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COMMENT

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This article is a comment on Byrne and Krishnamoorthy (2022), https://doi.org/10.1029/2021JE007040.

Key Points:

- Assuming that data from Earth can be scaled to Venus directly, I estimate that ~42 eruptions could take place on Venus annually
- Rift volcanism is significantly underestimated in the database, so the estimated volcanic eruption frequency on Venus is conservative
- The volcanic flux associated with the estimated volcanic eruption frequency aligns with previous estimates

Supporting Information:

Supporting Information may be found in the online version of this article.

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Comment on "Estimates on the Frequency of Volcanic Eruptions on Venus" by Byrne and Krishnamoorthy (2022)

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Abstract Byrne and Krishnamoorthy (2022), https://doi.org/10.1029/2021je007040 estimated the frequency of volcanic eruptions on Venus by scaling the eruption frequency obtained from a database containing Earth data. In reproducing their study, I found that the estimated number of new and ongoing volcanic eruptions on Venus in a given year is approximately 42, instead of the previously reported 120 eruptions. This updated estimate of Byrne and Krishnamoorthy (2022) based on the assumption that data from Earth can be scaled to Venus is an important step toward quantifying volcanism on Venus. However, it is important to note that in this estimate, the amount of volcanism associated with rifting is underestimated and subduction-related volcanism is overestimated. The annual volcanic flux on Venus resultant from the estimated amount of volcanic eruptions aligns with previous estimates of Venus' volcanic flux based on, for example, chemical reaction times and geological mapping. Applying the same method of estimating volcanic eruption frequency to the other terrestrial planets in the Solar System indicates that the Earth scaling method is perhaps not universally applicable, especially concerning bodies with vastly different tectonic regimes.

Plain Language Summary Much is still unknown about Venus, including how many volcanic eruptions might occur on its surface. This information is important as it would help with designing space missions and could greatly improve the understanding of the interior and dynamics of the planet. Byrne and Krishnamoorthy (2022), https://doi.org/10.1029/2021je007040 used statistical methods and a database containing information about volcanic eruptions on Earth to provide the first estimates of the amount of volcanic eruptions in a given year on Venus. They reported an estimated 120 volcanic eruptions on Venus per Earth year. I have reproduced their study and found that they made an error in their statistical method. Instead, the estimated amount of volcanic eruptions on Venus in an Earth year is approximately 42. This estimate contains uncertainties due to the lack of knowledge of volcanic eruptions in the oceans on Earth and the possibility of subduction occurring on Venus. However, despite these uncertainties, the updated estimate of Byrne and Krishnamoorthy (2022) is an important step toward exploring Venus as a volcanic world.

1. Introduction

Byrne and Krishnamoorthy (2022) used a database containing volcanic eruptions on Earth in combination with bootstrapping statistics to estimate the frequency of volcanic eruptions on Venus. In the absence of any other estimates, Byrne and Krishnamoorthy (2022) are the first to venture into this as-of-yet unexplored territory through a relatively simple scaling approach based on the planet's mass and surface area, as highlighted by King (2022). These kinds of estimates on eruptive frequency are essential for mission design and could potentially be tested by future missions (Mueller et al., 2017).

I have reproduced the study of Byrne and Krishnamoorthy (2022) and here point out a mistake in their statistical analysis and several important limitations of the database. Besides that, I put their findings into context with regards to previous estimates on Venus' annual extrusive volcanic flux and expand on their study by applying it to the other terrestrial planets in the Solar System.

2. Robustness of Byrne and Krishnamoorthy (2022)'s Results

When using the Global Volcanism Program's Volcanoes of the World (VOTW) v. 4.9.0 database (Global Volcanism Program, 2013; Krishnamoorthy & Byrne, 2021), Byrne and Krishnamoorthy (2022) assess the distribution of recorded Volcanic Explosivity Index (VEI) values through time (Figure 1 in Byrne and Krishnamoorthy (2022)). Based on this, they choose a cutoff date of 1 January 1980 to minimize a recording bias in the data set. However,

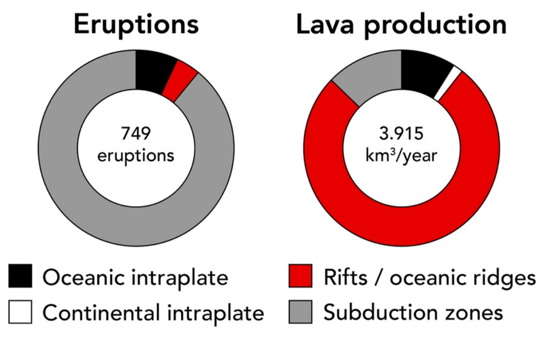

Figure 1. Pie diagrams showing the discrepancy between observed eruptions and estimated lava production on Earth. Left diagram shows the proportion of volcanic eruptions for oceanic and continental intraplate settings, and rift and subduction zones in the Volcanoes of the World 4.9.0 database used by Byrne and Krishnamoorthy (2022) from 2000 to 2021. Right diagram based on Crisp (1984) shows the proportion of estimated lava production (or volcanic flux) in similar tectonic settings. Note that the "rifts" classification used in Byrne and Krishnamoorthy (2022) includes continental as well as oceanic rifting. In contrast, Crisp (1984) considers oceanic rifting as a separate category ("oceanic ridges") and instead includes continental rifting within the "continental intraplate" category. Figure inspired by Siebert et al. (2011).

according to the Global Volcanism Program, the completeness of the VOTW 4.9.0 database can only be assumed from 2000 onwards. Rerunning the analysis of Byrne and Krishnamoorthy (2022) for Earth and Venus with the data from the VOTW 4.9.0 database from 2000 to 2021 changes the mean amount of estimated volcanic eruptions in a 60-day window (the expected life time of a balloon in Venus' atmosphere that could detect volcanic activity) up to ~0.7 eruptions (Tables S1 and S2 in Supporting Information S1). For example, Byrne and Krishnamoorthy (2022) predict 2.13 eruptions in the case of new and ongoing eruptions on Earth in an oceanic intraplate setting with a duration ≤1,000 days and here I predict 1.41 eruptions, which is a decrease of 66%.

Byrne and Krishnamoorthy (2022) estimate that as many as 120 discrete eruptions could take place on Venus per Earth year by multiplying the estimated number of new and ongoing eruptions (truncated to 1,000 days in duration) in a 60-day window by six, as there are six 60-day windows in a year. Although this simplified approach is valid to estimate the amount of new eruptions, it is incorrect to apply this to the estimates of new and ongoing eruptions since the eruption duration of 1,000 days exceeds the observational window of 60 days. This leads to the same eruption being counted multiple times. Rerunning the analysis with a 365-day window results in an estimated 26.59 new eruptions and 42.48 new and ongoing eruptions (instead of 120) on Venus per Earth year (Table S3 in Supporting Information S1).

3. Underestimation Rift Volcanism

Byrne and Krishnamoorthy (2022) discuss the underestimation of intraplate volcanism as one of the main limitations of their method and the VOTW 4.9.0 database. While this is indeed an important limitation, a far greater limitation of the database is its incomplete record of rift volcanism (Siebert et al., 2011). Since the VOTW 4.9.0 database records observed eruptions, it is incomplete when it comes to volcanic eruptions in the ocean at, for example, mid-oceanic ridges. The discrepancy between the eruptions recorded in the database and the extrusive lava production is illustrated in Figure 1 and shows that approximately 72.6% of the extrusive lava production is not accounted for by eruptions in the VOTW 4.9.0 database. Hence, using the VOTW 4.9.0 database for this type of statistical analysis significantly underestimates the amount of rift, and hence total, volcanic eruptions on both Venus and Earth, leading to the estimates of Byrne and Krishnamoorthy (2022) and the ones presented here to be conservative. It is, however, difficult to account for this discrepancy, because it is not possible to artificially scale up the amount of events in the database, although it is possible to scale the associated volcanic flux estimate (Section 5, Figure 2).

4. Overestimation Subduction Zone Volcanism

There is compelling evidence for subduction zone processes on Venus from observed topographic similarities to subduction troughs on Earth (Schubert & Sandwell, 1995) and modeling (Gerya, 2014; Gülcher et al., 2020). However, it is still unclear if the subduction processes on Venus would produce the same amount of volcanism as on Earth. In addition, the amount of subduction on Venus might be significantly less than on Earth with Schubert and Sandwell (1995) identifying approximately 10,000 km of potential subduction troughs on Venus in contrast to the total length of 51,310 km on Earth (Bird, 2003) as discussed in Byrne and Krishnamoorthy (2022). Hence, the amount of subduction-related volcanism might be overestimated by as much as 80.5%. Running the analysis while scaling additionally for the amount of subduction results in an estimated 1.22 new and 5.45 new and ongoing eruptions in a 60-day window and approximately 7.49 new and 11.80 new and ongoing eruptions on Venus in an Earth year (Tables S4 and S5 in Supporting Information S1).

5. Venus' Volcanic Flux

In order to determine how well the estimates of volcanic eruption frequency align with the current understanding of Venus, it is useful to look at the resulting volcanic flux. This has previously been estimated for Venus based on chemical reaction times (e.g., Fegley & Prinn, 1989), geological mapping (e.g., Head et al., 1992), and the eruptive fluxes associated with resurfacing and global overturns (e.g., Bullock et al., 1993; Strom et al., 1994; Figure 2). Here, the volcanic flux can be estimated by assuming the VEI of eruptions on Venus and linking that to the bulk tephra volume output associated with the index. To estimate Venus' VEI, I assume that the same frequency-magnitude relationship for eruptions on Earth holds for Venus. I then calculate the average VEI of the VOTW 4.9.0 database, that is, VEI = 1.67. Based on this average and since the VEI is a logarithmic scale, I choose an estimated VEI of 1–2 to provide a range of possible volcanic fluxes for Venus. These VEI values correspond to a volumetric output of $<10^{-3}$ and $<10^{-2}$ km^3, respectively. Then, multiplying the estimated minimum and maximum amount of eruptions in a year with the expected volumetric tephra output, I obtain a first order indication of the range in annual volcanic flux on Venus as illustrated in Figure 2. Clearly, the volcanic fluxes associated with the frequency of volcanic eruptions on Venus align well with previous estimates. Note that the resulting volcanic flux value is a low end member estimate, as it is based on the average VEI and therefore neglects the potentially significant contribution of larger volcanic eruptions.

6. Frequency of Volcanic Eruptions on Other Terrestrial Planets

The method of Byrne and Krishnamoorthy (2022) of estimating volcanic eruption frequency on Venus from Earth data can also be applied to the other terrestrial bodies in the Solar System. This results in estimates of 0.17 and 0.05 new and ongoing volcanic eruptions per Earth year for Mars and Mercury and automatically zero eruptions for the Moon, as there is not enough data in the VOTW 4.9.0 database from 2000 to 2021 for a full statistical analysis (Table S6 in Supporting Information S1). For these estimates, I assumed that there is only intraplate and rifting-related volcanism on these bodies (i.e., no active subduction zones). As discussed above, these estimates are conservative.

The probability that a volcanic eruption occurs in a year is low, with a 16% probability of an eruption occurring on Mars in an Earth year and a 5% probability of an eruption occurring on Mercury. However, when looking at longer time periods of 20 years, the terrestrial magnitude-frequency scaling of Byrne and Krishnamoorthy (2022)

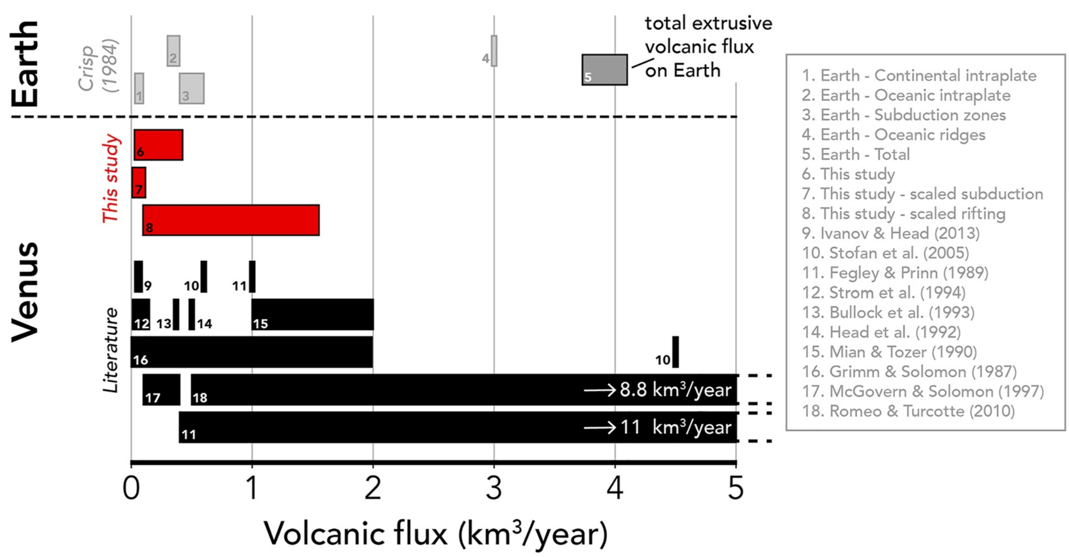

Figure 2. Comparison of the estimated annual extrusive volcanic flux on Venus based on the volcanic eruption frequency by Byrne and Krishnamoorthy (2022) using the corrected numbers calculated in this comment (6), including scaled subduction (7) and rifting volcanism (8), and previously published estimates of the extrusive volcanic flux of both Earth (1–5; Crisp, 1984) and Venus (9–18; Bullock et al., 1993; Fegley & Prinn, 1989; Grimm & Solomon, 1987; Head et al., 1992; Ivanov & Head, 2013; McGovern & Solomon, 1997; Mian & Tozer, 1990; Romeo & Turcotte, 2010; Stofan et al., 2005; Strom et al., 1994).

predicts a 92% probability of an eruption occurring on Mars and a 49% probability for Mercury, which are testable hypotheses. In the case of Mars, specifically, the global monitoring during the HiRISE era (McEwen et al., 2007) would most likely have resulted in observations of volcanic eruptions if this estimated level of volcanic activity is indeed accurate. The fact that no such volcanic eruptions have been observed implies that the terrestrial magnitude-frequency scaling of Byrne and Krishnamoorthy (2022) is perhaps not applicable to Mars and other bodies with vastly different tectonic regimes than Earth.

7. Conclusions

Assuming that data from Earth can be scaled to Venus, the method of Byrne and Krishnamoorthy (2022) predicts an estimated ∼42 new and ongoing volcanic eruptions on Venus annually. However, in this estimate the amount of volcanism associated with rifting is significantly underestimated as approximately 72.6% of rift lava production on Earth is not captured in the database. In contrast, subduction zone volcanism could be overestimated by as much as 80.5% in the estimate of Byrne and Krishnamoorthy (2022). Scaling the amount of subduction volcanism yields an estimate of ∼12 new and ongoing eruptions on Venus in an Earth year. The annual volcanic flux associated with these predictions is within the range of previous estimates and aligns with the current understanding of Venus.

Regardless of these uncertainties, each of these different estimates still predicts a significant amount of volcanic eruptions on Venus. Moreover, mission observations of Venus' fluctuating atmospheric sulfur dioxide content already appear to indicate that active volcanism could be currently ongoing (Esposito, 1984; Marcq et al., 2013). The missions that will fly to Venus in the coming decade will provide the first opportunity to test these different estimates.

Data Availability Statement

The Jupyter Notebook used to reproduce the findings of Byrne and Krishnamoorthy (2022) and produce the figures in this comment can be found in Van Zelst (2022). The VOTW 4.9.0 database and a list classifying the volcanoes in that database from 1955 to 2021 according to tectonic setting can also be found there. All generated results can be found in Supporting Information S1. Figures were made with Python and Adobe Illustrator.

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