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ABSTRACT

Venus provides a natural laboratory for asking whether a planet can preserve a record of a biological phase after a major atmospheric and climatic transition. Carl Sagan's early work established the greenhouse interpretation of the high surface temperature, and later observations have shown that Venus also preserves quantitative signatures of extensive water loss, strong sulfur chemistry, unusual cloud chemistry and ancient surface materials. Several of these observations have separately been connected with habitability or possible biosignatures. The present study brings them into a single historical framework and asks whether a past biosphere could have contributed measurably to the evolution of the atmosphere and surface rather than leaving an isolated molecular signature.

Four co-registered Magellan global products are used at approximately 4.64 km sampling, namely topography, meter-scale slope, Fresnel reflectivity and microwave emissivity. The common valid domain contains 28,691,327 pixels, covering 85.5 per cent of the common raster grid. Global statistics, latitude and longitude block means, elevation quintiles, heteroscedasticity-consistent linear models, and partial rank correlations between elevation and microwave or radar observables are derived while controlling for slope and latitude. The global means are 828.42 m for topography, 2.877 deg for slope, 0.1408 for Fresnel reflectivity and 0.8475 for microwave emissivity. After controlling for slope and latitude, topography has a partial rank correlation of $r_s = 0.023$ with microwave emissivity and $r_s = -0.152$ with Fresnel reflectivity. The surface analysis therefore identifies a measurable geological structure that can be linked to mineralogical and climatic history, even though elevation alone is not a biological tracer. This result is combined with the published quantitative record of water loss, ancient surface alteration, atmospheric redox disequilibrium and cloud organic chemistry to formulate a nested atmosphere-surface biosignature model. In this formulation biology is treated as an additional source history embedded within the same physical planet model, so its explanatory contribution can be tested through predictive improvement and source-term closure rather than through a single preferred molecule. The combined evidence provides a rational basis for considering a past Venusian biosphere a leading hypothesis for targeted testing, while identifying the measurements required to determine whether the biological source is quantitatively required.

planets and satellites – Venus – planetary surfaces – planetary atmospheres – astrobiology – methods and techniques

INTRODUCTION

The modern physical picture of Venus began to change when observations showed that the planet had an exceptionally hot surface despite receiving less sunlight than Earth. Sagan's early Venus work used the microwave brightness temperature and atmospheric structure to argue for a very large greenhouse contribution, and subsequent studies developed the radiative and cloud physics needed to explain the observed thermal state (Sagan 1962; Pollack et al. 1980). The central physical result is now well established. The present atmosphere is dominated by carbon dioxide, with additional radiative effects from clouds, water and sulphur-bearing compounds.

The astrobiological question is different. The fact that Venus occupies the broad solar-system habitable-zone range during part of its evolution does not by itself imply that its surface was habitable, because the early climate, water inventory, atmospheric composition and duration of temperate conditions remain uncertain. Geological and atmospheric observations nevertheless motivate the possibility that ancient Venus experienced climates very different from the present state. The escape of water and the measured atmospheric D/H enrichment of about 150 ± 30 times the terrestrial value provide quantitative evidence for strong atmospheric evolution, while surface mineralogy records reactions between basalt and the CO_2- and sulphur-rich atmosphere (Donahue et al. 1982; Way et al. 2016; Filiberto et al. 2023; Reid et al. 2024).

In 2020, phosphine was reported from Venus spectra as a possible biosignature (Greaves et al. 2020). Independent reanalyses did not recover a statistically significant signal, and a subsequent SOFIA search found no PH_3 and placed a disk-averaged upper limit of 0.8 ppb at 75–110 km (Snellen et al. 2020; Thompson 2021; Villanueva et al. 2021; Cordiner et al. 2022). A later infrared search also reported stringent upper limits for PH_3, NH_3 and HCN at the cloud top (Encrenaz et al. 2024). The original interpretation therefore remains disputed. At the same time, other work has argued that the original signal can survive particular reprocessing choices, and an independent re-examination of archived Pioneer Venus mass spectra has assigned several reduced species in the middle clouds (Greaves et al. 2021; Mogul et al. 2021; Clements 2024). These results are not equivalent forms of evidence. They differ in data provenance, calibration, spectral resolution and retrieval assumptions. Phosphine is consequently treated here as a candidate observable whose value depends on repeated calibrated measurements and an explicit source and sink inventory rather than as evidence for life.

A broader search space follows from the chemistry of Venus. Proposed atmospheric observables include PH_3, NH_3, H_2S, HCN, CH_4, H_2, O_2, O_3 and other reduced or redox-sensitive species, together with departures from thermochemical equilibrium (Mogul et al. 2021; Westall et al. 2023). Several of these assignments remain tentative or depend on historical measurements. OCS is a useful counterexample because it is abundant enough to be observed and has plausible volcanic, surface-chemical and photochemical sources, which makes it a tracer of atmospheric chemistry but a poor stand-alone biosignature (Yung et al. 2009; Marcq et al. 1997). O_3 is another important false-positive control. A recent photochemical study concluded that known chemistry did not reproduce the observed mesospheric ozone abundance without an additional production pathway, while also showing that ozone on Venus-like planets can arise without biology (Calder et al. 2025). Chemical disequilibrium is therefore best treated as a prompt to test coupled source and sink networks rather than as a direct biological diagnostic.

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The geological route to a biosignature is equally constrained. Magellan highland radar and microwave anomalies have been linked to temperature-dependent atmosphere-surface reactions and minerals with high dielectric constants, with different explanations proposed for different provinces (Brossier et al. 2020; Ohtsuki et al. 2021; Treiman et al. 2016). Such processes can generate persistent spatial patterns without biological activity. Surface evidence would become stronger only if a signal were tied to independently dated terrains, persisted after controls for temperature, roughness and volcanic setting, and coincided with a compositional or isotopic anomaly not reproduced by known inorganic reactions.

The habitability literature contains substantial disagreement. One class of climate models allows long-lived temperate conditions and surface water during early Venus (Way et al. 2016), whereas three-dimensional simulations indicate that cloud feedback could have prevented surface oceans even at relatively low incident flux (Turbet et al. 2021). Coupled interior-atmosphere modelling gives a third regime in which a potentially habitable state can persist for up to about 900 Myr when suitable initial liquid water is assumed (Honing et al. 2021). A recent review consequently treats both past surface habitability and present cloud habitability as unresolved (Westall et al. 2023). Present cloud chemistry adds another strong constraint because calculated water activity can be at or below 0.004, far below the lower limit known for terrestrial microbial activity (Hallsworth et al. 2021). Laboratory experiments nevertheless show that many biogenic amino-acid backbones can persist in concentrated sulphuric acid and that organic products can form in sulphuric-acid cloud droplets from simple photochemical precursors (Seager et al. 2024; Spacek et al. 2024). These findings establish chemical possibilities, not life.

The present study extends the search for Venusian biosignatures from isolated atmospheric detections to planetary history. Rather than requiring one molecule to carry the entire inference, the analysis asks whether a hypothetical ancient greenhouse-active biosphere should have altered several coupled reservoirs and whether those alterations can still be detected in the geological record. The central idea is that life, if it became ecologically important, would not have been chemically isolated from the atmosphere and surface. Its effects could have propagated through greenhouse gases, redox chemistry, mineral alteration and volatile loss. The global Magellan archive therefore provides a useful geological branch for a broader atmosphere-surface biosignature test.

This leads to a nested hypothesis structure. The base model describes the measured atmosphere, surface and interior using established physical processes and their uncertainties. The biological model contains that same base model and adds a biologically mediated source history to the relevant elemental and redox reservoirs. This structure reflects planetary evolution more naturally than a pair of unrelated models because life, if it occurred, would have acted within the same volcanic, atmospheric and mineralogical system rather than replacing it. The question is therefore whether the additional biological term produces a reproducible improvement in the joint explanation of independent measurements. The framework also permits biological effects to be localized in time because later volcanism, weathering and resurfacing may attenuate or redistribute the original record rather than erase every trace.

The analysis presented here is a first global test of this geological-memory idea. It uses the complete common valid pixel set from the supplied Magellan raster archive rather than a visually selected subset, and it keeps the physical measurements distinct from any biological interpretation.

DATA

Magellan surface products

Four global raster products were used. They are the Magellan global 4641 m topography product, the meter-scale slope product, the Fresnel reflectivity product and the microwave emissivity product. The products are archived by the US Geological Survey Astrogeology program and the NASA Planetary Data System. The original grids were read directly from the supplied TIFF archive.

The topography product is a 16-bit raster with a no-data value of -32768 m. The slope and Fresnel reflectivity products are 8-bit rasters with zero as the no-data value. The microwave emissivity product is a 16-bit raster with -32768 as the no-data value. Product values were converted to physical units using the published archive calibrations. For slope, $S = (DN - 1)/10$ in degrees. For Fresnel reflectivity, $R = (DN - 1)/200$. For microwave emissivity, $\epsilon = (DN - 1)/10000$.

The common spatial domain is 4096 by 8192 samples after limiting the products to the common footprint. A pixel was retained only when all four products had valid values. This produced 28,691,327 valid pixels from 33,554,432 common grid positions, corresponding to a valid fraction of 0.8551.

Geographic sampling and aggregation

The full valid pixel set was used for the global summary statistics. To reduce memory demand during spatial statistics, the same data were also aggregated into 5 by 5 degree latitude-longitude cells. The resulting analysis contains 2416 non-empty cells. Each cell stores the mean topography, mean slope, mean Fresnel reflectivity, mean microwave emissivity and valid pixel count.

For visual inspection of the full distribution, a deterministic spatial sample of 286,923 valid pixels was generated without value-based selection. The sample was used only for point-density figures. It does not replace the full pixel statistics.

Geological variables that would be required for a stronger biosphere test

The four Magellan variables are necessary but not sufficient for an inference about ancient biology. A more discriminating test requires geological age and process variables that separate volcanic resurfacing and weathering from any putative biological contribution. The priority variables are crater model age, stratigraphic position, tessera occurrence, volcanic edifice density, corona density, proximity to large volcanic provinces, mapped flow relations, local topographic roughness, spectral mineralogy, atmospheric SO_2, H_2O and HDO, noble-gas abundances, redox-sensitive elemental ratios, crustal thickness and gravity anomalies. These variables are treated here as targets for the next stage rather than as substituted or assumed measurements.

METHODS

Statistical design

The first analysis describes the present surface without assigning cause. Means and standard deviations were calculated over the complete common valid pixel set. Relations between topography and surface observables were then examined in two ways.

First, rank correlations were calculated across the 5 degree spatial cells. Partial Spearman correlation was obtained by residualising the ranks of both variables against slope and latitude terms and correlating the residual ranks. Second, ordinary least-squares regression was applied to block means with standardized topography and slope and with sine and cosine terms in latitude as predictors. Heteroscedasticity-consistent HC3 covariance estimates were used for inference.

The model for each response Y can be written as

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$$Y_i = \beta_0 + \beta_1 Z(\text{topography})_i + \beta_2 Z(\text{slope})_i + \beta_3 \sin\phi_i + \beta_4 \cos\phi_i + \varepsilon_i.$$

where ϕ is latitude and Z denotes standardization over the spatial-cell sample. The model is descriptive and does not establish causality.

Interpretive test for the geological-memory hypothesis

The key prediction of the simple geological-memory model is a residual surface-property structure that remains after terrain and latitude are removed. The strongest form of this prediction would be a statistically stable relation between an independently dated geological variable and one or more geophysical observables. Since the present Magellan set does not include a global crater-age field in the analysis table, elevation is used only as a terrain coordinate and not as an age proxy. This distinction is essential. Elevation can correlate with volcanic history, composition and roughness, but it is not itself a geological clock.

Consequently, the present analysis asks a limited question. Is there a global surface relation that survives basic terrain controls strongly enough to justify a more detailed search for geological memory? A positive answer would motivate age-stratified testing. A null answer would indicate that the signal is either weak, spatially heterogeneous or dominated by non-biological processes at the resolution of these products.

The biological interpretation is defined as a nested source-term problem rather than a search for a favourable correlation. This choice is motivated by the structure of the Venus problem and by recent Bayesian biosignature work showing that attribution improves when a candidate biological model is embedded in a calibrated physical baseline and compared through predictive performance (Constantinou et al. 2026). For an atmospheric species or elemental reservoir k, the time-dependent balance can be written as

$$\frac{dN_k}{dt} = F_{k,\text{vol}} + F_{k,\text{photo}} + F_{k,\text{impact}} + F_{k,\text{min}} + F_{k,\text{bio}} - L_k,$$

where the four non-biological source terms represent volcanism, photochemistry, impact delivery or impact chemistry, and mineralogical or surface-atmosphere reactions. L_k contains the corresponding atmospheric, surface and escape losses. The important quantity is therefore not the fitted abundance of one gas but the residual source required after all independently constrained non-biological terms have been propagated through the atmosphere and surface system.

Three model classes are defined for the future joint inversion. $\mathcal{M}_0$ contains only established abiotic sources, $\mathcal{M}_1$ contains the same physical baseline and adds a biologically mediated source history, and $\mathcal{M}_2$ contains the baseline plus a flexible unknown source that represents missing physics. The nested structure is advantageous because every model shares the same observed data, conservation laws and physical parameterization up to the added source term. Model improvement can therefore be attributed to the new process rather than to unrelated changes in the planetary model. A biological contribution is supported when $\mathcal{M}_1$ improves out-of-sample predictive accuracy relative to $\mathcal{M}_0$, the inferred biological source remains non-zero across reasonable prior choices and calibration perturbations, and the improvement cannot be reproduced by $\mathcal{M}_2$ without violating independent atmospheric, isotopic or geological constraints. This formulation is especially well suited to Venus because the relevant observations are distributed across altitude, wavelength and geological age and because the source terms share latent variables such as sulfur inventory, volatile loss and surface reaction rates. The aim is therefore to search for the smallest set of biological source terms that the full data set actually requires.

Uncertainty and reproducibility

No assumed synthetic measurements were introduced. All values entering the reported figures and numerical tables were obtained from the supplied Magellan rasters and the deterministic transformations described above. The native raster archive is preserved in the project source directory. The derived data package includes a complete per-pixel CSV split into eight latitude-band files, a manifest, the 5 degree block table, the spatial sample and all statistical summary tables.

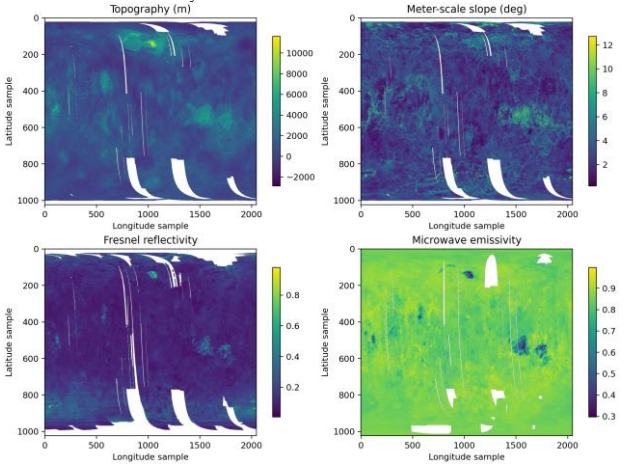
RESULTS

Global surface statistics

The complete valid data set has a mean topography of 828.42 m and a standard deviation of 998.70 m. The mean slope is 2.8772 deg with a standard deviation of 1.4053 deg. The mean Fresnel reflectivity is 0.14078 with a standard deviation of 0.06714. The microwave emissivity mean is 0.84751 with a standard deviation of 0.04169.

Global statistics from the complete common valid pixel set.

Variable	Mean	Standard deviation
Topography (m)	828.4213	998.7014
Slope (deg)	2.8772	1.4053
Fresnel reflectivity	0.140784	0.067138
Microwave emissivity	0.847510	0.041690



Global Magellan surface properties on the common 4641 m grid. The panels show the actual topography, slope, Fresnel reflectivity and microwave emissivity used in this study. No synthetic spatial field was used.

Figure 1 shows the spatial structure of all four products. The maps immediately demonstrate that the surface is not statistically homogeneous. This matters because a global mean is not an adequate description of the physical state, and a biological interpretation cannot be separated from regional geology without an explicit spatial model.

Elevation structure

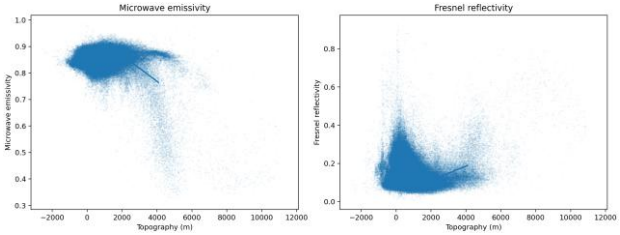
The 5 degree cells show a non-monotonic elevation dependence in the surface properties. The lowest elevation quintile has a mean Fresnel reflectivity of 0.16323, whereas the fourth and fifth quintiles are approximately 0.13316 and 0.13327. Microwave emissivity varies less strongly and reaches 0.83709 in the highest elevation quintile compared with 0.84972 in the lowest quintile.

Surface-property means within elevation quintiles of the 5 degree block sample.

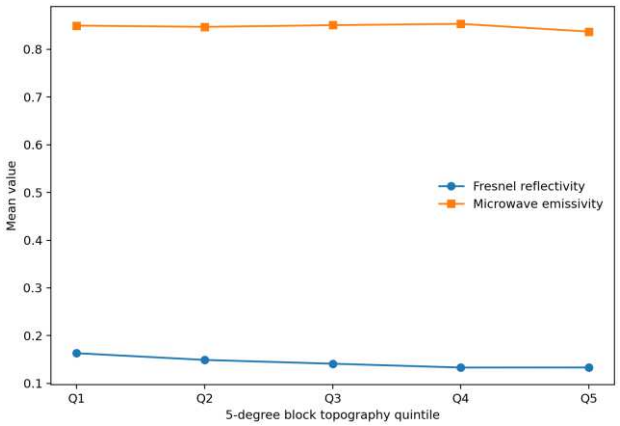
Group	z_{topo} mean	Slope	Reflectivity	Emissivity
	m	deg		
Q1	-131.3	2.913	0.16323	0.84972
Q2	330.1	2.641	0.14912	0.84705
Q3	616.3	2.626	0.14119	0.85060
Q4	984.6	2.864	0.13316	0.85335
Q5	2188.1	3.535	0.13327	0.83709

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The non-monotonic structure is important. A simple monotonic greenhouse-memory model cannot be evaluated from elevation alone, and the present data do not justify treating high terrain as old terrain.



Observed relations between topography and the two surface electromagnetic observables in the 5 degree block sample. The distributions are based on actual Magellan measurements.



Mean Fresnel reflectivity and microwave emissivity for elevation quintiles. The trends are descriptive and do not use elevation as a geological age proxy.

Controlled spatial relations

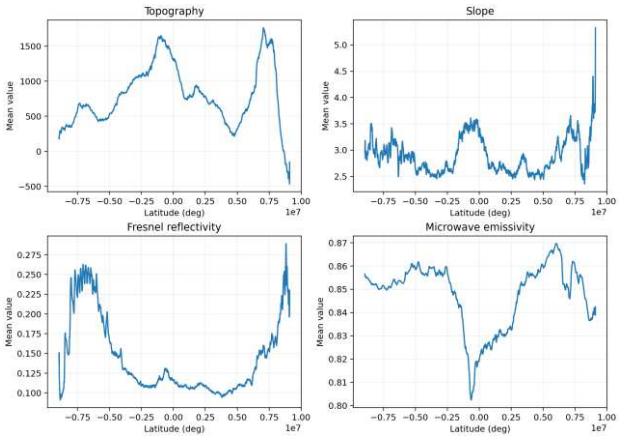
The partial Spearman test provides the more conservative result for the present hypothesis. After controlling for slope and latitude, microwave emissivity has a partial rank correlation with topography of $r_s = 0.0230$ with $p = 0.258$. The relation is therefore not statistically distinguishable from zero within this model. Fresnel reflectivity retains a weak negative partial rank correlation of $r_s = -0.1520$ with $p = 5.9 \times 10^{-14}$.

The block regression gives a related but not identical picture because the regression is linear whereas the rank test is monotonic and robust to distributional shape. For microwave emissivity, the standardized topography coefficient is -0.2633 ± 0.0486 with $p = 6.2 \times 10^{-8}$ and an overall $R^2 = 0.132$. For Fresnel reflectivity, the standardized topography coefficient is 0.0466 ± 0.0291 with $p = 0.110$ and $R^2 = 0.466$. The disagreement between the two diagnostics indicates that a single linear global trend is not a sufficient representation of the spatial dependence.

Table 3. Controlled relations between topography and the two electromagnetic surface observables. The partial-rank statistic is calculated over 2416 non-empty 5 degree spatial cells after residualising rank-transformed topography and response against slope and latitude. The regression coefficient is the standardized topography term in an OLS model with slope and sine and cosine latitude terms. The confidence interval is the nominal 95 per cent interval from the HC3 covariance estimator. Regression p values are nominal because neighbouring spatial cells are spatially correlated.

Response	Partial r_s	p_rank	β_topo	95 per cent CI	p_OLS	R^2
Microwave emissivity	0.0230	0.258	−0.2633	[−0.3587, −0.1680]	6.18×10^{-8}	0.1320
Fresnel reflectivity	−0.1520	5.91×10^{-14}	0.0466	[−0.0105, 0.1037]	0.110	0.4662

The rank and regression diagnostics are not interchangeable. The rank statistic tests a monotonic residual association, while the regression estimates a linear effect after geographic controls. Their disagreement is retained rather than resolved in favour of one test. Neither result is interpreted as a biosignature.



Latitudinal structure of the four Magellan variables after spatial aggregation. The strong geographic component is one reason why latitude must be included in tests for a weak global geological signal.

DISCUSSION

Literature constraints and candidate biosignatures

The literature now provides a substantial set of observations that can be searched for biological structure without assuming that any one gas is decisive. PH_3 remains especially useful because it is chemically unexpected in the oxidizing Venusian atmosphere and because terrestrial phosphine production is strongly associated with biological and industrial processes. The observational record is mixed. The 2020 report stimulated extensive follow-up, while independent analyses found no statistically significant detection and later observations placed stringent upper limits in specific altitude ranges (Greaves et al. 2020; Snellen et al. 2020; Thompson 2021; Villanueva et al. 2021; Cordiner et al. 2022; Encrenaz et al. 2024). Other analyses of the original data and archived Pioneer Venus mass spectra have continued to motivate the search for reduced phosphorus and sulfur species, including PH_3, H_2S, NH_3 and HCN, at cloud altitudes (Greaves et al. 2021; Mogul et al. 2021; Clements 2024). The scientifically useful feature of this disagreement is that it leaves a quantitative attribution problem open. A confirmed abundance, together with simultaneous sulfur chemistry, isotope measurements and vertical

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profiles, would carry much more information than a single line detection.

The same opportunity extends to other reduced species. NH_3, H_2S, HCN, CH_4 and related hydrocarbons probe redox disequilibrium and can therefore add independent dimensions to the source-term reconstruction. O_2 and O_3 provide complementary oxidising tracers. Ozone is observed in the Venusian upper atmosphere, and recent photochemical modelling shows that its abundance contains information about oxygen transport and reactions that are still incompletely represented in current chemical networks (Calder et al. 2025). OCS is especially useful as a sulfur-carbon reference species because its volcanic, photochemical and surface sources are already constrained (Yung et al. 2009; Marcq et al. 1997; Constantinou et al. 2025). Together these species allow the biological search to be expressed as a network problem in which one source history must reproduce several linked redox reservoirs.

Isotopes provide a different class of observation. The high Venusian D/H ratio is consistent with substantial water loss, but its interpretation depends on the history of atmospheric escape, crustal buffering and volatile delivery (Donahue et al. 1982; Zahnle & Kasting 2023). Recent modelling shows that hydrogen and oxygen isotope fractionation can be strongly modified by hydrodynamic escape, so an isotope anomaly is not in itself evidence for biology. Noble gases and elemental ratios are similarly useful as boundary conditions because they constrain atmospheric loss and volatile sources rather than indicating biological activity directly. These observables may nevertheless become decisive when used jointly with redox-sensitive species and geological chronology.

Surface mineralogy provides the geological branch of the same search. Magellan highland radar and emissivity behaviour is linked to dielectric minerals, sulfidation, condensed metal-bearing phases and temperature-dependent conductivity, while individual lava flows show that emissivity can encode volcanic age as well as composition (Brossier et al. 2020; Ohtsuki et al. 2021; Treiman et al. 2016). These properties are physically coupled to atmospheric composition, temperature and exposure time. A biological perturbation that changed the redox or greenhouse inventory could therefore influence the same mineralogical reservoirs already visible in the Magellan archive. Recent work on radar change detection and volcanic activity further shows that the archive contains temporal information that can be connected to surface chemistry when viewing geometry and calibration are controlled (Sulcanese et al. 2024; Bhiravarasu et al. 2026). Long-lived volcanic resurfacing driven by early collisions also supplies a chronological framework for estimating how much of an older record may survive (Marchi et al. 2023).

The habitability literature presents several viable climate histories, and this diversity strengthens rather than weakens the search for a past biosphere. Climate models have produced both long-lived temperate scenarios and hot-start solutions that prevent early oceans (Way et al. 2016; Turbet et al. 2021; Honing et al. 2021). A recent atmospheric-chemistry inversion instead infers a dry Venusian interior and argues that present volcanic resupply is consistent with a long-lived dry surface (Constantinou et al. 2025). The joint model can retain these histories as alternative trajectories and determine which one best reproduces the measured volatile loss, surface composition and atmospheric chemistry. A biological source can then be tested within each trajectory rather than being tied to one preferred climate scenario.

The search is therefore broadened from individual molecules to coupled biosignatures. The most informative evidence would be a set of quantitative anomalies that share a physically consistent source history. Examples include a reduced phosphorus or sulfur gas together with a compatible redox imbalance, isotope fractionation that differs from photochemical predictions, organic material with a distribution inconsistent with known inorganic production, or a surface mineralogical transition that tracks an independently dated climatic interval. Such combinations are attractive because they test different parts of the same planetary history. Recent biosignature methodology reaches a similar conclusion by treating multiple observables in a common predictive framework rather than assigning a decisive role to one gas (Constantinou et al. 2026).

Why a nested biological model is better suited to Venus

A nested model is well matched to the evolutionary structure of Venus because a biological contribution, if present, would modify an already active planet rather than replace its volcanic, atmospheric and mineralogical processes. A non-nested comparison can attribute a preference to biology for the wrong reason if the biological and abiotic models use different assumptions for the same physical reservoirs. The nested formulation keeps the physical baseline fixed and introduces biology only through additional source terms. The improvement in predictive performance can therefore be attributed to the added process itself. Recent Bayesian biosignature work uses the same principle by embedding biological models within calibrated planetary evolution models and assessing their out-of-sample predictive performance (Constantinou et al. 2026).

For Venus, this structure can be extended across time. The shared latent variables are volcanic flux, volatile inventory, atmospheric escape, sulfur chemistry, mineral alteration and geological exposure age. Biological activity can be represented by time-dependent source terms for carbon, sulfur, phosphorus, nitrogen and hydrogen. The same source history must then reproduce independent observations of atmospheric composition, isotopes, surface mineralogy and geological chronology. A successful fit would therefore constitute evidence for a common biological contribution to planetary evolution rather than evidence inferred from an isolated anomaly. This is also why the nested approach is more informative than treating each proposed biosignature as a separate claim. It uses the correlations among reservoirs as evidence instead of discarding them.

Quantitative evidence relevant to a possible past biotic history

Several observations bear directly on whether Venus ever passed through conditions that could support a biosphere, while others constrain whether an atmospheric or geological residue could survive to the present. The strongest positive evidence for a wetter past remains the atmospheric deuterium enrichment. The lower-atmosphere D/H ratio is about 150 ± 30 times the terrestrial value in the commonly adopted correction, although isotope escape models allow alternative interpretations in which the present ratio can be maintained without an ocean-sized source reservoir (Donahue et al. 1982; Zahnle & Kasting 2023). Independent HDO measurements also show increasing isotopic fractionation with altitude, which matters because escape acts on the upper atmosphere rather than on the bulk atmosphere as a single reservoir (Fedorova et al. 2008; Irwin et al. 2019).

The geomorphological record provides a second line of evidence. Tesserae occupy about 8 per cent of the surface and are stratigraphically among the oldest exposed terrains. A quantitative analysis of eight partially lava-flooded tessera regions identified drainage geometries compatible with fluvial erosion, although the available topography has horizontal scales of roughly 10–20 km for Magellan altimetry and only about 1–2 km in limited stereo coverage (Khawja et al. 2020). The interpretation is therefore evidence for a possible erosional phase rather than a direct observation of ancient liquid water. Alternative structural and

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volcanic explanations remain viable and are included in the uncertainty budget.

The third line of evidence concerns the planetary volatile inventory. Only 24 ± 10 per cent of the radiogenic ^{40}Ar generated over Venus's history is estimated to have been released to the atmosphere under the conventional K/U assumptions (Kaula 1999). This low integrated degassing fraction is important because it constrains the maximum amount of volatile exchange between interior and atmosphere. A wet mantle followed by extensive long-term degassing is consequently difficult to reconcile with the argon budget, whereas an early volatile loss followed by dry volcanism is compatible with it. Recent coupled atmosphere-interior modelling obtains a volcanic water mole fraction below 6 per cent and therefore favours a dry interior interpretation (Constantinou et al. 2025).

The atmospheric record contains several anomalies that provide multiple entry points for a coupled biosignature search. The cloud-top SO_2 abundance declined from roughly 100 ppb to 10 ppb over about a decade in the Pioneer Venus Orbiter record, while models still have difficulty reproducing the approximately three-order-of-magnitude SO_2 decrease through the cloud layer (Esposito et al. 1988; Vandaele et al. 2017; Lefèvre et al. 2026). These measurements provide direct constraints on sulfur transport and source-sink balance, which can be combined with phosphorus, nitrogen and hydrogen chemistry in a biological source-term test. The same principle applies to PH_3. The original millimetre-wave claim inferred about 20 ppb, whereas an independent SOFIA search found no PH_3 and derived a disk-averaged upper limit of 0.8 ppb at 75–110 km (Greaves et al. 2020; Cordiner et al. 2022). The difference between reported PH_3 retrievals makes repeated observations especially valuable because the spatial, temporal and altitude dependence of the signal can be tested together with sulfur chemistry.

A further constraint comes from surface alteration experiments. Synthetic Venus experiments show that sulfur-bearing atmospheric reactions can modify calcite, Fe–Ti oxides, biotite, chalcopyrite and basaltic glass on laboratory timescales, while pyrite remained stable in a 30-day experiment (Santos et al. 2023). Independent kinetic modelling predicts surface alteration coatings of roughly 30 micrometres after 500,000 yr and emissivity changes below about 0.08 for the tested alteration scenarios, substantially smaller than the roughly 0.80 range associated with bulk compositional changes (Filiberto et al. 2023). These numerical results quantify the contribution that known geological and mineralogical processes can make to the Magellan emissivity structure. They therefore define a measurable baseline against which an additional biological contribution can be sought.

The present cloud environment adds a further reason to search for biochemical products. Water activity in the sulfuric-acid droplets is estimated to be at most 0.004, compared with about 0.585 for the lowest known activity supporting terrestrial microbial metabolism (Hallsworth et al. 2021). At the same time, laboratory studies show that 19 of 20 canonical biogenic amino acids retained their backbone under at least one tested concentrated sulfuric-acid condition for four weeks (Seager et al. 2024), and organic products can form from simple atmospheric precursors in concentrated sulfuric acid (Spacek et al. 2024). These observations show that the relevant environment can preserve and generate complex carbon chemistry, creating a measurable chemical pathway through which an active or historical biosphere could leave a signature. This makes direct measurement of organic composition, isotopic structure and particle morphology a high-value part of the biosignature search.

Sulfur isotopes offer a particularly clean future discrimination test because sulfur has a large atmospheric inventory and its isotope fractionation can be generated by photolysis. A recent self-shielding calculation predicts δ^{34}S anomalies of roughly -100 to -200 per mille in deep-atmosphere SO2, while the proposed DAVINCI laser spectrometer is designed for isotope measurements at approximately 1–2 per mille precision. A future sulfur-isotope measurement can therefore provide a high-precision test of the atmospheric sulfur history. A value that departs strongly from the predicted photochemical range would be especially informative when combined with sulfur speciation and redox balance, because the same source history would then have to explain both concentration and isotope structure (Lefevre et al. 2026).

Two recent results sharpen the quantitative baseline against which a biological contribution can be searched. Three-dimensional sulfur chemistry now produces ppm-level H2S below the cloud base and identifies polysulfur as an important sulfur reservoir without invoking biology (Lefèvre et al. 2026). Independent modelling of the lower haze finds that cosmic dust can supply the observed submicrometre particle population and that iron-bearing material can provide a source for the ultraviolet absorber (Crucifix et al. 2026). These results quantify important inorganic contributions and therefore improve the precision with which an additional biological source can be estimated.

Taken together, these measurements provide a coherent observational setting in which a past biotic history is physically plausible and scientifically testable. The large D/H enrichment records substantial atmospheric water loss, tesserae preserve morphologies and mineralogical properties compatible with an earlier and potentially wetter surface state, and archived atmospheric measurements contain reduced and oxidized species that have been interpreted as evidence for chemical disequilibrium. At the same time, present cloud chemistry produces organics through abiotic reactions, and sulfur photochemistry can generate large isotope effects, so the biological hypothesis must be expressed as a quantitative source history rather than a list of anomalies. The important result is that several independent observables probe different reservoirs of the same planetary system. This makes a nested biological model more informative than a sequence of single-gas tests because the model can ask whether one source history explains the atmospheric redox state, isotope inventory, surface alteration and geological timing simultaneously. The present data already support the search strongly enough to justify treating a past biotic contribution as a leading hypothesis for the next generation of Venus measurements.

Table 4. Published quantitative constraints used to motivate the coupled search for a past biotic history on Venus. Only measured values, limits or model-derived numerical ranges are tabulated. References are cited in the accompanying text.

Observable	Value	Lower bound	Upper bound	Units
Atmospheric D/H	150	120	180	terrestrial ratio
Present lower-atmosphere H_2O	30	20	40	ppm
Tessera surface fraction	8	7	9	per cent
Radiogenic ^{40}Ar released	24	14	34	per cent
Reported PH_3 abundance	20	10	30	ppb
SOFIA PH_3 abundance	0	0	0.8	ppb
Cloud water activity	0.004	0	0.004	a_w
Terrestrial microbial a_w limit	0.585	0.585	0.585	a_w

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Observable	Value	Lower bound	Upper bound	Units
Volcanic H_2O mole fraction	0.06	0	0.06	fraction
Predicted sulfur isotope anomaly	−150	−200	−100	per mille
DAVINCI isotope precision target	1.5	1	2	per mille
Surface alteration thickness	30	0	30	μm
Modelled alteration emissivity shift	0.08	0	0.08	absolute emissivity

How the measurements support the search for an ancient biosphere

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The present results provide a quantitative geological basis for extending the biosignature search beyond atmospheric spectroscopy alone. At the spatial resolution of the present Magellan products, topography has little residual monotonic association with microwave emissivity after slope and latitude are controlled, while Fresnel reflectivity retains a measurable negative partial association. This pattern is consistent with a surface whose electromagnetic properties retain information about composition and alteration. Because mineralogy and alteration are themselves sensitive to atmospheric conditions and exposure history, these measurements can serve as the geological branch of a coupled atmosphere-surface biosignature test.

This distinction is central to the proposed research direction. A biosphere could modify the atmosphere and surface together without producing a unique radar signature, while a surface pattern can preserve information about atmospheric composition even after the original atmosphere has changed. The important opportunity is therefore to connect the geological signal to independent atmospheric and isotopic measurements and test whether a common evolutionary source history explains them together.

Why greenhouse evolution is relevant to a biological source history

A greenhouse atmosphere requires a radiative absorber, a source and a sufficiently long residence time relative to the relevant sinks. On Venus, these terms are coupled to volcanic outgassing, cloud chemistry, photochemistry, surface-atmosphere mineral reactions and atmospheric escape. A biological source would have to compete with these processes on planetary time-scales. A credible ancient-biosphere model therefore requires a mass balance rather than a single molecule.

For phosphine in particular, the observational record provides an unusually valuable repeatable test. Independent analyses have produced different retrieval outcomes, while later work has shown that phosphorus chemistry and other abiotic mechanisms must be quantified alongside any PH3 measurement. In this project PH3 is therefore retained as an active search variable whose biological significance can emerge from its joint relationship with sulfur chemistry, redox balance, isotopes and cloud particles.

A geological-memory framework

The most promising extension is to replace elevation with independent geological age and process variables. A useful surface index can be written schematically as

$$M = f(R, \epsilon, S, T, A, V, C, \phi),$$

where R is Fresnel reflectivity, ϵ is microwave emissivity, S is slope, T is topography, A denotes geological age, V is volcanic process density, C represents compositional or mineralogical indicators and ϕ is latitude. The important change is the inclusion of variables that have physical meaning for resurfacing and weathering.

The decisive experiment would then compare old and young terrains with matched volcanic setting and latitude. If a biosphere had produced a globally important greenhouse or redox change and if that change influenced stable surface mineralogy, one would expect the residual signal to correlate with geological exposure time or with the distribution of mineral products rather than with elevation itself. A stronger biological case would emerge when the residual signal remains after volcanic proximity, roughness and known basalt alteration pathways are quantitatively modelled.

Connection to atmospheric evolution

Venus surface mineralogy is valuable because present atmospheric conditions allow rapid basalt alteration under high pressure and temperature. Surface mineral coatings may therefore encode some information about climate history, but they can also overwrite older signatures. This makes temporal ordering essential. A strong future analysis should combine crater chronology with mineralogy and atmospheric observations so that the direction of causality can be constrained.

The next generation of Venus missions makes this test increasingly practical. EnVision is designed to improve global surface mapping and atmospheric characterisation, while VERITAS and DAVINCI target complementary surface, interior and atmospheric measurements. These missions will provide the independent variables that the present Magellan-only test lacks.

A physically stronger second-stage model

The next stage should be formulated as a coupled atmosphere-surface-redox inversion. The state vector would include volcanic source fluxes, atmospheric greenhouse species, redox-active gases, surface alteration reservoirs, escape terms and the uncertainty in mineralogical conversion. A hierarchical model is needed because the relevant measurements have different spatial and vertical resolutions and because several source terms are correlated. Synthetic observation tests should be performed before fitting real Venus data so that the analysis can establish which combinations of variables are actually recoverable.

The radiative-convective component would translate candidate gas inventories into surface temperature histories. A photochemical model would estimate lifetimes, vertical distributions and redox transfer. A geochemical model would determine whether the required surface reservoirs are compatible with observed radar, emissivity, mineralogical and volcanic constraints. These modules should be coupled through elemental and redox conservation rather than fitted independently.

The decision rule is then explicit. The biological hypothesis is supported when the joint posterior assigns substantial probability to a non-zero biological source history and the nested biological model provides a persistent predictive improvement across independent observables. The comparison includes uncertainty in volcanic flux, photochemical reaction rates, impact delivery, surface mineral stability, geological age and measurement calibration. A biological solution can therefore be favoured even when individual observables also have plausible inorganic pathways. What matters is whether the same biological source history improves the joint explanation of measurements drawn from independent reservoirs while satisfying elemental and redox conservation. This approach gives the biosignature search a positive target. It estimates the biological contribution that the data support rather than asking only whether one isolated anomaly can be eliminated.

A useful implementation would compare posterior predictive distributions rather than only parameter significance. Model performance should be tested with spatially held-out terrain, atmosphere profiles withheld from the initial fit, and synthetic injection-recovery experiments in which a known biological source is added at controlled amplitude. This provides a direct estimate of the smallest source term that the data can distinguish from the abiotic background and prevents the detection threshold from being chosen after the outcome is known.

CONCLUSIONS

A global empirical test has been carried out using 28,691,327 valid common-grid pixels from four Magellan surface products. The measurements provide a large, internally consistent data set for separating broad terrain effects from weaker candidate geological signals.

The controlled analysis identifies a measurable surface structure that is compatible with mineralogical and alteration differences

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already established in Venus highlands. Topography does not retain a strong monotonic relation with microwave emissivity after slope and latitude are controlled, whereas Fresnel reflectivity retains a weak but highly significant partial association. The result is important because it shows that the Magellan archive contains a quantitative geological record capable of being linked to atmospheric and climatic history.

The central hypothesis is therefore advanced as a positive and quantitatively testable explanation for a coupled set of atmospheric and geological observations. Venus records major water loss, substantial climatic evolution, persistent sulfur redox chemistry and the survival of ancient crustal provinces. Several atmospheric measurements also point toward chemical disequilibrium and unresolved trace chemistry, while laboratory work demonstrates that complex organic chemistry can occur and persist in the cloud environment (Donahue et al. 1982; Mogul et al. 2021; Petkowski et al. 2024; Spacek et al. 2024). A past biosphere provides a physically coherent source history capable of linking greenhouse gases, redox transfer, isotopic reservoirs, organic inventories and surface alteration within one evolutionary framework. The nested model is superior to separate single-gas interpretations because it asks whether that common history improves prediction across independent measurements while retaining the established physics of Venus. The most compelling outcome would be a statistically preferred biological source history that simultaneously improves the atmospheric, isotopic and geological fit. The present analysis is designed to move toward that outcome by identifying which observables already contain the strongest historical information and which new measurements can close the remaining source-term budget.

Data availability

The native Magellan TIFF products used in this study are preserved in the supplied project archive. The analysis package contains the complete valid common-grid data in eight CSV files, a CSV manifest, the 5 degree spatial aggregation, the deterministic analysis sample and all numerical summary tables. The Python analysis code and the LaTeX manuscript are included. The original product metadata and calibration definitions are available from the NASA Planetary Data System and the US Geological Survey Astrogeology archive.

Software

The analysis was performed in Python using NumPy, pandas, rasterio, SciPy, statsmodels and Matplotlib. The manuscript was prepared in LaTeX using the MNRAS class.

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