Estimates on the possible annual seismicity of Venus

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Key Points:

- An inactive Venus with global background seismicity like Earth's continental intraplate seismicity has a few hundred quakes $\geq M_w 4$ per year
- A lower bound on an active Venus where ridges, coronae, and rifts are seismically active predicts a few thousand quakes $\geq M_w 4$ annually
- The upper bound for an active Venus results in thousands ($\sim 5,000 - 18,000$) venusquakes $\geq M_w 4$ per year

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Abstract

There is a growing consensus that Venus is seismically active, although its level of seismicity could be very different from that of Earth due to the lack of plate tectonics. Here, we estimate upper and lower bounds on the expected annual seismicity of Venus by scaling the seismicity of the Earth. We consider different scaling factors for different tectonic settings and account for the lower seismogenic zone thickness of Venus. We find that 95 – 296 venusquakes $\geq M_w 4$ per year are expected for an inactive Venus, where the global seismicity rate is assumed to be similar to that of continental intraplate seismicity on Earth. For the active Venus scenarios, we assume that the coronae, ridges, and rifts of Venus are currently seismically active. This results in 1,161 – 3,609 venusquakes $\geq M_w 4$ annually as a realistic lower bound and 5,715 – 17,773 venusquakes $\geq M_w 4$ per year as a maximum upper bound for an active Venus.

Plain Language Summary

Venus could be seismically active at the moment, but it is uncertain how many earthquakes (or to use the proper term: venusquakes) there could be in a year. Here, we calculate the minimum and maximum number of venusquakes we could expect in a given year on Venus based on different assumptions. If we assume there is not much seismic activity on Venus (comparable to the interior of tectonic plates on Earth), we find that we could expect about a few hundred venusquakes per year with a magnitude bigger than or equal to 4. For an estimate of the maximum amount of venusquakes, we assume that Venus has regions with more seismic activity: the so-called coronae, ridges, and rifts. Depending on our assumptions, we then find that more than 17,000 venusquakes could occur in a year with a magnitude bigger than or equal to 4.

1 Introduction

After the successful mapping of the Venusian surface by Magellan from 1990 to 1992, for a long time the prevailing hypotheses for Venus's geodynamic regime were that of a catastrophic or episodic resurfacing regime. Reason for this was the observation of a relatively low number of craters (932; Strom et al., 1994) on the surface, from which people deduced a uniform, relatively young surface age of 800–240 Myrs (McKinnon et al., 1997; Feuvre & Wieczorek, 2011). In these catastrophic or episodic resurfacing scenarios, Venus is currently in a relatively quiet tectonic phase after the geologically-recent resurfacing event that led to the observed young surface age (Rolf et al., 2022; O'Rourke et al., 2023).

In recent years, however, the view on Venus's current tectonic activity has shifted towards a more active planet, rivalled in the Solar System only, perhaps, by our own Earth. From a geodynamical point of view, other theories for its geodynamic regime have been put forward, such as the plutonic squishy lid regime (Lourenço et al., 2020), which are consistent with ongoing activity on Venus today. Additionally, the shift towards an active Venus is partly induced by compelling evidence from Magellan, Pioneer Venus, and Venus Express data that Venus might be currently volcanically active. Data from Venus Express shows regions of high emissivity which could be associated with chemically unweathered, and therefore likely geologically young (~ 2.5 Myrs), surfaces. These anomalies correlate with volcanic highlands, such as Imdr Regio (Smrekar et al., 2010), indicating geologically recent volcanism in these regions. Later, weathering experiments under Venusian conditions indicated that the reduction of surface emissivity is a rapid process on the order of years. Filiberto et al. (2020); Brossier et al. (2022) therefore postulate that the low radar emissivity values in Ganis chasma could be the result of volcanic eruptions in the last 30 years, indicating that Venus is volcanically active now. The observed variability in SO_2 concentration in the clouds by Pioneer Venus and Venus Express from 1979-2011 could also be attributed to recent volcanic eruptions (Marcq et al., 2013). The most compelling evidence for active volcanism on Venus to date comes from Herrick and Hensley (2023), who observed changes in a volcanic region by analysing consecutive radar images acquired by Magellan. They interpreted these changes as volcanic flows and hence ongoing volcanic activity on Venus. In line with that, recent estimates from scaling the volcanism of Earth to Venus yield 12 – 42 volcanic eruptions on Venus in a year, depending on assumptions on the amount of volcanism associated with plume-induced subduction at coronae (Byrne & Krishnamoorthy, 2022; Van Zelst, 2022). Future missions such as VERITAS (Smrekar et al., 2020) and EnVision (Ghail et al., 2016) will provide better constraints on Venus's volcanic activity.

In the meantime, since Venus seems to be volcanically and geologically active, it is reasonable to assume that it is also seismically active. Indeed, its seismicity could be more extensive than that of Mars and the Moon, which both are believed to be significantly less tectonically active than Venus (Stevenson et al., 2015). On these bodies, despite being in a stagnant lid regime, seismicity has been observed with the successfully deployed Apollo Lunar Surface Experiments Package on the Moon (Nakamura et al., 1982) and on Mars with the InSight mission (Banerdt et al., 2020). As Venus is now thought to be in a more tectonically active geodynamic regime than a stagnant lid (Rolf et al., 2022), its potential seismicity is thought to be at least comparable with Earth's intraplate seismicity (Stevenson et al., 2015; Tian et al., 2023; Ganesh et al., 2023). On top of that, observed rift systems (Ivanov & Head, 2011), ridges, and coronae features linked to active subduction (Davaille et al., 2017; Gülcher et al., 2020) could be seismically active at present. There are even speculations that the Venera 14 lander recorded microseisms from far-away seismicity in the active Beta regio on Venus, although there are many other potential explanations for these recorded signals (Ksanfomaliti et al., 1982).

Besides a large variety of tectonic features with potential Earth analogues, the crust of Venus has properties similar to the Earth's crust. Direct compositional measurements from the Soviet landers have shown that the surface of Venus has a similar composition to that of mid-oceanic ridge basalts on Earth (e.g., Abdrakhimov & Basilevsky, 2002). Moreover, the average crustal thickness of Venus has been estimated to be about 15 – 20 km (James et al., 2013; Maia & Wieczorek, 2022), which is comparable to the thickness of Earth's oceanic crust. Considering these similarities, it is reasonable to use Earth's seismic activity as a starting point to better understand the level of seismicity expected for Venus.

Here, we estimate upper and lower bounds of the amount of seismicity that could be expected for an active Venus, as well as an inactive Venus with seismicity reminiscent of intraplate seismicity on Earth. By scaling the seismicity of the Earth to Venus in Section 2 for different tectonic settings, i.e., using the same philosophy as Byrne and Krishnamoorthy (2022) that Earth analogues can be applied to Venus, we obtain our results (Section 3). We discuss the assumptions in our method and the estimates of previous studies in detail in Section 4. This is followed by our conclusions in Section 5.

2 Methods

In order to make estimates of the seismicity of Venus, we use a global earthquake catalogue for Earth and sort the earthquakes into different tectonic areas on the globe, thereby obtaining an effective seismicity density for each tectonic setting. We then apply this same density to analogous Venusian settings to obtain three different possible estimates of Venus's current seismicity: an estimate for an inactive Venus and an upper and lower bound for an active Venus, depending on the assumptions that we make. Here, we present our methods in detail.

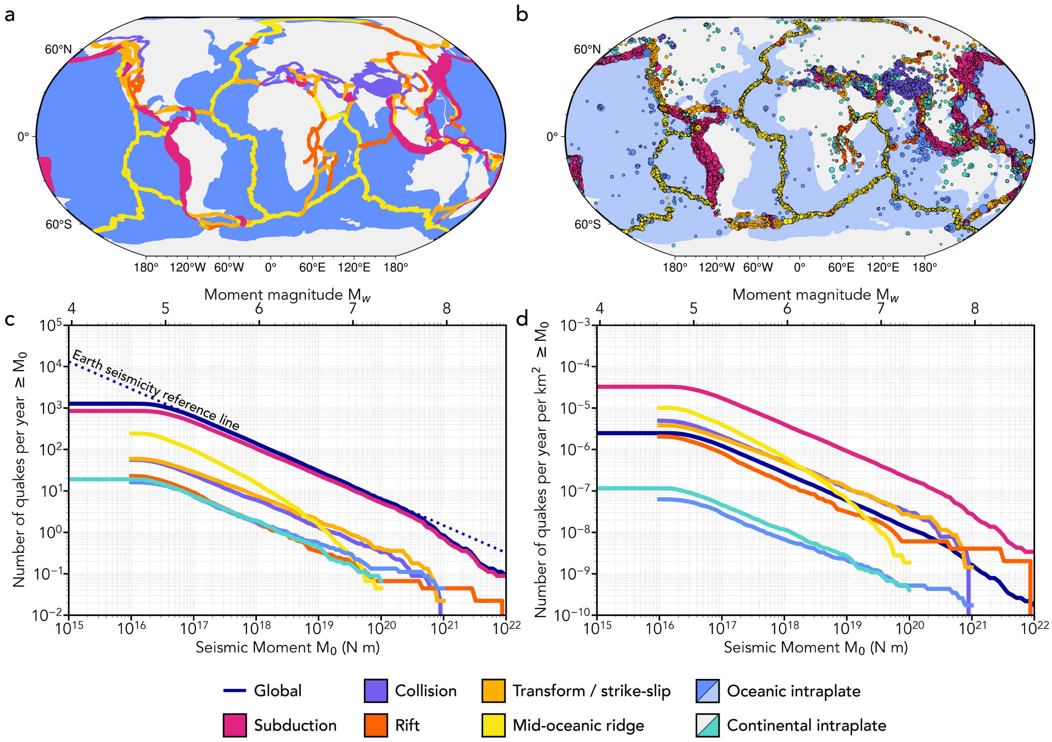

Figure 1. (a) Map of the Earth showing how its surface area is divided into seven discrete tectonic settings. (b) Earthquakes in the CMT catalogue from 1976 - 2020 coloured according to tectonic setting with the symbol size proportional to the earthquake magnitude. (c) Annual earthquake size-frequency distribution for the Earth based on the CMT catalogue and split into different tectonic settings. (d) Seismicity density on the Earth for different tectonic settings, i.e., number of earthquakes in the CMT catalogue per year per km^2. Maps are in Robinson projection.

2.1 Tectonic settings on Earth

To obtain the seismicity density of different tectonic settings on Earth, we calculate the area of seven different tectonic settings on the Earth. For this, we use the recent maps of global geological provinces and tectonic plates from Hasterok et al. (2022). We define subduction and collision zone areas according to the zones of deformation defined by Hasterok et al. (2022), as the location of the seismicity associated with these types of plate boundaries typically encompasses a large, diffuse area. We extend the deformation zones of Hasterok et al. (2022) to account for deep earthquakes associated with subduction zones that lie outside of the deformation zones defined at the surface of the Earth. We further define the areas of transform and strike-slip regions, rift zones, and mid-oceanic ridges according to the mapping of Hasterok et al. (2022) by defining a 150 km wide band on either side of the respective plate boundary and correcting for overlapping areas. The remaining surface area of the Earth is divided into oceanic intraplate and continental intraplate regions, according to the mapped oceanic and continental crust by Hasterok et al. (2022). Hence, the surface area of the Earth is divided into seven distinct (non-overlapping) tectonic settings: subduction zones (5.13% of Earth's surface area), collision zones (2.23%), transform and strike-slip regions (3.03%), rift zones (2.17%), mid-oceanic ridges (4.70%), and oceanic (50.44%) and continental intraplate (32.30%) regions (Figure 1a, Table S1).

2.2 Seismicity of the Earth

We use the global Centroid Moment Tensor (CMT) earthquake catalogue from 1976 – 2020 with a completeness magnitude of M_w5 to characterise Earth's annual seismicity. Throughout our study, we follow Beroza and Kanamori (2015) by using the following expression to convert from seismic moment M_0 (in N m) to moment magnitude M_w:

$$\log M_0 = 1.5M_w + 9.05. \tag{1}$$

We sort the earthquakes of the CMT catalogue in the predefined tectonic areas (Figure 1b) and obtain an earthquake size-frequency distribution for the different tectonic settings (Figure 1c). The seismicity density for each of the tectonic settings found on Earth is then calculated by dividing the earthquake size-frequency distribution by the surface area (Figure 1d; Table S1).

Subduction zones have the highest seismicity density, followed by the other plate boundary settings and the overall global seismicity density of the Earth (Figure 1d). The seismicity density of collision zones and strike-slip regions are similar, with a slightly lower seismicity density for the rift zones. Intraplate seismicity clearly has the lowest seismicity density (approximately one order of magnitude less than the global seismicity density) with continental intraplate seismicity density being slightly higher than oceanic intraplate seismicity density.

2.3 Tectonic settings on Venus

For Venus, we consider three different tectonic settings in this study: Venusian rifts, regions characterised by compressional deformation including ridges and mountain belts, and the volcano-tectonic corona features. For each of these tectonic settings, we assign plausible, potential Earth analogues to obtain an estimate of the potential annual seismicity of Venus. We refrain from including other tectonic settings found on Venus, such as tesserae and wrinkle ridges, as they do not have a clear Earth analogue, which makes their seismicity density unconstrained. Instead, we consider the remaining area of Venus as an intraplate tectonic setting (Figure 2a).

2.3.1 Rift zones

Rifts on Venus are typically defined as large, broad structural units of 100 km or more that are characterised by closely-spaced extensional structures (Price & Suppe, 1995; Ivanov & Head, 2011). They are similar to the so-called groove belts on Venus, which are smaller and typically contain less dense faulting patterns (Ivanov & Head, 2011). The extensional features in rift zones are often interpreted as normal faulting and horst-and-graben structures, which are typically associated with continental rifting on Earth (Foster & Nimmo, 1996). Indeed, many studies have pointed out both the morphological similarity and the similar amount of crustal extension between rifts on Venus and continental rifts on Earth (e.g., McGill et al., 1981; R. Phillips et al., 1981; Stoddard & Jurdy, 2012).

For example, Foster and Nimmo (1996) provide a detailed comparison between the East African Rift system on Earth and the rift systems of the Beta Regio on Venus. They identified many similarities, including maximum fault segment lengths, and concluded that differences stem from the lack of sediment and larger fault strength on Venus. As another example, Graff et al. (2018) suggested that the rift morphologies of Venus could be analogous to the Atlantic Rift System prior to ocean opening.

Modelling studies also indicate that continental rifting is a plausible mechanism to generate the rifting morphologies observed on Venus (Regorda et al., 2023). It is clear, however, that the difference in surface conditions between Venus and Earth plays a role in the rift mechanism as well (Regorda et al., 2023).

In general, the physical mechanisms governing the formation of rifts on Venus are still largely unclear. Continental rifting on Earth could be a reasonable analogue for Venus, especially since continental crust has been suggested for various regions on Venus (also see Section 2.3.2), including the tesserae where rift-like heavily-faulted structures called 'ribbons' can be found (Hansen & Willis, 1998; Hansen et al., 2000). However, considering Venus's basaltic crustal composition — potentially more similar to Earth's oceanic crust rather than it's continental crust (Head, 1990) — and increased surface temperature, the rifts on Venus might also bear resemblance to the mid-oceanic ridges on Earth. Although they are both extensional processes, continental rifting and mid-oceanic ridge formation display quite different dynamics on Earth and consequently have different seismic signatures (Section 2.2).

2.3.2 Ridges and mountain belts on Venus

There are several different types of compressional structures on the surface of Venus, including ridges, ridge belts (defined as closely-clustered ridges; Frank & Head, 1990), and mountain belts (Price & Suppe, 1995). These features typically resemble each other, but differ in terms of topography (Ivanov & Head, 2011). The origin of these compressional features has been debated, with early studies proposing early stage mantle downwellings as a mechanism (Zuber, 1990) and perhaps even subduction (Kryuchkov, 1990). However, nowadays a continental collision mechanism is one of the most favoured interpretations of Venus's mountainous structures. One of the lines of evidence for this is that felsic rock compositions typically associated with continental crust on Earth have been suggested for tessera terrain (Mueller et al., 2008; Gilmore et al., 2015, 2017) and the highlands of Venus (Hashimoto et al., 2008) based on thermal emission imaging observations (Smrekar et al., 2018). Hence, it has been suggested that the Ishtar Terra highlands (R. J. Phillips & Malin, 1984; Hashimoto et al., 2008) and Venus's crustal plateaus (Nikolaeva et al., 1992; Romeo & Turcotte, 2008; Romeo & Capote, 2011) are composed of continental crust. The observed compressional deformation structures — and in particular the highlands of Venus — are therefore thought to be the result of a process similar to continental collision on Earth (R. J. Phillips & Malin, 1984; Jull & Arkani-Hamed, 1995; Romeo & Turcotte, 2008).

2.3.3 Coronae and corona-like features

Coronae are roughly circular structures characterised by an annulus of high deformation (Price & Suppe, 1995). They are unique to Venus and are typically associated with volcanism and mantle upwellings (Smrekar & Stofan, 1997). There are various topographic signatures associated with coronae, which have been linked to differences in formation mechanisms and stages of formation (Smrekar & Stofan, 1997; Gülcher et al., 2020).

The most commonly-accepted hypothesis of corona formation nowadays is that of plume-induced subduction, where a rising plume impinges on the Venusian lithosphere and causes subduction-like dynamics and delamination at its edges (Gerya, 2014; Davaille et al., 2017; Smrekar et al., 2018; Gülcher et al., 2020; Baes et al., 2021). For example, Gülcher et al. (2020) used 3-D numerical models to show that different corona structures could represent different plume styles and stages of formation. Using these modelling insights and comparing to topographic data of Venus, Gülcher et al. (2020) found that 37 of 133 studied coronae (i.e., 27.8%) could be actively forming tectonic structures at present. The remaining coronae that they studied were either deemed to be inactive (26.3%) or inconclusive (45.9%) according to the modelled topography profiles. It is worth noting that the coronae studied in Gülcher et al. (2020) are not the complete set of observed coronae on Venus and are instead biased towards the larger corona structures with a diameter $\geq$ 300 km. Still, their modelling study provides compelling evidence that tectonic processes — and specifically subduction-like processes — in a subset of the coronae could still be active today.

2.3.4 The surface areas of different tectonic features on Venus

We calculate the surface area covered by rifts (8.25% of Venus's surface area; Jurdy & Stoddard, 2007), coronae (7.76%), and ridges or mountain belts (i.e., compressional regions; 1.64%) from maps by Price and Suppe (1995); Price et al. (1996) as shown in Figure 2a (also see Table S2). We manually ensure that there are no overlapping regions by including rift-associated coronae as part of the rift system. The remaining surface area of Venus that is not assigned an actively-deforming tectonic setting is then considered to be intraplate (82.35% of Venus's surface; Figure 2a).

2.4 Scaling from the Earth to Venus

2.4.1 Seismogenic thickness

The seismogenic thickness of a planet's lithosphere is the maximum depth at which earthquakes can nucleate, typically dictated by the temperature structure of the lithosphere and the location of the brittle-ductile transition. On Earth, the down-dip limit of the seismogenic zone in subduction zones is for example associated with the 350°C and 450°C isotherms (Hyndman & Wang, 1993; Hyndman et al., 1997; Gutscher & Peacock, 2003), although the 600°C isotherm is often cited as the maximum limit for brittle failure, stemming from observations of intermediate-depth seismicity (Jung et al., 2004; Wang et al., 2017). Taken over the entire surface area of the planet, the seismogenic thickness transforms into the seismogenic volume. As a measure of seismicity, the seismogenic thickness is of limited use as it merely defines the region where quakes could nucleate and slip. Indeed, earthquakes can propagate below the seismogenic depth (although they nucleate above it) and there are — depending on tectonic setting — vast regions with a significant seismogenic thickness that experience limited seismicity, e.g. the interiors of continental plates, which typically undergo limited deformation. Despite its limitations, seismogenic thickness is still a useful variable to look at when determining the maximum amount of seismicity that could occur on a given planet.

Since Venus has a higher surface temperature than Earth, assuming the same seismogenic thickness for both is likely incorrect. More specifically, we expect Venus to have a lower seismogenic thickness than Earth due to its higher surface temperature and hence shallower brittle-ductile transition in its lithosphere. We therefore need to take the likely difference in seismogenic thickness between the two planets into account when estimating the seismicity of Venus.

In order to estimate the seismogenic thickness scaling factor between Earth and Venus, we first estimate the average seismogenic thickness for the Earth, which is relatively well constrained. For oceanic crust, we assume a representative seismogenic thickness of 36.5 km, which is the depth of the 600°C isotherm (McKenzie et al., 2005; Richards et al., 2018) for the average age of 64.2 Myrs of the oceanic crust (Seton et al., 2020). Following Wright et al. (2013), we assume a seismogenic thickness of 14 km for continental crust. Then, applying the ratio of oceanic / continental crust from Hasterok et al. (2022), we obtain an average seismogenic zone thickness for the Earth of 26.93 km.

For Venus, we calculate a likely minimum and maximum seismogenic thickness from proposed end-member thermal gradients of Venus's lithosphere (Smrekar et al., 2023; Bjonnes et al., 2021). Like for our Earth estimate, we calculate the depth corresponding to the 600°C isotherm, as this seems to limit the seismogenic zone on Earth (McKenzie et al., 2005). To obtain a minimum estimate of Venus's seismogenic zone thickness, we calculate the average thermal gradient for Venusian rifts estimated by Smrekar et al. (2023), which results in a seismogenic thickness of 7.3 km. As a maximum estimate, we use the proposed minimum thermal gradient of 6 K/km for the Mead crater on Venus by Bjonnes et al. (2021), resulting in a seismogenic thickness of 22.7 km. We note that these estimates represent the thermal gradients during the formation of the associated features, but given the young ages predicted for Venus's surface these values are likely representative for its current thermal state.

Combining these estimates of the Venusian seismogenic thickness with that of Earth, we obtain minimum and maximum scaling ratios of 0.27 and 0.84, respectively, to account for the likely difference in seismogenic thickness between Venus and Earth.

2.4.2 Three end-member estimates

We consider three different scenarios when scaling the seismicity from the Earth to Venus (Table S3). First, we consider an inactive Venus where the only seismicity on the planet is a background seismicity similar to the continental intraplate seismicity on Earth. This minimum level of seismicity on Venus is a popular hypothesis that has been used by other studies as well (e.g., Stevenson et al., 2015; Tian et al., 2023; Ganesh et al., 2023). Here we obtain this estimate by scaling the entirety of Venus with continental intraplate seismicity on Earth.

As a second estimate, we consider an active Venus with conservative assumptions on its level of activity to provide a lower bound. Following Davaille et al. (2017); Gülcher et al. (2020); Byrne and Krishnamoorthy (2022), we assume that coronae are surface expressions of plume-induced subduction and therefore have a seismic signature similar to that of Earth's subduction zones. However, for this lower bound estimate, we do not consider the entire corona area to be active and associated with the high seismicity density of subduction zones. Instead, we assume that 27.8% of the area of coronae is active according to Gülcher et al. (2020) and we only scale this area with subduction zones on Earth. We further assume that the rift zones on Venus have seismicity similar to (continental) rift zones on Earth (Solomon, 1993; Foster & Nimmo, 1996; Basilevsky & McGill, 2007; Harris & Bédard, 2015; Graff et al., 2018). The observed ridges and mountain belts on Venus that result from compressional deformation are assumed to have a similar seismicity signature to collision zones on Earth. Like the inactive Venus scenario, the remaining area of Venus is scaled according to continental intraplate seismicity on Earth.

Our third and last estimate is for an active Venus with the most liberal assumptions of plausible tectonic activity on Venus. In this estimate, we assume that all coronae are active, since the amount of active coronae is still highly uncertain (Gülcher et al., 2020). So, we scale the entire corona area with the subduction seismicity of the Earth. For the rift zones on Venus, we now scale the seismicity with mid-oceanic ridge seismicity on Earth, instead of continental rifting (Graff et al., 2018). Like our lower bound estimate for active Venus, we scale the area of ridges on Venus with collision zones on Earth and we assume that the rest of the planet is equivalent to continental intraplate seismicity on Earth.

Combining the scaling for the seismogenic zone thickness (Section 2.4.1) with the three scalings based on the tectonic features allows us to arrive at three different end-member seismicity estimates for Venus. In short, we obtain the global amount of annual venusquakes for a certain magnitude $N_{\mathrm{vq|M_w}}$ by applying the following equation:

$$N_{\mathrm{vq}|M_w} = f_{\Delta D} \sum_{\substack{\text{tectonic} \\ \text{features}}} A_{t,V} \cdot \frac{N_{\mathrm{eq,t}|M_w}}{A_{t,E}} \tag{2}$$

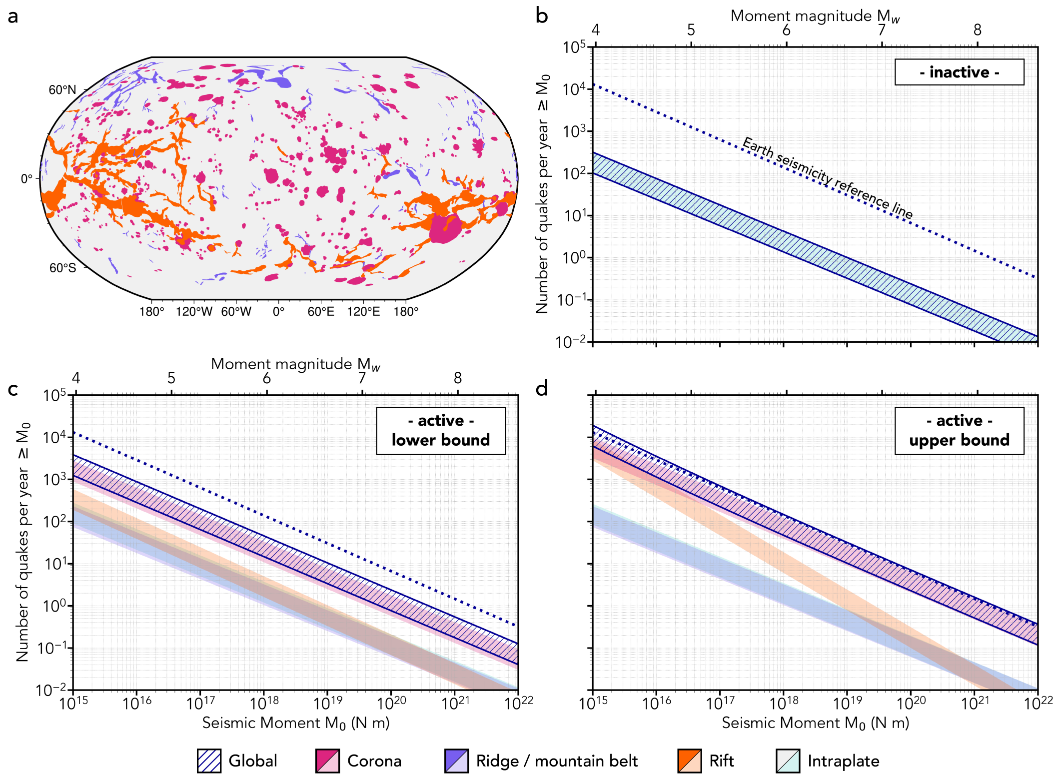

Figure 2. (a) Map of Venus (Robinson projection) showing the areas of mapped coronae, ridges and mountain belts, and rifts (Price & Suppe, 1995; Price et al., 1996). (b-d) Ranges of potential quake size-frequency distributions on Venus for (b) an inactive Venus with background seismicity analogous to Earth's continental intraplate seismicity; (c) a lower bound on an active Venus; and (d) an upper bound on an active Venus. The hatched area shows the global, accumulated annual seismicity that combines the seismicity of the different individual tectonic settings. Note that because of the log-log scale, the global estimate and the seismicity range of the highest individual tectonic setting are closely-spaced. Dotted dark blue line indicates the reference Earth seismicity line, which corresponds with the slope of the size-frequency distribution of global seismicity on Earth (Figure 1c).

where $f_{\Delta D}$ is the seismogenic zone scaling factor (i.e., 0.27 and 0.84); $A_{t,V}$ is the surface area A of a tectonic feature t on Venus V; $N_{\mathrm{eq,t}|M_w}$ is the number of annual earthquakes for a given analogous Earth tectonic feature at a given moment magnitude; and $A_{t,E}$ is the corresponding surface area of the analogous tectonic feature on Earth. The sum then indicates a summation over all the tectonic features that are scaled on Venus, up to and including the intraplate regions, such that we sum over the entire surface area of Venus. Scaling with the seismogenic thickness as well as the areas of the tectonic settings, effectively allows us to scale by seismogenic volume per tectonic setting to obtain estimates for Venus's seismicity (Table S3).

2.4.3 Extrapolating to other magnitudes

In order to actually calculate the potential amount of seismicity on Venus and to extrapolate to earthquake magnitudes below the completeness magnitude of M_w5 of the CMT catalogue, we effectively scale the average slopes of the size-frequency distribution for the different tectonic settings on Earth (equivalent to $N_{\mathrm{eq,t}}$ for all moment magnitudes; Figure 1c). We specifically assume that the size-frequency distribution of medium-sized earthquakes with a seismic moment of 10^{17} Nm to 10^{19} N m is representative for the size-frequency distribution of smaller earthquake magnitudes, i.e., the earthquakes follow Gutenberg-Richter statistics (Gutenberg & Richter, 1956; Beroza & Kanamori, 2015). This assumption allows us to provide estimates of the amount of venusquakes with moment magnitudes of M_w3 and M_w4. We refrain from reporting on the amount of venusquakes with lower magnitudes, because they are unlikely to be detected in future seismological exploration missions of Venus (Krishnamoorthy et al., 2020; Brissaud et al., 2021).

Calculating the amount of large venusquakes with magnitudes $\geq M_w8$ is less straightforward, as the (potential) maximum quake magnitude on Venus is unknown. In addition, there is a limited amount of data for Earth on earthquakes with magnitudes $\geq M_w8$, because of their large recurrence time (Figure 1). For these reasons, we do not explicitly comment on the occurrence of quakes $\geq M_w8$ on Venus in this study, although our methodology does provide estimates (e.g., Figure 2).

3 Results

Our results for the different Venus scenarios are summarised in Figure 2 and Table 1, 2, where we list the estimated annual number of quakes for a given moment magnitude and the global seismicity densities on Venus for our different estimates.

3.1 Inactive Venus

In our first estimate, we assume that the entirety of Venus can be scaled with the continental intraplate seismicity of the Earth, so the global estimate and the intraplate estimate overlap perfectly in Figure 2b. As expected, the amount of seismicity in this scenario is significantly less than that on Earth with 95 – 296 venusquakes $\geq M_w4$ estimated annually, compared to 12,207 earthquakes $\geq M_w4$ per year on Earth. The associated seismicity density for quakes $\geq M_w4$ lies between $0.21{\cdot}10^{-6}$ and $0.64{\cdot}10^{-6}$ year^{-1} km^{-2} (Table 2), which is on the same order of magnitude as that of intraplate seismicity on Earth.

3.2 Active Venus - lower bound

The lower bound for our active Venus estimate globally predicts more seismicity than the inactive, intraplate Venus estimate (Section 3.1). The ridge, rift, and intraplate tectonic settings on Venus have seismicity on the same order of magnitude in this estimate, as shown by the overlapping bands of seismicity in Figure 2c (also see Figure S1). The coronae have an order of magnitude more seismicity associated with them, although only 27.8% of them are assumed to have a subduction-like seismicity density in this estimate. Summing up the seismicity of the different tectonic settings results in estimates of 1,161 – 3,609 venusquakes per year with a moment magnitude $\geq$4 and a seismicity density of $2.52{\cdot}10^{-6}$ – $7.84{\cdot}10^{-6}$ year^{-1} km^{-2} globally for venusquakes $\geq M_w4$ (Table 2). This global seismicity density is significantly less than that of the Earth or any of its plate boundary settings.

3.3 Active Venus - upper bound

The upper bound of estimated seismicity for an active Venus (Figures 2d, S2) is very close to – and even slightly larger than – the annual seismicity observed on Earth, primarily due to the scaling of coronae with Earth's subduction zone seismicity in this estimate, which also dominates Earth's seismicity (Figure 1c). Since we scale the rifts on Venus with Earth's mid-oceanic ridge seismicity in this estimate, we have a different

Estimate	$M_w \geq 3.0$	$M_w \geq 4.0$	$M_w \geq 5.0$	$M_w \geq 6.0$	$M_w \geq 7.0$
Inactive Venus	826 - 2568	95 – 296	11 – 34	1 – 4	0 – 0
Active Venus - lower bound	10760 - 33460	1161 – 3609	126 – 391	14 – 42	2 – 5
Active Venus - upper bound	84263 - 262023	5715 – 17773	465 – 1446	44 – 136	4 – 15

Table 1. Number of venusquakes per year equal to or larger than a certain moment magnitude for our three possible Venus scenarios. A range is provided based on the uncertainties in the chosen scaling factor for the seismogenic thickness.

slope for Venusian rift seismicity. This results in an increase in smaller quakes with $M_w \leq 5$. There is no difference between the seismicity expected for the ridge tectonic setting compared to the lower bound for an active Venus (Section 3.2), as it is scaled in the same way.

Globally, we then estimate 5,715 – 17,773 venusquakes of moment magnitude ≥ 4, with the upper bound being larger than the number of $M_w \geq 4$ earthquakes estimated for the Earth (12,207). The seismicity density of quakes $M_w \geq 4$ varies from $12.42 \cdot 10^{-6}$ to $38.62 \cdot 10^{-6}$ year^{-1} km^{-2} (Table 2). This lowest possible seismicity density for an upper bound to our active Venus estimate is slightly lower than the Earth's seismicity density for continental rift zones ($16.98 \cdot 10^{-6}$ year^{-1} km^{-2}) and the highest possible seismicity density is larger than that of the seismicity density of collision settings on the Earth ($33.62 \cdot 10^{-6}$ year^{-1} km^{-2}) (Table S1).

4 Discussion

In this study, we provide three end-member estimates of possible Venusian seismicity by looking at Earth analogues, following the same philosophy of Byrne and Krishnamoorthy (2022) who previously applied this logic to determine the frequency of volcanic eruptions on Venus. In contrast to Byrne and Krishnamoorthy (2022), we calculate the seismic densities for individual tectonic settings and then scale according to their surface areas and appropriate Earth analogues.

Generally, we estimate that the seismicity of Venus is lower than that of the Earth, except for the most active end-member of Venus activity. Indeed, there are large differences between the various estimates, indicating a range of possible seismic activity on Venus at present, depending on the many assumptions we are forced to make given the limited amount of data from Venus.

4.1 Likely causes of differences between the seismicity on Earth and Venus

Before we assess the individual assumptions we made to obtain our different estimates of Venusian seismicity, it is useful to assess the overarching assumption that Earth's seismicity can be scaled to Venus.

One of the biggest and most straightforward differences between the Earth and Venus is their different surface temperatures. Since temperature plays a crucial role in seismicity through its control on the brittle-ductile transition (Tichelaar & Ruff, 1993; Hyndman et al., 1997; Peacock & Hyndman, 1999; Gutscher & Peacock, 2003; Scholz, 2019), it will have a large effect on the amount of seismicity that can occur. On a global scale, different surface temperatures can result in different tectonic regimes and deformation mechanisms (Lenardic et al., 2008; Foley et al., 2012; Weller et al., 2015) which could greatly change the seismic signatures. In its most extreme case some studies argue that there will be little to no seismicity on Venus, at least at higher magnitudes (e.g., Karato

Tectonic setting	**Minimum seismicity density** ($\cdot 10^{-6}$ year^{-1} km^{-2})	**Maximum seismicity density** ($\cdot 10^{-6}$ year^{-1} km^{-2})
Inactive Venus	0.21	0.64
Active Venus - lower bound	2.52	7.84
Active Venus - upper bound	12.42	38.62

Table 2. Estimated minimum and maximum seismicity densities on Venus for quakes $\geq M_w 4$ for three scenarios with different activity-level assumptions.

& Barbot, 2018). These studies argue that the high surface temperatures on Venus may exclude the possibility of any kind of substantial seismogenic zone and the unstable slip mechanisms responsible for earthquakes. Instead, the stresses that are built up in the Venusian lithosphere could be released through aseismic processes, such as creep. However, some of the assumptions in Karato and Barbot (2018) are unrealistically conservative (e.g., a global crustal thickness of 40 km; a seismogenic zone limit at 400°C) and not applicable to Venus. In our estimates, we have taken the difference in surface temperatures and its effect on seismicity into account through scaling end-member estimates of the seismogenic thickness of Venus with the average seismogenic thickness of Earth. While not a perfect solution encapsulating the complexity of the effect of increased surface temperatures, this at least forms a first approximation to take this difference into account.

Another important difference between Venus and Earth is likely to be the amount of water available in the crust. On Earth, water plays a vital role, especially in subduction seismicity, with the pore-fluid pressure crucial in determining the stresses in megathrust settings (Seno, 2009; Angiboust et al., 2012) and dehydration reactions responsible for intermediate-depth and deep seismicity in subduction zones (Green & Houston, 1995; Hacker et al., 2003; Jung et al., 2004; Houston, 2015; Wang et al., 2017). This water is typically added to the subduction system at the outer rise that underlies an ocean in subduction zones (Boneh et al., 2019). On Venus, the amount of water in the lithosphere is relatively unconstrained (Gillmann et al., 2022; Rolf et al., 2022), with some studies suggesting that Venus is currently relatively dry (Grinspoon, 1993; Namiki & Solomon, 1998; Smrekar & Sotin, 2012; Salvador et al., 2022), while others argue that there might still be a significant amount of water in Venus's mantle (Gillmann et al., 2022). This makes it highly uncertain how big a role water could play in the seismicity of Venus. Our estimates encompass the full spectrum of possible seismicity on Venus with our lower bound using Earth's intraplate seismicity, where water likely plays a smaller role, and our upper bound including subduction seismicity, where water is an important factor.

Strain rates play an important role in seismicity as well, because they determine the time scale of stress build-up and the recurrence time of earthquakes. On Venus, strain rates similar to Earth's active margins have been suggested by Grimm (1994). However, due to the lack of Earth-like plate tectonics and plate boundaries, there are overall potentially less large rupture areas, leading to less large-magnitude quakes on Venus. The decreased seismogenic thickness of Venus also plays a role in this by limiting the maximum rupture area. Although our estimates provide a range of potential venusquakes at large magnitudes (Table 1), it is therefore uncertain if large venusquakes could actually occur. Preliminary mission designs suggest that quake magnitudes of $M_w \geq 3$ could be feasibly observed by a range of plausible seismic detection methods (Krishnamoorthy et al., 2020; Brissaud et al., 2021) and our estimates are likely most plausible for this range of seismic magnitude $3 \leq M_w \leq 5$.

All in all, there are many uncertainties when it comes to estimating the seismicity of Venus from Earth's seismicity. Higher resolution data and missions focused on observing seismicity (discussed in Section 4.3) will help to obtain seismicity estimates for Venus independent of Earth. However, since those constraints are not yet available, scaling the seismicity of the Earth is a reasonable first-order approximation to gain some insights into the potential seismicity of Venus.

4.2 Assumptions in and limitations of our seismicity estimates

For our inactive Venus estimate, we assume that the global background seismicity of Venus is similar to the continental intraplate seismicity of the Earth. This is a common assumption that has also been suggested by e.g., Lorenz (2012); Stevenson et al. (2015); Byrne et al. (2021); Tian et al. (2023). The number of venusquakes $\geq M_w4$ per year for this estimate (95 – 296) is also the same order of magnitude as the estimate of Ganesh et al. (2023), who calculate an estimate of Venus's seismicity based on the cooling of the planet and the corresponding contraction of the lithosphere and thereby predict ~ 265 venusquakes $\geq M_w4$ per year.

For our estimates for an active Venus, we scale the areas of compressional deformation on Venus, i.e., the ridges and mountain belts, with the seismicity of collision zones on Earth. We believe this to be a reasonable assumption, considering that Venus's ridges and the Earth analogue are both compressional regimes and continental crust and collision has been previously suggested for the Venusian highlands. The rifts on Venus are scaled with continental rift seismicity on Earth in the lower bound estimate for an active Venus. This is also a reasonable assumption, with many studies pointing to the morphological and geological similarities between the rift zones on Venus and continental rifts on Earth such as the East African rift zone (Solomon, 1993; Foster & Nimmo, 1996; Kiefer & Swafford, 2006; Basilevsky & McGill, 2007; Stoddard & Jurdy, 2012; Graff et al., 2018; Regorda et al., 2023). For our upper bound, we scale the rift zones of Venus with mid-oceanic ridge seismicity since it is also an extensional setting and the higher temperatures at the mid-oceanic ridges and the corresponding different slope of the size-frequency distribution on Earth might be a better fit for rift seismicity under Venus's high surface temperature. On Earth, the different seismic signatures between continental rifts and mid-oceanic ridges is not purely temperature-related. Instead, the inherent tectonic differences between the two settings plays a role as well. Since it is unclear which of these two physical mechanisms (or their seismic signatures) best represents the rifting processes of Venus, we believe using one of them in the lower bound estimate and one in the upper bound estimate catches the uncertainty in governing mechanisms in our estimates. For the coronae, we scale with subduction, since multiple studies suggest that coronae are the surface expressions of plume-induced subduction (Davaille et al., 2017; Gülcher et al., 2020; Byrne & Krishnamoorthy, 2022). However, the seismicity associated with this type of plume-induced subduction is uncertain. Assigning the same seismicity density as regular subduction processes on Earth is a reasonable first-order approximation in the absence of other constraints, although the presumable lack of water in coronae and the higher surface temperature will certainly affect its seismic signature as well. Future modelling studies that combine geodynamic modelling with seismic cycle modelling and dynamic ruptures (e.g., van Dinther, Gerya, Dalguer, Mai, et al., 2013; van Dinther, Gerya, Dalguer, Corbi, et al., 2013; van Dinther et al., 2014; Van Zelst et al., 2019) are needed to assess the seismic signatures that could be expected at Venusian coronae. In the interest of providing an upper and lower bound, scaling the coronae by activity is a good first order approximation. However, it is also possible that coronae seismicity does not scale with Earth's subduction seismicity, but is instead more analogous to, for example, transform fault seismicity related to the observed fracture zones at the rims of coronae. In general though, our upper bound for Venusian seismicity results in seismicity levels slightly higher than, but similar to, that of the Earth, which has also already been suggested previously (e.g., Lorenz, 2012). Choosing a different seismic density for coronae, such as that of the transform fault setting, would result in a lower amount of estimated venusquakes. Since we are attempting to provide an upper limit to the possible amount of annual venusquakes, our assumption of a subduction seismic density is reasonable.

Apart from the uncertainty in scaling the chosen tectonic settings correctly, there are also tectonic settings on Venus that we neglect to scale explicitly. For example, we do not explicitly scale the tesserae of Venus with a tectonic setting on Earth, although they are implicitly scaled with the background intracontinental seismicity of the Earth. This is arguably one of the most reasonable assumptions for tesserae, considering that prevailing hypotheses include that they are continental crust analogues (Romeo & Turcotte, 2008; Gilmore et al., 2015). We also do not consider the observed extensive regions of wrinkle ridges as seismically active beyond the background intracontinental seismicity of the Earth. A recent study by Sabbeth et al. (2023a) presented a conservative estimate of $9.1 \cdot 10^{16}$ N m to $5.1 \cdot 10^{17}$ N m per year for the annual moment release for wrinkle ridges on Venus based on (low-resolution) mapped fault lengths. Assuming a maximum quake size on Venus of $M_w 4$, this translates to 81 to 455 wrinkle ridge quakes $M_w \leq 4$ on Venus per year. This is a similar amount of $M_w \leq 4$ quakes as predicted for the intraplate, ridge, and rift settings in our three different estimates ranging from inactive to active. The upper bound of 455 wrinkle ridge quakes is higher than the seismicity expected from the inactive Venus estimate that only considers an intraplate setting, indicating that our active Venus estimates are more appropriate when considering observed faulting patterns on Venus.

Note that in the estimates presented here, only one type of seismic source is considered, i.e. earthquakes, which by definition are associated with tectonics and volcanism. Other sources such as landslides (Pavri et al., 1992; M. Bulmer & Guest, 1996; M. Bulmer et al., 2006; M. H. K. Bulmer, 2012; Hahn & Byrne, 2023) could be responsible for seismic signals on Venus as well.

4.3 Determining the actual seismicity of Venus in the future

In the next decade, VERITAS (Smrekar et al., 2020) and EnVision (Ghail et al., 2016) will provide a wealth of new data, including high resolution topography, that will provide better constraints on the actual lengths, offsets, and displacements of Venusian faults. This will provide another basis of estimating Venus's seismicity through scaling relationships applied to surface fault observations (Sabbeth et al., 2023a, 2023b).

The new Venus missions will also indirectly provide stronger constraints on the seismogenic thickness, which is typically deduced from thermal gradients estimated from studies of the elastic and mechanical lithosphere thickness (e.g. Anderson & Smrekar, 2006; Borrelli et al., 2021; Maia & Wieczorek, 2022; Smrekar et al., 2023) or from impact crater modeling (Bjonnes et al., 2021). These studies rely on the analysis of gravity and topography data, for which a higher resolution will become available from the VERITAS (Smrekar et al., 2020) and EnVision (Ghail et al., 2016) missions. Estimates of the thermal gradient and associated seismogenic thickness could then be obtained with a higher accuracy and on a more global scale than currently available. They could be included in future studies of seismicity on Venus and improve on the estimates presented here.

Until the era of new Venus data, we are unfortunately limited by the currently-available data of Venus. The simplest, first-order estimate of the seismicity of Venus is therefore obtained here through scaling Earth analogues to Venus, without considering individual fault lengths or displacements and detailed seismogenic thickness estimates and instead uses the seismicity density characteristics of different tectonic settings on Earth.

To distinguish between the different scenarios presented in this study and determine how seismically active Venus is, a seismological or geophysical mission to Venus is required to measure seismic signals. Although the NASA- and ESA-selected missions to

Venus currently do not focus on this, there are promising proposals to measure Venus's seismicity in the not-too-distant future. For example, Kremic et al. (2020) presented a mission proposal for a long-duration Venus lander with a seismometer on board that can withstand Venus's high surface temperature. In addition, recent advances in the balloon-detection of earthquakes show great promise for applications to Venus (Garcia et al., 2022; Krishnamoorthy & Bowman, 2023). Our estimates for Venusian seismicity may help guide the design of these missions.

5 Conclusions

We estimate upper and lower bounds on the expected annual seismicity of Venus by scaling the seismicity of the Earth to Venus according to the surface area of different tectonic settings and the difference in seismogenic thickness between the two planets. Our most conservative estimate is an 'inactive Venus', where we assume the global seismicity of Venus is comparable to Earth's continental intraplate seismicity. This results in 95 – 296 venusquakes $\geq M_w 4$ per year depending on the assumption of seismogenic zone thickness. For our active Venus scenarios, we assume that the rifts, ridges, and coronae on Venus are seismically active. For a lower bound on an active Venus, we then find 1,161 – 3,609 venusquakes $\geq M_w 4$ annually, which increases to 5,715 – 17,773 venusquakes $\geq M_w 4$ for assumptions that constitute our most active Venus scenario. This latter scenario is slightly larger than the seismic activity level of the Earth. Future seismological and geophysical missions could measure the actual seismicity of Venus and distinguish between our three proposed end-members of Venusian seismic activity.

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Data availability statement

The Jupyter Notebooks used to make the results and plot the figures as well as the CMT database and geospatial vector data (shapefiles) of the tectonic setting areas on Earth can be found in *zenodo link to be finalised upon acceptance. For now the data is included as a zip file for the reviewer's convenience.* Explanation of individual files in this repository and additional figures and tables are provided in the Supplementary Material. Figures were made with Python and Adobe Illustrator. We used the colorblind friendly color map from the IBM Design Library (David Nichols, 2022; retrieved: February 16, 2023).

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