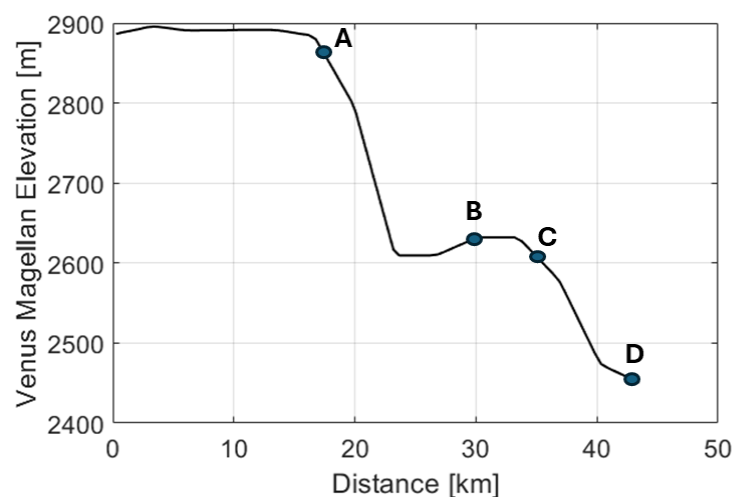
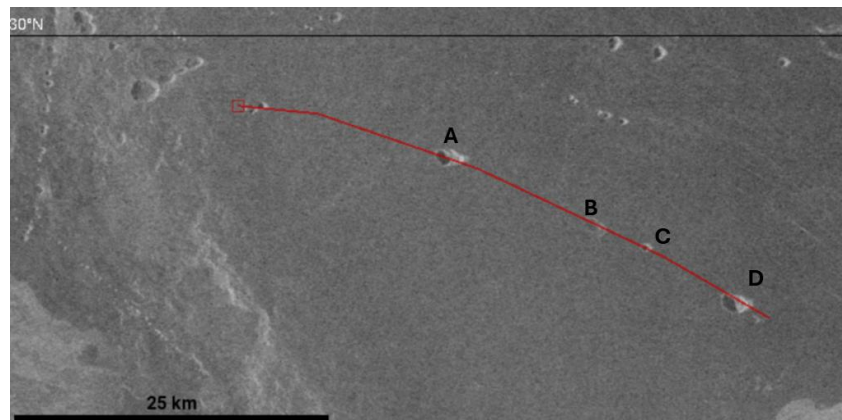
Ernst, R.E., Grosfils, E.B., and Mège, D., "Giant dyke swarms: Earth, Venus, Mars", *Annual Review of Earth and Planetary Sciences*, 2001 ,29(1): 489–534.

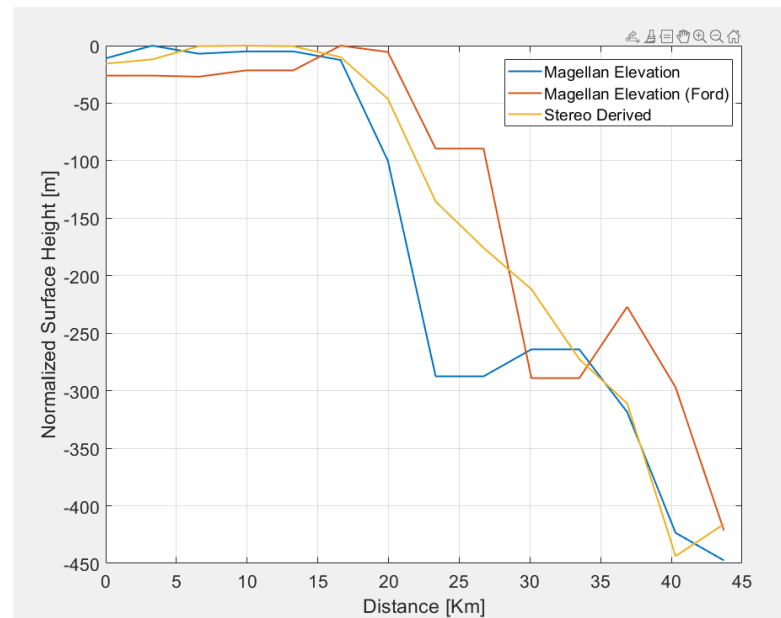
Riaz, M., Ernst, R.E., El Bilali, H., "Dyke Swarms of Bell Regio, Venus", 54th Lunar and Planetary Science Conference 2023, Abstract 1510.

[RC-3-2] A second concern of the skylight interpretation is the following: that “skylight A to belong to a winding (sinuous) collapse chain originating NW and progressively descending SE (see Supplementary Fig. 2).” But if this is the path of lava tube, then the downhill topography direction should be to the SE. Therefore available Magellan topography data needs to be discussed to reveal whether the downhill direction is to the SE (unfortunately, this may be difficult to do with the large uncertainty footprint of the Magellan altimetry data).

**Author Reply:** Thank you for raising this important point. We have conducted a comprehensive topographic analysis—now incorporated in the revised manuscript—using three independent datasets to assess whether Pit A lies downhill toward the SE (i) Magellan Altimetry (standard processing) (ii) Magellan Altimetry (Ford reprocessing) (iii) Stereo-derived topography from Magellan SAR stereo models. All the dataset confirm that the downhill direction is toward the South-East (see Figures). It is worth noting that we used JMARS for Venus (Herrick et al., 2017) to perform the analysis (<https://jmars.asu.edu/>).

Despite the relatively coarse resolution of Magellan altimetry all three datasets consistently indicate that the surface slopes toward the southeast from Pit A. This trend supports the idea that, if associated with a sinuous collapse chain, its orientation aligns with downhill topography as expected for a lava tube system. However, we agree that interpreting this result requires caution. The altimetric uncertainty limits our ability to resolve small topographic variations. We explicitly acknowledge this limitation in the manuscript revision.





Reference for this answer

Herrick, R. R., & Wren, P. (2017, November). JMARS: Collecting and ingesting data to create a useful scientific analysis tool. In 15th Meeting of the Venus Exploration and Analysis Group (VEXAG) (Vol. 15, No. 2061, p. 8021).

*[RC-3-3]A third concern is that while their geometric analysis of SAR data seems rigorous, I think represents an overinterpretation based on the poor resolution of the available Magellan data. There are large uncertainties in their analysis given the 75 m/ pixel resolution and potentially additional uncertainties such as a “layover effect” in SAR image interpretation --- I think the uncertainties in their analysis are large in comparison with the values they determined “a roof thickness of at least 150 m and an empty void height of no less than 375 m. The conduit extends in the subsurface for at least 300 meters from the skylight.” I suspect if they included uncertainties and error propagation in their analysis that the uncertainties would be of the scale of their preferred values. I should point out that their analysis approach may be useful for higher resolution data from future missions to Venus.*

**Author Reply:** Thank you for your comment. We already developed an uncertainty model in Carrer et al.,2024. In lights of the reviewer comment, we added the “Analysis of the uncertainties in the Determination of Skylight and Lava Tubes Geometric Parameters from Magellan Data” section to Methods.

Here we present the main equations. The measurement uncertainty is given by  $\delta R = R_r / \sqrt{2SNR} = 24.77 \text{ m}$  by assuming  $R_r = 88 \text{ m}$  and  $SNR = 8 \text{ dB}$ . Thus for Magellan we have that the uncertainty due to SNR is lower than the one given by the pixel resolution  $p$ :

$$\delta R < p$$

Given the incidence and look angle equal to 42.4 and 40 degrees, respectively, we can bound the errors to for the different estimated quantities. Estimated collapse depth uncertainty:

$$p \sin \theta_i \cdot \cos(\theta_l) = 38.74 \text{ m}$$

Radar Signal Propagation uncertainty:

$$p \sin \theta_i \cdot \sin(\theta_l) = 32.75 \text{ m}$$

Lava tube roof thickness (worst-case overestimation model) uncertainty:

$$p \sin \theta_i / \cos(\theta_i) = 66.02 \text{ m}$$

Cave height uncertainty:

$$p \sin \theta_i \cdot \cos(\theta_l) = 38.74 \text{ m}$$

Thus according to the above, the uncertainty is a fraction of the pixel resolution equal to 75 m and does not affect the conclusion of our analysis.

*[RC-3-4]Another comment on this text--- near the end of manuscript “The preserved layers within the conduit walls could serve as a detailed record of the planet’s volcanic history, enabling the reconstruction of geological timelines and aiding in the understanding of geological processes on Venus and other celestial bodies.” But the lava tube represents a single flow--- and ledges on the walls of the tube will simply reveal changes partial crystallization of the flow at different stages of the flow history of this particular flow--- NOT anything more grand about the “detailed record of the planet’s volcanic history”*

**Author Reply:** We decided to remove this sentence as suggested also by other Reviewers.

*[RC-3-5]Figure 1: needs a scale bar*

**Author Reply:** We added the scale bar

# Radar-Based Observation of a Lava Tube on Venus

Leonardo Carrer, Elena Diana & Lorenzo Bruzzone

We would like to thank the Reviewers for their valuable suggestions. We implemented all the requested modifications to the paper (see tracked highlights in yellow).

We address Reviewer #3's remaining concerns. The clarification on SAR uncertainties explains that the reviewer's 100–200 m values reflect ground-range resolution, whereas our measurements rely on the finer slant-range resolution appropriate for lava tube geometry. We also explain that the radar dark signature of the collapse material results from geometric shadowing within the pit (this was already stated in the Results section of the paper), consistent with previous Venus SAR studies. The alternative dyke-swarm interpretation is now introduced early in the Introduction for balance, and we added explicit discussion showing that the method is not sensitive to layover under the modest topography of the study area.

Detailed replies to all comments are provided below.

## Reviewer 1

*I was very happy to read this revised manuscript and the response to reviewers, and was impressed with how thoroughly they addressed my concerns and recommendations. The new references provide a stronger basis for their interpretations and better integrate this study into the existing body of work on planetary lava flows (and orbital detections of potential lava tubes on other planets), and introduced me to a few great new papers. The more over-the-top and less substantiated, generalized claims from the last version are gone, and we are left with a focused, well-supported, but still very exciting application of a novel radar processing method on Magellan data, yielding the first (to my knowledge) confirmed detection of a lava tube on Venus.*

**Author Reply:** Thank you for your comment and your useful suggestion. We promoted the figure to the main text as Fig. 2 and included all the Reviewer editorial comments in the manuscript.

## Reviewer 2

*1. I recommend a minor title change by removing the words “large” and “subsurface”. The new title would be “Radar-Based Observations of a Lava Tube on Venus”. My logic behind this is that we don't have constraints on how large Venusian lava tubes are. This one is large when compared to Earth lava tubes, but we don't know how it compares to other Venusian lava tubes, thus having “large” in the title may be misleading. As for “subsurface”, lava tubes, by definition, are a structure that is below the surface. Saying a “subsurface lava tube” is redundant. Please consider this title change.*

**Author Reply:** We modified the title according to the suggestion.

2. There are basic volcanology terms that are consistent throughout the peer-reviewed published literature. I have made note of these issues in my line edits. Please use established terms for describing volcanic features and processes.

**Author Reply:** We implemented all the Reviewer suggestions. Thank you.

### Reviewer 3

*Regarding the uncertainties: they have calculated the uncertainties given a SAR pixel size of 75 m. But actually the SAR uncertainty is 100-200 m, which larger than the pixel size--- I am not sure of the specific SAR uncertainty for the Nyx Mons area. Also in their modelling they infer that they are seeing into the interior of a lava tube >300 m deep. So the I think the "layover effect" (where variations in elevation may cause lateral offsets in the positioning of the returned radar signal) may be relevant and should be discussed.*

**Author Reply:** We believe that the discrepancy between our calculations and the values reported by the Reviewer (i.e., 100-200 m) arises from how ground resolution is measured in radar systems. In general, Synthetic Aperture Radar (SAR) images measure distances in the slant-range plane, meaning that pixel spacing is referenced to the radar line of sight (see Fig. 1). When the radar beam intersects the surface at an incidence angle, the slant-range pixel projects onto a larger footprint in ground range. As a result, the effective ground-range resolution becomes coarser depending on the incidence angle. This is summarized in the following well-known radar theory equations. The radar slant range resolution is equal to:

$$\Delta R_{slant} = c_0/2B$$

where  $c_0$  is the speed of light and  $B$  is the bandwidth. The ground range resolution is equal to:

$$\Delta R_{slant} = \frac{c_0}{2B \sin \theta_i} = \frac{\Delta R_{slant}}{\sin \theta_i}$$

Given the Magellan radar bandwidth  $B=2.26$  MHz (see [Ref-1] and [Ref-2]), we obtain a slant-range resolution of approximately 66 m. Some studies suggest using an effective slant-range value of 88 m (see [Ref-3]), which accounts for non-idealities. This is the value we adopt in this paper, consistent with Ref. 3. Assuming typical values of the Magellan radar incidence angle (see [Ref-4] and the figure reproduced from that paper), we obtain a ground range resolution that aligns with the values provided by the Reviewer (i.e., 100-200 m). Thus, the slant-range resolution is notably finer than the ground range resolution. In our radar methodology we convert the ground-range resolution to slant-range resolution before performing any geometric measurements related to lava tubes [Ref-4] [Ref-5]. This can always be performed on that by taking into account the geometric factor described by  $\sin \theta_i$  [Ref-4] [Ref-5]. The additional uncertainty is computed from the slant range using the model provided in [Ref-4] and reported in 'Analysis of the Uncertainties in the Determination of Skylight and Lava Tubes Geometric Parameters from Magellan Data' method applied specifically to Nyx Mons in this manuscript. As a result, considering our specific geometry that is pertinent for

lava tubes geometric analysis [Ref-4] [Ref-5], the measurement uncertainties are below the pixel resolution of 75 m as reported in the manuscript under revision.

As a note, when measuring the distance between two features in a Magellan SAR (or any SAR) image, the uncertainty in relative measurements differs from the absolute geolocation uncertainty of individual features. Relative distances are generally more accurate, as many systematic errors cancel out.

### Discussion on the Layover effect:

The methodology is independent of surface layover effects especially with the modest topography present in the study area, which is notably smooth (see Supplementary Fig. 1c). Indeed, it explicitly accounts for the layover of the tube interior when computing its depth. Variations in surface elevation do not appreciably affect the results as surface roughness does, as the measurement specifically targets the interior of the tube (analyzing the echo returns from those specific features) rather than the surface above it [Ref-4], [Ref-5], [Ref-6], [Ref-7]. To make this explicit, we added the following statement to the discussion section: “Previous studies have demonstrated that the methodology is not adversely affected by surface layover for small to moderate topographic variations, such as those present in this case” (refs. 14, 21, 24, 33, see Supplementary Fig. 1c).

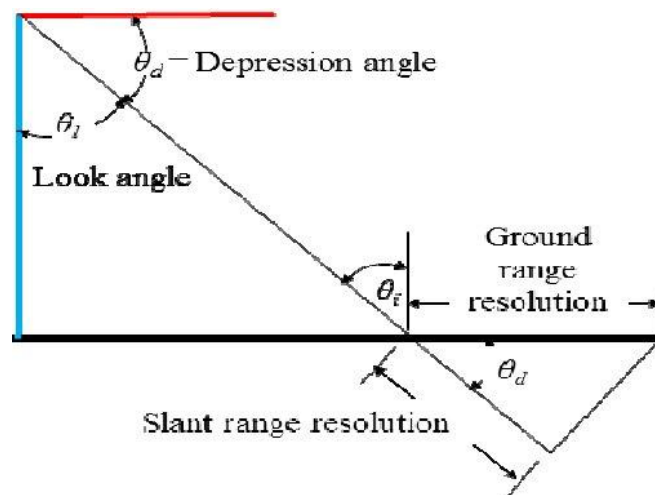


Figure 1. Typical geometry definition for a Synthetic Aperture Radar. The radar measures distances in the slant range plane.

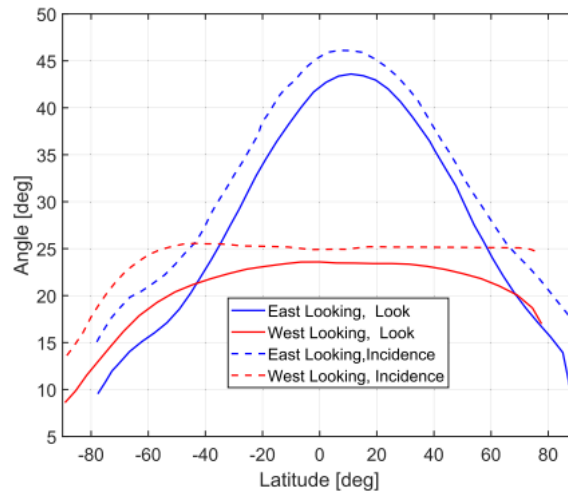


Fig. 7. Value of the Magellan SAR look and incidence angle versus the latitude. The radar was looking toward the East or West direction depending on the mission phase. Image reworked by combining data from [15], [30].

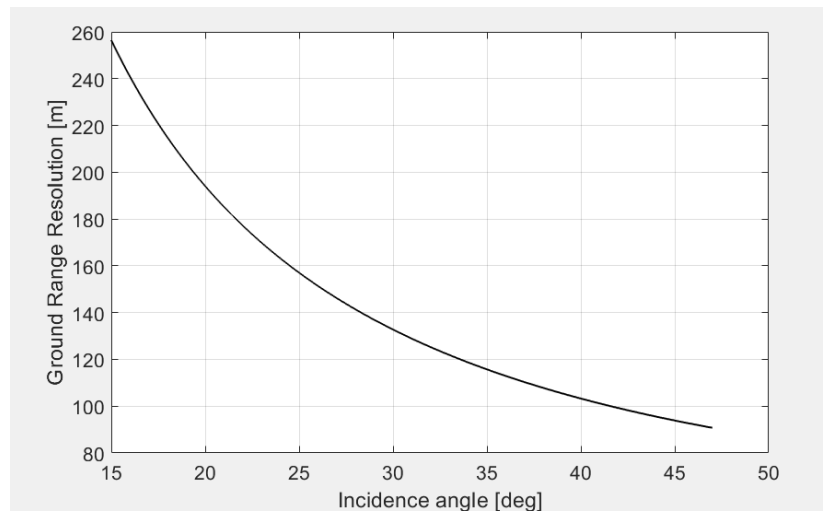


Fig. 2 Magellan Ground Range resolution as function of incidence angle. Ground range resolution is coarser than the slant range resolution.

#### References for this Answer

- [Ref-1] Saunders, R. S., Spear, A. J., Allin, P. C., Austin, R. S., Berman, A. L., Chandlee, R. C., ... & Wall, S. D. (1992). Magellan mission summary. *Journal of Geophysical Research: Planets*, 97(E8), 13067-13090.
- [Ref-2] Ford, J. P. (1993). Guide to Magellan image interpretation. National Aeronautics and Space Administration, Jet Propulsion Laboratory, California Institute of Technology.
- [Ref-3] S. Hensley and S. Shaffer, "Automatic DEM generation using Magellan stereo data," in *Proc. IEEE Int. Geosci. Remote Sens. Symp.*, vol. 3, Sep. 1994, pp. 1470–147
- [Ref-4] Carrer, L., Diana, E., & Bruzzone, L. (2024). Assessing the Morphometry of Pit Craters on Venus from Orbital Synthetic Aperture Radar Data. *IEEE Transactions on Geoscience and Remote Sensing*.
- [Ref-5] Carrer, L., Castelletti, D., Pozzobon, R., Sauro, F., & Bruzzone, L. (2022). A novel method for hidden natural caves characterization and accessibility assessment from spaceborne VHR SAR images. *IEEE Transactions on Geoscience and Remote Sensing*, 61, 1-11.
- [Ref-6] Carrer, L., Pozzobon, R., Sauro, F., Castelletti, D., Patterson, G. W., & Bruzzone, L. (2024). Radar evidence of an accessible cave conduit on the Moon below the Mare Tranquillitatis pit. *Nature Astronomy*, 8(9), 1119-1126.

[Ref-7] Carrer, L., Castelletti, D., Pozzobon, R., Sauro, F., & Bruzzzone, L. (2024). A method for the characterization of the interior of pits from single spaceborne SAR images. *IEEE Geoscience and Remote Sensing Letters*, 21, 1-5.

*The link between figure 1 and Figure 2 (with their model) is illustrated in Supplementary Figure 6. However, how do we know that the radar bright material on the east side (labelled Delta R g2 and Delta R g3) is the interior of a lava tube and not some rough surface lava flow material. Also the supposed rock pile (Delta R g1) is radar dark which would seem to indicate that it is smooth material--- That would NOT be consistent with representing collapse material from the top of the lava tube.*

**Reply:** These concerns were comprehensively addressed in [Ref-4], which also utilizes Magellan SAR data to study pit crater depths on Venus. The study demonstrates that it is highly unlikely that the radar-bright material represents rough lava flows, as the observed backscattering characteristics align with analogous features in terrestrial, lunar, and Venusian SAR datasets. Additionally, [Ref-4] includes 3D radar simulations based on laser scans of terrestrial analogues that specifically support this interpretation. The radar-dark appearance of Delta R g1 is attributed to shadowing effects within the pit rather than the intrinsic backscatter of the rock pile, explaining its low backscattering coefficient.

[Ref-4] Carrer, L., Diana, E., & Bruzzzone, L. (2024). Assessing the Morphometry of Pit Craters on Venus from Orbital Synthetic Aperture Radar Data. *IEEE Transactions on Geoscience and Remote Sensing*.

*When I look at the Figure 1, is it clear that their chosen pit /skylight is part of trend of at least 5 pits, and so if their chose pit (A) is a skylight then the 5 other pits should also be. So you should comment on the characteristics of these other pits and any evidence for or against them as skylights. But we know lines of pits associated with underlying dykes are common on Venus only; but the present text is focussed on the lava tube Skylight story. It still seems that the authors are pushing the skylight interpretation too hard, and should more fully address the underlying dyke swarm---in the revised manuscript, the dyke swarm interpretation is only addressed at the end of the paper.*

**Reply:** Taking into account the suggestion of the reviewer, in the revised paper we added since the introduction the possible interpretation of pits associated with underlying dykes among those plausible. Then later, as already done in the previous version, we analyze this interpretation and explain the reason for which in our opinion this is much less convincing than the lava tube one also using terrestrial analogous. Note that it is not our intention to push the skylight interpretation too hard (we do not completely rule out the dyke swarm interpretation in the text) but to align all the evidence obtained by our analysis that indicate the lava tube hypothesis as the most plausible.

The characteristics of 5 pits in Figure 1 are consistent with skylights whose entrances to the underlying lava tubes are obstructed by collapse material. Their radar and morphological signatures closely match those of analogous skylight features observed on Earth and the Moon [Ref-1][Ref-2]]. It is worth mentioning that there was already a sentence in the Results section addressing this point: "The other pits belonging to the chain denoted as B, C, and D

show no evidence of direct subsurface access as they have a radar response very similar to the one attributable to skylights with blocked conduit entrance as observed on Earth analogues<sup>24</sup>”

[Ref-1] Carrer, L., Castelletti, D., Pozzobon, R., Sauro, F., & Bruzzone, L. (2022). A novel method for hidden natural caves characterization and accessibility assessment from spaceborne VHR SAR images. *IEEE Transactions on Geoscience and Remote Sensing*, 61, 1-11.

[Ref-2] Carrer, L., Pozzobon, R., Sauro, F., Castelletti, D., Patterson, G. W., & Bruzzone, L. (2024). Radar evidence of an accessible cave conduit on the Moon below the Mare Tranquillitatis pit. *Nature Astronomy*, 8(9), 1119-1126.