



Sedimentary Processes on Venus

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Abstract

The sedimentary cycle, including the processes of erosion, transport, and lithification, is a key part of how planets evolve over time. Early images of Venus's vast volcanic plains, numerous volcanoes, and rugged tectonic regions led to the interpretation that Venus is a volcanic planet with little sediment cover and perhaps few processes for generating sedimentary rocks. However, in the years since the Magellan mission in the 1990s we have developed a better understanding of sedimentary process on Venus. Impact craters are the largest present-day source of sediments, with estimates from the current crater population suggesting an average sediment layer 8–63 cm in thickness if distributed globally. There is clear evidence of fine-grained material in volcanic summit regions that is likely produced through volcanism, and dune fields and yardangs indicate transport of sediments and erosion of rocks through wind. Landslides and fine-grained materials in highland tessera regions demonstrate erosive processes that move sediment downhill. It is clear that sediments are an important part of Venus's geology, and it is especially important to realize that they mantle features that may be of interest to future landed or low-altitude imaging missions. The sinks of sediments are less well known, as it has been difficult to identify sedimentary rocks with current data. Layering observed in Venera images and in Magellan images of some tessera regions, as well as calculated rock densities, suggest that sedimentary rocks are present on Venus. New data is needed to fully understand and quantify the present-day sedimentary cycle and establish with certainty whether sedimentary rock packages do, in fact, exist on Venus. These data sets will need to include higher-resolution optical and radar imaging, experimental and geochemical measurements to determine how chemical weathering and lithification can occur, and topography to better model mesospheric winds. Sediments and sedimentary rocks are critical to understanding how Venus works today, but are also extremely important for determining how Venus's climate has changed through time and whether it was once a habitable planet.

Keywords Venus · Sediments · Sedimentology · Regolith · Aeolian · Volcanism

Venus: Evolution Through Time

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1 Introduction

The production of regolith and the transport and lithification of sediments are key processes that are intimately tied to planetary climate and evolution. On Earth and Mars, erosion by water, wind, and ice lead to the production and re-working of sedimentary rocks, and outcrops of sedimentary rocks can record evidence of changing climates. At face value, Venus—currently a hot, dry planet with a thick atmosphere—is expected to have a considerably different history of erosion and sedimentation to that of modern Earth. However, the processes that create sediments and the nature of Venusian sedimentary rocks are still largely unknown.

The Magellan mission to Venus, with its 150 m-resolution radar imaging at a wavelength of 12.6 cm, provided the first detailed look at sediments on a global scale. At this resolution, it was possible to identify dunes, yardangs, and wind streaks (Greeley et al. 1992, 1995), as well as mass-wasting features in the tesserae (Bindschadler et al. 1992; Solomon et al. 1992; Malin 1992). Early analysis suggested there were few dune fields and possibly a lack of sand-sized particles that could be transported (Greeley et al. 1992). Radar-dark and -bright crater ejecta and parabolas suggested sediment production associated with impacts (Campbell et al. 1992; Schultz 1992), as well as a possible erosive process for these deposits (Izenberg et al. 1994; Basilevsky et al. 2003). But there was little evidence seen for widespread regolith cover in the synthetic aperture radar (SAR) imaging. Radar is capable of penetrating into the surface and imaging through mantling deposits, however, so the Magellan SAR data could possibly be missing the detection of deposits that would otherwise be visible in optical or higher-spatial-resolution radar data.

It was also clear from crater statistics that the Venus surface is mostly very young, with an average surface crater retention age of ~ 500 Mya (Phillips et al. 1991, 1992; Herrick et al. 2023). The presence of extensive volcanic plains led to the assumption that most of the former sedimentary history of Venus, provided it ever existed, is buried and inaccessible. In the absence of water, chemical weathering on Venus is thought to be a relatively slow process that may not produce considerable volumes of fines (e.g., sand size or smaller particles; Dyar et al. 2021). Images of the Venera landing sites show a variety of rock distributions and rock sizes (Florensky 1977; Florensky et al. 1983; Surkov and Barsukov 1985), but the rocks were largely interpreted as volcanic in origin, commensurate with their basaltic chemistry (Garvin et al. 1984). The Venera data do not show an abundance of fine sediments or landforms that would indicate the presence of extensive deposits of sand-size and smaller materials (Garvin et al. 1984). These observations together led to the general consensus that mantling deposits on Venus are localized, sediment transport is limited, and, aside from the highlands, the surface is composed of basaltic volcanic rocks.

Work in the decades since Magellan, including both new data and the application of new analysis techniques, have led to a different view of sediment cover and sedimentary rocks on Venus. These studies, including the identification of possible pyroclastic deposits, mapping of layering within tesserae, re-analyses of landing site data, and ground-based polarimetric radar imaging, reveal that Venus has a more complex rock record than was previously thought. The following sections present a summary of what we currently know about sediment sources and sinks on Venus, and provide a discussion of possible sedimentary rock sequences and their implications. These observations set the stage for future missions to Venus that can provide answers to the many questions that remain about Venus sedimentology, and what sediments there can reveal about the planet's surface processes, surface–atmosphere interactions, and climate evolution.

2 Sources of Sediment

The main processes leading to sediments on Venus today are impact cratering, volcanism, mass wasting and mechanical weathering, and the chemical breakdown of surface rocks. With our current data, it is difficult to completely assess how much sediment is generated through these various processes. Radar can image through thin deposits, and the currently available low-resolution orbital images likely miss smaller such deposits. In addition, there is usually little direct information available about the thickness of those deposits that have been recognized. However, there is still ample evidence that fine-grained (<1 cm) material covers a substantial part of the Venus surface and provides a material source for lithification and the potential generation of new sedimentary rocks.

2.1 Impact Craters

Impact cratering is likely to be one of the primary, if not the dominant, means of generating sediments on Venus today. The largest impact-related features are parabola-shaped deposits associated with some craters. Most of these parabolas are visible in SAR images, but there are several parabolas visible in microwave emissivity that are not always commensurately visible in SAR data (Campbell et al. 1992; Schaller and Melosh 1998). The parabola features likely form when debris from the impact is lofted into the atmosphere and then later carried downstream by the prevailing westward winds; models suggest that the settling time of cm-sized particles is a few hours (Campbell et al. 1992).

Individual parabolas can cover up to 2 million km², and the 58 parabolas currently recognized in the Magellan data cover cumulatively at least 40 million km² (or almost 9%) of the Venus surface (Campbell et al. 1992; Schaller and Melosh 1998). A two-layer radar backscattering model suggests that the parabola features may be at least 1–3 m thick (Campbell et al. 1992). In some cases, these parabolas appear to thin out as underlying plains features become visible in the radar data near the edges, supporting the idea that the deposits may be centimetres thick at the distal parts and metres thick in the central portions, consistent with the predictions of analytical models (Vervack and Melosh 1992). Wind streaks are associated with many of the parabolas, supporting the hypothesis of the presence of mobile fine materials (Greeley et al. 1992). In several cases, the parabolas clearly extend into nearby regions of tesserae, darkening the surface slightly and changing the local radar polarization signature of that terrain type (Campbell et al. 2015; Whitten and Campbell 2016).

The parabolas have a variety of morphologies and backscatter properties. In some cases, the parabolas are mostly radar bright, in others mostly radar dark, and in some instances, they consist of alternating bright and dark sections (Fig. 1). The radar-bright portions are likely rough at wavelength scales (Campbell et al. 1992). Low backscatter power values indicate smooth surfaces, either stripped of material or mantled in fines. These bright–dark patterns may indicate deposits with different particle sizes, differences in stripping of fine material, differences in composition, or possibly rippled surface textures.

Radar imaging polarimetry from the Arecibo observatory was used to measure the degree of linear polarization, an indicator of penetration of the radar wave and hence of the depths of possible surface mantling layers (Carter et al. 2004). The circular polarization ratio (CPR) is the ratio of the same-sense circular polarization that was transmitted to the opposite-sense circular polarization received. CPR is used as measure of surface roughness, with higher values indicating more rugged surface textures at the wavelength scale. The degree of linear polarization (values between 0 and 1) is the fraction of the received radar wave that is linearly polarized. When a circularly polarized wave is transmitted, such as with

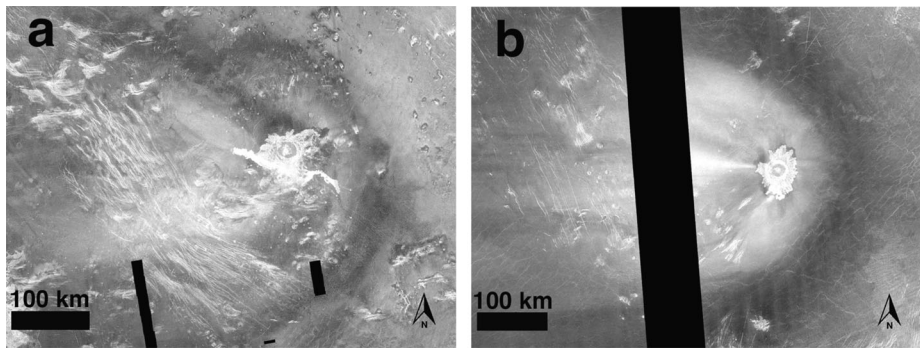


Fig. 1 Impacts are likely the dominant source of sediments on Venus. Parabola craters Carson (a) and Adivar (b) have both radar-bright and -dark markings that are probably caused by changes both in surface roughness and ejecta thickness (Campbell et al. 1992; Carter et al. 2004). These parabolas are both seemingly pristine, but over time parabola features erode (Izenberg et al. 1994), indicative of sediment removal by winds and/or physical or chemical modification occurring on timescales of tens of millions of years (Arvidson et al. 1992; Izenberg et al. 1994)

the Arecibo radar system, a linearly polarized component is introduced through interaction with the surface. For natural rock surfaces, this linearly polarized signal is most often generated by penetration into the surface and reflection from buried rocks or structures (Carter et al. 2011). These data reveal that high degree-of-linear polarization values are common near impact deposits, with both radar-bright and -dark deposits showing evidence of surface mantling (Carter et al. 2004). This finding suggests that there is fine material (i.e., low-density mantling deposits easily penetrable by radar) distributed across the parabolas, and that the observed variations in backscatter correspond to surface changes such as rock exposures or mantling deposits.

In addition to the parabolas, radar-dark halos around some craters are evidence of sediment deposition (possibly from pulverized rock) near the impact site (Izenberg et al. 1994). Similar features have also been seen around lunar craters, where they are interpreted to be areas of crushed and finer rock near the point of impact (Ghent et al. 2005). Small, dark haloes just outside the primary ejecta blanket are common on Venus, but there are some dark haloes that are tens to hundreds of kilometres in diameter (Campbell et al. 1992; Schaller and Melosh 1998). For example, Stanton crater (23.4°S, 199.90°E) has a 110 km-diameter halo (Schaller and Melosh 1998; Schaber et al. 1992). Radar polarimetric images of the largest haloes visible with the Arecibo telescope reveal polarimetric signatures (high degrees of linear polarization and low circular polarization ratios) indicative of fine-grained surface mantling and/or low-density rock (Carter et al. 2004).

A positive relationship between crater diameter and parabola size supports the hypotheses that the parabolas are generated in the impact process, and that all craters above ~ 11 km diameter—large enough to loft material into the upper atmosphere—will generate a parabola deposit during the impact process (Schaller and Melosh 1998; Campbell et al. 1992). Global maps of impact deposits on Venus (Fig. 2; Ganey et al. 2023) illustrate that up to $\sim 60\%$ of the planet's surface area was at one time blanketed with an ejecta deposit. This coverage includes the areal extent of all parabola deposits (both observed and modelled; see Fig. 2) associated with craters ≥ 11 km in diameter.

However, intact parabolas are associated with $\sim 10\%$ of impact all craters. Other craters are observed to have possible remnants of impact deposits, or have no associated impact deposits at all, suggesting that parabolas, once created, are altered and erased through time

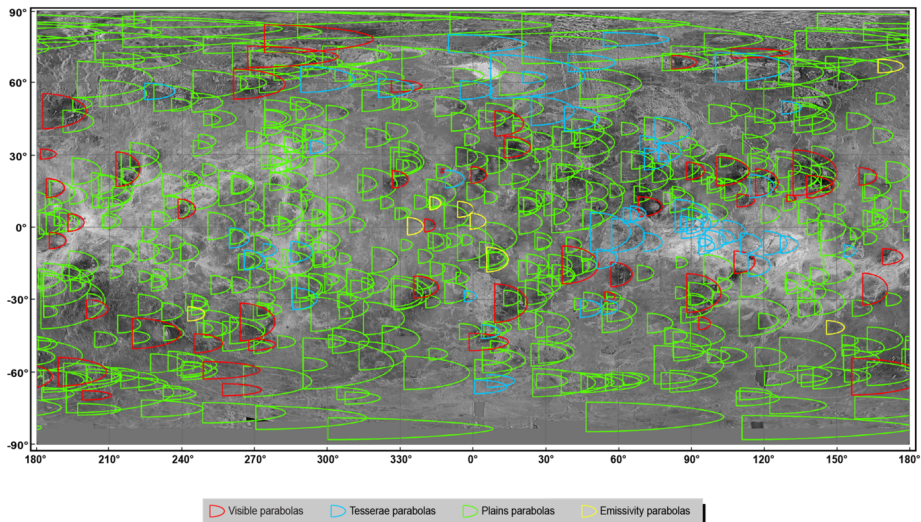


Fig. 2 Global map of Venus with parabola deposit outlines. The visible paraboloids (red outlines) are the 49 radar-dark deposits with dimensions reported by Campbell et al. (1992). The tesserae and plains paraboloids (blue and green outlines, respectively) are those paraboloids modelled from the method from Basilevsky et al. (2004), with the name indicating the terrain where the impact crater is located. The emissivity paraboloids (Campbell et al. 1992) are shown in yellow

(Izenberg et al. 1994; Schaller and Melosh 1998). Alternatively, some of the non-parabolic impact features may have formed during an earlier epoch when there was no atmospheric super-rotation (Kreslavsky and Bondarenko 2017). Crater ejecta can be erased via several processes, including volcanic resurfacing or aeolian erosion, both of which are observed on Venus. Chemical or physical weathering may also play a role (Izenberg et al. 1994). Whatever the mechanism(s) of removal, these observations suggest intact crater paraboloids have a lifetime of approximately 10% of the average age of the surface and are eroded on timescales of several tens of millions of years (Campbell et al. 1992; Arvidson et al. 1992). Yet impact ejecta may persist longer as an identifiable unit in tesserae than in plains. For example, there is evidence for some fine-grained mantling deposits in tessera terrain with no corresponding impact crater visible on adjacent plains regions, suggesting that volcanic resurfacing may have erased a crater and ejecta in the plains, but not that portion of the ejecta deposit that mantled the higher-elevation tessera (Whitten and Campbell 2016).

Estimates vary for the total volume of impact deposits on Venus. Garvin (1990) estimated a cumulative impact deposit volume of $5.5 \times 10^6 \text{ km}^3$ by applying the crater excavation models of Maxwell (1977) to the population of craters imaged by Venera (25% of the surface), extrapolated over the remainder of the planet. After Magellan, this estimate was revised using several methods. Schaller and Melosh (1998) modelled the distribution of particles produced by each impact crater as a function of a diameter, and then tracked the distribution of sand-size (60–2000 μm) particles as they were lofted into space, re-entered the Venus atmosphere, were transported by wind, and then settled to the surface. Applying this model to all craters $>2.5 \text{ km}$, Schaller and Melosh estimated a cumulative sediment volume of $3.5 \times 10^4 \text{ km}^3$. Lorenz (1999) derived an equation for sediment volume as a function of crater diameter based on the methodology of McGetchin et al. (1973); this equation applied to all craters with diameters greater than 11 km yields a volume of $1.2 \times 10^5 \text{ km}^3$. Basilevsky et al. (2004) used an empirical fit between crater diameter and the size of paraboloids visible

in the Magellan data and reported by Campbell et al. (1992), and assumed that all craters greater than 11 km in diameter would have produced a parabola. Basilevsky et al. (2004) modelled each parabola as a half ellipse, and then assumed that parabolas have an average thickness of 10 cm, which together yielded a total volume of $2.8 \times 10^4 \text{ km}^3$.

Ganey et al. (2023) mapped the location of known and inferred parabolas of craters >11 km in diameter (Fig. 2) and used the McGetchin et al. (1973) method to calculate a revised minimum global impact deposit volume of $2.9 \times 10^5 \text{ km}^3$. All of these estimates yield an average sediment layer 8–63 cm in thickness if distributed globally (Ganey et al. 2023). Several of the summarized approaches for estimating sediment volume rely on the McGetchin et al. (1973) relationship between ejecta thickness and distance from the host crater (Ganey et al. 2023; Lorenz 1999; Schaller and Melosh 1998; Vervack and Melosh 1992). Although this relationship was originally derived from lunar cratering models, laboratory experiments, and meteorite impacts, it has been verified against ejecta deposits on Earth and found to describe Venusian deposits reasonably well (Lorenz 1999). The McGetchin method may even underpredict deposit thickness by up to a factor of two, which suggests that some global volume estimates (e.g., Ganey et al. 2023) are most useful as minimum endmembers.

Other impact processes contribute to the production of sediments on a smaller scale. Radar-bright or -dark patches or haloes, called “splotches”, have been interpreted as evidence of airburst meteoroids (Kirk and Chadwick 1994; Schaber et al. 1992). These bursts may cause crushing and breakup of surface rocks and deposition of ablated impactor material (Schultz 1992). They may also be responsible for some sediment transport, for example by creating small dunes or blowing away fine materials. In addition, many craters on Venus have long runout flows with lobate margins and sometimes complex structures such as interior channels (Phillips et al. 1991; Schultz 1992). These features have typically been interpreted as impact melt deposits (Chadwick and Schaber 1993), but some have also been interpreted as ground-hugging debris flow deposits (Schultz 1992). Most models of these flows incorporate multiple phases of deposition, including both melted rock and ejected country rock admixed with vapor (Herrick et al. 1997). Although not as spatially extensive as parabolas, these impact features also contribute to local sediment deposits.

2.2 Volcanism

Pyroclastic volcanism is a source of sedimentary deposits on Earth, Mercury, Mars, the Moon, and Io, providing varying fractions of the sediment supply based on the nature of volcanism and (where applicable) prevailing atmospheric conditions. On Venus, the dense atmosphere likely inhibits pyroclastic volcanism unless there is a substantial volatile content (Garvin et al. 1982; Airey et al. 2015). Nevertheless, there have been numerous candidate pyroclastic deposits identified across the planet (Campbell et al. 2017; Ghail and Wilson 2013; Carter et al. 2006; Campbell and Rogers 1994; Guest et al. 1992).

These putative Venus pyroclastic deposits have a range of radar properties. For example, both radar-bright and radar-dark features have been proposed as pyroclastic deposits (Fig. 3), and these features can have irregular outlines or clearly delimited unit boundaries. These deposits sometimes also have higher or lower microwave emissivities compared to their surroundings, as mapped and calculated by the Magellan radiometer (Brossier et al. 2020; Carter et al. 2006; Campbell and Rogers 1994). On Earth, the Moon, and Mars, pyroclastic deposits are typically radar-dark because the deposits are smooth (e.g., Solikhin et al. 2015; Gaddis et al. 1985; Carter et al. 2009; Harmon et al. 2012). Such deposits also typically have low values of CPR due to the fine-grained nature of the deposits and lack of embedded rocks in the upper centimetres of the flow (e.g., Carter et al. 2009).

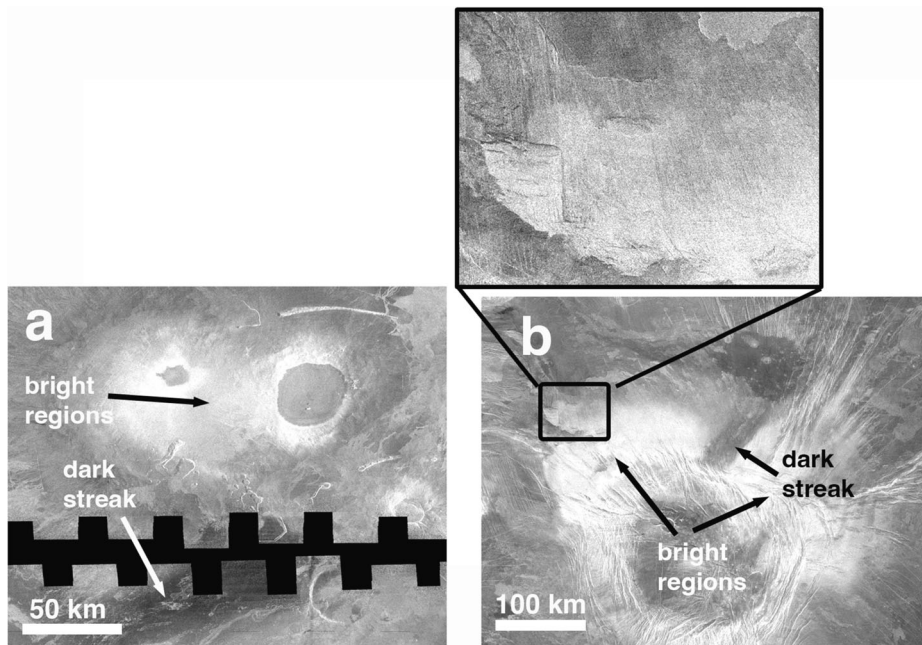
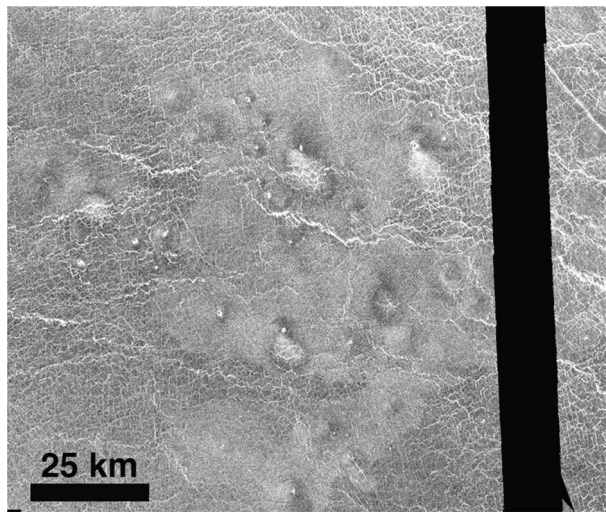


Fig. 3 The summits and flanks of volcanoes and coronae on Venus have diffuse deposits that are likely pyroclastic sediments (Magellan SAR images). A) The Tepev Mons summit has radar-bright, diffuse material between the two calderas, as well as a dark streak thought to be a fine-grained volcanic deposit (Campbell and Rogers 1994). B.) The summit of Irnini Mons has diffuse, radar-bright deposits downslope of the corona ring fractures that are likely ponded pyroclastic flows (Campbell et al. 2017; Ganesh et al. 2021). There is also a dark streak that is probably a relatively smoother tephra deposit. An inset shows detail of the edges of the diffuse bright material: fine, linear, dark streaks that cross the radar-bright lava flow and blend into the surrounding terrain imply that aeolian erosion is stripping or moving the fine material

Radar-dark streaks at Tepev and Irnini Montes on Venus are examples of features that have been proposed as pyroclastic deposits (Campbell and Rogers 1994; Carter et al. 2006; Ganesh et al. 2022), possibly as the result of an ash column blown by local winds or travelling downhill as pyroclastic flows (Fig. 3). Their radar-dark signatures suggest that the particles making up these deposits are small, and that their surfaces are smooth. The radar-dark streaks have low CPR in Arecibo data and there is no evidence of an increased degree of linear polarization, although these flows are almost too small to detect reliably given the Arecibo polarimetry resolution of 12–16 km/pixel (Carter et al. 2006).

In contrast, radar-bright deposits near some summits (e.g., Irnini, Anala, and Innini Montes, Pavlova Corona) have high CPR values suggestive of a rugged surface that was deposited as a column collapse or pyroclastic flow (Fig. 3, Campbell et al. 2017). These features have diffuse edges that may have been caused by some amount of erosion of fine material near the distal edges (Fig. 3, Campbell et al. 2017). Modelling of the radar-bright flows at Irnini Mons demonstrates that they can be deposited by pyroclastic density currents (Ganesh et al. 2021), and their backscatter and emissivity values suggest that they could be rough deposits consistent with a debris flow with cm-sized clasts (Ganesh et al. 2022). It is not clear if these deposits have been welded or partially welded, or consist solely of rock fragments, but the diffuse edges and dark streaks suggest that they may be relatively unconsolidated (Fig. 3).

Fig. 4 A shield field in the Venesian plains (22.08° N, 331.94° E) has wind-blown sediments and likely downstream scouring (Magellan SAR image). The origin of the sediments in uncertain. This small shield field is located north of the parabola crater Aurelia, so the debris may have come from the impact or directly from volcanic tephra. Multiple shield fields have radar polarimetric signatures indicative of sediment cover (Carter et al. 2006)



The summit regions of some volcanic edifices are also associated with wind streaks, providing evidence of sediment motion there. For example, plains shield fields sometimes have tails indicative of aeolian deposition and/or scouring of material (Fig. 4). Degree of linear polarization data for some of these volcanic fields (including that shown in Fig. 4) suggest that there is likely increased mantling material present relative to nearby plains regions (Carter et al. 2006). It is not possible to establish with certainty the source of the sediments; for example, the material could be generated by volcanism or be simply wind-blown sediment from elsewhere trapped by local topography. In some examples, the material appears to be sourced from a nearby parabola crater, such as in the case of dome fields near the crater Aurelia. Nevertheless, the increased concentrations of sediments in these dome fields suggest these deposits may in at least some instances be related to primary tephra deposition.

Even if pyroclastic volcanism is not widespread today on Venus, the features discussed above show that deposits of seemingly sedimentary material 10 s of km² in spatial extent can be generated. Ganesh et al. (2021) estimated the bulk volumes for pyroclastic deposits located in Eistla Regio: 310–780 km³ at Irnini Mons, and 140–280 km³ for the smaller deposits at Anala Mons and at Pavlova and Didilia coronae. Individual pyroclastic flow volumes are small, but an abundance of such deposits could potentially produce significant volumes of sediment. These deposits are likely later eroded by wind and could also potentially be lithified into volcanoclastic rocks (Byrne et al. 2021). It is also possible for pyroclastic flows to form lobate margins similar to lava flows (e.g., Ghail and Wilson 2013), and so it may be difficult to differentiate lava and pyroclastic deposits from radar backscatter data alone. Identifying pyroclastic deposits with future radar and microwave emissivity data is critical for the search for regions where lavas may have a high volatile content, and to understand the prevalence, erosion, and redistribution of volcanic sediments on Venus generally.

2.3 Mass Wasting and Mechanical Weathering

Mass wasting can contribute to the global breakdown of rocks and sediment production. New (i.e., present-day) landslides and avalanches have been observed with orbiting spacecraft on

both Mars and the Moon (McEwen et al. 2021; Speyerer et al. 2015), and these images provide key information on current surface changes, outcrop structural stability, mechanical rock breakdown, and seismic shaking.

2.3.1 Evidence for Mass Wasting Deposits

There is some evidence for landslides on Venus with current data. Venera 9 is inferred to have landed on a talus slope. Small-scale steep slopes are very common on Venus, most often associated with normal faulting and graben, and mass wasting appears to be a common occurrence in these steep areas (Malin 1992). Rock slumps, rock and/or block slides, rock avalanches, debris avalanches, and a possible example of a debris flow have all been identified in Magellan imagery, suggesting a range of rock failure mechanisms (slides, slumps, flows) and material types (regolith versus rock) (Malin 1992; Bulmer and Guest 1996). Although landslides have not yet been identified on the flanks of Venus shield volcanoes, likely due to shallow slopes, debris avalanches and rock slides have been observed on steep sided volcanic domes (Bulmer and Guest 1996). The lengths of the landslide runouts fall in between the typical sizes of Earth and Mars landslides and appear, based on radar imagery, to have a range of surface debris sizes ranging from metre-scale rubble to very fine (radar-dark) dust deposits at some of the distal edges (Malin 1992). More so than on Earth, Venusian landslides are found in groups, and most of them occur in areas where neighbouring escarpments are as steep or steeper than the one that failed. Therefore, either landslides occur at roughly the same time because of one triggering event, or rock failure occurs frequently in a given location due to steep slopes and frequent triggering events (Malin 1992).

Some of the largest landslides are located in Diana Chasma (Fig. 5), where there is evidence for ongoing tectonic activity on the basis of the proportion of highly fractured craters and the disruption of a parabolic dark halo (Ghail 2002). However, this example also clearly demonstrates that, although mass wasting does occur, the retention of steep slopes several kilometres high implies that mass wasting is likely slower on and thus modifies the landscape to a much lesser extent on Venus than on Earth. The lesser degree of thermal cycling, combined with the lack of surface water and ice, could in addition slow the fracturing and movement of rock relative to Earth. A reduction in joint formation would then help prevent slope failure, as well as inhibit further weathering by limiting access of the atmosphere to interior rock faces (Balme et al. 2004). A reduction in jointing could also be caused by the high atmospheric pressure (equivalent to 900 m water depth on Earth) (Balme et al. 2004). The net effect is that the styles, and probably rates, of mass-wasting-induced surface modification on Venus are different from those on Earth and Mars. Mass wasting on Venus may appear more similar to Earth's submarine than subaerial surfaces (Iversen et al. 1976)—and so thinking of the dense, supercritical fluid atmosphere as an ocean may be helpful when trying to understand its behaviour (Malin 1992). In particular, the entrainment of atmospheric gas may provide the fluidization needed for putative debris flows (Malin 1992).

As on Earth, fresh normal fault scarps are expected to form at angles of 60–70°, although mechanical weathering will serve to reduce those slopes to the angle of repose (~35°) over time. Radargrammetric measurements of 170 normal faults in Venus plains regions yield an average slope of $36.4 \pm 1.2^\circ$ (Connors and Suppe 2001). These observations are consistent with the formation of talus slopes across Venus. However, the resolution of Magellan images, as well as unfavourable look angles in rugged regions, makes it difficult to discern all but the largest and most obvious mass-wasting structures (Malin 1992).

The lack of small impactors on Venus may preclude some of the sources of seismic shaking that can cause mass wasting on the Moon and other planets, but Venus is likely

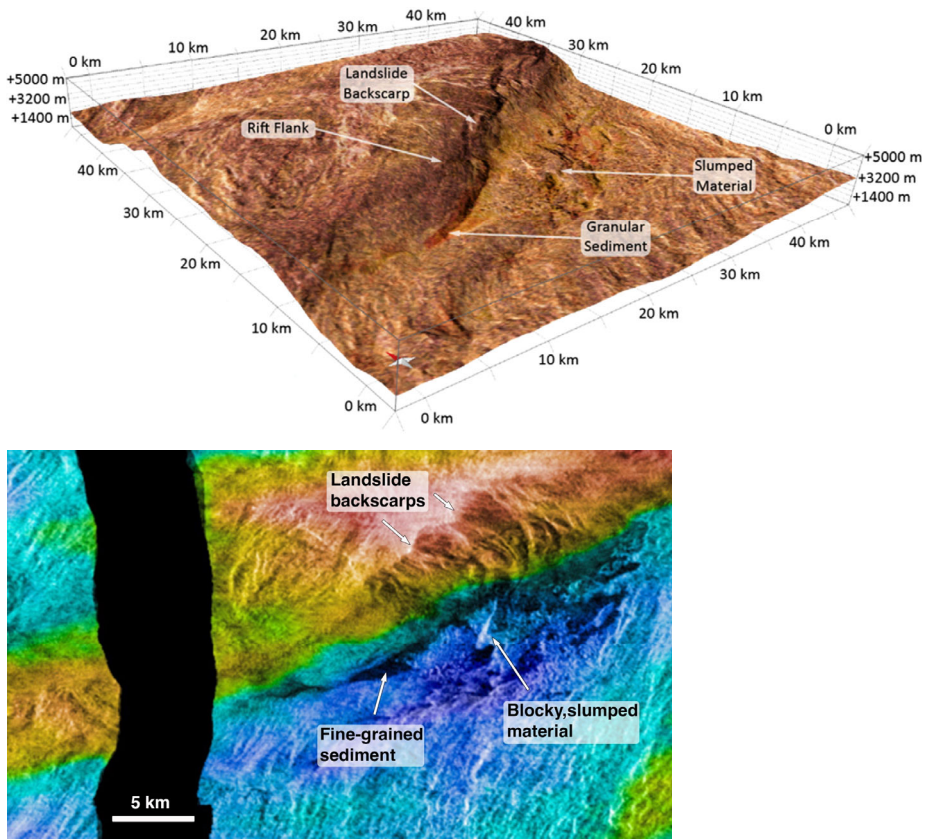


Fig. 5 One of a number of large landslides in Diana Chasma, this example is located at 19.09°S, 142.19°E. Top image: Topography is derived from stereo image pairs; the colour and shading is from right- and left-looking radar images, in which fine granular material is orange–red and bare rock is pinkish red, as seen on the rift flank and backscarp. The yellowish material is consistent with lithified weathered sediments. Bottom: Another, 2D, view of the landslide. The colour topography ranges from 400 m elevation in blue at the foot of the scarp to 3700 m in red at the top. Blocky slumped material is visible below the scarp; fine-grained (dark) material is visible along the scarp floor for tens of km. The fresh appearance of both the scarp and the slumped material implies either a recent origin or minimal erosion and transport, similar to submarine slides on Earth

to be tectonically and volcanically active seismically. Indeed, a primary source for mass movements on Venus is likely to be seismicity. If Venus has a level of seismic activity similar to intraplate levels on Earth, then we should expect 10 s to 100 s of events per year (Lognonné 2005; Lorenz 2012). Additionally, the Venera 14 vertical seismometer may have detected a ground-motion event that was unrelated to wind measurements (Ksanfomality et al. 1982; Lorenz and Panning 2018). A comprehensive mapping of landslides with future higher-resolution data could be used to identify areas more prone to seismicity (or possibly with weaker rock types or internal structures).

In summary, although landslides have been identified and contribute to local sediment budgets, it has been difficult to discern widespread evidence for mass wasting at the scale of the Magellan data. It has also been nearly impossible to search for active landslides with the differing look angles of the SAR images in the steep and rugged areas where landslides

form. New, considerably higher-resolution imaging and topographic data and monitoring over time are needed to reach any firm conclusions about the recent history of mass wasting on Venus. This requirement is especially relevant when it comes to detecting the smaller landslides ($\sim 500 \text{ m}^3$ volume) that are typically more common on Earth and Mars than larger mass-wasting events (de Haas et al. 2014).

2.3.2 Upland Erosion

Higher-elevation regions on Venus are cooler and experience different wind regimes than at low elevations (Lefèvre 2022), which could lead to differences in the production of sediments in uplands relative to the plains. Upland erosion via mass wasting from steeper surfaces and/or aeolian scouring from updraft or downdraft winds can produce materials that fill in depressions in mountainous regions and result in deposition of material at lower altitudes. At higher elevations, crustal materials appear to be strongly affected by surface winds (Fig. 6), but even these areas have dielectric constants consistent with lithified sediments, not loose accumulations. The low resolution of the Magellan altimeter nadir reflectivity data, from which the dielectric permittivity (Ford and Pettengill 1992) and thus density of surface materials is derived (Ulaby et al. 1988), returns a mixed signal; in Fig. 6, the blue areas (dielectric constant 4–8) may well be a mixture of high dielectric (highland) material and loose sediments with lower permittivity (such as talus), whereas the green areas to the east (dielectric constant 2–4) may likewise be a mixture of talus and volcanic rock. Even so, the relatively large areas of streamlined material have the dielectric constant signature of lithified sedimentary rock rather than loose regolith.

This area is tectonically active, or at least has been in the geologically recent past (Ghail 2002), so fresh sedimentary material, primarily talus from over-steepened slopes, may be continually generated. Mean wind speeds are strongly altitude dependent and are able to erode and transport material throughout the highland regions (e.g., Greeley et al. 1984; see below). In some areas, this upland material is deposited on adjacent plains—leading to the possibility that the largely featureless plains covering several tens of percent of the planet may be at least partly sedimentary, rather than purely igneous in origin. The settling out of sedimentary material is consistent with observed crater degradation, in which low-lying crater floors are infilled with some combination of sediments and lava flows first (Herrick and Rumpf 2011). In the Fig. 6 example, coarser material (i.e. centimetre-sized) from mass wasting is apparently mobilised locally by the wind (see windstreaks/yardangs label), to form streamlines that then at least partially lithify into rock with the observed somewhat higher dielectric constant than the unconsolidated sediments.

2.4 Chemical Weathering

The Venusian surface is also eroded via chemical weathering. Interactions between new surface materials, such as recent lava flows, and the Venus atmosphere produce a series of chemical reactions. Some of these reactions may drive volume changes, as well as a change in the surface composition through the development of coatings. This process may alter surface compositions on short timescales; for example, Dyar et al. (2021) extrapolated a weathering rate for basaltic glass from the experiments of Teffteller et al. (2022), predicting a surface alteration coating of $\sim 30 \mu\text{m}$ over 500,000 years. This coating is not expected to lead to the kind of blocky surface rocks seen at the Venera sites (Dyar et al. 2021). Models based on current Venus data have led to possible chemical alteration pathways for a variety of basaltic minerals, but the relative roles and rates of CO_2 , SO_2 , and H_2O in weathering processes are still unclear (Zolotov 2018). The role of supercritical CO_2 and mixtures of gasses

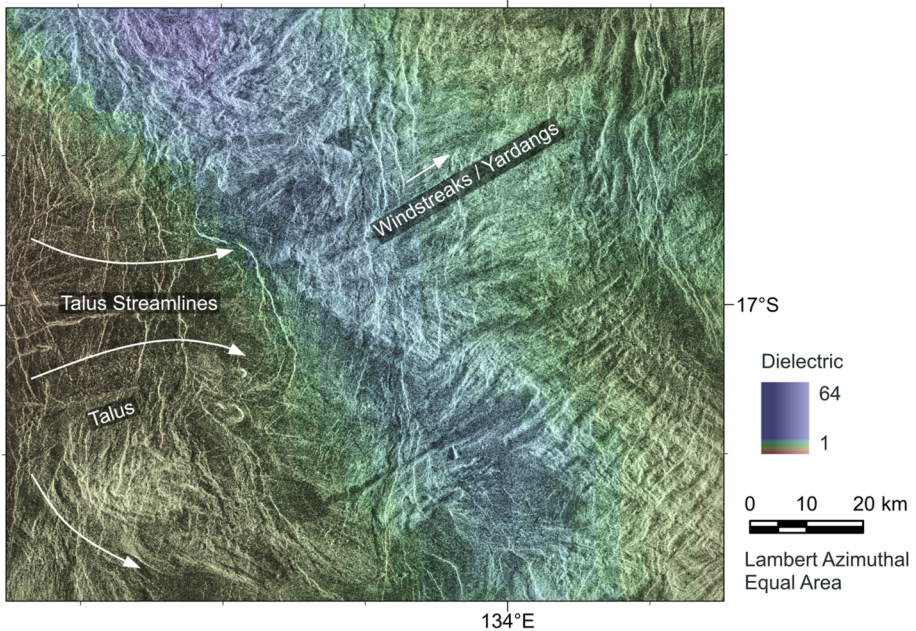


Fig. 6 Windblown sediments in south-east Thetis Regio shown with derived surface materials. Dielectric permittivity is calculated from Magellan altimeter nadir reflectivity; lower dielectric permittivity values indicate a relatively lower surface density. Radar-dark features ending in lobate shapes are interpreted to be talus (western side of image). A radar-bright hill in the southwest corner (above the arrow) has a streamlined shape, suggesting aeolian weathering. In the northeast part of the image, fine radar-dark and radar-bright alternating linear structures with a southwest to northeast orientation are interpreted as windstreaks or yardangs overprinting pre-existing topography. These features have dielectric constants consistent with lithified rock

and glass/solid rock are also currently unknown and could lead to unexpected weathering products or timescales (Zolotov 2018). Major sources of uncertainty remain in understanding the chemistry of Venus's surface–atmosphere interactions, and more laboratory experiments and measurements of surface chemistry and mineralogy are needed to fill these gaps (Filiberto et al. 2020; Dyar et al. 2021; Zolotov 2018). Our current understanding of surface weathering suggests that, over long timescales, it is possible that chemical weathering could contribute some volume to the sediment budget, but not at the scale of impacts, mass wasting, and volcanism (Dyar et al. 2021). For further information about surface mineralogy and weathering, see Gilmore et al. (2023, this collection).

In summary, sediment production on Venus is substantially different from sediment production on the Earth and Mars. Impact crater deposits cover larger areas on Venus and are thought to represent the major component of current sediment production, with volcanism as a possible secondary source. Compared to Earth and Mars, temperatures on Venus are remarkably constant, which reduces thermal cycling and resultant fatigue of rocks (which is also a major process on airless objects). The low surface wind speeds, thick atmosphere, and corresponding low saltation velocity mean that aeolian abrasion, an important source of erosion on Mars and in deserts on Earth, is considerably less effective on Venus (Kreslavsky and Bondarenko 2017). The lack of flowing and freezing water also dramatically reduces the weathering and erosion rate on Venus relative to Earth and prior warmer and wetter epochs on Mars. Water is also responsible for major chemical erosion rates and on Mars and

Earth. These aqueous processes will not occur on Venus, where chemical weathering is restricted to surface–atmosphere interactions or possibly volcanism-related interactions. The volume of sediments produced through each process and their timescales are poorly known for Venus, and require further data, laboratory studies, and modelling to reach a quantitative understanding.

3 Aeolian Transport

Once sediments are generated, they are transported from their place of origin by winds. Greeley et al. (1984) developed a Venus Wind Tunnel and demonstrated that sand grains of 60 to 2000 μm in diameter can become entrained by surface winds at Venus and are transportable by saltation. The empirical saltation threshold is 0.63 m s^{-1} , and bedforms (microdunes, ripples, etc.) will form below velocities of 1.5 m s^{-1} . Dust grains (below 40 μm diameter) move primarily in suspension, whereas coarser grains (2–16 mm diameter) move by creep, saltating at wind velocities over 2.5 m s^{-1} (Greeley et al. 1984; Greeley and Arvidsson 1990).

In order to assess how particles are transported, it is important to measure and model boundary-level wind velocities on Venus. Venus landers measured winds $< 2 \text{ m s}^{-1}$, and detected direct evidence of sediment motion (Lorenz 2016; Selivanov et al. 1982). Lorenz (2016) used a probability distribution (Weibull function) to estimate that surface wind speeds around 1 m s^{-1} are common and may keep sand-sized particles in constant saltation. The upper limit of surface winds estimated by the Lorenz (2016) probabilistic technique is $\sim 2.2 \text{ m s}^{-1}$, which is similar to an upper limit of 1.5 m s^{-1} derived through Global Circulation Model (GCM) simulations (Lebonnois et al. 2018). These findings suggest that coarse-grained materials probably do not saltate except during extreme weather events.

In addition, planetary boundary-layer models suggest that there are spatial and diurnal changes in winds. GCM models show slope-induced winds that change during the diurnal cycle, with downward katabatic winds at night and upward anabatic winds during the day that occur along the westward slopes of high-elevation terrains (Lebonnois et al. 2018). A turbulent-resolving boundary layer model by Lefèvre (2022) shows that at noon, for both high and low terrains (modelled as 1030 m and -230 m elevation, respectively), the friction velocity is above the saltation threshold, so turbulence can transport dust particles. At night, the velocities are lower and no transport occurs. In the low plains, the horizontal wind velocities are in the range where dunes can form, but at higher elevations the wind speed is too low to support dust transport. The Lefèvre (2022) model also produced convective vortices over the highlands; if present on Venus, such vortices could lift dust and produce dust devils.

The possibility of the movement of sediment on Venus is supported by a variety of independent observations (see also Kreslavsky and Bondarenko 2017). Firstly, the removal of crater parabolas over the timescale of 10 s to 100 s Myr requires redistribution by aeolian processes. A positive correlation between dark-floored craters and those with degraded or missing parabolas (Izenberg et al. 1994) is consistent with volcanic or aeolian infill of craters over time. On Mars, many impact craters are filled with layered sediments that may be the result of trapping of aeolian materials or wind-carried tephra deposits (e.g., Day and Catling 2019; Anderson et al. 2018), and a similar process could occur on Venus as sediment settles in basins. In addition, almost 6000 wind streaks have been identified on Venus, with various morphologies consistent with deposition and erosion of sedimentary materials (Greeley et al. 1995). These wind streaks have been used to infer local wind directions through mapping of

their orientations (Greeley et al. 1994). The wind streaks are predominantly oriented westward and towards the equator, but when local effects from impact cratering are removed, the equatorward component is dominant, as expected for a Hadley circulation of the lower atmosphere (Greeley et al. 1994).

In some regions of Venus, the radar backscatter of stratigraphically older volcanic flows is lower than younger flows in a manner consistent with the smoothing of lava flows on Earth by weathering (Arvidson et al. 1992). By comparison to radar images of flows on Earth, Arvidson et al. (1992) estimated that the degree of smoothing on Venus corresponds to ~ 1 m of surface modification, which translates to a vertical modification rate of $\sim 2 \times 10^{-3} \mu\text{m} \cdot \text{yr}^{-1}$, assuming a mean surface age of 0.6 Gyr. This sediment production rate is orders of magnitude lower than that on Earth, consistent with a lack of fluvial erosion. However, age dating of terrains on Venus, even relative relationships, is uncertain and the surface texture of emplaced flows on Venus are likely considerably different than that of lava flows on Earth. In situ imaging is likely needed to understand how lava flows are smoothed through aeolian weathering and deposition on Venus.

Bondarenko and Kreslavsky (2018) conducted a principal-component analysis of various surface properties related to Fresnel reflectivity and surface roughness to evaluate the hypothesis that small aeolian features may in fact be common on Venus. Their analysis showed that aeolian features below the resolution of Magellan (microdunes, ripples, sand sheets, etc.) could be ubiquitous, covering much ($\sim 40\%$) of the surface of the planet. Remaining unknown is the relative contributions of impact cratering, volcanism, aeolian erosion, or chemical erosion to the production, timing, and distribution of sediment on the planet generally.

Only two dune fields have been unequivocally identified in SAR imagery: Menat Undae (25°S , 339°E ; also named the Aglaonice dune field) and Al-Uzza Undae (68°N , 90°E ; also named the Fortuna–Meskhent dune field) (Greeley et al. 1992). Both fields are interpreted to contain transverse dunes because they demonstrate bright backscatter in Magellan images from slip faces oriented near-normal to the radar illumination, and their crests are perpendicular to the orientation of associated wind streaks (Greeley et al. 1992). Microdune fields have been suggested to lie near Stowe (47°S , 230°E ; diameter, $D = 75.3$ km), Guan-Daosheng (61°S , 178°E ; $D = 43$ km) and Eudocia (58°S , 160°E ; $D = 25.9$ km) craters based on differences in radar backscatter in left- and right-looking images of the regions (Weitz et al. 1994). Although too small to be directly resolved in Magellan SAR images, dunes with asymmetric slopes can produce the observed strong radar brightness if the slip faces are oriented near-normal to the radar illumination (Weitz et al. 1994). Venus also bears erosional aeolian landforms called yardangs; a field of such features has been identified southeast of Mead crater (Greeley et al. 1992). Our present information on dunes and yardangs may be limited by the available look angles and resolution of the Magellan data set. It will be important to search for evidence of dunes in new data from upcoming Venus missions to better quantify the sediment budget, and the spatial and temporal links between sediment sources and sinks, across the planet.

4 Sediments and Sedimentary Rocks

Venus sedimentary processes have been less studied than for other planets, largely from the assumption that initial Magellan data analysis showed little evidence for erosion and sediments—but expectations prior to Magellan were very different. The Venera landers, in

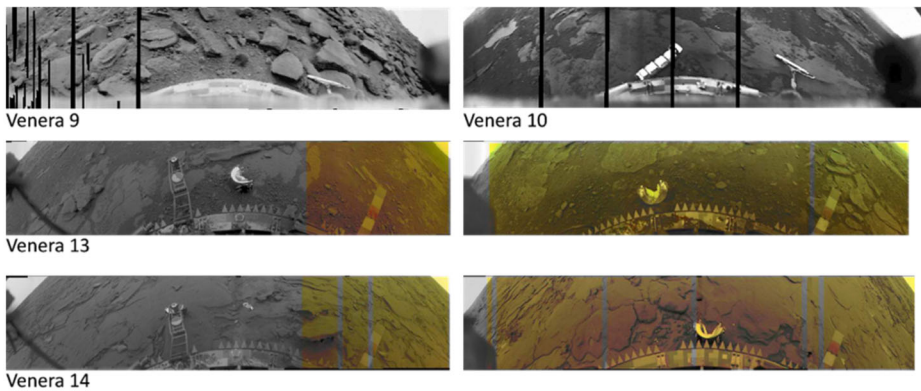


Fig. 7 Images of the Venus surface recorded by Venera Landers (reprocessed images © Don P Mitchell, used with permission). Venera 9 landed on a 15° – 20° slope, the top of which is visible to the upper right; downhill is behind the camera view at approximately the 8 o'clock position (Florensky 1977). The left images of Venera 13 and 14 are from the spacecraft Camera 1 (rear camera), and the right images are from Camera 2 (front camera). The color images had lower signal-to-noise, and here the color portions have been combined with the clear filter images (Don P Mitchell per processing description at http://mentallandscape.com/V_DigitalImages.htm)

particular, show a landscape originally interpreted to be dominated by sedimentary deposits (Florensky et al. 1983) that only later were reinterpreted as lava flows (Garvin et al. 1984).

Sedimentary rocks are formed through reworking and lithification of eroded sediments, through deposition and lithification of volcanic or landslide deposits, or (on Earth) through biological processes. They are a sink for sediments. These rocks record the history of planets and are a key part of determining past climate, so it is important to understand how sedimentary rocks form on Venus and where deposits of sedimentary rocks are located.

4.1 Evidence of Plains Regolith

Four Venera landers returned panoramic views of the Venus surface: Veneras 9, 10, 13, and 14 (Fig. 7). The lander images have a resolution of 10 mm per line pair for Venera 9 and 10, and 4–5 mm for Venera 13 and 14 (Garvin et al. 1984), so pebble and larger sized rocks could be resolved.

Although the surfaces in these images may be interpreted as thin, platy pahoehoe-type lava flows (Garvin et al. 1984), aerially extensive, thin flows are unlikely under Venus conditions, where rapid early cooling and a thick lava crust are expected (Head and Wilson 1986). Morphologically, the rocks in the lander images most closely resemble partially eroded, lithified clastic sediments (Florensky et al. 1983), with either expanses of fractured layered strata or areas of fragmented strata broken into cobbles and fine-grained sediment (Surkov and Barsukov 1985). This sediment always occurs as deposits in the localized topographic lows between bedrock outcrops, cobbles, and in the troughs between what appear to be ripples. Active aeolian transport is demonstrated by the removal of sediment from the lander ring of Venera 13 over a period of about an hour (Selivanov et al. 1982). In addition, photometric measurements at the Venera 9 and 10 landing sites suggest that dust clouds (particle sizes $<100\ \mu\text{m}$) were kicked up by the landing and then dissipated (Garvin et al. 1984; Moshkin et al. 1979).

Venera 9 recorded images of rock materials similar in appearance to the bedrock elsewhere, but in the form of subangular boulders up to 60 cm wide and 20 cm tall within a

coarse sediment or gravel on a 15° to 20° slope interpreted as talus (Florensky 1977). The gravels are subangular to subrounded and with a distinct anisotropy in sizes, with some rocks falling in the diameter range of 1–10 cm and some in the range of 30–70 cm (Garvin et al. 1984). The distribution of these two size groups is spatially continuous around the landing site (Garvin et al. 1984), suggesting the anisotropy may arise from weathering of local layered materials. Finer-sized materials are not apparent in those images; their absence may be a result of removal by wind, although the resolution of the images precludes detecting sand-sized particles. Even the sluggish 0.2–2 m s⁻¹ surface winds recorded by the landers are readily able to transport particles that are sand sized and smaller (Warner 1983; Lorenz 2016). More in-situ imaging of the Venus surface in multiple locations and at high resolution is needed to fully assess the detailed sizes and morphologies of sediment particles.

The bedrock imaged at the Venera 10, 13, and 14 sites consists of laminated or thinly bedded sheets a few centimetres thick, with varying degrees of coarse sediment or regolith in between the slabs (Garvin et al. 1984). The 5 cm-distance between notches on the lander rings of Venera 13 and 14 give an indication of scale of materials close to the landers. The Venera 14 images, which recorded the lowest sediment fraction of all the Venera landing sites, show that the bedrock consists of a series of interlocked, subangular to subrounded plates that are possibly jointed. Indeed, Florensky et al. (1983) described the Venera 14 layers as either sedimentary bedding or possibly basaltic volcanic tuffs formed by cycles of air fall or ground flow. Penetrometer measurements and landing stress–strain profiles from Venera 13 and 14 demonstrated that the surface has a low bearing strength and low density, properties that are consistent with porous materials such as ash or other sediments (Surkov et al. 1984; Basilevsky et al. 1985).

There is also evidence from Earth-based radar data that Venus may have widespread regolith cover, even in plains regions. Degree-of-linear polarization maps created with Arecibo Observatory radar data show some amount of surface penetration of the radar wave across much of the surface (Carter et al. 2011). In plains regions, the degree of linear polarization is ~7–10%—substantially lower than the values of 10–40% observed near impact craters and volcanoes, but still above the expected noise level of ~1–2% (Carter et al. 2004). At the relatively short wavelengths used by Arecibo (12.6 cm), these degree-of-linear polarization values suggest at least partial covering by low-density material such as fine regolith or a low-density upper crust on lithified sediments or volcanic rocks. The precise thickness of the surface covering is not easily determinable from current data sets, but must be at least a substantial fraction of the radar wavelengths to be detectable (i.e., at least a couple of centimetres in thickness). The origin of the surface regolith or coating is unknown, but it could be caused by rock weathering and/or transport of fine materials by winds.

Additional evidence for widespread sediments comes from quantitative analysis of Magellan radar backscatter. Modelling of Magellan altimeter radar backscatter profiles revealed a widespread anisotropy in the Doppler shifts of the echoes (Tyler et al. 1992). Mapping these Doppler shifts across the surface shows a latitude-dependent “striping”, a phenomenon most likely caused by sloping surfaces (Tyler et al. 1992) and interpreted as possible evidence for widespread, small aeolian bedforms (Bondarenko et al. 2006).

Impacts also produce deposits that correspond to the local environment and may provide evidence of relative sediment cover. For example, the meteoroid airburst splotches discussed in Section 2.1 have a non-uniform distribution on the surface, which has been interpreted as evidence for the presence of increased regolith in some regions relative to others (Bondarenko and Kreslavsky 2018). The emissivity parabolas, which do not have a strong radar backscatter parabola, are also strongly clustered, suggesting a possible difference in surface materials in these areas (Campbell et al. 1992). These parabolas are thought to have thinner

deposits than other SAR-visible parabolas (Campbell et al. 1992), but it is still not certain how these features form.

Finally, apparent aging of the surface also suggests that mantling deposits accumulate over time. Arvidson et al. (1992) noted a progression from fresh-looking to degraded lava flow morphology in Sedna Planitia. Younger flows, as determined from cross-cutting relationships, are brighter with clear lobate margins, whereas older flows have degraded or difficult-to-discern edges and darker centers (Arvidson et al. 1992). This progression appears similar to processes on other planets where lava flows are filled in and covered with sediment over time (Arvidson et al. 1992). Bondarenko et al. (2003) compared the radiophysical properties of lava flows with their stratigraphic position and found that locally older units usually had a lower permittivity, which is consistent with either the deposition of sedimentary material and/or weathering of the surface that produces a lower density material.

The current data suggest there is more substantial surface cover than what is observed in the Venera landing site panoramas, but equally those data make it difficult to determine the thickness and distribution of these materials. With a spatial resolution of 12–16 km/pixel, the Arecibo polarimetry radar data offer limited opportunity to map local changes in surface cover. Similarly, the low resolution of the Magellan emissivity data also makes it challenging to measure dielectric constants for small features. Observations of the surface with high-resolution (tens-of-metres) polarimetric radar and microwave emissivity at tens-of-kilometres spatial scales would help improve our identification and geological interpretation of present-day Venus surface cover.

4.2 Lithification

Weathering is an important process on Venus, but lithification may be equally important, rapid, and mask the sedimentary cycle in Magellan SAR data. Oxidation and the growth of sulphates and scapolites (a carbonate–sulphate mineral) likely rapidly cement loose material into a weakly lithified rock, akin to a marl (Berger et al. 2019; Filiberto et al. 2020). Sintering can also lead to lithification and is thought to be a very effective process on Venus due to the high temperatures and corresponding higher diffusion coefficients. Kreslavsky and Bondarenko (2017) estimate diffusion smoothing of particle shapes based on temperatures of 450 °C and diffusion coefficients of $\sim 10^{-7}$ cm/s, and found that 1 μm particles can be smoothed in ~ 2 days and 100 μm particles can be smoothed in $\sim 5 \times 10^5$ years. This process can readily lead to the rapid lithification of sand-sized particles.

Lithified rocks could appear similar to those observed in Venera lander images, and large deposits of loose materials by themselves may be uncommon. The simplest conclusion is that, although the surface materials are geochemically basaltic in composition, primary igneous rocks are weathered, transported, and deposited as wind-blown sand that rapidly lithifies into a sandstone. These rocks may then become jointed, perhaps by tectonic processes (e.g., unroofing), weathered, and disaggregated into gravels, with the fines removed by wind and deposited as the shale-like layered rocks seen in the plains. The sedimentary cycle may therefore have an important role in the exchange of materials, particularly volatiles, between the near-surface interior and atmosphere. More in-situ data as well as laboratory measurements are needed to understand the lithification process and timescales on Venus.

4.3 Evidence of Layered Deposits That Could Be Sedimentary

On the basis of their morphological appearance, the Venus uplands are far from pristine. In numerous places, highland tesserae show evidence for being composed of layers of some

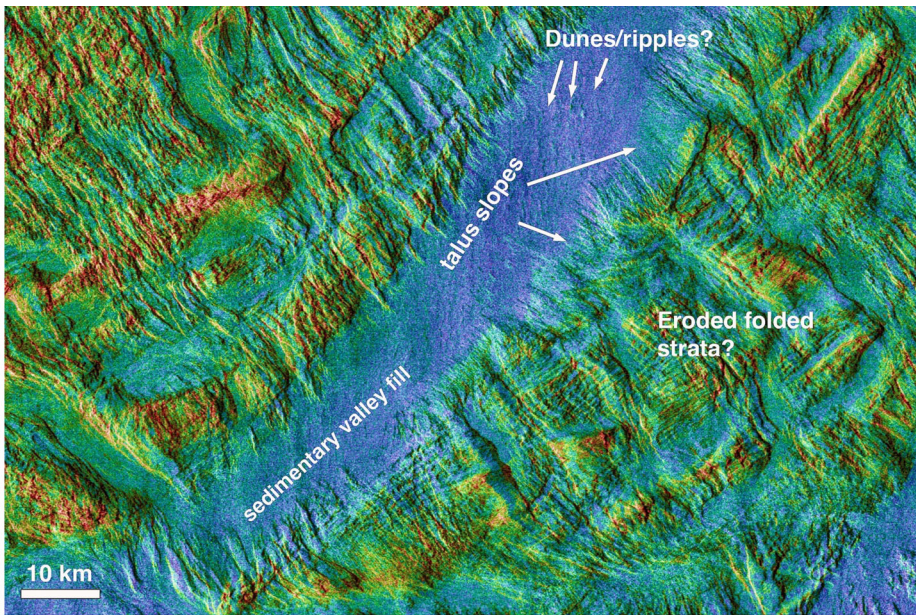


Fig. 8 Magellan left- and inverted right-look relief image, colour-coded with left- and right-look roughness, of tessera upland located at 1°S , 81°E . Blue corresponds to surfaces smoother than 2 cm (gravel or finer) and red to surfaces rougher than 8 cm (pebbles or coarser). Mass wasting (talus) material eroded from layered and possibly sedimentary rock layers lie on the steep slopes and fill the valley floor, possibly transported along the valley in dunes (north-south trending ridges indicated by arrows). The image is based on the magic airbrush technique of Kirk (1993), which combines normalised left- and inverted-right-look images to cancel out roughness variations and generate a shaded relief image. By also combining the normalised left and right look images, the opposite effect is achieved, primarily a roughness image (albeit with dielectric variations included). That image is colour-coded with a spectrum and the shaded relief image colourised with it to create a pseudo-full colour image that contains all the information of the left and right look pairs. This works perfectly on Earth, where the viewing geometries are almost identical and the topography is very well known, but not so well on Venus, where neither is true, so some warping of the right image is required to match it to the left (Ghail 1996)

material—presumably sediments, lithified volcanoclastics, lava flows, or some combination of the three (Byrne et al. 2021). Yet these layers are exposed along the flanks of locally high-standing terrain such as ridges and domes, and have outcrop patterns that seem to follow undulations in topography. By analogy with Earth, those units may have experienced considerable erosion (preceded by folding) to expose their tilted component layers. Given the current erosion rates, such a large amount of rock removal would likely need to have happened gradually over hundreds of millions of years or more, or occurred during an earlier epoch with higher erosion rates (Byrne et al. 2021). Slopes proximal to these exposed layers are characterized by likely mass wasting deposits (Fig. 8), which fill the valleys floors with material consistent with being sedimentary (e.g. smoother) and derived from those slopes. Those sediments, in turn, seem to be modified by the wind into linear features that may dunes. The nature of the layered strata, such as their age and composition, is still largely unknown and will be an important subject of research with upcoming missions.

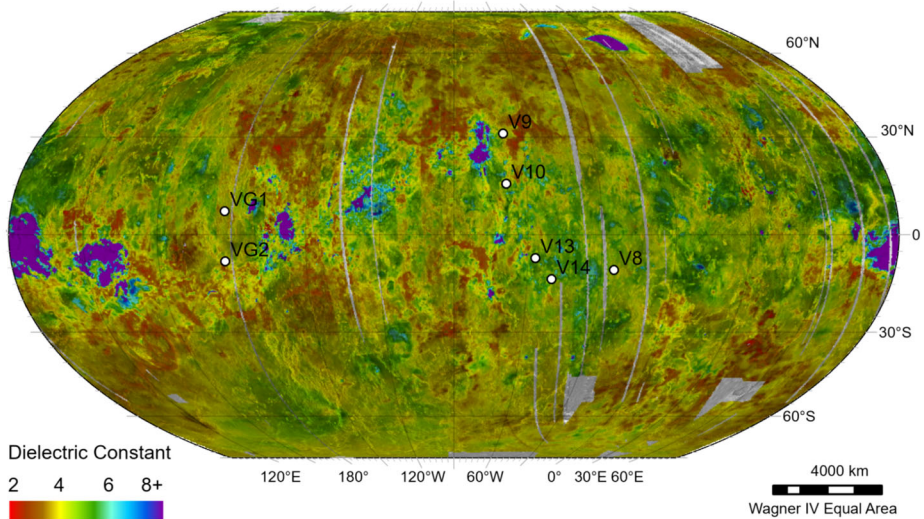


Fig. 9 Surface dielectric constant inferred from Magellan emissivity data, and using SAR backscatter as an approximation for roughness to correct for its effect on the dielectric constant. A dielectric constant of 2 to 3 is consistent with unconsolidated sediment or pyroclastic deposits; between 3 and 5 to lithified sedimentary rock or weathered volcanic rock; and > 5 to slightly weathered or fresh volcanic rock. Blue-to-violet regions have anomalously high dielectric constants as well as high radar reflectivity (see Gilmore et al. 2023, this collection). The approximate locations of the Soviet Venera and Vega landing sites are indicated with small circles

4.4 A Global View of Rock Densities

Evidence for a global sedimentary cycle is apparent in the Magellan emissivity data (Pet-tengill et al. 1992), when converted dielectric constant (Fig. 9) and used to infer densities (Ulaby et al. 1988). A few areas of loose, low-density sediment with low dielectric constant (2-3) are evident, but nearly half the planet has surface characteristics consistent with partially lithified sediments (yellow and green in Fig. 9), i.e., having dielectric constants < 5 and densities $< 2500 \text{ kg m}^{-3}$. Because the porosity and composition of the sediments and lithified rocks are not known, it is not possible to distinguish between sediments and rocks based solely on density. However, the denser surface materials are more likely to be lithified. Rocks with densities greater than 2500 kg m^{-3} (green-cyan in Fig. 9) are either fully lithified sediments, fresh volcanic rock, or welded pyroclastic flows. Although the 150 km-diameter landing circles of all the Venera and Vega landers include signatures from partially and fully lithified sediments and fresh rock, the regions in which the Venera 14 and Vega 2 sites are situated have the highest proportion of fully lithified and potentially fresh volcanic material—consistent with those landers' elemental analyses and panoramic images (Fig. 7).

Lithified sedimentary rock is consistent with the actual densities ($\sim 1500 \text{ kg m}^{-3}$) and porosities ($\sim 50\%$) inferred from mechanical data recorded by the Venera 13 and 14 probes (Florensky et al. 1983). Based on its measurements of sulphate content, Venera 14 sampled the least weathered material, in agreement with the morphological evidence of a smooth surface with little fine material (Garvin et al. 1984), but the modal mineralogy recorded by the lander nonetheless implies considerable loss of alkali feldspar, very possibly to scapolite. The likely more altered and relatively poorly bound grains imaged at the Venera 13 site may be easily transported by surface winds and therefore still mobile; it is not clear

whether these deposits were derived by erosion of the local bedrock, or were transported a long distance from elsewhere. The modal mineralogy, unconfined compressive strength, low porosity ($\sim 20\%$), and high density ($\sim 2600 \text{ kg m}^{-3}$) of the Vega 2 site implies a fully weathered and cemented clastic rock, but no images were acquired to confirm this inference (Marov and Grinspoon (1998) and references therein).

5 Summary and Future Measurements

5.1 Summary of Current Understanding of Sediments and Sedimentary Rocks

Our understanding of sediments and sedimentary deposits on Venus has advanced considerably since the Magellan mission, but there is still much to learn about the extent and formation of these deposits. The distribution of sediments is clearly non-uniform over the surface, with impact-related materials forming the bulk of these deposits and pointing to estimates of hundreds of thousands of cubic kilometres of impact-derived sediments on Venus overall. The parabolas and radar-dark haloes erode over time, indicating that wind transport and possibly lithification are happening at the surface today. Although there are only a few probable dune fields on Venus, the several hundred identified areas of wind streaks show that there is substantial transport of material. Pyroclastic deposits and mass wasting are also likely sources of sediment in regional to local areas, but it is impossible to estimate the contribution of these materials from our current data sets. The locations where these deposits are observed, however, may lead us to sites with recent volcanism and seismicity, assuming that sediments are dispersed by wind, buried, or otherwise altered over time.

Whereas the sources of sediment are rapidly becoming better understood, determining the timescales for their formation and the likely sediment sinks is much more challenging and will require additional study. Additional surface geochemical information is needed, coupled with surface optical and perhaps radar observations, to understand how new sedimentary rocks are being created on Venus today. Higher-resolution imagery, topography, and mesospheric wind data could help us determine how material is transported to form aeolian deposits.

Finally, our knowledge of sedimentary rocks on Venus is in the early stages but is already intriguing. Layering in the tesserae suggests that a complex history is available for us to decipher if we have higher-resolution radar data or surface optical imagery of this enigmatic terrain type. Tesserae are likely one of our best options for determining whether Venus was ever a habitable planet, so it is important that we understand how this terrain type formed and whether tesserae represent ancient sedimentary layers deposited in fluvial environments, or feature volcanic layering, or are the result of some yet-to-be recognized formational process.

5.2 Future Measurements of Sediments and Surface Sedimentary Rocks

Mantling deposits may have very different radar properties based on thickness, texture, and dielectric properties, and the radar backscatter is also subject to look angle and radar wavelength. To better understand the present sediment cycle on Venus it is critical to acquire a range of data products, including high-resolution orbital radar imagery (at scales of metres per pixel), radar polarimetry, and radiometry, as well as decent imagers, and imaging systems mounted on aerial platforms below the cloud deck. Differing radar look angles or wavelengths are important for identifying dune fields. In-situ ground-penetrating radar data

would also be extremely useful for assessing the depth of sediment layers. Long-term monitoring of areas such as cliff faces, volcanic centres, and aeolian fields at high resolution would also allow us to search for ongoing surface changes. Radar interferometry can also be used to detect surface changes; for example, repeat-pass interferometry can detect subtle aeolian movement through measurement of decorrelation signatures (Zebker et al. 1996). Laboratory measurements of chemical reactions using relevant compositions, temperatures, and densities are needed to determine how weathering and lithification progress on Venus at different altitudes and for different materials. And finally, more sensitive mineralogic measurements, high-resolution surface lander optical images able to differentiate transported grains, matrix and cement, and mechanical measurements of material properties to estimate density are needed in as many distinct locations as possible to fully understand the nature, properties, and origins of the surface rocks present today on Venus.

The planet Venus has had a unique climate evolution that may be recorded in surface sedimentary rocks from prior eras, such as in the tesserae. Mapping the sediments at the surface today can point us toward the story that tesserae hold, indicate active volcanoes and areas of possible seismic activity, and provide a planet-wide view of the rock cycle on a planet with a dense CO₂ atmosphere.

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Declarations

Competing Interests The authors have no competing interests to declare that are relevant to the content of this article.

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